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Energetic Particle dynamics induced by off-axis neutral beam injection on ASDEX Upgrade, JT-60SA and ITER

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In this paper we report on experimental and modeling results concerning the energetic particle (EP) dynamics in plasma scenarios with off-axis neutral beam (NB) injection at ASDEX Upgrade (AUG). The tools validated in this processes are applied to selected scenarios at JT-60SA and ITER pre-fusion plasmas.
Off-axis NB injection is an important tool to control and optimise the current profile in both conventional and advanced tokamak scenarios. Via tailoring the safety factor profile, rational surfaces can be avoided, the local magnetic shear can be changed or reversed shear regions can be established. Whereas in present devices the beam energies are typically 10-20 times larger than the plasma thermal energies and smaller than the Alfvén velocity (vNBI /vA ~ 0.3 – 0.4), in future devices such as JT-60SA and ITER these ratios will go up to 100 for vNBI/vthermal and to vNBI/vA ~ 1. Thus, it is expected that the related EP-driven instabilities and the relaxation of the spatial EP pressure gradients will be different (e.g. mode number spectrum, non-linear saturation) than in present-day experiments.The related EP transport is directed to deplete the gradients, i.e. inwards in the positive gradient region and outwards in the negative gradient region. Since the redistribution of the EP beam will affect the background plasma properties through various channels, it is of interest to analyse the EP redistribution and to test if stability predictions and related EP transport calculations are able to catch the experimental signatures and thus can be used with confidence in future comprehensive scenario simulations.
In 2017 a new scenario on ASDEX Upgrade has been established for the dedicated investigation of energetic particle (EP) physics [1] that is optimised to maximise βEP/βth and the ratio vNBI/vthermal. This scenario has been recently further developed into both an L-mode and an H-mode scenario with stable flat-top phases and with more complete diagnostic coverage. As in the previous discharges, we let impurities (mainly tungsten) accumulate in the core. Due to strong radiation losses the background temperatures and pressures of both ions and electrons stay low, despite 2.5 – 5 MW NB heating. In order to avoid transient q = 2 sawtooth-like crashes, as seen previously with a total plasma current of 800kA, the current has been reduced to 700kA. Under these conditions we reach an EP-β comparable to the background β and ratios of 100 and larger for vNBI/vthermal, whereas vNBI /vA ~ 0.3 – 0.4. A rich spectrum of modes is destabilised: EP-driven geodesic acoustic modes (EGAMs), beta-induced Alfvén eigenmodes(BAEs), reversed shear Alfvén eigenmodes (RSAEs) and toroidal Alfvén eigenmodes (TAEs). In particular the EGAM onset is triggered by TAE bursts indicating a coupling of these modes via EP phase space transport. Bicoherence analysis also reveals non-linear coupling signatures between various frequency bands. Comparisons of FIDA-measured EP profiles and neoclassical calculations are shown, and indications for anomalous background ion heating via EP-driven instabilities are investigated.
Using the linear gyro-kinetic code LIGKA [2], the onset conditions for various instabilities are analysed, as the experiment provides excellent data in this respect. Experimental mode properties are determined and compared to the LIGKA results. In particular, symmetry breaking signatures of non-perturbative mode structures [4] are investigated. Non-linear hybrid simulations (HAGIS/LIGKA [2, 3]) are carried out in order to quantify the difference between experimental measurements and this model. By comparing to other models such as non-linear hybrid kinetic MHD models and gyrokinetic codes, the importance of e.g. non-linear wave-wave coupling processes can be inferred. This analysis is linked [5] to a benchmark and validation exercise [6] including the codes HYMAGIC, MEGA and ORB5, that is based on this AUG case (see also refs in [6]).
The exploration of scenarios with off-axis NB deposition leading to non-inductive steady-state op- eration at high β is one of the main missions of the JT-60SA project starting operation in 2020 [7]. The high-energy negative ion sources (~500 keV) at JT-60SA deposit exclusively off-axis. An exhaustive kinetic-hybrid MHD analysis using the MEGA code has been performed in refs. [8]. Building on these results further gyro-kinetic analysis using the LIGKA/HAGIS tool is carried out (higher mode numbers, EGAM/BAE thresholds) in order to investigate the scaling of various parameters connected to linear onset and non-linear EP transport compared to the AUG case discussed above.
During the lifetime of ITER various scenarios with off-axis NB injection are forseen. Although a change of the beam geometry from on-axis to off-axis will be possible, it cannot be performed frequently since the cycles are limited due to the mechanical stress it induces on the various compo- nents connected to the beam source. For this reason a good understanding of the expected heating characteristics and deposition properties including a possible deposition broadening due to EP- driven instabilities can help to optimise the planning and operation of the experiments. Based on the fully IMAS [9] integrated heating and current drive workflow [10] the stability of pre-fusion H-plasmas is investigated for different beam deposition locations (off-axis, mixed on/off-axis). The analysis will also serve as a verification test of the recently IMAS-integrated LIGKA/HAGIS

workflow (see fig. 1). The results will be related and compared to the findings on AUG and JT-60SA.

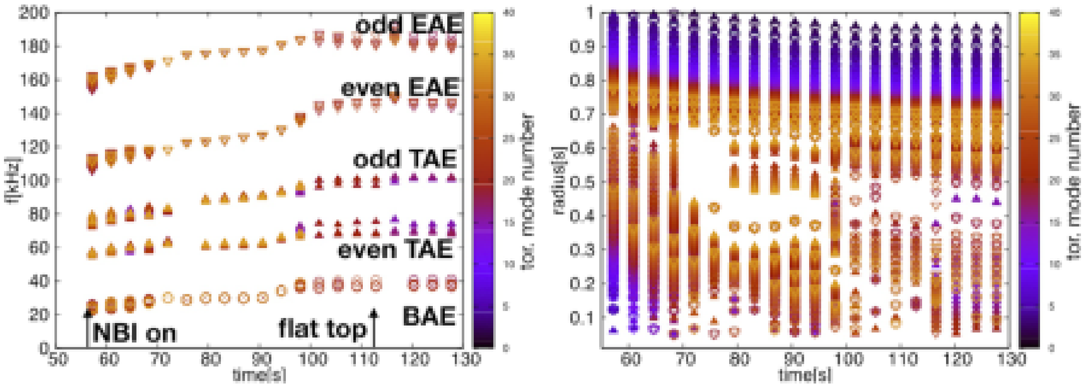

Figure 1: Left: evolution of various (stable and unstable) Alfvén eigenmode (AE) frequencies as a function of time during the ramp-up of a H-plasma in ITER as calculated by the LIGKA/HAGIS workflow based on a predictive METIS [11] run (#100015,1; B0 = −1.79T). All modes in the negative EP gradient region between 0.35 < s < 0.55 are shown. Right: the same dataset showing the evolution of the radial AE localisation with time. Regions of scarce AE population can be related to regions of low shear close to q=1.

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