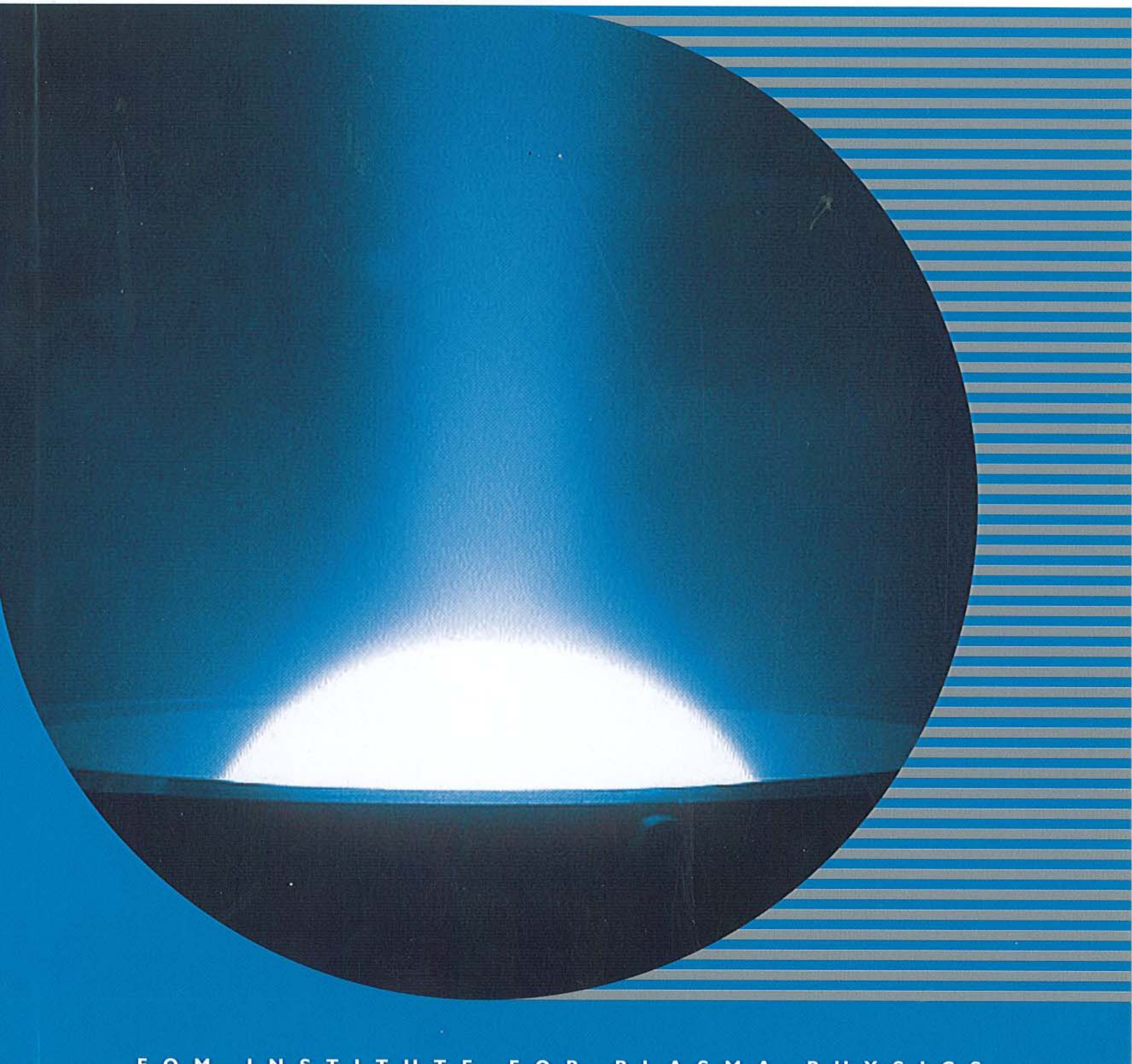
RIJNHUIZEN

Annual report 2009



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

1.1 The mission of Rijnhuizen

“We perform high-quality fundamental research in the field of sustainable energy, with emphasis on fusion. In addition, we train graduate and undergraduate students and technicians, and transfer high-level scientific and technical knowledge to industry and society at large.”

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. In addition to these 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 programmes.

The FOM Institute for Plasma Physics ‘Rijnhuizen’ was inaugurated in 1959 with the mission to be the Dutch centre for fusion research. Since then, the scientific programme has included fundamental (experimental and theoretical) plasma physics research and research on fusion technology. Gradually, the progress in fusion called for increasingly large experimental facilities. This led to the decision in 1995/1996 to form the Trilateral Euregio Cluster (TEC) with institutes in Jülich and Brussels for a joint programme on the TEXTOR tokamak in Jülich, Germany. Rijnhuizen has currently no large in-house experimental fusion experiments, but a new large facility to study plasma-surface interaction, Magnum-PSI, is almost completed at the institute. The research on this new facility will be important for the international ITER project, the next step in the development of fusion as a clean, safe and sustainable source of energy. Rijnhuizen is the home base for all Dutch researchers in high-temperature plasma physics. The fusion and plasma physics research at Rijnhuizen was reorganised during 2009, resulting in the (High Temperature) Fusion Physics department lead by Tony Donné, and the department Plasma Surface Interactions PSI lead by Jürgen Rapp, focussing on low temperature plasma physics. Materials processing and thin film deposition are also included in the PSI activities.

Around 1986, it was decided to broaden the mission of Rijnhuizen also beyond plasma physics. This resulted in the start of an activity in quantum electronics in 1987: the development of an infrared Free Electron Laser, FELIX. Later FELIX became a user facility. The institute started in 1998 an in-house programme to study the dynamics of molecular processes with FELIX. The extension of the facility by a Free Electron Laser for Intra-Cavity Experiments, FELICE, is almost completed. With FELICE, this type of research will have a bright future.

Another activity started in 1987 concerned the generation of and optical elements for extreme ultraviolet radiation for lithography (EUVL). This activity was carried out for a long time in the Laser plasma and XUV optics (LPX) group in the plasma physics department. The group focused on generation of EUV radiation by laser induced plasma, on laser wake field acceleration and on multilayer optical components. Due to the steady growth of notably the last activity, the LPX group has turned into the nanolayer Surface and Interface Physics (nSI) department managed by Fred Bijkerk.

1.2 Organisational Structure

The institute, with around 160 employees, has one director, Aart Kleyn. Rijnhuizen currently has four scientific divisions and within these divisions the research groups are headed by senior scientists. In 2009, the Fusion Physics department was split into two divisions – for more information on this topic, see Chapter 2. The split of the department took place in November 2009. For practical reasons, this annual report follows the old structure with only three departments. Apart from the scientific divisions there is a department for technical and facility support. The management of the institute is assisted by a personnel officer.

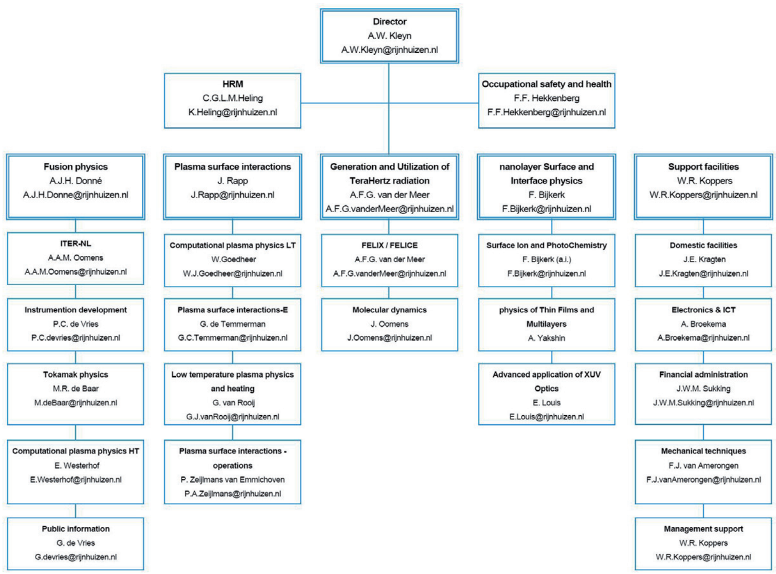


Figure 1.1: Organisational chart from November 2009.

The working units are research groups and support groups, which are each headed by a group leader, who is responsible for the output and the near future of the group. The research groups are embedded in four scientific divisions: the Fusion Physics division with Tony Donné as head, the Plasma Surface Interactions division lead by Jürgen Rapp, the nano-layer Surface and Interface Physics division managed by Fred Bijkerk, and the Generation and Utilization of THz Radiation division led by Lex van der Meer. The support groups are embedded in the Support Facilities division managed in 2009 by Noud Oomens, who was succeeded in 2010 by Wim Koppers. The overall management of the Institute is carried out by a management team consisting of all (deputy-) division leaders, and headed by the director. The personnel officer, Karijn Heling, attends all meetings of the management team.

The core of all groups in the diagram is funded by FOM programmes and the Mission Budget Rijnhuizen. The former support the temporary scientific staff and all costs related to the direct execution of the scientific programme. The mission budget supports most of the infrastructure and permanent staff needed to carry out the Institute's mission. In addition, considerable funding, about 50%, is obtained externally. Of this external funding, the long-lasting support by Euratom for the fusion research through the Euratom-FOM association should be mentioned. In 2007 another major source of funding for the fusion physics programme has been obtained via a so-called FES grant. This led to the ITER-NL organisation, jointly operated by FOM Rijnhuizen, the organisation for applied science TNO, and the Nuclear Research and Consultancy Group NRG. This activity has been extended until 2013, albeit with a smaller budget. The free electron laser facility FELIX is operated for its users under a FOM programme, and in addition is co-funded by EPSRC and the EU. The work in the nSI division is strongly supported by the Carl Zeiss (Oberkochen) company and a new lab will be set up at the premises of ASML. The support groups are funded by both directly charging the project concerned, and by support from the mission budget.

In this volume the annual reporting in the subsequent chapters will be arranged according to the organisational structure with three scientific departments that was in effect before November 2009. There is not always a one to one mapping of FOM programmes to research groups. Some groups are active in more than one programme. Therefore, the FOM programmes are not made visible in the organisational chart. For clarity this book is organised in the following fashion: the activities of all research and support groups are introduced in chapter 2. The achievements per group and division in 2009 are listed, with the remark that some research groups contribute to the same FOM programme. FOM programme support and Euratom-FOM funding are always indicated at the start of each section.

1.3 Overview of the research

The largest research programme of Rijnhuizen is in the field of fusion research. Fusion is a truly international research field. Europe has a well-coordinated European Fusion Programme (EFP) which includes both physics and technology, and is world-leading in this field. The EFP is coordinated and supported by the European Commission (Euratom), the research activities take place in national laboratories. The research programme of the joint European experiment JET, operated in Culham, UK, by UKAEA, is organised by EFDA, the European Fusion Development Agreement.

Rijnhuizen is the centre where the Dutch contribution to the physics research of the EFP is carried out. The fusion research is done in close collaboration with the ForschungsZentrum Jülich (FZJ) and the Royal Military Academy (ERM/KMS, Brussels). FOM-Rijnhuizen, FZJ and the ERM/KMS together form the Trilateral Euregio Cluster (TEC). The TEC partners have a joint research programme, of which the experimental part is concentrated on the tokamaks TEXTOR (in Jülich) and JET (Culham), and on the plasma generators presently being developed at Rijnhuizen as part of PSI-lab. The universities of Eindhoven and Groningen are involved in parts of the fusion physics programme, coordinated by Rijnhuizen. The Nuclear Research and Consultancy Group (NRG in Petten) also contributes to the EFP with research on materials for fusion reactors.

At Rijnhuizen, all fusion research is accommodated in the Fusion Physics division. The two FOM-programmes involved concern, on the one hand, the physics of the hot plasma inside a fusion reactor and, on the other hand, the very intense plasma surface interaction where the plasma touches the containing vessel. A short introduction to these two research lines is given here.

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. For the experiments, TEXTOR was the home base up to July 2009 and within the same research programme, experiments are also carried out at the world's largest fusion experiment JET. In the new research programme "Advanced control of magnetohydrodynamic modes in burning plasmas", the experimental and theoretical efforts are fully integrated.

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. 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 have been achieved that exceed those expected in ITER. This indicates that the very ambitious targets set for Magnum-PSI can be reached. Big differences between Pilot-PSI and Magnum-PSI are the intensity and duration of magnetic field pulses, the size of the beam, and the available on-line diagnostics.

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 produce multilayer mirrors that have unprecedented high reflectivity for 13.5 nm radiation, to be 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 nm lithography. The key issue in the research is the reflectivity and lifetime of the mirrors developed under the harsh operation conditions. 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 a Industrial Partnership Programme of FOM with strong 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 CP3E of this successful work started in 2009.

Rijnhuizen has designed and constructed the Free Electron Laser for Infrared eXperiments, FELIX, attracting user groups from all over the world. 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 multi-colour 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.

A major extension of the FELIX facility with a project named FELICE, the Free Electron Laser for Intra-Cavity Experiments, involves the construction of a third beamline which can be operated interleaved with one of the two original beamlines of FELIX, with the aim to double the amount of beam time available to the users. The purpose of FELICE is to provide significantly higher infrared energies for low-absorption, gas-phase experiments. FELICE allows these experiments to be conducted at unprecedented intensities in the infrared spectral range from 3 - 100 μm. The first experimental campaigns on FELICE already indicated that a broad user community can benefit from this new installation.

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. In the various experiments performed in this group, the FELIX radiation is used to study the IR optical properties and dynamics of complex molecules, clusters and nanocrystals in the gas-phase. This work is carried out in collaboration with the Action Spectroscopy chair at Amsterdam University.

The work described above is supported through the following four approved 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: Active control of magneto-hydrodynamic modes in burning plasmas (2010-2014)
- FP-110: eXtreme UV multilayer optics – XMO (2006-2010).

Rijnhuizen participates in the following open FOM Programmes:

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

1.4 Highlights of 2009

50 years FOM Rijnhuizen

In 1959, the FOM Institute for Plasma Physics Rijnhuizen was founded to become the Dutch home base for research into fusion energy. Fifty years later, Rijnhuizen is a succesful and diverse research institute with international standing. On November 10th, speakers Jan Terlouw, Dave Blank, Mattanjah de Vries and Niek Lopes Cardozo talked about the past and future of Rijnhuizen during a special anniversary seminar. During the event the anniversary book "Hittebarrière - Vijftig jaar plasmafysica bij FOM-Rijnhuizen" ('Heat barrier - fifty years of plasma physics at FOM Rijnhuizen') was presented. "The Wrong Assumptions", a band consisting of Rijnhuizen members, performed a spectacular closing act to the personnel party celebrating the 50 year anniversary.

Figure 1.2: Cover anniversary book "Hittebarrière - Vijftig jaar plasmafysica bij FOM-Rijnhuizen" ('Heat barrier - fifty years of plasma physics at FOM Rijnhuizen')

Fission of Fusion Physics

In 2009, it was decided to split the Fusion Physics department into two parts: (High Temperature) Fusion Physics and Plasma Surface Interaction. Tony Donné succeeded Niek Lopes Cardozo as leader of the Fusion Physics department and Head of Research Unit, while Jürgen Rapp has been appointed as head of the PSI department. The split of the department took place in November 2009. A number of new staff have been hired to lead the new groups thus created.

Stabilising fusion plasmas in new FOM programme

The new research programme FP-120 will investigate the properties of high temperature fusion plasmas. Instabilities in these plasma's decrease the performance of the fusion reactor and tend to amplify themselves. The researchers have taken up the task of actively stabilising the plasma with microwaves. The expected results of the research would be a crucial contribution to the operation of ITER

SenterNovem grant for photoconversion research

The institute has received a SenterNovem EOS-NEO grant ('Energie Onderzoek Subsidie - Nieuw Energie Onderzoek') of €100.000 for research on cheap metal oxide semiconductors for photoconversion. Photoconversion of sunlight in solar fuels is a promising technology to harvest and store solar energy in the form of hydrogen. The research will be carried out in close collaboration with the Technical University of Delft, in order to apply the knowledge from well-defined model systems to real photo-electrodes.

Eight million euros for ITER-NL2

The "Fonds Economische Structuurversterking" has announced support of 8 million euros for ITER-NL2, the follow-up programme of ITER-NL. The aim of ITER-NL2 is to enable a strong contribution of Dutch companies to ITER and to facilitate front-line participation of Dutch research in the scientific exploitation of the experiment. The original ITER-NL programme prepared Dutch companies for participation in the construction of ITER via financial support for the development of prototypes. As part of the initiative, two instruments for monitoring and controling the hot fuel (plasma) of the fusion reactor were developed.

New FOM-Zeiss-ASML Industrial Partnership Programme

In line with the successfully running IPP programme XMO, focussed on the basic physics of advanced multilayer mirrors for Extreme UV wavelengths, a new IPP has been launched. This new programme, called CP3E, short for 'Controlling photon and plasma-induced processes at EUV surfaces', is focussed on the plasma physics and photochemistry taking place in such multilayer systems once exposed to extreme photon and plasma fluxes as in the final practical application. The programme includes a FOM EUV laboratory within the premises of ASML research.

FELICE operations

The new FELICE beam line of the FELIX infrared free electron laser is now operational and interleaved operation of the old two beam lines and the FELICE beam line has become routine operation, effectively doubling the available beam time for users. In 2009 FELICE has been open to internal and external users and has produced almost 50% of the beam time of FELIX. One FELICE intra-cavity setup, the molecular beam apparatus, is fully operational and equipped with different sources. The second FELICE beam line is currently being commissioned and its highly sensitive FTICR mass spectrometer will come online in the summer of 2010. The first experimental campaigns on FELICE already indicated that a broad user community can benefit from this new installation. Results are described in Chapter 2.10.

First plasma in Magnum-PSI

The first generation plasma source (45 kW) delivering plasma parameters similar to those expected in the ITER divertor plasma has been developed, tested and installed on Magnum-PSI. The first plasma was achieved on Magnum-PSI on 18 June 2009, a milestone in the project (see Figure 1.3).

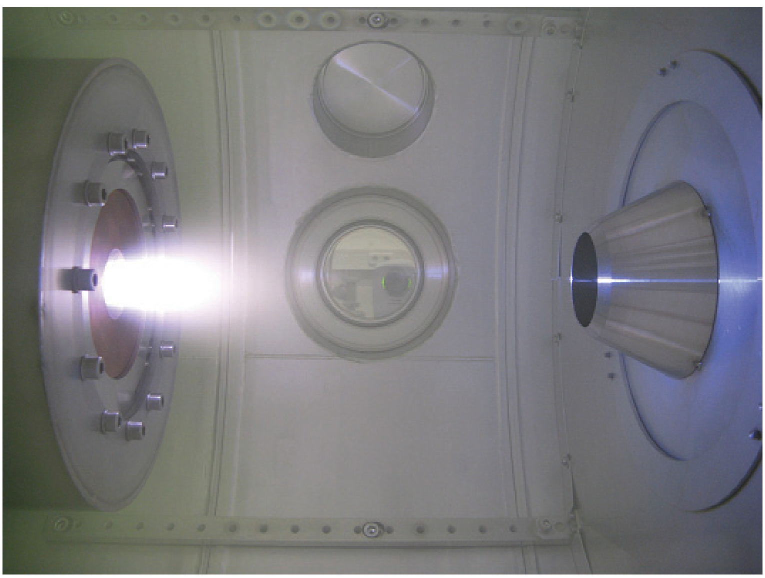


Figure 1.3: First plasma operation of Magnum-PSI on June 18th 2009.

Next generation plasma sources are being developed on the forerunner experiment Pilot-PSI, including a multi-channel cascaded arc aimed to broaden the plasma beam diameter to the specified 10 cm and a pulsed plasma source to simulate transient heat loads with duration of 0.5 – 1 ms as they occur during so-called ELM instabilities in the tokamak.

Farewell to Jülich's TEXTOR-tokamak
On Friday, July 10th, the permanent Rijnhuizen delegation said goodbye to their colleagues at the Jülich TEXTOR-tokamak. Researchers from Rijnhuizen did experiments at Jülich since the late '90s. Now, 10 years later, the 'TEXTOR-group" has returned to Rijnhuizen. The successful cooperation between the two institutes will continue as the new TEC takes shape. This will focus on plasma-wall interaction studies with the linear plasma machines Magnum-PSI at Rijnhuizen and JULE-PSI in Jülich, addressing the vital role that the interaction between wall materials and plasma in the fusion machine will have in optimizing future fusion reactors. TEC will thus stay at the leading edge of fusion research.

Appointments, awards and valorisation
In 2009, Niek Lopes Cardozo left Rijnhuizen to accept a full-time professorship at Eindhoven University, there to start a new Masters programma en fusion science and technology. Niek was also appointed the new Chairman of the Board of Governors and of the Executive Board of FOM. Jos Oomens was appointed professor of Action Spectroscopy at Amsterdam University. Anouk Rijs received both the Athena and FOm/v fellowships, while one of the prestigious EFDA Fusion Fellowships was awarded to post-doctoral researcher Jan Willem Blokland. PHD-student Jonathan Citrin received the Weizmann Institute science prize for his Masters thesis. Finally, Tim Tsarfati won the first FOM Valorisation Chapter award and signed on as valorisation officer at FOM Rijnhuizen. He will investigate possible applications of Rijnhuizen's scientific research.

Science
In terms of scientific output 2009 was a very successful year for Rijnhuizen. The output exceeded that of the previous year both in the total number of publications and in particular in the number of publications in high profile journals. The Institute produced the following output: 4 PhD theses, one Edited book, 3 Book chapters, 133 publications in refereed scientific Journals and 3 Patents. Of these publications 28 were published in high profile Journals, which we define as having in 2008 an impact factor exceeding 4 and Applied Physics Letters, the leading letters journal in applied physics. Most frequently used Journals were: Applied Physics

Letters (4 papers), the Journal of the American Chemical Society (9 papers), and Physical Review Letters (3 papers). These papers reflect some of the many highlights that Rijnhuizen researchers were involved in this year. For the scientific highlights in each of the research programmes, the reader is referred to chapter 2. A total of 20 PhD students is working at Rijnhuizen and 4 students succesfully defended their thesis in 2009.

2

Activities at Rijnhuizen in 2009

2 Activities at Rijnhuizen in 2009

FOM Programmes

Manipulation of mesoscale structures in hot, magnetised plasmas

In the frame of research on fusion, the study of high temperature plasmas as an energy source was carried out under the FOM-programme 74: 'Manipulation of meso-scale structures in hot, magnetised plasmas' led by Niek Lopes Cardozo. This research explored and developed the concept that hot plasmas have a rich structure on the mesoscale with a significant impact on plasma dynamics and performance. The major objectives were the understanding and control of this structure. The objectives mainly achieved through high-resolution measurements and manipulation of this structure in experiments, along with numerical magneto-fluid simulations and the advancement of relevant theoretical models. The experimental part of this programme was concentrated in the plasma physics laboratory in Jülich, where about half of the team was permanently stationed, until the middle of 2009 when this programme came to an end.

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 I10, 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 I23, '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. This 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 TEC-partners FZ-Jülich and ERM/KMS-Brussels. Throughout this annual report, activities that are supported by Euratom as part of the European Fusion Programme are marked with an asterisk (*).

2009 – a very dynamic year

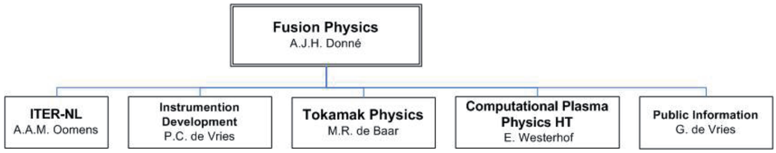
The year 2009 has been probably one of the most dynamic years for fusion physics at Rijnhuizen. At the start of the year it was announced that the Eindhoven University of Technology was opening a chair on the 'Science and Technology of Fusion'. This implied a broadening and strengthening of the Dutch fusion programme. Niek Lopes Cardozo, Head of the Fusion Physics Department and Head of the Research Unit EURATOM-FOM left the FOM-Institute for the vacancy in Eindhoven. In June an official farewell symposium was organised in which Niek was thanked by many of his colleagues for all his contributions to Rijnhuizen.

The position of Head of Research Unit EURATOM-FOM was taken over by Tony Donné. Furthermore, it was decided to split the Fusion Physics department, in size comparable to the other two departments GUTHz and nSI together, into two parts: (High Temperature) Fusion Physics and Plasma Surface Interaction. Tony Donné still leads the Fusion Physics department, while Jürgen Rapp has been appointed as head of the PSI department. The split of the department took place in November 2009. For practical reasons, this Annual Status Report follows the old group structure.

New groups – new faces

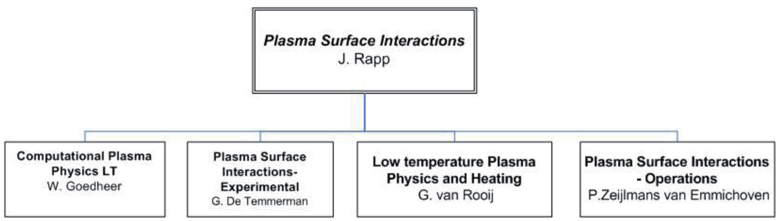
As a result of the very positive evaluation of the institute in 2008, we received the green light for hiring two additional permanent scientific staff members. Apart from Jürgen Rapp, who was already mentioned above, Peter de Vries, presently Deputy Task Force Leader at JET, has been employed to strengthen the team.

When splitting the department into two parts, a number of new groups has been formed and some further senior scientists have joined us to act as group leader. The two organisation charts below show the basic structure of the two departments from November 2009 onwards (the group leaders mentioned depict the situation on 1 January 2010).



Fusion Physics has presently four groups and one project:

- Instrumentation Development Group: until December this group was led by Roger Jaspers. Since Roger will follow Niek Lopes Cardozo to Eindhoven in the course of 2010, Peter de Vries has taken over the group leaders position;
- Tokamak Physics: headed by Marco de Baar;
- Computational Plasma Physics – High Temperature: headed by Egbert Westerhof. This new group has been created by splitting the former Computational Plasma Physics Group under Wim Goedheer into two parts. Also some people moved from Tokamak Physics to this group;
- Public Information: headed by Gieljan de Vries;
- The ITER-NL project: in 2009 headed by Tony Donné, but since New Year's Day taken over by Noud Oomens.



Plasma Surface Interaction also has four groups:

- Computational Plasma Physics – Low Temperature: headed by Wim Goedheer;
- Plasma Surface Interactions – Experimental: a new group headed by a newly appointed person – Gregory De Temmerman;
- Low Temperature Plasma Physics and Heating: a new group headed by Gerard van Rooij;
- Plasma Surface Interactions – Operations: a new group headed by Pedro Zeijlmans van Emmichoven who has been appointed to succeed Wim Koppers.

Two FOM programmes in fusion

The fusion research at Rijnhuizen has two main branches:

The first concerns the control and manipulation of turbulence and confinement in the hot core of fusion plasmas, and aims at the optimisation of the conditions in a fusion reactor. This research was carried out within the FOM-programme 74, 'Manipulation of mesoscale structures in hot magnetised plasmas', which has been officially closed early 2009. A successor to this work, FOM-Programme 120, 'Advanced control of magnetohydrodynamic modes in burning plasmas', has been approved in December. This programme will start in 2010 and will be performed in close collaboration with groups from Eindhoven University of Technology and the Centre for Mathematics and Informatics. This programme will be carried out by the Fusion Physics Department.

The second main line concerns the interaction of a plasma with a material surface, in the extreme conditions typical of the divertor of a fusion reactor. It aims at developing means to handle the very large flux of heat and particles to the wall of a fusion reactor. This research is carried out within FOM-programme 75, 'PSI-lab, an integrated laboratory on plasma surface interaction'. Central device in the PSI-lab is MAGNUM-PSI, a plasma simulator that almost reached completion by the end of 2009. One of the highlights in the MAGNUM-PSI project was the achievement of first plasma on June 18th. A proposal to extend the MAGNUM facility with an Ion Beam Analysis facility has been submitted to NWO-Groot. The decision on this proposal will be taken in the course of 2010.

ITER-NL

In 2007, FOM formed a strategic alliance with TNO and NRG, with the aim to optimise 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 materials expertise by NRG. The Dutch government made 15 Million Euro available for the programme of this consortium, for the period 2007-2009. On the 8th of August 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 of high enough quality 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.

This programme encompasses four work packages. Work package 1 and 2 concern the R&D for the ITER CXRS and ECRH systems, respectively. Work package 3 and 4 concern the support to industry and technology transfer. Thus, 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 various European institutes.

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.

The work of the PSI department will be more or less fully embedded in this TEC agreement.

Centre of Excellence on Fusion Physics and Technology

In 2008 the Dutch government has awarded Rijnhuizen, via funding agency NWO, a Centre of Excellence-grant for cooperation with four major Russian research labs. Dr. Tony Donné from the Rijnhuizen-institute will lead the collaboration, with dr. Boris Kuteev from the Kurchatov-institute as second chair.

The new Centre of Excellence for Fusion Physics and Technology involves scientists from the Russian Institute of Applied Physics and the Kurchatov, Ioffe and TRINITI-institutes, as well as the Rijnhuizen Institute. They will investigate the fundamental physics of fusion plasmas produced in ITER-like installations. Energy transport, plasma instabilities and plasma-surface-interaction are the main areas of research.

The Centre of Excellence officially started on April 1st and the first activity was the kick-off meeting that took place from 25 – 27 May. At the kick-off workshop, which was attended by ten Russian and 14 Dutch scientists, the detailed work plan of the Centre of Excellence for the first year was drafted.

Figure 2.1: Centre of Excellence at Rijnhuizen.

JET

In 2009, FOM-staff also participated in JET experimental campaigns and data analysis. 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.

Education, Training, Outreach and Public information

Finally, the substantial effort in the field of Public Information on fusion related issues is reported under 'Outreach to academia, education and industry', Chapter 3.

2.1 Tokamak Physics

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Funding:*	*FP-74, EFP, ITER-NL*

In November 2009, the Tokamak Physics Group was split into two; Marco de Baar remains leader of the Tokamak Physics Group, while Egbert Westerhof became leader of the new group for High Temperature Computational Plasma Physics (CPP-HT). For more information, see page 26.

Research programme

The Tokamak Physics Group has extensive expertise using localised 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. Experiments were done in 2009 in the TEXTOR tokamak, and will be continued on Asdex Upgrade in 2010. In addition the group participated in experiments to assess the interaction between fast particles and the sawtooth mode in JET.

Mission

The mission of the group is to develop an integrated understanding of the physics of the burning ITER core, including fast particle effects and MHD, and to develop control schemes for the confinement and MHD stability

* SUPPORTED BY THE EUROPEAN FUSION PROGRAMME (EFP)

of the burning plasma core. The group is also involved in R&D tasks associated with the design and construction of the Upper Port ECRH/CD launcher for ITER.

Highlights

The TPG highlight for 2009 was the demonstration of real-time tracking and suppression of magnetohydrodynamic modes in TEXTOR. This was the culmination of years of preparation in which the sensor and the actuators for the control loop were optimised. In addition, a new type of scattering was discovered in 2008, and systematically analysed in 2009. The analysis shows that the scattering stems from the rotating instabilities in TEXTOR, an observation that is likely to refine the theory of wave-propagation in plasmas.

Collaborations

The group interacts closely with the instrumentation development group, the high temperature computational plasma physics group and the Magnum-PSI team at Rijnhuizen and Eindhoven University in the fields of mm-wave design for diagnostics, computational physics, plasma-wall interaction, and control. The work for ITER is done within the frame of the ITER-NL consortium (FOM, TNO and NRG) and in cooperation with international partners: CRPP Lausanne, Karlsruhe Institute for Technology, CNR Milano, and IPP Garching.

Experimental Programme

The 2009 experimental programme focused on the control of magnetic instabilities (MHD modes) in the TEXTOR tokamak plasma at the Forschungszentrum Jülich in Germany. In TEXTOR, MHD modes can systematically be destabilised for a detailed study of the effect of the Electron Cyclotron Current Drive (ECCD) power deposition. An in-transmission line radiometer for Electron Cyclotron Emission measurements (ECE) has been developed to exactly determine the location of the instabilities relative to the location of the power deposition. The hardware for this project has been constructed and installed in TEXTOR. Model-based system identification and specific control experiments allow for the design of dedicated controllers for suppression and stabilisation of magnetic islands. In 2008 and 2009 the modelling and data acquisition for the feedback system were set-up, and the mechanical properties of the launcher were determined. In 2009 the data-acquisition for the system was set up, and the control loop was closed. Successful tracking of the instability and heating in the correct phase of the instability were demonstrated.

Identification experiments were done to support control oriented modelling of the sawtooth instability.

Theory and modelling effort

The Rutherford equation for tearing mode evolution was used in a study to assess the contributions of heating and current drive to the temporal evolution of tearing modes. Analytical expressions depending on the power deposition width W_{dep}, location and modulation have been found. For large island widths, the heating term approaches a constant and is proportional to (w/W_{dep}) for small island widths. For ITER, the current drive efficiency is expected to be significantly larger. The effects of asymmetry of tearing modes are being investigated in the context of the Rutherford equation. These investigations are being extended to non-linear MHD, using the JOREK code.

