DIFFER

Annual Report 2011

Dutch Institute for Fundamental Research

FOM Institute DIFFER

Annual report 2011

DIFFER is one of the three research institutes of the Foundation for Fundamental Research on Matter (FOM). FOM is part of the Netherlands Organisation for Scientific Research (NWO). The institute is part of the Association EURATOM-FOM and is partner in the Trilateral Euregio Cluster (TEC).

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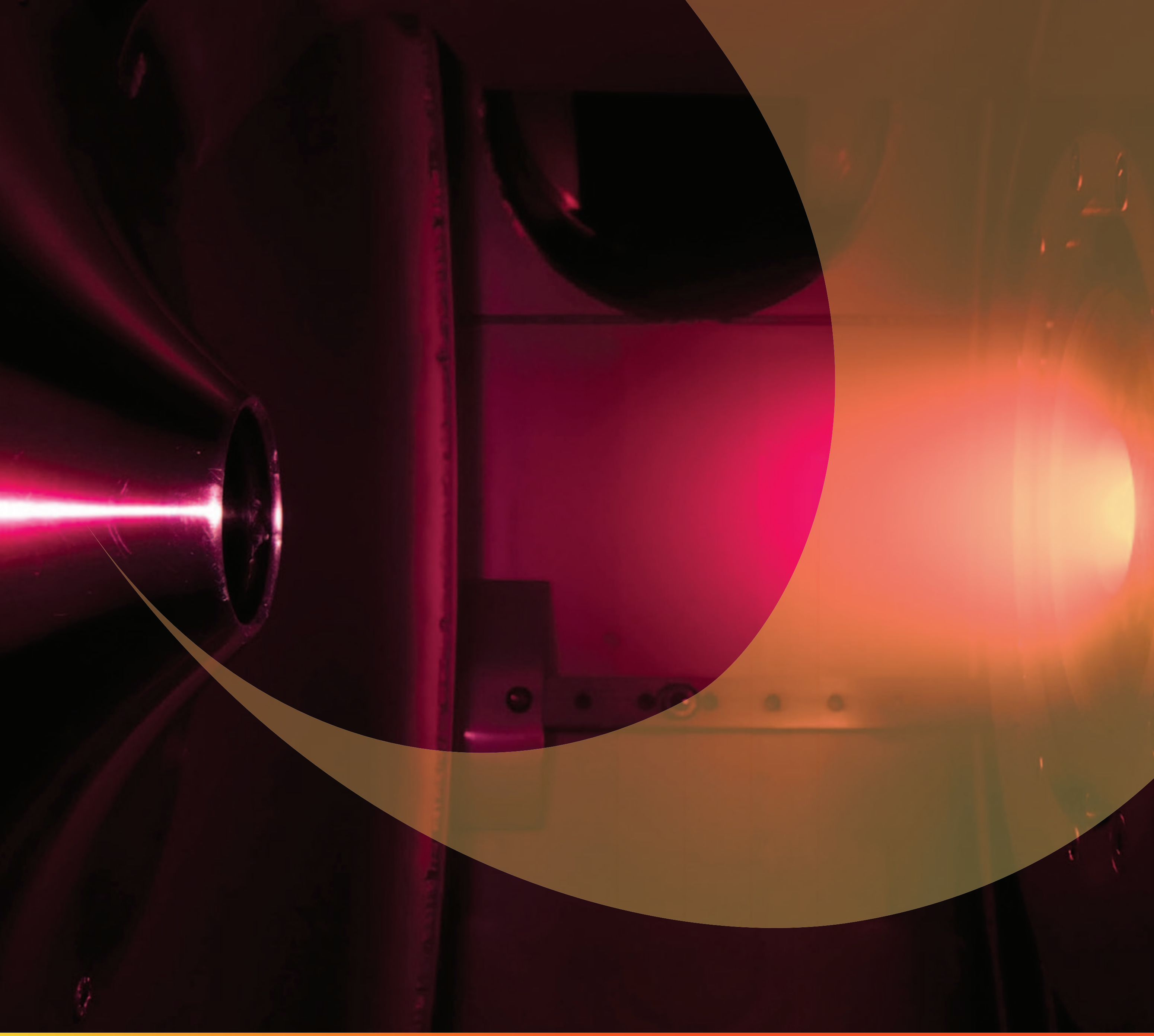


1 Introduction

1.1 Preface

In 2012, the FOM Institute for Plasma Physics Rijnhuizen changed its name to reflect its new mission of Science for Future Energy. Starting 2012, the institute is named FOM Institute DIFFER, the Dutch Institute for Fundamental Energy Research. DIFFER was created to perform leading fundamental research in the fields of fusion energy and solar fuels and has the ambition to play a leading role in coordinating and facilitating fundamental energy research in the Netherlands.

This document reports on the research activities at the FOM Institute Rijnhuizen in 2011, prior to the start of DIFFER. Therefore, this annual report will refer to the institute as FOM Rijnhuizen or simply Rijnhuizen. Where the new research program of 2012 and onwards is concerned, the name DIFFER will be used. DIFFER's new mission is described in detail in section 1.3 of this report.

Mission of Rijnhuizen

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

Rijnhuizen / DIFFER is one of the three research institutes of the Foundation for Fundamental Research on Matter (FOM). FOM is part of the Netherlands Organisation for Scientific Research (NWO).

1.2 Highlights

External evaluation by NWO – top marks for Rijnhuizen and DIFFER

The Dutch science organisation NWO conducts regular evaluations of its research institutes and in 2011, all eight NWO institutes were visited by international committees evaluating their past results and future plans over six-year periods. For the institute, this was an ideal opportunity to both present accomplishments at Rijnhuizen and to showcase the newly written research strategy for DIFFER. The evaluation committee was led by Prof.Dr. Ron Parker (MIT) and visited Rijnhuizen from 28-30 September 2011. The committee held interviews with the management team, scientific group leaders and the chairman of the Scientific Advisory Committee, visited the research facilities and spoke with young (PhD and postdoc) researchers at the institute.

In its report, the evaluation committee gave Rijnhuizen the highest possible score ('excellent') for the quality and scientific relevance of its research and for its forward-looking strategy. The institute's knowledge transfer activities (section 3.3) were praised, notably the valorisation performance of the nSI department, which is reflected in the 'more than excellent' score given by the panel for the societal relevance of the institute's work. The new mission of Science for Future Energy was given full support and was described as a bold, high risk, high payoff strategy to address one of society's most urgent needs.

Plasma Surface Interactions – mimicking the ITER divertor load

In 2011, Rijnhuizen completed the construction phase of its Plasma Surface Interactions set-up Magnum-PSI. This is the first experiment in the world capable of simultaneously producing the plasma conditions expected at the ITER divertor. Magnum-PSI was designed specifically to investigate the interaction between a fusion plasma and the wall of the reactor vessel.

Although delivery of the facility's superconducting magnet is delayed, installation of a pulsed conventional magnet allowed the institute to already start experiments on Magnum-PSI in 2011. The first magnetized hydrogen plasma was produced in October 2011. The experiment now produces plasmas with ITER-relevant conditions for the plasma temperature, flux and density. Magnum-PSI can already deposit a power of 8 MW per square meter on the target, comparable to the expected load on the ITER divertor. Further plasma-wall-interactions experiments will start in early 2012. The experimental set-up is scheduled for an upgrade with a superconducting magnet in the future, enabling investigation of truly long-term effects of the interplay between a fusion plasma and the reactor vessel.

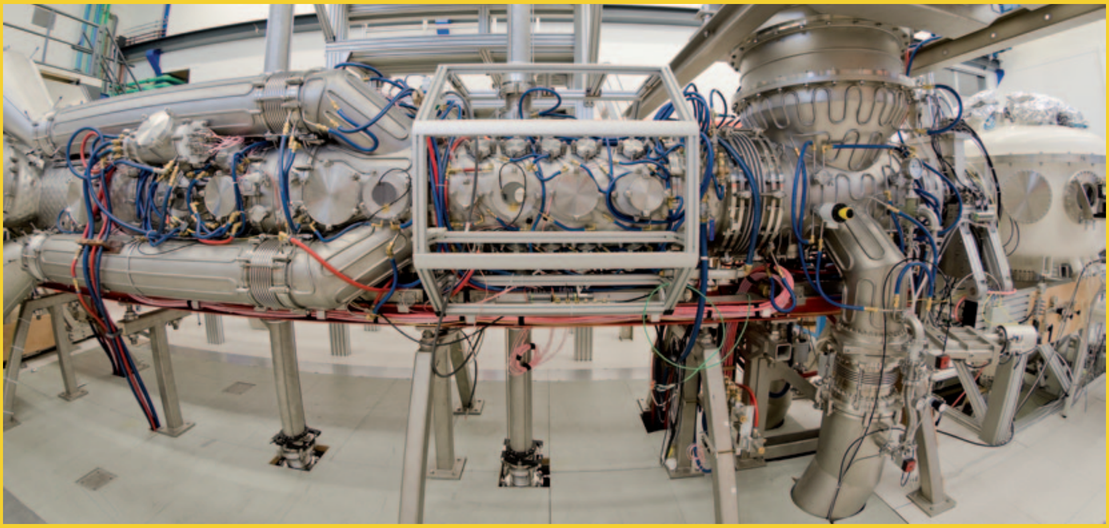


Figure 1.1 Plasma surface Interactions set-up Magnum-PSI, without the pulsed copper magnet.

Fusion Physics – plasma diagnostics at key fusion facilities

The Fusion Physics division operated Electron Cyclotron Emission (ECE) diagnostics at both the ASDEX-U and JET tokamak experiments. The flagship of the division's diagnostics has been the 2-dimensional Electron Cyclotron Emission Imaging (ECEI) system. This system is now in routine operation at ASDEX-U, providing unique insights into the temperature evolution of magnetic perturbations in the plasma core as well as in the plasma edge. The focus of the investigations shifted towards the study of the plasma edge and so-called Edge Localized Modes (ELMs). The diagnostic revealed in great detail various instabilities that developed in the presence of the edge transport barrier. The division is involved in the exploitation of similar systems at KSTAR and DIII-D.

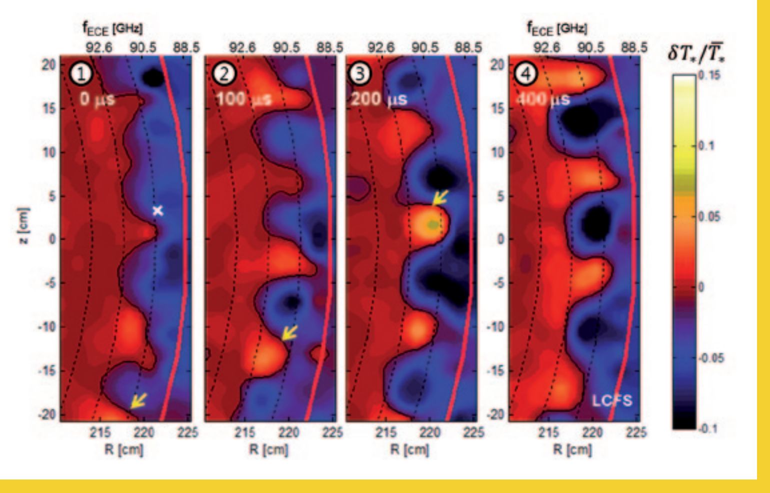


Figure 1.2 Formation of filaments at the edge of the KSTAR plasma as measured with two-dimensional ECE-Imaging. Depicted are the temperature fluctuations. The red curved line is the separatrix.

Nanolayer Surface and Interface Physics – new group EUV Lab in-house at ASML

In the Industrial Partnership Programme CP3E, the nSI division, ASML and Carl Zeiss work together to investigate the physics and chemistry of multilayer systems under high flux and plasma loads. As part of the agreement, nSI started the new EUV Lab research group at the ASML site in Veldhoven in 2011. EUV Lab's research program is focused on understanding the surface chemistry in the harsh environment of plasmas and extreme ultraviolet radiation (EUV). Understanding and control of these processes is of paramount importance for the EUV applications. A diverse collection of approaches is being used, ranging from numerical studies to experiments using state-of-the-art surface science set-ups combined with high-intensity EUV light sources.

The latter has now been established in a separate FOM research Lab within the Research Department of ASML at Veldhoven. The lab allows PhD students and supervisors to work directly in an industrial environment while focussing on fundamental physics aspects of EUVL.

The CP3E programme consists of nine PhD projects, of which four are carried out at the new FOM EUV lab at ASML as well as at the associated Russian ISAN institute and at Moscow State University. The remainder is based at Rijnhuizen in the nSI department as well as in the CPP-LT group of Wim Goedheer.

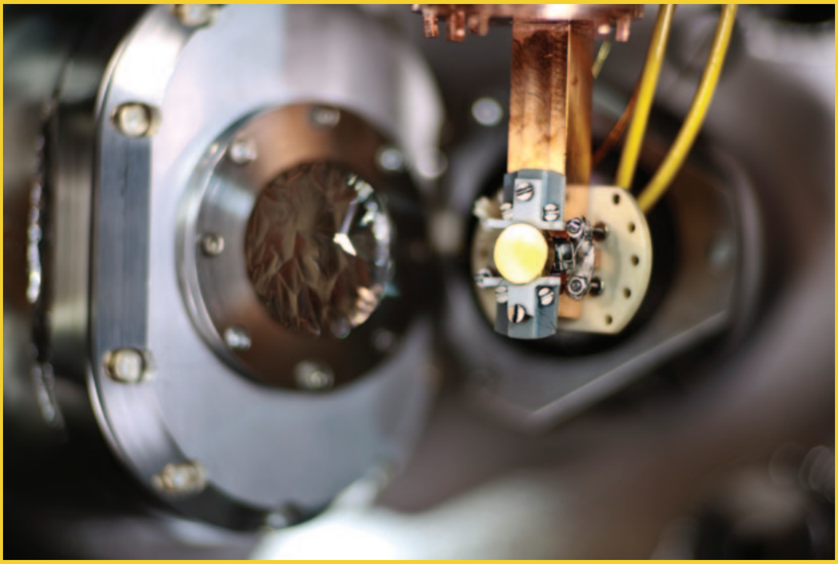


Figure 1.3 Set-up to investigate the surface chemistry in the harsh environment of plasmas and extreme ultraviolet radiation (EUV), located in the EUV Lab.

Generation and Utilization of THz radiation – IR-spectra of metal clusters with FELICE

A new method for determining the vibrational spectra of anionic metal clusters – infrared resonance enhanced multiple photon electron detachment (IR-REMPED) – has been demonstrated using FELICE, the Free Electron Laser for Intra-Cavity experiments.

The physical and chemical properties of nano-sized metal particles are often strongly size-dependent and can vary drastically from those of the bulk. The charge of the nanoparticles can also substantially influence their characteristics and is known to be crucial, for instance, for the catalytic activity of deposited gold nanoparticles. Therefore it is of fundamental interest to develop novel experimental methods that allow to unravel the geometric and electronic properties of metal nanoparticles of a given size and charge. This new way to investigate metal cluster anions is expected to be applicable to a wide range of clusters allowing the determination of their geometric properties.

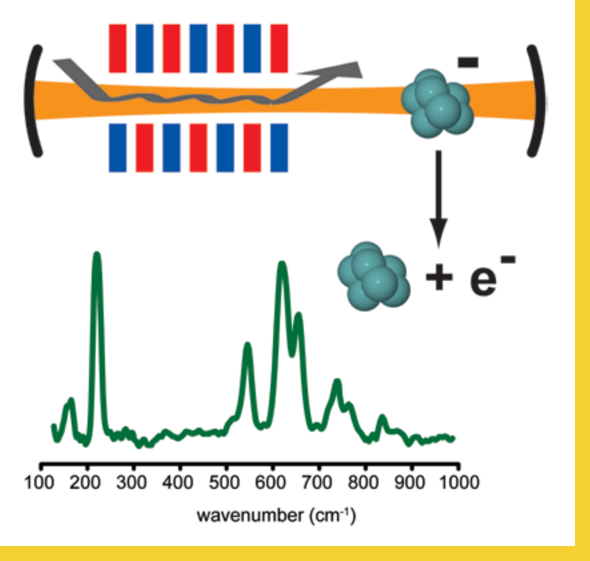


Figure 1.4 Illustration of an anionic cluster irradiated by infrared light inside the FELICE cavity.

1.3 From Rijnhuizen to DIFFER

Sustainable energy is one of the key research themes in the mission of the Netherlands Organization for Scientific Research (NWO) and the Foundation for Fundamental Research on Matter (FOM).

Mission

DIFFER's mission is to perform leading fundamental research in the field of fusion energy and solar fuels, in close partnership with academia and industry, and to have a national coordinating role in the field of fundamental energy research.

The institute pursues four equally important goals to achieve its mission:

1. Fundamental energy research: the institute is in an excellent position to make major contributions to the development of fusion energy and solar fuels, potentially providing breakthrough solutions to the energy and climate change issues.

2. High-quality technical infrastructure: DIFFER will use its expertise in designing, developing and operating large scale experimental equipment to enable the novel research on Solar Fuels and to advance its Fusion research.

3. Acquiring a national coordinating role: DIFFER aims to join together the fundamental energy research in the Netherlands into one coherent national research program. DIFFER strives for potential industrial applications and increased valorisation of energy research.

4. Further intensifying collaborations: the institute will set up strategic collaborations and joint research programs with universities and Large Technological Institutes (LTI's).

By converting intermittent sustainable energy into chemical fuels, solar fuels addresses the global challenge of energy storage and transport. The institute has an excellent opportunity to make major contributions to this field in the coming years via a plasma-chemical route. Six new Solar Fuels group leaders in tenure tracks positions will be actively scouted among talented young researchers. DIFFER will pursue a balanced gender ratio in the staff, in line with FOM's "20 in 2020" strategy.

DIFFER's two fusion research programs are both high priority areas within the ITER program. The unique high-flux plasma generator Magnum-PSI enables studies of plasma-surface interactions at plasma facing components under future fusion reactor conditions. Research into the control of burning plasmas, in particular of magneto-hydrodynamic (MHD) modes, aims at developing pertinent physics, diagnostics and technologies for ITER.

Spin-out: GUTHz and nSI

The successful division Generation and Utilization of TeraHertz radiation at Rijnhuizen will not become part of DIFFER but will instead move to the Radboud University Nijmegen at the start of 2013. There, the facility will join forces with the Nijmegen free electron infrared laser FLARE in the new user facility FELIX – Free Electron Lasers for Infrared eXperiments. The FELIX/FELICE-activities will certainly prosper in their new environment.

The nanolayer Surface & Interface physics (nSI) division, headed by Professor Fred Bijkerk will not relocate to Eindhoven with the rest of DIFFER. The division will instead become part of the MESA+ institute for nanoscience at Twente University. The division's move to Twente will take place gradually and the division will be settled in its new home by mid 2014.

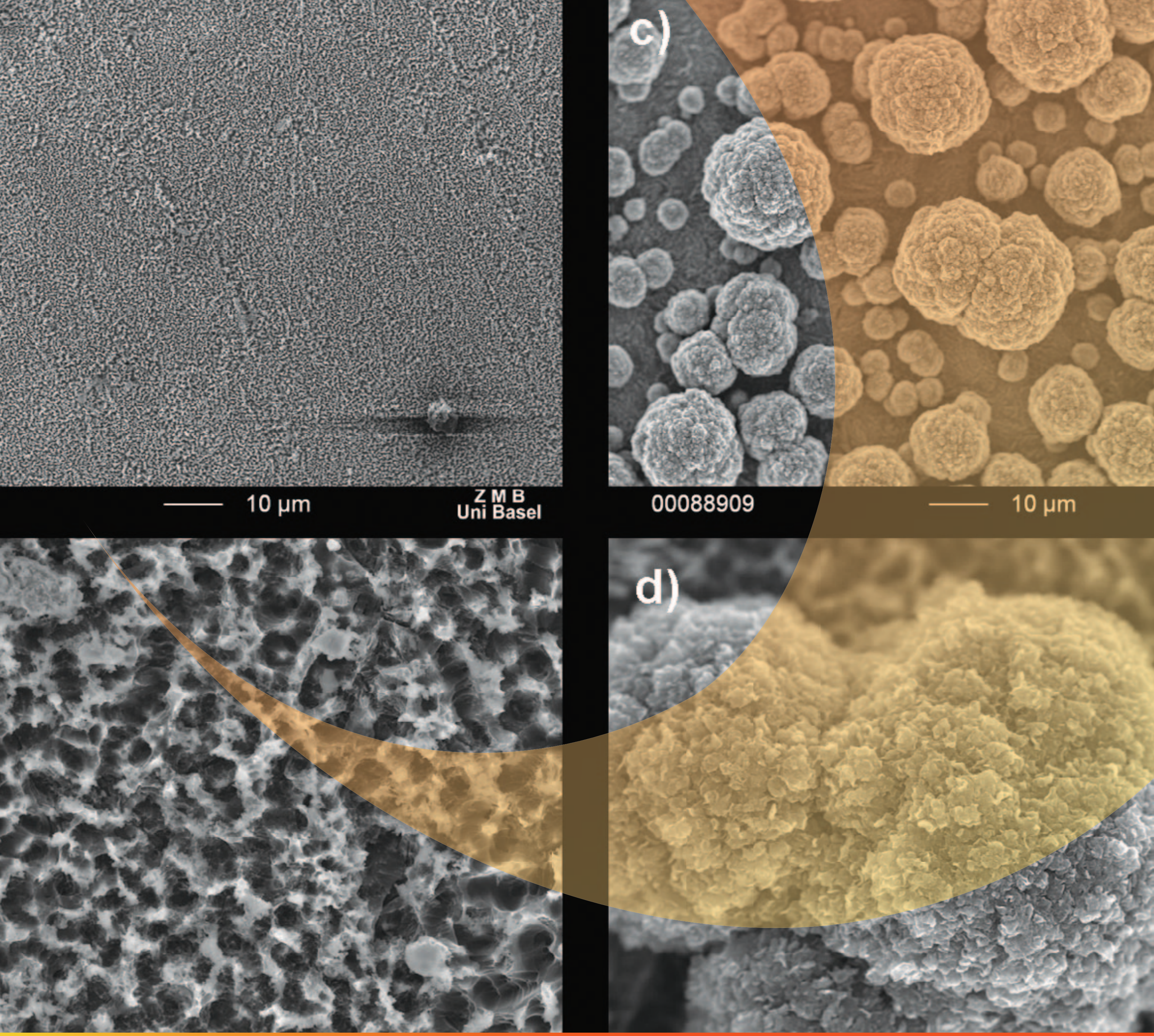
National coordinating role – Council for Energy Research

The course to DIFFER's national coordinating role in fundamental energy research will be charted by a Council for Energy Research, consisting of key players representing Dutch academic and industrial energy research. They will identify and stimulate new (inter-)national cooperation. To increase the focus and mass of DIFFER's research, FOM will install five or more focus groups on fundamental energy research within Dutch universities or institutes. Two focus groups were installed in the beginning of 2011.

A center of excellence on IP management will advise DIFFER and the focus groups regarding Intellectual Property, knowledge transfer and valorization, maintaining the patent portfolio and developing a clear vision on promoting start-up companies.

Relocation to Eindhoven University Campus in 2015

In order to support these new research activities and expand existing ones, a new building will be constructed on the campus of Eindhoven University of Technology. The new institute will provide for an optimum research environment. The relocation is also instrumental in intensifying the collaborations with universities and acquiring a national coordinating role in fundamental energy research. This includes joint research programming, the exchange and training of students, the cross appointment of staff and active stimulation of concerted energy education by means of the development of courses by DIFFER's staff. DIFFER will move to its new location in 2015.



2 Research

2.1 Fusion Research

Rijnhuizen is the centre for physics research in the frame of the European Fusion Programme in the Netherlands. As part of the international effort to develop controlled fusion as a clean, safe and sustainable source of energy, with the ITER experiment as focal point, this research is carried out under the Euratom-FOM association agreement, with financial support from NWO and Euratom.

2011 – a productive year

Work in the division is largely concentrated around the FOM Programme 120: Advanced Control of Magnetohydrodynamic Modes in Burning Plasmas. Within this programme there is an intensive collaboration with the 'Science and Technology of Fusion' and 'Control Systems Technology' groups at Eindhoven University of Technology (TU/e) and with the Centre Mathematics and Informatics (CWI) in Amsterdam. The work is also closely connected to the Dutch-Russian Centre of Excellence on Fusion Physics and Technology which is directed by Tony Donné. The experimental focus of the division is presently on the ASDEX-U tokamak (Germany) and the Joint European Torus (UK); these two devices are considered to be the two most relevant European tokamak devices. Apart from that experiments have been performed at Tore Supra (France), TCV (Switzerland), TEXTOR (Germany) and KSTAR (Korea).

2011 was an extremely productive year. Members of the department have (co-) authored in total 83 papers in peer-reviewed journals, and 7 PhD students have successfully defended their PhD thesis.

The fusion physics department received the ranking 'excellent' in all categories during the evaluation by an international panel in September, while the Dutch-Russian Centre of Excellence on Fusion Physics and Technology successfully passed its midterm evaluation.

Research groups

The Fusion Physics Division consists of three groups and one project:

- In the Plasma Diagnostics group, headed by Peter de Vries, state-of-the-art diagnostics are developed and applied to study fusion experiments. The emphasis of the group is largely focused on diagnostics to observe electron cyclotron emission from the plasma and on Thomson scattering systems. The group is also involved in Charge Exchange Recombination Spectroscopy (CXRS) and in preparations for the ITER CXRS system and the ITER LIDAR Thomson scattering system.
- The Tokamak Physics group, headed by Marco de Baar, is exploiting its expertise by developing advanced control tools and algorithms for stabilizing MHD modes in

contemporary plasma devices. Additionally the group is involved in the system engineering of the microwave plasma heating systems for the ITER Upper Port Launcher. This is a system for MHD control of the ITER plasma by means of Electron Cyclotron Resonance Heating (ECRH).
- The Computational Plasma Physics – High Temperature group, headed by Egbert Westerhof, uses mathematical and numerical modelling to obtain a deeper understanding of hot fusion plasmas. Until the end of 2010 this also included research on astrophysical plasmas.
- Additional to the groups there is the ITER-NL project which was headed in the first half of the year by Noud Oomens, and ion the second half by Tony Donné, both also also acting as ITER-NL Programme Director. ITER-NL is a consortium consisting of TNO, NRG, TU/e and FOM with the goal to stimulate Dutch industry to get involved into ITER and also to participate in the development of scientific components for ITER (specifically the core CXRS and LIDAR diagnostics and the ECRH Upper Port Launcher).

The reports of the substantial activities of the three groups and the ITER-NL project can be found in Chapters 2.2 – 2.5.

Appointments

- Tony Donné joined the Board of Editors of the prestigious journal Nuclear Fusion. He presented his inaugural lecture at Eindhoven University of Technology in January 2011. He has taken over the role of Programme Director of ITER-NL from Noud Oomens.
- Marco de Baar has been nominated member of the Science and Technology Advisory Committee (STAC) of EFDA.
- Noud Oomens became member of the F4E Technical Advisory Panel.

Strategic highlights

- A first grant from Fusion for Energy has been obtained, focused on Remote Handling studies for the ITER Upper Port Launcher for Electron Cyclotron Resonance Heating. Furthermore, a small study grant was obtained in the field of LIDAR Thomson scattering for ITER.
- With the signature of the CXRS (Charge Exchange Recombination Spectroscopy) consortium agreement in the summer of 2011, FOM is participating now via ITER-NL in three consortia (the other two are focused on LIDAR and the ECRH Upper Port Launcher)
- A new control room for virtual remote handling operations was taken into operation.
- Two Lorentz workshops have been organized at the Lorentz Centre in Leiden on Control of Burning Plasmas and on Advanced Magnetohydrodynamics, respectively. Additionally the department organized the 20th meeting of the ITPA Topical Group on Diagnostics in Noordwijk.

- A bilateral collaboration agreement has been signed between the Japanese National Institute for Fusion Sciences and FOM-Rijnhuizen in the field of MHD physics, plasma-surface interaction and diagnostics.

2.1.1 Plasma Diagnostics

Division:	Fusion Physics
Group leader:	P.C. de Vries
Senior scientists:	I.G.J. Classen, M.G. von Hellermann, M. Kantor (also Ioffe and FZJ)
Post-Docs:	O.Lischtschenko, M. Tsalas, T. Gerbaud, D. Moseev, E. Delabie
PhD students:	J.E. Boom, T.W. Versloot, A. Kappatou, J. Hawke, A. Bogomolov
Undergraduate students:	V. Burgmeister, H. Jansen, P. Ribault.
Collaborators:	R.J.E. Jaspers (TU/e, the Netherlands), W.Biel, O. Marchuck, O. Neubauer (FZJ, Germany), E. Germany), A. Hermann, W. Suttrop, R. Dux (IPP, Germany), N.C. Hawkes, C. Giroud, G. Naylor, R. Scannel (CCFE, UK), N.C. Luhmann Jr. (UC-Davis, US), H.K. Park (U. Pohang, Korea), B. Snijders (TNO, the Netherlands)
Funding:	FP-120, EURATOM, TU/e, US-DOE, INTAS, NWO, EFDA, ITER-NL

Introduction

The Plasma Diagnostics Group develops high resolution diagnostics to observe the dynamics of hot magnetized fusion plasmas. The study of the physics phenomena that are revealed by these diagnostics is an integral part of the group's research efforts. Furthermore, the aim is to expand and use the available expertise to develop diagnostics for ITER.

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

- Thomson scattering diagnostics, such as a multi-pass system, have been developed to study the electron temperature and density profiles in hot plasmas. The multi-pass system adopts a novel concept in which the plasma is part of the laser cavity. The diagnostic reaches unprecedented resolution, allowing it not only to study the dynamics of the temperature and density profiles but also to determine electron drifts and associated current densities. The group furthermore participates in the development of the LIDAR Thomson scattering system for ITER.
- Electron cyclotron emission diagnostics, in particular a 2-dimensional imaging variant (2D-ECEI), to measure temperature structures and fluctuation in the plasma core. The ECEI 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 image the emission from the plasma on the array, now a 2D area in the poloidal plane is imaged, with a resolution of about a 1.5 cm in all directions.

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

Results

2010 marked the start of the new FOM Programme 120, the study of physics of burning plasmas, of which the experimental work is largely concentrated at JET and ASDEX-U. Final experiments at TEXTOR were done in 2011. The main FOM diagnostics have been, or are in the process of being transferred to ASDEX-U.

Thomson scattering

In 2011, the group started a new activity looking into the details of the design of a LIDAR Thomson scattering system for ITER. Besides this, final experiments were carried out at TEXTOR with the multi-pass high-resolution Thomson scattering system. The system is able to attain excellent specifications with total laser energies of up to 3 kJ in about 50 pulses in a 10 ms interval, yielding high sub-cm spatial resolutions with a

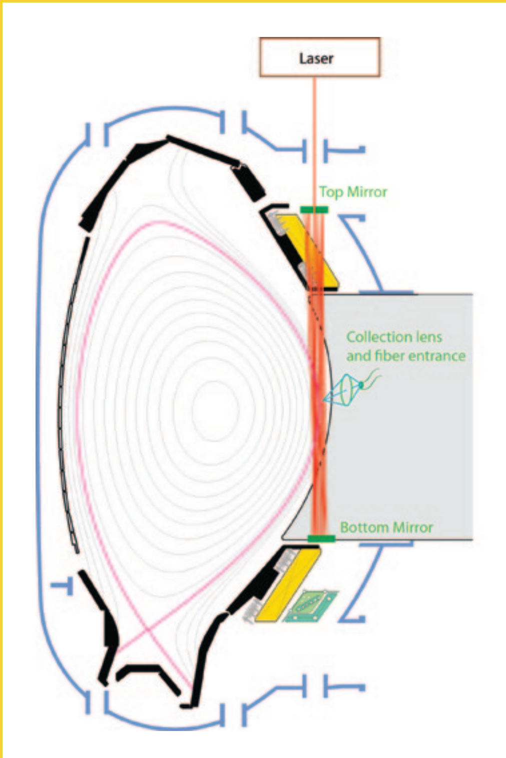


Figure 2.1 Schematic overview of the new multi-pass Thomson Scattering system designed for ASDEX-U. The diagnostic focuses on the plasma edge, with the tangentially observing collection optics, in order to measure electron drifts and associated plasma currents that may arise in connection with the edge transport barrier.

typical accuracy of respectively 2% and 1% in electron temperature and density. The experiments at TEXTOR focused on the dynamics of the pressure profile in the presence of magnetic island or during plasma disruptions.

