MEASURING A FUSION PLASMA WITH CAMERAS

One of the biggest challenges of operating a nuclear-fusion reactor is preventing the scorching heat from damaging the reactor wall. A Swiss-Dutch team is heavily engaged in investigating solutions to this challenge. They use camera images to measure how the reactor exhaust is behaving, and use this information to keep the reactor wall alive.

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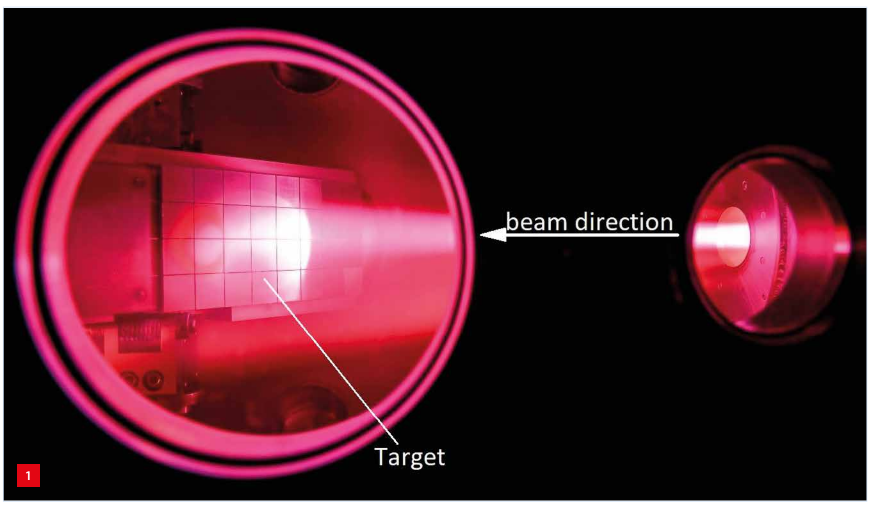
Introduction

When two hydrogen isotopes are fused together, a huge amount of energy is released. In order to harvest this energy, a nuclear-fusion reactor design called a tokamak has been under heavy research for the last 70 years. In such a reactor, hydrogen isotopes are magnetically confined in the form of a plasma, creating the right conditions for their fusion.

Unlike nuclear fission, fusion produces only short-lived radioactive products, making it a very safe and reliable energy source. However, important steps still need to be taken in this 21st century to achieve commercial fusion. Next to creating and sustaining energy-producing fusion reactions, an important challenge is the exhaust of the resulting helium byproduct and the energy it contains.

At DIFFER, we research and develop the technology to analyse and safely control this exhaust. For example, DIFFER hosts one of the largest linear plasma generators in the world, called MAGNUM-PSI [1]. This machine is used to test wall materials for future fusion reactors, such as ITER, which is presently being built in France. Figure 1 shows a snapshot of wall material exposure to a hot plasma during an experiment at DIFFER.



A look inside the linear plasma generator MAGNUM-PSI. The highly energetic plasma beam enters the chamber from the right, and hits the wall material (or simply target) at the left. The target can be exposed to different conditions and loading, resulting in deformation, melting and recrystallisation.

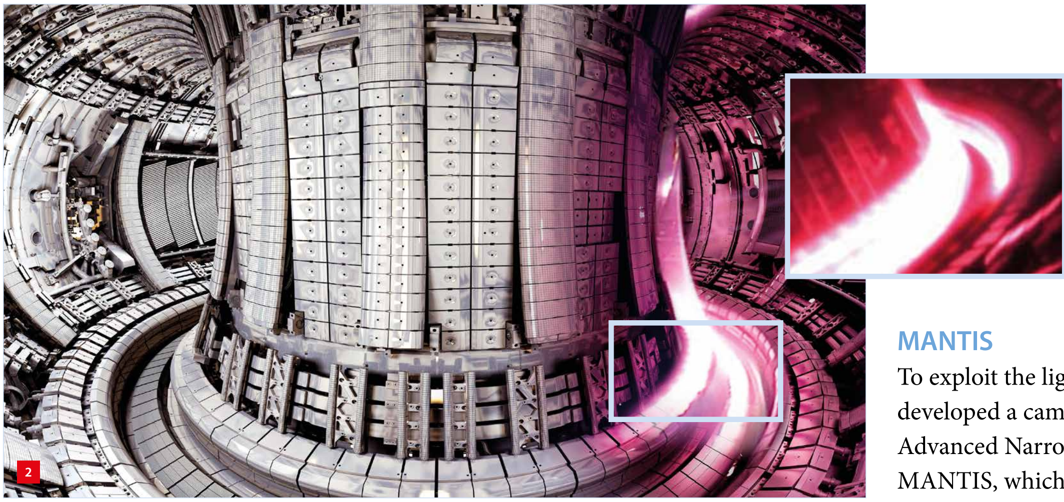
Moreover, DIFFER develops diagnostics for fusion reactors, to which the most recent addition is a tangential camera system. This camera system is called the Multispectral Advanced Narrowband Tokamak Imaging System or MANTIS [2] [3]. It is used for the analysis and feedback control of the plasma exhaust, exploiting the specific light emitted by the reactor exhaust plasma. So, why is this reactor exhaust so challenging?

