Study of turbulence and transient events in fusion plasmas with beam emission spectroscopy

PhD thesis

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1. Introduction

This thesis contributes to the study of magnetically confined high temperature fusion plasmas. To achieve sufficient nuclear fusion reaction rate, the plasma is to be heated to 100 million Kelvin, and should be insulated from the environment in order to keep the above temperature and a proper density. Already in the 1950's, at the beginning of the experimental studies, the transport perpendicular to the magnetic field lines was found to be too large compared to expectations, thus hindering the achievement of the plasma confinement quality necessary for fusion energy production. The experiments of the following decades have shown that the anomalously high transport rate, compared to the classical theories, is caused by the turbulent state of the plasma.

A major achievement in the history of the magnetic fusion studies was the discovery of the H-mode, which is characterised by improved particle and heat confinement. This finding was not just a major step towards the commercial fusion reactors, but also a revelation of a very exciting physical phenomenon. During the L-H transition the plasma spontaneously jumps from the original L to the H state, which is characterised by typically two times better energy confinement time. The L-H transition is thought to be caused by complicated interactions between the plasma turbulence and device sized plasma flows. Although the discovery of the transition is more than 25 years old, still no theory has emerged which would explain the phenomena, neither is there a simulation, which would show this feature.

The extremely steep pressure profile, which is the result of the H-mode, generates large edge instabilities called Edge Localised Modes (ELM), which have not been observed previously. The ELMs are useful from one hand as they clean the edge plasma from impurities and He ash, but they are dangerous on the other hand as up to 10-20% of the plasma energy is lost in a millisecond, which can damage the plasma wall structures by the enormous heat load. Understanding the physics of H-mode and ELMs will enable us to control these phenomena, which will be essential in a future nuclear fusion reactor.

It is essential for the theoretical and numerical studies of the above phenomena to improve the experimental observations and give a feedback from real experiments. This requires the development of new plasma diagnostics and perfection of existing techniques. One of the diagnostics, which is capable of observing the above mentioned physical phenomena with appropriate temporal and spatial resolution, is Beam Emission Spectroscopy (BES). This thesis describes BES developments and observations using the constructed diagnostics on various magnetic fusion experiments.

2. Background, objectives, used methods

The basic objective of my research was to measure and study the edge plasma fluctuations caused by plasma turbulence, and to develop diagnostic tools for the observations. I joined a group, which builds and improves BES diagnostics since more than a decade. In this technique a neutral atomic beam is applied for the measurement of plasma density and high frequency plasma density fluctuations. The objectives of my work can be split into two parts; the development of the BES diagnostics and the analysis of the measurement results.

Development of the BES diagnostics

BES diagnostics have been used for several decades in different fusion experiments, although there are huge differences between the realized setups. The BES diagnostics on dedicated alkali atomic beams are mostly used to measure edge density profiles. On the W7-AS stellarator experiment this technique was successfully used for edge plasma fluctuation and flow measurements as well. Later an accelerated lithium beam was installed at the TEXTOR tokamak and an optimal fast detector was needed, which detects the beam emission in the visible light range and provides the optimal signal to noise ratio for the expected signal level. To fulfil these requirements the following objectives were set up as part of my Ph.D. student work:

- Construction of a fast (1MHz) observation system with the selected detector type, which fulfils the optical and electrical requirements.
- Building the digitizer and data acquisition system, which suits the harsh tokamak environment.
- Installation and computer control of beam manipulation system.
- Integration and synchronization of the beam manipulation system to the data acquisition control system.

After the successful measurements with the new detectors at TEXTOR more BES applications became possible which were also part of my Ph.D. studies:

- Trial BES system installation to the MAST spherical tokamak observing light fluctuations on a heating beam

- Demonstration BES system installation to the JET tokamak on the Lithium beam

The next level of the diagnostics development became possible after the successful demonstration measurements, when more manpower and financial resources were available to build proper fluctuation BES experiments. As part of a team I participated in the design and construction of the following BES experiments:

- Two dimensional fluctuation BES on the MAST spherical tokamak
- Multichannel fast BES camera unit for the existing JET observation system

Analysis of the measured BES data

The following physical objectives were set up for the analysis of data obtained with the above diagnostic systems:

- Study of the edge plasma fluctuations at TEXTOR during various operation scenarios.
- Study of the limiter H-mode and L-H transition at TEXTOR, documentation of the effect of the edge transport barrier to the plasma fluctuations.
- Characterization of edge and core plasma turbulence at MAST tokamak, especially the mezo-scale (~10 cm) low amplitude MHD turbulence predicted by simulations.
- Study of the L-H transition at MAST, characterization of bulk plasma turbulence during and after the transition.
- Study of the formation and the evolution of ELMs at the MAST tokamak with microsecond temporal resolution.

