Fast-ion dynamics at ITER-relevant densities in ASDEX Upgrade measured with collective Thomson scattering

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1. Introduction: Energy transfer from confined fast ions will play a key role in maintaining the core plasma at fusion-relevant conditions in future fusion devices such as ITER. The dynamics of such ions is experimentally well characterized in low-density plasmas, owing to good fast-ion coverage with diagnostics such as fast-ion D-α spectroscopy (FIDA), neutron/γ-ray spectrometry, and collective Thomson scattering. In contrast, this applies much less to high-density discharges, in which the relevant diagnostic performance is more limited by the shorter slowing-down time of energetic particles, the reduced neutral beam (NBI) penetration, and the significantly increased Bremsstrahlung emission. Collective Thomson scattering (CTS) is less hampered by the latter of these limitations and will be the main diagnostic for measuring confined fast ions in ITER across their full energy range [1, 2, 3]. Although ITER will achieve a combination of high density n and low core collisionality $\nu \propto nT^{-3/2}$ that cannot be accessed in present devices, it remains relevant to experimentally test predictions of energetic-ion dynamics at high density as a step in preparing for ITER operation. Here we present the first CTS measurements of fast-ion dynamics in ASDEX Upgrade (AUG) performed at a local density of $n_e \approx 9 \times 10^{19}$ m^{-3}, i.e., similar to projections for the high-density ITER baseline scenario [4].

2. Measurements and analysis: Our measurements are based on AUG discharge #39648, with timetrace shown in Figure 1. This H-mode discharge involved 5 MW of NBI heating and 3.2 MW of electron cyclotron resonance heating (ECRH). The discharge was divided into an intermediate– and a high-density phase, with the central line-integrated density increasing to $(7.0 \pm 0.2) \times 10^{19}$ m^{-2} at $t > 4.0$ s. In both phases, NBI source Q3 was active throughout to allow FIDA measurements, while Q8 (on-axis deposition) and Q6 (off-axis) were interspersed in order to vary the fast-ion distribution function.

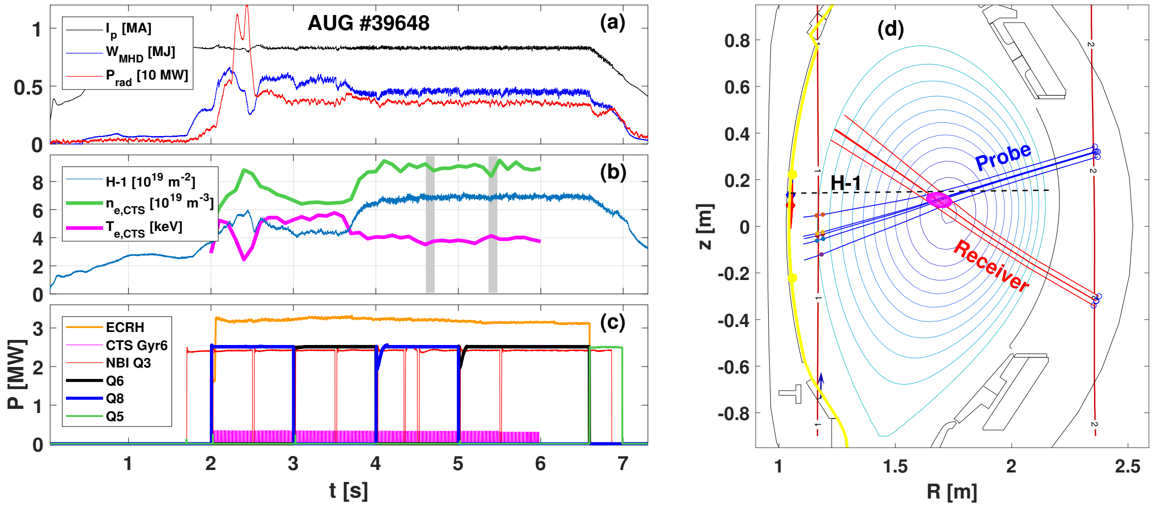

Figure 1: (a) Timetrace of AUG discharge #39648 (plasma current I_p, stored energy W_{MHD}, radiated power P_{rad}). (b) Line-integrated density "H-1" along the sightline shown in panel (d) and n_e and T_e in the CTS measurement volume. Shaded areas mark the TRANSP fast-ion output times discussed in Section 3. (c) Auxiliary heating power and power of the 105 GHz CTS probe gyrotron Gyr 6. (d) CTS geometry at $t = 4.7$ s, showing the CTS probe and receiver beams and the resulting scattering volume (ellipsoid).