The exhaust of a fusion reactor

The reaction of fusing the hydrogen isotopes deuterium and tritium (the reactor fuel) produces a neutron and a helium particle. The neutron is not charged, and will escape the magnetic fields used to confine the fuel, and hit the reactor wall. The main wall of the reactor is sufficiently protected by water cooling.

However, the helium byproduct and impurities contained in the core of the reactor are charged, and will therefore not escape the magnetic fields. But they do need to be exhausted in order to avoid choking the fusion process by diluting the plasma with fuel that has already reacted. Therefore, the magnetic configuration is designed to allow these burning products to be exhausted to a specific wall region on the bottom of the reactor. This specific wall region is known as the divertor, and must sustain a plasma flow containing helium particles.

The helium particles carry 1/5th of the energy produced in a fusion reaction, and must be safely exhausted. This means their energy must be dissipated to prevent damage of the divertor region. Two (or more) so-called 'divertor legs' are formed where the plasma is cooled before interacting with the wall. A continuous injection of neutral gas is required to control the level of mitigation in the divertor legs to protect the divertor area. Actively adjusting this injection (actuation) in real-time is done by a control system, which



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The Joint European Torus (JET) is the largest tokamak (type of fusion reactor) in the world, located in Oxfordshire, UK, with a plasma radius of 2.96 m, a volume of 79 m^3 and a magnetic field strength of 3.45 T [4]. On the left, the torus without plasma, and on the right, with plasma (pink haze). The zoom-in shows specifically the divertor region where the emitted light is brightest. (JET Image: EUROfusion)

requires millisecond-range observation of the relevant mitigation processes. Here is where light emitted by the plasma plays a key role.

Light emitted by the plasma

Inside the JET reactor (Figure 2), a fusion plasma emits light, in this case depicted in pink. This light is brightest near the wall elements at the bottom, in the vicinity of the divertor. The reason is that plasma only emits light at relatively low temperatures and such conditions are only attained at the periphery near the wall. This light is most intense near the divertor, where a lot of cooling plasma-wall interaction is taking place, making it an ideal diagnostic to analyse what is happening with the exhaust.

The idea is as follows: in the analysis of stars, their emitted light is used to determine age, distance and composition. For the plasma near the divertor, it is possible to use the intensity and spectral distribution of its emission to estimate temperature, density and reactions taking place. As most of the particles in the exhaust are hydrogen, in particular we analyse the relevant spectral content originating from the hydrogen atoms. This is known as Balmer lines, which originate from the hydrogen-plasma interaction, reflecting the (electron) temperature, density and formation of molecules when atoms and electrons cool down.

To perform this kind of analysis, we also need information from other atoms, such as helium. Figure 3 shows a few of these spectral lines, which correspond to different lines (wavelengths) in the visible spectrum, such as red (656.279 nm), ultraviolet (397.0075 nm), blue (434.0472 nm), aqua (486.135 nm) and violet (410.1734 nm). Similar spectral lines for helium can be identified, as Figure 3 shows. By now using filters, we can isolate certain atomic processes and analyse the edge plasma.

MANTIS

To exploit the light emitted from the plasma, we have developed a camera-based diagnostic: the Multispectral Advanced Narrowband Tokamak Imaging System, or MANTIS, which name is inspired by the high visual acuity and high resolution the eyes of mantis insects can achieve necessary to examine potential prey and hunt.