Used methods

A wide spectrum of experimental and data analysis techniques were used during my work. These techniques are detailed in the thesis; just a short list is given here: Fourier-spectra, power-spectra, coherence, phase spectra, correlation and covariance functions. For the interpretation of results of the BES diagnostics other diagnostic signals were also used: Mirnov coils, fast cameras, Soft X-ray camera, reflectometry, etc. These diagnostics are also introduced in the thesis.

3. New results

I. A simulation model has been developed of various high frequency detectors sensible for visible light with the aim of calculating the noise level and finding the optimal signal to noise ratio detector depending on the incident light level. My results show that in case of 1MHz bandwidth and a photon flux less than ~$5*10^8$ photons/sec the photomultiplier tube is the optimal solution. If the incident photon flux exceeds this level Avalanche Photodiodes (APD) should be considered. An amplifier for APD detector has been designed and built using the results of the model calculations. These calculations were checked against experimental results measured with calibrated laser beam.

In case of a typical BES experiment the incident photon flux is between 10^6-10^{10} photons/sec. The above statement is valid for this range. The signal to noise ratio of a detector also depends on the measurement bandwidth, so the choice of the optimal detector also depends on the bandwidth. The developed simulation is applicable for wide frequency and photon flux range.

II. I have designed and with the help of engineer colleagues built the detector system of the accelerated lithium beam BES at TEXTOR, which contains a low frequency CCD camera based observation branch and a high frequency APD detector based branch. For the study of the fast transient events and flow patterns the application of a beam manipulation system is essential. I have synchronised the beam manipulation system to the data acquisition (daq) system and tested the whole setup. The design, installation and the software development for the complete daq system was a part of my work. The control of the integrated daq and beam manipulation system was solved via a graphical interface, which made possible various applications of the diagnostics. The measured light level with the APD detectors was ~ $2*10^{10}$ photons/sec at the peak of the emission profile, which corresponds to a signal to noise ratio of ~50-60 at 500 kHz bandwidth. Using correlation data analysis technique the detection limit to light fluctuations is ~ 0.1%.

III. I have installed an 8 channel APD detector unit on the MAST spherical tokamak utilizing the existing optics of the Charge Exchange Resonance Spectroscopy (CXRS)

system. The signal to noise ratio of the measured light level is 5-10, which does not allow the investigation of <1% core fluctuation, but is sufficient to study the edge plasma turbulence and fast transient events. The beam current fluctuation and background emission imposes additional difficulties for the data evaluation. A simulation model was developed in collaboration with the Culham Centre for Fusion Energy (CCFE), which calculates the beam stopping and the beam emission profile. This code was validated with the measurement results. Spectral measurements showed that the background emission is dominated by Carbon line emission. The validated code and the measurement results were used during the design and prediction of the capabilities of the proper optimized 2D turbulence imaging system. I participated in the design and I was responsible for the construction of the detector system and electrical control. The system has already been successfully installed in mid 2010 on MAST. First experiments are expected in the next MAST campaign.

IV. I have built and installed a 4 channel trial fast detector system on to the existing observation system of the accelerated lithium beam diagnostics of the JET tokamak. Optical fibres are used in this diagnostics to couple the light from the torus to the detectors. The trial system was sufficient to demonstrate fluctuation measurement in the edge and scrape off layer plasma and the special observation direction made possible to demonstrate the plasma flow measurements. After this successful demonstration the design of a multichannel system has been started

V. I measured the behaviour of various plasma turbulence properties such as fluctuation amplitude, eddy lifetime and structure size in different scenarios of TEXTOR plasmas with Lithium beam emission spectroscopy. In ohmic plasmas the fluctuation amplitude in the scrape off layer plasma is a few times 10%, the lifetime of the structures is 10-100 μs and characteristic frequencies cannot be observed. In the edge plasma quasi-coherent modes, a broadband wavelike structure in the 30-100 kHz frequency range, dominates the turbulence. The fluctuation amplitude drops from 4-5% to 0.5 % towards the core in the observation range of the beam. The density dependence of the frequency of these structures has been observed. The poloidal tilting of the eddies can be assumed from the spatial-temporal correlation functions. The turbulence behaviour changes significantly with heating method, in case of neutral beam heating the QC

mode disappears. With high frequency beam deflection method the poloidal plasma flows and their modulations, GAMs could be determined.