Control of neoclassical tearing modes (NTMs) is the major tasks of the ITER Upper Port Electron Cyclotron Current Drive (ECCD). For instability control, the ITER ECCD system should drive non-inductive currents with a very narrow profile. A numerical analysis of the effect of the radial diffusion of the EC-driven current carrying electrons has been performed in order to estimate the effectiveness of ECCD for NTM stabilisation. Fokker-Planck calculations including radial diffusion show a significant decrease of the local current density when radial diffusion at a rate of only 1 m^2/s is included and consequently a broadening of the profile and a drop in the predicted efficiency for NTM control.

The codes for equilibrium and Magnetohydrodynamic (MHD) stability Finesse and Phoenix have been interfaced with the fast-particle MHD code Hagis, and simulations have been carried-out to assess the drive of TAE modes in realistic JET conditions.

Engineering effort

Engineers in the Tokamak Physics Group are responsible for the development of remote handling procedures and tools for maintenance of the Upper Port Launcher (UPL) in the ITER Hot Cell. A mm-wave design for the Upper Port Launcher based on Remote Steering was finalised in 2009.

2.2 Instrumentation Development

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Undergraduate students:	*M. Jakobs (TU/e), F. Castelijns (TU/e)*
Research Engineers:	*M.J. van de Pol, J. Koning*
Guests:	*M.F. de Bock (UKAEA), C.W. Domier, B. Tobias (UC-Davis), J. Howard, A. Diallo (ANU-Canberra), J. Chung (NFRI-Korea), P. Bohm (IPP.CR- Prague), Q. Zang (ASIPP-China)*
Collaborators:	*W.Biel, O. Marchuck, O. Neubauer (FZJ), N.C. Hawkes (UKAEA), C. Giroud (JET), N.C. Luhmann Jr. (UC-Davis), H.K. Park (U. Pohang-Korea), S. Tugarinov (Troitsk), N. Naumenka (Minsk), F. Klinkhamer, B. Snijders (TNO), A. Hogenbirk (NRG), T. Fülöp (Chalmers)*
Funding:	*FP-74, EURATOM, TU/e, US-DOE, INTAS, NWO, EFDA, ITER-NL*

Introduction

The Instrumentation Development Group develops advanced high-resolution diagnostics for high temperature plasmas. The exploitation of the physics revealed by these diagnostics is an integral part of the research effort of the group. The goal is to advance novel concepts in optical and microwave diagnostics, as well as expanding and using the available expertise on optical diagnostics for application on ITER and support of the fusion physics programme.

The instrumentation development group focuses on three pillars:

- The Thomson scattering system, used to study the electron temperature and density profiles in hot plasmas. Our system, developed on TEXTOR, adopted a novel concept in which the plasma is part of the laser cavity. Up to 50 pulses, at a frequency of 5 kHz, can be injected. With the latest addition of a multi-pass capacity each laser pulse can effectively provide 60 J of probing energy.
- The 2D-electron cyclotron emission imaging system (2D-ECEI) used to measure temperature structures and fluctuation in the plasma core. This system has been developed in collaboration with the groups from UC-Davis and 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. This charge exchange recombination spectroscopy (CXRS) is foreseen for ITER to be the prime diagnostic for providing information on ion temperature, plasma rotation and ion concentrations. The efforts of the instrumentation group in this field have resulted in a leading role in the development of such a CXRS system for ITER.

Results

The year 2009 marked the transition of the TEXTOR oriented work of the Instrumentation Development Group towards a new research programme around the active control of MHD instabilities to be executed mainly on Asdex Upgrade (AUG) and partly on JET. As a preparation for that, the ECE imaging diagnostic has been upgraded and transferred to AUG. The Thomson scattering system continued to support the physics programme on TEXTOR. For this system, too, plans to transfer it to AUG are under consideration. The continuing activity for the development of the ITER CXRS system has culminated in the manufacturing of an ITER prototype spectrometer.

Thomson scattering

The Thomson Scattering system at TEXTOR has been finalised in 2009 and is now able to attain unprecedented specifications with a total laser energy of up to 3 kJ in about 50 pulses in a 10 ms interval. This, in combination with the high spatial resolution of sub cm, allows for following the dynamics of small scale structures in the plasma, with an experimentally confirmed accuracy in electron temperature and density of typically 2% and 1% respectively in each pulse.

The system has contributed to the unraveling of the physics of several phenomena:

- during the sawtooth period, both the precursor oscillations as well as the heat pulse following the crash could be imaged
- during the excitation of the tearing modes by perturbation coils, the system could follow both the temperature as well as the density evolution in the rotating islands
- even during the thermal crash of a disruption, the system could provide valuable information and finally a detailed investigation of the heat transport during the switch on of the ECRH system has been undertaken. As an example of the latter, the pressure increase immediately following switch on is visualised in Figure 2.2.

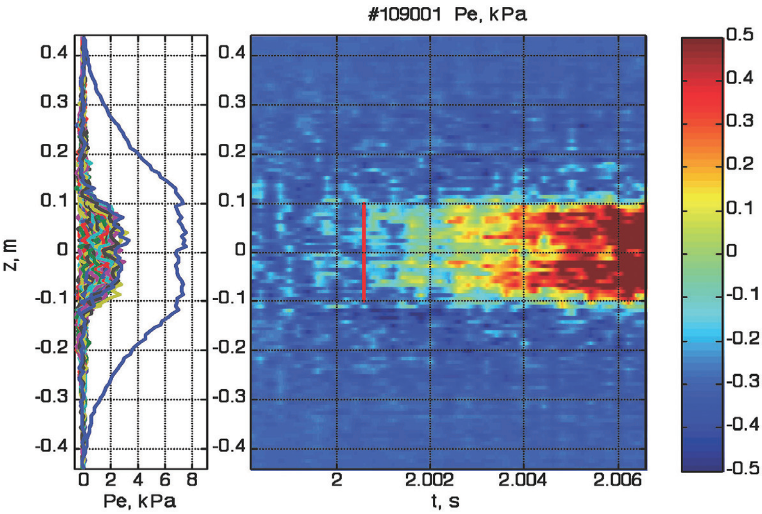

Figure 2.2: Contour plot of Thomson Scattering profiles of the electron pressure upon application of ECRH (indicated by the red line at t=2.0005s) at TEXTOR, measured with 5 kHz. The figure shows the deposition region as well as the time scale on which the pressure rises.

The physics results obtained from this multi-pass intra-cavity Thomson system have proven the high potential of this approach in Thomson scattering diagnostics in general and could be exploited on other fusion devices in the world. A transfer of this system towards AUG is now under consideration, as to provide the necessary support of the new FOM programma on the active control of MHD instabilities.

2D electron cyclotron emission imaging

In 2009 the TEXTOR system has been transferred to AUG and is now in routine operation, providing unique insights into the temperature evolution inside magnetic structures in the plasma. The main improvements compared to the TEXTOR system are in the optical path, which now allows for a wider field, zoom capability and better focusing, and even simplifying the set-up. Moreover, the 16-channel microwave array has been equipped with mini-lenses in front of every single antenna element, resulting in dramatic increases in sensitivity, RF-bandwidth (increased tunable radial coverage) and ECRH-shielding. The system provides a true 2D image of temperature fluctuations with a total of 128 channels, arranged in a matrix of 8 (horizontal) × 16 (vertical) sample volumes.

The focus over the last year is devoted mainly to study edge instabilities (ELMs), neoclassical tearing modes and Alfvén eigenmodes. For this latter item, a study of the loss rate of fast ions was correlated with location of the reversed shear and other Alfvén eigenmode as observed with ECEI. An illustration of this observation is given in Figure 2.3, where clearly the mode structure of the Alfvén modes can be visualised.

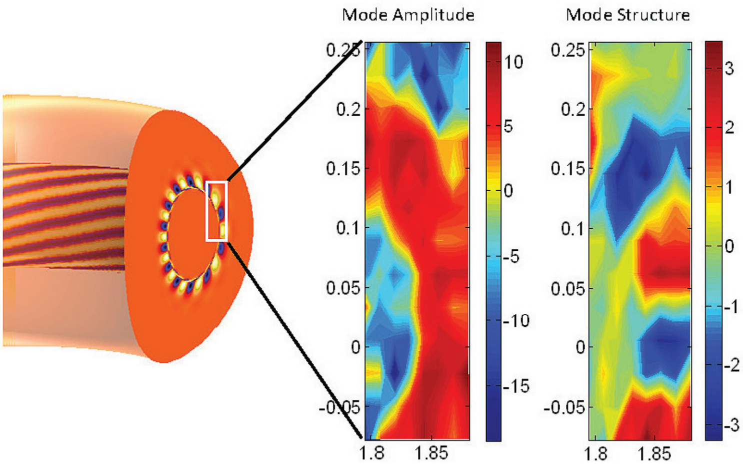

Figure 2.3: Left: expected mode structure of Alfvén eigenmodes in AUG. Right: contour plots of the mode amplitude and mode structure as determined from the experimental data of the 2D ECE imaging system. The resemblance with the theoretical picture shows the potential of the ECE imaging system.

Active beam spectroscopy

The largest effort in the instrumentation development group in 2009 has been devoted to the spectroscopy of the light emitted upon injection of high energetic (50-100 keV) atoms into the plasma. The major goal here is to develop a CXRS system for ITER. This work is done within the framework of ITER-NL and in collaboration with other European fusion institutes. The focus of the instrumentation development group has been to address the scientific issues of the design, such as the feasibility, the performance, the validation of the atomic data, the data analysis procedure etc. Furthermore the group exploits or is involved in CXRS systems on several devices (mainly TEXTOR and JET) to build up the expertise to run such a system on ITER.

The main activities in this respect in 2009 consisted of:

- The organisation of an international workshop on active beam spectroscopy.
- The study of plasma rotation and momentum transport at JET. It was shown that the loss of momentum during an ELM differs from the heat loss, indicating different transport processes for both parameters.
- Assessing the validity of the known beam emission cross-section data. Efforts to deduce the beam density from measurements have resulted in improved atomic modeling. However, experimental data from JET and TEXTOR still show unacceptable discrepancies between code calculations and measurement of the beam density.
- The development of an ITER prototype spectrometer, of which the high etendue is essential for the feasibility of the ITER CXRS system.

(see Figure 2.4). The system will be tested on TEXTOR in 2010 and the plan is to use it on JET after that.

- Assessing the measurement capabilities of the CXRS system: in addition to ion temperature, rotation and density, a study has been performed to investigate in how far this system also can contribute information on fast ions and the fuel ion ratio.

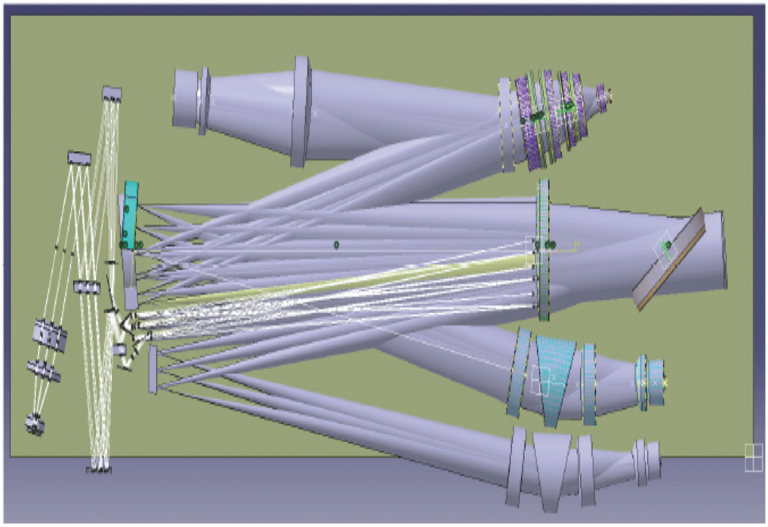

Figure 2.4: Design of the prototype spectrometer for the ITER CXRS system. This incorporates three wavelength bands simultaneously, with an etendue of the order of 1 mm^2sr each, spectral resolution of 0.2 nm and a dispersion of 0.25 nm/mm.

2.3 Computational Plasma Physics

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External advisors:	*Em. Prof. D.C. Schram, Em. Prof. J.P. Goedbloed, R. Keppens*
Funding:	*FP-74, FP-75, FP120*

Research Programme

The research of the CPP group is done within the framework of Fusion Energy and is embedded in the FOM programs FP75, FP74 and its follow-up FP120. These research lines of the institute on Plasma Surface Interaction and High Temperature Plasma Physics, respectively, require 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 various aspects of a fusion plasma, ranging from control and manipulation of the core to exhaust and plasma surface interaction. These studies are done in close collaboration with the experimental groups, optimizing the possibilities for validation of the models against experimental data. The main topics covered in high temperature plasma physics are Tokamak discharge simulations, Edge Localised Modes (ELMs), and magnetic reconnection.

In low temperature plasma physics 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 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 Tokamak Physics, Instrumental Development, and PSI-E groups. 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.

Magnetic reconnection and turbulent heat transport

Studies of the tokamak core plasma cover magnetic reconnection phenomena and turbulent heat transport. Theoretical studies of internal electron thermal barriers and hybrid plasma discharges are combined with experiments, carried out mainly at TEXTOR and JET. This work involves transport simulations with the CRONOS and ASTRA codes, and tests of predictions of transport barriers by the so-called paleo-classical transport model. Heat transport in and around magnetic islands is studied in TEXTOR, where such islands are created and controlled with the Dynamic Ergodic Divertor.

Within the framework of the ITER Scenario Modelling group an optimisation study is made of the plasma start-up and performance of hybrid discharges, by varying the contribution of non-inductively driven currents.

The theoretical study of the break-up and reconnection of magnetic field lines aims to understand this process in perfectly conducting hot plasmas where the energy exchange between the plasma particles is weak. The study of reconnecting instabilities shows effects of temperature gradients on magnetic field ergodisation and nonlinear effects such as a transient scale collapse in the reconnection zone.

Edge localised modes and L-mode / H-mode transitions

A numerical study of edge localised modes (ELMs) has been started with the MHD stability analysis of rotating tokamak equilibria with the Phoenix (spectral MHD) and Finesse (equilibrium) codes. New, numerically found, low-frequency toroidal-flow-driven modes are being compared to analytic solutions derived from existing theory for low magnetic shear.

In addition, ELM cycles and L-mode H-mode transitions are studied from the plasma-control viewpoint. Bifurcation theory is being developed for the characterisation in parameter space of regions with L-mode, ELM-free H-mode, and various ELMy regimes. The transitions and bifurcations between these regimes are of particular interest.

Low temperature plasma

Modelling of low temperature plasma focuses on various aspects of the plasma and plasma surface interaction in Pilot and Magnum-PSI. Details of the plasma surface interaction are modelled with the HCPARCAS molecular dynamics code. The interaction of layers of amorphous hydrogenated carbon and tungsten carbide with an intense beam of atomic hydrogen are studied, as well as the redeposition of eroded species.

Plasma recycling, including the behaviour of excited molecules is addressed with the SOLPS5.1 package, yielding a self-consistent description of the plasma beam and the neutral species. Special attention is paid to additionally heated beams, simulating the effect of a current through the beam or RF heating by an elevated temperature at the inlet. The modelling of plasma beams includes the description of radial electric fields, plasma rotation, and the radial current density profile in the beam, caused by source potentials and radial variations of the target plasma sheath.

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 microcrystalline and amorphous silicon are studied.

Modelling of the Magnum-PSI and Pilot-PSI plasma

Parallel to the experimental programme, numerical modelling addresses a number of topics regarding the source, plasma beam, and plasma-surface interaction in Magnum-psi and Pilot-psi.

The B2.5 code (a fluid description of the plasma beam) is used to study the interaction between the plasma beam and recycling neutrals from the target and the walls. The model includes self-generated current density distributions and allows for the application of a bias potential. The neutral species are also treated as a fluid. This is a drawback, as the large mean free path of some neutral species necessitates a kinetic approach. A start was made with a kinetic description of the neutrals, based on the EIRENE code.

The modelling of plasma wall interactions was done with the HCPARCAS molecular dynamics code. In collaboration with the group Reactive Plasma Processes at the IPP Garching (W. Jacob) the evolution of samples of amorphous hydrogenated carbon (a-C:H) and diamond under extremely high atomic hydrogen fluxes has been studied.

A study of redeposition of hydrocarbons on previously bombarded a-C:H samples has shown that the redeposition is larger for samples previously bombarded with a higher flux. In collaboration with SARA these simulations were run on the DutchGrid.

Simulations of bombardment of amorphous tungsten carbide show the formation of subsurface molecular hydrogen concentrations that lead to blistering. This phenomenon depends on the tungsten to carbon ratio of the simulated sample.

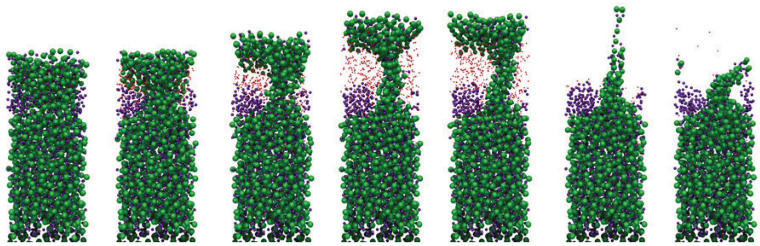

Figure 2.5: Bombardment of 50/50 W/C with 100 eV D atoms, showing the accumulation of deuterium and the formation of a blister in a carbon Rich zone.

Modelling of radio-frequency discharges

Modelling of dusty plasmas mainly addressed the behaviour of the dust-free central void and its reaction to changes in the applied power and pressure. Possibilities to create homogeneous grain distributions were investigated further. Kinetic modelling also addressed the influence of the pressure.

The modelling of silane-hydrogen radio-frequency discharges concentrated on high-pressure discharges for the deposition of micro-crystalline and amorphous silicon layers. The results of the simulations showed that a frequently used criterion to predict the properties of the deposited material that is based on the emission of hydrogen and silicon is often not reliable. A criterion based on the number of H atoms arriving at the surface per deposited Si atom is more reliable. It also holds in situations with a strong depletion of silane and a strong dilution with hydrogen.

2.4 Plasma Surface Interaction Experimental

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Research engineer:	*H.J. van der Meiden*
Technicians:	*P.H.M. Smeets, B. de Groot, H. van Eck, S. Brons, R. Prins, O. Kruyt, J. Scholten, R.S. Al, T. Oyevaar, K. van der Geer*
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Funding:*	*FP-75, EFP, NWO-Groot, NWO-RFBR, EFDA*

Scientific programme

With the FOM-programme 'PSI-lab, an integrated laboratory on Plasma-Surface interaction', Rijnhuizen is strongly expanding its research effort in the field of low temperature plasma physics, plasma surface interactions and material science. In this programme, the group PSI-E joins forces with the nSI and Surface-PSI groups, sharing the common physics as well as part of the analysis facilities. For the PSI-E group, the central experiment will be the high ion flux (>10^{24} $m^{-2}s^{-1}$), high power (10 MW/m^2) linear steady-state plasma generator, Magnum-PSI operating in a magnetic field of 3 T (superconducting magnet). This experiment is unique in the world and is designed to reach the parameter range of a plasma in front of the high-flux plasma facing components of the next step fusion reactor ITER. This will allow the fundamental study of very pressing problems associated with the erosion of materials, near surface material transport and hydrogenic retention in materials. The extreme parameters will also considerably stretch the available parameter space for fundamental studies of the plasma physics, plasma chemistry, and plasma-surface interaction at high flux density. Numerical modelling, addressing the physics and chemistry of PSI, is an integral part of this research programme,

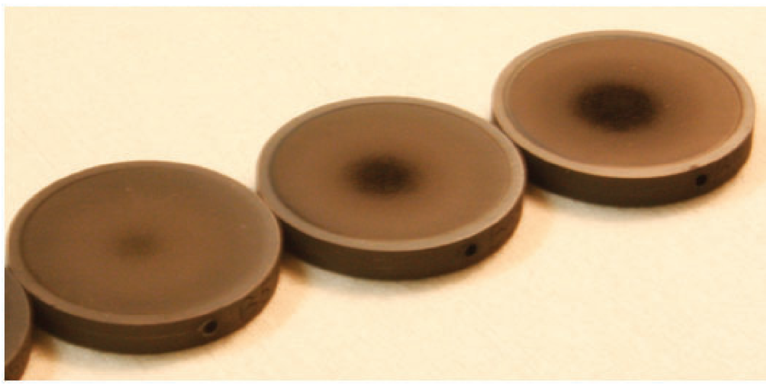
* SUPPORTED BY THE EUROPEAN FUSION PROGRAMME (EFP)

providing the link with PSI research in present day tokamaks and ITER. This research program is being developed jointly with the TEC-partners.

To prepare for this project, a pilot experiment has been set up in which the hydrogen plasma source is developed to the level that it can produce the fluxes given above. This experiment, called Pilot-PSI, is a collaborative research project with the Eindhoven University of Technology. A cascaded arc is used as the plasma source. The plasma beam in the Pilot-PSI device can be confined by a magnetic field of up to 1.6 T for short pulses. Diagnostics are being developed and tested at Pilot-PSI, which will be used later at the Magnum-PSI device.

Additionally, a dedicated R&D program on the RF heating of a low temperature plasma jet is being carried out on Pilot. In addition to the R&D program in support of Magnum-PSI, a research programme focusing on hydrogenic retention, chemical erosion, physics of the plasma jet and sheath physics is being carried out on Pilot-PSI.

Figure 2.6: Carbon samples exposed to the Pilot-PSI plasma; erosion after 50, 100 and 200 sec.



Research areas

The PSI-E research concentrates on the following areas:

1 The search for mechanisms to create surfaces that are dynamically stable under intense plasma or radiation bombardment.
2 The physics of plasma jets, in particular those in close contact with a material surface.
3 The physics of dust formation during intense plasma-surface interaction.

The research programme aims to contribute at a fundamental level to the solution of problems that arise when a surface is subjected to an extreme flux of ions, radicals, or photons, or a mixture of those. The primary area of interest is nuclear fusion: in the fusion reactor the wall in the so-called divertor receives some 10 MW/m^2 carried by hydrogen radicals, yet must survive several years without eroding or melting. PSI-lab also covers research on optical elements for lithography, which must survive intense photon fluxes.

The plasma-surface interaction at extreme flux densities is also a novel area of fundamental interest per se. Therefore, the programme takes a fundamental approach, with relevance to other areas such as the formation of dust in astrophysical systems.

A plasma is a unique source of chemical radicals that allows for tuning chemistry at surfaces with opportunities beyond classical chemistry. However, the plasma-surface system is complex, governed by non-linearities, in particular at high densities. The plasma in front of the surface (composition, temperature, density, etc) is strongly influenced by the plasma-surface interaction. The surface, through radical reactions, erosion and deposition, in particular the deposition of clusters and compounds formed in the plasma, is modified by the plasma. The formation of clusters of molecules and their evolution in the plasma is in itself a process that heavily depends on the PSI conditions, while the clusters in turn influence both the plasma and the surface. Thus, plasma and surface cannot be treated separately. Together they form a strongly coupled physical system in dynamic equilibrium.

To study and employ plasma-surface interaction (PSI), four experiments will be built, sharing surface analytical equipment. The centre piece is a worldwide unique linear plasma generator, Magnum-PSI, which will allow access to the strongly coupled regime of PSI. A smaller, already operational facility (Pilot-PSI) is used for source development and testing of diagnostics. A novel, versatile thin film deposition machine (Thin-Film PSI) is employed for the deposition of layered structures for XUV optics. Finally, the Surface-PSI device allows basic PSI studies under well-defined low flux conditions. The latter two experiments are operated within the nSI department, largely in the frame of the FOM-IPP programme XMO. The experiments are complementary, e.g. layered structures prepared in Thin-Film PSI will be used in erosion studies in Magnum-PSI, and Magnum-PSI is used to study the aging of optical elements developed in the XMO programme. Running in parallel and integrated with the experimental research programme is a strong computational effort. The controlled and well-diagnosed experiments in PSI-lab are ideally suited for the benchmarking of computational models, which in turn can guide further experiments.

Studies of plasma surface interaction for ITER and fusion reactors beyond ITER are carried out primarily with experiments in the Magnum-PSI plasma generator, in parallel with numerical modelling studies. Through the modelling, the link to PSI experiments in tokamaks is made, where circumstances are more complex (geometry, influence of hot core plasma) and diagnostic access much worse. The focus in these studies is on the materials carbon (Carbon Fiber Composite) and tungsten, with hydrogen, deuterium and helium as the elements of choice for the plasma. Around the Pilot-PSI and Magnum-PSI devices an extensive network of collaborations is growing, in particular with fusion research institutes in Europe and the USA. These include the partners in the TEC agreement, with PSI-studies evolving into the central theme of this collaboration.

ITER-relevant Plasma conditions in PILOT-PSI

ITER-Relevant research on material erosion and hydrogen retention in Pilot-PSI

Pilot-PSI started as a true pilot experiment to prepare for the design of Magnum-PSI and to develop a scientific basis for the physics of plasma surface interactions at high densities and low temperatures. Meanwhile, it has become a high-performance linear plasma generator in its own right on the basis of its unique, extremely high plasma fluxes of 10^{25} $m^{-2}s^{-1}$. These fluxes have been exploited to perform unique ITER-relevant experiments on the chemical erosion of carbon. Research into carbon-based materials has been focused on chemical erosion by hydrogen plasmas. Results from plasma exposure to high-flux ($>10^{23}$ H^+/m^2s) and low-temperature hydrogen plasma indicate silicon carbide has a lower relative rate of gross erosion than other carbon-based materials (e.g. graphite, diamond, carbon-fibre composites) by a factor of ~10. Pyrometry and literature indicates this lower gross erosion yield of SiC is not a surface temperature effect. The indications from this study are that the best choice from an erosion and lifetime perspective, for a carbon-based material as a divertor plasma-facing component in future fusion devices, would be SiC.

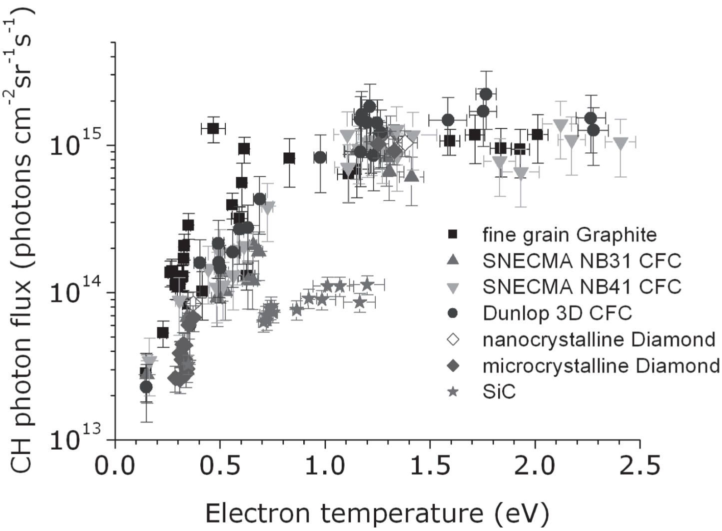


Figure 2.7: CH photon flux as a function of plasma electron temperature in the range 0.1-2.5 eV for a range of carbon-based materials.

Hydrogen retention in refractory metals like Mo and W has been studied extensively in Pilot-PSI. It appears that the hydrogen retention is mainly a function of the surface temperature, making those metals attractive plasma facing components for future fusion reactors. However, neutron irradiation of materials might alter the hydrogen retention in those metals. To study this effect tungsten targets were exposed to high energy tungsten ion beams in IPP-Garching to simulate the displacement of lattice atoms. The damage induced by irradiation of W targets with 12.3 MeV $W4^{+}$ ions has been found to enhance hydrogenic retention by a factor of 2.5-4.1 (see Figure 2.8). When exposed to plasma with high surface temperature conditions (T_{surf}>650 K) , this enhancement is due to the introduction of a high-energy trap site. However at lower surface temperatures (T_{surf}<600 K) during plasma exposure, this enhancement is due to the addition of both high and low energy trap sites, perhaps indicating that the defects in the material caused by the irradiation undergo further evolution during the plasma exposure, depending on the exposure conditions. Across the damage levels examined in this study (0.5 dpa – 10 dpa) there was no change in retention, indicating a saturation of the enhancement of retention at levels >0.5 dpa.

Plasma-facing materials in future fusion reactors will also experience high thermal stresses both from steady-state heatloads (≤30 MW/m^2) and transient events such as ELMs (≤1 GW/m^2). These thermal stresses can lead to extensive cracking of the surface. It is unclear the impact this cracking has one hydrogenic retention properties. In this investigation,

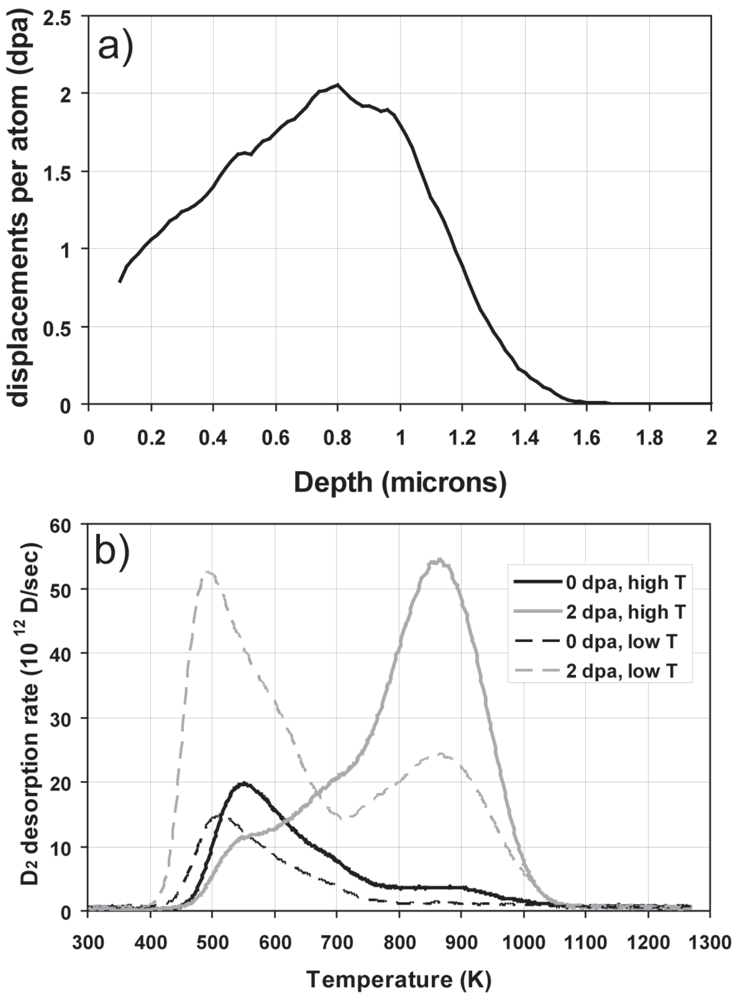


Figure 2.8: a) Damage profile from irradiation with 12.3 MeV W^{4+} ions for 2 dpa case as determined with TRIM [16] simulations. b) TDS spectra for W targets irradiated with 12.3 MeV W^{4+} ions to a peak damage of 2 dpa at high (T_{surf}>600 K) and low (T_{surf}<600 K) surface temperatures during plasma exposure in Pilot-PSI. Unirradiated targets are also plotted for comparison.

W targets were exposed to high thermal heat loads in the JUDITH e-beam facility which resulted in cracking of the surface. The targets with surface cracking were then exposed to high flux deuterium plasma in Pilot-PSI as well as a reference target with no prior thermal stressing in JUDITH.

TDS analysis was used to determine the retention properties of these different surface conditions. From the TDS profiles it is clear that the lower temperature desorption peaks seen on the irradiated W targets are not present meaning the lower energy traps have been removed from these targets.