The main goal of this diagnostic is to analyse the exhaust plasma in the divertor with ten cameras (Figure 4), each looking at a specific emission line. This image is transformed to a 2D cross-section employing tomographic inversion techniques, and then analysed to interpret the physical quantities. These quantities are for example the electron temperature and density, but also more complex quantities, such as particle sources and sinks due to several atomic and plasma-molecule interactions.

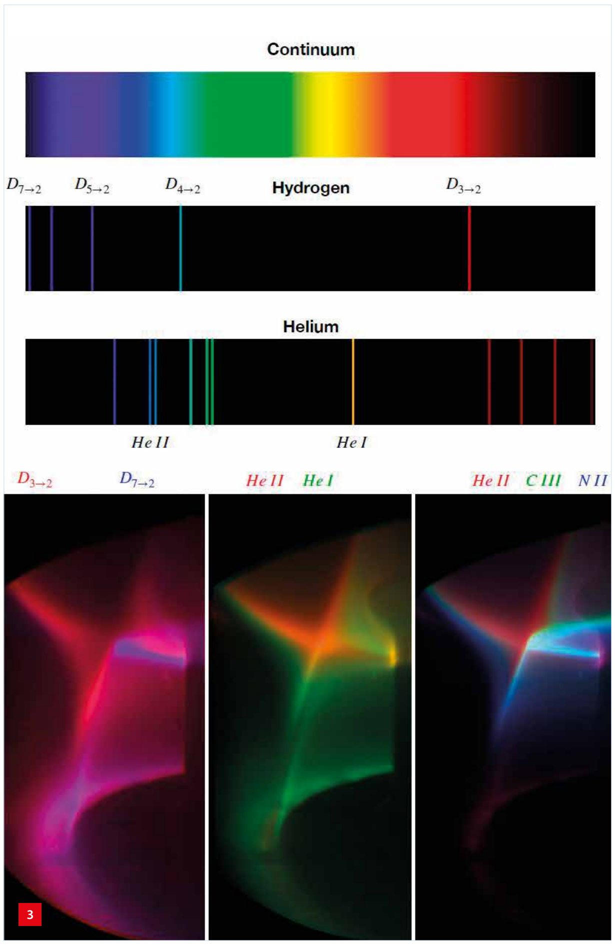
The design, construction and calibration of such a system presents considerable precision engineering challenges. First, the concave mirrors reflecting incoming light must be held in machined slots with micrometer precision to maintain the image quality. The light is reflected to the other side (see Figure 5), where ultra-narrow bandpass interference filters are housed in 3-axis Thorlabs kinematic mounts allowing for adjustments in pitch and yaw, as well as forward and backward. These filters are a crucial part of the system and determine the final image quality.

The filters pass a nanometer-range-wide spectral band of light to the cameras, while reflecting the remaining light to the next channel of the system. The quality of the reflection is just as important as the quality of the transmission; when unfolded, the optical path the light needs to travel through the system is approximately 15 meters long. Any optical aberrations the filters introduce will accumulate through the remaining reflections and deteriorate the image quality.

In order to reach the required specifications, each filter must provide an exceptionally good reflection, with a surface flatness of approximately 80 nm peak-to-valley variation per inch. Normally this is achieved by splitting the spectrally active coatings forming the filter's bandpass cavity between the front and back surfaces, balancing the coating-induced stresses.

However, this standard solution cannot be used, as it causes reflections on multiple surfaces of the filter, ruining the image with a reflection resembling that of a double-glazed window. Instead, a low-stress coating process was introduced, while the resulting stresses were countered with a thicker filter substrate and an extra-thick anti-reflective coating at the back side to balance the remaining stresses. This ensures both a good image quality and a good reflective quality to reflect the light to the next filter.

Apart from maintaining the image quality, the filters must also be easily interchangeable without misaligning the channels downstream in the cavity (Figure 4). To ensure that realignment is not needed when changing a filter, the kinematic mounts were modified with a custom filter-holder mechanism with a spring-loaded retention system to ensure constant contact with the reference surface. As a result, an exchange of the first filter can be done in seconds



Example of line filtering from the electromagnetic spectrum.
Top: The continuum of electromagnetic light, ranging from ultraviolet (left) to infrared (right).
Middle: Indication of emission lines from hydrogen and helium, each located at a discrete point along the continuum. The MANTIS filters only allow light near these spectral lines to pass, and reflect all other light.
Bottom: An overlayed camera image taken of a plasma inside the TCV (tokamak à configuration variable) at EPFL, depicting scaled emission line intensities encoded into red, green and blue channels. (Figures adapted from [4])

and will result in a displacement of the multiply reflected beam by only a millimeter at the end of the cavity, which is well within the requirements.

