Control of energetic particle modes on the TCV tokamak

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Introduction - In future fusion reactors, fast-ion confinement is crucial to maintaining efficient plasma heating and protecting plasma-facing components [1]. Alfvén eigenmodes (AEs), driven by the resonant interaction of fast ions with the plasma, can enhance transport and energy losses, while fast ions themselves can also drive MHD instabilities. To mitigate AE activity, various actuators are being explored, including resonant magnetic perturbations (RMPs), which redistribute fast ions [3], and electron-cyclotron resonance heating and current drive (ECRH/ECCD), which modify local kinetic and shear profiles to influence mode damping [4]. Additionally, negative triangularity (NT) configurations—known to improve bulk confinement—have shown promise in reducing AE activity under similar conditions [5].

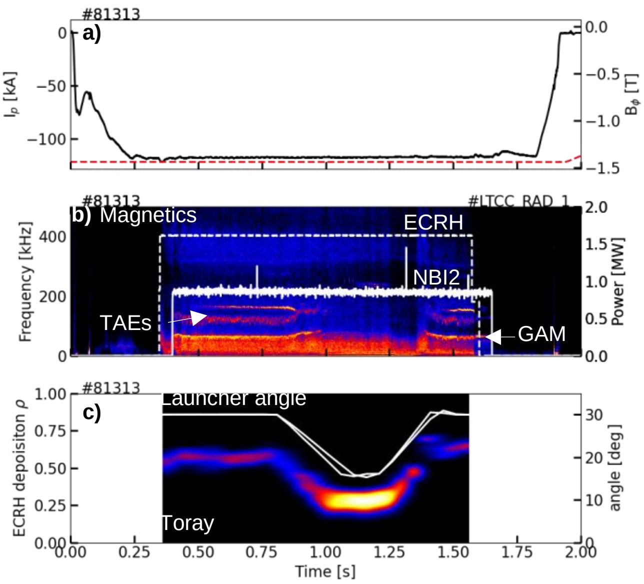

Figure 1 – (a) Time trace of the plasma current (black) and toroidal magnetic field strength (red-dashed). (b) Spectrogram of the magnetic pickup coils with time traces of the ECRH (dashed) and NBI2 power (solid) overplotted. (c) Colormap of the Toray calculated ECRH power absorption as a function of radial position (y-axis) and time (x-axis). Overplotted are the two ECRH mirror

Summary of Main Results - This contribution presents results on EP-driven instabilities and AE mitigation at the Tokamak à Configuration Variable (TCV), along with supporting results from other devices. Systematic AE control experiments using ECRH and ECCD demonstrated robust AE suppression, particularly with mid-axis ECRH deposition, as shown in Fig. 1. Suppression occurred independently of whether deposition scans began on-axis or off-axis, and both NBI1 and NBI2 were found to excite AEs, with suppression observed in both cases. Mode localization using measured frequencies and dispersion relations, supported by MISHKA modelling, indicated that suppression correlates with ECRH deposition overlapping the mode location. ECCD experiments further showed that mid-axis co-current drive mitigates AEs, while counter-current drive effectively suppresses them. These findings suggest that suppression

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mechanisms involve not only shear profile modifications but also significant changes in plasma density and temperature.

Additionally, fast-ion confinement studies were performed in NT and positive triangularity (PT) plasmas. In MHD-quiescent conditions, confinement was found to be comparable between NT and PT, consistent with neoclassical predictions from TRANSP and ASCOT. However, persistent energetic geodesic acoustic modes (EGAMs) were observed in NT plasmas, appearing to limit TAE activity. Localized ECRH application suppressed EGAMs, allowing TAEs to re-emerge. Nevertheless, when compared with PT plasmas, TAE amplitudes were reduced in NT, further confirming its role as a potentially beneficial configuration for reducing AE activity.

Experimental Details **-** TCV's flexible shaping capabilities make it an ideal testbed for exploring plasma geometries, while the combination of neutral beam injection (NBI) and ECRH enables systematic AE stabilization studies. Recent upgrades, including enhancements to the NBI system and new fast-ion diagnostics, have significantly expanded TCV's capabilities. A second neutral beam (52 keV, NBI2) now complements the existing 28 keV (NBI1) system, increasing the total NBI power to 2.6 MW [7]. Furthermore, the recently upgraded fast-ion loss detector (FILD), capable of measuring escaping fast ions, and the Motional Stark Effect (MSE) diagnostic, which provides experimental information on the shear profile, have enabled more detailed investigations into energetic particle-driven instabilities, including Alfvénic modes, and fast-ion transport across various plasma configurations.

These studies provide valuable insights into mode properties and associated fast-ion transport in MHD-active plasmas, contributing to a deeper understanding of plasma confinement and AE control in fusion-relevant scenarios.

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