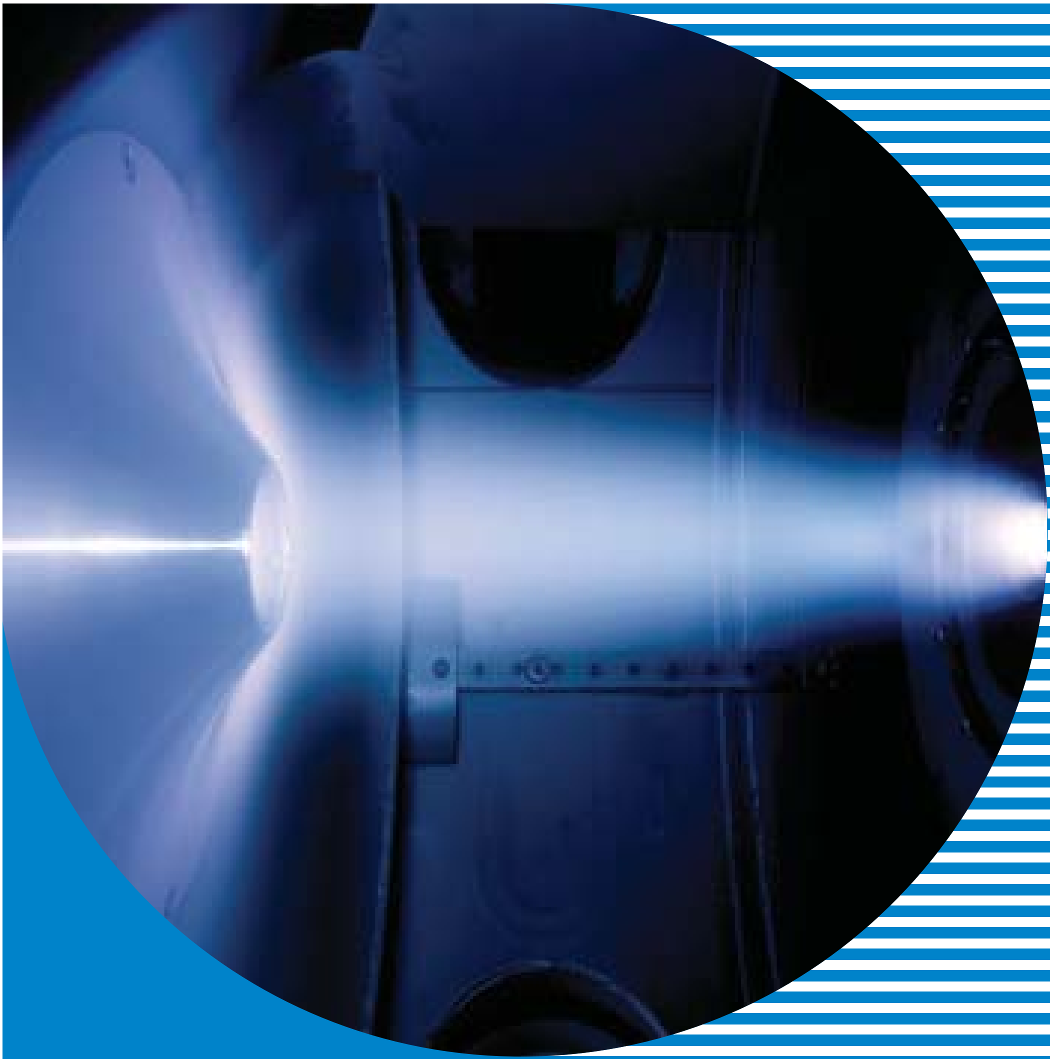
FOM-RIJNHUIZEN

Annual report 2010



FOM INSTITUTE FOR PLASMA PHYSICS

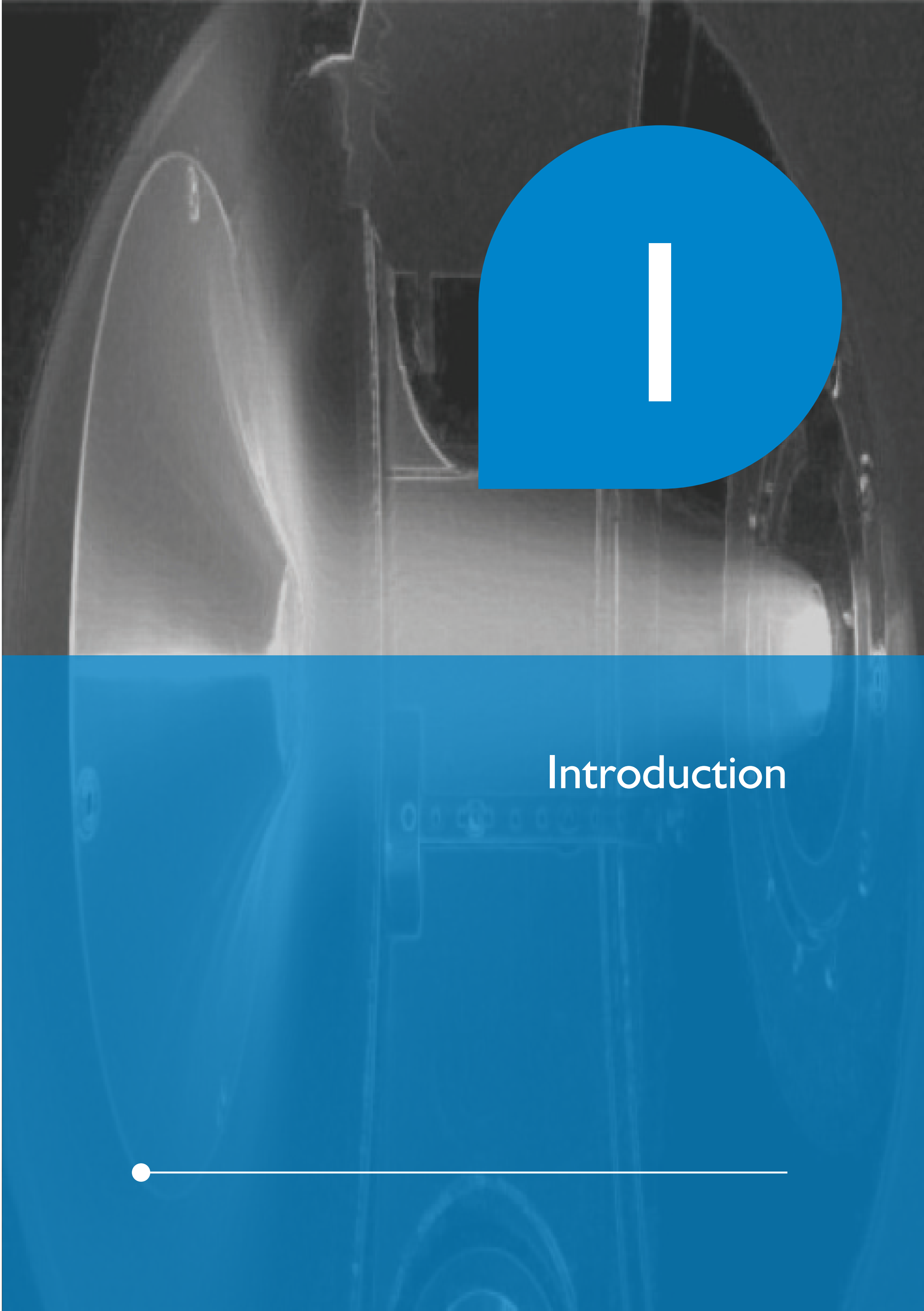
FOM-RIJNHUIZEN

Annual report 2010

FOM INSTITUTE FOR PLASMA PHYSICS

This document contains information of a preliminary or tentative nature, and must not be quoted in publications nor listed in abstract journals. The work described was performed as part of the research programme of the "Stichting voor Fundamenteel Onderzoek der Materie" (FOM) with financial support from the "Nederlandse Organisatie voor Wetenschappelijk Onderzoek" (NWO). The part of the work on nuclear fusion, indicated by European Fusion Programme (EFP), is supported by Euratom in the framework of the Association Agreement Euratom-FOM

Index



1

Introduction

1 Introduction

Rijnhuizen is one of the three research institutes of the Foundation for fundamental research on matter (FOM), the funding organization for physics in the Netherlands. The institute performs research on fusion physics, plasma surface interaction, generation and uilization of THz radiation, and nanolayer surface and interface physics.

In addition to its three institutes, FOM supports a large fraction of the physics research at Dutch universities. The primary goal of FOM is to promote fundamental research on matter for the advancement of science. The research funded by FOM is nationally coordinated in some 100 comprehensive research programmes, so-called 'FOM programmes'. Currently, Rijnhuizen hosts 4 of these FOM programmes that run at Rijnhuizen only, and participates in 1 nationwide FOM programme.

Structure of this report

The current chapter gives an overview of the research performed at the institute and outlines the organisational structure. Chapter 2 describes the activities of both research and support groups in 2010. FOM programme support and Euratom-FOM funding are always indicated at the start of each section. Chapter 3 gives information on outreach to academia, education, industry, and general public. Chapter 4 lists the scientific publications and the final chapter is an appendix with general information on the institute.

Mission

"We perform high-quality fundamental research and develop methods and techniques with that aim, in the fields of Fusion Physics, Plasma Surface Interaction, Generation and Utilization of THz Radiation and Nanolayer Surface and Interface Physics. In addition, we train graduate and undergraduate students and technicians, and transfer high-level scientific and technical knowledge to industry and society at large."

1.1 Overview of the research

Fusion Physics

The FOM-programme on the physics of the hot plasma inside a fusion reactor is performed in the Fusion Physics division. Over the years, Rijnhuizen has specialised in the study of the spontaneous formation and external control of mesoscale structures in the hot, magnetised plasma in a fusion reactor. These are structures with a size much larger than the smallest relevant size in the plasma (the electron cyclotron radius), while being much smaller than the system size. Interesting about these structures is that they arise from the turbulence in the plasma through a process of self-organisation. Despite their being small, they have a large influence on the plasma. In the new research programme FP-120, "Advanced control of magnetohydrodynamic modes in burning plasmas", the experimental and theoretical efforts are fully integrated.

Real-time, autonomous suppression and stabilization of tearing modes

The Tokamak Physics group constructed an experimental proof-of-principle of a feedback control approach for real-time, autonomous suppression and stabilization of tearing modes in a tokamak. The system combines an Electron Cyclotron Emission (ECE) diagnostic for sensing of the tearing modes in the same sight-line with a steerable Electron Cyclotron Resonance Heating and Current Drive (ECRH/ECCD) antenna. A methodology was developed for fast detection of 2/1 tearing modes and retrieval of their location, rotation frequency and phase. In real-time, these data are forwarded in closed loop to the steerable launcher and as a modulation pulse train to the gyrotron. Experimental results demonstrate the capability of the control system to track externally perturbed tearing modes in real-time. For more information on this highlight, see section 2.2.

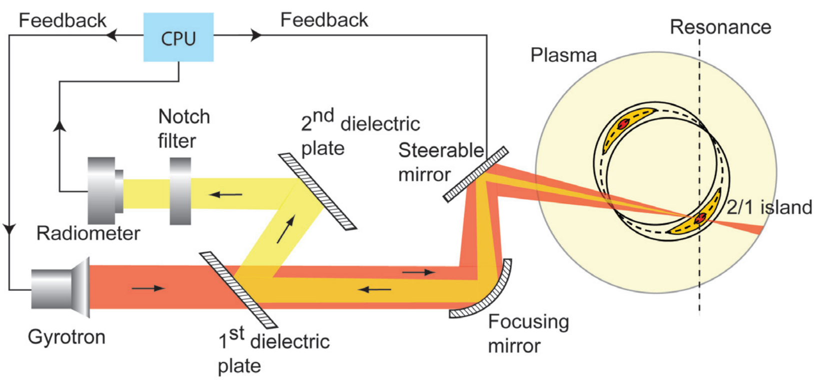


Figure 1.1: An experimental proof-of-principle of a feedback control system was produced for real-time, autonomous suppression and stabilization of tearing modes in a tokamak.

PSI – Plasma Surface Interaction

The research on the interaction of plasma with a material wall in the extreme conditions that occur in a fusion reactor is a relatively new field of research for Rijnhuizen. In a machine like ITER, the flux of plasma that reaches the wall, and the associated energy flux, are so high that the interaction reaches the so-called ‘strongly coupled’ regime. In this regime, the impact of the plasma modifies the surface to a depth of many monolayers, whereas conversely the plasma in the interaction zone is dominated by the particles that come off the surface. The interaction is governed by strongly non-linear processes. What the erosion and redeposition will be in such conditions is basically unknown, yet of prime importance for the fusion reactor. The PSI division performs studies on such interactions in the research programme “FP-75: PSI-lab, an integrated laboratory on plasma-surface interaction”.

Reaching this regime requires a very powerful plasma generator, a strong magnetic field to confine the particles, and a versatile target surrounded by diagnostic equipment. Such an experiment, Magnum-PSI, is almost operational at Rijnhuizen. The forerunner of Magnum-PSI is Pilot-PSI, in which plasma fluxes to surfaces exceeding those expected in ITER have already been achieved.

Pulsed plasma source for ELM simulations

After succesful testing of the first generation plasma source in 2009, 2010 saw succesful testing on Pilot-PSI of a pulsed plasma source capable of simulating the transient heat and particle fluxes of ELMs. The cascaded arc plasma source can be connected to a capacitor bank for pulsed operation with a variety of gases, as

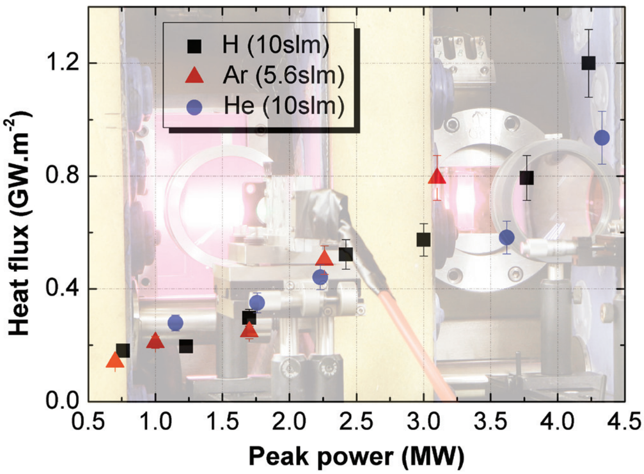


Figure 1.2: Pilot-PSI now features a pulsed plasma source capable of simulating the transient heat and particle fluxes of ELMs with a peak surface heat flux of up to 1 GW.m-2.

well as with gas mixtures. Peak surface heat fluxes of up to 1 GW.m^{-2} have been generated with a pulse duration of about 0.5 - 1 ms (up to 1MJ.m^{-2}). The shape and the duration of the pulse can be adapted to the needs of the researcher, and a pulsed bias system has been developed to vary the ion energy during the pulse. For further information on this highlight, see section 2.6.

nSI – Nanolayer Surface and Interface Physics

In the area of surfaces and thin films, Rijnhuizen is world leader in the production of highly reflective extreme ultraviolet (EUV) mirrors. This line of research aims to understand and develop the physics of multilayer mirrors including the fabrication of such optics with unprecedented high reflectivity for 13.5 nm radiation. These are used in the optical system of lithography machines for the semiconductor industry. The institute has three dedicated thin film deposition machines for this purpose. The work is done in close collaboration with Carl-Zeiss Oberkochen, and is part of the roadmap of ASML towards 13.5 nm lithography. The key issue in the research is the reflectivity and lifetime of the mirrors developed under the harsh operation conditions in lithography machines. The concerns here are the top layer, which can be contaminated from the gas phase, and interdiffusion of the multilayers by prolonged heating. Funding for this research is secured through running an Industrial Partnership Programme of FOM with substantial financial support of Carl-Zeiss Oberkochen. Some of the issues concerning lifetime of optics are investigated together with M2I (The Materials Innovation Institute) and ASML. The thematically related follow-up programme CP^3E of this successful work started in 2009 and includes a unique FOM laboratory at the premises of ASML Research.

EUV Photochemistry Laboratory at ASML

Wtihin the frame of the new CP^3E industrial partnership programme with Carl Zeiss and ASML, Rijnhuizen has been granted space at the research facilities at ASML in Veldhoven. At this location, a unique surface science set-up has been constructed, enabling EUV induced photo-chemistry experiments, exploiting state-of-the-art EUV light sources from ASML. The new UHV instrumentation allows RAIRS, Thermal Desorption Spectroscopy, and TOF Mass Spectroscopy. This Veldhoven-based laboratory is led by a FOM group leader carrying out PhD research projects with FOM PhD students, a scheme that is expected to further enhance valorization of the multilayer research of the nSI department.

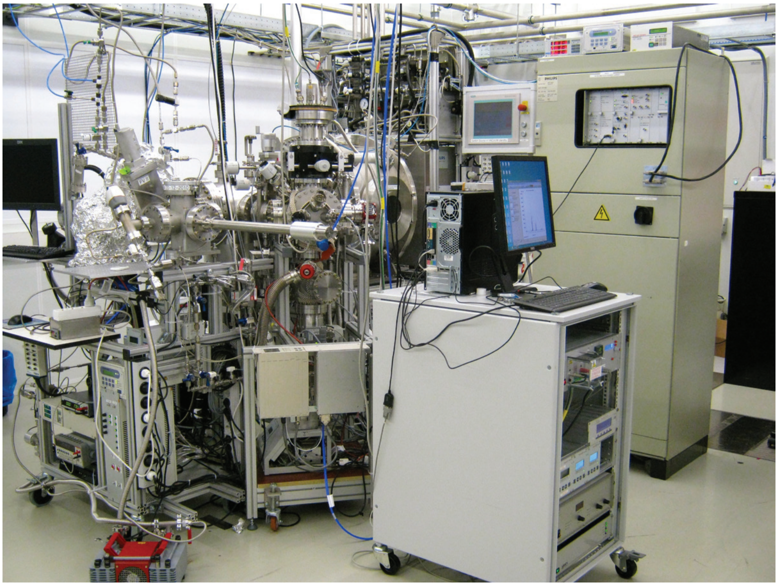


Figure 1.3: Cross-sectional representation of the unique Extreme UV photon - surface interaction chamber available at the newly established FOM research laboratory at ASML in Veldhoven.

GUTHz – Generation and Use of TeraHertz Radiation

Rijnhuizen has designed and constructed the Free Electron Laser for Infrared eXperiments, and runs the international user facility FELIX, attracting user groups from all over the world. Molecular physics studies with FELIX radiation are performed in the Molecular dynamics group. This in-house user group grew out of a collaboration with the University of Nijmegen, and is now using approximately 25% of the total FELIX beam time. The group studies the IR optical properties and dynamics of complex molecules, clusters and nanocrystals in the gas-phase in collaboration with the Action Spectroscopy chair at Amsterdam University.

Over the years, sophisticated diagnostics and control systems have been set up, enabling the users to fully control the relevant characteristics of the FEL radiation for their particular application (laser frequency, bandwidth, power, temporal pulse structure). Auxiliary laser systems, synchronised to FELIX, have been installed to provide multicolour capabilities. EPSRC supports the operation of the laser for British users, and the EU has granted FELIX the status of a European facility. Various external users are willing to make substantial investments to be able to perform experiments at the FELIX facility, evidenced, for instance, by the National Science Foundation (NSF, USA) supported installation of an FT-ICR (Fourier Transform – Ion Cyclotron Resonance) mass spectrometer at our institute.

FELICE creates hologram of an atom with its own electrons

The major extension of FELIX with the FELICE beam line for intra-cavity experiments is now operational at full specifications and covers a wavelength range between 3 – 100 μm, delivering an increase in intensity to the experiment of at least a factor of 50 as compared to FELIX. It is routinely operating interleaved with the two conventional FELIX beam lines, effectively doubling the available beam time for users. The first experimental campaigns on FELICE already indicate that a broad user community can benefit from this new installation. This is convincingly demonstrated by the results of an experimental campaign of the Vrakking group from AMOLF recently accepted for publication in Science. In these experiments it has been observed for the first time that a hologram of an atom is produced using its own electrons. It is concluded that this hologram contains important information that can potentially be exploited to characterize processes on very short timescales and thereby might give insights in important chemical processes. These results are described in more detail in Chapter 2.12.

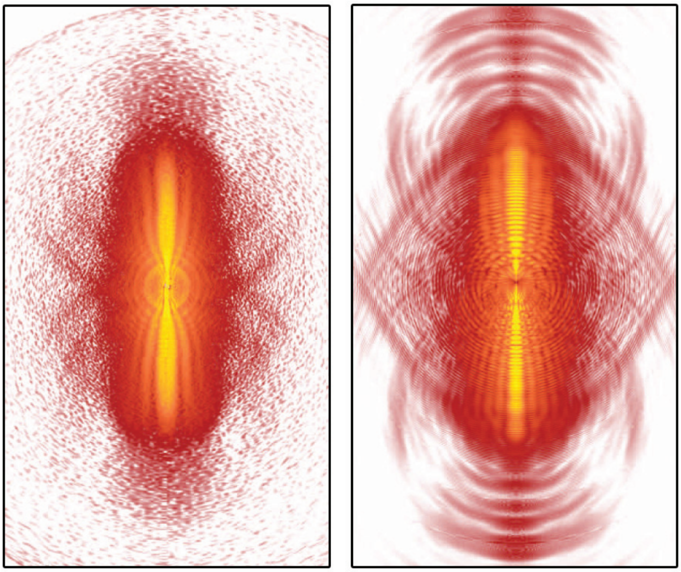


Figure 1.4: In FELICE, it has been observed for the first time, by the Vrakking group at AMOLF, that a hologram of an atom can be produced using its own electrons.

1.2 Institute for fundamental energy research

Energy is one of the central themes in the strategic plans of both FOM and NWO. Its current research direction of Physics for Energy makes Rijnhuizen ideally suited to become a nationally coordinating Dutch Institute for Fundamental Energy Research (Differ), located at the campus of a Dutch university.

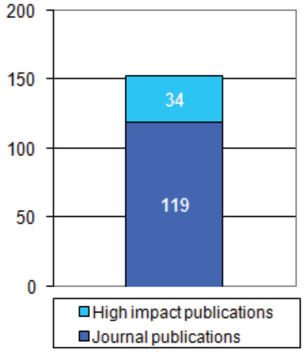
Early 2010, FOM issued a call to Dutch universities, asking them to present the case for a relocation of Rijnhuizen to their campus and an indication of possible synergies between their researchers and the new FOM institute. The FOM Executive Board, after reviewing the proposals received, expressed its preference for the campus of Eindhoven University of Technology (TU/e). After further talks between FOM and the TU/e, the FOM Governing Board decided on the Eindhoven university campus as an excellent environment for Differ. The proces of detailing requirements for a new institute building has started and the new FOM institute for fundamental energy research is expected to be able to move into the new facility in 2015. Under the motto of Science for Energy, Differ will perform fundamental research of a multi-disciplinary nature into sustainable energy.

The GUTHz division and its free electron infrared laser user facility FELIX / FELICE are the only parts of Rijnhuizen that will not relocate to Eindhoven. The user facility and its attending staff will instead move to the Radboud University in Nijmegen, there to become part of the complex for free electron lasers (FELs) housing the three FELs FLARE, FELIX and FELICE. Expansion of the building housing FLARE is already under way and FELIX / FELICE are planned to go in operation in Nijmegen in 2013.

1.3 Highlights for 2010

Science

In 2010, Rijnhuizen exceeded the scientific output of 2009 in the total amount of publications. The output of the institute is given in table 1.5. Of these publications, 22% were published in high profile journals.



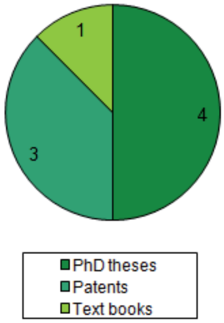


Figure 1.5: Overview of journal publications (left) and other scientific output (right) over 2010.

Awards

This year, the FOM Valorisation Prize was awarded to Fred Bijkerk for his work on multilayer optics for short wavelength light, such as Extreme Ultraviolet (EUV) light. The prize, worth 250 thousand Euro, was awarded together with the other scientific FOM prizes during the annual Physics@FOM conference on 18 January 2011. The prize is intended as an inspiring example for other researchers to stimulate valorisation of physics research.

1.4 Organisational Structure

The institute, with around 160 employees, has one director. In 2010, then director Aart Kleyn accepted a position as director of the Van 't Hoff Institute for Molecular Sciences. He was succeeded for the remainder of 2010 by interim director Tony Donné. In 2010, Richard van de Sanden accepted the position of director of Rijnhuizen, starting January 2011. He will guide the institute to its new role as nationally coordinating institute for fundamental energy research.

Rijnhuizen currently has four scientific divisions: the Fusion Physics division headed by Tony Donné, the Plasma Surface Interactions division lead by Jürgen Rapp, the nanolayer Surface and Interface Physics division managed by Fred Bijkerk, and the Generation and Utilization of THz Radiation division lead by Lex van der Meer. The support groups are embedded in the Support Facilities division managed by Wim Koppers. Within these divisions the research groups are headed by senior scientists, responsible for the output and the near future of the group. Apart from the scientific divisions there is a department for technical and facility support, and some staff reporting directly to the director.

The overall management of the Institute is carried out by a management team consisting of all (deputy-) division leaders, and headed by the director.

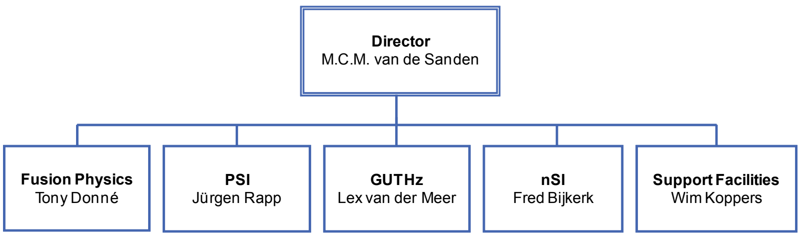


Figure 1.6: Organisational chart from Januari 2011. The chart lists the four scientific divisions and the support facilities division. A breakdown of divisions in groups is given in chapter 2.

Funding

The mission budget Rijnhuizen supports most of the infrastructure and permanent staff needed to carry out the Institute's mission. Support groups are funded by both directly charging the project concerned, and by support from the mission budget. The core of all scientific groups is funded by FOM programmes (see Chapter 2) and the Mission Budget Rijnhuizen. The former support the temporary scientific staff and all costs related to the direct execution of the scientific programme. In addition, considerable funding, approximately 50% in 2010, is obtained externally. Figure 1.7 lists the various contributing partners.

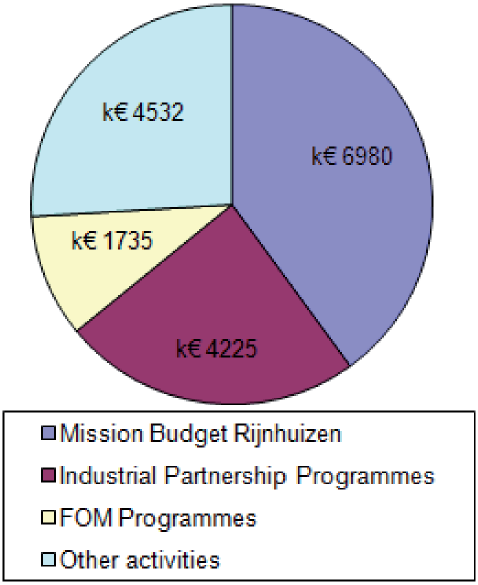


Figure 1.7: Funding for the activities at Rijnhuizen in 2010. The institute succeeds in attracting considerable funding – around 50% – from external sources. EURATOM funding (a total of k€ 1.338) makes up part of the mission budget, FOM programmes and other activities.

2

Activities at Rijnhuizen in 2010

2 Activities at Rijnhuizen in 2010

FOM Programmes

The work described is supported through the following three FOM programmes (FP), with their duration given in the brackets:

- FP-58: The IR user facility FELIX, expanded with FELICE (2003-2012)
- FP-75: PSI-lab, an integrated laboratory on plasma-surface interaction (2004-2015)
- FP-120: CBP – Active control of magneto-hydrodynamic modes in burning plasmas (2010-2014)

Rijnhuizen participates in the following open FOM Programme:

- FP-10: Physics for technology (1997-2011)

Two industrial partnerschip programmes support the work done in the nSI division:

- I10: XMO – Extreme UV multilayer optics (2005-2013)
- I23: CP3E – Controlling photon and plasma induced processes at EUV optical surfaces

Active control of magneto-hydrodynamic modes in burning plasmas

FOM-programme 120, led by Tony Donné, focuses on high temperature plasmas and investigates ' Active control of magneto-hydrodynamic modes in burning plasma'. A new phenomenon in burning plasmas (e.g. ITER) is that the alpha particles, a minority carrying a large fraction of the plasma kinetic energy, can collectively drive or suppress magneto-hydrodynamic (MHD) modes. In some cases these MHD modes can both have desirable effects on, as well as be detrimental to the plasma. Active control of these modes is therefore required to balance their desired and detrimental effects. An additional complication in a burning plasma arises from the fact that the external heating power is small compared to the internal heating power of the alpha particles and therefore external heating is of limited use for active control, in contrast to current tokamak operation. The relevance of the programme lies in the fact that active control of MHD modes will help to enhance the performance of a fusion reactor and to improve its operation, in the first place ITER.

PSI-lab, an integrated laboratory on plasma-surface interaction

The FOM-programme 75: ‘PSI-lab, an integrated laboratory on plasma-surface interaction’, under the joint management of Aart Kleyn and Niek Lopes Cardozo (replaced by Jürgen Rapp), focuses on the interaction of extreme plasma and/or photon fluxes with material surfaces, and brings together research on XUV optics for lithography and that on plasma-surface interaction in conditions relevant to fusion reactors. An important aim of the investigation is to access the strongly coupled regime, in which the particles that come of the surface are kept in the system and define the plasma-surface interaction. The main application of this research is the plasma-surface interaction in fusion experiments and in future fusion power plants.

The IR user facility FELIX, expanded with FELICE

The operation of the IR user facility FELIX, which offers the international science community access to a very bright, tuneable mid- and far-IR source, is one of the objectives of FOM programme (58) ‘The IR user facility FELIX, expanded with FELICE’ led by Lex van der Meer. Every year, more than 25 groups from all over the world, working in various research fields, come to Rijnhuizen to perform experiments that make use of the unique properties of FELIX. The other objective of the programme is the expansion of the FELIX facility with FELICE, a new beam line for intra-cavity experiments. For this beam line, which provides much higher intensities at the two dedicated experimental setups, additional investment money was obtained under the ‘NWO-groot’ funding scheme.

Extreme UV multilayer optics

The FOM Industrial Partnership programme 110, named ‘Extreme UV multilayer optics (XMO)’ and headed by Fred Bijkerk, focuses on the physics of multilayer structures for the demanding application of short-wavelength photolithography. Key is the physics and associated process technology of compounded periodic multilayer structures, which have atomically sharp, flat interfaces, are chemically stable and dimension controlled down to the sub-nanometer range. The goal is to closely approach the theoretical reflectivity values for the EUV wavelengths.

Controlling photon and plasma induced processes at EUV optical surfaces

The new Industrial Partnership Programme 123, ‘Controlling photon and plasma induced processes at EUV optical surfaces’ or shortly ‘CP3E’, was granted late 2009. CP3E builds on XMO, though the focus changed to the numerous photochemical and plasma physics phenomena which occur once multilayer optics are exposed to EUV radiation and plasma beams at high intensity. CP3E is carried out with Carl Zeiss SMT and ASML, and includes a FOM-operated EUV laboratory at ASML.

Physics for Energy and other surface and thin film programmes

The nSI department carries out a pilot project within the theme 'Physics for Energy', namely a study on the photon-driven conversion of water into hydrogen as a clean, solar-generated fuel. Other research topics in nSI are aimed to wavelengths beyond the Extreme UV, as in the case of the European FLASH XUV research, or to wavelengths in the UV. These areas contain related physics and chemistry, but are outside the scope of the IPP XMO and CP3E programmes.

Fusion Research

Rijnhuizen is the centre for physics research in the frame of the European Fusion Programme in the Netherlands. As part of the international effort to develop controlled fusion as a clean, safe and sustainable source of energy, with ITER experiment as focal point, his research is carried out under the Euratom-FOM association agreement, with financial support from NWO and Euratom. The Rijnhuizen fusion research programme is performed in close cooperation with the Trilateral Euregio Cluster (TEC) at the TEXTOR tokamak in Jülich, Germany, together with the partners Forschungszentrum Jülich (FZJ) and the Laboratory for Plasma Physics at the KMS/ER M in Brussels.

2010 – a dynamic year

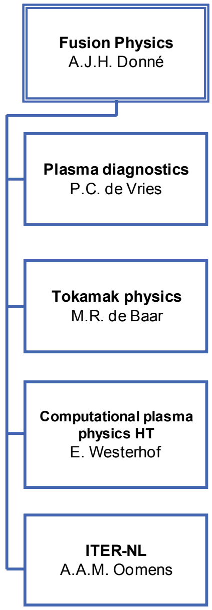
Until the end of 2009 the Fusion Physics Division had two main lines of research: 1) the study and control of mesoscale structures in hot, magnetized plasmas, and 2) studies in the field of Plasma Surface Interaction (PSI). Because of the large size of the department and the increase of the PSI activities, it was decided to split the division into two.

The division is directly involved in work on the design of ITER components. Most of the effort is devoted to studying the physics underlying the active control of magnetohydrodynamic (MHD) instabilities in burning plasmas. Until the end of 2008 the experimental work of the division was performed in the framework of the Trilateral Euregio Cluster (TEC) at the TEXTOR tokamak in Jülich, Germany, together with the partners Forschungszentrum Jülich (FZJ) and the Laboratory for Plasma Physics at the KMS/ERM in Brussels. Since 2009 the experimental focus of the division has shifted to the ASDEX-UG tokamak in Garching (Germany) and the Joint European Torus (UK). These two devices have been rated the two most relevant tokamak devices.

Work in the division is presently largely concentrated around the FOM Programme 120: *Advanced Control of Magnetohydrodynamic Modes in Burning Plasmas*, which started on 1 January 2010 and will run for five consecutive years. Within the FOM Programme there is an intensive collaboration with the 'Science and Technology of Fusion' and 'Control Systems Technology' groups at Eindhoven University of Technology (TU/e) and with the Centre Mathematics and Informatics (CWI) in Amsterdam. The work is also closely connected to the Dutch-Russian Centre of Excellence on Fusion Physics and Technology which is directed by Tony Donné.

Research groups

The Fusion Physics Division consisted in 2010 of four groups and one project:



- In the Plasma Diagnostics group, headed by Peter de Vries, state-of-the-art diagnostics are developed and applied to study fusion experiments. The emphasis of the group is largely focused on diagnostics to observe electron cyclotron emission from the plasma and on Thomson scattering systems. The group is also involved in Charge Exchange Recombination Spectroscopy (CXRS) and in preparations for the ITER CXRS system and the ITER LIDAR Thomson scattering system.
- The Tokamak Physics group, headed by Marco de Baar, is exploiting its expertise by developing advanced control tools and algorithms for stabilizing MHD modes in contemporary plasma devices. Additionally the group is involved in the system engineering of the microwave plasma heating systems for the ITER Upper Port Launcher. This is a system for MHD control of the ITER plasma by means of Electron Cyclotron Resonance Heating (ECRH).
- The Computational Plasma Physics – High Temperature group, headed by Egbert Westerhof, uses mathematical and numerical modelling to obtain a deeper understanding of hot fusion plasmas. Until the end of 2010 this also included research on astrophysical plasmas.
- The Public Information group, headed by Gieljan de Vries, is responsible for public information activities, with a focus on nuclear fusion as an energy source of the future. The group promotes public knowledge about the work done at Rijnhuizen through a diverse set of activities, such as brochures, websites, open days and lab tours, press releases, and public lectures. The group actively promotes fusion energy in outreach activities such as the Fusion Road Show, a mobile show demonstrating plasma experiments, and more general presentations for students, politicians, the general public and energy specialists. Since 2011 the Public Information group has become a staff group directly under the director.
- Additional to the groups there is the ITER-NL project which is headed by Noud Oomens, who is also acting as ITER-NL Programme Director.

The reports of the substantial activities of the four groups and the ITER-NL project can be found in Chapter 2.

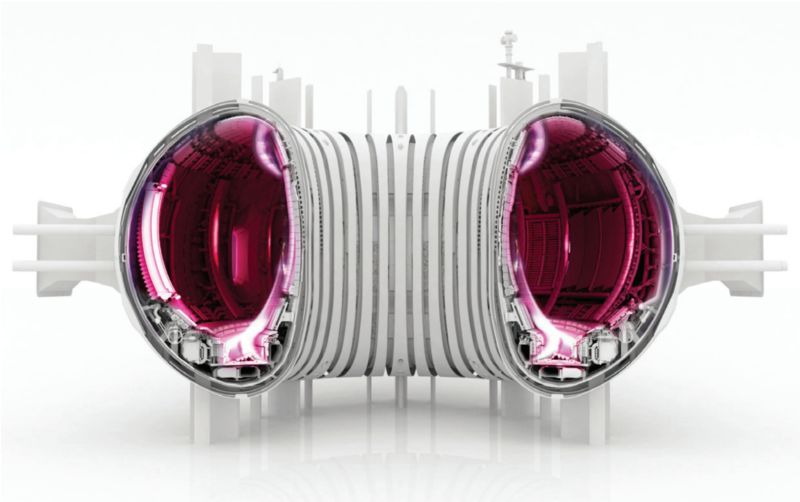


Figure 2.1: Blend of 3D imagery and photography showing the vessel of the Joint European Torus (JET) equipped with the ITER-Like Wall and containing a plasma. JET is one of the two foci of the experimental work of the fusion physics department.

Appointments

- Tony Donné has been appointed chairman of the LIDAR consortium, and additionally he has been appointed as part-time professor at the Eindhoven University of Technology: Diagnostics and Heating of Fusion Plasmas. By the end of year he has joined the Board of Editors of the prestigious journal Nuclear Fusion.
- Marco de Baar has been appointed part-time professor at Eindhoven University of Technology: Plasma fusion operation and control.
- Peter de Vries is Deputy Leader of the JET E2 Task Force and co-chair of the EFDA Transport Topical Group.
- Noud Oomens has been appointed as Programme Director of the ITER-NL Consortium.

ITER-NL

In 2007, FOM formed a strategic alliance with TNO and NRG, with the aim to optimize the scientific and industrial participation of the Netherlands in ITER. To this end, the consortium ITER-NL was established. In this consortium, the partners each bring in their core competences: fusion science and network by FOM, industrial network and technology transfer, project management and specific technologies by TNO, and nuclear know-how and material expertise by NRG. The Dutch government made 15 Million Euro available for the programme of this consortium, for the period 2007-2009. In August 2009 it was announced by the Minister of Economic Affairs Mrs. Maria van der Hoeven that two of the proposals that have been submitted to the Fund Economic Structure Strengthening were to be immediately granted. One of them was the proposal for continuation of ITER-NL. This proposal was awarded an amount of 8 million Euro for the period 2010 – 2014. In 2010 TU/e joined as fourth partner in the ITER-NL consortium.

This ITER-NL programme encompasses three work packages. Work package 1 and 2 concern the R&D for the ITER CXRS and LIDAR diagnostics, and for the ITER ECRH systems, respectively. The work in these packages is, at Rijnhuizen, largely carried out in the Plasma Diagnostics and the Tokamak Physics groups. The aim of work package 3 is to stimulate Dutch industry to become involved in the ITER project. This work package is not funded by Euratom. Those R&D activities that need to be carried out for ITER but are rather technological in FOM terms, are carried out outside the FOM-programmes, by teams within ITER-NL in which FOM groups are strongly represented. It is important to note that the scientific activities of ITER-NL are done in close collaboration with consortia of various European institutes.

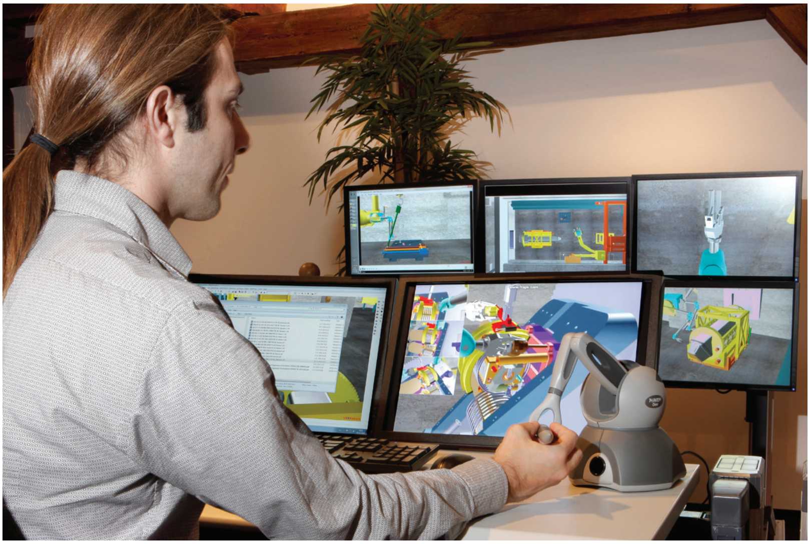


Figure 2.2: In 2010, operation of the Remote Handling Study Centre started. This project is part of the work for ITER-NL, and aims to validate Remote Handling compatibility for ITER components.

JET, ASDEX-U and other devices

In 2010, FOM-staff participated in JET data analysis (due to the shutdown of JET in 2010 there were no experimental campaigns). As this work is thematically fully embedded in the FOM-programmes, reports on the activities that involve JET are integrated in the text. The work of long-term secondees to the JET operator or the EFDA Close Support Units is not separately reported here.

Researchers from the Fusion Physics division are involved in a number of other devices, including ASDEX-U and TEXTOR in Germany, DIII-D in the United States, T-10 in Russia, HL-2A in China and KSTAR in South-Korea. Long-term secondees stationed at ASDEX-U operate the ECE Imaging diagnostic. In 2011 the Thomson scattering diagnostic will be moved from TEXTOR to ASDEX-U.

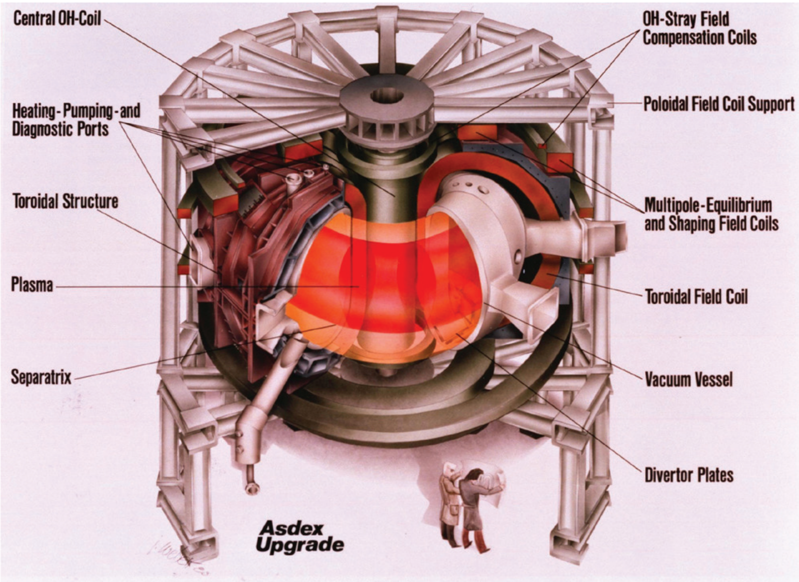


Figure 2.3: Schematic drawing of the ASDEX-U tokamak – one of the two devices on which the work of the fusion physics division is concentrated.