Comparison of the TDS results (see Figure 2.9) reveals that the thermally-stressed W has a total retention a factor of 2.1±0.2 higher than the

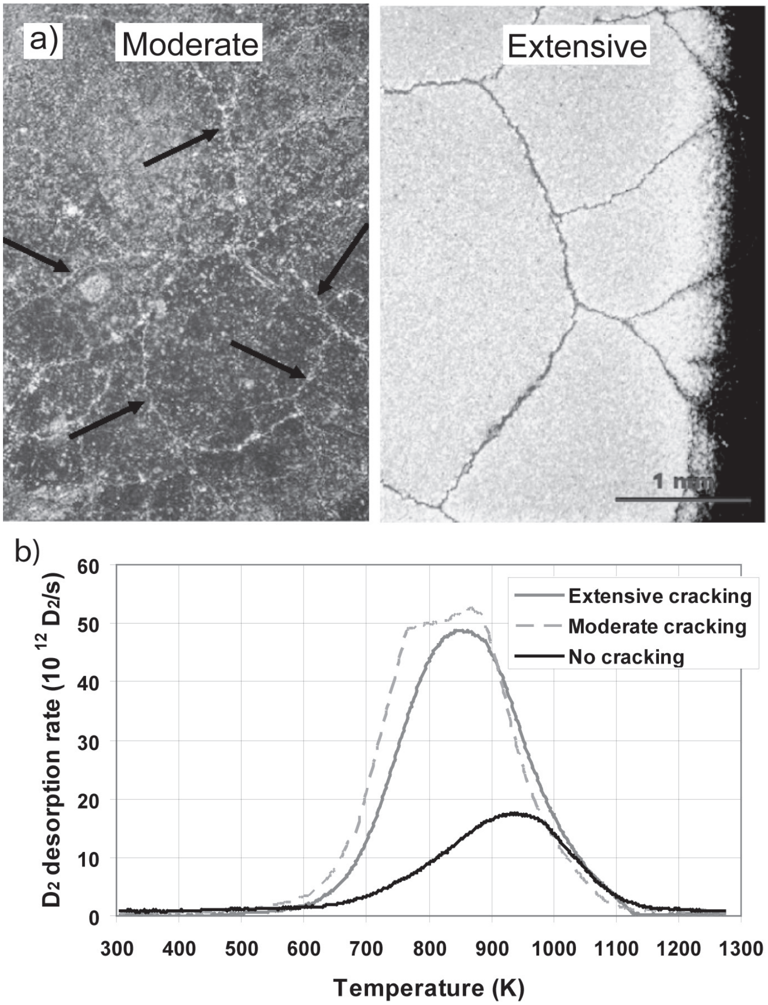


Figure 2.9: a) SEM images of W targets with "moderate" and "extensive" surface cracking due to thermal cycling via e-beam irradiation. b) TDS spectra for thermally-stressed W with various degrees of surface cracking and exposed in Pilot-PSI. Target with no cracking was not thermally-stressed.

unstressed W. Some or perhaps all of this difference could be attributed to the slightly higher surface temperature during plasma exposure for the unstressed W ($T_{surf} \sim 1150$ K) than for the thermally-stressed W ($T_{surf} \sim 1100$ K). Although a 50 K difference in surface temperature may not seem like a large difference, we see this is in a region with strong temperature dependence on surface temperature. It is important to note that the difference in hydrogenic retention between the moderate cracking and extensive cracking scenarios is negligible. This indicates that any enhancement of retention is not related to the physical manifestation of the thermal stressing (i.e. cracking, surface roughening) but rather through the introduction of thermal defects in the lattice that enhance the retention.

Magnum-PSI: scientific and technical challenges

As part of the TEC collaboration and within the framework of Euratom, the FOM Institute Rijnhuizen is building a new machine to study plasma wall interactions. This apparatus, Magnum-PSI, will be world-wide unique and will provide an important new experimental facility in the range of experiments that are available to PSI research for ITER and reactors beyond ITER. The uniqueness of Magnum-PSI lies in its ability to access simultaneously the several aspects of PSI in the combination of which ITER essentially differs from present day experiments:

- Large ion fluency and continuous operation, which leads to 'macroscopic' modification of plasma-facing surfaces.
- High power density (5-10 MW m^{-2}) with low plasma temperature (< 5 eV) such that materials are close to, or at the energy threshold for sputtering, but have high surface temperature and are therefore near their materials limits for stress/strain, etc.
- Strong plasma-surface coupling: the high plasma density leads to short mean free paths for dissociation/ionisation of eroded atoms or molecules in comparison with the linear dimensions of the plasma.
- Access to plasma diagnostics and in-situ surface analysis.

The steady-state high flux of up to 10^{24} ions $m^{-2}s^{-1}$ at a plasma temperature in the eV range, magnetic field of 3 T, and large beam diameter make Magnum-PSI a unique experiment, bringing the relevant parameters typically an order of magnitude beyond what is presently available in linear plasma devices, and into the realm of the ITER divertor. It will be the only device so far to enter the strongly coupled regime, in which molecules and dust particles that come off the surface are trapped and remain part of the plasma-surface interaction system, and thus will allow relevant studies of dust formation, re-deposition, migration and hydrogen retention. The steady-state and high flux capability, combined with the large flexibility and easy access, allow post mortem analysis which in present devices normally occurs only every 1-2 years.

Design activities in the Magnum-PSI project

The main part of the design phase of the Magnum-PSI project has now been completed. Magnum-PSI is under construction. In the following the installation and assembly process of Magnum-PSI is described. The only remaining design activities are related to the full power plasma source and the auxiliary heating systems.

Vacuum system

The vacuum system is designed to (a) ensure low neutral gas pressure in the vicinity of the target and (b) to cope with the high heat fluxes to the wall components resulting from Charge Exchange particle losses and black body radiation from the target during the steady state operation of the device. To ensure a pressure of 1 − 3 Pa near the target a differential pumping is foreseen with 3 roots pumps each having a pump capacity of 17500 m^3/hr in the pressure regime between 0.5 and 100 Pa. The system has been manufactured and installed. The pumping systems (turbo molecular and roots blower systems) have been commissioned. The source chamber, the heating chamber and the target chamber are separated by skimmers. The design and position of those skimmers was optimised by gas dynamics simulations. In order to test the vacuum system performance, measurements and simulations have been done with cold neutral gas inlet. For these tests the vacuum vessel was fitted with two straight non-cooled skimmers. Inserts with different opening diameters are available. During the measurement the pressures in the separate chambers were recorded while the gas flow was varied up to 40 slm. A pressure reduction between the source and target chamber of a factor 8 is achieved with skimmers with a 10 cm diameter orifice.

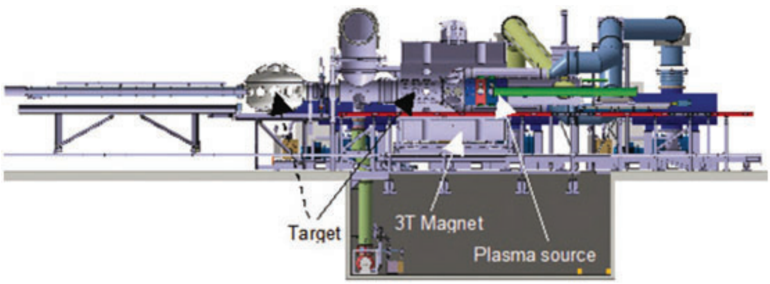


Figure 2.10: Total overview of the Magnum-PSI experiment with target station and target manipulator. Shown are (from right to left) the source-, heating- and target chamber with pump ducts. Next to these, the pumping station for the third stage is shown. On the left hand side, the target station with target and target manipulator are visible. In the target analysis station, the targets can be analyzed in detail with surface analysis equipment.

Superconducting magnet system for Magnum-PSI

The magnet has a warm bore of 1300 mm and the axial length is 2450 mm. The magnet system has eight evenly distributed radial access ports of 210 mm diameter, located at two axial positions. These ports allow for good diagnostic access of the experiment. A schematic picture of the superconducting magnet system is given in Figure 2.11.

The superconducting magnet system is now under construction at the manufacturer site. The winding of the magnetic coils has been completed. The assembly of the superconducting magnet (coil, shield, magnet housing) is ongoing. The magnet is supposed to be delivered to FOM Rijnhuizen in April 2010.

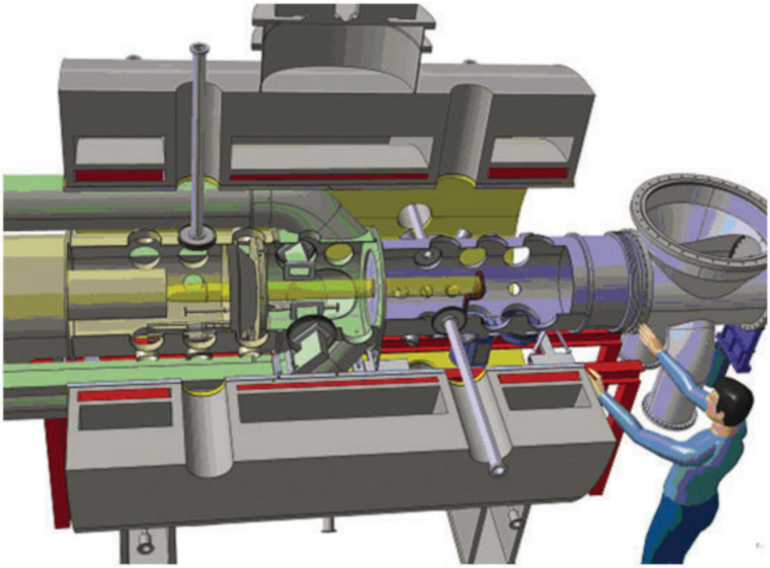


Figure 2.11: The Magnum-PSI experiment with the 3 T superconducting magnet. Shown are (from left to right) the source-, heating- and target chamber with pump ducts and wave guides inside the superconducting magnet. The plasma beam is guided through two skimmers by the magnetic field to the target plate. A beam dump is inserted in the plasma beam. The target is brought in place after the desired plasma parameters have been established.

Plasma beam and additional heating

Extensive experiments occurred in the Pilot-PSI experiment on the high flux plasma source and additional heating methods (so-called Ohmic heating and RF heating). The output of the plasma beam (flux density) is within specifications. The plasma source system has been installed and commissioned. First plasma of the Magnum-PSI plasma source was achieved on the 18th of June 2009. Current activities concentrate on broadening of the plasma beam diameter to the specified 10 cm. This design is based on a multi-channel cascaded arc. First tests were encouraging. With a 3-channel source a full-width-half-maximum (FWHM) of more than 3 cm has been achieved with argon and hydrogen plasmas. The mixing of the multiple hydrogen plasma jets to reach a homogenous plasma jet is currently in optimisation with a ring electrode placed between the source and the target. The largest plasma source will be a 270 kW plasma source, utilizing all available power produced by 4 individual power supplies, which were manufactured at the Technical University Eindhoven. Each power supply is able to deliver a maximum of 100 kW.

In addition a pulsed plasma source is being developed to simulate transient heat loads with duration of 0.5 − 1 msec as they occur during so-called ELM instabilities in the tokamak. A target value of 2 GW/m^2 for 0.5 msec is planned. For this transient operation a capacitor bank (8400 μF) is connected parallel to the steady-state power supplies. First results with a smaller capacitor bank yielded already a transient power of 350 kW injected into the plasma source leading to more than 200 MW/m^2 on the target (Te $\approx$ 6 eV and ne $\approx 5 \times 10^{21}$ m^{-3}).

Extensive testing has occurred on RF heating of the plasma beam. Experiments on PILOT-PSI show that with a 45 kW plasma source, plasma electron temperatures up to 5 eV can be achieved. In order to extend the performance of Magnum-PSI and to reach electron temperatures up to 10 eV, additional heating by means of electromagnetic wave power in the radio frequency (RF) range is planned. The RF waves will be injected in the second differentially pumped vacuum chamber of Magnum-PSI between plasma source and target. The RF power level currently considered is approximately 50 kW. Two RF heating methods are proposed: lower hybrid (LH) heating and ion cyclotron resonance (ICR) heating. Both methods are studied and will be tested on PILOT-PSI. Originally, heating above the LH resonance (approximately 1 GHz for typical Magnum-PSI parameters) was proposed because of the availability of relatively inexpensive RF sources in this frequency range: magnetrons, which typically operate at 2.45 GHz. However, at this frequency, only waves with a relatively high parallel wave number k will penetrate into the high density core of the Magnum-PSI plasma beam. The design of an antenna that launches these waves is a significant challenge. Several antenna types have been considered, of which a phased waveguide array seems to be the most promising. In order to produce the required high $k_{parallel}$ values and to be able to fit the array into limited access space of the Magnum-PSI heating chamber, the size of the waveguides needs to be reduced. This can be accomplished with the use of Electromagnetic Bandgap (EBG) material or by dielectric-filled waveguides. An EBG waveguide array, including a vacuum window and a tapered transition to standard sized rectangular waveguide, will be designed with CST MICROWAVE STUDIO. As an alternative, heating in the ICR frequency range (typically 5 to 50 MHz for Magnum-PSI) is considered. Typical ICR antennas consist of multiple current loops, depending on the power requirements. Different configurations will be evaluated and optimised by means of the cylindrical version of TOPICA, a self-consistent numerical code that incorporates a commercial graphic interface (GiD) to generate the antenna geometry and an accurate plasma model. The validation of antenna circuit parameters (impedance and scattering matrices) calculated by TOPICA, is in progress. The work on RF heating is done in close collaboration with KMS/RMS Brussels and the Politecnico di Torino.

Target Station

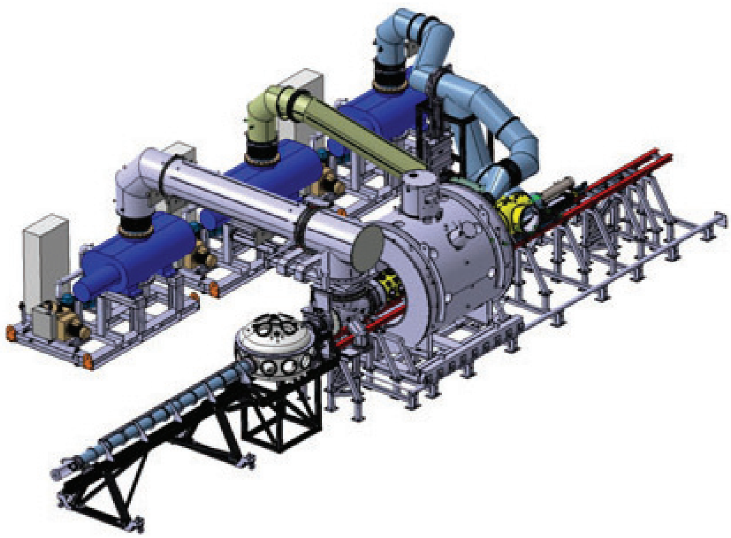
The target station has been installed and assembled at Magnum-PSI. The testing and the control of the target station including the target manipulator are ongoing.

Control and Data Acquisition

The control and data acquisition system for the Magnum-PSI experiment is being installed and commissioned. The safety system has been designed and is being procured.

Outlook

The Magnum-PSI project is close to completion. The superconducting magnet is expected to be delivered in April 2010 and the project completion is planned to be in May 2010. From May 2010 to September 2010 Magnum-PSI will be commissioned and hydrogen operation will be prepared. It is expected that the scientific exploitation of Magnum-PSI will start in October 2010.



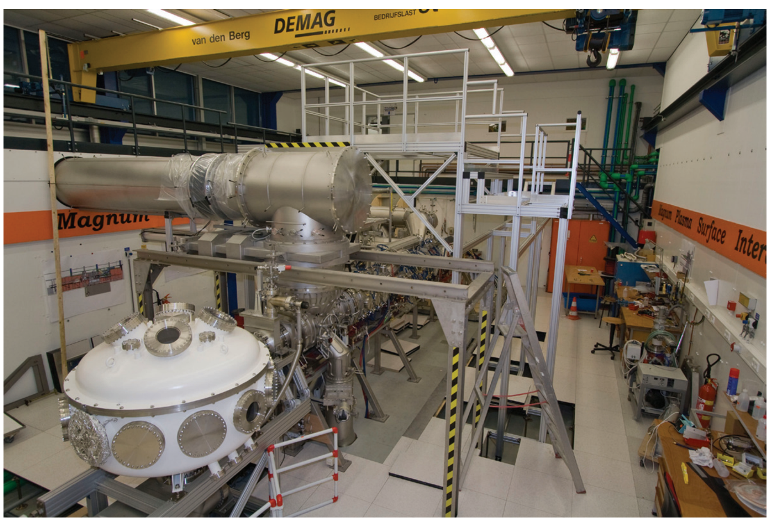


Figure 2.12: Overview of the final set-up (top) and pictures of the experiment under construction (bottom).

2.5 ITER-NL

Project leader:	*A.J.H. Donné*
Industrial Liaison Officer:	*A.G.A. Verhoeven*
Senior Scientist:	*A.P.H. Goede*
Funding:	*Fonds Economische Structuurversterking*

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 since 1 January 2007 by the ITER-NL consortium in which FOM, NRG (Nuclear Research and consultancy Group) and TNO (Organisation for Applied Scientific Research) 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 are being formed around the UPL (main players: FZK, CRPP and FOM) and the UPV (main players: FZJ and FOM). The LIDAR Consortium has already been established in the summer of 2009. 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.

Organisation

ITER-NL is led by the Executive Board with one member of each organisation (TNO, NRG, FOM). The programme director is based at TNO. The FOM-Rijnhuizen Executive Board member in 2009 was Tony Donné, but his role will be taken over from 2010 onwards by Noud Oomens. The Executive Board reports to the ITER-NL Council with two members from each organisation (in 2009 Hendrik van Vuren and Niek Lopes

Cardozo representing FOM). The ITER-NL Council has an independent industrial advisor.

Work Packages

The work within ITER-NL is organised in four work packages:

- WP1: Upper Port Viewer (and LIDAR) led by Bart Snijders (TNO)
- WP2: Upper Port Launcher led by Marco de Baar (FOM)
- WP3: Technology Transfer led by Renée Pohlmann (TNO)
- WP4: Knowledge Transfer led by Tony Donné (FOM)

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. Within FOM-Rijnhuizen the work on the Upper Port Viewer is done fully in the Instrumentation Development Group. Roger Jaspers is 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 Technology Transfer 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 2.13: An important event in 2009 was the return mission of French companies to The Netherlands – an answer to the mission of Dutch companies to ITER Cadarache in 2008. Representatives of 14 French companies visited the Netherlands to have business-to-business meetings with managers from 22 different Dutch companies.

WP4 is a relatively small work package that aims to transfer knowledge to industry and to the public, and also to organise political support.

Progress report

In 2009 the ITER-NL project has been carried out according to plan and has made good progress. The LIDAR Consortium has been established in the summer of 2009. The consortium is led by the Culham Centre for Fusion Energy (CCFE), and Tony Donné has been elected chair of the Steering Committee of this consortium. The partners in the ECHUL Consortium (ECRH Upper Port Launcher) have agreed on the text of the consortium agreement. Signature is foreseen in early 2010. This consortium will be led by Karlsruhe Institute for Technology (KIT). Finally the partners in the CXRS Consortium, which will be jointly led by ITER-NL and Forschungszentrum Jülich are close to reaching consensus on the text of the consortium agreement.

Good scientific results have been achieved in both the field of CXRS and ECRH. Since this work is already presented in the group reports of the Instrumentation Development Group (Section 2.2) and Tokamak Physics Group (Section 2.3), respectively, it will not be repeated.

Results in the ITER-NL technology transfer package have exceeded the expectations. Many Dutch industries have become interested in ITER (also thanks to the active public relations by ITER-NL). When ITER-NL was started in 2007 a total of 11 technology transfer trajectories were foreseen. At the end of 2009 a total of 14 of these trajectories were reached. Five of them have been closed. In the technology transfer trajectories companies are subsidised by ITER-NL to demonstrate that they have the competence and expertise to develop certain products and/or skills. This can then help these companies to be more successful in the tendering process.

An important event in 2009 was the return mission of French companies to The Netherlands – an answer to the mission of Dutch companies to ITER Cadarache in 2008. Representatives of 14 French companies visited the Netherlands to have business-to-business meetings with managers from 22 different Dutch companies. About 110 of these bilateral discussions have taken place and more or less all of the companies were rather satisfied with the final result, since they see good opportunities to set up collaborations in the near future. The French delegation was accompanied by the High Commissioner for Atomic Energy, Mrs. Catherine Césarsky and the French Ambassador Jean-François Blarel. Mrs. Césarsky brought a formal visit to the Dutch Minister of Economic Affairs, Mrs. Maria van der Hoeven in which she gave support to the good work and the pioneering role of ITER-NL.

Additional to the above return mission there was a separate meeting organised for Dutch building companies to inform them about the opportunities within the ITER project. The representatives of the companies were informed by experts from Fusion for Energy (F4E), ITER-NL and the Ministry of Economic Affairs.

ITER-NL organised industrial exhibits at a number of international conferences: ICOPS/SOFE in San Diego; ISFNT in Dalian, China; ICFRM and the International Business Forum on Fusion and Fission Energy in Sapporo; and Fusion Tech in Milan. At most of these events a number of representatives from Dutch companies joined the Dutch delegation to have meetings with representatives from ITER, the various Domestic Agencies and other companies.

Visit to JET

The invitation of ITER-NL to the Minister of Science, Culture and Education, Ronald Plasterk to visit the Joint European Torus was accepted. The visit took place on the 15th of April. Apart from the Minister, Mrs. Babs van den Bergh, Director Research and Education Policy of the Ministry of Science, Culture and Education, Mrs. Renée Bergkamp, Director-General of Innovation of the Ministry of Economic Affairs and the Dutch Ambassador in the United Kingdom, Pim Waldeck joined the Dutch delegation. The visitors were welcomed by Francesco Romanelli, director of the JET programme, and by Yvan Capouet of the European Commission. After a number of presentations on fusion in general and the JET project in particular, the group toured the JET torus hall. In the control room the Minister spoke with several of the Dutch researchers, including PhD students. The Minister asked them sharp questions about their work and about fusion research in particular. From the discussions it became evident that fusion research is an important endeavour in the challenge to ascertain the future energy supply for mankind.

Many items have appeared in Dutch press (newspapers as well as television and radio). The ITER-NL website has been extended and renewed to make it more accessible for industry. Parts of the website are translated into English (and possibly French). Calls for tender, calls for grants and calls for expression of interest from F4E and ITER are posted on the website, and they are also directly send to companies that might potentially be interested.

2.6 Public Information

Group leader: *G. de Vries*
Members: *E. Min, M. Huisman-Stam*
Funding:* *Missionbudget, EFP, EFDA, FOM-outreach*

The Public Information group at FOM-Rijnhuizen focuses on public information on fusion as a future sustainable energy source and supports the various Rijnhuizen departments in their (press) outreach. The group actively promotes fusion energy in outreach activities such as the Fusion Road Show, and in more general presentations for students, politicians, the general public energy specialists. Production of the annual report is also coordinated by the group.

Fusion Road Show

The continued succes of the Fusion Road Show is one of the most important highlights of the PI group. This interactive show with many live demonstrations familiarises the audience with nuclear fusion as an energy source of the future. Currently, the show is presented at secondary schools over thirty times per year, and as part of the FOM activities on science communication. It is suitable for a large range of audiences and its contents and level of interaction can be easily adapted to the audience and the occasion.

The most important performances of the Fusion Road Show in 2008 included its presence at the European Committee Open Day in Brussels, an event visited by over 70.000 people, at the EurekaCup applied science contest kickoff and finale events, at the opening of the Delft University Energy Club and at the Fusion Days organised by Antwerp University (Belgium) for over 3600 secondary school students and teachers.

Visits to the institute

Each year, the institute organises two open house days in October, one for students and one for the general public. The PI group is strongly involved in the organisation and realisation of these days. In 2009, FOM-Rijnhuizen received over 1000 visitors during these two days. Throughout the year, many other groups visit Rijnhuizen, including students from secondary schools and universities.

* SUPPORTED BY THE EUROPEAN FUSION PROGRAMME (EFP)

50 year anniversary

In 2009, the PI-group was also involved in the organisation of the Institute's 50 year anniversary symposium and the production of the anniversary book "Hittebarrière", which was well received wide outside the institute and given positive reviews in the press.

ITER-NL

The PI group is intensively involved in the outreach and PR-activities of the Dutch consortium ITER-NL, a cooperation between the research institutes FOM, NRG and TNO. ITER-NL aims at preparing Dutch companies and industry for tenders from the ITER-organisation and the Rijnhuizen PI group supports the consortium by writing press releases, visiting conferences, by maintenance of the iter-nl-website and by lectures for specialist audiences.

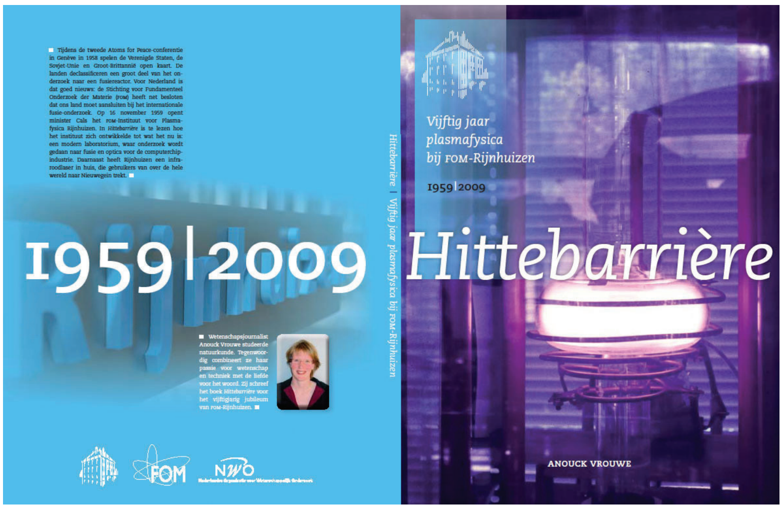


Figure 2.14: Front cover of Hittebarrière – Vijftig jaar plasmafysica bij FOM-Rijnhuizen, the book celebrating the Institute's 50-year anniversary in 2009.

nanolayer Surface and Interface Physics

The overall goal of the nSI division is to perform high-quality scientific research in the field of surface science, and thin film and interface physics. Current topics include photo-chemical phenomena, photo-conversion processes, plasma physics, and short-wavelength, notably XUV, optics. Of special interest are the boundary areas between these fields: the use of XUV optics, for instance, generates also research questions in the field of photo-induced surface chemistry, as in EUV-induced optics contamination. In turn, this theme is 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 the kernel for a solar energy research program.

Essential 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 know-how in plasma surface interaction phenomena as e.g. in advanced photo-lithography optics, in thermonuclear fusion processes, or in the utilisation 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. The new Rijnhuizen Valorisation Officer, Tim Tsarfati, emerged from the nSI department (see Chapter 3).

Research in the nSI department is mainly enabled by two large research programmes: the FOM-Zeiss Industrial Partnership Programme named ‘eXtreme UV multilayer optics’ or ‘XMO’, and PSI-lab, an integrated laboratory on plasma surface interaction. The XMO objective is to develop and apply the physics and associated process technology of compounded periodic multilayer structures. Such multilayers need to have atomically sharp, flat interfaces, and be chemically stable and dimension controlled down to the sub-nanometer range.

Late 2009, a new, third FOM Programme was added to that: the Industrial Partnership Programme CP3E with Carl Zeiss and ASML. In line with the running XMO programme, this new programme focusses on the physics and chemical processes relevant for final usage of multilayer optics under high flux and plasma loads. In addition to these 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

SenterNovem Catrene Programme ('EXEPT'), the Materials Innovation Institute/ASML Project 06.245, called 'ISitCLEAR', and Valorisation Funding through FOM, a FOM-Pilot project on Multilayer optics for 4th generation XUV sources, the Beyond-EUV - Technology Foundation project 10302, Photolytic Salt Formation - Materials Innovation Institute/ASML project 06.244, FOM-Pilot project on 'Metaaloxideoppervlakken als modelsystemen voor watersplitsing met zonlicht' with support by SenterNovem through the NEO Programme NEO07005, and the NWO-'Dynamiseringsfonds'.

The research in the department is carried out in three research groups, with a sub-division that follows the core expertise in the groups:
- Surface ion- and photochemistry, (SIPC), headed ad interim by Fred Bijkerk,
- Physics of thin films and multilayers (TFM), led by Andrey Yakshin and
- Advanced applications of XUV optics (AXO), led by Eric Louis.

In the next sections, these groups and their results accumulated during 2009 are described.

Extreme UV multilayer optics

The FOM-Zeiss Industrial Partnership programme I10 on 'Extreme UV multilayer optics (XMO)', headed by Fred Bijkerk, focuses on the physics of multilayer, EUV reflective structures with atomically sharp interfaces and optimised optical response. 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.

The 'XMO' Programme feeds a large part of the research in the nSI department. The programme started in 2005 and runs until early 2012, with currently two PhD students already graduated and another five still executing their projects in progressing stages. The total number of PhDs having received, or expected to receive their PhD through this programme is two more then the five originally planned. XMO is also enabling a number of 'satellite' projects which lean on the main programme but yet have additional funding resources and widened research aims.

The common research themes arise from the demanding applications of multilayers in the future lithography application. This primarily concerns EUV- and thermally-induced phenomena in the sub-nanometer critically layered systems, phenomena that become appearent as detrimental, lifetime limiting processes within or at the layered coatings under practical EUV lithography. The next section describes some of these physics aspects of the EUV optics.

The XMO programme is being continued in a further evolved direction with the emphasis changing from the understanding of the physics of the structures themselves, to their interaction with EUV photons at high intensity, including fundamental photo- and plasma induced surface processes. From the start of 2010 this work is addressed in the new IPP project named CP3E: ‘Controlling photon and plasma induced processes at EUV optical surfaces’.

Surface and thin film processes beyond EUV applications

Next to the comprehensive 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.

Figure 2.15: Plasma source for the sputter deposition of thin films as a part of the infrastructure of the nSI department.

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 photo-conversion studies under the theme 'energy'.

2.7 Surface ion- and photochemistry (SIPC)

Group leader:	*F. Bijkerk (a.i.)*
Scientific advisors:	*K.N. Koshelev, A.W. Kleyn*
Scientist:	*M. Gleeson*
Postdocs:	*M. Grecea, M. Sturm*
Postgraduate students:	*H. Ueta, A. Kuznetsov*
Funding:	*FP-110, FP-75, FP-55, Carl Zeiss SMT, ASML, M2i, SenterNovem*

Research programme

The Surface Ion- and Photochemistry group (SIPC) in the nSI department addresses the surface science component of a number of research projects, collectively executed within the department. Central themes are the physical and chemical phenomena at optical surfaces, induced either by photons or plasma beams. These photons and plasmas are incident at the surfaces at high photon energies or particle fluxes, creating new, challenging research questions. One example concerns the interaction of Ar or H plasmas, created by very bright Extreme UV light sources, with the surface of EUV optics. Such plasmas may cause surface atom sputtering, a phenomenon which is only partially understood under these conditions, and which is very detrimental for the application in lithography. In this case the goal of the research is to both model and experimentally isolate the various processes.

This particular example is part of the ACHieVE project ('Advanced multilayer coatings for high volume EUV lithography') which is executed jointly with ASML, the major manufacturer of semiconductor manufacturing equipment. For the in-house experiments Surface-PSI is employed, a unique UHV system allowing advanced studies of ion and plasma beams 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 the differentially pumped beamline of Surface-PSI, 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.

The SIPC group also carries out experiments on the lab-wide research theme 'physics for energy'. Alternative sources of energy are highly wanted and solar energy is expected to be an important one. One goal is to develop model systems for and investigate the fundamental aspects of photo-electrochemical cells for production of hydrogen from sunlight and water. This follows the path of 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. The goal is to study the basics of photo-conversion on simple, flat metal oxide films.

Other research topics are part of the FOM Industrial Partnership Programme XMO, FOM Programme 75 ('PSI Lab'), and the earlier mentioned M2i/ASML project. These topics are described below.

Model systems for photoconversion: photochemistry of water on well-defined metal oxide films

Photo-electrochemical cells based on metal oxide photo-electrodes have great potential as future devices for harvesting solar energy. The active materials, such as TiO_2, Fe_2O_3, and $BiVO_4$, are cheap and abundant and production processes can be low-cost. Photo-electrochemical cells can be used to split water with the aid of sunlight, such that solar energy can be converted into solar fuel.

Photo-electrodes in actual devices are usually complex porous, nanostructured films, which complicates the investigation of the photochemical processes taking place at the surface. From a fundamental point of view, it is therefore required to study the photochemistry of water on well defined thin metal oxide films, prepared in ultra-high vacuum. This approach is similar to using model catalysts to study the surface science of catalytic reactions. The use of model systems offers the possibility to control the chemical state of the surface, for instance by creating oxygen vacancies or hydroxyl groups.

In 2009 the detailed design of a dedicated UHV system for these photochemical studies has been finished. This design is based on a current UHV system for photochemical experiments, used for studying photolytic salt formation on quartz surfaces. The new design includes the possibility to mount e-beam evaporators for in-situ deposition of thin metal oxide films and a LEED system to determine the surface structure. Like the current photochemistry system, the new system will be equipped with a quadrupole mass spectrometer for temperature-programmed and laser-induced desorption and reflection absorption infrared spectroscopy to characterise the species present at the surface. This set-up is expected to pave the way to a comprehensive set of energy-related surface studies.

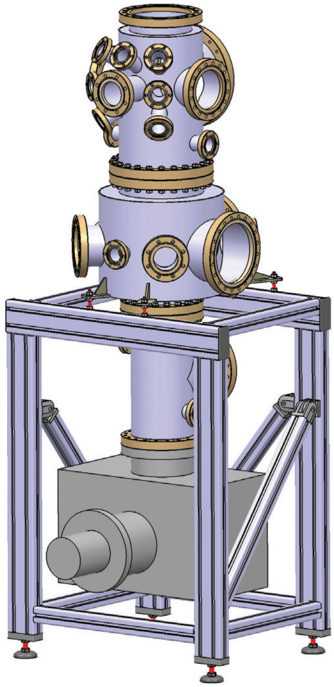


Figure 2.16: Design of UHV system for photo-chemistry studies on in-situ deposited metal oxide films.

