FOM Focusnotitie Fusiefysica

Nuclear Fusion Research
Vision for the years 2010 - 2020

Summary
Nuclear fusion research focuses on the behaviour of hot plasmas confined by magnetic fields with the aim to develop a fusion power plant. It is a field in which many disciplines of physics and technology come together. The field is characterized by extensive international collaboration, with the joint ITER project as the focus.

The Dutch fusion physics programme makes significant contributions in a few selected research areas, in which a position of excellence has been built up over the years. These thrust areas are:

- *Burn Control:* the control of a self-heating fusion plasma, which requires firstly a sound theoretical basis for the prediction of the behaviour of the plasma, sensors, actuators and finally an integrated control strategy.
- *Plasma Surface Interaction and Materials Research:* the exhaust of power, helium and other impurities produced in the fusion reactor via the plasma facing materials. New materials need to be characterized that can withstand the harsh environment in a fusion reactor with high fluxes of neutral particles, neutrons and gammas, and that do not lead to significant tritium co-deposition.

Next to the physics research, Dutch groups – in particular NRG (Petten) contribute to the development of neutron-hard materials for fusion reactors. A group at Twente University is involved in research in the field of superconducting coils for ITER and DEMO (the demonstration reactor). These activities which are more of engineering nature are not discussed in this 'focusnotitie'.

Nuclear Fusion Research in Context
The agreed road map of international research in the field of magnetic confinement fusion is the so-called *Fast track*, which implies first building ITER – a device in which the (thermal) fusion power is 10 times the input power – and then DEMO – a demonstration power plant, while in parallel to ITER reactor materials are developed using the International Fusion Materials Irradiation Facility (IFMIF).
To focus the European research on the fast track (DEMO operation is foreseen from 2035 onwards), seven R&D missions have been defined within the European Fusion Development Agreement (EFDA):

1. Burning Plasmas;
2. Reliable Tokamak Operation;
3. First Wall Materials & Compatibility with ITER/DEMO Relevant Plants;
4. Technology and Physics of Long Pulse & Steady State;
5. Predicting Fusion Performance;
6. Materials and Components for Nuclear Operation;
7. DEMO Integrated Design: towards High Availability and Efficient Electricity Production.

The Dutch fusion programme has recently strongly focused on the first (FOM Programme 'Active control of magneto-hydrodynamic modes in burning plasmas', (CBP), nr. 120), the third (FOM Programme 'PSI-lab: an integrated laboratory on plasma-surface interaction', (PSIL), nr. 75) as well as on the sixth topic, and builds on expertise available at FOM

Rijnhuizen (topics 1,3,6), Eindhoven University of Technology (topics 1,3), the Nuclear Research and consultancy Group (NRG) in Petten (topics 3,6), the Centre for Mathematics and Informatics in Amsterdam (topic 1) and Twente University (topic 6).

Burn Control

FOM-programme CBP: 'Active control of magneto-hydrodynamic modes in burning plasmas' (nr. 120)
FES project: ITER-NL - Innovation for and by ITER

In the future generation of tokamaks like ITER the power generated by the fusion reactions substantially exceeds the external input power ($P_{fusion}/P_{in} \geq 10$). When this occurs one speaks of a burning plasma. Twenty percent of the generated fusion power in a burning plasma is carried by the charged alpha particles, who transfer their energy to the ambient plasma in collisions, a process called thermalization. A new phenomenon in burning plasmas is that the alpha particles, which form a minority but carry a large fraction of the plasma kinetic energy, can collectively drive certain types of magneto-hydrodynamic (MHD) modes, while they can suppress other MHD modes. These MHD modes can have both desirable and unwanted effects on the plasma. For example, the so-called saw tooth instability on the one hand helps the transport of the thermalized alpha particles out of the core (desirable), but on the other hand may result in the loss of the energetic alphas before they have fully thermalized (unwanted). A further undesirable effect of the saw tooth instability is that it may trigger other MHD modes such as neoclassical tearing modes (NTMs). These NTMs are detrimental to the plasma confinement and in some cases may even lead to disruptive termination of the plasma. At the edge of the plasma, finally, so-called Edge Localized Modes (ELMs) occur, which result in extremely high transient heat and particle loads on the plasma facing components of a reactor. In summary, active control of MHD-modes is required to optimize the mix of desired and detrimental effects. An additional complication occurs in a burning plasma as the external heating power, which is nowadays generally used for plasma control, is small compared to the heating power of the alpha particles.

