INVESTIGATING THE INTERACION OF SOLID DEUTERIUM PELLETS WITH HOT PLASMAS

PhD thesis

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Introduction and history

The type-I ELMy H-mode [Aymar, 2002], discovered in 1982 on the ASDEX tokamak [Wagner 1982], is foreseen as the baseline operating scenario for future power plants and experimental devices such as ITER [ITER, 1999]. Beside reactor-relevant parameter range, this scenario is characterised by repetitive instabilities called ELMs (*Edge Localised Mode*) [Zohm 1996], which can cause intolerably high peak power loads on plasma facing components – therefore, the mitigation of ELM effects is highly desirable. It was observed experimentally that the amount of energy expelled per ELM is inversely proportional to the ELM repetition rate [Herrmann 2002], i.e. the ELM power loads can be mitigated by increasing the ELM rate.

A promising technique to increase the ELM rate is the so-called ELM pacemaking by pellets. As experiments have shown, fuelling pellets injected into type-I H-mode discharges promptly (within 1 ms) trigger ELMs after entering the confined plasma [Lang 1996, Baylor 2001], which implies that by applying a sufficiently high pellet injection rate we can gain control over the ELMs. According to observations, when the pellet rate exceeds the spontaneous ELM rate by a factor of 1.5 or more, only triggered ELMs are detected, i.e. full control over the ELM activity can be achieved, and the ELM rate can be set by the pellet rate [Lang 2005].

In present-day experiments, applying high pellet injection rates is problematic because the pellet mass is comparable to the main plasma particle content, that is, the target plasma scenario is considerably changed by the pellets. Therefore one important aim of the present investigations is to decrease the mass of ELM-triggering pellets. Such a development is ongoing at the Institut für Plasmaphysik (IPP) Garching in Germany [Lang 2007], aiming at the production and acceleration of pellets with a volume less than 1 mm^3, at a rate up to 80 Hz.

However, the ELM-triggering process (which gives the basis for ELM pacemaking) is not yet fully understood. The perturbation causing the ELM has to be identified and characterised in order to be able to predict the necessary pellet parameters for ELM-triggering in a future fusion device. Experiments at ASDEX Upgrade (AUG) tokamak have shown that at the moment of the ELM birth the pellet (the source of perturbation) is located in about the middle of the pedestal ('trigger location'), and the ELM can be detected ca. 50 μs later (the growth time of the instability, 'internal delay time') [Kocsis 2007]. Furthermore it was observed that the pellet-driven perturbation is dependent on the pellet's position inside the plasma, therefore the perturbation has to be studied along the pellet trajectory.

Objectives

During my PhD work I have joined three closely related research topics, conducted at MTA KFKI-RMKI and at IPP Garching in the framework of EURATOM: commissioning the new pellet injector ("Blower-gun") at ASDEX Upgrade and optimising its operating parameters; investigation of pellet dynamics in hot tokamak plasmas; investigation of ELM-triggering and pellet-driven perturbations related to the ELM trigger.

The first online results with the Blower-gun (contrary to laboratory tests) showed a rather weak efficiency: almost no pellets could make it into the plasma. In order to identify the problem, the pellet shadowgraphy diagnostic system, capable of photographing pellets during their flight, was re-installed for the Blower-gun. My tasks in this field were as follows:

- Upgrading the outdated shadowgraphy system with digital cameras.
- Commissioning and operating the new shadowgraphy system.
- Estimating the pellet mass using the shadowgraphy photographs.
- Optimising the injector settings based on the estimated pellet mass (to maximise pellet mass arriving into the plasma).

Later on in my PhD work, I investigated the dynamics of pellets in the plasma – an important contribution to the pellets' penetration depth and fuelling. I used the experimental results to validate pellet ablation models. My tasks were the following:

- Extending the existing AUG pellet camera system by two new cameras and three additional views.
- Operating and maintaining the AUG pellet camera system.
- Determining pellet trajectory, velocity and acceleration based on camera images.
- Developing a simple model to describe the radial acceleration of pellets, and validating the model with measurements.

