Fast ions in tokamak plasmas

Christian SCHLATTER,
École Polytechnique Fédérale de Lausanne (EPFL),
Centre de Recherches en Physique des Plasmas (CRPP),
CH-1015 Lausanne, Switzerland

December 10, 2004

Thesis research plan

1 Introduction and current state of the field

An ignited fusion tokamak plasma is essentially kept burning through the continuous production of highly energetic α-particles, which need to be confined (during their thermalization) within the magnetic structure of the reactor for a time long enough, so that the temperature of the background plasma (and therefore the fusion reaction rate) is maintained at optimum level [2]. Confinement can be a difficult challenge, since the fast ions can drive collective instabilities causing anomalous transport (accompanied with important heat losses) [12], [4].

The role of fast particles in tokamak plasmas has been studied on various experimental facilities and remains a current and future research field. Further progress is necessary for the understanding of the redistribution of fast ions by magnetohydrodynamics instabilities or the stabilization of internal kink modes through kinetic effects of fast particles [10].

Large tokamaks as the today biggest reactor, JET, at the Culham Science Center in Oxford (England) already operated with D-T fueled plasmas including important fusion born α-particle populations. Additional heating schemes such as waves in the ion- or electron-cyclotron range of frequencies (ICRF/ECRF) [5] or neutral beam injection (NBI) [8] can produce a significant population of fast suprathermal particles.

The presence of ions may be detected using neutral particle analyzers (NPA), which measure the neutrals escaping the plasma (carrying the signature of the fast ions before they were neutralized through charge-exchange reactions with plasma neutrals) [7].
Some tokamaks use neutron detectors and highly energetic ions are conveniently analyzed using gamma ray measurements.

For an experimental overview of the behavior of fast ions in tokamak experiments, see [6].

2 Research plan

This thesis is devoted to the study of fast particles using data from past and future experiments in the mid-sized Tokamak à Configuration Variable (TCV) at the Plasma Physics Research Center (CRPP) at EPFL and JET in Culham.
Both machines are equipped with low- and high-energy neutral particle analyzers and the database of experimental data at JET is already well populated.

2.1 TCV

On TCV the plasma is heated by electron-cyclotron waves, the fast ions are thought to be created through the thermalization of the fast electrons on the ions. A diagnostic neutral beam injector (DNBI) is also available for active measurements and to inject a range of neutral energies. A new high-energy neutral particle analyzer for simultaneous measurements of hydrogen/deuterium or deuterium/helium ion species was installed in 2004.
First experiments with fast particle populated plasmas will be possible at the beginning of 2005. A code (1D in space, 2D in velocity) for the modeling of the neutral emissivity spectrum based on experimental input profiles of ion and electron densities and temperatures is already available for TCV (KN1D, [9]), a multi-species (H/D/T/He) code (DOUBLE-TCV) will be available at the beginning of 2005. The tools necessary to determine fast ion temperature and distribution function f_i^{fast} are under development.
Validation of experiments with simulation will be an important part of this thesis. Various scenarios with implication of fast ions are not well understood yet but can be studied in the frame of this work. These include the question of the type (classic or anomalous) of the slowing down of the DNBI beam, the degradation of the electron-cyclotron current drive (ECCD) efficiency in plasmas heated with ECRH, the process of fast ion generation or the sawteeth stabilization - in special the associated radial transport of fast ions.

2.2 JET

Part of this thesis has already (and will) be devoted to experiments on JET, which use additional ion heating by ion-cyclotron wave launchers and neutral beam injectors. The high-energy NPA is going to be refurbished and recalibrated for experiments in the 2005 campaign. The neutralization code for the calculation of the temperature, density and distribution function of fast ions available for JET experiments [1] was reactivated during a stay in Q4/2003-Q1/2004 and its accuracy was studied [11]. A next step will be the characterization of the various heating schemes of the JET tokamak with the aim of validating the plasma heating theory used for the simulation of the experiments. As on TCV, the radial ion transport in the presence of MHD modes will be studied. Depending on the decision of a experimental programme at JET after 2005, further understanding of the role of the fast ions in driving the plasma core rotation may be strived for (ITER, the proposed International Thermonuclear Experimental Reactor, will need sufficient core rotation for the stabilization of its various MHD modes).

3 Importance of the subject

Self-sustained ignition of a plasma in ITER depends on heating by highly energetic α-particles. The instabilities related to these particles decide whether or not a bigger and hotter fusion reactor will be feasible. Estimates for ITER indicate that α-particle losses greater than 5% being repeated from shot to shot may be sufficient to cause damage to the first wall, whilst higher losses may even lead to the quench of ignition [3]. For a discussion of energetic ions in the frame of ITER see [2].

References

[1] A.A.Korotkov, A.Gondhalekar, and A.J.Stuart, *Impurity induced neutralization of megaelectron-volt energy protons in jet plasmas*, Nuclear Fusion **37** (1997), no. 1, 35–51.

[2] ITER Physics Basis Editors, *Physics of energetic ions*, Nuclear Fusion **39** (1999), no. 12, 2471–2495.

[3] C.Z. Cheng et al., Proceedings of the 16th IAEA International Conference on Fusion Energy (Montreal, Canada), International Atomic Energy Agency IAEA, Vienna, volume 2, paper IAEA-CN-64/FP-23, pp. 953–962.

[4] P. Smeulders et al, *High-beta regimes in jet*, 17th EPS conference on controlled fusion and plasma heating (Amsterdam, Netherlands), European Physical Society, 1988, pp. 323–326.

[5] V. E. Golant and V. I. Fedorov, *Rf plasma heating in toroidal fusion devices*, Plenum, New York, 1989.

[6] W. W. Heidbrink and G. J. Sadler, *The behaviour of fast ions in tokamak experiments*, Nucl. Fusion **34** (1994), no. 4, 535–615, see corrigendum in NF 35 (1995) 243.

[7] I. H. Hutchinson, *Principles of plasma diagnostics*, Cambridge University Press, Cambridge, 2002.

[8] R. K. Janev and K. Katsonis, *Recent progress in production and evaluation of atomic data for fusion*, Nuclear Fusion **27** (1987), no. 9, 1493–1546.

[9] Brian LaBombard, *Kn1d: A 1-d space, 2-d velocity, kinetic transport algorithm for atomic molecular hydrogen in an ionizing plasma*, Tech. Report PSFC/RR-01-9, MIT Plasma Science & Fusion Center (PSFC), 175 Albany St., Cambridge, MA 02139, USA, 2001.

[10] F. Porcelli, *Fast particle stabilisation*, Plasma Physics and Controlled Fusion **33** (1991), no. 13, 1601–1620.

[11] Christian Schlatter, Duccio Testa, Marco Cecconello, Andrea Murari, and Marko Santala, *Error estimation and parameter dependence of the calculation of the fast ion distribution function, temperature, and density using data from the kf1 high energy neutral particle analyzer on joint european torus*, Review of Scientific Instruments **75** (2004), no. 10, 3547–3549.

[12] R. B. White, R. J. Goldston, K. McGuire, Allen H. Boozer, D. A. Monticello, and W. Park, *Theory of mode-induced beam particle loss in tokamaks*, Physics of Fluids **26** (1983), no. 10, 2958–2965.

Approval of the thesis plan

PhD candidate

Christian SCHLATTER

Thesis director

Dr. Basil DUVAL