The unprecedented accuracies that can be achieved with this multi-pass Thomson scattering diagnostic will allow it to measure not only the electron temperature and density, but also the current density. This year, a large effort was devoted to designing a new multi-pass Thomson Scattering system for the ASDEX-U experiment (Figure 2.1). In the high confinement mode (H-mode) transport barriers develop at the plasma edge, and the Thomson scattering diagnostic might be able to determine the dynamics of the edge current density profile which is key to the understanding of the transport barrier stability. First elements have been installed in 2011, and further construction is foreseen in 2012.

2D Electron Cyclotron Emission Imaging

The group operated Electron Cyclotron Emission (ECE) diagnostics at both the ASDEX-U and JET tokamak experiments. The flagship of the group's diagnostics has been the 2 dimensional Electron Cyclotron Emission Imaging (ECEI) system. This system is now in routine operation at ASDEX-U, providing unique insights into the temperature evolution of magnetic perturbations in the plasma core as well as in the

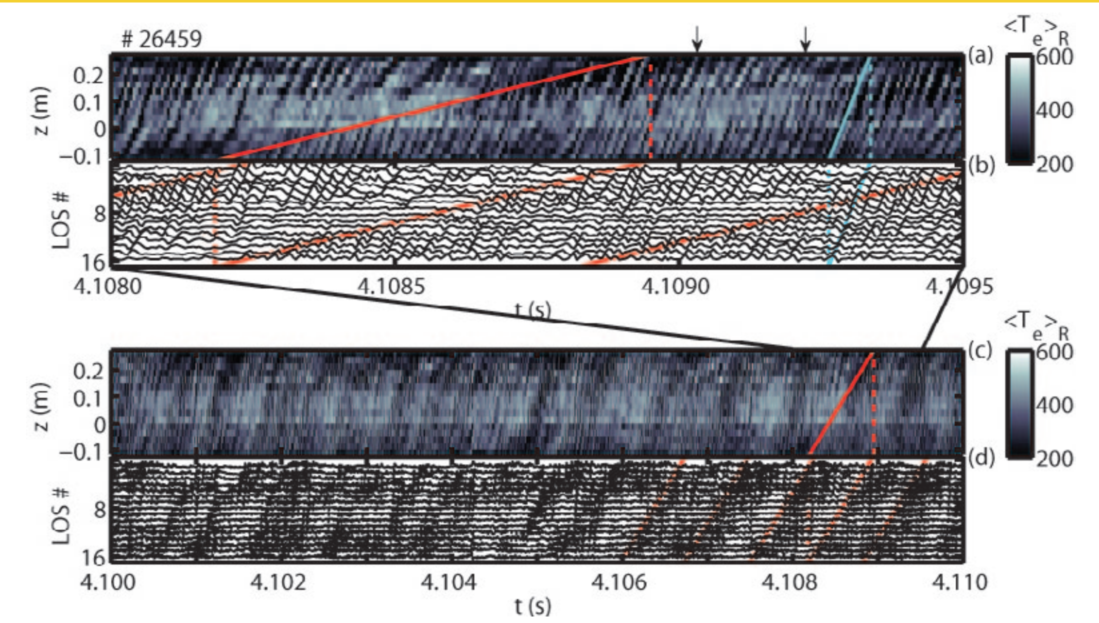


Figure 2.2 Temperature perturbations observed with the ECEI diagnostic at various vertical positions at the edge of an ASDEX-U plasma. Under specific circumstances, in the presence small, so called type II, Edge Localised Modes, a typical mode is observed that that rotates past the diagnostic. A characteristic beat wave pattern can be found in the ECE signals.

plasma edge. The system combines the advantages of ‘classical’ ECE systems and multiple lines of sight to provide a true 2D image of T_e fluctuations with a total of 128 channels, arranged in a matrix of 8 (horizontal) × 16 (vertical) sampling volumes. The group is involved in the exploitation of similar systems at KSTAR and DIII-D.

Studies on core Alfvén eigenmodes continued, but the focus of the investigations over this year shifted towards to the study of the plasma edge and so-called Edge Localized Modes (ELMs). The diagnostic revealed in great detail various instabilities that developed in the presence of the edge transport barrier, as illustrated in Figure 2.2. Under specific circumstances, a typical mode is observed that rotates through the diagnostic viewing window. A characteristic beat wave pattern suggests that this might not be a single mode but a signature of multiple instabilities with different mode numbers or frequencies.

Active beam spectroscopy

In close collaboration with the fusion research team at the TU/e, a considerable effort in the Plasma Diagnostics Group has been devoted to Charge Exchange Recombination Spectroscopy (CXRS). The focus has been on addressing the scientific issues of the design, such as the scientific feasibility. A prototype CXRS spectrometer for ITER has been developed by the ITER-NL consortium. The group furthermore exploits CXRS systems on JET and TEXTOR to build up the expertise to run such a diagnostics on ITER.

The specifications of the ITER CXRS spectrometer are more than an order of magnitude better than those of presently used diagnostics on fusion devices. In 2011, the proto-type spectrometer was commissioned extensively at TEXTOR. The high resolution and etendue would allow this diagnostic to be used for monitoring the fast ion population in fusion experiments. A feasibility study showed that the specifications of the spectrometer are such that fast ions in ITER,as well as in present devices, can be monitored . The diagnostic is now being employed at ASDEX-U, specifically for fast ion studies.

2.1.2 Tokamak Physics

Division:	Fusion physics
Group leader:	M. de Baar
Senior scientists:	W. Bongers
Technicians:	D. Ronden and B. Elzendoorn
PhD students:	M. van Berkel, H. Boesenkool, G. Hommen, M. Lauret, G. Witvoet, B. Hennen
Undergraduate student:	R. Voorhoeve, J. Perez, B. Maljaars
Collaborators:	M. Steinbuch, P. Nuij, S. Djordjevic, N. Lopes Cardozo, R. Jaspers, M. de Bock (TU/e, the Netherlands), D. Strauss (KIT, Germany), T. Goodman (EPFL, Switzerland), D. Farina (CNR, Italy), H. Zohm, J. Stober (MPG-IPP Garching, Germany), V. Erckmann (MPG-IPP Greifswald, Germany), W. Kasparek (MPG-IPF Stuttgart, Germany), N. Doelman, B. Snijders, P. Eendebak (TNO, the Netherlands), L. Machielse (NRG, the Netherlands), R. Akers (CCFE, UK), G. Giruzzi (CEA, France), A. Tessini, M. Henderson, M. Walsh, V. Udintsev (ITER IO, France), G. Saibene (F4E, Spain).
Funding:	FP120, GOT-IF Fusion, GOT-RH, F4E GRT 161, ITER-NL

Research programme

The mission of the group is:

- to develop an integrated understanding of the burning plasma core, including the interaction between magnetohydrodynamic (MHD) instabilities and energetic particles,
- to develop controllers for the MHD modes in the (burning) plasma core,
- to participate in the design of one of the actuators for MHD control in ITER, the Upper Port launcher for electron cyclotron resonance heating (ECRH).

The work of the group is embedded in FOM program 120 (2010-2014) "Advanced control of magnetohydrodynamic modes in burning plasmas".

Research Highlights

Feedback controllers for the sawtooth period
A systematic methodology for structured design of feedback controllers for the sawtooth period was developed. For this, a combined Kadomtsev–Porcelli model of a sawtoothing plasma, actuated by an electron cyclotron current drive system, has been set-up. The model evolves the diffusion of the current density until the Porcelli stability condition is violated. This condition states that if the radial derivative of the magnetic winding number exceeds a pre-set critical value, a sawtooth crash will occur. For the sawtooth a simple Kadomtsev reconnection model has been used that reorganises the

flux within the mixing radius. The model has been used to derive a variety of closed loop sawtooth controllers. These will all be tested on ASDEX-U in the coming years. The control-oriented sawtooth model introduced above was used to study this phenomenon. In the simulations, the deposition location is kept constant while the gyrotron power is modulated with a certain period and duty cycle. Extensive simulations show that when the modulation is properly chosen, the sawtooth period quickly synchronizes to the same period and remains locked at this value. It is shown that the range of modulation periods and duty cycles over which sawtooth period locking occurs, depends on the deposition location, but is particularly large for depositions near the q = 1 surface. These simulation results reveal a novel approach to control the sawtooth period in open loop, based on injection locking, which is a well-known technique to control limit cycles of non-linear dynamic oscillators. Injection locking appears to let the sawtooth period converge to the modulation period quickly. Moreover the method has an intrinsic robustness against general uncertainties and disturbances.

Locking has been demonstrated experimentally on the TCV tokamak in Lausanne, in experiments in which the power, the duty cycle, and the modulation frequency have been varied. An open loop sawtooth period controller has been designed. The duty cycle and power modulation period were preprogrammed to change in time. The sawtooth period in Figure 2.3 locks to the modulation period and follows the changing modulation period very well, even for the step in modulation period. This shows that the sawtooth period remains locked when the modulation period changes continuously in time. Therefore precise, fast and robust sawtooth period control can be achieved by using the locking phenomenon. This control method has the added advantage that it does not need any real-time measurements of the sawtooth period, so faulty sawtooth detections have no influence on the control. Corroborating evidence for sawtooth period locking has been presented, in which the sawtooth

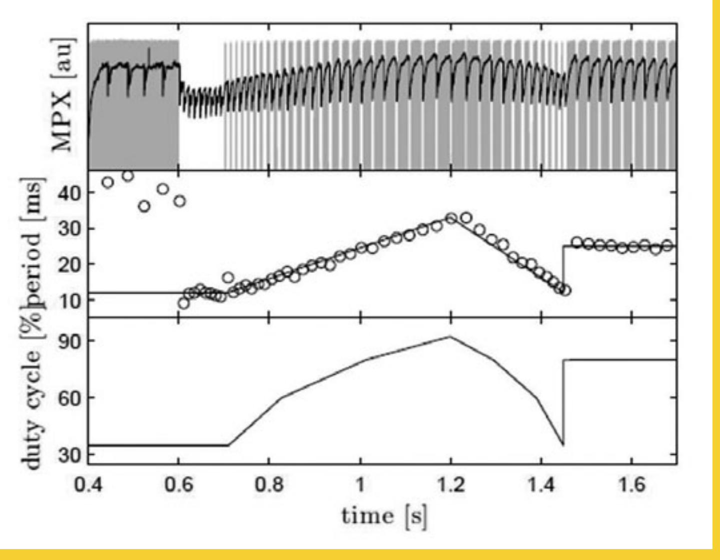


Figure 2.3 Open loop sawtooth control in TCV. A Sawtooth cycle as measured with central soft-Xray and ECRH power. B Measured sawtooth period (open circles) versus the reference (line). C Power modulation period. At t = 0:7 s, the modulated gyrotron is enabled. During the modulation phase, the modulation period and duty cycle are preprogrammed to achieve locking.

period follows the modulation frequency of an externally applied high power Electron Cyclotron wave source. High precision, fast and robust sawtooth period control has been demonstrated from 10 to 35 ms. This is almost the full range of achievable sawtooth periods with the used gyrotrons on TCV for the chosen experimental conditions. This opens the possibility of open loop control for physics studies and performance control.

Both the simulations and the experiment show that the locking effect is not associated with the crash. Rather, the modulated ECCD non-linearly affects the evolution of the resistive current evolution of subsequent crashes until locking occurs.

In-line ECE for TEXTOR
A new (ITER relevant) In-Line ECE system for MHD control has been installed in ASDEX-U.

ASDEX-U will be equipped with a novel Electron Cyclotron Resonant Heating (ECRH) / Current Drive (ECCD) system based on multi-frequency gyrotrons, tuneable in four steps over the range of 105 to 140 GHz. A special feature of the ASDEX-U ECCD system is the fast directional switch FADIS. FADIS' prime functions are to serve as power or beam combiner and as a FAst Directional Switches (hence the name FADIS). FADIS is suited as a first step in decoupling the high-power gyrotron source signal from the weak Electron Cyclotron Emission signal (ECE).

A dedicated FADIS system for In-Line ECE (FADIS MKIII) has been developed and constructed. A system of sensors for power-leakage and phase at the FADIS exits has been set-up. Recent closed-loop experiments under high power have shown that the mover coil can compensate for the thermal gyrotron effects and lock the FADIS notch within 5 ms on the varying frequency. This resolves the issue of the high power notching. A Mach-Zehnder interference filter works in tandem with FADIS to deal with stray radiation from the gyrotron and cross talk between the two output ports operating at slightly different frequencies.Acceptance tests of the Mach-Zehnder filter show very good agreement with phase-dependent model calculations. The compact, waveguide-compatible design, features a feedback-controlled mirror drive for tracking of the resonator to the gyrotron frequency.

The installation of this system is a milestone for all research lines in FP120. The system enables the control of MHD modes and a variety of controllers for MHD modes can be tested on plasma, and used for advanced experimentation on impurity transport, energetic particle transport, or the interaction between the sawtooth and neo-classical tearing modes.

2.1.3 Computational Plasma Physics – High Temperature

Division:	Fusion physics
Group leader:	E. Westerhof
Senior scientists:	H.J. de Blank, G.M.D. Hogeweij
Postdoc:	J.W.S. Blokland
PhD students:	B. Ayten, J. Citrin, D. De Lazzari, B. van Es, J.W. Haverkort, F. Jaulmes, W. Weymiens, D. Zhelyazhov
Undergraduate student:	H. van den Brand
VWO docent op onderzoek:	A. Westra (until 6/2011)
Collaborators:	Prof. B. Koren, J. Rademacher, Prof. U. Ebert (CWI, the Netherlands), F. Jenko, E. Poli, M.J. Pueschel (IPP Garching, Germany), S. Pinches (CCFE, UK), S.B. Korsholm, S. Kragh Nielsen, F. Meo (DTU Risø, Denmark), M.D. Tokman, A.A. Balakin, A.G. Shalashov (IAP, Russia), E.Z. Gusakov, A.Yu. Popov (Ioffe Institute, Russia), K.S. Razumova (Kurchatov Institute, Russia), G. Huysmans (ITER IO, France), C. Bourdelle, P. Cottier (CEA Cadarache, France), R. Keppens (KU Leuven, Belgium)
Funding:	FP120, EFP, NWO-RFBR CoE

Research programme

The mission of the group is:

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

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

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

Research highlights 2011

Requirements on localized current drive for the suppression of neoclassical tearing modes

In the generalized Rutherford equation (GRE) the destabilizing term caused by the cancelation of the bootstrap current inside the magnetic island and the stabilizing term from non-inductive current drive inside the island share a common physical origin. By exploiting this common origin, a criterion for the full suppression of neoclassical tearing modes has been obtained, which depends solely on the main geometrical parameters, i.e. the saturated island width w_{sat} and the power deposition width w_{dep} normalized to the marginal island width w_{marg}, and the ratio of the peak driven current density over the local bootstrap current density η ° $j_{CD,max}/j_{bs}$. In particular, for large saturated island widths one finds that the minimum required driven current for full suppression of the NTM should satisfy the dual criterion of $w_{dep} < 2.5\ w_{marg}$ and $\eta < 2.5$. Application of this criterion to the ITER Upper Port ECRH Launcher suggests a further optimization of the current ITER design by increasing the toroidal injection angle by 2 to 4 degrees.

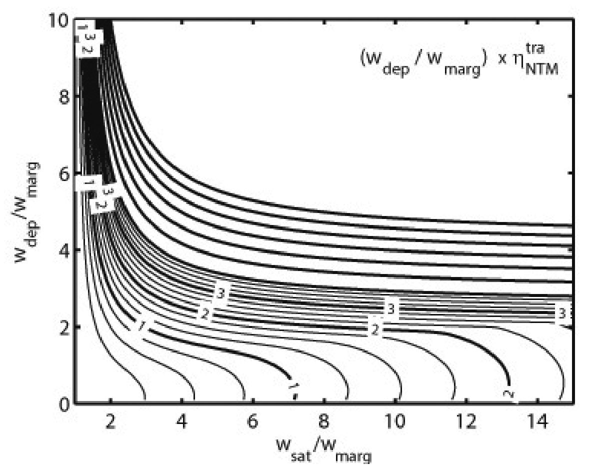


Figure 2.4 Contours of the non-inductively driven current in terms of $(w_{dep}/w_{marg})\eta$ that is required for the full suppression of an NTM.

Toward detailed prominence seismology

The computational tools developed for the analysis of the tokamak plasma equilibrium including finite equilibrium flow (FINESSE) and linear MHD spectrum (PHOENIX) have been applied to the study of solar prominences. Highly accurate solar prominence equilibria have been constructed. These are flux ropes consisting of cold condensed plasma embedded in the hot plasma environment of the solar corona. Subsequently, these equilibria have been analyzed to obtain the complete continuous linear MHD spectrum. This represents a first step to a more detailed prominence seismology in which observed oscillations may be used to conclude about the interior structure of a prominence.

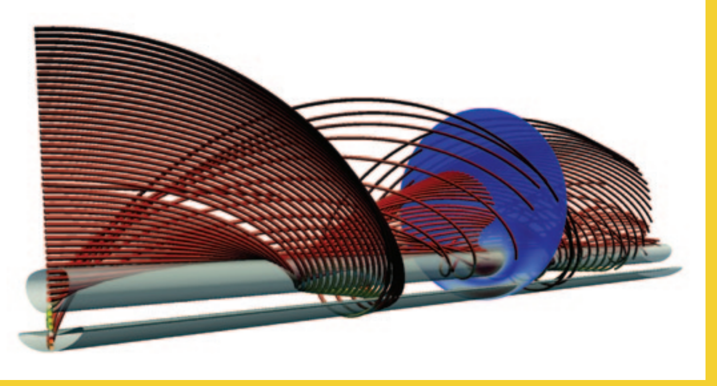


Figure 2.5 Cut-away diagram of a prominence (plasma arch on the sun's surface). In grey: two condensates, regions with higher pressure than their surroundings. The blue cross-section indicates the pressure in the entire prominence. The model shows that the magnetic lines (red) in a prominence rotate in a helix around the areas with higher pressure.

Low-frequency Alfvén gap modes in rotating tokamak plasmas

The magnetohydrodynamic (MHD) spectra of stable and unstable modes in toroidally rotating tokamaks have been studied both analytically, and numerically using the PHOENIX code. The work provided new insights in the effects of plasma rotation on the stability of radially localized modes. The highlighted publication predicts sequences of new global modes due to toroidal rotation. The frequencies of these Alfvén modes lie inside gaps of the continuous MHD spectrum that are created or enlarged by toroidal flow. A criterion for mode existence was obtained analytically.

Because of their low frequencies, these modes may be easily destabilized by energetic particles.

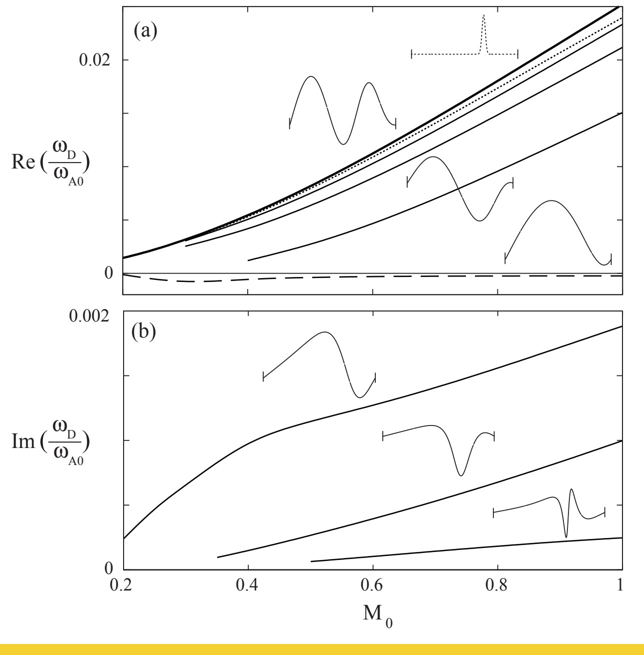


Figure 2.6 Shown are magnetohydrodynamic modes that strongly depend on the rotation velocity of the plasma, given by the Mach number M0 on the horizontal axis: (a) the frequency of the mode when co-rotating with the plasma.
Dotted line: zonal flow mode; thin solid lines: Alfv'en modes; dashed line: the most unstable interchange mode. In (b) the growth rate of the most unstable interchange modes is shown.Insets: radial structures of these modes from plasma center (left) to edge (right).
Toward detailed prominence seismology.

Transport code modelling
The modeling effort in preparation for ITER operation has progressed along two lines: first the validation on existing experiments of the modeled optimization of the hybrid ITER scenario, as published in 2010; second the optimization and sensitivity analysis of the current ramp-up phase of ITER.

Regarding the first research line: the role of s/q (s is the magnetic shear, q the magnetic winding number), as found in the predictive ITER modelling, was validated in a detailed analysis of pairs of discharges, which were similar apart from the s/q profile, in ASDEX-U and JET.

With respect to the second item: During the current ramp-up phase of ITER, MHD instabilities have to be avoided, flux consumption has to be minimized, and this has to be achieved within the narrow operational window of ITER. Ramp-up for the hybrid scenario moreover requires that, at the end of the ramp-up, the q profile is shaped such that $q_{min} \approx 1$ and q has a wide flat region. A systematic effort has been performed to optimize, within the operational limits, the current ramp-up phase for the ITER hybrid scenario. Moreover it was analyzed how the heating scheme should be adapted when the assumptions would be modified. The figure shows the effect of a more peaked or flatter density profile, and how this can be counteracted by shifting forward or backward the start of the additional heating of the plasma.

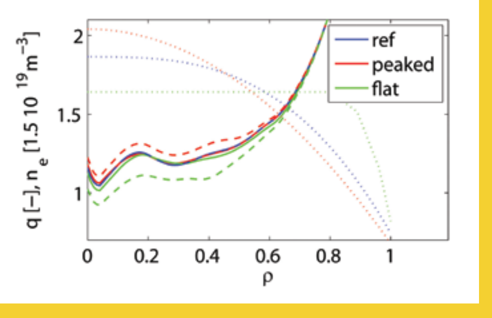


Figure 2.7 Effect of flat or extra peaked ne profile on q. Plotted are ne and q profiles as function of dimensionless minor radius (ρ) at the end of the current ramp-up for 3 cases (see legend), without (dashed lines) and with adapted heating scheme (full lines). With an adapted heating scheme the optimum q profile can be restored.

2.1.4 ITER-NL

Project leader:	A.A.M. Oomens (until 1-7-2011); A.J.H. Donné (from 1-07-2011)
Industrial Liaison Officer:	A.G.A. Verhoeven
Senior Scientist:	A.P.H. Goede
Main collaborators:	M. Durkut, R. Pohlmann, B. Snijders, P. Verhoeff (TNO, the Netherlands), R.J.E. Jaspers (TU/e, the Netherlands), S. de Groot, L. Magielsen (NRG, the Netherlands), P. van Otterloo (Dutch Scientific, the Netherlands)
Funding*:	Fonds Economische Structuurversterking

* supported by the European Fusion Programme (EFP)

Introduction

The ITER-NL consortium is a strategic alliance of FOM with TNO, NRG and TU/e, with the aim to optimise the scientific and industrial participation of the Netherlands in ITER.

ITER-NL is focused on a substantial Dutch participation in three scientific components for ITER: the Upper Port ECRH Launcher (UPL), the Upper Port CXRS Viewer (UPV) and the Equatorial Port LIDAR Thomson scattering system. The development of these components is done in the framework of European consortia that have been established around the UPL (main players: FZK, CRPP and ITER-NL); LIDAR (main players: CCFE and ITER-NL); and the UPV (main players: FZJ and FOM; consortium agreement signed in 2011). Apart from design and R&D work on these three instruments, the ITER-NL consortium helps Dutch industry in preparing for ITER, to maximise the chances of successful tendering in the procurement phase.

The scientific activities of ITER-NL (basically work packages 1 and 2) are done within the framework of the EURATOM-FOM association agreement, and in close collaboration with European institutes.

Organisation

ITER-NL is led by the Executive Board with one member of each organisation (FOM, NRG, TNO and TU/e). The FOM-Rijnhuizen Executive Board member who is also programme director of ITER-NL was Noud Oomens until he was succeeded on 1 July 2011 by Tony Donné. The Executive Board reports to the ITER-NL Council with two members from each organisation (with Hendrik van Vuren and Richard van de Sanden representing FOM in 2011). The ITER-NL Council has an independent industrial member, who acts as chair.

Progress report

In 2011, the ITER-NL1 programme, which ran from 2007-2010, and had a budget of 15 M€, was officially closed. The final report of ITER-NL1 was handed over to Mrs. Van den Bergh, Director Research and Science Policy of the Ministry of Education, Culture and Science. 2011 was also the second year of the ITER-NL2 programme, which runs from 2010-2013, with a budget of 8 M€.

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

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

The highlight in WP1 are:

- Within the LIDAR consortium, ITER-NL has been involved in a small F4E grant with the focus on analyzing the diagnostic integration with the shielding concept in the port plug, to identify risks in the design of the collection path optics that require testing and to develop an alignment strategy.
- The prototype spectrometer for charge exchange recombination spectroscopy has been successfully tested at the TEXTOR Tokamak. It has been demonstrated that the spectrometer can be used to diagnose fast ions, in ITER with energies up to 1 MeV. The beam emission is used to absolutely calibrate the ion density measurements. At the end of 2011 the spectrometer has been upgraded with three fast cameras for further tests on ASDEX-U (see chapter 2.2 - Plasma Diagnostics Group).
- Much emphasis has been devoted to the conceptual design of the Upper Port Plug for CXRS.

The highlights in WP2 are:

- Beautiful results have been obtained in the field of sawtooth and tearing mode control at various tokamak devices (see 1.2 - Tokamak Physics Group).
- An in-line ECE system has been installed at ASDEX Upgrade, in conjunction with the FADIS Fast Diplexer Switch. This system is installed in the ECRH transmission line at ASDEX and can be used to separate the small ECE signal from the high ECRH background (see 2.3 - Tokamak Physics Group).
- The Remote Handling Study Centre (RHSC) for virtual remote handling was opened at the beginning of the year. A delegation from F4E visited the RHSC in October 2011.
- ITER-NL (and especially FOM) takes part in F4E grant GRT-161 on the conceptual design of the ECRH Upper Port Launcher. ITER-NL is focusing within this grant on the Remote Handling procedures and tooling.

The main events in WP3 were:

- An information day for industry was organized at FOM Rijnhuizen on March 16th with 72 participants from 45 companies.
- On May 31st a business-to-business matching event was organized at NRG, Petten, participated by 10 foreign and 26 Dutch industries, resulting in 126 B2B talks.
- In June a small delegation of ITER-NL visited F4E in Barcelona.
- ITER-NL participated in an information meeting for Dutch industry focused on Big Science projects in October in Amsterdam as well as in the ITER Business Forum in Manosque, France in December.
- ITER-NL has actively supported the establishment of a network of Dutch ILO's covering the various Big Science projects.

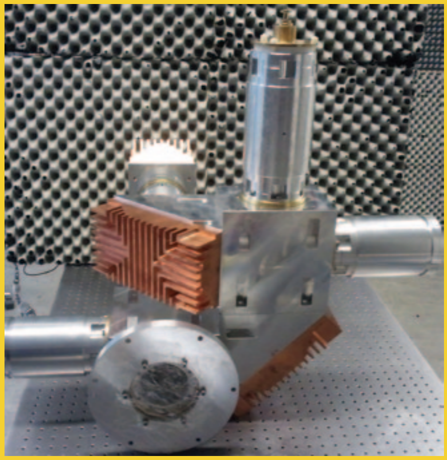


Figure 2.8 Table-top test of the in-line ECE system (shown is the Mach-Zehnder interferometer)

Figure 2.9 Business-to-business meeting at NRG Petten in May 2011.

2.2 Plasma-Surface Interactions

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

The research in the division is mainly based on the research of plasma surface interactions for future fusion reactors. However, general aspects and fundamental plasma surface interaction science is also being carried out. For example, plasma assisted catalysis for the development of novel catalyst materials is a new area of research, which will be investigated for new routes to sustainable energy sources.

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

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

Research groups

The division consists of four research groups:

- In the PSI-Operations (PSI-O) group the Magnum-PSI project has been finalized. This group organizes the operations of Magnum-PSI and Pilot-PSI linear devices. In addition, materials research has been started at a low level in this group.
- The PSI-Experimental (PSI-E) group performs fundamental studies of the surface modification processes under extreme heat and particles fluxes. The research aims at bringing a fundamental understanding to plasma-material research in modern fusion devices and help numerical code benchmarking. In parallel, novel synthesis techniques for nano-structured materials are being developed.
- The Low Temperature Plasma Physics & Heating (LTPP&H) group is focusing on the experimental investigation of low temperature plasma physics characterizing the

plasma of the linear plasma generators Magnum-PSI and Pilot-PSI. Furthermore this group develops the plasma sources and the RF heating for those two devices.
- The Computational Plasma Physics – Low Temperature (CPP-LT) group is modelling the plasma, formation of dust in the plasma, the plasma surface interaction and the molecular dynamics occurring in the linear plasma generators Magnum-PSI and Pilot-PSI.

Strategic highlights

- Following the leave of division leader Juergen Rapp, Prof.Dr. Richard van de Sanden became division leader a.i. of the PSI division starting 15 August 2011.
- After the failure of the factory acceptance test for the superconducting magnet, and in order to start Magnum-PSI operations as soon as possible, it was decided to immediately implement a contingency plan consisting of 4 conventional copper coils. This involved serious redesign and construction work. All work was finished within five months and first magnetized hydrogen plasma on the target was achieved on October 4th, 2011. Thomson scattering was used to show that the electron densities are in the range of 10^{20} m^{-3} at electron temperatures of 3-4 eV, leading to power densities on the target of close to 10 MW m^{-2}. The scientific program will start early in 2012.
- A collaboration agreement has been signed between the Princeton Plasma Physics Laboratory (PPPL) in the USA and FOM to study the behavior of liquid metals in fusion-relevant plasmas.

2.2.1 Plasma Surface Interactions - Experimental

Division:	Plasma Surface Interactions
Group Leader:	G. De Temmerman
Postdoc:	T. Morgan
Guest scientist:	F. Liu
PhD students:	K. Bystrov, I. Tanyeli, H. Xu, J.J. Zielinski
Undergraduate students:	J. Daniels, B. Hensen, V. Guyon, T. Olivier, L. van der Vegt
Research technician:	M. van den Berg
Collaborators:	L. Marot (University Basel, Switzerland), D.C. Schram (TU/e, the Netherlands), S. Brezinsek, J. Linke, A. Litnovsky, J.W. Coenen, V. Philipps (FZ-Juelich. Germany), C. Arnas (University Marseille, France), S. Porro (Heriot-Watt, UK), J. Dodson (E6, UK), B. Lipschultz, D.G. Whyte, G. Wright (MIT, USA), R.P. Doerner, M.J. Baldwin (USCD, USA), M. Jaworski, R. Goldston (PPPL, USA), J.P. Allain (Purdue Univ., USA), J. Rapp (ORNL, USA), A. Hakola (TKK, Finland), P. Paris (TEKES, Finland), E. Delchambre, T. Loarer, J.M. Travere (CEA, France), M. Balden (IPP Garching, Germany), W. Liu (Tsinghua University, China), S. Kajita, N. Ohno (Nagoya University, Japan)
Funding:	FP-75, EFP, EFDA

Introduction

The goal of the PSI-E group is to reach a fundamental understanding of the material modification processes under the high heat loads and intense ion fluxes expected in a fusion reactor.

