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Nuclear Fusion Project

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including the contributions of

the TEC Partners
ERM/KMS Brussels and FOM Nieuwegein

and the IEA Partners

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CONTENTS PAGE

A. INTRODUCTION

Fusion research is conducted in the European Union within the framework of a collaborative overall programme coordinated within EURATOM. Now that a reliable design is available for an experimental fusion reactor with an energy gain factor of 10 (International Thermonuclear Experimental Reactor: ITER) the continuous operation of a fusion power station comes into the focus of research. This relates above all to the further investigation of plasma wall interaction, but also of energy and particle confimenent, especially near the operational limits.

Accordingly, the programme of the Institute of Plasma Physics concentrates on the interaction of the magnetically confined high-temperature plasma with the surrounding walls and on methods of influencing it as well as on linking these issues with the transport of particles and energy in the plasma core.

The findings so far obtained have made it increasingly clear that, due to the strong nonlinear coupling of the physical processes in the individual regions of plasma core, plasma boundary layer and wall, a coherent – i.e. equally covering all plasma regions – experimental physics approach must be selected to be able to successfully deal with this issue for future fusion machines. The EURATOM-associated fusion laboratories in the three-frontier region (ERM/KMS Brussels, FOM Nieuwegein and Research Centre Jülich) have joined forces in the sense of a joint research team forming the Trilateral Euregio Cluster (TEC) to jointly handle this comprehensive programme.

The TEC partners' central facility is the TEXTOR tokamak which has been designed for these tasks and upgraded to longer pulse operation. Further apparatus oriented to the programme goal is under construction or at the planning stage. On the part of Research Centre Jülich this is primarily the Dynamic Ergodic Divertor (DED), which represents a novel technique for influencing the particle and energy transport in the plasma boundary layer by "magnetic edge layer vortexing". The installation of the DED in the TEXTOR vessel will be completed by autumn 2002. Extensive new installations in TEXTOR are realized by the Dutch TEC partner. They comprise new diagnostics and electron cyclotron resonance heating (ECRH) with a 1 MW gyrotron.

The scientific programme of TEXTOR is currently divided into seven general issues: plasma-wall interaction, impurity transport, energy confinement, magnetohydrodynamics, advanced tokamak scenarios, new concepts and special components as well as modelling and theory. The IPP's R&D projects as well as research by the TEC partners ERM/KMS and FOM contribute towards dealing with these issues. Analogously, the instrumental and diagnostic equipment of TEXTOR is jointly provided and coordinated by the TEC partners. This manifests itself in two separate R&D projects, whose staff and financial resources are provided by the TEC partners.

The research team is involved in the JET joint European project (Joint European Torus) by planning, implementing (partially heading) and scientifically evaluating experimental campaigns on selected issues. Mutual enrichment plays an important part in the research on JET and TEXTOR. Participation in the stellarator programme of the Max Planck Institute of Plasma Physics (Garching, Berlin, Greifswald) covers work on specific physical problems, intensive cooperation in the conceptual design of selected boundary layer and core diagnostics for the Wendelstein 7-X project as well as the further development of equally TEXTOR- and stellarator-relevant numerical models.

A cooperation agreement on the joint use of TEXTOR with the International Energy Agency (IEA) regulates the participation of scientists from Japan, the USA and Canada, the provision of equipment from these countries and the implementation of self-contained programme elements of the partner countries.

Several infrastructure departments of FZJ are involved in the further development of TEXTOR. Staff members from the IWV[2] participate in the research programme on TEXTOR. An agreement with the Technical University of Braunschweig comprises work in the field of electrical engineering. Several cooperations with German universities contribute to the research programme, especially within the framework of the Special Research Programme 191 and the DFG's postgraduate support organization "High-Temperature Physics", the Association of Plasma Physics (APP) and the "Euroregional University Club for High-Temperature Plasma Physics", which also comprises neighbouring Belgian and Dutch universities.

B. GENERAL PROGRAMME ON TEXTOR

B.1. MAIN TOPIC I – PLASMA WALL INTERACTION

Dr. V. Philipps *(v.philipps@fz-juelich.de)*

Understanding and control of the interaction processes of fusion plasmas with the surrounding walls and their interrelation with the global plasma performance is a major element in fusion research. These processes affect the energy release and fuel dilution in the plasma core by impurities released from the walls, the lifetime of wall components by erosion and the long term retention of the fuel gas in the walls. The goal is to minimise these consequences by tailoring the conditions in the plasma edge, use of proper wall materials, and active control of the processes. The activities were concentrated on erosion and deposition, on hydrogen recycling and retention and on the further evaluation of alternative, non carbon-based wall materials. A relevant part of the activities were done at JET (UK) within the Task Force E (exhaust and edge physics).

Quantification of the net-erosion of the graphite limiter tiles in TEXTOR has been addressed by depth profiling of grooves machined on the plasma facing side. A total loss rate of about 22 g carbon integrated over 1 h plasma operation time has been identified. On the bottom of the grooves a net-material deposition is observed, even on areas of net-erosion. A major part of the eroded material (10 g/h) is deposited on the limiter itself near the tangency point but some part is also deposited on obstacles in the scrape-off layer of TEXTOR and is found on rear areas of the toroidal limiter. There, a total amount of 23 g has been found integrated over a total plasma time about 24 h. Obviously, the present limiter configuration in TEXTOR where the surface follows the field lines (angle of incidence mostly < 2°) can lead to relatively large short range material transport over the limiter surface. Also in the pump ducts of the ALT, a carbon layer is deposited - but accounting only for a small amount and having a highly non-uniform spatial distribution. These layers originate from deposition of hydrocarbons with low sticking probabilities.

The nature of hydrogen/deuterium recycling on the plasma-facing components in fusion devices has been further investigated. The recycled deuterium flux has been characterised by passive and active spectroscopy from a graphite test limiter in TEXTOR and near the wall of the main chamber in JET. A coupling between the molecular vibrational and rotational temperatures has been found, which leads to an efficient evaluation method for the determination of molecular fluxes. Deuterium is released from graphite predominantly via molecules; the dissociation of molecules leads to low energetic atoms, hot surfaces emit only atoms with thermal energies.

As alternative to non-carbon based plasma-facing components, B_4C coated wall components, a tungsten brush-like and Ta test limiter have been explored in TEXTOR. B_4C coated wall components are recommended for the first wall in the W7-X stellarator which is under construction in Greifswald. The coatings show enhanced arcing but this is not expected to become harmful.

In JET, helium plasma operation has been performed to compare important plasma wall effects in deuterium and helium plasmas and to assess in detail the effect of chemical erosion. In L-mode He plasmas the density limit is about twice of that in equivalent D plasmas and terminated by a radiation collapse near the 100 % radiation limit. The H-mode density limit is very similar in D and He. Carbon and beryllium deposition on the plasma facing sides of the JET divertor has been modelled with a Monte-Carlo Code. A satisfactory agreement with measurements is obtained for Be, but carbon deposition still shows larger discrepancies.

B.2. MAIN TOPIC II – CONFINEMENT

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The studies of confinement aim at the development of an integrated scenario which combines good energy confinement at high plasma densities with acceptable power and helium ash exhaust. The method pursued to realise such a scenario is the formation of a cold plasma mantle with the help of impurity injection. This plasma regime (Radiative Improved Mode - RI-mode) requires physical understanding of the transport processes in both the core and the edge region of the plasma. In the latter, effects due to drifts and the occurrence of sheared rotation are important for the resulting transport. The application of external electric fields is an important tool to investigate these mechanisms.

Experiments have been performed in JET to study plasmas with a radiating boundary in the divertor configuration foreseen for ITER. Using argon as the radiating impurity it has been possible to reach high confinement and high density as needed at the operational point of ITER in the presence of a radiating plasma mantle where 65% of the input power is distributed uniformly to the wall. Furthermore, measurements indicate a reduced transient heat loss owing to edge localised modes. In experiments using neon injection a confinement improvement due to the impurity injection could well be reproduced by theoretical modelling already benchmarked against experiments at TEXTOR.

In TEXTOR the plasma density in the RI-mode has been maximised with an optimised scheme to fuel the plasma by external deuterium injection. A clear dependence of the global energy confinement on the amount of gas injected has been established. Moderate injection rates allow to increase the plasma density substantially without loosing the improved confinement while stronger gas injection leads to a degradation of the energy confinement without a considerable increase of density. The impact of the gas injection on the plasma edge characteristics like density, neutral pressure and density fluctuations triggers the changes in core performance. Modelling shows that an increase of turbulence driven edge transport is essential to provoke the re-appearance of instabilities which are generally suppressed in the RI-mode. Increased edge turbulence can be attributed to the strong localised source caused by external gas injection. Compared to deuterium plasmas the sensitivity of the energy confinement against external gas fuelling is even stronger in discharges fuelled by hydrogen.

The application of very localised heating with electron cyclotron waves at different radial positions in the plasma has confirmed that this heating method can efficiently increase the energy in the very centre of the plasma where the confinement is especially good.

Plasma drifts have important effects on the edge structure. Flows and asymmetries of the plasma density observed experimentally are well reproduced by 2D modelling if drifts are incorporated. Imposing external electrical fields in the scrape-off layer allows to optimise particle removal by channelling the plasma flow towards the toroidal pump limiter installed at TEXTOR. Also the reduction of anomalous radial transport in the edge region due to sheared plasma rotation as a consequence of electric field gradients can only be modelled in agreement with experiments if drifts are properly treated.

B.3. MAIN TOPIC III – IMPURITY TRANSPORT AND RADIATION

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Impurity transport plays a crucial role in the performance of thermonuclear plasmas. Impurities are either produced by the fusion reaction (helium ash) or introduced to the plasma by erosion of plasma facing wall material, or added artificially to improve the radiation properties (radiation cooling). A better understanding of underlying transport and radiation processes will widen the operational range of future devices. Two particular aspects are addressed in TEXTOR transport experiments: One is the bench-marking of experimental transport data against modelled predictions. Another is the investigation of the ‘trace’ character of impurities and the transition to bulk ion transport.

Argon impurity transport has been studied in ohmic discharges at TEXTOR by means of a fast gas puffing technique. Applying short gas puffs to the discharge, the time evolution of spectral lines from various ionisation stages of argon was measured using new VUV spectrometers with high time resolution. The experiments were analysed by a transport model, yielding the radial distribution of the diffusion coefficient. The results indicate that the impurity transport is anomalously enhanced.

Helium enrichment and helium ash removal is a critical issue for a fusion reactor requiring a helium residence time not more than 10 times the energy confinement. A good compression of helium in the divertor is a key parameter for sufficient He ash removal. In order to optimise the particle exhaust, the helium removal of different divertor strike point configurations in the JET gas box divertor has been investigated.

One of the most severe problems for fusion reactors is the power load on the divertor target plates. In order to reduce the power load in the divertor to those values radiation cooling by seeding of impurities is essential. In recent experiments at JET it has been demonstrated that with seeding of nitrogen a radiative power fraction of 90% can be achieved and both the steady-state power flux to the divertor target and the electron temperature in front of the divertor target are reduced to acceptable levels. The profile of fully ionised nitrogen is hollow during the highest radiative power fractions reflecting the high collisionality of the transport regime.

The potential of X-ray spectra of He-like ions for a continuous core electron temperature measurement was examined. Besides the widely used K-alpha spectra, which require detailed modelling, K-beta spectra were investigated at TEXTOR. The ratio between transitions in the K-beta triplet and singlet system depends sensitively on local electron temperatures and may therefore be used as a diagnostic tool. This applies to fusion as well as to astrophysical plasmas.

A combined use of Beam Emission Spectroscopy and Charge Exchange Recombination Spectroscopy extends the application range of the latter method to high-density-plasmas reducing considerably the uncertainties of deduced impurity ion densities associated to conventional neutral beam attenuation calculations. Dedicated studies at TEXTOR have allowed the validation of underlying atomic physics data.

B.4. MAIN TOPIC IV – MAGNETOHYDRODYNAMICS

Dr. H.R. Koslowski *(h.r.koslowski@fz-juelich.de)*

The operational space of a next step fusion device is constraint by operational limits. Many of them result from magnetohydrodynamic (MHD) instabilities. Most dangerous are disruptions which result in large forces on the vessel and loads on plasma facing components (PFC). The energy confinement is limited by the onset of so-called neo-classical tearing modes (NTM) which are driven by the plasma pressure and occur in high-confinement regimes. Edge localised modes (ELM) lead to the periodic ejection of particles and energy out of the plasma and restrict the lifetime of PFCs. The work performed focused on various aspects of the above mentioned instabilities.

Experiments aiming on the early detection of disruptions and their avoidance by imposed rotational shear using the tangential neutral beam injection systems were done on TEXTOR. A real-time signal correlation module allowed to detect the precursor mode and to trigger a heating beam. In some cases the disruption was avoided, but a sheared rotation could not always be established. A fast gas valve to inject helium, which should suppress the generation of runaway electrons (high-energetic, non-thermal electrons) during the disruption and reduce the impact on first wall materials, was utilised on TEXTOR, JET, and ASDEX Upgrade. Helium has been selected because it is not swallowed by the walls, has a high fuelling efficiency, and diffuses fast into the whole volume. The application of helium injection showed that the runaway production was completely suppressed.

Investigations of ELM instabilities in the high confinement regime (H-mode) on JET have revealed two new modes. The so-called palm tree mode, which is excited by the ELM, has been found over a wide range of plasma parameters and may be attributed to ergodisation of the edge plasma during the ELM collapse. A magnetic precursor mode with small to intermediate toroidal mode numbers prior to the ELM has been clearly identified. The understanding of both new modes may become a key element in the development of ELM models.

JET experiments on NTM onset triggered by the sawtooth instability in the plasma core showed that sawtooth destabilisation by ion cyclotron current drive, resulting in more frequent but smaller sawteeth, allows to enhance the beta limit due to a reduction in induced island size. NTMs occurring in plasma regimes with high collisionality due to impurity seeding were often destabilised by an unfavourable current density distribution without a preceding trigger instability.

TEXTOR experiments to investigate magnetic islands in detail were performed. The temperature profile within a magnetic island is peaked and proves an enhanced confinement in the island region. The temperature as well as the density fluctuations are larger in the vicinity of the X-points where the magnetic flux reconnects. Small-scale structures (possibly sub-islands) were detected around the island separatrix.

