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Association Euratom - DTU, Technical University of Denmark, Department of Physics - Annual Progress Report 2012

R-Report

Edited by: S.B. Korsholm, S.K. Nielsen, J.J. Rasmussen and C.M. Westergaard

November 2013

DTU Physics
Department of Physics

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Abstract (max. 2000 char.):

The programme of the Research Unit of the Fusion Association Euratom – DTU, Technical University of Denmark covers work in fusion plasma physics and in fusion technology. The fusion plasma physics research focuses on turbulence and transport, and its interaction with the plasma equilibrium and particles. The effort includes both first principles based modelling, and experimental observations of turbulence and of fast ion dynamics by collective Thomson scattering. Within fusion technology there are activities on fusion materials research (Tungsten and ODSFS). Other activities are system analysis, initiative to involve Danish industry in ITER contracts and public information. A summary is presented of the results obtained in the Research Unit during 2012

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Preface

In 2006 seven parties, EU, Japan, Russia, China, USA, Korea and India, signed the agreement to build and exploit ITER, and to place ITER in Cadarache in France. ITER is a major experimental facility for the development of fusion as an energy source. It is expected that ITER will be ready for scientific exploitation in the early 2020ies. The mission of ITER is to demonstrate that nuclear fusion can be exploited as an energy source. Fusion holds the promise of providing a sustainable source of energy, which is environmentally sound, and presents considerable scientific and engineering challenges. ITER represents an unprecedented international cooperation in the field of science and technology. It also represents a valuable opportunity for cooperation between public research organisations and private industry.

In 2012 EFDA adopted a detailed and ambitious roadmap towards commercialisation of fusion power plants by 2050. This roadmap shows a clear path towards achievement of fusion. DTU participates in the internationally coordinated activities to develop fusion, with our activities being aligned and in full support of the roadmap strategy. We further see ourselves with a key role in facilitating the participation of Danish industries in the international fusion programme.

The fusion of hydrogen isotopes into form helium is the principle used in ITER. To obtain a large number of fusion events the hydrogen gas must be heated to high temperatures where it ionises and turns into a plasma. ITER will use magnetic fields to confine the plasma. Two key issues in the final steps towards realising fusion energy production are our main drivers:

Improving energy confinement, that is the ratio between the energy of the plasma and the heating power required to sustain the plasma energy, demands a reduced energy transport out of the plasma, which principally is due to turbulence. Thus we work to understand and control plasma turbulence.

Channelling the energy of fast ions, produced in fusion reactions, into heating the bulk plasma without driving turbulence and without premature exit of the fast ions from the plasma requires understanding and control of the dynamics of the fast ions in interaction with other particles and with waves.

Since January 2012 the activities within fusion plasma physics research are located within the Department of Physics (DTU Physics) as section for Plasma Physics and Fusion Energy (PPFE). Simultaneously the Research Unit for the Contract of Association is hosted by DTU Physics and the Association is termed EURATOM – DTU. The PPFE provides the main activities within the Research Unit. Additionally there are contributions to investigations of materials (Tungsten and ODSFS) , socio economic studies and the potential for activities related to robotic handling are presently explored.

The main DTU contributions to fusion research in 2012 have been:

1) Models for investigating turbulence and transport. A better agreement between SOL modelling and experiments has been achieved, giving rise to better understanding of processes leading to flow formation at the edge SOL transition. DTU also worked on extensions of the validity range of gyrokinetic equations into that challenging region of a magnetically confined plasma.

2) Central to understanding the dynamics of fast ions is temporally and spatially resolved measurements of the fast ion velocity distributions in the plasma. DTU, in collaboration with EURATOM partners, is exploiting and developing millimetre wave based collective Thomson scattering (CTS) diagnostics at the ASDEX upgrade tokamak at the Max-Planck Institute for plasma physics in Garching (near Munich). Progress has been made towards readying the diagnostic for scientific exploitation and for extending the range of measured quantities, f.x. measuring the composition of the plasma fuel.

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  Host of the association EURATOM - DTU
- **DTU Management Engineering**
  Socio-Economical studies – Fusion in the Energy system
  Poul Erik Grohnheit
- **DTU Mechanical Engineering**
  Fusion Technology – Thermal stability of Tungsten
  Wolfgang Pantleon

1 Summary of Research Unit activities

The activities in the Research Unit are in **Fusion Plasma Physics**:

- *Theoretical and numerical turbulence studies*. Turbulence and the associated anomalous transport of particles, energy and momentum is investigated developing and using first principles based models. Application of the models is performed by numerical codes exploiting full toroidal geometry. These models are continuously being developed and benchmarked against experimental data and codes at partner associations. The activities are focused on topics related to edge and scrape-off-layer (SOL), i.e. the transition from magnetic confined plasma to plasma in contact with material interfaces. The work is performed in collaboration with EFDA partners and in particularly with EFDA/JET.
- *Fast Ion Collective Thomson Scattering.* The research unit is developing and exploiting a fast ion collective Thomson scattering diagnostics at ASDEX Upgrade (AUG). The diagnostic will enable researchers to obtain time, space and velocity resolved information about the energetic particles in the plasma as well as information on the plasma fuel composition. This project is carried out in close collaboration with the AUG team. The group is working towards being awarded the corresponding design task for the ITER device, which will demonstrate energy production from magnetic confinement fusion, and thus have specific need for diagnosing “hot” ions.

Other activities in 2012 have been:

1 Investigations in the properties of Tungsten as a material in fusion power plants.

2 Participation in the EFDA programme on developing a multi-region global long term energy modelling framework called EFDA-TIMES.

3 Activities to inspire Danish companies and make them aware of the possibilities of being a supplier to the construction of ITER.

4 Activities on public information about fusion energy. This includes development and presentation of the “Danish Fusion and Plasma Road Show”.

The **global indicators** for the Research Unit in 2012 (2011) are:

Professional staff:	9.21	man-years
Support staff:	2.9	man-years
Total expenditure - incl. mobility:	2.04	Million Euro
Total EURATOM support:	0.59	Million Euro

2 Plasma Physics and Technology

2.1 Introduction

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Plasma is a dense collection of free ions and electrons. The transitions from solids to fluids to gases are associated with increases in internal energy, the breaking of bonds and changes of physical properties. The same is true for the transition from a gas to a plasma. The plasma is rightfully described as the fourth state of matter, its physics differing as much from that of gases as that of solids does. As solid state physics is involved in a broad range of applications, it should be no surprise that plasmas have a wide range of applications, that their physics and chemistries are rich, and that the methods of generation and diagnosis are wide and complex.

Our activities in high temperature plasmas, aimed at developing fusion energy, are coordinated with the European EURATOM fusion programme through an agreement of association on equal footing with other fusion laboratories in Europe. Our EURATOM association facilitates extensive collaboration with other fusion research laboratories in Europe, crucial in the ongoing build-up of competencies at DTU, and gives us access to placing our experimental equipment on large fusion facilities at, e.g., the Max-Planck Institute for Plasma Physics in Garching, Germany. Our association with EURATOM also provides the basis for our participation in the exploitation of the European fusion research centre, JET, located in England. With its organisation of national programmes as EURATOM associations, the European fusion programme is a successful example of a large *European Research Area.* Our activities in high temperature plasma research and the development of fusion energy are introduced in subsection 2.1.1, and described in further detail in subsection 2.2 discussing turbulence and transport in fusion plasmas, and in subsection 2.3 discussing our use of millimetre waves for investigating the dynamics of fast ions in fusion plasmas.

2.1.1 Fusion plasma physics

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Producing significant amounts of fusion energy requires a plasma with a temperature of 100 to 200 million degrees and densities of 1 to 2 times 10^{20} particles per cubic metre, corresponding to a pressure of 1 to 5 atmosphere. Unlike gases, plasmas can be confined and compressed by magnetic fields. At the required temperatures the plasma must be lifted off material walls to prevent the plasma from rapid cooling. This is done by suspending the plasma in a toroidally shaped magnetic field that also acts to balance the plasma pressure. The required temperature and densities have been achieved in the joint European fusion experiment, JET. The production of net energy adds the requirement that the energy in the plasma be confined at least on the order of six seconds. The confinement time is the characteristic time for cooling off if heating was switched off or, equivalently, the ratio of plasma energy to required heating power to sustain that energy content. Achieved confinement times are on the order of one second. Higher density could compensate shorter confinement time and vice versa, so a simplified statement of the target is that the product of temperature, density and confinement time should be six atmosphere $\times$ seconds and is currently one atmosphere $\times$ seconds. Progress towards the goal principally involves improving the confinement time or, equivalently, reducing the energy transport in the plasma. The energy transport in fusion grade plasmas is principally due to turbulence, one of our main research activities reported in subsection 2.2. Significant progress towards the goal is expected with the next step fusion experiment, ITER. In ITER significant fusion rates are expected and with that the fast ion populations in the plasma will increase dramatically compared with present machines. The fast ions may then influence the plasma significantly. As a consequence, the dynamics of fast ions and their interaction with the rest of the plasma is one of the central physics issues to be studied in ITER. This is another of our main research topics in fusion as reported in subsection 2.3.

The fields of turbulence transport and fast ions are closely knit. With steep gradients in plasma equilibrium parameters and with populations of energetic ions far from thermal equilibrium, fusion plasmas have considerable free energy. This energy drives turbulence, which in turn acts back on the equilibrium profiles and on the dynamics of the fast ions. The turbulence naturally gives rise to enhanced transport, but also sets up zonal flows that tear the turbulent structures apart and result in transport barriers. The edge transport barrier being most likely at the root of the poorly understood, but experimentally reliably achieved, high confinement mode (H-mode). This non-linear interplay between turbulence and equilibrium also supports transient events reminiscent of edge localised modes (ELMs) where energy and particles are ejected from the plasma edge in intermittent bursts.

This set of topics is the focus of our fusion plasma physics research: With first-principles based codes we seek to model the interplay between plasma turbulence, transport and equilibrium. This modelling is tested against experimental data in collaboration with other fusion plasma physics institutes. To elucidate the physics of fast ions and their interplay with turbulence, waves and transient events, we are engaged in the diagnosis of confined fast ions by collective Thomson scattering (CTS) at the ASDEX upgrade tokamak in the Max-Planck Institute for Plasma Physics in Garching, Germany.

2.2 Turbulence and transport in fusion plasmas

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The transport of heat, particles, and momentum across the confining magnetic field of fusion plasmas is one of the most important, but also most difficult areas of contemporary fusion research. It is well established that the “anomalous” transport component due to low frequency turbulence is usually far larger than the classical and neo-classical collisional transport, in particular in the edge region. Therefore, it is of highest priority to achieve a detailed understanding of anomalous transport and the underlying turbulence for the design of an economical viable fusion reactor based on magnetic confinement schemes. In spite of the dramatic progress in experiment, theory and computations during recent years, the quantitative understanding is still sparse and lacking predictive capability. Even fundamental phenomena such as transitions from low confinement regime (L-mode) to high confinement regime (H-mode), the profile resilience and the particle pinch that are routinely observed and classified experimentally have no generally accepted explanations.

The activities within plasma turbulence and transport are mainly focused on topics related to edge and scrape-off-layer (SOL) regimes of toroidal plasmas, but also investigations of core turbulence and transport are taken up. Generally, it is acknowledged that the conditions near the edge of the plasma are dictating the global performance, which seems natural since all transport has to go through the edge region, but certainly the coupling to the core plasma dynamics is essential. Theoretical and numerical investigations of first principle models form the majority of the work performed. We emphasize benchmarking of results and performance, both with other codes and analytic results (verification) and then also with experimental observations (validation).

The activities are fully integrated into the EURATOM fusion program, and we have active collaborations with several EURATOM laboratories on theoretical issues as well as on direct comparisons of our results with experimental observations. We are involved in the EFDA-JET program. We are actively participating in the Integrated Tokamak Modeling (ITM) Task Force on validation and benchmarking of codes as well as defining the ITM data structures. A. H. Nielsen is deputy leader for project IMP4. We have a significant involvement in the EFDA ITER Physics tasks (IPH). V. Naulin is deputy chair for IPH - activities.

Several of our numerical codes are in use at different European laboratories, where they are employed for specific purposes, ranging from experimental comparisons to education of students.

The work carried out through 2012 includes:

The activities within the ITER Physics tasks are summarized in sections 2.2.1 - 2.2.2. This covers participation in the planning and reporting of the TG Transport activities together with participation in specific tasks on the modeling and measurements in the SOL/edge region of toroidal devices.

Examples of the involvement in the ITM activities are provided in sections 2.2.3. The emphasis is here on the involvement in IMP4 on validation and benchmarking of codes as well as developing the Kepler workflows. Specifically, we organized an IMP4 Working Session at DTU Physics during May 21-25.

Investigations of the turbulence and transport at the edge and SOL of toroidal plasmas are continued by participating in experimental investigations and applying edge/SOL turbulence codes. These investigations are an integral part of our contributions to IPH tasks. Section 2.2.4 describes simulations of the turbulence and transport in the Edge-SOL of L-mode MAST plasmas, while section 2.2.5 discusses a comparison of ESEL simulations with measurements in the EAST tokamak. In both cases fine agreements are reached between the simulation and experimental results; thus, extending the benchmarking of the ESEL model. Section 2.2.6 is concerned with an extension of the ESEL model including ion temperature dynamics and lowest order FLR corrections, making it possible to simulate ion temperature fluctuations and profiles and compare with experimental results. The new model is termed HESEL and preliminarily test have been successfully performed for medium sized tokomak parameters. Further extensions of the models are described in section 2.2.7 with a discussion of the so-called thin-layer approximation and in section 2.2.8, where a global gyrofluid model for the edge/SOL is presented. To further add to the development of gyrokinetic modelling a fully consistent gyrokinetic collision operator has been derived in section 2.2.9.

The work on filamentary current structures during edge localized modes is continues both within the IPH tasks (Sec. 2.2.1) and also in the EAST tokamak see section 2.2.10.

We have discussed a simple mechanism for rotation reversal in ohmic L-mode plasmas based on a non-local transport model in section 2.2.11. Finally, we have performed a detailed investigation of L-H transition dynamics as described by predator prey type models, Sec. 2.2.12.

The involvement in the JET work program is summarized in Section 2.2.13. It is focused on areas of edge turbulence, transport and evaluation of electron temperature measurements.