Hyper thermal nitrogen atom interactions with the Ag(111) surface

The purpose of this research is to add to the fundamental knowledge of gas-surface interaction and to improve the understanding of surface processes at the atomic level. Processes involving radicals are of particular interest due to their reactive nature and chemical relevance. Nitrogen (N) radicals are among the most challenging to study due to the difficulty of cracking N_2 molecules. The cascaded arc, used in our experiments, is one of the few sources capable of producing a high fraction of N radicals.

A highlight is the scattering of hyperthermal N and argon (Ar) atoms from a Ag(111) surface (see Figure 2.17). Unlike the sharp Ar distribution (blue data points in Figure 2.17 a)), the scattered N atom distribution (red data points) has two components, one broad and one sharp. This is due to the fact that N atoms can have both an attractive and a repulsive interaction with the surface, whereas the (noble) Ar atom interacts in a purely repulsive fashion. Scattering as a result of a repulsive interaction leads to a sharp peak near the specular direction (θ_f=60°), which is akin to scattering from a flat surface. In contrast, an attractive potential leads to particle acceleration at the surface. The incident atoms lose the "memory" of their initial momentum and are scattered into a very broad range of angles.

In addition to the differences in the angular distributions, N atoms lose significantly more energy at the surface than Ar. This is illustrated in Figure 2.17 (b) by comparing the measured data to simple binary collision models. The latter assumes simple impulsive collisions (between the incident atoms and a single, isolated surface atom) in which the energy lost by the scattered particle is a function of the mass ratio between the two atoms involved in the collision. As can be seen in Figure 2.17 (b), the measured data points for Ar are substantially above the binary collision model (far less energy is lost than is anticipated by the model). In contrast, the data points for the N atoms are generally slightly below the corresponding binary collision model, but still in good agreement. The exceptions to this are the N atoms that undergo very grazing scattering (small total scattering angle). The average energy of these particles exceeds that of the incident beam, indicating that there is an energy requirement for the atoms scattered along these trajectories. These results demonstrate the remarkably different surfaces that are "seen" by reactive atoms as compared with inert atoms.

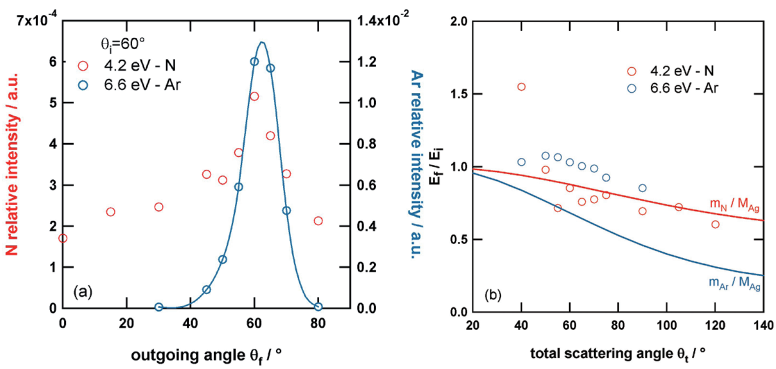


Figure 2.17: a) shows angle-resolved intensity distributions of N atoms ($<E_i>=4.2$ eV) and Ar atoms ($<E_i>=6.6$ eV) scattered from Ag(111) at a surface temperature $T_S=600$ K at incident angle $\theta_i=60°$. b) shows the angle-resolved ratios of final to initial energy (E_f/E_i) plotted as a function of the total scattering angle for N atoms and Ar atoms. The solid lines in (b) represent the corresponding binary collision models.

Desorption studies of sulphur dioxide based adsorbate-surface interactions

Contamination of the optical elements during operation of photolithographic equipment represents a serious challenge for the semiconductor industry. This might be caused by trace impurities present in the environment close to the optical surfaces. In order to unravel the contamination mechanism at the fundamental level, surface science model-studies under Ultra-High Vacuum (UHV) conditions (base pressure ~ 3 ´ 10^{-10} mbar) have been carried out.

The adsorption/desorption behavior of the gas molecules of interest – sulphur dioxide (SO_2), ammonia (NH_3) and water (H_2O) – on relevant surfaces was studied. Temperature-Programmed Desorption (TPD) was employed to probe the strength of the adsorbate-surface interaction. TPD consists of applying a constant temperature ramp to the surface and detecting the desorbed species (on the basis of the mass-to-charge (m/z) ratio) by a mass spectrometer. A typical TPD profile of SO_2 desorbing from a quartz (0001) surface following exposure of sub-monolayer coverage of SO_2, NH_3 and H_2O is shown in Figure 2.18. A new and more stable desorption feature is observed at 220 K in the TPD spectra of SO_2 (red curve) upon triple adsorption of SO_2 with NH_3 and H_2O, indicating a stronger bound configuration at the surface. This can be seen by comparison with the TPD curves of co-adsorbed SO_2+NH_3 (blue), SO_2+H_2O (green) and singly dosed SO_2 (black). Further insight on the triple adsorption of SO_2, NH_3 and H_2O on dielectric surfaces, as potential precursors for Deep Ultraviolet (DUV) and Extreme Ultraviolet (EUV) photochemistry, is scheduled to be gained from experiments of laser-induced desorption and RAIRS. To this end, a dedicated high-sensitivity Reflection-Absorption InfraRed Spectroscopy (RAIRS) was installed and tested.

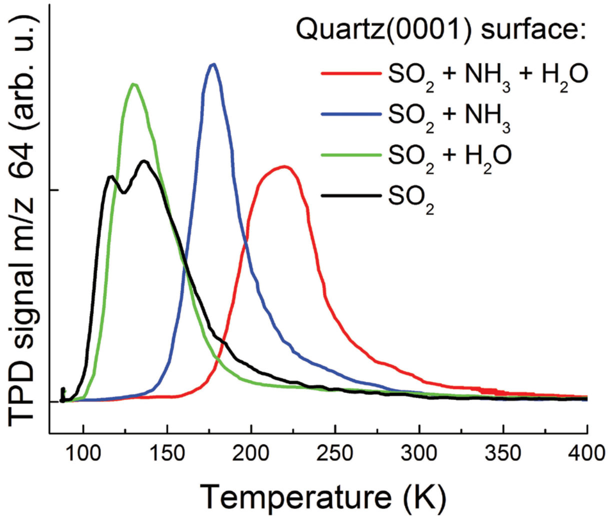


Figure 2.18: TPD spectrum of SO_2 (m/z = 64) from a quartz (0001) surface after triple exposure of SO_2, NH_3, and H_2O at 87 K (red curve). The other curves represent TPD spectra of SO_2 from the SO_2 and NH_3 (blue), SO_2 and H_2O (green) and single SO_2 (black) systems for comparison. The higher desorption temperature of SO_2 from the triple-adsorbate system indicates a more strongly bound species at the surface.

Implementation of a high sensitivity FT-IR system for UHV surface studies

The quality of feed gases used in the production of integrated circuits has been improved to the point where the levels of impurity are close or even below standard detection techniques. Nevertheless, the trace impurities present still lead to the formation of contaminants on a long time scale as a result of photo-chemical processes. In order to investigate the onset mechanisms of these processes, we are undertaking a programme of research involving the study of model systems under controlled ultra-high vacuum conditions.

Initial research has focused on studying the species that are removed from the surfaces of interest by thermal and/or photo-processes. In order to enhance these analytical capabilities, a customised fourier transform infra-red (FT-IR) instrument was commissioned. IR spectroscopy is an ideal complement to the pre-existing desorption techniques since it is sensitive to the vibrations of chemical bonds of species absorbed at the surface. Hence, it can give information on the molecular configurations prior to desorption and on the formation of stable (non-desorbing) species on the surface. As an example, Figure 2.19 shows the development of typical IR peaks as a function of increased coverage, obtained for adsorption of NH_3 on a deposited gold film.

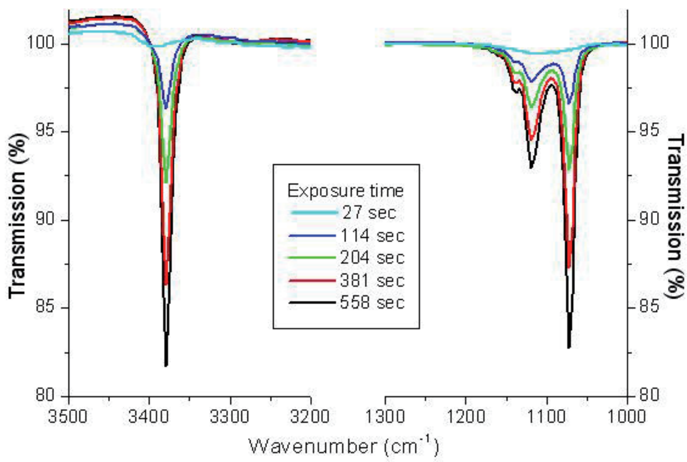


Figure 2.19: Emergence of the IR vibrations of NH_3 upon adsorption on a deposited gold film.

The spectroscopic system selected was custom-designed and built by Varian Inc. (the FT-IR spectrometer) and OMT Solutions (the external optical components). The combined package provides a high beam throughput with a suitably small beam footprint (10 mm) at the sample position. The system was designed to maximise the wavenumber range that was available to the spectrometer in order to allow access to the wavenumber region that contains metal-oxygen vibrations. Many UHV installations of FT-IR systems are limited on the low wavenumber side due to absorption by the materials typically used to produce UHV-compatible IR-transparent windows. The solution was to use specially designed differentially-pumped KBr windows, which permit the system to measure down to 400 cm^{-1}.

Secondary electron yield measurements of EUV optical surfaces

(research performed in AXO group)

In a joint project with ASML and M2i, several surface methods are explored to monitor the occurrence and nature of surface contamination of Extreme UV optics in lithographic exposure tools. Besides spectroscopic ellipsometry (SE) and the use of laser-generated surface acoustic waves (LG-SAWs), the use of secondary electron yields (SEY) has also been investigated in order to determine the most appropriate technique. In this process low energy electrons escape from a solid surface under bombardment from high energy primary electrons, ions, or photons, though we limit ourselves to the influence of electron bombardment.

We performed in situ monitoring of the build-up and removal of carbon contamination on a Mo/Si EUV multilayer by measuring secondary electron yield as a function of the primary electron energy. An electron beam with energy of 2 keV was used to simulate the EUV radiation induced carbon contamination. Figure 2.20 shows an overview of target current versus primary electron energy for both carbon deposition and atomic hydrogen cleaning cycles. According to the relation $SEY=1-I_T/I_P$ the SEY at each primary electron energy can be calculated from the measured target current I_T. The primary current IP was pre-measured by a Faraday cup. As shown in Figure 2.20, the overall secondary electron yield or target current spectra decrease when a carbon layer was deposited on a EUV multilayer and recovered again after the carbon is cleaned away. For a clean EUV multilayer, the maximum secondary electron yield is about 1.5 electrons per primary electron at an energy of 467 eV. The maximum yield reduced with a well-quantified amount when the surface was covered by a non-uniform carbon layer with a thickness of few nanometers. By analyzing the change in the maximum secondary electron yield with a changing carbon layer thickness, a sensitivity of about 0.1 nm was obtained. This way secondary electron yield measurements were shown to be an appropriate method to precisely determine deposited C-layers, with clear applications.

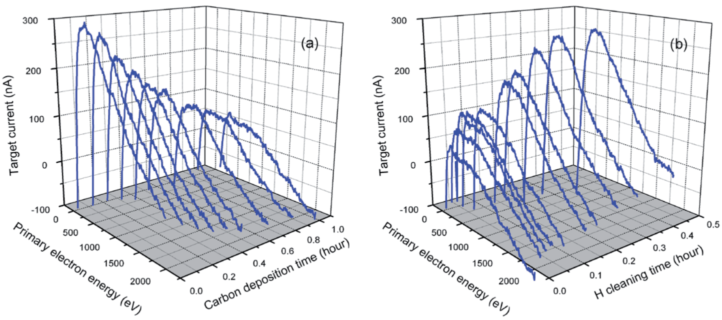


Figure 2.20: Overview of target current versus primary electron energy of carbon depositions a) and atomic hydrogen cleaning cycles b) on a multilayer mirror.

2.8 Physics of thin films and multilayers (TFM)

Division:	*nanolayer Surface and Interface physics*
Group leader:	*A.E. Yakshin*
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Senior scientist:	*R.W.E. van de Kruijs*
Postgraduate students:	*T. Tsarfati, V. de Rooij-Lohmann, S. Bruijn, J. Bosgra, S. Nyabero*
Undergraduate student:	*R. Stijl*
Guest scientist:	*I. Kozhevnikov (Crystallography Inst. Moscow)*
Funding:	*FOM Industrial Partnership Programme-I10, Carl Zeiss SMT, SenterNovem*

Research programme

The general goal of the TFM (thin films and multilayer) group is developing the basic physics of thin single and multilayered films and interfaces of nanometer thicknesses. This includes physics processes occurring inside the multilayers as resulting from the applications of these films, with the emphasis on core physics issues. The research in 2009 followed two running research programmes: the FOM Industrial Partnership Programme 'Extreme UV multilayer optics' (I10) and the SenterNovem funded 'Advanced multilayer coatings for high volume EUV lithography' ('ACHieVE').

The aim was to develop and apply the physics required for a particularly advanced application of multilayer structures: optical elements operating at Extreme UV wavelengths, notably 13.5 nm. The structures investigated represent fundamental challenges in thin layer and surface physics as well as in multilayer optics. The multilayer systems are targeted to meet the requirements of Extreme UV lithography, following the development road map of the associated industrial partners. The TFM group is dealing with solid-state aspects of these research projects related to ultrathin films. Other aspects are carried out at the SIPC and AXO groups.

The 2009 programme of TFM was based on the descriptions of each of the granted and running research projects and consisted of two parts: diffusion and interactions in thin films and interfaces, and thin film growth. This included studies on the formation and the properties of interface layers, the growth and structuring of ultra-thin artificial diffusion barrier layers at the interfaces, and the interdiffusion processes at cryogenic and elevated temperatures. Studying the chemical and diffusion mechanisms in the multilayers has allowed to develop methods of manipulating processes at the interfaces at thickness scales down to single atom dimensions.

The research is carried out using a unique suite of thin film deposition and surface analysis tools, including state-of-the-art UHV e-beam and magnetron deposition facilities, 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.

Hydrogen interaction with mirrors for EUV lithography

The aim of this work is an understanding of processes leading to a degradation of mirrors for Extreme UV photolithography (EUVL) in conditions of commercially-oriented devices. A buffer gas environment, which is used in lithography equipment in order to reduce optics contamination, can cause some undesirable effects. For instance, it was experimentally confirmed that aggressive plasma can be created during EUV pulses by photoionisation processes. Interaction of this plasma with multilayer mirrors might lead to their degradation. Nowadays, hydrogen is the most prominent candidate buffer gas for EUV lithography tools. However, besides surface sputtering processes, hydrogen retention in a multilayered structure might lead to additional negative consequences. Swelling of silicon layers due to enhanced hydrogen content causes inter-layer spacing changes and, consequently, reflectivity losses. Additionally, hydrogen is known to be a reason of enhanced diffusion processes in two-component structures, which can also lead to major disturbance of the mirror surface and decrease of its optical performance.

As an example of recent studies, irradiations of standard, uncapped Mo/Si multilayers by low-energy deuterium ions were performed to mimic exposure of mirrors to EUV-driven plasma. It was shown that the outermost silicon layer was fully eroded even for energies as low as 5 eV per D ion; this fact implies a chemical mechanism of interaction between deuterium (hydrogen) and silicon, a phenomenon not observed so far, and of major impact for the optics lifetime. Besides, samples irradiated with energies ≥ 25 eV/D showed a detectable hydrogen retention. An assumption was made on a model of deuterium subsurface distribution, which predicts the major amount of deuterium to be trapped in the second Si layer or deeper. This fact confirms the possibility of the inter-layer spacing changes due to swelling.

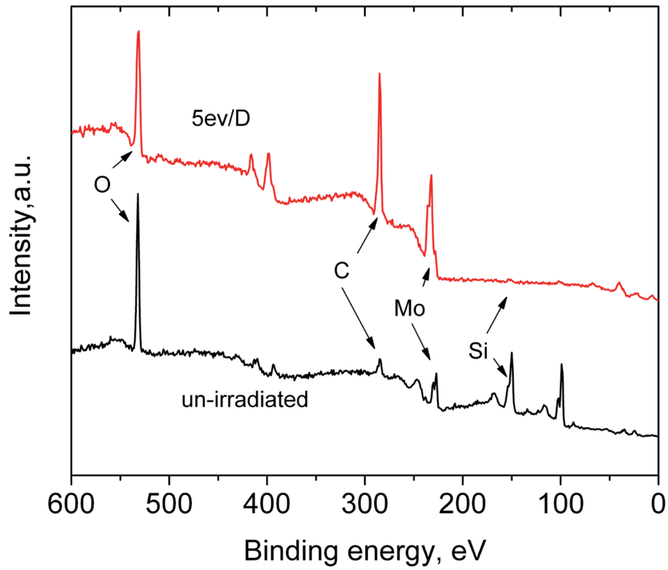


Figure 2.21: Survey XPS spectra of a un-irradiated sample and a sample irradiated with 5 eV D ions, showing the full disappearance of the top Si layer upon low energy D-ion impact.

Lifetime of high temperature resistant Mo/B_4C/Si/B_4C multilayer structures

The growth of compound $MoSi_2$ interfaces during high-flux photon exposure of Mo/Si multilayer structures is a severe threat to their application as optical structures used in future EUV lithography tools. It would reduce the optics lifetime expectation from several years down to as little as several hours. The required improvement in radiation hardness of the structures involves solving the problem of atom interdiffusion at the interfaces, or at least slowing down these processes by several orders of magnitude.

Recent work in the Mo/Si system has focused on placing a thin B_4C layer between the Mo and Si layers. Although such a layer would be expected to act as a physical barrier against diffusion between Mo and Si, it appears that the actual mechanism that is responsible for the enhanced thermal stability is a specific chemical reactivity at the interfaces during thermal loading.

Using grazing incidence x-ray reflectivity, wide angle x-ray diffraction, and x-ray photo-emission spectroscopy, we studied the structural and chemical changes that take place upon annealing. From these experiments, we can conclude that it is the decomposition of B_4C and subsequent formation of a more stable MoB layer at the interfaces that is responsible for the improved thermal stability in these systems.

Figure 2.22 shows an Arrhenius plot for diffusion obtained in Mo/B_4C/Si/B_4C multilayer structures, with diffusion data for Mo/Si multilayer structures without barriers given as a reference. It is clear that the introduction of B_4C barrier layers dramatically reduced the diffusion speeds through the interfaces. In addition, the modified chemical environment at the interfaces also noticeably affected the temperature scaling of diffusion, which can be recognised in a change of the activation energy for interface formation. This research increases the optics lifetime from only several hours up to the required several years. The results were obtained at Rijnhuizen in collaboration with IPP-XMO partner Carl Zeiss.

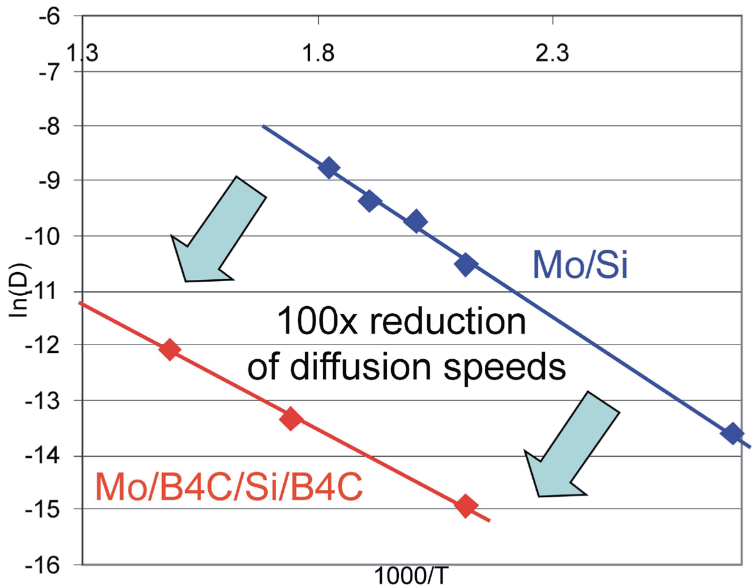


Figure 2.22: Arrhenius plot for diffusion in Mo/Si and Mo/B_4C/Si/B_4C systems. The reduction of diffusion speed was attributed to decomposition of the B_4C barrier layer upon annealing and subsequent formation of a MoB compound interface, effectively reducing the interdiffusion speed at the Mo-Si interface.

Optical performance of Ru/Si based multilayer structures

In general, a periodic multilayer structure will optically act as an angular band pass filter for incident radiation, i.e. the reflectivity is maximum at a specific angle and drops off rapidly for smaller or larger angles of incidence. Since the multilayer angular acceptance range for high reflectance is connected to the demagnification factor in photolithography applications, it is imperative to improve this range: this way lithographic printing of continuously smaller feature sizes is further enabled. Improving the angular acceptance range for current, Mo/Si-based multilayer structures involves both the development of layered structures with an in-depth gradient in the layer thicknesses, as well as fundamental research into possible replacement of the molybdenum layers.

In collaboration with Carl Zeiss, pilot studies have been performed on a number of alternative multilayer structures. Figure 2.23 shows an example of the optical response of Ru/Si and Mo/Si based structures, demonstrating the increase in the angular acceptance range. For actual replacement of Mo/Si multilayer based optical structures, the alternative system also has to show a good resistance against thermally enhanced diffusion. Recent experiments showed that the incorporation of B_4C barrier layers at the Ru/Si interfaces is able to slow down interdiffusion between Ru and Si. Further studies into the chemical interactions that take place at the interfaces of broadband multilayer systems upon annealing will take place in the industrial partnership project "CP3E", starting in 2010.

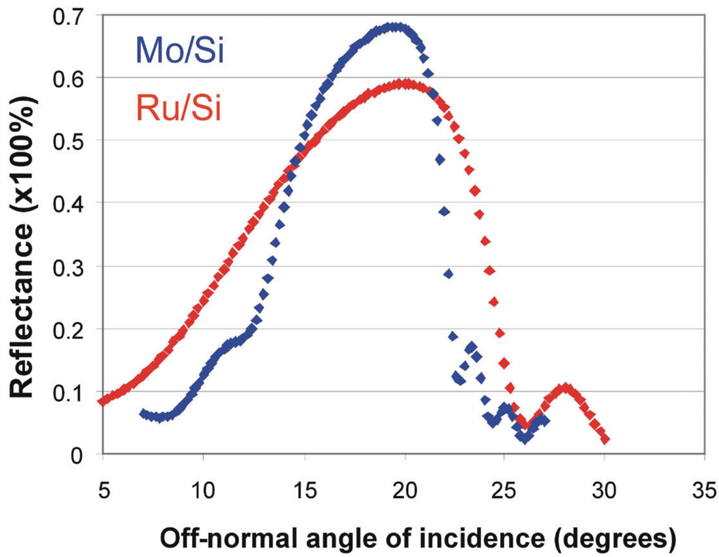
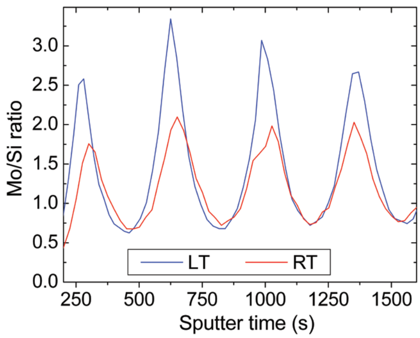


Figure 2.23: Optical response of Mo/Si and Ru/Si based multilayer structures. The angular acceptance range for Ru/Si based structures is considerably higher than for Mo/Si based structures. The Arrhenius-type plot (insert) for diffusion processes in Ru/Si shows enhanced activation energies compared to Mo/Si systems.

Layer deposition at cryogenic conditions

In general, the performance of multilayer optics is decreased by interdiffusion of materials of adjacent layers causing formation of interlayers with unfavorable optical properties. These interlayers are formed already in the course of depositing the films, with the structure and thickness of the interlayers being dependent on the energy available in the system for interatomic rearrangements. Earlier, we initiated an investigation of increasing the optical contrast between thin films, as applied to the Mo/Si system, by affecting the kinetics of the silicide interlayer formation during the film growth. Using physical vapour deposition, multilayer structures were grown on Si substrates mounted on an actively liquid-N_2 cooled substrate holder. We found that the low energy of the deposited atoms, combined with the reduced substrate temperature, lead to a significantly reduced interaction between Mo and Si (Figure 2.24 (left)) reducing the total silicide interlayer at both interfaces from about 1.6 nm to only 0.9 nm. This reduced interface width was observed upon subsequent heating of the samples up to room temperature, suggesting lower atom mobility directly during the growth. Consequently warming up to room temperature did not anymore lead the interdiffusion process as it occurs during film growth at room temperature. This first experiment was carried out at an external facility with limited experimental conditions. To facilitate further research, a substrate holder that can be filled with liquid nitrogen has been designed, constructed, and implemented on the ADC (Figure 2.24 (right)). The complex holder is designed for maximum experimental freedom and allows sample rotation with ion smoothening and temperature monitoring of the substrate holder.



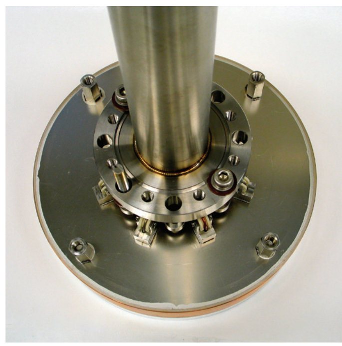


Figure 2.24: The Mo/Si ratio in the samples deposited at room and low (cryogenic) temperatures detected by XPS depth profiling. The increased Mo/Si ratio for the low-temperature-deposited sample indicates significantly reduced interaction between the Mo and the Si layers (left). Right: the new substrate holder that was manufactured to facilitate further research on cryogenic deposition of multilayer mirrors.

Doping of thin molybdenum films by carbon

Thin Mo films used in Mo/Si multilayer structures exhibit an amorphous-to-polycrystalline phase transition at a critical thickness of 2-3 nm. The polycrystalline state is disadvantageous when ultra-smooth surfaces are desired. This is due to the finding that ion treatment can be used to smoothen amorphous surfaces, whereas it generally roughens polycrystalline surfaces. Therefore, control over the morphology of Mo and inhibition of the crystallisation is useful for roughness reduction. For this reason we investigated the influence of carbon doping on the crystallisation of thin Mo films. The choice for carbon was inspired by the observation that the critical thickness for crystallisation of Mo depends on the purity of the material. Furthermore, Si and C are both IV group elements, and Si is known to inhibit crystallisation of Mo. Wide Angle X-ray Diffraction (WAXRD) analysis was used to investigate the crystallinity of Mo layers with the C concentration varying from 0 to 20%. Figure 2.25

shows the WAXRD of a pure Mo reference sample and a sample with 20% of C. The peaks in the spectrum of the latter sample are wider than the peaks of the reference sample. This suggests that the presence of carbon indeed suppresses the crystalline phase and reduces the size of the crystallites, as Scherrer's formula dictates that the width of the peak is inversely proportional to the (average) size of the crystallite. Even though the presence of peaks in the sample with the highest carbon concentration (20%) indicates that the crystallisation was not completely suppressed, the crystallite size has reduced by a factor of 4 with respect to the pure Mo sample. Further experiments would have to demonstrate whether this reduction is sufficient to enable the desired ion beam smoothening.

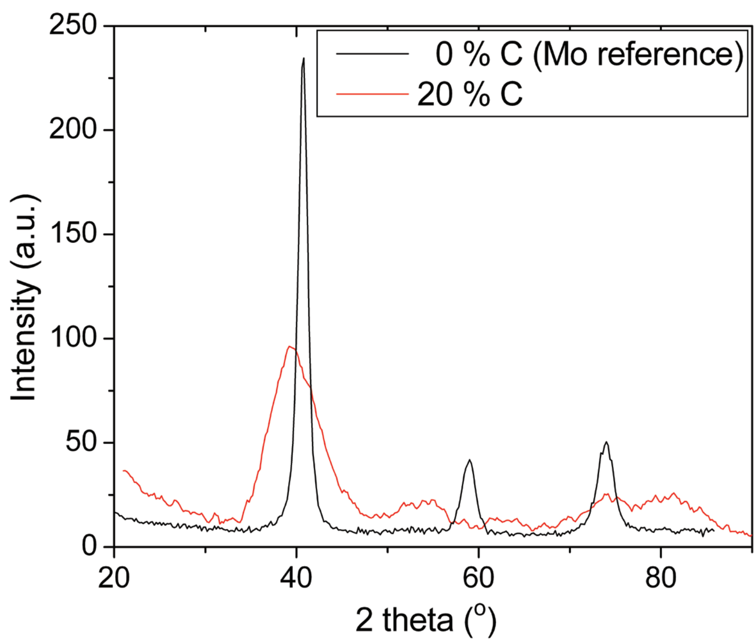


Figure 2.25: Wide angle X-ray diffraction spectra of a pure Mo sample and a sample with 20 at.% C.

Dynamic scaling exponents in ion bombardment of Si surfaces

Ion bombardment of Si surfaces has being used to smoothen growing Mo/Si multilayer structures and proved to be very important for the quality of advanced reflective X-ray and Extreme UV optics. However the physics behind the smoothening process during the ion bombardment is not yet entirely explored. A surface that is growing or eroding under non-equilibrium conditions often develops as a fractal-like structure. This effect has been observed and formalised within the theoretical framework of surface dynamics. In this concept, two parameters, known as the static and the dynamic scaling exponents, can be used as the signatures in space and time of the growth or etch processes. By comparing the experimental scaling exponent values with the theoretical predictions, one can establish, in principle, a differential equation describing the film growth or erosion. This equation can be used to improve understanding of the evolution of the roughness of surfaces under ion treatment, and assist in determining the parameters resulting in the best surface characteristics.

The roughness evolution of a Si surface during Ar^+ ion erosion of Si surfaces has been studied at the European Synchrotron Radiation Facility (Grenoble, France). Analysis of real-time Grazing Angle X-ray Scattering measurements of the eroding surfaces provided us with the evolution of the roughness, as displayed in Figure 2.26. At an ion energy of 1000 eV, it was observed that after a short treatment time of 30 s, the rms roughness σ of the sample surface was independent of the initial surface roughness: σ_{final} was 0.18 nm and equal for two samples, while $\sigma_{initial}$ differed notably with 0.15 and 0.28 nm. After 30 s of ion erosion, the surface dynamics were the same for both samples, regardless of the original surface roughness. Smoothening (from σ = 0.28 nm down to 0.23 nm) was also observed during ion erosion at the reduced ion energy of 300 eV. The data in Figure 2.26 was fitted using the model proposed by Majaniemi. Within the experimental uncertainty, the static scaling exponent was demonstrated to be independent of the ion energy: $\alpha = 0.23 \pm 0.08$ for etching at 1000 eV, and $\alpha = 0.30 \pm 0.05$ for etching at 300 eV. The dynamic scaling exponent β, on the contrary, was found to increase with

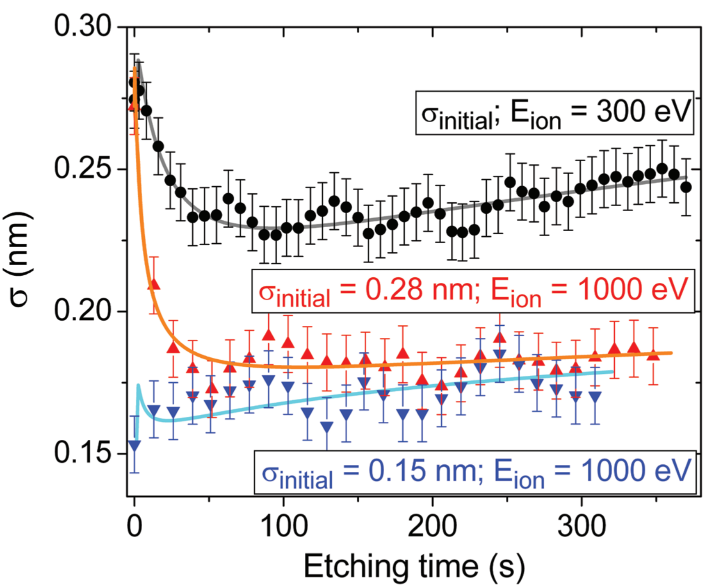


Figure 2.26: The evolution of the root-mean-square roughness σ upon etching for each of the three samples described above. The thick, solid lines represent the best fits in the framework of the Majaniemi model. While a roughening term is dominant in the first seconds of the ion treatment, a smoothening term takes over for 10-70 seconds, then followed by slow roughening.

decreasing ion energy: $\beta = 0.07 \pm 0.01$ at $E = 1000$ eV and $\beta = 0.14 \pm 0.02$ at $E = 300$ eV. However, a larger part of the experimental parameter space needs to be explored in order to be able to establish a master equation that would allow prediction of the dependence of the roughness evolution on the experimental parameters.