CTS measurements were taken from $t = 2.0$–6.0 s, using both "active" and "passive" receiver views [5]. The measurement geometry derived from raytracing is illustrated in Figure 1(d). Here we focus on results obtained during the high-density phase at $t = 4.0$–6.0 s, in which the average electron density and temperature in the CTS measurement volume at $\rho_t = 0.11 \pm 0.02$ was $n_e = (9.0 \pm 0.3) \times 10^{19}$ m^{-3} and $T_e = 3.9 \pm 0.2$ keV, respectively, with a measurement angle relative to the local magnetic field of $\phi = 108 \pm 1^\circ$. To aid the interpretation of the measurements, we performed forward modelling of the acquired CTS spectra based on the CTS scattering geometry in Figure 1(d), along with n_e, T_e, and ion temperature in the CTS volume from integrated data analysis [6] where relevant, and the fast-ion distribution function predicted by TRANSP/NUBEAM v. 20.3 [7]. TRANSP was here run without anomalous ion diffusion, given the absence of clearly identifiable MHD modes at the times of interest.

3. Results and comparison to modelling: Resulting CTS spectra obtained during phases with NBI Q3+Q8 and Q3+Q6 heating are shown in Figure 2, together with the corresponding forward models. The data represent results from the CTS filterbank alone and from averaging the filterbank and fast digitizer [8] data. Both data sets reveal reasonable overall agreement with the TRANSP-based forward model, whereas a model without fast ions cannot reproduce the observed spectra. In particular, the CTS spectrum is observed to narrow from $t = 4.7$–5.4 s in

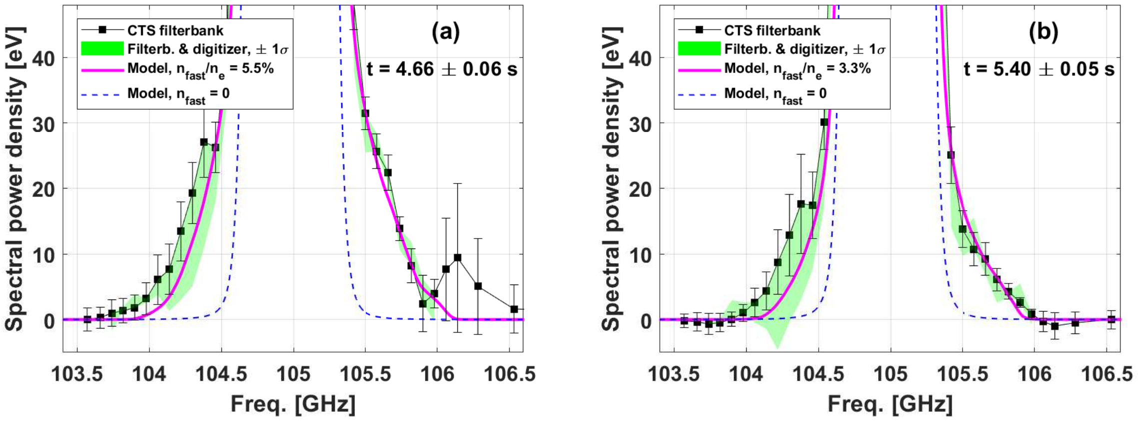

Figure 2: CTS spectra and corresponding forward models based on TRANSP simulations during the high-density (a) NBI Q3 + Q8 phase at $t \approx 4.7$ s and (b) Q3 + Q6 phase at $t \approx 5.4$ s. Solid magenta lines represent a model using the fast-ion concentration n_{fast}/n_e predicted by TRANSP in the CTS measurement volume, while dashed blue lines show a model with no fast ions.

response to the reduced fast-ion concentration predicted by the model. Nevertheless, there are indications of deviations from the model predictions, notably at $f \approx 106.0$–106.5 GHz in Figure 2(a). This feature is not related to fast ions, which generate a monotonic spectrum for this geometry, but is possibly associated with parametric decay of the probe beam [9].