2.2.1 EFDA tasks in the turbulence group

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The turbulence group was in 2012 involved in the following EFDA ITER physics activities:

- **WP12-IPH-A06-1-1-05**: Measurements of SOL transport by probes in H-mode during inter-ELM intervals
- **WP12-IPH-A06-2-1-05**: Measurements of SOL transport by probes in H-mode during ELM intervals

These tasks were performed in close collaboration with the associations: ÖAW/Innsbruck, ENEA_RFX/Padova, MHEST/Ljubljana, and IPP/CR Prag. The activities comprised measurements of SOL profiles and transport PDFs on AUG using the mid-plane manipulator and the Innsbruck probe setup. The fluxes of different quantities, specifically momentum, particle and electron heat were obtained and compared selected by phases in the discharge. That is inter ELM, during ELM, total H mode, and L-mode. Magnetic fluctuation measurements under RMP operations in AUG have clearly shown the difference between odd and even configurations. The even configurations are effective in suppressing ELMs with the disappearance of current filaments; while odd configurations only partly suppress ELMs and clear signatures of current filaments are conserved.

See also sections 2.2.4 and 2.2.6 for related work.

- **WP12-IPH-A08-2-08**: Current in ELM and blob filaments

The task was performed in close collaboration with the associations: ÖAW/Innsbruck and ENEA_RFX/Padova. The main activities comprised measurements of current filaments in AUG by applying the so-called Innsbruck probe setup. A detailed picture on filaments in toroidal devices has been obtained, but further analyses are mandatory to obtain a comprehensive picture. The analysis of data from the AUG campaign in November 2012 is still in progress in collaboration with ENEA-RFX and ÖAW. New tasks have been proposed for IPH2013 to continue and to expand the investigations.

See also section 2.2.10 for similar investigations at the EAST tokamak, which supplement the activities.

- **WP12-IPH-A08-2-13**: Emissive probes for AUG class tokamaks and beyond

The task is performed in close collaboration with the associations: ÖAW/Innsbruck, and MHEST/Ljubljana. The activities during 2012 has been centered around feasibility studies for probe arrangement that could be built into an AUG and/or COMPASS probe head. This include design studies and investigations on possible materials and available electron sources, but no construction took place as yet. Other important preparatory work such as the simulation of probe arrangements and the fundamental behavior of emissive probes in various plasmas were carried out. From the start of the project a longer duration for its accomplishment had to be envisaged. The project will be continued in 2013.

- **WP12-IPH-APL-01**: Topical Group Vice-Chair Transport

This project is referenced in the following section 2.2.2.

2.2.2 EFDA Topical Group Transport Vice Chair

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The work as vice chair of the topical group transport focused on the design and implementation of the 2012 EFDA work programme in that area and was initiated by the general planning meeting and continued in the stipulation of participation, the selection of proposals and help in the implementation of the work programme's tasks.

A key activity for the topical group was the organization of the he 17th Joint EU-US Transport Task Force Meeting in combination with the 4th EFDA Transport Topical Group Meeting in Padua (Italy) from September 3 - 6, 2012, where about 90 participants presented results from the EFDA work programme and the corresponding US activities.

Discussions with the project coordinators, ensuring reporting and evaluation of the reports close the circle of the EFDA annual cycle.

2.2.3 Integrated Tokamak Modelling Engagement

A.H. Nielsen, B.D. Scott and the ITM-IMP4 team (*IPP-Garching, D)*
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The engagement in the Integrated Tokamak Modeling (ITM) has been concentrated in the project #4 in which DTU holds the deputy project leader position. Project #4 is responsible for numerical codes and associated Kepler workflows for instabilities, turbulence, and transport, as well as standards are maintained for the simple modules commonly used in transport modeling codes.

The activities in Project #4 in 2012 emphasized high-performance computing (HPC) capability within ITM Kepler workflows, progress on general implementation into European-Transport-Solver workflows, interfacing to experiments, and incorporation of standard transport and neoclassical models used by ITER Scenario Modeling. DTU Physics hosted the ITM-IMP4 working session in the week 21 to 25 of May. The focus of the working session was IMP4 core benchmark using the ITM infrastructure, either a Kepler or FORTRAN work-flow on the HPC-FF.

During 2012, the basic infrastructure to read the SOL parameters from the Langmuir CPO was developed. Data consisted of two JET shots, 57756 and 57757. Combined these shots hold both basic plasma parameters and Langmuir probe data. The extracted data was interpolated and fed to the DTU code ESEL as initial parameters. The code was then used to compute the plasma turbulence near the edge, and the results were output in HDF5 format. The work will be extended in the future to remove some of the current approximations, and also produce output as a computational Langmuir CPO. From what is learned from this project we have identify the following items which will have to be addressed in the continuation of this project in 2013;

- The current position of last-close-flux-surface is an approximation taken from equilibrium CPO. For better results, this should be computed from the edge CPO.

- Further validations of the experimental and computational results are needed. The code may need to be tuned to match the experimental results.

- The output of the probe data from the SOL-capable code is in an HDF5 file. The output should be written out as a Langmuir CPO

For the core benchmark effort, CENTORI was the only IMP4 code which delivered new data. The technical part of the ATTEMPT simulation for the core benchmark simulation procedure has been finalized. Standardized data have been produced and have been collected in the pool of IMP4 data for comparison. The analysis is still on-going. The benchmark results were discussed among the participant during IMP4 working session and at two Code Camps (Garching,Nicosia). New simulations were performed on HPC-FF to ensure consistency with the data format specified by the IMP4 standard and HDF5 format. All data are placed on the Gateway and a set of standardized Matlab routines have been created to extract results from the data produced by the different codes. A report based on these results was placed on the Gateway and GForge for access by IMP4 participants. It is still open whether this report should be extended to an internal/external publication.

2.2.4 ESEL simulations of MAST plasmas

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The L-mode interchange turbulence in the edge and scrape-off-layer (SOL) of the tight aspect ratio tokamak MAST was investigated numerically. The dynamics of the boundary plasma were studied using the 2D drift-fluid code ESEL, which previously had shown good agreement with large aspect ratio machines.

Scans of various edge parameters, such as density, temperature and current, were performed in the simulations with the aim of characterizing the profiles, fluctuation level and statistics of the edge/SOL density and temperature. In addition changes with the length of the divertor leg were investigated with the aim to gain initial understanding of the regime of operation of the Super-X divertor which will be implemented on MAST-Upgrade. The results obtained qualitatively agree with experimental observations. In particular, a universal behaviour of the fluctuation statistics was found for disparate edge conditions. Furthermore, the density and temperature decay lengths were found to be inversely proportional to the plasma current and the edge temperature, while they are rather insensitive to the edge density (not to be confused with the line-averaged density).

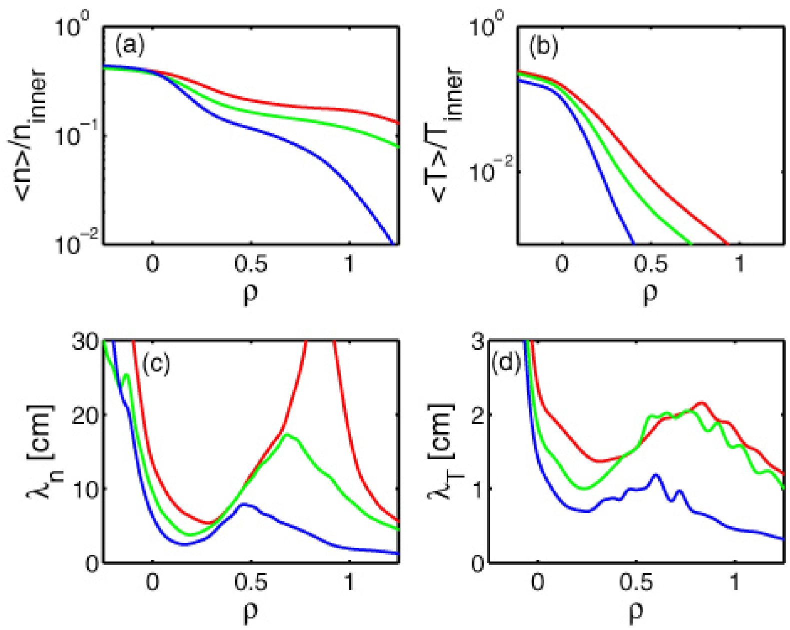

Figure 1. Current scan for MAST: Density (a) and temperature (b) profiles normalized to the value at the inner boundary. Density (c) and (d) temperature e-folding lengths associated. The blue, green and red lines represent q = 7 and $L_{//}$ = 10 m, q = 8.7 and $L_{//}$ = 12 m and q =10 and $L_{//}$ = 14 m, respectively. Larger q and $L_{//}$ represent smaller total currents (from F Militello et al [1])

1. F Militello et al Plasma Phys. Control. Fusion **54** 095011 (2012).

2.2.5 Measurement and simulation of intermittent characteristics in the boundary plasma of the EAST tokamak

N. Yan[1,3], A. H. Nielsen[1], G.S.Xu[2], V. Naulin[1], J. Juul Rasmussen[1], J.Madsen[1]
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Intermittent characteristics of turbulent fluctuations have been investigated in the edge and the scrape-off layer (SOL) by fast reciprocating Langmuir probe measurements in L mode plasma on the **E**xperimental **A**dvanced **S**uperconducting **T**okamak (EAST). Plasma structures, blobs and holes are observed and found to originate inside the edge shear layer [1]. Recently, the two dimensional ESEL code [2] is used to simulate the probe measurements on EAST [3]. Generally, we find a good agreement between the ESEL simulation and experimental results on EAST.

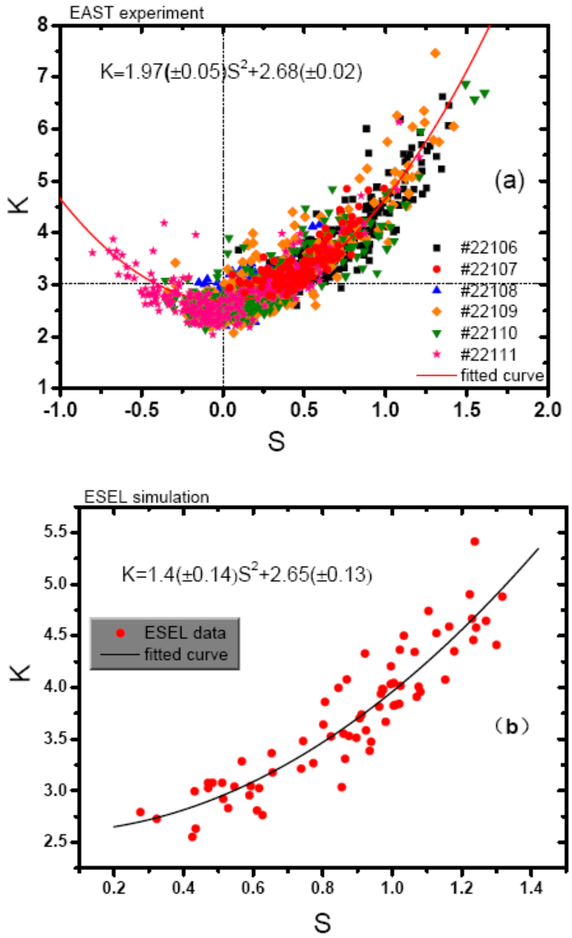

Figure 2.(a) Parabolic relationship between skewness and kurtosis of the PDF of ion saturation current in probe measurements on EAST (b) Parabolic relationship between skewness and kurtosis of the PDF of electron density in ESEL simulation.

In particular, the statistical properties of the turbulent fluctuations are investigated and depicted in Figure 2. The skewness and kurtosis of probability density function (PDF) of ion saturation current exhibits a parabolic relation across the edge shear layer on EAST (see Fig. 2 (a)). A similar parabolic curve is also obtained in the skewness and kurtosis of electron density fluctuations in ESEL output (see Fig. 2 (b)). Furthermore, the conditional averaged structures of blobs, PDF of turbulent density fluctuations, lifetime of blobs, and turbulent particle and energy transport in EAST experiments are compared to ESEL simulations. A good agreement between simulations and probe measurements is reached both on the equilibrium profiles and the statistical characteristics of turbulent fluctuations in the SOL. This strongly suggests that the interchange driven turbulence is the prime candidate for the generation of plasma coherent blob structures and intermittent transport in Edge/SOL plasma.

1. N. Yan et al, Plasma Sci. Technol. **13** 410 (2011)
2. O. E. Garcia et al Phys. Plasmas **12**, 062309 (2005)
3. N. Yan et al, submitted to Plasma Phys. Control. Fusion (2013)

2.2.6 2D fluid simulations of interchange turbulence with ion dynamics

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In this project we investigate a first principle global two-dimensional fluid model. The model is an extension of the so-called ESEL model [1,2]. It is a four field Braginskii model including generalized vorticity, density, electron and ion pressure equations. The generalized vorticity consist of the ExB vorticity as well as the ion diamagnetic vorticity. The collisional terms are obtained from first principal and include self-consistently the energy exchange between the four fields. The 2D geometry include both open and closed field lines and is located on the out-board mid plane of a Tokamak.

We have used typically L-mode parameters for medium size Tokamaks, as a first test of the model. We observe that simulation results are in good agreement with experimental results obtained from Langmuir probe measurements from both ASDEX Upgrade and EAST. The radial transport of plasma is very intermittent in SOL and has been shown both experimentally and numerically mainly to be carried by hot filaments, so-called blobs. Figure 3 shows the ejection of such a hot filament from the closed field line region, the plasma edge, into the scrape-off-layer - SOL. Electron and ion pressure, (b) and (c), are strongly correlated with the density, (a), as the ejection is a very fast process and the dissipation processes working on these fields are much slower. The radial movement of the filament is due to a dipolar structure of the electrical potential, clearly observed in (f). These results are somewhat in agreement what are observed in ESEL, which may be considered as a simplified version of HESEL in the limit of constant ion temperature. The ExB vorticity, (d) is concentrated to the position of the strongest ion pressure gradients, a feature not observed in ESEL. Being now able also to access the ion pressure allow estimates the energy content of the hot filaments and thus also the energy transfer to the outer wall.

The project is ongoing and a detailed comparison between numerical and experimental results will be performed in 2013. We plan to compare ion temperature fluctuations and profiles with ball-pen-probe measurements from ASDEX Upgrade and COMPASS. Also the H-mode regime will be addressed.

