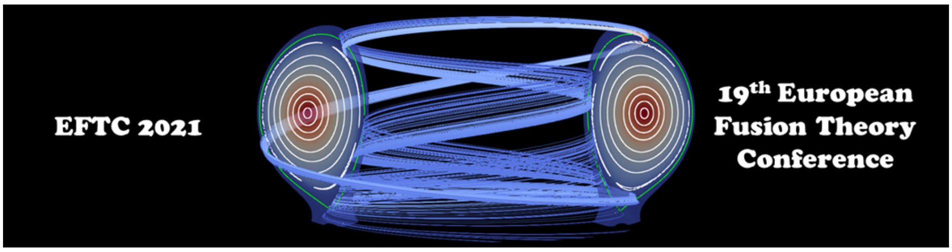

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Fast particle instabilities in magnetic fusion: experiment vs theory

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Magnetic fusion is now approaching next-step D-T burning plasma experiments in ITER, which will be mostly self-heated by fusion-born alpha-particles. Burning plasmas will be a highly nonlinear medium, and predicting with confidence the alpha-particle heating and alpha-particle losses in such plasmas is a very challenging task. To advance it, dedicated experimental studies are being performed on present-day machines worldwide with fast ions matching the key ITER dimensionless parameters βfast/βthermal, Vfast/VA, R0·d(βfast)/dr. Progress with experimental studies is closely coupled with the development and validation of theoretical analyses and numerical simulations, together with their extrapolation to future burning plasmas. Among all alpha-particle effects, instabilities excited by wave-particle resonances with the super-Alfvénic alpha-particles constitute the largest uncertainty in the predictions for ITER. Thus, studying of fast-ion driven instabilities is one of the highest priority experimental and theoretical research tasks. In Europe, fast particle experimental studies are mostly performed on the largest tokamak JET, and on several medium-size tokamaks: ASDEX-Upgrade (AUG), TCV, MAST, and on stellarators Wendelstein 7-X and TJ-II. The JET machine leads the research on fast ions in the MeV energy range. In view of the upcoming D-T campaign (2021), JET has performed dedicated experiments on scenarios for alpha-particle-driven Alfvén eigenmodes (AEs), and on investigating alpha-particles born in aneutronic D-3He fusion. A rich variety of AEs with frequencies ranging from ~50 kHz to ~500 kHz were excited in recent D-3He experiments on JET, part of which were attributed to alpha-particles with a bump-on-tail distribution self-sustained by periodic modulation of the fusion source with sawteeth. The medium-size tokamaks AUG and TCV have contributed to the development of novel methods for controlling AEs with ECRH/ECCD, which could be used eventually for burning plasma control. Finally, both the spherical tokamak MAST and the TJ-II stellarator have observed beam-driven Alfvén instabilities with fast frequency sweeping (the "chirping modes"), successfully interpreted in the framework of the non-linear Berk-Breizman theory as discussed in this talk. First observations of fast-ion driven instabilities have been also reported from Wendelstein 7-X. The wealth of fast-ion experimental data described above was validated with fast-ion modelling tools. High-confidence exists now for the predictive capabilities of linear spectral MHD codes used in EUROfusion such as CASTOR-K, MISHKA, and HALO to compute the spatial structure of AEs and their frequencies. This very accurate computational analysis has resulted in a new technique 'Alfvén spectroscopy', providing valuable information on the evolution of the q-profile and plasma density from the observed AE spectrum. The MHD codes are routinely used to identify the wave-particle resonances and compute energetic-ion drive mechanisms. Concurrently, kinetic codes such as LIGKA have been advanced to provide fairly accurate estimates of the kinetic damping effects, some of which are exponentially sensitive to plasma parameters. In this talk, we illustrate that strongly nonlinear codes have become an accurate tool to describe the dynamics of energetic-particle modes well above the threshold of the mode excitation. We also discuss further developments and needs in fast-ion theory, modelling and experiment towards a better understanding of AEs in burning plasmas. These include studies of multiple fast-ion driven modes with high toroidal mode numbers as expected for ITER. The resonance overlap and global stochasticity of fast-ion orbits could play a dominant role in the case of multiple modes, but such conditions have not been sufficiently studied yet. This advancement will require a dedicated effort both in developing appropriate diagnostics and modelling tools.

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