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

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

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

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

Research highlights 2011:

Erosion of carbon under ITER-like conditions

Experimental investigation of carbon erosion and re-deposition under ITER divertor-relevant conditions is needed for optimizing the plasma-facing components of the future fusion reactors. Exposure of fine-grain graphite samples to hydrogen plasma leads to release of volatile hydrocarbons, such as methane, into the plasma. Dissociation products of methane can be detected by optical emission spectroscopy, quantifying the gross amount of sputtered carbon. It was established that the amount and the temporal behavior of the gross erosion yield depends strongly on the plasma conditions, namely, on the electron temperature. In addition, for T_e = 0.5 eV the gross erosion practically does not change with time. On the contrary, for T_e = 1.3 eV it decreases exponentially. In parallel, the measured surface temperature increases strongly with time for the highest electron temperature while it is almost constant for the lowest plasma temperature. Such behavior can be linked to strong surface modification due to carbon re-deposition. Indeed, large fraction of eroded carbon atoms return to the surface under high plasma flux conditions. In fact, larger gross erosion provokes stronger return flux of carbon. Figure 2.10 illustrates the morphology of the plasma- exposed graphite for the two temperature regime. While the lowest electron temperature exposure leads to morphology typical to that of chemically eroded carbon, the sample exposed to the highest electron temperature is covered with cauliflower particles with sizes up to 20 microns. The progressive growth of those

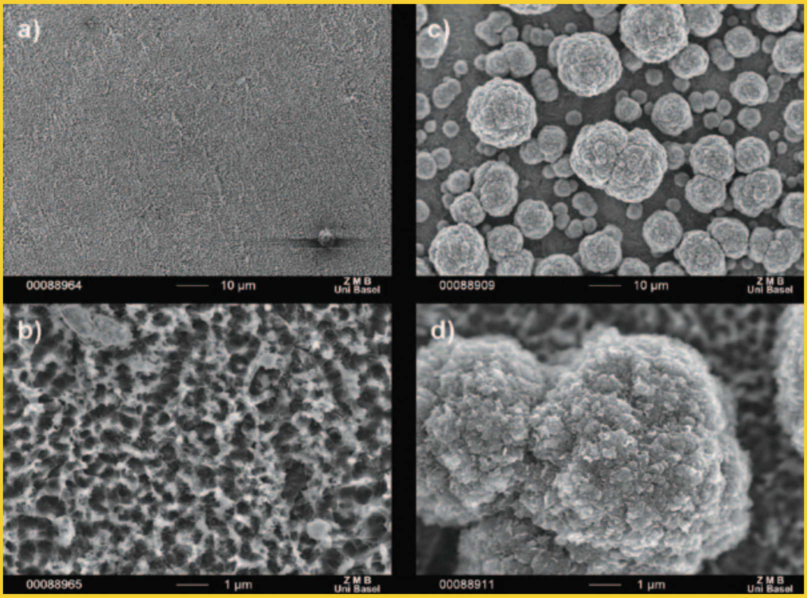


Figure 2.10 Characteristic SEM images of a graphite surface where no re-deposition is observed (a and b) and a surface covered with cauliflower-like dust structures.

particles and their bad thermal contact with the bulk sample can account for the progressive increase of the surface temperature and consequent decrease of the apparent erosion yield. In such a situation, the strong carbon re-deposition strongly reduces the net material loss from the surface.

Thermal shock resistance of diamond under extreme heat loads
Owing to its excellent thermal and mechanical properties- the highest thermal conductivity of all known materials, diamond is a very promising material for utilisation under extreme heat and particle loads. Its etching rate by thermal atomic hydrogen is two orders of magnitude smaller than that of graphite while the displacement energy of carbon atoms in the diamond lattice is 80eV compared to 25eV in graphite making diamond more resistant to damage by energetic particles. In addition, the thermal shock resistance being dependent on its thermal and mechanical properties, diamond, with a low thermal expansion, high fracture strength and high thermal conductivity, offers excellent prospects for use under extreme heat loads.

Preliminary experiments were carried out in the framework of a pilot project initiated with Element Six Ltd (Ascott, UK) to assess the thermal shock resistance of thick free-standing boron-doped diamond samples. 5mm-thick wafers were produced by Element Six, and subsequently tested in the JUDITH electron gun facility, located at Forschungszentrum Juelich, under extreme heat loads (up to a heat flux parameter of $176 MW.m^{-2}s^{1/2}$ for 5ms- three times the melting threshold of tungsten). The thermal shock resistance of the produced material under such conditions was outstanding, with neither material degradation (cracks, amorphization) nor any material erosion 100 cycles at $176 MW.m^{-2}s^{1/2}$. The latter value is more than 3 times the melting threshold of tungsten- the current material of choice for high heat flux components in a fusion reactor. In comparison, a polycrystalline graphite sample was tested under similar conditions and suffered from severe erosion (up to 0.5 mm) after 1000 cycles at $70.5 MW.m^{-2}s^{1/2}$

Tungsten surface modifications during combined steady-state/transient loading
Edge Localized Modes (ELMs) are a major concern for the lifetime of the divertor plasma-facing materials (PFMs) in ITER. The very high localized heat fluxes resulting from ELMs will lead to material erosion, melting and vaporization. A new experimental setup has been developed for ELM simulation experiments with relevant steady-state plasma conditions and transient heat/particle source. The plasma source of Pilot-PSI has been modified to allow for transient heat and particle pulses superimposed on the steady-state plasma. The plasma source can be operated with a variety of gases (e.g. Ar, H, D, He, N) as well as with gas mixtures. Peak surface heat fluxes of up to 1 $GW.m^{-2}$ have been generated with a pulse duration of about 0.5-1 ms (up to $1 MJ.m^{-2}$). The shape and the duration of the pulse can be adapted to the needs of the researcher in question. In addition, a pulsed bias system has been developed to vary the ion energy during the pulse. The pulsed plasma properties have been studied using Thomson scattering, fast visible and infrared imaging for H, He and Ar operations. The effect of combined steady-state/pulsed plasma exposures on polycrystalline tungsten targets was studied. Under such conditions, the threshold for tungsten release and surface roughening is found to be much lower

than in previously reported experiments (Figure 2.11). This suggests that the combination of the high flux plasma and the transient plasma pulse leads to strong synergistic effects.

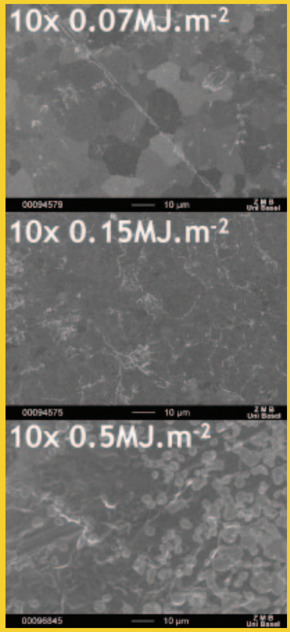


Figure 2.11 Evolution of the surface morphology of tungsten exposed to a constant steady-state plasma flux (40s) and superimposed ELM-like plasma pulses with increasing energy densities. Surface roughening occurs at low energy densities and burst blister caps are observed on the surface at $0.5 MJ.m^{-2}$.

2.2.2 Plasma Surface Interactions – Operations

Division:	Plasma Surface Interactions
Group leader:	P.A. Zeijlmans van Emmichoven
PhD student:	M.H.J. 't Hoen
Undergraduate student:	L. van Swieten
Research engineer:	H.J. van der Meiden
Technicians:	R.S. Al, S. Brons, H.J.N. van Eck, O.G. Kruyt, A. Lof, R. Prins, J. Scholten, P.H.M. Smeets
Collaborators:	D.C. Schram (TU/e, the Netherlands), H. Schut (TU/d, the Netherlands), V. Philipps. B. Schweer (FZ-Juelich, Germany), M. Mayer, K. Ertl (IPP Garching, Germany), E. Gauthier (CEA, France)
Funding:	FP-75, NWO-Groot, EFP, EFDA

Research goal

The group aims at making Magnum-PSI a successful and internationally recognized research facility where relevant work is carried out on plasma-wall interactions at ITER-like conditions.

Research highlights 2011

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

The focus of the group this year was on finalizing the construction of Magnum-PSI and its commissioning. Apart from the superconducting magnet, all essential components needed to operate the device are available and work well. The complete vacuum system is available, targets can be transported through the system and rotated in any given orientation, and plasmas are made on a routine basis. An experimental study has been carried out on Magnum-PSI for an expanding argon plasma. Numerical simulations were performed for similar conditions. The results help to understand the behavior of the gas flow in the machine, validate the modeling, and show that the differential pumping scheme leads to sufficiently low neutral densities in the target area. All safety issues (hydrogen, large magnetic fields, intense lasers) and their control have furthermore been resolved. An important event taking place in January 2011 and nicely illustrating the status of Magnum-PSI was the production of the first hydrogen plasma.

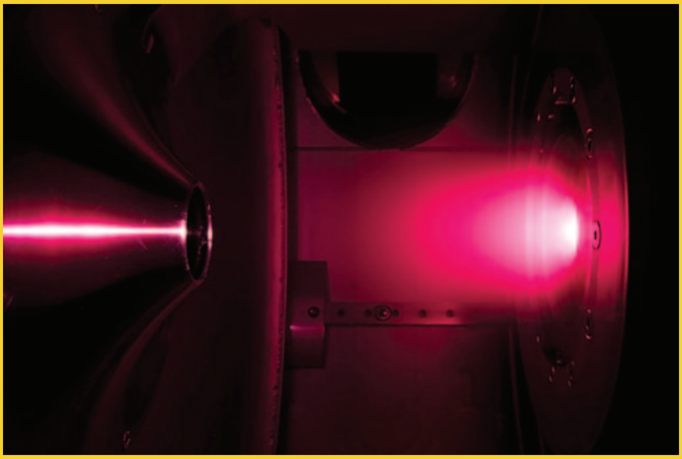


Figure 2.12 First hydrogen plasma in Magnum-PSI.

Diagnostics on Magnum-PSI

The progress in the implementation of the diagnostics and their control was significant this year. Thomson scattering, an excellent laser based technique to obtain densities and temperatures of electrons in plasma, is now used on a routine basis. The same holds for Optical Emission Spectroscopy to study light emission from plasma, calorimetry for study of power deposition in targets and other plasma facing components, and several fast cameras for infrared and visible light. In the framework of EFDA, several laser based surface analysis techniques have been further developed for use on Magnum-PSI as well as for possible application on ITER. It is anticipated that these techniques will be brought to full performance next year.

First magnetized hydrogen plasma in Magnum-PSI

The only component missing so far is the superconducting magnet to confine the plasma to a magnetized beam. The second factory acceptance test of the magnet system failed in May 2011. Repair work on the superconducting magnet is ongoing. An expert group was involved to review the activities of the manufacturer. Their recommendations are followed. An independent consultant in quality control has been hired to monitor the assembly process of the magnet system. Several members of the PSI-O group are actively involved in the monitoring process as well. The third factory acceptance test is planned for June 2012 and, if successful, the magnet will be delivered to the FOM institute in July 2012.

After the failure of the factory acceptance test, we decided to immediately implement a contingency plan consisting of 4 conventional copper coils. This involved serious redesign and construction work: one of the vacuum chambers had to be replaced to make the coils fit, one of the skimmers had to be removed, high-current cabling had to be installed to empower the coils, and some of the diagnostics had to be relocated. All work was finished within five months and first magnetized hydrogen plasma on the target was achieved on October 4th, 2011. Thomson scattering was used to show that the electron densities are in the range of 10^{20} m^{-3} at electron temperatures of 3-4 eV, leading to power densities on the target of close to 10 MW m^{-2}. A first measurement campaign to explore the operational space of Magnum-PSI has been carried out. Thomson scattering, Optical Emission Spectroscopy, calorimetry and the fast cameras were used to determine the properties of argon, helium and hydrogen plasmas and their power densities and particles fluxes on target. The results are very promising and enable first scientific operation of the device with pulsed field to start early 2012.

Deuterium retention in tungsten

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

Polycrystalline, annealed W targets were pre-irradiated with 12.3 MeV W^{4+} ions to various damage levels. Deuterium was implanted by high-flux plasmas in Pilot-PSI ($>10^{24}$ ions m^{-2} s^{-1}) at surface temperatures below 525 K. Deuterium retention has been studied by nuclear reaction analysis and by thermal desorption spectroscopy. We found that the retention is strongly enhanced by the tungsten bombardment and that saturation occurs at a W^{4+} fluence of about 3 10^{17} m^{-2}. The maximum deuterium concentration in the damaged region was measured to be 1.4 at.%. This is in accordance with experiments by others that were carried out at much lower fluxes, from which we conclude that the saturation behavior and the maximum retention are not affected by the high fluxes used in our experiments.

A simple geometric model was developed that assumes that the saturation solely originates in the tungsten irradiation and that explains it in terms of overlapping volumes. The saturated volume per incident MeV ion amounts to 3 10^4 nm^{-3}. From our results, we are able to deduce an approximate value for the average occupation number of the vacancies. This number was found to be at least close to 1 and is anticipated to increase for higher plasma fluences.

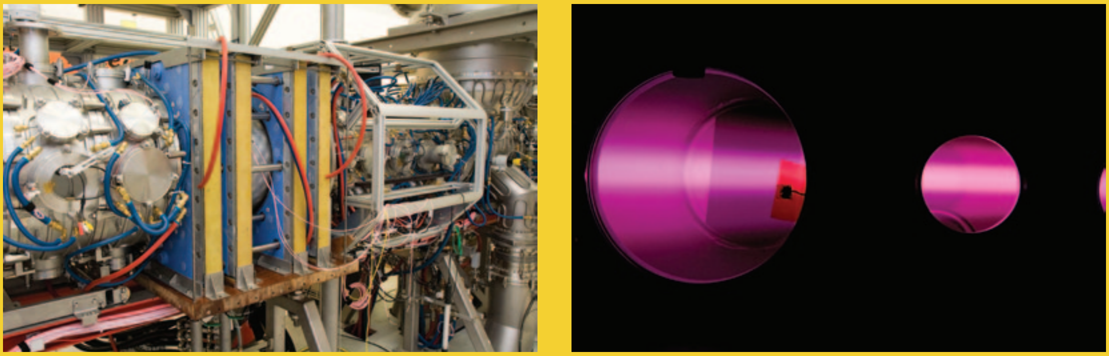


Figure 2.13 a) Picture of Magnum-PSI equipped with 4 conventional copper coils. One of the Magnum-PSI vacuum chambers was redesigned, constructed and manufactured; b) Magnetized hydrogen plasma in Magnum-PSI.

2.2.3 Low Temperature Plasma Physics and Heating

Division:	Plasma Surface Interactions
Group leader:	G.J. van Rooij
PhD students:	N. den Harder
Undergraduate students:	N. den Harder, G. van der Star
Research Engineer:	M.J. van de Pol
Research Technician:	M.F. Graswinckel
External Advisors:	R.A.H. Engeln, D.C. Schram (TU/e)
Collaborators:	D. Borodin, S. Brezinsek, A. Pospieszczyk (FZ-Juelich, Germany), D.G. Whyte (MIT, USA), G. Popa, M.L. Solomon, V. Anita (Cuza University, Rumania), F. Tabares, J. Ferreira, E. Oyarzabal (CIEMAT, Spain), F. Gou (Sichuan University, China)
Funding*:	FOM, NWO, FP-75, EURATOM baseline support, NWOGroot, NWO-RFBR, EFDA

* supported by the European Fusion Programme (EFP)

Scientific programme

The group investigates nuclear fusion reactor grade divertor plasma and applies the insight in such plasma for understanding of plasma wall interaction in fusion devices and to enhance the plasma parameters in the in-house linear plasma devices.

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

How is the transport of particles and power to a material wall changed if the returning secondary particles are captured by the plasma, both for perpendicular and grazing incidence? This question lies at the heart of the original FP75 research programme as far as the plasma is concerned: plasma physics in the strongly coupled regime of plasma surface interactions due to an extremely high plasma density. These particles will equilibrate with the upstream high density plasma and act as a volumetric power and ionization sink that depends on the nature of the secondary particles (fast or slow, atoms or molecules, both determined by incoming ion energy and surface material). As a consequence, a mix of plasma and neutrals with different energies than in the usual lower density case will arrive on the target. It is evident that full knowledge on these properties is required to predict plasma surface interaction in (future) fusion devices as well as to interpret experiments carried out it Pilot-PSI and Magnum-PSI.

What determines the axial and radial (e.g. blobby) transport in, and how do impurities and particulates interact with a divertor grade plasma? Two currently pressing issues within the field of divertor tokamak research connect to this question and are being researched within the LTPPH group: radiation of nitrogen seeded to the plasma and the transport of dust.

How can the plasma parameters be enhanced in Pilot-PSI and particularly in Magnum-PSI? This question covers research that is currently being performed within the Magnum-PSI sub-projects on the development of the plasma source and the post-heating of the plasma with Ohmic and RF power by the LTPPH group. It will continue after the completion of the project, which is presently being foreseen for 2011, within the LTPPH group. Increasing the plasma beam diameter from the present record of 3 cm towards the Magnum specification of 10 cm (footprint of parabolic profile), efficient coupling of RF power to the plasma, minimization of source erosion and source efficiency are continued to be investigated.

Research highlights 2011

Development of an external anode for the cascaded arc plasma source
The anode of the cascaded arc is the region where the heat loads on the source components as well as the electric field strengths are at maximum. In addition, the exact shape of the anode determines to a large extend the efficiency at which hydrogen plasma emanates from the source. We have investigated the use of an external electrode that (partly) acts as anode. It was found that up to 50% of the discharge current was easily diverted in the way. This increased the plasma temperature and overall source efficiency as well as relieving the heat loads and electric fields inside the arc.

Plasma acceleration near a negatively biased target in a linear plasma generator
Negative target potential scanning is a standard technique for plasma flux measurements in linear plasma devices. The electron density is sufficiently low in these plasma generators that current densities as well as ion-neutral coupling are negligible. Consequently, the upstream plasma is not affected by the negative target potential. In our linear device Pilot-PSI, variations in the upstream plasma conditions have been observed in the pre-sheath region in front of the target. Its uniquely high plasma densities of $>10^{20}$ m^{-3} ensure a significant interaction between the neutral particle flux coming off the surface and the incoming plasma flux, so that the ‘strongly coupled regime’ is entered. Indeed, we measured, to our knowledge for the first time, changes in the upstream plasma. Particularly, the plasma velocity was measured to increase by up to a factor of five. We have shown that this is explained by heating of the heavy particles in the plasma close the surface. These heavy particles gain thermal energy due to their interaction with fast neutrals that originate from ions that were accelerated over the bias potential.

Tungsten erosion in ASDEX Upgrade and JET
The current design of ITER projects for its active phase tungsten (W) as plasma-facing components (PFCs) in the divertor areas, i.e. the areas receiving the highest particle and energy flux densities. An important issue in this respect remains the physical sputtering of W by impurities, especially when extrinsic impurities are seeded to reduce the power loads on the PFCs. A high local W source in the divertor may cause unduly high W concentrations in the centre, cooling of the plasma and thus deterioration of the fusion performance. We utilized the present ITER-like Wall at JET,

matching the environment for ITER closely, to gain insights into relevant aspects of divertor W erosion and W transport into the main plasma. The W erosion was quantified in dependence of a wide range of low-Z impurity species, divertor particle flux densities and plasma temperatures and thus to allow for an extrapolation to ITER as well as fusion devices beyond. Experiments in the all-W device ASDEX Upgrade were carried out that focused on a strong nitrogen (N2) seeding regime leading to small Edge localized Modes (ELMs). The strong N2 seeding in the ASDEX upgrade H mode experiments reduced the W erosion to an intra-ELM event of which the strength dropped with increasing nitrogen seeding. It means that the beneficial effect of nitrogen seeding by reducing the divertor plasma temperature and thus the impurity impact energy dominates over the detrimental effect of increasing the flux density of sputtering impurities in the high seeding regime. Nitrogen seeding is therefore a candidate approach to manage the heat loads in the divertor of ITER.

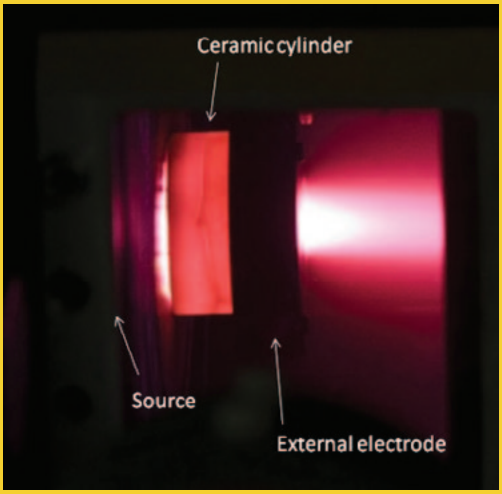


Figure 2.14 Photograph of an experiment with an external ring electrode in Pilot-PSI. In this case, the output of the source was confined inside a ceramic cylinder between the source and the ring.

2.2.4 Computational Plasma Physics – Low temperature

Group Leader:	W.J. Goedheer
Scientist:	H.J. de Blank (50%)
Junior Scientist:	H. Tober
PhD students:	R.C. Wieggers, G.A. van Swaaij, K.C.E. Peerenboom (TU/e, the Netherlands), D. Astakhov (CP3E, France)
Collaborators:	J.J.A.M. van der Mullen (TUE, the Netherlands), J.K. Rath (University, the Netherlands), D. Reiter (FZ-Jülich, Germany), A. Kirschner (FZ-Jülich, Germany), U. von Toussaint (IPP-Garching, Germany), D. Coster (IPP-Garching, Germany)
External advisor:	D.C. Schram
Trainees:	S.A. Wolbers
Funding*:	FP75, FP120, CP3E

Research Programme

The research of the CPP-LT group is performed within the framework of Fusion Energy and is embedded in the FOM program FP75. The CPP-LT group aims to position itself within the institute as the counterpart of the experimental program, executing a scientific program with strong links with the experimental research in the PSI department. This includes the development of new and modification of existing numerical models for plasmas in contact with a material wall.

The framework for collaboration within EURATOM is provided by the EFDA task forces for Integrated Tokamak Modeling (ITM) and Plasma Wall Interaction (PWI). Relevant models will be made available to the EFDA Taskforce for Integrated Tokamak Modeling, to become part of the set of numerical tools needed to support the design of future reactors like DEMO.

Application of the models covers studies of the source and plasma beams of the in-house experiments Pilot-PSI and Magnum-PSI, plasma surface interaction, and transport and re-deposition of eroded material. These studies are done in close collaboration with the PSI experimental groups, optimizing the possibilities for validation of the models against experimental data. Knowledge transfer to the fusion community is provided by applying the models to divertor plasmas. Where possible, the models will be adapted for use in industrial applications.

Research highlights 2011

Break-up and transport of hydrocarbons
The transport and break-up of hydrocarbon molecules in the plasma beam of Pilot-PSI is studied with the kinetic code ERO. This is done in collaboration with FZ-Juelich.

Experiments with a methane gas puff released into the plasma beam provide well-defined conditions for validation of ERO. An important issue is the Gerö-band emission of CH, often used to analyse carbon erosion.

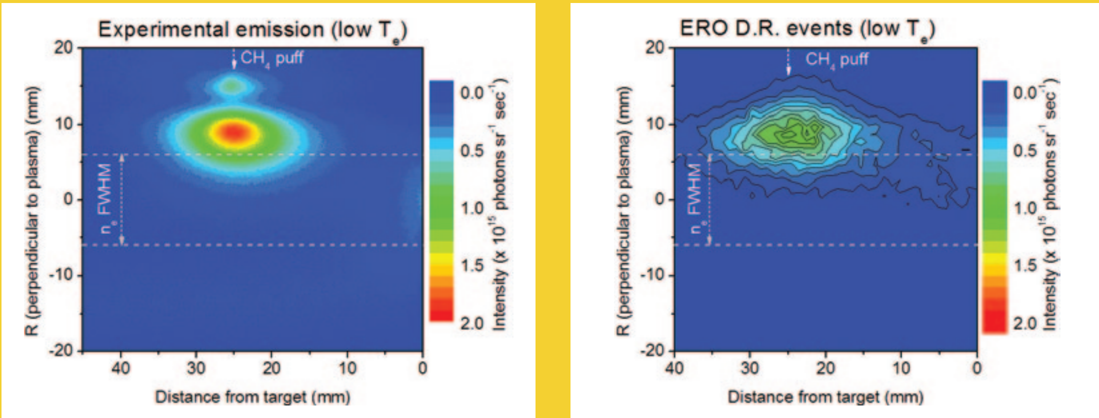


Figure 2.15 shows an example of measured emission from a methane puff release at the side of a low-Te (0.25 eV) Pilot-PSI plasma beam compared to the count of simulated dissociative recombination reactions. This figure shows that dissociative recombination satisfactorily explains the observed CH emission at low Te.

Modelling of low-temperature high-density plasmas

Similar to the plasma expected in the divertor of ITER, the plasma beams of Pilot-PSI and Magnum-PSI have a low temperature and a high density and are characterized by a strong recycling. To study these plasmas a combination of a multi-fluid plasma description (B2.5) needs to be coupled to a kinetic description of the neutral atoms and molecules (EUNOMIA). The modelling of plasma beams includes the description of radial electric fields, plasma rotation, and the axial and radial current density profile in the beam, caused by source potentials and radial variations of the target plasma sheath. The EUNOMIA kinetic code is built from first principles, and is partly based on the existing EIRENE code. Specific items addressed are the non-linearity (neutral – neutral collisions), statistics (adaptive weight of the trace particles) and parallelisation. Currently, both stand-alone EUNOMIA simulations, taking Thomson scattering data as input, and coupled B2.5 – EUNOMIA simulations are possible. Distinguishing vibrational states of the hydrogen molecule enables a study of Molecular Activated Recombination and negative ion formation. A collisional radiative model is used to simulate the hydrogen line radiation, enabling validation of the EUNOMIA results against experiments.

2.3 Nanolayer Surface and Interface Physics

The nSI division aims to perform high-quality scientific research in the fields of surface science and thin film solid state physics. The topics addressed in the course of 2011 include photo-chemical phenomena, photo-conversion processes, plasma physics, and the solid state and interface physics of short-wavelength optics. The latter primarily concerns multilayered reflective coatings of relevance for the soft X-ray to VUV wavelength range, often denoted as the XUV band. In particular, the division studies the boundary areas between these topics: the use of XUV optics, for instance, generates exciting research questions in the field of photo-induced surface chemistry, as in Extreme UV-induced optics contamination ('EUV' refers to the particular wavelength of 13,5 nm). This theme is also linked to a new activity on photo-conversion of water into hydrogen, of relevance for the generation of clean solar fuels. This way, the nSI research has provided Rijnhuizen with a kernel for a solar energy research programme.

A key feature of the research in the nSI division is the industrial and societal relevance of the research: the investigations are usually motivated by application of the knowledge in plasma surface interaction phenomena as e.g. in advanced photo-lithography optics, in thermonuclear fusion processes, or in the utilization of multilayer reflective optics for advanced radiation sources. The societal relevance of the work in nSI was especially highlighted by the 2011 external evaluation panel which rated the institute's performance over the last years.

Research in the nSI division has been mainly enabled in 2011 by three large research programmes:

- the FOM-Zeiss Industrial Partnership Programme 'eXtreme UV multilayer optics' or 'XMO', concluded late 2011,
- PSI-lab, a FOM-funded programme on plasma surface interaction, and
- the FOM-Industrial Partnership Programme 'CP3E' with Carl Zeiss and ASML.

In addition to these, several 'satellite' projects were carried out on specific physics topics via additional financing. These sources included:

- the European programme Catrene, through a large European effort on photolithography ('EXEPT' project),
- the M2i funding scheme, through two new surface science projects also lithography motivated (projects 'SECURE' and 'No-HIO'),
- the Technology Foundation STW, through three projects on advanced schemes of multilayer optics ('NanoArrays', 'SMILE' with the University of Twente and 'Beyond-EUV'), nd one on atomic scale layer growth (with Leiden University)
- two FOM and NWO funded Valorisation projects,
- a FOM pilot study on the use of multilayer optics at the new XFEL fre electron laser, and
- the EOS-NEO programme, through a project on the photocatalytic splitting of water.

Extreme UV multilayer optics: 'XMO'
The objective of XMO has been to develop and apply the physics and associated process technology of compound periodic multilayer structures. Such multilayers serve as XUV reflecting Bragg mirrors and need to have atomically sharp, flat interfaces. The dimensioning of the layered structure of these mirrors needs to be controlled down to a fraction of the XUV wavelength, down to the picometer range. Key issues were the development and application of the physics and supporting fabrication technology of these periodic structures for a most demanding imaging application, namely ultra high resolution photolithography. The programme started in 2005 and has formally been concluded in 2011, with two more PhDs currently finalizing their research. The total number of PhDs finally having received their PhD through this programme is four more then the five originally planned. The programme has also yielded a world record of EUV reflectivity of a multilayer mirror, a much quoted standard in the optics community.

Controlling photon- and plasma induced processes at EUV optical surfaces: 'CP3E'
The new CP3E programme continues where XMO ended by focusing on the physics and chemical processes relevant for final usage of multilayer optics under high flux and plasma loads. Here, the scientific interest has broadened to include photo- and plasma driven chemistry. The collective processes concern photo- and plasma chemistry induced by irradiation with EUV photons or low-temperature plasmas, physical sputtering of surfaces by ions, thermally induced interdiffusion between the different layers of the multilayer system, and modification of the optical response of multilayer optics. Understanding and control of these processes is of paramount importance for the EUV applications. A diverse collection of approaches is being used, ranging from numerical studies to experiments using state-of-the-art surface science set-ups combined with high-intensity EUV light sources.

The CP3E programme consists of nine PhD projects of which four are carried out at the new FOM EUV lab at ASML as well as at the associated Russian ISAN institute and at Moscow State University. The remainder is based at Rijnhuizen in the nSI department as well as in the CPP-LT group of Wim Goedheer.

The department also 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.

Physics for energy
An explorative line of research addresses the theme 'physics for energy', which theme was selected based on the nSI background in thin films and surfaces, ensuring ample cohesion and synergy with the other research activities within nSI. For instance, a new powerful infrared surface spectroscopy (RAIRS) set-up, developed originally for delicate surface studies in photolithography, proved very perspective for photoconversion studies under the theme 'energy'. Figure 2.16 pictures the synergy of the different applications of the surface science studies. The 2011 focus has been on the photo-catalytic splitting of water using sunlight to provide in clean solar fuels.

Obviously this has been done in the context of the shift of focus of the Rijnhuizen institute into energy-relevant research, and the main schedule of relocation of the institute to the campus of the Eindhoven University of Technology by the year 2015.