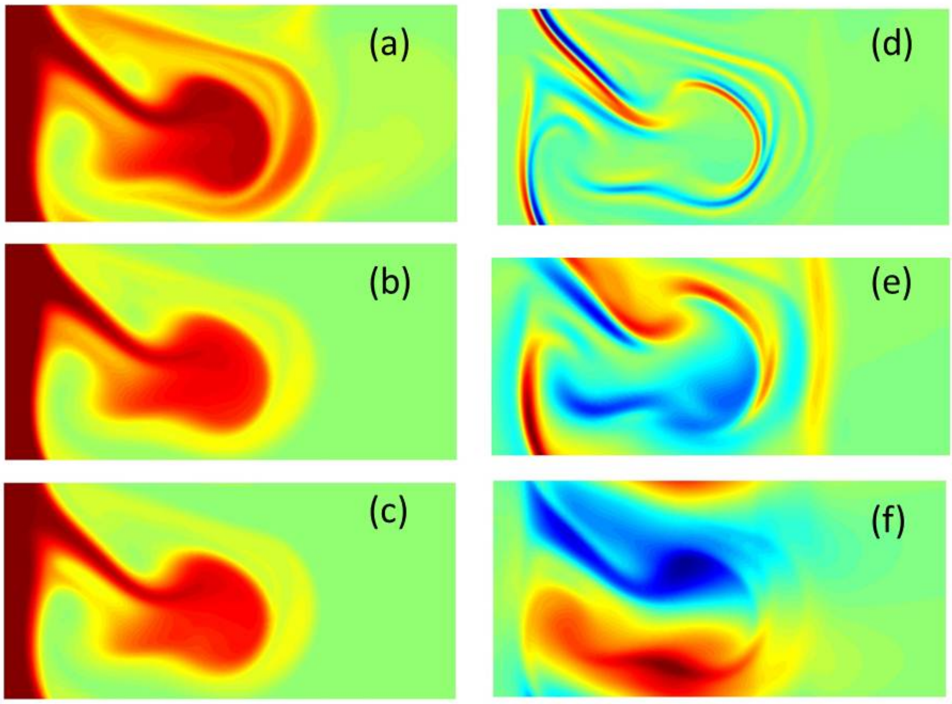

Figure 3. Snapshot of a blob being injected into the SOL. (a) Density, (b) ion pressure, (c) electron pressure, (d) ExB vorticity, (e) generalized vorticity and (f) electrical potential. Red designates positive values; while blue refer to negative values.

1. O E Garcia et al, Plasma Phys. Control. Fusion **48**, L1-L10 (2006).
2. F Militello et al, Plasma Phys. Control. Fusion **55**, 025005 (2013).

2.2.7 Numerical study of the feasibility of the thin layer approximation in models for plasma dynamics

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In numerical studies of the plasma in tokamaks, the thin-layer approximation is ubiquitous – essentially this approximation states that fluctuations in the density relative to the background is small and the scale length of the fluctuations are much smaller than the scale length of the background density. While good correspondence to experiments have been achieved with this approximation, it is unclear whether or not this approximation is still feasible in more extreme situations, such as ELM (Edge Localized Mode) events. The understanding of these events is of crucial importance for running the ITER device, where the significance of ELM events rises due to the larger size of the experiment and the higher plasma pressure, compared to present experiments.
In order to evaluate the feasibility of the approximation, we study the qualitative and quantitative error incurred by this approximation against known benchmarks. New numerical methods will be developed to solve the more advanced equations, which arise when the thin-layer approximation is abolished.

The conclusion of this study will be an evaluation of whether, and in which situations, this approximation is still warranted and useful.

2.2.8 Global gyrofluid model applicable to edge and scrape-off layer regions

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Gyrofluid models and fluid models in general, are widely applied in studies of basic plasma phenomena. The reduced dimensionality compared with more precise kinetic models provides much less computationally expensive tools to advance the understanding of plasma turbulence and the associated transport.

Non-linear simulations of the edge and scrape-off-layer (SOL) regions in magnetically confined fusion plasmas are particularly numerically demanding. These regions are characterized by fluctuation amplitudes that approach or even exceed unity. This especially holds true in the SOL which is dominated by intermittent transport [1] mainly carried by coherent structures created in the vicinity of the last closed flux surface and expelled into the empty SOL. In most situations a stationary equilibrium is never reached. Profiles are formed by the interplay between flows, magnetic topology, turbulence, and the conditions at the plasma edge. The characteristic time-scale for the evolution of profiles is in low-confinement (L-mode) operation an order of magnitude longer than the turbulence de-correlation time, but the two time-scales are comparable in the low to high (L-H) confinement transition and in edge-localized mode (ELM) events when large turbulent structures are expelled into the SOL. Furthermore, the characteristic gradient length-scale of the background profiles in the edge region becomes comparable with the poloidal gyroradius. Simulations of the edge and SOL region plasmas therefore require long time-series due to the disparate, but equally important, time-scales, high resolution due to strong gradient and large fluctuation amplitudes, and finally the usage fully non-linear models.

Previous gyrofluid models (e.g. [2–3]) were all partly linearized by splitting fluid fields into small amplitude fluctuation and stationary background parts. The models were based on the partly linearized delta-F version of the gyrokinetic model. Essentially, only the E × B-advection non-linearity was kept. In the Maxwell's equations polarization and magnetization effects were linearized, parallel advection was likewise linearized, and gyro-averages were everywhere evaluated using a fixed background thermal gyro-radius. These models are therefore not well-suited for studying edge/SOL turbulence.

We have derived a fully non-linear electromagnetic gyrofluid model consisting of continuity equations for the six first gyrofluid moments, a quasi-neutrality constraint, and the component governing the perturbed perpendicular magnetic field. The gyrofluid model is derived from the so-called full-F gyrokinetic model which is characterized by not splitting the distribution function into background and perturbed parts. The gyrokinetic Maxwell's equations are made tractable by taking terms associated with polarization and magnetization in the long wave-length (LWL) limit. All approximations are made at the gyrokinetic level. This includes the quasi-neutrality assumption and the neglect of parallel magnetization currents in Ampère's law. The gyrofluid continuity equations are obtained by approximating the gyrokinetic distribution function as a finite order Hermite-Laguerre polynomial. The gyro fluid model satisfies an exact energy conservation law. The energy invariant equals the gyrofluid moment of the corresponding full-F gyrokinetic energy invariant. The knowledge of an exact and physically sensible energy invariant is especially important for non-linear simulations because unintended violation of energy conservation can lead to sources or sinks of free energy.

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2.2.9 Gyrokinetic linearized Landau collision operator

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Gyrokinetic theory plays a central role in analytical and numerical investigations of low-frequency turbulence and the associated anomalous transport in magnetized laboratory plasmas and in nature. The theory eliminates the fast time scale associated with the fast cyclotron gyration from the equations of motion, and reduces the dimensionality of the kinetic equation from six to five. However, gyrokinetic theory was originally developed without taking collisions into account. Collisions strongly influence low-frequency turbulence and the associated transport, they determine the steady state, and they are responsible for entropy production, ultimately making processes irreversible. Accounting for collisions in gyro kinetic theory has therefore been the subject of significant research efforts, e.g. [1-4].

We have calculated the full electrostatic gyrokinetic linearized Landau collision operator including the equilibrium operator. The obtained operator is valid for arbitrary temperatures and masses, and finite Larmor radius effects are accounted for in all parts. The gyrokinetic operator is obtained by performing an explicit gyroaverage of the linearized Landau collision operator expressed in gyrocenter coordinates. The obtained equilibrium operator is responsible for energy exchange between species, and therefore plays an important role in the thermalization process. The collisional energy exchange rate between species a and b is proportional to the ratio of the corresponding masses. Therefore, the equilibrium operator is particularly important in multiple ion-species plasmas such as fusion and astrophysical plasmas. Furthermore, the equilibrium operator describes drag and diffusion of the magnetic field aligned component of the vorticity associated with the $E \times B$ drift. The corresponding terms have the same order of magnitude as the test- and field-particle operators. The equilibrium operator is therefore required in order to describe the influence of collisions on electrostatic turbulence and the associated transport correctly. Contrary to conventional wisdom, it is shown that the equilibrium operator must be retained even for like-particle collisions [5].

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2.2.10 Observation of current structures during edge localized modes in the EAST superconducting tokamak

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In H-mode with type-I edge localized modes (ELMs) on ASDEX Upgrade tokamak, it is observed that the magnetic-field-aligned ELM filaments carry considerable current during the propagation through the scrape-off layer (SOL). The current flows along the magnetic field lines and has a uni-directional nature [1]. To contribute the further understanding of the ELM structure, measurements of current filaments are performed by a pair of superposed triple magnetic coils separated radially by 1cm on the **E**xperimental **A**dvanced **S**uperconducting **T**okamak (EAST) [2]. The probe head stays in the limiter shadow to avoid overheating by the high injected heating power.

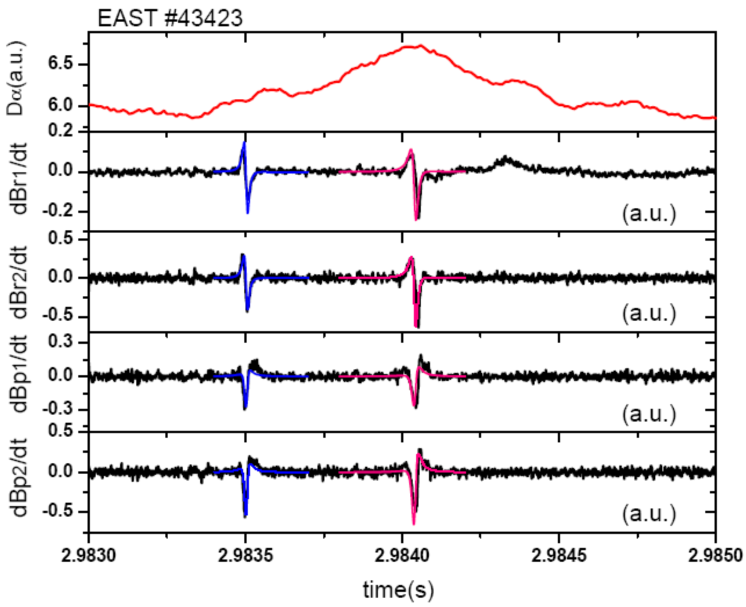

Figure 4. Time evolution of D_{α} signal, time derivative of the radial (dBr1/dt from outer coil and dBr2/dt from inner coil with respect to the plasma) and poloidal (dBp1/dt from outer coil and dBp2/dt from inner coil with respect to the plasmamagnetic field components from one ELM event. The blue curve and pink curve is the predictive magnetic perturbation from a monopolar current.

During one ELM event, we can detect 1-3 ‘current structures’. As is shown in Figure 4, two magnetic perturbations consecutively occur during one ELM cycle. It is worth commenting that transport is not localized as in the usual ELM process, which could be inferred from the broad D_{α} signal. The poloidal magnetic field fluctuation exhibits a detectable ‘right shoulder’ rather than a symmetric pattern, suggesting a poloidal propagation. Such magnetic perturbation can be well described by the time evolution of self-induced magnetic fluctuations from a monopolar current filament (blue line and pink line in Figure 4). The degree of incidence is deduced from the approaching match between the measurements and the monopolar current filaments mode as Vp/Vr ~75%±10% . Here, the Vr and Vp denote the radial and poloidal propagating velocities respectively. As can be seen from Figure 4, the signals from inner coils and outer coils evolve qualitatively in the same way. It suggests that the current filaments does not sweep across the region between the inner and outer coils, otherwise the signals from inner coils and outer coils will be opposite in sign. Furthermore, the signals from the inner coils are stronger than from outer coils. Thus, the current filaments are identified propagating in the region further inside than the inner coils. The further study of the movement of current structures is assisted by using the Mirnov coil array on EAST. The poloidal propagating velocity of current filaments amounts to 2km/s, pointing against the ion B ×▽B direction, and is propagating in the electron diamagnetic drift direction in the experiment. The current filament sweeps across the magnetic coils with a perpendicular distance $d_{\perp}$~1.6 cm and is carrying a current I_f ~15A in the scrape-off layer (SOL) These results provide the strong evidence the ELM filaments carry a monopolar current at their propagation in the SOL in EAST [3].

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2.2.11 A simple mechanism for rotation reversal in ohmic L modes

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Rotation of L-mode plasmas is a complex issue, with many different effects having been observed [1]. In general the L-mode rotation behaviour, unless there is a strong external source of momentum, is far less well understood than the rotation of H-mode discharges. H-mode rotation seems to be more robust, either because the H-mode is usually achieved at high heating power including external momentum input by beams or due to high rotation at the pedestal, which allows for a robust boundary condition for the rotation.

For plasmas with no obvious external momentum source spontaneous spin up poses a problem to transport theory, since without initial rotation velocity or seed flow the momentum flux is zero everywhere and so no build-up of rotation, neither of net plasma rotation nor of differential plasma rotation, can take place.

While the most prominent source of plasma toroidal momentum is the tangential injection of neutral beams, there are several effects which allow for momentum input from the edge. None of these mechanisms can so far explain the observed rapid transition from co- to counter-rotation observed in Alcator C Mod and other devices when the edge density is increased in ohmic L-mode plasmas.

It has been suggested that turbulent momentum transport can lead to differential transport of positive and negative momentum fluctuations, thus leading to a differential rotation source, which can lead to spin-up. This local momentum flux, which is generated in the plasma itself, cannot be expressed in terms of a transport term as it is neither proportional to the gradient of the velocity profile, e.i., to be expressed as a diffusion like term, nor to the velocity itself, e.i., a convective or pinch velocity like term. Its appearance in a transport equation is like a localised source.

Several experiments have tried to measure this effect, but it is notoriously difficult to separate from other sources of momentum and moreover only during spin up and spin down of the plasma it leads to measurable momentum fluxes out of the plasma. This Residual Stress – RS - exerts a zero net torque on the plasma but can create nonzero momentum fluxes. It is usually not captured by transport models.

We have demonstrated in a transport model accounting for turbulence spreading and including the combined transport of particles hear and momentum that RS can lead to rotation reversal in ohmic L-mode plasmas [2].

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2.2.12 Bifurcation Analysis of Low-Dimensional Models for L-H mode transition in magnetically confined plasmas

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The confinement of particles and energy and thereby the performance of a fusion reactor is strongly influenced by turbulent transport. The transport is generally increasing as the input power is ramped up until a threshold power, where the edge heat flux reaches a critical value. Then confinement is drastically improved and the plasma enters a state of high confinement, the so-called H – mode, contrasting the low confinement state - the L-mode. The transition from L to H mode is routinely observed and controlled for more than three decades, but still lacks a first principles explanation. It is thus one of the high-priority topics of fusion research.

The formation of a transport barrier at the edge as the transition occurs is believed to be connected with the appearance of large scale shear flows. Significant insight into the L-H transition dynamics has been gained from models of the predator prey type, basically describing the self-regulation of the turbulence by means of the shear flow that is fed by the turbulence. These models are in the simplest form 0-dimensional in space, i.e., coupled ordinary first order differential equations for the development of the turbulence and the flow (see, e.g., ref. 1).

We have performed a detailed bifurcation analysis of predator prey type models for the L-H transition exemplified by the 3-field model by Kim and Diamond [1]. The model contains three equilibrium points that can be stable. These correspond to a low confinement mode (L), a transient mode (T) (also termed the dithering phase, I-mode, see e.g. [2]) and a high confinement mode (H). As the input power is raised the model either shows a L-T-H transition with the oscillating T-mode between the L- and H-mode, or the transition occurs without the transient mode. The stability of all equilibrium points is determined and a bifurcation analysis is carried out. The model is found to contain a slow and a fast feedback loop and a reduced model consisting of the full model restricted to the flow on the critical manifold is investigated. The reduced model is found to contain all the same dynamical features as the full model.