B.5. MAIN TOPIC V – ADVANCED TOKAMAK SCENARIOS

Dr. R. Jaspers *(r.jaspers@fz-juelich.de)*

For a fusion reactor to become economically attractive, a compact size with high confinement and a large non-inductive current drive is required. To obtain this ultimate goal advanced operational scenarios are envisaged. The current profile shape is a key parameter determining the transport of energy in a tokamak. Modification of the current profile such that an optimised or reversed shear is obtained may lead to the formation of transport barriers. Due to these barriers the advanced operational scenarios combine a high confinement with a large bootstrap current. The latter is due to the resulting strong gradients. The studies in this topic group were focussed on four items: 1) the development of a scenario with negative central shear in TEXTOR, 2) the study of electron transport barriers in JET, 3) a theory on the formation of ion transport barriers, and 4) the study on filaments.

1) Experiments were performed on TEXTOR with ECRH and neutral beam heating during the current ramp phase. The existence of a double electron transport barrier in case of central ECRH was observed. By varying the ECRH deposition position the discharges divide into classes depending on the heating position relative to these two barriers. The appearance of sawteeth just before the end or immediately after central ECRH indicates a strong evolution of the q-profile into a regime where no negative central shear is present as corroborated by current diffusion calculations. Stable discharges were only achieved with counter neutral beam injection. In other cases MHD activity developed which finally leads to a disruption.

2) The study of electron internal transport barriers (eITBs) at JET revealed that they could be established and sustained only with reversed shear. Moreover, it was found that no power threshold existed for the formation of eITBs. The relation of the position of eITBs with rational values of the safety factor was not conclusive.

3) The formation of ion ITBs was treated in a first principle theory valid for the case of low magnetic shear. At the position of minimum q an ITB will be initiated due to quenching of ITG (ion temperature gradient) turbulence. The ensuing strong variation of the ion temperature gradient on both sides will lead in turn to a large radial electric field gradient. The latter will further quench the turbulence and broaden the ITB until neo-classical transport comes into play.

Filaments are self organised, meso-scale structures with high confinement and thus can have temperatures largely in excess of the background plasma. These are studied as they could provide a clue in the still not fully understood mechanism of energy transport. Recent investigations in TEXTOR showed some remarkable results: i) filaments are always present independent of the heating method, ii) they exist everywhere in the plasma, iii) the amplitude of the filaments feature a universal scaling with collision time.

B.6. MAIN TOPIC VI – NEW CONCEPTS AND SPECIAL COMPONENTS

Dr. K.H. Finken *(k.h.finken@fz-juelich.de)*

Aim of the topical group is the understanding of the physics due to the operation of the Dynamic Ergodic Divertor (DED) and the test of new diagnostics and special components for TEXTOR. The perturbation currents of the DED superimpose a resonant perturbation magnetic field to the equilibrium field of the plasma; this additional field “weaves” the magnetic field lines and increases the plasma transport at the boundary such that the deposited heat will be distributed over a larger area at the wall – in a future fusion reactor, the high heat flux density to the walls is one of the critical issues. In addition, the DED of TEXTOR is unique in so far as the perturbation field can rotate with a velocity up to the order of the ion drift velocity in the plasma edge. By this rotation, new possibilities may open up for improving the plasma confinement.

For the analysis of the DED, several tasks have been performed:

- In order to characterise the perturbed edge zone, an atlas is in preparation showing the ergodic zone, the field line connection length of the laminar zone and the strike zones of the magnetic field lines at the divertor target plate.

- The development of a 3-D model of the plasma in the laminar zone has been continued. In the model, the MHD-fluid equations are solved by iteration for the transport perpendicular and parallel to the magnetic field lines.

- For investigating the particle transport in the ergodic area, a new mapping method for the guiding centre motion has been derived.

- The penetration of the time dependent perturbation field into the plasma edge has been computed taking into account equilibrium plasma flows.

- Diagnostics were modified and adapted for the DED operation.

- In order to co-ordinate DED activities even beyond the institute and the TEC partners, an international workshop is organised yearly. The main topic of the recent workshop was 3-D modelling of the plasma edge transport.

Special Components:

- A solid state detector has been applied for high-energy particles. In an overlap region the data have shown good agreement with values obtained from other diagnostics.

- At TEXTOR a new fast reciprocating probe system has been attached that will be a user facility for particle collection as well as for electrical and magnetic probes.

- A highly repetitive (20 kHz) Thomson scattering system with a plasma core and a separate plasma edge observation system is being developed in a FOM/FZJ collaboration. Up to three bursts of 40 laser pulses each will allow to study the dynamics of fast events in the plasma such as sawteeth, filaments, and islands with high spatial resolution (8 mm core, 2 mm edge).

B.7. MAIN TOPIC VII – THEORY AND MODELLING

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A substantial fraction of the theoretical activity of the TEC, closely related to experimental research, is reported in the corresponding topic group sections. The present review covers complementary activity.

Transport, impurities and RI-mode. The neo-classical approach to transport theory was further developed. Results cover new phenomena such as toroidal and poloidal plasma rotation, sub-neoclassical heat transport and fluxes due to turbulence in presence of RF heating. The role played by various instabilities in heat transport was investigated and the corresponding transport coefficients incorporated into the codes. The transport was also studied from guiding centre drifts in stochastic magnetic fields.

Transport modelling covers the whole plasma from centre to edge and deals with all aspects recently recognised as important for an accurate description: impurities, radial electric field, and transport of neutrals. The 1-D code RITM covers the innermost part of the plasma, the TECXY code describes the plasma edge, and the EIRENE code describes neutral gas transport.

Theory and modelling were applied not only to discharges in TEXTOR and JET, but as well to the tokamaks C-Mod, MAST, Tore Supra and ITER. The MARFE instability was investigated. In stellarators, the breathing instability was studied in LHD and the edge plasma structure in W7-AS.

Plasma heating physics. In ion cyclotron heating, Fokker-Planck codes were improved by including particle orbit effects, self-collisions, momentum-conserving diffusion coefficients and coupling to a full-wave code. Poloidal rotation induced by kinetic RF heating effects was estimated. Inclusion of finite temperature modes in the antenna coupling code via adequate boundary conditions was investigated. Wave frequency sweeping, as a means to restore interaction between waves and fast particles, was found promising. The re-evaluation of the ion cyclotron heating scenarios for ITER was completed.

In the electron wave domain, a new scheme for non-linearly driving currents by counter-streaming cyclotron waves was investigated. The modification of wave propagation in regions of resonant absorption was studied.

Non-linear plasma dynamics and turbulence. The study of anomalous diffusion using hamiltonian mappings was pursued. Partial transport barriers were found. In MHD turbulence, the large eddy simulation technique, based on a filtering of small scale turbulence, was further developed.

A substantial amount of work was also devoted to the study of current filamentation and to the evaluation of its impact on transport. Main research topics are the dynamics and interaction of current-vortex patches, the merging of plasma currents and the coherence and stability of kinetic Drift-Alfven current-vortex filaments. The problem is also approached by statistical analysis of point vortex systems. Temperature effects are brought into the picture through the study of kinetic effects in finite size islands and of reconnection of flux tubes of different temperatures.

B.8. METHODS OF PARTICLE CONTROL AND ENERGY EXHAUST

Dr. K.H. Finken *(k.h.finken@fz-juelich.de)* IPP[1], 22.73.5[§]

The scientific activities on TEXTOR, JET and ASDEX-U are described by the topical groups. This R&D project concentrates on work related to the optimisation of methods of particle removal and energy exhaust from fusion devices. In this context, the Dynamic Ergodic Divertor (DED) has been developed as a new means to distribute the energy to a large area of the wall. The pump limiter ALT-II is now already a standard sub-system of TEXTOR for removing particles including the “fusion ash” helium and suitable for intercepting high heat fluxes; recently, the very high heat fluxes during disruptions are of particular interest in the fusion community as well as novel schemes for mitigating its detrimental effects which are developed here as well. As complement to the particle exhaust scheme, a pellet injector for deep particle fuelling is used for density control. Finally, high-energy runaway electrons – which can also occur during disruptions – are treated in the group.

In the recent year of the extended TEXTOR shut down, the R&D work was concentrated on the preparation of installations for the DED and on maintenance work of other components.

A set of 18 Langmuir probes for measuring electron densities and temperatures at the divertor target plate of the DED was fabricated. In addition, thermocouples with high time resolution for measuring the heat flux have been tested and prepared for the DED target plates. Finally, a set of Hall probes is ready for the installation on a fast probe drive; these probes will measure the modification of the magnetic field at the low field side due to the influence of the DED. A new fast IR camera has been delivered which was extensively tested. These tests are going on and require intense discussions with the manufacturer.

The pump limiter blades were removed from TEXTOR for the surface analysis and subsequent exchange of the graphite tiles and for the replacement of thermocouples, probes and gas lines.

The pellet injector system was removed from TEXTOR and re-installed for testing and improvement in the laboratory. The main items of improvements concern the test of the pellet path alignment and the microwave cavities for measuring the pellet mass.

For experiments on the mitigation of the adverse effects of disruptions, a new fast valve has been developed. The valve opens in less than a millisecond after a trigger signal and releases some hundred millibar-liter of gas into a discharge chamber.

B.9. OPERATION AND IMPROVEMENT OF TEXTOR

DI B. Giesen *(b.giesen@fz-juelich.de)* IPP[1], 22.74.5[§]

Aiming at a fusion reactor, experimental efforts concentrate mainly on conceptual improvements of plasma confinement and stationary operation requiring sufficient heat and particle exhaust as well as adequate impurity control. The Dynamic Ergodic Divertor (DED) for the long pulse tokamak TEXTOR is a novel concept to control energy and particle exhaust in high confinement plasmas which can be studied in TEXTOR for pulse durations of up to 10 seconds. The integration of the DED requires a complex disassembling of the TEXTOR core and a shutdown of more than one year. Due to late delivery of DED components and the drop out of internal manpower the shutdown, scheduled for August 2000, had to be shifted to March 2001.

Operation

Due to the integration of DED, TEXTOR was operated during the first two months of 2001 only. The experimental programme benefited from the three additional plasma heating methods: NBI (4 MW), ICRH (4 MW), ECRH (0.5 MW) and from the high availability (75%) of TEXTOR. Thus, the envisaged tight experimental programme has been realised successfully.

Integration of DED

Most of the engineering efforts were concentrated on preparing and realising the integration of DED. In particular, the following tasks were executed:

Monitoring the fabrication of DED components and performing commissioning tests, removal of diagnostics, disassembling of the TEXTOR core, dismantling and modification of the inner liner, assembly of the coil and limiter support structure, construction and alignment of a laser system to allow for precise positioning of the in-vessel components, assembly of the coaxial feed throughs, and installation of a new cooling system for the DED coils.

For in-house production of the DED coils special vacuum leak test equipment had been developed. The new bumper limiter graphite tiles and part of the ZrO_2-tiles have been delivered and tested under high temperature conditions.

The DED power supply system consisting of 9 power converters and one common control unit has been installed and commissioned. The system has already fed nominal current to a dummy load at all required frequencies. A first series of bus bars feeding the DED coils has been manufactured. Magnetic circuit modelling and tests on the 1:1 test bench have been performed to support the DED design optimisation.

Improvements

In the framework of the German/Russian WTZ-contract essential improvements regarding DED and TEXTOR operation have been achieved. Thus, unwanted displacements of the vessel segments during plasma disruptions could be reduced from 1.5 mm to 0.3 mm (at standard 350 kA operation) by special bearings which allow for both thermal expansions and compensation of forces acting on the vessel segments.

The poloidal limiters have been redesigned and are at present in production.

The water cooling of neutral beam injection ducts has been redesigned to allow for long pulse operation. The plasma box of the diagnostic injector has been equipped with an inner shield and additional permanent magnets to increase the proton fraction of the beam.

The central control system has been upgraded and equipped with visualisation based on WINCC technique. New controls for the DED power supply and cooling system have been completed.

B.10. Data Acquisition, Processing and Computer Communication for TEXTOR

Dr. M. Korten *(m.korten@fz-juelich.de)* IPP[1], 22.75.0[§]

This R&D programme provides technological developments and operational services for experimental diagnostic and data analysis systems at TEXTOR, including standardisation, tele-operation, and data communication systems within the TEC community and external partners.

In 2001 the programme of modernising the handling of experiment data and of the related computing infra structure has been continued. Most of the development efforts went into the new data acquisition system JDAQ (Java Data Acquisition System), and the new data distribution scheme, TWU (the "TEC Web Umbrella"). These are intended to replace aged systems which do no longer cope with new requirements and technical developments. Also, it was one of the primary objectives to open the data handling system towards TEC and the fusion data management community at large.

The new data acquisition system development has been already launched in the previous years to achieve better performance along with raising data volumes and more sophisticated data acquisition and processing requirements. Under the name JDAQ, a modern object oriented design concept has been realised, using state of the art computer hardware and software with continuing support of existing, well established TEXTOR diagnostic systems.

The Common Storage Facility (CSF) aims at providing a central vault for TEC raw and processed data. Beside the archive of experimentally acquired data, a TEXTOR Physics Database running an ORACLE database engine, will concentrate all processed and validated physic data derived during the scientific evaluation process. Ideas have been developed for an automatic data processing chain to derive main physics quantities from the raw data between subsequent discharges.

Many experiment related data sources around TEXTOR can now be accessed via the TWU scheme; access to others is regularly added. In particular, this scheme can be used to access data from both the IPP TEXTOR front-end and FOM diagnostics in a common way. A data browser/viewer/plotter (jScope) developed by Consorzio RFX (Padua, Italy) has successfully been adapted to the TWU data access scheme; other support codes are in different stages of development.

Remote participation, both between the TEC partners and between TEC and JET has been a recurring theme. The TEC Web-Umbrella is an example; it had remote data access built-in from the start, being based on the core technologies of the World Wide Web. Remote data access was demonstrated, i.e., during a real-time remote-participation session whereby collaborators in Canada were involved in the TEXTOR operation, using the TWU.

A modern, fibre optic switched computer network in a star configuration is being installed in the IPP buildings at the time of writing, which will provide considerably faster data throughput rates than previously obtained.

B.11. Instabilities and Transport in the Plasma

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In the R&D project, the physics of the plasma in the core is investigated. This includes instabilities caused by the magnetic properties of the plasma, fluctuations and periodic sudden changes of the central plasma parameters, the so-called “sawtooth oscillations”, as well as the transport properties of plasma energy and plasma particles.

The scientific results are described in the topical groups, mainly “Magnetohydrodynamics”, “Impurity transport and radiation” and “Confinement”; some of the tasks have been delayed due to the shift of DED installation.

The Electron Cyclotron Emission (ECE) radiometers have been equipped with imaging devices to improve the spatial resolution of the electron temperature measurement. To protect the detectors against the ECRH signals, frequency variable notch filters with high selectivity have been developed. The notch frequency is remotely controlled and the quality factor is much higher than for commercially available filters (patent pending). The magnetic diagnostics have been upgraded to detect not only poloidal and toroidal, but also radial components. The number and the frequency response of the pick-up coils have been increased to measure structures with higher mode numbers and up to higher frequencies.

