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High-Resolution Imaging Neutral Particle Analyzer Measurements of the Local Fast Ion Distribution Function and Instability Induced Transport in DIII-D

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The recently developed imaging neutral particle analyzer (INPA) on DIII-D enables fast ion velocity-space tomography of unprecedented fidelity, as well as resolution of local phase space dynamics under the action of classical and non-classical transport mechanisms. The INPA itself measures charge-exchanged energetic neutrals by viewing an "active"neutral beam through essentially a 1D pinhole camera with a rear collimating slit that defines the neutral particle collection sightlines. The incident neutrals are ionized by stripping foils and the local tokamak magnetic field acts as a magnetic spectrometer to disperse ions on the scintillator. A fast camera provides 2D images of the escaping neutrals mapped to energy and radial position in the plasma –thus providing energy-resolved radial profiles of confined fast ions in DIII-D. The local phase space measurements enabled by the INPA are ideally suited to studies of instability-induced fast ion transport, and recent data clearly show transport due to sawteeth and Alfven eigenmodes (AEs). Measurements in reversed magnetic shear experiments have revealed large AE induced preferential transport of different orbit classes at nearby radii, something that would be impossible to distinguish with fast ion diagnostics that weight broad regions of phase space such as fast ion D-alpha (FIDA) or neutron emission.
The 10,000 simultaneous INPA measurements allow velocity space tomography computation of the local distribution function with unprecedented accuracy in the plasma at the INPA measured pitch. To accomplish this, the weight function of the INPA is calculated by FIDASIM [2] and INPASIM [3]. FIDASIM computes the spatial and energy distributions of neutral flux towards the carbon stripping foils and INPASIM simulates the diagnostic response to this flux, including the foil-particle interactions, the particle trajectory towards the phosphor, phosphor response on the incident ion flux and camera imaging. The computed tomography, using the Ridge regression method, benefits from the very localized phase space weights of each pixel and remarkable signal to noise of the system. In test cases, the inversion is able to successfully reconstruct fine-scale velocity-space structure produced by multiple neutral beams at different voltages. Using the technique, the impact of sawtooth crashes on passing fast ions is studied and the inverted data reveal a prompt phase-space dependent redistribution across the q=1 flux surface. At full beam energy, a transition from originally peaked profiles to a flattened profile occurs, however, at half energy, a hollow profile after the crash is found. Fast ion distributions computed by combining tomographic analysis with the INPA data can significantly advance the understanding of phase-space dynamics of fast ions and related model validation, which is a crucial effort for predicting the fast ion behavior in future fusion reactors.

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