Instabilities and fast ion confinement on the TCV tokamak

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1. Introduction

A newly installed neutral beam injector (NBI) combined with the electron cyclotron heating and current drive (ECH-ECCD) system allows the TCV [1] to contribute to worldwide (DIII-D, AUG, TJ-II, etc.) research studying wave − fast ion (FI) interaction phenomena of interest for burning plasma tokamak-based fusion devices, including ITER and DEMO. Sufficient fast-ion confinement is essential for the success of fusion devices. A large FI plasma population may, however, excite Alfvén eigenmodes (AEs) that can degrade fusion performance and increase energetic ion losses through FI transport.

Alfvén mode activity observed on TCV [2,3] during the 2017/18 EUROfusion MST1 campaign, in the presence of simultaneous off-axis sub-Alfvenic NBI ($v_A/3 < v_{beam} < v_A$) and off-axis ECRH. The EM fluctuations (AEs and GAMs) were studied from Mirnov signals and soft-X emission. Their impact on the plasma performance and on FI confinement was examined by comparing neutron emission rates, total plasma energy (DML), fast ion D-α (FIDA) spectra [2] and CX NPA signals from integrated modelling employing the TRANSP/NUBEAM, ASTRA and FIDASIM codes.

2. Experimental setup and TCV scenario with Alfvén modes

The TCV Tokamak ($R_O \cong 0.88$ m, $a \leq 0.25$ m) [1] is characterised by the widest plasma shaping capability worldwide, the highest ECH power density, and high flexibility in its heating and control schemes. The neutral beam injector (NBI) delivers up to 850 kW power along a tangential (double-pass) line of sight at energies in the 10-25 keV range.

A reduced magnetic field of 1.3 T was chosen to obtain Alfvén velocities below three times the NBI FI velocities ($m_D \times (v_A/3)^2 = 23.3$ keV for $n_i = 2 \times 10^{19}$ m$^-$
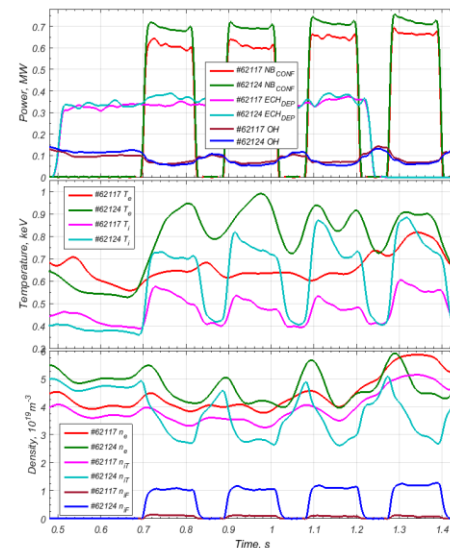

Figure.1: NB, EC and ohmic power; on-axis electron and ion temperature; on-axis electron, thermal and FI density in TCV discharges with on-axis (#62124) and off-axis (#62117) NBI: Z$_0$:+11.9&+3.4 cm; W$_{DML}$:4.39/5.57 kJ
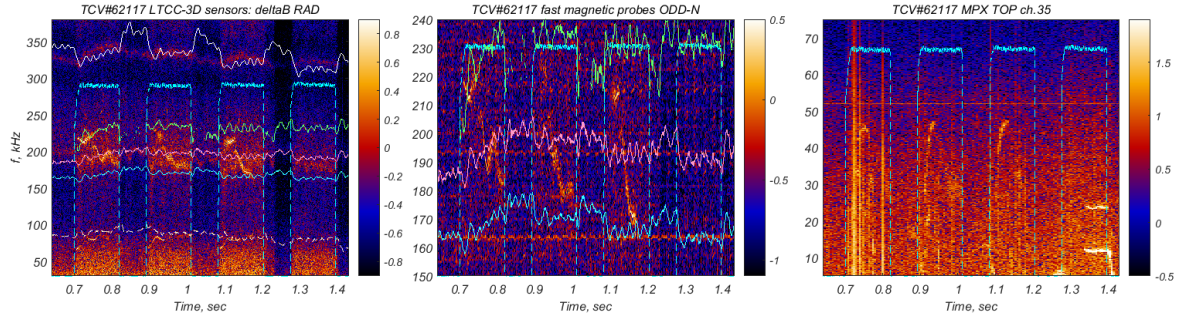
Figure.2: Spectrograms from high frequency LTCC-3D magnetic sensors, Mirnov poloidal pick-up coils and Duplex Multiwire Proportional soft X-ray counter (DMPX). Toroidal Alfvén eigenmodes (TAEs) at 170-230 kHz; expected TAE frequency at q=1.5, 2.0 &2.5 (solid lines); elongation- induced Alfvén eigenmode (EAEs) at 310-360 kHz; Energetic particles driven geodesic acoustic modes (EGAMs) at ~80 & 40 kHz.

