Measurement of transient events in hot magnetized plasmas

PhD Thesis Booklet

Balazs Tal

Supervisor: Dr. Gabor Veres

Department of Plasma Physics
Wigner Research Centre for Physics

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Introduction

The most promising way to produce energy from fusion reactions is the tokamak concept, where the hydrogen fuel is heated up to 150 million ºC and confined in a magnetic field. Under the arising circumstances the electrons are not bounded to their nuclei but the components are coupled to each other by electromagnetic forces. Additionally, external fields, produced by the machine, interact with this mixture, too. The parameters of the performed plasma discharge are governed by heat and particle transport and thus these processes determine the distance to fusion-grade conditions. Although stationary profiles are generally formed, the achieved equilibria are dynamic and they are the consequences of fast processes on the microsecond-millisecond timescale. Additionally, the crossing of the stability boundaries of the tokamak plasma operation space can initiate transient transport processes which cause either global or local collapses in the profiles acting on the machine or deteriorate confinement.

Approaching transient plasma transport events from the global perspective the most grandiose one is the disruptive plasma termination. It is frequent in present-day devices since even major stability limits are only partially understood and errors in plasma control are likely in non-industrial equipment. However, unmitigated disruptions would have deleterious effects already on the next-generation fusion device (International Tokamak Experimental Reactor - ITER) caused by the high heat loads due to sudden loss of energy confinement and owing to localized impact of accelerated electron beams. Additionally, intolerable high mechanical forces would arise due to the interaction between the magnetic field and the plasma current directed into the structural elements. Hence, the physical phenomena initiating the collapse and the occurrence of this process must be studied to accurately determine the stability limit and suggest techniques to mitigate the damage the tokamak suffers. Since the termination implies intensive plasma-wall interaction and high energy losses, it can be studied e. g. with fast detectors the sensitivity of which cover the majority of the total electromagnetic power loss spectrum of the hot magnetized plasma.

When the external heating power exceeds a certain threshold (depending on the parameters of the discharge) a transport barrier arises at the edge of the plasma. This improves particle and energy confinement and makes the plasma form a pedestal in density and temperature profiles at the edge (High confinement mode). The fast transport processes which cause the crash of this pedestal are called Edge Localized Modes (ELMs). These collapses occur with a repetition frequency in the Hz - kHz range depending on plasma and operation conditions. Although ELMs are considered useful due to their capability to prevent impurity accumulation in the core, they eject significant fraction of plasma energy outside the confined region on a short timescale. This is transported towards the wall mainly in a narrow Scrape-Off Layer (SOL) region causing such high heat loads which would exceed the tolerance limits of the plasma facing components (around 10 MW/m^2) in the future devices. Hence, new divertor solutions have been being developed, which aim to repartition the transported heat to a higher interaction area and to dissipate the ejected energy by radiation. ELM radiation loss measurements in these divertor configurations contribute to the optimization of these novel plasma exhaust solutions.

Considering transient events in a more smaller spatial scale one deals with turbulent eddies. Their sizes perpendicular to the magnetic field are typically orders of magnitudes smaller than the size of the machine. They are often related to the material propagation in the major part of the confined region especially radially outwards the plasma. However, they can unite into global structures existing on a millisecond timescale. One possible arising structure is the zonal flow, which modulates the plasma flow velocity uniformly on the magnetic flux surfaces and it changes radially on a short spatial scale. This latter property is responsible for the shearing of small-scale eddies and thus for the regularization of transport. Hence, fast velocity profile measurement techniques play a crucial role in its understanding.

Objectives

My thesis work aimed to deal with several transient processes which were related to the transport in magnetically confined plasmas. This goal required both diagnostic improvement and calibration, development of numerical and statistical analysis methods and physics studies using the developed tools on various machines.

A bolometer-type diagnostic system based on semiconductor detectors had been available on the Tokamak à Configuration Variable (TCV) in Lausanne, Switzerland, before I began my thesis work. Although it had provided some scientific results, the quality of radiation profile measurements had been below the expected level. This had hampered the beginning of disruption studies on the machine. The problem with the system became a crucial issue when the snowflake divertor configuration was established for the first time, the study of which soon became the major objective of the device. Its assessment required the knowledge of radiation profiles during ELMs. Hence, from the technical point of view I aimed

- To study the detector system and identify which errors had hampered high-quality profile reconstructions.
- To suggest and manage a major upgrade on the cameras, including spatial calibration and installation.
- To assess the data provided by the system. I intended to carry it out by comparing the obtained distributions to data measured by other diagnostics, e. g. by the foil bolometers. This required the recommissioning of the latter system, too.