2.1 Plasma Diagnostics Group

Division:	*Fusion Physics*
Group leader:	*P.C. de Vries*
Senior scientists:	*I.G.J. Classen, M.G. von Hellermann, M. Kantor (Ioffe)*
Postdocs:	*O.Lischtschenko, M. Tsalas, T. Gerbaud*
Graduate students:	*J.E. Boom, T. Versloot, A. Kappatou, E. Delabie*
Undergraduate students:	*S.A.M. Oosterveer, R. Millar, V. Burgmeister, F. Bernachy*
Research Engineers:	*J. Koning*
Guests:	*J. Howard (ANU-Canberra)*
Collaborators:	*R.J.E. Jaspers (TU/e, Eindhoven), W.Biel, O. Marchuck, O. Neubauer (FZJ, Jülich), W. Suttrop, E. Wolfrum, H. Zohm (IPP-Garching), N.C. Hawkes, C. Giroud, G. Naylor, R. Scannel, M. Townsend (CCFE, Culham), C.W. Domier, N.C. Luhmann Jr., B. Tobias (UC-Davis), H.K. Park, G.S. Yun (Postech, Pohang), B. Snijders (TNO, Delft), E. Mukhin (Ioffe, St. Petersburg), S. Tugarinov (Triniti, Troitsk)*
Funding:*	*FP-120, EURATOM EFDA), TU/e, US-DOE, NWO, ITER-NL*

Introduction

The Plasma Diagnostics Group develops high resolution multi-channel diagnostics in order to measure small-scale structures in hot magnetized plasmas. The exploitation of the physics revealed by these diagnostics is an integral part of the research effort of the group. Furthermore, the aim is to expand and use the available expertise to develop ITER diagnostics.

The diagnostic group focuses on the development and utilization of three main diagnostic systems:

- Thomson scattering diagnostics such as the high resolution system that has been developed to study the electron temperature and density profiles in hot plasmas. This system adopts a novel concept in which the plasma is part of the laser cavity. The diagnostic reaches unprecedented spatial resolution and in addition fast dynamics in the plasma can be diagnosed with it, a feature mostly lacking for other Thomson systems. The group furthermore participates in the development of a Thomson scattering system for ITER.
- Electron cyclotron emission diagnostics and in particular a 2-dimensional imaging variant (2D-ECEI) to measure temperature structures and fluctuations in the plasma core. This system has been originally developed in collaboration with groups from UC-Davis, Princeton, US. By using innovations in microwave array technology and an optical setup to couple the emission from the plasma on the array, now a radial/vertical area is imaged,

with a resolution of about a 1 cm in all directions.

- Active Beam Spectroscopy using charge exchange recombination spectroscopy (CXRS) is foreseen for ITER to be the prime diagnostic for ion temperature, plasma rotation and ion concentrations. In collaboration with the TU/e within the ITER-NL consortium, and in collaboration with other European fusion institutes, the Plasma Diagnostics Group will contribute to the development of a CXRS system for ITER.

Results

2010 marked the start of the new FOM Programme 120, the study of physics of burning plasmas, as well as a transition from mostly TEXTOR-oriented work towards experiments on ASDEX-U and JET. The main FOM diagnostics have been, or are in the process of being, transferred to the first experiment, while the group will participate directly in the operation of JET diagnostics. The continuing activity for the development of the ITER CXRS system has culminated in the manufacturing of an ITER prototype spectrometer while new activities towards the development of an ITER LIDAR Thomson Scattering system are planned.

Thomson scattering

The high-resolution Thomson Scattering system developed at the TEXTOR tokamak was finalized in 2009 and is now able to attain unprecedented specifications with total laser energies of up to 3 kJ in about 50 pulses in a 10 ms interval. This, in combination with the high sub-cm spatial resolution allows the observation of small scale structures and their dynamics in hot tokamak plasmas, with an experimentally confirmed accuracy per pulse of typically 2% and 1% in electron temperature and density, respectively.

The system contributes to the unraveling of the physics of several phenomena. For example the system could follow both the temperature as well as the density evolution in the rotating magnetic islands. Figure 2.4 shows an example of the simultaneous measurement of temperature and density profile perturbations due to rotating magnetic islands. An offset between perturbations of both profiles near the X-point of the island was revealed, suggesting that these parameters were not constant on flux-surfaces at this specific location.

The physics results based on the multi-pass intra-cavity Thomson scattering system have proven the high potential of this approach in Thomson scattering diagnostics on most fusion plasma devices in the world. A further possibility is to utilize this diagnostic for studies of the so-called edge transport barriers seen for example at ASDEX-U. A transfer of the system from TEXTOR towards the ASDEX-U experiment is now in preparation.

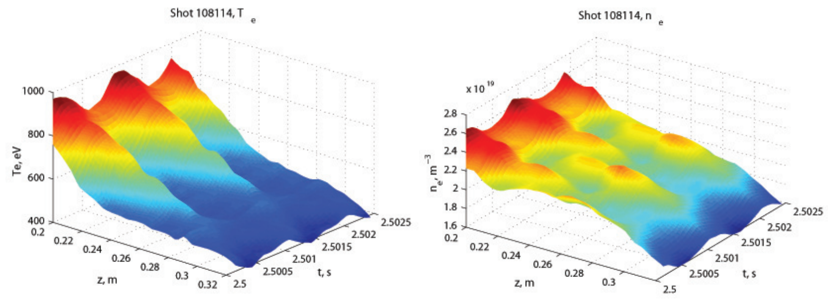


Figure 2.4: Contour plot of simultaneous temperature (T_e) and density (n_e) profiles over rotating magnetic islands in TEXTOR, simultaneously measured by the FOM Thomson Scattering diagnostic. The structure shows up differently, indicating that near these magnetic perturbations, these two parameters are not flux-functions.

2D Electron Cyclotron Emission Imaging

The group operates Electron Cyclotron Emission (ECE) diagnostics at both the ASDEX-U and JET tokamak experiments. The flagship of the group's diagnostics has been the 2-dimensional Electron Cyclotron Emission Imaging (ECEI) system. In 2009 it was transferred from TEXTOR to ASDEX-U, upgraded, and is now in routine operation, providing unique insights into the temperature evolution of magnetic perturbations in the plasma core as well as in the plasma edge. The system combines the advantages of a wideband radiometer and 'classical' ECE systems to provide a true 2D image of T_e fluctuations with a total of 128 channels, arranged in a matrix of 8 (horizontal) $\times$ 16 (vertical) sample volumes.

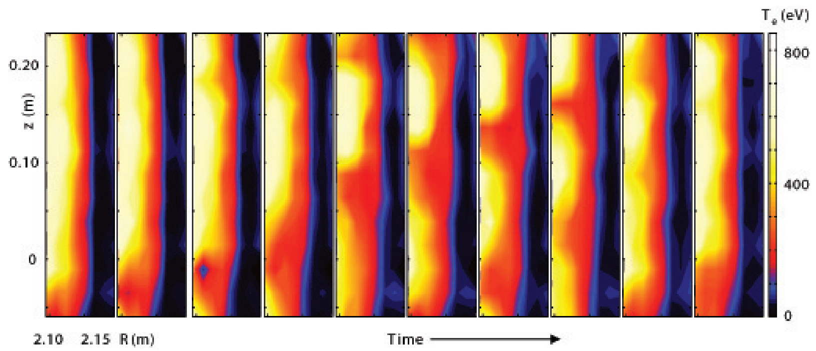


Figure 2.5: Time sequence (from left to right) of a 2-D temperature profile measurements near the edge of an ASDEX-U plasma. A clear mode structure develops, after which the edge temperature collapses.

Studies on core Alfvén eigenmodes continued but the focus of the investigations in 2010 shifted towards to the study of Edge Localized Modes (ELMs).

The diagnostic revealed in great detail the development of such an instability that formed in the presence of an edge transport barrier, as illustrated in Figure 2.5. The perturbation of the edge can be clearly visualized enabling the determination of mode characteristics.

Active beam spectroscopy

A large effort in the Plasma Diagnostics Group has been devoted to active beam spectroscopy. From 2010 on this work is done in close collaboration with the new team at the TU/e. The major goal here is to develop a Charge Exchange Recombination Spectroscopy (CXRS) system for ITER. The focus has been to address the scientific issues of the design, including the scientific feasibility. The group furthermore exploits CXRS systems on JET and TEXTOR to build up the expertise to run such a system on ITER.

Essential to the feasibility and performance of the ITER CXRS system is the availability of a high resolution, high etendue spectrometer. Since the specifications of such a device are about an order of magnitude higher than those spectrometers presently in use on fusion devices, a new type has been developed (see Figure 2.6) and is now being tested. An extensive study into beam emission spectroscopy finally resolved previous discrepancies between experimental data from JET and TEXTOR and code calculations. Furthermore, physics studies at JET and utilizing the observation of passive CX emission, quantified the profile of colder penetrating neutrals and their impact on plasma rotation.

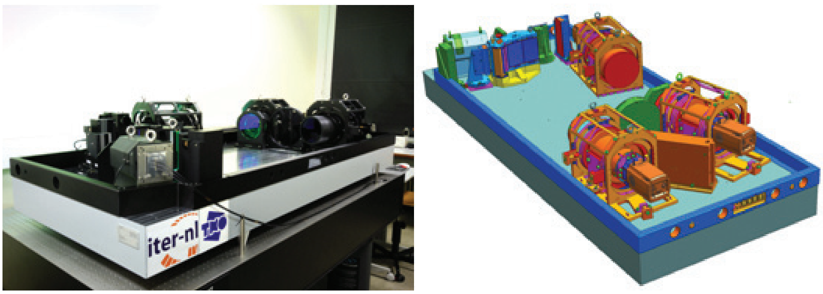


Figure 2.6: Prototype spectrometer for the ITER CXRS system (a). This incorporates three wavelength bands simultaneously, with an etendue of the order of 1 mm^2 sr each, spectral resolution of 0.2 nm and a dispersion of 0.25 nm/m (b).

2.2 Tokamak Physics

Division:	*Fusion Physics*
Group leader:	*M.R. de Baar*
Scientists:	*A.P.H. Goede, W.A. Bongers*
Engineers:	*B.S.Q. Elzendoorn, D.M.S. Ronden*
Graduate students:	*B. Hennen, G. Witvoet, G. Hommen, M. Lauret*
Collaborators:	*J. Gafert, D. Strauss (Karlsruhe Institute of Technology),A. Moro, G. Ramponi (CNR, Milan), R. Chavan, T. Goodman (CRPP, Lausanne), S. Bremond, G. Giruzzi, R. Magne (CEA, Cadarache), H. Zohm, E. Poli, J. Stober (IPP, Garching), S.B. Korsholm, S.K. Nielsen, F. Meo (DTU, Risø), M. Steinbuch, P. Nuij, N. Lopes Cardozo, L. Kamp. G.J. van Heijst (TU/e, Eindhoven), P. Verhoeff, N. Doelman, B. Snijders (TNO, Delft), V. Erckmann (IPP, Greifswald), W. Kasparek (IFP, Stuttgart), M. Henderson, A. Tesini (ITER-IO, Cadarache), K. Takahashi (JAEA, Naka), G. Denisov (IAP, Nizhny Novgorod)*
Funding:*	*FP-120, EURATOM, EFDA, NWO, ITER-NL, TU/e*
	** supported by the European Fusion Programme (EFP)*

Introduction

The mission of the Tokamak Physics group is to develop an integrated understanding of the physics of the burning ITER core, including that of fast particle effects and magnetohydrodynamic (MHD) modes, and to develop control schemes for the confinement and MHD stability of the burning plasma core. The group has extensive expertise using localized Electron Cyclotron Resonance Heating (ECRH) and Current Drive (ECCD) for control of magnetic instabilities in nuclear fusion plasmas. The team is involved in heating and MagnetoHydroDynamic (MHD) studies. In 2010, an EFDA Goal Oriented Training position was opened on the real time reconstruction of the plasma boundary in tokamaks using optical information. The group is also involved in R&D tasks associated with the design and maintainability of the Upper and Equatorial Port ECRH launchers for ITER.

Results

The 2010 experimental programme focused on the preparation of the control hardware required for the extension of the MHD control experiments on ASDEX-U. The mechanical control of the ASDEX-U ECRH system has been improved. A Mach-Zehnder interferometer has been constructed which, in conjunction with a high-power diplexer, will be used for measurements of the electron temperature in the line-of-sight of ECRH, using Electron Cyclotron Emission. Real-time cavity control of the diplexer was developed. As the diplexer is foreseen for a number of ITER operational modes, all requiring real-time control, this development is highly ITER-relevant. In addition to the line-of-sight measurements, this also allows for fast switching and power combining (two ITER requirements). A prototype direct digitizing radiometer was tested on TEXTOR.

Visible wavelength plasma boundary diagnostic

A new plasma boundary diagnostic was developed using visible wavelength images. Exploiting the plasma's edge localized and toroidally symmetric emission profile, a new coordinate transform was presented to reconstruct the plasma boundary from a wide-angle visible camera image. The plasma boundary reconstruction is implemented in MATLAB and applied to camera images of Mega-Ampere Spherical Tokamak (MAST) discharges. The optically reconstructed plasma boundaries are compared to magnetic reconstructions from the offline reconstruction code EFIT, showing very good qualitative and quantitative agreement. Average errors are within 2 cm and correlation is high. In the current software implementation, plasma boundary reconstruction from a single image takes 3 ms. The applicability and system requirements of the new optical boundary reconstruction, called OFIT, for use in both feedback control of plasma position and shape and in offline reconstruction tools have been investigated. A mathematical mapping has been derived to infer the plasma boundary from 2D optical images. The mapping has been assessed systematically for a large number of discharges of MAST.

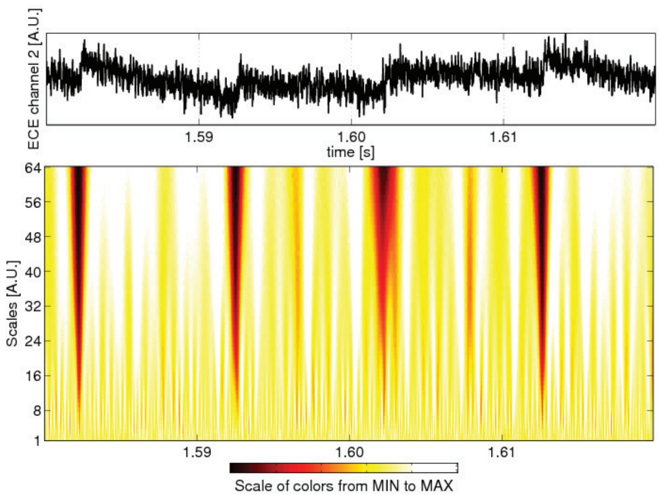


Figure 2.7: A mapping has been derived to reconstruct the plasma boundary in real-time. The possible applications of this mapping vary from experimental physics studies to real-time control of the plasma boundary position and shape, and protection of the vessel.

Determination of sawtooth period using beta-spline wavelets

Sawtooth oscillations affect the refuelling of the plasma core, can excite secondary instabilities such as neo-classical tearing modes (NTMs), and influence the fast particle concentration and its dynamics. The conflicting requirements of these processes motivate the necessity of sawtooth controllers. Experiments have been conducted to show that the sawtooth period can be affected, but dedicated, structured controller designs are lacking. A methodology was developed for structured design of feedback controllers for the sawtooth period, based on dedicated identification of the sawtooth dynamics. A combined Kadomtsev-Porcelli model of a sawtoothing plasma actuated by an Electron Cyclotron Current Drive (ECCD) system has been setup. This is used to derive the linearized input-output relations (transfer functions) from the varying deposition location of the EC waves to the sawtooth period. These transfer functions are derived around a large collection of operating points. Assessment of these control-relevant transfer functions shows that a sawtooth period controller requires an integral action to guarantee closed-loop stability with zero steady-state error. Additional proportional-integral action can be applied to further increase the closed-loop performance. The parameters of both the integral and proportional-integral controllers have been optimized in terms of stability, performance and robustness. Moreover, the effect of the mechanical ECH launcher on the closed loop performance is studied for realistic cases. It is shown that the launcher dynamics seriously affects the achievable closed loop performance in present-day experiments.

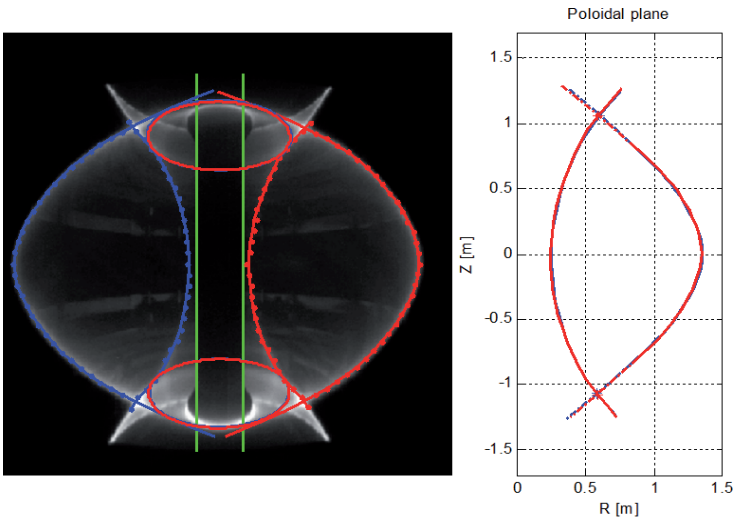


Figure 2.8: Beta-spline wavelet for edge detection. The theory of beta-spline wavelets has been extended for real-time edge detection. The result is a method to find sharp changes in real-time time-dependent data. Here the system is used for the detection of the sawtooth instability, an instability in the core of a tokamak plasma that periodically modulates the core parameters in crash-like events.

Real-time, autonomous suppression and stabilization of tearing modes

At high beta operation, the sawtooth oscillation is likely to trigger NTMs. An experimental proof-of-principle of a feedback control approach for real-time, autonomous suppression and stabilization of tearing modes in a tokamak was constructed. The system combines an Electron Cyclotron Emission (ECE) diagnostic for sensing of the tearing modes in the same sight-line with a steerable Electron Cyclotron Resonance Heating and Current Drive (ECRH/ECCD) antenna. The group developed a methodology for fast detection of q = m/n = 2/1 tearing modes and retrieval of their location, rotation frequency and phase. Set-points to establish alignment of the ECRH/ECCD deposition location with the centre of the tearing mode are generated in real-time and forwarded in closed loop to the steerable launcher and as a modulation pulse train to the gyrotron. Experimental results demonstrate the capability of the control system to track externally perturbed tearing modes in real-time.

Engineering effort

The ITER Hot Cell will be operated from two control rooms with in total 12 work cells. Each work cell will be manned by four operators. In the loft of the Rijnhuizen castle, a single work cell has been set up and connected to a virtual ITER Hot Cell. The work cell is used for systematic remote handling studies, and to assess the complex, multi-operator remote handling maintenance procedures required for ITER In 2010, the maintainability of two ECRH systems has been studied.

Figure 2.9: ITER foresees 12 remote maintenance work cells, each of which is manned by four operators. In Rijnhuizen one work cell is set-up, and connected to a virtual Hot Cell (a computer model of the maintenance area). In this centre, the complex, multi-operator maintenance procedures can be developed and assessed.

2.3 Computational Plasma Physics - High Temperature

Division:	*Fusion Physics*
Group Leader:	*E. Westerhof*
Senior scientists:	*H.J. de Blank, G.M.D. Hogeweij*
Postdocs:	*N. Bertelli, J.W.S. Blokland*
Graduate students:	*B. Ayten, J. Citrin, D. De Lazzari, B. van Es, J.W. Haverkort, W. Weymiens*
Secondary school teacher on research internship:	*A. Westra*
Collaborators:	*B. Koren (CWI, Amsterdam), E. Poli (IPP, Garching), S. Pinches (CCFE, Culham), S.B. Korsholm, S.K. Nielsen, F. Meo (DTU, Risø), M.D. Tokman, A.A. Balakin, A.G. Shalashov (IAP, Nizhny Novgorod), E. Gusakov (Ioffe, St. Petersburg), N. Kirneva, V.D. Pustovitov, K.S. Razumova (Kurchatov, Moscow), G. Huysmans (ITER IO, Cadarache), C. Bourdelle (CEA, Cadarache)*
Funding:*	*FP-120, EURATOM, NWO, EFDA*
	** supported by the European Fusion Programme (EFP)*

Research programme

The research programme of the group is derived from its mission, which is to develop the theory of burning plasma in the core of a fusion reactor, including the effects of fast particles, MHD stability, and the heating and current drive applied for its start-up and control; to develop the tools for the integrated modelling of the burning plasma core and its control, and to collaborate with the Computational Plasma Physics - LT (CPP-LT) Group on the grand challenge of integrated tokamak modelling; to provide theoretical and modelling support to the Tokamak Physics and Plasma Diagnostics Groups in the Fusion Physics Department.

In particular, the group aims to develop state of the art integrated modelling tools required to describe the MHD behaviour of burning plasma as controlled by localized electron cyclotron resonance heating (ECRH) and current drive (ECCD). This work is performed in collaboration with the EFDA Task Force on Integrated Tokamak Modelling. Within the Institute the group collaborates closely with the CPP-LT group.

The work of the group is embedded in FOM program 120 (2010-2014), "Advanced control of magnetohydrodynamic modes in burning plasmas" executed jointly with the TPG, and PDG. It is also part of the NWO-RFBR Centre of Excellence for Fusion Physics and Technology (2009-2013) through which the collaborations with our Russian colleagues from IAP, Ioffe, and Kurchatov are coordinated.

Results

Electron cyclotron wave physics

The efficiency of the suppression of NTMs by ECCD depends largely on the precise localization and width of the absorbed power density and driven current density profile. Since this is one of the main applications of the ITER ECRH system, an accurate prediction of the EC driven current density profile is essential for the evaluation and improvement of the ITER ECRH system design. A quasi-optical EC beam tracing code in combination with an adjoint calculation of the EC driven current has been used to obtain accurate predictions of the ECCD profiles in different ITER scenarios. The broadening of the driven current density profile by radial transport has been quantified. In addition, a study has been initiated to analyse the effects of edge density fluctuations on the wave beam propagation. Preliminary results show that the passage of the electron cyclotron wave beam through the turbulent edge region can potentially result in fragmentation of the entire EC wave beam (see Figure 2.10).

Figure 2.10: The picture shows iso-surfaces of the amplitude of an electron cyclotron wave beam in ITER obtained from quasi-optical calculations. As a consequence of a large amplitude perturbation of the phase front, the beam is seen to be fragmented.

Tearing mode control

The nonlinear dynamics of tearing modes as described by the generalized Rutherford equation (GRE) is studied with particular attention to the terms describing the effects from localized heating and current drive inside the magnetic islands. A detailed analysis of the effects of various asymmetries in the island shape has shown that these have only minor effects on the different terms in the GRE. In addition, the term from localized heating in the GRE has been benchmarked on the 2/1 tearing mode suppression experiments as performed on TEXTOR.

In case of suppression by ECCD, the requirement for full suppression of an NTM is commonly expressed in terms of the ratio of the maximum of the EC driven current density over the local bootstrap current density: $\eta_{NTM} \equiv j_{ECCD} / j_{bs}$. A systematic study has been performed of the required η_{NTM} depending on various parameters like the saturated island size, the width of the ECCD power deposition or driven current density profile. The results are being used to calculate the minimum required power for full NTM suppression in ITER.

Energetic particle interaction with sheared Alfvén waves

A theoretical model for the interaction between fast particles and sheared Alfvén waves has been developed which includes the flow in a consistent way. The model is implemented in the new code suite FINESSE-PHOENIX-HAGIS, and has been applied to the well known Toroidal Alfvén Eigenmode (TAE) in the presence of flow. The application has been done for both a tokamak with a circular cross-section and JET-like equilibria. The study has revealed that the growth rate of the TAE mode has a complex dependency upon the flow. Besides the precise flow description also the pitch distribution of the fast particles plays an important role in determining the stability of the TAE mode in the presence of flow.

Low frequency MHD spectrum in Rotating Tokamak Plasmas

The effects of toroidal flow on the MHD stability and wave spectrum have been studied. In the presence of toroidal flow, the ideal MHD equations leave the freedom to specify which thermodynamic quantity is constant on magnetic surfaces, e.g. the density, temperature, or entropy. Introducing a general parameterisation of this choice, analytical expressions have been derived for the low-frequency continuous Alfvén spectrum, including the Geodesic Acoustic Mode (GAM), and zonal flow frequencies. Due to the centrifugal convective effect, these continuum modes acquire a finite 'Brunt-Väisälä frequency' or become unstable, depending on which thermodynamic quantity is constant on the magnetic surfaces.

A stability criterion has been derived for localized interchange modes. Numerical calculations of the linearized MHD equations show that besides these interchanges, also other types of modes cluster below the Alfvén continuum. An infinite sequence of nonsingular non-axisymmetric zonal-flow like modes has been found. Above a critical Mach number, new global flow-induced Alfvén modes have been found to arise below both the GAM and the zonal flow frequencies (see Figure 2.11).

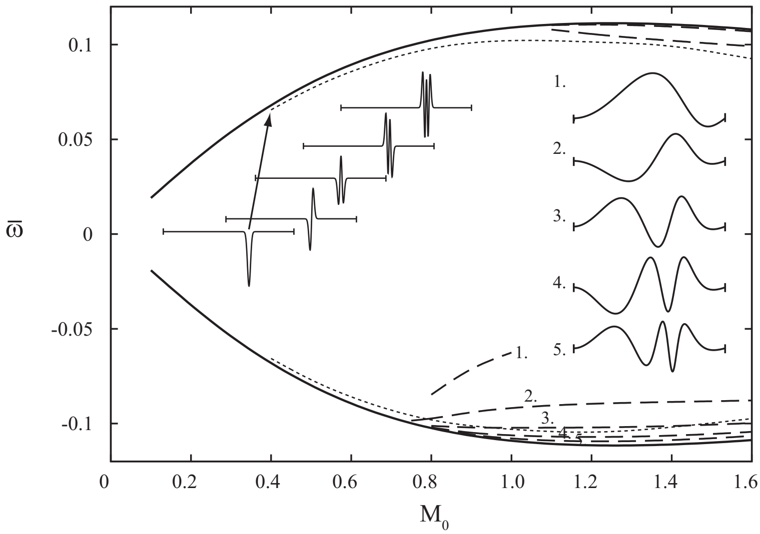


Figure 2.11: Frequencies plotted against the Mach number of toroidal plasma rotation for toroidal flow-induced gap modes (solid line), the first zonal flow-like mode (dotted) and several global modes (dashed). Radial mode structures of the first five zonal flow-like modes and of the first five global modes are displayed for Mach number equal to 1.

Transport code modelling

Modelling of the ITER hybrid scenario has shown a strong dependence of fusion power on the choice of external current drive application (see Figure 2.12). Simulations point to the importance of upgrading the ECCD system to higher powers. This work was supported by dedicated studies of the current ramp-up phase in ITER. The results are now validated against ASDEX-U and JET discharges.

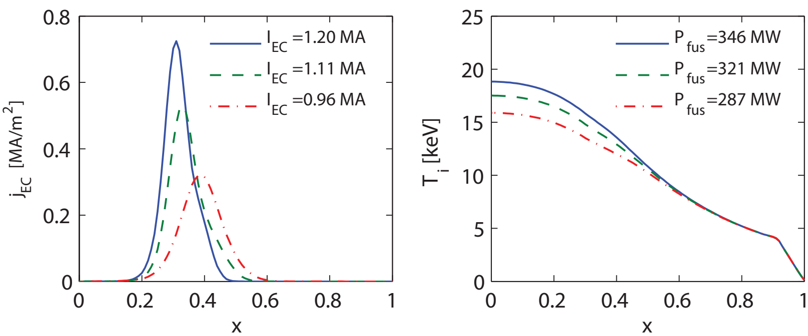


Figure 2.12: Effect of 37 MW electron cyclotron current drive on plasma performance. The left panel shows the driven current density, the right panel the resulting Ti profile.

The effect of plasma rotation on energy confinement was studied by comparison of JET discharges with different types of external heating, and by comparison of discharges with internal transport barriers in JET and JT-60U.

The L-H transition

Tokamak plasmas reach a high (H) confinement mode when, for sufficient heating power, a transport barrier emerges near the last closed magnetic surface. This transition exhibits hysteresis: the back-transition to low (L) confinement happens at lower heating power than the power required for transition from L- to H-mode.

The mechanism of this L-H transition is poorly understood: The limited range of quantitative experimental tests cannot discriminate between the many proposed models. Instead we have compared the highly nonlinear dynamics of different models by means of bifurcation analysis. Effects that are detrimental to H-mode have been distinguished as either removing the bifurcation or raising the H-mode power threshold. The L-H bifurcation is seen to vanish via two distinct paths: either the bifurcation and hysteresis shrink gradually and vanish, or the two stable bifurcated states turn unstable, leading to an oscillating state (see Figure 2.13).

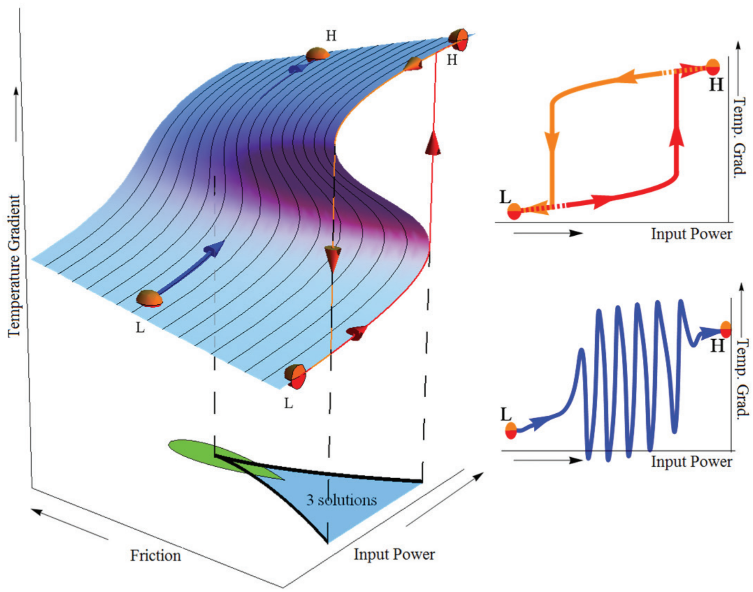


Figure 2.13: The simulated time evolution during the transition of a fusion plasma from the low (L) to high (H) energy confinement mode during gradually increased heating power. Depending on e.g. friction in the rotating plasma's edge, the transition can either be in a sudden jump (red: L to H, orange: H to L) or via oscillatory behaviour (blue).

2.4 ITER-NL

Project leader:	*A.A.M. Oomens*
Industrial Liaison Officer:	*A.G.A. Verhoeven*
Senior Scientist:	*A.P.H. Goede*
Collaborators:	*R. Pohlmann, B. Snijders, P. Verhoeff (TNO, Delft), R.J.E. Jaspers (TU/e, Eindhoven), S. de Groot, L. Magielsen (NRG, Petten), P. van Otterloo (Dutch Scientific, Almelo)*
Funding:*	*Fonds Economische Structuurversterking*
	** supported by the European Fusion Programme (EFP)*

Introduction

In August 2006, an amount of 15 million Euro was granted for the period 2007 - 2009 from the Dutch Fund for Economic Structure Strengthening (FES) to the programme 'A frontline Dutch contribution to ITER'. The main goals are to create a good entry position for Dutch scientists into the ITER scientific exploitation via delivery of advanced scientific equipment, and to put Dutch industry in a good position to successfully tender on ITER components in the procurement phase. The programme is executed by the ITER-NL consortium in which FOM, NRG (Nuclear Research and consultancy Group), TNO (Organisation for Applied Scientific Research), and Eindhoven University of Technology (TU/e) collaborate.

ITER-NL is focused on a substantial Dutch participation in three scientific components: the Upper Port ECRH Launcher (UPL), the Upper Port CXRS Viewer (UPV) and the Equatorial Port LIDAR Thomson scattering system. The development of these components is done in the framework of European consortia that have been established around the UPL (main players: FZK, CRPP and ITER-NL, the agreement has been signed in the summer of 2010) and LIDAR (main players: CCFE and ITER-NL). The agreement of the UPV Consortium (main players: FZJ and FOM) still needs to be signed. Apart from design and R&D work on the above three instruments, the ITER-NL consortium helps Dutch industry in preparing for ITER, to maximise the chances of successful tendering in the procurement phase.

In the course of 2009 ITER-NL has been granted an additional 8 million Euro from FES for continuation of especially the more scientific oriented topics in the period 2010 – 2013 in the project called `ITER-NL2, Innovation for and by ITER'.

Organisation

ITER-NL is led by the Executive Board with one member of each organisation (FOM, NRG, TNO and TU/e). The FOM-Rijnhuizen Executive Board member until 1-2-2010 was Tony Donné; then his role was taken over by Noud

Oomens, who became programme director of ITER-NL in July. The Executive Board reports to the ITER-NL Council with two members from each organisation (in 2010 Hendrik van Vuren and Tony Donné representing FOM). The ITER-NL Council has an independent industrial member.

Work Packages

The work within the ITER-NL2 project is organised in three work packages:

- WP1: Upper Port Viewer (and LIDAR) led by Bart Snijders (TNO)
- WP2: Upper Port Launcher led by Marco de Baar (FOM)
- WP3: Industrial Participation led by Renée Pohlmann (TNO)

The first two work packages are focused largely on the first goal of ITER-NL: creating a good scientific entry point for Dutch physicist into ITER. The involvement of FOM-Rijnhuizen in the work on the Upper Port Viewer has been transferred to the TU/e, following Roger Jaspers as principal scientist in this work package. The work on the Upper Port Launcher is led by Marco de Baar and is fully done in the Tokamak Physics Group.

Rijnhuizen has a relatively small effort within the Industrial Participation work package. This work package aims at preparing Dutch industry for successfully tendering in ITER procurement packages. Toon Verhoeven is part of the leadership of this work package, and he is also appointed as ITER Industrial Liaison Officer.

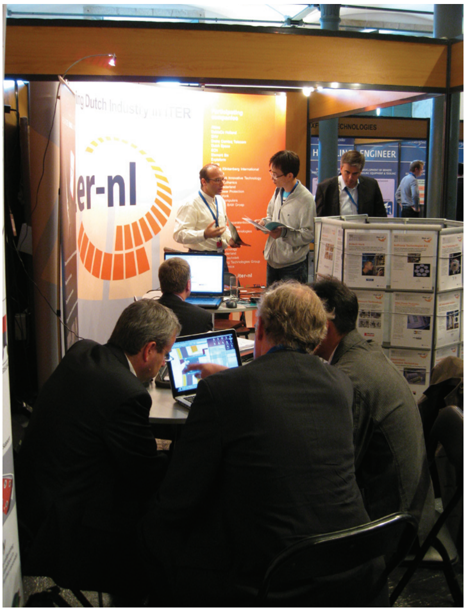


Figure 2.14: An important event in 2010 within all three work packages was the SOFT conference in Porto. The scientific work was reported in an invited oral and numerous poster contributions and many Dutch companies participated in the ITER-NL stand at the industrial exhibition.

Progress report

In the first months of 2010 much effort of the Executive Board went into redrafting the programme of ITER-NL2. In the original proposal the requested budget was 35 M€, of which only 8 M€ were granted. On June 28th the new proposal and budget were officially approved by the funding agency.

In July 2010 full agreement was reached with the board of the Eindhoven University of Technology (TU/e) on the participation of the TU/e as a fourth partner in the ITER-NL consortium. The tasks and the budget have been redistributed and a new consortium agreement has been drafted. These modified documents are awaiting official approval by the funding agency. In the meantime the activities in the three work packages continued.

The highlight in WP1 was the delivery of a prototype CXRS spectrometer. The first tests with the spectrometer prototype have been performed at the TEXTOR tokamak. Whereas the performance of the spectrometer is optimized for ITER conditions, additional improvements are required to use it for dedicated investigations at present devices like JET or ASDEX-U. A small tender has been submitted to Fusion for Energy for risk mitigation and cost estimations in the field of LIDAR Thomson scattering.

Figure 2.15: Prototype CXRS spectrometer developed in the ITER-NL's WP1. The first tests with the spectrometer prototype have been performed at the TEXTOR tokamak. The system is optimized for ITER conditions.

The highlights in WP2 are:

- The successful testing of the high power diplexer "FADIS" at IPP, Greifswald. The diplexer is part of the ECRH system which has to heat the plasma and has to stabilise instabilities.
- The performance of the in-line ECE system installed at ASDEX Upgrade.
- The Control room for virtual remote handling has been completed. Two small ITER contracts have been obtained in the field of Remote Handling.

The main events in WP3 were:

- A meeting with Chris Ibbott and Dutch companies organised by ITER-NL to discuss the establishment of a Fusion Industry Innovation Forum on March 22nd;
- A workshop 'Qualification of Nuclear Components', held the 16th of April in Petten and attended by 40 participants from 18 companies;
- An ITER-NL seminar on remote handling systems, held May 20th at Rijnhuizen with representatives from ITER-IO, F4E, ITER-NL, and a large number of Dutch companies. As a result a consortium of Dutch companies in the field of Remote Handling is being formed.

The results obtained in WP1 and WP2 have been reported during the 23rd SOFT conference in an oral contribution and about 16 posters and, within the framework of WP3, Dutch industry was represented at the industrial exhibition.

Plasma Surface Interaction

The research in the Plasma Surface Interaction division is mainly related to the power and particle exhaust in future fusion reactors. In general the system "plasma–material" is relevant in many areas of science, but in magnetic fusion devices it is characterized by a particularly strong exchange of matter, high dimensionality of compressible flows and extremely unsteady burst-like behaviour. Both controlling individual processes and the characterization of the entire system still provide huge challenges in fusion research, and this is likely to remain so in the future.

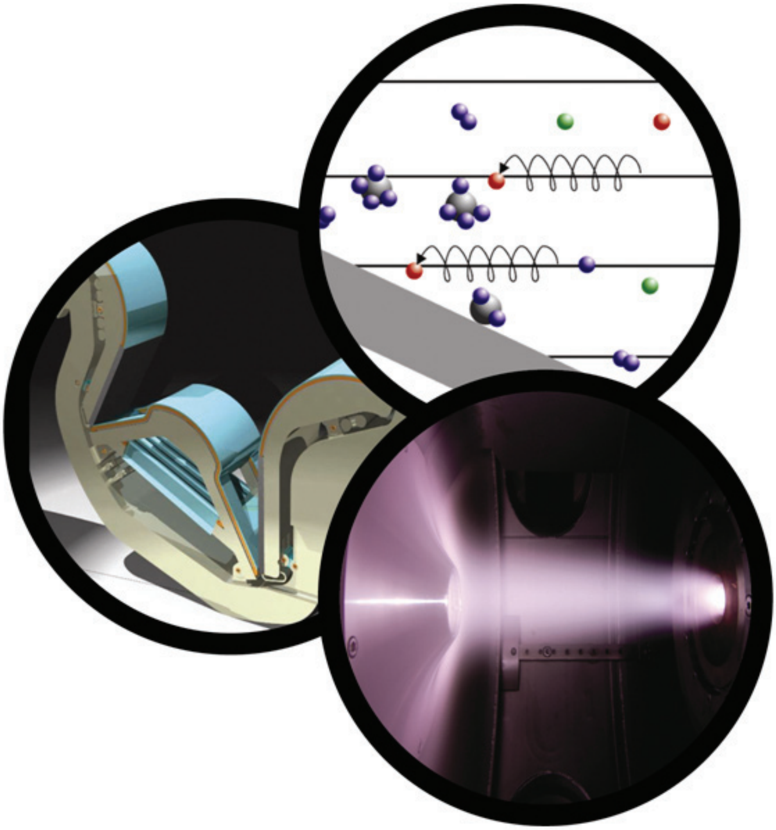
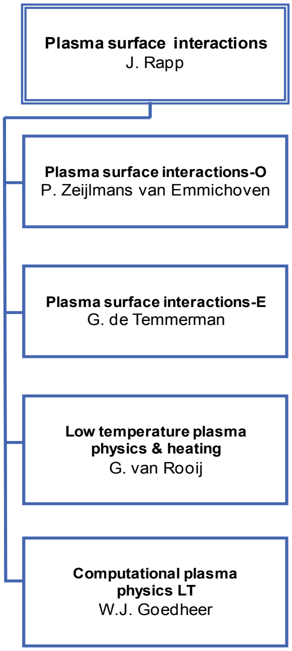


Figure 2.16: From left to right: ITER divertor cassette, impression of plasma impinging on material wall, expanding supersonic plasma jet in Magnum-PSI.

Within the PSI division Magnum-PSI, a new linear plasma generator, is being built to address those plasma surface interaction issues for future fusion reactors. It is designed to access the plasma conditions of a future fusion reactor grade divertor plasma. The uniqueness of Magnum-PSI is its continuous, very high flux, and large area plasma beam in combination with a suite of diagnostics techniques. The forerunner (satellite) experiment Pilot-PSI has already demonstrated the feasibility of high flux operation. Due to its success the satellite Pilot-PSI was already used for experimental work on plasma surface interactions.



The research in the division is mainly based on the study of plasma surface interactions for future fusion reactors. However, general and fundamental aspects of plasma surface science are being studied. The PSI facilities will also be used for new areas of research investigating new routes to sustainable energy sources.

2010 – the first year of the PSI department

The PSI division was formed in late 2009. The division is a result of the fusion of the formerly PSI-Experimental group, and the part of the Computational Plasma Physics group which is related to the investigation of low temperature plasma physics. The original PSI-Experimental group was formed in 2006 by the fusion of the experimental low temperature plasma physics group and the Magnum-PSI project team.

Most of the PSI research at FOM is part of the EURATOM-FOM association agreement and thereby is part of the European Fusion Research Programme. The PSI division of FOM Rijnhuizen is actively involved in the European activities within this programme, organized under the European Fusion Development Agreement (EFDA). This includes work in Task Forces, Topical Groups and Ad Hoc groups as well as memberships of the various EFDA committees. In particular, the engagement in the EFDA Plasma Wall Interaction Task Force should be mentioned, which is defining most of the work within the PSI division. Furthermore, it is anticipated that the work for the European Domestic ITER agency, Fusion for Energy (F4E), will increase in the coming years.

The various groups in the division have a natural strong interaction. All groups work within the FOM programme “PSI-lab, an integrated laboratory on plasma surface interaction” FP75. The synergy is clear from the fact that part of the scientific output and highlights are the result of cooperations between the groups.