[3]) so Alfvén eigenmodes could be excited (29 keV NBI for B_T 1.45 T). A plasma current of 121 kA with 400kW of off-axis ($\rho_{pol} \approx 0.55 \pm 0.07$) X2 (89 GHz) ECH heating have been applied (Fig.1). NBI deposition profiles (on-/off-axis) were studied [2,3] by vertically displacing magnetic axis (Z_0=+3…+15 cm) retaining similar plasma shapes and ECH profiles. Alfvén activity was observed with $Z_0 \cong 12$ cm, with no beam-driven instabilities detected (1) without ECH, (2) for NB energy $\leq$23 keV, (3) at B_T>1.35 T, (4) $Z_0 \leq 8$ cm and $Z_0 \geq 14.5$ cm.

The EM fluctuation properties (AEs and GAMs) are monitored from the Mirnov signals and soft-X emission (Fig. 2). TRANSP and ASTRA transport modelling of plasma heating are used to estimate FI CX losses and current drive from experimental T_e, n_e and T_i profiles (Fig.3). The high edge neutral density, combined with off-axis NBI population, yields strong charge-exchange losses (up to 50%). The energy and density of the incoming neutrals was estimated using KN1D code and baratron pressure gauge measurements with TRANSP/NUBEAM and FIDASIM used to interpret FIDA and NPA [2,3] measurements.

3. Impact of Alfvén modes on fast ion distribution and confinement

TRANSP/NUBEAM simulations with neoclassical (NC) FI transport agree well with the DML energy (W_{DML}, ("model"-"exp")/"exp" ratio in the range of -4.2…+1.1 %), neutron rates (-6.3…+0.8 %) and loop voltage (V_{LOOP}, -0.4…+0.6 %) in phases without TAEs (Fig.4, #62124 and

