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Comparison of Collective Thomson Scattering Diagnostic Results to TRANSP Simulations on ASDEX Upgrade

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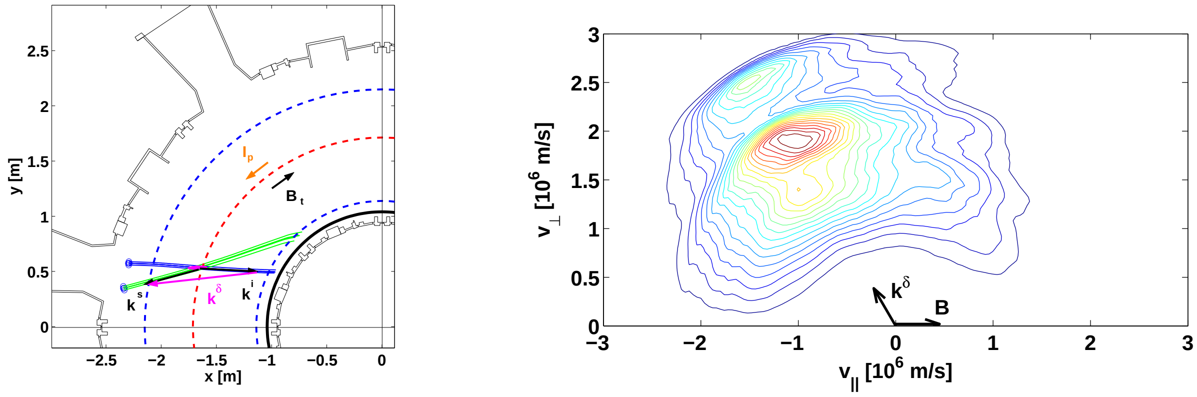
Introduction

The Collective Thomson Scattering (CTS) technique offers the ability to measure projections of the confined ion velocity distributions in tokamak plasmas. The ion velocity distribution can be inferred from the spectrum of received scattered radiation when a powerful probe beam is incident on plasma fluctuations driven by the ion motion [1, 2]. Fluctuations with wave vector $\mathbf{k}^\delta = \mathbf{k}^{\mathrm{s}} - \mathbf{k}^{\mathrm{i}}$ will scatter probe radiation to frequencies shifted by approximately $\omega^\delta = \mathbf{v}_{ion} \cdot \mathbf{k}^\delta$, and the component of the ion velocity $\mathbf{v}_{ion}$ in the direction of $\mathbf{k}^\delta$ can be inferred. Here $\mathbf{k}^{\mathrm{s}}$ and $\mathbf{k}^{\mathrm{i}}$ are the wave vectors of the received scattered radiation and the incident probing beam respectively. It is of particular interest to obtain the velocity distributions of energetic non-thermal ions resulting from fusion processes or externally applied heating. These fast ions may contain a large fraction of the plasma energy which must be channeled into heating the bulk plasma. However, they also constitute a source of free energy which can excite plasma waves and turbulence which in turn affect the confinement of both fast ions and bulk plasma.

First scattering results of the CTS system installed on ASDEX Upgrade (AUG) have been achieved using gyrotron radiation at 105 GHz as the probing beam [3]. This paper presents the methodology of comparing experimental CTS results to TRANSP/NUBEAM simulations of the fast ion velocity distribution in AUG. We use plasma heating by neutral beam injection (NBI) as an example. A detailed account of the results is also presented at this conference in [4].

CTS measurements in the NBI heated AUG discharge 24089

In AUG discharge 24089 an H-mode plasma was generated with a magnetic field of 2.6 T on axis with two phases of NBI heating, i.e. with one and two neutral beams respectively. The two beams deposited deuterium ions with similar injection angles, beam energies of respectively 93 keV and 60 keV and a power of 2.5 MW each. The fast ion population was measured by CTS in each phase with the scattering geometry illustrated in Fig. 1(a) where the beams and relevant



(a) Scattering geometry

(b) TRANSP/NUBEAM simulation

Figure 1: (*a*) Sketch of the scattering geometry in discharge 24089 projected onto the toroidal plane. The probe beam is shown in blue, the receiver beam in green. The scattering volume lies at the intersection of probe and receiver beams and is shown in magenta. The direction of the toroidal magnetic field, the plasma current, and the projected wave vectors are indicated. (*b*) Equally spaced contours of the fast ion velocity distribution in the scattering volume calculated by TRANSP/NUBEAM for the phase with two neutral beams. The bulk ion distribution is not included which leads to low densities near the origin. The directions of the magnetic field and $\mathbf{k}^{\delta}$ are indicated.

wave vectors are shown projected onto the toroidal plane. The angle between $\mathbf{k}^{\delta}$ and the magnetic field – which is also the angle between the resolved velocity component and the magnetic field – was $122 \pm 1^{\circ}$. The measurement is spatially resolved with a resolution of approximately 10 cm at the location of the probe and receiver beam intersection which was located at the center of the plasma. In order to subtract background ECE radiation emanating from the plasma, the gyrotron was modulated. For the present purpose of comparing heating regimes we shall present data averaged over 15 gyropulses spanning 100 ms. A more detailed account of the AUG CTS system and its capabilities can be found in [3].