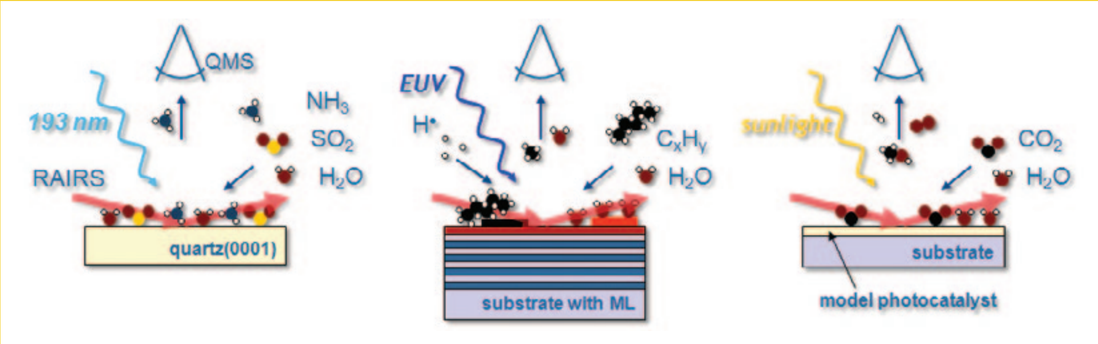


Figure 2.16 Schematic representation of the synergy among the different experimental conditions of the nSI surface studies for, from left to right, photolithography-relevant surface processes at Deep UV and Extreme UV wavelengths, and solar conversion for fuel production.

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

- Surface ion- and photochemistry, (SIPC), headed by Fred Bijkerk,
- Physics of thin films and multilayers (TFM), by Andrey Yakshin,
- Advanced applications of XUV optics (AXO), by Eric Louis, and
- The FOM-EUV Laboratory (EUV Lab), by Chris Lee.

The groups have many interfaces through the definition of tasks in the different research programmes, both mutually as well as with other departments, notably the PSI-E group of Gregory De Temmerman, and CPP-LT by Wim Goedheer. The next section describes the nSI groups and their results accumulated during 2011.

2.3.1 Surface Ion and Photo-chemistry (SIPC)

Division:	nanolayer Surface and Interface physics
Group leader:	F. Bijkerk
Scientific advisors:	A.W. Kleyn
Research engineer:	M. Gleeson
Postdocs:	T. Zaharia
PhD students:	A. Kuznetsov
Funding:	FP-I10 ('XMO'), Carl Zeiss SMT, ASML, M2i

Research Programme

The Surface Ion- and Photochemistry (SIPC) group does fundamental research on the interactions of particles and photon with surfaces. Central themes are the physical and chemical phenomena induced at the surface as a result of such exposures. Exposure of surfaces to (high) photon and particle fluences can induce unexpected and challenging processes. The research goal is to investigate and understand at the atomic level the processes that are occurring. A particular focus of the group is to understand how the state (ionization; energy; excitation) of incident particles and the composition of the irradiating flux modifies the processes that are operative. The research program receives support from various industry.

Highlights

Surface interactions of hyperthermal atoms and molecules
The plasma sources in the Surface PSI setup produces primarily neutral particles with hyperthermal energies in the range from 1-to-15 eV. Most typical neutral beam sources cannot produce particle energies significantly higher than ~1 eV, while it becomes increasing difficult to produce well focused ions beams as the ion energy drops below 50 eV. Hence, the Surface PSI setup is particularly useful for expanding the experimental database regarding atomic and molecular interactions at surfaces.

The 1-to-15 eV energy range is of particular interest because it encompasses typical values for strong chemisorption of adsorbates at surfaces and molecular bond strengths. Hence, the setup is ideal for studying processes such are displacement, abstraction and pick-up reactions. This is also the energy regime in which structural scattering from well-ordered surfaces becomes evident. Thus, information regarding the stiffness of the surface can be obtained. Figure 2.17 shows a comparison of angular distributions of Ar atoms scattered for bare Ag(110), bare Ru(0001) and D-covered Ru(0001). The increased corrugation evident in the distributions from the different surfaces indicates increasing stiffness of the surface atoms.

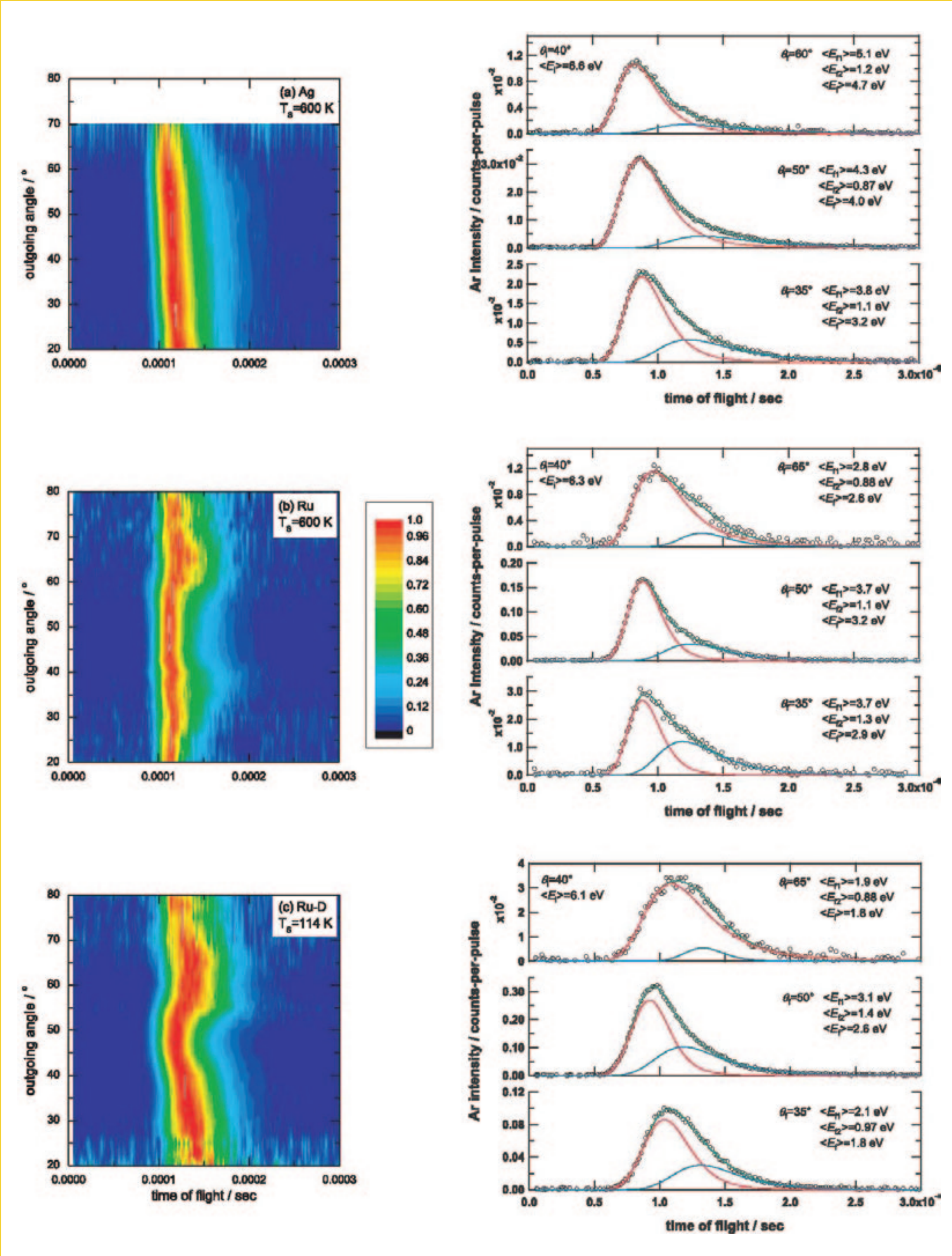


Figure 2.17 Comparison of time-of-flight spectra collected as a function of outgoing angle for Ar scattered from bare Ag(111), bare Ru(0001) and D-covered Ru(0001). The differences reflect how relative rigidity of the surface as “seen” by the incident hyperthermal Ar atoms.

Blistering of multilayer mirror (MLM) surfaces
One on-going research topics focuses of the process of blister-formation on MLM surfaces that are subjected to particles irradiation. Surfaces that are exposed to (energetic) particles can be degraded by a variety of processes. These can include change of chemical state (e.g. oxidation), contamination (e.g. carbon accumulation), and physical degradation (e.g. implantation of impurities and physical sputtering). This is of relevance for optics in space telescopes as well as for thermonuclear fusion (e.g. divertor conditions).

A focus of the work has been on blistering induced by hydrogen irradiation. Recently it has been demonstrated that the type and number of blistered formed is highly dependent on the composition and energy of the incident particles. Two distinct processes have been identified: one induced by neutral particles that is facilitated by the presence of low energy ions and one induced directly by energetic ions. Figure 2.18 shows examples of the types of blisters that are induced by irradiation of a MLM sample by a flux containing both atomic and molecular hydrogen together with both low and high energy hydrogen ions. Two distinct blister sizes are evident. The large blisters are due to a hydrogenation process related to in incident neutral hydrogen, while the small blisters are induced by energetic ions. The results demonstrate complexity in the blistering of MLMs and are relevant to the development of structures that are resistant to blister formation.

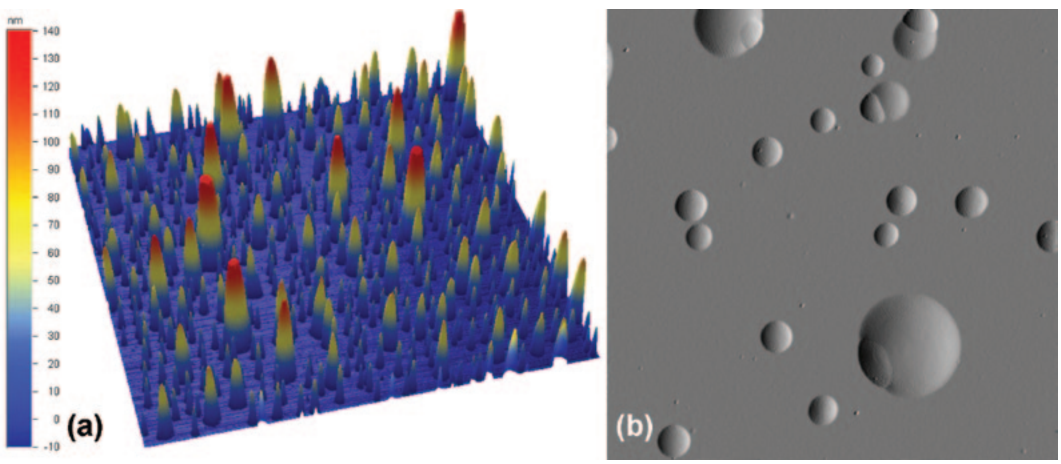


Figure 2.18 (a) 3-D representation of an atomic force microscopy (AFM) scan of a 25×25 μm^2 region of a MLM illustrating the blisters that develop as a result of exposure to a mixed beam of neutral and ionized hydrogen. (b) 2-D representation of an AFM scan from a 5´5 μm^2 region of the same surface.

Stability of EUV caps under reactive environments (SECURE)
SECURE is a newly commenced M2i project in collaboration with ASML. It is one of two new M2i projects that started in 2011. These represents a vote of confidence in the value of fundamental research since it is a continuation of a collaborative effort of more than four years. The SECURE project also represents a spin-off of work on the interaction of hyperthermal beams with surfaces outlined above, which was carried out as part of FOM programme 75. The aim of the project is to study the interactions of reactive atoms (H, O, N) with surfaces. It has already been demonstrated as part of FP75 that the excitation state of incident nitrogen atoms can have a dramatic effect on the interaction with a silver surface (attractive versus repulsive). In addition, evidence N-atom abstraction from the Ru(0001) surface by incident N atoms has been observed. SECURE will follow up on this work, expanding the range and mixture of species observed. It will study the dependence of the reactivity of incident species on the excitation state. The work will focus on adsorption/desorption behaviour, and on recombination and abstraction reactions. These results will be used in evaluating the stability of potential cap layer materials. The ultimate aim is the selection of materials that is resistant to exposure to reactive species or one that can be periodically regenerated.

2.3.2 Advanced applications of XUV optics (AXO)

Group leader:	E. Louis
Scientific advisors:	J. Verhoeven, A.W. Kleyn
Senior scientists:	E. Zoethout
Postdocs:	E.D. van Hattum, R.A. Loch
PhD students:	J. Chen, A.J.R. van den Boogaard, I. Makhotkin
Undergraduate students:	F. Lui, D.M. Paardekooper
Research engineers:	S. Alonso van der Westen, A.J. van Calcar, K. Grootkarzijn, R.H. Harmsen, P. Sallé, M. Zee
Funding:	FP-I10, FP-I23, Carl Zeiss SMT, EC, M2i, ASML, STW, AgentschapNL, FOM

Research Programme

The general aim of the AXO group is to investigate and develop new XUV- and soft X-ray processes related to multilayer optical components for various fields of science and technology. This includes the physics phenomena of extremely thin, smooth and dense layers and the particular research as originating from their applications. During 2011 the group focused on research topics related to EUV lithography with emphasis on applied topics within the FOM Industrial Partnership Programmes XMO (eXtreme UV Multilayer Optics) and CP3E (Controlling Photon and Plasma induced Processes at EUV optical surfaces). Also activities in the EXEPT programme (AgentschapNL) and an M2i project were undertaken. Within these programmes, the group has shown the applicability of some of its deposition processes by coating large demonstration optics that are now being used in the latest ASML lithographic machines.

Furthermore, AXO is an active member of the European consortium that investigates optics contamination issues. The topics explored include the development of an advanced ellipsometry diagnostic to measure the presence and nature of carbon containing contamination layers on EUV optics with sub nm accuracy. Also methods were studied to enhance the spectral purity of EUV optical systems by suppressing parasitic longer wavelength radiation emitted by candidate light sources for EUV lithography.

To further enhance the resolution of future lithography optics, the group carries out an STW (Dutch Technology Foundation) funded project on multilayers based on La and B_4C for an even shorter wavelength, namely 6.7 nm. This work is subject of a PhD program and focuses on interface phenomena that become increasingly important for multilyer systems fo this wavelength.

Finally, AXO focuses on multilayer applications in beam lines and user stations of X-ray Free Electron Lasers. Extensive studies to multilayer damage mechanisms have been carried out in order to improve the coating stability under high photon fluxes. A second research topic is the development of multilayer based beam splitters for the EUV and soft X-ray range. This work is part of a FOM financed pilot study to explore the multilayer optics possibilities for this type of lasers.

Research highlights 2011

Superior interface sharpness by high-Z ion beam smoothing

Traditionally, ions are applied to reduce the roughness evolving during film growth, and this has led to world record reflectance values. However, the dependence of the smoothing process on the mass of the noble gas ions was still largely unknown. Therefore, we applied various noble gases (Ne, Ar, Kr, Xe) and analysed the interface morphology by grazing incidence small angle x-ray scattering (GISAX) and atomic force microscopy (AFM), x-ray photoelectron spectroscopy (XPS), and by extreme ultraviolet (EUV) reflectometry. While AFM shows an almost identical roughness value for all used noble gases, GISAX shows that for both the average roughness level and the vertical correlation length the roughness is reduced significantly with increasing ion mass. Xe^+-polishing did result in a superior structure, but maximal EUV reflectance is observed for Kr^+-polishing. This apparent contradiction is explained by taking into account the absorption from noble gas residuals in the amorphous silicon (a-Si) layers. The extremely low roughness obtained by Xe-polishing can be used if scatter light from EUV optics has to be minimized.

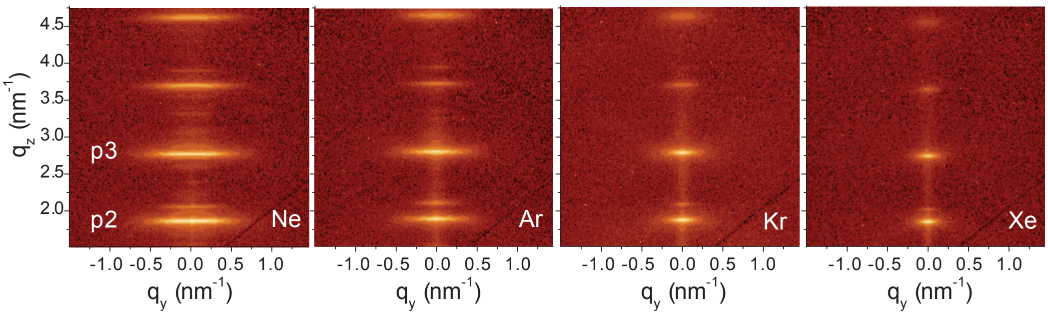


Figure 2.19 CCD images of multilayer x-ray scatter for the several polishing ion species

Multilayer behaviour near the boron absorption edge

For the next generation of EUV optics, multilayers in the 6.5-6.9 nm wavelength range are considered the best candidate. For this wavelength range the spectral properties of lanthanum/boron based multilayers were investigated. It was experimentally verified to what extent measured and tabulated optical constants are applicable to simulate the performance of these mirrors. Measured maximum reflectances at wavelengths around the boron absorption edge were compared to calculated values. The measured reflectance profiles of La/B and La/B_4C showed a maximum at a slightly larger wavelength than measured B and B_4C optical constants would predict. This is an important finding and indicative for the influence (or formation) of the boron-lanthanum compounds on the position of the absorption edge and therefore on the wavelength of maximum reflectance.

The maximum reflectance profiles of LaN/B and LaN/B_4C multilayers could only be described by using the same boron atomic scattering factors, indicating the boron in the LaN/B multilayer to be similar to boron in the LaN/B_4C multilayer. It also indicates that nitridation of the lanthanum layer in the multilayer prevents the formation of boron-lanthanum compounds.

Optics under extreme photon fluxes

The next generation of extreme ultraviolet (EUV) radiation sources may induce radiation damage in optical coatings, including multilayer mirrors. To select material combinations that can withstand such intense radiation, it is essential to understand the underlying damage processes. Previously, we found the damage mechanism in Mo/Si multilayers to be thermally induced. Based on this we investigated the much more stable MoN/SiN multilayers under two extreme conditions: thermal annealing and irradiation with single shot intense EUV pulses from the free-electron laser facility in Hamburg - FLASH. The damage was studied "post-mortem" by means of X-ray diffraction, interference-polarizing optical microscopy, atomic force microscopy, scanning electron microscopy (SEM), and scanning transmission electron microscopy (STEM). Although the timescale of the damage processes and the damage threshold temperatures were different (in the case of annealing it was the dissociation temperature of Mo_2N and in the case of EUV irradiation it was the melting temperature of MoN) the main damage mechanism was found to be very similar: molecular dissociation and the formation of N_2, leading to large voids inside the multilayer structure.

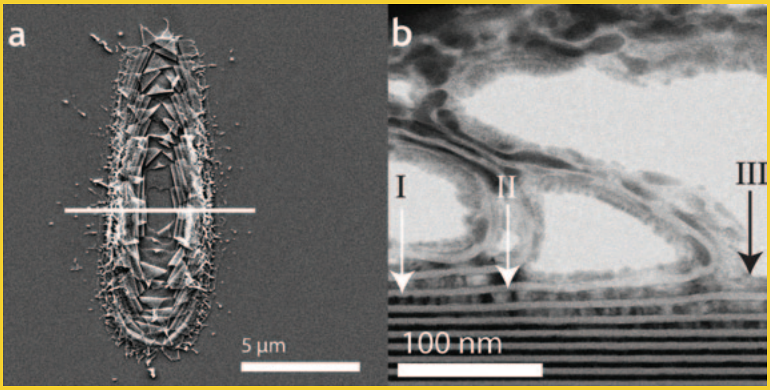


Figure 2.20 SEM image of a crater formed after a single shot intense EUV irradiation

Phase shift on reflection

We also characterized the phase shift induced by reflection on a broadband multilayer mirror in the EUV range (80–93 eV) using two very different techniques: one based on high order harmonic generation and attosecond metrology, and a second based on synchrotron radiation and measurements of standing waves. The experiments show an excellent agreement between the results from the two measurements and a flat group delay shift (+/-40 as) over the main reflectivity peak of the mirror. This is not trivial and therefore an important result, since it shows that both techniques give reliable results. Moreover, such measurements are crucial for the further development of attosecond science since more and more experiments employ EUV mirrors.

2.3.3 Physics of thin films and multilayers (TFM)

Division:	nanolayer Surface and Interface physics
Group leader:	A.E. Yakshin
Scientific advisors:	J. Verhoeven, A.W. Kleyn
Senior scientist:	R.W.E. van de Kruijs
PhD students:	S. Bruijn, J. Bosgra, S. Nyabero, V. Medvedev
Scientific researcher:	P. Veldhuizen
Research Engineers:	F. Boekhout, M. Zee
Guest scientist:	I. Kozhevnikov (Crystallography Inst. Moscow)
Funding:	FOM Industrial Partnership Programmes I10, I23, Carl Zeiss SMT, ASML, AgentschapNL

Research programme

The general goal of the group is developing the basic physics of thin single and multilayered films and interfaces of nanometer thicknesses, including the specific multilayer physics resulting from applications of these films. The emphasis of this research is on the core physics issues. The research follows two FOM Industrial Partnership Programmes: 'Extreme UV multilayer optics' (I10) and 'Controlling photon and plasma induced processes at EUV optical surfaces' (I23), carried out in collaboration with Zeiss and ASML. The group also participated in the European CATRENE programme EXtreme uv lithography Entry Point Technology development.

The advanced multilayer structures developed in the group are required for optical elements operating at Extreme UV wavelengths, around 13.5 nm, targeted to meet the requirements of Extreme UV photolithography. Other applications are solar X-ray telescopes and short-wavelength free electron lasers. The structures represent fundamental challenges in thin layer and surface physics as well as multilayer optics. The TFM group is dealing with the solid-state aspects of these research projects. Other aspects are carried out at the SIPC and AXO groups, and the EUV group at the ASML Lab at Veldhoven.

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

Evolution of diffusion characteristics during nanoscopic Mo-Si interlayer growth
Due to the high intensity EUV exposure in lithography equipment, Mo/Si multilayer structures are subjected to elevated temperatures, potentially causing interdiffusion and deterioration of the mirror's optical characteristics. For prediction of the lifetime of this optics it essential to know the interdiffusion rate and activation energy of the interdiffusion process at the very early stages of interdiffusion. Using a super-sensitive

in situ X-ray reflectometry method developed earlier, we studied diffusion dynamics separately at Si-on-Mo and Mo-on-Si interfaces with pm-accuracy. Our analysis revealed that at one type of interface the interlayer grows non-parabolically, exhibiting nonconstant interdiffusion characteristics. Remarkably, during the interlayer growth the activation energy for interdiffusion at one, namely the Si-on-Mo interface increases smoothly from 1.7 eV to 2.5 eV, whereas the activation energy at the other, the Mo-on-Si interlayer stays nearly constant, namely about 2.6 eV. Furthermore, wide angle X-ray diffraction at different stages of the annealing cycle showed the evolution of Mo crystallites to be strongly correlated to the interlayer growth. This leads to the conclusion that the stoichiometry of the growing Mo-on-Si and Si-on-Mo interlayers is noticeably different and much determined by the template of the surface. This example of our research is aimed to identification of such phenomena since they contain new physics which is additionally of vital interest for the practical application of multilayer optics.

Competition between interface reaction mechanisms in Mo/B_4C/Si/B_4C multilayers
Another example on the stability of multilayer optics concerns new designs with diffusion barrier layers. The placement of such barriers between Mo and Si layers effectively lowers Mo-Si interdiffusion rates and thereby extends optics lifetime to application relevant timescales. However, in spite of their success the physical and chemical processes occurring at the interfaces are not yet fully understood. In contrast to standard Mo/Si multilayers, where a single process of high density Mo-Si formation at the interfaces leads to a continuous reduction in the multilayer period when increasing the temperature, a typical barrier system like Mo/B_4C/Si/B_4C surprisingly exhibits first a period expansion followed by a period compaction. To study this, annealing experiments were carried out on the individual Mo/B_4C, Si/B_4C, Mo/C, Mo/B, Si/B, and Si/B systems. It was found that the initial period expansion in Mo/B_4C/Si/B_4C is caused by formation of low density silicon borides at the Si/B_4C interfaces. In addition, the temperature dependence of the period reduction in Mo/B_4C/Si/B_4C strongly suggested that high density Mo-Si formation still takes place in Mo/B_4C/Si/B_4C

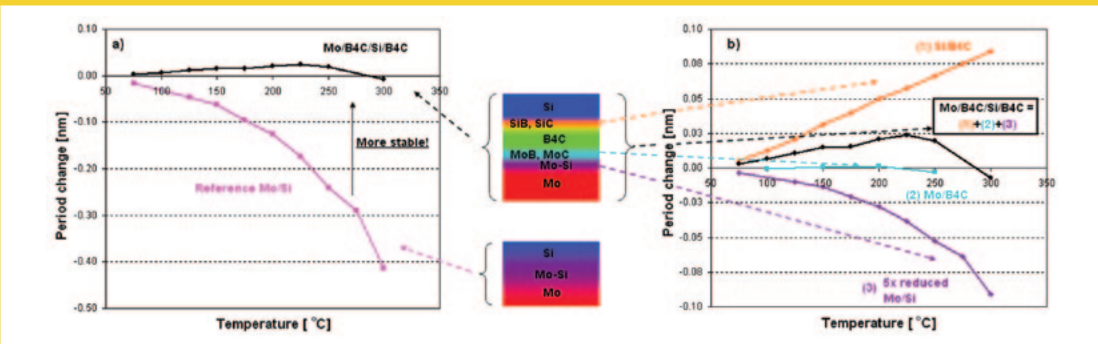


Figure 2.21 (a) Change of multilayer period in Mo/Si and Mo/B_4C/Si/B_4C multilayers. The picture shows the effectiveness of diffusion barriers in mitigating layer compaction. (b) The change of periodicity in Mo/B_4C/Si/B_4C can be explained accurately by the formation of Si-B at Si/B_4C interfaces(1), during which the B_4C barrier slows down, but not fully stops the Mo-Si formation (3).

multilayers, albeit with formation rates reduced by a factor of 5. In effect, the period reduction related to formation of high density Mo-Si partially compensates for the period expansion that is related to the formation of low density Si-B compounds.

Developing spectral purity enhancement systems

The spectral output of most EUV light sources is by far not monochromatic and often shows large contributions outside the 13.5 nm band used for imaging. Unfortunately, the current multilayer designs have high efficiency in reflecting such out-of-band radiation, resulting in exposure to this “parasitic radiation”. The examples of research given below concern anti-reflectance (AR) coatings to filter out the radiation of several wavelengths in the DUV (100-400 nm) and IR (10.6um) range.

The AR coating for suppressing the DUV range, for instance, need to follow critical design rules with respect to the film thickness, as well as to the refractive and absorptive parts of the optical constants. Especially a low absorption coefficient is critical, and this effectively limits the materials that could be used to a short list of low density elements. However, this list can be extended by considering new compounds of such elements, tailoring the optical constants to the required values by modifying film composition and structure. Experiments were carried out where thin films of Si_XB_Y, B_XC_Y, Si_XC_Y, and $Si_XC_YN_Z$ were deposited, and the relation between film composition and optical constants was explored. Spectroscopic ellipsometry measurements showed that $Si_XC_YN_Z$ films are good candidates for AR coatings, based on their refractive and (low) absorptive behaviour.

To suppress the out-of-band IR radiation, another case of spectral filtering, we developed a multilayer structure that uses resonant absorption effects in thin metal films. A system consisting of parallel thin metal films separated by a dielectric layer of certain thickness acts like a resonator. By depositing IR-transparent multilayer structures on such an absorptive system it appeared to be possible to achieve very good spectral filtering properties. We found that B_4C/Si multilayer systems are sufficiently IR-transparent and at the same time can provide high EUV reflectance. The described systems were implemented using in-house UHV deposition facility. The measured spectral characteristics showed up to 3 orders of magnitude reduction of the IR reflectivity, while retaining a high EUV reflectivity (Figure 2.22).

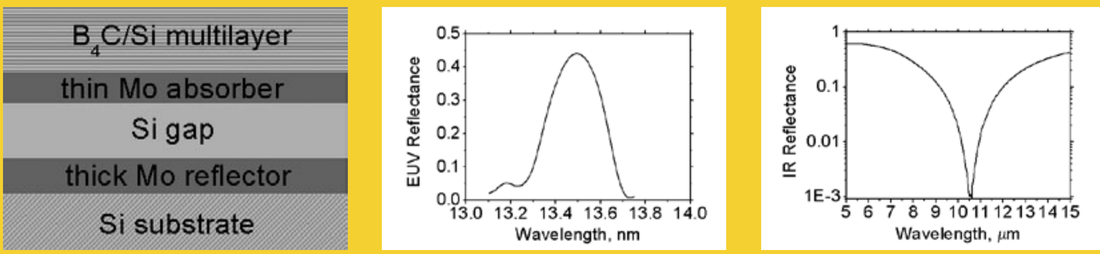


Figure 2.22 Sketch of the EUV reflecting multilayer structure with the resonant absorbing structure (left), measured spectrum of EUV reflection (middle), and measured spectrum of the IR reflectance (right) for the B_4C/Si multilayer integrated with IR absorbing structure.

2.3.4 Extreme Ultraviolet Group (EUV)

Division:	nanolayer Surface and Interface physics
Group leader:	C. J. Lee
Postdoctoral scientist:	J. M. Sturm
PhD students:	A. Gao, F. Liu, A. Dolgov
Funding:	FOM Industrial Partnership Programmes I23, M2i, Carl Zeiss SMT, ASML

Research programme

The research program of the EUV group is focused on understanding the surface chemistry in the harsh environment of plasmas and extreme ultraviolet radiation (EUV). The research is funded by 'Controlling photon and plasma induced processes at EUV optical surfaces' (I23), which is a FOM Industrial Partnership Programme, and the M2i consortium. Our research facilities are based at ASML, who are both cofounders and participants in the research program.

The advanced multilayer structures developed in the nSI group are required for optical elements operating at Extreme UV wavelengths. However, the high photon energy also creates, through direct and indirect processes, ions and radicals. These highly reactive species interact with each other and the mirror surface to create new species, some of which are stably adsorbed on the mirror surface. These surface layers may act as a protective coating against further depositions, or they may simply be the beginning of a process that degrades the surface, and, in the case of mirrors, reduce their reflectivity.

Alternatively, one can view this process as a controllable deposition method that can be used to create novel materials. The photo-induced nature of the physical and chemical processes that lead to deposition mean that it may be possible to create structures with lateral dimensions on the order of the resolution of an imaging process.

Taken together, the goal of the research program can be summed up as understanding and controlling photochemical processes in an EUV environment with a view to either preserving existing structures or depositing new ones.
To achieve this, the EUV group has a vacuum chamber equipped with temperature programmed desorption spectroscopy (TDPS), reflection absorption infrared spectroscopy (RAIRS), an ion gun, and a gas dosing system. This chamber is located at ASML, where it is attached to an EUV source.

Instrumentation development and commissioning
The EUV group is a new group, and, as a result, much of the past year has been devoted to setting up and commissioning new instruments.

For ex-situ characterization of samples, we have developed a multi-wavelength photoluminescence spectroscopy imaging system. We are able to collect excitation and emission spectra, as well as Raman spectra. This system is now fully operational and is being used to perform Raman spectroscopy measurements on samples modified by EUV radiation as well as photoluminescence studies on particles.

The chamber, as delivered to ASML, has had several minor modifications in order to ensure that samples can be adequately cleaned in situ. The TDPS system is operational, and an effective sample cleaning recipe is currently being developed. The RAIRS system is not yet fully operational, with a new detector expected to arrive in the first quarter of 2012.

As a part of setting up these existing instruments, we are also working on novel instrumentation and techniques with better sensitivity and/or specificity. An in situ fiber ellipsometer is being developed, and other optical techniques, such as tip-enhanced Raman spectroscopy are under consideration.