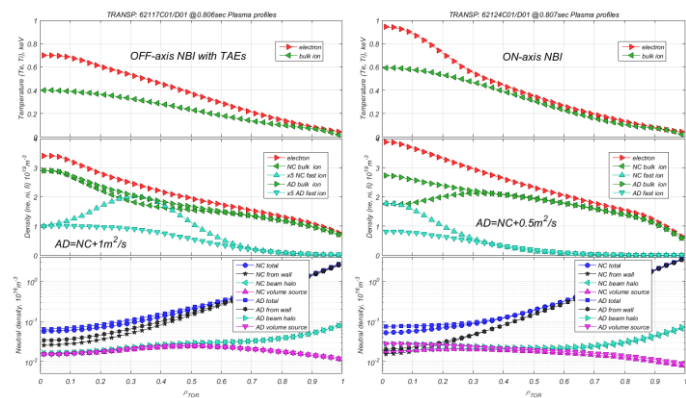

Figure.3: Profiles in TRANSP simulation with neoclassical (NC) and with NC+anomalous (AD, +0.5/+1.0 m²/s) fast ion diffusion. Electron density and temperature from Thomson scattering, ion temperature from CXRS; density of fast and thermal (bulk) ions and neutrals are calculated by TRANSP. Fast ion density multiplied by ×5 for off-axis NBI case (TCV#62117).
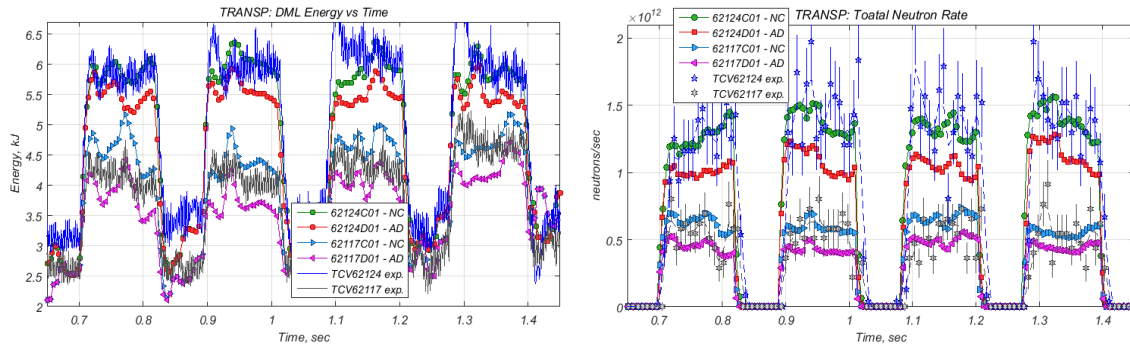
Figure.4: DML (MHD) plasma energy and total neutron rate: experiment and TRANSP prediction

#62117@1.3...1.4 s). W_{DML}=3/2$W_\perp$ is sensitive to the FI pressure, the neutron rate depends on the FI distribution function, V_{LOOP} depends on the NBCD. The deviations of experimental data from neoclassical expectations (NC) with TAEs (TCV#62117@0.7...1.2 s – W_{DML}:+6.1…+11 %; neut.:+11…+22 %; V_{LOOP}:-7.9…-2.7 %) can be attributed to anomalous FI transport and incorporated by an additional, ad-hoc 0.5…1 m^2/s (AD), radial FI diffusion term. The experimental data lie between the NC and AD predictions (NC+1 m^2/s – W_{DML}:-9.9…-6.2 %; neut.:-21…-8.3 %; V_{LOOP}:+2.1…+6.3 %). An anomalous FI diffusion of 0.5…1 m^2/s is sufficient to reduce the FI density (Fig.3) and pressure by a factor of 2.

The CNPA energy distribution and FIDA spectra (Figs. 5&6) agree with FIDASIM [5] predictions with NC FI diffusion for on-axis NBI (#62124). FIDA signals are over-predicted with NC and under-predicted with AD (+1m^2/s) FI diffusion for off-axis NBI
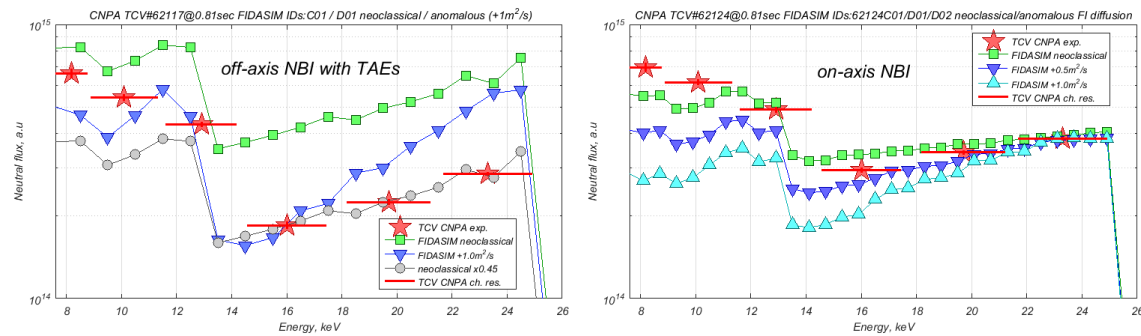