2.9 Advanced applications of XUV optics (AXO)

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Funding:	*FP-I10, Carl Zeiss SMT, EXEPT, EC, TFF, M2i, ASML, STW, FOM*

Research Programme

The general aim of the AXO group is to carry out research and development of XUV- and soft X-ray single- and multilayer systems. This notably includes multilayer optics for new applications in science and technology. The AXO programme also addresses the particular physics research on these applications. The focus is currently on EUV photolithography including the execution of the more applied and technological parts of the FOM Industrial Partnership Programme XMO (eXtreme UV Multilayer Optics). The group also deals with the transfer of new techniques and processes, tested on small laboratory samples, to the miscellaneous applications. An example of this is the successful fabrication of demonstration optics which include new processes developed elsewhere in the nSI department.

The group also investigates methods to enhance the spectral purity of EUV optical systems, in particular the suppression of parasitic infrared radiation originating from the driver laser of the EUV light sources. Experimental work on the feasibility of the methods and verification including the modeling of the multilayers involved is the subject of PhD researches.

Another EUVL related topic is the ISitCLEAR project (In situ monitoring of contamination layers on EUV optics at Ångstrom resolution), aiming at the development of a surface sensitive method to probe ultrathin contamination layers on multilayer systems and to build a functional model that has the potential to be used in EUV equipment.

A second focus of the group is the study of multilayer properties under exposure by extremely intense femtosecond pulses, carried out at the Free Electron Laser facility FLASH in Hamburg. This work has resulted in a first understanding of the phenomena responsible for irreversible damage of Mo/Si multilayers when used under extremely high fluence. Other types of multilayers are presently being studied in order to develop new radiation resistant multilayers. Such optics can be applied on beam lines or dedicated experimental set ups at FLASH or XFEL, the new X-ray Free Electron Laser to be built in Hamburg.

Additionally, also in the framework of application at short wavelength Free Electron Lasers, is the development of multilayer based beam splitters aiming at an equal distribution of reflected and transmitted intensity.

Finally, in the framework of a new STW (Dutch Technology Foundation) project on even shorter wavelength lithography, further studies on multilayers for 6.7 nm radiation have been carried out in close cooperation with the TFM group. This work continues in the frame of a PhD program that started late 2009.

STM investigation of molybdenum growth

Nanometer thin molybdenum and silicon films can be deposited with a very high degree of perfection. However, much details of the growth processes, nor the exact chemical composition, are fully understood at the atomic level. Recently, a scanning tunneling microscope (STM) has been implemented and connected through a vacuum sample transfer system to one of the deposition facilities (ADC) as well as to an x-ray photo-electron spectroscope (XPS), enabling the in vacuum study of the morphology and chemical composition of the thin layers of the thin films. For example an amount of molybdenum sufficient to form a layer of 0.5 nm thickness has been deposited on an atomically flat graphite substrate, and is probed by STM shortly after deposition. Figure 2.27 depicts the topography of 50x50 nm of the surface, showing a root-mean-square roughness of 0.6 nm. Hillocks of typically 5 nm diameter are observed together with height differences of several nanometers. The molybdenum layer is not completely covering the graphite, as is shown by the nanometer deep trenches. The large height differences compared to the as deposited amount can be understood from the carbon data taken by XPS (Figure 2.28). The observed carbide shows that the original graphite has been modified by the molybdenum deposition and contributed to the morphology of the layer.

This example of interaction of substrate and layer material on an atomic scale together with the nanometer size features shows the importance of studies on a more fundamental level to further understand the properties of the multilayered systems.

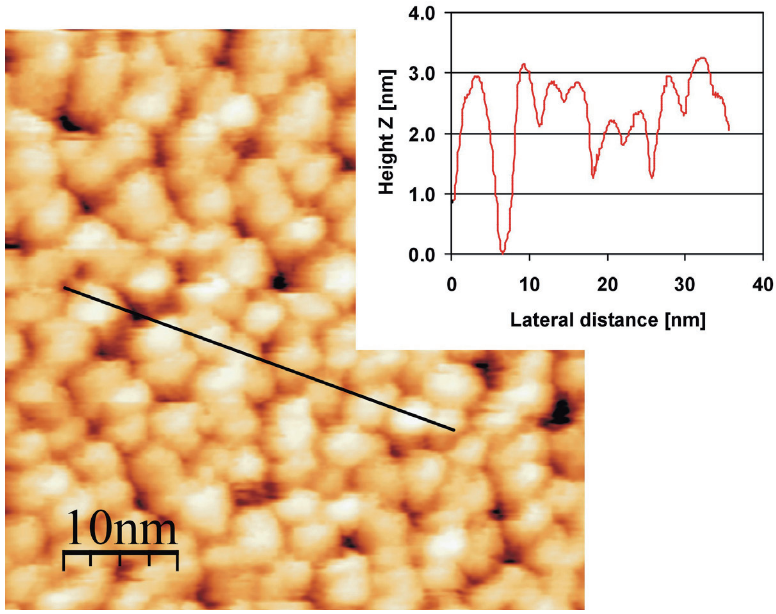

Figure 2.27: Topographic picture and height profile of 0.5 nm Mo on top of graphite. Features with a typical diameter of 5 nm and height differences of several nanometers are observed.

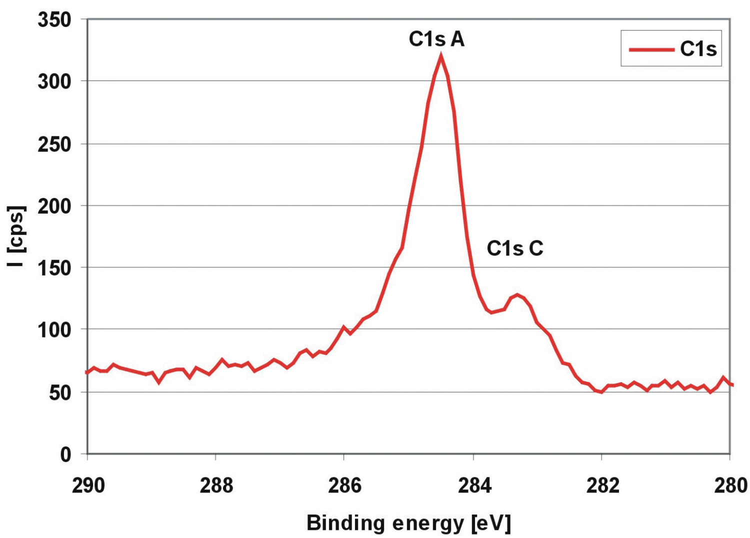

Figure 2.28: XPS measurement of a carbon containing layer, showing a clear carbide signal (C1s C) besides the graphite signal (C1s A) of the substrate.

Reflective multilayer optics for the wavelength range beyond the Extreme UV

The recent success in EUV lithography at a wavelength of 13.5 nm has triggered the desire to develop optical elements for the even smaller wavelength of 6.7 nm. Such optics can also be used in the new generation soft X-ray and XUV Free Electron Lasers like FLASH in Hamburg. Other applications include focussing optics in astrophysics, medical radiology, DNA imaging and cancer treatment.

Previous research has shown that one of the most promising material combinations to develop multilayer Bragg reflectors for the 6.7 nm wavelength is La/B_4C or La/B. Due to the chemical reactivity that results in e.g. LaB_6 formation, layer interfaces in these structures are not sufficiently sharp, resulting in a lower optical contrast and therefore in a poor performance of the mirror. We have found that passivation of La at the interface to LaN by N_2^+-treatment increases the optical contrast and reflectivity of such multilayers substantially by decreasing layer intermixing, as can be seen in Figure 2.29.

The best reflectivity can be obtained with nitridation of La at the interfaces. Post N-ion treatment of each La layer and N_2^+-assisted La deposition was applied and showed comparable results. As a preliminary result with a 250 period multilayer we achieved 41.5% reflectivity at 6.67 nm wavelength and 1.5° off normal angle of incidence. A new PhD research project that has recently started in the framework of the STW programme on Thin Film Nanomanufacturing is expected to result in reflectivities closer towards the theoretic limit of approximately 65%.

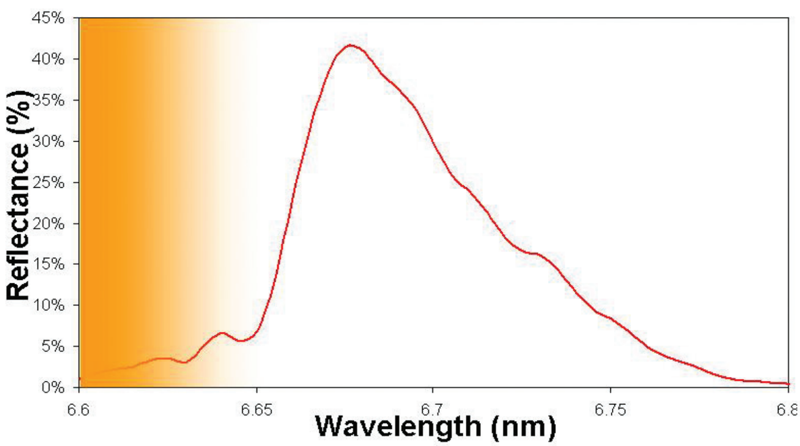

Figure 2.29: Reflectivity spectrum of La/B_4C multilayer with post-treated La layer.

Mo/Si multilayer systems on grating-like topographies

CO_2 Laser produced plasma sources are generally considered attractive as high power radiation source for Extreme Ultra Violet Lithography (EUVL). In the spectrum of these sources a significant amount of undesired infrared will be present. It has been shown by rigorous calculations that a Mo/Si multilayer on a blazed grating substrate having a saw-tooth surface profile, can be employed for a) a high EUV reflectance and b) diffractive separation of the infrared and EUV radiation.

To get insight into the phenomena related to Mo/Si multilayer growth on blazed gratings we use a model system to mimic its most critical feature: a sharp step edge. Near the step edge the Mo/Si multilayer is expected to show modifications in periodicity and shape of the layers while far from the edges on the grating facets it will behave as on a flat substrate. As a model system a cleaved crystalline Si wafer is used, having a sharp breaking edge along a crystal lattice orientation. On the cleaved wafer a Mo/Si multilayer is grown using thermalised particle magnetron spattering as well as e-beam evaporation deposition and an additional ion polishing treatment to reduce layer roughness.

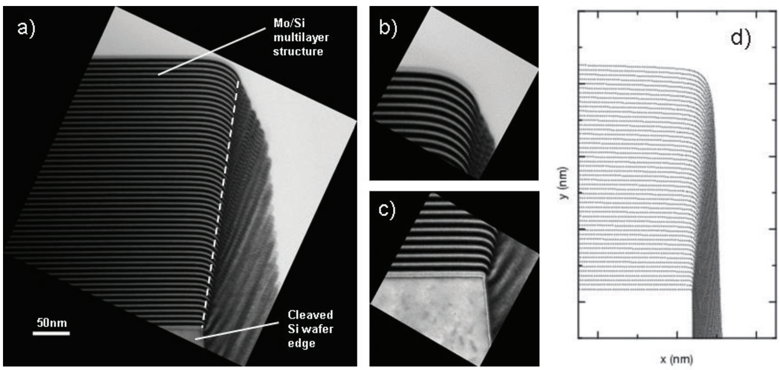

Figure 2.30: Cross-section TEM analysis with the black frames representing a) 50 period Mo/Si multilayer stack on a cleaved wafer edge, b) top of the stack c) bottom of the stack and Si wafer edge. Frame d) represents a simulation based on continuum growth model.

The multilayer structure shows a gradual rounding of the sharp edge, visible in frames a)-c), while the layers have a smooth and closed morphology. This behavior is described accurately by a continuum model taking into account the kinetics related to the ion polishing treatment and compaction of the structure due to silicide formation. The abrupt change in layer morphology from smooth to disordered (as indicated by the dashed line in a)) seems to indicate columnar layer growth at the steep slope of the step edge due to a very grazing growth direction with respect to the local surface normal.

Demonstration optics for EUV Lithography

An everlasting special task within the AXO group is to further develop the deposition processes to enable coating of large curved surfaces and obtain the same multilayer performance in terms of reflectance and periodicity control as can be achieved on small super polished laboratory samples. This requires advanced processing of in-situ reflectometry data to control individual layer thicknesses and periodicity of the multilayer up to the 0.1% level as well as development of deposition flux masking techniques to enable bringing the lateral thickness profile within specification, e.g. up to 0.1%.

The above mentioned, in combination with the latest multilayer improvements obtained by the TFM group, has been applied during the coating of demonstration optics for EUV lithography. This has resulted in a reflectance of 69.6% for 13.5 nm radiation, measured on a multilayer deposited on a real EUVL substrate at the angle of incidence at which the mirror will be used. The obtained reflectance is close to the best laboratory result of 70.2% and is to be compared with a theoretical value of ~75% when neglecting atomic dimension roughness. Simultaneously it was taken care that the overall non correctable multilayer thickness error was minimised to 35 pm rms, as was already reported previously. The thus obtained optics will be installed in the pre-production tools presently under construction at Carl Zeiss SMT and ASML.

Figure 2.31 shows he reflectance curve of one of the demonstration optics coated in 2009 and indicates the significant improvement with respect to the reflectance achieved in the past on real optics coated for the first two prototype wafer scanners, the Alpha Demo Tools. The improvement of the reflectance leads to a 50% increase of the optical throughput of the tool, thus resulting in a considerable larger number of wafers that can be exposed per unit of time.

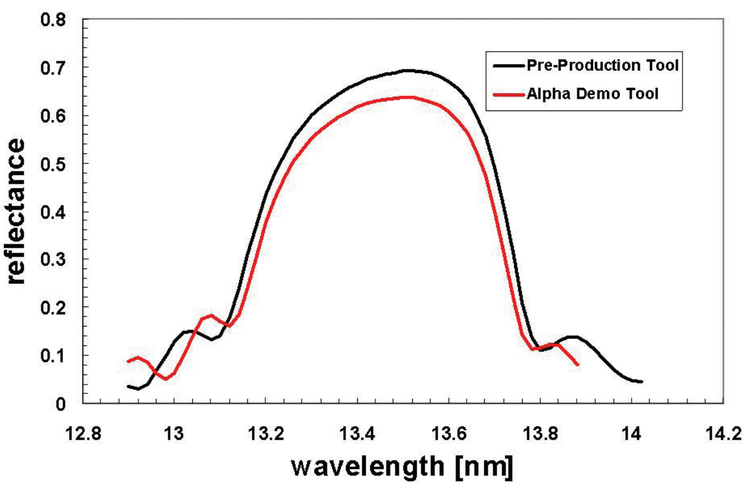

Figure 2.31: Reflectance curves of an element of an EUVL projection optic. The black curve shows the recently obtained value for the Pre-Production Tool, the red curve represents the coating of the prototype tool coated in 2006.

MoN/SiN multilayer structures under extreme UV laser irradiation

Multilayer structures are used for the control of XUV radiation in many fields of science and technology, notably nowadays in Extreme UV photolithography. Another field of their possible application is at short wavelength Free Electron Lasers. The photon flux from these sources is extremely high (1011- 1014 W/cm^2) and is at least 10 orders of magnitude higher than in the case of EUV lithography. We studied single shot damage mechanisms in Mo/Si multilayer systems where both the Mo and Si layers were treated with N^+ ions with the purpose of layer passivation (resulting in the formation of MoN and SiN layers). In thermal annealing experiments these structures showed significantly higher thermal stability (to above 800°C) compared to the untreated Mo/Si structures (below 150°C). In our experiments we used the FLASH facility in Hamburg at a wavelength of 13.5 nm and a pulse duration of 20 fs. Atomic Force Microscopy (AFM) showed the first traces of damage of the surface of the studied multilayer structure at 48 mJ/cm^2. At fluencies up to 120 mJ/cm^2 a smooth hill was formed on the surface, transforming into a crater at higher fluencies. Scanning Tunneling Electron Microcope (STEM) pictures of the crater are shown in Figure 2.32a. The pictures suggested that the hill observed is caused by gas formation inside the multilayer which was found in a separate experiment to be N_2. A more detailed look in Figure 2.32b shows that only the MoN layers (dark) delaminated upon exposure, with the SiN layers still visible (light).

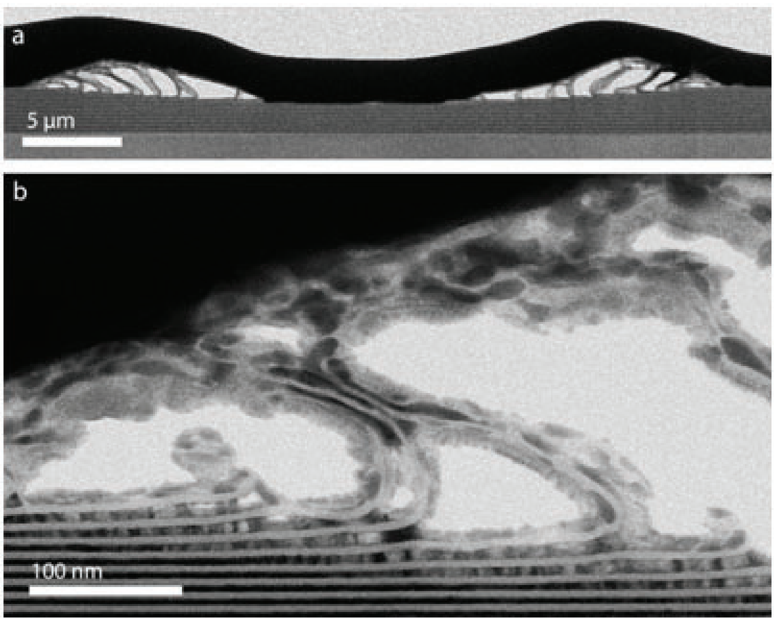

Figure 2.32: STEM pictures of the damaged part of a MoN/SiN multilayer structure exposed to a single short FEL pulse. a) Overview over the complete crater formation, with many layers visibly delaminated from the multilayer stack (the black layer on top is a protective W layer needed for the STEM process). b) A detailed view showing delaminated MoN layers (dark color), with the SiN layers (light color) being in tact.

Before delamination the MoN layer was found to first crystallise, suggesting that a part of the nitrogen cannot be build into the lattice forming a gas in the course of the crystallisation. Therefore, the crystallisation of the layer is considered to be the onset of the destruction process observed in these multilayer structures. Further analytical studies will be used for exploring damage mechanisms, eventually leading to improved compositions. These will then be applied for short wavelength FEL optics and other demanding thin film applications.

Amplitude division beam splitter for XUV radiation

Numerous new optical applications become possible once beam splitters are available for the XUV wavelength range. They include pump-probe measurements, interferometry and holography. Therefore, the goal of this research topic was to develop and test an XUV amplitude division beam splitter based on a semitransparent membrane coated with a multilayer Bragg reflector. The main scientific issues were: (a) the deposition of multilayers on thin (50 nm thick) membranes, (b) optimisation of the membrane and coatings with respect to the reflectivity, absorption and transmission, wavefront perturbation and radiation scattering, (c) design and development of the precise short wavelength beam splitters. Silicon nitride membranes of lateral sizes up to 5x5 mm and thicknesses ranging from 50 to 200 nm were coated with various multilayers. The coatings were optimised for a specific reflectivity to transmission ratio for 13.5 nm radiation for near normal and 45 degrees incident angle and the strain of the multilayer structure was minimised.

Characterisation of the multilayers at the Advanced Light Source synchrotron facility (Berkeley, USA) lead to (a) a uniform transmission and reflectivity over almost the entire membrane within $\pm$ 2% error, (b) an absorption of the energy in the multilayer coated membrane similar to the design, but a deviation of the optical contrast (reflectivity over transmission). The latter is explained by an increased roughness of the membrane (up to 0.8 nm RMS) in comparison to the value specified by the membrane supplier (0.5 nm RMS).

Flatness characterisation of the membranes, carried out by the Helmholtz Zentrum Berlin by means of optical interferometry (see Figure 2.33) shows that the shape of the membrane is determined mostly by the deformations of the frame and that the roughness of the central part of the membrane obtained after subtracting the background is around 0.2 nm, which is well below the $\lambda/10$ limit for 13.5 nm radiation. Furthermore, the slope errors of the membrane surface from a plane reference are smaller than 20-30 μrad, which is sufficient for most of the applications with the incoherent light. Two of the coated membranes were successfully used as beam splitters for pump and probe experiments at the FLASH free electron laser facility.

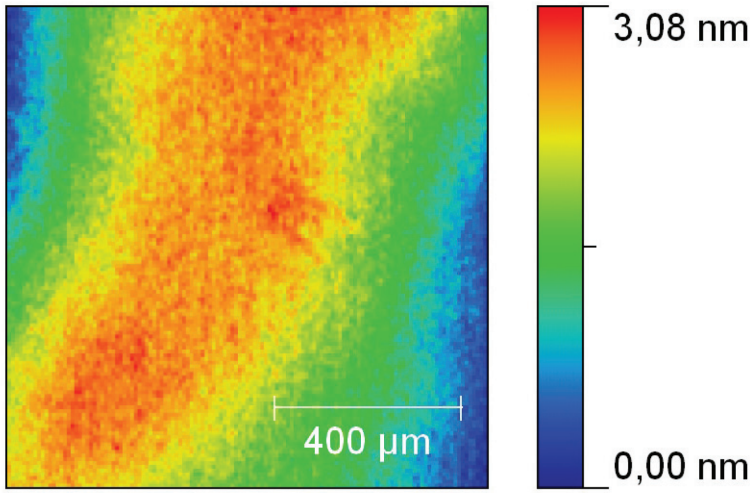

Figure 2.33: Height map of a multilayer coated thin membrane. The central, optically used part of the sample shows a very low peak-to-valley value of ~3 nm.

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 IA-SFS and ELISA projects, integrated infrastructure initiatives under the European frame work programmes 6 and 7, respectively, that comprise all European synchrotron and free electron laser facilites; the Molecular Dynamics group has been granted an NWO –'middelgroot' and within the group Dr. A.M. Rijs was supported by a CW/NWO-Veni grant.

FELIX

Rijnhuizen has designed and constructed the Free Electron Laser for Infrared eXperiments, FELIX, attracting user groups from all over the world. First of all, the division exploits the Free-Electron Laser for Infrared Experiments (FELIX). Since 1994, FELIX is operated as a user facility, providing continuously tunable radiation in the infrared spectral range of 3-250 μm, at peak powers ranging up to 100 MW in (sub)picosecond pulses. 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, synchronised to FELIX, have been installed to provide multi-colour 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 beamline which can be operated interleaved with one of the two existing beamlines 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. In the summer of 2007, phase I of the FELICE beamline became operational and it is now operated routinely and open to 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 gas-phase 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.

2.10 The IR user facility FELIX / FELICE

Division:	*Generation and Utilisation of THz Radiation*
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UK-station master:	*N.Q. Vinh*
Funding:	*FP-58, EPSRC, IA-SFS, ELISA, NWO-Groot*

The Free Electron Laser for Infrared eXperiments, FELIX, has been designed and constructed 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, with less than 5% unscheduled downtime. A view into the FELIX vault is shown in Figure 2.34. Sophisticated FEL diagnostic equipment is set up, and the users have full computer-control over all relevant characteristics of the FELIX-radiation, such as wavelength, bandwidth, pulse-energy and duration. 25% of the beam-time is reserved for the in-house research programme on molecular dynamics. A further 20% is earmarked for researchers from the UK

Figure 2.34: Picture of the FELIX and FELICE free electron laser showing the three beam lines in the accelerator vault.

under the EPSRC contract. This leaves 55% of the beam time to be allocated on the basis of submitted research proposals, which are evaluated half-yearly by a user selection committee and includes 10% for users from EU-countries supported under the IA-SFS and ELISA contracts.

Many improvements and extensions have been made to the facility since it became operational in 1994. 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 feature that really distinguishes FELIX from all other light sources, including almost all other FELs, is its high output energy per μs in the wavelength range from 5 to 250 μm.

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. To this end, the lasers are locked to FELIX with a rms jitter of less than a ps, while control of the relative delay with sub-ps accuracy has been incorporated in the user interface. There are currently ten user stations operational at the facility and one of them houses the high-resolution FTICR mass spectrometer, originally funded by the National Science Foundation in the USA, in collaboration with two university from the US. The most recent development is a laser-desorption molecular beam apparatus coupled to a Nd:YAG pumped dye laser and an IR OPO laser system funded by a ‘NWO middelgroot’ grant.

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, most of which make use of the existing setups — several molecular beam machines, a small ion trap or the high-resolution, high-sensitive FTICR mass spectrometer equipped with different external ion sources. Other users installed large, dedicated equipment.

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. Major funding for upgrade of the facility was received from NWO in 2002 for a project with the acronym FELICE (Free Electron Laser for Intra-Cavity Experiments). In 2003 the design and layout phase for this major extension of the FELIX facility. This project involves the construction of a third beam line dedicated to gas-phase, intra-cavity experiments in the wavelength range from 3 to 100 μm and operated interleaved with one of the two existing beam lines at a maximum repetition rate of 10 Hz for each line, thereby effectively doubling the amount of beam time available to the users. Figure 2.35 shows the two existing beam lines (FEL 1 and 2) as well as a new beam line with the FELICE undulator located under the ceiling of the vault. The cavity of FELICE sticks through the ceiling and includes on each end a 2-m long horizontal part in which the experimental setups are placed.

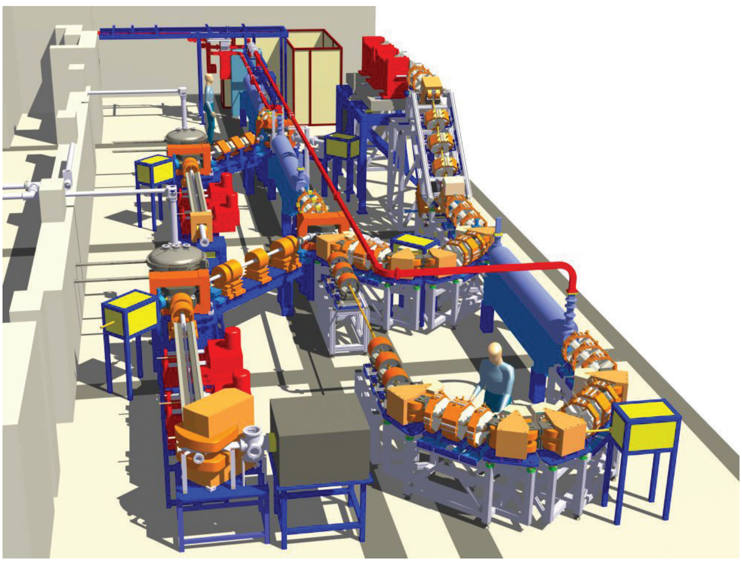

Figure 2.35: Artist's view of the layout of the FELIX and FELICE free electron laser showing the three beam lines in the accelerator vault.

The purpose of FELICE is to provide significantly higher infrared intensities for low-absorption, gas-phase experiments. The increase as compared to FELIX is up to a factor of hundred in the spectral range from 3 to 100 μm. The gas-phase experiments to be performed on FELICE will be done in two specialised intra-cavity setups — one containing a molecular beam apparatus and the other an FTICR mass spectrometer.

After demonstration of first lasing in the summer of 2007 FELICE is now operational covering the wavelength range from 5 to 50 microns at a micropulse repetition rate of 1 GHz or 16.6 MHz and interleaved with one of the FELIX beamlines. The intensities reached are according to specifications and the beam line operates reliably and reproducibly. 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 can reach values as high as 2 mJ per micropulse. Interleaved operation of the old beam lines (FEL 1 or 2) and the FELICE beam line has become routine operation, effectively doubling the available beam time for users. In 2009 FELICE has been open to internal and external users and has produced almost 50% of the beam time of FELIX. In view of the still ongoing developments of the laser as well as the user experiments an unexpectedly high number. The two intra-cavity experiments will be used for infrared spectroscopy of gas-phase species ranging from small clusters to large biomolecules. One FELICE intra-cavity setup, shown in Figure 2.36, the molecular beam apparatus, is fully operational and equipped with different sources including a laser-ablation source, and an ion trap with spatial imaging device. The second FELICE beam line is currently commissioned and the setup, a highly sensitive FTICR mass spectrometer will come online in the summer of 2010.

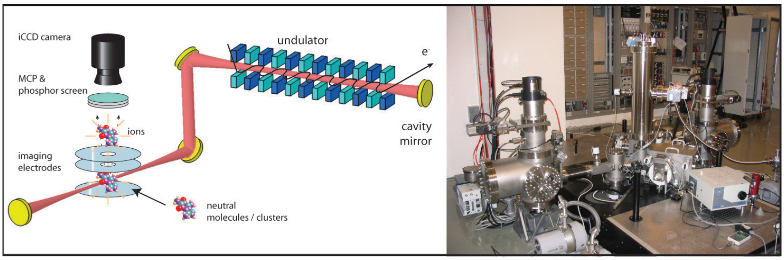

Figure 2.36: Schematic view (left) of the intra-cavity ion imaging setup and photograph (right) of the FELICE molecular beam setup.

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. As indicated by these topics, 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.

The first experimental campaigns on FELICE already indicated that a broad user community can benefit from this new installation. So far 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. Some highlights of user experiments performed in 2009 at the FELIX facility are described in the next paragraphs, whereas the results of the in-house user group can be found in section 2.11.

Highlights of user experiments

The role of sequence in salt-bridge formation

A collaboration between an external user group from the University of California, Berkeley, and the in-house user group has demonstrated that the sequence of a dipeptide can determine the relative stabilities of the formation of charge-solvated (CS) or salt-bridge (SB) structures when cationised by an alkali metal ion. In the case of the sequence ArgGly•Li^+ a CS structure is found whereas the reversed order of the amino acids with the sequence GlyArg•Li^+ changes the structure to be SB. This comparatively simple example already shows that sometimes even minute changes e.g. in the electrostatic interactions, hydrogen bonding, sequence and gas-phase basicity can become very important in molecular structure and reactivity.

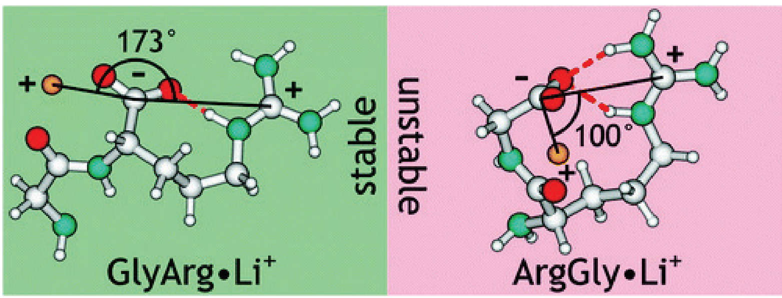

Figure 2.37: Molecular representation of the salt-bridge structures of GlyArg•Li^+ and ArgGly•Li^+, the latter being an unstable configuration.

Structure of silicon clusters

A collaboration between external user groups from the Fritz-Haber Institut der Max-Planck-Gesellschaft in Berlin and the University of Leuven initiated the search for the structure of silicon clusters in the gas phase. Silicon clusters have received considerable attention partly due to the dominant role of silicon nanostructures in the semiconductor industry. With the current trend in miniaturisation, components in electrical devices may eventually reach cluster size ranges. A particular characteristic of small clusters is the size dependence of their chemical and physical properties and therefore size-dependent studies are very timely.

In this study the vibrational spectra of cationised clusters have been measured by means of photodissociation of their complexes with rare gas atoms. Multiple photon dissociation spectra are recorded in the range of the structure-specific vibrational fundamentals of the silicon clusters, i.e. their finger-print range. Photodissociation signals are obtained from as low as 166 cm^{-1} to about 600 cm^{-1} for clusters possessing 6 to 21 silicon atoms. By comparing these experimental spectra with theoretical predictions based on density-functional theory unambiguous structural assignments for most of the Si_n^+ clusters have been made. In particular for Si_8^+ an edge-capped pentagonal bipyramid structure, hitherto not considered, was assigned (see Figure 2.38). These structural assignments for the series of clusters provide direct experimental evidence for a cluster growing motif.

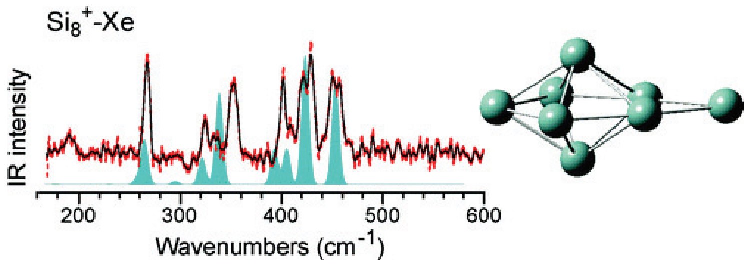

Figure 2.38: Infrared Photodissociation spectrum of Si_8^+-Xe together with the theoretical calculations and the resulting structure of the cluster being a edge-capped pentagonal bipyramid.

Gas-phase conformations of Crown Ether complexes

The inclusion complexes formed by crown ethers with alkali metal cations constitute a textbook prototype of host/guest molecular recognition. They provide a relatively simple benchmark to elucidate the competition of intrinsic intermolecular interactions versus solvent effects leading to selective complex formation. A collaboration between the University Pablo de Olavide, Seville, and the in-house user group has recorded infrared multiple photon dissociation action spectra of the binary (15c5-K^+) and ternary (15c5-K^+-15c5) gas-phase complexes formed by 15-crown-5-ether with potassium cations. The spectra cover the 800-1500 cm^{-1} infrared range and exhibit particularly significant differences in the position and structure of the CO-stretching band of the two types of complexes (see Figure 2.39). The computational predictions agree well with the experimental results and provide a correlation between the spectral differences and the structural changes associated with the coordination of the ether oxygens with the alkalication.