Scientific challenge
The scientific challenge in the field of burn control is to optimize the mix of desired and detrimental effects of the various MHD modes and to develop the tools for their active control in burning plasmas. Therefore, it is necessary to understand the mutual interactions between the fast alpha particles and the MHD instabilities. Since burning plasmas do not yet exist, the relevant experimental work until 2026 (when ITER comes into operation at full performance) needs to be largely based on alpha-particle simulation experiments in which the alpha particles are accelerated to high energies by means of special heating techniques. The precise conditions of a burning plasma can be only partly mimicked in present tokamaks. Computational models need to be developed to describe the MHD instabilities and the fast particles. These models need to be benchmarked to experimental data and – in case of satisfactory agreement - can then be used to model the behaviour of MHD instabilities and fast particles in a burning plasma; ITER being the first target of these modelling calculations.

Ingredients
To address these questions, a dedicated research programme has recently been started (FOM-programme CPB, nr. 120) in the Netherlands, based on the already available expertise in the following areas:
- Plasma wave interaction, and in particular on Electron Cyclotron resonance Heating and Current Drive (Rijnhuizen);
- Advanced diagnostics for MHD modes and fast particles (Rijnhuizen and TU/e);
- Control Systems technology (TU/e);
- MHD physics and physics of fast particles (CWI, Rijnhuizen, TU/e);
- Numerical mathematics (CWI, Rijnhuizen, TU/e, LEI).

The experimental work is carried out on leading international facilities. The two most relevant tokamaks in Europe (according to a international facility review performed under EFDA in 2008) are: JET (***J****oint* ***E****uropean* ***T****orus*) in the United Kingdom – the largest operational tokamak worldwide, jointly operated by all European fusion institutes associated with EURATOM, and ASDEX-Upgrade (***A****xially* ***S****ymmetric* ***D****ivertor* ***EX****periment - Upgrade*) in Germany. High performance plasmas are routinely made in ASDEX-UG and JET and fast particles can be generated by means of minority heating techniques (often referred to as alpha particle simulation experiments). Although of course this is not in the regime with dominant alpha heating it is still possible to study most of the relevant interactions and to prepare the control techniques for utilization in ITER. It is likely that also tokamaks in the USA and Asia will be used as test bed if they are better suited for some specific research programmes.

It is important to note that modelling and control – thus far separate activities in fusion research - should be brought together in a single activity. This is because the advanced control loops envisaged for burn control need to be based on adequate, real-time measurements that feed into a fast, simplified model of the plasma, to steer the actuators (in particular the ECRH/CD system). The computational modelling will be done in close collaboration with the European Task Force on Integrated Tokamak Modelling. The aim of this Task Force is to build a comprehensive computer model to simulate the full tokamak plasma by combining the many individual models that all describe specific features of the plasma. The FOM physicists concentrate on the packages describing the behaviour of MHD instabilities in hot plasma including their interaction with fast particles and with microwaves.

Hardware and valorisation
Hardware developments and valorisation in the framework of the ITER project are in the Netherlands coordinated by the ITER-NL consortium comprising of FOM, TNO, NRG and - very soon – TU/e and which is funded via FES (Fonds Economische Structuurversterking). ITER is a driver of innovation. Companies that deliver equipment, components and/or knowledge to ITER innovate and increase their competence level by which they can enter new markets and enhance their financial outturn. The ITER-NL consortium aims at maximum the involvement of Dutch industry into the ITER project and has set up a number of specific valorisation activities.

The focus of ITER-NL is the realization of a number of dedicated scientific instruments needed for performing burn control physics in ITER. Namely, the optimum entry ticket to getting involved in experiments at international facilities is to provide specific hardware like diagnostics and heating equipment. To ensure a significant role for Dutch scientists in the experimental programme of the international ITER project it is therefore important to develop diagnostic and heating equipment for ITER. Synergistically the optimum result is achieved if similar equipment that has been developed for FOM-programme CBP (nr. 120) can be developed for research in the field of burn control on ITER. The most obvious choices are to focus on Charge Exchange Recombination Spectroscopy and (LIDAR) Thomson scattering as diagnostic techniques and on Electron Cyclotron Resonance Heating and Current Drive as heating technique. These instrumental developments are done in European consortia of fusion institutes in which ITER-NL is the Dutch partner. Dutch industry is involved as much as possible in the project right from the start to enhance their chances to get orders from the ITER project.