In addition to the activities on Plasma Surface Interaction at FOM Rijnhuizen, the division is also carrying out a limited research programme on plasma surface interaction and divertor physics on the tokamaks (Joint European Torus) JET in Culham, UK, the tokamak MAST in Culham, UK, and ASDEX-U in Garching, Germany.

Within the Netherlands, the PSI division is mostly working together with Eindhoven University of Technology and the Technical University Delft. The PSI division has strong links to many research groups around the world. In particular the collaborations within the Trilateral Euregio Cluster with Forschungszentrum Juelich, SCK-CEN Mol and the Ecole Royale Militaire should be mentioned. Members of those research laboratories are strongly involved in the design of Magnum-PSI and the research on Plasma Surface Interactions at FOM Rijnhuizen. Among the other collaborating institutes are: University Cuza, Iasi, Romania; CIEMAT, Madrid, Spain; MIT, Cambridge, USA; University of California San Diego, USA; Heriot Watt University, Edinburgh, UK; IRFM, CEA, Cadarache, France; University Basel, Switzerland; Tartu University, Estonia; TEKES, Helsinki, Finland; and the Kurchatov Institute, Moscow, Russia.

Research groups

The Plasma Surface Interactions Division consisted in 2010 of four groups:

- In the PSI-Operations (PSI-O) group the Magnum-PSI project has been finalized. In the future this group will organize the operations of Magnum-PSI and the satellite Pilot-PSI, which is a test-bed for Magnum-PSI. In addition materials research has been started at a low level in this group.
- The new PSI-Experimental (PSI-E) group undertakes plasma surface interaction studies, which started on the satellite Pilot-PSI and will be carried out in the future on Magnum-PSI. This group also has a good link to the SIPC (Surface Ion Photo Chemistry) group in the nSI department.
- The new Low Temperature Plasma Physics & Heating (LTPP&H) group is focusing on the experimental investigation of low temperature plasma physics characterizing the plasma of the linear plasma generators Magnum-PSI and Pilot-PSI. Furthermore this group develops the plasma sources and the RF heating for those two devices.
- The Computational Plasma Physics – Low Temperature (CPP-LT) group is modelling the plasma, formation of dust in the plasma, the plasma surface interaction and the molecular dynamics occurring in the linear plasma generators Magnum-PSI and Pilot-PSI.

Appointments

- Juergen Rapp became member of the EFDA Science and Technology Advisory Committee.
- Gregory De Temmerman has been appointed as Special Expert Working Group Leader in the EFDA PWI Task Force.

Trilateral Euregio Cluster

Based on the successful work since 1996 within the Trilateral Euregio Cluster (TEC) program *"Coherent concept for energy- and particle-transport and*

-*exhaust and their control in fusion reactors"* and in view of the challenging R&D needs along the 7 missions as defined in the EU-programme for a rapid and efficient realisation of fusion energy and taking into account the outcome of the European facility review which describes the need for focussing on certain experimental facilities as well as experimental gaps which call for adequate developments the TEC partners agree on a new focus of the scientific program: *"Integrated Approach to Plasma Surface Interaction (PSI) in Fusion Reactors"*.

This new TEC-programme puts more emphasis on energy and particle exhaust in fusion devices, which are crucial issues for tokamaks and stellarators and a longterm high priority R&D field on the road towards high power steady state operation of fusion reactors. The complementary expertise of, and devices operated by the TEC partners, will ensure the integrated approach to the PSI issues and in this way provide the added value of this collaboration. In addition to existing devices like the tokamak TEXTOR, which will be phased out during the coming years, new plasma simulator devices will take over the key role for a joint use of facilities within the TEC. In addition the partners team up on an accompanying scientific program dedicated to the ITER-like wall project on JET, the development of ITER/DEMO technology and computational models. Members of the PSI department are strongly involved within the TEC and the experimental devices within the PSI department serve the missions of the new TEC programme.

JET, ASDEX-U and other devices

In 2010, FOM-staff also participated in JET data analysis (due to the shutdown of JET in 2010 there were no experimental campaigns. As this work is thematically fully embedded in the FOM-programmes, reports on the activities that involve JET are integrated in the text.

Researchers from the Fusion Physics division are involved in a number of other devices, including ASDEX-U and TEXTOR in Germany and MAST in the United Kingdom.

2.5 Plasma Surface Interactions – Operations

Division:	*Plasma Surface Interactions*
Group leader:	*P.A. Zeijlmans van Emmichoven*
Graduate student:	*M.H.J. 't Hoen*
Research engineer:	*H.J. van der Meiden*
Technicians:	*R.S. Al, S. Brons, H.J.N. van Eck, O.G. Kruyt, A. Lof, R. Prins, J. Scholten, P.H.M. Smeets*
Collaborators:	*D.C. Schram (TU/e), H. Schut (TU/d), V. Philipps. B. Schweer (FZ-Juelich, D), M. Mayer, K. Ertl (IPP Garching, D), E. Gauthier (CEA, F)*
Funding:	*NWO, FOM, FP-75, NWO-Groot, EURATOM baseline and preferential support, EFDA*

Introduction

Magnum-PSI is a magnetized linear plasma generator designed to study the interaction of a magnetized plasma with materials. The experiment will provide new insights in the complex physics and chemistry that will occur in the divertor region of the fusion reactor ITER. The uniqueness of Magnum-PSI is its continuous, high ion flux ($>10^{24}$ m^{-2}s^{-1}), high power (10 MW m^{-2}), and large area plasma beam, in combination with a suite of diagnostics techniques.

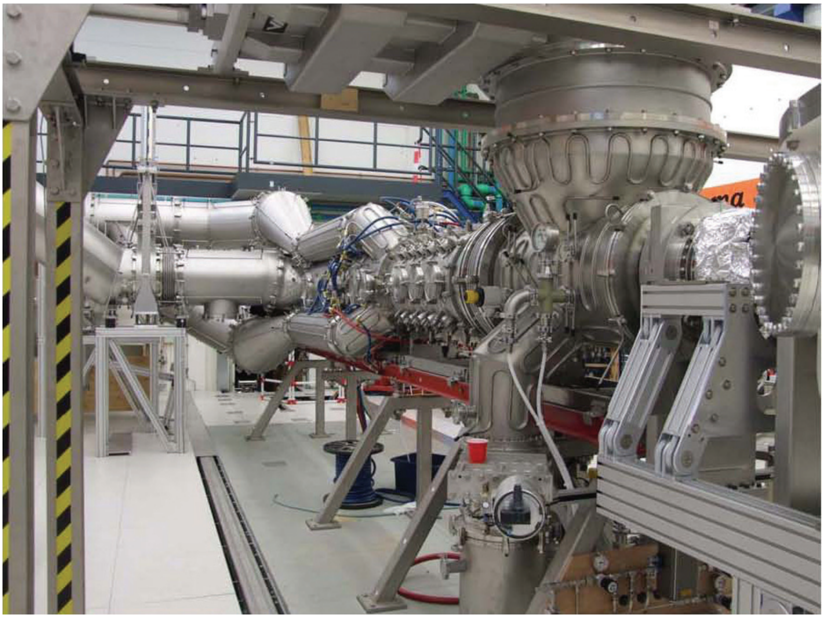


Figure 2.17: *Picture of Magnum-PSI.*

Most technicians of the PSI-O group are primarily involved in the construction of Magnum-PSI. Basic construction of Magnum-PSI has been finished. The complete vacuum system with its most critical components is available. Targets can be transported through the system as well as rotated in any given orientation. Plasmas can be made on a routine basis. As soon as scientific exploitation of Magnum-PSI starts, the PSI-O group will be responsible for its proper and reliable operation.

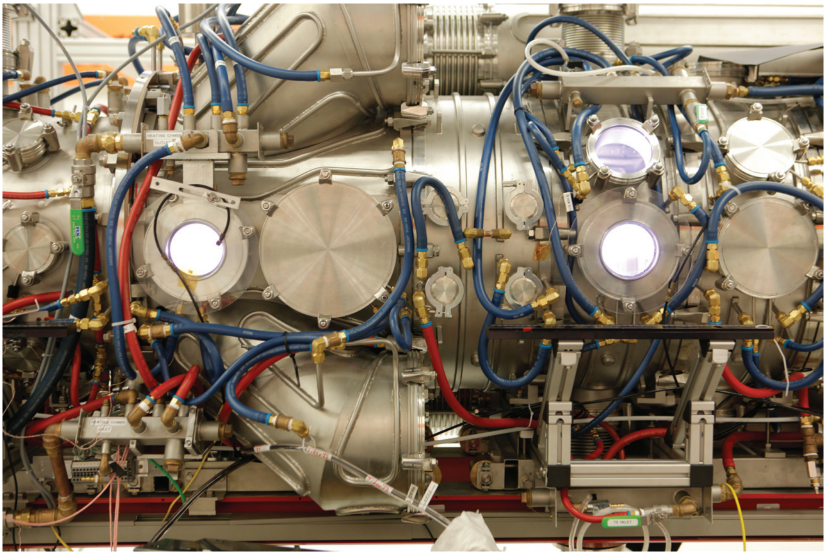


Figure 2.18: Vacuum vessel of Magnum-PSI with argon plasma. To resist the high heat load from the plasma beam, vacuum vessels as well as in-vessel components are water cooled.

Tritium retention in tungsten is a major concern for ITER, because of safety issues and fuel cycle efficiency. The graduate student of the PSI-O group carries out experiments on Pilot-PSI to investigate deuterium (as proxy for tritium) retention in tungsten targets. Via collaborations, the targets are pre-damaged to simulate neutron damage and analyzed by advanced techniques. In the future, the experiments will be carried out on Magnum-PSI.

Results 2010

Magnum-PSI (FP75, NWO-Groot, EFP)

The vacuum system with all vacuum pumps and cooling systems is operational. This includes the target station with manipulator and movable target, and the source system with the movable plasma source. The two water cooled skimmers have been designed, manufactured and installed. The three-stage differentially pumped system with both skimmers has been tested and the whole works according to specifications. The main part of the control system has been implemented and commissioned. The design and realization of the data acquisition system is in progress. All safety items concerning use of hydrogen, large magnetic fields, and intense lasers have been implemented.

The present focus of the group is on the implementation of several diagnostics techniques and on reaching the specified plasma parameters. Thomson scattering, the elastic scattering of electromagnetic waves by the electrons in a plasma, has been implemented and is fully operational. Measurement of the scattered waves gives direct and very accurate information on the electron density and temperature. This powerful technique has been implemented both near the source and near the target via two dedicated laser beam lines linked to the vacuum system. Since the plasma source can be moved in and out along the axis of Magnum-PSI, a density profile along the axis of the plasma beam can easily be made. Besides Thomson scattering, several other diagnostics techniques have been prepared and will soon be operational.

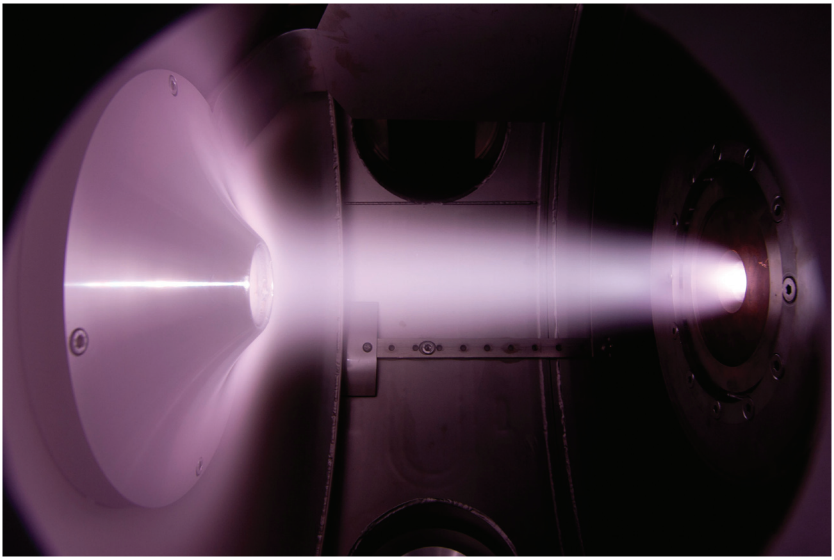


Figure 2.19: Photograph of the inside of the vacuum vessel of Magnum-PSI with argon plasma at high ambient pressure (30 Pa). The so-called source skimmer on the left limits the gas flow to the next chamber.

These include: optical emission spectroscopy for study of light emission from the plasma, calorimetry for study of power deposition in the target and in the other plasma facing components, imaging with an infra-red camera for observation of the temperature profile of the target, and laser induced desorption and ablation for study of desorption and ablation of atoms/molecules from the target by an intense laser pulse. First laser-induced-desorption experiments have been carried out on a carbon target saturated with deuterium. With the recently purchased and installed Quadrupole Mass Spectrometer, desorption of D_2 and CD_4 was observed in addition to smaller quantities of D, HD, C, CD, CD_2, and CD_3.

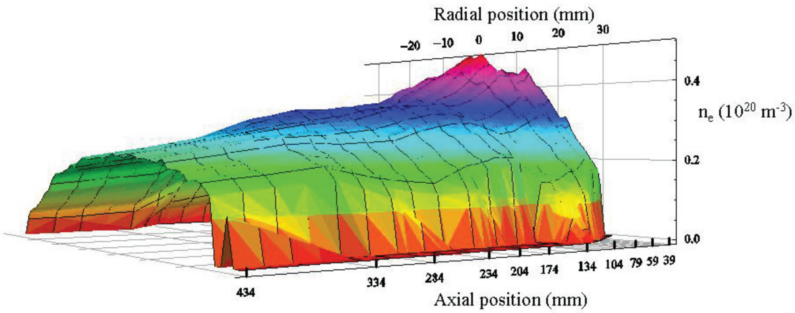


Figure 2.20: Electron density profile of argon plasma at high ambient pressure (30 Pa) as determined by Thomson scattering. The axial position is given in mm from the plasma source exit.

Next generation plasma sources, such as a three-channel cascaded arc source, to broaden the plasma beam diameter to the specified 10 cm are being developed by members of the low temperature plasma physics group. This also holds for implementation of RF heating of the plasma to reach electron temperatures of 10 eV.

The only essential part of Magnum-PSI missing so far is the superconducting magnet to confine the plasma to a magnetized beam. The magnet system failed the factory acceptance test in April 2010. The manufacturer has disassembled the magnet and identified serious problems. Several members of the PSI-O group are actively involved in monitoring the activities concerning the magnet. The institute also hired an independent consultant in quality control who is monitoring the process at the manufacturer site. The assembly process has recently started again and the next factory acceptance test is scheduled for April 2011. When successful, the magnet will be delivered to the institute in May 2011 and, after a short commissioning period, scientific exploitation of Magnum-PSI should start mid 2011.

Deuterium retention in tungsten (FP75, EFDA)

Polycrystalline, annealed W targets were pre-irradiated in collaboration with IPP Garching with 12.3 MeV W^{4+} ions to peak damage levels in the range of 0.1 to 1.0 dpa (displacements per atom). Damage profiles in the targets were simulated by the Monte-Carlo simulation code TRIM. The damaged targets have been exposed to high-flux plasmas in Pilot-PSI (>10^{24} ions m^{-2} s^{-1}). The surface temperature of the targets during exposure was determined by the local plasma flux on the target and by its cooling. Two different ways of cooling have been used, leading to two distinct temperature regimes on the target. Deuterium retention has been studied by Nuclear Reaction Analysis and by Thermal Desorption Spectroscopy. We found that deuterium retention is significantly enhanced by pre-irradiation and that saturation occurs at 0.2-0.5 dpa. The saturation level seems to depend on target temperature. The values found for the saturation level are in good agreement with experiments from others. Since those experiments have been carried out at much lower plasma fluxes, it can be concluded that the saturation level is not significantly affected by the high fluxes used in our experiments.

In parallel, a research activity was started in collaboration with the Technical University Delft on Positron Annihilation Spectroscopy. First results indicate that irradiation of a target gives rise to a very clear change in Doppler broadening profile in the depth range of ion implantation. Plasma exposure of the irradiated targets results in an additional, but smaller change in profile. The aim of these experiments is to get information on the creation and behavior of vacancies by pre-irradiation and by plasma exposure

2.6 Plasma Surface Interactions – Experimental

Division:	*Plasma Surface Interactions*
Group Leader:	*G. De Temmerman*
Graduate students:	*K. Bystrov, J.J. Zielinski*
Undergraduates:	*L. van der Vegt, S. van Diepen*
Research technician:	*M. van den Berg*
Collaborators:	*L. Marot (Uni. Basel, CH), D.C. Schram, R.A.H. Engeln (TU/e), S. Brezinsek, J. Linke, A. Litnovsky, J.W. Coenen, V. Philipps (FZ-Juelich. D), S. Porro (Heriot-Watt, UK), J. Dodson (E6, UK) D.G. Whyte, G. Wright (MIT, USA), R.P. Doerner, M.J. Baldwin (USCD, USA), A. Hakola (TKK, Fi), P. Paris (TEKES), E. Delchambre, T. Loarer (CEA, F), M. Balden (IPP, D)*

| *Funding:* | *FP-75, EFP, EFDA* |

Introduction

The mission of the PSI-E group is to perform basic plasma-surface interaction research needed for the design of the plasma facing components of future fusion devices.

The research carried out by the PSI-E group is organized around three main axes. First, experimental studies are done under well-controlled plasma and surface conditions to bring a fundamental understanding to plasma-material research in modern fusion devices and help numerical code benchmarking.

Second, the specific achievable plasma conditions are used to identify and study plasma-material related issues in next generation fusion devices whose conditions cannot be reproduced in today's fusion devices. Those results feed into the R&D programme of large-scale devices.

Finally, the ability of steady-state and pulsed high flux plasma operations is to be used for tests of technical solutions for the development of plasma-facing components compatible with extreme heat loads.

These aims should be achieved through the exploitation of the Rijnhuizen PSI experiments, with Magnum-PSI as the central experiment, in conjunction with international collaborations within the fusion community.

Important results 2010

Development of a pulsed plasma source for ELM-simulation experiments

Edge Localized Modes (ELMs) are a major concern for the lifetime of the divertor plasma-facing materials (PFMs) in ITER. The very high localized heat fluxes will lead to material erosion, melting and vaporization. A new experimental setup has been developed for ELM simulation experiments with relevant steady-state plasma conditions and transient heat/particle source. The plasma source of Pilot-PSI has been modified to allow for transient heat and particle pulses superimposed on the steady-state plasma. The high flux plasma is generated by the cascaded arc plasma source which is powered by a current regulated power supply. In parallel, a capacitor bank (8400μF, 4.2 kJ) is connected to the plasma source and discharged in the plasma source to transiently increase the input power (Figure 2.21a). This results in a transient increase of the electron density and temperature. The plasma source was modified to accommodate the high heat fluxes generated during such pulses. Peak discharge currents of about 14 kA have been generated, corresponding to a peak input power in the plasma source of about 5.5 MW. The plasma source can be operated in a pulsed with a variety of gases (e.g. Ar, H, D, He, N) as well as with gas mixtures. Peak surface heat fluxes of up to 1 GW.m^{-2} have been generated with a pulse duration of about 0.5-1 ms (up to 1MJ.m^{-2})- as illustrated in Figure 2.21b. The shape and the duration of the pulse can be adapted to the needs. In addition, a pulsed bias system has been developed to vary the ion energy during the pulse.

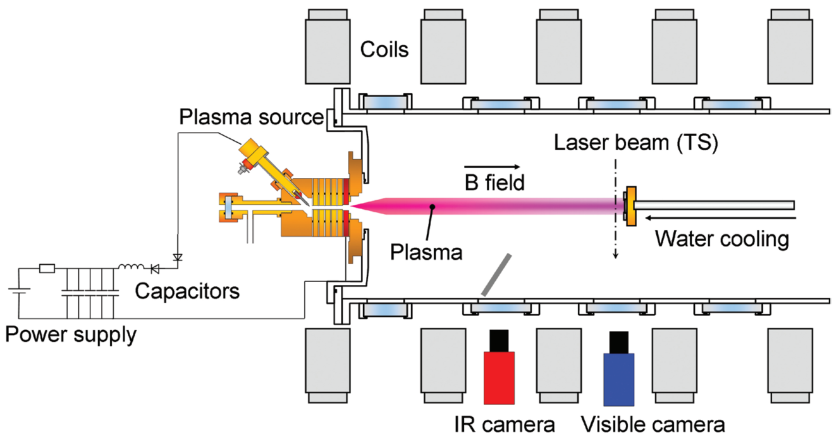


Figure 2.21: (a) Schematic overview of Pilot-PSI with the pulsed source system.

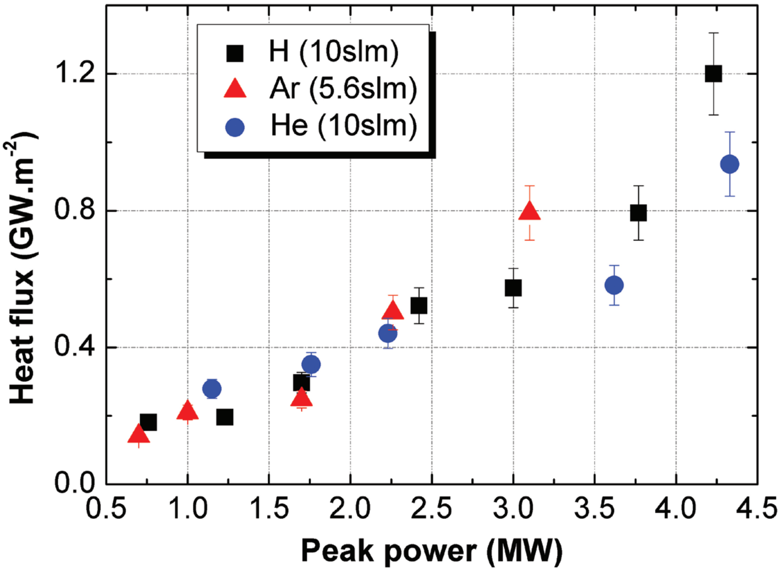


Figure 2.21 cntd: (b) Evolution of the peak heat flux to the target surface as a function of the peak input power in the plasma sources for different gases.

The influence of the surface morphology of tungsten exposed to combined steady-state/ pulsed plasma has been investigated for hydrogen plasmas using Secondary Electron Microscopy. Figure 2.22a shows the morphology of a reference tungsten sample exposed for 40 s to the steady-state plasma only. No morphology changes can be noticed compared to a polished non-exposed sample. On the other hand, significant morphology changes are observed when the surface is also exposed to plasma pulses. Surface roughening is already noticeable after 10 pulses at 0.07 MJ·m^{-2} (Figure 2.22b), and increases with the pulse number (Figure 2.22d). For higher energy densities the effect is much more pronounced as illustrated by Figure 2.22c and also evolves with the number of pulses (Figure 2.22e). This is attributed to the plastic deformation of the heated grains due to compressive stresses during the transient heating which leads to irreversible swelling after the cool-down. Such an effect is observed when the base temperature of the material is already above the ductile to brittle transition temperature (DBTT) which is clearly the case in the present experiments.

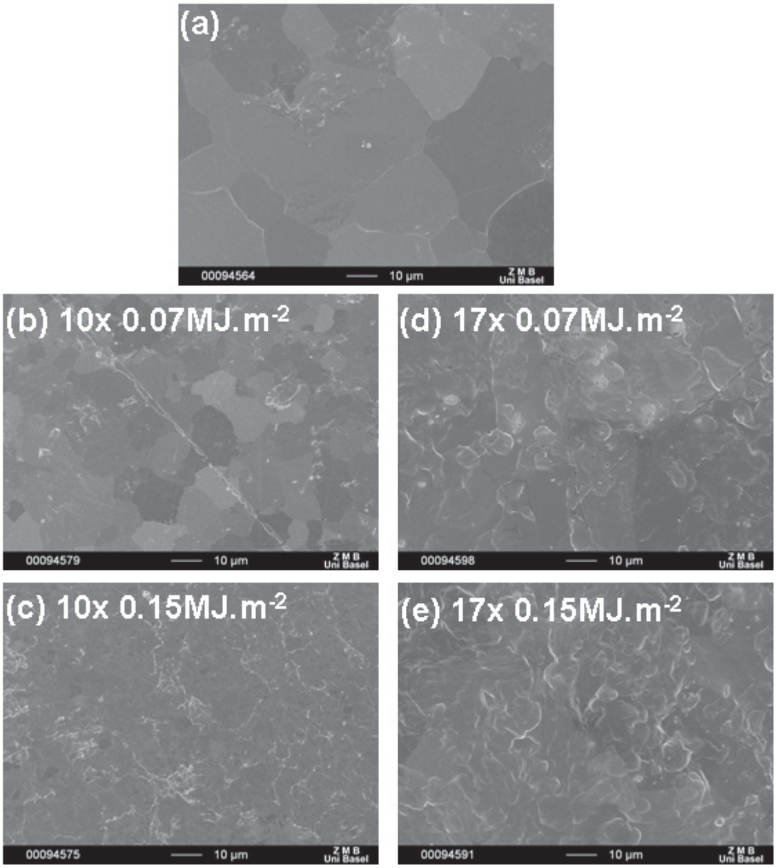


Figure 2.22: SEM pictures of tungsten samples after exposure to 40s of steady-state hydrogen plasma (a), 40 s of steady-state plasma and 10 plasma pulses with energy density 0.07 MJ·m^{-2} (b) and 0.15 MJ·m^{-2} (c), and 68 s of steady-state plasma with 17 plasma pulses with energy density 0.07 MJ·m^{-2} (d) and 0.15 MJ·m^{-2} (e).

Formation of helium-induced nanostructure on high-Z metals

Helium bombardment of tungsten surfaces can lead to strong microstructural changes such as dislocation loops, helium holes and bubbles, and formation of a fibreform nanostructure (also referred to as fuzz). The occurrence of those effects is strongly dependent on the surface temperature. The formation of helium-induced nanostructure on molybdenum and tungsten surfaces has been studied in Pilot-PSI. Tungsten and molybdenum samples were exposed to high fluxes (around 10^{24}m^{-2}s^{-2}) of pure helium plasmas in the temperature range 600-2400 °C. Figure 2.23 illustrates the different morphologies observed by scanning electron microscopy after plasma exposure for tungsten (a and b-b is a cross-section image of a) and molybdenum (c and d). The structure size varies along the surface, the maximum size is observed in the middle of the plasma beam (highest temperature and flux) and is the smallest towards the edge (lower temperature and fluxes).

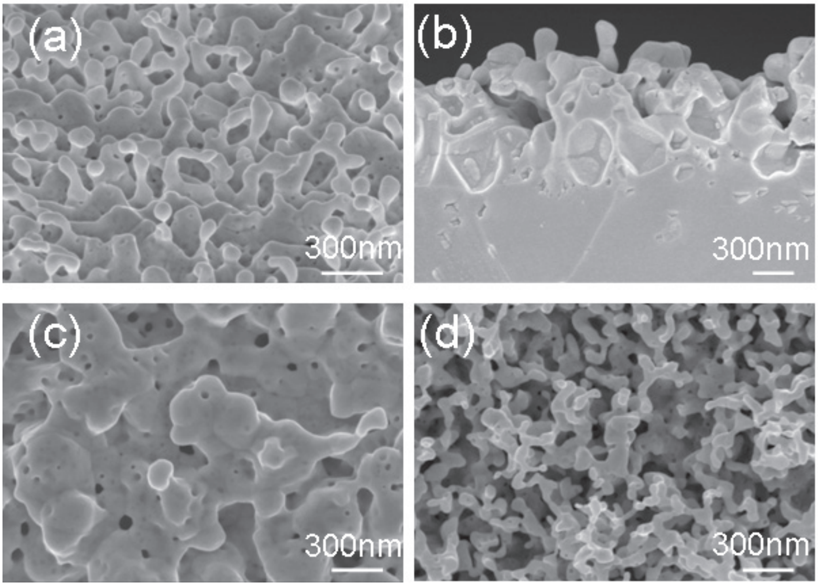


Figure 2.23: Scanning electron microscope images of tungsten (a and b) and molybdenum surfaces after exposure to a high flux helium plasma with a surface temperature higher than 1000 °C.

Carbon erosion and re-deposition (FP-75, EFDA)

The issue of gross and net erosion of carbon under ITER relevant plasma conditions remains an open question, especially the importance of local re-deposition and the structure of the deposits formed under such conditions. It has been observed that thick co-deposits are readily formed on the surface of graphite targets exposed to ITER-relevant hydrogen and mixed hydrogen/argon plasmas ($n_e \sim 10^{24}$ m^{-3}, $T_e \sim 1$ eV) in Pilot-PSI. These co-deposits consist of cauliflower-like dust particles and, surprisingly, accumulate in the region exposed to the peak particle and heat flux. Observations show that increasing the ion energy in hydrogen plasma prompted formation of large ($D > 30\,\mu$m) dust particles, which are not detected on the surface of targets with floating potential (Figure 2.24).

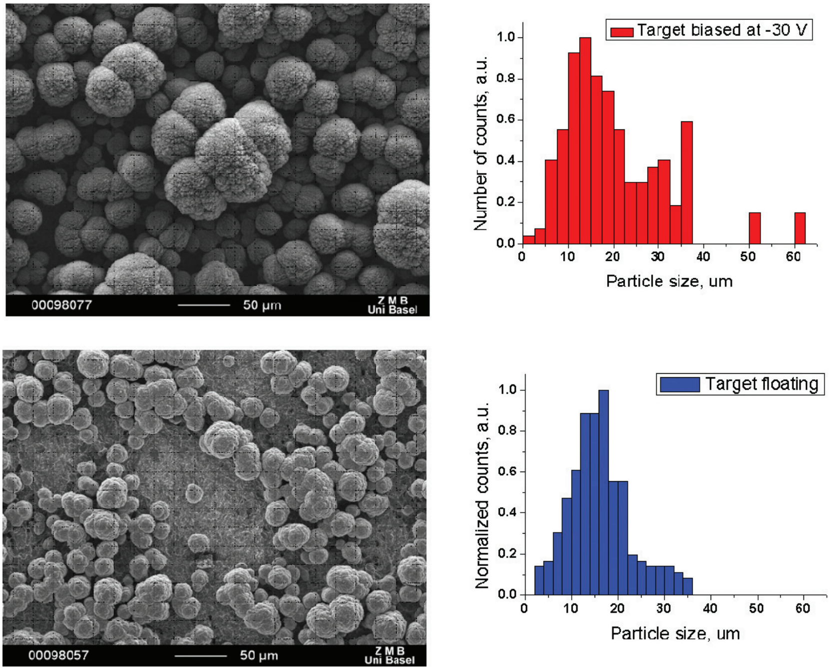


Figure 2.24: Scanning electron microscope images of the plasma exposed surfaces of negatively biased (a) and floating (b) carbon target. Corresponding size distributions of the formed co-deposits are shown on the right.

2.7 Low Temperature Plasma Physics and Heating

Division:	*Plasma Surface Interactions*
Group leader:	*G.J. van Rooij*
Graduate students:	*J. Westerhout, W.A.J. Vijvers, A. Shumack*
Undergraduates:	*N. den Harder, O. Rottier, W.J. Smit, G. van der Star, T.J. Vink*
Research Engineer:	*M.J. van de Pol*
Research Technician:	*M.F. Graswinckel*
External Advisors:	*R.A.H. Engeln, D.C. Schram (TU/e)*
Collaborators:	*D. Borodin, S. Brezinsek, A. Pospieszczyk (FZ-Juelich, D), D.G. Whyte (MIT, USA), G. Popa, M.L. Solomon, V. Anita (Cuza University, RO), F. Tabares, J. Ferreira, E. Oyarzabal (CIEMAT, E)*
Funding:*	*FOM, NWO, FP-75, EURATOM baseline support, NWO-Groot, NWO-RFBR, EFDA*
	** supported by the European Fusion Programme (EFP)*

Scientific programme

The mission of the Low Temperature Plasma Physics and Heating group is to contribute to the understanding of nuclear fusion reactor grade divertor plasma and to apply the new insights in such plasma to control plasma wall interaction in fusion devices and to enhance the plasma parameters in the in-house linear plasma devices.

In particular, the group aims at answering the following research questions:

- How is the transport of particles and power to a material wall changed if the returning secondary particles are captured by the plasma? We call this regime of plasma surface interactions the strongly coupled regime, which is uniquely achieved in the FOM PSI lab. The consequence is that plasma surface interaction products will have an impact on the plasma conditions in front of the surface as well as will contribute to the plasma surface interaction processes.
- What determines the axial and radial transport in, and how do impurities and particulates interact with, a divertor grade plasma? Two currently pressing issues within the field of divertor tokamak research connect to this question and are being researched within the LTPPH group: radiation of nitrogen seeded to the plasma and the transport of dust.
- How can the plasma parameters be enhanced in Pilot-PSI and particularly in Magnum-PSI? This question covers research on the development of a more efficient plasma source delivering an increased plasma beam diameter and the post-heating of the plasma with Ohmic and RF power.

Plasma acceleration near a negatively biased target in a linear plasma generator (FOM-Programme 75)

Negative target potential scanning is a standard technique for plasma flux measurements in linear plasma devices. The electron density is sufficiently low in these plasma generators that current densities as well as ion-neutral coupling are negligible. Consequently, the upstream plasma is not affected by the negative target potential. In our linear device Pilot-PSI, variations in the upstream plasma conditions *have* been observed in the pre-sheath region in front of the target. Its uniquely high plasma densities of $>10^{20}$ m^{-3} ensure a significant interaction between the neutral particle flux coming off the surface and the incoming plasma flux so that the 'strongly coupled regime' is entered. Indeed, we measured, to our knowledge for the first time, changes in the upstream plasma. Particularly, the plasma velocity was measured to increase by up to a factor of five. We currently interpret the observed acceleration as a rise in the local sound speed due to the kinetic energy of the reflected neutrals changing with the target potential.

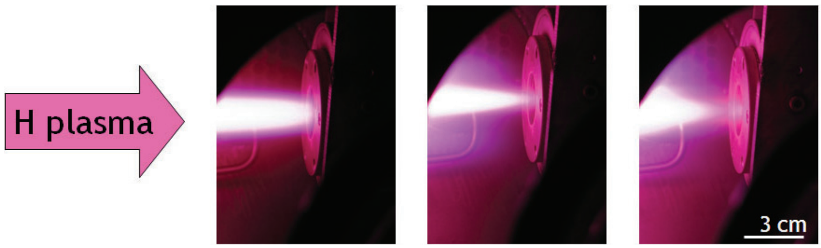


Figure 2.25: Photographs of the hydrogen plasma light emission near the target of Pilot-PSI in a scan of the target bias potential. The light emission is observed to reduce with increasing negative bias, which reflects a decreasing plasma density due to plasma acceleration.

New light on carbon erosion in fusion experiments (FOM-Programme 75 and EFDA)

The erosion of the wall is a key issue for the success of the future fusion reactor ITER. Carbon can withstand extreme heat loads and will therefore be used as wall material in the areas of strongest particle and power loads. A serious weakness of carbon is that chemical processes induce erosion of the wall even at the lowest achievable incident particle energies. The chemical erosion will be monitored in ITER, just like is routinely done in present day devices, via the light that is emitted by the accordingly produced hydrocarbon molecules. The LTPPH group discovered on the basis of experiments in Pilot-PSI, and in a comparison with numerical modeling results, that these molecules emit orders of magnitude more light than was predicted for low temperature plasma conditions as expected in ITER. A mechanism based upon the underlying plasma chemistry was proposed that explains the extra light emission. These results put hydrocarbon spectroscopy for ITER in a new light.

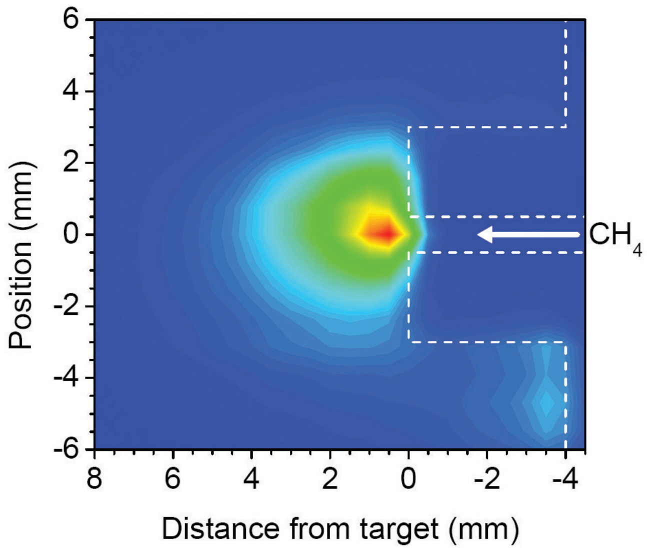


Figure 2.26: The emission profile of light emitted by the CH radical that was measured in Pilot-PSI. Methane was flowed from an orifice in the target (indicated by the dashed line) into ITER relevant hydrogen plasma. The amount of light was orders of magnitude higher than predicted.

Increasing the plasma beam diameter by mixing three individual beams (FOM-Programme 75 and NWO-groot)

Current activities related to the development of the plasma source for Magnum-PSI concentrate on broadening of the plasma beam diameter to the specified 10 cm. A promising option is to use a plasma source with several individual plasma channels. In argon operation, this source already produced a homogeneous full-width-half-maximum (FWHM) beam of more than 3 cm. Homogeneous mixing has also been achieved in the latest experiments in hydrogen. A remote anode ring was used to impose plasma rotation, which merged the hydrogen beams to a total beam diameter of 3 cm FWHM.

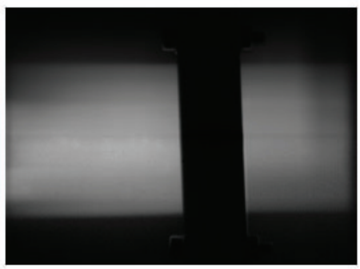



Figure 2.27: Photographs of the plasma light near the output of the three channel plasma source. Three individual beams that do not interact are produced in hydrogen operation (left). Homogeneous mixing is achieved by diverting 50% of the source current to a remote ring electrode at 10 cm downstream (right).

2.8 Computational Plasma Physics – Low Temperature: CPP-LT

Group Leader:	*W.J.Goedheer*
Scientist:	*H.J. de Blank (50%)*
Graduate Students:	*E.D. de Rooij, R.C. Wieggers, G.A. van Swaaij*
Collaborators:	*J.J.A.M. van der Mullen (TUE, Eindhoven), J.K. Rath (Un. Utrecht), D. Reiter (FZ-Jülich), A. Kirschner (FZ-Jülich), U. von Toussaint (IPP-Garching)*
External advisor:	*Em. Prof. D.C. Schram*
Funding:*	*FOM, NWO, EURATOM baseline support, FP-75, FP120*
	** supported by the European Fusion Programme (EFP)*

Research Programme

The research of the CPP-LT group is done within the framework of Fusion Energy and is embedded in the FOM program FP75. The research line of the institute on Plasma Surface Interaction requires support from simulations and analysis with sophisticated numerical and theoretical models. The aim of the Computational Plasma Physics group is to develop new and modify existing models for this purpose. Relevant models will be made available to the EFDA Taskforce for Integrated Tokamak Modeling, to become part of the set of numerical tools needed to support the design of future reactors like DEMO.

Application of the models covers studies of the plasma beams of the in-house experiments Pilot-PSI and Magnum-PSI, plasma surface interaction, and transport and re-deposition of eroded material. These studies are done in close collaboration with the experimental groups, optimizing the possibilities for validation of the models against experimental data.

A number of simulation tools have been and will be acquired or developed to study all aspects of plasma surface interaction in Magnum- and Pilot-PSI. Part of the tools will be used to transfer knowledge to the ITER team, through simulation of divertor plasmas.

The CPP-LT group aims to position itself within the institute as the counterpart of the experimental program, executing a scientific program with strong links with the research in the PSI department. Where possible, the models will be adapted for use in industrial applications. The framework for collaboration within EURATOM is provided by the EFDA task forces for Integrated Tokamak Modeling (ITM) and Plasma Wall Interaction (PWI). The sections below describe the research topics covered in the group.

Plasma Surface Interaction

In collaboration with IPP-Garching, the HCPARCAS molecular dynamics code is used to study erosion and re-deposition on the atomic scale. Specific for the simulations is the high flux of hydrogen atoms bombarding the surface. For hydrogenated amorphous carbon, the studies so far revealed no flux dependence of the erosion yield, while redeposition is larger on heavily bombarded layers. Bombardment of carbon-rich tungsten carbide showed phenomena like blister formation, although on a different scale than observed in experiments.

Transport of erosion products

The transport of hydrocarbons in the plasma beam of Pilot-PSI is studied with the kinetic code ERO. This is done in collaboration with FZ-Juelich. Experiments with a methane gas puff released into the plasma beam provide well-defined conditions for validation of ERO. An important issue is the emission of CH, since that is often used to analyse carbon erosion.

Modelling of low-temperature high-density plasmas

The plasma beam of Pilot-PSI and Magnum-PSI as well as the plasma expected in the divertor of ITER has a low temperature and a high density. It is furthermore characterized by a strong recycling. To study these plasmas, a combination of a multifluid plasma description (B2.5) needs to be coupled to a kinetic description of the neutral atoms and molecules (EUNOMIA). The modelling of plasma beams includes the description of radial electric fields, plasma rotation, and the axial and radial current density profile in the beam, caused by source potentials and radial variations of the target plasma sheath. The EUNOMIA kinetic code is built from first principles, and is partly based on the existing EIRENE code. Specific items addressed are the non-linearity (neutral – neutral collisions), statistics (adaptive weight of the trace particles) and parallelisation.

Dusty plasma

Work on dusty plasma addresses the strong coupling between the plasma and the immersed grains. In collaboration with de SID group of the Utrecht University, silane-hydrogen RF discharges for deposition of micro-crystalline and amorphous silicon are studied.

nanolayer Surface and Interface Physics

The nSI division within Rijnhuizen aims to perform high-quality scientific research in the field of surface science, and thin film solid state physics. The particular topics investigated include photo-chemical phenomena, photo-conversion processes, plasma physics, and short-wavelength, i.e. XUV optics. Especially the boundary areas between these fields are of interest: the use of XUV optics, for instance, generates exciting research questions in the field of photo-induced surface chemistry, as in EUV-induced optics contamination. This theme is also linked to a new activity on photo-conversion of water into hydrogen, of relevance for the generation of clean solar fuels. Thus nSI research provides Rijnhuizen with a kernel for a solar energy research programme.

Typifying for the research in the department is the industrial or societal relevance of the research: the investigations are usually motivated by the application of the knowledge in plasma surface interaction phenomena as e.g. in advanced photolithography optics, in thermonuclear fusion processes, or in the utilization of multilayer reflective optics for advanced radiation sources. The latter include high flux EUV plasma sources, and XUV free electron lasers, like FLASH in Hamburg. Hence, valorisation of research results is not an incidental event, but takes place on a regular basis. This societal and industrial engagement is examplified by the granting of the prestigious FOM Valorization Prize 2010 to the nSI department head Fred Bijkerk, for his collective works on EUV sources and multilayer optics, both at FOM Rijnhuizen and at the MESA+ Institute for Nanotechnology at the University of Twente (see Figure 2.28). Also the Rijnhuizen Valorization Officer, Tim Tsarfati, emerged from the nSI department (see chapter 3).