Condensed matter physics (CMP) is another field of research for which FELIX presents a very valuable tool. The UK user programme in CMP, largely based on a contract between the British research council EPSRC and FELIX, presently comprises work from user groups in several UK universities and receives about 20% of the beam time being divided over different experimental programmes. Below we present some projects from this field.

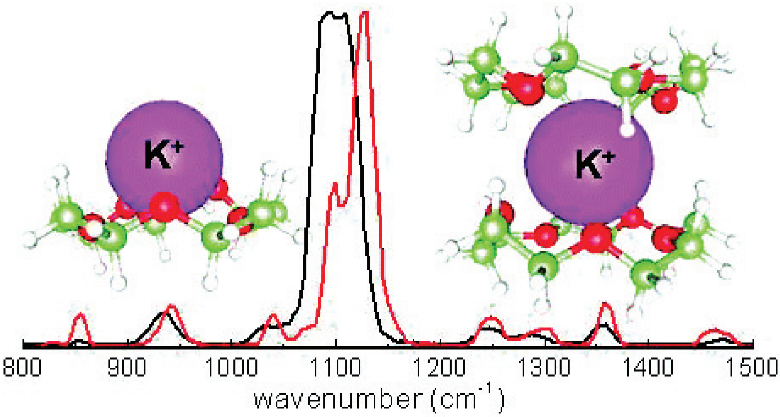

Figure 2.39: Infrared action spectrum of the binary (black) and ternary (red) potassium complex with 15-crown-5-ether. The structures found by the combination of infrared spectroscopy and computational calculations for the complexes (binary – left and ternary – right) are shown as insets.

Spin-galvanic effect in quantum wells

In previous FELIX studies an interesting effect known as the spin-galvanic effect was investigated, in which radiation induced spin polarisation of carriers can spontaneously produce a current in a semiconductor crystal of low symmetry. This optically induced spin-galvanic effect in zero magnetic field was demonstrated and it was shown that the wavelength dependence of the effect is characteristic of the spin-galvanic effect. The results improved the knowledge of the energy splitting of the spin states in zero magnetic field for GaAs based structures, and represent a first step towards generation of spin polarisation using (unpolarised) currents. Recently, spin-current experiments have been performed using more novel systems, i.e. GaN and HgTe semiconductor quantum well structures.

In a recent development the application of narrow low dimensional HgTe structures for the measurement of the elliptically polarised light by an all-electric detection scheme in the midinfrared to THz spectral regime has been demonstrated. The observed sensitivity and the linearity of the detection scheme are sufficient to characterise the polarisation of laser radiation from low-power cw-lasers to high power laser pulses.

Lifetimes of excited states of shallow donor and acceptors in silicon

Hydrogen-like transitions in donors such as phosphorus and arsenic in silicon are of considerable technological interest.
Using non-linear optical techniques, the relaxation and dephasing of the

excited states of the shallow centers (P, As, Sb) in silicon have been investigated in detail.

For the 1s-2p0 transition in phosphorus-doped silicon, a lifetime was measured that is close to the inverse of the linewidth measured in isotopically pure silicon. This implies that the dominant decoherence mechanism for excited states is lifetime broadening, just as for atoms in ion traps. These results are important because they indicate that coherent control and manipulation of atomic-like quantum levels - key to many well known schemes for quantum computing- in the most common semiconductor may be feasible.

The importance of these results has recently been recognised by the British research council EPSRC which supports a programme to develop these schemes further with a five year grant worth in total about 7 Mill. £. The grant is a collaborative effort led by the University of Surrey and the London Centre for Nanotechnology and involves installation of advanced ESR spectrometers interfaced to the FELIX beam time and a contract for the use of 10% FELIX beam time.

FELICE infrared action spectra of strongly bound anionic clusters

In a collaborative effort between the Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, and the FELIX team the method of infrared multiple photon electron detachment (IR-MPED) spectroscopy of metal carbide cluster systems has been demonstrated using FELICE. The structure of anionic clusters are so far mainly studied using photoelectron spectroscopy. Although for some systems vibrational resolution has been achieved, most structures have been assigned by probing only the electronic structure and comparing with theory, which can be rather challenging for the excited state. IR spectroscopy has so far been limited either to complexes of the anions with ligands only or to systems with very high IR cross sections. The high infrared intensities available in FELICE, especially in the far infrared, bring vibrational spectroscopy of those systems into reach. This method is very similar to IR multiple photon ionisation, the main difference being the significantly lower electron affinity of the metal cluster as compared to the ionisation potential. Resonant excitation of a vibrational mode will, after rapid internal vibrational redistribution, lead to thermal heating of the cluster. Whereas for neutral clusters fragmentation is usually energetically favoured over the ionisation process, this is different for many anionic transition metal clusters. As their electron affinity is clearly lower than the bond energy, electron detachment becomes the more likely process. For the benchmark system of tantalum carbide anionic clusters IR-MPED spectra have been recorded and e.g. for the Ta_4C- cluster the structure has been assigned based on the comparison of theoretical calculations with these spectra (see Figure 2.40). Using FELICE this method allows to directly record vibrational spectra of anionic metal and metal oxide/carbide clusters in the gas phase.

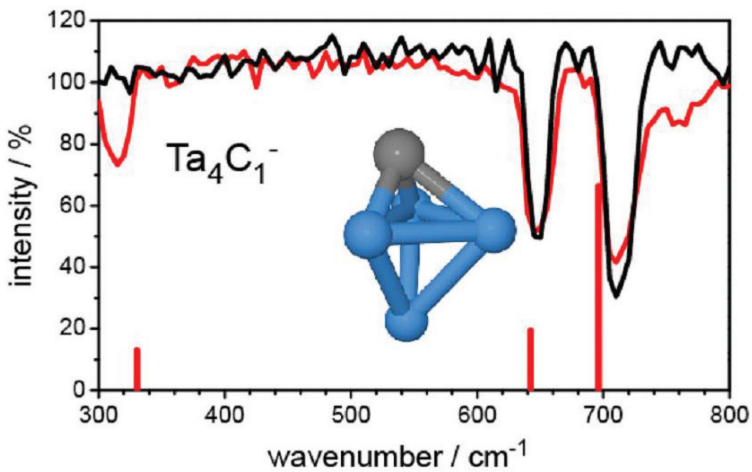

Figure 2.40: Infrared multiple photon electron detachment spectrum of the Ta_4C- cluster obtained with FELICE different infrared intensities compared to vibrational modes for the calculated global minimum structure. The corresponding cluster structure is also shown.

2.11 Molecular Dynamics: action spectroscopy with FELIX

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Technician:	*J. Pluijgers*
Funding:	*NWO-Middelgroot, NSF-PIRE, CW/NWO-VENI, FOM/v, NWO/CW – Athena*

Research program

As in-house user of the FELIX / FELICE free electron laser facility, the Molecular Dynamics group uses IR radiation from FELIX 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 conformers. 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 make FELIX excellently suited for several so-called action spectroscopy schemes. The systems are studied using various experimental methods, all based on IR excitation followed by mass spectrometric ion detection (TOF and FTICR). Among others, molecular beam, laser double resonance, and ion storage techniques are applied. Our scientific interest focuses mainly on systems of biomolecular, mass-spectrometric, nano-technological and astro-chemical interest. In addition, many collaborative studies are carried out with international users of the FELIX facility.

Mission

To exploit the unique capabilities of FELIX and FELICE in molecular physics, several types of experiments have been set up to investigate the energy flow processes in molecular systems and/or to study the infrared optical properties of low-density gas-phase species. Individual projects focus mainly on IR ion dip spectroscopy of gas-phase (bio-)molecules in different conformations, IR multiple photon ionisation spectroscopy of small metal clusters and IR multiple photon dissociation of a variety of molecular ions in ion traps.

Memory effects in electrospray ionisation mass spectrometry

Infrared ion spectroscopy has been used to show that the solvent used in ElectroSpray Ionisation (ESI), a commonly used ionisation method in mass spectrometry, can influence the structure of relatively simple molecules. ESI transfers molecules from solution into the gas phase, while at the same time ionising them, so that they can be analysed in a mass spectrometer. ESI creates a fine mist of a solution of the sample under study, using a steel capillary at high voltage. The small, charged droplets that develop, gradually evaporate, leaving the bare, ionised molecules in the gas phase. Details of the ESI-process are, however, not well understood. It is commonly assumed that the ionised molecules adopt their lowest energy state in the gas phase, irrespective of the structure they had in solution. The current study shows that this is not always the case.

Deprotonation of para-hydroxybenzoic acid (p-HBA) may occur on two different sites resulting in two isomeric anions: the phenolic proton may be lost giving a phenoxide structure or the carboxylic acid proton may be detached, giving a carboxylate structure. IR spectroscopy of the deprotonated form of p-HBA now indicates that the starting conditions of the ESI-process – in this case, the type of solvent used – determine the site of deprotonation. From protic solvents such as methanol and water, the carboxylate form is produced, but aprotic solvents such as acetonitrile result in the phenoxide form. This finding suggests that the anion retains the structure it had in solution and does not isomerise to the lowest energy structure, as is often assumed.

Further experiments have shown that p-HBA is not the only molecule where the ESI-conditions can influence the resulting anion structure. Some related molecular anions show the same behaviour. Hence, counter to what has been generally assumed, even for small molecules such as those investigated here, ESI can play a decisive role in the structure formed in the gas phase.

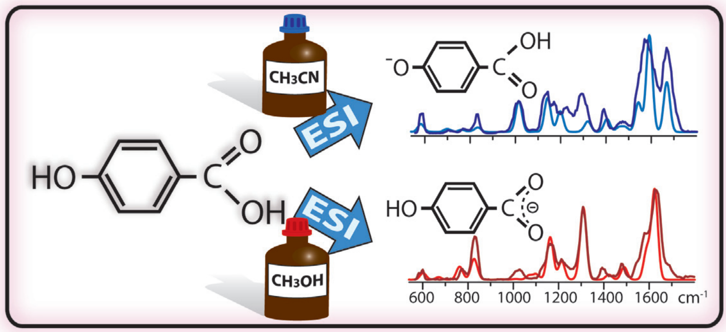

Figure 2.41: IR spectra of the conjugate base of p-HBA sprayed from protic and aprotic solutions and compared to calculated spectra of the carboxylate and phenoxide isomers of the anion.

The fine balance between Zwitterionic and Canonical structures

Mass spectrometry is a key analytical tool in the study of biomolecular species. Unlike in their natural environment, biomolecules in a mass spectrometer are isolated in the gas phase, which can alter their structure compared to the native state. For instance, simple amino acids are zwitterionic in solution, but non-zwitterionic (canonical) in the gas phase (see Figure 2.42a). To be able to study solution-phase structures in the vacuum of a mass spectrometer, much effort has been devoted to determine how zwitterionic structures can be induced in the absence of a solvent. It is for instance known that complexation of amino acids with alkali metal ions can induce zwitterionic structures, where the charge separation is stabilised by the presence of the alkali metal ion forming a salt-bridge structure. However, whether or not a zwitterion structure is indeed formed depends sensitively on the amino acid side chain as well as on the alkali metal ion. Our spectroscopic investigations have shown that most amino acids adopt non-zwitterionic structures upon alkali metal complexation.

Complexation with a divalent (2+) alkaline earth metal ion on the other hand, efficiently induces zwitterionic structures. Upon addition of more residues, i.e. going from amino acids to peptides, more Lewis-basic sites become available to solvate the charge and the peptide tends to adopt a non-zwitterionic structure. This is nicely seen in the series of spectra for poly-alanine peptides complexed with Ba_2^+. A sudden change in the spectrum is observed upon going from Ala_2 to Ala_3. The spectra of the complexes with Ala_3 and Ala_5 are very similar to each other and also to that of the singly-charged K^+Ala_2 complex, in which the peptide has the canonical structure. Not only the peptide length but even the amino acid sequence in a dipeptide may reverse the relative stabilities of zwitterionic and canonical structures. This delicate balance between isomeric structures can hardly be probed with mass spectrometric methods alone.

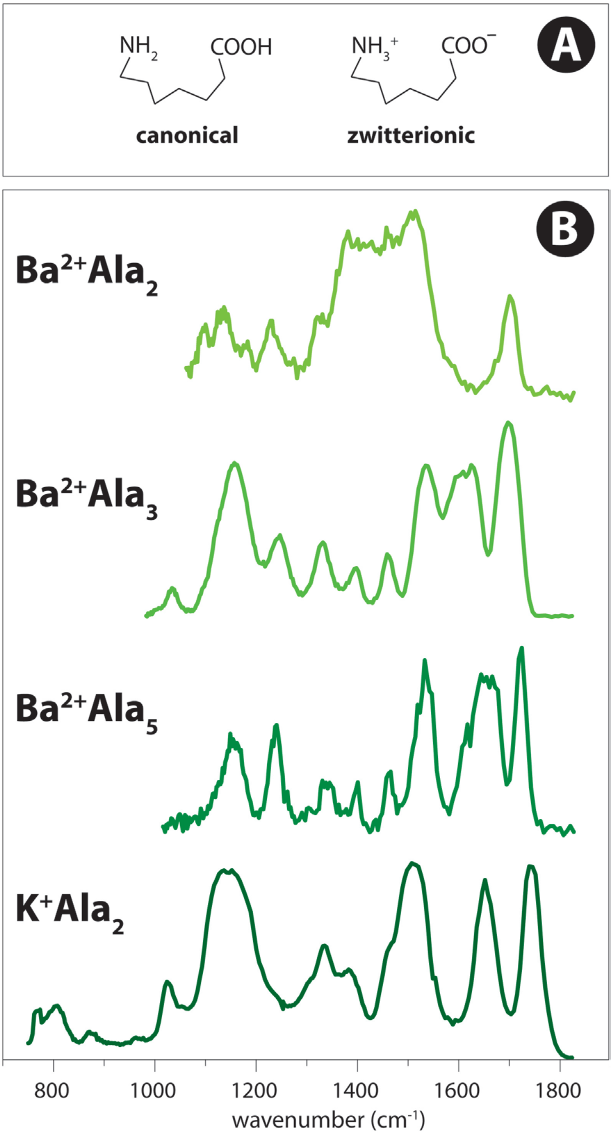

Figure 2.42: a) Proton transfer from an acidic to a basic site changes the canonical structure of an amino acid or peptide into a zwitterionic structure. b) The IR spectra of poly-alanine peptides with Ba_2^+ show a sudden change upon going from Ala_2 to Ala_3. The change is caused by the transition from zwitterionic to non-zwitterionic (canonical) structures.

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 cyclisation 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 (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 from characteristic vibrational bands relating to a protonated amide carbonyl (CO-H$^+$), versus an N-terminal protonated (NH_3^+) structure for linear peptide fragments. The IR spectroscopic 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.

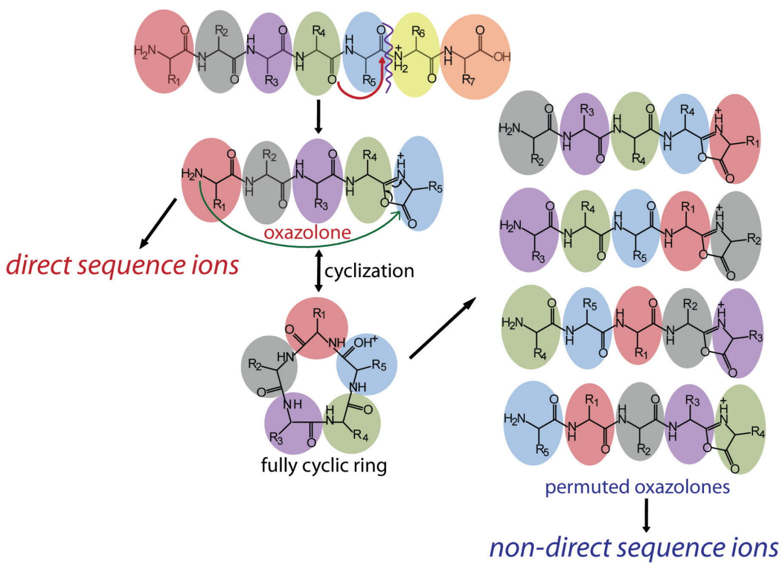

Figure 2.43: The so-called b/y fragmentation pathway entails the cleavage of the amide bond of a peptide and results in a fragment with a 5-membered ring type structure. Subsequent rearrangement reactions may generate macrocyclic structures, which upon re-opening may result in permuted peptide sequences.

Controlled uncoupling of a rotaxane via microsolvation

Rotaxanes are proving useful structural prototypes for helping realise the concept of artificial molecular machinery. They are composite molecular systems consisting of a macrocycle mechanically trapped onto a linear thread by bulky end groups (stoppers). Recently, the first detailed spectroscopic studies of isolated rotaxanes have demonstrated that the IR spectra provide a direct view on the effects of interlocking in these prototypical rotaxanes.

The first step to induce molecular motions is to uncouple the two components, i.e. to affect and break the hydrogen bond interactions between the macrocycle and the thread. The key idea is to tune the hydrogen-bond interactions between the components in a quasi-continuous manner by adding solvent molecules one at a time. Hydrogen bonding with the solvent molecules replaces the hydrogen bonds between thread and macrocycle, thus uncoupling the rotaxane constituents. In a collaboration with researchers from Amsterdam, Edinburgh and Bologna, the uncoupling is probed with gas-phase IR spectroscopy, which directly reveals the number of methanol molecules required to release the macrocycle from the thread. The observed uncoupling of macrocycle and thread is confirmed by molecular simulations of the macrocycle – thread – solvent system.

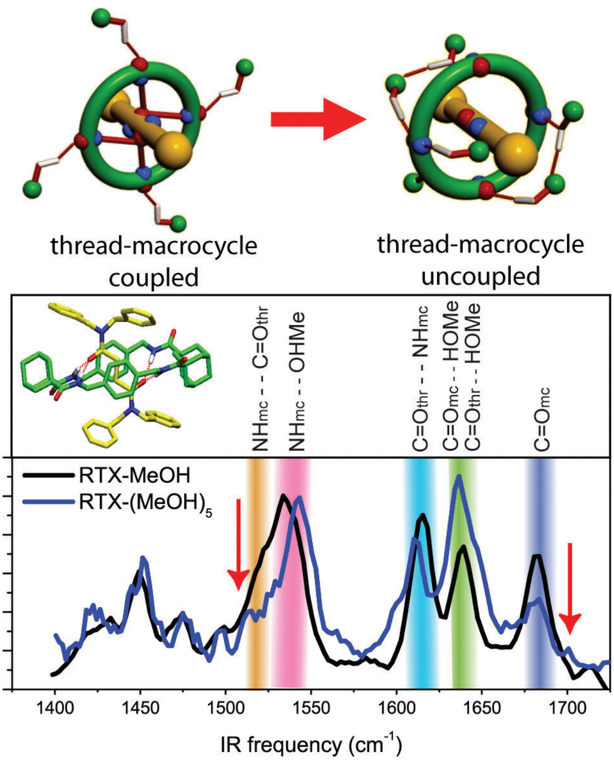

Figure 2.44: IR spectra of the rotaxane with 1 (black) and 5 (blue) methanol molecules attached. In the orange part of the spectrum, the band at 1525 cm^{-1}, which is associated with NH bending vibrations of the macrocycle that are hydrogen-bonded to C=O groups in the thread, disappears in the 5 methanol cluster. Hence, the macrocycle is no longer locked to the thread.

Gas-phase anion spectroscopy

Whereas the spectroscopy of positively charged ions (cations) in the gas phase has rapidly grown over the past years, this is not the case for anionic species. Using the FTICR-MS at FELIX we have investigated the gas-phase structure of several anionic species of fundamental interest.

Unlike for cationic species, infrared excitation of an anion may not only result in fragmentation of the ion but also in detachment of the electron. For many anionic species, activation energies for dissociation and detachment are roughly comparable, so that the two processes may compete. In the FT mass spectrometer, the detached electron cannot be detected since its ICR frequency ($\omega = qB/m$) is much too high for the detection electronics. We have developed a method where the detached electrons can be 'made visible', which relies on capturing the free electrons with an efficient gas-phase electron scavenger such as SF_6. Note that this is possible since the detached electrons remain trapped in the ICR cell, which would not be the case for an rf ion trap.

Ion spectroscopy based on detachment rather than on dissociation can be used to obtain spectra for anionic species that do not yield charged fragments upon dissociation. For instance, a small anion such as acetate (see Figure 2.45) may dissociate into fragments with small (or even negative) electron affinities; activation then only yields neutral fragments (CH_3 and CO_2 in the case of acetate) and a free electron. This method has also been applied to obtain a background-free spectrum of C_{60} and C_{70} fullerenes, which are too stable to be dissociated with FELIX.

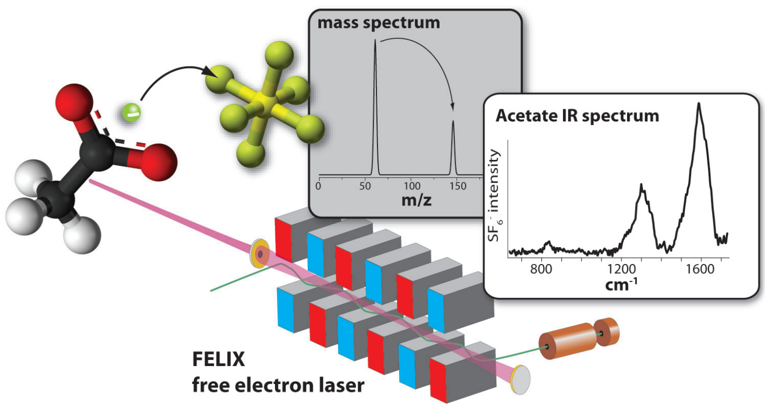

Figure 2.45: Infrared action spectroscopy based on electron detachment in an FT mass spectrometer. A low pressure of SF_6 picks up the electrons that are detached from the species under study (acetate anion in this case) upon IR activation.

Direct IR action spectroscopy of transition metal clusters

The discovery of enhanced catalytic activity of small gold clusters has led to a surge in the interest in size-dependent catalytic properties of metal clusters. To gain better insight into the catalytic mechanisms, it is essential to know the structures of these clusters. Such structural information on size-selected gas-phase clusters can be obtained using IR action spectroscopy. By comparing the experimental spectra to predictions from quantum chemical calculations for various candidate structures, the metal cluster structure can be inferred.

Due to the relatively high elemental masses of transition metals and the typically rather weak metal-metal bonds, the vibrational fingerprint region for these clusters is found at long IR wavelengths ($\lambda > 30\ \mu m$). Due to the low energy per photon in this spectral region and the rather weak IR absorption cross-sections, it has thus far proven impossible to sufficiently excite pure metal clusters to observe fragmentation or ionisation. Using the high IR fluences available at the intracavity free electron laser FELICE, it has now been possible to resonantly excite neutral niobium and tantalum clusters to internal energies where ionisation can be observed. The IR-REMPI (IR resonance-enhanced multiple photon ionisation) spectra of size-selected niobium clusters exhibit characteristic vibrational resonances, which allow for a structural assignment based on the comparison with spectra calculated using quantum-chemical methods.

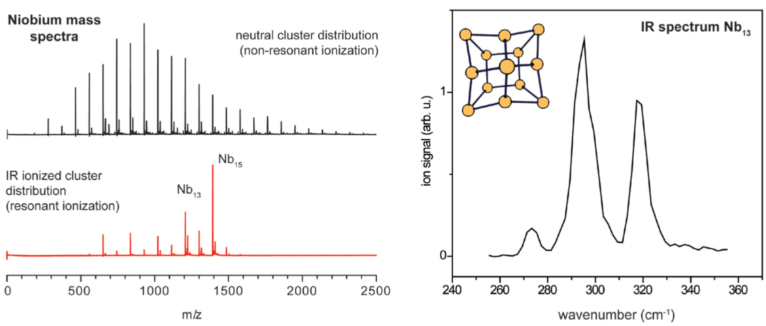

Figure 2.46: Mass spectra of the niobium cluster distribution after non-resonant UV ionisation (top left) and resonant IR ionisation with FELICE (bottom left). IR-REMPI spectrum of Nb_{13}, with one of the candidate geometric structures (right).

Internal proton transfer in a neutral isolated peptide

The biological function of a protein is determined by its three-dimensional geometry, which results from a subtle combination of intrinsic conformational preferences and interactions with its biological environment. Gas-phase spectroscopy has resulted in the structural characterisation of many amino acids and small peptides. However, gas-phase peptides generally adopt a neutral form, whereas in their natural environment, charge separated structures play an important role.

In collaboration with researchers from Lyon and Paris, we demonstrate that "auto-zwitterionisation" can occur in the local environment of a 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 zwiterionic form. In addition, the symmetric carboxylate stretch mode (yellow) provides a complementary probe of the zwitter-ionic structure. The strong propensity of the peptide to undergo internal proton transfer is confirmed by theoretical investigations.

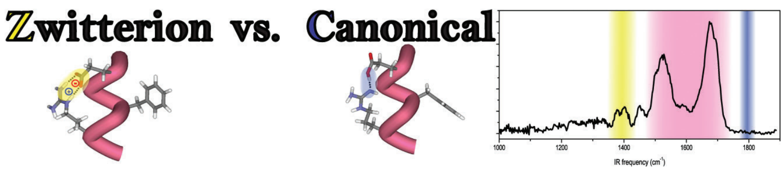

Figure 2.47: Structure of the canonical and zwitter-ionic forms of the peptide (left). IR spectrum of the peptide showing the presence of a carboxylate stretching mode (yellow) and absence of a carboxylic acid band (blue). The peptide amide vibrations are shaded in pink.

2.12 Support Facilities

Division: *Support Facilities*
Department Head: *A.A.M. Oomens*

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*
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The Mechanical Techniques group designs and manufactures 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.

For designing equipment, several systems with Catia V5 are available. Catia is the leading solid modeling software used in fusion research. It provides the possibility of building assemblies, automatic generation of workshop drawings, and performing several kinds of analyses such as finite element analysis, heat load analysis, kinematical analysis and frequency analysis. All documents produced, like Catia, Word, Excel and all others are stored by a PDM system called SmarTeam.

The manufacturing of the designed equipment is done using several machines, including CNC-milling and -lathing machines. The group also has the knowledge and equipment required for vacuum and high temperature brazing and TIG welding. The CAM software used as the interface between design software and CNC machines has been successfully replaced in this period by the user-friendly application Hypermill.

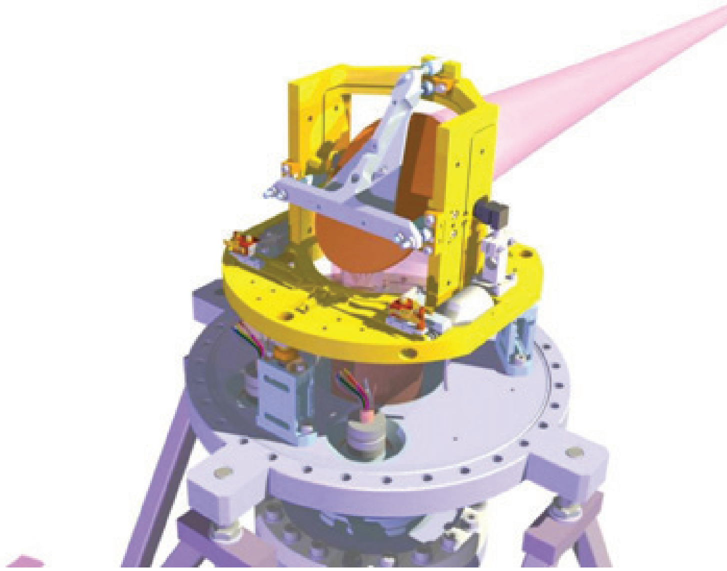


Figure 2.48: Design of an adjustable mirror system for Felix/Felice.

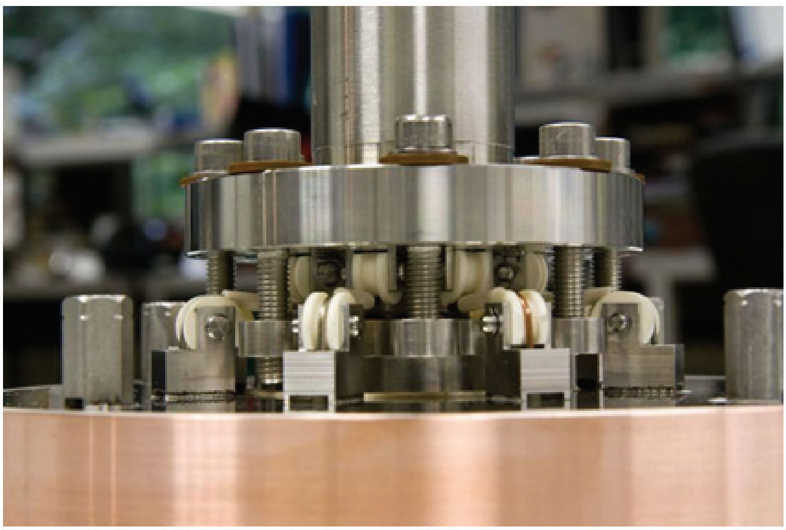


Figure 2.49: Cryogenic sample holder for nSI.

Electronics & Information Technology

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, A.P. Visser, F. Wijnoltz, R.W. Zimmerman.*

The Electronics & Information Technology group is responsible for the electronic equipment for all programmes and projects of the Institute. The equipment is either selected from commercial suppliers or designed and manufactured in-house. This includes a variety of analog, digital, high voltage, and power electronics.

The electrical engineers of the group have been working on a large number of projects, many of them for the FELIX/Felice system. Additionally, support has been given to the research group in Jülich, and in-house groups such as Magnum-PSI, Pilot-PSI, Moldyn and nSI.

The group also designs and implements automated control and data acquisition systems of the various diagnostics and experiments under development in the Institute. The main focus in 2009 was on the control systems for Felice, Magnum-PSI, and the nSI coater (ADC).

Finally, the group is responsible for all the computer and informatics related technology in the Institute: all PCs, network servers, printers, network infrastructure, data storage, backup and restore, etc.

The internal helpdesk process has been redesigned and improved. The network infrastructure has been reconfigured to implement several VLAN's (virtual local area network). This improves security at the network level, which is essential for the security and safety of installations that are controlled through the network. The mailsystem has been upgraded to MS Exchange 2007. All centralised Windows servers have been upgraded to MS Server 2008. Part of the Linux-cluster has been renewed.

More information on the work of the group can be found on the Rijnhuizen public website.

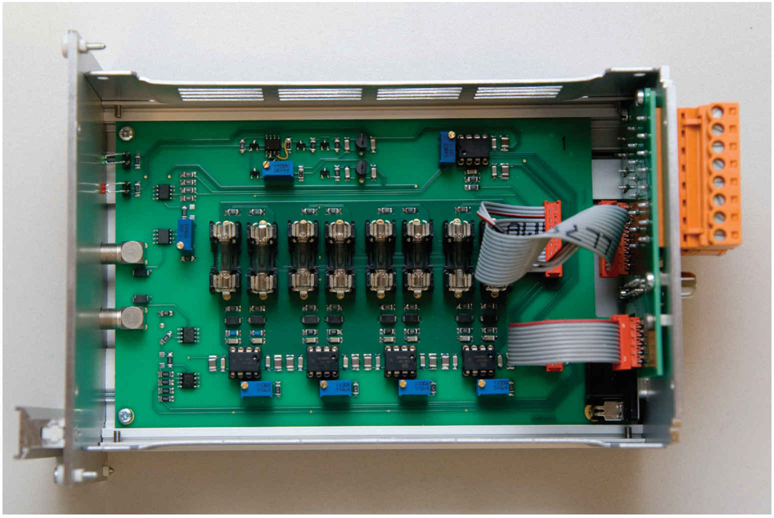


Figure 2.50: a) The Magnum-PSI project needs monitoring for the future plasma target and ring. The monitoring will be done with a PLC. Both the ring and the target will get an individual interface box. This interface will convert the voltage and current of the ring or target to the 10V input of the PLC.

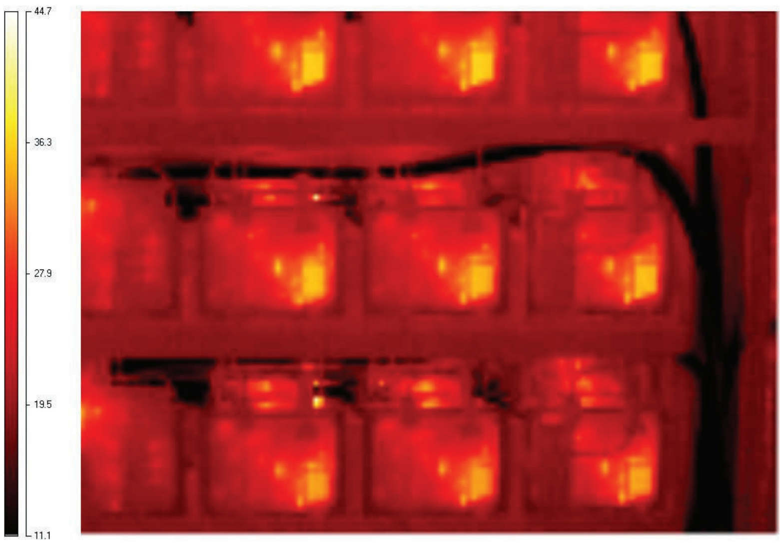


Figure 2.50: b) Heat profile obtained during a test of the Magnum-PSI power supply.