Links to other research fields
The area of burn control has strong links with plasma-astrophysics (MHD), turbulence in fluids, large-scale computational physics, atomic physics, advanced control of complex systems, instrumentation, microwave technology, spectroscopy, fast data acquisition and analysis.

Plasma Surface Interaction and Materials Research

FOM-programme PSIL: 'PSI-lab: an integrated laboratory on plasma-surface interaction' (nr. 75)

Materials in nuclear fusion reactors have to withstand high heat and particle fluxes by ions and atoms having energies from a few eV to a few hundred eV, particle fluxes to the divertor that are in steady state up to 10 MW/m^2 and transiently up to 15 GW/m^2, high neutron fluences (causing up to tens of dpa), and chemically aggressive hydrogen environments. Powerful plasma flows in the boundary region of magnetically confined fusion plasmas connect the hot, burning plasma core, the edge plasma, the main chamber and the divertor region, and this currently even under highly transient conditions (Edge Localised Modes). Exposed to such an environment, the materials should have a minimal impact on the fusion plasma performance and hence have very low erosion and maximized lifetime for economical reasons. For safety and efficiency reasons those materials should retain as little hydrogen isotopes as possible. The materials should have a high heat conductivity, low diffusion of hydrogen, and a favourable neutron irradiation resistance. Neutron irradiation resistance is important in the context of nano-structural changes to the material, which influences many of the material properties. For the plasma facing materials of the main chamber wall of a tokamak irradiation resistance for structural integrity is important, whereas for the plasma facing materials in the divertor irradiation resistance with respect to heat load capability, surface morphology and tritium retention is more important.

Scientific challenges and objectives
The scientific challenges and overall objectives of the Plasma Surface Interaction and Materials Research are related to:
- Investigation of erosion and re-deposition for lifetime prediction of plasma facing components and contamination of plasma;
- Investigation of tritium retention (and removal) for safety and fuel cycle;
- Investigation of dust for safety;
- Investigation of structural integrity of the plasma facing components under the influence fo high particle and heat fluxes including irradiation;
- Investigation of processes in the plasma boundary;

- Development of advanced plasma surface interaction diagnostics and control tools;
- Development and validation of computational models for interpretation and prediction to fusion reactors.

The knowledge gained within this programme should form the basis for the solution to the problem of plasma surface interactions. The research programme in the next 10 years will be centred on:

- Development of new operation scenarios
  The final recipe to achieve fusion is not established yet. Future fusion plasma operation scenarios have to be compatible with both (a) good plasma confinement and (b) the boundary conditions imposed by the plasma facing materials. Operation scenarios have to be developed, which reduce the power fluxes to the plasma facing materials to acceptable levels in order to maximize their lifetime as well minimize the plasma core pollution by erosion products. Operation scenarios have different demands on the power exhaust strategies. Understanding of the plasma surface interaction under the influence of different seed impurities (e.g. N_2, Ne, Ar), different plasma temperatures, different plasma densities, temporal and spatial power flux evolution will help to make choices for the best power exhaust strategy, which will have consequences on the fusion plasma operation scenario. To be able to make predictions for ITER and other fusion reactors it is important to develop computational models describing the plasma-surface interaction and the effect of those on the material properties and to validate these models with experimental data.

- New energy exhaust systems
  The divertor concept that will be employed in ITER is definitely not suited for the DEMO demonstration reactor and the commercial reactors to follow, because the power loads on the divertor components would be too high. Therefore, new energy exhaust systems need to be tested, like pebble divertor concepts, liquid metal divertor targets, while giving emphasis to geometry aspects, the effect of additional electric fields, incorporation of perturbation fields, etc. New divertor concepts have to be first tested in test beds like those linear divertor generators, which features excellent diagnostic access, to study the various plasma-surface processes in great detail.