This development is part of a European Horizon project and was done together with the Swiss Plasma Center of EPFL, and MIT. The resulting MANTIS diagnostic is heavily used for the TCV tokamak at EPFL [5]. It can process incoming images to estimate the plasma state up to 1,000 frames per second with a feature-tracking algorithm (Figure 6), which next to physics studies is an important application of the real-time exhaust control system [6] [7]. Below, we give some insight into this system.

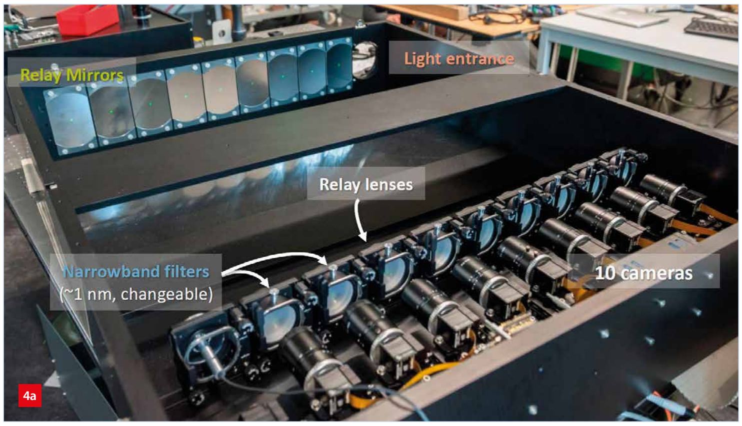
Real-time plasma exhaust control

The expected heat load impacting the divertor targets is approximately 1/5th of the power generation by fusion reactions in the core plasma. To protect the divertor area active local mitigation of this incoming heat load is required. In order to control the level of mitigation local cooling of the plasma is achieved by injecting neutral gas into the divertor area. This neutral gas interacts with the plasma, taking away momentum and energy, thus mitigating the load being endured by the divertor area.

The question now is: how much neutral gas should be injected to protect the divertor? With too much gas injection, the fusion-generating core plasma will cool down as well, stopping the fusion reactions. However, too little injection will cause the divertor target to melt away, as the plasma will hit the wall with too much energy and momentum. This trade-off can be perfectly controlled by a real-time control system. Such a system consists of a sensor and an actuator linked to the process to be controlled. A control loop is created by means of feedback from measurements, in this case obtained from the MANTIS system. The final performance of the control algorithm is a trade-off between tracking behaviour (is the desired reference reached?) and robustness (will the controller continue to operate in different conditions?).

In our application, one of the MANTIS cameras looks at the light of twice-ionised carbon ions, C^{2+}, inherently present in the TCV due to its carbon wall. This emission is measured by filtering the spectral line CIII (carbon III), which provides insight into the status of the plasma: the amount of light is strongly dependent on the local temperature.

The decrease of light in a certain direction can be used to make a temperature estimate. Specifically, the 50% decrease from a hot region to a cold region corresponds to a temperature of around 80,000 °C, which is significantly colder than the core plasma. This can be seen as the 'cold front'. The position of this front gives an idea of the

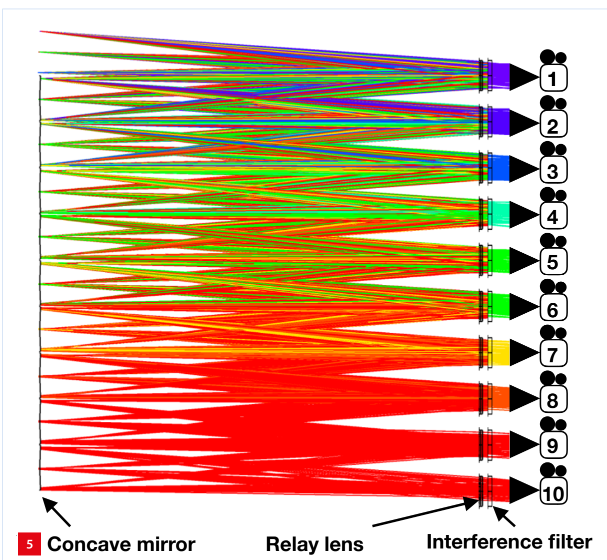


MANTIS set-up and components.
(a) Set-up with the ten cameras with the lenses; in front, the spectral filters, and opposite, the mirrors, which reflect the light to the next spectral filter.
(b) From right to left: the camera, the spectral filter and its holder. (Photo: Curdin Wüthrich)

temperature of the divertor plasma. The farther the front is from the divertor target, the colder the plasma hitting the target. We define the position of this front by the variable L_{pol}, which is determined 800 times per second by means of an image processing algorithm applied to the CIII-filtered images taken by MANTIS [8].