Management Support

Group Leader: *A.A.M. Oomens*

Personnel: *E.M. Khan, P.J.C.E. Reimus, 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 pulication a significant reduction in hard copy journals has been achieved.

Since Rijnhuizen is rather unique in the way in which it has organised 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 organisation 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 to subsidisers. 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 organisation. The goal is to present the implementation plan to the management in the spring of 2010.

Financial Administration

Group Leader:	*J.W.M. Sukking*
Personnel:	*N. Nobbenhuis-Versluis, A. Reinders, M.J. Lubbers*

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 4000 incoming invoices and 2000 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. Starting in 2008 a web-based time registration system is gradually 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 resposibilities 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. The institute aims at having at least 18 graduate students in the research programme at any one time, i.e. an average of 4.5 PhD exams per year. Six members of the staff hold part-time 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, 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 2009 three graduate students received their PhD, and there were 20 PhD students in the institute. In 2009, 12 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 specialised lecture courses at several universities. In 2009, the following courses were given:

Prof. Dr. N.J. Lopes Cardozo, *Physics of Nuclear Fusion as an Energy Source*, Eindhoven University of Technology.
Prof. Dr. N.J. Lopes Cardozo, *Fusion on the Back of an Envelope¸ 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. R. Jaspers, Dr. G.M.D. Hogeweij, *Magnetic confinement in fusion reactors*, Eindhoven University of Technology
Prof. Dr. R. Keppens, *Introduction to (Solar) Plasma-Astrophysics*, contribution to the Plasma Physics-course, Utrecht University.
Prof. Dr. F. Bijkerk, *Fundamentals of Photonics*, University of Twente.
Prof. Dr. F. Bijkerk, *Tutorial XUV Optics*, 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*, contribtion to the Bachelor Honours Programme, 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 2009, a total of 20 undergraduate physics students from universities and trainees were accommodated.

Finally, groups of students are welcome to visit the Institute and receive a tour of the various experiments and other activities. Such visits are mostly concentrated in one Open House day for students, which is organised in conjunction with the Open House day for the general public, but students from universities and other institutions also visit on other occasions.

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. It 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.

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 was developed. The module is in use at several secondary schools and participating students can visit Rijnhuizen to do experiments at the Pilot-PSI experiment. An English translation for international schools in the Netherlands and for wider European use is underway.

Students from various secondary schools visited Rijnhuizen, either individually, or in a school-organised trip. The director of Rijnhuizen, prof. Kleyn, has given two guest lectures at secondary schools, and the fusion road show visited some 30 schools.

The Dutch website www.fusie-energie.nl has proven to be a very effective tool to reach secondary school students, science journalists, and the general public. It provides general information on fusion, and the latest fusion news. In 2009, about 50 visitors to the site requested more information on nuclear fusion. A great deal of these requests came from students preparing a paper on fusion.

Society

Activities directed at politicians

On 15 April 2009, Rijnhuizen organised a visit by the Minister of Education, Culture and Science, Ronald Plasterk, to JET in Culham. For more about this visit, see the appropriate paragraph in the ITER-NL section, Chapter 2.5.

On 18 August 2009, Member of Parliament mrs. Cisca Joldersma visited Rijnhuizen for a series of lectures about the international aspects of fusion and the way it is embedded in European frameworks.

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 37^{th} time. A separate day for students (Thursday October 15^{th}) is organised in addition to the Open House day for the general public (Sunday October 25th). The students day was attended by 282 visitors, while the general open day attracted 960 people.

In 2009, the Fusion Road Show was performed a total of 40 times, for a very large variety of audiences and at varying venues. Apart from traveling across the country performing at different high schools, the show took part in several large-scale events – see section 2.6 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. In 2009, this led to eight articles in major newspapers and magazines, radio interviews about the work on Plasma Surface Interaction and its link to the broader fusion community, and a large number of invited talks for different general audiences.

Figure 3.1: The Fusion Road Show was performed for 3600 Flemish secondary school students and teachers in a series of 6 Shows at Antwerp University.

Industry

Valorisation at Rijnhuizen

Rijnhuizen continuously pursues industrial collaboration possibilities in research projects, in which much attention is given to the transfer of usable scientific results to the public domain and the application as new technology. With his PhD thesis, former Rijnhuizen PhD student Tim Tsarfati has won the FOM Valorisation Chapter award 2009. Several of the research topics are continued as STW projects and in the framework of IPPs.

Valorisation Officer

As a part of the granted "ValoRIGHT" proposal, Tim Tsarfati has now been appointed as Valorisation Officer at Rijnhuizen. He coordinates the policy at the institute in general, and collaborates with the involved scientists on several topics in particular to make the connection to potential end-users. A proposal has been submitted in the framework of the NWO "stimuleringsbijdrage kennisbenutting" for investments in several projects. More elaborately described in chapter 2.8 TFM and 2.9 AXO, these include further research on the realisation of dispersive multilayer optics on a blazed grating (patented), multilayer optics with high reflectivity in a broader, and at a shorter wavelength region (patented). Inquiries are currently made with several companies and possible end-users that could supply essential components or possibly be involved through collaboration projects. Contacts with the AMC are established for the use of soft X-ray multilayer optics in DNA and cancer research.

Figure 3.2: Tim Tsarfati (left) receives the FOM Valorisation chapter award from Tini Hooymans during Physics@FOM. Photo by Bram Saeys.

Valorisation – Fusion and PSI

Another project for which the collaboration possibilities with industry are explored, is the manufacture and testing of potential ITER fusion reactor target materials and mockups at Magnum-PSI, currently being build at Rijnhuizen. Unique in the world, Magnum-PSI will help in the development of fusion reactor materials and provide new experimental research opportunities on plasma-surface interaction. It is part of the TEC collaboration and within the framework of Euratom. Collaboration with the nSI department on surface exposure and analysis will continue to expand, and external parties will be able to apply for use of the facility. Via ITER-NL, further detailed in chapter 2.5 ITER-NL, contacts have been established with over 200 Dutch companies. Several dozens of these are actively involved in the development of essential components for ITER, which will be instrumental to delivering sustainable energy via commercial nuclear fusion. Rijnhuizen is actively involved in the international ITER project via Fusion for Energy (F4E), and contributes the Dutch Industrial Liaison Officer in the person of Toon Verhoeven.

Valorisation – nSI

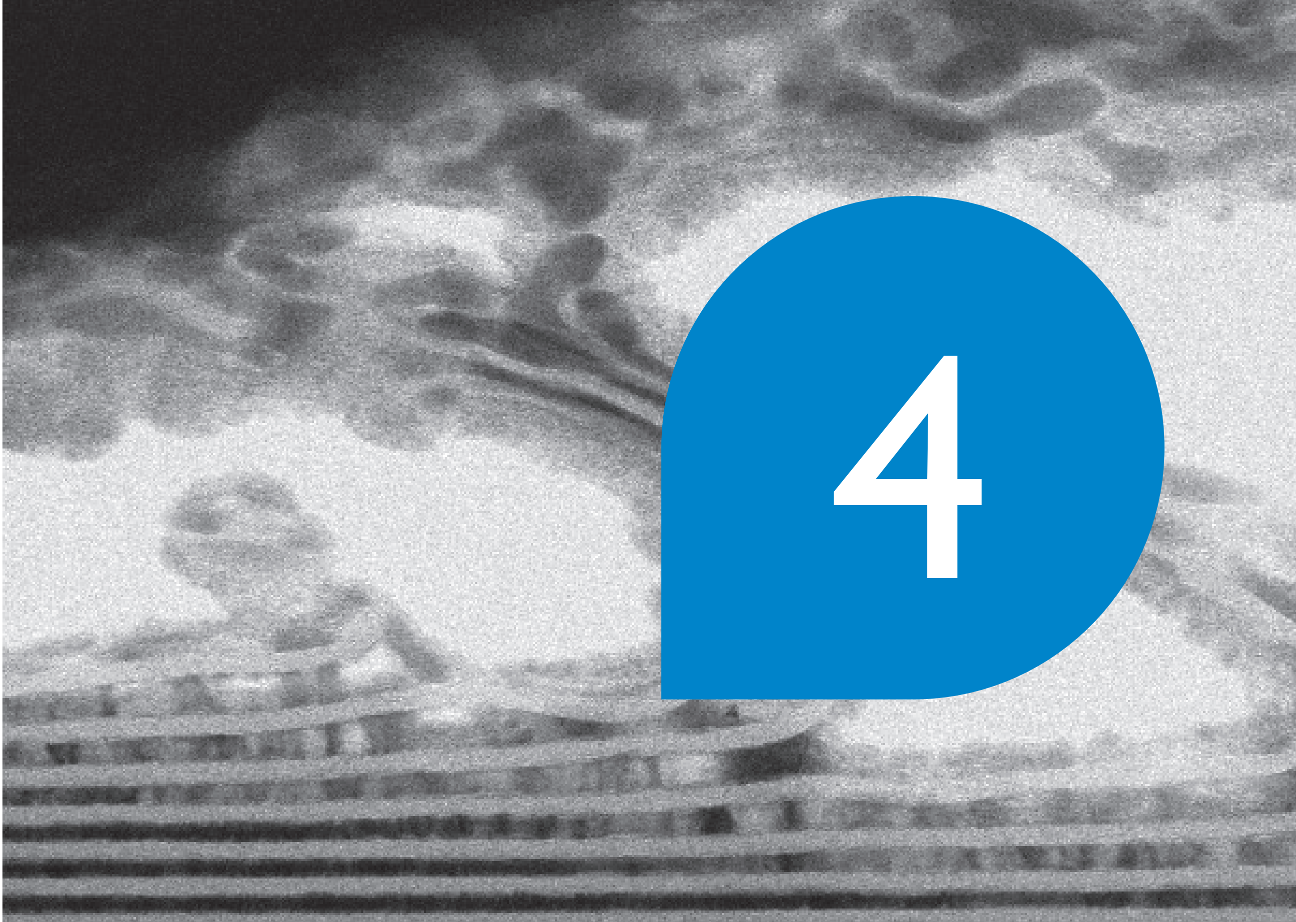
In the new CP3E Industrial Partnership Program (IPP), the nanolayer Surfaces & Interfaces (nSI) department collaborates with both ASML and Carl Zeiss SMT AG. The CP3E program builds further on the know-how at Rijnhuizen that has enabled the special type of multilayer optics at the heart of new generations of photolithography for the future production of integrated circuits. Numerous other projects on the topic of applied surface and material science are carried out as well, among which photo-electrochemical cells for production of hydrogen from sunlight and water. The research on multilayers regularly results in patents and applications, next to scientific publications and PhD degrees.

Valorisation – GUTHz

Contacts with numerous international universities and institutes exist that use the International Free Electron Laser User Facility FELIX to carry out experiments, in particular in the fields of biomedical, -chemical, and -physical research as well as condensed matter physics. With her FOm/v and Athena grant awarded in 2009, Anouk Rijs is expanding her research that exploits FELIX to study processes that lie at the origin of molecular motion in the biomolecular motor F_0F_1-ATPase. Biomolecular motors are increasingly pursued as structures for nanotechnological applications. FELIX is open on a fee basis for proprietary research by industry and explicitly in the frame of an IPP.

Other activities

To further promote the awareness and knowledge of valorisation at Rijnhuizen, one of the initiatives is to organise regular in-house seminars on technology transfer and applied research, given by people from SME, industry and patent bureaus. The seminars, also announced on the central FOM website, provide a forum to establish new contacts and discuss possibilities for valorisation. Centralised subscription of Rijnhuizen PhD students for the FOM valorisation course is facilitated to organise specialised course days on technology transfer in e.g. surface science. The Rijnhuizen website has been expanded with a chapter on the valorisation activities and output.



4

Output

4 Output

4.1 Output on Fusion Physics

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A.W. Kleyn, *Introduction to Fuel cells and new transport approaches*

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M. Beurskens, A.J.H. Donné, N. Hawkes, A. Murari, F. Serra, M. Walsh, H. Weisen, S. Zoletnik, *Diagnostics for ITER ramp-up/down*

Instituto de Astrofísica de Canarias, 5 November 2009, La Laguna, Tenerife, Spain

R. Keppens, *Relativistic hydro and magnetohydrodynamic models for AGN jet propagation and deceleration*

17th European Fusion Physics Workshop, 7-9 December 2009, Velence, Hungary

G.M. Wright, *Change of W morphology under high simultaneous fluxes of D/T, He*

International Workshop on Frontiers in Space and Fusion Energy Sciences, 30 November - 3 December 2009, Tainan, Taiwan

A.J.H. Donné, *Challenges in diagnostics for ITER*

19th International Toki Conference (ITC19) on Advanced Physics in Plasma and Fusion Research, 8-11 December 2009, Toki, Japan

H.K. Park, G. Yun, W. Lee, M.J. Choi, N.C. Luhmann Jr., C.W. Domier, A.J.H. Donne, I. Classen, T. Munsat, *Visualization techniques for MHD and transport physics in tokamaks*

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

Physics@FOM, Veldhoven, 2009, 20&21 January 2009
H.J. de Blank, *Kinetic model of magnetic reconnenction and plasma turbulence* (poster) PA7.02

E. Delabie, R.J.E Jaspers, M.G. von Hellermann, *Measurements of supra-thermal ion populations in fusion plasmas* (poster) PO7.06

D.D.L. De Lazzari, *Stabilization of magnetic island in fusion plasmas by localized heating and current drive* (poster) PO7.10

T.W. Versloot, P.C. de Vries, C. Giroud, M.-D. Hua, I. Jenkins, T. Tala, I. Voitsekhovitch, and JET EFDA Contributors, *Studies into core/edge rotation and momentum confinement in JET plasmas* (poster) PO7.12

R.C. Wieggers, W.J. Goedheer, H.J. de Blank, *Numerical simulations of plasma in contact with surfaces in experiments for fusion*, PO7.13

B. Hennen, M.R. de Baar, E. Westerhof, *Detection and suppression of magnetic islands in fusion plasmas* (poster) PO7.19

W.J. Goedheer, J. Venema, V. Land, *Modeling of complex plasmas under microgravity*, PO4.01

E.D. de Rooij, U. von Toussaint, A.W. Kleyn, W.J. Goedheer, *Fusion-relevant surfaces under extremely high hydrogen fluxes*, PO5.22

5th IAEA TM on ECRH Physics and Technology for Large Fusion Devices, Gandhinagar, India, 18-20 February 2009
E. Westerhof, A.A. Balakin, and N. Bertelli, *Physics aspects limiting the achievable localization of the EC driven current in ITER* (oral)

M.R. de Baar, E. Westerhof, W.A. Bongers, A.J.H. Donné, B.A. Hennen, D.D.L. De Lazzari, P.W.J.M. Nuij, J.W. Oosterbeek, F.C. Schüller, M. Steinbruch, and the TEXTOR-Team, *A tearing mode track-and-suppress system for TEXTOR* (oral)

21st NNV/CPS Symposium Plasma Physics & Radiation Technology, 3 & 4 March, 2009, Lunteren, The Netherlands
D.D.L. De Lazzari and E. Westerhof, *On the merits of heating and current drive for tearing modes stabilization* (oral) O1

J. Biesheuvel, A.E. Shumack, R.S. Al, W.J. Goedheer, A.W. Kleyn, N.J. Lopes Cardozo, H.J. van der Meiden, J. Rapp, D.C. Schram, M.H.J. 't Hoen, W.A.J. Vijvers, J. Westerhout, G. Wright, R. Engeln, G.J. van Rooij, *Laser Induced Fluorescence (LIF) and absorption on the Balmer-α line at high electron densities* (oral) O4

M.H.J. 't Hoen, R.S. Al, A.W. Kleyn, N.J. Lopes Cardozo, H.J. van der Meiden, J. Rapp, D.C. Schram, W.A.J. Vijvers, J. Westerhout, D.G. Whyte, G.M. Wright, A.E. Shumack, G.J. van Rooij, *Plasma acceleration near a negatively biased target in the linear plasma generator Pilot-PSI* (oral) O11

N. Bertelli and E. Westerhof, *Consequences of finite transport on the effectiveness of ECCD for neoclassical tearing mode stabilization in ITER* (poster) A2

J.E. Boom, I.G.J. Classen, W. Suttrop, N.K. Hicks, R.J.E. Jaspers, *Visualisation of edge instabilities with 2D electron cyclotron emission on the ASDEX Upgrade tokamak* (poster) A3

R.C. Wieggers, H.J. de Blank, and W.J. Goedheer, *Numerical simulations of plasma in contact with surfaces in experiments for fusion* (poster) A5

K.S.C. Peerenboom, J. van Dijk, W.J. Goedheer, J.J.A.M. van der Mullen, Modeling the interaction between transonic flow and electromagnetic fields with Plasimo (poster) A23

G.W. Spakman, R.J.E. Jaspers, F.C. Schüller and the TEXTOR-team, *Electron Temperature dynamics due to Sawteeth* (poster) B13

M.A. van den Berg, O.G. Kruijt, S. Brons, J. Scholten, B. de Groot, M.P.A. van Asselen, H.J.N. van Eck, P. Smeets, N.J. Lopes Cardozo, A.W. Kleyn, W.R. Koppers, *The target for the new plasma/wall experiment Magnum-PSI* (poster) B17

J.J. Zielinski, Richard Al, N.J. Lopes Cardozo, H.J. van der Meiden, W. Melissen, G.J. van Rooij, D.C. Schram and J. Rapp, *A pulsed plasma source to investigate transient heat loads on Pilot-PSI* (poster) B25

A.E. Shumack, R.S. Al, J. Biesheuvel, H.J. de Blank, W.J. Goedheer, N.J. Lopes Cardozo, H.J. van der Meiden, J. Rapp, D.C. Schram, M.H.J. 't Hoen, W.A.J. Vijvers, J. Westerhout, G. Wright, G.J. van Rooij, *The influence of electric currents on fusion relevant plasma surface interaction* (poster) B26

4th International Workshop on Stochasticity in Fusion Plasmas, Jülich, Germany, 2-4 March 2009

H. Stoschus, S. Bozhenkov, H. Frerichs, U. Kruezi, D. Schega, O. Schmitz, B. Schweer, G. W. Spakman, B. Unterberg and the TEXTOR Team, *Investigation of plasma edge structures imposed by the rotating Dynamic Ergodic Divertor at the Tokamak TEXTOR in comparison with the magnetic vacuum topology*

O. Schmitz, J.W. Coenen, T.E. Evans, A. Krämer-Flecken, H. Stoschus, E.A. Unterberg, M. Clever, H. Frerichs, A. Greiche, M. Jakubowski, M. Lehnen, G.W. Spakman, D. Reiser, D. Reiter, U. Samm, M. Tokar, B. Unterberg, Y. Xu and the TEXTOR Team, *Particle transport in stochastic boundary experiments at TEXTOR-DED*

NNV Symposium Enegy en Klimaat, KNMI, De Bilt, Netherlands, 12 March 2009

A.P.H. Goede, *Satelliet monitoren van klimaat* (oral)

ITER Scenario Modelling Working Group meeting, Lisbon, Portugal, 23-17 March 2009

G.M.D. Hogeweij, *CRONOS simulations of JET pulses with NBI or RF heated current ramp-up*

Frontiers of Space Astrophysics: Neutron Stars & Gamma Ray Bursts, Recent Developments & Future Directions, March 27 - 29, 2009: Public Outreach Program, Cairo & Alexandria, Egypt

A.J. van Marle, R. Keppens, Z. Meliani, *On the circumstellar medium of GRB or SN progenitors* (poster)

ITPA Meeting on Transport and Confinement, March 31 – April 2, 2009, Naka, Japan

F. Imbeaux, F. Kochl, V. Basiuk, J. Fereira, J. Hobirk, G.M.D. Hogeweij, X. Litaudon, J. Lonnroth, V. Parail, G. Pereverzev, Y. Peysson, G. Saibene, M. Schneider, G. Sips, G. Tardini, I. Voitsekhovitch, *Simulation of current ramp-up and ramp-down*

Belgian Physical Society & Belgian Biophysical Society, General Scientific Meeting 1 April 2009, Hasselt University, Belgium

R. Keppens, *Linear wave propagation in relativistic magnetohydrodynamics* (oral)

P. Delmont, R. Keppens, *An exact Riemann-solver-based solution for regular shock refraction* (oral)

Workshop on the EFDA Diagnostics Work Programme, 1 - 2 April 2009, Garching, Germany
A.J.H. Donné, M. Beurskens, A. Murari, D. Pacella, *The EFDA Diagnostics Work Programme*

BUKS2009, 6-8 April 2009, Leuven, Belgium
Workshop on MHD waves and seismology of the solar atmosphere
R. Keppens, *Linear wave propagation in relativistic magnetohydrodynamics* (poster)

16th Meeting of the ITPA Topical Group on Diagnostics, 20 – 24 April 2009, St. Petersburg, Russia
A.J.H. Donné, M. Beurskens, A. Murari and D. Pacella, *The EFDA Diagnostics Workprogramme: status and future plans*

9th International Reflectometry Workshop (IRW9), Lisbon, Portugal, 4 - 6 May 2009
S. Soldatov, A. Krämer-Flecken, M.Yu. Kantor, B. Unterberg, G. van Oost, D. Reiter, *Reflectometry study on turbulence and ELM dynamics in H-mode plasmas with and without RMP in TEXTOR*

ITPA Div-SOL meeting, 5-8 May 2009, Amsterdam, Netherlands
G.M. Wright, *Simultaneous high fluence He + H plasmas on tungsten in Pilot-PSI*

Meeting on Control for Tokamak Plasmas, 8 May 2009, Nieuwegein, Netherlands
A.J.H. Donné, *Active control of magnetohydrodynamic modes in burning plasmas*

B. Hennen, *Tearing mode control*

G. Witvoet, *Sawtooth control*

12th International Workshop on Plasma-Facing Materials and Components for Fusion Applications, Jülich, Germany, 11-15 May 2009
J. Rapp, A. Litnovsky, L. Marot, G. De Temmerman, J. Westerhout, G.J. van Rooij, J. Westerhout, *Study of the temperature effect on hydrocarbon*

deposition on molybdenum mirrors under ITER-relevant long term plasma operation in Pilot-PSI (oral)

G.J. van Rooij, J. Rapp, R. Dux, A. Kallenbach, A. Manhard, R. Neu, A. Pospieszczyk, S. Potzel, *Tungsten divertor erosion and prompt redeposition in nitrogen seeded discharges measured by W I and W II spectroscopy* (oral)

J. Westerhout, D. Borodin, R.S. Al, S. Brezinsek, M.H.J. ‘t Hoen, A. Kirschner, S. Lisgo, H.J. van der Meiden, V. Philipps, M.J. van de Pol, A.E. Shumack, G. De Temmerman, W.A.J. Vijvers, G.M. Wright, J. Rapp, N.J. Lopes Cardozo, G.J. van Rooij, *Comparison of the chemical erosion of different carbon composites under ITER-relevant plasma conditions* (oral)

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, and J. Rapp, *Carbon film growth and hydrogenic retention of tungsten exposed to CH4-seeded plasmas in Pilot-PSI* (oral)

ITER-NL Remote Handling Workshop, 15 May 2009, Nieuwegein, Netherlands
A.J.H. Donné, *ITER-NL: Innovation for and by ITER*

JET Science Meeting, Culham, UK, 18 May 2009
X. Litaudon, F. Imbeaux, J. Garcia, J. Decker, G. Giruzzi, M. Goniche, I. Jenkins, G.M.D. Hogeweij, D. Moreau, V. Parail, Y. Peysson, M. Schneider, I. Voitsekhovitch, on behalf of ITER Scenario Modelling group, *Integrated modelling of steady-state scenarios*

Kick-off Workshop of the Dutch-Russian Centre-of-Excellence on Fusion Physics and Technology, 25 – 27 May 2009, Driebergen, The Netherlands
J. Rapp, *Plasma Surface Interaction at FOM*

A.J.H. Donné, *The burn control programme at FOM*

G.M.D. Hogeweij, *Transport Physics*

E. Westerhof, *ECW Physics*

W. Bongers, *ECW Technology*

R. Jaspers, *Diagnostics*

36th International Conference on Plasma Science and 23rd Symposium on Fusion Engineering, San Diego, California, USA, 31 May - 5 June 2009
W.A.J. Vijvers, W.J. Goedheer, B. de Groot, W.R. Koppers, A.W. Kleyn, N.J. Lopes Cardozo, H.J. van der Meiden, M.J.van de Pol, G.J. van Rooij, D.C. Schram, A.E. Shumack, J.Westerhout, G.M. Wright, J. Rapp, *High performance plasma source development to simulate ITER divertor conditions* (oral)

Dutch-French collaboration on the ITER project, 29 - 30 June 2009, Nieuwegein, Netherlands
A.J.H. Donné, *The FOM Fusion Programme*

ASTRONUM – 2009, 4th International Conference on Numerical Modeling of Space Plasma Flows, June 29th - July 3rd 2009, Chamonix, France
R. Keppens, Z. Meliani, *Relativistic hydro and magnetohydrodynamic models for AGN jet propagation and deceleration* (oral)

9th Carolus Magnus Summer School on Plasma and Fusion Energy Physics August 31 - September 11, 2009, Herbeumont-sur-Semois, Belgium
H. Stoschus, O. Schmitz, B. Unterberg, G.W. Spakman, H. Frerichs, M.W. Jakubwoski, J.W. Coenen, K.H. Finken, U. Kruezi, U. Samm, D. Schega, B. Schweer and the TEXTOR-Team, *Investigation of electron transport with rotating resonant magnetic perturbations at TEXTOR-DED*

LMCC Workshop on Modeling and Simulation of multi-scale and multi-physics systems, September 8-9, 2009, Leuven, Belgium
R. Keppens, *Multi-scale simulations with MPIAMRVAC* (poster)

Inter-academia, 8th International Conference on Global Research and Education, 14-17 September 2009, Warsaw, Poland
M.L. Solomon, I. Mihaila, V. Anita, C. Costin, G. Popa, H.J van der Meiden, R. Al, G.J. van Rooij, N.J. Lopes Cardozo, J. Rapp, C. Ionita, R. Staerz, R. Schrittwieser, *Measurements of plasma diffusion coefficient in Pilot-PSI device using Katsumata probe*

ITER Scenario Modelling Working Group meeting, Culham, UK, 5-9 October 2009

J. Citrin, J.-F. Artaud, J. Garcia, G.M.D. Hogeweij, F. Imbeaux, *Optimization of ITER Hybrid Scenario performance with the CRONOS suite of codes*

13th European Fusion Theory Conference, 12-15 October 2009, Riga, Latvia

J. Citrin, J.-F. Artaud, J. Garcia, G.M.D. Hogeweij, F. Imbeaux, *ITER hybrid scenario modelling with CRONOS*

21st International Conference on Numerical Simulation of Plasmas 2009, 6-9 October 2009, Lisbon, Portugal

Z. Meliani and R. Keppens, *Decelerating magnetized relativistic two-component jets* (poster)

13th European Fusion Theory Conference, 12-15 October 2009, Riga, Latvia

N. Bertelli, E. Westerhof; *The effect of anomalous radial transport on electron cyclotron current drive for neoclassical tearing mode stabilization in ITER* (poster)

J. Citrin, J. Garcia, G.M.D. Hogeweij, F. Imbeaux, *ITER hybrid scenario modelling with CRONOS* (poster)

R. C. Wieggers, H. J. de Blank, W. J. Goedheer, *B2-Eirene study of the current and velocity distributions in a linear plasma device* (poster)

9th International Symposium on Fusion Technology, 11-16 October 2009, Dalian, China

A.P H Goede, W A Bongers, B S Q Elzendoorn, M R de Baar, *Test strategy for an ECRH&CD microwave launcher for ITER*

J. Rapp, W.R. Koppers, H.J.N. van Eck, G.J. van Rooij, W.J. Goedheer, B. de Groot, R. Al, M. Graswinckel, M. van der Berg, O.G. Kruyt, P. Smeets, H.J. van der Meiden, W. Vijvers, J. Scholten, M.J. van de Pol. S. Brons, 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* (oral)

3rd meeting of the Integrated Operation Scenarios ITPA Topical Group, Frascati, Italy, 20-23 October 2009

J. Citrin, J.-F. Artaud, J. Garcia, G.M.D. Hogeweij, F. Imbeaux, *ITER hybrid scenario modelling with CRONOS*

V. Parail on behalf of ITER Scenario Modelling Working Group: J. Citrin, G. Corrigan, P. da Silva Aresta Belo, R. Dux, J. Ferreira, L. Garzotti, G.M.D. Hogeweij, F. Imbeaux, J. Johner, R. Kemp, F. Kochl, L. Lauro Taroni, X. Litaudon, J. Lonnroth, V. Parail, G. Pereverzev, S. Saarelma, G. Saibene, R. Sartori, M. Schneider, G. Sips, G. Tardini, M. Valovic, I. Voitsekhovitch, S. Wiesen, M. Wischmeier, R. Zagorski, *Progress in ITER modeling in EU*

51st Annual Meeting of the APS Div. of Plasma Physics, 2 - 6 November 2009, Atlanta, GA, USA
B.J. Tobias, C.W. Domier, X. Kong, T. Liang, N.C. Luhmann, Jr., R. Jaspers, A.J.H. Donné, H.K. Park, *Dual-array electron cyclotron emission imaging (ECEI): a new millimeter wave imaging system for electron temperature fluctuation on the DIII-D tokamak*

ITER-NL Industriedag, 5 November 2009, Nieuwegein
A.J.H. Donné, *Status van het ITER-NL programma*

A.G.A. Verhoeven, *Strategie voor ITER procurements*

Frontiers in Diagnostic Technologies, 25-27 November 2009, Frascati, Italy
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*

O. Marchuk, Yu. Ralchenko, W. Biel, R. Janev, E. Delabie and A. Urnov, *Non-statistical populations of magnetic sub-levels of hydrogen beam in a fusion plasma*

12th Workshop on the Exploration of Low Temperature Plasma Physics, November 26-27, 2009, Kerkrade, Netherlands
W.J. Goedheer, J.K. Rath, A.D. Verkerk, Y. Liu, and R.E.I. Schropp, *Optical emission spectroscopy in strongly diluted silane-hydrogen discharges* (poster)

2nd Belgian Mathematical Society - London Mathematical Society Conference, 4 – 5 December 2009, Leuven, Belgium
R. Keppens, *Relativistic hydro and magnetohydrodynamic models for astrophysical jet flows* (oral)

Asia-Pacific Microwave Conference, 7 - 12 December 2009, Singapore
B. Tobias, C.W. Domier, A.J.H. Donné, R.J.E. Jaspers, X. Kong, T. Liang, N. C. Luhmann, Jr., and H.K. Park, *A new and highly flexible dual array electron cyclotron emission imaging diagnostic for DIII-D,* paper 1953

48th IEEE Conference on Decision and Control, December 16-18 2009, Shanghai, P.R. China
G. Witvoet et al, *Control oriented modeling and simulation of the sawtooth instability in nuclear fusion tokamak plasmas*

Seminar

13 January 2009
J. Rapp, *Magnus-PSI and the PSI-E programme at FOM Rijhuizen,* Oak Ridge National Laboratory, USA

12 February 2009
M.Yu. Kantor, *Multi-pass Thomson scattering diagnostic for study of fast events in TEXTOR plasma*, FOM-Institute for plasma Physics Rijnhuizen, Nieuwegein, The Netherlands

19 February 2009
A.W. Kleyn, *Fusie de energiebron van de zon*, Marnix Gymnasium in Rotterdam, gastles

13 March 2009
J. Rapp, *Magnum and the Plasma Surface Interaction Research Programme at FOM Rijnhuizen*, CEA sur la Fusion controlee, Cadarache, St. Paul lez Durance, France

20 March 2009
R.Jaspers, *Fusie: oplossing voor een brandend probleem?!,* Radboud Universiteit Nijmegen

7 April 2009
J. Rapp, *Performance, Safety and Economy of a Fusion Reactor*, TUe, Eindhoven, The Netherlands

7 April 2009
N.J. Lopes Cardozo, *Kernfusie op 'Energy Day'*, TUe, Eindhoven, The Netherlands

15 April 2009
N.J. Lopes Cardozo, *Kernfusie,* bezoek minister Plasterk aan JET, Culham, England

22 April 2009
N.J. Lopes Cardozo, *Studium Generale, lezing kernfusie*, Utrecht, The Netherlands

26 May 2009
N.J. Lopes Cardozo, *FP7 conferentie, lezing kernfusie + discussion panel,* Brussel, Belgium

9 June 2009
A.J.H. Donné, *The FOM Fusion Programme,* Visiting students from Technical University Eindhoven, FOM-Institute for plasma Physics Rijnhuizen, Nieuwegein, The Netherlands