VI. I measured the different fluctuation behaviour of L-mode and H-mode plasmas of the MAST spherical tokamak. In the H-mode MHD waves have been observed at the pedestal, which are correlated with Mirnov coil signals. I could detect and radiallly localise high frequency fast particle driven MHD activity, which is induced by the fast ion population originating from the heating beam.

VII. The limiter H-mode ELMs and the L-H transition have been investigated with fast chopping measurement technique on TEXTOR with beam emission spectroscopy. High time resolved background light corrected measurements were done to study density profile evolution during L-H transitions and pedestal collapse during ELMs. It has been observed that after the L-H transition a steep density pedestal develops in a millisecond timescale. The changes of ambient turbulence have been studied during the transition, and the turbulence suppression has been observed. In the edge plasma the 5% fluctuation amplitude drops below 1%, and the structures cannot be well resolved.

VIII. A12 kHz MHD mode has been identified in the pedestal during H-mode phase in the TEXTOR. These modes perform non-linear growing and show non-sinusoidal behaviour before ELMs. The pedestal collapses during ELM instability, multiple crashes were often observed, the pedestal recovers in inter ELM periods.

IX. Precursor wave behaviour was observed before type I. ELMs in Single Null Divertor configuration plasmas with beam emission spectroscopy at MAST. Although this phenomenon was known previously, my high frequency and well localised measurements with the trial BES diagnostics showed additional features. Before the appearance of the ELM plasma filaments appear in the SOL plasma, which contact a limiter or wall element. After the wall contact the fingers retreat and impurity influx is observed, which in most cases triggers an ELM. In some cases the ELM does not follow the impurity inflow, so it has been proved that the precursor waves do not necessary cause ELMs.

4. Publications

Publications connected with the thesis

1. A.R. Field, **D. Dunai**, N. J. Conway, S. Zoletnik, J. Sárközi, "*Beam emission spectroscopy for density turbulence measurements on the MAST spherical tokamak, Rev. Sci. Instrum.* **80** 073503 (2009)

2. I Pusztai, G. Pokol, **D. Dunai**, D. Réfy, G. Pór, G. Anda, S. Zoletnik, and J. Schweinzer *Deconvolution-based correction of alkali beam emission spectroscopy density profile measurements, Rev. Sci. Instrum.* **80** 083502 (2009)

3. S. Zoletnik, M. Agostini, E. Belonohy, G. Bonhomme, **D. Dunai** et al., *Summary of the Workshop on Electric Fields, Turbulence and Self-organization in Magnetized Plasmas (EFTSOMP) 2009: 6–7 July 2009, Sofia, Bulgaria, Nuclear Fusion* ***50*** (2010) *047001 (5pp)*

4. H. Meyer, R.J. Akers, …., **D. Dunai**, et al., *Overview of physics results from MAST, Nuclear Fusion* **49** 104017 (2009)

5. **D. Dunai,** A.R. Field, N. J. Conway, A. Thyagaraja, S. Zoletnik, J. Sárközi, *„Beam Emission Spectroscopy for density turbulence measurements on MAST"* 34th EPS Conference on Plasma Phys. Warsaw, 2 – 6 July 2007 ECA Vol.31F, P-5.082 (2007)

6. G. Anda, **D. Dunai,** G. Petravich, J. Sárközi, S. Zoletnik, B. Schweer, *„First Measurements with the re-installed accelerated Lithium beam diagnostics on TEXTOR"*, *35th EPS Conference on Plasma Phys. Hersonissos, 9 – 13 June 2008 ECA Vol.**32D**, P-5.076 (2008)*