Figure 6 gives an overview of this image processing. The processing and its output information are handled with a real-time accuracy of 50 ms and passed to the control system. The image-processing algorithms have been developed in the Matlab-Simulink environment and compiled into shared object libraries that are dynamically linked at runtime. This allows for rapid development and testing.

The MANTIS system has provided the capability to control this front position in real-time by specifically designing control algorithms based on earlier measurements to identify the plasma response to neutral gas injection. Presently implemented control algorithms range from simple PI controllers to more advanced multiple-input multiple-output (MIMO) control schemes, all based on models obtained through system identification experiments. Extensive work is being done to extend this to model-predictive control, which employs a model to look ahead in time allowing for pre-emptive action against disturbances.



Schematic of the MANTIS set-up with the ten cameras, showing the propagation of light through the relay lenses and concave mirrors.

Outlook

In this article, we have shown the use of only one of the cameras of the MANTIS system to obtain an active measure of mitigation in the divertor. However, the MANTIS system consists of ten cameras. By combining the information in all ten images, a better measurement of the plasma can be obtained.

In future reactors, more than one type of gas will also be injected, each with its own effect on the divertor plasma. The use of multiple gases and cameras can be used in a MIMO control configuration to achieve even better results. The continuation of the collaboration between DIFFER and EPFL focuses on the use of multiple gases and cameras at the same time and is currently in full swing.

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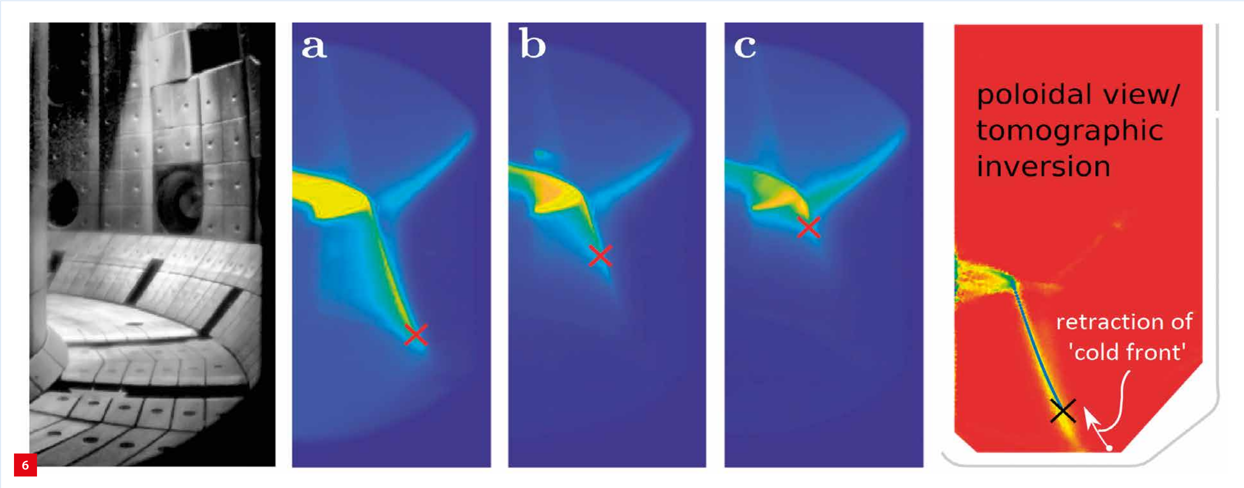

Depiction of the image-processing algorithm applied to CIII-filtered images and used for real-time exhaust control.
Left: The camera view from the MANTIS system inside the TCV tokamak.
Middle: Retraction of CIII emission with the cold front defined at 50% emission extinction; retraction of this emission from the target as shown from left to right (a to c) indicates cooling of the divertor area.
Right: Tomographically inverted image showing the retracted distance of the cold front used as a control parameter (adapted from [6]).

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