A new essential model of the L-H transition is proposed and analyzed. The proposed model is mathematically simpler than the other model of the L-H transition, but it still contains the same dynamics.

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2.2.13 Participation in C28 at JET

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In 2011 Morten Stejner was on secondment at JET during C29 from January 16 to February 10. At JET he participated in work within the electron kinetics group to validate data from electron temperature diagnostics based on incoherent Thomson scattering measurements and electron cyclotron emission spectroscopy (the KE3, KE11, KK1 and KK3 diagnostics). Measurements with these diagnostics had previously shown discrepancies between the inferred electron temperatures, and the origin of these discrepancies was investigated based on both historical data and more recent data from C28 and C29 incorporating updated calibrations for both types of diagnostics. This work was continued from another secondment period in late 2011.

In February Volker Naulin visited JET for a secondment. His task was to participate in ELM and pedestal physics experiments and to work towards the density modulation parasitic experiment. Simulations with a turbulence code concerning the influence of poloidal location of gas-fuelling were initiated and potential measurements and diagnostics, specifically usage of probe data was discussed in collaboration with the Austrian Association.

2.3 Diagnosing fusion plasmas by millimetre wave collective Thomson scattering

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Millimetre waves, corresponding to frequencies in the 100 GHz range, permit probing and imaging on the centimetre scale and transmission of signals with bandwidths in excess of 10 GHz. Coherent sources are now available from the micro- to the single megawatt range.

In the world of fusion, millimetre waves are used extensively both as a diagnostic tool and for heating and manipulating the plasma locally as well as globally. Central to achieving these objectives is the fact that millimetre waves, like laser light, can be projected in narrow focused beams, but unlike laser light, the millimetre waves can interact more strongly with the plasma.

At DTU, the millimetre wave collective Thomson scattering (CTS) diagnostic is developed and exploited with two diagnostic aims: for measuring the velocity distribution of confined energetic ions and for measuring the isotope composition (the so-called fuel ion ratio in a D-T fusion reactor) in fusion plasmas. The measurements are spatially localized with a resolution on the centimetre scale and have a temporal resolution on the millisecond scale.

The most energetic ions are the result of fusion reactions and auxiliary heating. Their interaction with the bulk plasma is the main mechanism by which the fusion plasmas reach and sustain the high temperatures of 100-200 million degrees Kelvin required for fusion. The considerable energy associated with the fast ions can also drive turbulence and cause instabilities in the plasma, and hence degrade the confinement of the plasma and of the fast ions themselves. Understanding and controlling the dynamics of fast ions are central tasks in the development of fusion energy and one of the main research topics for the next large fusion facility, ITER. It is a task we seek to contribute to by developing and exploiting the unique diagnostic capability of millimetre wave based collective Thomson scattering (CTS). The importance of the fast-ion CTS diagnostic was further underlined by the fact that in 2008 the front-end of a fast ion CTS diagnostic system was enabled in the new ITER baseline design. In 2009 the updated ITER Baseline Design was finally approved by the ITER Council. DTU has developed the feasibility study and preliminary design of the ITER CTS diagnostic under EFDA task agreements. The work on CTS at ASDEX Upgrade and formerly TEXTOR should be seen in the context of maturing the diagnostic for future use on ITER.

In addition to the use of CTS to diagnose fast ions, the diagnostic technique may also be used to measure the fuel ion ratio in a fusion plasma – both temporally and spatially resolved. This can be done by choosing particular scattering geometries and measure the effect of ion Bernstein waves and ion cyclotron motion on the CTS spectrum. This novel use of CTS is welcomed by the community since the measurement of the fuel ion ratio in ITER is a challenge with the current diagnostic set.

The group has developed and implemented CTS diagnostic systems at the TEXTOR and ASDEX Upgrade tokamaks, which are located at the Research Centre Jülich and at the Max-Planck Institute for Plasma Physics in Garching, both in Germany. In the last year, a new milestone for CTS has been reached at ASDEX Upgrade where a novel background subtraction technique has paved the way for a reliable evaluation of the scattering spectra. The dynamics of both the bulk- and fast-ions can now be diagnosed and the system is ready to contribute to the general physics exploration at ASDEX Upgrade. The activities on ASDEX Upgrade are described in sections 2.3.2 - 2.3.9.

The operation of the TEXTOR CTS diagnostic was concluded in 2010 as the gyrotron used as a source for the CTS was decommissioned. However, results of the previous campaigns still give rise to new publications as the data are being analyzed. The new results from TEXTOR deal primarily with measurements of bulk ion properties such as temperature drift velocity, and fuel ion composition, as described in sections 2.3.10-2.3.11. The operation of the CTS diagnostic at TEXTOR was conducted in collaboration with the TEC[1] consortium.

The activities of the CTS group also involved development of new components, key to the CTS receiver as well as other millimeter wave diagnostics. During 2012 this has particularly included the design of new universal polarizers described in Section 2.3.13 as well as components in the quasi-optical transmission line at ASDEX Upgrade as described in sections 2.3.2 and 2.3.14.

Finally, work on integrating experimental information from several fast ion diagnostics has been performed. The results of these efforts are given in Section 2.3.12

2.3.1 EFDA tasks in 2012 for the DTU CTS group

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During 2012, the CTS group has participated in the following EFDA tasks:

- **WP-11-DIA-01-01-01**: Experiments on confined fast particles.
- **WP-11-DIA-01-03-01**: Experiments of IBW modulations for fuel ion ratio measurement and purchase of a fast digitizer.
- **WP12-IPH-A04-1-15**: Demonstration and benchmarking of plasma rotation measurements by CTS in AUG.

1 TEC: The Trilateral Euregio Cluster, comprising Association EURATOM-Forschungszentrum Jülich GmbH, Institut für Plasmaphysik, Jülich, Germany; Association EURATOM-FOM, Institute for Plasma Physics, Rijnhuizen, The Netherlands; and Association EURATOM-ERM/KMS, Belgium.

- **WP12-IPH-A09-2-03**: Multi-diagnostic measurements of fast ions on ASDEX Upgrade.
- **WP12-IPH-A10-2-08**: Impact of gas fuelling on core plasma composition by Collective Thomson scattering.

2.3.2 Status on ASDEX Upgrade CTS receivers

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Two CTS receivers are presently installed and operational at ASDEX Upgrade. One receiver is located in the gyrotron hall (receiver one) and is installed on the transmission line of gyrotron 6. The second CTS receiver (receiver two) is presently installed on the transmission line of gyrotron 5 which is not used for ECRH during the second half of 2012 and the beginning of 2013. Receiver two is located in the newly constructed CTS room and has a flexible design which allows it to be moved to different ECRH transmission lines depending on the gyrotron availability and physics program. A microwave periscope was constructed and installed in 2012 to make the coupling of the second receiver to the ECRH transmission flexible. A CATIA drawing of the second receiver and the coupling to the ECRH2 transmission lines is shown in Figure 5. A number of commissioning development tasks were also completed in 2012. Some of these tasks are described in sections 2.3.4 - 2.3.7.

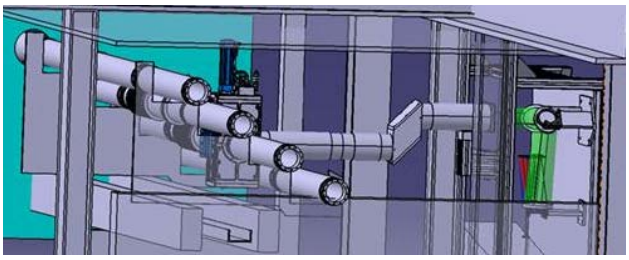

Figure 5a. Example of receiver two coupling to ECRH2 waveguides using microwave periscope and waveguide switch. RIGHT: CTS optical transmission line and receiver. LEFT ECRH2 waveguides. The RF switch seen on the third waveguide from the top allows the CTS receiver to couple to the ECRH transmission line.

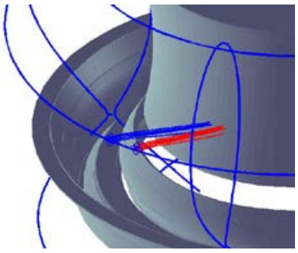

Figure 5b: Example of beam patterns in the tokamak for receiver one (red) and receiver two (blue) in the present setup.

2.3.3 Adjustment of gyrotron operation parameters

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Gyrotron 5 on ASDEX Upgrade has previously been used as probe beam in CTS experiments. However, this gyrotron has been unavailable during the second half of 2012 and during the first part of 2013. This means that a significant amount of time has been used to prepare a new gyrotron for CTS probe beam. Both gyrotrons 7 and 8 have been commissioned for CTS experiments. One important step in the gyrotron commissioning is the adjustment of the notch filters to match the gyrotron frequency development. The notch filter tuning is described in section 2.3.8. The frequencies of both gyrotrons were measured. The gyrotron beams were launched into a dummy load while the two CTS receivers observed the stray radiation. During these tests, it was confirmed that the main part of the gyrotron stray radiation was attenuated by the improved notch filters in both receivers. In a few cases spurious signal was observed in one of the receivers at a frequency of about 800 MHz from the main gyrotron frequency on both sides of the spectrum.

2.3.4 Dual receiver technique (passive measurements)

S. K. Nielsen, J. Holm, M. Jessen, F. Leipold M. Stejner, S. B. Korsholm, M. Salewski, P. K. Michelsen

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The second receiver has been commissioned in 2012 and tests with the receiver installed on ECRH transmission lines 7 and 5 have been performed. With receiver two installed in ECRH transmission 5, is it possible to obtain identical beam patterns in the poloidal cross section for both CTS receivers. The ECE background for the two receivers has been compared for different launcher settings and has shown good agreement. An example of such a time trace from both receivers during a discharge with moving antenna angles as a function of time is shown in Figure 6a and the ray tracing from two time points during this time trace is shown in Figure 6b. Both receivers were set to accept O-mode. The relative time evolution of the two time traces agrees remarkable well which confirms both the alignment of the two systems and the polarizer settings.

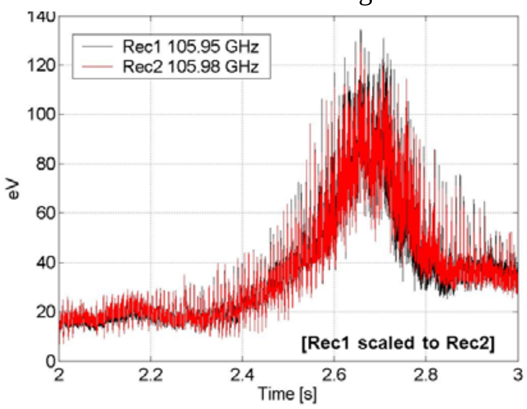

Figure 6a. Time traces of raw signal in a channel at 105.95 GHz in receiver one and a channel at 105.98 GHz in receiver two.

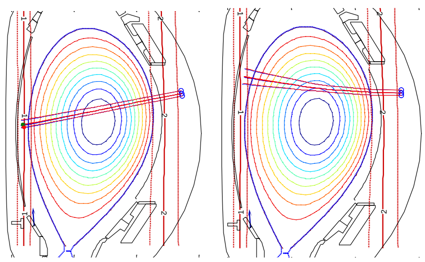

Figure 6b: Raytracing for O-mode 105 GHz for CTS receiver beams at t = 2.7s (LEFT) and t = 3.0 s (RIGHT).

2.3.5 Dual receiver technique (active measurements)

S. K. Nielsen, J. Holm, M. Jessen, F. Leipold M. Stejner, S. B. Korsholm, M. Salewski, P. K. Michelsen

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In CTS discharges we frequently observe signal which is not expected to originate from the scattering overlap – so-called secondary emission. In order to study these signals we have operated the receivers in an active view/passive view setup such that one receiver had an overlap with the gyrotron beam (active view) and the other receiver beam (passive view) had the same launch angles as the active view, just without overlap. This technique has demonstrated that it is possible to subtract the unexpected signals when the signal level is comparable to the expected CTS signals levels. In Figure 7 the time traces of the raw signal in two channels at similar frequencies from the active and passive view is shown for a so-called overlap sweep. At the time of overlap between the active view and the gyrotron beam a clear increase in the active signal (red minus blue) is observed while no increase is observed in the passive view. A close-up of the beginning of the time period, where none of the receiver views cross the gyrotron beam, is shown in the bottom. Good agreement between the signals from the two receivers is found which illustrates the basis of the subtraction principle.

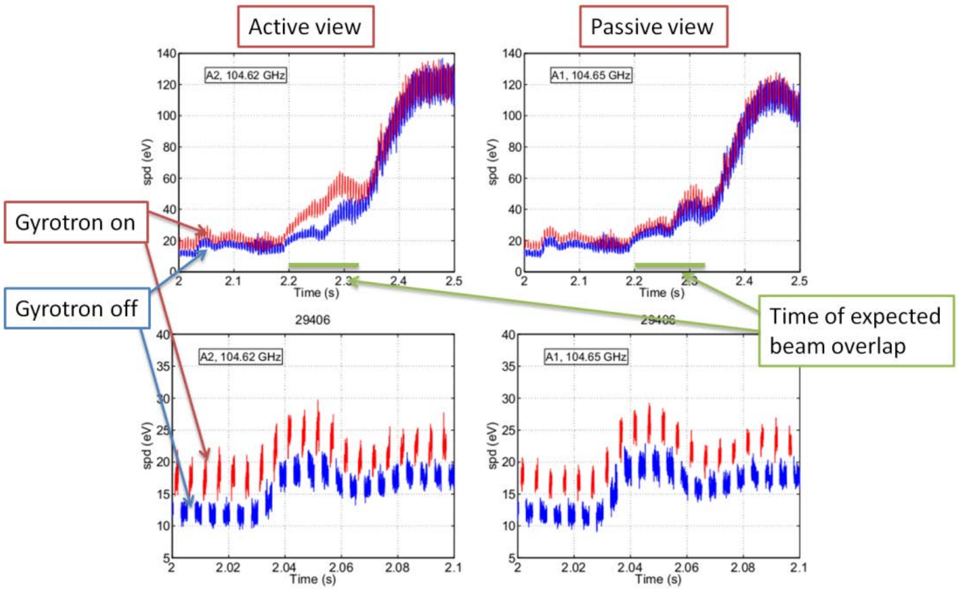

Figure 7. Time traces of raw signal in two channels at similar frequencies in the receiver with an active view (left) and a passive view (right.). The red time traces indicate periods when the gyrotron is switch on and the blue time traces indicate periods when the gyrotron is switch off. The active receiver view crosses the gyroptron beam at t=2.25 s. At this time a clear increase in the active view.