For plasma impurity studies at TEXTOR and W7-X, an imaging X-ray spectrometer and a set of three new VUV flat-field spectrometers are being developed:

The X-ray spectrometer is a new design, consisting of a modified Johann spectrometer with spherically bent crystals. These crystals utilize the astigmatism to obtain simultaneously wavelength and positional focussing of the plasma onto a 2-D detector. Crystal cuts with appropriate diffraction efficiencies were identified and the focussing properties were optimised by ray tracing calculations. It was found that the geometrical errors are negligible, if the crystal surface is shaped appropriately. The design includes the resonance lines of H- and He-like ions from Si to Kr. X-ray CCD detectors with high wavelength and time resolution but moderate space resolution are being developed.

The VUV flat-field spectrometers are of near grazing incidence design. The diffraction gratings are numerically optimised with respect to minimum aberrations while keeping the efficiency (throughput) high, thus allowing for an operation at high time resolution (spectra rate). In total, the spectrometers will fully cover the range from 3 to 100 nm, where all of the low- and medium-Z impurities ($Z < 30$) have strong resonance lines. In particular, the ionisation stages up to H- and He-like ions (B, C, N and O) as well as the Be-like and Li-like ionisation stages (from B up to Zn) are accessible. The instruments shall be used to determine the densities and transport properties of all low- and medium-Z impurities.

B.12. Wall Conditioning and Plasma Wall Processes

Dr. V. Philipps *(v.philipps@fz-juelich.de)* IPP[1], 22.77.0[§]

The main aim of this R&D group is to investigate the various processes of erosion and redeposition of wall material and the development of suitable models which describe the lifetime of wall components, the analysis of fuel recycling and long-term retention for reasons of minimisation of the tritium inventory in future devices and the exploration of high-Z materials as plasma facing components as an alternative to graphite. Contributions at JET were focused on impurity radiation tomography in the divertor, helium plasma operation and on modelling of erosion/deposition. Major results are described in main topic "Plasma Wall Interaction".

The TEXTOR wall is erosion dominated with higher rates at the bottom of the machine. Carbon net deposition is mainly found adjacent to the ALT II limiter. Long term operation leads to massive carbon transport and accumulation in remote areas. Local transport of W and Re over several cm has been observed.

New atomic data for the methane break-up chain and the sticking probabilities of the species were implemented into the ERO-TEXTOR code and analysed. The computed redeposition efficiencies can decrease (up to a factor of 10 at high T_e) and approach experimental values better than achieved with the old data set.

A quartz microbalance diagnostic has been developed to measure in-situ material deposition or erosion on remote areas of fusion devices. The system has been installed in front of the louvers of the inner JET divertor. It is suited to operate at base temperatures up to 475 K.

The hydrogen content of carbon deposits removed from the rear side of ALT II ranges between about 10^{-3} and 5×10^{-2} (H+D)/C in comparison to 0.4 for amorphous carbon films at room temperature. This is due to thermal outgassing during temperature excursions by plasma operation.

A ‘macro brush’ tungsten limiter (as designed for ITER) was operated to heat loads up to 15 MW, but beginning with temperatures below the ductile brittle transition temperature. Crack ignition and propagation are effectively suppressed. The intersections modify the power distribution compared with a solid limiter and indicate an influence on the plasma sheath. A tantalum limiter exposed in TEXTOR showed strong grain grow due to the temperature excursions. The D content is nearly uniform in the bulk (roughly 10^{-4} D/C).

First exposures of samples in the edge region were made by means of the new collector probe system. In-situ desorption of deuterium and ablation of graphite and titanium has been investigated using laser heating aiming at simulating transient power loads in future machines during edge localised modes (ELMs) and disruptions.

Systematic comparison of He and D plasma operation revealed the contributions of physical and chemical carbon erosion. Carbon at the inner divertor is mainly chemically eroded while at the outer divertor chemical and physical erosion balance each other and depend on plasma density. Carbon erosion in the main chamber is decreased due to reduced charge exchange fluxes to the walls. In general, the carbon content in He plasmas is drastically reduced compared with equivalent D plasmas.

B.13. Theory and Modelling

Dr. M. Tokar' *(m.tokar@fz-juelich.de)* IPP[1], 22.80.0[§]

The activity was concentrated on the development of theoretical models and numerical tools for the understanding of transport phenomena in tokamaks under diverse conditions, e.g. in the radiative improved (RI) mode, at internal transport barriers (ITB) and in future experiments with the dynamic ergodic divertor (DED). Here, a coherent approach is of importance, which should combine (i) the determination of transport coefficients from “first principle” models and (ii) the application of these characteristics in computations of plasma profiles by numerical transport codes.

In tokamak plasmas the main contribution to transport comes from low frequency drift instabilities. A model for the most dangerous ion temperature gradient instability has been improved by taking into account the large distance between resonant magnetic surfaces in the region where the ITB is usually located and plasma flows generated by instabilities themselves. For a study of the transport mechanisms at the plasma edge a new model is elaborated which includes a direct influence of neutral particles on instabilities. This model allows to interpret a dramatic increase of electromagnetic fluctuations seen in TEXTOR and other machines by a strong puff of the working gas.

The transport coefficients describing adequately both the L and RI confinement modes and being highly non-linear functions of the gradients of plasma parameters, were implemented into the 1-D transport code RITM in order to model impurity seeded plasmas in TEXTOR and JET. The computations performed reveal an extraordinary importance of transport characteristics at the very plasma edge both for transitions between different confinement regimes and for the global plasma behaviour.

For a more sophisticated modelling of the edge plasma region the 2-D transport code TECXY has been generalized by including a differential equation for the radial electric field in the transition layer between the plasma core and the limiter shadow. This equation ensures a zero global radial electric current in standard situations or presumes a given value of the current when a biased electrode is inserted into the plasma. Simulations of discharges with biasing in TEXTOR and Tore Supra were performed.

In order to study situations with perturbations externally imposed onto the tokamak magnetic field, e.g. as it will be done in experiments with DED on TEXTOR, 3-D computation tools are required. The MHD code E3D based on a Monte Carlo approach to solve the transport equations has been applied to verify the idea of a heat transport barrier near resonant magnetic surfaces when the field perturbation has a broad spectrum. For this purpose the precision of the mapping technique employed in E3D has been increased significantly, now permitting to separate the effects on transport from classical coulomb collisions and motion along stochastic magnetic lines.

B.14. Impurity Sources in Tokamaks

Dr. A. Pospieszczyk *(a.pospieszczyk@fz-juelich.de)* IPP[1], 22.87.5[§]

This project deals with the determination of the major impurity sources in the main phases of the discharge, with the measurement of fluxes, velocities and penetration depths via spectroscopic methods and their dependence on the material and plasma parameters. Important for this are both the determination of atomic & molecular data needed and the development of techniques for the injection of impurities. The implementation of re-designed diagnostics could not be performed yet because of the delayed DED operation as described in 22.74.5.

The B_4C poloidal limiters, tested for W7-X, displayed no severe damages after removal. Heat transport calculations showed that the coating can sustain loads with no damage up to 8 MW/m^2. Intensive arcing studies with long distance microscopy, current measurements and subsequent surface analysis via various surface analysis techniques were carried out.

The spectroscopic measurements of hydrogen molecules (Fulcher band) released from the wall and a test limiter, respectively, revealed a strong coupling between the molecular rotational and vibrational temperatures. This led to a strong reduction of the number of discharges needed and allowed the interpretation of similar data from JET and Tore Supra.

The velocity distributions of atomic deuterium have been measured in-situ in front of the same test limiter as above by laser-induced fluorescence in the VUV for the same plasma conditions. Evaluation of their change with increasing surface temperature revealed the growth of a thermal component.

The laser blow-off-system has been used to study fluctuations of the electron density on the stellarator W7-AS at IPP Garching. For this purpose Li-atoms have been injected and the radial distribution has been detected at eight radial positions with high temporal resolution. Simultaneously, time integrated pictures have been taken to evaluate profiles of the electron density with high radial resolution. The results indicate a different behaviour of the fluctuations on both sides of the separatrix. The system has also been used in a common project "laser injection of condensing materials" with the Department of Plasma Physics at the Central Institute for Physics of the Hungarian Academy of Science (RMKI). In the frame of this project aluminium micro pellets have been injected into W7-AS plasmas and the distribution of Al atoms and ions has been measured.

The local ADAS-site has been upgraded to the latest version (Atomic Data and Analysis Structure v.2.5.4) and steps have been taken to provide the atomic helium data with measured coefficients for due consideration of proton collisions.

Rate coefficients for electron impact excitation and ionisation for B I, C II and O II were calculated by the use of the codes ATOM and AKM developed by the P.N. Lebedev Institute (Moscow), compared with other databases (ADAS, etc.) and implemented into the appropriate collisional-radiative models. For comparison, measurements of O II spectra in the TEXTOR boundary plasma were carried out. The results predicted are in agreement with the experiment. From this, specific undisturbed lines with reliable rate coefficients could be proposed for oxygen flux measurements in fusion boundary plasmas. Semi-empirical scaling laws for hydrocarbon rates have been compiled.

B.15. Particle and Energy Transport in the Plasma Boundary

Dr. B. Unterberg *(b.unterberg@fz-juelich.de)* IPP[1], 22.88.5[§]

The study of transport at the plasma boundary by means of optical methods and the investigation of its impact on both the plasma wall interaction and the global confinement properties of the plasma are the main subjects of this R&D project. Major results have already been described in the main topic group "Confinement". Large progress has been made to adapt the diagnostics for the operation of the Dynamic Ergodic Divertor (DED). The start of the DED operation is delayed as described in the report of R&D 22.74.5.

Two continuously emitting helium sources have been routinely used to measure the electron density and temperature profiles at the low and high field side of TEXTOR. Systematic studies have been performed to characterise in-out asymmetries as a function of global plasma parameters like current, field, power flow into the edge, plasma density and the isotopic composition of the plasma. The scaling of the perpendicular diffusion coefficient at the edge with these global parameters has been determined.

The use of the helium beam for charge exchange recombination spectroscopy (CXRS) with C^{6+} ions to determine the poloidal plasma rotation and flows in the scrape-off layer has been continued. These measurements have been complemented by toroidal rotation measurements using the neutral heating beam of TEXTOR. The changes of the plasma rotation have been investigated in presence of strong gas injection.

The supersonic helium beam has been upgraded with the aim to increase the beam density for applications to measure fast processes in the plasma edge of TEXTOR. Compared to the former set-up a factor of ten could be gained by optimising the geometry and going to a pulsed operation.

The ion temperature profiles in ohmic plasmas determined with the 50 keV hydrogen diagnostic beam have been used to investigate profile changes at high plasma densities in transitions from the saturated ohmic confinement state to an improved ohmic confinement state which can be triggered by a sudden reduction of the external gas flow. Theoretical studies indicated that anomalous transport owing to instabilities driven by the ion temperature gradient is substantially reduced in the improved confinement state.

Radial profiles of plasma currents have been measured in the scrape-off layer of Tore Supra (CIEL limiter project). The perpendicular flux owing to these currents is in the order of 10% of the anomalous diffusive flux.

At Wendelstein 7-X ion temperatures will be determined by neutral particle analysis (NPA) and CXRS using a hydrogen diagnostic beam similar to that at TEXTOR. The required beam parameters have been defined. This was the basis for a feasibility study by the Budker INP in Novosibirsk which will build the diagnostic beam in collaboration with FZJ and MPI Greifswald. The ion species fraction of a radio frequency and a high current ion source - both are potential types for the W7-X diagnostic beam - were measured by a magnetic mass spectrometer and the Doppler shift of the beam emission.

B.16. TEC-ERM/KMS – CONTRIBUTIONS FROM ECOLE ROYALE MILITAIRE / KONINKLIJKE MILITAIRE SCHOOL

Prof. R. Weynants *(roger.weynants@rma.ac.de)*

In 2001, the LPP-ERM/KMS activity has been characterised by a strong participation in the exploitation of the JET facilities, by a continued and intense exploitation of TEXTOR and by an active theory programme.

In JET, LPP-ERM/KMS provided the Confinement Task force leadership and took the lead in impurity seeding experiments aimed at the simultaneous realisation of high confinement and high density. Impurity seeding or strong deuterium puffing reduced the power to the divertor. These experiments allowed substantiating the ITER design parameters. In the Heating Task Force, interpretative help was provided for several scenarios envisaged for ITER.

LPP-ERM/KMS is the leading Association in the JET Enhanced Performance project aiming at constructing an ITER-like ICRH antenna. A large effort went into project management and detailed design of a system capable of 8 MW/m^2 multi-second pulses with adequate ELM resilience under H-mode conditions. Another project, second harmonic protection of the existing JET ICRH antennae, is now reaching completion.

The work related to TEXTOR was mostly devoted to the Radiative Improved Mode and conditions to reach it. Density peaking and low edge neutral pressure are found to be its most robust features. Inclusion of mechanisms explaining gas injection effects enhanced the RI-mode modelling. Lost fast ion measurements were performed. Probe measurements, backed-up by theory, showed that radial velocity shear suppresses turbulence. For the first time in the same fusion machine, the wall conditioning capabilities of ICR and ECR discharges were compared. The TEXTOR ICRH system is now being modified and partly redesigned to accommodate the new configuration with the new diagnostic beam.

In theory, the need for properly accounting particle orbit topology and poloidal inhomogeneity in RF absorption processes was recognised and implemented in a Fokker-Planck code, while a new toroidal co-ordinate system was constructed for the wave code. The development of a non-linear Fokker-Plank code is progressing. The antenna coupling code was improved and the inclusion of finite temperature modes via adequate boundary conditions is investigated. Wave frequency sweeping, as a means to restore interaction between waves and fast particles, was found promising. The re-evaluation of the ion cyclotron heating scenarios for ITER was completed. The potential of ICRH for heating and current drive was confirmed. Heating scenarios with improved power transfer to the background ions were singled out. The scenarios of the non-activated ITER phase were also investigated.

LPP-ERM/KMS also contributed to modelling of the Dynamic Ergodic Divertor (DED), focussing on the study of the penetration of the DED fields into the plasma. Study of the waves dispersion showed that the equilibrium particle drifts strongly affect the interaction of DED fields with the plasma near the resonance layer.

B.17. TEC-FOM – CONTRIBUTIONS FROM FOM INSTITUUT VOOR PLASMAFYSICA

Prof. Ch. Schüller *(schuller@rijnh.nl)*

Most of the advanced diagnostics and ECRH hardware that have been installed by FOM were operated routinely during the first two months of 2001. The physics results obtained with these systems are presented under the topic groups contributions.