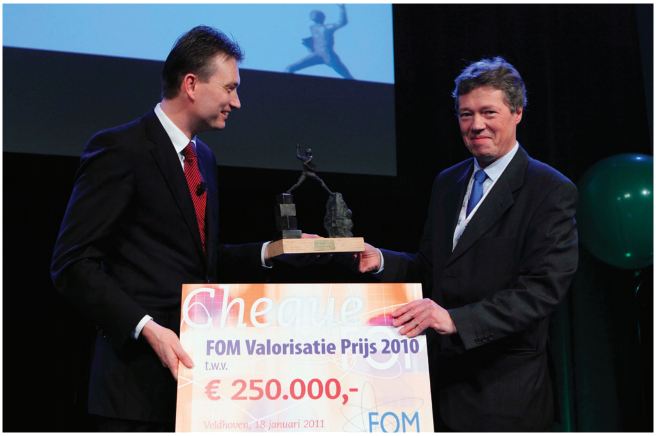
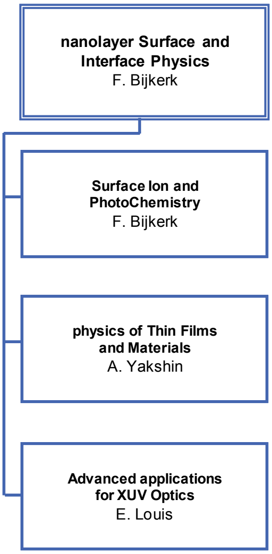


Figure 2.28: Professor Fred Bijkerk receives the FOM Valorization Prize 2010 from the State Secretary for Education, Culture and Science, Halbe Zijlstra during a ceremony at the Physics@ FOM Veldhoven Symposium in January 2011.



Research in the nSI department is mainly enabled by three large research programmes:

- The FOM-Zeiss Industrial Partnership Programme 'eXtreme UV multilayer optics' or 'XMO',
- PSI-lab, a FOM-funded integrated laboratory programme on plasma surface interaction, and
- The FOM-Industrial Partnership Programme 'CP3E' with Carl Zeiss and ASML.

Extreme UV multilayer optics: 'XMO'

The XMO objective is to develop and apply the physics and associated process technology of compounded periodic multi-layer structures. Such multilayers serve as XUV reflecting Bragg mirrors and need to have atomically sharp, flat interfaces, and be chemically stable. The dimensioning of the layered structure of these mirrors needs to be controlled down to a fraction of the wavelength for which they are designed, in cases down to the picometer range. Key issues are the development and application of the physics and supporting fabrication technology of these compounded periodic structures for a most demanding imaging application, namely ultra high resolution photolithography. State-of-the-art lithography equipment, for which these mirrors play an essential, technology-enabling role, is being developed by our research partners ASML, Veldhoven, and Carl Zeiss SMT GmbH, Oberkochen, Germany. XMO is headed by Fred Bijkerk and Andrey Yakshin and builds on a long tradition of research programmes carried out with funding from industry, notably Carl Zeiss SMT, as well as public bodies as the Technology Foundation (STW), EU programmes, and AgentschapNL. The programme started in 2005 and runs until early 2012, with currently three PhD students already graduated and four more still executing their projects in progressing to final stages. The total number of PhDs finally receiving their PhD through this programme is two more then the five originally planned.

Controlling photon- and plasma induced processes at EUV optical surfaces: 'CP3E'

In line with the XMO programme, the new CP3E programme focuses on the physics and chemical processes relevant for final usage of multilayer optics under high flux and plasma loads. Here, the scientific interest has broadened to include photo- and plasma driven chemistry. The collective processes, see Figure 2.29, basically concern: photo- and plasma chemistry induced by irradiation with EUV photons or low-temperature plasmas, physical sputtering of surfaces by ions, thermally induced interdiffusion between the different layers of the multilayer system, and modification of the optical response of multilayer optics. The complexity of these processes arises from the fact that they occur simultaneously, leading to a multi-dimensional parameter domain and new process interactions. Understanding and control of these processes is of paramount importance for advanced optical applications at EUV wavelengths, including photolithography. A diverse collection of approaches is being used, ranging from numerical studies to experiments using state-of-the-art surface science set-ups combined with high-intensity EUV light sources.

The CP3E programme consists of nine PhD projects of which four are carried out at the new EUV lab at ASML as well as at the associated ISAN institute and Moscow State University. The remainder is based at Rijnhuizen in the nSI department as well as in the CPP-LT group of Wim Goedheer. The CP3E programme started formally on August 2010 and runs until late 2015; it is headed by Fred Bijkerk and Andrey Yakshin.

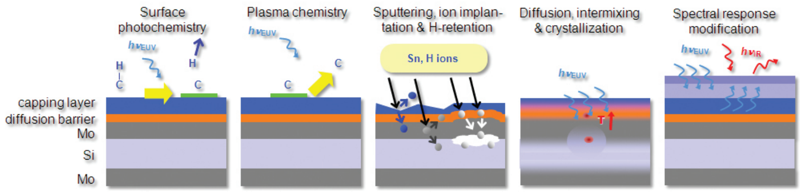


Figure 2.29: Collective processes occuring in EUV optics irradiated at high intensity.

PSI-lab

PSI Lab is a FOM programme (labeled FP75) jointly executed with the PSI department and described in detail in sections 2.5 up to 2.8 (PSI division). It represents the ambition to run an integrated laboratory programme on plasma surface interaction, originally with a fusion of research on XUV optics interacting with EUV sustained plasmas, and applications in thermonuclear research, notably divertor studies. In view of hardware development and staffing demands the current emphasis is on thermonuclear research. The nSI related content in 2010 was limited to elementary studies on the interaction of N-radicals with surfaces, with excursions to DUV and EUV photochemistry studies.

Surface and thin film processes beyond EUV applications

Next to the XMO and CP3E programmes, the nSI department carries out a number of research topics which are related to different applications than EUV photolithography. These are either more distantly aimed to wavelengths beyond the Extreme UV, as in the case of the European FLASH XUV Free Electron Laser research, or, contrary, to longer wavelengths, namely 193 nanometer as in so-called Deep UV lithography. Both areas generate ample opportunities for challenging new physics and chemistry, either photo- or ion-induced at surfaces. These separate projects are funded by miscellaneous programmes, often in conjunction with industry or academic partners.

Physics for energy

The youngest line of research addresses the theme ‘physics for energy’, in response of the large societal request for renewable energy resources. The specific theme selected is based on the nSI background in thin films and surfaces, ensuring ample cohesion and synergy with the other research activities within nSI. For instance, a new powerful infrared surface spectroscopy (RAIRS) set-up, developed originally for delicate surface studies in photolithography, proved very perspective for photoconversion studies under the theme ‘energy’. Figure 2.30 pictures the synergy of the different applications of the surface science studies. The current focus is on the photo-catalytic splitting of water using sunlight to provide in clean solar fuels, but from this core activity other options on solar fuel production are also being explored. Obviously this is being done in the context of the shift of focus of the Rijnhuizen institute into energy-relevant research, and the main schedule of relocation of the institute to the campus of the Eindhoven University of Technology by the year 2015.

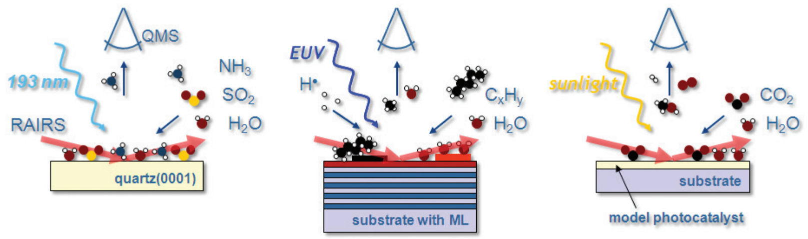


Figure 2.30: *Schematic representation of the synergy among the different experimental conditions of the nSI surface studies for, from left to right, photolithography-relevant surface processes at Deep UV and Extreme UV wavelengths, and solar conversion for fuel production.*

Satellite projects

In addition to the main FOM programmes, and in many aspects acting as smaller ‘satellite’ projects to them, a number of related research projects are carried out with themes that connect to the main programmes. These satellite projects are funded through the AgentschapNL Catrene Programme (‘EXEPT’), the Materials Innovation Institute/ASML Project ‘ISitCLEAR’, FOM funded Valorisation projects, a FOM-Pilot project on Multilayer optics for 4th generation XUV light sources, the Technology Foundation project on multilayer optics beyond the EUV range ‘Beyond-EUV’, the Materials Innovation Institute/ASML project on Photolytic Salt Formation, the M2i/ASML project on EUV-photochemistry instrumentation ‘E-PhID’, a FOM-Pilot project on ‘Metaaloxideoppervlakken als modelsystemen voor watersplitsing met zonlicht’ with support by AgentschapNL through the NEO Programme, and the NWO-‘Dynamiseringsfonds’.

Subdivision in research groups

The research in the department is carried out in three research groups, with a sub-division that follows the core expertise in the groups, and a fourth one being established at the premises of ASML Research at Veldhoven:

- Surface ion- and photochemistry, (SIPC), headed ad interim by Fred Bijkerk,
- Physics of thin films and multilayers (TFM), headed by Andrey Yakshin,
- Advanced applications of XUV optics (AXO), led by Eric Louis, and
- The FOM-EUV Laboratory, led ad interim by Maarten van Kampen (ASML) and Fred Bijkerk.

The groups have many interfaces through the definition of tasks in the different research programmes, both mutually as wel as with other departments, notably the PSI-E group of Gregory De Temmerman. The next section describes the nSI groups and their results accumulated during 2010.

2.9 Surface ion- and photochemistry (SIPC)

Group leader:	*F. Bijkerk (a.i.)*
Scientific advisors:	*A.W. Kleyn*
Technical researcher:	*M. Gleeson*
Postdocs:	*M. Grecea, M. Sturm*
Postgraduate students:	*H. Ueta, A. Kuznetsov*
Funding:	*FP-110 ('XMO'), FP-123 ('CP3E'), FP-75 ('PSI-Lab'), Carl Zeiss SMT, ASML, M2i, the EU Catrene programme, and AgentschapNL*

Research programme

As a part of the nSI department, the Surface Ion- and Photochemistry (SIPC) group addresses the surface science component of a variety of collectively executed research projects within the department. Central themes are the physical and chemical phenomena induced at optical surfaces by photons and/or plasma particles. Surfaces are exposed to high photons and particles fluences, creating new and challenging processes. The research goal is both to model and to experimentally isolate these, in particular a number of the processes that are addressed in the new CP3E research programme on photon and plasma induced processes at multilayer surfaces (also illustrated in Figure 2.29).

As a part of the SIPC share of CP3E, a dedicated FOM-laboratory is being established on-site at the ASML campus. That activity is scheduled to grow to a separate extramural FOM group of the nSI department. First equipment, a versatile surface science set-up allowing the use of Extreme UV photons, has been constructed at the FOM-lab at ASML (see Figure 2.31).

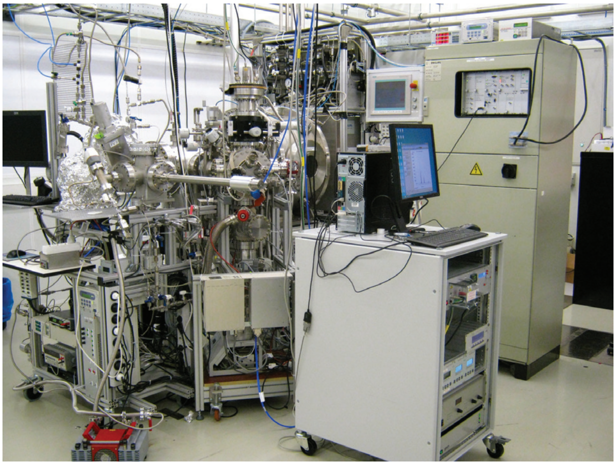


Figure 2.31: The new FOM UHV set-up at the premises of ASML Research, constructed to allow the EUV surface science studies aimed for in CP^{3}E, using an ASML high-brightness EUV light source.

For the in-house experiments at Rijnhuizen a range of equipment is available. Surface-PSI is a unique ultra-high vacuum (UHV) system that permits precise study of details of ion and plasma interactions with surfaces. Plasma environments are typically very complex, and hence are not generally compatible with the standard surface science approach (UHV and a highly controlled system). However, the issues involved are surmounted by the combination of a cascaded arc source with a differentially pumped beam-line, allowing the use of plasma beams for "traditional" surface science investigations. The research is also linked to other research activities on plasma-surface interactions at Rijnhuizen, notably those taking place at Pilot-PSI and, in the near future, at Magnum-PSI. A special relevance exists w.r.t. possible plasma-chemical research topics being prepaired within the new theme on energy-research within Rijnhuizen.

There is a dedicated chamber for atom and ion irradiation of model optical surfaces in order to simulate the damage processes outlined above. Much of the work on this chamber has focused on effects induced by hydrogen, which were sofar relatively poorly understood. This work is a precursor to the wider programme that is outlined in the CP3E proposal.

A relatively new line of research is the study of photo-conversion at surfaces. The goal is to investigate the fundamental aspects and to develop model systems for the production of hydrogen from sunlight and water. This involves using oxide semiconductors in photo-electrochemical cells. Such cells, with aqueous electrolytes, can be used for photo-induced splitting of water in hydrogen and oxygen, thereby providing a clean chemical fuel. Alternative sources of energy are urgently required and solar energy is expected to be an important one. This programme is part of the lab-wide focus on energy-related research themes and is ideally suited to the long term plans to convert the institute into a world-class centre of fundamental research on energy.

Some highlights from the group are outlined below.

Hydrogen interactions with multilayer mirror surfaces

Within CP3E, the study of particle and photon interactions at the surfaces of multilayer structures, intended for use in lithography instrumentation, is a core topic of SIPC. In 2010 this has primarily involved studying the damage that can be induced in the multilayer structures as a result of exposure to hydrogen particles. This research has identified a variety of damage types, including chemical erosion, sub-surface H-retention, and H-induced layer stress and even delamination. Figure 2.32 illustrates an example of one of the more extreme effects that can be induced by hydrogen. This type of delamination is attributed to H-enhanced, compressive stress in the Mo layers, as supported by NRA analysis showing a strong localization of the H in the Mo layers. The task is to further identify and tune the processes that induce the various damage types observed. This, and other topics are executed in close collaboration with the industrial and academic partners.

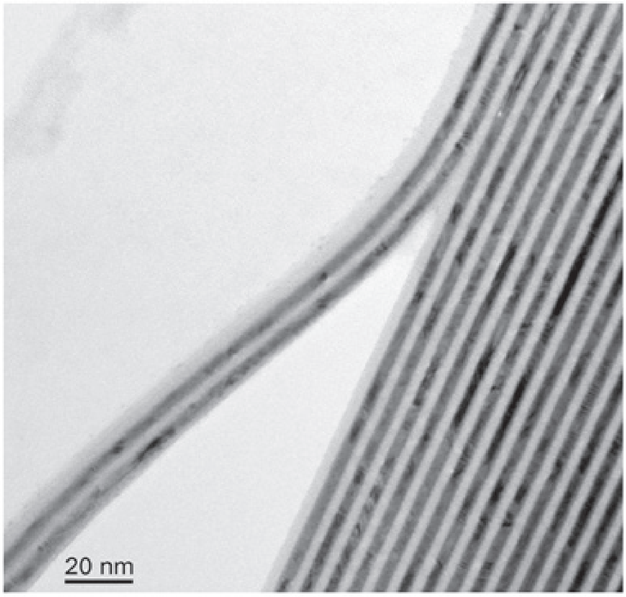


Figure 2.32: Example of hydrogen-induced damage to a multilayer structure.

Surface science studies of materials for solar fuel production

Solar energy is by far the most abundant source of renewable energy, but current use of solar energy remains very limited. Harvesting solar energy in the form of a solar fuel is currently a hot research topic. Solar fuels can be produced by splitting water with the aid of a photocatalyst, resulting in hydrogen as gaseous fuel. Combining this process with the photocatalytic reduction of CO_2 offers the possibility to generate liquid fuels, such as methanol. Solar fuel production would offer a practical solution for dealing with daily and seasonal variations in solar irradiance and is a potentially cheaper way of harvesting solar energy.

The basic photochemical reactions on photo-catalysts are mostly not well understood. In the SIPC group we run a project to investigate the relevant photo-induced processes with surface science techniques on thin film model catalysts. Figure 2.33 shows a new UHV system constructed to enable deposition and characterization of such catalysts using low-energy electron diffraction, as well as fundamental studies on photo-induced reactions with the aid of temperature-programmed desorption, laser-induced desorption and reflection-absorption infrared spectroscopy.

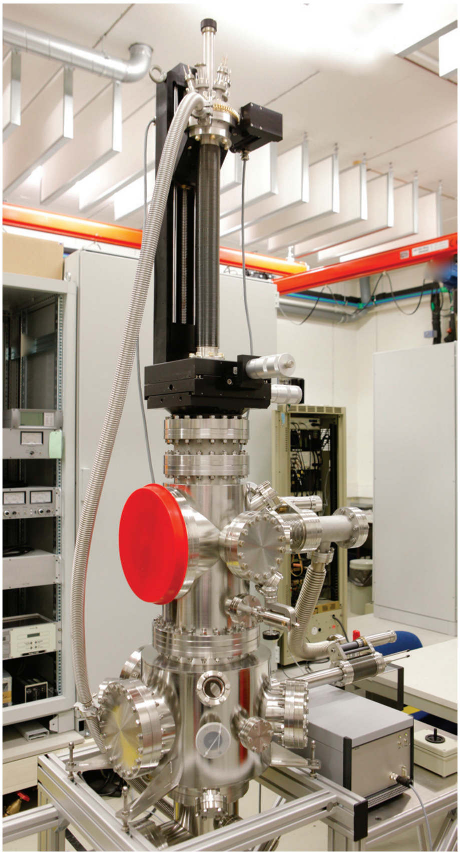


Figure 2.33: The new UHV chamber dedicated to photo-catalytic studies, relevant for solar energy research.

Gas-surface interaction studies

One of the objectives of SIPC is to add to the fundamental knowledge of gas-surface interactions and to improve the understanding of surface processes at the atomic level. Interactions at gas-covered surfaces are of relevance for industrial synthetic and catalytic processes. Since many such processes are operated under conditions of high temperature and pressure, it is particularly interesting to study the interaction of hyperthermal particles with such surfaces.

A highlight of this work from 2010 was the interaction of hyperthermal (~6 eV) argon atoms with a carbon monoxide covered ruthenium single-crystal surface. The primary effect observed was that the incident Ar atoms induced desorption of CO molecules from the surface. The interaction was studied by tracking both the scattering of the Ar atoms from the surface and the (collision-induced) desorption of CO. By tracking both the CO desorption signal and the scattered

Ar signal as a function of time and outgoing angle it was possible to build up a picture of the desorption process and of how Ar modified the adsorbed overlayer. The time-dependent changes to the scattered Ar signal as a result of progressive desorption of CO are illustrated in Figure 2.34. The picture that emerged from the work can be broken down in relatively discrete stages:

- *Scattering of Ar from the CO-saturated surface:* It is difficult for Ar to dislodge CO from the closed overlayer, so the rate of desorption is low. Ar tends to be scattered in a series of soft collisions for the exposed oxygen atoms.
- *Scattering of Ar from the surface with a high fractional coverage of CO:* The more open overlayer makes desorption of CO easier and a period of relatively high desorption is observed. CO molecules are removed as a result of repulsive CO-CO interactions induced by the Ar collision. The surface structure appears rougher leading to a broader distribution of scattered Ar.
- *Scattering of Ar from the surface with a low fractional coverage of CO:* In the low coverage regime CO-CO interactions are no longer significant. The desorption rate drops as Ar tends to displace CO across the surface rather than remove it. The distribution of scattered Ar begins to resemble that observed from the clean surface, but still shows a broadening that arises for modification of the trajectories of the scattered atoms by the remaining CO molecules.

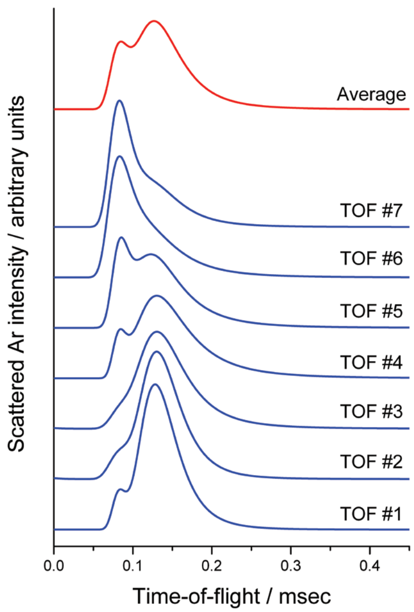


Figure 2.34: Ar time-of-flight spectra collected as a function of time. The spectra are collected sequentially from the bottom. The initial surface is saturated with CO. The progressive changes in the spectra reflect the gradual removal of CO from the surface. The top spectrum is an average derived from the lower seven.

EUV Photochemistry Instrumentation Demonstration (E-PhID)

Supported by M2i and ASML, a new, one year project was executed aimed at developing advanced surface science instrumentation, allowing EUV exposure of various surfaces. This equipment is a further development of the set-up developed successfully in the preceeding research programme on Deep-UV-photo-induced contamination on transparent optical surfaces. The E-PhID project aimed to act as a bridge between the completed research and the newly granted CP3E program. The new UHV chamber, designed and manufactured, is the first piece of entirely-new instrumentation to be created as part of the effort to realize the goals set for CP3E. It is currently being commissioned in the FOM-laboratory at ASML and will be available for full-time research in 2011. See also the nSI highlight described on page 10.

2.10 Physics of thin films and multilayers (TFM)

Division:	*nanolayer Surface and Interface physics*
Group leader:	*A.E. Yakshin*
Scientific advisors:	*J. Verhoeven, A.W. Kleyn*
Senior scientist:	*R.W.E. van de Kruijs*
Postgraduate students:	*T. Tsarfati, V. de Rooij-Lohmann, S. Bruijn, J. Bosgra, S. Nyabero*
Undergraduate student:	*P. Veldhuizen*
Guest scientist:	*I. Kozhevnikov (Crystallography Inst. Moscow)*
Funding:	*FOM Industrial Partnership Programmes 110 and 123, Carl Zeiss SMT, ASML, AgentschapNL*

Research programme

The general goal of the TFM (thin films and multilayer) group is to develop the basic physics of thin single and multilayered films and interfaces of nanometer thicknesses. This includes the particular physics processes occurring inside the multilayer structures as resulting from the applications of these films. In 2010 the research was based on two FOM Industrial Partnership Programmes: 'Extreme UV multilayer optics' (110) and 'Controlling photon and plasma induced processes at EUV optical surfaces' (123) carried out in collaboration with Zeiss and ASML. In addition, the group contributed to the European CATRENE programme EXtreme uv lithography Entry Point Technology development (EXEPT).

TFM developed the physics required for an advanced application of multilayer structures: optical elements operating at Extreme UV wavelengths, notably 13.5 nm. The multilayer systems are aimed at meeting the requirements of EUV photolithography, a technique which is pursued by the associated industrial partners. The requirements for the optics represent fundamental challenges in thin layer and surface physics as well as in the multilayer optics. The TFM group is dealing with solid-state aspects of these research tasks related to ultrathin films. Other aspects are carried out at the SIPC and AXO groups.

The programme carried out during 2010 consisted of two parts: diffusion and physical and chemical interactions in thin films and interfaces, and thin film growth. This included studies of the fine structure of sub nanometer thick artificial interlayers introduced at the interfaces in the multilayer systems, the influence of the crystalline structure on the interaction of the diffusion barriers with the materials, and chemical processes at the initial stages of interdiffusion. Studying period behavior *in situ* during annealing with picometer accuracy allowed us to discover a time dependent activation energy process for interdiffusion at the materials interface. This is the first time that the activation energy was determined for the interdiffusion process on a sub-nanometer scale.

A unique infrastructure of thin film deposition and surface analysis tools is used in the research, including state-of-the-art UHV e-beam and magnetron deposition facilities (see Figure 2.35), various surface ion treatment equipments, Angle Resolved-XPS, Auger Electron Spectroscopy and Scanning Tunneling Microscopy as surface analysis set-ups, as well as hard X-ray reflectometry.

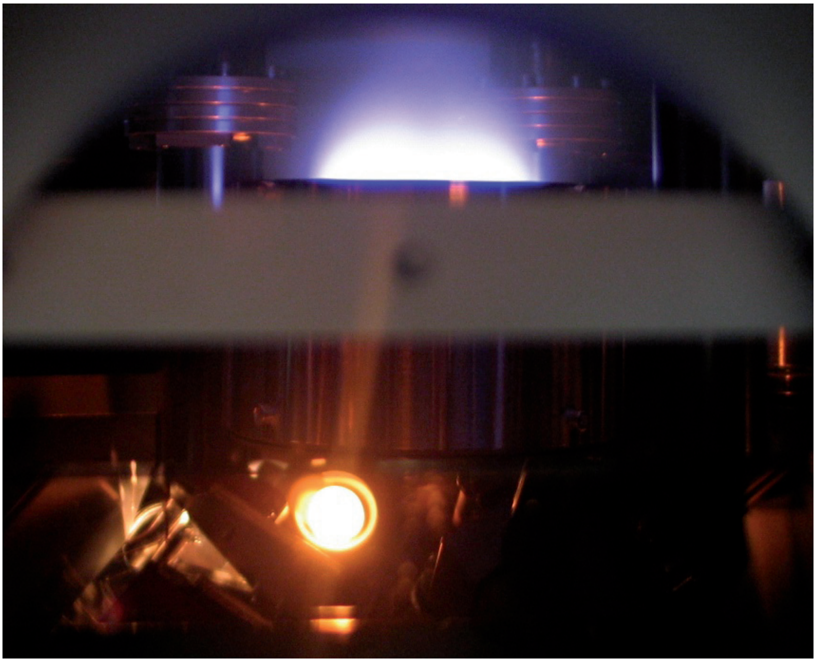


Figure 2.35: A view inside the Advanced Development Coating (ADC) facility, a versatile UHV deposition set-up, showing physical vapor deposition and magnetron sputtering combined in one deposition process.

Time dependence of the interface activation energy

In EUV lithography equipment very high light intensities will be utilized. As a result of this, layer interdiffusion may increase, and Mo-silicide interlayer structures may grow in the multilayer mirrors. Earlier, an *in situ* grazing incidence X-ray reflectivity method was developed to measure such interdiffusion processes with pm-accuracy, even during thermal annealing. The method was used to determine both the interdiffusion rate and the activation energy of the interdiffusion process. Both parameters are important for lifetime studies of the multilayer structures. Normally, it is assumed in calculations that the interlayer would obey a so called parabolic growth law, according to which the interlayer width squared increases linearly with time. However, during the growth of an interlayer at the initial stage of the interdiffusion process, the concentration profile of the interlayer and its structure can change dramatically. Therefore, it is not necessarily true that the diffusion rate and the activation energy for interdiffusion remain constant at that early stage of interlayer growth. If indeed both parameters change during the interdiffusion process, life time prediction studies may dramatically over- or underestimate the thermal stability of the multilayer structure.

In this research topic, the *in situ* X-ray reflectivity method developed earlier was used to measure the interdiffusion process at the Si-on-Mo interface in more detail during annealing up to 300°C. Interdiffusion effects at the other interface (Mo-on-Si) were reduced by introducing a relatively thick B_4C diffusion barrier layer at that interface. A model was developed to calculate the evolution of the diffusion rate and the activation energy of interdiffusion at different stages of the interlayer growth. It was found that the activation energy is *not* constant, but smoothly increases from about 1.6 eV at the beginning of the processs to about 2.5 eV for the additionally grown interlayer of 0.5 nm (see Figure 2.36). This is the first time that the activation energy was determined at such an early stage of interdiffusion. Essentially, this study illustrated that conditions for interdiffusion do change during the initial stage of the interlayer growth.

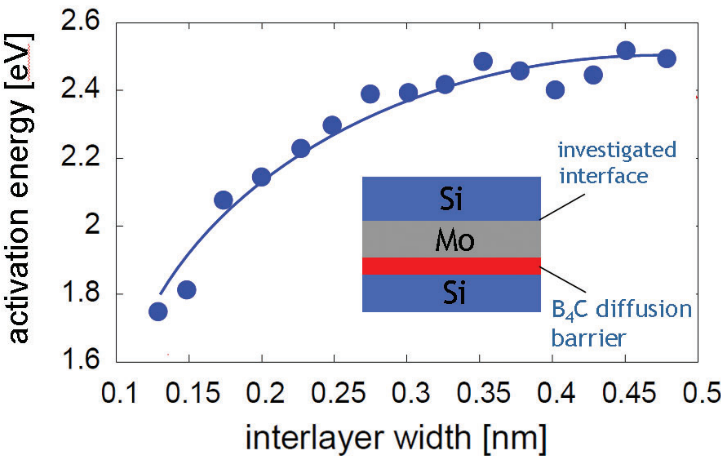


Figure 2.36: Activation energy dependence on the interlayer growth at the Si-on-Mo interface during a thermal annealing process, determined by in situ X-ray reflectivity measurements.

Chemical interaction of diffusion barrier layers

To enhance the thermal stability of multilayered structures, diffusion barrier layers are often added to the layered designs. Although it is known that the properties of such barriers are frequently governed by chemistry, detailed knowledge is often lacking. For instance, the chemical interaction between

B_4C, a most common diffusion barrier material, and Mo or Si, as present in the most common multilayer mirror, is largely missing. Therefore, the chemical processes during thermal annealing of a Mo/B_4C/Si layered structure have been investigated *in situ* with Hard X-ray Photoelectron Spectroscopy (HAXPES) and *ex situ* with depth profiling X-ray Photoelectron Spectroscopy (XPS). These techniques have a high sensitivity for chemical processes. Mo/B/Si and Mo/C/Si structures have also been analyzed as reference systems. The chemical processes in these systems could indeed be identified, with two major stages being distinguished. In the first stage, B and C diffuse and react predominantly with Mo. A $MoSi_x$ silicide forms only in a second stage. In all three of the multilayer systems explored, the first interaction to occur is that of the interlayer material with Mo and, to a lesser extent, with Si. Another process the systems have in common is the formation of $MoSi_x$ with x close to 2, and the segregation of MoB_x or MoC_x that it induces. A major *difference* between the samples is that only when the barrier layer contains C, it forms compounds at two different locations, namely in the Si and the Mo layer, squeezed out from the initial position at the interface by the $MoSi_x$ silicide formed. The presence of C also affects the behaviour of B. In the Mo/B_4C/Si system, for example, B can also be found at two different locations, namely in the bulk and at the surface of the structure, in the form of binary and ternary B-C-compounds (B_xC/SiB_xC_y), and Mo-B componds (MoB_x/MoB_xC_y) (see Figure 2.37 a and b). The non-destructive HAXPES measurements confirmed these compounds, due to its sensitivity already at a lower temperature. This research suggests that it is this complex structure of compounds that determines the diffusion barrier properties of the barrier layer, rather than the barrier itself. These new chemical findings thus suggest formulations of barrier materials with even better properties then the standard B_4C material only.

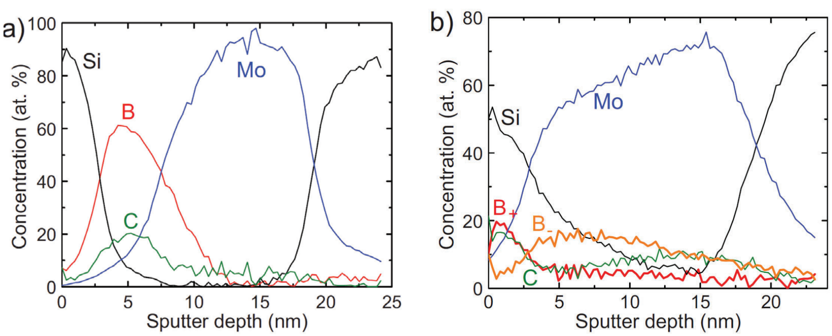


Figure 2.37: XPS sputter depth profiles of the Mo / B_4C / Si sample (a) before and (b) after the annealing treatment. In the sample after annealing the B peak is split into two components, where the B_+ signal is associated with binary and ternary B-C-compounds (B_xC/SiB_xC_y), and B_- with Mo-B componds (MoB_x/MoB_xC_y).

Period changes in boroncarbide-based multilayers

High-flux photon exposure of multilayers may lead to the growth of the materials interfaces, which consequently reduces the optics lifetime expectation from years to, eventually, hours. The required radiation hardness of the optics involves slowing down atom interdiffusion by several orders of magnitude or even fully stopping these processes. Introducing a thin B_4C diffusion barrier layer between the Mo and Si layers is one of the options to reduce interdiffusion. Although such a layer is expected to act as a physical barrier, it seems that the true mechanism is a complex combination of processes involving also a number of chemical reactions at the interfaces. Experiments have shown that $Mo/B_4C/Si/B_4C$ multilayers exhibit a complex response to the applied temperature. At high temperatures (i.e. more than 300 °C), the multilayer period *decreases* during annealing, which is explained by $MoSi_2$ silicide formation. However, at lower temperatures (100 – 250 °C), the multilayer period *increases*. Using grazing incidence x-ray reflectivity, the period changes that take place upon annealing were investigated in six different multilayer systems to identify the particular compound formation responsible for period expansion.

Figure 2.38 shows the period change of Si/B, Si/B_4C, Si/C, Mo/B_4C, Mo/C and Mo/B multilayer systems upon annealing at 200 °C. It can be seen that some material combinations (Si and B, Si and C) tend to form compounds that *expand* the periodicity of the multilayer, while others (Mo and B, Mo and C) form compounds that *compact* the multilayer. From these measurements a conclusion on the chemistry at the interfaces can be made: it is the decomposition of B_4C and subsequent formation of silicon boride which is responsible for the prominent period expansion at low annealing temperatures.

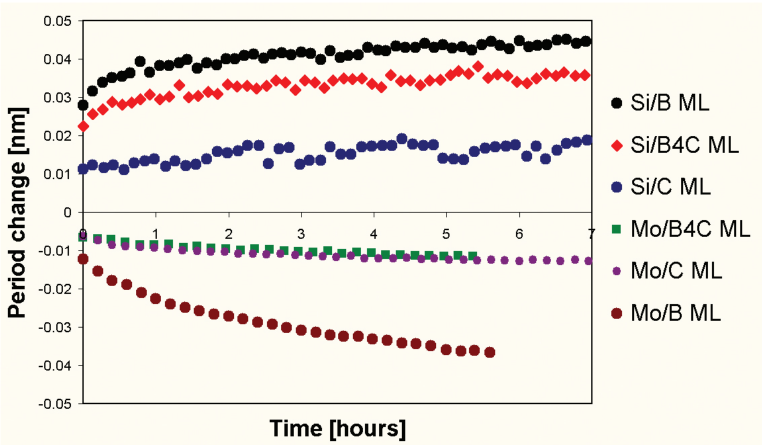


Figure 2.38: Period change as a function of time for various boroncarbide-based multilayer structures during annealing. The Si/B and Si/C multilayer (ML) systems show expansion, as a result of silicon boride formation at the interfaces.

Crystallinity dependent diffusion

Diffusion at interfaces plays a critical role in the development of thin film applications in general. Obviously, the materials state at the interface should be taken into account, since diffusion is known to be dependant on the crystallinity, at least in single interface systems. We have successfully explored the more complex multilayer case in detail. In a Mo/Si multilayer system, the Mo layers grow amorphous up to approximately 2 nm, and become crystalline above this critical thickness. We investigated samples with crystalline (2.8 nm layer thickness) and amorphous (1.3 and 1.7 nm) Mo layers, while applying a thin B_4C barrier layer on either the Mo-on-Si or the Si-on-Mo interface. All samples were annealed at different temperatures for 48 hours in a vacuum environment.

It is known from our previous work that the period change is directly linked to the additional amount of a Mo-silicide interface that is formed during annealing. In Figure 2.39 the period change, determined from X-ray reflectivity measurements, is plotted against annealing temperature. We observed that the period change, and therefore also the diffusion, was clearly larger when the Mo is crystalline than when it is amorphous. In the crystalline case the period change is also dependant on the position of the B_4C barrier layer. This asymmetric diffusion is connected to the differences in the Mo-on-Si and the Si-on-Mo interfaces. Surprisingly, such an asymmetry is not observed in amorphous Mo. This effect is explained by a model that takes into account decom-

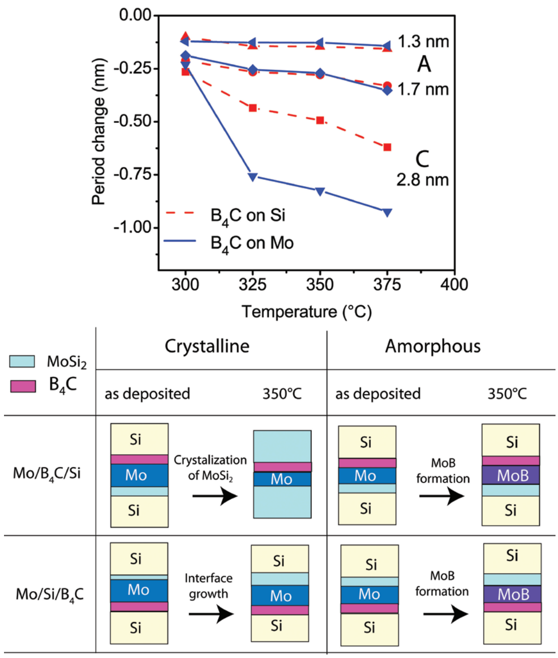


Figure 2.39: Top figure: period change during annealing at several temperatures for multilayers with a single-side B_4C diffusion barrier and amorphous (A) or crystalline (C) Mo layers. Table: morphological changes occuring during annealing in multilayer structures with amorphous or crystalline Mo layers and single-side diffusion barriers.

position of B_4C barrier material and subsequent formation of a MoB compound, which slows down further formation of the Mo-silicide. The changes in the multilayer during annealing are summarized in the table in Figure 2.39. It was concluded that an amorphous morphology of the Mo layers in Mo/Si multilayer structures with B_4C diffusion barriers can lead to improved multilayer stability.

Densification of diffusion barrier layers

Boron carbide (B_4C) is a diffusion barrier material that is most commonly used to improve the thermal stability of Mo/Si multilayer optics, but the dependence of the barrier functionality on the barrier layer properties is sofar largely uncharacterized. We have applied Kr^+ ions during the deposition of these B_4C layers to systematically change its layer properties. Then the multilayered structures were annealed at 200°C and *in situ* X-ray reflection measurements were performed during annealing to monitor the period of the multilayer.

Figure 2.40 shows the multilayer period change as a function of time for multilayer structures with B_4C barrier layers which were partially polished by Kr^+ ions. The percentage of the layer which was polished is indicated in the graph. We observed a clear relation between the thermal stability and the polished layer fraction. This improvement could either be caused by an increased density of the B_4C layer, or by an increased chemical interaction with the material underneath the barrier material. Analysis of the data showed a linear dependence of the diffusion coefficients on the fraction of the barrier layer polished with ions. From this, one can conclude that the effect of improved stability originates from the bulk, rather than from the interface. A verification experiment using thicker B_4C layers showed that the density does indeed

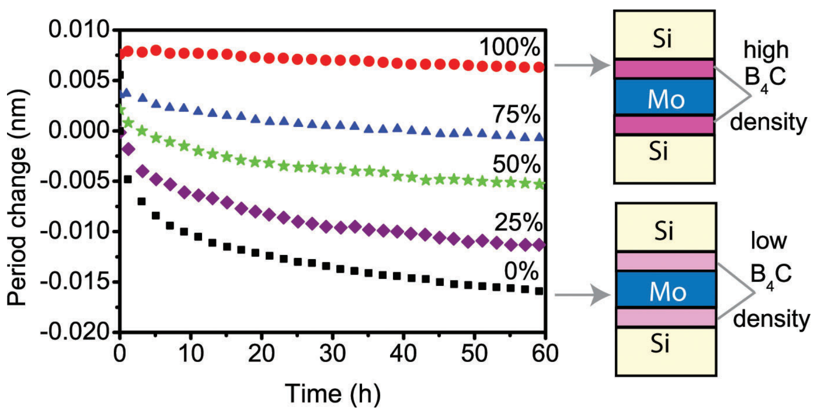


Figure 2.40: Period change versus time for multilayered structures with a part of the B_4C barrier layer polished with ions (percentages indicated). The ion polishing is found to increase the density of the diffusion barrier, which improves the multilayer thermal stability.

increase with the ion polishing. This ultimately leads to the conclusion that the enhanced density of the barrier is the main cause for the increased thermal stability of the multilayer structures in which the barrier layers are ion-polished.

Structural properties of subnanometer thick Y layers

Extreme Ultra Violet light in lithography equipment will be reflected by several multilayer mirror elements. As a consequence, increasing the reflectance of the multilayer structures by even a few tenths of a percent can significantly improve the total throughput of the lithography equipment. Calculations show that the reflectance of Mo/Si based multilayer structures at 13.5 nm radiation can be increased when introducing ultrathin layers to the period. These layers should be of subnanometer thickness to achieve optimal constructive interference. The pilot experiments on introducing 0.2 to 0.6 nm Y layers between the Mo and the Si confirmed these calculations: reflectances of, respectively, 69.1%, 70.0% and 70.3% were measured for Mo/Si, B_4C/Mo/B_4C/Si, and B_4C/Mo/Y/Si multilayer mirror structures, each 50-period stacks. Although these are world records of reflectivity, the full potential has not been realized, since layers tend to intermix during deposition of the multilayer structures. As a result, the reflectance of these multilayer structures is lower then from ideal, non-intermixed structures. Another important parameter limiting the specular reflectance is the roughness of the interfaces of the interlayers.

In order to experimentally approach the reflectivity potential of ideal multilayer systems, the fine structure of the layers was studied at the atomic level. Structural properties of the Y-improved structure were measured using X-ray reflectometry and Extended X-ray Absorption Fine Structure analysis (EXAFS). Rocking curves using Cu-Ka radiation for the Mo/Si, B_4C/Mo/B_4C/Si and B_4C/Mo/Y/Si structures showed no significant differences in average interface roughness to relatively affect their reflection at 13.5 nm. An EXAFS study at the Y K-edge, however, showed that Si indeed diffuses into the Y layer, forming a compound resembling that of YSi2. Measurements at the Mo K-edge showed some even more interesting results. To improve the EXAFS sensitivity to the interface region of Mo and Y, we replaced the major part of the Mo layer by Nb (Nb has very similar crystallographic properties as Mo). The EXAFS measurements at the remaining 0.5 nm Mo below the 0.2-0.6 nm Y layer showed that only 1/5th of the Mo layer formed a Mo_5Si_3 structure. This result is quite remarkable, since for standard Mo/Si systems a much higher intermixed zone of 0.5-1.0 nm is reported in literature. Apparently, even a 0.2 nm thick Y layer could significantly reduce the Mo-silicide formation, and thus improve the reflective properties of such multilayers.