The spectrum at the time of the overlap between the active receiver view and the gyrotron is shown in Figure 8. When the background effect from the passive receiver is not taken into account, a signal is present at frequencies between 102 and 104 GHz. After the background is subtracted, using the dual receiver technique, the measured spectrum agrees well with the theoretical CTS spectrum.

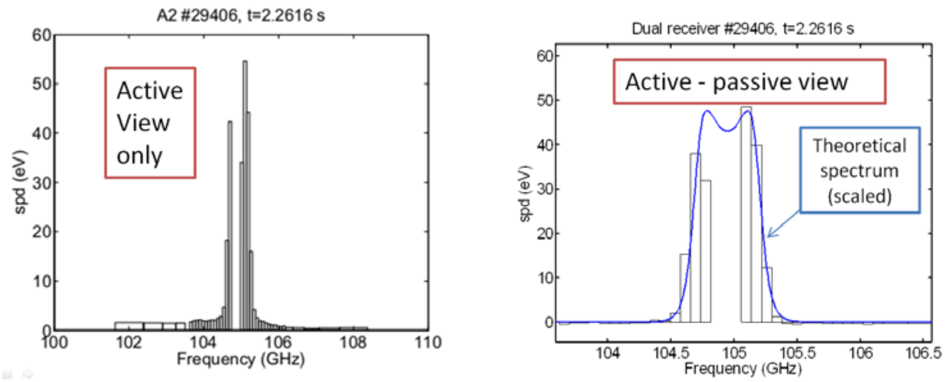

Figure 8. Example of measured spectrum with one receiver only (left) and with the Dual receiver principle used for background subtraction (right). A theoretical CTS spectrum is plotted on top of the measurements (blue).

Overlap sweeps have been performed in time periods with and without neutral beam injection. These spectra are compared in Figure 9. During no neutral beam injection the plasma stays in L-mode and when neutral beams are injected, the plasma goes into H-mode. The CTS spectra obtained in L-mode are significantly narrower than the spectra from H-mode plasmas. This is partly due to the higher ion temperatures in the H-mode plasmas but could also be due to the fast-ion contribution which we expect to be present in the CTS spectra for frequencies above 105.5 GHz and for frequencies below 104.5 GHz.

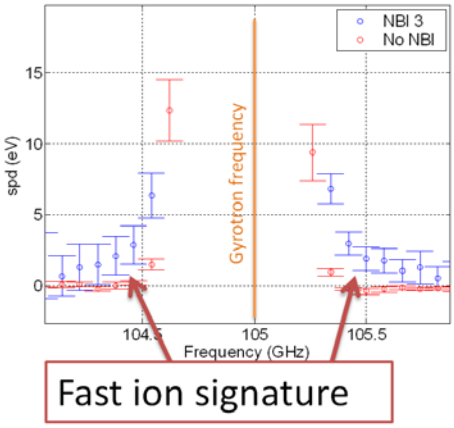

Figure 9. Spectra at maximum overlap at a time without fast ions in the plasma (red) and with fast ions in the plasma (blue). The wings in the blue spectra indicate that fast-ion information is present in the CTS spectra.

2.3.6 CTS receiver upgrade with fast digitizer and calibration

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In order to study ion cyclotron spectra in the CTS spectra one of the CTS receivers at AUG has been equipped with a fast digitizer. The frequency separation between individual peaks in the ion cyclotron structure is on the order of 20-40 MHz. The ion cyclotron structure can therefore not be resolved with the standard filter bank setup used in fast-ion CTS measurements, which provides a frequency resolution of roughly 100 MHz. In order to achieve the required frequency resolution the CTS system at AUG was upgraded to include a system for direct digitization and Fourier analysis of the CTS signal. This system, illustrated in Figure 10, includes an additional mixing stage with a band pass filter and a low pass filter selecting the appropriate frequency range. The down converted signal is passed to a fast digitizer: the NI PXIe-5186, 5 GHz, 12.5 GS/s, 8-Bit digitizer. With this setup the CTS spectrum can now be resolved with a frequency resolution below 1 MHz in a 2 GHz wide frequency band centred on the probing frequency.

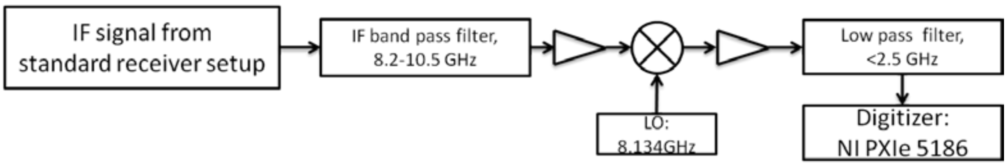

Figure 10. A block diagram illustrating the additional mixing stage and fast digitizer now included in the CTS receiver for measurements with high frequency resolution through direct digitization and Fourier analysis of the CTS signal.

The CTS system on AUG now includes two separate CTS receivers (the receiver previously used on TEXTOR has been moved to AUG). Both receivers were equipped with an additional mixing stage and appropriate band pass filters. Only one NI PXIe-5186 digitizer is available, but it can then flexibly be moved to either of the two receivers as needed.

It is necessary to perform an accurate absolute calibration of the upgraded CTS receivers in order to gain a useful CTS signal, and some effort was devoted to development of appropriate calibration techniques. Two different techniques were tested:

- Cross calibration to simultaneous ECE measurements with the standard filter bank. Assuming the ECE background measured by the CTS receiver to be spectrally smooth, the fast digitizer system can be cross calibrated to the standard filter bank setup. This is a simple and convenient method of calibration, but it may not be as accurate as required, and it will not work if the ECE background contains spectral features not resolved by the filter bank.

- Hot/cold source calibration. An absolute calibration can be performed through measurements of the spectral power density emitted by different sources with known spectral properties. Here we use two black body sources: one at room temperature and one cooled with liquid nitrogen. This method does not rely on assumptions like those of the cross calibration method, and it is in principle more accurate. However, long integration times resulting in large amounts of data are needed to achieve the required accuracy. The method is therefore time-consuming to employ.

In the initial experiments reported below the cross calibration method was used, as a technique had not yet been developed to handle the large amounts of data resulting from the hot/cold source method. Subsequently, techniques were developed to perform calibrations with the hot/cold source method, which will likely be the preferred option for future experiments. Figure 11 shows an example of a calibration curve measured with this technique.

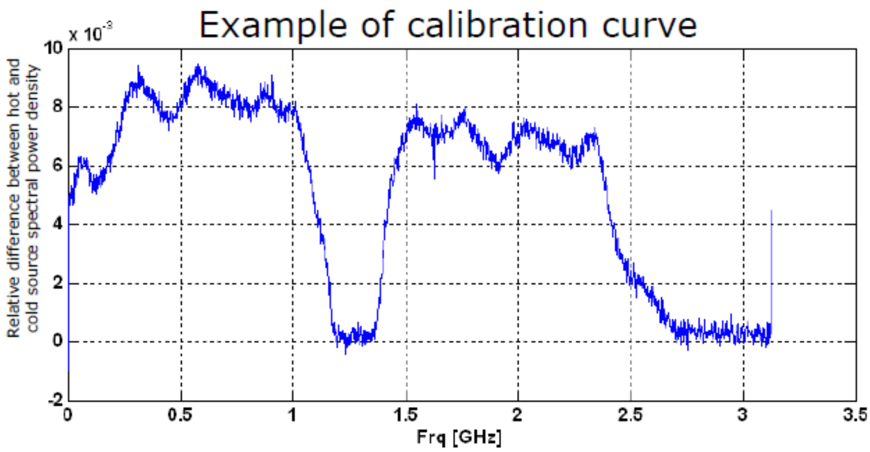

Figure 11. An example of results from a hot/cold source calibration. The figure shows the relative difference between the measured spectral power density from black body sources at room temperature and cooled with liquid nitrogen.

2.3.7 First measurements of ion cyclotron structures in CTS spectra on AUG

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The first data were taken with the modified CTS system in discharges 27827 and 28296. The goal of discharge 27827 was to test several different scattering geometries to find one appropriate for ICS measurements. Based on results from that discharge a scattering geometry was selected and used for subsequent measurements in discharge 28296. That discharge contained 4 different phases during which measurements were taken:

- An overlap sweep where the receiver beam was swept past the probe beam to verify the location of the overlap and the presence of ICS in the CTS spectrum.
- A reference measurement in the centre of the plasma with no auxiliary heating.
- A measurement after a 4He gas puff to test the sensitivity of the spectrum to 4He gas fuelling
- A neutral beam heated phase in order to benchmark against CXRS measurements, to perform the first such measurements in H-mode and to change the bulk plasma rotation.

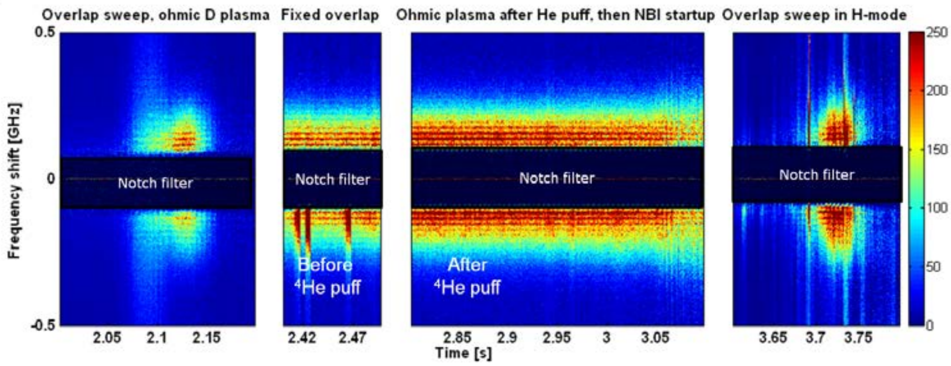

Figure 12. Spectrogram of the CTS measurements taken in AUG discharge 28296. ICS can be seen as horizontal lines in the frequency range just outside the region covered by the notch filter installed in the CTS receiver. The plasma was fuelled with helium from t=2.6-2.8 s (just before the third frame and NBI was turned on at t=2.95 s.

Figure 12 shows a spectrogram of the data taken in discharge 28296. The ICS is seen as nearly horizontal bands at frequencies just outside the frequency range covered by the notch filters (installed in the CTS receiver to protect the electronics against stray probing radiation). During the two overlap sweeps in L- and in H-mode the CTS spectrum, including the ICS, appears and disappears with the beam overlap as expected.

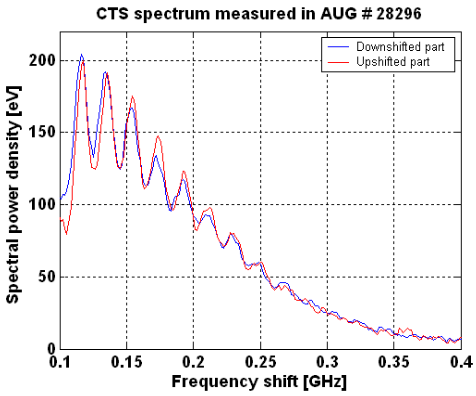

Figure 13. CTS spectrum measured with φ = 87° during an Ohmic phase in AUG discharge 28296. The downshifted part of the spectrum (blue line) is mapped to the positive frequency shift axis. Peaks in the ion cyclotron structure appear shifted by 1.4 MHz.

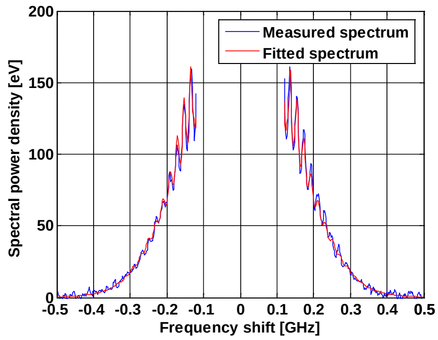

Figure 14. An example of results for least squares fitting of the measured spectra with a theoretical model for CTS.

Figure 13 shows an example of a spectrum measured in these experiments during the Ohmic phase in discharge 28296. The spectrum shows an asymmetry corresponding to a Doppler shift of 1.4 MHz. Figure 14 shows results from a least squares fit with a theoretical model for CTS to the measured spectrum. The fitted spectrum reproduces the measured spectrum with reasonable accuracy and indicates a rotation velocity of 16 km/s. After NBI turn-on the inferred rotation velocity gradually drops to around zero during the overlap scan in the H-mode phase. Unfortunately the CXRS data for this discharge were corrupted by gas fuelling from a valve near the CXRS spectrometer, so a comparison with CXRS data is not possible. While the rotation velocities inferred from the fits appear to be robust, it may, however, also be noted that the fits are not very accurate in the up-shifted part of the spectrum. This is most likely due to inaccuracies in the calibration of the data, which should be addressed and improved in future experiments using the cross calibration method discussed above.

- Results from discharges 27827 and 28296 thus demonstrate that:
- It is now possible to measure temporally resolved CTS spectra with ion cyclotron structure in AUG.
- The measured spectra correspond well to theoretical expectations and for some plasma conditions contain a Doppler shift consistent with a rotation velocity around 16 km/s.
- The spectra can be fitted with a theoretical model for CTS, but further improvements in calibration accuracy would be beneficial for reliable plasma rotation measurements.

2.3.8 Notch filter adjustment

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Both 105 GHz Notch filters and 140 GHz notch filters have been adjusted at DTU in 2012. The 105 GHz notch filters where adjusted to be compatible with the new gyrotrons used for probing beam during CTS experiments. The filters were adjusted by using a

Network analyser and the results are displayed in Figure 15. The main modification was widening the filters to cover frequencies in the range between 105.00 and 105.05 GHz. Three 140 GHz filters where also adjusted to match the 140 GHz gyrotrons operating at ASDEX Upgrade.

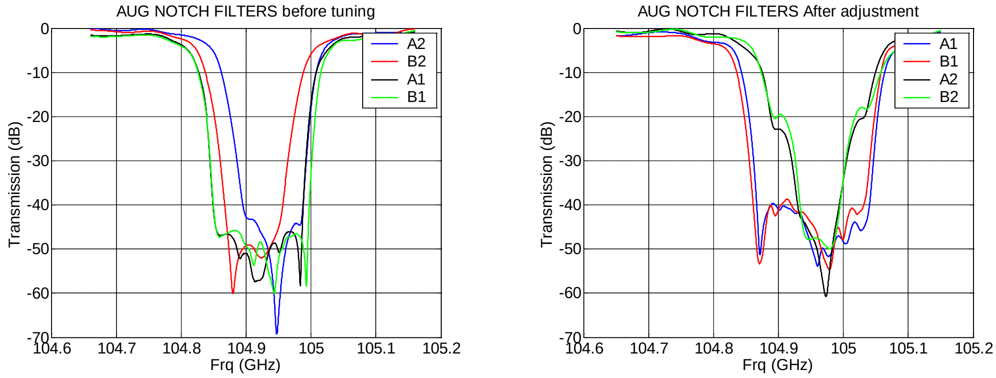

Figure 15. 105 GHz notch filter curves before and after tuning.

