TRANSIENT WAVES IN FUSION DEVICES STUDIED BY STATISTICAL METHODS AND THEORETICAL MODELS

PhD theses

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Research background

The application of nuclear fusion for energy production is a possible way to escape form the complex problem of rising energy demand and global warming [European Physical Society, 2007]. However, fusion of atomic nuclei takes place only in high energy collisions, and therefore technical realization of fusion energy production is still a job for the future. Taking the energy dependence of the fusion reaction cross-sections into account, the criterion for fusion energy production is: confinement of sufficiently high density material with good enough isolation (long characteristic cooling time) at a temperature of about 100 million K, even for the most favorable deuterium-tritium reaction. The most promising concept for plasma confinement is through the application of magnetic fields. In magnetical confinement devices, a relatively low density – atmospheric pressure, despite the high temperature – plasma is confined by a strong, torus-shaped magnetic field for relatively long time.

Throughout their fifty-year development, magnetic confinement fusion devices have developed two successful subtypes: the tokamak and the stellarator. Both concepts utilize a closed, toroidal magnetic geometry, so that charged plasma particles moving along magnetic field lines cannot leave the device. In a stellarator, the magnetic field structure necessary for stable confinement is created by outer magnetic coils, while tokamaks make use of a strong toroidal plasma current driven in the plasma. Research is intense in both directions: the ITER tokamak [ITER Physics Basis Editors et al., 1999] is being built supported by experience with smaller tokamaks (e.g. ASDEX-Upgrade), while construction of the Wendelstein 7-X stellarator was motivated by promising results of its predecessor, Wendelstein 7-AS [Hirsch et al., 2008].

My results in the field are connected to the transient waves in magnetically confined fusion plasmas. High temperature and low density plasmas frequently exhibit such phenomena, which – through non-linear processes – may have severe effects on transport processes and fast particle populations. Reflecting the importance of the topic, transient plasma waves and related transients are widely researched both from experimental and theoretical sides.

Research aims

The present dissertation aims at understanding issues in the interaction of transient waves and transport processes in fusion devices by processing experimental data by statistical methods and by theoretical calculations. From this wide range of problems, I have concentrated on two special problems:

1. Study of the interactions of edge localized transient waves and transport phenomena on the Wendelstein 7-AS stellarator (ELM-like modes, quasi-coherent modes), and supporting a similar study on the ASDEX-Upgrade tokamak (ELM, pellet). Development and application of data processing methods to perform a comparative study between different plasma diagnostics, setting up theoretical models explaining the observed sequence of events.

2. Theoretical description of the interaction of the runaway electron beams of large tokamaks and whistler plasma waves. Search for a threshold for the destabilization of wave and model its effect on the relativistic runaway electron population.

Research methods

Several physical quantities have been measured at the Wendelstein 7-AS stellarator at sampling frequencies enabling the resolution of transient transport events. In the cross-diagnostics correlation analysis presented in the thesis, measurements of magnetic field fluctuations, plasma density, plasma temperature and intensity of millimeter-scale plasma waves were used [Hirsch et al., 2008]. Related transient waves – both at Wendelstein 7-AS and ASDEX-Upgrade – were characterized primarily using data from magnetic pick-up coils.

The set of traditional noise diagnostics methods used, included Fourier spectra, coherence, phase and correlation functions [Schnell, 1985]. I have generalized these methods to be used for transient signals based on continuous linear time-frequency transforms [Mallat, 2001].

The theoretical calculations presented, are based on kinetic description of the plasma: the linear stability of the plasma wave and the quasi-linear particle-wave interaction can both be derived from the collisionless Boltzmann equation [Stix, 1992].

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New scientific results

1. **Thesis:** I developed a bandpower-correlation signal processing method, in which the signal is decomposed to components having different frequency contents by an appropriate continuous linear time-frequency transform, and the resulting bandpowers are further processed using cross-correlation functions to reveal statistical dependencies. I analyzed the questions of applicability and parametrization of the method in detail. [P1,P10]

2. **Thesis:** I applied and analyzed the traditional – with frequency shift invariant smoothing – wavelet coherence and short-time Fourier transform based time-frequency coherence. I introduced the wavelet coherence with scale invariant smoothing. This enhanced the general applicability of wavelet coherence, as it allowed the error of coherence estimation to be uniform on the time-frequency plane, while time-frequency resolution resembles that of the wavelet transform itself. By applying the method on magnetic signals of the Wendelstein 7-AS stellarator and the ASDEX-Upgrade tokamak, I detected globally coherent transient waves. [P2,P3,P7,P8,P11,P12]

3. **Thesis:** I gave an algorithm to estimate the mode numbers of transient waves from multipoint measurements with optimum time-frequency resolution. The method is based on cross-spectrum-like quantities – cross-scalogram or cross-spectrogram – calculated from continuous linear time-frequency transforms and provides a time-shift invariant time-frequency mode number map. With this method, I determined poloidal mode numbers of transient waves in the Wendelstein 7-AS stellarator and toroidal mode numbers in the ASDEX-Upgrade tokamak. [P3,P7,P8,P11]

4. **Thesis:** I analyzed the connection of ELM-like events and transient MHD modes in the Wendelstein 7-AS stellarator in an cross-diagnostic comparative study applying bandpower-correlation and other noise diagnostics methods. This study involved raw signals and bandpowers of poloidal magnetic field (Mirnov-coils), local electron density fluctuation and radial electron density profile (LiBES), electron temperature profile (ECE) and electron density turbulence (LOTUS) measurements. I concluded that, in the case of bad confinement, complex and spatially extended transport events take place affecting global confinement. Through the comparison of different types of discharges, I arrived to the conclusion that ELM-like modes are responsible for a small fraction of the total transport. Spatial structure of the transient waves is often resonant to the magnetic field geometry, but other modes appear, as well. [P1,P9,P13,P14,P15]

5. **Thesis:** Based on the kinetic theory of magnetized plasmas, I estimated the threshold of the destabilization of magnetosonic-whistler waves due to the effect of runaway electrons generated in tokamak disruptions through the anomalous Doppler resonance. Results showed that in the disruptions of large tokamaks this wave can indeed be destabilized, and threshold is lower for lower magnetic field. [P4,P5,P16,P17]

6. **Thesis:** Based on the quasi-linear theory of wave-particle interaction, I modeled the effect of whistler waves on the distribution function of runaway electrons. My results showed

that this effect is a rapid pitch angle scattering. The process evolves in successive phases, whose dynamics depends sensitively on plasma parameters. However, the end result is always the scattering of the runaway electron beam. The above results provide a possible explanation to the experimental observation, that in large tokamaks runaway electrons are absent below a critical magnetic field. [P6,P7]

International journal papers connected to the theses

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[P12] E. Belonohy, G. Papp, **G. Pokol**, K. McCormick, S. Zoletnik and W7-AS Team:
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[P13] **G. Pokol**, G. Por, S. Zoletnik, N. P. Basse and W7-AS team,
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15. **G. Pokol** and G. Por:
ALPS loose parts monitoring system and wavelet analysis,
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1. **G. Pokol** and S. Zoletnik:
   Application of BES for MHD and turbulence measurements,
   Workshop on Active Beam Spectroscopy for control of the fusion plasma (24-27 March 2009, Leiden, Netherlands).

2. **G. Pokol**:
   Interesting problems from the field of fusion plasma physics - Érdekes feladatok a fúziós plazmafizika területéről,
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3. **G. Pokol**, T. Fülöp, P. Helander, M. Lisak and D. Anderson:
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