In the last part of my work, I studied the reaction of the plasma to pellet injection, focusing on the magnetic perturbations driven by the pellet. My aim was to determine whether the pellet-driven magnetic perturbation is capable of triggering an ELM. My tasks were the following:

- Defining a quantity related to the 'strength' of the pellet-driven magnetic perturbation.
- Determining the characteristics of the pellet-driven magnetic perturbation in three different plasma scenarios.
- Investigation of type-III ELM-triggering (determining the internal delay time and pellet location at the instance of the ELM-trigger).

The points listed here show that beside physics investigations my work also involves, to a considerable extent, technical and methodology tasks. Throughout my work I am trying to emphasise the scientific achievements, while the rest serves understanding and clarity. Additionally, the operation of the camera systems, as well as the evaluation of camera images and measurement data involved a considerable amount of programming, out of which only the applied methods or algorithms will be presented here (in order to ensure reproducibility).

Methods

One of the key points of my PhD work has been the evaluation (calibration) of camera images. A camera image is "calibrated" if there exists a transformation that maps real space coordinates into the right place on the image. With the necessary additional information this transformation is reversible, that is, the real space coordinates of any object on the image may be determined. The necessary additional information to determine the pellet trajectory was that the pellet's toroidal movement is negligible (i.e. the pellet moves in a fixed poloidal plane). I have determined the pellets' trajectory, penetration depth and radial acceleration based on camera images. The penetration can also be determined using the so-called ablation monitor signal (wide-angle observation of the visible light emitted by the pellet cloud with a photodiode): the monitor signal reveals the pellet's 'lifetime' in the plasma; multiplying this with the pellet speed gives an estimate of the penetration depth.

To determine the pellet volume, a Bayesian probability analysis was used to evaluate the shadowgraphy images. The basic assumption of my analysis was that the pellet remains cylindrical at all times – this enables us to estimate the pellet volume using only one photograph. Using three predefined parameters of the pellet shadow, I calculated the probability density function (PDF) of the pellet's radius, height and orientation (the normal vector of the cylinder's base). Using these, I calculated the PDF of the pellet volume, and used the mean value as the final result of the volume estimation process.

In order to compare the pellet-driven perturbation to other plasma diagnostics, the pellet trajectory as the function of time has to be known. For this the pellet trajectory and the time stamp of at least one point on the trajectory is necessary – this reference point was chosen as the location and time of the pellet-separatrix crossing. I used special camera images to identify this reference point: a very short exposure image was made about the pellet (already in the plasma!); then, its location was determined; assuming straight and acceleration-free movement between the injection tube and the point identified on the image, the separatrix intersection could be calculated. By knowing the camera frame time and the pellet velocity, the time instance of the separatrix-crossing can be calculated.

To characterise the strength of the pellet-driven perturbation, I introduced the quantities envelope and band power. To produce the envelope first the studied signal was high-pass filtered; then the Vpp value was determined in 25 μs boxes. The band power was produced from the signal's Fourier spectrogram by integrating the power density between 100 and 300 kHz. Using the high-pass filter or the mentioned frequency range is necessary because the studied phenomena show a high level of activity also in this range, whereas below 100 kHz many plasma modes are detectable which would disturb my observations.

An important property of the magnetic perturbations is the so-called mode number. In tokamaks plasma modes are usually assumed as waves that close upon themselves; the toroidal/poloidal mode number gives the number of (e.g.) wave crests per toroidal/poloidal turn around the torus. The sign of the mode number usually represents the direction of movements: in my work positive mode numbers denote modes that follow the electron drift direction. The mode number can be determined by the simultaneous study of several magnetic probes. The principle of the method is that the relative phase between the signals of two probes is proportional to the distance (angle!) between the probes, i.e. using more probe pairs the data points lie on a straight line (for a coherent mode) – the slope of the line gives the mode number. The mode numbers presented in this study were determined by Gergő Pokol.

New scientific results (theses)

The new scientific results achieved during my PhD work are summarised in the following theses:

1. I have compared the *pellet-driven magnetic perturbation* along the pellet trajectory in three different plasma scenarios with the aim to determine whether the pellet-driven magnetic perturbation is able to act as a trigger for type-I ELMs.