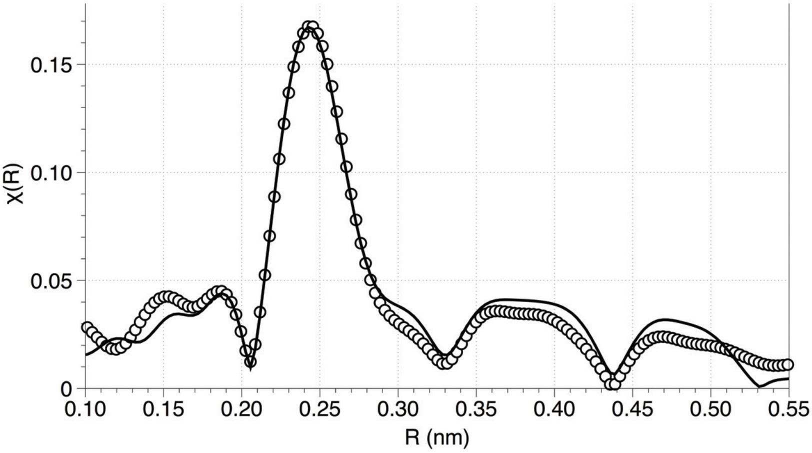


Figure 2.41: Results from EXAFS measurements showing the so-called $\chi(R)$ distribution at the Mo K-edge for a Mo/Y/Si structure with 0.4 nm Y layers (dots) and the model fit to the data (solid line). The model combines contributions from two different structures: Mo and Mo_5Si_3, evidently present in the multilayer stack.

2.11 Advanced applications of XUV optics (AXO)

Group leader:	*E. Louis*
Scientific advisors:	*J. Verhoeven, A.W. Kleyn*
Scientist:	*E. Zoethout*
Postdocs:	*E.D. van Hattum, R.A. Loch, R. Sobierajski*
Graduate students:	*J. Chen, A.J.R. van den Boogaard, I. Makhotkin*
Technicians:	*S. Alonso van der Westen, A.J. van Calcar, K. Grootkarzijn, R.H. Harmsen, P. Sallé, M. Zee*
Funding:*	*FP-110, FP-123, Carl Zeiss SMT, EC, M2i, ASML, STW, FOM*
	** supported by the European Fusion Programme (EFP)*

Research Programme

The general aim of the AXO group is to investigate and develop new XUV- and soft X-ray multilayer processes as well as optical components for applications in various fields. This goal includes research on the physics phenomena of extremely thin, smooth and dense layers and the particular research as originating from their applications.

The focus of the group is currently on various multilayer topics related to EUV lithography with the emphasis on the more applied and technological parts of the FOM Industrial Partnership Programmes XMO (eXtreme UV Multilayer Optics) and CP3E (Controlling Photon and Plasma induced Processes at EUV optical surfaces). Part of these programmes, for instance, is the deposition of multilayers on real mirror substrates to demonstrate the applicability of the processes developed in the AXO group or elsewhere in the nSI department. Such demonstration optics are used in the first EUV lithography machines of ASML.

The group also investigates optical methods to enhance the spectral purity of EUV optical systems. This involves the suppression of two wavelength ranges of parasitic radiation: – UV radiation, e.g. from 100 to 400 nm, intensely present in most light sources for EUV lithography, and – 10.6 μm IR radiation from the laser used for generating plasma EUV light sources. Experimental work on the feasibility and the verification of these methods, including modeling activities, is addressed within a separate PhD project.

Another EUVL related topic is the monitoring of radiation induced contamination on multilayer mirrors. Within the ISitCLEAR project (In situ monitoring of contamination layers on EUV optics at Ångstrom resolution), carried out with M2i, we have developed a functional model based on spectroscopic ellipsometry. This work demonstrates the viability of this detection method for usage in EUVL equipment.

To allow a further enhancement of the resolution of future lithography optics, the group carries out an STW (Dutch Technology Foundation) funded project on multilayers for the short wavelength of 6.7 nm. This work, carried out together with the TFM group, is subject of another PhD programme.

A second line of research of the AXO group is on multilayer applications in beam lines and user stations of X-ray Free Electron Lasers. Extensive studies on damage mechanisms have been carried out and recently a method to study the time and spectral behavior of the femtosecond pulses from this type of lasers has been developed. The hardware has been designed and constructed in 2010 and the proof of principle is expected to be given in one of the 2011 beam time periods at the Free Electron Laser facility FLASH in Hamburg.

Density of ultrathin films through X-ray standing waves

Through STW and Zeiss funding, nSI executes a pilot project on multilayers for the next generation of lithography optics, currently aimed at 6.7 nanometer. One of the most promising material combinations for such Bragg reflectors is La/B_4C or La/B. However, because of the value of its formation enthalpy, La is likely to form LaB_6 instead of pure La when in such layered contexts. A strong indication of this effect is the density of the layer, since this should be reduced by the formation of LaB6. Unfortunately, accurate determination of the density of ultrathin films represents a basic challenge in research on multilayer structures. The commonly used technique of grazing incidence X-ray reflectivity analysis does not provide unique solutions for layers thinner than 10 nm. A solution for this problem is found by analyzing the intensity of the X-ray standing wave formed above a thin La layer when exposed to X-rays at grazing incidence. For a single layer this is difficult to measure, but we enhanced the effect by placing another thin film, a marker film, above the reflector layer (see Figure 2.42), thus forming an X-ray waveguide. As a waveguide cavity material we used B_4C. In this way it was possible to study the La layer in its 'natural' habitat, namely the environment of the buried layer, as opposed to studying it as a delicate thin top layer as in most existing techniques. By measuring the evolution of the X-ray fluorescence from the marker layer while scanning the angle of incidence of the X-rays, we determined the intensity of the electromagnetic field in the waveguide.

Using this technique we have found that the density of a 3 nm thin La layer is much lower then the density of bulk La and equal to the bulk density of LaB_6. In parallel measurement on a similarly thin LaN layer we obtained a density equal to the literature value for bulk LaN. This result clearly demonstrates that in this new way it is possible to reliably determine the density of our thin layers, thus confirming the reduction of the density of a La layer surrounded by B_4C, indicating the formation of LaB_6. This obvious finding is now used to optimize further designs for 6.7 nm optics.

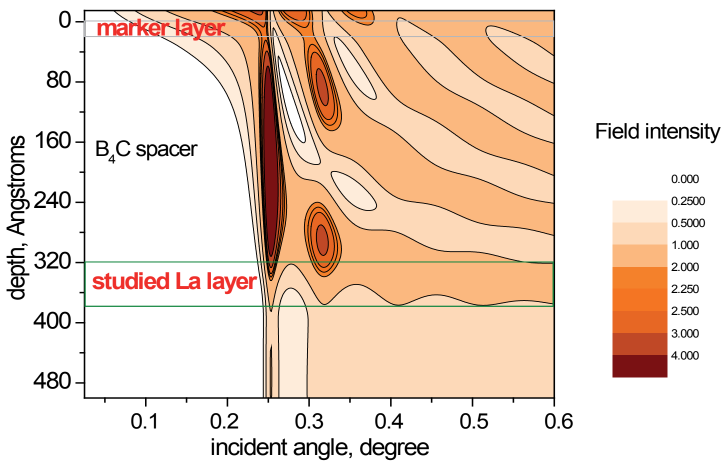


Figure 2.42: Calculation of the angular dependent X-ray standing wave pattern.

Scanning tunneling microscopy on molybdenum silicon layers

An extensive study of molybdenum silicon systems has been performed under the STW project "nano-engineering rules for X-ray and EUV optics: atomic-scale controlled deposition" carried out in collaboration with the University of Leiden. Within this project, a scanning tunneling microscope (STM) has been connected to the Advanced Development Coating facility (ADC), enabling in-vacuum sample transport and probing of as-deposited EUV relevant systems without exposing them to atmospheric circumstances. EUV reflective Mo/Si bilayers have been deposited in a three step process that is repeated several times to produce the desired multilayer. The first two steps consist of the growth of molybdenum and silicon layers and the third step is an ion treatment of the silicon layer to enhance the smoothness of the interface. Figure 2.43 shows STM images of the top surface of 10-period molybdenum/silicon films, the top layer being Mo to assure electrical conductance during STM imaging. Here, Figure 2.43a displays the morphology of growth without ion treatment while Figure 2.43b shows the morphology with periodic ion treatment of the silicon layers. The height contrast is the same for both pictures. It is clearly observed that these height variations are reduced by a factor of 4 due to the ion treatment of the silicon layers. Whereas the height differences of Figure a lead to an unacceptably low reflectivity for EUV optics, the ion treatment applied in Figure 2.43b results in sufficiently smooth interfaces to achieve a near theoretical reflectance, an absolute requirement for EUVL optics.

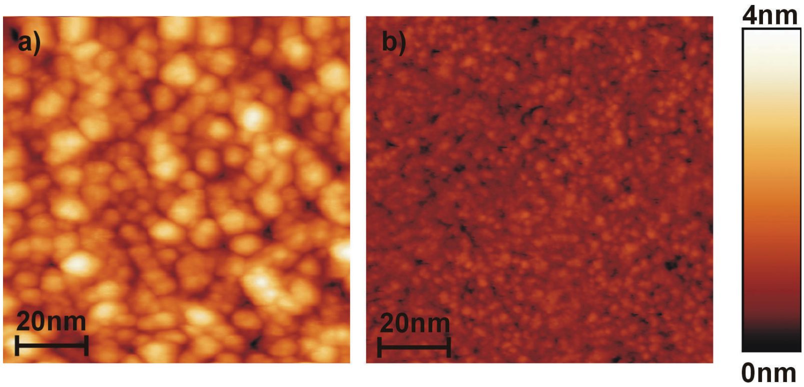


Figure 2.43: Top surface of Si/Mo multilayer film (10 periods) without (a) and with (b) periodic ion treatment of each of the Si layers. The height variations are reduced by a factor of four due to the polishing process.

Influence of H retention in a-Si layer on noble ion induced surface smoothing

In previous years, the practical method of ion polishing was discovered to strongly reduce the surface roughness of mirror substrates. This method relaxes the requirement on the surface finish of mirror substrates and can be applied prior to the deposition of high reflectance multilayer mirrors. However, the physics behind the surface smoothing process has so far not fully been understood. By applying a continuum model of surface roughness evolution, we found that the smoothing kinetics are mainly governed by viscous flow. In the literature, this type of ion-induced viscous flow is reported to have a strictly surface confined character, due to the finite penetration depth (h) of the ions (Figure 2.44 - left). In our analysis, however, we found strong indications of a non-localized component, e.g. mass transport through the bottom interface of the viscous layer (Figure 2.44 - right). This can be associated with in-layer free volume annihilation as facilitated by the relatively porous structure of our Si layer, having a few percent lower than bulk density. To experimentally verify the hypothesis that the in-layer free volume is a determinative parameter in the ion-induced smoothing process, ion-polishing experiments on hydrogenated a-Si layers were performed. Such layers mimick low density silicon, due to the presence of nanoscale in-layer voids filled with chemically bound H or physically trapped H_2. Polishing such films would enable Si atoms to replace H atoms and thus annihilate free volume. The thus obtained experimental data on such porous Si films confirms our hypothesis on a description in terms of viscous flow and free volume annihilation. This means that in practical applications, H-retention in a-Si may be employed to further optimize ion-polishing of surfaces towards ultra-smooth roughness levels (<0.1 nm).

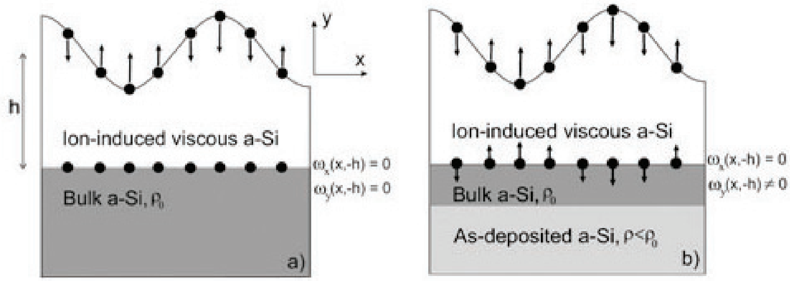


Figure 2.44: a) Ion-induced viscous flow as traditionally assumed to be surface confined. b) An in-layer flow component at the liquid-solid interface is postulated to be caused by annihilation of buried free volume.

Visible-light ellipsometric characterization of EUV optics

Contamination of multilayer EUV optics by carbon is a major threat in the final application of such optics in lithography equipment. Determining the state and composition of the contamination by EUV reflectance measurements is laborious and expensive, since it can only be done in few specialized laboratories world wide.

In a joint project with ASML and M2i, other less demanding methods have been investigated that can monitor the thickness and nature of the mirror contamination equally well. In-situ spectroscopic ellipsometry has been found as a most appropriate method.

Since the reflectance loss of a multilayer mirror is determined by the layer thickness as well as by the density of the carbon layer, it strongly depends on the morphology of the carbon. To study the influence of the various forms of carbon, mirrors contaminated with three types of carbon were investigated: EUV induced carbon, hot filament deposited carbon, and carbon deposited by electron beam evaporation. Spectroscopic ellipsometry was used to determine the carbon layer thickness and the optical constants for the wavelength range from the ultraviolet to the near infrared. The carbon density was determined from the optical constants using both Bruggeman's effective medium approximation (BEMA), and the Clausius-Mosotti (CM) equation. This, in combination with the layer thickness, enabled the calculation of the EUV reflectance loss.

Figure 2.45 shows the comparison between the measured and estimated values based on the two models: both models show a similar reflectance loss that is close to the value measured with EUV light. Most importantly, very good agreement is achieved for EUV induced carbon up to 7% reflectance loss, the range which is most important to the EUV lithography process. This result shows that the more simple method of spectroscopic ellipsometry avoids the need for the laborious EUV characterization, a major advantage for the application of multilayer optics in lithography or other equipment.

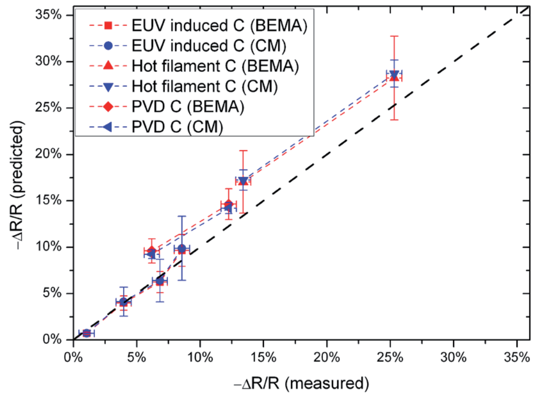


Figure 2.45: Comparison of the relative EUV reflectance loss between the measured and estimated values based on visible light spectroscopic ellipsometry.

X-ray Free Electron Laser single pulse characterization

To take full advantage of the unique properties of the new generation of intense light sources, the short-wavelength Free Electron Lasers (FELs), several challenges have to be surpassed. We are tackling one of the main challenges: to directly characterize the time and frequency structure of single FEL photon pulses of femtosecond duration. We have designed a new type of autocorrelator that records the interferogram of a first part of the XFEL pulse and a time-delayed second part of that pulse. From the Fourier transform of the corresponding interferogram the autocorrelation function can be calculated. The latter is equivalent to a spectrogram because the total interferogram is the superposition of the interferograms from each frequency present in the pulse.

To demonstrate this, we have designed and constructed a flexible diagnostic instrument based on a Fabry-Perot interferometer that contains two semi-transparent multilayer mirrors that can be adjusted with respect to each other. By adding a small tilt to the second mirror, a ‘scan’ of time delays is included in the CCD recorded interferogram (see Figure 2.46). Because of the ultrashort pulse duration (few femtoseconds) and the short wavelength of the radiation, a high accuracy is required. The spacing and angle between the two mirrors can be remotely controlled and monitored with an accuracy of a few nanometers (~10 attosecond time delay precision) by using piezo-controllers and capacitive sensors. The semi-transparent mirrors consist of multilayer beam splitters, as discussed in last years annual report. Further characterization and a first demonstration of the principle of pulse characterization are planned for 2011.

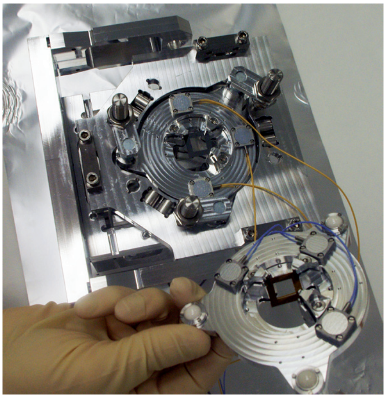
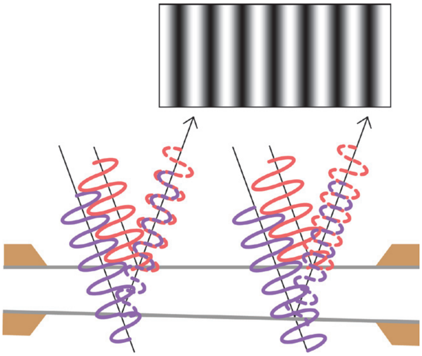



Figure 2.46: Left: part of the interferometer-setup showing the two holders that contain the semi-transparent multilayer mirrors and the capacitive sensors. Right: a schematic drawing of the interferometer with two semi-transparent mirrors.

Demonstration optics for EUV Lithography

A special task within several of our industrially motivated research projects is to apply the latest research findings and verify the processes on realistic mirror systems. The task then is to demonstrate that, also in an industrial process, the strict requirements on reflectance, multilayer induced stress, lateral thickness profile, and matching of the multilayer periodicity to the operating wavelength of full EUV systems, can be met. This can only be shown convincingly by depositing real, so-called demonstration optics to be used in EUV lithography machines of ASML. In this framework several large, both concave and convex optics have been multilayer-deposited and EUV characterized. In this way for instance several new types of diffusion barrier systems could be verified for further inclusion in the industrial roadmap of our partner Carl Zeiss SMT. In order to meet the strict specifications, the coating of the real optics is preceded by iteration runs on dummy substrates that have the same size and shape as the real mirrors.

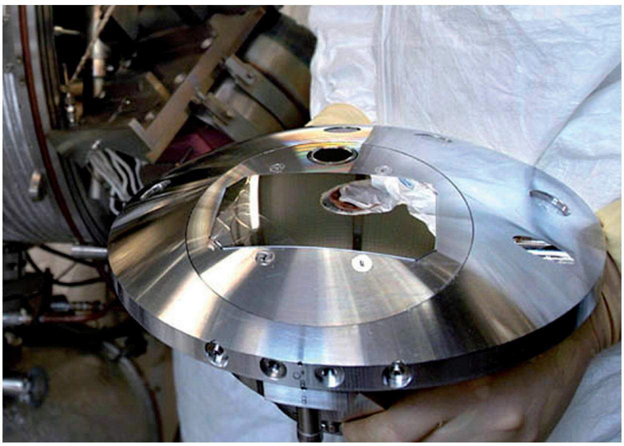
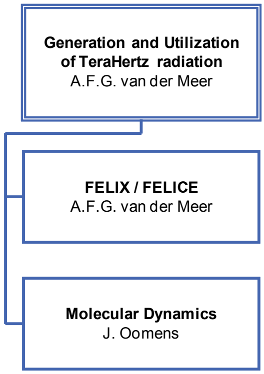


Figure 2.47: Multi-layer coated convex EUV optical element.

Generation and Utilisation of THz-Radiation Division



The Generation and Utilisation of THz-Radiation Division comprises two groups – the FELIX group and the Molecular Dynamics group – that develop free electron laser based terahertz sources and perform experiments in the terahertz spectral range where they among others employ new schemes e.g. in molecular spectroscopy. The division receives financial support under FOM-programme 58. Additional funding is provided through a contract with the British Research council EPSRC and via the ELISA project, an integrated infrastructure initiative under the European framework programme 7, that comprise all European synchrotron and free electron laser facilities; the Molecular Dynamics group participates in the Dutch Astrochemistry Network, and within the group, Dr. A.M. Rijs was supported by a FOm/v grant.

FELIX

First of all, the division exploits the Free-Electron Laser for Infrared Experiments (FELIX) providing continuously tunable radiation in the infrared spectral range of 3-250 μm, at peak powers ranging up to 100 MW in (sub)picoseconds pulses. Since 1994, FELIX is operated as a user facility, attracting user groups from all over the world. Over the years, sophisticated diagnostics and user control have been set up, enabling the users to fully control the relevant characteristics of the FEL radiation for their particular application (laser frequency, bandwidth, power, temporal pulse structure). Auxiliary laser systems, synchronized to FELIX, have been installed to provide multicolour capabilities and dedicated setups for e.g. time-resolved investigations and action spectroscopy using molecular beams and ion traps. The radiation of FELIX is used by scientists from all over the world for research in (bio-) medicine, (bio-) chemistry and (bio-) physics.

FELICE

FELICE stands for Free Electron Laser for Intra-Cavity Experiments. This project, a major extension of the FELIX facility, involves the construction of a third beam line which can be operated interleaved with one of the two FELIX beam lines at a maximum repetition rate of 10 Hz for each line and is therefore in fact doubling the amount of beam time available to the users. The purpose of FELICE is to provide significantly higher infrared intensities for low-absorption, gas-phase experiments. The FELICE beam line is now providing full specifications, and is operated routinely for in-house and external users.

Molecular Dynamics

As an in-house user of FELIX, the Molecular Dynamics group applies the FELIX and FELICE radiation for various experiments in the field of molecular spectroscopy and dynamics, mainly of low-density species in the gas phase. FELIX and FELICE are ideally suited to perform such experiments, as they combine a wide wavelength tuning range, covering the infrared molecular fingerprint region, with high power and fluence. Systems studied include molecular ions, complexes, radicals, metal clusters (complexed with small organics), and biomolecules in specific conformers. The group is now using approximately 25% of the total FELIX beam time.

2.12 The IR user facility FELIX / FELICE

Division:	*Generation and Utilisation of THz Radiation*
Group Leader:	*A.F.G. van der Meer*
Scientists:	*G. Berden, B. Redlich*
Technicians:	*R. van Buuren, G.W. Hendriks, J.F. van Leusden, M. Riet, J.J.B. Stakenborg, C.J. Tito*
Funding:	*FP-58, EPSRC, ELISA, NWO-Groot*

Research Programme

The Free Electron Laser for Infrared eXperiments, FELIX, has been designed with the aim to supply the scientific community with tunable radiation of high brightness in the mid- and far-infrared. The objective of the FELIX-group is twofold: to operate the IR User Facility FELIX and to extend its capabilities in order to offer the international scientific community access to a state-of-the-art IR source.

Since 1994, FELIX operates as a user facility and the number of beam hours produced yearly typically exceeds 3000. Of the beam-time 25% is reserved for the in-house research programme on molecular dynamics, a further 20% for researchers from the UK under a contract with the British research council EPSRC. This leaves 55% of the beam time to be allocated on the basis of submitted research proposals, including 10% for users from EU-countries supported under the ELISA contract. A view into the FELIX vault is shown in Figure 2.48.

Figure 2.48: Picture of the FELIX and FELICE free electron laser showing the three beam lines in the accelerator vault.

Sophisticated FEL diagnostic equipment is available, and the users have full computer-control over all relevant characteristics of the FELIX-radiation, such as wavelength, bandwidth, pulse-energy and duration. Many improvements and extensions have been made to the facility since it became operational. Currently the output of FELIX consists of a few-μs long burst (macropulse) of micropulses. The micropulse spacing within the burst can be either 1 or 40 ns, while the macropulses are repeated with a maximum rate of 10 Hz. The wavelength range covered extends from 40 cm^{-1} to 3700 cm^{-1}. Continuous tuning over an octave is possible in less than a minute. Optical pulses of only 6 cycles, corresponding to a pulse duration of 200 fs at 1000 cm^{-1}, and with peak intensities in excess of 100 MW, can be produced. The maximum micropulse duration is about 100 cycles, which results in a minimum bandwidth of 0.4%. The temporal and transverse beam profiles are close to transform respectively diffraction limited.

The infrastructure of the facility has been continuously improved by installing additional equipment available to the FELIX users including dedicated laser setups that can be used stand alone as well as in conjunction with FELIX. There are ten user stations operational; one of these houses the high-resolution FTICR mass spectrometer, originally funded by the National Science Foundation, in collaboration with two universities from the US. The most recent developments are a laser-desorption molecular beam apparatus funded by a 'NWO middelgroot' grant and the construction of a cold 22-pole ion trap in collaboration with a group from the University of Cologne.

FELIX has been successfully used in a large variety of user-experiments, e.g. pump-probe studies on quantum well and dot structures, vibrational modes of proteins, studies of impurities in transparent solids and multiple photon excitation and ionisation experiments on atoms, (bio)molecules, clusters and nanocrystals. In short, the facility is used by scientists with a range of scientific backgrounds, from materials engineering and physics to chemistry and biology, coming both from the Netherlands and abroad.

Over the last decade, the in-house group 'Molecular Dynamics' has shown that the FELIX output has some unique features that make it highly suitable for IR-spectroscopy of (bio)molecules and clusters, providing structural information which is very difficult to obtain otherwise. The results obtained by the in-house group attracted a number of other user groups. However, as it becomes more and more difficult to put sufficient energy in a single molecule as the wavelength increases, the practical limit for many studies is between 20 and 30 micron. A very significant gain is however possible by performing the experiments inside the laser cavity. The NWO funded project FELICE (Free Electron Laser for Intra- Cavity Experiments), which involved the construction of a third beam line dedicated to gas-phase, intra-cavity experiments, does provide this capability. FELICE can be operated interleaved with one of the two other beam lines, thereby effectively doubling the amount of beam time available to the users. Figure 2.49 shows the present layout.

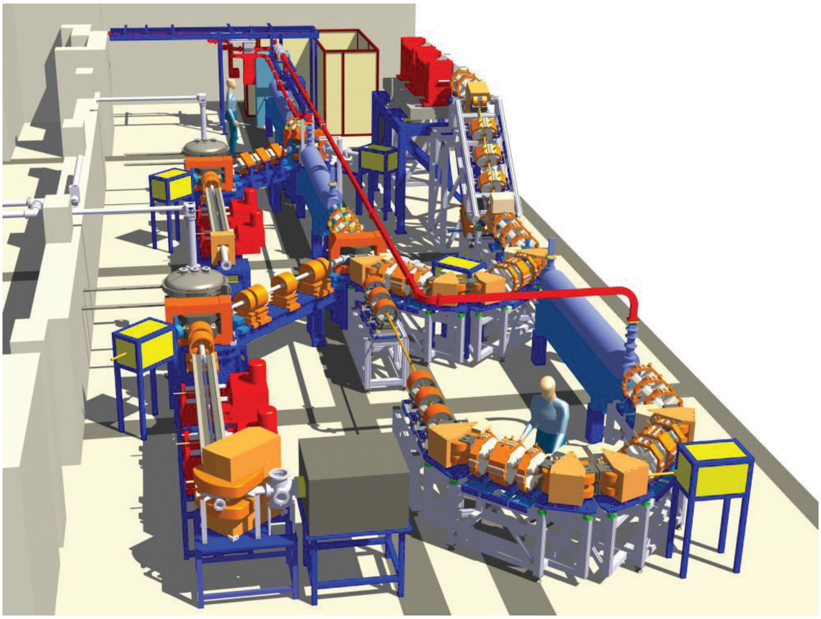


Figure 2.49: Artist's view of the layout of the FELIX and FELICE free electron laser showing the three beam lines in the accelerator vault.

FELICE is now fully operational, covering the wavelength range from 3 to 100 microns at a micropulse repetition rate of 1 GHz or 16.6 MHz. The intra-cavity power available to the experiment is typically a factor of 50 higher than the intensity provided by FELIX at the user stations and the micropulse energy can reach values as high as 2 mJ. One FELICE intra-cavity setup, the molecular beam apparatus, is fully operational and equipped with different sources and detection methods. The capabilities of the second FELICE beam line setup, a highly sensitive FTICR mass spectrometer shown in Figure 2.50 (next page), are currently being explored.

The first experimental campaigns using FELICE already indicated that a broad user community can benefit from this new installation. Experiments on trapped ions, i.e. C_{60}^{+}, on metal-carbides and metal clusters (neutral and charged) and on strong-field ionisation have been performed (see Figure 2.51 on next page).

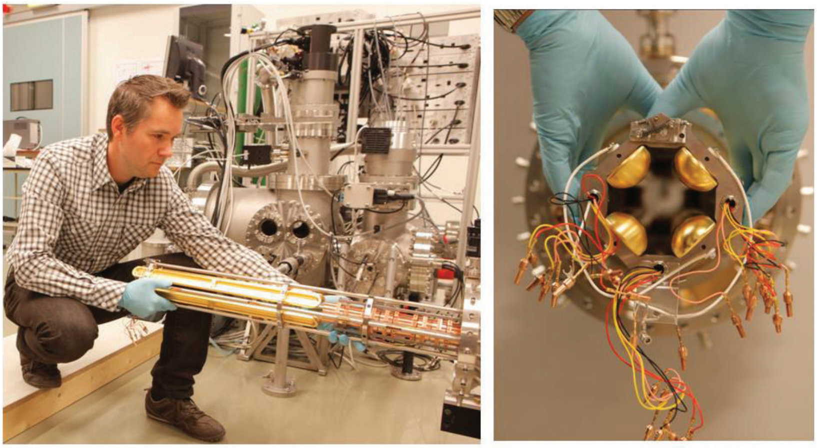


Figure 2.50: The photograph shows the upper part of the FELICE cavity which houses the second intra-cavity experiment, the FTICR mass spectrometer. On the left, besides the mirror chamber, the quadrupole ion guide and the sequence of ICR cells inside the magnet are shown; on the right the quadupole guide is depicted that guides the ions into the FTICR cell.

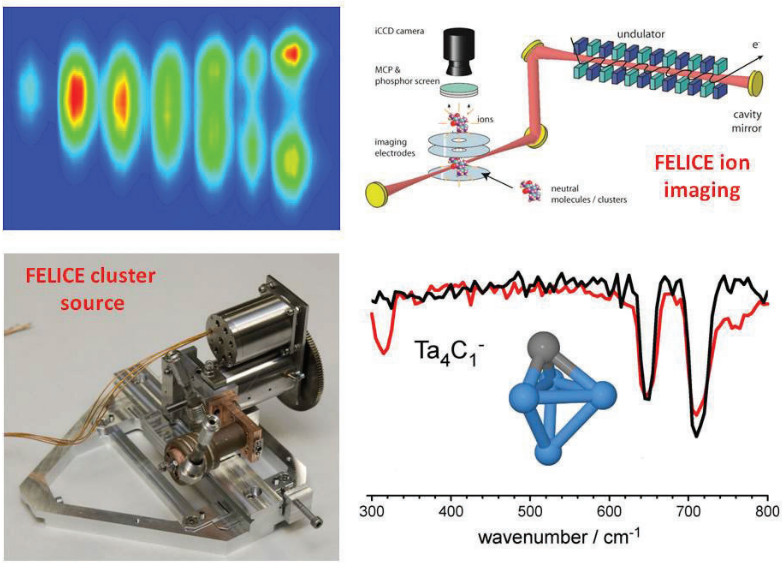


Figure 2.51: The upper part shows the schematic layout of the intra-cavity ion imaging setup and a spatially resolved image of the ionization of C_{60} with FELICE. In the lower part a photograph of the FELICE laser ablation source is depicted together with an infrared multiple photon electron detachment spectrum of the Ta_4C- cluster obtained with FELICE.

Some highlights of user experiments performed in 2010 at the FELIX facility are described in the next paragraphs, while the results of the in-house user group Molecular Dynamics can be found in section 2.13 Molecular Dynamics.

Highlights of user experiments

Quantum-induced symmetry breaking explains infrared spectra of CH_5^+ isotopologues

For decades, protonated methane, CH_5^+, has provided new surprises and challenges for both experimentalists and theoreticians. This is because of the correlated large-amplitude motion of its five protons around the carbon nucleus, which leads to so-called hydrogen scrambling and causes a highly fluxional molecular structure. Here, a group from the University of Cologne has recorded the infrared spectra of all its H/D isotopologues employing the 'Laser Induced Reaction' technique using FELIX. The shapes of the IR spectra measured are found to be extremely dissimilar and to depend strongly on the level of deuteration. All spectra can be assigned based on ab initio quantum simulations. It is found that the occupation of the topologically different sites by protons and deuterons turns out to be strongly non-combinatorial and thus non-classical.

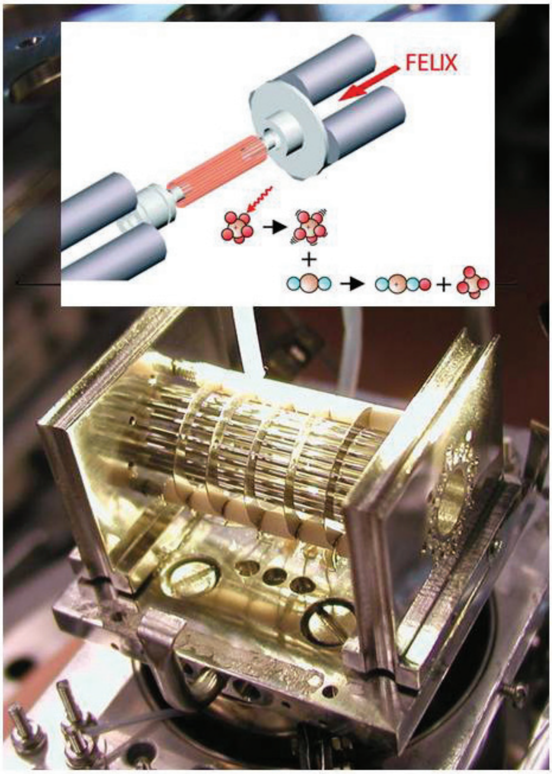


Figure 2.52: Photograph of the cold 22-pole ion trap, the heart of the experimental set-up. The insert shows a schematic representation of the laser-induced reaction scheme.

Coherent control of Rydberg states in silicon

The energy levels of impurities in a silicon host often resemble those of a hydrogen atom. Excited Rydberg states are of particular interest, because these can be used in the quantum control of one impurity atom by another. After excitation, the wavefunction expands from the ground-state extent of less than 0.1 nm to several nanometers and even beyond. This provides a distance range for which two atoms, that are non-interacting in their ground states, are strongly interacting in their excited states. Groups from the University of Surrey and the London Center for Nanotechnology demonstrate the coherent control of electron wavefunctions of the most ubiquitous donor in a semiconductor, phosphorus-doped silicon by using FELIX to stimulate and observe photon echoes and Rabi oscillations. The work adds coherent terahertz radiation, as a particularly precise regulator of electron orbitals, to the list of controls and is a first step towards the realization of a scheme suggested for all solid state quantum computing.

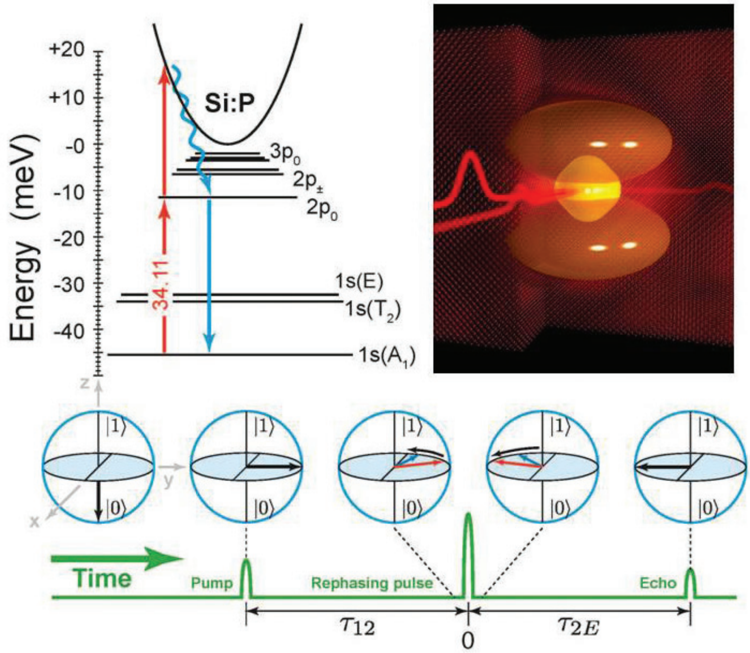


Figure 2.53: The energy levels of a phosphorus donor in silicon are shown together with the experimental pulse sequence resembling the classical Hahn echo. On the right, the electron of a phosphorus atom embedded in the silicon lattice is shown; the ground state electron density distribution and that of the excited state are depicted. The laser pulses indicate the creation of the superposition of states, the control action and the system response in the form of the echo.

Infrared Induced Reactivity: Dissociation of N_2O on Rhodium Clusters

Infrared multiple photon dissociation spectroscopy (IR-MPD) has recently emerged as a powerful technique in determining the structures of small gas-phase transition metal clusters. Monitoring either the depletion of the parent cluster signal or the enhancement of the fragment signal as a function of wavelength provides a highly sensitive method to record the vibrational spectrum of naked and/or decorated metal clusters. This way, a collaboration between groups from the University of Oxford and the Fritz-Haber-Institute in Berlin, has provided evidence for infrared radiation driven surface chemistry on $Rh_nN_2O^+$ clusters. IR-pumping of any vibrational mode of a molecularly adsorbed N_2O molecule results in the dissociation of the adsorbate with the concomitant loss of N_2 and the production of a partially oxidized rhodium cluster.

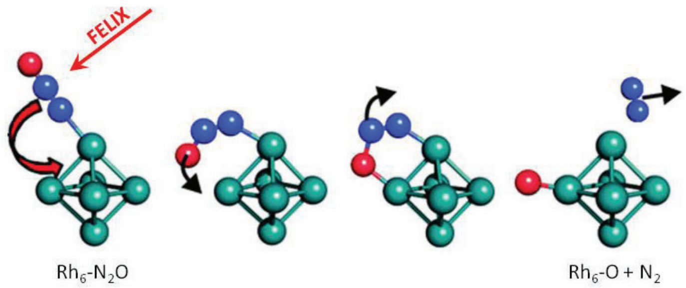


Figure 2.54: Multiple photon infrared excitation of size-selected $Rh_6N_2O^+$ clusters by FELIX drives the surface chemistry resulting in partially oxidized rhodium clusters and the desorption of nitrogen.

Secondary structure of peptides: Helical or not?

The polyalanine-based peptide series Ac-Ala_n-$LysH^+$ ($n = 5-20$) is a prime example for showing that a secondary structure motif that is well-known from the solution phase (here: helices) can be formed in vacuo. Groups from Berlin revisited the series members $n = 5,10,15$, using density functional theory for structure predictions, which are then corroborated by room temperature gas-phase infrared vibrational spectroscopy recorded with FELIX. Employing a quantitative comparison and in particular, including anharmonic effects into calculated spectra by way of ab initio molecular dynamics produces remarkably good agreement between experiment and theory. In summary, calculations for longer molecules ($n = 10,15$) produce similarly good IR spectra based on essentially only one conformer (α-helical). In contrast, the lowest-energy conformer of Ac-Ala_5-$LysH^+$ is not a simple helix. At finite T, both non-helical and α-helical H-bond networks are competitive in energy. The predicted structures lead to AIMD-derived anharmonic IR spectra, which match experimental IRMPD results convincingly well.

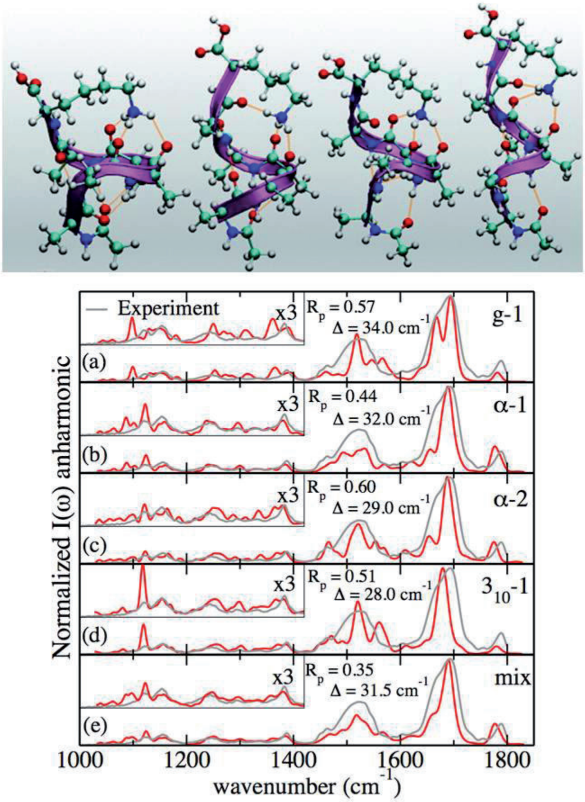


Figure 2.55: Top: Visualization of four low-energy Ac-Ala_5-$LysH^+$ conformers. Bottom: (a−d) Theoretical anharmonic vibrational spectra (red lines) for the four chosen conformers of Ac-Ala_5-$LysH^+$ compared with experiment (gray line); (e) optimum calculated spectrum when assuming a coexistence of more than one conformer in experiment. The lowest Pendry R-factor indicates the best fit for the mixed conformer spectrum.

FELICE : Time-resolved holography with photoelectron waves

Ionization is the dominant response of atoms and molecules to intense laser fields and is at the basis of important new techniques, such as the generation of attosecond pulses by high-harmonic generation (HHG), laser-induced diffraction and high-harmonic imaging. Under suitably chosen experimental conditions, an angle- and energy-resolved measurement of photoelectrons produced by a strong laser field can be viewed as a hologram of the atomic or molecular core. A group from the AMOLF Institute in Amsterdam has performed experiments where metastable Xenon atoms are ionized by intense 7 μm laser pulses from the free electron laser for intra-cavity experiments FELICE. The ionization process is monitored using velocity map imaging. The observed structures in the recorded hologram result from the underlying electron and nuclear dynamics. The interference effects occur on a sub-laser cycle (i.e fs or sub-fs) time scale, opening the way to photoelectron spectroscopy with a time resolution almost two orders of magnitude higher than the duration of the ionizing pulse, which can e.g. give insight in important chemical reactions.

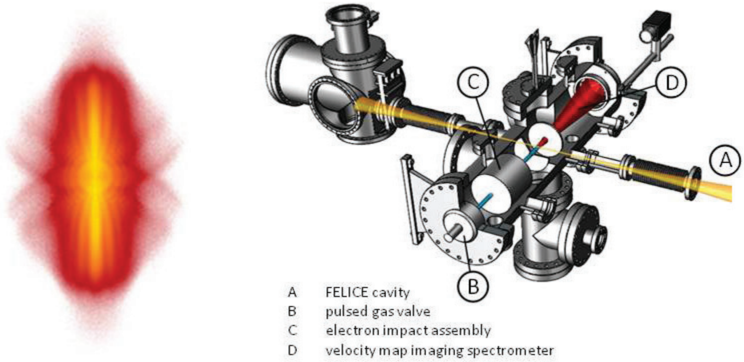


Figure 2.56: Velocity Map Imaging of the ionization of Rydberg atoms using FELICE. An image of the Xe atom ionized at 7 μm is shown on the left. The experimental configuration of the VMI set-up in the FELICE resonator is depicted on the right.