TEXTOR is the first tokamak on which fast ion collective Thomson scattering has become a routine diagnostic. The system has been successfully used to measure the velocity distribution of fast ion populations created by NBI and ICRH. Significant results were obtained on generic fast ion dynamics (e.g. the evolution of the fast ion velocity distribution after switch-on/off of NBI and ICRH was measured; redistribution by sawteeth; the detailed heating mechanisms of ICRH).

Early in 2001 a successful pilot demonstration was given of the Microwave Imaging Reflectometer (MIR). One of the most significant results is the demonstration of the ‘virtual’ cut-off surface. The pilot tests have resulted in a number of ideas to further improve the diagnostic. Since March 2001 a significant effort has been on-going to develop a combined 2D ECE-imaging/MIR system for TEXTOR. The detailed design of the optical and microwave set-up of this system has been completed, and the manufacture of various parts has been initiated.

A collaboration in the field of Thomson scattering funded by the ‘Innovationsfonds’ of FZJ has been started involving physicists from FOM and FZJ/IPP. The present double-pulse system will be upgraded to a 20 kHz burst-mode operated system. The duration of each burst is 1-2 ms, and in total three bursts can be generated during a TEXTOR discharge. Successful laboratory tests of the new concept have been performed.

A special pneumatic construction has been developed to position the cameras of the ultra-soft X-ray tomography system for studying impurity transport very close to the plasma boundary. When not in operation, the cameras are retracted and positioned behind a vacuum valve for protection. The test of a pneumatically operated camera in February 2001 was successful, and as a result it was decided to incorporate pneumatic drivers on all five cameras to make it possible for each individual camera to observe the full poloidal plasma cross section.

A prototype MSE (Motional Stark Effect) system with in-vessel optics has been tested. The first measurements were very encouraging and led to the decision to mount the front-end optics on a similar pneumatic driver as used for the ultra-soft X-ray tomography system to protect it from deposition when not in use. At the same time the system is further improved and upgraded to a total of 20 channels.

The Electron Cyclotron Resonance Heating system using a 200 ms, 500 kW, 110 GHz source, has been extensively used for a wide range of physics studies, that are reported in the topic groups section. The upgrade of the ECRH system to 3-10 s, 800 kW, 140 GHz is well underway. The gyrotron source has already been demonstrated. Technical work has concentrated on improvements to the control and data acquisition and on the extension of the pulse length. The latter is possible thanks to the application of a diamond vacuum window. The 110 GHz system will remain available for diagnostic studies.

B.18. COMPOSITE MATERIALS FOR HIGH HEAT FLUX COMPONENTS

Dr. J. Linke *(j.linke@fz-juelich.de)* IWV-2[2], 11.20.0[§]

Plasma facing materials in future fusion devices are primarily based on boron, carbon or silicon as well as tungsten in combination with copper as a heat sink. A major aim of the R & D activities is to develop and fabricate new materials and to characterize and test them under simulated service conditions, i.e. at thermal loads up to 20 MWm^{-2}. Plasma-interactive components for TEXTOR-94 and Wendelstein W7-X are being developed and examined with respect to their thermo-mechanical behaviour.

Materials development

The development of new materials for high heat flux components is mainly focused on the processing of new plasma compatible materials with favourable thermal and mechanical properties. Today in most of the existing fusion devices carbon based materials, in particular isotropic and carbon fibre reinforced graphites (CFC), are the prime candidates for the first wall protection or the divertor armour. To reduce the sputter erosion during plasma exposure and to improve the oxidation resistance, different manufacturing processes for siliconised CFCs are being developed. Beside these monolithic wall concepts thick coatings have been produced in IWV by a low pressure plasma spraying process: boron carbide coatings on stainless steel substrates for the Wendelstein W7-X and tungsten coatings on copper substrates for ITER.

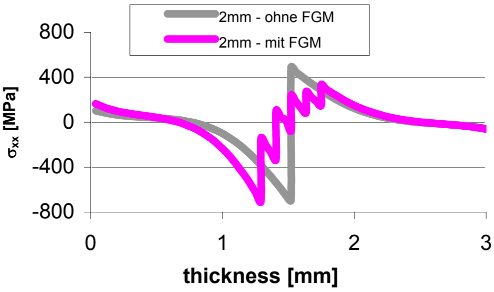

Fig. 1: Comparison of calculated σ_{xx}-stresses in a tungsten-copper-test samples with a conventional and a graded interface (FGM).

C. TECHNOLOGY PROGRAMME

C.1. COMPOSITE MATERIALS FOR HIGH HEAT FLUX COMPONENTS

Dr. J. Linke *(j.linke@fz-juelich.de)* IWV-2[2], 11.20.0[§]

Optimised candidate materials are used to develop plasma-interactive components for ITER (International Thermonuclear Experimental Reactor) and future electricity generating fusion reactors. Major aim of this research programme is the characterization of plasma facing materials and components and their evaluation with respect to their thermo-mechanical and neutron irradiation behaviour.

Thermal fatigue and thermal shock behaviour

The performance of plasma facing materials and components under fusion relevant thermal loads (cyclic quasi stationary thermal loads up to ≈ 20 $\mathrm{MWm^{-2}}$ during normal operation, and short transient thermal spikes with energy densities of several 10 $\mathrm{MJm^{-2}}$ during plasma disruptions or vertical displacement events) may be associated with intense thermal fatigue and thermal shock damage. To evaluate the component behaviour and the resulting material damage under W7-X or ITER relevant conditions high heat flux simulation tests are being performed in powerful electron beam (JUDITH, hot cells at FZJ) and ion beam test facilities (MARION, IPP at FZJ). These experiments are focussed on different design options of high heat flux components with beryllium, carbon, B_4C and tungsten armour.

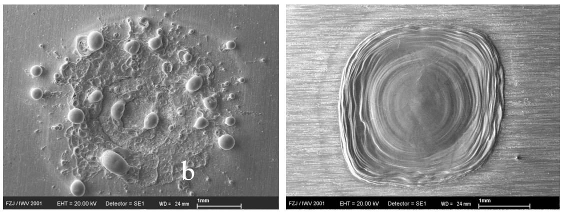

Fig. 2: Scanning electron micrographs from plasma sprayed tungsten (a) and pure molybdenum (b) which have been exposed to intense thermal shocks with an incident energy density of 24 $\mathrm{MJm^{-2}}$ at a pulse duration of 5 ms.

(EFDA/00-542, TW1-TVP-MAN1)

Neutron induced material degradation

The degradation of materials and components under moderate neutron fluences is analysed in complex neutron irradiation campaigns which are carried out in the High Flux Reactor (HFR), Petten (NL). Here ITER-specific neutron fluences (up to 1 dpa) are applied to Be, CFC, W and Cu samples at irradiation temperatures ranging from 200 to 700°C. The post irradiation examination of the test samples includes comprehensive analyses of thermal and mechanical properties as well as thermal fatigue and thermal shock tests in the hot cell electron beam test facility JUDITH.

(GB8 - DV6, TW1-TVP/TU1)

C.2. MECHANICAL PROPERTIES OF FUSION MATERIALS

`Dr. P. Jung` *`(p.jung@fz-juelich.de)`* IFF^3, 23.80.5§

The general topic of these tasks are the effects of the transmutation products hydrogen and helium on materials in the first-wall and blanket of a fusion reactor. It comprise investigations of elastic and mechanical properties, analysis of surfaces and microstructure, and eventually attempts to identify the underlying mechanisms. The materials investigated are reduced activation martensitic stainless steels, at present mainly EUROFER97, tungsten and ceramic materials. Because an intense high-energy neutron source is not available, hydrogen and helium ions are loaded by implantation, mainly from the Jülich compact cyclotron CV28. In the case of hydrogen also loading from plasma and from gas-phase is employed.

C.2.1. Long Term Programme / Task Area: Materials Development

Subtask: TW1-TTMS-003 (Compatibility with Hydrogen and Liquids)

The contributions to this subtask comprise measurements of permeation and diffusion of deuterium in pre-irradiated material, permeation and diffusion measurements under simultaneous proton irradiation, and the diffusion of implanted protons. The studies are supplemented by investigations of the retention of deuterium in helium-implanted EUROFER97 steel and in cold-worked (dislocations) pure iron.

Permeation and diffusion of deuterium in pre-irradiated EUROFER97

Permeation experiments were performed on EUROFER97 at different temperatures and deuterium pressures. Permeability and diffusivity for deuterium pressures of 1 bar are shown

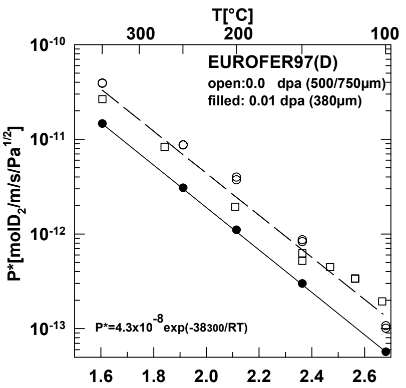

Fig.1 Effect of pre-irradiation on D_2 permeation

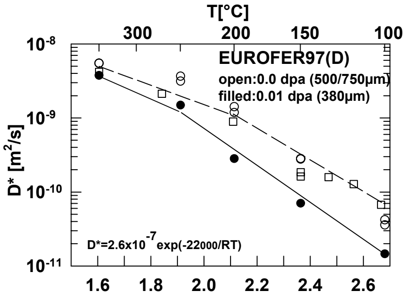

Fig.2 Effect of pre-irradiation on D_2 diffusivity

in Figs. 1 and 2, respectively. Permeability as well as diffusivity of the specimen pre-irradiated to 0.01 dpa fall below the results of the unirradiated material. While permeability of both materials show Arrhenius behaviour in the total temperature range (100 to 350°C), the Arrhenius plots for diffusivity show changes in slope around 200°C and 250°C, respectively. The slope at low temperatures increases with decreasing gas pressure in both cases and is ascribed to trapping. Solubility of deuterium is obtained from the ratio of permeability to diffusivity and tends to become almost independent of temperature at low temperatures.

Retention of deuterium in helium implanted EUROFER97

Helium3 was implanted homogeneously to a depth of about 11 µm to various concentrations up to about 0.28 at%. Specimens were loaded with deuterium in a plasma after implantation or after annealing for 10 hours at 1023 K to produce gas bubbles, visible by TEM. The depth analysis of deuterium obtained by SIMS and RGA (residual gas analysis) are shown in Fig.3. The deuterium content increases with increasing implantation dose, but is drastically decreased after annealing. As previous studies have shown that these defects are practically completely annealed below 1023K, this indicates that retention is probably mainly due to lattice defects produced by the implantation.

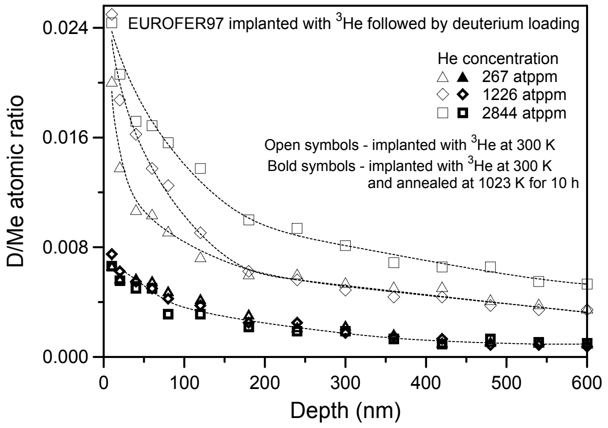

Fig.3: Depth profiles of deuterium atoms trapped in EUROFER97, pre-implanted with ^{3}He ions uniformly across the depth up to concentrations of 267, 1226 and 2844 atppm and then exposed to D plasma at 403 K to a fluence of ~2×10^{24} D/m^2. The mean energy was ~180 eV/D ion, ion flux density was ~1.2×10^{21} D/m^2 /s).

Retention of deuterium in cold-worked pure iron

In an attempt to get more information on the interaction of hydrogen with dislocations, pure iron specimens were deformed up to 50% by cold rolling and than loaded from gas phase at 573K. The thermal desorption curves (Fig.4) show two peaks which increase with the degree of cold working and with heating rate.

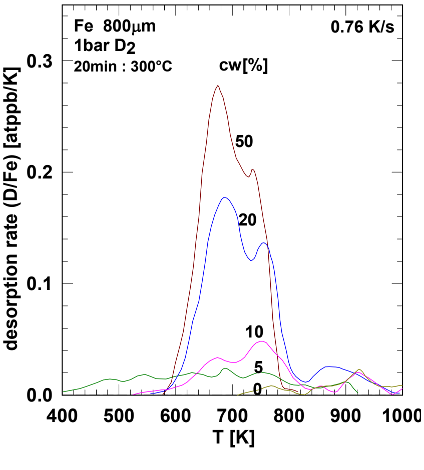

Fig.4: Thermal desorption of D_2 from cold worked iron

C2.2. Underlying Technology

C.2.2.1. Field: 1.TP Physics / Task Area: 1.4.TPH: Heating and Current Drive

Subtaske: Microstructure of Carbon-based Materials and Oxide Ceramics Containing High Helium Concentrations

Diamond and oxides are candidates for special purpose materials, mainly insulators and HF-windows. The irradiation field in a fusion reactor will affect their electrical as well as mechanical properties by atomic displacements and by producing transmutation products, mainly hydrogen and helium. In the present subtask diffusion and desorption of helium is investigated, as well as microstructural and mechanical changes induced by high helium concentrations.

Microstructural changes due to helium

The development of microstructure in helium implanted Al_2O_3 after implantation and after subsequent annealing was investigated by transmission electron microscopy (TEM) as a function of implantation dose and annealing time at 1273K. A complex mutual dependence of the development of dislocation loops and bubbles was observed. In an attempt to reduce implantation time, some specimens were only implanted to part of their thickness. It was found that this caused sufficient lattice strain to disintegrate the specimens from the heat sink, thus interrupting cooling. This caused some inconsistencies in the results which called for additional implantations.

Single crystal diamond specimens, implanted up to 0.2 at% helium showed no microstructural changes also after annealing. It is speculated that this may be due to extremely low trapping of helium in this material. For comparison polycrystalline diamond was implanted. As specimen preparation of diamond is extremely tedious, thermal desorption experiments are intended to be performed to possibly identify the most suitable temperature regime for annealing, before pursuing the TEM work..

Helium induced lattice strains

The strain measuerements on the oxide-, nitride-, and carbide ceramics are now complete over a range of helium concentrations from 0.3 to 300 atppm and annealing temperatures up to 1600°C.