25 June 2009
N.J. Lopes Cardozo, *Fusie-onderzoek, Onderzoeksdag* TU/e, Eindhoven, The Netherlands

29 June 2009
N.J. Lopes Cardozo, *Dinner speech French Economic Mission*. In presence of French Ambassador and Haute Commissaire de l'energie atomique, Utrecht, The Netherlands

22 October 2009
A.J.H. Donné, *High-temperature Plasma Physics at FOM,* Visiting students from Technical University Eindhoven, FOM-Institute for plasma Physics Rijnhuizen, Nieuwegein, The Netherlands

16 November 2009
A.J.H. Donné, *Plasma diagnostics for ITER,* University of Ghent, Belgium
A.J.H. Donné, *New Physics Insights by Diagnostic Advances,* University of Ghent, Belgium

24 November 2009
A.J.H. Donné, *Kernfusie - van fictie naar realiteit,* Symposium 'The Science of Fiction', Delft

10 December 2009
R. Keppens, Modern solar physics: the power of simulations and observations, FOM Rijnhuizen, Nieuwegein

16 December 2009
A.W. Kleyn, *Fusie: de energiebron van de zon*, De Goudse Scholengemeenschap Leo Vromans, gastles

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18 March 2009
A.J.H. Donné, W. Koppers, A. Shumack, Hoe?Zo!, Teleac, *De betekenis van MAGNUM-PSI voor het internationale ITER project*

10 November 2009
R.Jaspers, M. Houkema, H. Groeneveld, Programma Denktank, BNR nieuwsradio

4.2 Output on Nanolayer Surface and Interface Physics

Publications in peer-reviewed scientific journals

S. Bruijn, R.W.E. van de Kruijs, A.E. Yakshin, F. Bijkerk, *The effect of Mo crystallinity on diffusion through the Si-on-Mo interface in EUV multilayer systems*, Defect and Diffusion Forum, Diffusion in Solids and Liquids IV, 283-286 (2009) 657-661

J. Chen, C.J. Lee, E. Louis, F. Bijkerk, R. Kunze, H. Schmidt, D. Schneider, R. Moors, *Characterization of EUV induced carbon films using laser-generated surface acoustic waves*, Diamond and Related Materials, 18 (2009) 768-771

J. Chen, E. Louis, C.J. Lee, H. Wormeester, R. Kunze, H. Schmidt, D. Schneider, R. Moors, W. van Schaik, M. Lubomska and F. Bijkerk, *Detection and characterization of carbon contamination on EUV multilayer mirrors,* Opt. Express, 17 (2009) 16969-16979

D. Göbke, Y. Romanyshyn, S. Guimond, J.M. Sturm, H. Kuhlenbeck, J. Döbler, U. Reinhardt, M.V. Ganduglia-Pirovano, J. Sauer und H.-J. Freund, *Formaldehydbildung auf den Vanadiumoxidoberflächen V_2O_3(0001) und V_2O_5(001): Wie bildet sich der stabile Methoxy-Zwischenzustand?* Angew. Chem. 2009, 121, 3750-3753

D. Göbke, Y. Romanyshyn, S. Guimond, J.M. Sturm, H. Kuhlenbeck, J. Döbler, U. Reinhardt, M.V. Ganduglia-Pirovano, J. Sauer und H.-J. Freund, *Formaldehyde Formation on Vanadium Oxide Surfaces V_2O_3(0001) and V_2O_5(001): How does the Stable Methoxy Intermediate Form?* Angew. Chem. Int. Ed. 2009, 48, 3695-3698

F. Gou, M.A. Gleeson, A.W. Kleyn, R.W.E. van de Kruijs, A.E. Yakshin, F. Bijkerk, *Growth of silicon nitride films by bombarding amorphous silicon with N^+ ions: MD simulation*, Nucl. Instrum. Methods B, 267 (2009) 3245-3248

R.A. Loch, A. Levy, T. Ceccotti, F. Quere, C. Thaury, H. George, F. Bijkerk, K.-J. Boller, P. Martin, *Enhanced ion acceleration with extremely thin foils*, European Physical Journal-Special Topics (175) 133-138 (2009)

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X.D. Lu, Y. Qin, J. Ning, T. Zhou, C.Y. Deng, Ch. Meng, Q. Qiu, Zhang Chuanwu, Yan Ying, Jiang Ming, F. Gou, *Molecular dynamics simulations of CH^+ ions interaction with silicon carbide*, Nucl. Instrum. Methods B, 267 (2009) 3242-3244

B. Nagler et al, among them R. Sobierajski and A.R. Khorsand, *Turning solid aluminium transparent by intense soft X-ray photoionization*, Nature Physics, 5 (2009) 693-696

I. Nedelcu, R.W.E. van de Kruijs, A.E. Yakshin, and F. Bijkerk, *Microstructure of Mo/Si multilayers B_4C diffusion barrier layers*, Appl. Optics, 48 (2009) 155-160

A.J. Nelson, S. Toleikis, H. Chapman, S. Bajt, J. Krzywinski, J. Chalupsky, L. Juha, J. Cihelka, V. Hajkova, L. Vysin, T. Burian, M. Kozlova, R.R. Fäustlin, B. Nagler, S.M. Vinko, T. Whitcher, T. Dzelzainis, O. Renner, K. Saksl, A.R. Khorsand, P.A. Heimann, R. Sobierajski, D. Klinger, M. Jurek, J. Pelka, B. Iwan, J. Andreasson, N. Timneanu, M. Fajardo, J.S. Wark, D. Riley, T. Tschentscher, J. Hajdu, R.W. Lee, *Soft x-ray free electron laser microfocus for exploring matter under extreme conditions*, Opt. Express, 17 (2009) 18271-18278

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R. Stijl, *Inhibiting the amorphous to crystalline phase transition of molybdenum thin films using carbon doping*, Utrecht University

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Damage to VUV, EUV, and X-ray Optics II (XDam2), 20 -23 April 2009, Prague Congress Centre, Prague Czech Republic
J. Cihelka, L. Juha, J. J. Chalupský, F.B. Rosmej, O. Renner, K. Saksl, V. Hájková, L. Vysin, E. Galtier, R. Schott, A.R. Khorsand, D. Riley, T. Dzelzainis, A. nelson, R.W. Lee, P. Heimann, B. Nagler, S. Vinko, J. Wark, T. Whitcher, S. Toleikis, T. Tschentscher, R. Faustlin, H. Wabnitz, S. Bajt, H. Chapman, J. Krzywinski, R. Sobierajski, D. Klinger, M. Jurek, J. Pelka, S. Hau-Riege, R.A. London, J. Kuba, N. Stojanovic, K. Sokolowski-Tinten, A.J. Gleeson, M. Strömer, J. Andreasson, J. Hajdu, and N. Timneanu, *Optical emission spectroscopy of various materials irradiated by soft x-ray free-electron lasers*, Proc. SPIE 7361, 73610P (2009)

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R. Sobierajski, A.R. Khorsand, E. Louis, S.Bruijn, R.W.E. van de Kruijs, E.D. van Hattum, M. Jurek, D. Klinger, K.Sokolowski-Tinten, U.Shymanovich, S. Toleikis, H. Wabnitz, K. Tiedtke, N.Stojanovic, L. Juha, J. Chalupský J. Cihelka, V. Háková,.E.M. Gullikson and F. Bijkerk, *Damage of multilayer optics induced by intense femtosecond XUV pulses*

Invited lectures at conferences and meetings

Damage to VUV, EUV, and X-ray Optics II (XDam2), 20 - 23 April 2009, Prague Congress Centre, Prague Czech Republic
E. Louis, A.R. Khorsand, R. Sobierajski, E.D. van Hattum, T. Tsarfati, F.

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A.W. Kleyn, *Stereodynamics and gas-surface interactions*

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

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M.A. Gleeson, A.W. Kleyn, H. Ueta, *Characterization of plasma beams for surface interaction studies*, PO2.09

S. Bruijn, R.W.E. van de Kruijs, A.E. Yakshin, F. Bijkerk, *Time dependant diffusion in Mo/Si multilayered EUV optics*, PO5.06

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18th International Mass Spectrometry Conference, August 30 – September 04 2009, Bremen, Germany
A.M. Rijs, *Controlled shuttling of neutral and charged rotaxanes*

Gordon Research Conference: Biomolecules in the gas phase (and solution), July 5-10, Tilton, USA
A.M. Rijs, *Charge transfer in neutral peptides: the appearance of salt-bridge structures*

HRSMC symposium, 15th anniversary, November 12-13 2009, Amsterdam, The Netherlands
A.M. Rijs, *Zwitterions without solution?*

Workshop on Cavity Enhanced Spectroscopy, November 2-6, 2009, Leiden, The Netherlands
Giel Berden, *Cavity Ring-Down Spectroscopy*

Third International Workshop on Electrostatic Storage Devices (ESD 2009), June 21-25, 2009, Aarhus, Denmark
J. Oomens, *Infrared spectroscopy of stored molecular ions: application to anions*

EPITOPES meeting, June 10-12, 2009, Orsay, France
J. Oomens, *The thin line between charge-solvation and salt-bridge structures in metal ion peptide complexes*

J.M. Bakker, *Resonant IR ionization of fullerenes and metal clusters in an intracavity FEL experiment*

Asilomar Conference on Mass Spectrometry, 16-20 October 2009, Asilomar Conference Center, Pacific Grove, California, USA
J. Oomens, *Anion spectroscopy with FELIX*

Belgian Doctoral School of Photonics, Oostduinkerke, Belgium, 16-18 March 2009
A.F.G. van der Meer, *FELs: a short tutorial*

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

Physics@FOM, 20&21 January 2009, Veldhoven, Netherlands
A.M. Rijs, *Activation of a molecular switch in the gas phase*, PA09.06

N.Q. Vinh, B. Redlich, A.F.G. van der Meer, C.R. Pidgeon, B.N. Murdin, *Dynamics of levels involved in the terahertz emission fromacceptor centers in Si*, PO1.12

H. Alvaro Galue, J.D. Steill, *Infrared multiple photon dissociation spectroscopy of mass-selected molecular ions*, PO2.11

W.J. van der Zande, R. Jongma, A.F.G. van der Meer, P. Michel, U. Lehnert, R. Wuensch, K. van der Geer, *Design of the Nijmegen Thz-FEL*, PO2.17

J.M. Bakker, B. Redlich, J. Oomens, A.F.G. van der Meer, *Experiments with FELICE: gas-phase molecules and ions in intense IR laser fields*, PO2.37

NWO-CW studiegroep bijeenkomst Spectroscopie & Theorie, 26-27 January 2009, Lunteren, The Netherlands
A.M. Rijs, I. Compagnon, G. Ohanessian, and J. Oomens, *Charge transfer in neutral peptides*

V.J.F. Lapoutre, J. Bakker, J. Oomens, B. Redlich, A.F.G. van der Meer, A. Fielicke, G. von Helden and G. Meijer, *Intra-cavity IR multiple photon absorption experiments with clusters and fullerenes,* (poster)

Symposium for size-selected clusters, 8-13 March 2009 Brand, Austria
J.M. Bakker, V.J.F. Lapoutre, B. Redlich, A. Fielicke, G. von Helden, G. Meijer, J. Oomens, & A.F.G. van der Meer, *Intra-cavity IR multiple photon absorption experiments with metal clusters and fullerenes*

Tulip Summer School, 15-18 April 2009, Noordwijk
V.J.F. Lapoutre, J. Bakker, J. Oomens, B. Redlich, A.F.G. van der Meer, M. Haertelt, A. Fielicke and G. Meijer, *Resonant IR ionization of pure metal and metal carbide clusters* (poster)

American Society for Mass Spectrometry (ASMS) 57th Annual meeting on mass spectrometry and allied topics, May 31 - June 4, 2009, Philadelphia, PA, USA
Jos Oomens, *Deprotonation site determined by IR spectroscopy* (oral)

TUPC84, FEL09, 23rd -28th August 2009, Liverpool, UK
R. Jongma, A. Engels, R. Lof, P. can Dael, W.J. van der Zande, A. van Roij, A. van Vliet, F. Wijnen, G. Wulterkens, V. Zhaunerchyk, A.F.G. van der Meer, U. Lehnert, P. Michel, W. Seidel, R. Wuensch, K. Dunkel, C. Piel, *Realization of the Nijmegen FEL*, (poster)

WEPC80, FEL09, 23rd -28th August 2009, Liverpool, UK
G. Berden, A.F.G. van der Meer, S. Jamison, A. MacLeod, W.A. Gillespie, P.J. Phillips, *Longitudinal electron beam diagnostics via upconversion of THz to visible radiation* (poster)

Clustertreffen 2009, 4-9 October 2009, Herzogenhorn, Schwarzwald, Germany
V.J.F. Lapoutre, J. Bakker, J. Oomens, B. Redlich, A.F.G. van der Meer, M. Haertelt, A. Fielicke and G. Meijer, *Resonant IR ionization of pure metal and metal carbide clusters* (poster)

Annual Dutch meeting on Molecular and Cellular Biophysics, 6 & 7 October 2009, Veldhoven
J. Oomens, B. Redlich, J.D. Steill, N.C. Polfer, M.J. van Stipdonk, *Peptide fragment structures in MS determined by IR spectroscopy*, P.056 (poster)

Invited seminars

January 13, 2009
J. Oomens and B. Redlich, *Direkt reingeschaut: FELIX* (remote video lecture), Universitat Bielefeld, Germany

April 8, 2009
J. Oomens, *Infrared ion spectroscopy: resolving ion structures in MS*, University of Basel, Switzerland

September, 7, 2009
J. Oomens, *Identifying molecular structures in mass spectrometry using free electron laser IR spectroscopy,* SOLEIL Synchrotron, Saint-Aubin, France

October 21, 2009
J. Oomens, *Gas-phase infrared ion spectroscopy at FELIX,* University of California, Riverside, CA, USA

4.4 Output from Collaborators

User Groups of the FELIX facility

This list includes all work both the internal and external user groups of the FELIX facility

Publications in peer-reviewed scientific journals

R.H. Austin, A. Xie, D. Fu, W.W. Warren, B. Redlich, A.F.G. van der Meer, *Tilting the Dutch windmills: probably no long-lived Davydov solitons in proteins,* J. Biol. Phys. 35 (2009) 91-101

M.F. Bush, J. Oomens, and E.R. Williams, *Proton affinity and Zwitterion stability: new results from infrared spectroscopy and theory of cationized lysine and analogues in the gas phase*, J. Phys. Chem. A. 2009, 113, 431-438

X. Chen, L. Yu, J.D. Steill, J. Oomens and N.C. Polfer, *Effect of peptide fragment size on the propensity of cyclization in collision-induced dissociation: oligoglycine* b_2-b_8, J. Am. Chem. Soc., 2009, 131, 18272-18282

S.N. Danilov, B. Wittmann, P. Olbrich, W. Eder, W. Prettl, L.E. Golub, E.V. Beregulin, Z.D. Kvon, N.N. Mikhailov, S.A. Dvoretsky, V.A. Shalygin, N.Q. Vinh, A.F.G. van der Meer, B. Murdin, and S. D. Ganichev, *Fast detector of the ellipticity of infrared and terahertz radiation based on HgTe quantum well structures*, J. Appl. Phys. 105, 013106 (2009)

G. Davies, K.K. Kohli, P. Clauws and N.Q. Vinh, *Decay mechanism of the* v_3 *865* cm^{-1} *vibration of oxygen in crystalline germanium*, Phys. Rev. B 80, 113202 (2009)

M.K. Drayß, D. Blunk, J. Oomens, N. Polfer, C. Schmuck, B. Gao, T. Wyttenbach, M.T. Bowers, M. Schäfer, *Gas-phase structures of solution-phase zwitterions: Charge solvation or salt bridge?*, Int. J. Mass Spectrom. 281 (2009) 97-100

M.K. Drayß, D. Blunk, J. Oomens, B. Gao, T. Wyttenbach, T. Bowers and M. Schäfer, *Systematic study of the structures of potassiated tertiary amino acids: salt bridge structures dominate*, J. Phys. Chem. A, 2009, 113, 9543-9550

R.C. Dunbar, J.D. Steill, N.C. Polfer and J. Oomens, *Dimeric complexes of tryptophan with M^{2+} metal ions,* J. Phys. Chem. A 2009, 113, 845-851

R.C. Dunbar, J.D. Steill, N.C. Polfer, J. Oomens, *Gas-phase infrared spectroscopy of the protonated dipeptides H+PheAla and H+AlaPhe compared to condensed-phase results*, Int. J. Mass Spectrom. 283 (2009) 77-84

R.C. Dunbar, A.C. Hopkinson, J. Oomens, C.-K. Siu, K.W.M. Siu, J.D. Steill, U.H. Verkerk and J. Zhao*, Conformation switching in gas-phase complexes of histidine with alkaline earth ions,* J. Phys. Chem. B 2009 113, 10403-10408

R.C. Dunbar, J.D. Steill, N.C. Polfer, J. Oomens, *Peptide length, steric effects, and ion solvation govern zwitterion stabilization in barium-chelated di- and tripeptides*, J. Phys. Chem. B, 113 (2009) 10552-10554

A. Fielicke, P. Gruene, G. Meijer, D.M. Rayner, *The adsorption of CO on transition metal clusters: A case study of cluster surface chemistry*, Surf. Sci. 603, 1427-1433

A. Fielicke, J.T. Lyon, M. Haertelt, G. Meijer, P. Claes, J. de Haeck, and P. Lievens, *Vibrational spectroscopy of neutral silicon clusters via far-IR-VUV two color ionization,* J. Chem. Phys. 131, 171105 (2009)

R. Gehrke, P. Gruene, A. Fielicke, G. Meijer, and K. Reuter, *Nature of Ar bonding to small* Co^{+}_{n} *clusters and its effect on the structure determination by far-infrared absorption spectroscopy,* J. Chem. Phys. 130, 034306 (2009)

D.J. Goebbert, T. Wende, R. Bergmann, G. Meijer, and K.R. Asmis, *Messenger-Tagging Electrosprayed Ions: Vibrational Spectroscopy of Suberate Dianions*, J. Phys. Chem. A 113, 5874-5880 (2009

D.J. Goebbert, E. Garand, T. Wende, R. Bergmann, G. Meijer, K.R. Asmis, and D.M. Neumark, *Infrared Spectroscopy of the Microhydrated Nitrate Ions* $NO_3^-(H_2O)_{1-6}$, J. Phys. Chem. A 113, 7584-7592 (2009)

R.P. Green, A. Tredicucci, N.Q. Vinh, B. Murdin, C. Pidgeon, H.E. Beere, D.A. Ritchie, *Gain recovery dynamics of a terahertz quantum cascade laser*, Phys. Rev. B 80, 075303 (2009)

G.S. Groenewold, C.M Leavitt, R.P. Dain, J. Oomens, J.D. Steill and M.J. van Stipdonk, Infrared spectrum of potassium-cationized triethylphosphate generated using tandem mass spectrometry and infrared multiple

photon dissociation, Rapid Commun. Mass Spectrom. 23 (2009) 2706–2710

A.L. Heaton, V.N. Bowman, J. Oomens, J.D. Steill and P.B. Armentrout, *Infrared multiple photon dissociation spectroscopy of cationized asparagine: effects of metal cation size on gas-phase conformation*, J. Phys. Chem. A, 2009, 113, 5519-5530

H. Knorke, J. Langer, J. Oomens, O. Dopfer, *Infrared spectra of isolated protonated polycyclic aromatic hydrocarbon molecules*, ApJ 706 (2009) L66-L70

K.K. Kohli, N.Q. Vinh, P. Clauws, G. Davies, *Strange lifetimes of the vibrations of interstitial oxygen in SiGe alloys*, Physica B: Condensed Matter, 404 (2009) 4689-4692

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J.T. Lyon, P. Gruene, A. Fielicke, G. Meijer, E. Janssens, P. Claes, and P. Lievens, *Structure of Silicon Cluster Cations in the Gas Phase,* J. Am. Chem. Soc. 131, 115-1121 (2009)

J.T. Lyon, P. Gruene, A. Fielicke, G. Meijer, and D.M. Rayner, *Probing C-O bond activation on gas-phase transition metal clusters: Infrared multiple photon dissociation spectroscopy of Fe, Ru, Re, and W cluster CO complexes,* J. Chem. Phys. 131, 184706 (2009)

B. Martínez-Haya, P. Hurtado, A.R. Hortal, J.D. Steill, J. Oomens and P.J. Merkling, *Spectroscopic investigation of the gas-phase conformations of 15-crown-5 ether complexes with* K^+, J. Phys. Chem. A, 2009, 113, 7748-7752

S. Minissale, N.Q. Vinh, A.F.G. van der Meer, M.S. Bresler, and T. Gregorkiewicz, *Terahertz electromagnetic transitions observed within the* $^4I_{15/2}$ *ground multiplet of* Er^{3+} *ions in Si*, Phys. Rev. B 79, 115324 (2009)

S. Minissale, N.Q. Vinh, T. Gregorkiewicz, *On relation between 1.5 μm Er-related emission and 9 μm vibrational modes of oxygen in silicon*, Physica E 41 (2009) 1052-1054

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J. Oomens, J.D. Steill and B, Redlich, *Gas-phase IR spectroscopy of deprotonated amino acids*, J. Am. Chem. Soc., 2009, 131, 4310-4319

K. Pagel, P. Kupser, F. Bierau, N.C. Polfer, J.D. Steill, J. Oomens, G. Meijer, B. Koksch, G. von Helden, *Gas-phase IR spectra of intact α-helical coiled coil protein complexes*, Int. J. Mass Spectrom. 283 (2009) 161-168

S.G. Pavlov, U.Böttger, J.N. Hovenier, N.V. Abrosimov, H. Riemann, R.Kh. Zhukavin, V.N. Shastin, B. Redlich, A.F.G. van der Meer, and H.-W. Hübers, *Stimulated terahertz emission due to electronic Raman scattering in silicon,* Appl. Phys. Lett. 94, 171112 (2009)

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N.C. Polfer, J. Oomens, *Vibrational spectroscopy of bare and solvated ionic complexes of biological relevance*, Mass Spectrom. Rev. 28 (2009) 468-494

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P. Rauter, T. Fromherz, N.Q. Vinh, B.N. Murdin,G. Mussler, D. Grützmacher, and G. Bauer, *Continuous voltage tunability of intersubband relaxation times in coupled SiGe quantum well structures using ultrafast spectroscopy*, Phys. Rev. Lett. 102**,** 147401 (2009)

A.M. Rijs, I. Compagnon, J. Oomens, J.S. Hannam, D.A. Leigh and W.J. Buma, *Stiff, and sticky in the right places: binding interactions in isolated mechanically interlocked molecules probed by mid-infrared spectroscopy*, J. Am. Chem. Soc., 131, 2428-2429

B. Steffen, V. Arsov, G. Berden, W.A. Gillespie, S.P. Jamison, A.M. MacLeod, A.F.G. van der Meer, P.J. Phillips, H. Schlarb, B. Schmidt, P. Schmueser, *Electro-optic time profile monitors for femtosecond electron bunches at the soft x-ray free-electron laser FLASH,* Physical Review Special Topics - Accelerators and Beams, 12, 032802 (2009)

J.D. Steill and J. Oomens, *Action spectroscopy of gas-phase carboxylate anions by multiple photon IR electron detachment/attachment*, J. Phys. Chem. A, 2009, 113, 4941-4946

J.D. Steill and J. Oomens, *Gas-phase deprotonation of p-hydroxybenzoic acid investigated by IR spectroscopy: Solution-phase stucture is retained upon ESI*, J. Am. Chem. Soc. 2009, 131, 13570-13571

M. Vala, J. Szczepanski, R. Dunbar, J. Oomens, J.D. Steill, *Infrared multiphoton dissociation spectrum of isolated protonated 1-azapyrene*, Chemical Physics Letters, 473 (2009) 43-48

M. Vala, J. Szczepanski, J. Oomens and J.D. Steill, *H_2 ejection from polycyclic Aromatic hydrocarbons: infrared multiphoton dissociation study of protonated 1,2-dihydronaphthalene*, J. Am. Chem. Soc., 2009, 131, 5784-5791

N.Q. Vinh, N.N. Ha, T. Gregorkiewicz, *Photonic properties of Er-doped crystalline silicon*, Proc. IEEE, 97 (2009) 1269-1283

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Thesis Work

Miriam Katharina Drayß**,** *Multidimensionale Untersuchungen von Ionenstrukturen in der Gasphase,* Universität zu Köln, Mai 2009

Philipp Grüne, *Structure and Reactivity of Metal and Semiconductor Clusters in the Gas Phase,* Technische Universität Berlin, Februar 2009

Salvatore Minissale, *Optical Properties of Er-doped Si-based media,* Universiteit van Amsterdam, March 2009.

4.5 Output on education, training, outreach and public information

Developed material

A. Vrouwe, *Hittebarrière – Vijftig jaar plasmafysica bij FOM-Instituut Rijnhuizen*, produced to celebrate the institute's 50 year anniversary.

Activities at Rijnhuizen

Student Open House Day, October 15th, 2009

General Open House Day, October 25th, 2009

The Fusion Road Show was presented 8 times at Rijnhuizen, for visiting students and other groups including two performances during the General Open House Day.

Rijnhuizen organised 13 guided tours of the institute for visiting groups and dignitaries, such as Member of Parliament mrs. Cisca Joldersma.

8 secondary school students and 10 university students visited Rijnhuizen individually in 2009 to conduct interviews on fusion research.

A. Rijs, *Is laserlicht altijd gevaarlijk?*, lecture aimed at primary school students and performed twice during the General Open House Day.

Via the website www.fusie-energie.nl, which welcomes some 300 visitors a day, Rijnhuizen received about 50 requests for information, most of which from secondary school students writing a paper ('profielwerkstuk') on fusion.

Two groups of 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 30 times outside of Rijnhuizen, including its presence at the European Committee Open Day in Brussels, an event visited by over 70.000 people, at the EurekaCup applied science contest kickoff and finale events, at the opening of the Delft University Energy Club and at the Fusion Days organised by Antwerp University (Belgium) for over 3600 Belgian secondary school students and teachers.

Other presentations directed at a more or less general public or at secondary school students are mentioned below:

N.J. Lopes Cardozo, *The Seven Scientific and Technological Challenges on the Road to Commercial Fusion Power*, Presentation at the TU/e Holst Symposium, Eindhoven.

N.J. Lopes Cardozo, *ITER and Fusion Energy*, Presentation at the TU/e Energy Days, Eindhoven.

N.J. Lopes Cardozo, *ITER and Fusion Energy*, Presentation at the TU/e Studium Generale, Eindhoven.

N.J. Lopes Cardozo, *Fusion Energy*, Presentation at the opening of the TU Delft's Delft Energy Club, Delft

A.J.H. Donné, *Fusie, van fictie naar realiteit*, Presentation at the Science of Fiction Symposium, Delft

J. Rapp, *Performance, safety and economy of a Fusion Reactor*, Presentation at the TU/e Energy Days, Eindhoven.

G. de Vries, *Energiecrisis – een rol voor kernfusie?*, Presentation for the Soroptimisten, Deventer

G. de Vries, *Fusie, energie voor de toekomst*, Presentation for Politieke Scholing Geldermalsen

G. de Vries, *Staat van Fusie*, Presentation for the E.on energy company, Rotterdam

External Publications and Interviews

Around eight articles about nuclear fusion appeared in the largest Dutch newspapers. The majority of articles featured Rijnhuizen as the Dutch centre for fusion research, following news about the international ITER-project, or were instigated by press releases about the ITER-NL economic mission to France. At least sixteen more articles were published in newspapers and in science and technology magazines. Four columns about the energy crisis were published in an energy-focused magazine and radio programmes such as Hoe?Zo! featured work on Magnum- and Pilot-PSI after the first plasma milestone in June. BNR News Radio featured the ITER-NL project in an hour-long interview in November.

N.J. Lopes Cardozo, interview in NRC, Margriet vd Heijden, "Interviewgesprek met directeuren – trekt EU grote faciliteiten naar zich toe?" (8 February 2009)

N.J. Lopes Cardozo, interview in Volkskrant, Peter van Ammelrooij (29 May 2009)

N.J. Lopes Cardozo, interview in Eindhovens dagblad, Patrick Wiercx (May 2009)

N.J. Lopes Cardozo, interview in Cursor, Ingrid Magilsen about Energy (Energiedag) and new group (May 2009)

N.J. Lopes Cardozo, interview by telephone Margriet vd Heijden, NRC, about ITER scenario 1.(3 June 2009) and published in NRC (4 June 2009)

N.J. Lopes Cardozo, interview in Kijk, Patrick Marx (12 June 2009)

N.J. Lopes Cardozo, interview in Ingenieur, Erwin vd Brink TU/e (15 June 2009)

N.J. Lopes Cardozo, interview in Energie+ (Column) (2009)

N.J. Lopes Cardozo, interview in KRO/Trouw, Raymond van de Klundert about science and religion (18 June 2009)

N.J. Lopes Cardozo, Lecture at Studium Generale Eindhoven, 300 p. (2 September 2009)

N.J. Lopes Cardozo, interview in DELTA, Van Dijk (about lecture) (4 September 2009)

N.J. Lopes Cardozo, interview in Cursor about Fusenet (9 September 2009)

N.J. Lopes Cardozo, interview in Matrix about Fusenet (9 September 2009)

N.J. Lopes Cardozo, presentation at Holst symposium Eindhoven (9 December 2009)

N.J. Lopes Cardozo, presentation at Batteries Low, Utwente (9 December 2009)

N.J. Lopes Cardozo, interview in Interview, Theunissen, Interview for brochure TU/e (21 December 2009)

5

Appendix

5 Appendix

5.1 Funded projects

Fusion Physics Department

Title	Source of Funding
Manipulation of mesoscale structures in hot, magnetized plasmas	FOM (FP-74)
PSI-lab, an integrated laboratory on plasma-surface interaction	FOM (FP-75)
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
PSI-Lab, an integrated laboratory on plasma-surface interaction	NWO-Groot
The role of turbulence and electric fields INTAS in the formation of transport barriers and the establishment of improved confinement in tokamak plasmas through inter-machine comparisons	INTAS
European Fusion Training Scheme	EODI (042884)
European Fusion Training Scheme	ECTECH

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

Nanolayer surface and interface Physics Department

Title	Source of Funding
eXtreme UV Multilayer Optics (IPP-XMO) (SoW5)	Carl Zeiss SMT AG, FOM Industrial Partnership Programme I-10, SenterNovem (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 (project 10302), Carl Zeiss SMT AG
Multilayer optics for 4th generation XUV sources	FOM-Pilot project
Laser Wakefield Accelerators	FOM (FP-55)

Title	Source of Funding
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 AG
In situ monitoring of contamination layers on EUV optics at Angstrom resolution, 'ISitCLEAR'	M2i, ASML
Photolytic salt formation at oxide surfaces	M2i, ASML
Dynamic Scaling of Ion-Etched Silicon Surfaces	ESRF, Grenoble
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 AG
Development of Extreme UV multilayer coating technology towards production tool optics (SoW7)	Carl Zeiss SMT AG
Controlling photon and plasma induced processes at EUV optical surfaces 'CP3E'	FOM Industrial Partnership Programme (FP I-23), ASML, Carl Zeiss SMT AG
Valorisation of research results Rijnhuizen, 'ValoRIGHT	Valorisation Funding FOM

GUTHz Department

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 conformational dynamics	NWO-Middelgroot
A US - Dutch mass spectrometry consortium for advanced modelling and biological structure and imaging applications	NSF-PIRE
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	23.4
PhD-students	25
temporary (postdoc's etc.)	12.5

Technical staff

permanent	29.2
temporary	7.1

Support staff

permanent	46.4
temporary	6.4
Total	**150**

Output

Scientific Publications	135
Invited Lectures	42
Other Scientific Products	256
Other non-scientific output	42
PhD Theses	4
Master Theses	3
Bachelor Theses	5
Patents	3

Budget (k€)

Personnel	7366
Consumables	6183
Investments	200
Total	**13749**

5.3 Advisory committees

Scientific Advisory Committee

Prof. Dr. G. van Middelkoop (chairman)
NIKHEF, Amsterdam, The Netherlands

Prof. Dr. H.H. Bolt
Forschungszentrum Juelich GmbH, Germany

Prof. Dr. M.S. de Vries
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Prof. Dr. J. Jacquinot
Centre de Recherche Nucleaire de Cadarache, France

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ASML, Veldhoven, The Netherlands

Dr. B. Lipschultz
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Per December 2009:

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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

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AMOLF / University of Amsterdam, Amsterdam, The Netherlands

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Radboud University, Nijmegen, The Netherlands

Colophon

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Vocking in Vorm, Nieuwegein

Printing
Drukkerij Ten Brink, Meppel

On the Cover:
Visible light emitted from a magnetron discharge plasma, as employed for the sputter deposition of thin films (nSI department).

Between the Chapters:
Electron microscopy pictures of a damaged part of a MoN/SiN multilayer mirror after exposure to XUV radiation at extremely high intensity. This research, carried out by nSI staff, is aimed at unraveling the physical damage mechanisms in order to determine the feasibility of these mirrors for XUV free electron lasers, like the Hamburg FLASH facility.