2.13 Molecular Dynamics

Group leader:	*J. Oomens*
Senior Scientist:	*J.M. Bakker, A.M. Rijs*
Postdocs:	*J.D. Steill*
Graduate students:	*H. Alvaro Galué, V. Lapoutre, S. Jaeqx, J. Grzetic*
Undergraduate students:	*J. van Maurik, G. van Zundert*
Collaborators:	*P.B. Armentrout, (Salt Lake City, UT), W.J. Buma, (UvA, Amsterdam), I. Compagnon (Lyon, France), R.C. Dunbar (Cleveland, OH), J.R. Eyler, A. Bratjer-Toth, N. Horenstein, N.C. Polfer M.T. Vala (Gainesville, FL), J.A. Fernández (Leioa, Spain)I. Fischer (Wurzburg, Germany), G. Giorgi (Siena, Italy), G. Glish(Chapel Hill, NC), G. von Helden (Berlin) B. Martinez-Haya (Seville, Spain), T.H. Morton (Riverside, CA), R. Nieckarz, (ETH Zurich, Switzerland), M.T. Rodgers (Detroit, MI),V. Ryzhov (DeKalb, IL), M. Schäfer (Cologne, Germany), M. van Stipdonk (Wichita, KS), V. Turco Liveri, L. Ceraulo (Palermo, Italy) U. Verkerk (Toronto, Canada), M.S. de Vries (Santa Barbara, CA),E.R. Williams (Berkeley, CA), W. v.d. Zande, R.T. Jongma (RU, Nijmegen)*
Technician:	*J. Pluijgers*
Funding:	*NSF-PIRE, CW/NWO-VENI, FOM/v, CW/NWO – Athena, CW/NWO-Dutch Astrochemistry Network*

Research program

As in-house user of the FELIX free electron laser facility, the Molecular Dynamics group uses IR radiation from FELIX and FELICE to investigate the spectroscopy and structure of a variety of low-density species in the gas phase. Systems studied include molecular ions, complexes, radicals, metal clusters, and biomolecules in specific conformations. These gas-phase species are produced in minute quantities only, so that direct absorption spectroscopy cannot be applied. The wide wavelength coverage of FELIX combined with its high pulse energies provide an excellent opportunity to apply several so-called *action spectroscopy* schemes. To this end, various experimental methods are deployed, all based on IR excitation followed by mass spectrometric ion detection (TOF and FTICR). These methods include molecular beam, laser double resonance, and ion storage techniques. Our scientific interest focuses mainly on systems of biomolecular, mass-spectrometric, nano-technological and astrochemical interest. In addition, many collaborative studies are carried out with international users of the FELIX facility.

Mission

To employ the high IR spectral brightness of FELIX and FELICE to investigate the structure, spectroscopy and dynamics of gas-phase molecules, ions and clusters of interest in fields as biochemistry, mass spectrometry, astrochemistry, catalysis and nano-technology. We constantly aim to improve and develop spectroscopic methods to increase the information that can be extracted from the interaction with intense IR radiation.

Reaction mechanisms underlying peptide sequencing

The primary structure of peptides and proteins, i.e. the amino acid sequence, is nowadays routinely determined by collision induced dissociation (CID) of the peptides in a tandem mass spectrometer. Comparison of the resulting fragment mass peaks with fragment mass spectra in a database is then used to reconstruct the original amino acid sequence. Although the molecular weights of the parent and fragment ions can be determined to high accuracy, the reaction mechanisms underlying low-energy peptide dissociation remain only partially understood. An important question is whether rearrangement reactions following collisional activation and dissociation induce scrambling of the amino acid sequence. Such scrambling could occur if cyclization and subsequent re-opening of the macrocyclic ring occur. IR spectroscopy of protonated peptides and their fragments is therefore used to investigate CID fragment structures.

In a collaboration with Prof. Nick Polfer (University of Florida), IRMPD spectra of a number of *b*-type CID fragments of oligoglycine peptides of varying length have been recorded. Depending on the length of the fragment, these spectra give clear evidence for the formation of macrocyclic structures. These structures can be identified by comparing their IR spectra with those of synthetically prepared cyclic peptides with the same sequence, which is done in collabora-

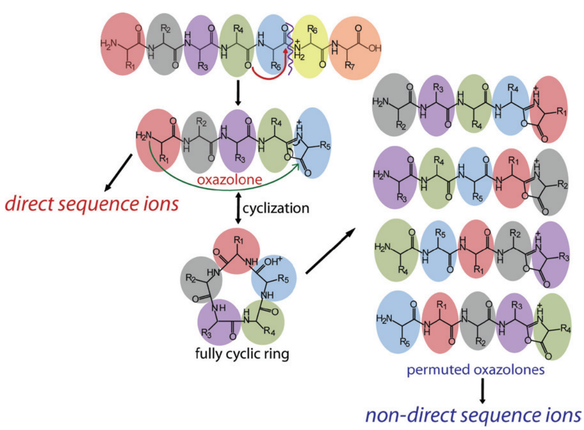


Figure 2.57: The so-called b/y fragmentation pathway entails the cleavage of the amide bond of a peptide and results in a fragment with a 5-membered ring type structure. Subsequent rearrangement reactions may generate macrocyclic structures, which upon re-opening may result in permuted peptide sequences.

tion with the group of Dr. Jan van Maarseveen at the University of Amsterdam. Furthermore, the IR studies have been combined with gas-phase H/D exchange studies on the CID fragments performed at the University of Florida, which yield complementary information in the sense that they give the ratio of macrocyclic over linear fragment structures.

IR spectroscopy of polyaromatics: N-containing PAHs

Based on a set of typical IR emission features observed toward many galactic (and even extra-galactic) sources, large polyaromatic hydrocarbons are believed to incorporate around 10% of the interstellar carbon. Details of the interstellar emission spectrum can be used to determine the local physical conditions, if such spectral details can be related to specific classes of PAHs, for which laboratory spectra are available. For instance, the local degree of ionization can be assessed from specific band ratios in the IR spectra of the PAHs.

The interstellar emission band near 6.2 μm ($\approx$1610 cm^{-1}) has been subject of considerable debate as its position is not easily explained by the spectra of the regular PAH series. The exact position of this band has been suggested to be influenced by the incorporation of a nitrogen atom in the hexagonal carbon framework. Here we investigate the spectra of such N-containing PAHs experimentally in their cationized state. The N-PAH can be ionized by UV irradiation forming a radical cation, but can also be protonated forming a closed-shell species. Our experiments show that the IR spectra of these species are considerably different, particularly in the 6.2 μm spectral range: the closed shell species have the aromatic CC stretching mode located closer to 6.2 μm, whereas the radical species feature this band at a somewhat red-shifted position, around 6.4 μm. Further experiments have shown that a similar shift is observed for regular PAH ions (i.e. not containing a nitrogen atom).

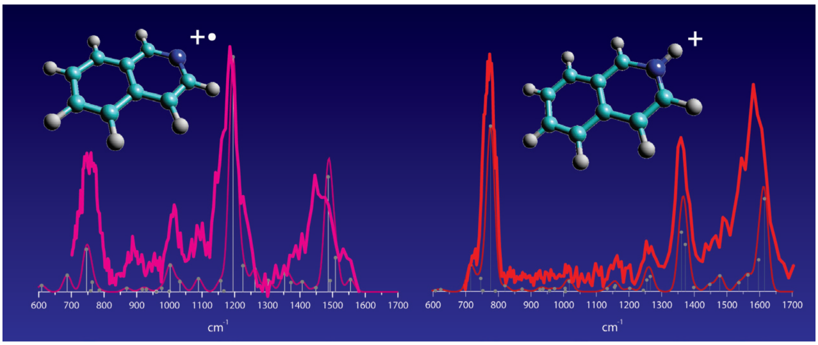


Figure 2.58: IR spectra of the ionized nitrogen containing PAH isoquinoline. Note how the CC stretching band in the 1500 – 1600 cm^{-1} region shifts to the blue in the closed-shell species as compared to the radical cation.

The structure of anionic peptide fragments

The structures of collision induced dissociation products of protonated peptides have been under detailed scrutiny because of their importance in understanding the chemical reactions that occur in mass-spectrometry based peptide sequencing methods. While such methods are commonly applied using protonated peptides, most modern mass spectrometers can easily switch between positive and negative ion mode and sequencing information from the anionic, deprotonated peptide is a straightforward way to increase sequence coverage. The dissociation chemistry of anionic peptides has not nearly been investigated as much as that of protonated peptides and here we set out to determine product ion structures of anionic peptide fragments.

Anionic peptides containing no acidic residues are likely deprotonated on the C-terminus, forming a carboxylate anion. Upon dissociation, both N- and C-terminal fragments are formed. While C-terminal fragments likely have the negative charge on the carboxylate terminus, an important question is where the charge is located in N-terminal fragments. Here we investigate the structure of the a_3 fragment of deprotonated trialanine, which is formed by CO_2 loss from the parent peptide anion.

In the fragment, deprotonation can occur along the peptide backbone either on one of the amide nitrogen atoms, forming an amidate anion, or on one of the C_α-atoms, forming an enolate anion. Both structures are resonance stabilized, effectively delocalizing the negative charge over multiple heavy atoms. Comparison of the FELIX-recorded IR spectrum of the a_3- fragment anion with that of the conjugate base of N-methylacetamide (a model system for an amide bond) and with spectra calculated for the two possible motifs, it is shown that the fragment has an amidate structure.

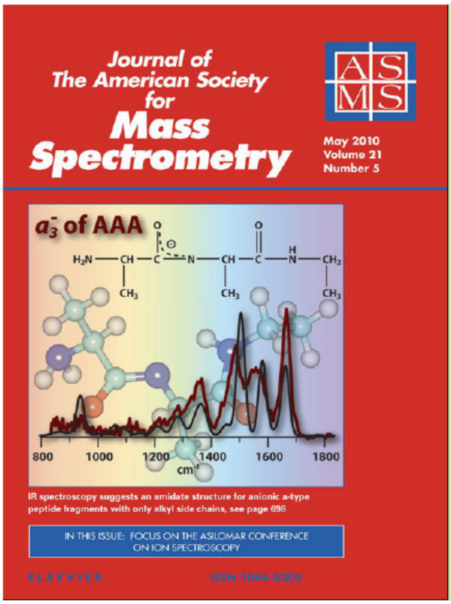


Figure 2.59: Comparison of the experimental IR spectrum of the anionic a3 fragment of deprotonated trialanine with the theoretically predicted spectrum for an amidate (amide N deprotonated) fragment structure. The figure was featured on the cover of the May 2010 issue of JASMS.

Far-infrared spectra of ionic polyaromatics

Although polycyclic aromatic hydrocarbon (PAH) species are widely accepted to be an important source of IR emission detected from the interstellar medium, in particular in the form of the so-called Unidentified IR bands (UIRs), no direct match for an individual PAH has been established to date. The far-infrared spectral range may be of interest in the identification of specific PAHs as the spectra are known to be more species-specific at longer wavelengths. Recently commissioned spacecraft based IR instruments have extended the observational data into the far-IR, so that the need for laboratory data at longer wavelengths has become urgent.

In our aim to extend IR spectroscopy of cationic PAHs towards longer wavelengths, we have used the FELICE intracavity free electron laser to record the IR spectra of several PAH cations down to 200 cm^{-1} (corresponding to wavelengths of 50 μm). The spectra are measured via IR multiple photon dissociation (IR-MPD) spectroscopy, in which the absorption of hundreds of resonant IR photons leads to the fragmentation of the ion of interest. The recorded spectra will be used as benchmark for quantum-chemical calculations that are employed to model the molecular composition of the interstellar medium and for direct comparison with observations to identify individual ions.

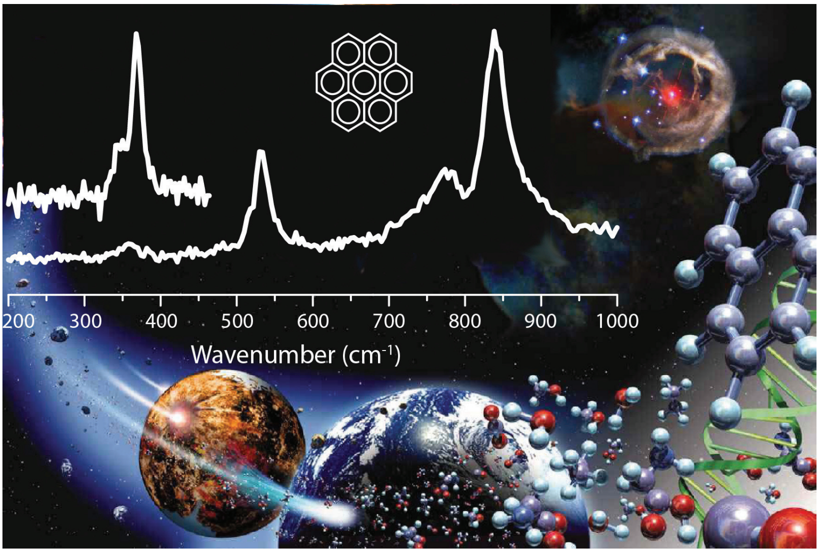


Figure 2.60: Far-infrared spectrum of the gas-phase coronene cation ($C_{24}H_{12}^{+}$) recorded at FELICE.

Peptide structures in hydrophobic environments

In their natural physiological environment, proteins and peptides carry electric charges due to protonation and deprotonation of basic and acidic residues, respectively. These local charges are stabilized by interactions with surrounding ionic and polar species. Once this stabilizing environment is removed, one may wonder whether charged sites can still exist. Such questions may provide further insight into the structures of hydrophobic pockets, which occur as the reaction centers of many proteins.

In collaboration with researchers from Lyon and Paris, we demonstrate that "auto-zwitterionization" can occur in the local environment of an overall neutral, isolated peptide, in complete absence of interactions with the external biological environment. The transition from the canonical to the zwitterionic form is induced by designing a peptide with an acidic (Glu) and a basic (Arg) residue. The absence of a free acid C=O stretching vibration in the 1740-1800 cm^{-1} region (blue) suggests that the peptide is purely in its zwitterionic form. In addition, the symmetric carboxylate stretch mode (yellow) provides a complementary probe of the zwitterionic structure. Note that the peptide termini have been protected so that they cannot protonate or deprotonate. The strong propensity for internal proton transfer is confirmed by theoretical investigations.

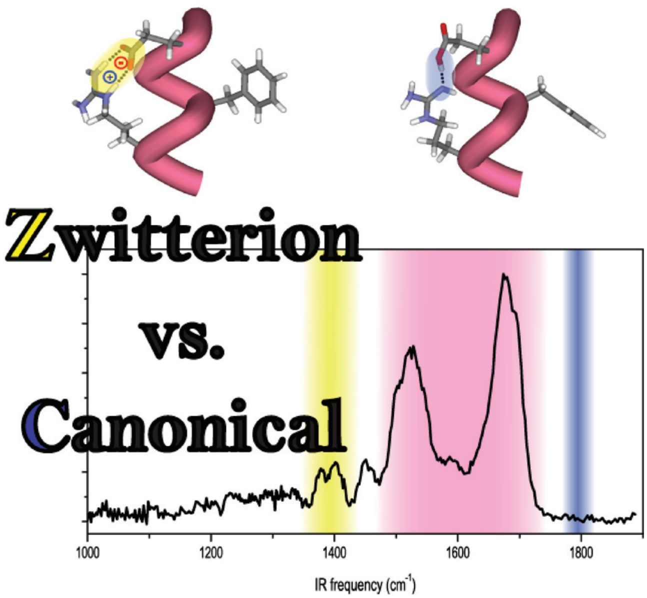
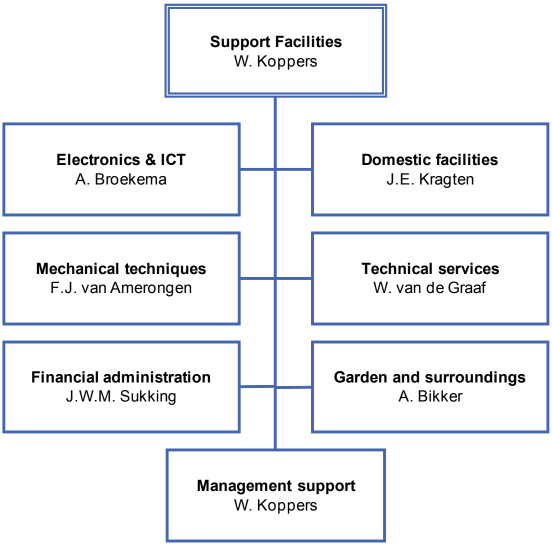


Figure 2.61: Structure of the canonical and zwitterionic forms of the peptide (left). IR spectrum of the peptide showing the presence of a carboxylate stretching mode (yellow) and absence of a carboxylic acid band (blue). The peptide amide vibrations are shaded in pink.

2.14 Support Facilities

Division: *Support Facilities*
Department Head: *W.R. Koppers*



The Support Facilities division, which is headed by the institute manager, consists of two technological groups, i.e. Mechanical Techniques and Electronics and IT, and three groups responsible for general support:

Technical groups:
- Mechanical Techniques
- Electronics and Information Technology

General support:
- Management Support
- Financial Administration
- Domestic Facilities

Mechanical Techniques

Group leader: *F.J. van Amerongen*
Personnel: *M.P.A. van Asselen, A.G.M. van den Bogaard, J. Lagerweij, B. Lamers, R. van de Meer, R.S. van Mourik, L.W.E.G. Römers, A. Tamminga, C.R. Wolbeer, P.M. Wortman*

The group Mechanical Techniques consists of the two subgroup Design department and Workshop. The main responsibility of the group is the design and manufacturing of equipment used for scientific research. The group also advises scientific groups and research technicians on mechanical constructions, and provides help with the assembly of the experiments.

The design software in use is Catia V5, the leading solid modeling software used in fusion research. It provides the possibility of modeling assemblies and automatic generation of workshop drawings. For more complex analyses, like strength and stress analysis, heat load analysis, kinematical analysis and frequency analysis Abaqus is used. All data, used and produces during the design face is stored and managed with the help of SmarTeam, a PDM system. The manufacturing of the designed equipment is done using several machines, including CNC milling and lathing machines. Hypermill is the CAM software used as an interface between design software and CNC machines. The group also has the knowledge and equipment required for vacuum and high temperature brazing and TIG and laser welding.

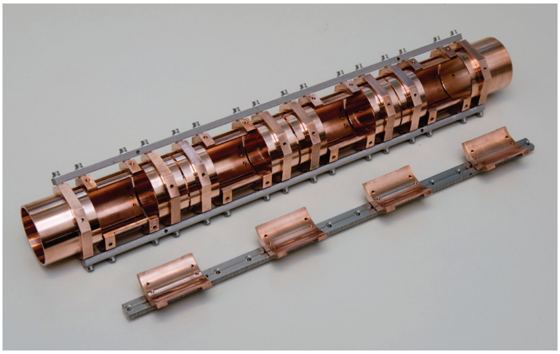


Figure 2.62: Part of the Fourier-Transform Ion Cyclotron Resonance Mass Spectrometer made for Felice.

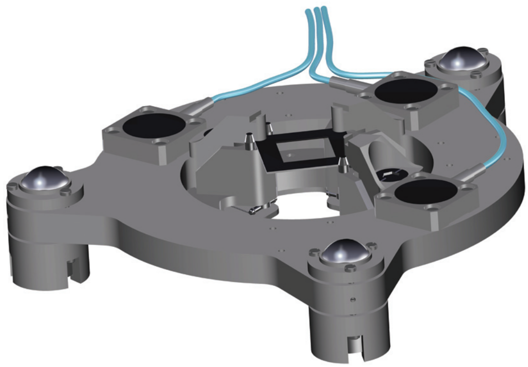


Figure 2.63: Membrane holder, part of the Puls Duration Interferometer, designed for Xfel.

Electronics & ICT

Group Leader: *A. Broekema*

Personnel: *V. van Beveren, M.T. Breugem, P.J. Busch, J.W. Genuit, E.B.W. Goes, A.F. van der Grift, P.W.C. Groen, M. van der Kaaij, G. Kaas, J.J. Kamp, B.J.M. Krijger, S.W.T de Kroon, G. Land, W. Melissen, A.J. Poelman, C.J. Theunissen, A.J.H. Tielemans, F. Wijnoltz, R.W. Zimmerman.*

The Electronics & ICT (E&I) group consists of three subgroups: Electronics, Software Engineering and IT-Support. E&I is responsible for electronics and IT equipment used in all programs and projects, and for the general IT infrastructure. The equipment is selected either from commercial suppliers, or custom designed and manufactured in-house. The latter includes a wide variety of analog, digital, high voltage, and power electronics. The electrical engineers in the group cover a broad range of disciplines to meet the need for general electronics designs.

Additionally, specialisations in VHDL-FPGA-based designs and applications with a mix of high frequency, high voltage and/or high current allow the engineers to meet the challenging requirements of advanced experimental setups. Projects during 2010 include to name a few, a high power capacitor bank to pulse 60 kA into a plasma, computer simulations of magnetic fields, ohmic heating, a study about an extreme low noise amplifier, remote control and cross point switch for Felix / FELICE, many PCB (Printed Circuit Board) designs.

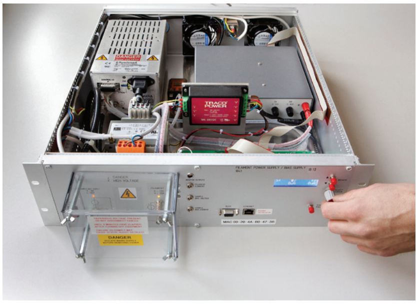
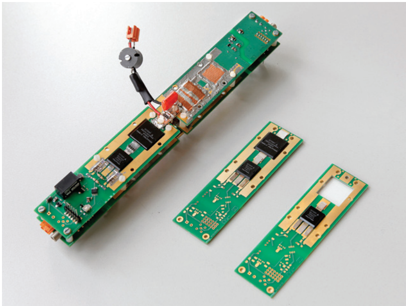



Figure 2.64: Prototype of a scalable high voltage switch, capable of switching 2 kilovolt in 5 nanoseconds

The software engineers in the E&I group design, implement and maintain automated safety, control and data acquisition systems of the various diagnostics and experiments. This includes FELIX / FELICE, the ADC and MUCO coater setups of nSI, and the new Magnum-PSI facility. The designs are based on available software packages such as LabVIEW, Python and HDF5, and hardware platforms such as commercial PLCs (programmable logic controller), PC's with PCI and/or PXI I/O cards, and in specific cases, in-house custom electronics. The software project for the Magnum-PSI project has been made ready during 2010 for basic operation. The development team will now focus on diagnostics.

The general Rijnhuizen IT infrastructure includes all computer, communication and information related technology in the institute, including all PCs, laptops, servers, storage, printers, and network infrastructure. Both Windows and Linux operating systems are supported. An in-house computing cluster is available for running small computation jobs and developing computation jobs for the large Lisa cluster at the SARA computation facility at the University of Amsterdam. In 2010 a new issuetracker has been introduced to strengthen the software development process, the software revision system has been upgraded from cvs to Subversion, a complete new intranet build with Drupal went life, the storage system has been replaced, ca. 50 systems migrated from

Windows XP to Windows 7, stand-alone PGP functionality was replaced by a central PGP server and last but not least, the last remaining hardware servers have been virtualized.

Figure 2.65: Control, Data Acquisition and Communication systems of the Magnum-PSI linear plasma experiment.

Management Support

Group Leader:	*W.R. Koppers*
Personnel:	*E.M. Khan, A.A. de Ridder, T. Tsarfati, M.J. van Veenendaal, M.D. van der Vlis, I.H. Vörös, E.C.M. van Wijk*

The main tasks of the secretariat are to provide management support to the director and the division heads, handling travel requests, managing agendas and supporting various boards and meetings. The library provides access to all relevant journals in the fields of research. Following trends in electronic publication a significant reduction in hard copy journals has been achieved. Since Rijnhuizen is rather unique in the way in which it has organized access to the technical support groups, the procedure is described in more detail below.

Planning

The central planning group supports project managers, the heads of the technical departments and the Institute Management at Rijnhuizen by:

- Providing insight into the activities related to the technical (sub-) projects necessary for running FOM-programmes;
- Making visible the anticipated duration of projects;
- Identifying milestones for (sub-) projects;
- The coordination of activities related to the running projects, which is necessary for an optimal use of the resources of the technical groups;
- Providing insight into bottlenecks.
- Producing personal planning lists for each individual employee;
- Spreading the workload;
- Generating managerial information from the project planning schemes.

Planning meetings

Projects are constantly on the move and the planning needs to be adjusted continuously. Therefore, project planning meetings are held on a regular basis to discuss project progress. Planning and milestone overviews are discussed during the 3-weekly Technical Coordination Committee (TCC) meetings.

Project Information Feedback

In addition to the planning meetings once every 3 weeks, the heads of the technical departments, the project-leaders and the assistant project leaders are requested to fill in the hours that their staff members have worked on a project in a project-progress-information-form, in order to enable adjustment of the project plans. This information is used to monitor the project progress and to revise the personal planning lists of the employees of the Technical and Experimental groups.

Planning tools

Oracle Primavera P6 is used as planning tool. With Primavera P6 we have a powerful and future-proof planning tool, which gives us the opportunity to further improve the quality of the planning. Primavera P6 has the possibility to interface with several time-registration programs. At Rijnhuizen we use TimEnterprise as time registration program. A part of the project progress information is obtained via this time-registration system. In addition to this, Primavera P6 has features to improve information provision to project members and heads, such as the Web-based user interface. In the future a further implementation of Primavera P6 is foreseen.

Project control

There is a trend within the FOM Rijnhuizen organization that scientists experience an increase of project management tasks in their work load. Therefore there is a need for a project control officer to support scientists with tasks as contract formation, tracking and reports and accountability t subsidizers. Early in 2009 a working group project control was formed to investigate the needs and to come up with a plan to implement project control within the FOM Rijnhuizen organization. The plan was presented to the management in the spring of 2010 and is now implemented in the institute.

Financial Administration

Group Leader:	*Interim Financial manager: C.M Visser*
Personnel:	*J.W.M. Sukking, N. Nobbenhuis-Versluis, A. Reinders, M.J. Lubbers, E.C.M. van Wijk.*

The activities of the financial administration group include ordering goods, checking invoices, charging the appropriate budgets, project administration and managing the storeroom. The bookkeeping is done on a FOM-wide system. As an example, each year about 4300 incoming invoices and 1600 outgoing orders have to be handled. The large number of externally acquired projects and contracts from a variety of funding agencies, often with different rules regarding accountability and matching, makes project administration an increasingly complex activity. A web-based time registration system is implemented for all employees. In close collaboration with the institute manager the detailed budget for each year is drafted and implemented. Information for the budget holders is provided on a web server by means of in-house developed software application.

Domestic facilities

Group Leader:	*J.E. Kragten*
Personnel:	*A. Bikker, J.C. Bleijenberg-Maarsseveen, W.K. van der Graaf, F.F. Hekkenberg, M. Kloosterman, E.P.A. de Korte, J.M. Rietveld-Nieuwhoff, S. van Schaik, P. Stekelenburg, J.B. Uwland, L.M. van de Ven-van den Akker*

Technical and domestic services are responsible for building maintenance and installations, such as heating, cooling and power. Also the maintenance of the historical mansion and park surrounding the buildings is included. The reception desk handles all incoming general phone calls and monitors admittance to the Rijnhuizen buildings. The safety officer is responsible for safety and taking all necessary measures to ensure healthy working conditions. The responsibilities include radiological and environmental safety. Rijnhuizen has a team of about 15 employees trained in first aid, fire extinguishing and accident prevention.

Personnel services (Human Resources)

Group leader:	*C.G.L.M. Heling (personnel advisor)*
Members working for this group:	*P.J.C.E. Reimus and C.T.M. Vermeulen – Stavenuiter (Management Support)*

Tasks of Personnel Services Rijnhuizen are:

- Application of the Collective Labour Agreement for the Dutch Research Centers and of FOM/Rijnhuizen regulations; arrangement of contracts with employees and administration of personnel information.
- Advice and assistance to group leaders and the Management Team with respect to personnel management tasks and HR-instruments such as: recruitment; performance and appraisal interviews; support for sick employees; job profiles and remuneration; training and education.
- Advice and assistance with respect to organisational issues.
- Information to employees and supervisors about internal policies and regulations. Information and assistance on external regulations and procedures: retirement pensions, social security (unemployment / sickness / disability); work- and residence permits for foreign employees
- Development of new personnel management policies and instruments.

3

Outreach to academia, society and industry

3 Outreach to academia, society and industry

The Institute considers the education of students and trainees in a research environment, as well as the communication of scientific results and the excitement of scientific research to a wider public, of great importance. Over the last few years, secondary schools have become an important target of the outreach programme. In this chapter we report on the activities of the institute in the following categories:

- Training and education of graduate students
- Activities aimed at undergraduate students of science at universities, and trainees at different levels of technical education
- Activities directed at the top forms of secondary schools
- Activities aimed at the general public
- Activities aimed at industry

Academia

Training and education of graduate students

At Rijnhuizen, like at other FOM-institutes, the research carried out by graduate students under supervision of members of the scientific staff constitutes a vital part of the research. In 2010, the number of graduate students was raised to 34, four students received their PhD in 2010 and another 11 students are expected to graduate in 2011. Seven members of the staff hold parttime professorships at Dutch universities, and act as promotors for the academic promotions.

There is a strong awareness of the need for graduate students to finish their PhD-projects within the regular four years. The PhD students follow several courses — within a wider FOM framework — to help them achieve this goal. Rijnhuizen succeeds in attracting very motivated high quality graduate students. Around half of them are, understandably given the number of physics students in Western Europe, not from the Netherlands. Australia, Belgium, China, Germany, Israel, Japan, Serbia, Russia and Romania are among the states from which students have been attracted, giving the research groups a truly international flavour.

In the plasma physics subjects, the education of the students is organised in the frame of the 'research school' CPS (Centre for plasma physics and radiation technology), and includes participation in the Carolus Magnus summer school on Fusion physics (biannual, it was organised in Belgium in 2009), the Erasmus summer school on low temperature plasma physics, as well as the annual national plasma physics conference. It is the norm that graduate students in these subjects go abroad for prolonged research stays, often in Jülich (D) or at JET (UK). In 2010 four graduate students received their PhD, and there were 34 PhD students in the institute. In 2010, 11 scientists held a postdoc or other temporary scientific position.

Education of undergraduate students and trainees

While the influx of foreign graduate students is perceived quite positively in the research groups, the institute is also keen on playing a role in the education of Dutch students of physics and technology. As a central activity on this front, members of the staff of the institute give lecture courses at several universities. In 2010, the following courses were given:

- Prof. dr. A.W. Kleyn et al., Big issues in energy materials, University of Amsterdam and Vrije Universiteit Amsterdam
- Prof. Dr. A.J.H. Donné, Dr. E. Westerhof, Diagnostics and heating of fusion plasmas, Eindhoven University of Technology
- Prof. dr. M. de Baar, Dr. ir. P.W.J.M. Nuij, Dr. ing. J.W. Oosterbeek, Drs. B. Hennen, Advanced control of MHD modes, Eindhoven University of Technology
- Prof. dr. M. de Baar, Dr. ir. P.W.J.M. Nuij, Drs. B. Hennen, Control and operation of tokamaks, Eindhoven University of Technology
- Prof. dr. M. de Baar, Dr. ir. C.J.M. Heemskerk, Remote handling - contribution to honours programme, Eindhoven University of Technology
- Dr. H.J. de Blank, Routes to Fusion Power, Eindhoven University of Technology
- Dr. R. Jaspers, Dr. G.M.D. Hogeweij, Magnetic confinement in fusion reactors, Eindhoven University of Technology
- Dr. G.J. van Rooij, Plasma wall Interaction in fusion reactors, Eindhoven University of Technology
- Prof. Dr. W.J. Goedheer, Dr. H.J. de Blank, Dr. G.M.D. Hogeweij, Plasma Physics, Utrecht University
- Prof. Dr. W.J. Goedheer, Deposition methods, contribution to the lecture Device Physics, Utrecht University
- Dr. P. Zeijlmans van Emmichoven, Electrodynamics 2, Utrecht University.
- Prof. Dr. R. Keppens, Introduction to (Solar) Plasma-Astrophysics, contribution to the Plasma Physics-course, Utrecht University
- Prof. Dr. F. Bijkerk, Tutorial XUV Optics, MESA+, University of Twente.

Next to the regular lecture courses special lectures on specific topics were given:

- Prof. Dr. A.J.H. Donné, Plasma diagnostics for burning plasma devices, Ghent University, Belgium
- Prof. Dr. W.J. Goedheer, Energy from controlled nuclear fusion, contribution to the Bachelor Honours Programme, Utrecht University
- Prof. Dr. W.J. Goedheer, Energy from controlled nuclear fusion, contribution to the Master course on Energy Conversion, Utrecht University.

Undergraduate students are welcomed in the research groups to carry out one of the compulsory research projects in the frame of their studies. Likewise, students of various levels of technical education are welcome as trainee in either the Division for Technological and Facility support, or in the research groups. In 2010, a total of 20 undergraduate physics students from universities and trainees were accommodated.

Activities directed at the top forms of secondary schools

To promote physics in general, and fusion as an energy option in particular at secondary schools, a one-hour interactive performance called the 'Fusion Road Show' has been developed, including live physics demonstrations and computer animations. In 2010, the experiments, storyline and performance were improved in cooperation with a theatre expert, and will be further upgraded in 2011. The show is offered free of charge to secondary schools, where it fits well in the curriculum of such subjects as 'general natural sciences', a subject meant to inform students on scientific subjects that have a clear bearing on society, such as the energy problem. The fusion road show visited some 20 schools.

An important goal of the Public Information Group at Rijnhuizen is to provide secondary schools with good educational material on the energy problem and on fusion energy. As a part of this effort, a lessons module for the new high school science subject NLT was developed. The module is in use at several secondary schools and participating students can visit Rijnhuizen to do experiments at a new, dedicated Paschen-curve set-up was started in 2010 and will receive its first visiting students early 2011.

During the year, some 200 students from various secondary schools visited Rijnhuizen, either individually, or in a school-organised trip.

The Dutch website www.fusie-energie.nl reaches secondary school students, science journalists, and the general public. It provides general information on fusion, and the latest fusion news. To better showcase the various secondary school activities (Fusion Road Show, NLT lessons module, and experiment for visiting students), the site is being redesigned and will go live in 2011.

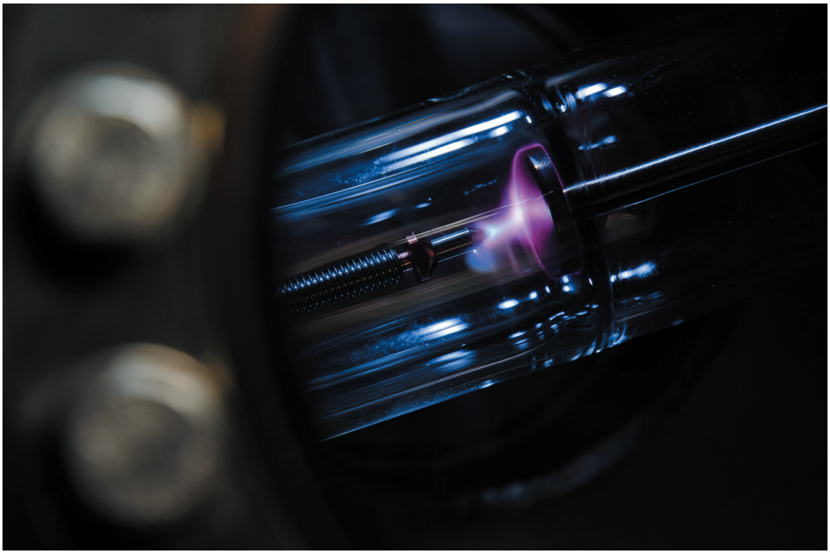


Figure 3.1: Detail of Paschen curve experiment for secondary school students. The project is intended for two to four students participating in the NLT lessons module on fusion and takes an afternoon to complete.

Society

Activities directed at the general public

The most concentrated outreach effort to the general public is the annual Open House day. This year, the event was organised for the 38th time. A separate day for students (Thursday October 14th) is organised in addition to the Open House day for the general public (Sunday October 24th). The students day was attended by 296 visitors, while the general open day attracted 852 people.

In 2010, the Fusion Road Show was performed a total of 30 times, for a very large variety of audiences and at varying venues. Apart from performances at high schools, the show took part in the Netherlands' largest music festival Lowlands, reaching over 2000 people – see section 2.12 on the Public Information Group.

Other activities

Alongside these specific activities, members of the staff gave lectures to general audiences and performed radio, newspaper and television interviews on various occasions. The planned relocation to Eindhoven and move of the FELIX / FELICE-user facility to Nijmegen attracted a lot of media attention, including four articles in major newspapers. Also, newspapers, magazines and radio interviews covered the scientific work at Rijnhuizen. Finally, a large number of invited talks for different general audiences were given by the institute staff – see chapter 4.

Valorisation at Rijnhuizen

The FOM Institute for Plasma Physics Rijnhuizen is very active in the field of industrial collaboration, the transfer of scientific results to the public domain and the application as new technology, i.e. valorisation. Extra funds were obtained from FOM and NWO to carry out a range of promising valorisation projects. More elaborately described in chapter 2.10 TFM, 2.11 AXO and below, these include further research on the realization of dispersive, broadband, and shorter wavelength multilayer optics. Funds have also been granted for the commercialization of materials to be investigated with Magnum-PSI. Inquiries are currently made with several companies and possible end-users that could supply essential components or possibly be involved in the development process. PhD students at Rijnhuizen take part in valorisation courses that aim to improve awareness of application perspectives and intellectual property. In many research projects, weekly seminars, and at the website, attention is paid to the technology transfer of research. We describe valorisation efforts per division in the text below.

Nanolayer Surface & Interface physics (nSI)

Optics specialist Carl Zeiss and lithographic equipment producer ASML have joined in the new Industrial Partnership Program CP3E: *Controlling Photon and Plasma induced Processes at EUV optical surfaces*. It has a total budget of 11.3 million euro and allows for a strengthening of the collaboration with partners at the Institute for Plasma Spectroscopy ISAN, and the Moscow State University, both joining as partners in CP3E. ASML will accommodate half of the CP3E researchers at its laboratories in Veldhoven, where they will have access to state-of-the-art EUV light sources. The research enables the special type of multilayer optics at the heart of new generations of photolithography for the fabrication of integrated circuits. Numerous other projects on the topic of applied surface and material science are carried out as well, among which research into photoelectrochemical cells for production of hydrogen from sunlight and water.

Projects concerning dispersive multilayer optics on a blazed grating (being patented), multilayer optics with high reflectivity in a broader, and at a shorter wavelength region (patented), for which extra funding was obtained, are currently in the proof-of-principle phase. These have applications in future generations of photolithography, X-ray Free Electron Lasers (FLASH, ZFEL), and e.g. astrophysics and radiology. State-of-the-art gratings are being developed in collaboration with SRON, while the Amsterdam Medical Centre has shown interest in optics for a 'water window' microscope.

Apart from scientific publications and PhD degrees, the research in nSI results in an average two patents per year. Division head Fred Bijkerk recently won the FOM valorisation prize for the activities of nSI. In the previous year, the first edition of the prize was awarded to Richard van de Sanden, now director of Rijnhuizen. The current Valorisation Officer, Tim Tsarfati, then won the FOM valorisation chapter prize for his PhD research on e.g. the patented 'beyond EUV' optics, now continued in the STW TFN project 10025.

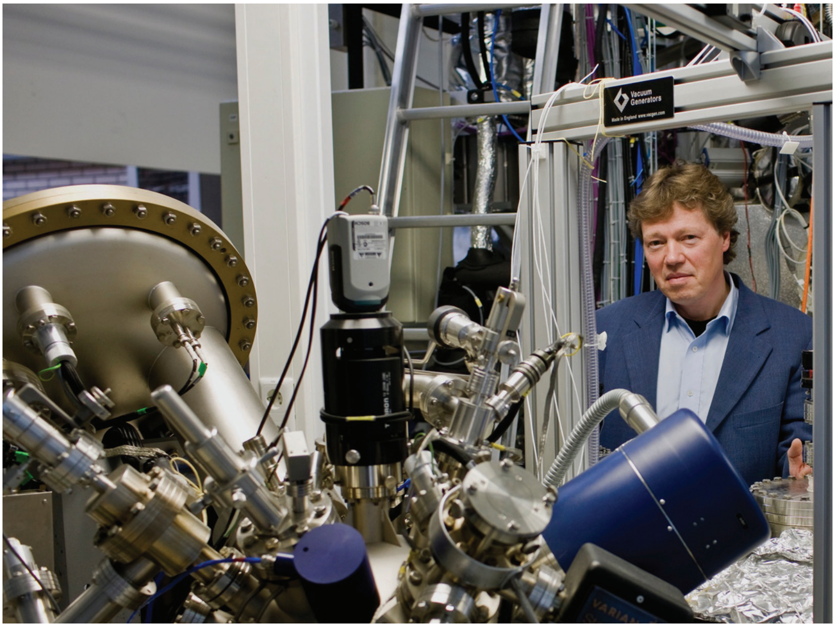


Figure 3.2: Fred Bijkerk won the FOM valorisation prize 2010 for the close and succesful cooperation of the nSI division with industrial partners.

Fusion Physics

In 2010, the consortium ITER-NL2, consisting of FOM, TNO, NRG and the new partner TU/e, was started as follow up of the ITER-NL program with the aim to facilitate a strong contribution of Dutch companies and front-line participation of Dutch research in the scientific exploitation of ITER. Contacts are established with over 200 Dutch companies, of which several dozen are involved in the development of essential components. In the words of the R&D director of 3D-Metal Forming BV: "*Developing our technology for ITER applications really helped us to cross technological boundaries. This was rapidly appreciated by many high-tech industries. Not only for fusion and fission applications, but also for other energy sectors and even for several aerospace applications.*" The company is actually a spin-off from an ITER business case and exploits their technology in a range of sectors; from art to architecture, and parts of prototype cars. They have also obtained a contract from power company ABB to manufacture turbine components. For Airbus, they produce large airplane segments made from one piece by explosive forming. This creates huge advantages in terms of weight and quality.

The Remote Handling-activity, on which Heemskerk Innovative Technology contributes for the Upper Port Launcher and expectedly also in the Hot Cell equipment, is widely applicable in other fields. Rijnhuizen actively participates in the international ITER project via Fusion for Energy (F4E), supplies the Dutch Industrial Liaison Officer, and delivers an important scientific and technical contribution to the buildup of ITER. The research on burn control in plasmas is of relevance beyond the framework of ITER for e.g. the optimization of combustion in engines.