2.3.9 Scattering and passive measurements at 140 GHz

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Receiver two has in a limited period during 2012 been operating at a frequency range around 140 GHz. This is motivated by both the possibility to do real time suppression of neo-classical tearing modes, and scattering experiments using a 140 GHz gyrotron as probe. In order to make the receiver compatible with 140 GHz operating, the front-end has been replaced with new notch filters, a new high-pass filter, a new mixer and a new local oscillator. The ECE radiation from the centre of AUG has been measured during a number of discharges and the analysis of these measurements will take place in 2013.

2.3.10 Measurements of ion temperature and plasma composition across the plasma profile by collective Thomson scattering in neutral beam heated discharges at TEXTOR

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As discussed elsewhere in this report we developed techniques to enable temporally resolved measurements of ion cyclotron structures (ICS) in CTS spectra from which information about the plasma composition and ion temperature can be inferred [1,2]. In addition we here report work to exploit these techniques to develop a method to perform profile measurements by gradually moving the scattering volume across the outer midplane of the plasma. Assuming steady plasma conditions during the scan this technique can provide measurements of the plasma composition and ion temperature profile. Results for the ion temperature were compared with ion temperatures measured by active charge exchange recombination spectroscopy.

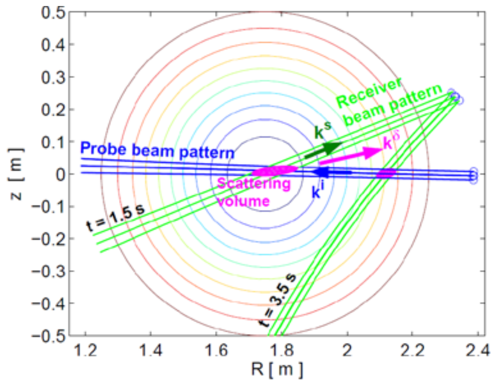

Figure 16. A poloidal map illustrating the radial sweep of the CTS scattering volume in TEXTOR discharge 111795. Beam patterns representing the incident and received scattered radiation are shown along with the relevant wave vectors (not to scale). The scattering volume is shown as an ellipsoid at the intersection of the probe and receiver beams, and magnetic flux surfaces are indicated by circular contours. The scattering volume can be moved along the probe beam by adjusting the orientation of the receiver mirror.

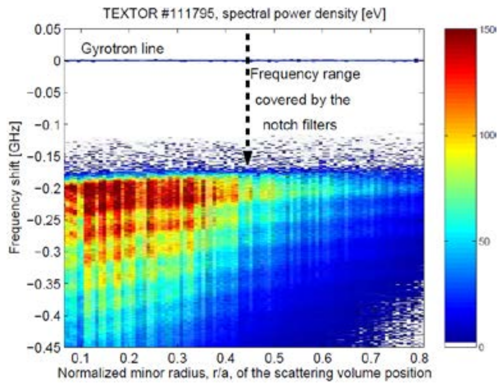

Figure 17. A spectrogram showing the CTS spectra recorded during a radial sweep in discharge 111795. As the scattering volume is moved the CTS spectrum becomes more narrow due to the lover temperature and density in the scattering volume. Similarly, the ion cyclotron structure is here seen as bands with an inclination corresponding to the changing magnetic field strength, which causes the peaks to move towards smaller absolute frequency shift.

As illustrated in Figure 16 the CTS measurement volume can be moved radially by moving the receiver mirror to scan the receiver beam along the probe beam, and a scattering geometry with $\angle(\mathbf{k}^\delta,\mathbf{B}) \simeq 90°$ can be maintained throughout the scan due to the near radial injection angle of the probe beam. Figure 17 shows a spectrogram obtained with this technique in TEXTOR # 111795. The scattering volume was moved gradually from R = 1.78 m (near the plasma center) at t = 1.5 s to R = 2.12 m at t = 3.5 s. As the scattering volume is moved towards the outboard plasma edge, the local magnetic field strength, plasma density and temperature decrease, and the CTS spectrum correspondingly narrows. The ion cyclotron structure in the CTS spectrum is seen in the spectrogram as almost horizontal bands which gradually move towards smaller absolute frequency shift as the local magnetic field strength in the scattering volume decreases. Qualitatively, the observed behavior of the CTS spectrum during the radial scan therefore corresponds closely to expectations. Figure 18 shows a comparison of the ion temperature profile inferred from the CTS spectra in Figure 17 to ion temperatures measured by active CXRS and electron temperatures measured by ECE spectroscopy.

Figure 19 compares ion temperature measurements by CTS and CXRS in the plasma core for a broader range of neutral beam heated discharges. The temperatures are in reasonable agreement although there is indication of a small, but systematic, difference for discharges with central electron densities below $5{*}10^{19}$ m^{-3}. The CXRS measurements are based on line emission from carbon impurities while the CTS measurements are sensitive to the bulk ion (hydrogen and deuterium) temperatures. The measurements could therefore be interpreted as indicating a difference in temperature between these ion species, which would be in general agreement with results of earlier work to compare carbon and deuterium based CXRS ion temperature measurements [3].

Results of this work have been submitted to PPCF [4] and are expected to be published in 2013.

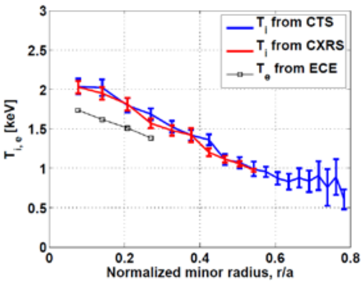

Figure 18. Results of ion temperature measurements by CXRS and CTS in discharge 111795 as well as the electron temperature measured by ECE spectroscopy in the plasma core.

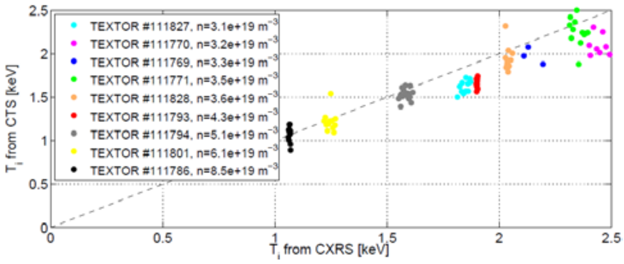

Figure 19. Comparison of ion temperatures measured by CTS to ion temperatures measured by CXRS for a number of discharges with neutral beam heating and CTS measurements near the plasma center. The central electron density for each discharge is given in the legend. The ion temperatures measured by CXRS are systematically higher than those from the CTS measurements except in discharges 111786, 111794 and 111801 where the electron density was within the range where carbon and deuterium based CXRS measurements agree.

1. M. Stejner, S. B. Korsholm, S. K. Nielsen, M. Salewski, H. Bindslev, F. Leipold, P. K. Michelsen, F. Meo, D. Moseev, A. Bürger, M. Kantor, and M. de Baar, The Review of Scientific Instruments 83, 10E307 (2012).
2. M. Stejner, S. B. Korsholm, S. K. Nielsen, M. Salewski, H. Bindslev, S. Brezinsek, V. Furtula, F. Leipold, P. K. Michelsen, F. Meo, D. Moseev, A. Bürger, M. Kantor, and M. de Baar, Plasma Physics and Controlled Fusion 54, 015008 (2012).
3. E. Busche, H. Euringer, and R. Jaspers, Plasma Physics and Controlled Fusion 39, 1327–1338 (1997).
4. M. Stejner, M. Salewski, S. B. Korsholm, H. Bindslev, E. Delabie, F. Leipold, F. Meo, P. K. Michelsen, D. Moseev, S. K. Nielsen, A. Bürger, and M. R. de Baar, Submitted to PPCF (2013).

2.3.11 Temporally resolved plasma composition measurements by collective Thomson scattering in TEXTOR

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As reported in the 2011 Annual Report, fusion plasma composition measurements by collective Thomson Scattering (CTS) were demonstrated in proof-of-principle measurements in TEXTOR[1,2]. Such measurements rely on the ability to resolve and interpret ion cyclotron structure (ICS) in CTS spectra. Here we report work to extend these techniques to enable temporally resolved plasma composition measurements by CTS in TEXTOR.

The acquisition technique used to resolve ICS in CTS spectra relies on an oscilloscope with a very high sample rate (at least a few 10^9 samples/s) to achieve the required frequency resolution. The limited memory on the oscilloscope then constrains the total measurement time to 50 ms. Measurements over long time spans therefore requires careful management of the available memory.

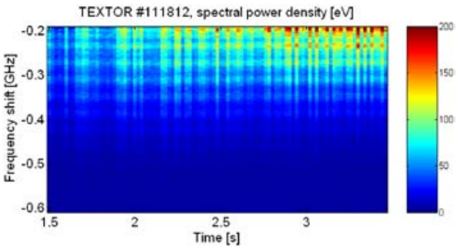

Figure 20. The CTS spectral power density measured during a density scan in discharge 111812. The ion cyclotron structure can be seen as horizontal bands of elevated signal intensity. The spectral power density grows and the ion cyclotron structure becomes more prominent as the density increases with time.

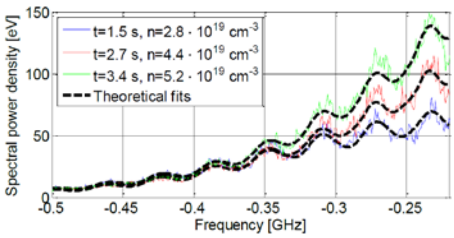

Figure 21. Examples of fits to CTS spectra measured in discharge 111812. From the bottom, the spectra are plotted in order of increasing time and density. The fits reproduce the spectra with reasonable accuracy: residuals are within or close to the noise level estimated as the standard error of the mean spectrum within each gyrotron pulse.

To enable temporally resolved measurements over longer time spans, a method was developed to trigger short oscilloscope acquisition periods synchronized to individual gyrotron pulses. For the present work the gyrotron was modulated in a 2 ms on / 18 ms off cycle. Data were recorded with the oscilloscope in 0.5 ms long time windows for each gyrotron pulse. With the 2 ms on / 18 ms off cycle it was thus possible to cover 99 gyrotron pulses over a 2 second time interval. Figure 20 shows examples of spectra measured with this technique during a density scan in TEXTOR #111812. Figure 21 compares individual spectra with theoretical fits from which the plasma composition may be inferred. Figure 22 shows the hydrogen isotope ratios inferred from measurements with this technique in TEXTOR # 111794 and 111812. Discharge 111794 was fuelled with hydrogen through neutral beam injection (P_{NBI} = 1.26 MW) and with deuterium through gas puffing during the discharge. Here the CTS results indicate a composition dominated by hydrogen - with RH decreasing slightly from values around 0.7 to values around 0.6 during the measurement interval. Discharge 111812 was fuelled only with deuterium through gas puffing, but wall recycled hydrogen may be expected to contribute to the composition. In this discharge the results indicate a lower hydrogen concentration, RH 0.4, and no appreciable change in composition is detected during the density scan.

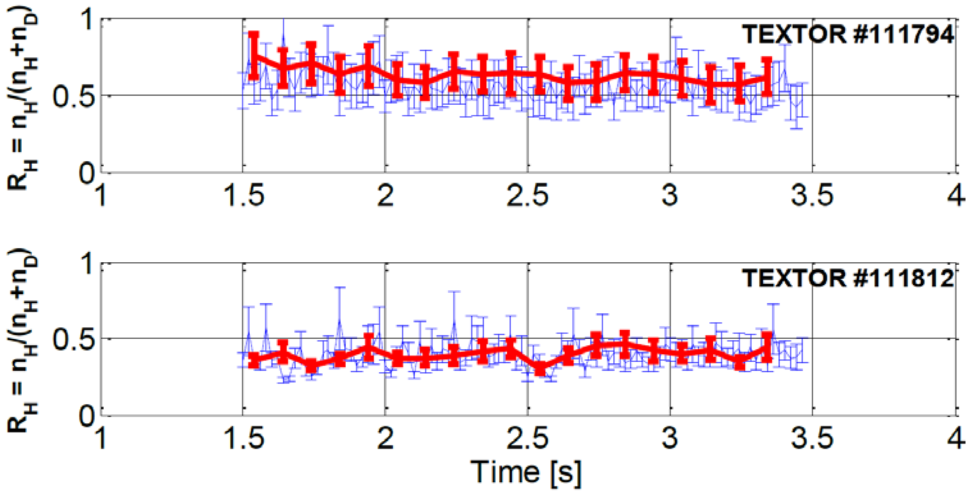

Figure 22. Hydrogen isotope ratios, $R_H = n_H/(n_H+n_D)$, inferred from the CTS measurements in discharges 111794 (upper panel) and 111812 (lower panel). The thin lines show results of fits to spectra measured in individual gyrotron pulses. The thick lines represent results of fits to spectra obtained by averaging over 5 gyrotron pulses. The error bars represent intervals of two standard deviations of the posterior probability distribution for R_H.

A broad overview of results from our project to demonstrate plasma composition measurements by CTS were presented in an invited talk at the 19th Topical Conference on High-Temperature Plasma Diagnostics (HTPD 2012) in Monterey, CA, May 6-10, 2012. Details of techniques described above for temporally resolved measurements were presented in the conference proceedings published in Review of Scientific Instruments[3]. A similar technique is now being implemented with the newly upgraded CTS system at AUG.

1. S. B. Korsholm, M. Stejner, H. Bindslev, V. Furtula, F. Leipold, F. Meo, P. Michelsen, D. Moseev, S. Nielsen, M. Salewski, M. de Baar, E. Delabie, M. Kantor, and A. Bürger, Physical Review Letters 106, 165004 (2011).
2. M. Stejner, S. B. Korsholm, S. K. Nielsen, M. Salewski, H. Bindslev, S. Brezinsek, V. Furtula, F. Leipold, P. K. Michelsen, F. Meo, D. Moseev, A. Bürger, M. Kantor, and M. de Baar, Plasma Physics and Controlled Fusion 54, 015008 (2012).
3. M. Stejner, S. B. Korsholm, S. K. Nielsen, M. Salewski, H. Bindslev, F. Leipold, P. K. Michelsen, F. Meo, D. Moseev, A. Bürger, M. Kantor, and M. de Baar, The Review of Scientific Instruments 83, 10E307 (2012).