Figure.5: Compact NPA energy distribution and TRANSP/NUBEAM/FIDASIM prediction with neoclassical and anomalous FI diffusion in TCV
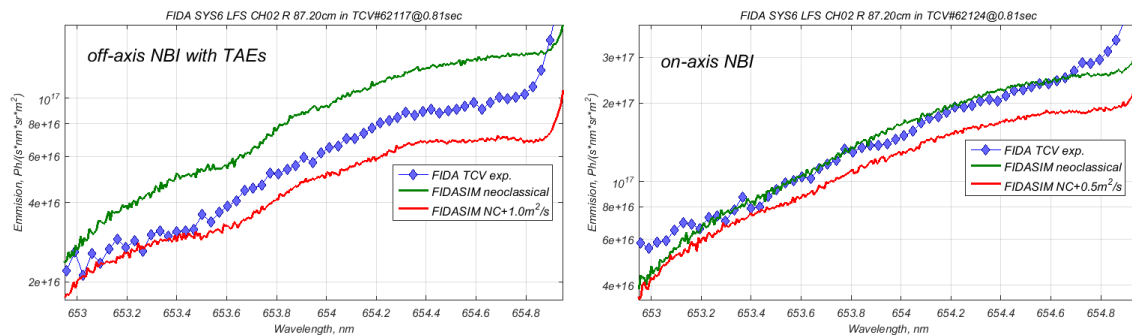

Figure.6: Measured FIDA spectrum compared with predictions from FIDASIM for a central horizontal (toroidal) line of sight (intersection with NBI at 87.2cm).
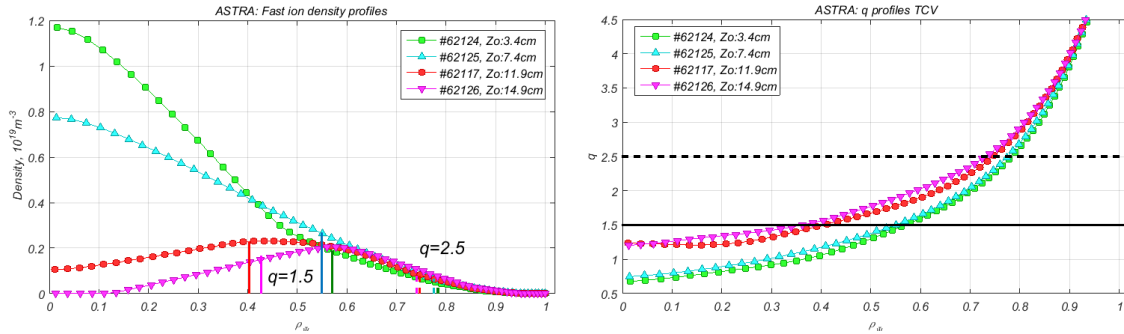
Figure.7: FI density and safety factor (q) profiles calculated in ASTRA for TCV discharges with different Zo (vertical shift) – on-/off-axis NBI. TAEs observed in TCV#62117 only.

with TAEs (#62117). The anomalous diffusion in physical (radial) space is insufficient to simulate the CNPA result in TAE regimes. The theory based representation of FI anomalous TAE induced redistribution in velocity and coordinate phase space $(R,z,E,v/v_{\parallel})$ is necessary for detailed fast ion transport modelling.

4. Discussion and perspectives

The comparison of TRANSP/NUBEAM- /FIDASIM modelling with experimental data indicates clearly the impact of electromagnetic fluctuations (Alfven Eigenmodes) on the FI distribution function and confinement. TAEs on TCV are observed for a relatively narrow range of experimental conditions (off-axis NBI and ECH, low I_P and ne). This may be explained by a dependence of TAE excitation/dumping on beam energy (v_{NB}/v_A), safety factor (q) and magnetic shear (S) profiles [4]. The dependence of FI density (and pressure) and current (q-, S-profiles) on the NB deposition (Zo shift, on-/off-axis NBI), illustrated with ASTRA simulation in Fig.7.

Experimental work in 2019-2021 will benefit from the installation of new diagnostics (Fast Ion Loss Detector and Imaging Neutral Particle Analyser), installation of a second high energy (50-60 keV) neutral beam [1] and the availability of more numerical tools.

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* See author list of "S. Coda et al 2019 Nucl. Fusion accepted (https://doi.org/10.1088/1741-4326/ab25cb)

** See author list of "B. Labit et.al. 2019 Nucl. Fusion accepted (https://doi.org/10.1088/1741-4326/ab2211)