Inversions of both spectra to infer the underlying fast-ion distribution functions are shown in Figure 3(a). The results broadly agree with the TRANSP neoclassical predictions, although minor discrepancies are seen close to the thermal bulk. As a further comparison, we show in Figure 3(b) the FIDA signal in AUG #39648 normalized by the corresponding beam emission, a proxy for fast-ion density [10]. Although the density step at $t \approx 3.7$–4.0 s reduces the FIDA signal-to-noise ratio (whereas that of CTS is largely unaffected), useful FIDA data are still obtained at high n_e. The FIDA profiles would suggest a drop in fast-ion content in the CTS volume from the Q3+Q8 to the Q3+Q6 phase by a factor ≈ 2.0, consistent with the factor ≈ 2.1 inferred outside the thermal bulk from both CTS and TRANSP in Figure 3(a).

4. Conclusions and outlook: To our knowledge, these results represent the first CTS measurements at reactor-relevant densities ($\sim 1 \times 10^{20}$ m^{-3} [4]) in any tokamak. Forward modelling of the acquired CTS spectra in this high-density discharge demonstrates that a measurable fast-ion population is present in the plasma core ($\rho_t \approx 0.11$) at a level of 3–5% of n_e. Comparison to TRANSP simulations suggests core fast-ion dynamics consistent with neoclassical transport in both real space and velocity space at high density in ASDEX Upgrade. Our measurements thus provide experimental validation of the ability of CTS to characterize fast-ion dynamics under

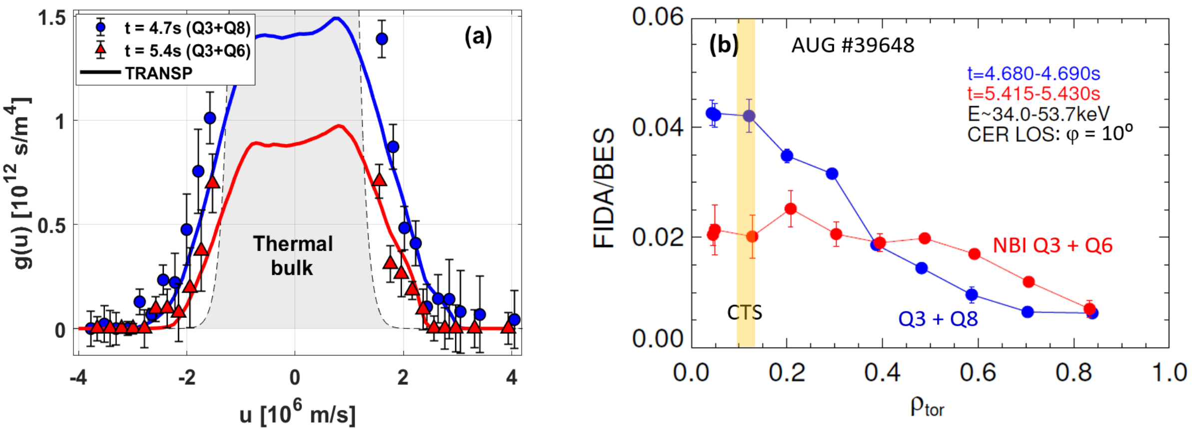

Figure 3: (a) 1D fast-ion distribution functions $g(u)$ outside the thermal bulk versus projected ion velocity u along the CTS measurement angle. (b) FIDA signal normalized by beam emission (BES) at the times of interest, integrated over wavelengths corresponding to fast-ion energies of 34.0–53.7 keV. Shaded region marks the location of the CTS volume at the relevant times.

conditions that may be challenging for certain other diagnostics and at fast-ion levels of just a few % of n_e, as will be relevant for CTS at ITER [3]. Full inference of the underlying 1D ion velocity distribution from the measured CTS spectra across the discharge will be presented elsewhere [Verdier et al., in prep.] and will allow detailed comparison of our results to TRANSP predictions with and without anomalous diffusion.

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