Plasma Surface Interaction (PSI)

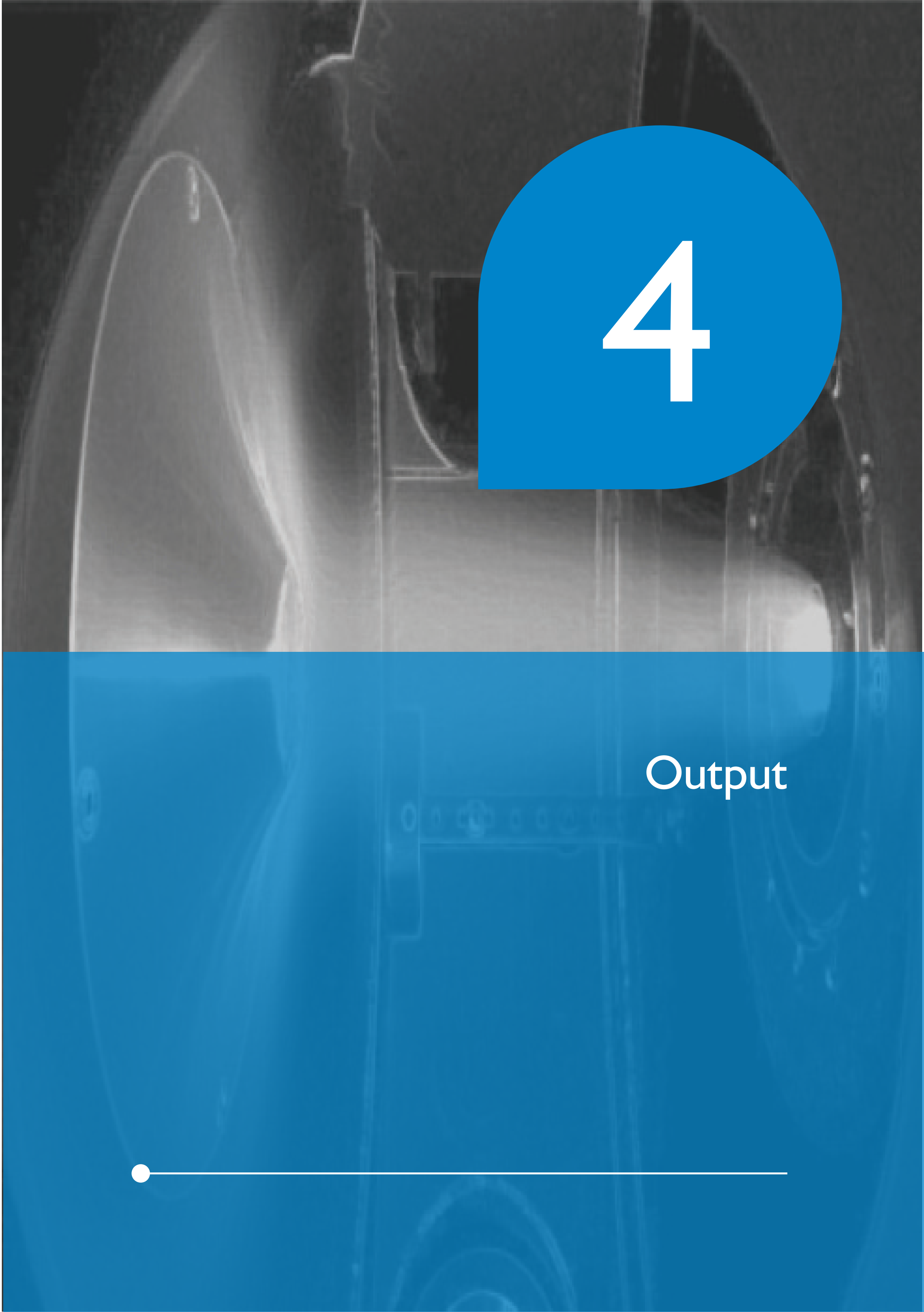
Aiming to develop and test potential ITER wall materials and mock-ups, Magnum-PSI is currently being finalised at Rijnhuizen. Unique in the world, Magnum-PSI will contribute to the development of advanced plasma facing materials. Relevant for the development of fusion energy and e.g. formation of dust in astrophysical systems, the research on plasma surface interaction at high particle and/or photon fluxes is of interest for the production of components for XUV optics in e.g. next generation photolithography and X-ray Free Electron Lasers. In this field, ample collaboration occurs with the nSI department that has a long history of industrial involvement. An investment fund has now been created to bridge the gap from pure scientific research to commercialization.

Together with Element6, a company specialised in advanced industrial diamond materials, a boron doped diamond test substrate has been produced that shows a very high shock resistance, with potential applications beyond ITER in e.g. (aero)space industry. For tungsten test substrates, Urenco is involved in the enrichment for tracers and collaborate projects on the further development of tungsten processing are also explored. Magnum-PSI can be exploited for industrial R&D in the framework of projects on materials endurance and power dissipation testing for a range of applications.

Generation and Utilization of TeraHertz radiation (GUTHz)

Contacts are established with numerous international institutions that employ the free electron laser FELIX, stationed at Rijnhuizen, to carry out biomedical, -chemical, and -physical research in particular. All kinds of pure metal, metal-carbide, metal-oxide, and metal-nitride clusters are investigated to obtain structural information. These studies bear relevance to current problems in heterogeneous catalysis, a field with a wide range of applications in the production of many materials as well as e.g. the removal of pollutants emitted from car engines. In other studies, IR/UV double resonance laser techniques are applied to obtain conformer selective spectra jet-cooled biomolecules, such as amino acids, peptides, sugars, as well as model systems for molecular motors, which are increasingly being pursued for nanotechnological applications.

In a collaborate effort with the nSI department, research on photochemical properties of molecules aims to develop materials for photoconversion that capture solar energy for the production of chemical compounds or electricity. Together with a UK-Dutch team from the University of Surrey, University College London, and Heriot-Watt University, the ability of an electron to simultaneously exist in two places has been controlled in silicon. This marks a significant step towards the making of an affordable 'quantum computer'. The work shows that some of the quantum engineering already demonstrated by atomic physicists in atom traps can be implemented in the type of silicon chip used in making the much more common transistor.



4

Output

4 Output

4.1 Output on Fusion Physics

Books

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Computational Relativistic Astrophysics: Frontiers of MHD, 13-16 January 2010, Princeton University, Princeton, USA

R. Keppens, *Relativistic hydro and magneto-*

hydrodynamic models for AGN jet propagation and deceleratio

22nd NNV-symposium on Plasma Physics and Radiation Technology 9-10 March 2010, Lunteren, the Netherlands

R. Keppens, *Relativistic hydro and magneto-hydrodynamic models for astrophysical jet propagation and deceleration*

37th IoP Annual Conference on Plasma (29 March, Windemere, UK)

P.C. de Vries, *An overview of JET physics*

Opening Eindhoven Energy Initiative, Eindhoven, 6 april 2010

A.J.H. Donné, *Fusion Energy*

16th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Sanya, China, 12-15 April 2010

B.A. Hennen, E. Westerhof, P.W.J.M. Nuij, B. Ayten, M.R. de Baar, W.A. Bongers, A. Bürger, D. De Lazzari, J.W. Oosterbeek, D.J. Thoen, M. Steinbuch and the TEXTOR team, *Feedback control of tearing modes through ECRH with launcher mirror steering and power modulation using a line-of-sight ECE diagnostic*

H.K. Park, B. Tobias, G.S. Yun, W. Lee, M. Choi, I.G.J. Classen, C.W. Domier, A.J.H. Donné, J.C. Kim, X. Kong, T. Liang, N.C. Luhmann, Jr., T. Munsat and L. Yu, *2D ECE Imaging Program for Fluctuation Studies on the KSTAR and DIII-D Tokamaks*

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A.J.H. Donné, B. Tobias, H. Park, J. Boom, M.J. Choi, I.G.J. Classen, C.W. Domier, X. Kong, W. Lee, T. Liang, N.C. Luhmann, Jr., T. Munsat, L. Yu, G. Yun, *Imaging Techniques for Microwave Diagnostics*

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I.G.J. Classen, J.E. Boom, W. Suttrop, E. Schmid, B. Tobias, C.W. Domier, N.C. Luhmann Jr., A.J.H. Donné, R.J.E. Jaspers, P.C. de Vries, H.K. Park, T. Munsat, M. Garcia-Munoz, P.A. Schneider, ASDEX Upgrade team, *2D Electron Cyclotron Emission Imaging at ASDEX Upgrade*

NNV symposium `Het klimaat en de invloed van de zon', 20 May 2010, Utrecht

R.Keppens, *De magnetische grillen van de zon: van dynamowerking tot ruimteweersvoorspellingen*

5th European Conference on Computational Fluid Dynamics, ECCOMAS CFD 2010, 14-17 June, 2010, Lisbon, Portugal

R. Keppens, *Implicit and semi-implicit treatments for MHD computations*

37th Conference on Plasma Physics, 21-25 June 2010, Dublin, Ireland

B.A. Hennen, E. Westerhof, P.W.J.M. Nuij, J.W. Oosterbeek, M.R. de Baar, W.A. Bongers, A. Bürger, D.J. Thoen, M. Steinbuch and the TEXTOR team, *Control of tearing modes in a tokamak using a line-of-sight electron cyclotron emission diagnostic*

Conference on Gyro-kinetics (1 July 2010, Cambridge, UK)

P.C. de Vries, *Internal transport barriers in JET*

International Conference on Plasma Physics (8-13 August, Santiago, Chile)

T.W. Versloot et al., *Rotation and momentum transport studies in Tokamak plasmas*

J.P. Goedbloed et al, *New approach to MHD spectral theory of stationary plasma flows*

5th Japan/Korea seminar: Advanced diagnostics for steady state fusion plasmas (26–29 August, 2010), Kyushu, Japan

A.J.H. Donné, M. Beurskens, A. Murari, D. Pacella, *European activities in Burning Plasma Diagnostics*

A.J.H. Donné, *Fusion: from fiction to reality*

35th International Conference on Infrared Millimeter and Terahertz Waves, 5-10 September, Rome, Italy

W.A. Bongers, W. Kasparek, A.J.H. Donné, A. P. H. Goede, M. R. de Baar, F. C. Schüller, V. Erckmann, J. Stober, E. Westerhof, F.J. Amerongen, B.A. Hennen, P.W.J.M. Nuij, J.W. Oosterbeek, D.M.S. Ronden, D.J. Thoen, T. Tongerlo and D. Wagner, *Utilization of collinear ECE detection/ECRH heating for active stabilization of plasma instabilities*

H.K. Park, G.S. Yun, M. Choi, I. Hong, M. Kim, J.C. Kim, W. Lee, B. Tobias, C.W. Domier, X. Kong, T. Liang, N.C. Luhmann, Jr., I. Classen, J.E. Boom, A.J.H. Donné, *Visualization of Fusion Plasma Physics via Millimeter Wave Imaging Techniques*

52nd Annual Meeting of the APS Div. of Plasma Physics, 8–12 November 2010, Chicago, USA

M.A. van Zeeland, W.W. Heidbrink, R K. Fisher, M García-Muñoz, G Kramer, D.C. Pace, R.B. White, S. Aekaeslompolo, M.E. Austin, J. Boom, I.G.J. Classen, S. da Grasa, B. Geiger, M. Gorelenkova, N.N. Gorelenkov, A.W. Hyatt, N. Luhmann, M. Maraschek, G.R. McKee, C. Muscatello, R. Nazikian, H. Park, S Sharapov, B.J. Tobias, Y. Zhu, ASDEX Upgrade Team, *Measurements and Modeling of Alfven Eigenmode Induced Fast-Ion Transport and Loss in DIII-D and ASDEX Upgrade*

Symposium on the occasion of the opening of the CWI building, Amsterdam, 11 November 2010

A.J.H. Donné, *Control of a burning fusion plasma: a multi-disciplinary scientific challenge*

20th Int. Toki Conf. (ITC20) on Advanced Physics in Plasma and Fusion Research, Toki, Japan, 7-10 December 2010

N. C. Luhmann, Jr., C.W. Domier, X. Kong, T. Liang, S. Che, L. Chen, G.S. Yun, W. Lee, H.K.Park, I.G.J. Classen, J.E. Boom, A.J.H. Donné, M. Van Zeeland, R. Boivin, R. Nazikian, B. Tobias, Y. Nagayama, T. Yoshinaga, D. Kuwahara, S Yamaguchi, Y. Kogi, A. Mase and T. Munsat, *Recent Progress on Microwave Imaging Technology and New Physics Results*

Other oral and poster presentations at (international) conferences and meetings

Physics@FOM, Veldhoven, 2010, 19-20 January 2010, Veldhoven, Netherlands

J.W.S. Blokland, S.D. Pinches, *Toroidal flow, fast particles and magnetohydrodymanical waves in fusion reactors*, P06.31

W. Haverkort, H.J. de Blank, J.W.S. Blokland, B. Koren, *Waves and instabilities in rotating tokamak plasmas*, P06.18

O.Lischtschenko, R. Jaspers, M.G. von Hellermann, E. Delabie, T. Versloot, The CCXRS Consortium, *The ITER core CXRS system*, P06.30

EFDA MHD TG (17-19 March 2010, Culham, UK)

E. Westerhof et al., *Feedback control of tearing modes through ECRH with launcher mirror steering and power modulation using a line-of-sight ECE diagnostic*

P.C. de Vries, *Prevention and mitigation of disruptions: the experience of present day experiments*

ITPA Transport and Confinement Meeting (1 March 2010, Culham, UK)

T.W. Versloot, *Momentum losses by Charge Exchange friction with neutral particles in JET* (oral)

P.C. de Vries, *Momentum transport studies in JET H-mode discharges with an enhanced toroidal field ripple* (oral)

P.C. de Vries, *Studies on Internal Transport Barriers at JET* (oral)

22nd NNV-Symposium on Plasma Physics and Radiation Technology 9-10 March 2010, Lunteren, the Netherlands

J.W. Haverkort, H.J. de Blank, J.W.S. Blokland, B. Koren, *Continuous spectra of tokamak plasmas with toroidal flow* (oral)

B.A. Hennen, E. Westerhof, P. Nuij, M.R. de Baar, W. Bongers, A. Bürger, H. Oosterbeek, D. Thoen, M. Steinbuch and the TEXTOR team, *Feedback stabilization of tearing modes in a tokamak plasma* (oral)

B. Ayten, D. De Lazzari, M.R. de Baar, B. Hennen, E. Westerhof, and the TEXTOR team, *Simulation of tearing mode suppression experiments in TEXTOR base don the generalized Rutherford equation* (poster A2)

H.J. Janssen and H.J. de Blank, *Fusion burn criteria for exotic electron and ion temperatures* (poster A6)

E. Delabie, M. Brix, R.J.E. Jaspers, C. Giroud, O. Marchuk, M.G.O. O'Mullane, M.G. von Hellermann, K.D. Zastrow and EFDA JET contributors, *Consistency of hydrogen beam emission data* (poster A9)

R.J.E. Jaspers, J.W. Oosterbeek, J.P. Balm, P.G.M. Bezembinder, N.J. Lopes Cardozo, *NEW: the Group FUSION at the TU/e* (poster A19)

O. Lischtschenko, R.J.E. Jaspers, R. König, and J. Howard, *Coherence imaging techniques applied to divertor-like plasma conditions* (poster B3)

J. de Valenca and H.J. de Blank, *Bifurcation theory of fusion plasma performance and periodic istabilities* (poster A8)

T.W. Versloot, P.C. de Vries, C. Giroud, M.-D. Hua, M. Beurskens, T. Eich, E. de la Luna, T. Tala, V. Naulin, K.D. Zastrow and JET EFDA contributions, *Effect of ELMs on rotation and momentum confinement in H-mode discharges at JET* (poster B18)

JET Science Meeting, Culham, UK, 15 March 2010

F. Imbeaux, F. Köchl, G.M.D. Hogeweij, J. Citrin, J. Hobirk, X. Litaudon, V. Basiuk, J. Fereira, J. Lönnroth, V. Parail, G. Pereverzev, Y. Peysson, G. Saibene, M. Schneider, G. Sips, G. Tardini, I. Voitsekhovitch, *Modelling of JET current ramp-up experiments*

4th Transport and Confinement ITPA Group Meeting, Culham, UK, 22-25 March 2010

F. Imbeaux, F. Köchl, G.M.D. Hogeweij, J. Citrin, J. Hobirk, X. Litaudon, V. Basiuk, J. Fereira, J. Lönnroth, V. Parail, G. Pereverzev, Y. Peysson, G. Saibene, M. Schneider, G. Sips, G. Tardini, I. Voitsekhovitch, *Modelling of JET, Tore Supra and Asdex Upgrade current ramp-up experiments*

29th Benelux Meeting on Systems and Control, 30 March-1 April 2010, Heeze, Netherlands

B.A. Hennen, E. Westerhof, M.R. de Baar, P.W.J.M. Nuij, M. Steinbuch, *Real-time control of magnetic islands in a fusion plasma*

G. Witvoet, M. Steinbuch, E. Westerhof, N. Doelman, M.R. de Baar, *Feedback control of the sawtooth behavior in nuclear fusion*

16th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Sanya, China, 12-15 April 2010

W. Bongers et al., *Fourier Transform based ECE systems for Real Time Tearing Mode Control in Tokamaks*

W. Kasparek, V. Erckmann, F. Hollmann, G. Michel, F. Noke, F. Purps, B. Plaum, P. Brand, C. Lechte, E. Filipovic, M. Saliba, Y. Wang, M. Petelin, E. Koposova, L. Lubyako, N. Doelman, R. van den Braber, A. Bruschi, W. Bongers, D.J. Thoen, J. Stober, D. Wagner, et al. *Developments of compact resonant diplexers for ECRH: design, recent results, and plans*

G. Witvoet, E. Westerhof, M. Steinbuch, M.R. de Baar, N. Doelman, *Control oriented system analysis and feedback control of a numerical sawtooth instability model* (poster)

1st European Energy Conference: A New Forum for Energy Research, 20-23 April 2010, Barcelona, Spain

A.P.H. Goede, J. Burrows, M. Buchwitz, O. Schneising, *Global CO2 monitoring from space* (oral)

18th Topical Conf. on High-Temperature Plasma Diagnostics, Wildwood, NJ, USA, 16-20 May

E. Delabie, M. Brix, C. Giroud, R.J.E. Jaspers, O. Marchuk, M.G. O'Mullane, Y. Ralchenko, E. Surrey, M.G. von Hellermann and K.D. Zastrow, *Consistency of atomic data for the interpretation of beam emission spectra* (poster)

S. B. Korsholm, M. Stejner, S. Conroy, G. Ericsson, G. Gorini, M. Tardocchi, M. von Hellermann, R. J. E. Jaspers, O. Lischtschenko, E. Delabie, H. Bindslev, V. Furtula, F. Leipold, F. Meo, P. K. Michelsen, D. Moseev, S. K. Nielsen, and M. Salewski, *Development of novel fuel ion ratio diagnostic techniques* (poster)

O. Lischtschenko, K. Bystrov, G. DeTemmerman, J. Howard, R.J.E. Jaspers and R. Koenig, *Density measurements using Coherence Imaging Spectroscopy based on Stark broadening* (poster)

B. Tobias, C.W. Domier, T. Liang, X. Kong, L. Yu, G.S. Yun, H.K. Park, I.G.J Classen, J.E. Boom, A.J.H. Donné, T.L. Munsat, R. Nazikian, R.L. Boivin, and N.C. Luhmann, Jr., *Commissioning of Electron Cyclotron Emission Imaging (ECEI) Instrument on the DIII-D Tokamak and First Data*

4th ITER International Summer School "Magnetohydrodynamics and Plasma Control in Magnetic Fusion Devices, Austin, USA, 31 May - 4 June 2010

B. Ayten, D. De Lazzari, M.R. De Baar, B.A. Hennen, E. Westerhof, and the TEXTOR Team, *Simulation of Tearing Mode Suppression Experiments in TEXTOR Based on the Generalized Rutherford Equation*

24th Symposium on Plasma Physics and Technology, 14-17 June 2010, Prague, Czech Republic

P. Delmont and R. Keppens, Parameter regimes for intermediate MHD shocks (oral)

ECCOMAS CFD 2010, 14-17 June 2010, Lisbon, Portugal

R. Keppens, A.J. van Marle, C. Xia, *Implicit and semi-implicit treatments for MHD computations*

Workshop on Electric Fields, Turbulence and Self-Organisation in Magnetised Plasmas EFTSOMP, 15 June 2010, Dublin, Ireland

S. Soldatov, A. Kraemer-Flecken, E. Delabie, M.Yu.Kantor, G. Van Oost, *Rotation induced by ICR heating in the tokamak TEXTOR*

1st WG Meeting of the COST Action MP0905, Black Holes in a violent Universe, June 24-25 2010, Bonn, Germany

R. Keppens, Z. Meliani, RH and RMHD models for AGN jet propagation and deceleration (oral)

39th Liège International Astrophysical Colloquium, The multi-wavelength view of Hot, Massive Stars, July 12-16 2010, Liège, Belgium

A.-J. van Marle, R. Keppens, A multidimensional study of circumstellar nebulae around massive stars (oral)

47th Culham Plasma Physics Summer School, Culham, UK, 12-23 July 2010

W. Weymiens, H.J. de Blank, G.M.D. Hogeweij, J. de Valença, *Bifurcation theory for the dynamics of H-mode transitions in fuison plasmas* (poster)

IAUS 274: Advances in Plasma Astrophysics, September 6-10, 2010, Catania, Giardini Naxos, Italy

R. Keppens, P. Delmont, Z. Meliani, *Shock refraction from classical gas to relativistic plasma environments* (oral)

3rd EFDA Transport Topical Group Meeting; 15th EU-US Transport Task Force Workshop, 7-10 Sept. 2010, Córdoba, Spain

S. Soldatov, A. Kraemer-Flecken, E. Delabie, M.Yu.Kantor, G. Van Wassenhove and G. Van Oost, *Rotation induced by ICR heating in the tokamak TEXTOR*

23rd IAEA Fusion Energy Conference, 11-17 October 2010, Daejon, Republic of Korea

M.R. de Baar, *Control of MHD modes with a line-of-sight ECE diagnostic*, EXW/P2-01

26th Symposium on Fusion Technology, 27 September – 1 October 2010, Porto, Portugal

T. Omori, M. Henderson, F.V. Albajar, S. Alberti, U.K. Baruah, T. Bigelow, B. Beckett, R. Bertizzolo, T. Bonicelli, A. Bruschi, J. Caughman, R. Chavan, S. Cirant, A. Collazos, D. Cox, C. Darbos, M.R. de Baar, G. Denisov, D. Farina, F. Gandini, T. Gassmann, T. Goodman, R. Heidinger, J. Hogge, O. Jean, K. Kajiwara, W. Kasparek, A. Kasugai, A., Kern, S., Kobayashi, N., Kumric, H., Landis, J., Moro, A., Nazare, C., Oda, I. Pagonakis, B. Piosczyk, P. Platania, B. Plaum, E. Poli, L. Porte, D. Purohit, G. Ramponi, S. Rao, D. Rasmussen, D. Ronden, T. Rzesnicki, G. Saibene, K. Sakamoto, F. Sanchez, T.A. Scherer, M. Shapiro, C. Sozzi, P. Spaeh, D.Strauss, O. Sauter, K. Takahashi, R. Temkin, T. Manfred, M. Tran, V. Udintsev, H. Zohm, *Overview of the ITER EC H&CD System and its capabilities*, P3-086

C.J.M. Heemskerk, B.S.Q. Elzendoorn, *Verifying elementary ITER maintenance actions with the MS2 benchmark product*, P2-043

C.J.M. Heemskerk, M.R. de Baar, H. Boessenkool, B. Graafland, M. Haye, J.F. Koning, M. Vahedi, M. Visser, *Extending Virtual Reality simulation of ITER maintenance operations with dynamic effects* P2-042

B.S.Q. Elzendoorn, M.R. de Baar, D. Hamilton, C.J.M. Heemskerk, J.F. Koning, D.M.S. Ronden, *Virtual reality facility for analysis and validation of ITER maintenance scenarios*, P3-050

P van Gelder, R. van Deelen, N. Cornejo, M.R. de Baar, B.S.Q. Elzendoorn, N. Koster, *Concept for lacalization of coolig water leaks in the ITER primary vavuum system*, P4-136

J.F. Koning, B.S.Q. Elzendoorn, D.M.S. Ronden, F. Klinkhamer, W. Biel, Y. Krasikov, C.I. Walker, *Feasibilty of Upper Port Plug tube handling*, P1-127

J.W. Pustjens, J.P. Friconneau, C.J.M. Heemskerk, J.F. Koning, J.P. Martins, P.C.J.N. Rosielle, M. Steinbuch, *Upper Port Plug handling cask system assessment and design proposals*, P1-169

D.M.S. Ronden, M.R. de Baar, R. Chavan, B.S.Q. Elzendoorn, K.K. Gotewal, C.J.M. Heemskerk, M.A. Henderson, J.F. Koning, G. Saibene, P. Spaeh, A. Tesini, *Analysis of Remote Hnadling compatibility of the ITER ECH Upper Port Launcher*, P1-065

D.M.S. Ronden, M.R. de Baar, R. Chavan, B.S.Q. Elzendoorn, K.K. Gotewal, T. Goodman, C.J.M. Heemskerk, M.A. Henderson, J.F. Koning, G. Saibene, P. Spaeh, D. Strauss, A. Tesini, *The ITER EC H&CD Upper Launcher: Analysis of Remote Handling compatibility*, P3-048

Yu. Krasikov, T. Baross, W. Biel, A. Litnovsky, N. Hawkes, G. Kiss, F. Klinkhamer, J.F. Koning, A. Krimmer, O. Neubauer, A. Panin, *Development of design options for the fort plug components of the ITER core CXRS diagnostic*, P3-110

A. Krimmer, F. Klinkhamer, W. Biel, N. Hawkes, G. Kiss, J.F. Koning, Yu. Krasikov, O. Neubauer, *Alternative system design concepts for the ITER CCXRS Upper Port Plug front end*, P1-113

F. Klinkhamer, A. Krimmer, W. Biel, N. Hawkes, G. Kiss, JF. Koning, Yu. Krasikov, O. Neubauer, *Optimization of the availability of the core CXRS diagnostics for ITER*, P3-149

52nd Annual Meeting of the APS Div. of Plasma Physics, 8-12 November 2010, Chicago, USA

B. Tobias, R.L. Boivin, J.E. Boom, I.G.J. Classen, C.W. Domier, A.J.H. Donné, W.W. Heidbrink, N.C. Luhmann, Jr., T. Munsat, C. Muscatello, R. Nazikian, H.K. Park, D.A. Spong, A. Turnbull, M.A. Van Zeeland, G.S. Yun, and the ASDEX-Upgrade, DIII-D, KSTAR, and TEXTOR teams, *Electron cyclotron emission imaging as a validation tool for theoretical modeling of magneto-hydrodynamic activity* (poster)

G. S. Yun, W. Lee, M. J. Choi, J. B. Kim, H. K. Park, C. W. Domier, B. Tobias, T. Liang, X. Kong, N. C. Luhmann, Jr., and A. J. H. Donné, *KSTAR ECE Imaging system for visualization of MHD physics* (poster)

KIVI-NIRIA Symposium: Fusie – van fictie naar realiteit, 30 November 2010, FOM-Rijnhuizen, Nieuwegein

H.J. de Blank, *Energiewinning uit fusie*

A.J.H. Donné, *Fusie: van fictie naar realiteit*

J. Koning, *Remote Handling for ITER*

Seminar

20 February 2010

P.C. de Vries, *Internal Transport Barriers at JET*, Oxford University

1 March 2010

P.C. de Vries, *Causes of Disruptions at JET*, Princeton Plasma Physics Laboratory

10 March 2010

J. Citrin, *Optimization of ITER Hybrid Scenario performance by integrated modelling*, CEA, Cadarache

16 March 2010

R. Keppens, *Astrophysical jets and accretion disks*, popular science lecture to visiting high-school students, Leuven

25 March, 1 April and 22 April 2010

R. Keppens, Computational *Magneto-Fluid dynamics*, series of 4 two-hour guest lectures at Utrecht University, within master of astronomy course by prof. A. Achterberg

1 April 2010

P.C. de Vries, *Plasma Rotation and Momentum Transport Studies at JET*, Culham Centre for Fusion Energy

4 April 2010
M.Yu. Kantor, *Multi-Pass Thomson Scattering*, Max-Planck-Institut fur Plasma Physik, Garching

13 April 2010
A.J.H. Donné, *Imaging Techniques for Microwave Diagnostics,* FOM Institute for Plasma Physics Rijnhuizen, Nieuwegein

3 May 2010
P.C. de Vries, *Plasma Rotation and Momentum Transport Studies at JET,* Lecture at GOTiT course, Culham

3 May 2010
P.C. de Vries, *Physics of Internal Transport Barriers at JET*, Lecture at GOTiT course, Culham
21 May 2010
J.P. Goedbloed, *Magnetohydrodynamic spectroscopy of stationary plasma flows*, Plasma Science and Fusion Center, MIT, USA

18 October 2010
A.J.H. Donné, *The Dutch Fusion Programme,* Students of the Eindhoven University of Technology

18 October 2010
M.R. de Baar, *Plasma Control and Remoter Handling,* Students of the Eindhoven University of Technology

24 October 2010
A.J.H. Donné, *Research at FOM Rijnhuizen*, Popular scientific lecture Day of the Open House FOM-Rijnhuizen
29 November 2010
A.J.H. Donné, *Fusion: from fiction to reality,* Rijksuniversiteit Gent, Dept. of Applied Phys.

29 November 2010
A.J.H. Donné, *Diagnostics in view of ITER,* Rijksuniversiteit Gent, Dept. of Applied Phys.

8 December 2010
A.J.H. Donné, *Fusion: from fiction to reality,* STW Student Day, Nieuwegein

Radio Interview
20 July 2010
A.J.H. Donné, *The ITER project*, Business News Radio

4.2 OUTPUT ON PLASMA SURFACE INTERACTIONS

Publications in peer-reviewed scientific journals

E. Alves, L.C. Alves, N.P. Barradas, R. Mateus, P.A. Carvalho, G.M. Wright, *Influence of temperature and plasma composition on deuterium retention in refractory metals,* Nucl. Instrum. Methods B 268 (2010) 2124-2128

C. Arnas, C. Pardanaud, C. Martin, P. Roubin, G. De Temmerman, G. Counsell, *Analyses of dust samples collected in the MAST tokamak*, J. Nucl. Mater. 401 (2010) 130-137

C. Arnas, C. Martin, P. Roubin, B. Pegourie, G. De Temmerman, K. Hassouni, A. Michau, G. Lombardi, X. Bonnin, *Similarities and differences between dust produced in laboratory plasmas and in the MAST and Tore Supra tokamaks,* Plasma Phys. Contr. Fusion 52 (2010) 124007

D. Borodin, A. Kirschner, D. Nishijima, R. Doerner, J. Westerhout, G. J. van Rooij, J. Rapp, A. Kreter, R. Ding, A. Galonska, and V. Philipps, *Modelling of impurity transport in the linear plasma devices PISCES-B and Pilot-PSI using the Monte-Carlo code ERO*, Contrib. Plasma Phys. 50, 432 - 438 (2010)

O. Lischtschenko, K. Bystrov, G. De Temmerman, J. Howard, R.J.E. Jaspers and R. König, *Density measurements using coherence imaging spectroscopy based on Stark broadening*, Rec. Sci. Instrum. 81 10E521 (2010)

Y. Liu, A.D. Verkerk, J.K. Rath, R.E.I. Schropp, and W.J. Goedheer, *Effects of pressure and interelectrode distance on deposition of nanocrystalline silicon under high pressure conditions*, Phys. Status Solidi C, 7, 575-578 (2010)

G. Maddison, C. Giroud, K. McCormick, A. Alonso, B. Alper, Y. Andrew, G. Arnoux, P. Belo, M. Beurskens, A. Boboc, A. Brett, S. Brezinsek, M. Brix, I. Coffey, E. de la Luna, S. Devaux, P. de Vries, P. Devynck, T. Eich, R. Felton, W. Fundamenski, J. Harling, D. Harting, J. Hobirk, A. Huber, S. Jachmich, I. Jenkins, E. Joffrin, A. Kallenbach, M. Kempenaars, M. Lehnen, T. Loarer, P. Lomas, D. McDonald, A. Meigs, P. Monier-Garbet, P. Morgan, D. Moulton, V. Riccardo, F. Rimini, G. Sergienko, A. Sirinelli, M. Stamp, G. Telesca, H. Thomsen, I. Voitsekhovitch, JET EFDA contributors, *Moderation of target loads using fuelling and impurity seeding on JET*, Journ. Nucl. Mater. 12 (2010)

Ch. Maszl, V. Naulin, M. Brix, T.W. Versloot, R. Schrittwieser and JET EFDA Contributors O. Marchuk, Yu. Ralchenko, R.K. Janev, E. Delabie, W. Biel, A. Urnov, *Palm trees and islands – Current filaments in the edge of JET*, J. Nucl. Mater. 12 (2010) 245

H.J. van der Meiden, *Collective Thomson scattering for ion temperature and velocity measurements on Magnum-PSI: a feasibility study*, Plasma Phys. Control. Fusion 52 (2010) 045009

K.S.C. Peerenboom, W.J. Goedheer, J. van Dijk and J.J.A.M. van der Mullen, *Integral simulation of the creation and expansion of a transonic argon plasma*, Plasma Sources Sci. Technol. 19 (2010) 025009

S. Porro, G. De Temmerman, D.A. MacLaren, S. Lisgo, D.L. Rudakov, J. Westerhout, M. Wiora, P. John, I. Villalpando, J.I.B. Wilson, *Surface analysis of CVD diamond exposed to fusion plasma,* Diamond Relat. Mater. 19 (2010) 818-823

J. Rapp, G. Pintsuk, Ph. Mertens, H. Altmann, P.J. Lomas, V. Riccardo, *Geometry and expected performance of the solid tungsten outer divertor row in JET,* Fusion Eng. Design, 85 (2010) 153-160

J. Rapp, W.R. Koppers, H.J.N. van Eck, G.J. van Rooij, W.J. Goedheer, B. de Groot, R. Al, M.F. Graswinckel, M.A. van den Berg, O. Kruyt, P. Smeets, H.J. van der Meiden, W. Vijvers, J. Scholten, M. van de Pol, S. Brons,W. Melissen, T. van der Grift, R. Koch, B. Schweer, U. Samm, V. Philipps, R.A.H. Engeln, D.C. Schram, N.J. Lopes Cardozo, A.W. Kleyn, *Construction of the plasma-wall experiment Magnum-PSI*, Fusion Eng. Des. 85 (2010) 1455-1459

E.D. de Rooij, A.W. Kleyn and W.J. Goedheer, *Sticking of hydrocarbon radicals on different amorphous hydrogenated carbon surfaces: a molecular dynamics study*, Phys. Chem. Chem. Phys. 2010, 12, 14067-14075

G.J. van Rooij, *Laboratory experiments and devices to study plasma surface interaction*, Fusion Sci. Technol. T 57 (2010) 313-319

G.J. van Rooij, G.M. Wright, *Diagnostics for erosion and deposition processes in fusion plasmas*, Fusion Sci. Technol. T 57 (2010) 437-444

M. Rubel, J.P. Coad, G. De Temmerman, A. Hakola, D. Hole, J. Likonen, I. Uytdenhouwen, A. Widdowson and Jet- EFDA Contributors, *First mirrors test in JET for ITER: An overview of optical performance and surface morphology*, Nucl. Instrum. Meth. Phys. Res. A 623 (2010) 818-822

A.V. Snytnikov, V.A. Vshivkov, W.J. Goedheer, *Adaptive mass alteration to model ion–ion recombination in a Particle-in-Cell simulation of silane radio-frequency discharges*, Comput. Phys. Comm. 181 (2010) 1743-1749

M.L. Solomon, V. Anita, C. Costin, I. Mihaila, G. Popa, H.J. van der Meiden, R. Al, M.J. van de Pol, G.J. van Rooij, and J. Rapp, Multi-channel analyzer investigations of ion flux at the target surface in Pilot-PSI, Contrib. Plasma Phys. 50, 898-902 (2010)

K.R. Sütterlin, A. Wysocki, C.Räth, AV. Ivlev, H.M. Thomas, S. Khrapak, S. Zhdanov, M. Rubin-Zuzic, W.J. Goedheer, V.E. Fortov, *Non-equilibrium phase transitions in complex plasma*, Plasma Phys. Control. Fusion 52 (2010) 124042

F.L. Tabarés, J.A. Ferreira, A. Ramos, G.J. van Rooij, J. Westerhout, R. Al, J. Rapp, A. Drenik, and M. Mozetic, *Suppression of tritium retention in remote areas of ITER by nonperturbative reactive gas injection*, Phys. Rev. Lett. 105 175006 (2010)

G. De Temmerman, E. Delchambre, J. Dowling, A. Kirk, S. Lisgo and P. Tamain, *Thermographic study of heat load asymmetries during MAST L-mode discharges*, Plasma Phys. Control. Fusion 52 (2010) 095005

G. De Temmerman, J.J. Zielinski, H.J. van der Meiden, W. Melissen, and J. Rapp, *Production of high transient heat and particle fluxes in a linear plasma device*, Appl. Phys. Lett. 97, 081502 (2010)

G. De Temmerman, M. Bacharis, J. Dowling and S. Lisgo, *Dust creation and transport in MAST*, Nucl. Fusion 50 (2010) 105012

W.A. Vijvers, D.C. Schram, A.E. Shumack, N.J. Lopes Cardozo, J. Rapp and G.J.van Rooij, *Experimental and theoretical determination of the efficiency of a sub-atmospheric flowing high power cascaded arc hydrogen plasma source*, Plasma Sources Sci. Technol. 19 (2010) 065016

J Westerhout, D. Borodin, S. Brezinsek, N.J. Lopes Cardozo, J. Rapp, D.C. Schram, G.J. van Rooij, *The breakup of methane under ITER divertor hydrogen plasma conditions for carbon chemical erosioni analysis with CH spectroscopy*, Nucl. Fusion 50 (2010) 095003

G.M. Wright, R.S. Al, E. Alves, L.C. Alves, N.P. Barradas, A.W. Kleyn, N.J. Lopes Cardozo, H.J. van der Meiden, V. Philipps, G.J. van Rooij, A.E. Shumack, W.A.J. Vijvers, J. Westerhout, E. Zoethout, J. Rapp, *Carbon film growth and hydrogenic retention of tungsten exposed to carbon-seeded high density deuterium plasmas*, J. Nucl. Mater. 396 (2010) 176-180

G.M. Wright, E. Alves, L.C. Alves, N.P. Barradas, P.A. Carvalho, R. Mateus and J. Rapp, *Hydrogenic retention of high-Z refractory metals exposed to ITER divertor-relevant plasma conditions*, Nucl. Fusion 50 (2010) 055004

G.M. Wright, M. Mayer, K. Ertl, G. de Saint-Aubin and J. Rapp, *Hydrogenic retention in irradiated tungsten exposed to high-flux plasma*, Nucl. Fusion 50 (2010) 075006

PhD theses

E.D. de Rooij, *Molecular dynamics simulations in interactions between hydrogen and fusion-relevant materials*, PhD thesis at the Utrecht University, 24 February 2010

J. Westerhout, *Carbon chemical erosion in high flux and low temperature hydrogen plasma*, PhD thesis at the Eindhoven University of Technology, 1 July 2010

Bachelor thesis

W.J. Smit, *Characterization of tungsten ion light to asses prompt redeposition in ASDEX Upgrade*

O. Rottier, *Continuum and Line Emission Measurements on Pilot-PSI*

Invited lectures at conferences and meetings

15th Conference on Plasma Physics and Applications (CPPA2010), 1-4 July 2010, Iasi, Romania

J. Rapp, G. De Temmerman, G.J. van Rooij, P.A. Zeijlmans van Emmichoven, A.W.

Kleyn, *Plasma-facing materials research for fusion reactors at FOM Rijnhuizen*

37th IOP Annual Conference on Plasma Physics, 29 March – 1 April 2010, Windermere, UK

G. De Temmerman, *The role of linear plasma devices in plasma-surface interaction studies*

1st Workshop on Fusion Frontiers and Interfaces, May 2010, York, UK

G. De Temmerman, *Tokamak exhaust physics and plasma-wall interactions*

18th International Workshop on Inelastic Ion Surface Collisions (IISC-18), 26 September – 1 October 2010, Gatlinburg, USA

P.A. Zeijlmans van Emmichoven, Hydrogenic retention in tungsten exposed to high flux plasmas

Other oral and poster presentations at (international) conferences and meetings

Physics@FOM, Veldhoven, 2010, 19 - 20 January 2010, Veldhoven, Netherlands

W.J. Goedheer, J.K. Rath, A.D. Verkerk, Y. Liu, R.E.I. Schropp, *Optical emission spectroscopy in strongly diluted silane-hydrogen discharges*, P06.20

Y. Liu, A.D. Verkerk, J.K. Rath, R.E.I. Schropp, W.J. Goedheer, *Revisiting Paschen's law for deposition of nanocrystalline silicon at high process pressure*, P03.73

22nd NNV-Symposium on Plasma Physics and Radiation Technology 9-10 March 2010, Lunteren, the Netherlands

K.S.C. Perenboom, J. van Dijk, W.J. Goedheer, J.J.A.M. van der Mullen, *Modeling of multicomponent diffusion in a magnetic field* (oral)

O.G. Rottier, U. Fantz, A.E. Shumack, D. Wünderlich, G.J. van Rooij, *Hydrogen excitation pathways in an ITER divertor relevant plasma beam* (poster B9)

G.J. van Rooij and J. Westerhout, *Gross and net erosion of carbon under high flux densities of low temperature hydrogen plasma* (poster B17)

R.C. Wieggers, H.J. de Blank, and W.J. Goedheer, *Characterisation of Magnum-PSI and Pilot-PSI with the B2.5 code* (poster B21)

19th International Conference on Plasma Surface Interaction, May 24-28, 2010, San Diego, CA, USA

G.J. van Rooij, J. Westerhout, S. Brezinsek, J. Rapp, *Chemical erosion of carbon at ITER relevant plasma fluxes: results from the linear plasma generator Pilot-PSI* (oral) O-33

G.M. Wright, M. Mayer, K. Ertl, G. de Saint-Aubin, J. Rapp, *Deuterium Trapping in Pre-irradiated tungsten exposed to high-flux plasma* (poster) P1-2

G. De Temmerman, A. Kirk, E. Nardon, P. Tamain and the MAST Team, *Heat load asymmetries in MAST* (poster) P1-29

J.J. Zielinski, R. Al, A.W. Kleyn, H.J. van der Meiden, W. Melissen, J. Rapp, G. De Temmerman *Production and characterization of transient heat particle pulses in Pilot-PSI* (poster)

E. Delchambre-Demoncheaux, G. de Temmerman, T. Loarer, E. Gauthier, G. Dunand, J.L. Gardarein, A. Kirk, V. Moncada, J.M. Travere, *Surface temperature measurement in the medium and long wavelength infrared range on MAST* (poster) P3.33

