28th IAEA Fusion Energy Conference (FEC 2020)

Contribution ID: **1212** Type: **Regular Poster**

Study of fast ions redistribution and losses due to energetic particle modes in MAST

Friday 14 May 2021 12:10 (20 minutes)

Understanding the confinement of Fast Ions (FI) in tokamaks is fundamental for the successful operation of ITER and the development of fusion power plants based on DT reactions. Spherical tokamaks make it possible to test confinement and operational regimes in ITER-like scenarios in the presence of energetic particle modes and Alfvén instabilities. Descriptive and predictive modelling of the confinement and redistribution of fast ions are key ingredients, for example, to the successful implementation of non-inductive current drive scenarios.
To this end, dedicated experiments were carried out in the Mega Amperical Spherical Tokamak (MAST) to measure and simulate the redistribution and loss of neutral beam injected FIs due to their interaction with Energetic Particle Modes (EPMs) by combining observations from Fast Ion D-alpha diagnostics (FIDA), a multi-channel Charged Fusion Product Detector, a Fission Chamber (FC) and a Neutron Camera (NC) with simulations performed using the TRANSP/NUBEAM code 1. In reference 1, the experimental observations were modelled using a combination of an "ad-hoc"time-dependent Anomalous Fast Ion Diffusion (AFID) coefficient AD(t) and the so-called "Fish-Bone"(FB) model employed in NUBEAM. By adjusting the free parameter AD(t) and the region in energy and pitch in which the FI distribution was suppressed (thus simulating the effect of "fishbones"), it was possible to obtain a good agreement between predicted and measured global neutron rates as shown in figure 1. The main limitation of this approach was the lack of a physical justification for the chosen values of AD(t) and for the selected regions of energy and pitch in which the FI distribution was suppressed. An additional problem, was that it had not been possible to obtain a single FI distribution which simultaneously agreed with both FIDA and NC observations.
In this work, in an attempt to address both issues, a second modelling approach has been used in which the experimental observations have been predicted using the so-called "kick model"2. In this model, FI transport emerges from Monte Carlo simulations of test particle trajectories in the presence of perturbations of the plasma equilibrium with which the FI resonate. A Probability Density Function (PDF) for energy and toroidal canonical angular momentum "kicks"imparted to the FIs in their interactions with the perturbations has been estimated using the guiding-centre ORBIT code in which the equilibrium, the perturbation eigenfunctions and amplitudes, and the FI initial conditions, sampled from a TRANSP/NUBEAM computed FI distribution, were provided as input. The perturbation eigenfunctions were estimated using a combination of i) simple analytical expressions for the internal plasma displacement and ii) information on electron density fluctuations derived from Soft X-Ray (SXR) measurements. In this study, the spatial profile of the perturbation was assumed to be time independent. On the other hand, its amplitude was taken to be proportional to the time evolution of the root mean square value of the magnetic field perturbation at the edge measured by Mirnov coils with the proportionality constant as the single free parameter.

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As shown in figure 1, good agreement between observed and predicted global neutron rates was achieved by adjusting the proportionality constant of the perturbation amplitude of the "kicks"in energy and toroidal canonical angular momentum imparted to the fast ions. Global neutron measurements alone, however, did not make it possible to disambiguate between these two modelling strategies. For this reason, FI distributions and non-flux averaged neutron emissivity profiles were calculated at selected times during the plasma discharge for both AD and "kick"models. Before the EPM burst, the spatial FI distributions computed using the AFID and "kick"model approach were rather similar. The two, however, differed significantly in the post EPM burst phase as shown in figure 2.

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The synthetic measurements calculated on the basis of these two modelling approaches were compared to FIDA and NC measurements. An example of this comparison is shown in figure 3. The results clearly indicated that the FI hollow profiles predicted by the "kick"model do not match the experimental observations either in absolute values or in shape. Possible explanations for this disagreement are i) the constant spatial shape of the eigenfunction used to model the EPM induced perturbation and ii) the guiding-centre approach used to estimate and apply "kicks"in energy and toroidal canonical momentum in spherical tokamak conditions where the magnetic moment at the first order is not conserved. Work is in progress to address both these issues. In particular, a full orbit implementation of the "kick"model but in the full orbit HALO code 3 is underway.

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1 Cecconello M et al. "Energetic ion behaviour in MAST"Plasma Phys Control Fusion. 2015 57 014006.
2 Podestá M. "A reduced fast ion transport model for the tokamak transport code TRANSP"Plasma Phys Control Fusion 2014 56 055003.
3 M. Fitzgerald et al. "Full-orbit and drift calculations of fusion product losses due to explosive fishbones on JET"Nucl. Fusion 2019 59 016004

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053, from the Swedish Research Council and from the RCUK Energy Programme [grant number EP/P012450/1]. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Session Classification: P7 Posters 7

Track Classification: Magnetic Fusion Experiments