Having finished the development of the diagnostic I intended to exploit its capabilities and study two of the aforementioned transient transport processes, namely

- To compare the radiation properties of ELMs in standard and snowflake-diverted configurations with the upgraded diagnostic. The studies focused on the following questions: are the additional third and fourth (called secondary) strike points activated, is the peaking of radiation mitigated in the vicinity of the original first and second (called primary) strike points, does the radiation volume increase as ideal snowflake divertor is approached.
- To use the system in the investigation of plasma-wall interaction during disruptions initiated by the excess of the density limit.

Another transport-related topic which I aimed to study was connected to turbulent flows in hot magnetized plasmas. The velocity profiles of zonal flows are often measured with time delay estimation techniques. A simple implementation is based on the calculation of the cross-correlation functions in short consecutive time periods, which are measured with two slightly separated probes, and the determination of their maximum location. Additionally, a modified version of this method exists, which can reveal velocity modulations from a signal recorded by only one probe. Several experiments had been done in my department with fast probes measuring density fluctuations. However, for the correct interpretation of the extracted flow velocities, the inherent noise of the calculation method needed to be known. I aimed

- To analytically determine the standard deviation of these velocity estimation methods.
- To validate the calculations with numerical simulations and in a realistic environment.
- To utilize the obtained analytical formulas in the interpretation of velocity spectra measured in the Tokamak EXperiment for Technology Oriented Research (TEXTOR) in Jülich, Germany.

Investigation methods

My studies related to fast radiation measurements were carried out in the TCV tokamak in Lausanne, Switzerland. I used the uniquely fabricated AXUV tomographical system which had been installed on the machine but it was in a bad condition at the beginning of my thesis work. The detectors which measured the radiation emitted by the plasma in a wide spectral range were semiconductor detectors of Absolute Extreme UltraViolet type purchased from International Radiation Detectors, Inc. Their specialty consisted in their thin entrance window (8 nanometers) and in the absence of surface dead layers which allowed the detection of light even in the 10 electronVolts spectral range. The slow radiometer system I used as a standard was also unique but its detector modules were routinely used in other tokamaks, too. It had been out of operation and required recommissioning. For tomographical reconstruction of radiation profiles I implemented an algorithm based on publications written by L.C. Ingesson.

In the investigation of fast velocity measurement techniques I was inspired by the calculation done by Dr. Attila Bencze, who had derived a formula for the standard deviation of another velocity evaluation technique. The measurement data I used in this part of the thesis was recorded by the beam emission spectroscopy system on the TEXTOR tokamak. The diagnostic had been designed and operated by my colleagues.

New scientific results (theses)

The main conclusions of my Ph.D. work are summarized in the following thesis points:

1. I have carried out the upgrade of the bolometer-type AXUV system on the TCV tokamak with the following achievements [[1]]:

    a. I have implemented and optimized an existing reconstruction method, which provides appropriate results near the boundaries and thus it is suitable to determine the distribution of the total plasma radiation in either attached or detached divertor conditions.

    b. I have identified the main drawback of the original AXUV diagnostic as the decrease of sensitivity of its detectors at different degrees for different channels. This observation required a significant upgrade of the system including the installation of protective shutters and of a twin detector array set in order to monitor the radiation damage. With a calibration procedure I have reliably determined the Line-of-Sights and the etendues of the cameras.

2. I have shown that near the density limit the radiation of the TCV plasma is peaked not only in the plasma-limiter wall contact zone but also on the magnetic axis. However, only one high intensity peak exists in the high-density snowflake-diverted case which is slightly shifted to the high field side from the magnetic null-point [[1]],[[2]],[[3]].

3. I have revealed the effect of core modes on plasma-wall interaction during the density limit induced disruptive termination of the TCV plasma with the AXUV diagnostic [[1]].

4. I have studied the radiation dynamics of snowflake-diverted H-mode discharges. I have shown that in the interELM phase approaching the snowflake configuration the radiation pattern moves away from the wall in the direction of the null-point with increasing volume and constant amplitude. The bottom strike point radiation is only slightly activated. On the contrary, I have observed

enhanced emission around this secondary strike point at the ELM peak and simultaneously radiation is decreased by a factor of five in the vicinity of the primary strike point. These observations refer to radiation repartitioning among strike points during ELMs [[4]].

5. I have analytically determined the variance of the crosscorrelation-based time delay estimation (TDE) technique according to a plausible model of turbulent events. I have confirmed the results of the provided formula with numerical simulations, general analytic calculations and measurement in the CASTOR tokamak [[5]], [[6]].