Thermal desorption measurements

At concentrations above a few atppm some helium is retained in most materials up to the melting temperature. A device to allow controlled heating up to 2500°C was set up in 2000. First experiments showed the need for further technical improvement in the upper temperature regime and the control. This work has been completed in 2001 and first desorption experiments are now in progress.

C.2.2.2. Field: 2.TV Vessel in Vessel / Task Area: 2.1.TVP Plasma Facing Components

Subtask: Microstructure of Carbon-Based Materials and Tungsten Containing High Helium Concentrations

First wall and divertor materials of future fusion reactors will experience severe changes of their microstructural and mechanical properties by irradiation effects due to atomic displacement and transmutation product, mainly hydrogen and helium. In the present subtask, which continues work on graphite-related materials and SiC, the effects of helium on microstructural and mechanical properties is studied and attempt are made to identify the underlying mechanisms.

Microstructure of helium implanted tungsten

Specimens of polycrystalline tungsten were homogeneously implanted at room temperature with 3 atppm helium to about 1/3 of their thickness. After implantation and after subsequent isochronal annealing in steps of 50°C up to 1350°C, the evolution of lattice strains was measured by surface profilometry. At annealing temperatures up to 800°C annealing of lattice defects is identified, while now indications of bubble growth was found at this low concentration. Experiments at higher concentrations and comparison to microstructure are in progress.

Trapping of deuterium in helium implanted tungsten

Tungsten single crystals, implanted with helium to various concentrations up to 0.46 at% were loaded with deuterium from plasma at room temperature. The distribution of the deuterium derived from SIMS and RGA (residual gas analysis) are shown in Fig.5. Deuterium retention clearly increases with increasing implantation dose. On the other hand, the fact that the trapping of deuterium in helium implanted specimens after annealing to 1350°C coincides with the behaviour of virgin material, may indicate that trapping is mainly due to displacement defects which are annealed at that temperature. But more investigation is needed on the trapping behaviour of helium in atomic versus clustered (bubbles) state.

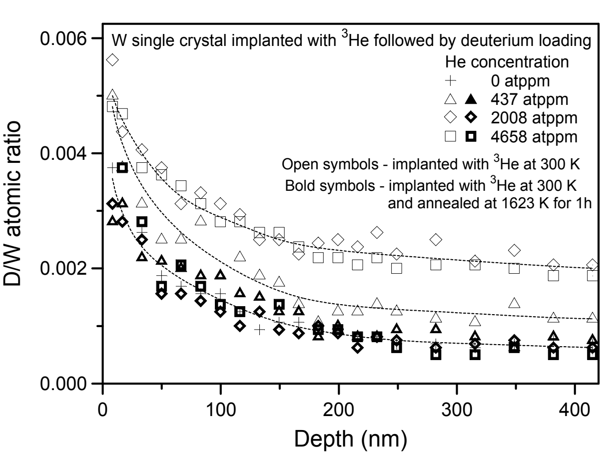

Fig.5: Depth profiles of deuterium atoms trapped in W single crystal pre-implanted with ^{3}He ions uniformly up to concentrations of 437, 2008 and 4658 atppm and then exposed to D plasma at 383 K to a fluence of ~2×10^{24} D/m^2. The energy was ~180 eV/D ion, ion flux density was ~1.2×10^{21} D/m^2/s. Deuterium depth profiles in the virgin W crystal (without ^{3}He implantation) exposed to D plasma is shown for comparison.

C.3. OXIDATION MEASUREMENTS ON FIRST WALL MATERIALS OF FUSION DEVICES

Dr. R. Moormann *(r.moormann@fz-juelich.de)* ESS-FZJ[4] – Task GB9-V65

Important Results:

- Isothermal outgassing of different metals for fusion application at 600 °C reveals a broad scatter of the outgassed amount. HIPed specimen show the lowest outgassing

Use of metals in vacuum requires good knowledge of the outgassing rate of adsorbed and absorbed impurities and -particularly for use in fusion technology- some knowledge about the chemical composition of the released gases: It is often assumed, that mainly hydrogen, carbon oxides, nitrogen and sometimes methane and -at low temperatures- steam are released, but quantitative data are rarely given.

In our work we examine eight different fusion relevant specimen from six different ITER relevant metallic materials, being candidates for use in components within the vacuum vessel, with respect to their quantitative outgassing behaviour and with respect to the chemical composition of the released gases. Main data of these materials are given in table I:

SPECIMEN NO	Characterisation	Nomenclature (USA/Germany)	Composition [%]
1	Cast Iron DIN 1694	GGG-NiMn137 0.7652	C max:3.0; Ni:12-14; Mn:6-7; Si:2-3; Cr max: 0,2
2	Forged Steel (Mod. 1)	ASTM A 182 F 316 LN mod. 1.4406	C: 0.018; Ni:13.5; Mn:2.0; Si:0.37; Cr:17.2; Mo:2.5; S:0.002; P:0.028
3	GTAW/SAW weld deposit	GTAW 2684A/B SAW 2676F/G/H	C:0.01-0.03; Ni:15.5-21.5; Mn:4.4-7.4; Si:0.15-0.5; Cr:20-24.5; Mo:2-3.2; S:0.005-0.009; P:0.011-0.018
4	Cast Steel CF8	ASTM 351A/351M 304 LN mod. 1.4311	C:0.08; Ni:9-12;Mn:1.5; Si:1.5; Cr:18-21; Mo:2-3; S:0.04; P:0.04

5	Trial Casting CLI	316 LN mod. 1.4406	C:0.016; Ni:14.0; Mn:6.0; Si:0.78; Cr:17.6; Mo:3.01; S:0.0048; P:0.022
6 a - c	HIP (powder-HIPed at 1050°C)	316 LN 1.4406	C:0.022; Ni:12.1; Mn:1.76; Si:0.32; Cr:17.8; Mo:2.5; S:0.009; P:0.016

TABLE I: DATA OF TEST SPECIMENS

The three HIPed specimens are identical with respect to their fabrication procedure; three specimen are examined here in order to get a feeling of data scatter in these measurements. We outgassed these eight specimens at 600°C in our UHV facility DEREX, which was originally developed for oxidation measurements on codeposited layers, but is suitable for these kinds of measurements, too. Gas analysis was performed with a Quadrupole Mass Filter (QMF).The facility DEREX used in our experiments is described in detail in former annual reports; basically it consists of an ultra high vacuum apparatus with the specimen container placed in a furnace; the outgassed species are sent to the QMF.

From the original probes submitted to us we cut pieces of a size of about 60*15 mm with a thickness between 2.0 and 2.9 mm, by using a saw; the total geometrical surface of these specimen was between 1970 and 2260 mm^2. The specimen were cleaned in acetone (p.a.) in an ultrasound bath for about 1 h; in the next step a specimen was taken into the specimen holder and evacuated at room temperature for about 24 h. After reaching sufficient vacuum, heating started. It has to be noted, that for reaching of the nominal temperature of 600°C a time of about 0.5 h is required. During this heat-up time the QMF was already measuring, because outgassing becomes significant at temperatures > 250°C. At 600°C the outgassing rate was measured up to 48 h, when a nearly constant outgassing rate was established. Results obtained from these experiments are the total pressure in the system and in the QMF, which allows calculation of the amount of released gases and - for certain time intervals - the mass spectra for the mass range 1 - 100; these time intervals were in the range of 6 h. The weight difference due to outgassing was measured, too.

It has to be noted, that due to the operation of the QMF a continuous flow out of the specimen container exists. The size of this flow is given by the power of the vacuum pump. Because of this flow, the measured total pressure depending on time shows a maximum for most specimens and slows down when the outgassing decreases. A calculation of the total molar amount of outgassing from measured total pressure was performed as follows:

$$n(t) = p(t) \cdot V / (R \cdot T) + S / (R \cdot T_{QMF}) \cdot \int_0^t p_{QMF} \cdot dt \qquad (1)$$

with

n(t) = number of moles outgassed at time t

p(t) = measured total pressure in DEREX at time t

pQMF = measured pressure in mass spectrometer (behind pressure reduction system of DEREX)

T = average gas temperature in the vacuum part of

DEREX = 473 K (for a specimen temperature of 600°C)

TQMF = average gas temperature in the QMF = 306 K

V = volume of the vacuum part of DEREX $=1.24 \cdot 10^{-3}$ m^3

S = gas flow rate out of the QMF = 0.145 m^3/s.

Fig. 1 gives an overview on the time dependent total pressures of the 8 specimens in the DEREX vacuum chamber. Time t = 0 is selected for the time point, when the temperature of 600 °C is reached, but pressures for the heat-up period are also given. In Fig. 1 a only the data for the HIPed specimen 6 a-c are presented together with a measurement without specimen. This 'zero'-line is far below the data of the specimen.

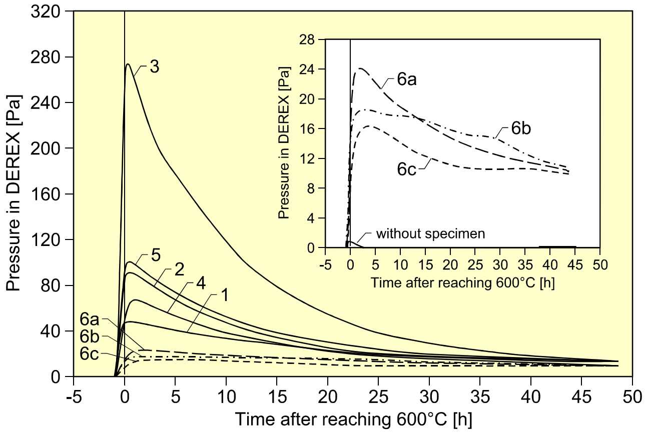

Fig 1: Pressure in the DEREX vacuum chamber during outgassing

Evaluation of the total mole number released by the method described before indicates, that the outgassing process consists of two steps, a 'fast' release, which is finished at least after about 2 h, and a 'slow' outgassing, which continues even after 48 h ($1.73 \cdot 10^5$ s) with only a small decrease; as an example, evaluated data for specimen 1 are given in fig. 2. It is well known, that hydrogen exists in different states in metals, which influences the kinetics of outgassing.

SPECIMEN NO	**Fast outgassing [mol/m²] *10^3**	**Rate of slow outgassing [mol/m²/s] *10^8**	**Weight before outgassing [g]**	**Weight-loss 48 h [mg]**
1	8.5	5.1	12.8447	0.3
2	13	3.9	16.3469	0.1
3	40	3.9	13.3114	0.0
4	11	4.7	19.8260	0.1
5	17	7.8	12.1298	-0.2

6a	4.5	5.0	16.1305	-0.2
	3.5	7.2	14.5345	-0.3
	2.1	5.6	15.1745	-0.1

TABLE II: OUTGASSING PARAMETERS (873 K = 600°C) OF EXAMINED METALLIC SPECIMEN

Evaluation via formula (1) contains some uncertainties; so we guess an average error of the absolute released mole numbers of about ± 40 %; the error of values of an individual specimen in relation to another one is however much smaller. Table II contains the released amount by the initial fast outgassing process and the outgassing rate by the slow process; the total amount released in 48 h ranges between 0.012 (No 6 c) and 0.047 (No 3) mol/m^2.

The 'slow' process, which is probably connected to transport from inner material parts, is with rate values of $4 - 8 \cdot 10^{-8}$ mol/m^2/s more similar for all materials. Concerning only 'fast' outgassing it is obvious, that there are larger differences than for the 'slow' outgassing rate: Material 3 has the highest outgassing amounts, followed by a group of the materials 5, 2, 4 and 1 with average amounts and the HIPed materials 6 a - c, having the lowest outgassing amount by this mechanism.

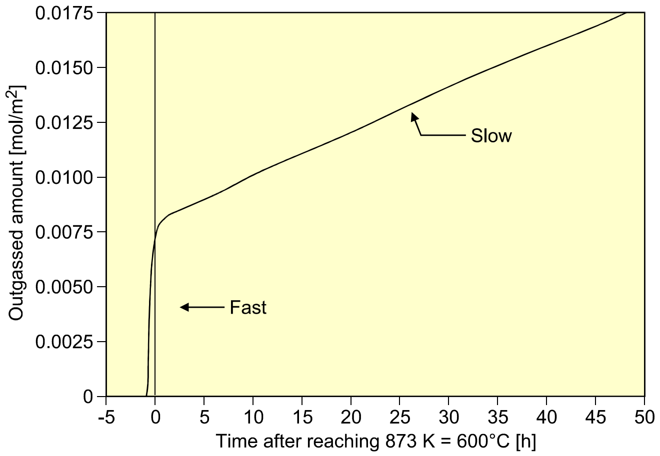

Fig 2: Evaluation of specimen 1 by formula (1): Fast and slow outgassing

Table II contains also the total weight of the specimen before outgassing and the weight difference induced by 48 h outgassing. There is obviously no clear coincidence between outgassing and weight chance; this might be due to different adsorption properties with respect to the surrounding atmosphere; the order of magnitude of weight change is consistent with the mole number released (measured by QMF).

Results on composition of the released gas

Fig. 3 contains the time dependence of the peak ion current for the main peaks of a.m.u.: 2 (H_2), 16 (CH_4), 18 (H_2O), 28 (mainly N_2, some CO), 40 (Ar) and 44 (CO_2) for specimen 3 and 6 b; the zero-line (underground spectrum) is subtracted.

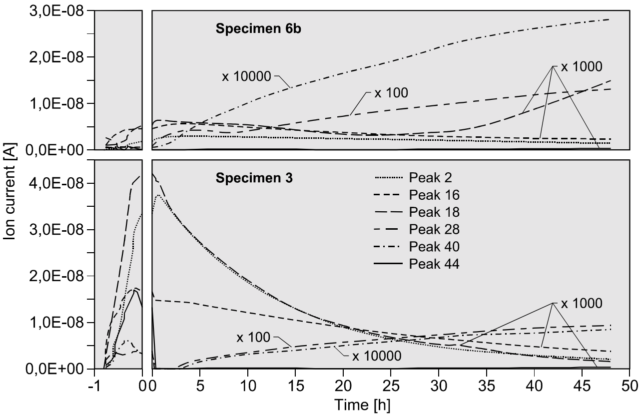

Fig. 3: Time dependent ion current of main peaks for specimens 3 and 6b

Considering calibration factors, which are substantial particularly for hydrogen, it becomes obvious, that by far the largest amount of outgassing comes from hydrogen (> 95 %); this result is validated by the similarity of shape of the total pressure behaviour in DEREX (fig. 1) and the time behaviour of the hydrogen peak, whereas the other time dependent peaks (except peak 18/steam for specimen 3) do not resemble the time dependence of the total pressure. This means also, that the 'fast' and 'slow' outgassing is an effect mainly of hydrogen. In addition it has to be noted, that the comparatively high release of specimen 3 is mainly due to a larger outgassing of hydrogen, whereas for the other gases it behaves similar to the other materials. In contrast to our results, hydrogen was not dominating the outgassing of fusion relevant austenitic and ferritic steels examined in Japan, where oxygen containing species (H_2O, carbon oxides) played the major role; however, the experimental times in these measurements were much smaller.