Collaborative work
The EUV group has strong links with ISAN, located in Russia. At ISAN, the work concentrates on understanding the plasma conditions in the vicinity of the multilayer mirror or surface of interest. Early work focused on carbon contamination and direct atomic hydrogen cleaning. The end goal of this work, however, is to create a self-cleaning environment. To achieve this goal, the production of hydrogen radicals, which are produced during the EUV light's interaction with the background gas, must be optimized. This optimization depends on understanding the plasma parameters during and after the EUV light pulse. The characterization of such low density plasmas is a challenge. FOM students at ISAN are developing Langmuir probes and numerical models to understand the plasma conditions. In addition, optical and microwave methods for plasma characterization are being explored.

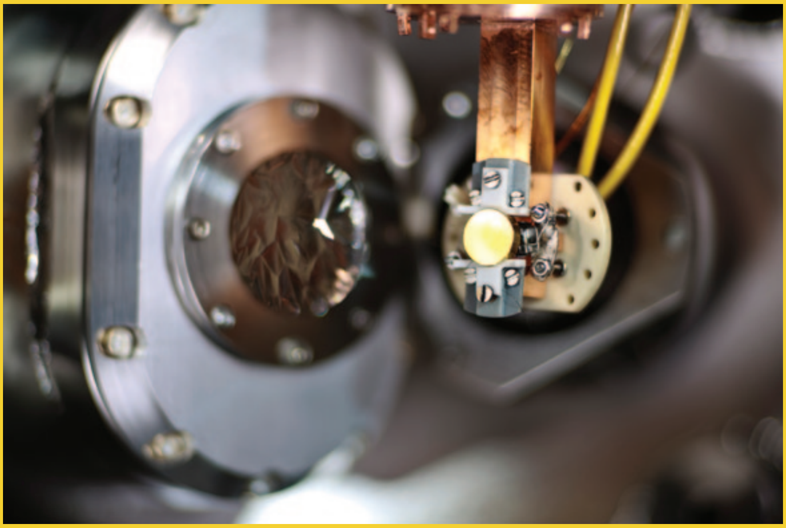


Figure 2.23 Gold sample in the vacuum chamber. At the left, the spectral purity filter, through which the EUV is incident on the sample, is visible.

2.4 Generation and Utilization of TeraHertz radiation

Mid- and far-infrared radiation, or Terahertz (THz)-radiation is the key element of the activities in the division GUTHz. The infrared region, commonly referred to as the molecular 'fingerprint' region, allows for identification of molecules and molecular structures by the position of the bands in the vibrational spectra. Towards longer wavelengths into the THz regime, the radiation probes structures of solids and low frequency collective modes in soft condensed matter including e.g. proteins.

The objectives of the department are:

- To operate a world-leading infrared user facility that offers the international community access to very bright, infrared radiation sources, tunable over the spectral range from 3 μm - 250 μm.
- To run a molecular physics program focused on elucidating the structure and dynamics of (complex) molecules, ions and clusters in the gas phase, with applications to life sciences, catalysis and astrophysics.
- To create a stimulating scientific environment for visiting user groups active in various fields of research, such as solid state physics and ion spectroscopy of biomolecules.

The division receives financial support under FOM-program 58. Additional funding is provided through a contract with the British Research council EPSRC and via the ELISA project, an integrated infrastructure initiative under the European frame work programme 7, that comprises all European synchrotron and free electron laser facilities; the Molecular Dynamics group participates in the Dutch Astrochemistry Network and within the group Dr. A.M. Rijs was supported by a FOm/v grant.

Group Description

The GUTHz department consists of the FELIX group and the Molecular Dynamics group. The FELIX group operates the international infrared user facility FELIX (Free Electron Laser for Infrared eXperiments). This facility was designed and constructed to provide the scientific community with tuneable, high brightness radiation in the mid- and far-infrared. The group's prime responsibility is to push the performance and development of the Free Electron Laser (FEL) based infrared and THz sources that are at the heart of this facility. With the recent commissioning of the Free Electron Laser for Intra-Cavity Experiments (FELICE) beam line, the capabilities of the facility in the field of action spectroscopy have been greatly enhanced. By enabling experiments inside the laser resonator, the intensity in the interaction region is boosted by a factor of more than fifty over the spectral range from 3 to 100 μm.

The in-house user group Molecular Dynamics exploits the radiation generated by FELIX and FELICE for a variety of studies in the field of molecular sciences. The success of the in-house group attracted a large number of other user groups, some of which made use of the existing setups, while others installed large, dedicated equipment. More than 50% of the beam time is nowadays devoted to this kind of action spectroscopy experiments.

FELIX

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

FELICE

FELICE stands for Free Electron Laser for Intra-Cavity Experiments. This project, a major extension of the FELIX facility, involves the construction of a third beam line which can be operated interleaved with one of the two FELIX beam lines at a maximum repetition rate of 10 Hz for each line and is therefore in fact doubling the amount of beam time available to the users. The purpose of FELICE is to provide significantly higher infrared intensities for low-absorption, gas-phase experiments and the beam line is now operated routinely for in-house and external users. For experiments in the gas phase, two specialized intra-cavity setups, a molecular beam apparatus and a Fourier Transform Ion Cyclotron Resonance (FTICR) mass spectrometer, have been constructed.

Figure 2.24 Close-up of the quadrupole ion guide that transfers the ions into the ICR cells of the second FELICE experiment, the FTICR mass spectrometer.

Molecular Dynamics
As an in-house user of FELIX, the Molecular dynamics group applies the FELIX and FELICE radiation for various experiments in the field of molecular spectroscopy and dynamics, mainly of low-density species in the gas phase. Systems studied include (bio) molecular ions, complexes, radicals, metal clusters (complexed with small molecules), and biomolecules. These are studied using various experimental methods, such as molecular beam, laser double resonance, and ion storage techniques, all based on IR excitation followed by mass spectrometric ion detection. 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 using approximately 25% of the total FELIX beam time.

Strategic highlights 2011

As the ambition of the GUTHz department is to run the FELIX facility with world-wide unique capabilities, the development of new infrastructure and in particular the new FELICE beam line have been vital activities. Concerning infrastructure, several experimental set-ups have been developed, e.g. the high-resolution FTICR mass spectrometer and the versatile molecular beam apparatus. In 2011 the FELICE project has reached all of its milestones with the successful commissioning of the FELICE electron beam line, the two intra-cavity setups, interleaved operation, i.e. in parallel with one of the FELIX beam lines and the full specified spectral range of 3 – 100 μm.

The by far most important strategic highlight however, is the recent decision to relocate the facility and the personnel of the GUTHz department to the Institute for

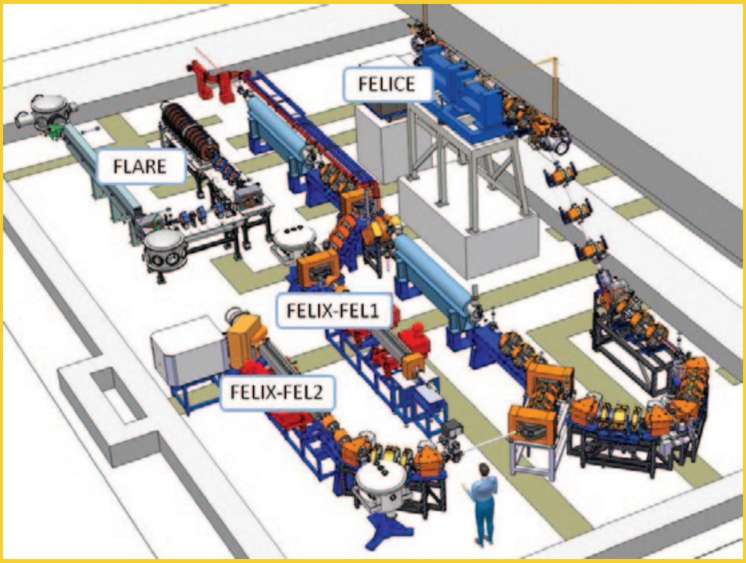


Figure 2.25 Artist's view of the FELIX free-electron laser facility in Nijmegen, combining FLARE, FELIX and FELICE. The four infrared and THz beam lines of the FELIX facility are shown: FLARE (100 – 1500 μm), FELIX-FEL1 (30 – 140 μm), FELIX-FEL2 (3 - 45 μm), and FELICE (5 - 100 μm).

Materials and Molecules (IMM) of the university of Nijmegen (RU), to merge into a new facility with the acronym FELIX. The free-electron laser FLARE, which is presently under commissioning at RU and achieved first-lasing in September 2011, has been designed to cover the spectral range from 100 to 1500 μm. Therefore, it is complementary to the FELIX specifications. Apart from the conventional short-pulse mode, it will also have a special narrow bandwidth mode of operation. The latter is particularly suited for EPR experiments in the high magnetic fields provided by the next-door High Field Magnet Laboratory (HFML). The FELIX facility at Nijmegen will be able to provide experimental opportunities that are world-wide unique. The possibility to combine the outputs of FELIX and FLARE in one single experiment, and the opportunity to perform studies in the very high magnetic fields of HFML in combination with infrared radiation over the entire spectral range from 3 – 1500 μm, stand out in this respect.

An agreement between FOM and RU has been signed, on the transfer (in 2012/2013) of the personnel and equipment and the sharing of the costs of the facility for the period 2013 - 2023.

2.4.1 The IR user facility FELIX / FELICE

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

The Free Electron Laser for Infrared eXperiments, FELIX, has been designed and constructed with the aim to offer the international scientific community access to very bright, tunable mid- and far-IR sources, to keep these sources at a world-wide competitive level, and to enable complex user experiments by providing a sophisticated infrastructure.

The FELIX group operates the international infrared user facility FELIX and it's prime responsibility is to push the performance and development of the Free Electron Laser (FEL) based infrared and THz sources at the heart of this facility. In line with this goal, the efforts are aimed at providing the best possible conditions for the user experiments, including optimization of the FEL output, availability and reliability, user support, and upgrades of the FELs and the infrastructure.

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. 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 program on molecular dynamics. A further 20% is earmarked for researchers from the UK under the EPSRC contract leaving 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 ELISA contract.

Many improvements and extensions have been made to the facility since it became operational. To name a few key parameters: 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, the length of the optical pulses is adjustable between ~6-100 cycles, and 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 as well as several molecular beam machines and advanced ion traps with different external ion sources.

A major upgrade - the Free Electron Laser for IntraCavity Experiments “FELICE” - involves the construction of a third beam line dedicated to gas-phase, intra-cavity experiments in the wavelength range from 3 to 100 µm. It was recently fully commissioned and operates 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. The increase as compared to FELIX is more than a factor of fifty in the spectral range from 3 to 100 µm. The experiments performed on FELICE are done in two specialized intra-cavity setups – one containing a molecular beam apparatus and the other an FTICR mass spectrometer.

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 wide range of scientific backgrounds, from materials engineering and physics to chemistry and biology, coming both from the Netherlands and abroad.

The first experimental campaigns using FELICE already indicated that a broad user community could benefit from this new installation. For example 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.

Highlights of user experiments in 2011

FELIX: Infrared spectroscopy on a two-stage artificial motor rotaxane
Molecular motors are used in nature to drive a large number of fundamental processes by converting chemical energy into directed motion. These biomolecular motors have inspired the development of artificial motors of which the so-called [2]rotaxanes have attracted considerable attention. They are molecular systems composed of a macrocyle mechanically locked onto a linear thread by two bulky stoppers. In general the thread contains one or more recognition sites (stations) with which the macrocycle can form hydrogen bonds and therefore prefers to reside on. The possibility of a controlled translocation – “shuttling” – of one component with respect to the other makes rotaxanes promising candidates for applications as molecular devices.

Here, high resolution IR spectroscopy using FELIX has been employed to study isolated, switchable [2] rotaxanes. IR absorption spectra of a two-station rotaxane, their separate thread and macrocycle as well as the individual stations that are incorporated into the thread have been measured. The analysis gives a comprehensive picture of the conformational structure and binding interactions between the mechanically interlocked components of the rotaxane. It is inferred that the frequency changes of the characteristic vibrations of the C=O stretching and the NH bending modes allow a detailed study of the shuttling process of the rotaxane under isolated conditions. This opens exciting new ways to experiments in which the shuttling is triggered by an external stimulus that will eventually lead to a better understanding of the functioning of molecular machinery.

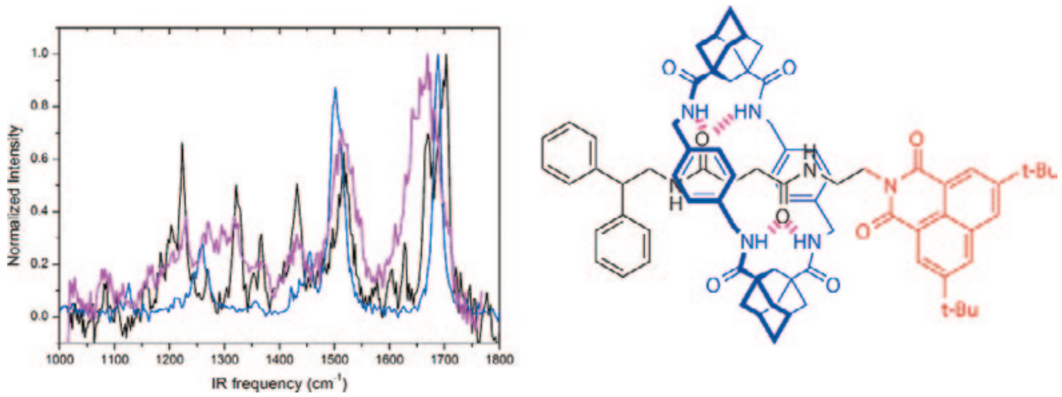


Figure 2.26 Left: The infrared spectra of the thread (black) with its two “stations”, the macrocycle (blue) and the complete rotaxane with the macrocycle onto the thread (purple). Right: The studied two-stage rotaxane showing the linear thread with its two stations in black and red and the mechanically locked hydrogen bonded macrocycle in blue.

FELICE: Structure Determination of Anionic Metal Clusters

Using FELICE, the Free Electron Laser for Intra-Cavity experiments, a new method for determining the vibrational spectra of anionic metal clusters – infrared resonance enhanced multiple photon electron detachment (IR-REMPED) – has been demonstrated.

The physical and chemical properties of nano-sized metal particles are often strongly size-dependent and can vary drastically from those of the bulk. The charge of the nanoparticles can also substantially influence their characteristics and is known to be crucial, for instance, for the catalytic activity of deposited gold nanoparticles. Therefore it is of fundamental interest to develop novel experimental methods that allow to unravel the geometric and electronic properties of metal nanoparticles of a given size and charge.

Variants of IR absorption spectroscopy developed for (strongly-bound) neutral and cationic metal clusters in the gas phase have produced a wealth of structural information. For anionic metal clusters, however, IR spectra have not been recorded so far, in part because the application of similar techniques is prohibitively difficult. Moreover the fundamental vibrations of bare metal clusters often have low IR intensities and are found in the far-infrared. Measuring the infrared spectrum via e.g. electron detachment therefore requires the absorption of many IR photons as provided by free electron laser based sources.

The experiments with FELICE on anionic niobium and niobium carbide clusters show that electron detachment by multiple photon excitation is possible even for the weak IR bands of transition metal clusters. IR-REMPED spectroscopy is a new way to investigate metal cluster anions and is expected to be applicable to a wide range of clusters allowing the determination of their geometric properties.

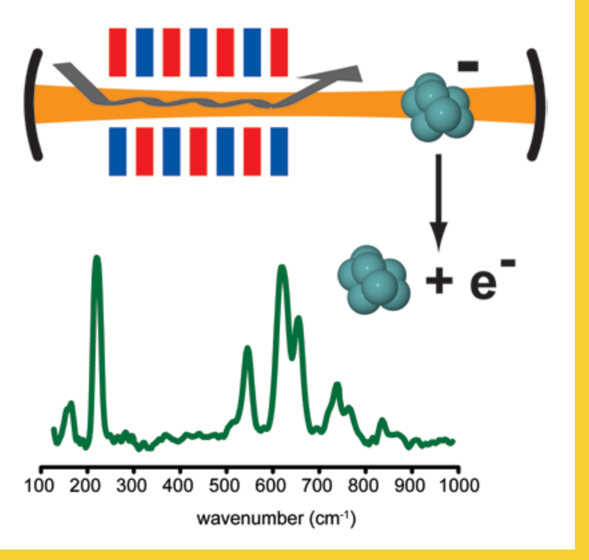


Figure 2.27 Illustration of an anionic cluster irradiated by infrared light inside the FELICE cavity. If the infrared frequency is in resonance with a vibration of the cluster an electron is detached and by measuring the detachment as a function of wavelength the infrared spectrum of the cluster under study can be determined.

2.4.2 Molecular dynamics

Division:	Generation and Utilisation of THz Radiation
Group Leader:	J. Oomens
Senior scientists:	A.M. Rijs, J.M. Bakker
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Undergraduate students:	G.C.P. van Zundert, M. Almasian
Technician:	J. Pluygers
Collaborators:	P.B. Armentrout, A. Mukherjee, A. Sweeney, R. Thomas, O. Wheeler (U Utah, Salt Lake City, UT), W.J. Buma (University of Amsterdam, The Netherlands), M.S. de Vries, M. Ligare (UC Santa Barbara), O. Dopfer, A. Gunther, J. Langer (Technical University, Berlin, Germany), R.C. Dunbar (Case Western Reserve University, Cleveland, OH), J.R. Eyler (University of Florida, Gainesville, FL), J. Fernandez, E. Cocinero, I. Leon, E. Alonso (University of Bilbao, Spain), I. Fischer (University of Wurzburg, Germany), V. Gabelica, F. Rosu, E. de Pauw (University Liege, Belgium), A. Kirilyuk, J. Jalink (Radboud U, Nijmegen, The Netherlands), B. Martinez-Haya (U Pablo Olivade, Seville, Spain), E.J. Meijer (U of Amsterdam, The Netherlands), M. Mons, E. Gloaguen, M. Cirtog, Y. Loquais (CEA Paris, France), T.H. Morton, J. Bendo (UC Riverside, CA), N.C. Polfer, M. Tirado (University of Florida, Gainesville, FL), D.P. Ridge, K. Papson (University of Delaware), M.T. Rodgers, D. Nei (Wayne State U, Detroit, MI), V. Ryzhov, S. Osburn (University of Northern Illinois, DeKalb, IL), M. Schäfer (U Cologne, Germany), K.W.M. Siu, U. Verkerk (York University, Toronto, Canada), J.D. Steill (Sandia NL, Livermore, CA), M.T. Vala (U Florida, Gainesville, FL), W.J. van der Zande (Radboud University, Nijmegen, The Netherlands), J. van Maarseveen (University of Amsterdam, The Netherlands), M.J. van Stipdonk (Wichita State University, Wichita, KS), G. von Helden, K. Pagel, S. Warnke (MPG Berlin, Germany), E.R. Williams, T. Chang, M. Demireva (UC Berkeley)
Funding:	FOm/v grant (A.M. Rijs), NWO Athena grant, NWO CW/EW Dutch Astrochemistry Network: The photochemical evolution of PAHs

Research goals

To address research questions in molecular physics and chemistry, in particular by exploiting the capabilities of the FELIX facility for recording gas-phase infrared spectra of extremely low-density species of interest in bio-chemistry, mass spectrometry, astrochemistry, catalysis and cluster science.

Highlights 2011

Electronic versus geometric stability in polyaromatic carbocations
Carbocations play a fundamental role as reaction intermediates in organic chemistry. However, characterizing their physico-chemical properties is often impeded by their high reactivity. For instance, the electronic character of the phenyl cation (Figure 2.28a) has long been under discussion.

With its even number of electrons, one may anticipate the phenyl cation to possess a singlet electronic ground state in which all electrons are paired, similar to nearly all stable organic molecules. However, the empty σ-orbital on the positively charged carbon atom changes the hybridization of this C-atom from sp^2 to sp, causing a strong deformation of the hexagonal symmetry of the carbon frame. It was therefore suggested that an electron moves from the π-system to the empty σ-orbital restoring the six-fold symmetry, at the expense of electronic stability as the system now possesses two unpaired electrons resulting in a triplet electronic state.

It is now well known that electronic stability wins over geometric stability in the phenyl cation, such that the singlet state is 70 kJ/mol lower in energy than the triplet state.

Increasing the aromatic π-system lowers the energy required to remove an electron from it, so that it becomes easier to sacrifice a π-electron to fill the vacant σ-orbital. Calculations suggest that singlet and triplet states are equally stable for the naphthyl cation, which consists of two aromatic rings (Figure 2.28a). In order to experimentally establish the electronic character of the naphthyl cation, FELIX has been used to record an infrared spectrum of the isolated (i.e.

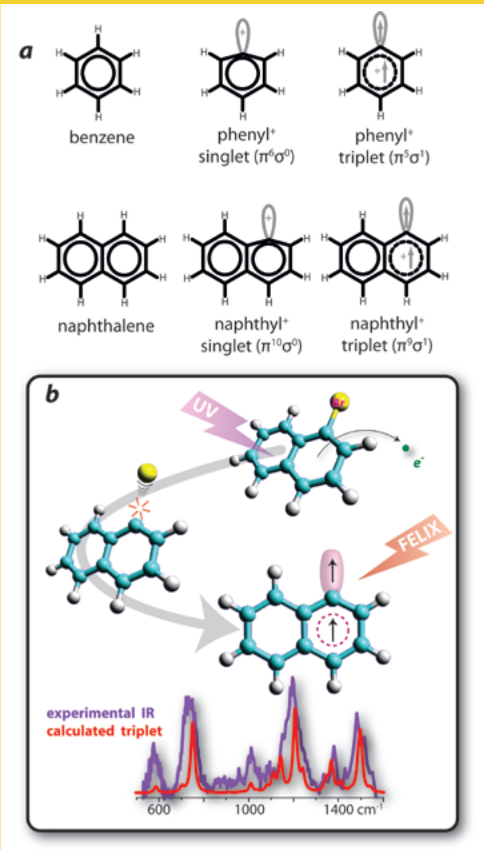


Figure 2.28 Geometric (black) and electronic (gray) structure of the two smallest members of the series of aryl cations, phenyl and naphthyl, in their singlet and triplet states (a). The empty s-orbital (+) in the singlet state induces a deformation of the hexagonal structure. In the triplet state, the hexagonal symmetry is restored at the expense of an open-shell electronic configuration with two unpaired electrons (‘). UV photoionization of bromonaphthalene is employed to produce the naphthyl cation (b), which is then stored in an ion trap. The ions are irradiated with FELIX to record an IR spectrum. Comparing this spectrum to calculated spectra for both electronic states indentifies the electronic character.

gas-phase) naphthyl cation. The very different geometric structures of both electronic states result in different, and hence diagnostic, infrared signatures.

Comparing the recorded infrared spectrum with calculated spectra shows that the naphthyl cation is in a triplet state (Figure 2.28b). In contrast to the phenyl cation, geometric stability wins over electronic stability in the naphthyl cation. Still larger polyaromatic carbocations possess a triplet state that is further stabilized relative to the singlet state. The electronic ground state character is of importance in organic chemistry, but also in astrochemistry, as polyaromatic species are believed to occur abundantly in interstellar clouds; the character of the electronic state influences the behavior of the molecule in chemical reactions, as well as its optical absorption properties.

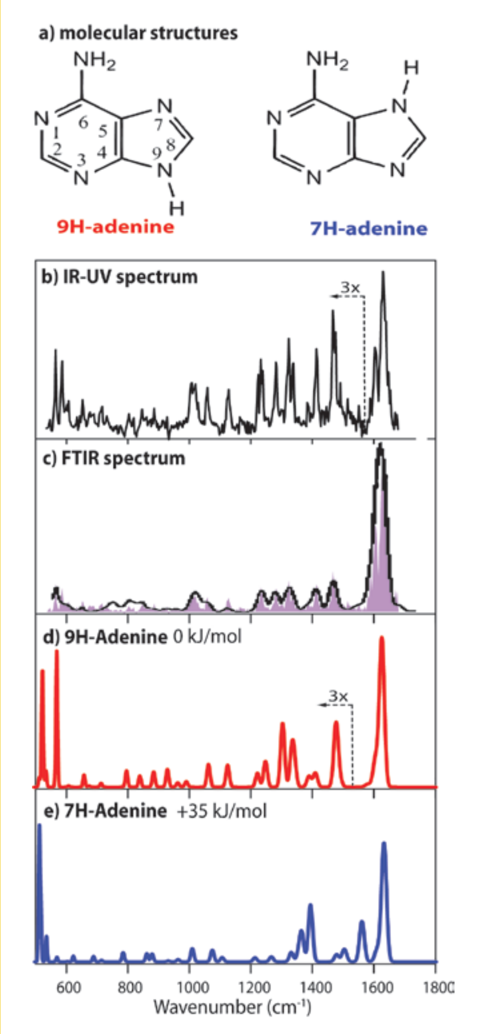
The tautomeric structure of the nucleobase adenine

The biological importance of nucleobases can hardly be overstated and numerous experimental and theoretical studies have been reported on the structural properties of the molecules referred to as G, C, T and A. In addition to its role as a DNA building block, adenine (A) and its derivatives constitute the basis of various other biochemically relevant compounds, such as the energy storing molecule adenosine triphosphate (ATP). The high photostability of adenine under UV irradiation is an intriguing property that has been suggested to be essential for the preservation of the genetic information. The various tautomeric forms of adenine have been under scrutiny as they have been proposed to play a role in mutagenic and carcinogenic processes.

In order to understand the tautomeric preference of adenine, calculations at different levels of theory have been conducted, which consistently predict 9H-adenine to be the most stable tautomer, followed by the 7H-tautomer (Figure 2.29) being about 35 kJ/mol higher in energy.

Some of the first infrared spectra of adenine were recorded in low-temperature inert gas matrices and date back to 1985. The absorption bands observed in these studies were attributed to the 9H-tautomer. To eliminate all possible external influences on the molecular structure, adenine has been studied in the gas phase using a wealth of spectroscopic methods, covering the microwave to UV spectral ranges. Nearly all of these studies suggested that only the 9H-tautomer was present. However, from a spectrum recorded using a heated gas cell and a Fourier-Transform (FTIR) spectrometer in the critically diagnostic infrared range, it was suggested that the sample contained a significant fraction of the 7H-tautomer.

We therefore recorded the IR spectrum of gas-phase adenine in the same IR frequency range using FELIX, an IR-UV double resonance technique and a molecular beam apparatus. The supersonic molecular beam provides expansion cooling reducing the temperature of the molecules to on the order of 30 K, resulting in an improved spectral resolution. The double resonance scheme allows selecting one specific tautomer in the UV excitation step, even if more structures are present in the sample. The IR radiation then selectively probes this tautomeric structure.



The IR spectrum obtained using these methods (Figure 2.29b) is compared to the FTIR spectrum of the heated sample in Figure 2.29c. The two spectra are remarkably similar – apart from the difference in resolution – suggesting that the 9H-tautomer is the dominant contributor in the sample studied with FTIR spectroscopy. This conclusion is further supported by the substantially different calculated spectra of the two tautomers of adenine (Figures 2.29d and 2.29e).

Figure 2.29 Structures and atom numbering for the 9H and 7H tautomeric forms of adenine (a). The IR-UV double-resonance spectrum of adenine (b); the FTIR spectrum of adenine at 280°C, where the IR-UV spectrum of the 9H-tautomer is shown as a silhouette (c); calculated spectra of 9H-adenine (d) and 7H-adenine (e).

2.5 Support Facilities

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

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

Technical groups:

- Mechanical Techniques
- Electronics and Information Technology

General support:

- Management Support
- Financial Administration
- Domestic Facilities

2.5.1 Mechanical Techniques

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

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

The design software in use is Catia V5, the leading solid modeling software used in fusion research. It provides the possibility of modeling assemblies and automatic generation of workshop drawings. For more complex analyses, like strength and stress analysis, heat load analysis, kinematical analysis and frequency analysis, Abaqus is used. All data, used and produces during the design face is stored and managed with the help of SmarTeam, a PDM system.

The manufacturing of the designed equipment is done using several machines, including CNC milling and lathing machines. Hypermill is the CAM software used as an interface between design software and CNC machines. The group also has the knowledge and equipment required for vacuum and high temperature brazing and TIG and laser welding.

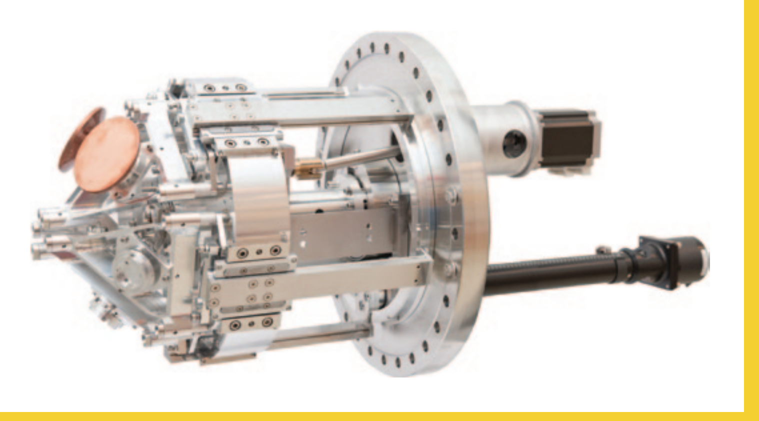


Figure 2.30 Mirror exchange unit for Felix/Felice

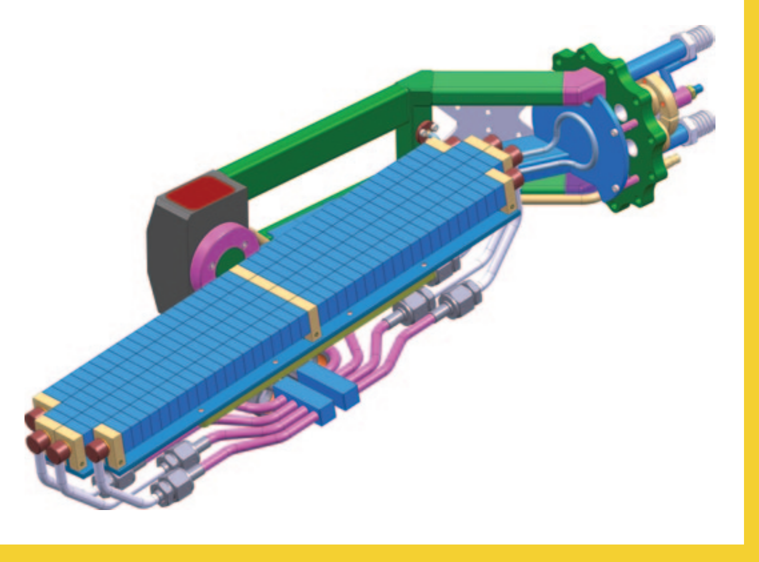


Figure 2.31 Second generation target manipulator for Magnum Psi

2.5.2 Electronics & ICT

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

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

Additionally, specialisations in VHDL-FPGA-based designs and applications with a mix of high frequency, high voltage and/or high current allow the engineers to meet the challenging requirements of advanced experimental set-ups.

Projects during 2011 include a phase-frequency detector for the FADIS project (Garching), remote control unit and crosspoint switch for FELIX, and a completely new and modular design for the high power capacitor bank for pulsed operation in Pilot-PSI. On Magnum-PSI copper coils have been installed. In order to run the copper coils the 20 MW rectifier has been revised and the control and the safety system (BK1) has been completely rebuild.

The software engineers in the E&I group design, implement and maintain automated safety, control and data acquisition systems of the various diagnostics and experiments. In 2011 more emphasis has been put on the software engineering process itself and issue tracking. In this way bug-reports, issues, user feedback of the Magnum team are controlled.

The general Rijnhuizen IT infrastructure includes all computer, communication and information related technology in the institute. An in-house computing cluster is available for running small computation jobs and developing computation jobs for the large Lisa cluster at the SARA computation facility at the University of Amsterdam.