6. I have revealed that the wideband parts of the temporal spectra of the ACF-min calculations, which are performed on Lithium beam emission spectroscopy signals measured in the TEXTOR tokamak, are not caused by real fluctuations in the flow velocity. They are indeed the consequences, i. e. the inherent noise, of the ACF-min calculation method. This demonstration has been carried out by adjusting the TDE variance formula to this latter technique [[6]].

List of publications related to the thesis points

[[1]] B Tal, B Labit, D Nagy, R Chavan, B Duval and G Veres *Plasma radiation dynamics with the upgraded Absolute Extreme Ultraviolet tomographical system in the Tokamak a Configuration Variable* Review of Scientific Instruments **84,** 123508 (2013), doi:10.1063/1.4848155

[[2]] NA Kirneva, R Behn, GP Canal, S Coda, BP Duval, TP Goodman, B Labit, NA Mustafin, AN Karpushov, A Pochelon, O Sauter, M Silva, B Tal and The TCV Team *Experimental Investigation of Plasma Confinement in Reactor Relevant Conditions in TCV Plasmas with Dominant Electron Heating* Proceedings of the 24th IAEA Fusion Energy Conference EX/P3-05 (2012)

[[3]] F Piras, S Coda, I Furno, J-M Moret, RA Pitts, O Sauter, B Tal, G Turri, A Bencze, BP Duval, F Felici, A Pochelon, C Zucca S*nowflake divertor plasmas on TCV* Plasma Physics and Controlled Fusion **51**, 055009 (2009) doi:10.1088/0741-3335/51/5/055009

[[4]] WAJ Vijvers, GP Canal, B Labit, H Reimerdes, B Tal, S Coda, GC De Temmerman, BP Duval, TW Morgan, JJ Zielinski and The TCV Team *Power exhaust in the snowflake divertor for L- and H-mode TCV tokamak plasmas* Nuclear Fusion **54,** 023009 (2014) doi:10.1088/0029-5515/54/2/023009

[[5]] B Tal, A Bencze, S Zoletnik *Statistical analysis of two point correlation functions for flow velocity measurements* Europhysics Conference Abstracts **Vol. 31F,** P-2.140 (2007)

[[6]] B Tal, A Bencze, S Zoletnik, G Veres and G Por *Cross-correlation based time delay estimation for turbulent flow velocity measurements: Statistical considerations* Physics of Plasmas **18,** 122304 (2011) doi:10.1063/1.3662432

Miscellaneous publications

[1] VA Soukhanovskii, RE Bell, A Diallo, S Gerhardt, S Kaye, E Kolemen, BP LeBlanc, A McLean, JE Menard, SF Paul, M Podesta, R Raman, DD Ryutov, F Scotti, R Kaita, R Maingi, DM Mueller, AL Roquemore, H Reimerdes, GP Canal, B Labit, W Vijvers, S Coda, BP Duval, T Morgan, J Zielinski, G De Temmerman, B Tal *Advanced divertor configurations with large flux expansion* Journal of Nuclear Materials **438,** S96-S101 (2013) doi:10.1016/j.jnucmat.2013.01.015

[2] H Reimerdes, GP Canal, BP Duval, B Labit, T Lunt, WAJ Vijvers, S Coda, G De Temmerman, T W Morgan, F Nespoli, B Tal and The TCV Team *Power distribution in the snowflake divertor in TCV* Plasma Physics and Controlled Fusion **55,** 124027 (2013) doi:10.1088/0741-3335/55/12/124027

[3] G Veres, B Tal *Gyors (AXUV) bolométerek alkalmazása a plazmadiagnosztikában* Nukleon **2,** 44 (2009)

[4] G Veres, RA Pitts, A Bencze, J Marki, B Tal, R Tye and The TCV Team *Fast radiation dynamics during ELMs on TCV* Journal of Nuclear Materials **390-91,** 835-838 (2009) doi:10.1016/j.jnucmat.2009.01.220

[5] G Van Oost, M Berta, J Brotankova, R Dejarnac, E Del Bosco, E Dufkova, I Duran, MP Gryaznevich, J Horacek, M Hron, A Malaquias, G Mank, P Peleman, J Sentkerestiova, J Stockel, V Weinzett, S Zoletnik, B Tal, J Ferrera, A Fonseca, H Hegazy, Y Kuznetsov, A Ossyannikov, A Singh, M Sokholov, A Talebitaher *Joint experiments on small tokamaks: edge plasma studies on CASTOR* Nuclear

Fusion **47,** 378 (2007) doi:10.1088/0029-5515/47/5/002