Phase-space resolved fast-ion flows due to MHD fluctuations in the ASDEX Upgrade tokamak

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Fast-ions (FI) are a key source of heating, momentum and current drive for future fusion reactors. The loss of FI may lead to a degradation of the fusion power throughput and to a non-affordable reduction of the plasma facing components lifespan [1]. Understanding the mechanisms that can produce radial transport and losses of fast-ions, such as cross-field transport due to 3D symmetry breaking fields that can arise from internal magnetohydrodynamics (MHD) fluctuations or external perturbations, is capital to develop future fusion machines. The fast-ion population can resonate with the 3D fields breaking toroidal symmetry, and thus a rapid fast-ion transport can be produced [2]. This resonant interaction occurs when the resonance conditions of the wave-particle interaction are satisfied, which happens only for certain phase-space volumes. Phase-space resolved measurements are, thus, necessary to understand, and eventually control, the fast-ion transport.

The ASDEX Upgrade tokamak (AUG) is well equipped to conduct FI transport studies due to its powerful heating systems (6MW of ion cyclotron resonance heating, ICRH, and 20 MW of neutral beam injection, NBI) and its comprehensive suite of FI diagnostics. This set of diagnostics has been upgraded with the installation of an imaging neutral particle analyzer (INPA) [3] which is able to obtain, for the first time at the AUG tokamak, the energy and location of the confined FI and therefore gives access to characterize the FI transport with high spatial and energy resolution (9 keV and 3 cm) [4]. The INPA diagnostic combines the working principles of the neutral particle analyzers (NPA) and scintillator fast-ion loss detectors (FILD). Similar to NPA systems, INPA analyzes neutral particles produced in charge exchange (CX) reactions. After being collimated, CX neutrals are ionized by an ultra-thin (20 nm) carbon foil and deflected toward a scintillator plate. The strike position of the particles in the scintillator is determined by their energy and pitch ($\lambda = -v_{\parallel}/v$), which is directly related with the FI position inside the plasma [3].

The transport of FI under the effect of Toroidal Afven Eigenmodes (TAEs) was clearly observed by the INPA diagnostic. Auxiliary heating power (4 MW of ICRH and 5 MW of NBI) was added into a low density discharge in order to achieve strong FI-driven modes. During these instabilities, clear indications from anomalous transport are observed in the INPA signal. Particles are redistributing following the stream lines; these are the lines in phase space where both the magnetic moment and E' ($E' = E - (\omega/n)P_{\zeta}$) are conserved, as observed in [5] under the presence of RSAE. The observed redistributions are in good agreement with full orbit ASCOT simulations when using the mode structure predicted by the LIGKA code [7].

The experimental results presented here shed light on the physics underlying fast-ion confinement in the presence of FI-driven plasma instabilities. Localized redistribution in energy and space are found with unprecedented details opening new avenues to understand the interactions of fast-ions with plasma fluctuations; which is basic for future control of the instabilities.

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