2.5.3 Management Support

Group leader:	W.R. Koppers
Personnel:	E.M. Khan, M.J. van Veenendaal, M.D. van der Vlis, I.H. Vörös, E.C.M. van Wijk

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

Planning

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

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

Planning meetings

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

Project Information Feedback

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

Project control
There is a trend within the organization that scientists experience an increase of project management tasks in their work load. Therefore there is a need for a project control officer to support scientists with tasks as contract formation, tracking and reports and accountability to subsidizers. To address this, project control has been implemented within the organization.

2.5.4 Financial Administration

Group leader:	M.P.M. Schoonen
Personnel:	Y.E.M. Janssen, M.J. Lubbers, N. Nobbenhuis-Versluis, A. Reinders, J.W.M. Sukking, D.Nguyen

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 3900 incoming invoices and 1300 outgoing orders have to be handled. The large number of externally acquired projects and contracts from a variety of funding agencies, often with different rules regarding accountability and matching, makes project administration an increasingly complex activity. A web-based time registration system is implemented for all employees. In close collaboration with the institute manager the detailed budget for each year is drafted and implemented. Information for the budget holders is provided on a web server by means of in-house developed software application.

2.5.5 Domestic facilities

Group leader:	J.E. Kragten
Personnel:	F.F. Hekkenberg, J.C. Bleijenberg-Maarsseveen, J.M. Rietveld-Nieuwhoff, S. van Schaik, P. Stekelenburg – van Woudenberg , J.B. Uwland, LM. van de Ven-van den Akker

The reception desk handles all incoming general phone calls and monitors admittance to the Rijnhuizen buildings. The safety officer is responsible for safety and taking all necessary measures to ensure healthy working conditions. The responsibilities include radiological and environmental safety. Rijnhuizen has a team of about 15 employees trained in first aid, fire extinguishing and accident prevention.

2.5.6 Personnel services (Human Resources)

Group leader:	W.R. Koppers (personnel advisor a.i.)
Personnel:	J.M. van Achthoven and C.L.M. Tonen (Management Support)

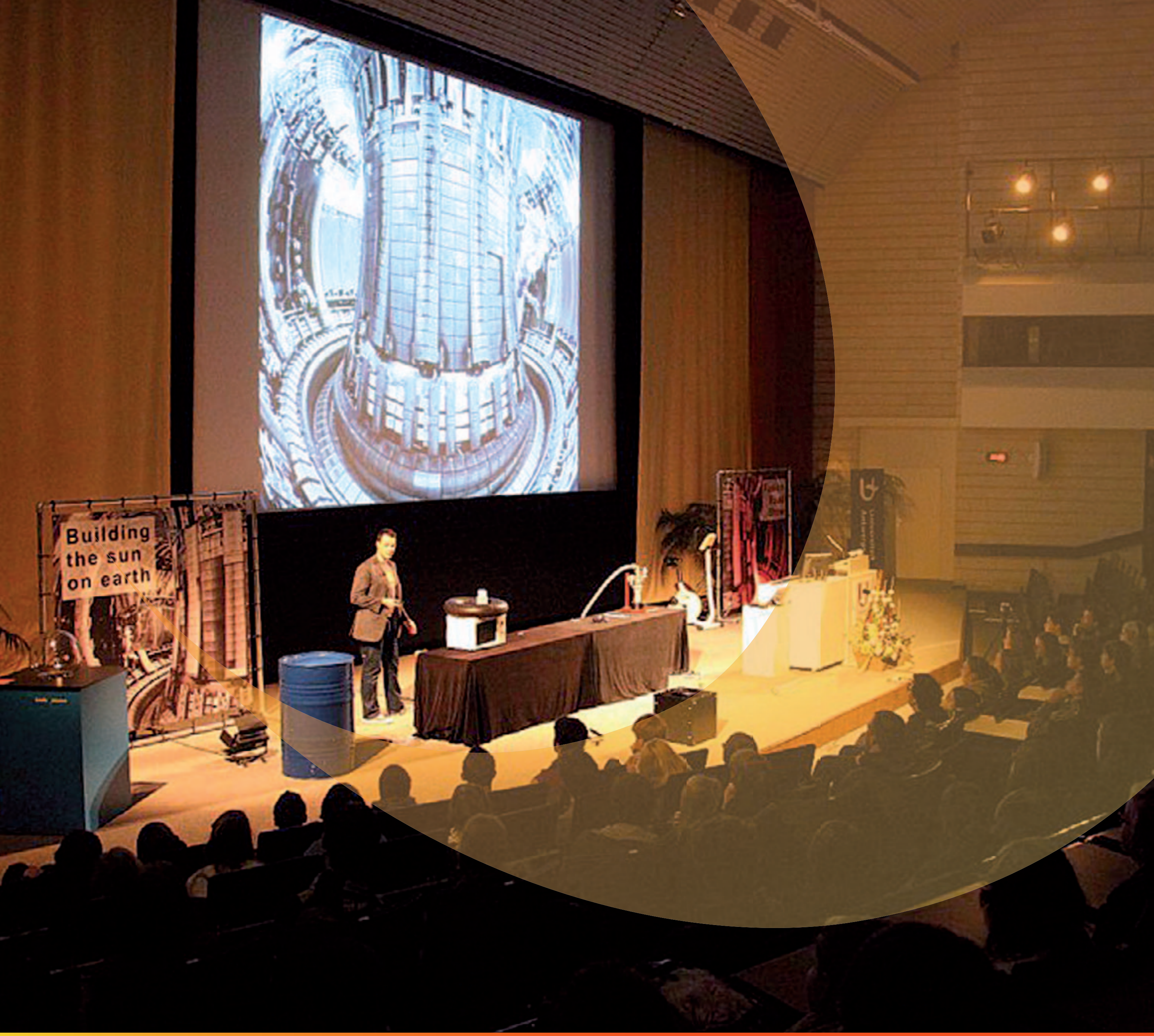
Tasks of Personnel Services Rijnhuizen are:

- 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.

2.5.7 Public Information

Group leader:	F.T.M.E. de Vries
Personnel:	A.P. Visser

The public information group is responsible for the outreach to the general public of the institute. The public information officers are the first point of contact for questions about the research and activitites of the institute. They are also responsible for press releases, websites maintained by the institute, public lectures, open house days and visits to the institute, various educational products and media contacts.



3 Outreach to academia, society and industry

As a government-funded research institute, Rijnhuizen considers knowledge transfer to society of great importance. The institute trains students in a research environment, is involved in formal education at the secondary school to university level, runs a highly visible public information effort, and places particular emphasis on the succesful 'valorisation' of its research by cooperating with and transfering knowledge to industry. This chapter reports on all these activities.

3.1 Education

Training and education of PhD students

At Rijnhuizen, like at other FOM-institutes, the research carried out by PhD students under supervision of members of the scientific staff constitutes a vital part of the research. In 2011, the number of PhD students grew to 40 as a result of a strategic initiative to raise the ratio of temporary to permanent scientific staff at the institute. Thirteen students succesfully defended their PhD thesis in 2011. Around half of the PhD students are not from the Netherlands, which is understandable given the number of physics students in Western Europe. There is a strong awareness of the need for PhD 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.

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 the Netherlands in 2011), the Erasmus summer school on low temperature plasma physics, as well as the annual national plasma physics conference. It is the norm that PhD students go abroad for prolonged research stays, often in Jülich (D) or at JET (UK).

Figure 3.1 Participants in the 2011 Carolus Magnus summer school on fusion physics at FOM Rijnhuizen.

Education of undergraduate students and trainees

While the influx of foreign PhD 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. In 2011, 7 members of the staff held parttime professorships at Dutch universities, and acted as thesis advisors for the academic promotions. As a central activity on the education front, members of the institute staff give lecture courses at several universities. In 2011, the following courses were given:

- Prof.Dr. M. de Baar, B. Hennen MSc et.al., Advanced control of MHD modes, Eindhoven University of Technology
- Prof.Dr. M. de Baar, B. Hennen MSc et.al., Control and operation of tokamaks, Eindhoven University of Technology
- Prof.Dr. M. de Baar et.al., Remote handling – contribution to honours programme, Eindhoven University of Technology
- Prof.Dr. F. Bijkerk, Tutorial XUV Optics, MESA+, University of Twente
- Prof.Dr. A.J.H. Donné, Dr. E. Westerhof, Diagnostics and heating of fusion plasmas, Eindhoven University of Technology
- Prof.Dr. A.J.H. Donné, The 7 challenges of nuclear fusion research, Contribution to Honours Masterclass on Fusion Physics, 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. G.J. van Rooij, Dr. H.J. de Blank, Introduction to Plasma Physics, Eindhoven University of Technology
- Dr. G.J. van Rooij, Thomson scattering and the determination of electron energy distributions, “Atelier FDE”, Institut de Combustion Aérothermique Réactivité et Environnement - CNRS, Orléans, France
- Dr. P. Zeijlmans van Emmichoven, Electrodynamics 2, Utrecht University

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

- Prof.Dr. A.J.H. Donné, Plasma diagnostics for burning plasma devices, Ghent University, Belgium
- Prof.Dr. W.J. Goedheer, Energy from controlled nuclear fusion, contribution to the Bachelor Honours Programme, Utrecht University
- Prof.Dr. W.J. Goedheer, Energy from controlled nuclear fusion, contribution to the Master course on Energy Science, Utrecht University
- Prof.Dr.Ir M.C.M. van de Sanden, Capitalize your scientific results, FOM Young Scientists’ Day

Undergraduate students are welcomed in the research groups to carry out research projects as part of their academic studies. Likewise, students of various levels of technical education are welcome as trainee in either the Division for Technological and Facility support, or in the research groups. In 2010, a total of 35 undergraduate students from universities and trainees were accommodated. To help attract students for an internship, the institute organised 10 visits to the lab for undergraduate or technical school students.

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, the institute offers a one-hour interactive performance called the 'Fusion Road Show', including live physics experiments and audience participation. In 2010, the show underwent a major overhaul of its storyline, main experiments, and style in cooperation with a theater expert. This process was completed in 2011 with the addition of a custom sound track and intro animation. Feedback from teachers and students shows that the new show is more attractive to students of both the sciences and the arts, evoking more questions during the discussion that immediately follows the show and prompting more students to take home information materials about fusion. The show fits well into various parts of the secondary school curriculum, such as physics, general science and societal topics such as energy use.

The Fusion Road Show was performed an all-time record of 40 times in 2011, reaching 7000 students during secondary school visits, and 300 8-12 year olds at three primary schools interested in the energy theme. The Fusion Road Show was the main act at the third edition of the bi-annual Fusion Days at Antwerp University, where 4200 Flemish and Dutch secondary school students and teachers saw one of the seven performances.

As part of the institute's effort to provide secondary schools with good educational material on the energy problem and on fusion, a lessons module for the new high school science subject NLT was developed. The module is in use at several secondary schools and participating students can visit Rijnhuizen to do experiments at a new, dedicated Paschen-curve. In 2011, 13 students (max. 4 per visit) participated in this experiment. During the year, some 130 students from various secondary schools visited Rijnhuizen, either individually, or in a school-organised trip.

The Dutch website www.fusie-energie.nl reaches secondary school students, science journalists, and the general public. It was redesigned in 2011 and now provides information on all the secondary school activities at the institute: the Fusion Road Show, NLT lessons module, and the experiment for visiting students.

3.2 Outreach to society

Activities directed at the general public

The most concentrated outreach effort to the general public is the annual Open House day. This year, the event was organised for the 39th time and attracted over 1000 visitors, a five-year record. In 2011, the Fusion Road Show was performed a total of 10 times in venues other than schools. The show took part in the Utrecht Cultural Sunday and the Groningen Night of Science and Arts, two events where a city's cultural venues open their doors and facilitate science and arts exhibits for the public. Two Rijnhuizen employees manned a fusion stand at the Netherlands' largest music festival Lowlands, where over 13.000 out of 55.000 festival visitors entered the LLowlab Science Center. The duo presented two exhibits from the EFDA-managed travelling Fusion Expo science exposition.

Other outreach activities

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

Figure 3.2 The Fusion stand in the LLowlab science centre at the Netherlands' largest music festival Lowlands. Hands-on demonstrations were used to attract visitors and engage them in the story of fusion energy.

3.3 Knowledge transfer or valorisation

The institute executes an active knowledge transfer programme or valorisation. In 2011, the Industrial Partnership Programme CP3E, where nSI cooperates with ASML and Carl Zeiss on multilayer EUV photolithography optics entered its second year. Part of CP3E is the installation of the FOM group EUV Lab, which works in-house at ASML in Veldhoven. The group is focused on understanding the surface chemistry in the harsh environment of plasmas and extreme ultraviolet radiation (EUV). The goal is understanding and controlling photochemical processes in an EUV environment with a view to either preserving existing structures or depositing new ones.

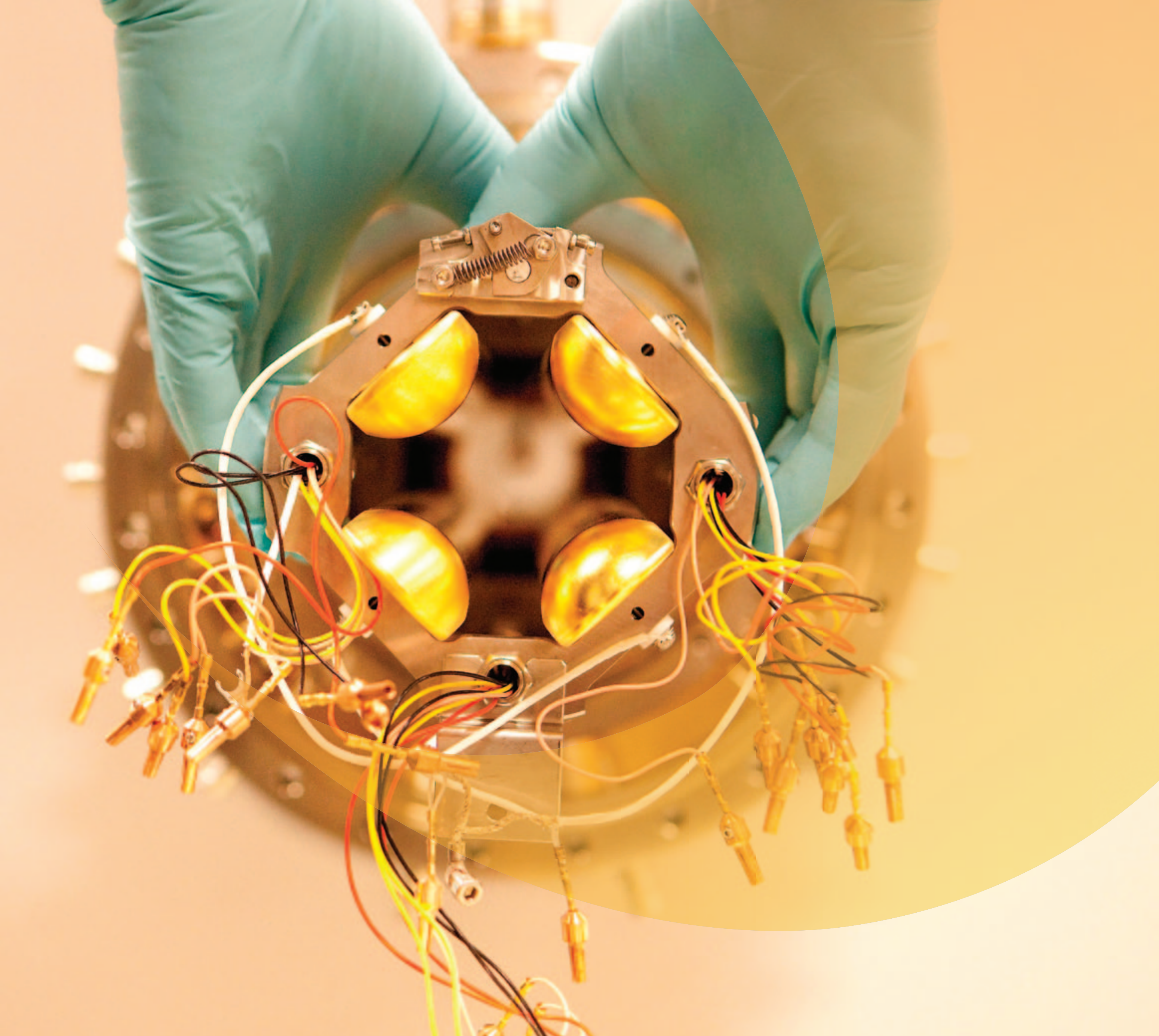
Another prominent valorisation activity at Rijnhuizen is its partipation in the consortium ITER-NL. This cooperation of FOM, TNO, NRG and TU/e aims to position Dutch science and industry for an optimal participation in the construction and scientific exploitation of ITER. Together with the companies Heeze Mechanics, Dutch Space and Nedinsco, ITER-NL has developed prototype plasma diagnostics for ITER.

Another concrete example of the ITER-NL activity is the start of the Remote Handling Study Center at the institute, a cooperation of Rijnhuizen and Heemskerk Innovative Technology. Here, proposed components for ITER can be analysed in virtual reality to improve their compatibility with remote handling maintenance procedures at ITER. The Study Center offers world-wide unique capabilities in simulating remote handling procedures and has already completed studies for the ITER organisation and for the Japanese Domestic Agency for ITER.

Figure 3.3 Remote Handling Study Center at the institute, a cooperation of Rijnhuizen and Heemskerk Innovative Technology.

In the PSI division, researchers cooperated with the company Element6 on advanced schock-resistant materials with applications in fusion and beyond, such as in aerospace. Together with Urenco, a project is undertaken to develop new techniques of treating tungsten, the main candidate material for the ITER divertor.

For ITER-NL, Rijnhuizen supplies the Industrial Liaison Officer, who assists Dutch companies in succesful participation in the ITER construction. ITER-NL maintains a comprehensive overview or company browser, which matches the areas of expertise of Dutch companies interested in tendering for ITER with the ITER work packages. Companies are alerted to interesting tenders via news letters and are supported via information meetings and an annual day for industry. The ILO represents and accompanies companies at conferences. In 2011, the ITER-NL ILO joint forces with ILO's for other Big Science projects, the Ministry of Economic Affairs (Agentschap-NL), Dutch science organisation NWO and employers' organisation VNO-NCW to start up a Dutch ILO-network. The will serve as a point of contact for all Dutch high-tech companies interested in contracts from Big Science.



4 Output

Output of Fusion Physics

PhD theses

H.J. van der Meiden, *Thomson scattering on low and high temperature plasmas*, PhD thesis at the Eindhoven University of Technology, 14 February 2011

G.W. Spakman, *Two-dimensional heat transport in tokamak plasmas*, PhD thesis at the Eindhoven University of Technology, 18 May 2011

D. De Lazzari, *Stabilization of magnetic islands in tokamaks by localized heating and current drive*, PhD thesis at the Eindhoven University of Technology, 23 May 2011

E.G. Delabie, *Neutral beam driven hydrogen spectroscopy in fusion plasmas*, PhD thesis at the Eindhoven University of Technology, 23 May 2011

T.W. Versloot, *Edge rotation and momentum transport in JET fusion plasmas,* PhD thesis at the Eindhoven University of Technology, 12 September 2011

B.A. Hennen, *Feedback control for magnetic island suppression in tokamaks*, PhD thesis at the Eindhoven University of Technology, 12 October 2011

G. Witvoet, *Feedback control and injection locking of the sawtooth oscillation in fusion plasmas*, PhD thesis at the Eindhoven University of Technology, 21 December 2011

Bachelor theses

S.J. Wouda*, Remote Handling maintenance for the Mid-Section Optics*

Publications in peer-reviewed scientific journals

B. Ayten, D. De Lazzari, M.R. de Baar, B.A. Hennen, E. Westerhof and the TEXTOR Team, *Modelling of tearing mode suppresssion experiments in TEXTOR based on the generalized Rutherford equation*, Nucl. Fusion 51 (2011) 043007

A.A. Balakin, N. Bertelli and E. Westerhof, *Wave beam propagation through density fluctuations*, IEEE Trans. Plasma Sci. 39 (2011) 3012-3013

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P.C. de Vries, *Experiments at JET in preparation of ITER*

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M.R. de Baar, *Sensing and sensibilising*

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A.J.H. Donné, *Japanese-Dutch collaborations in fusion physics*

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A.J.H. Donné (presented by M.F.M. de Bock), *Control of a burning plasma with a limited set of diagnostics*

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A.J.H. Donné, J. Rapp and J.G. van der Laan, *Outlook of the Dutch fusion physics and technology programme, 2011 - 2020*

1st EFDA General Planning Meeting, 5-6 May 2011, Garching, Germany
M. Garcia-Munoz, F. Meo, S. Äkäslompolo, J. Boom, I. Classen, B. Geiger, G. Gorini, M. Nocente, G. Tardini, M. Tardochi and the ASDEX Upgrade Team, *Fast-Ion Diagnostics in AUG*

19th Topical Conf. on Radio Frequency Power in Plasmas, 1-3 June, Newport, RI, USA
N. Bertelli, D. De Lazzari and E. Westerhof, *ECCD requirements for the NTM suppression*

480th Wilhelm and Else Heraeus Seminar: Active control of instabilities in hot plasmas, 16-18 June 2011, Bad Honneff, Germany
B. Ayten and E. Westerhof, *Dynamics of tearing mode stabilization*

5th International ITER Summer School on Fast Particles, 20-24 June 2011, Aix-en-Provence, France
A. Kappatou, *Feasibility of Charge Exchange Spectroscopy fast helium measurements on ITER*

Symposium on Fusion Engineering, 26-30 Jun 2011, Chicago, USA
D. Strauss et al, among them M. de Baar, and D. Ronden, *Preliminary Design of the ITER ECH Upper Launcher*

EPS 2011 - 38th European Physical Society Conference on Plasma Physics, 27 June – 1 July 2011, Strasbourg, France
M.J. Choi, G.S. Yun, J. Lee, H.K. Park, C.W. Domier, N.C. Luhmann, Jr, B. Tobias, A.J.H. Donné, and KSTAR team, *Detailed 2-D imaging of growth and burst of edge-localized filaments in KSTAR H-mode plasmas* (poster P1.082)

S. da Graça, G.D. Conway, P. Lauber, V. Igochine, D. Borba, D. Curran, I.G.J. Classen, M. Garcia-Muñoz, M. Marachek, M.A. Van Zeeland, A. Silva, F. Serra, M.E. Manso, N.C. Luhman, H.K. Park and the ADEX Upgrade Team, *Fast particle mode studies with NBI heating on ASDEX Upgrade using reflectometry* (poster P1.084)

J.P. Goedbloed and J. Freidberg, *Poloidal and toroidal plasma rotation and resistive wall modes in tokamaks* (poster P1.091)

S. Djordjevic, M.R. de Baar, M. Steinbuch, J. Citrin, G.M.D. Hogeweij, *Controllability analysis for the magnetic flux in ITER* (poster P1.108)

J.E. Boom, E. Wolfrum, I.G.J. Classen, P.C. de Vries, B.J. Tobias, C.W. Domier, N.C. Luhmann Jr, H.K. Park and the ASDEX Team, *2D ECE-imaging measurements of Type-II Edge Localized modes (ELMs) at ASDEX Upgrade* (poster P1.123)

J. Citrin, J. Hobirk, M. Schneider, J.F. Artaud, C. Bourdelle, K. Combre, G.M.D. Hogeweij, F. Imbeaux, E. Joffrin, F. Koechl, J. Stober, the AUG Team, JET-EFDA contributors, and the ITM-TF ITER Scenario Modelling Group, *Predictive transport analysis and AUG hybrid scenarios* (poster P1.133)

J. Citrin, J.F. Artaud, C. Bourdelle, J. Hobirk, G.M.D. Hogeweij, F. Imbeaux, E. Joffrin, *Role of q-profile shaping in JET and ASDEX hybrid scenario confinement* (poster P1.134)

T. Tala, A. Salmi, P. Mantica, C. Angioni, G. Corrigan, P.C. de Vries, C. Giroud, J. Ferreira, J. LÖnnroth, V. Naulin, A.G. Peeters, W. Solomon, D. Strintzi, M. Tsalas, T.W. Versloot, J. Weiland, K.-D. Zastrow and JET-EFDA contributors, *NBI modulation experiments to sudy momentum transport and magnetic field induced ripple torque on JET* (poster P1.139)

A. Kappatou, E. Delabie, R.J.E. Jaspers, M.G. von Hellermann, *Feasibility of charge exchange spectroscopy fast helium measurements on ITER* (P2.059)

J.W. Haverkort, H.J. de Blank, B. Koren, *Low-frequency MHD spectrum of rotating tokamak plasmas* (poster P2.077)

M. Hölzl, W.-C. Müller, P. Merkel, G. Huysmans, C. Konz, S. Günter, R. Wenninger, J.E. Bloom, M. Dunne, ASDEX Upgrade Team, *Non-linear simulations of ELMs in ASDEX Upgrade with JOREK* (poster P2.078)

G.M.D. Hogeweij, T. Casper, J. Citrin, F. Imbeaux, F. Köchl, X. Litaudon, ITM-TF ITER Scenario Modelling group, *Optimization of the current ramp-up phase for hybrid ITER discharges* (poster P2.134)

D. Moseev, M. Steijner, S.B. Korsholm, F. Meo, H. Bindslev, A. Bürger, V. Furtula, F. Leipold, A. Listopad, P.K. Michelsen, S.K. Nielsen, M. Salewski, E. Westerhof and the TEXTOR Team, *Ion cyclotron emission from NBI heated TEXTOR plasma* (poster P4.079)

M.F.F. Nave, T. Johnson, L.-G. Eriksson, C. Giroud, V. Kiptily, M.-L. Mayoral, J.-M. Noterdaeme, J. Ongena, G. Sabeine, F. Rimini, R. Sartori, S. Sharapov, T. Tala, P.C. de Vries, K.-D. Zastrow, JET-EFDA Contributors, *MHD effects on JET intrinsic rotatio*n (poster P4.083)

B.J. Tobias, J.E. Boom, S. Che, I.G.J. Classen, C.W. Domier, A.J.H. Donné, X. Kong, G.J. Kramer, N.C. Luhmann Jr, R. Nazikian, H.K. Park, G.S. Yun and M.A. Van Zeeland, *Diagnosics of local harmonic poloidal structure in core and edge MHD from electron cyclotron emission imaging* (poster P5.051)

B. van Es, B. Koren, H.J. de Blank, *Numerical modeling of strongly anisotropic dissipative effects in MHD* (poster P5.087)

G.S. Yun, H.K. Park, W. Lee, M.J. Choi, C.W. Domier, N.C. Luhmann, Jr, B.J. Tobias, A.J.H. Donné and KSTAR team, *Merge and crash process of the sawtooth oscillation in tokamak plasmas* (poster P5.091)

H.K. Park, B.J. Tobias, M.J. Choi, G.S. Yun, C.W. Domier, N.C. Luhmann, Jr, T. Munsat, A.J.H. Donné, G.W. Spakman, TEXTOR team, *Incomplete crash process of the sawtooth oscillation in tokamak plasmas* (poster P5.092)

G. van Wassenhove, P. Dumortier, R. Koch, E. Lerche, A. Messiaen, I. Stepanov, M. Vervier, S. Brezinsek, M. Kantor, H.R. Koslowski, A. Krämer-Flecken, O. Schmitz and TEXTOR Team, *Impact of gas injection on ICRF antenna loading properties on TEXTOR* (P5.098)

W. Weymiens, H.J. de Blank, and G.M.D. Hogeweij, *Bifurcation theory for the L-H transition* (poster P5.131)

Working Session of the ITER Scenario Modelling Group, 4-8 July 2011, Rijnhuizen, The Netherlands
J. Citrin, J. Hobirk, M. Schneider, J.F. Artaud, C. Bourdelle, K. Crombé, G.M.D. Hogeweij, F. Imbeaux, E. Joffrin, F. Köchl, J. Stober, the AUG team, JET-EFDA contributors, and the ITM-TF ITER Scenario Modelling group, *Predictive transport analysis of JET and AUG hybrid scenarios*

S. Djordjevic, J. Citrin, G.M.D. Hogeweij, M.R. de Baar, M. Steinbuch, *Controllability analysis of the magnetic flux distribution in ITER hybrid scenarios*

G.M.D.Hogeweij, *Optimization of the current ramp-up phase for hybrid ITER discharges*

8th International Workshop "Strong Microwaves and Terahertz Waves: Sources and Applications", July 9 - 16, 2011 Nizhny Novgorod, Russia
W. Bongers, W. Kasparek, M. Petelin, L. Lubyako, E. Eminoglu, M.R de Baar, V. van Beveren, R.van den Braber, N. Doelman, A.J.H. Donné, V. Erckmann, A. P. H. Goede, B. Krijger, P.W.J.M. Nuij, B. Plaum, J. Stober and D. Wagner, *Progress of CW compatible implementations of line-of-sight ECE measurements within waveguide based ECRH transmission systems* (oral)

M.R. de Baar*, Real-time control applications of ECRH in fusion plasmas* (oral)

M. Henderson, M.R. de Baar, D. Ronden, *Present status of the 24 MW 170 GHz ITER ECH&CD system* (oral)

12th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems, 8 September 2011, Austin, TX, USA
M. Garcia-Munoz, J Boom, I G. J. Classen, B Geiger, W W. Heidbrink, M A. Van Zeeland, S Akaslompolo, V Bobkov, G D. Conway, S da Graca, V Igochine, Ph Lauber, N Luhmann, M Maraschek, H Park, M Schneller, G Tardini, the ASDEX Upgrade Team, *MHD Induced Fast-Ion Redistribution and Loss in the ASDEX Upgrade Tokamak*

10th Carolus Magnus Summer School on Plasma and Fusion Energy Physics, September 4-16, 2011, Weert, The Netherlands
M.R. de Baar, *How to fly a tokamak*

H.J. de Blank, *Guiding Center Motion*

H.J. de Blank, *Plasma Equilibrium in Tokamaks*

A.J.H. Donné, *Plasma diagnostics in view of ITER*

G.M.D. Hogeweij, *Degraded confinement & turbulence in tokamak experiments*

G.M.D. Hogeweij, *Transport studies using perturbative experiments*

E. Westerhof, *Electron Cyclotron Resonance Heating and Current Drive*

E. Westerhof, *Non-Inductive Current Drive*

12th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems, Austin, TX, USA, 8 - 10 September 2011
B. Tobias, C.W. Domier, A.J.H. Donné, W.W. Heidbrink, N.C. Luhmann, Jr., R. Nazikian, H.K. Park, D.A. Spong, and M.A. Van Zeeland, *Alfvén Eigenmode Structure During Off-Axis Neutral Beam Injection*

14th European Fusion Theory Conference, Frascati, Italy, 26-29 September 2011
W. Weymiens, H.J. de Blank, G.M.D. Hogeweij, J. de Valenca, *Radially resolved bifurcation theory for the dynamics of L-H mode transitions*

J. Citrin, C. Bourdelle, P. Cottier, G.M.D. Hogeweij, F. Jenko, M.J. Pueschel, *Quasilinear transport modeling at low magnetic shear*

Multi-conference on Systems and Control, 28-30 September 2011, Denver, USA
M.R. e Baar et al, among them Pieter Nuij, M. Steinbuch, Bart Hennen, Gillis Hommen, G. Witvoet, *Control of sawteeth and neo-classical tearing modes in tokamaks using electron cyclotron waves*

NWO-RFBR working session on anomalous scattering in magnetic islands, 3-7 October 2011, Nieuwegein, The Netherlands
E. Westerhof, Overview of experimental observations of anomalous scattering on TEXTOR

W.A. Bongers, et al, *Progress of CW compatible implementations of line-of-sight ECE measurements within waveguide based ECRH transmission systems*