- New materials
  After the analysis of plasma surface interaction with the standard plasma facing materials (fine grain graphite, CFC, tungsten and molybdenum) novel materials will be tested (e.g. SiC, Li, diamond). Furthermore, approaches to new plasma facing materials will be endeavoured. This will be done in close co-operation with Dutch universities (TUD, TU/e, UT), TNO, NRG and other partners from industry and research organizations outside of the Netherlands, where materials can be designed and manufactured. An emphasis will be given on the development of nano-structured materials. The emphasis of the FOM programme is on the materials testing and understanding the detailed processes taking place at the surfaces and in the bulk of the materials. FOM has the ambition to complement its linear plasma generator Magnum-PSI with an in-situ Ion Beam Analysis facility (Nuclear Recoil Analysis, Rutherford Backscattering, elastic recoil detection), which will be an essential diagnostic in detailed investigations of processes like the diffusion of vacancy clusters and voids as well as hydrogen diffusion in the materials for example.

Hardware
Although some of the above points can be addressed in contemporary fusion devices like tokamaks, it is evident that experiments at dedicated plasma surface devices are an absolute necessity to perform state-of-the-art research in this field. The Trilateral Euregio Cluster (TEC) constituted of the Forschungszentrum Jülich (FZJ), the Royal Military School (ERM/KMS) Brussels, the Centre for Nuclear Studies (SCK.CEN) Mol and FOM-Rijnhuizen, is world leading in the field of plasma surface interaction. TEC exploits a number of unique plasma devices of which MAGNUM-PSI at FOM-Rijnhuizen is by far the largest and also the leading device. Apart from MAGNUM-PSI research is done on Pilot-PSI. The latter device is smaller, but much more flexible and is ideally suited to test all kinds of new thoughts and concepts before they are implemented on MAGNUM. Pilot is also used to test and prototype many of the components for MAGNUM.

To be able to carry over the experimental results in linear device to real tokamak geometries it is important to develop computational models to describe the detailed plasma-surface interaction, to benchmark those with the experimental data and then – in case the models give satisfactory results – to use the models in real tokamak geometries.

Ingredients
The work in the field of Plasma Surface Interaction and Materials Research involves widespread expertise in The Netherlands:
- Operation of large scale plasma generators (Rijnhuizen);
- Plasma diagnostics and surface diagnostics (Rijnhuizen, TU/e, UT);
- Modelling of processes involved in plasma surface interaction (Rijnhuizen, TU/e, RU, CWI);
- Materials research (TUD, TU/e, UT, NRG/ECN, TNO, industry) with emphasis on the characterisation of materials.

Links to other research fields
The area of plasma-surface interaction is related to low-temperature plasma physics (industrial plasmas, plasma sources, deposition and erosion), plasma chemistry, materials research, surface chemistry and catalysis.

Conclusion
Thanks to the recent focusing of the fusion activities onto the two main research lines *Burn Control* and *Plasma Surface Interaction and Materials Research,* the Dutch researchers have a coherent research programme with clear goals for each of the lines. The prospects for maximizing the scientific impact in both research lines in the coming decade are very good. Fusion research, which was until a few years ago a sole activity of FOM-Rijnhuizen, has nowadays a much broader basis in the Netherlands with involvement of TU/e, RU, UT, TUD, NRG, CWI with a potential to even broaden further in the future.

Both FOM programmes PSIL (nr. 75) and CBP (nr. 120) will come to an end in 2014. But already at this stage it can be stated that also in the second half of this decade *burn control* and *plasma surface interaction and materials research* will stay high priority areas that need to be continued. Also realizing that FOM aims to play an important role in these fields in the scientific exploitation of ITER, one needs to continue these activities until the start of the ITER scientific programme.

The areas of *Burn Control* and *Plasma Surface Interaction and Materials Research* are presently performed as rather independent activities (albeit that there is some cross fertilization in the area of diagnostics). In the future (i.e. the second half of this decade) one could consider to bring the two topics slightly closer by strengthening the link between them. The FOM programme PSIL (nr. 75) and FOM-programme CBP (nr. 120) 'touch' each other in the research of the Edge Localised Modes (ELMs). The ELMs take place at the very plasma edge. The aim of FOM-programme CBP is to develop methods to control MHD instabilities including ELMs. In FOM programme PSIL the impact of ELMs on material surfaces is studied by using high-power pulsed plasma beams. A second link are the impurities: in FOM programme PSIL the release of impurities from material surfaces is studied, whereas in FOM-programme CBP the transport of impurities towards the core plasma is investigated. In the second half of this decade the link between the programme lines can be further strengthened, which will lead to an increased coherence of the Dutch fusion programme.