    - I have ascertained that the pellet drives Alfvén waves in the plasma, the structure (mode number) of which is entirely different from that of pre-ELM modes or ELMs themselves. Therefore I have concluded that the pellet-driven magnetic perturbation is unlikely to trigger the ELM. (Section 4.3.2) [3] [4] [5] [8] [9] [12]
    - I have determined that the strength of the pellet-driven magnetic perturbation depends on the plasma parameters at the instantaneous position of the pellet. Plotting the perturbation strength against the plasma electron pressure, all data points fall onto the same curve. (Section 4.3.2) [3] [5] [8] [9] [12]

2. I have determined the *delay time of type-III ELMs* compared to the instance of pellet injection as the function of pellet velocity. I have ascertained that the pellet, similarly to type-I ELM case, has to reach a certain point of the plasma in order to trigger a type-III ELM. This trigger location is within the pedestal, which complies with present ELM theories. (Section 4.3.3) [3]

3. I have studied both experimentally and theoretically the *radial acceleration of pellets* along the pellet trajectory. I have achieved the following results:

   - I have developed a *model* that describes the radial acceleration by assuming that the acceleration is caused by the asymmetry in pellet ablation ("asymmetric model"). In all studied cases an asymmetry of 10% or less was sufficient to reproduce the experimentally observed acceleration values; this asymmetry is low enough to explain the fact that no asymmetry in the light emission of the pellet cloud (proportional to the ablation rate) was seen on the camera images. (Section 4.2.3) [2] [6] [7] [13]
   - I have compared the experimentally measured penetration depth and radial acceleration of pellets to the results of my simulations. Although the model can reproduce the experimentally measured radial acceleration fairly well, a notable discrepancy was seen in the penetration depth. The model could reproduce the penetration only for 600 m/s pellets, for slower pellets the penetration was underestimated, while for faster pellets it was overestimated. (Section 4.2.3) [2] [7]

4. To support the conducted experiments, I have developed the following procedures (which include a considerable amount of physics and experimental knowledge):

   - Using Bayesian analysis I have developed a method that is able to *estimate the volume of a cylindrical pellet* automatically, using a single camera image as input. Using this method I have optimised the parameters of the Blower-gun pellet injector. (Section 4.1) [1]
   - I have developed a method to *determine the pellet's trajectory, penetration depth, radial acceleration along the path and the separatrix crossing time* using a "standard" camera image. I have used this method to achieve the results of the above three thesis points. [6] [13] I have compared this penetration to the penetration depth calculated from the pellet's lifetime and nominal speed. I have concluded that the latter significantly lower than the real penetration because it cannot account for the pellet's radial acceleration in the plasma. (Section 4.2.1) [10] [11]
   - I have developed a method, which can – by using the ablation rate scaling of an arbitrary ablation model – estimate the mass of a pellet based on the measured pellet trajectory and plasma parameters. Using this method the asymmetry introduced in thesis point 3. can be determined along the pellet trajectory. I have found that the asymmetry can be regarded as constant along the trajectory in the plasma, which justifies the use of constant asymmetry in the asymmetric model. (Section 4.2.5) [6] [13]

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Exploitation of the results

The new shadowgraphy diagnostic system (and the volume estimation algorithm) is now one of the key diagnostics helping the development of the Blower-gun injector. Presently the production of pellets with 1 mm diameter and 1-1.5 mm length is in an experimental phase; the effect of any change in the injector settings on the pellets' volume and speed can be instantly monitored through the shadowgraphy images, therefore the mapping of the injector parameters is faster and more effective.

In my study of the pellet-driven magnetic perturbation I have concluded that the ELM is not triggered by the pellet's magnetic perturbation. Consequently, the study of the ELM trigger mechanism can be focused onto other phenomena, such as the high pressure pellet cloud or the cooling wave caused by the pellet.

Related publications

Papers published in scientific journals

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[8] G. Kocsis, A. Aranyi, V. Igochine, S. Kálvin, K. Lackner, P.T. Lang, M. Maraschek, V. Mertens, G. Pokol, G. Pór, T. Szepesi and ASDEX Upgrade Team
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Determining Pellet Penetration Depth in ASDEX Upgrade Plasmas using Video Observation
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[11] Szepesi T., Kálvin S., Kocsis G., P.T. Lang, ASDEX Upgrade Team
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