ITPA Transport & Confinement Topical Group Meeting, Cadarache, France, 5-7 October 2011
I.Voitsekhovitch, G.M.D.Hogeweij, C.Giroud, X.Litaudon and ITM/ISM contributors, *Update on current ramp up modelling*

H.J.Sun, P.H.Diamond, L.Wang, J.M.Kwon and WCI group, Z.B.Shi, X.T.Ding, J.Q.Dong, L.H.Yao, Z.H.Wang and HL-2A team, N.Tamura, K.Ida, S.Inagaki and LHD team, S.W.Yoon, G.S.Yun, W.C.Kim, J.G.Kwak and KSTAR team, G.McKee, B.J.Tobias and DIII-D team, G.M.D.Hogeweij, J.Citrin and FOM group, P.Mantica, J.Rice, F.Ryter, X.L.Zou, N.J.Luhmann, *ITPA joint experiment proposal: Physics of nonlocality phenomenon*

13th Int. Workshop on H-mode Physics and Transport Barriers, 10 - 12 October 2011, Oxford, UK
R. Wenninger, H. Zohm, J. Boom, T. Eich, M. Garcia-Munoz, M. Hölzl, T. Lunt, M. Maraschek, H.W. Müller, F. Sommer, E. Viezzer and the ASDEX Upgrade team, *Solitary magnetic perturbations at the ELM onset*
W. Weymiens, H.J. de Blank and G.M.D. Hogeweij, *Bifurcation theory for the L-H transition*

15th International Symposium on Laser-aided plasma diagnostics, 9 - 13 October, 2011, Jeju, Korea
M.Yu. Kantor, *A possibility of local measurements of ion temperature and drift velocity in a high-temperature plasma by laser induced ionization*

53rd Annual Meeting of the APS Division of Plasma Physics, 14 - 18 November 2011, Salt Lake City, USA
G.S. Yun, H.K. Park, W. Lee, M.J. Choi, S.W. Yoon, Y.M. Jeon, J.H. Lee, C.W. Domier, N.C. Luhmann Jr., B. Tobias, A.J.H. Donné, *Dual Hot Flux Tubes in the Tokamak Core*

16th Workshop on MHD Stability Control, General Atomics, San Diego, USA, 20-22 November 2011
H. van den Brand, M.R. de Baar, N.J. Lopes Cardozo and E. Westerhof, *Consequences of mode locking for requirements on real-time neoclassical tearing mode control in ITER*

21st International Toki Conference (ITC-21) on Integration of Fusion Science and Technology for Steady State Operation, Toki-City, Gifu, Japan 28 November - 1 December 2011
G.M.D.Hogeweij, V.Basiuk, J.Citrin, F.Imbeaux, F.Köchl, X. Litaudon, V. Parail, I. Voitsekhovitch, contributors of the EU-ITM ITER Scenario Modelling group, *Optimizing the current ramp-up phase for the hybrid ITER scenario*

19th European Fusion Physics Workshop, 5-7 December 2011, Heringsdorf, Germany
P.C. de Vries, *Results of the variable toroidal field ripple experiments at JET*

Seminar

5 January 2011
Weizmann Institute, Rehovot, Israel
J.Citrin, *Integrated modelling of tokamak turbulence*

28 January 2011
Inaugural lecture, Eindhoven University of Technology
A.J.H. Donné, *A diagnostic dilemma*

8 March 2011
Hogeschool van Amsterdam
A.J.H. Donné, *Fusion: Merits and prospects*

24 March 2011
FOM-Instituut voor Plasmafysica Rijnhuizen, Nieuwegein
O. Lischtschenko, *Coherence Imaging Spectroscopy at FOM Rijnhuizen*

11 April 2011
FOM Institute AMOLF, Amsterdam
A.J.H. Donné, *A diagnostic dilemma: Challenges in sensing hot magnetically confined plasmas*

4 May 2011
Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University Prague
M.R. de Baar, *Track- and kill system for tearing instabilities in tokamaks*

7 June 2011
Colloquium CWI-MAC, Amsterdam
E. Westerhof, *Modelling of high temperature magnetized plasmas for fusion: a case study*

30 June 2011
FOM-Instituut voor Plasmafysica Rijnhuizen
B.A. Hennen, *Feedback control for magnetic island suppression and stabilization in tokamaks*

3 October 2011
TU/e Technical University Eindhoven, Department of Electrical Engineering
A.J.H. Donné, *Diagnosing hot magnetically confined plasmas*

1 November 2011
Visit of Dutch journalist to the Joint European Torus, Culham
A.J.H. Donné, *The Dutch research programme in the field of thermonuclear fusion*

3 November 2011
Seminar for Young Tennet, Arnhem
A.J.H. Donné, *Fusion from fiction to electricity*

10 November 2011
FOM-Instituut voor Plasmafysica Rijnhuizen
T. Versloot, *Edge rotation and momentum transport in JET plasmas*

23 November 2011
Chalmers University, Göteborg, Sweden
C.Bourdelle et al, among them J.Citrin and G.M.D.Hogeweij, *Gyrokinetic quasi-linear modelling of transport*

24 November 2011
FOM-Instituut voor Plasmafysica Rijnhuizen
J.W. Goedbloed, *Instabilities of rotating plasmas in fusion and astrophysics*

Courses

7 February 2011
Honors Masterclass Fusion Physics, Eindhoven University of Technology
A.J.H. Donné, *The 7 challenges of nuclear fusion research*

April – June 2011
Mastercourse Eindhoven University of Technology
A.J.H. Donné, R.J.E. Jaspers and E. Westerhof, *Diagnostics and heating of Fusion Plasmas*

12 December 2011
Rijksuniversiteit Gent, Dept. of Applied Physics
A.J.H. Donné, *Plasma diagnostics in view of ITER and DEMO*

Television interviews

21 September 2011
VPRO -Labyrint
A.J.H. Donné, *Interview on the status of Nuclear Fusion Research*

Output of Plasma Surface Interactions

PhD theses

H.J. van der Meiden, *Thomson scattering on low and high temperature plasmas*, PhD thesis at the Eindhoven University of Technology, 14 February 2011

W.A.J. Vijvers, *A high-flux cascaded arc hydrogen plasma source*, PhD thesis at the Eindhoven University of Technology, 28 February 2011

A.E. Shumack, *The influence of electric fields and neutral particles on the plasma sheath at ITER divertor conditions*, PhD thesis at the Eindhoven University of Technology, 22 June 2011

Master theses

N. den Harder, *Optical Emission Spectroscopy on the linear plasma generator Pilot-PSI,* 23 August 2011

L. van der Vegt, *Carbon erosion and re-deposition during hydrocarbon puffing experiment in Pilot-PSI,* 13 December 2011

G. van der Star*, Cavity ring down absorption spectroscopy on Pilot-PSI,* 23 August 2011

Bachelor theses

C.J. van Diepen, *Optical analyzes of Hydrogen plasma pulse in Pilot-PSI*, 14 October 2011

Publications in peer-reviewed scientific journals

V.Kh. Alimov, B. Tyburska-Püsche, M.H.J. 't Hoen, J. Roth, Y. Hatano, K. Isobe, M. Matsuyama and T. Yamanishi, *Hydrogen isotope exchange in tungsten irradiated sequentially with low-energy deuterium and protium ions*, Phys. Scr. T145 (2011) 014037

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H.T. Beyene, F.D. Tichelaar, M.A. Verheijen, M.C.M. van de Sanden, M. Creatore, *Plasma-assisted deposition of Au/SiO_2 multi-layers as surface plasmon resonance-based red-colored coatings,* Plasmonics 6 (2011) 255-260

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A.C. Bronneberg, A.H.M. Smeets, M. Creatore, M.C.M. van de Sanden, *On the oxidation mechanism of microcrystalline silicon thin films studied by Fourier transform infrared spectroscopy*, J. Non-Crystalline Solids, 357 92011) 884-887

K. Bystrov, J. Westerhout, M. Matveeva, A. Litnovsky, L. Marot, E. Zoethout, G. De Temmerman, *Erosion yields of carbon under various plasma conditions in Pilot-PSI*, J. Nucl.Mater. 415 (2011) S149-S152

E. Delchambre-Demoncheaux, G. De Temmerman, T. Loarer, E. Gauthier, G. Dunand, JL Gardarein, A. Kirk, V. Moncada, H.M. Travere, *Surface temperature measurements in the medium and long wavelength infrared range on MAST*, J. Nucl. Mater. 415 (2011) S1178

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M.C.M. van de Sanden, *Sustainable energy storage in chemical fuels for CO_2 neutral energy generation: a new challenge for plasma science* (oral)

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M.C.M. van de Sanden, *On expanding plasmas used for high rate deposition: the role of metastable vs. ion induced dissociation of precursor gases*

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T.A.R. Hansen, M.C.M. van de Sanden, R. Engeln, *H2: the critical juncture between polymerization and dissociation of hydrocarbons in a low-temperature plasma* (poster)

J.W. Oosterbeek, J.P. Balm, M.F.M. de Bock, R.A.H. Engeln, G.A. Harkema, R.J.E. Jaspers, H.M.M. de Jong, G.M.W. Kroesen, N.J. Lopes Cardozo, H.C.J. Mulders, M.C.M. van de Sanden, M. Scheffer and E.M. van Veldhuizen, *TU/e plasmaLab* (poster)

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G.A. van Swaaij, D. Borodin, A. Kirschner, W.J. Goedheer, K. Bystrov, L. van der Vegt, R. Wieggers, O. Lischtschenko, G. De Timmerman, *Relevant processes for hydrocarbon transport, break-up, and light emission in an ITER divertor-relevant plasma* (oral)

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M.H.J. 't Hoen, B. Tyburska, K. Ertl, H. Schut, A.W. Kleijn, J. Rapp and P.A. Zeijlmans van Emmichoven, *Deuterium retention in Tungsten exposed to high-flux plasmas* (poster)

K.S.C. Peerenboom, J. van Dijk, W.J. Goedheer, J.J.A.M. van der Mullen, *Challenges in the modeling of multi-component diffusion in Magnum PSI* (poster)

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M.H.J. 't Hoen, *Deuterium retention in tungsten investigate the effect of irradiation damage on deuterium retention in W exposed to high fluxes in Pil*ot (oral)

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H.T. Beyene, M.A. Verheijen, M.C.M. van de Sanden, M. Creatore, *Hybrid sputtering-remote PECVD deposition of dielectric metal nanocomposites for surface Plasmon resonance based decorative coatings* (oral)

G. Dingemans, M.C.M. van de Sanden, W.M.M. Kessels, *On the chemical and field-effect passivation of c-Si by Al_2O_3 and SiO_2/Al_2O_3 stacks* (oral)

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A.P. Peter, M.C.M. van de Sanden, S. Starostin, H. de Vries, *Investigation on the discharge formation mechanisms and surface analysis of SiO_2-like layers on polymers synthesized using DBD assisted CVD at atmospheric pressure* (oral)

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S.A. Strola, M.S. Hanssen, M.M. Mandoc, R.M. Joy, M.G. Hussein, R.C. Bosch, F.C. Dings, W.M.M. Kessels and M.C.M. van de Sanden, *Hydrogen diffusion in PECVD stack layer of silicon oxide and hydrogenated amorphous silicon nitride* (oral)

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M.C.M. van de Sanden, A. Premkumar Peter, S.A. Starostin, H.W.D. de Vries, M. Creatore, *Investigation on the discharge formation mechanisms and surface analysis of* SiO_2*-like layers on polymers synthesized using high current dielectric barrier discharge at atmospheric pressure* (oral)

T. Zaharia, R. Groenen, M.C.M. van de Sanden, *Improved adhesion and tribological properties of hard graphite-like hydrogenated amorphous carbon films grown by a remote plasma on steel substrates* (poster)

9th Workshop on Frontiers in Low-Temperature Plasma Diagnostics (FLTPD), 9-12 May 2011, Zinnowitz, Germany
S. Welzel, M. Creatore, S. Ponduri, M.C.M. van de Sanden, R. Engeln, *Synthetic fuel synthesis through plasma-enhanced hydrogenation of* CO_2 (poster)

13th International Workshop on Plasma-Facing Materials and Components for Fusion Applications / 1st International Conference on Fusion Energy Materials Science, May 9th -13th, 2011, Rosenheim, Germany
M.H.J. 't Hoen, B. Tyburska-Püschel, K. Ertl, H.Schut, A.W. Kleijn, J. Rapp, P.A. Zeijlmans van Emmichoven, *Deuterium retention in tungsten exposed to high flux plasmas* (poster)

NanoMaterials for Sustainable Energy workshop (NMSE 2011), MESA+ Instituut voor Nanotechnologie, 17 June 2011, Enschede, University of Twente, The Netherlands
M.C.M. van de Sanden, *Rijnhuizen in 2020: Institute for Fundamental Energy Research*

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S. Welzel, F. Brehmer, S. Ponduri, M. Creatore, M.C.M. van de Sanden, R. Engeln, *Plasma-assisted* CO_x *conversion: An alternative approach for synthetic fuel production* (oral)

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A.C.Bronneberg, M. Creatore, and M.C.M. van de Sanden, *On the role of atomic hydrogen during microcrystalline silicon thin-film deposition* (poster)

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W.M.M. Kessels, G. Dingemans, C.A.A. van Helvoirt, M.M. Mandoc, M.C.M. van de Sanden, *ALD of SiO2 and Al2O3 for surface passivation of c-Si solar cells* (oral)

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8th International Colloquium on Plasma Processes (CIP 2011) July 4-8, 2011. Nantes, France
J.J. Zielinski, *Development and characterization of a pulsed cascaded plasma source* (oral)

20th International Symposium on Plasma Chemistry, July 24-29, 2011, Philadelphia, USA
M.C.M. van de Sanden, P.A. Premkumar, S.A. Starostin, H. de Vries, M. Creatore, *Investigation on the discharge formation mechanisms and surface analysis of SiO2-like layers on polymers synthesized using DBD assisted CVD at atmospheric pressure* (oral)

S. Welzel, A. Creatore, S. Ponduri, M.C.M. van de Sanden, R. Engeln, *Plasma-assisted CO_2 hydrogenation for clean synthetic fuel production* (oral)

M. Creatore, H.T. Beyene, M. Ponomarev, M.C.M. van de Sanden, *Plasma deposition of metal/dielectric structures exhibiting surface Plasmon resonance behavior: from red-colored coatings to light trapping in solar cells* (oral)

W.E.N. van Harskamp, D.C. Schram, M.C.M. van de Sanden, R. Engeln, *A novel diagnostic detecting H- ions in a magnetized hydrogen plasma expansion* (poster)

İ. Doğan, M.A. Verheijen, K. Dohnalova, T. Gregorkiewicz, M.C.M. van de Sanden, *High rate deposition of silicon nanocrystals in expanding thermal plasma* (poster)

24th ICANS, 22 – 26 August 2011, Nara, Japan
A.C. Bronneberg, M.C.M. van de Sanden, ans M. Creatore, *On the role of atomic hydrogen during microcrystalline silicon thin-film deposition* (oral)

30th International Conference on Phenomena in Ionized Gases, 28th August – 2nd September 2011, Belfast, Northern Ireland, UK
L. Sirghi, C. Costin, V. Anita, M. L. Solomon, G. Popa, M. van de Pol, R. S. Al, J. Rapp, *Turbulence of magnetized plasma column at a floating and current-driving target surface in Pilot-PSI* (poster)

S. Welzel, F. Brehmer, S. Ponduri, M. Creatore, MC.M. van de Sanden, R. Engeln, *Plasma-assisted CO_2 conversion as alternative to conventional fuel processing,* D16-278 (poster)

International Workshop on Positron Studies of Defects 2011 (PSD-11), Delft, 28 August - 2 September 2011
M.H.J. ‘t Hoen, B. Tyburska-Püschel, K. Ertl, M. Mayer, H. Schut, J. Rapp and P.A. Zeijlmans van Emmichoven, Hydrogen retention in tungsten exposed to high-flux plasmas (poster)

26th European Photovoltaic Solar Energy Conference and Exhibition (26th EU PVSEC) 5-9 September 2011, Hamburg, Germany
P. Kudlacek, R.M. Joy, K. Sharma, M. Creatore, M.C.M van de Sanden, R.C.M. Bosch, *Hydrogenated amorphous silicon for various photovolataic applications on the DEPx platform* (oral)

R.M. Joy, L. Gautero, S. Keipert-Colberg, M. Rinio, S.A. Stola, M.S. Hanssen, M.C.M. van de Sanden, D.M. Borsa, and R.C.M. Bosch, *Fast industrial rear surface passivation dielectric stack deposition and low cost metallization* (poster)

P. Kudlacek, R.M. Joy, K. Sharma, M. Creatore, M.C.M van de Sanden, R.C.M. Bosch, *a-Si:H for various PV applications on the DEPx platform,* (poster)

9th Optics of Surfaces and Interfaces (OSI9) International Conference, 19 – 23 September 2011, Akumal, Mexico
N.M. Terlinden, G. Dingemans, M.M. Mandoc, M.C.M. van de Sanden, W.M.M. Kessels, *SiO2 interlayer thickness dependence of the density and polarity of charges in Si/SiO_2/Al_2O_3 stacks* (oral)

V. Vandalon, N.M. Terlinden, M.C.M. van de Sanden and W.M.M. Kessels, *Built-in charges in Al2O3 and SiO2 thin films on Si(100) studied by second-harmonic intensity and phase spectroscopy* (poster)

2nd International Workshop on Plasma-Material Interaction Facilities for Fusion Research, (PMIF 2011), 19 - 21 September 2011, Jülich, Germany
G. De Temmerman, *ELM-simulation experiments under ITER-like conditions* (oral)

Workshop on Ion Implantation as a Neutron Irradiation Analogue, 25-28 September 2011, Oxford, UK
M.H.J. 't Hoen, B. Tyburska-Püschel, K. Ertl, H.Schut, A.W. Kleyn, J. Rapp, P.A. Zeijlmans van Emmichoven, *Saturation of deuterium retention in self-damaged tungsten exposed to high-flux plasmas* (poster)

15th ICFRM (15th International Conference on Fusion Reactor Materials) October 16-22, 2011, Charleston, South Carolina, USA
G. De Temmerman, *Erosion and morphology changes of high-Z metals exposed to high flux helium plasmas at elevated temperatures* (oral) O6-B-C1

AVS 58th International Symposium & Exhibition, October 30 - November 4, 2011, Nashville, Tennessee, USA
G. Aresta, J. Palmans, M.C.M. van de Sanden and M. Creatore, *Initiated-chemical vapor deposition of organosilicones from growth mechanism to multilayer moisture diffusion barriers* (oral) (TF-MoM4)

G. De Temmerman, J.J. Zielinski, L. Marot, D. Mathys, W. Melissen and M.C.M. van de Sanden, *A versatile magnetized pulsed cascaded arc source for surface modifications and efficient material deposition* (oral) (SE+PS-ThA2)

P.H. Tchoua Ngamou, M.C.M. van de Sanden and M. Creatore, *Structure of organo-silicon polymeric films obtained by expanding thermal plasma chemical vapor deposition* (oral) (PS+TF-ThM6)

H.B. Profijt, M.C.M. van de Sanden and W.M.M. Kessels, *Impact of VUV photons and ions on metal oxide films prepared by plasma-assisted ALD with substrate biasing* (oral) (PS+TF-ThM9)

M.C.M. van de Sanden, A. Premkumar, S. Starostin, H. de Vries and M. Creatore, *Investigation on the discharge formation mechanisms and surface analysis of SiO_2-like layers on polymers synthesized using high current dielectric barrier discharge at atmospheric pressure* (oral) (PS+SE-WeM12)

M. Creatore, K. Sharma and M.C.M. van de Sanden, *On the influence of the amorphous silicon microstructure on the crystallization kinetics towards poly-crystalline silicon for solar cells* (oral) (EN+TF-TuA3)

S. Welzel, S. Ponduri, F. Brehmer, M. Creatore, M.C.M. van de Sanden and R. Engeln, *Synthetic fuel processing through plasma-assisted CO_2 conversion* (oral) (EN+PS-MoM3)

F.M.M. Souren, J. Rentsch and M.C.M. van de Sanden, *Effective light trapping for crystalline silicon solar cells by plasma texturing* (oral) (EN+PS-MoM4)

İ. Doğan, N.J. Kramer, M.A. Verheijen, K. Dohnalova, T. Gregorkiewicz and M.C.M. van de Sanden, *Spontaneous and high rate synthesis of nanocrystalline silicon by expanding thermal plasma* (oral) (EN+PS-MoM6) (EM+TF-TuM11)

N.M. Terlinden, G. Dingemans, M.M. Mandoc, M.C.M. van de Sanden, W.M.M. Kessels, *Interlayer thickness dependence of the density and polarity of charges in $Si/SiO_2/Al_2O_3$ stacks* (oral) (EM+TF-TuM11)

M.C.M. van de Sanden, P.A. Premkumar, S.A. Starostin, H. de Vries, M. Creature, *Investigation on the discharge formation mechanisms and surface analysis of SiO2-like layers on polymers synthesized using a high-current dielectric barrier discharge at atmospheric pressure*, IL-12

J.W. Weber and M.C.M. van de Sanden, *Infrared optical conductance of CVD-grown grapheme* (poster) (GR+EM-TuM5)

FOM-Jülich meeting, 10 November 2011, Jülich, Germany
M.H.J. 't Hoen, *Overview of deuterium retention experiments at Pilot-PSI* (oral)

ENHANCE - MC-ITN, Workshop 6, 21 - 25 November 2011, Eindhoven, The Netherlands
S. Welzel, F. Brehmer, S. Ponduri, M. Creatore, M.C.M. van de Sanden, R. Engeln, *Synthetic fuel synthesis through plasma-assistedCO_2 hydrogenation* (oral)

S. Welzel, S.A. Starostin, H. de Vries, M.C.M. van de Sanden, R. Engeln, *Gas Phase IR absorption studies in air-like atmospheric pressure plasmas* (oral)

Plasma-Assisted Catalysis: Recent Advances and Perspectives, 28 November 2011, Antwerp, Belgium
M.C.M. van de Sanden, *Solar fuels: a plasma perspective* (oral)

14th Workshop on the Exploration of Low Temperature Plasma Physics (WELTPP-14) 1 - 2 December 2011, Kerkrade, The Netherlands
S. Welzel, F. Brehmer, S. Ponduri, M. Creatore, M.C.M. van de Sanden, R.Engeln, *Fuel processing through plasma-assisted CO_2 conversion* (oral)

F. Brehmer, S. Welzel, M.C.M. van der Schans, S. Ponduri, M.C.M. van de Sanden, R. Engeln, *CO_2 conversion in an atmospheric pressure DBD* (poster)

İ. Doğan, S. Weeks, S. Agarwal, M.C.M. van de Sanden, *The origin of bimodal size distribution of silicon nanocrystals synthesized in a remote expanding thermal plasma* (poster)

B. Macco, K. Sharma, M. Creatore, M.C.M. van de Sanden, *Solid phase crystallization of amorphous silicon: an in-situ XRD and Raman studies* (poster)

S. Ponduri, S. Welzel, F. Brehmer, M. Creatore, M.C.M. van de Sanden, R. Engeln, *Plasma assisted CO_2 reduction for synthetic fuels* (poster)

S. Welzel, S.A. Starostin, H. de Vries, M.C.M. van de Sanden, R. Engeln, *Gas phase IR absorption studies of air-like atmospheric pressure DBDs* (poster)

R.H.J.Westermann, R. Engeln, M.C.M.van de Sanden, *Shock front phenomena in expanding Argon plasmas* (poster)

FOM Workshop Young Scientists' Day, 2 December 2011, Amsterdam, The Netherlands
M.C.M. van de Sanden, *Capitalize your scientific results*

Other

17th International Summer School on Vacuum, Electron and Ion Technologies, 19-23 September 2011, Sunny Beach, Bulgaria
M. Creatore, G. Aresta, J. Palmans, M.C.M. van de Sanden, *Initiated chemical vapor deposition of organosilicones: from growth mechanism to multilayer moisture diffusion barriers,* IL-10

M.C.M. van de Sanden, P.A. Premkumar, S.A. Starostin, H. de Vries and M. Creature, *Investigation on the discharge formation mechanisms and surface analysis of SiO2-like layers on polymers synthesized using a high-current dielectric barrier discharge at atmospheric pressure*, IL-12

Seminars

17 May 2011
M.C.M. van de Sanden, *Het energie vraagstuk: technologische perspectief op duurzame opties,* Science Café, Tilburg (outreach)

4 July 2011
M.C.M. van de Sanden*, Atmospheric plasma deposition; a new paradigm in plasma processing,* Fujifilm Headquarters Roppongi, Tokyo, Japan

4 July 2011
M.C.M. van de Sanden and İ. Doğan*, High rate deposition of free standing silicon nanocrystals in expanding thermal plasma,* Department of Materials Engineering, Tokyo University, 4 July 2011, Tokyo, Japan

15 July 2011
M.C.M. van de Sanden, *Plasma-surface interaction during the growth of micro-crystalline silicon thin films: In situ plasma and surface studies,* Bosch Research Center, Gerlingen-Schillerhöhe, Germany

21 November 2011
M.C.M. van de Sanden, *DIFFER: Dutch institute for Fundamental Energy Research*, ECN, NRG Petten

1 December 2011
M.C.M. van de Sanden, *Solar fuels*, Shell Research Center, Joint Solar Panel meeting

Output of Nanolayer Surface and Interface Physics

PhD theses

S. Bruijn, *Diffusion phenomena in chemically stabilized multilayer structures*, PhD thesis at the University of Twente, 27 April 2011

J.Q. Chen, *Characterization of EUV induced contamination on multilayer optics*, PhD thesis at the University of Twente, 1 July 2011

A.J.R. van den Boogaard, *Ion-enhanced growth in planar and structured Mo/Si multilayers*, PhD thesis at the University of Twente, 13 December 2011

Publications in peer-reviewed scientific journals

J. Andreasson, B. Iwan, A. Andrejczuk, E. Abreu, M. Bergh, C. Caleman, A.J. Nelson, S. Bajt, J. Chalupsky, H.N. Chapman, R.R. Fäustlin, V. Hajkova, P.A. Heimann, B. Hjövarsson, L. Juha, D. Klinger, H. Krzywinski, B. Nagler, G.K. Pálsson, W. Singer, M.M. Seibert, R. Sobierajski, S. Toleikis, T. Tschentscher, S.M. Vinko, R.W. Lee, J. Hajdú, and N. Timneanu, *Saturated ablation in metal hydrides and acceleration of protons and deuterons to keV energies with a soft-x-ray laser*, Phys. Rev. E 83, 016403 (2011)

A. J. R. van den Boogaard, E. Louis, and E. Zoethout, K.A. Goldberg, F. Bijkerk, *Characterization of Mo/Si multilayer growth on stepped topographies*, J. Vac. Sci. Technol. B 29 (2011) 051803

S. Bruijn, R.W.E. van de Kruijs, A.E. Yakshin, F. Bijkerk, *In-situ study of the diffusion-reaction mechanism in Mo/Si multilayered films*, Appl. Surf. Sci. 257 (2011) 2707-2711

J.Q. Chen, E. Louis, H. Wormeester, R. Harmsen, R.W.E. van de Kruijs, C.J. Lee, W. van Schaik and F. Bijkerk, *Carbon-induced extreme ultraviolet reflectance loss characterized using visible-light ellipsometry*, Meas. Sci. Technol. 22 (2011) 105705

J.Q. Chen, E. Louis, R. Harmsen, T. Tsarfati, H. Wormeester, M. van Kampen, W. van Schaik, R.W.E. van de Kruijs, F. Bijkerk, *In situ ellipsometry study of atomic hydrogen etching of extreme ultraviolet induced carbon layers*, Appl. Surface Sci. 258 (2011) 7-12

S.D. Farahani, J. Chalupsky, T. Burian, H. Chapman, M.A. Gleeson, V. Hajkoya, L. Juha, M. Jurek, D. Klinger, H. Sinn, R. Sobierajski, M. Störmer, K. Tiedtke, S. Toleikis, T. Tschentscher, H. Wabnitz, J. Gaudin, *Damage threshold of amorphous carbon mirror for 177 Ev FEL radiation*, Nucl. Instrum. Meth. A, 635 (2011) S39-S42

E. Galtier, F.B. Rosmej, T. Dzelzainis, D. Riley, F.Y. Khattak, P. Heimann, R.W. Lee, A.J. Nelson, S.M. Vinko, T. Whitcher, J.S. Wark, T. Tschentscher, S. Toleikis, R.R. Fäustlin, R. Sobierajski, M. Jurek, L. Juha, J. Chalupsky, V. Hajkova, M. Kozlova, J. Krzywinski and B. Nagler, *Decay of cystalline order and equilibration during the solid-to-plasma transition induced by 20-fs microfocused 92-eV free-electron-laser pulses*, Phys. Rev. Lett., 106, 164801 (2011)

E. Galtier, F.B. Rosmej, T. Dzelzainis, D. Riley, F.Y. Khattak, P. Heimann, R.W. Lee, A.J. Nelson, S.M. Vinko, T. Whitcher, J.S. Wark, T. Tschentscher, S. Toleikis, R.R. Fäustlin, R. Sobierajski, M. Jurek, L. Juha, J. Chalupsky, V. Hajkova, M. Kozlova, J. Krzywinski and B. Nagler, *Decay of cystalline order and equilibration during the solid-to-plasma transition induced by 20-fs microfocused 92-eV free-electron-laser pulses*, Phys. Rev. Spec. Top. – Accelerators and Beams, 14 (2011) 164801

M.L. Grecea, M.A. Gleeson, W. van Schaik, A.W. Kleyn, F. Bijkerk, *Co-adsorption of NH_3 and SO_2 on quartz(0001) surface: formation of a stabilized complex*, Chem. Phys. Lett. 511 (2011) 270-276

M.L. Grecea, M.A. Gleeson, W. van Schaik, A.W. Kleyn, F. Bijkerk, *Erratum to "Co-adsorption of NH_3 and SO_2 on quartz(0001): Formation of a stabilized complex" [Chem. Phys. Lett. 511 (2011) 270]* ,Chem. Phys. Lett. 516 (2011) 111

I.M.N. Groot, A.W. Kleyn and L.B.F. Juurlink, *The energy dependence of the ratio of step and terrace reactivity for H2 dissociation on stepped platinum*, Angew. Chem. Int. Ed. 2011, 50, 1-5

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P.N. He, J.P. Ning, Y.M. Qing, C.L. Zhao, F.J. Gou, *Molecular dynamics simulations of low-energy Cl atoms etching Si(100) surface*, Acta Physica Sinica, 60 (2011) 045209

P.N. He, X.D. Lu, C.L. Zhao, J.P.Ning, Y.M. Qing, F.J. Gou, *Molecular dynamics simulations of energy effects on atorn F interaction with SiC(100)*, Acta Physica Sinica 60 (2011) 095203

B. Iwan, J. Andreasson, A. Andrejczuk, E. Abreu, M. Bergh, C. Caleman, A.J. Nelson, S. Bajt, J. Chalupsky, H.N. Chapman, R.R. Faustlin, V. Hajkova, P.A. Heimann, B. Hjorvarsson, L. Juha, D. Klinger, J. Krzywinski, B. Nagler, G.K. Palsson, W. Singer, M.M. Seibert, R. Sobierajski, S. Toleikis, T. Tschentscher, S.M. Vinko, R.W. Lee, J. Hajdu and N. Timneanu, *TOF-OFF: a method for determining focal positions in tightly focused free-electron laser experiments by measurement of ejected ions*, High Energy Density Phys. 7 (2011) 336-342

A.W. Kleyn, *Atomic quantum scattering and molecular diffraction*, Progress in Surface Science, 6 (2011) 163-168

I.V. Kozhevnikov, R. van der Meer, H.M.J. Bastiaens, K.-J. Boller, and F. Bijkerk, *Analytic theory of soft x-ray diffraction by lamellar multilayer gratings*, Opt. Express, 19 (2011) 9172-9184

R.A. Loch, A. Dubrouil, R. Sobierajski, D. Descamps, B. Fabre, P. Lidon, R.W.E. van de Kruijs, F. Boekhout, E. Gullikson, J. Gaudin, E. Louis, F. Bijkerk, E. Mével, S. Petit, E. Constant, and Y. Mairesse, *Phase characterization of the reflection on an extreme UV multilayer: comparison between attosecond metrology and standing wave measurements,* Opt. Lett. 36 (2011) 3386-3388

E. Louis, A.E. Yakshin, T. Tsarfati, F. Bijkerk, *Nanometer interface and materials control for multilayer EUV-optical applications*, Progress in Surface Science, 86 (2011) 255-294

I.A. Makhotkin, S.N. Yakunin, A.Yu. Seregin, D.S. Shaitur, M.B. Tsetlin, and E.Yu. Tereshchenko*, Investigation of the formation of quasicrystalline.Al70–Pd20–Re10 phase in situ during annealing,* Crystallography Reports, 56 (2011) 871-874

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A. Rouzée, P. Johnsson, E.V. Gryzlova, H. Fukuzawa, A. Yamada, W. Siu, Y. Huismans, E. Louis, F. Bijkerk, D.M.P. Holland, A.N. Grum-Grzhimailo, N.M. Kabachnik, M.J. J. Vrakking, and K. Ueda, *Angle-resolved photoelectron spectroscopy of sequential three-photon triple ionization of neon at 90.5 eV photon energy*, Phys. Rev. A 83, 031401(R) (2011)

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H. Ueta, M.A. Gleeson, and A.W. Kleyn, *Scattering of hyperthermal argon atoms from clean and D-covered Ru(0001)*, J. Chem. Phys. 134, 034704 (2011)

H. Ueta, M.A. Gleeson, A.W. Kleyn, *The interaction of hyperthermal argon atoms with CO-covered Ru(0001): Scattering and collision-induced desorption*, J. Chem. Phys. 134, 064706 (2011)

H. Ueta, M.A. Gleeson, and A.W. Kleyn, *The interaction of hyperthermal nitrogen with N-covered Ag(111)*, J. Chem. Phys. 135 074702 (2011)

Publications in other journals and conference proceedings

A.W. Kleyn, *Interaction of atomic radicals with metal surfaces*, Abstr. Pap. Am. Chem. Soc.241 (2011) 143PHYS

Advances in X-Ray/EUV Optics and Components VI, 21 - 25 August 2011 San Diego Convention Center, San Diego, California United States
R.W.E. Kruijs, S. Bruijn, A. Yakshin, I. Nedelcu, and F. Bijkerk, *Interface diffusion kinetics and lifetime scaling in multilayer Bragg optics*, Proc. SPIE 8139, 81390A (2011)

R. van der Meer, B. Krishnan, I.V. Kozhevnikov, M.J. de Boer, B. Vratzov, H.M.J. Bastiaens, J. Huskens, W.G. van der Wiel, P.E. Hegeman, G.C.S. Brons, K.-J. Boller, F. Bijkerk, *Improved resolution for soft-x-ray monochromatization using lamellar multilayer gratings*, Proc. SPIE 8139, 81390Q (2011)

Invited lectures at conferences and meetings

Physics@FOM, Veldhoven, 2010, 19 - 20 January 2010, Veldhoven, Netherlands
F. Bijkerk, *Multilayer extreme UV optics, or how science can benefit from its application*

241st ACS National Meeting & Exposition (Spring Meeting), 29 March 2011, Anaheim, CA, USA
A.W. Kleyn, *Interaction of atomic radicals with metal surfaces*

Fysica 2011, VU Amsterdam, 15 April 2011
F. Bijkerk, *Multilayer extreme UV optics*

SPIE Damage to VUV, EUV, and X-ray Optics Conference, 18 April 2011, Prague, Czech Republic
E. Louis, R. Sobierajski, R.A. Loch, C. Bostedt, J. Bozek, T. Burian, J. Chalupsky, J. Gaudin, A. Graf, J. Grzonka, V. Hajkova, S.P. Hau-Riege, E.D. van Hattum, L. Juha, D. Klinger, J.