2.3.12 Combination of fast-ion diagnostics in velocity-space tomographies

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ASDEX Upgrade is equipped with collective Thomson scattering (CTS) and fast-ion D_α (FIDA) diagnostics. Both diagnostics measure fast ions in small volumes compared with the plasma size. In either diagnostic one pre-selects a projection direction through geometric arrangement of the experiment and measures a 1D function of the fast-ion 2D velocity-space distribution function f. In principle three FIDA views and two CTS views are available at ASDEX Upgrade, and a fourth FIDA view is likely going to be installed in 2013. Traditionally, fast-ion CTS or FIDA measurements are often compared with simulated spectra to investigate if the measurements match the expectation or if they are anomalous [1]. However, if the real measurements disagree with the synthetic measurements, it is often unclear what caused this discrepancy. Our final goal is to experimentally determine f, and this might help establish where in 2D velocity space the measurements disagree with the simulation. Inference of velocity-space tomographies from CTS or FIDA measurements was recently shown to be an achievable goal [2-3]. This year we developed methods to account for uncertainty in the CTS or FIDA measurements and to allow the use of CTS and FIDA measurements together to compute a joint velocity-space tomography (Figure 23) [4]. Applying our prescription to a set of real 1D fast-ion measurements will yield an entirely experimentally determined 2D fast-ion velocity distribution function.

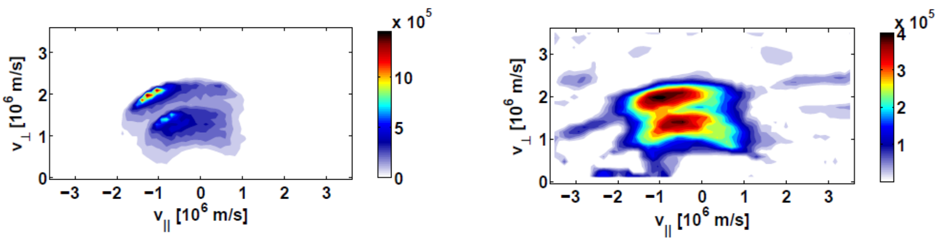

Figure 23 Tomography of a realistic beam ion distribution functions at ASDEX Upgrade. Left: Original function. Right: Tomography using simultaneous synthetic measurements in 2 CTS views and 2 FIDA views. Information that would be experimentally inaccessible due to scattering from bulk ions has not been used.

1. M Salewski et al. 2010 *Nucl. Fusion* **50** 035012
2. M Salewski et al. 2011 *Nucl. Fusion* **51** 083014
3. M Salewski et al. 2012 *Nucl. Fusion* **52** 103008
4. M Salewski et al. 2013 *submitted Nucl. Fusion*

2.3.13 Feasibility of sapphire windows to serve as polarizer in the CTS receiver

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Scattered radiation originating in a tokamak is in general elliptically polarized. In order to convert the signal to linearly polarized waves, mirrors with grooved surfaces are currently employed in our collective Thomson scattering diagnostic. Cheaper and compacter microwave receiver design can be achieved if these mirrors can be substituted by windows manufactured from birefringent materials. The utilization of sapphire windows with the crystal axis lying in the window plane is investigated.

The reflection of radiation at the surface of a sapphire window at a frequency on the order of 100 GHz is quite substantial. This is attributed to the high refractive index of approximately 3 [1]. Approximately 25% of the radiation energy is reflected. In order to improve the transmission, two infrasil windows with a refractive index of 1.8 [1] and a thickness of 0.38 mm each were in contact with both surfaces of the sapphire window. The infrasil windows serve as an anti-reflection layer at 105 GHz. The calculated transmission energy for such a window assembly is shown in Figure 24. The transmission within our region of interest (100 GHz to 110 GHz) is better than 98% (Figure 24).

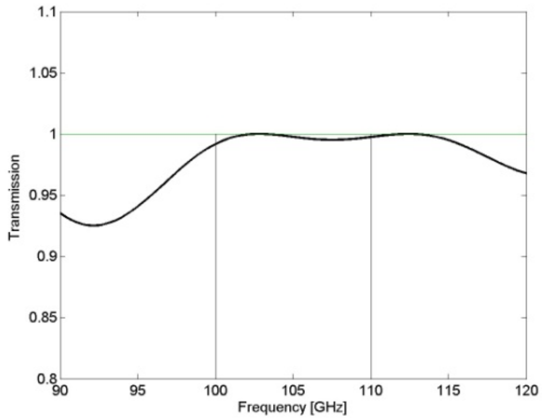

Figure 24. Transmission vs. frequency of a sapphire window in contact with a 0.38 mm thick suprasil window on either side.

The experimental setup is shown in Figure 25. The micro wave source emits linearly polarized light with a frequency of 98 GHz and the electrical field vector pointing in the x direction.

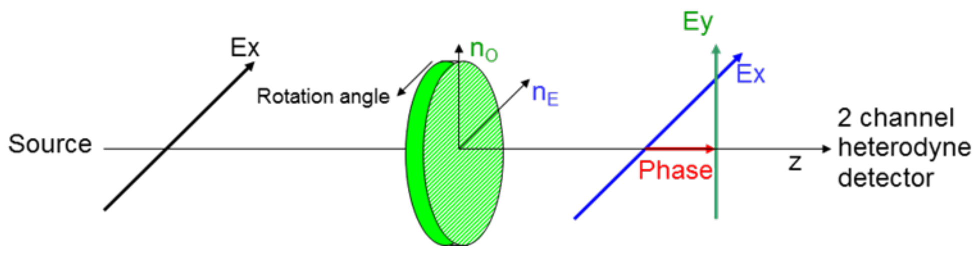

Figure 25. Experimental setup with sapphire window (green)

The radiation is detected by means of a two channel heterodyne receiver which detects the Ex and Ey components of the electrical field separately and measures the phase shift between Ex and Ey. The two channel heterodyne receiver is detailed in [2]. The sapphire window is inserted between source and detector and can be rotated around the z axis. The measurements obtained from the two channel heterodyne detector can be compared to modeling. The thickness of the sapphire window was estimated in a way that the phase between waves polarized in n_E and n_O direction is 90 degree at 105 GHz. The refractive indices n_E and n_O were taken from [1]. The indices were given for a frequency of 140 GHz. Therefore an error may occur if these values were assumed for 105 GHz. The thickness was found to be 2.1 mm. Due to the lack of a source radiating at 105 GHz, a 98 GHz source was used instead. This affects the phase shift between Ex and Ey, however, the quality of the results is not affected. Since the phase shift depends on the difference between n_E and n_O the refractive index must be known with a high accuracy in order to calculate the correct thickness for a certain phase shift. Since this is usually not the case, the phase shift used in the calculation is varied for best fit with the measurements. Figure 26 shows measurements and calculations of the phase shift. The best fit was found for a phase shift of 77.5 degree. This result can be used in order to calculate the correct thickness for a sapphire window resulting in a 90 degree phase shift for the design of a CTS receiver.

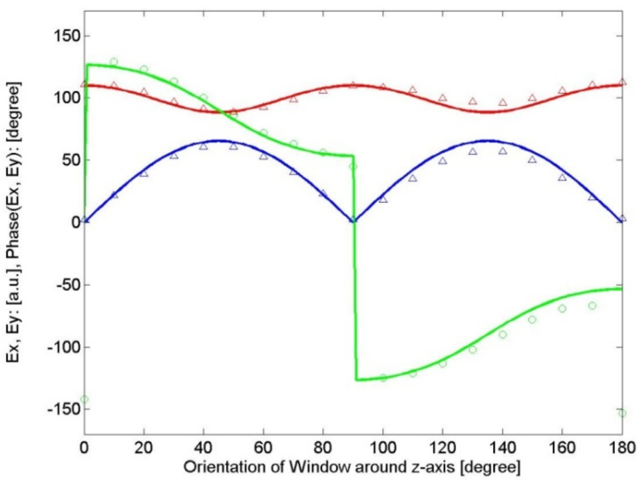

Figure 26. Measurement and calculation of the electrical field in x (red) and y (blue) direction vs. the rotation angle of the sapphire window. The phase between Ex and Ey is shown in green. The symbols represent the measurements and the solid lines show the calculation. The best fit was found for a phase shift of 77.5 degree

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2. F. Leipold, S. K. Nielsen, and S. Michelsen, Rev. Sci. Instrum. 79 (6) (2008)

2.3.14 Design of a compact CTS receiver with sapphire windows as polarizers

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Scattered radiation originating in a tokamak is in general elliptically polarized. In order to convert the signal to linearly polarized waves, mirrors with grooved surfaces are currently employed in our collective Thomson scattering diagnostic. Cheaper and compacter microwave receiver design can be achieved if these mirrors can be substituted by birefringent windows (Sapphire).

The general design is shown in Figure 27. The beam radius at the exit port of the waveguide at ASDEX Upgrade is 28 mm (Position A in Figure 27). This is also the beam waist. The beam is focused to 7.8 mm by means of a hyperbolic mirror. This is the required beam dimension at the horn antenna in our CTS receiver at ASDEX. Two sapphire windows at position B in Figure 27 serve as polarizers. Each window causes a phase shift of 90 degrees between waves where the electrical field vectors are oriented parallel to the direction of nE and nO respectively. nE and nO represent the refractive indices in a birefringent crystal. The subscripts ‘E’ and ‘O’ refer to the commonly used terms ordinary and extraordinary wave, respectively This allows a conversion of any elliptically polarized wave coming from the Waveguide to a linearly polarized wave where the electrical field vector is oriented parallel to the y-axis at the receiver antenna. Geometrical constraints may require a flat mirror between the mirror and point B. This would relocate the receiver antenna, but it will not change the beam geometry.

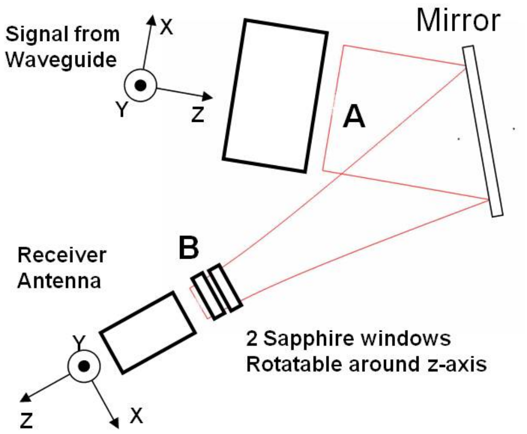

Figure 27. Sketch of the CTS receiver consisting of 1 curved mirror and 2 sapphire windows as polarizers. An additional flat mirror between the Mirror and location B is optional for design purpose and is not shown here.

The beam details are shown in Figure 28. The yellow dashed line shows the position of the mirror. The blue curve shows the beam from the waveguide (location A in Figure 27) to the mirror and the red curve shows the beam from the mirror to the receiver antenna (location B in Figure 27). The total optical length from the Waveguide to the receiver antenna is 350 mm. Two sapphire windows with a thickness of 2.6 mm serve as polarizers. Each sapphire window is in contact with an infrasil window of 0.38 mm thickness of either side in order to reduce reflections. The final design made in CATIA is shown in Figure 29.

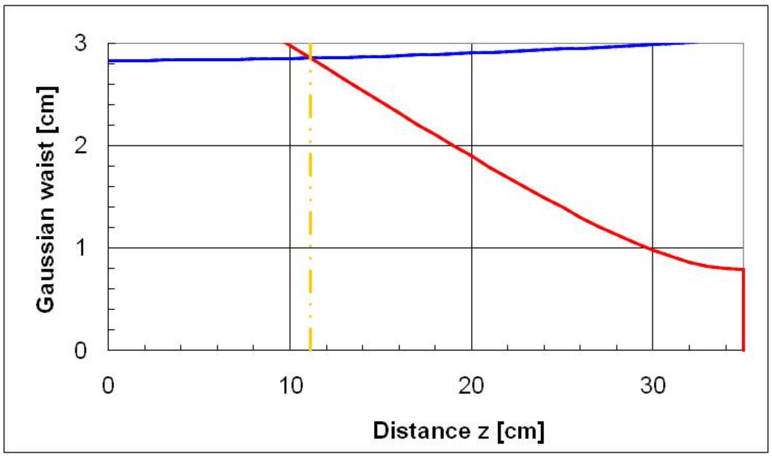

Figure 28: Beam dimensions in the newly designed CTS receiver

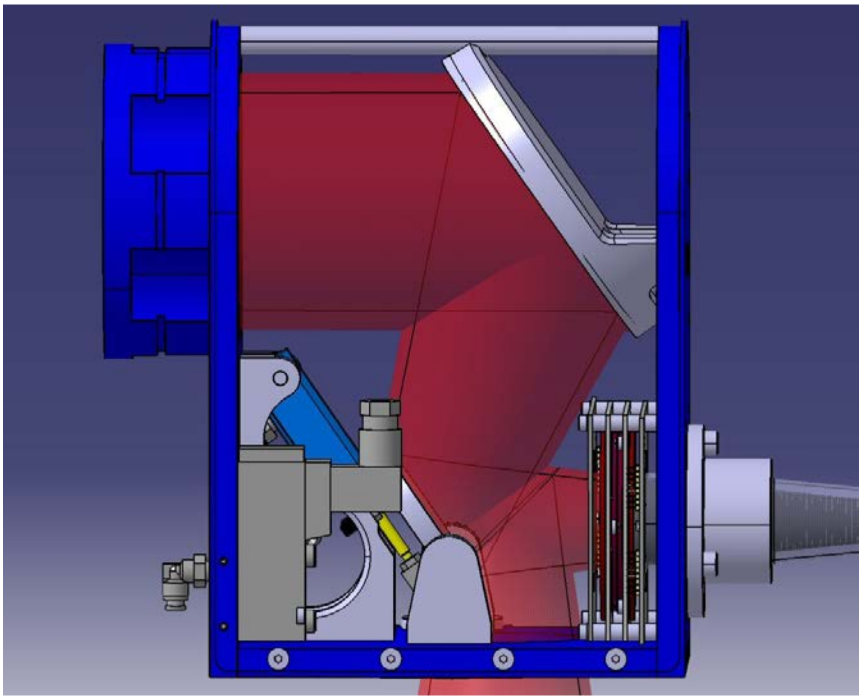

Figure 29. Final design of the CTS receiver. The second mirror in the design is flat and was inserted due to geometrical constraints

2.3.15 Application for F4E framework partnership agreement on the development of a CTS diagnostic for ITER

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In the autumn of 2012, Fusion for Energy published a Call for Proposals for a framework partnership agreement (FPA) for Diagnostic Development and Design: LFS Collective Thomson Scattering. The deadline for answer was set to 16th October and postponed (on our request) to 30th October.