The highest level of non-hydrogen outgassing was detected for specimen 1. The intensities of some of the less intense peaks (28, 40, for specimen 6 b: 18) increase during the slow release phase. Furtheron fig. 3 shows, that specimen 3 shows a pronounced (burst like) release in the fast phase for peaks 16, 28, 40 and 44, whereas specimen 6 b reveals such behaviour to some extent only for peaks 28 and 44. For specimen 3 peak 44 exists only during fast release. The general time behaviour of the main peaks for the specimen not shown in fig. 3 was found between that of specimen 3 and 6 b. Besides the beforementioned main peaks (and peaks corresponding to these main peaks), some smaller peaks were detected, as is shown in fig. 4, containing mass spectra of specimen 3 for start and end of outgassing.

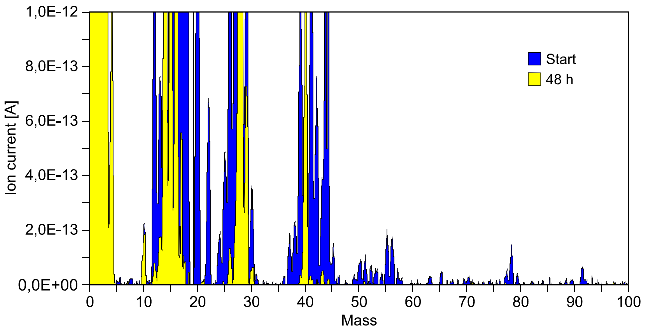

Fig. 4: High sensitivity mass spectra of specimen 3 for start and end of outgassing

Groups of peaks at around 27, 40 and 55 were found in most specimen (except of peak group 55, which is not detected in specimen 6) vanish respectively reduce its size during outgassing; these peaks are probably due to lower aliphatic hydrocarbons other than methane (ethane, propane etc.). In contrast a peak at 20 increases substantially for most materials; we are not yet able to make a clear assignment of this peak: Ar^{++} should (in contrast to our results) be less than the 40 (Ar^{+}) peak, HF should give an additional peak at 19 (which is not the case) and Ne should have a peak at 22, being 10 % of the size of the 20 peak (which is found for specimen 3 but not for all specimen). No peak typical for sulphur compounds was detected, but in most cases (except of 2 HIPed specimen) we found at start a peak arrangement characteristic for benzene (at around 78). Furtheron, the tropylium ion at 91 was detected at outgassing start in specimen 1 - 5; this ion is known to be a conversion product of aromatic hydrocarbons. Probably, these compounds are used during fabrication of the metals in cleaning procedures and are for some unknown reason not completely removed by our ultrasonic treatment in acetone. Also for higher aliphatic hydrocarbons and aromatic hydrocarbons we found the highest level in specimen 1.

Publications (also for Task GB8-DV7a and former tasks):

Hinssen, H.-K.; Krüssenberg, A.-K.; Moormann, R.; Wu, C.H.: Oxidation of innovative carbon based materials for future energy systems; Proc. 10th Int. IUPAC-Conf. on High Temperature Materials Chemistry (HTMC-X); Jülich 10.-14.04.2000; (2001) p.565-8

Moormann, R.; Hinssen, H.-K.; Wu, C.H.: Oxidation of carbon based first wall materials of ITER. Proc.18th IAEA Fusion Energy Conference, Sorrento, Italy, 4-10 October 2000, CD (2001) FTP1/29

Moormann, R., Hinssen, H.-K., Wu, C.H.: Corrosion behaviour of Carbon based materials for HTRs and Fusion reactors in oxidising gases. Proc. Eurocorr 2001, Riva, 30.09.-4.10.01, CD (2001), ISBN88-85298-41-9

Lectures/Posters:

Hinssen, H.-K., Moormann, R., Wu, C.H.: Outgassing measurements on selected metals for fusion application. Poster ICFRM-10, Baden-Baden (2001)

D. PARTNERS OF THE IEA TEXTOR IMPLEMENTING AGREEMENT

D.1. CANADA

Simulation of the Influence of Impurity Seeding on Turbulence in TEXTOR Plasmas

(R. Sydora, University of Alberta, Edmonton)

Simulations of L- and RI-Mode discharges in TEXTOR have been made a nonlinear gyrokinetic particle simulation code. The code takes into account the toroidal geometry, experimental plasma profiles and multiple ion species, and is the most complete tool available up to now for such studies. Simulations are typically done with more than 100 million particles on the most powerful parallell computer systems. Direct stabilisation of ITG turbulence has been found together with an improvement in the ion thermal confinement by a factor of about 10 during Ne seeding. These results and further details are published in Physics of Plasmas (J.Ongena et al., May 2001)

Edge Flow Measurements with Probes

(C. Boucher, INRS)

The biasing experiments of the ALT-II limiter were pursued in February. The results obtained confirmed those obtained the previous summer, showing that the pumping could be optimised by the application of a bias voltage between the limiter and the plasma, steering the plasma towards the scoop of the limiter. Both experimental and theoretical papers were prepared and submitted.

For the revival of the fruitful collaboration with INRS on flow measurements several short-term projects have been defined, which will be carried out by students from the Canadian partner. The discussions have resulted in a first draft for a new probe design to be mounted on the fast probe drive, which is operated by the German partners as a user facility. The expected flows during DED-operations have been analysed in order to specify the probe dimensions and layout. A student has just started to study the imposed stresses and to finalise the design.

Bias Experiment

(C. Boucher, INRS)

The ALT-II limiter blades have been biased with respect to the inner bumper limiter. The induced plasma flows have been used to improve the modelling of flows in radial electric fields. The results can help to improve the design of the pumping duct of the future CIEL toroidal pump limiter at Tore Supra.

Development of Langmuir Probes for the DED

(C. Boucher, INRS)

The INRS-Group has agreed to develop and build a set of Langmuir probes for the divertor target plate of the DED. 18 probes will be installed into the graphite tiles; 16 of those tiles form a toroidal set and the rest a poloidal one. These probes will be distributed over one quadrant of the torus. This arrangement will allow the measurement of the electron density and temperature at the target plate and will be complementary to IR-thermography.

The design and fabrication of the embedded probes for the TEXTOR DED neutraliser plates were completed. The probes were delivered to Jülich in September 2001 for installation. The control and data acquisition electronics that was used on the TdeV flush probes was recuperated and is now being adapted and prepared for shipping to Jülich to be used on the embedded probes

Plasma Theory and Modelling

(R. Sydora, University of Alberta, Edmonton)

The collaboration on the influence of impurity seeding in TEXTOR discharges, which started in 1997, is being pursued. A detailed study of such discharges using the gyrokinetic code developed by Sydora et al., including multiple ion species, shows: (i) a significant reduction of the growth rate of the Ion Temperature Gradient (ITG) instability in discharges with Ne seeding as compared to similar discharges without Ne seeding; (ii) a reduction of the particle and heat fluxes and associated reduction of the ion heat diffusivity; (iii) the location of the turbulent zones; (iv) the turbulence spectrum.

The stabilising influence of ion collisions has been investigated analytically in Jülich; numerical work including collisions is planned by Prof. Sydora. Furthermore, the ITG theory has now been reassessed for weak magnetic shear, the results providing a very clear interpretation of Internal Transport Barriers (ITBs) observed in Negative Central Shear (NCS) discharges. It is planned to run the initial value gyrokinetic code under similar conditions with the goal of comparing the eigenmode structures, frequencies and growth rates (i.e., the dispersion relation).

Electric field formation at the plasma wall

(M. Shoucri, Hydro-Québec)

The aim of this collaboration is to describe the magnetic presheath for small angles of incidence (less than a few degrees) of the magnetic field. This small angle of incidence can lead to an excessive power density deposited on the first few milimeters near the tip of the limiter roof. A fully kinetic code solving the Vlasov equation for the ions and an adiabatic approximation for the electrons is further developed.

Further Development of EIRENE

(S. Lisgo, University of Toronto)

The focus of the collaboration is the development and application of the EIRENE computer code for the purpose of modelling neutral particle behaviour in a tokamak divertor environment. EIRENE has been made part of OEDGE; a suite of computer codes used to study the edge plasma and associated vacuum regions. It provides the neutral solution throughout the modelling region, and also neutral particle related mass, momentum and energy source terms for solving the plasma conservation equations. Presently, EIRENE is being used to model neutral behaviour in the divertor plenum chamber on Alcator C-Mod. The experimentally measured plenum pressures indicate a collisional gas, requiring the neutral model to include collisions between neutral particles. This application of EIRENE is unique, since it is the first to focus on the properties of a non-linear neutral particle solution, see figure 1. However, the results and methodologies are also applicable to other collisional gas environments that might occur on TEXTOR, ITER and JET.

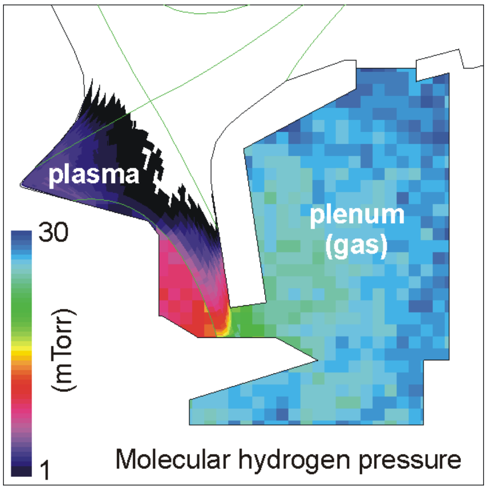

Figure 1: Poloidal cross-section of the molecular hydrogen pressure distribution in the Alcator C-Mod divertor. Momentum exchange between thermal molecules in the plenum chamber and high-energy atoms from the divertor plasma result in a non-linear neutral solution in the plenum.

Work is also underway at IPP Jülich to include radiation transport in EIRENE, which is important for high density plasmas such as those found in the private flux zone of the C-Mod divertor, and eventually in ITER. EIRENE development associated with this collaboration has been incorporated into the circulated version of OEDGE, to the benefit of modelling efforts at IPP Garching, JET and DIII-D.

D.2. JAPAN

Millimeter-Wave Imaging Diagnostics

A. Mase (Kyushu University)

Aims:

To develop 2D and 3D millimeter-wave imaging system for measurement of temperature and density profiles and fluctuations.

Work performed:

1) A dichroic plate to separate radiation in the ECE range of frequencies (> 100 GHz) from the low-frequency radiation of reflectometry (< 100 GHz) which is used to the MIR system on TEXTOR has been manufactured in Japan and successfully tested in the USA. An improved version of the dichroic plate is now fabricating in Japan.

2) Drs. Tony Donné, Hyeon Park (PPPL), and Neville Luhmann (UCD) have visited Kyushu to attend the 10th International Symposium on Laser-Aided Plasma Diagnostics held from 24-28 September, 2001. They provided the special talk and invited talks at the conference. We had discussions on the imaging diagnostics during the conference.

3) The US-Japan Workshop on "Development of Fluctuation Visualization Technology" has been held at UC Davis from 26 February to 1 March, 2002. The main issues of the workshop were the experimental results of TEXTOR-MIR and LHD-ECEI systems. The future plans for the imaging diagnostics have also been discussed.

4) The experiment of ECE imaging has been performed at LHD. The cross-correlation spectra between two different detectors and different IF channels were obtained from NBI and ICRF heated plasmas

Work planned:

The ECE imaging and MIR were successfully applied to LHD and TEXTOR respectively. In the next experimental campaign, the imaging system will give the physics results on density and temperature fluctuations.

Investigations of Collisional Radiative Models of Hydrogen Molecule

(K. Sawada, Shinshu University)

Aims:

Investigations of collisional radiative models of hydrogen molecules which have been developed by (a) T. Greenland, (b) U. Fantz and D. Wunderlich, and (c) K. Sawada, independently.

Work performed:

We found that the above three models have the following advantages.

(a) Greenland code; it is mainly used to investigate the validity of the quasi-steady-state solution theoretically.

(b) Fantz and Wunderlich code; it has been developed to analyze the fulcher emission of hydrogen molecule.

(c) Sawada code; it is suitable to calculate effective rate coefficient for various reactions including, e.g. the molecular assisted recombination.

Work planned:

(1) We are planning to unite the above three codes.
(2) We will discuss the radiation trapping in the divertor plasmas.
(3) We will discuss (a) the collisional excitation and de-excitaion between excited levels, and (b) the effect of collisions of heavy particles.

Experiments on helium removal performance by an application of a Radio Frequency filter

(T. Shoji, Y. Sakawa, Nagoya University)

Aims:

Demonstration of selective He pumping by RF ponderomotive force.

Work performed:

In order to measured the Helium pumping efficiency, helium neutrals are injected in the exhaust channel (scoop) of a pump limiter. The neutrals are ionized by the plasma in the scoop and flow back to the main plasma. When frequency slightly above the helium ion cyclotron frequency is applied by the antenna placed in front of the scoop, the ponderomotive potential caused by an RF electric field perpendicular to the magnetic field can resonantly suppress the He+ flow. The exponential decay of helium partial pressure after the helium gas puff is measured at the pumping duct and evaluate the improvement of the helium pumping efficiency by the RF. It is demonstrated that only helium pumping efficiency is improved by the RF while that of deuterium is unchanged. The effective conductance for He back flow is reduced by increasing RF power and the electron density in the scoop.

Work planned:

The demonstration of steady state operation of the selective He pumping by using RF will be performed in the linear device in Nagaya.

PMI studies related High Z materials in TEXTOR 2001

(T. Tanabe, Nagoya University)

Aims:

(1) Investigations of behavior of high Z impurity in main, and boundary plasmas
(2) Understanding of local phenomena (sputtering, reflection redeposition, etc.) in front of the high Z limiter surface.
(3) Examination of high Z materials behavior exposed to plasma heat load
(4) Tritium distribution analysis on PFM tiles by imaging plate technique
(5) Simulation of PMI

Work performed:

(1) Ta/W twin limiter test

Following W/C twin limiter experiments in 2000, Ta/W twin limiter experiments were conducted Owing to characteristic difference of Ta and W for hydrogen, i.e. the former is an exothermic hydrogen occluder and the latter endothermic one, Balmer series emission intensity in front of the W and Ta sides showed significant difference. At lower temperatures, hydrogen recycling at the Ta side was smaller than that at the W side. With increasing the temperature, both became similar. At elevated temperature, emission of excited molecules and/or atomic reemission was observed.