Krzywinski, R. London, M. Messerschmidt, S. Moeller, T. Plocinski, A. Wawro, P. Zabierowski, and F. Bijkerk, *Damage in Mo/Si multilayer optics irradiated by intense short-wavelength FELs*

NEVACdag 2011, Enschede, NL, 26 April 2011
J.M. Sturm, F. Bijkerk, F. and A.W. Kleyn, *The surface science of solar fuel production*

International Workshop on EUVL, 13-18 June 2011, Maui, Hawaii
E. Louis, S. Muellender, F. Bijkerk, *Reflective multilayer coatings, an enabling component of ectreme ultraviolet lithography and beyond*

Y. Platonov, J. Rodriquez, M. Kriese, E. Louis, T. Feigl, S. Yulin, *Status of multilayer coatings for EUV lithography*

V.V. Medvedev, A.E. Yakshin, R.W.E. van de Kruijs, V.M. Krivtsun, S.N. Yakunin, F. Bijkerk, *B4C/Si based EUV multilayer mirror with suppressed reflectivity for CO_2 laser radiation*

ICTF 15 (15th International Conference on Thin Films 2011), Kyoto, Japan, 7 Nov - 11 November 2011
F. Bijkerk, E. Louis, A.E. Yakshin, R.W.E. van de Kruijs, E. Zoethout, A.J. Gleeson, E.D. van Hattum, C.J. Lee, H.J.M. Bastiaens, F. van Goor, J. Chen, A.J.R. van den Boogaard, V.I.T.A. de Rooij Lohmann, S. Brujn, S. Nyabero, T. Tsarfati, I. Nedelcu, R. van der Meer, M. Bayraktar, F. Liu, E.G. Keim, A.S. Kuznetsov, J. Bosgra, I. Makhotkin and K.J. Boller, *Multilayer extreme UV bragg optics*

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

Physics@FOM, Veldhoven, 2010, 19 - 20 January 2010, Veldhoven, Netherlands
M. Bayraktar, C. Lee, G. Rijnders, F. Bijkerk, *Adaptive XUV Bragg reflectors, fabricated from piezoelectric materials,* P.03.03

F. Bijkerk, *Multilayer extreme UV optics, or how science can benefit from its application,* PA18.03

J. Bosgra, R.W.E. van de Kruijs, E. Zoethout, J. Verhoeven, A.E. Yakshin, F. Bijkerk, *Structural properties of sub nanometer thick layers to enhance EUV multilayer mirror reflectance*, P05.60

M.A. Gleeson, H. Ueta, A.W. Kleyn, *The interaction of hyperthermal argon atoms with CO-covered Ru(0001): scattering and collision-induced desorption*, P02.42

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V.M. Krivtsun, A.M. Yakunin, F. Bijkerk, *Diffraction of EUV radiation on free-standing grid structures: theory and experiment*, P03.31

A. Kuznetsov, R.W.E. van de Kruijs, M. Gleeson, F. Bijkerk, *Behavior of transition metal and metal oxide surfaces under oxidative and reductive environment*, P05.43

R. Loch, R. Sobierajski, C. Bostedt, J. Bozek, S. Bruijn, Y. Feng, J. Gaudin, E.D. van Hattum, A.R. Khorsand, D. Klinger, R.W.E. van de Kruijs, J. Krzywinski, E. Louis, M. Messerschmidt. S. Moeller, K. Tiedke, T. Burian, J. Chalupsky, A. Graf, S. Hau-Riege, L. Juha, R. London, F. Bijkerk, *Damage in Mo/Si multilayer irradiated by intense short-wavelength FELs*, P05.47

I. Makhotkin, E. Louis, R.W.E. van de Kruijs, A.E. Yakshin, E. Zoethout, A.Seregin, S. Yakunin, F. Bijkerk, *Determination of the density of ultrathin films using x-ray standing waves*, P05.42

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R. van der Meer, B. Krishnan, I. Kozhevnikov, B. Vratzov, B. Bastiaens, J. Huskens, W. van der Wiel, K. Boller, F. Bijkerk, *Improved resolution for soft x-ray monochromatization using lamellar multilayer amplitude gratings*, PA05.04

S. Nyabero, V.I.T.A. de Rooij-Lohmann, L.W.E. Veldhuizen, E. Zoethout, A.E. Yakshin, R.W.E. van de Kruijs, B.J. Thijsse, F. Schäfers, F. Bijkerk, *Chemical interaction of B4C diffusion barriers with mo/Si layered nanostructures*, P05.46

XFEL/HASYLAB UserMeeting, 26-28 Jan 2011, Hamburg, Germany
R.A. Loch, R. Sobierajski, C. Bostedt, J. Bozek, S. Bruijn, T. Burian, J. Chalupsky, Y. Feng, J. Gaudin, A. Graf, E.D. van Hattum, S. Hau-Riege, L. Juha, A.R. Khorsand, D. Klinger, R.W.E. van de Kruijs, J. Krzywinski, R. London, E. Louis, M. Messerschmidt, S. Moeller, W. Schlotter, K. Tiedtke, and F. Bijkerk, *Comparative damage studies in multilayer optics induced by intense short-wavelength pulses from FLASH and LCLS* (poster)

6th Workshop Ellipsometry 21 February 2011, Berlin, Germany
J. Chen, E. Louis, H. Wormeester, R. Harmsen, R.W.E. van de Kruijs, C.J. Lee, W. van Schaik, and F. Bijkerk, "*EUV optics cleanliness qualification using spectroscopic ellipsometry* (poster)

23rd NNV-symposium on Plasma Physics and Radiation Technology, March 15-16, 2011, Lunteren, The Netherlands
R. van der Meer, B. Krishnan, I.V. Kozhevnikov, M.J. de Boer, B.Vratzov, H.M.J. Bastiaens, J. Huskens, W.G. van der Wiel, K.-J. Boller and F. Bijkerk, *Improved resolution*

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SPIE Optics & Optoelectronics 2011, 18-21 April 2011, Prague, Czech Republic
A.S. Kuznetsov, A.J. Gleeson, R.W.E. van de Kruijs, and F. Bijkerk, *Blistering behavior in Mo/Si multilayers*

R.A. Loch, R. Sobierajski, E.M. Gullikson, D. Klinger, R.W.E. van de Kruijs, E. Louis, F. Siewert, A. Wawro, and F. Bijkerk, *Multilayer XUV/SXR beam splitters for short-wavelength FEL applications* (oral)

International Workshop on EUVL, 13-18 June 2011, Maui, Hawaii
E. Louis, S. Muellender, F. Bijkerk, *Developing reflective multilayer coatings, an enabling component of extreme ultraviolet lithography and beyond* (oral)

V.V. Medvedev, A.E. Yakshin, R.W.E. van de Kruijs, V.M. Krivtsun, S.N. Yakunin, F. Bijkerk, *B4C/Si based EUV multilayer mirror with suppressed reflectivity for CO_2 laser radiation* (poster)

12th ASML Technology Conference, 28-29 June 2011
I. Makhotkin, *Multilayers for the lithography generation beyond EUVL* (oral)

6th International Workshop on High-Resolution Depth Profiling HRDP6, June 27th – 30th, 2011, Paris, France
E. Zoethout, E. Louis, F. Bijkerk, *Depth profiling of Mo/Si multilayers: the effect of Ar-ion energy on layer structure* (oral)

8th International Conference on Diffusion in Materials (DIMAT), 3-8 July 2011, Dijon, France
J. Bosgra, A.E. Yakshin, and F. Bijkerk, *Non-constant diffusion rate in sub nanometer thick Mo-Si interlayers* (oral)

SPIE Optics and Photonics 2011, 21-25 August, 2011, San Diego, CA, USA
R.W.E. van de Kruijs, S. Bruijn, A.E. Yakshin, F. Bijkerk, *Interface diffusion kinetics and lifetime scaling in multilayer Bragg optics* (oral)

Smart Optical Systems Meeting, 12 September 2011, Delft, The Netherlands
M. Bayraktar, F. Van Goor, W. Wessels, G. Rijnders, G. Koster, C. J. Lee and F. Bijkerk, *Smart multilayer interactive optics for lithography at EUV wavelengths* (oral)

17th International Summer School on Vacuum, Electron and Ion Technologies, 19-23 September 2011, Sunny Beach, Bulgaria
I. Makhotkin, E. Zoethout, E. Louis, F. Bijkerk, *Nitrogen passivation in La/B4C layered structures* (oral)

35th annual conference of the Division of Atomic, Molecular, and Optical Physics (35th NNV AMO Conference), Lunteren, De Werelt, 11 en 12 October 2011
M. Bayraktar, C. J. Lee, F. van Goor, G. Koster, G. Rijnders and F. Bijkerk, *Reflectance tuning at extreme ultraviolet (EUV) wavelengths with active multilayer mirrors* (poster)

2011 International Symposia on Extreme Ultraviolet Lithography and Lithography Extensions, October 17-19 and October 20-21 2011, Miami, Florida, USA
E. Louis, S. Muellender, F. Bijkerk, *Developing reflective multilayer coatings, an enabling component of Extreme Ultraviolet Lithography and beyond* (oral)

I. Makhotkin, *Wavelength selection for multilayer coatings for the lithography generation beyond EUVL* (oral)

V.V. Medvedev, A.E. Yakshin, R.W.E. van de Kruijs, V.M. Krivtsun, S.N. Yakunin, F. Bijkerk, *EUV multilayer mirror with suppressed reflectivity for* CO_2 *laser radiation* (poster)

ICTF 15 - 15th International Conference on Thin Films 2011, 8th – 11th November 2011, Tokyo, Japan
A.E. Yakshin, R.W.E. van de Kruijs, R. Sobierajski, E. Louis, V.I.T.A. de Rooij-Lohmann, S. Bruijn, R. Loch, and F. Bijkerk, *Thermal damage in Mo/Si based multilayers for short-wavelength FELs*, (oral)

RSNE Conference 2011, 14 – 18 November 2011, Moscow, Russia
S.N. Yakunin, M.A. Chuyev, I.A. Subbotin, A.Y. Seregin, E.M. Pashayev, I. Makhotkin, E. Louis, F. Bijkerk, E. Lichachev, M.V. Kovalchuk and V.V. Kvardakov, *Simultaneous analysis of Grazing Incidence X-Ray Reflectivity and X-ray Standing Waves from multilayer periodic structures* (oral)

Netherlands MicroNanoConference '11, 15 – 16 November 2011, Hotel and Congrescentrum the ReeHorst, The Netherlands
M. Bayraktar, C.J. Lee, F. van Goor, G. Kooster, G. Rijnders, F. Bijkerk, *Reflectance tunning at extreme ultraviolet wavelenghts with active multilayer mirrors* (oral)

MicroNano Conference 2011, 16 November 2011, Ede, Netherlands
F. Bijkerk, *Multilayer extreme UV optics* (oral)

M2i Annual Conference, 12 December 2011, Noordwijkerhout, The Netherlands
J.M. Sturm, M.A.Gleeson, R.W.E. van de Kruijs, C.J. Lee, A.W. Kleyn, and F. Bijkerk, *Negating HIO-induced metal and carbide EUV surface contamination*, (poster)
T. Zaharia, M.A. Gleeson, W. van Schaik, M. van Kampen, C.J. Lee, F. Bijkerk, and A.W. Kleyn, *Stability of EUV caps under reactive environments (Secrure-N)* (poster)

Seminar

6 June 2011
E. Louis, *EUV and 'beyond' EUV multilayer research and development at FOM Rijnhuizen,* Center for X-Ray Optics, Lawrence Berkeley National Laboratory

Output of Generation and Utilization of TeraHertz radiation

Book chapter

PAHs and the Universe – A Symposium to Celebrate the 25th Anniversary of the PAH Hypothesis, 31 May – 4 June 2010, Toulouse, France
J. Oomens, *Laboratory infrared spectroscopy of PAHs*, PAHs and the Universe, C. Joblin and A.G.G.M. Tielens (eds), EAS Publication Series, 46 (2011) 61-73

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H. Alvaro Galué, C.A. Rice, J.D. Steill, and J. Oomens, *Infrared spectroscopy of ionized corannulene in the gas phase*, J. Chem. Phys. 134, 054310 (2011)

H. Alvaro Galué and J. Oomens, *Spectroscopic evidence for triplet ground state in the naphthyl cation,* Angewandte Chemie, 2011, 123, 7142-7145

H. Alvaro Galué and J. Oomens, *Spectroscopic evidence for triplet ground state in the naphthyl cation,* Angewandte Chemie, Int. Ed, 2011, 50, 7004-7007

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G.J.O. Beran, E.L. Chronister, L.L. Daemen, A.R. Moehlig, L.J. Mueller, J. Oomens, A. Rice, D.R. Santiago-Dieppa, F.S. Tham, K. Theel, S. Yaghmaei and T.H. Morton, *Vibrations of a chelated proton in a protonated tertiary diamine*, Phys. Chem. Chem. Phys., 2011, 13, 20380-20392

D.J. Brown, S.E. Stefan, G. Berden, J.D. Steill, J. Oomens, J.R. Eyler, B. Bendiak, *Direct evidence for the ring opening of monosaccharide anions in the gas phase: photodissociation of aldohexoses and aldohexoses derived from disaccharides using variable-wavelength infrared irradiation in the carbonyl stretch region,* Carbohydrate Research, 346 (2011) 2469-2481

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T.E. Cooper, D.R. Carl, J. Oomens, J.D. Steill, and P.B. Armentrout, *Infrared spectroscopy of divalent zinc and cadmium crown ether systems*, J. Phys. Chem. A, 2011, 115, 5408–5422 doi: 10.1021/jp202646y

R.P. Dain, G. Gresham, G.S. Groenewold, J.D. Steill, J. Oomens, M.J. Stipdonk, *Infrared multiple-photon dissociation spectroscopy of grout II metal complexes with salicylate*, Rapid Commun. Mass Spectrom. 25 (2011) 1837-1846

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G.S. Groenewold, M.J. van Stipdonk, J. Oomens, W.A. de Jong, M.E. McIlwain, *The gas-phase bis-uranyl nitrate complex* $[(UO_2)_2(NO_3)_5]^-$*: infrared spectrum and structure,* Int. J. Mass Spectrom. 308 (2011) 175-180

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Invited lectures at conferences and meetings

Colloquium Department of Molecular and Biophysics, February 18 2011, Radboud University Nijmegen, The Netherlands
J.M. Bakker, *IR action spectroscopy of strongly bound systems using the Free Electron Laser for Intracavity Experiments (FELICE)*

Wayne State University, Detroit, February 23, 2011, MI, USA
J. Oomens, *Ion spectroscopy and structure using a free electron laser*

York University, February 24, 2011, Toronto, Canada
J. Oomens, *Ion spectroscopy and structure using a free electron laser*

University of Toronto, February 25, 2011, Toronto, Canada
J. Oomens, *Ion spectroscopy and structure using a free electron laser*

Gordon Research Conference on Gaseous Ions, February 27 – March 4, 2011, Galveston, TX, USA
J. Oomens, *CID product structures of protonated and deprotonated peptides by IRMPD spectroscopy*

American Chemical Society, 2011 Spring Meeting, March 27 - 31, 2011, Anaheim, CA, USA
J. Oomens, *CID product structures of protonated and deprotonated peptides by IRMPD spectroscopy*

NWO Workshop Astrochemistry: Molecular Networks Connecting the Universe, April 18-20, 2011, Amsterdam, The Netherlands
J. Oomens, *Laser spectroscopy and tandem mass spectrometry: opportunities in Astrochemistry*

1-Day Symposium in Honor of Prof. J. Lisy, June 15, 2011, Université Evry Val d'Essonne, France
J. Oomens, *Structural characterization of peptide fragments using FEL-based IR spectroscopy*

GRC Biomolecules in the gas phase and in solution, 31 July -5th August 2011, Andover, USA
J.D. Steill, G. Berden and A.M. Rijs, *Nature's energy source probed by IR action spectroscopy: Can ATP act as a fuel in the gas phase?*

Conference on Molecular Energy Transfer (COMET 2011), Sept 11-16, 2011, Oxford, UK
J. Oomens, *The chemistry of peptide sequencing elucidated by IR spectroscopy*

Workshop "large amplitude motions" / Atelier "Mouvements de grande amplitude", Orsay, France, 21 October 2011
A.M. Rijs, *Probing Rotaxane Molecular Motion by IR Spectroscopy*

Tokyo University of Science, Tokyo (Shinyuku), Japan, Nov 29, 2011
J. Oomens, *Spectroscopy and structure using a free electron laser*

Annual Meeting of the Spectroscopical Society of Japan, Nov 30 – Dec 2, 2011, Yokohama, Japan
J. Oomens, *Bridging the gap between IR spectroscopy and mass spectrometry*

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

Annual Meeting of the Astrophysical Chemistry Group of the Royal Chemical Society and Royal Astronomical Society on progress in astrochemistry, 5-7 January 2011, University of Technology Eindhoven, The Netherlands
H.Alvaro Galué, *Spectroscopic evidence for the triplet state of dehydrogenated PAH cations: potential implications to the diffuse interstellar bands*, (oral C6)

J.M. Bakker, *Gas-phase IR spectroscopy of PAH cations in the 10-50 micron spectral range* (poster P4)

V.J.F. Lapoutre, J. Oomens, B. Redlich, A.F.G. van der Meer, T.R. Walsh, M. Haertelt, G. Meijer, A. Fielicke and J.M. Bakker, *Gas-phase IR spectroscopy of PAH cations in the 10-50 micron spectral range* (poster P4)

Physics@FOM, Veldhoven, 2010, 18 - 19 January 2011, Veldhoven, Netherlands
V. Lapoutre, J.M Bakker, B. Redlich, A.F.G. van der Meer, J. oomens, T. Walsh, M. Haertelt, G. Meijer, A. Fielicke, *Direct far-infrared spectroscopy of transition metal clusters*, PA03.06

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H. Alvaro Galué, *IR spectroscopy of ionized corannulene in the gas phase*, P02.32

J. Oomens, A.M. Rijs, *Infrared absorption spectroscopy on active site mimics of F0F1-ATPase*, P02.45

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Joliot-Curie Physics Seminar, 2 February 2011, Nijmegen, The Netherlands
A.M. Rijs, *On the origin of (bio)molecular motion* (oral)

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J.M. Bakker, B. Redlich, A.F.G. van der Meer, and J. Oomens, *Far-IR action spectroscopy PAH cations,* Poster presentation 4 (Studygroup Spectroscopy & Theory)

V.J.F. Lapoutre, J. Oomens, B. Redlich, A.F.G. van der Meer, T.R. Walsh, M. Haertelt, G. Meijer, A. Fielicke, J.M Bakker *Structure determination of metal and metal carbide clusters by resonant IR excitation* (poster)

S. Jaeqx, J. Oomens, A.M. Rijs, *Towards an active site mimic of* F_0F_1*-ATPase: Proton transfer from glutamic acid to arginine,* Spectroscopy & Theory, nr. 30

S.Jaeqx, M. Schmitt, W.J. van der Zande and A.M. Rijs, *Can backbone vibrations reveal the secondary structure of peptides?* (oral)

Symposium on Size Selected Clusters, S3C, 2011, 20 – 25 March 2011, Davos, Switzerland
V.J.F. Lapoutre, M. Haertelt, A. Mookherjee, A. Sweeney, J. Oomens, B. Redlich, A.F.G. van der Meer, P.B. Armentrout, T.R. Walsh, G. Meijer, A. Fielicke, J.M Bakker, *Structure determination of metal clusters and metal carbene cations by IR multiple photon spectroscopy*, A24

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S. Jaeqx, M. Schmitt, W.J. van der Zande, and A.M. Rijs, *Can backbone vibrations reveal the secondary structure of peptides?,* (poster)

S. Jaeqx, G.C.P van Zundert, J. Oomens, and A.M. Rijs, *A cool look at biomolecular motion: Structural analysis of its fuel and active site mimics by IR spectroscopy* (poster)

Workshop Astrochemistry: Molecular Networks Connecting the Universe, April 18-20, 2011, Amsterdam, The Netherlands
V.J.F. Lapoutre, J. Oomens, B. Redlich, A.F.G. van der Meer, T.R. Walsh, M. Haertelt, G. Meijer, A. Fielicke, and J.M. Bakker, *Far-IR action spectroscopy of PAH cations and transition metal clusters* (poster)

XXIV International Symposium on Molecular Beams, May 23 - 26, 2011, Bordeaux, France
J.M. Bakker, *Far-Infrared multiple-photon action spectroscopy of strongly bound systems*, (oral) OC05

American Society for Mass Spectrometry (ASMS) 58th Annual meeting on mass spectrometry and allied topics, June 5 – 9, 2011, Denver, CO, USA
J. Oomens, *Spectroscopic evidence for a triplet ground state in dehydrogenated polyaromatic cations*

35th Annual Meeting NNV AMO, October 11-12, Lunteren, The Netherlands
V.J.F. Lapoutre, A. Sweeney, A. Mookerjee, P. B. Armentrout and Joost M. Bakker, *IR Structural Characterization of Transition Metal Carbene Cations: Ta, W, Ir, Pt,* (poster) P3

V.J.F. Lapoutre, J. Oomens, J.M Bakker, *Probing the adsorption of carbon monoxide on transition metal clusters using IR photodissociation spectroscopy*, O14

S. Jaeqx, M. Schmitt, W.J. van der Zande, A.M. Rijs, *The Far-Infrared region as secondary probe for the secondary structure of peptides*, O11

Jeffrey D. Steill, Giel Berden and Anouk M. Rijs, *The energy source of cells probed by IR spectroscopy: Can ATP be a fuel in the gas phase, or not?*

R.T. Jongma, A.F.G. van der Meer, B. Redlich, W.J. van der Zande, *FELIX user facility Nijmegen: advanced MIR/FIR sources,* O16

CHAINS2011 (Chemistry As INnovating Science), November 28-30, Maarssen, The Netherlands
J.M. Bakker, *Infrared structural characterization of the interaction between bare transition metals and small molecules*, (oral)MON A.3.3

V.J.F. Lapoutre, J. Oomens, J.M Bakker, *Probing the adsorption of carbon monoxide on transition metal clusters using IR photodissociation spectroscopy, A65*

S. Jaeqx, J. Oomens, A.M. Rijs, *Towards an active site mimic of F_0F_1-ATPase: Proton transfer from glutamic acid to arginine,* A48

33rd International Free Electron Laser Conference, 22-26 August 2011, Shanghai, China
G. Berden, R. T. Jongma, F.J.P. Wijnen, H.J.F.M. van der Pluijm, *A simple spectral calibration technique for terahertz FEL radiation, TUPA16*

The Chemical Cosmos, 12 – 14 October 2011, Floriana, Malta
A. Petrignani, J. Eyler, J.M. Bakker, B. Redlich, A.F.G. van der Meer, A.G.G.M. Tielens, J. Oomens, *The infrared spectra of highly stable PAH ions using a free electron laser with intra-cavity mass spectrometry*

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A.M. Rijs, G. Berden, W.J. van der Zande, and J.D. Steill, *High-Resolution IR spectroscopy as a tool to probe molecular motion,* (oral)

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Output from Collaborators

User groups of the FELIX facility

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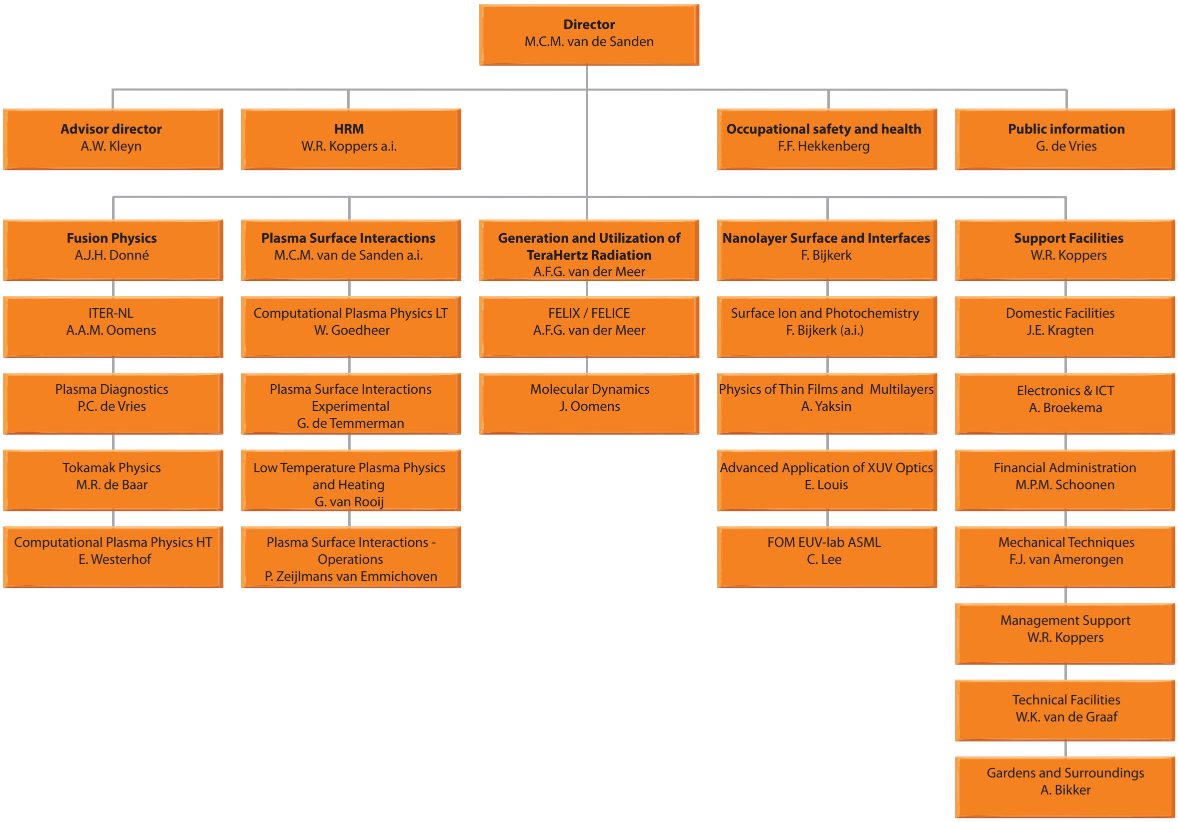
5 Organization

5.1 Organization scheme



5.2 Organization

Management Team
M.C.M. van de Sanden (institute director, chairman)
F. Bijkerk
A.J.H. Donné
W.R. Koppers
A.F.G. van der Meer
J. Rapp until August 15

Scientific Advisory Committee (SAC)
G. van der Steenhoven (chairman)
V.I.Y. Banine
D.J. Campbell
A. von Keudell
B. Lipschultz
J.R. Schneider
M.S. de Vries

FELIX Program Advisory Committee
M. Helm (chairman)
H. Bakker
A.J.R. Heck
A. Krier
P. Maître
H.N. Rutt
W. van der Zande

Employees Council
G. Kaas (chairman)
G.M.D. Hogeweij
A.P. Visser
J.W. Genuit
F.J. van Amerongen
J. Citrin
A.M. Rijs

5.3 Rijnhuizen in numbers

Staff (ppy)

Scientific staff	62.9
Permanent	21.1
Temporary	9
PhD students	32.8
Technical staff	54.1
Permanent	50.3
Temporary	3.8
Support staff	27.1
Permanent	23.8
Temporary	3.3
Total	**144.1**

Output

Refereed articles	275
Non-refereed articles	31
Books / monographs	0
Book chapters	1
PhD theses	13
Master theses	3
Bachelor theses	2
Conference papers	58
Professional publications	237
Publications for general public	27
Patents	0

Budget (k€)

Personnel	10,418
Consumables	3,488
Investments	1,231
Total	**15,137**

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