R. Neu, R. Dux, A. Janzer, A. Kallenbach, R. McDermott, H.W. Mueller, S. Potzel, T. Puetterich, M. Sertoli, G.J. van Rooij, *Tungsten behaviour in radiatively cooled discharges in ASDEX-Upgrade*

A. Kallenbach, M. Balden, R. Dux, T. Eich, C. Giroud, A. Huber, G.P. Maddison, M. Mayer, K. McCormick, R. Neu, T. Petrie, T. Puetterich, J. Rapp, M. Reinke, K. Schmid, J. Schweinzer, S. Wolfe, *Plasma Surface Interactions in impurity seeded plasmas* (oral) R4

T. Eich, H. Thomson, W. Fundamenski, G. Arnoux, S. Devaux, A. Herrmann, S. Jachmich, J. Rapp, *ELM power deposition wetted area and temporal shape in JET* (oral)

F.L. Tabares, J.A. Ferreira, A. Ramos, D. Alegre, G.J. van Rooij, J. Westerhout, R. Al, J. Rapp, M. Mozetic, A. Drenik *Inhibition of C:H Co-deposit formation by ammonia injection in remote areas: studies in Pilot-PSI and IC-RF plasmas* (poster)

S. Porro, G. De Temmerman, S. Lisgo, D.L. Rudakov, A. Litnovsky, P. Petersson, P. John, J.I.B. Wilson, *Diamond coatings exposure to fusion-relevant plasma conditions* (poster)

R.C. Wieggers, D. Coster, H.J. de Blank, W.J. Goedheer, *Characterization of Magnum-PSI and Pilot-PSI with the B2.5 Code* (poster)

K. Bystrov, A.E. Shumack, J. Westerhout, E. Zoethout, G. De Temmerman, *Characterization of carbon re-deposition patterns on carbon targets exposed under different plasma conditions in Pilot-PSI* (poster)

E. Nardon, P. Cahyna, S. Devaux, A. Kirk, A. Alfier, E. de la Luna, G. De Temmerman, P. Denner, T. Eich, T. Gerbaud, D. Harting, S. Jachmich, H.R. Koslowski, Y. Liang, Y. Sun, *Strike-point splitting induced by external magnetic perturbations: observations on JET and MAST and associated modelling*

37th Conference on Plasma Physics, 21-25 June 2010, Dublin, Ireland

M.L. Solomon, V. Anita, C. Costin, I. Mihaila, L. Sirghi, G. Popa, M. van de Pol, R.S. Al, G.J. van Rooij, J. Rapp, *2D distributions of current and floating potential at the target surface in Pilot-PSI* (poster) P5.132

IEA International Workshop on Requirements for Next Generation PMI Test Stands in Fusion Research, 31 August – 2 September 2010, Oak Ridge, USA

J. Rapp, *Design criteria and Status of Magnum-PSI*

26th Symposium on Fusion Technology, 27 September – 1 October 2010, Porto, Portugal

M.A. van den Berg, S. Brons, O.G. Kruijt, J. Scholten, R. Pasquet, G. De Temmerman, *The target for the new plasma/wall experiment Magnum-PSI*

J. Scholten, P. Smeets, S. Brons, H.J. van Eck, M. van den Berg, O. Kruyt, A. Lof, H.J. van der Meiden, M. van de Pol, G.J. van Rooij, Pedro Zeijlmans van Emmichoven, Status of the plasma-wall experiment Magnum-PSI

O.G. Kruijt, J. Scholten, P.H.M. Smeets, S. Brons, H.J.N. van Eck, R.S. Al, M.A. van den Berg, H.J. van der Meiden, G.J. van Rooij, P.A. Zeijlmans van Emmichoven, *Thermal effects and component cooling in Magnum-PSI*

R.S. Al, A.R. Lof, M.A. van den Berg, B. de Groot, O.G. Kruijt, H.J. van der Meiden, M.J. van de Pol, A.E. Shumack, J. Westerhout, W.A.J. Vijvers G..J. van Rooij, *A cascaded arc with diverging discharge channel and external nozzle for improved efficiency in hydrogen plasma production*

B. Unterberg, R. Jaspers, R. Koch, V. Massaut, J. Rapp,D. Reiter, S. Kraus, A. Kreter, V. Philipps, H. Reimer, U. Samm, L. Scheibel, B. Schweer, J. Schuurmans, I. Uydenthouwen, R. Al, M.A. van den Berg, S. Brons, H.J.N. van Eck, W.J. Goedheer, M.F. Graswinckel, T. van der Grift, A. Kleyn, W.R. Koppers, O. Kruyt, A. Lof, H.J. van der Meiden, W.Melissen, M. Van de Pol, G.J. van Rooij, P. Smeets, J. Scholten, D.C. Schram, G. De Temmerman, W. Vijvers, P.A. Zeijlmans van Emmichoven, J.J. Zielinski, *New linear plasma devices for an integrated approach to plasma surface interactions in Fusion Reactors*

23rd IAEA Fusion Energy Conference, 11-17 October 2010, Daejon, Republic of Korea

A. Kirk, E. Nardon, P. Tamain, P. Denner, G. De Temmerman, G. Fishpool, Y.Q. Liu, H. Meyer, D. Temple, and MAST Team, *Magnetic Perturbation Experiments on MAST using Internal Coils,* EXD/8-2

G. De Temmerman, J.J. Zielinski, H. van der Meiden, W. Melissen, and J. Rapp, *ELM Simulation Experiments on Pilot-PSI using Simultaneous High Flux Plasma and Transient Heat/Particle Source*, EXD/P3-07

J. Rapp, G.M. Wright, E. Alves, L.C. Alves, N.P. Barradas, G. De Temmerman, K. Ertl, J. Linke, M. Mayer, G.J. van Rooij, J. Westerhout, P.A. Zeijlmans van Emmichoven, and A.W. Kleyn, *Plasma-Facing Materials Research for Fusion Reactors at FOM Rijnhuizen*, FTP/3-3Ra

M. Rubel, G. De Temmerman, J.P. Coad, D. Hole, J. Likonen, M. Rödig, A. Schmidt, I. Uytdenhouwen, A. Widdowson, A. Hakola, A. Semerok, M. Stamp, P. Sundelin, J. Vince, and JET-EFDA Contributors, *Comprehensive First Mirror Test for ITER at JET with Carbon Walls*, FTP/P6-34

A. Litnovsky, V. Voitsenya, D. Thomas, M. Rubel, G. De Temmerman, L. Marot, K.Yu. Vukolov, I. Orlovskiy, W. Vliegenthart, C. Skinner, D. Johnson, V. Kotov, J.P. Coad, A. Widdowson, G. Vayakis, R. Boivin, M. Joanny, J.M. Travere, and Members of the ITPA Specialists Working Group on First Mirrors, *Mirrors for ITER Diagnostics: New R&D Developments, Assessment of the Mirror Lifetime and Impact of the Mirror Failure on ITER Performance*, ITR/P1-05

H. Thomsen, T. Eich, S. Devaux, G. Arnoux, S. Brezinsek, E. De La Luna, W. Fundamenski, A. Herrmann, A. Huber, S.

Jachmich, P. Lomas, A. Kallenbach, I. Nunes, J. Rapp, G. Saibene, A. Scarabosio, J. Schweinzer, and JET-EFDA Contributors, *Power Load Characterization for Type-I ELMy H-Modes in JET*, EXD/6-6Rb

R. Neu, J.C. Fuchs, A. Kallenbach, J. Rapp, R. Dux, T. Eich, O. Gruber, A. Herrmann, H.W. Müller, T. Pütterich, V. Rohde, K. Schmid, J. Schweinzer, M. Sertoli, G.J. van Rooij, and ASDEX Upgrade Team, *Power and Particle Exhaust Control in All W ASDEX Upgrade*, EXD/P3-24

F.L. Tabarés, J.A. Ferreira, A. Ramos, D. Alegre, G.J. van Rooij, J. Westerhout, R. Al, J. Rapp, A. Drenik, M. Mozetic, *Inhibition of C: H Co-deposit Formation by Ammonia Injection in Remote Areas of ITER*, EXD/P3-33

ITPA Div-SOL meeting, 19-21 October 2010, Seoul, Republic of Korea

G. De Temmerman, *Erosion and morphology changes of W under high fluxes*

J. Rapp, *T retention in damaged tungsten*

J. Rapp, *Chemical erosion studies at FOM*

52nd Annual Meeting of the APS Division of Plasma Physics, 8-12 November 2010, Chicago, USA

H.J.N. van Eck, A.W. Kleyn, W.R. Koppers, J. Rapp, P.A. Zeijlmans van Emmichoven, *The high-flux plasma generator Magnum-PSI*

1st joint ITER-IAEA Meeting on Analysis of ITER materials and Technologies, 23-25 November 2010, Monte Carlo, Monaco

G. De Temmerman, J.J. Zielinski, H.J. van der Meiden, L. Marot, W. Melissen, J. Rapp, *ELM simulation experiments under ITER-like conditions*

G.J. van Rooij, K. Bystrov, J. Westerhout, G. De Temmerman, J. Rapp, *Gross and Net Chemical Erosion of Carbon at High Fluxes of Low Temperature Hydrogen Plasma*

J. Rapp, G.M. Wright, E. Alves, L.C. Alves, N.P. Barradas, G. De Temmerman, K. Ertl, M.H.T. 't Hoen, M. Mayer, P.A. Zeijlmans van Emmichoven, *Deuterium retention in refractory metals under fusion reactor conditions*

13th EUREGIONAL WELTPP - Workshop on the Exploration of Low Temperature Plasma Physics, 25-26 November 2010, Kerkrade, The Netherlands

G.A. van Swaaij, *Modeling of hydrocarbon transport and break-up in Pilot-PSI* (oral)

N. den Harder, A.E. Shumack, G.J. van Rooij, *Molecular spectroscopy on a magnetized hydrogen plasma* P13 (poster)

K.S.C. Peerenboom, J. van Dijk, W.J. Goedheer, J.J.A.M. van der Mullen, *A 2-D axially symmetric model of a magnetically confined jet* P20 (poster)

G. van der Star, J. Westerhout, G.J. van Rooij, *Cavity ringdown spectroscopy in the linear plasma generator Pilot-PSI* P26 (poster)

G. van Hunnik, R.C. Wieggers, W.J. Goedheer, and F. Bijkerk, *Modeling of EUV driven plasmas* P28 (poster)

Seminar

24 March 2010
G. De Temmerman, *The role of linear plasma devices in plasma-surface interaction studies*, Imperial College, London, UK

27 May 2010
J. Rapp, *Plasma Surface Interaction in the context of ITER*, Technical University Delft, Delft, The Netherlands

8 July 2010
J. Rapp, *The New TEC Research Programme,* Signing of the New TEC Agreement, Forschungszentrum Juelich, Juelich, Germany

Annual EFDA PWI Task Force Meeting, 4 November 2010, Vienna, Austria

J. Rapp, *Highly radiative type-III ELMy H-modes at JET and ASDEX-U*

4.3 OUTPUT ON NANOLAYER SURFACE AND INTERFACE PHYSICS

Publications in peer-reviewed scientific journals

A.J.R. van den Boogaard, E. Louis, and E. Zoethout, S. Müllender, F. Bijkerk, *Surface morphology of Kr^+-polished amorphous Si layers*, J. Vac. Sci. Technol. A 28, 552-558 (2010)

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J. Chalupský, J. Krzywinski, L. Juha, V. Hájková, J. Cihelka, T. Burian, L. Vyšín, J. Gaudin, M.A. Gleeson, M. Jurek, A.R. Khorsand, D. Klinger, H. Wabnitz, R. Sobierajski, M. Störmer, K. Tiedtke, and S. Toleikis, *Spot size characterization of focused non- Gaussian X-ray laser beams*, Opt. Express 18 (2010) 27836-27845

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S. Dobrovolskiy, A.E. Yakshin, F.D. Tichelaar, J. Verhoeven, E. Louis, F. Bijkerk, *Formation of Si/SiC multilayers by low-energy ion implantation and thermal annealing*, Nucl. Instrum. Methods B 268 (2010) 560-567

I.M.N. Groot, J.C. Juanes-Marcos, C. Diaz, M.F. Somers, R.A. Olsen, G.-J. Kroes, *Dynamics of dissociative adsorption of hydrogen on a CO-precovered Ru(0001) surface: a comparison of theoretical and experimental results*, Phys. Chem. Chem. Phys., 2010, 12, 1331-1340

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C. Hahn, J. Shan, I.M.N. Groot, A.W. Kleyn, L.B.F. Juurlink, *Selective poisoning of active sites for D_2 dissociation on platinum*, Catalysis Today, 154 (2010) 85-91

S.P. Hau-Riege, R.A. London, A. Graf, S.L. Baker, R. Soufli, R. Sobierajski, T. Burian, J. Chalupsky, L. Juha, J. Gaudin, J. Krzywinski, S. Moeller, M. Messerschmidt, J. Bozek, C. Bostedt, *Interaction of short x-ray pulses with low-Z x-ray optics materials at the LCLS free-electron laser*, Opt. Express 18 (2010) 23933-23938

M. Jiang, F.J. Gou, A.Y. Yan, C.W. Zhang, F. Miao, *Energy and spectrum of BeO molecule under the electric field from different directions*, Acta Physica Sinica, 59 (2010) 7743-7748

A.R. Khorsand, R. Sobierajski, E. Louis, S. Bruijn, E.D. van Hattum, R.W.E. van de Kruijs, M. Jurek, D. Klinger, J.B. Pelka, L. Juha, T. Burian, J. Chalupsky, J. Cihelka, V.

Hajkova, L. Vysin, U. Jastrow, N. Stojanovic, S. Toleikis, H. Wabnitz, K. Tiedtke, K. Sokolowski-Tinten, U. Shymanovich, J. Krzywinski, S. Hau-Riege, R. London, A. Gleeson, E.M. Gullikson and F. Bijkerk, *Single shot damage mechanism of Mo/Si multilayer optics under intense pulsed XUVexposure*, Opt. Express, 18 (2010) 700-712

I.V. Kozhevnikov, R. van der Meer, H.M.J. Bastiaens, K.-J. Boller and F. Bijkerk, *High-resolution, high-reflectivity operation of lamellar multilayer amplitude gratings: identification of the single-order regime*, Opt. Express, 18 (2010) 16234-16242

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V.I.T.A. de Rooij-Lohmann, I.V. Kozhevnikov, L. Peverini, E. Ziegler, R. Cuerno, F. Bijkerk, A.E. Yakshin, *Roughness evolution of Si surfaces upon Ar ion erosion*, Applied Surface Scie, 256 (2010) 5011-5014

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G.M. Wright, R.S. Al, E. Alves, L.C. Alves, N.P. Barradas, A.W. Kleyn, N.J. Lopes Cardozo, H.J. van der Meiden, V. Philipps, G.J. van Rooij, A.E. Shumack, W.A.J. Vijvers, J. Westerhout, E. Zoethout, J. Rapp, *Carbon film growth and hydrogenic retention of tungsten exposed to carbon-seeded high density deuterium plasmas*, J. Nucl. Mater. 396 (2010) 176-180

A.E. Yakshin, I.V. Kozhevnikov, E. Zoethout, E. Louis, and F. Bijkerk, *Properties of broadband depth-graded multilayer mirrors*

for EUV optical systems, Opt. Express, 18 ((2010) 6957-6971

PhD Theses

V.I.T.A de Rooij-Lohmann, *Nanoscale diffusion, compound formation and phase transitions in Mo/Si multilayer structures*, PhD thesis at the University of Twente, 1 October 2010

H. Ueta, *Knocking on surfaces – interactions with hyperthermal particles with metal surfaces,* PhD thesis at the University of Leiden, 16 November 2010

Publications in other journals and conference proceedings

M. Huisjes, *De grens tussen chemie en fysica is altijd al vaag geweest*, in de CW Jaarboek NWO 2010 - Chemische Wetenshappen, 2010, 62-63

T. Tsarfati, *Oppervlaktechemie van nanolaagspiegels*, NTvN 76, 2010, 276-278

T. Tsarfati, E. Zoethout, R.W.E. van de Kruijs, F. Bijkerk, *Gestapelde nanolaag spiegels voor x-rays*, NTvN 76, 2010

Advanced Lithography 2010, 21-25 February 2010, San Jose Convention Center, San Jose, California, USA

E. Louis, E.D. van Hattum, S. Alonso van der Westen, P. Sallé, K.T. Grootkazijn, E. Zoethout, F. Bijkerk, G. von Blanckenhagen, and S. Müllender, *High reflectance multilayers for EUVL HVM-projection optics*, Proc. SPIE 7636, 76362T (2010)

A.J.R. van den Boogaard, E. Louis, K.A. Goldberg, I. Mochi, and F. Bijkerk, *EUV-multilayers on grating-like topographies,* Proc. SPIE 7636, 76362S (2010)

32nd International Free Electron Laser Conference FEL 2010, 23-27 August, 2010, Malmö, Sweden

J.P.M. Beijers, S. Brandenburg, K.S.E. Eikema, S. Hoekstra, K. Jungmann, T. Schlathölter, R.G.E. Timmermans, L. Willmann, R. Hoekstra, KVI, P.H.M. van Loosdrecht, B. Noheda, T.T.M. Palstra, O.J. Luiten, F. Bijkerk, *ZFEL: a compact, soft x-ray FEL in the Netherlands*

Invited lectures at conferences and meetings

International Workshop on X-ray Diagnostics and Scientific Application of the European XFEL, 14-17 February 2010, Ryn, Poland

R. Sobierajski, *Multilayer optics for XFEL*

EOS Topical Meeting on Diffractive Optics, 14-18 February 2010, Koli, Finland

F. Bijkerk, and E. Louis, *Progress in multilayer XUV reflecting elements; building blocks for Bragg-Fresnel optics*

The Nanoworld in Action - Workshop on soft X-ray FEL Physics and Applications, June 7-8, 2010, Groningen, the Netherlands

F. Bijkerk, E. Louis, R. Sobierajski, R.A. Loch, R. van der Meer, R.W.E. van de Kruijs, and S. Bruijn, *Multilayer optics for XUV and X-ray free electron lasers*

7th International Conference on Thin Films and Applications (TFA), Shanghai, China, 24-27 September 2010

E. Louis, S. Muellender, and F. Bijkerk, *Developing reflective multilayer coatings, an enabling component of Extreme Ultraviolet Lithography*

Passion for Knowledge (DIPC10), 28 September – 1 October 2010, San Sebastian, Spain

A.W. Kleyn, *When energy is not a problem: interactions with fast and excited particles at surfaces*

Thin Film Nanomanufacturing - Annual TFN meeting, 7 December 2010, Nieuwegein, FOM Rijnhuizen, the Netherlands

F. Bijkerk, E. Louis, A.E. Yakshin, R.W.E. van de Kruijs, E. Zoethout, M.A. Gleeson, E.D. van Hattum, C.J. Lee, H.J.M. Bastiaens, F.A. van Goor, J. Chen, A.J.R. van de Boogaard, V.I.T.A. Lohmann, S. Bruijn, T. Tsarfati, I. Nedelcu, R. van der Meer, M. Bayraktar, A.S. Kuznetsov, J. Bosgra, and I. Makhotkin, *Thin Film Nanomanufacturing at Rijnhuizen, an introduction*

Other oral and poster presentations at (international) conferences and meetings

Physics@FOM, Veldhoven, 2010, 19-20 January 2010, Veldhoven, Netherlands

V.I.T.A. de Rooij-Lohmann, A.E. Yakshin, R.W.E. van de Kruijs, E. Zoethout, A. Kleyn, R. Keim, M. Gorgoi, F. Schäfers, H. Brongersma, F. Bijkerk, *Crystallization-accelerated diffusion at the nanometer scale,* P03.80

E. Zoethout, E. Louis, F. Bijkerk, *Growth of silicon nitride thin films at room temperature*, P05.24

H. Ueta, M.A. Gleeson, A.W. Kleyn, *Hyperthermal nitrogen atoms interaction with Ru(0001)*, P05.28

A.J.R. van den Boogaard, E. Louis, E. Zoethout, F. Bijkerk, *Morphology of Kr-polished thermally grown amorphous Si layers*, P05.48

J. Chen, E., Louis, R. Harmsen, Ch. Lee, H. Wormeester, W. van Schaik, F. Bijkerk, *In situ monitoring of mimicked carbon contamination of EUV optics by spectroscopic ellipsometry*, P05.52

A.S. Kuznetsov, R.W.E. van de Kruijs, M.A. Gleeson, K. Schmid, F. Bijkerk, *Hydrogen interaction with mirrors for euvl lithograph,* P05.56

J. Bosgra, A.E. Yakshin, F. Bijkerk, *Dependence of interdiffusion on intolayer phase in naoscale multilayered films*, P05.62

S. Bruijn, R.W.E. van de Kruijs, A.E.Yakshin, F. Bijkerk, *Control of thermal diffusion in nanoscale multilayered films*, P05.51

10th International Conference on the Physics of X-Ray Multilayer Structures (PXRMS), Montana, USA, 14-18 February 2010

J. Bosgra, A.E. Yakshin, R.W.E. van de Kruijs, and F. Bijkerk, *Dynamic diffusion rates during evolution of Mo/Si interlayers under annealing* (poster)

E. Louis, A.R. Khorsand, R. Sobierajski, E.D. van Hattum, T. Tsarfati, M. Jurek, D.

Klinger, J.B. Pelka, L. Juha, J. Chalupsky, J. Cihelka, V. Hajkova, U. Jastrow, S. Toleikis, H. Wabnitz, K. Tiedtke, J. Gaudin, and F. Bijkerk, *Damage studies of multilayer optics for XUV FELs* (oral)

V.I.T.A. de Rooij-Lohmann, S. Nyabero, A.E. Yakshin, E. Zoethout, J. Verhoeven, and F. Bijkerk, *Reduction of interlayer thickness by low-temperature deposition of Mo/Si multilayer mirrors for X-ray reflection* (poster)

R.W.E. van de Kruijs, S. Bruijn, V.I.T.A. de Rooij-Lohmann, A.E. Yakshin, and F. Bijkerk, *Diffusion in Mo/Si based multilayers, a story from 77K to 770K* (oral)

T. Tsarfati, I. Makhotkin, E. Louis, R.W.E. van de Kruijs, F. Bijkerk, *Nitridated B_4C/La multilayer optics for 6.7nm* (poster)

EOS Topical Meeting on Diffractive Optics, 14-18 February 2010, Koli, Finland

A.J.R., van den Boogaard, E. Louis, F. van Goor, and F. Bijkerk, *Mo/Si multilayer coating of grating-like topographies for IR diffractive-filtering* (oral)

Advanced Lithography 2010, 21-25 February 2010, San Jose Convention Center, San Jose, California, USA

E.D. van Hattum, E. Louis, S. Alonso van der Westen, P. Sallé, E. Zoethout, G. von Blanckenhage, H. Enkish, S. Müllender, and F. Bijkerk, *High reflectance multilayer coating technology for 3100 EUVL projection optics* (poster)

First Annual Meeting of the Smart Optical Systems Programme, June 14th, 2010, Scheveningen, the Netherlands

C.J. Lee, G. Rijnders, R. Sobierajski, F. Bijkerk, U. Dinger, S. Müllender, and K. Tiedtke, *Smart Multilayer interactive optics for Lithographic at Extreme UV wavelengths* (oral)

11th ASML Technology Conference, 16 June 2010, Veldhoven, the Netherlands

A.S. Kuznetsov, A.W. Kleyn, K. Koshelev, S. Muellender, P. Kurz, M. van Kampen, M., V.Y. Banine, G.C. de Temmerman, W.J. Goedheer, and F. Bijkerk, *Introducing CP3E* (oral)

I. Makhotkin, T. Tsarfati, E. Louis, R.W.E. van de Kruijs, E. Zoethout, and F. Bijkerk, *Nitridated B4C/La multilayer optics for 6.7 nm* (poster)

A.J.R. van den Boogaard, E. Louis, F. van Goor, and F. Bijkerk, *Mo/Si multilayer coating of grating-like topographies for IR diffractive-filtering* (poster)

EuroFEL Workshop on Photon Beamlines & Diagnostics, 28-30 June 2010, Hamburg, Germany

R.A. Loch, R. Sobierajski, C. Bostedt, J. Bozek, S. Bruijn, T. Burian, J.C. Castagna, J. Chalupsky, Y. Feng, J. Gaudin, A. Graf, V. Hajkova, E.D. van Hattum, S. Hau-Riege, R.W.E. van de Kruijs, D. Klinger, J. Krzywinski, U. Jastrow, L. Juha, E. Louis, M. Messerschmidt, S. Moeller, K. Tiedtke, and F. Bijkerk, *Damage mechanismes in Mo/Si multilayer optics for short-wavelengths FELs* (poster)

R.W.E. an de Kruijs, R. Sobierajski, E. Louis, V.I.T.A. de Rooij-Lohmann, S. Bruijn, A.E. Yakshin, R.A. Loch, and F. Bijkerk, "*Thermal damage in Mo/Si based multilayers for short-wavelength FELs* (oral)

37th International Conference on Vacuum Ultraviolet and X-ray Physics, VUVX 2010, 11-16 July 2010, Vancouver, BC, Canada

F. Bijkerk, *Progress in multilayer XUV reflecting Bragg optics,* 2P103

27th European Conference on Surface Science (ECOSS 27), 29 August - 3 September 2010, Groningen, the Netherlands

M.L. Grecea, M.A. Gleeson, W. van Schaik, A.W. Kleyn, and F. Bijkerk, *SO_2+NH_3+H_2O on the quartz(0001) surface: formation of stabilized complex and photochemistry pathways* (oral)

H. Ueta, M.A. Gleeson, and A.W. Kleyn, *Ar scattering from the Ru(0001) surface* (oral)

XTOP 2010, 10th Biennial Conference on High Resolution X-Ray Diffraction and Imaging, 20-23 September 2010, University of Warwick, UK

I. Makhotkin, E. Louis, R.W.E. van de Kruijs, A.E. Yakshin, A.Y. Seregin, M.Y. Lubomirskii, S.N. Yakunin, E.Y. Tereschenko, M.V. Kovalchuk, and F. Bijkerk, *Determination of the density of ultrathin films using x-ray standing waves* (poster)

Passion for Knowledge (DIPC10), 28 September – 1 October 2010, San Sebastian, Spain

H. Ueta, M.A. Gleeson, and A.W. Kleyn, *Hyperthermal Ar interactions with bare and adsorbate-covered Ru(0001) surfaces* (poster)

European Summer School on Low Temperature Plasma Physics, 10-16 October 2010, Bad Honnef, Germany

A.S. Kuznetsov, R.W.E. van de Kruijs, M.A. Gleeson, K. Schmid, and F. Bijkerk, *Plasma interaction with mirrors for EUV lithography* (poster)

2010 International Symposium on Extreme Ultraviolet Lithography, October 17-20, 2010, Kobe, Japan

J. Chen, E. Louis, H. Wormeester, R. Harmsen, R.W.E. van de Kruijs, C.J. Lee, W. van Schaik, and F. Bijkerk, *EUV Optics cleanliness qualification using spectroscopic ellipsometry*, (poster)

R.W.E. van de Kruijs, S. Bruijn, A.E. Yakshin, and F. Bijkerk, *Thermal stablility lifetime scaling of multilayer EUVL optics* (oral)

WELTPP-13 _ 13the Workshop on the Exploration of Low Temperature Plasma Physics, 25–26 November 2010, Kerkrade, the Netherlands

G.J. van Hunnik, R.C. Wieggers, W.J. Goedheer, and F. Bijkerk, *Modeling of EUV driven plasmas* (poster)

Inaugural ToF-SIMS LEIS Workshop, 24 November, 2010, Department of Materials, Imperial College, London, UK

V.I.T.A. de Rooij-Lohmann, A.E.Yakshin, R.W.E. van de Kruijs, E. Zoethout, A.W.

Kleyn, E.G. Keim, M. Gorgoi, F. Schäfers, H.H. Brongersma, F. Bijkerk, *Diffusion in a Layered Mo/B4C/Si System Probed with LEIS*

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I.A. Makhotkin, E. Zoethout, E. Louis, R.W.E. van der Kruijs, A.E. Yakshin, T. Tsarfati, A.Yu. Seregin, S.N. Yakunin, and F. Bijkerk, *Influence of N-ion treatment on the structure of La-B4C layered films*

M2i Conference 2010, Materials to innovate Industry and Society, 13 - 14 December 2010, Noordwijkerhout, the Netherlands

J. Chen, E. Louis, H. Wormeester, R. Harmsen, R.W.E. van de Kruijs, C.J. Lee, C.J., W. van Schaik, and F. Bijkerk, *EUV optics cleanliness qualification using spectroscopic ellipsometry* (poster)

M.L. Grecea, *High-brightness Extreme UV (EUV) exposure beam line for advanced, optics surface contamination studies under UHV*, (oral)

M.L. Grecea, M.A. Gleeson, M. van Kampen, A.W. Kleyn, and F. Bijkerk, *The UHV Extreme UV exposure beam line at the FOM EUV Lab @ ASML* (poster)

Seminar

15 January 2010
J.M. Sturm, D. Göbke, S. Guimond, Y. Romanyshyn, H. Kuhlenbeck, and H.-J. Freund, *Vanadium oxide films on Au(111): model catalysts for methanol oxidation*, Van Marum Colloquium, Leiden
18 February 2010

R.W.E. van de Kruijs, *Physics of multilayers for EUV and beyond*, Rigaku Innovative Technologies, Michigan, US

17 August 2010
A.E. Yakshin, V.I.T.A. de Rooij-Lohmann, J. Verhoeven, R.W.E. van de Kruijs, E. Louis, and F. Bijkerk, *Reduction of interface zones in X-ray Mo/Si multilayer mirrors by low temperature deposition*, Institute of Microelectronics Technology and High Purity Materials, Chernogolovka, Russia

Patents

F. Bijkerk, F.A. van Goor, and A.J.R. van den Boogaard, Method for splitting a beam with electromagnetic radiation having wavelengths in the extreme ultraviolet (EUV) and the infrared range, and optical grating and optical device therefore, - 2002545 publication date: 26-08-2010
T. Tsarfati, E. Zoethout, E. Louis, and F. Bijkerk, Reflektives optisches Element und Verfahren zu seiner Herstellung/Method to enhance layer contrast of a multilayer for reflection at the B absorption edge", - Publication no.:DE 10 2008 040 265 A1, publication date: 14-01-2010

Research contract

F. Bijkerk, *EUV Photochemistry Instrumentation Demonstration*, partner: ASML, funded by: M2i "E-PhID"; Rijnh-10-03-P, 2010

J.M. Sturm, *Metaaloxideoppervlakken als modelsystemen voor watersplitsing met zonlicht*, partner: TU Delft, funded by: Agentschap.nl "EosNEO"; Rijnh-09-26-P, 2010

4.4 OUTPUT ON GUTHz

Publications in peer-reviewed scientific journals

S. Ard, N. Mirsaleh-Kohan, J.D. Steill, J. Oomens, S. Brøndsted Nielsen, R.N. Compton, *Dissociation of dicarboxylate and disulfonate dianions*, J. Chem. Phys. 132, 094301 (2010)

J.M. Bakker, V.J.F. Lapoutre, B. Redlich, J. Oomens, B.G. Sartakov, A. Fielicke, G. von Helden, G. Meijer, and A.F.G. van der Meer, *Intensity-resolved IR multiple photon ionization and fragmentation of* C_{60}, J. Chem. Phys. 132, 074305 (2010)

B.J. Bythell, R.P. Dain, S.S. Curtice, J. Oomens, J.D. Steill, G.S. Groenewold, B. Paizs and M.J. Van Stipdonk, *Structure of* $[M + H - H_2O]^+$ *from protonated tetraglycine revelaed by tandem mass spectroscopy and IRMPD spectroscopy*, J. Phys. Chem. A, 2010**,** 114, 5076-5082

D.R. Carl, T.E. Cooper, J. Oomens, J.D. Steill and P.B. Armentrout, *Infrared multiple photon dissociation spectroscopy of cationized methionine: effects of alkali-metal cation size on gas-phase conformation*, Phys. Chem. Chem. Phys., 2010, 12, 3384-3398

X. Chen, J.D. Steill, J. Oomens, N.C. Polfer, *Oxazolone versus macrocycle structures for Leu-Enkephalin* b_2*-*b_4*: insights from infrared multiple-photon dissociation spectroscopy and gas-phase hydrogen/deuterium exchange*, J. Am. Soc. Mass Spectrom. 2010, 21, 1313-1321

M. Citir, E.M.S. Stennett, J. Oomens, J.D. Steill, M.T. Rodgers, P.B. Armentrout, *Infrared multiple photon dissociation spectroscopy of cationized cysteine: Effects of metal cation size on gas-phase conformation*, Int. J. Mass Spectrom. 297 (2010) 9-17

C.S. Contreras, N.C. Polfer, A.C. Chung, J. Oomens, J.R. Eyler, *Hydrogen/deuterium exchange of phenylalanine analogs studied with infrared multiple photon dissociation*, Int. J. Mass Spectrom. 297, 162-169

R.P. Dain, C.M. Leavitt, J. Oomens, J.D. Steill, G.S. Groenewold and M.J. van Stipdonk, *Infrared multiple photon dissociation spectroscopy of sodium and potassium chlorate anions*, Rapid Commun. Mass Spectrom. 24 (2010) 232-238

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J. Oomens: *Laboratory IR spectroscopy of PAHs*

European Conference on Atoms, Molecules and Photons (ECAMP-10), July 4 – 9, 2010, Salamanca, Spain

J. Oomens: *Ion spectroscopy using FELIX*

Infrared Plasma Spectroscopy 2010, August 25–27, 2010, Rolduc (Kerkrade), The Netherlands

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S. Jaeqx, J. Oomens, A.M. Rijs: *Structural analysis of F0F1-ATPase active site mimics by IR spectroscopy*

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J.M. Bakker: *Far-Infrared multiple-photon action spectroscopy of strongly bound systems*

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4.5 Output from Collaborators

User Groups of the FELIX facility

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4.6 Output on outreach to academia, society and industry

Activities at Rijnhuizen

Student Open House Day, October 14th, 2010

General Open House Day, October 24th, 2010

The Fusion Road Show was presented 7 times at Rijnhuizen for visiting students and other groups, including 2 performances during the General Open House Day.

Rijnhuizen organised 10 guided tours of the institute for visiting groups and dignitaries.

Via the website www.fusie-energie.nl, which welcomes some 300 visitors a day, Rijnhuizen received about 40 requests for information, many of which from secondary school students writing a paper (‘profielwerkstuk’) on fusion.

Two groups of four secondary school students participated in measurements on Pilot-PSI as part of a physics class on nuclear fusion.

External Presentations

The *Fusion Road Show* was presented around 20 times at secondary schools and 7 times at Rijnhuizen, including 2 performances during the General Open House Day, reaching a total of 2300 students. Large scale performances included the three day continuous performance of the show at the 55.000 visitor Lowlands music festival in August, reaching over 2000 people; and at the Innovatielab of the Beta Platform Techniek in October, with around 1000 visitors to the stand.

External Publications and Interviews

The institute received a lot of media attention regarding the relocation of Rijnhuizen to the TU/e campus and its change of focus to become a nationally coordinating energy research institute. All major newspapers featured articles on the various stages of the decision process, and specialised popular science journals took up the news as well in over 20 print articles and radio shows. The presence of the Fusion Road Show at the Lowlands music festival was mentioned in 5 print and 10 online publications.

5

Appendix

5 Appendix

5.1 Funded projects

Fusion Physics Division

Title	Source of Funding
Advanced control of magnetohydrodynamic modes in burning plasmas	FOM (FP-120)
Fusion Research	Euratom (EFP)
Support to ITER Diagnostic Design	F4E (EFDA-1)
EFDA ITER design of an ECRH upper Launcher	F4E (EFDA-2)
Development of a combined two-dimensional ECE Imaging/microwave imaging reflectometry system	US-DOE, POSTECH
Engineering of Optical Diagnostics for ITER (EODI)	European Fusion Training Scheme
Electron Cyclotron heating TECHnology (EC-TECH)	European Fusion Training Scheme
Global Orented Training in Remote Handling	EFDA Goal Oriented Training
Imaging For Fusion (IF-Fusion)	EFDA Goal Oriented Training

Title	Source of Funding
Many tasks in the field of diagnostics, transport physics, MHD, Integrated Tokamak Modelling and Public Information	EFDA
ITER-NL: innovation for and by ITER	OC&W (FES-Grant)
Centre of Excellence for Fusion Physics and Technology	NWO-RFBR
FUSENET	Euratom
European Fusion Research Fellowship	EFDA

Plasma Surface Interactions Division

Title	Source of Funding
PSI-lab, an integrated laboratory on plasma-surface interaction	FOM (FP-75)
Fusion Research	Euratom (EFP)
PSI-lab, an integrated laboratory on plasma-surface interaction	NWO-Groot
Many tasks in the field of plasma wall interaction, diagnostics and emerging technologies	EFDA
Centre of Excellence for Fusion Physics and Technology	NWO-RFBR
Valorisation of materials research in Magnum-PSI	NWO Kennisbenutting

Nanolayer surface and interface Physics Division

Title	Source of Funding
eXtreme UV Multilayer Optics (IPP-XMO) (SoW5)	Carl Zeiss SMT GmbH, FOM Industrial Partnership Programme I-10, Agentschap NL (WBSO)
Metaaloxide-oppervlakken als modelsystemen voor watersplitsing met zonlicht	SenterNovem through the NEO Programme NEO 07005, and the NWO-'Dynamiseringsfonds'
Multilayer Optics for Lithography Beyond the Extreme Ultraviolet Wavelength Range ('Beyond-EUV')	STW, Carl Zeiss SMT GmbH
Multilayer optics for 4th generation XUV sources	FOM-Pilot project
Valorisation of research results Rijnhuizen, 'Valo-RIGHT	Valorisation Funding FOM
Dynamics of plasma activated surface processes	FOM-99TF24 (TF)
PSI-lab, an integrated laboratory on plasma-surface interaction	FOM (FP-75)
PSI-Lab, an integrated laboratory on plasma-surface interaction	NWO-Groot
Nanostructured Arrays	STW, PANalytical, ASML
Advanced Development Coater ('ADC')	FOM, Carl Zeiss SMT GmbH

Title	Source of Funding
Controlling photon and plasma induced processes at EUV optical surfaces 'CP3E'	FOM Industrial Partnership Programme (IPP I-23), ASML, Carl Zeiss SMT GmbH
In situ monitoring of contamination layers on EUV optics at Angstrom resolution, 'ISitCLEAR'	M2i, ASML
Advanced multilayer coatings for high volume EUV lithography (ACHieVE)	SenterNovem Internationale Samenwerkingsprojecten
EXtreme uv lithography Entry Point Technology development ('EXEPT')	SenterNovem CATRENE Programme
Nano-engineering rules for X-ray and EUV optics: Atomic-scale controlled deposition	STW, Carl Zeiss SMT GmbH
Development of Extreme UV multilayer coating technology towards production tool optics (SoW7)	Carl Zeiss SMT GmbH
Valorisation of research results Rijnhuizen, 'ValoRIGHT	Valorisation Funding FOM
'E-PhID', EUV Photochemistry Instrumentation	M2i, ASML
Valorisation of new multilayer concepts	NWO Kennisbenutting

GUTHz Division

Title	Source of Funding
The IR user facility FELIX, expanded with FELICE	FOM (FP-58)
Beam time on FELIX for UK scientists	Materials Division EPSRC, UK
Furthering Access to the IR-light source FELIX	ELISA, 7th FP, EU
Furthering Access to the IR-light	IA-SFS, 6th FP, EU
A versatile facility for vibrational studies confor-mational dynamics	NWO-Middelgroot
A US - Dutch mass spectrometry consortium for advanced modelling and biological structure and imaging applications	NSF-PIRE
Beam time on FELIX for UK scientists	EPSRC, UK
Subcontract with University of Surrey as part of the Coherent Optical and Microwave Physics for Atomic-Scale Spintronics in Silicon (COMPASSS) Programme Grant from the EPSRC, UK	EPSRC, UK
Furthering Access to the IR-light source FELIX, ELISA	7th FP, EU
From rings to chains and cages: the photoche-mistry of interstellar PHAs	NWO/CWDutchAstro-chemistry Network
A US - Dutch mass spectrometry consortium for advanced modelling and biological structure and imaging applications	NSF-PIRE

Title	Source of Funding
Controlled solvent induced shuttling in molecular motors in the gas phase.	CW/NWO-VENI (A.M. Rijs)
The way they move: a cool look at conformational changes in biomolecular motors	FOM/v (A.M. Rijs)
A cool look at biomolecular motion	NWO/CW – Athena (A.M. Rijs)

5.2 Rijnhuizen in figures

Staff (FTE)

Scientific staff

permanent	24.2
PhD-students	31.1
temporary (postdoc's etc.)	11.2

Technical staff

permanent	55.6
temporary	7

Support staff

permanent	19.8
temporary	3.5
Total	**152.4**

Output

Scientific Publications	135
Invited Lectures	35
Other Scientific Products	225
Other non-scientific output	74
PhD Theses	4
Master Theses	1
Bachelor Theses	4
Patents	2

Budget (k€)

Personnel	11,998 [1)]
Consumables	5,007 [2)]
Investments	477

1) Including k€ 2.434 concerning 2009 but budgeted in 2010
2) Including k€ 1750 of in kind consumables

Total	**17,459**

5.3 Advisory committees

Scientific Advisory Committee

Prof. Dr. G. van Steenhoven (chairman)
University of Twente, The Netherlands

Prof. Dr. M.S. de Vries
University of California, Santa Barbara, USA

Dr. B. Lipschultz
Massachusetts Institute of Technology, Cambridge, USA

Dr. V.I.Y. Banine
ASML, Veldhoven, The Netherlands

Dr. D.J. Campbell
ITER Organisation
St Paul lez Durance Cedex, France

Prof. Dr. A. von Keudell
Ruhr-University Bochum, Germany

Prof. Dr. J.R. Schneider
Deutsches Elektronen-Synchrotron DESY
Center for Free-Electron Laser Science CFEL, Germany

FELIX Programme Advisory Committee

M. Helm (chairman)
University of Dresden / Forschungszentrum Dresden (FZD), Rossendorf, Germany

H. Bakker
AMOLF / University of Amsterdam, Amsterdam, The Netherlands

A.J.R. Heck
University of Utrecht, Utrecht, The Netherlands

A. Krier
Lancaster University, Lancaster, UK

P. Maître
Université de Paris-Sud, Orsay, France

H.N. Rutt
University of Southampton, Southampton, UK

W. van der Zande
Radboud University, Nijmegen, The Netherlands

Colophon

Edited and coordinated by
Gieljan de Vries
Marianne de Boeij, Organize4u, Nieuwegein

Layout-editor
Marianne de Boeij, Organize4u, Nieuwegein

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On the Cover:
False colour photograph of the inside of the vacuum vessel of Magnum-PSI with argon plasma at high ambient pressure (30 Pa). The so-called source skimmer on the left limits the gas flow to the next chamber.

FOM-RIJNHUIZEN

Address

FOM INSTITUTE FOR PLASMA PHYSICS

Edisonbaan 14
P.O. Box 1207
3430 BE Nieuwegein
The Netherlands
www.rijnhuizen.nl