7. S. Zoletnik, **D. Dunai**, A.R. Field, A. Kirk, A. Bencze, S. Saarelma, B. Ayed, G. Veres, „Observations of ELM pre-cursor structures using Beam Emission Spectroscopy in MAST", *35th **EPS** Conference on Plasma Phys. Hersonissos, 9 – 13 June **2008** ECA Vol.**32D**, O-4.031 (**2008**)*

8. S.D. Pinches , L.C. Appel , I.T. Chapman , G. Cunningham , **D. Dunai** , et al.,,Fast Particle Instabilities in MAST", *Proceedings of the 22nd IAEA Fusion Energy Conference, (13-18 October 2008Geneva, Switzerland), IAEA-CN-156, EX/P8-7 (2008)*

9. R.J. Akers, D.J.Applegate, J.Candy, G.Colyer, **D.Dunai,** A.R. Field, et al., „Transport studies in the MAST spherical tokamak", *Proceedings of the 22nd IAEA Fusion Energy Conference, (13-18 October 2008Geneva, Switzerland), IAEA-CN-156, EX/2-2 (2008)*

10. **D. Dunai,** S. Zoletnik, G. Anda, G. Petravich, S. Kálvin, J. Sárközi ,A. Krämer-Flecken, B. Schweer, S. Soldatov, „Turbulence properties of the edge plasma at TEXTOR measured by Beam Emission Spectroscopy", *36th **EPS** Conference on Plasma Phys. Sofia, 29 June - 3 July*

11. S. Zoletnik, L. Bardoczi, G. Anda, **D. Dunai,** G. Petravich, A. Krämer-Flecken, S. Soldatov , „Poloidal flow velocity measurement at the edge of the TEXTOR tokamak using quasi twodimensonal Lithium Beam Emission Spectroscopy", *36th **EPS** Conference on Plasma Phys. Sofia, 29 June - 3 July*

12. G. Petravich, G. Anda, **D. Dunai,** S. Kálvin, S. Zoletnik, „Light profile measurement on the 35keV Lithium beam on TEXTOR", *36th **EPS** Conference on Plasma Phys. Sofia, 29 June - 3 July*

13. S. Kálvin, G. Anda, **D. Dunai**, G. Petravich, S. Zoletnik, G. Pokol, B. Játékos, I. Pusztai3, D. Réfi, 36th EPS Conference on Plasma Phys. ECA Vol.**33E**, P-5.211 (2009)
14. **D. Dunai**, S. Zoletnik, J. Sárközi, A.R. Field, Avalanche Photodiode based Detector for Beam Emission Spectroscopy, *Rev. Sci. Instrum.*, **81,** 1 (2010)

Other scientific publications

M. Gryaznevich, G. Van Oost,…,M. Berta, **D. Dunai**, B. Tál, S. Zoletnik, et al. *Results of Joint Experiments and other IAEA activities on research using small Tokamaks, Nuclear Fusion* **49** *104026 (2009)*

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„Combined density-temperature fluctuation measurement with beam emission spectroscopy";
31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.28G, P-5.151 (2004)

S. Zoletnik, N.P. Basse, A. Bencze, **D. Dunai**, et al.: Anomalous *transport events in the core plasma of the Wendelstein 7-AS stellarator,* 32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.29C, P-5.023 (2005)

I. Pusztai**, D. Dunai,** G. Pokol, G. Pór, J. Schweinzer, S. Zoletnik „*Capabilities of alkali Beam Emission Spectroscopy for density profile and fluctuation measurements*" 34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.31F, 2.137 (2007)

Conference talks

Second Hungarian Plasma Physics Workshop, Budapest, 22.-24. 04. 2004.
Combined density-temperature fluctuation measurement with BES

Hungarian Plasma Physics and Fusion Technology Workshop
2008. March 26. – 28., Győr
High frequency Beam Emission Spectroscopy measurements

COMPASS PROGRAMMATIC CONFERENCE, Prague, April 2 - 3, 2009
Beam emission spectroscopy for reinstalled COMPASS tokamak

The Fifth Hungarian Plasma Physics and Fusion Technology Workshop, 2010
2D-BES Imaging diagnostics on MAST

The Fifth Hungarian Plasma Physics and Fusion Technology Workshop, 2010
ELM observations with Beam Emission Spectroscopy on MAST and on TEXTOR