The difference of thermal conductivity between Ta and W, 3 times lower for Ta than W, shows larger temperature increase of the Ta side than that of the W side under the same heat load, confirming the importance of high thermal conductivity of PFM. Thermal desorption analysis showed that deuterium retention in W was negligiblly small, while certain amount of deuterium was homogeneously distributed in Ta with some precipitation of hydride.

(2) Brush tungsten limiter

Brush W limiter which was made by Evlemov Inst. based Russian design for ITER divertor. The performance of the limiter was generally the same as that of the sole W limiter previously examined. Because of the separate structure, each block showed different temperature response during the plasma exposure, which lead us to analyze heat load distribution on the limiter surface very successfully. After an extremely high heat load shots, one block was damaged, while the neighboring blocks was not damaged as expected. On the other hand, melted Cu layer was spilt over one block. Probably the temperature of the brazed region became above the melting point of Cu, because Cu base was only initially cooled Significant redeposition was found between each block, which is very important for future use of this type of divertor tiles.

(3) Tritium distribution measurements by imaging plate technique

The surface distributions of deuterium and tritium on graphite limiter tiles used in TEXTOR under D-D operation were analyzed by means of an ion beam analysis and tritium imaging plate technique, respectively.

Tritium produced by D-D reaction did not fully lose their energy before implanted on the plasma facing surfaces. As a results tritium distribution on the tiles were generally homogeneous. High energy injection was confirmed by the observation of tritium beneath the deposited layer. Tritium was detected even in the plasma shadow, tritium was detected probably owing to their gyration in the scrape-off layer. The profiles of deuterium were completely different from the tritium. They are co- or re-deposited with carbon and boron on plasma facing surfaces at the deposition dominated regions, whereas little deuterium was observed at the erosion dominated regions.

(4) Simulation of hydrogen recycling in front of the limiter

With using a hybrid simulation code EDDY, penetration depth of spectroscopic lines of deuterium and impurities were successfully simulated, indicating that the large part of hydrogen reflected at high Z limiter is likely in electrically excited states. It also successfully showed that most of released high Z impurities are promptly redeposited.

Work planned:

(1) CVD-W coated Cu limiter experiments
(2) Simultaneous measurements of several Blamer lines emissions with using parallel detector
(3) Gas puffing on high Z limiter experiments
(4) Impurity transport and hydrogen recycling in DED configuration

Development of a Tangentially Viewing Soft X-ray Camera System

(K. Toi, S. Ohdachi, NIFS)

Aims:

Since plasma deformations tend to extend along the confining magnetic field lines, a tangentially viewing soft X-ray (SX) camera system is a useful tool to study detailed structures of magnetic islands and deformations caused by MHD instabilities and/or externally applied magnetic field perturbations. This diagnostic technique will provide answers to some standing problems like transport enhancement due to magnetic islands.

Work performed:

In the last year, a basic idea of a tangentially viewing soft X-ray camera(TSXC) was tested on TEXTOR using a slow CCD camera up to 200 Hz framing rate. We transferred it to the Large Helical Device (LHD) during a beak of TEXTOR operation due to mounting DED coils. The SX emission is measured through a pin hole camera with beryllium foil of 40 µm thickness to eliminate visible and UV-light. The TSXC consists of seven major parts: (1) a Cs(I) phosphor screen which converts SX photons into visible light, (2) a 9 m long plastic fibre-bundle which transfers photons away from the strong magnetic field region, (3) a large sized SX image intensifier (100 mm diameter), (4) optical coupling, (5) a second stage image intensifier, (6) a CCD camera, and (7) data acquisition system. In LHD experiments, we employed a fast CCD camera up to 4.5 kHz framing rate in a full frame mode, instead of the slow CCD camera. The dynamic range of the fast CCD camera is 8 bit. Therefor, this TSXC could measure two dimensional structure of MHD oscillations that evolve with up to 2 kHz characteristic frequency and a few % fluctuation amplitude.

Two interesting new results were successfully obtained in the LHD plasmas which are basically net current free, that is, (1) m=2/n=1 pressure driven modes, and (2) low frequency oscillations induced by ice pellet injection. The frequency of these SX-fluctuations is in the range of 0.3-2 kHz and the relative amplitude is relatively low to be 1-3 % or less. A m=2/n=1 structure that rotates poloidally having higher harmonic deformation was revealed in two dimensional SX-images taken with 4.5 kHz framing rate. A clear m=1/n=1 rotating structure in the ice-pellet induced low frequency oscillations was found in the TSXC data. We are now developing a new inversion method of TSXC data in order to derive more detailed internal structures of local SX emission image.

Work planned:

This fast TSXC system will still be applied to LHD plasmas in the next year experimental campaign where stronger MHD modes might be excited on the condition of higher heating power more than 10 MW. More clear SX fluctuation images will be obtained. We have a plan to use a new fast CCD camera with 10 bit dynamic range. At the beginning of 2003, we will re-install this system to TEXTOR for more detailed feasibility study of TSXC.

Edge plasma diagnostics

(A. Tsushima, Yokohama National University)

Aims:

Measurement of boundary plasmas.

Work performed:

In order to measure edge plasmas, two probe methods have been studied as follows.

(1) Ion sensitive probe

In order to measure ion temperature, an ion sensitive probe has been analyzed. Because positive bias to an electrode might give significant disturbance to plasma in strong magnetic field, the ion energy is selected by changing a depth of an ion collector. The numerical result shows that the geometry of the probe needs to be taken into account for evaluating an ion temperature from a dependence of ion current on the depth of the ion collector.

(2) Facing double probe

On the basis of the fluid model, a new probe method for plasma flow measurement has been proposed and analyzed. The probe consists of two electrodes placed face-to-face each other and detects difference between the floating potentials of the two electrodes as an index of the plasma flow. It is the most distinguished point that this probe has the spatial resolution of the distance of the two electrodes, because the plasma that diffuses into the region between the two electrodes affects the floating potentials of the two electrodes.

Work planned:

Test of the ion sensitive probe and the facing double probe.

Utilization of ferritic steel as a first wall material

(New proposal initiated by K. Tsuzuki, JAERI)

Aims:

To examine the response of ferritic material under plasma exposure, or the influence of (local) magnetic field on PMI

Work performed:

1) The purpose of the experiment was presented in detail by JAERI.
2) The measuring system such that the spectroscopy and the thermometry were discussed.
3) Structure of the sample was discussed, which is suitable for the measurement and strong enough to support the electro-magnetic force.

Work planned:

1) Experimental plan

Test limiter experiments will be performed with the limiter partly including a ferritic steel and/or magnetic material like Fe, Ni.

2) What shall be observed

Spectroscopy

Influence of the local magnetic filed on spatial distributions of Fe, Ni and Balmer lines in front of ferritic materials. The effect can be compared between magnetic and nonmagnetic materials parts on the limiter.

Thermometry

Influence of the local magnetic field on heat load pattern , Postmortem analysis (in Japan?)
Influence of the local magnetic filed on deposition pattern, (Boundary between magnetic and nonmagnetic materials is in particular interest, even in plasma shadow)

3) To be prepared

Limiter: partly including a ferritic steel and/or magnetic material like Fe, Ni.
Concerns: Magnetic forth given to the limiter lock and Cr lines from SS
Optical filters for Fe or/and Ni lines

D.3. UNITED STATES OF AMERICA

IEA Collaborations on TEXTOR

(repared by D.L. Hillis, ORNL)

Main activities during the past year for the US/TEXTOR collaboration have been focused on:

1. a combined electron cyclotron emission imaging (ECEI) and microwave imaging reflectometer (MIR) system, which is being implemented on TEXTOR-94 for T_e and n_e fluctuation measurements by a combined effort between University of California at Davis(UC-Davis) and Princeton Plasma Physics Laboratory (PPPL),
2. a Fast Ion Collective Thomson Scattering Diagnostic with Massachusetts Institute of Technology (MIT),
3. joint participation with Oak Ridge National Laboratory (ORNL) in JET Experiments via the Trilateral Euregio Cluster, and
4. publication of previous TEXTOR collaborative experiments by the University of California at San Diego.

1. A combined ECEI and MIR Diagnostic System (UC-Davis/PPPL)

(prepared by N.C. Luhmann, Jr.)

Overview

UC Davis (N.C. Luhmann, Jr., C.W. Domier, and B.H. Deng) in collaboration with PPPL (E. Mazzucato, T. Munsat, and H.K. Park) are developing revolutionary 2-D and 3-D microwave electron cyclotron emission imaging (ECEI) and microwave imaging reflectometer (MIR) systems for imaging T_e and n_e fluctuations (both turbulent and coherent) and profiles (including transport barriers) on toroidal devices such as tokamaks, spherical tokamaks and stellarators. In collaboration with researchers from the FOM Institute for Plasma Physics Rijnhuizen (A.J.H. Donné and M.J. van de Pol), a combined ECEI and MIR system is being implemented on TEXTOR-94, permitting simultaneous spatial and temporally resolved measurements of $n_e, \tilde{n}_e, T_e$, and $\tilde{T}_e$ at the same location, as well as making possible the correlation between n_e and T_e fluctuations. Major aims are the provision of high resolution temperature profiles and the study of the physics of the ion temperature gradient (ITG) mode where these high resolution imaging diagnostics, combined with conventional techniques, will permit the visualization of complicated 2-D and/or 3-D structures which is essential for definitive comparisons to be made with the predictions of ab-initio computer simulations results based on gyrokinetic simulation.

History and Background

Installation on TEXTOR-94 of the prototype ECEI portion of the system took place in February 2000, with commissioning and first results obtained in March 2000 (see Fig.1). ECE Imaging data collected on TEXTOR have been utilized to support FOM research programs in the areas of (i) electron temperature filaments, (ii) internal transport barriers, (iii) negative central shear, and (iv) islandography. Drs. Domier and Munsat traveled to Jülich, Germany in September 2000, and temporarily replaced this ECE Imaging diagnostic with a prototype lens-based Microwave Imaging Reflectometer (MIR) system. Data collected with this first prototype system were subsequently analyzed, and led to the development of a new prototype MIR system that replaced the plasma facing lenses with large diameter reflective optics. Here, the use of reflective optics eliminates much of the deleterious interference caused by reflections of the plasma illumination beam off each surface of the plasma facing lenses. This was installed on TEXTOR-94 in late February, 2001 just prior to the planned 10-month shutdown of the TEXTOR-94 device (beginning in March, 2001) for installation of a dynamic ergodic divertor system. Although the operating time was short, interesting physics data were collected on core density fluctuations that have verified the basic principles of the MIR diagnostic technique (see below).

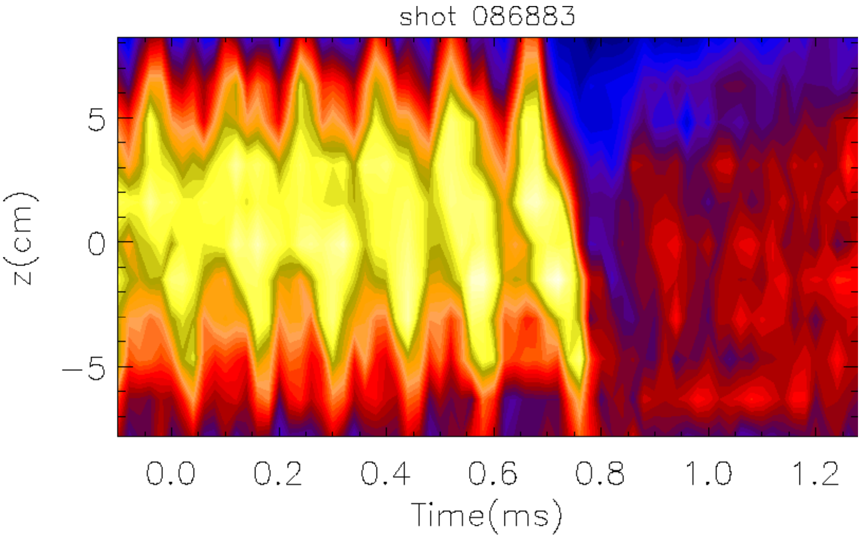

Figure 1. Complex island structure during high power ECRH on TEXTOR.

The multichannel electron cyclotron emission imaging (ECEI) concept was conceived by UC Davis and makes use of receiver arrays developed under the Advanced Diagnostic program. The concept was first demonstrated on the TEXT device with subsequent developments carried out on the RTP tokamak at FOM as part of a collaborative effort under terms of the “US/Euratom Umbrella Agreement: Cooperation in the Field of Controlled Thermonuclear Fusion.” While in operation from October 1997 until the RTP tokamak was shut down in August 1998, this system collected data on both coherent electron temperature fluctuations (such as MHD) as well as electron temperature microturbulence.

The microwave imaging reflectometer concept was conceived by E. Mazzucato, and addresses a fundamental limitation of conventional (i.e., non-imaging) reflectometry based fluctuation diagnostics where the multidimensional (radial and poloidal) turbulent fluctuations result in the reflected field propagating in multiple directions, and consequently result in a complicated random interference pattern at the detector plane. Detailed theoretical studies by Mazzucato together with experimental data from TFTR revealed the serious problem in the interpretation of data from conventional reflectometers that are perforce located a long distance (meters from the plasma edge). This collaboration represents the first experimental implementation of the MIR approach.