The DTU effort was focused on forming a consortium with an appropriate partner in order to meet all the requirements to competences as well as human, financial, and managerial resources. We identified IST-IPFN as a potential partner and a very efficient and constructive collaboration was established between our two associations. The resulting answer to the Call for Proposals was submitted to F4E in due time basically fulfilling all requirements.

In late December F4E sent a Request for Clarifications, to which the DTU/IST consortium responded by end of January 2013. The next step from F4E is currently pending.

2.4 Publications

International journal publications

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3 Fusion Technology

3.1 Thermal stability of tungsten

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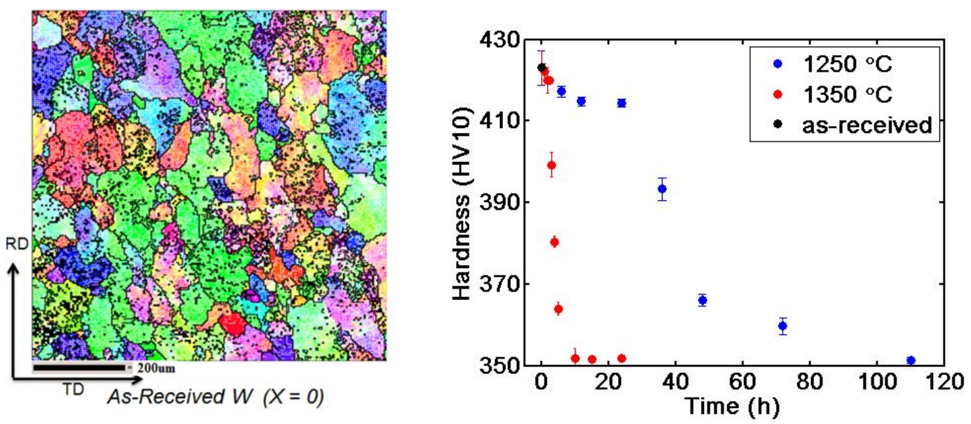
EFDA/PPP&T Task: WP12-MAT-01-HHFM-03-01/RISØ

Pure tungsten is considered as preferred candidate material for the plasma-facing first wall and the diverter of future fusion reactors due to its excellent mechanical properties, the highest melting point of all metals, a high recrystallization temperature, high heat conductivity and chemical inertness. Both parts have to withstand high temperatures during service which will alter the microstructure of the material and cause degradation of the materials properties as for example a loss in mechanical strength.

The thermal stability of a pure tungsten plate warm rolled to 67% thickness reduction was investigated by isothermal annealing in the temperature range between 1250 °C and 1350 °C. The microstructural changes during annealing are characterized by electron backscatter diffraction: the deformation structure of the warm rolled plate (see Figure 30 (a)) with weak texture is replaced by a recrystallization structure with random texture.



(a) (b)

Figure 30. (a) *Orientation map of warm rolled tungsten before annealing. Different colors indicate different crystallographic orientations. High angle boundaries are marked black. (b) Vickers hardness of warm rolled tungsten plate after annealing for different times at 1250 ºC and 1350 ºC, respectively. The hardness drops from the value of the as-received plate (423±4 HV10) to the value of a fully recrystallized plate (351±1 HV10) in a characteristic manner.*

During annealing, softening of the material is caused by recovery and recrystallization processes. Changes in hardness are quantified by Vickers hardness measurements on the rolling plane and illustrated in Figure 30 (b). Two stages can be distinguished: Initially, a slight decrease in hardness occurs indicating recovery (up to 24 h in case of 1250 ºC), followed by a decrease showing the sigmoidal shape characteristic for recrystallization. The recrystallized volume fraction is determined quantitatively and the recrystallization kinetics analyzed in terms of Johnson Mehl Avrami Kolmogorov kinetics. The observed times required for recrystallization and the obtained value for the activation energy of the recrystallization process (of about 6.3 eV) indicate a sufficient thermal stability of the tungsten plate during operation at 800 °C. For a more reliable determination of the activation energy, annealing treatments at lower temperatures are initiated.

4 DTU Contribution to EFDA-TIMES

4.1 Modelling fusion in the energy system

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EFDA Task: WP12-SER-ETM-3-01/RISØ

Within the Socio-Economic Research on Fusion (SERF) programme EFDA and the Associations has developed a multi-region global long-term energy modelling framework (EFDA-TIMES) with time horizon 2100. This horizon will allow a significant contribution by fusion power, if the ongoing research and development become successful during the next 3-4 decades.

In this model technologies are organised into a network of energy flows linking demand and supply. Forecasts of energy demands in the various sectors come from global economic models. The energy system is divided into the following main sectors: Upstream, Electricity, Industry, Residential, and Transport.

Fusion units will operate very similar to other large-scale thermal generating units for supply of industrialised regions and population centres. Other technologies with very large potentials are likely to become significant earlier than fusion. However, these technologies are dependent either on natural resources and long-distant transmission of electricity, such as solar CSP and off-shore wind, or small-scale units, mainly solar PV or micro CHP to be integrated in local grids. The development, deployment and integration of these technologies into the energy system may be even more challenging than that of fusion. It will require far more resources for research and subsidies than the limited research budget, which is currently allocated to fusion.

In the model the energy system is optimised by minimising discounted total system cost, subject to constraints that reflect infrastructure, technology availability and policy objectives, e.g. reduction of CO_2 and other greenhouse gasses. It means that the quality of model results is dependent – not only on the consistency of techno-economic data, but also of the key economic assumptions, such as future energy prices and the choice of discount rates.

EFDA-TIMES is a variant of the models used by the IEA Implementing Agreement ETSAP (Energy Technology Systems Analysis Programme), in particular TIAM. Of these models EFDA-TIMES has the longest history – used by a modelling team with both continuity and gradual change of scientists with different backgrounds. The archive of model results also contains systematic analyses of different methods of discounting, including hurdle rates for different technologies and decreasing discount rates for very long-term optimisation.

The model development during 2012 has focused on three issues:

- enhancement of key technologies that are competing with fusion, in particular variable renewables and nuclear fission,

- revision of regions - now 17 regions with separate regions for the BRIC countries – Brazil, Russia, India and China,
- update of the base year from 2000 to 2005.

An agreement was made between the EFDA Leader and ETSAP, which will allow comparison of model assumptions and results. Together with contributions to semi-annual collaboration workshops on TIAM this will allow the small EFDA-TIMES team to benefit from the much larger TIAM community.

Contributions to EFDA-TIMES from the Systems Analysis Division of DTU Management Engineering) are co-ordinated within the work on the TIAM model within ETSAP. These activities include 2 senior scientists and 3 PhD students.

1. Grohnheit PE. 2012. Input documentation for ETSAP-TIAM and EFDA-TIMES. TIAM Workshop, Sophia Antipolis, France, 15-02-12
2. Cabal H, Lechón Y, Ciorba U, Gracceva F, Eder T, Hamacher T, Lehtila A, Biberacher M, Grohnheit PE, Ward D, Han W, Eherer C, Pina A. 2012. Analysing the Role of Fusion Power in the Future Global Energy System. 2nd European Energy Conference (E2C 2012), Maastricht, Netherlands, 17-04-12
3. Grohnheit PE 2012. Modelling infrastructures, Final Report: Socio Economic Research on Fusion EFDA Technology Workprogramme 2011. Activity 1.3.6. 53 p.

5 Industry awareness activities towards ITER

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Following the ITER site decision on June 28th 2005, Risø DTU was the main driver in the launch of activities to inspire Danish companies and make them aware of the possibilities of being a supplier to the construction of ITER as described in some detail in [1]. This effort originally initiated in 2005 was further developed and maintained in 2006-2010. In 2009 public funds in the order of 1 M Euro over three years was granted to the Danish Big Science Secretariat (BSS); fostered at and administered by DTU. In 2012, a successful effort to secure funds for a continuation of BSS (2013-2015) was completed. BSS is described in more detail below.

The Danish representative of the F4E ILO network is Søren B. Korsholm of Association Euratom -DTU. The network now comprises 18 European ILOs. During 2012 the tasks and procurements from the ITER Organisation (IO) and F4E have received some attention from Danish companies, and a few bids and expression of interests have been placed during 2012 – still so far without success. The opportunities for participation in procurements and events are announced via the webpage and newsletter of the Big Science Secretariat.

5.1 The Big Science Secretariat – Denmark

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With offset in the Risø DTU initiative on promoting the ITER industrial opportunities to Danish companies, a partnership was made between Risø DTU, FORCE Technology, and Teknologisk Institut (TI – Danish Technological Institute) – both latter are non-profit technology service institutes. The aim of the partnership was to create a unit and a project which aims at increasing the Danish industrial involvement in the construction of

(European) big science facilities. The project is called Big Science Sekretariatet in 'Danish' or The Danish Big Science Secretariat (BSS). The project is lead and coordinated by DTU Physics.

The aim of the BSS initiative is two-fold: to increase the awareness of Danish companies on the potential for commercial participation in the construction phase of big science projects, and to assist companies in the required competence and network building phase prior to being able to bid for contracts on ITER, ESS, CERN, XFEL, ESO etc. At the same time, BSS is connecting to the big science facilities to make the Danish company competences known to them. To facilitate this better BSS partners are now taking care of the ILO roles at F4E/ITER, ESO, CERN, and ESRF.

The pivot of the BSS project is the BSS secretariat (located at DTU Risø Campus) which is managed by a full time professional. In addition, a number of experts at DTU, FORCE, and TI are connected to BSS, in order to assist Danish companies in their need for competence building and expert advice in the preparation phase. A few awareness activities were conducted in 2012, while the emphasis has been more on targeted thematic events often with participation of big science organisations like, ESS, CERN, and ESO. The project has received positive attention and remarks from Danish companies as well as several of the European big science facilities. The BSS project has also received quite some attention by the Danish press with more than 50 articles in 2011-2012, and radio- and TV news appearances. Furthermore, other European countries are considering similar initiatives. A main source of news from BSS to the 70+ members and about 200 additional subscribers is the weekly BSS newsletter with news, events announcements, and lists with current tenders.

The project is further described in the BSS webpages www.bigscience.dk.

In 2012, negotiations between the partners and the Danish Agency for Science, Technology, and Innovation lead to the continued funding of BSS as a partnership between TI and DTU running from 2013-2015. Combined with additional funds relating to ESS and the Capital Region of Denmark, the total public support to BSS sums up to a total of 10 mio Danish kr. over three years.

1. Association Euratom - Risø National Laboratory, Technical University of Denmark, Annual Progress Report 2006.

6 Public information in Denmark

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The public information activities in the Danish fusion association comprise a broad range of activities from press contact and assisting students to talks about fusion at different venues. In 2012 the level of activity has been somewhat lower than the preceding years. A major part of the activities is normally the performances of the Fusion and Plasma Roadshow, described below, but in 2012 the usual participation in the national science festival was cancelled due to the work on the F4E FPA call. A public information EFDA task was continued in 2012 since Risø DTU and FOM in 2010 took up the EFDA task of *Interactive Exhibits for the Fusion Expo*. This task was prolonged to include 2011 and 2012, and it is described in Section 6.2.

Over the last couple of years a good contact has been established between DTU and the national science talent center (ScienceTalenter) in Sorø. This has resulted in several talks to high school teachers and/or students. However, most importantly, ScienceTalenter received a grant to make a fusion physics master class in 2010-2011 for 25 science talents from 5 high schools. This was conducted with one initial camp for the teachers followed by two camps for the students with homework projects. This gave all a solid foundation in the field of fusion physics, and the master class was concluded by a 4 days travel to England in the spring of 2011 with the main attraction being a visit to JET and MAST. The event is currently (2012-2013) being repeated with 30 high school students and the visit to JET will take place in Mid-April 2013.

For brevity the activities are put in list form below

- Popular lectures on fusion energy
- Assisting students from primary and high school in fusion oriented projects.
- Contact to journalists (web, newspapers, radio and TV) on fusion and ITER related news
- Continued participation in the *Scientarium* - the Panel of Experts of Ingeniøren – Engineering Weekly News Magazine

6.1 The Danish Fusion and Plasma Road Show

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As part of the ongoing public information activities, the Danish Fusion and Plasma Road Show have been created by members of Association Euratom-DTU. The show was initiated in 2007 having the Dutch Fusion Road Show from FOM-Institute for Plasma Physics Rijnhuizen as inspiration. The show was funded for three years (2007-2009) by the Danish Research Council for Nature and the Universe under the Ministry for Science, Technology and Innovation – by a total of approx. 40,000 Euro. Since the funds have ceased the show has been maintained and used for a few events.

The objective of the road show is to inform students and the general public about present fusion energy and plasma research and in that way give them an insight and hopefully an interest in science and its uses. In particular we hope that the students get inspired by the physics and see that fusion energy research is an exciting field with many possibilities. Another important objective is to inform about the use of fusion as a source of energy, and in that way clarify the benefits and challenges of fusion power.

The show is a combination of a regular slide based presentation and a number of small experiments that demonstrate or is related to a topic described in the presentation. The experiments are intended to surprise and excite people and also work as intermezzos in the talk. This is intended to help keep people focused on the topics. In the presentation a great effort is put in simplifying the advanced topics, and it is intended to bring the involved phenomena close to people’s experiences from everyday life. This is done e.g. by converting enormous numbers in strange units into meaningful sizes, and also by asking questions or giving small exercises to the audience. The show has its own website: http://roadshow.risoe.dk, where descriptions of the experiments can be found.

In the course of the road show the following experiments are conducted

- An exercise bike connected to a generator and an inverter to be able to supply household appliances with power produced by the bike. This is a very popular experiment, where volunteers in the audience can get a feel for how much we should work to cover our consumption.

- Jacob's Ladder: Plasma created by 10.000 V between two copper wires
- Plasma in a microwave oven: Example of a RF generated plasma
- A ball on a rotating disc/turntable: Ball will move like a charged particle in EM-field
- Smoke rings: Example of the torus shape
- Electromagnet and compasses: Example of electricity generating a magnetic field
- Eddy currents in a copper plate with a strong magnet: Example of the connection between temperature and conductivity
- Superconductor – levitated magnet above superconductor
- Plasma ball lamp

6.2 Interactive Exhibits for the Fusion Expo

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FOM and Risø DTU jointly took up the EFDA task WP09-PIN-INTEX "Creating interactive exhibits for Fusion Expo". The aim of the task is to create new and more interactive exhibits for the Fusion Expo within a number of categories. It is a multistep task, where inspiration and ideas were explored and discussed.

A range of ideas have been developed and prioritized, and the high priority ideas have been described in greater detail. All the selected exhibits have been ordered and most are already created and in the Fusion Expo.

The task has successfully been finalized with a final report submitted in December 2011. However, as one of the exhibit items was the development of an iPad fusion game, and this development was extended, the FOM and DTU representatives agreed to continue supporting the task in order to complete the last exhibit. The current deadline for the iPad game is April 2013.

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