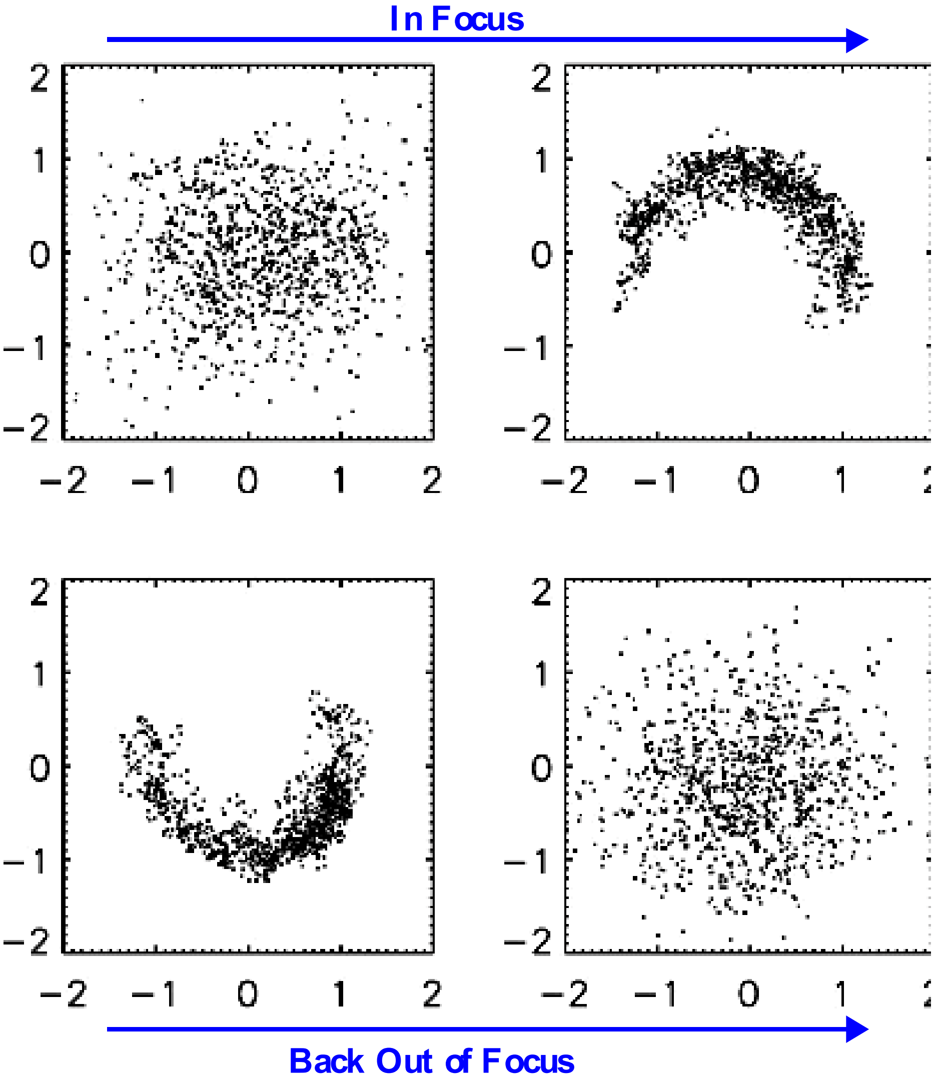

Figure 2. Complex field amplitude from the prototype TEXTOR-94 MIR system as the cutoff layer is swept through the focal plane of the imaging optics. Each frame represents a 3 ms time window.

Data from the prototype MIR instrument installed on TEXTOR (see Fig.2) confirmed the fundamental theoretical expectation: when the cutoff is properly imaged onto the detector plane, a clean phase signal results; conversely, when the cutoff is “out of focus” (i.e. not imaged), a complicated interference pattern essentially randomizes the reflected signal. Simultaneously with the installation of an improved instrument on TEXTOR, a series of off-line experiments using the TEXTOR MIR system on target reflectors of known shape has further illustrated the fundamental difficulty with conventional reflectometry and the advantage of imaging. Figure 3 shows a measurement of a corrugated target surface with (a) the TEXTOR MIR system (located 235 cm from the target), and (b) a conventional reflectometer (located 50 cm from the target). For comparison, each reflectometer measurement is plotted with a reference measurement, produced independently with a visible-laser interferometer. Basically, it was observed that for target wavenumbers and amplitudes of relevance to tokamak fluctuations, the nonimaging refelectometer signal suffered significant degradation and decorrelation at distances as short as 25 cm.

To provide a perspective for the critical importance of the result, it should be noted that reflectometer horns are often sited at meter distances from the plasma edge.

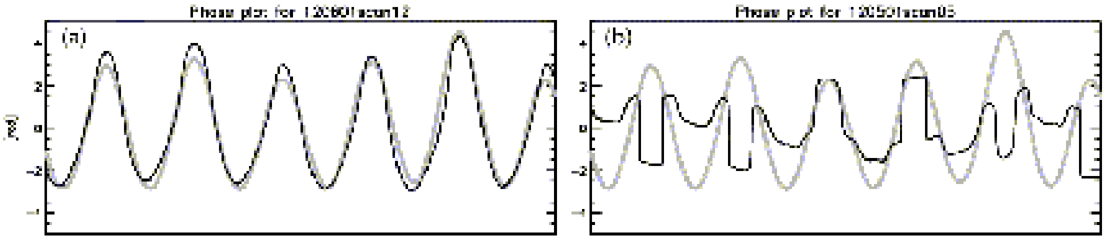

Figure 3. Laboratory test of MIR using a corrugated target mirror. Phase reconstruction of known target surface using (a) MIR imaging system, located 235 cm from reflection surface, and (b) conventional reflectometry system, located 50 cm from reflection surface. The light gray curve represents the actual surface, as measured by a separate visible-laser interferometer.

Work Plan and Schedule

The tasks of the combined ECEI and MIR system (see schematic below) diagnostic development are divided among UC Davis, PPPL, and FOM as follows. The UC Davis team is responsible for developing the technologies necessary for the implementation of the proposed diagnostic systems, including new imaging arrays, signal detection circuits, phased antenna arrays, quasioptical notch filters and diplexers/beam splitters. UCD also has the lead in the system design, coordinating with the PPPL and FOM scientists. Imaging lenses are designed by the UCD team. PPPL scientists have the responsibility of fabricating the large mirrors together with conducting the basic studies of imaging reflectometry. FOM scientists and personnel design and fabricate the mechanical framework, fabricate the lenses, and provide the data acquisition system for both ECEI and MIR. The physics experiments with the developed systems are the joint responsibility of the collaborating scientists and will be integrated into the FOM fusion program in the TEXTOR-94 collaboration.

The current schedule is to install the ECEI/MIR system and to be ready for measurements for first plasma operation when TEXTOR resumes plasma operations on August 1, 2002. In parallel with the physics studies, a new ultra-wideband ECEI capability will be developed, with the upgrade installed during the summer vent in 2003. In addition, electronic beam-shaping capability will be developed for the MIR portion of the instrument. The current plan is to first test the concept on NSTX and then extend the operating frequency as required for TEXTOR. It is anticipated that the installation will occur during the summer vent in 2004.

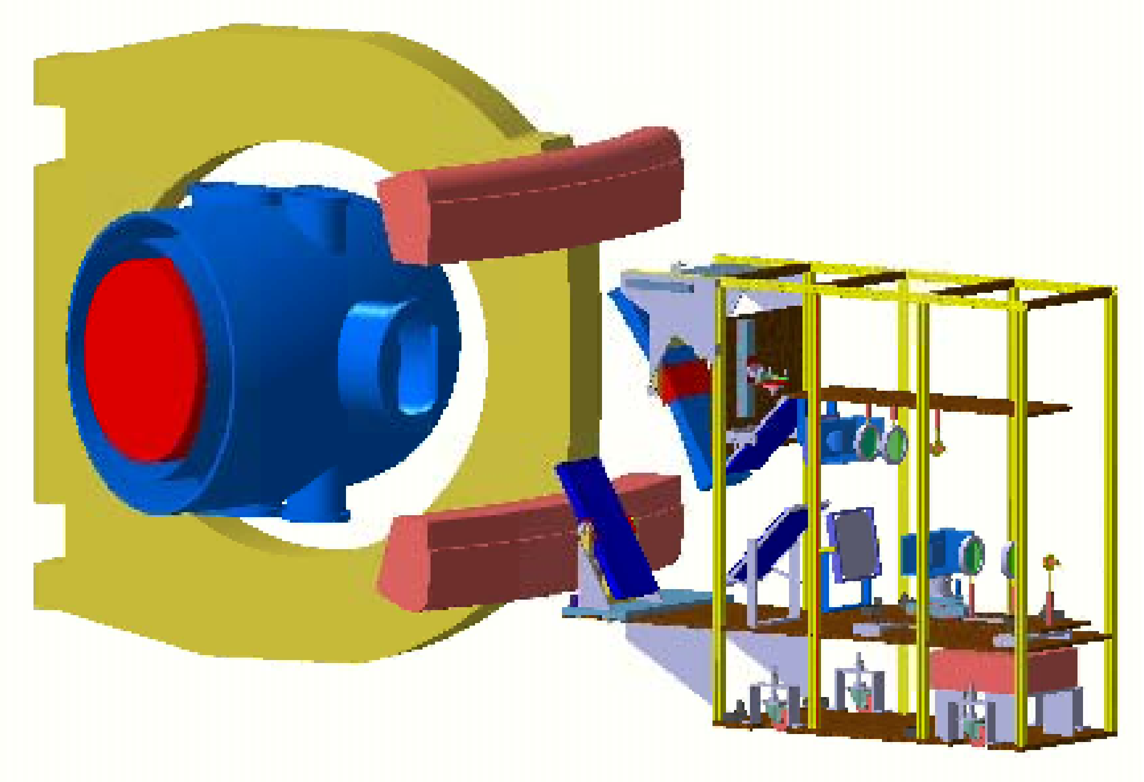

Figure 4. Combined ECEI/MIR Diagnostic for TEXTOR.

2. Fast Ion Collective Thomson Scattering Diagnostic (MIT)

(*prepared by Paul Woskov)*

Scope

Collective Thomson Scattering (CTS) is being developed as a localized diagnostic of fast ion velocity distributions. Fast ions (0.1 - 5 MeV) are an important component of fusion energy plasmas for which good diagnostic data is lacking. Fast ions include those generated by ICRH, NBI, and fusion product alpha particles. CTS can measure the phase space distribution (location, energy distributions, velocity anisotropies, and time) of fast ions. The U. S. is providing one post doc on site at TEXTOR and the sensitive millimeter-wave receiver system for detection of the scattered signals. In the process of developing this diagnostic on TEXTOR we also hope to gain initial novel data on fast ion physics of importance to the development of future burning plasma experiments.

Brief History

A major advance in CTS diagnostic development was achieved on TEXTOR in its last campaign, which ended March 2001. Up to 100 CTS spectra were obtained per plasma shot allowing the time resolution of the fast ion velocity distribution to be observed with changes in ICRH, NBI, and saw tooth crashes. This was the first time that more than one CTS spectra was obtained per shot. Thousands of scattered spectra were obtained from four CTS run weeks over the course of about one year. The analysis of the data is providing new insights into fast ion dynamics. Since the TEXTOR shut down, the CTS diagnostic system was dismantled along with TEXTOR to install a new divertor. The MIT receiver is being upgraded with new A to D electronics and prepared for reinstallation on TEXTOR this summer.

Plans

The CTS system will be reinstalled on TEXTOR this summer. Problems observed with the system during the initial campaign will be addressed. This includes the interference observed with ICRH when power levels exceeded 1 MW. Also the frequency chirping of the gyrotron will be studied and mitigation methods developed. Studies of generic fast ion physics will continue. The synergy of ICRH with NBI injection on the fast ions and background emission will be investigated. Close contact with the ASDEX group will also be maintained as they bring up their CTS system.

3. Joint participation in JET Experiments via the Trilateral Euregio Cluster (ORNL)

(prepared by D. Hillis)

The main activities during the past year for the ORNL/TEXTOR collaboration have been focused on joint participation in JET Experiments via the Trilateral Euregio Cluster in the areas of:

- RI-mode (Ar Impurity Seeding) at JET
- He Transport and exhaust at JET
- He wall changeover experiments at JET
- Evaluation of possible participation in DED Experiments

During Jan 2001 radiation improved (RI) mode experiments were performed on JET with Argon being the seed impurity. These experiments resulted in two presentations at the Division of Plasma Physics Meeting of the American Physical Society in Long Beach, CA (Oct 2001) entitled “Importance of Divertor Configuration and Argon Recycling on Confinement in Impurity seeded discharges on JET” (D. Hillis) and Comparison of Enhanced Confinement L-Mode Regimes in JET and DIII-D with Impurity Seeding”(G. Jackson-GA and M. Murakami-ORNL). Three US proposals for work on JET were submitted through TEXTOR to be performed during 2002. Those proposals were:

1. “Influence of Ar recycling and divertor Configuration on Confinement in Radiative Mantle Discharges on JET” (D.L. Hillis, et al.) JET experiments scheduled for April 2002.

2. “Perform similarity experiments on DIII-D and JET to understand the physical mechanisms relating to the JET afterpuff impurity scenarios and associated ELM behavior” (G. Jackson, M. Murakami, D. Hillis, et al.) JET experiments scheduled for Summer 2002.

3. “High Performance L-mode Discharges using Impurity Seeding” (G. Jackson, M. Murakami, D. Hillis, et al.) JET experiments scheduled for June 2002.

During March 2001 joint experiments were performed on JET to investigate He transport and exhaust in ELMing H-modes and in plasmas with Internal Transport Barriers (ITB). Data was evaluated and published at the 2001 European Physical Society Meeting by K-H Finken(TEXTOR). In collaboration with V. Phillips (TEXTOR) experiments at JET were performed to investigate the He wall changeover experiments. In these experiments 100% He gas is injected into the JET vacuum vessel with the graphite walls previously saturated with deuterium. The global particle balance analysis provides a time history of the wall loading of He and is exploited to make estimates of the particle-induced desorption coefficient which governs the rate of change-over of the wall. Analysis is currently underway and results will be presented at the 2002 Plasma Surface Interaction Meeting in Japan in a paper entitled “Deuterium to Helium Plasma-Wall Change-over Experiments in the JET MkII-Gas Box Divertor” (D. Hillis). Finally, discussions are in progress to determine possible US participation in the TEXTOR DED Experiments.

4. Publication of previous collaborative experiments by UCSD

(prepared by J. Boedo)

Current activities have focused on publishing results from previous UCSD collaborative experiments on TEXTOR-94. Analysis has focused on plasma turbulence suppression in tokamak discharges. This work has resulted in an invited talk at the May 2001 Transport Task Force (TTF) Conference in Fairbanks Alaska. This work has since been published in Nuclear Fusion as “Scaling of plasma turbulence suppression with velocity shear,” J.A. Boedo, et al., Nucl. Fusion, 42 (2002) 117. Other recent publications that resulted from the TEXTOR collaborations are:

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E. SCIENTIFIC PUBLICATIONS

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E.3. ARTICLES IN BOOKS

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Atomic and Plasma-Material Interaction Data for Fusion
Particle Induced Erosion of Be, C, and W in Fusion Plasmas, Part B: Physical Sputtering and Radiation-Enhanced Sublimation
Published by: Clark, R.E.H.
Vol. 7B, 198 pages, 2001
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F. TABLE OF EXPLANATION

I) Institutes of Forschungszentrum Jülich being involved

1	Institute of Plasma Physics
2	Institute for Materials and Processes in Energy Systems (Materials Microstructure and Properties)
3	Institute of Solid State Research
4	European Spallation Source
§	Identification number of associated research projects of Forschungszentrum Jülich

II) Home Affiliation of external Authors (Section E)

X)	Not a member of Forschungszentrum Jülich