TRANSP/NUBEAM simulations

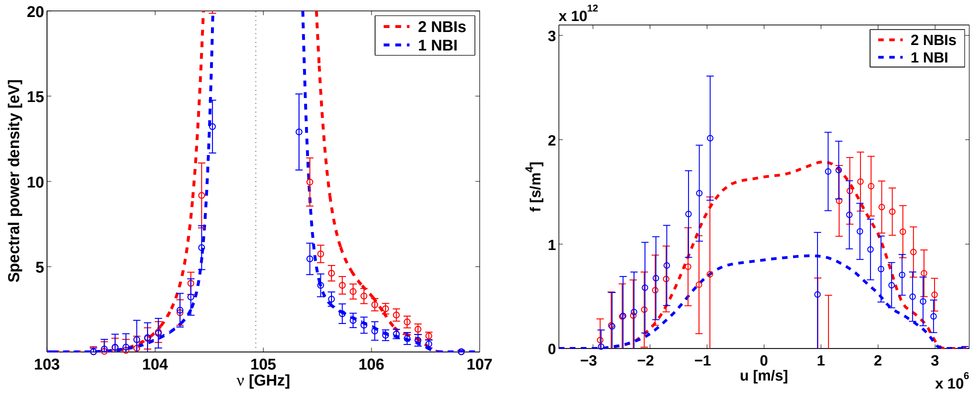
Theoretical two-dimensional fast ion velocity distributions were calculated for each NBI configuration at the location of the CTS beam overlap in the plasma center using the plasma analysis code TRANSP coupled with the neutral beam module NUBEAM [5, 6]. The NUBEAM module is a comprehensive computational model for neutral beam injection in tokamaks. NUBEAM computes the time-dependent deposition and slowing down of the fast ions produced by NBI, taking into consideration beam geometry and composition, ion-neutral interactions (atomic physics), anomalous diffusion of fast ions, the effects of large scale instabilities, the effect of magnetic ripple, and finite Larmor radius effects. Fig. 1(b) shows the resulting velocity distribution for the two-beam heating regime as well as vectors indicating the directions of the magnetic field and the resolved velocity component. The largest densities for both beams are found at a pitch angle of 120° which is the same velocity component measured by the CTS receiver. For comparison with the measured CTS spectrum we use the projection of the ion velocity distribution along the direction of the resolved $\mathbf{k}^\delta$ vector.

Comparison and interpretation of experimental and theoretical results

The CTS spectra measured during each heating regime are shown in Fig. 2(a). The contribution from bulk ions dominates at frequencies in the range 104.3–105.5 GHz which corresponds to ion velocities below two times the ion thermal velocity. The beam ions have a preferred velocity direction, so the spectrum is asymmetric with the beam ions contributing mainly at high frequencies. The decrease in the fast ion population after the 60 keV beam is switched off can be clearly seen as a decrease in signal strength at high frequencies – the magnitude of which is outside the error bars.

Experimental CTS results can be compared to theoretical expectations in two complementary ways. The comparison can either be done in frequency space if a synthetic CTS spectrum is calculated from a theoretical ion velocity distribution, or it can be done in velocity space if the ion velocity distribution can be inferred from the experimental CTS spectra. A forward model exists which – given an ion velocity distribution and estimates of relevant plasma parameters – can calculate synthetic CTS spectra based on a kinetic and fully electromagnetic description of the scattering process [1, 2]. However, no direct mapping from frequency space to velocity space has been formulated, so the inference of ion velocity distributions from measured CTS spectra requires the solution to an inverse problem based on forward modeling. This problem can be reliably solved using a least squares type method of inference based on Bayesian analysis which fully takes into account the uncertainties of all relevant plasma parameters as well as those of the measured CTS spectrum [7].

Fig. 2(a) shows the measured spectra and the synthetic spectra calculated by forward modeling based on the fast ion velocity distribution functions from TRANSP/NUBEAM and assuming Maxwellian velocity distributions for all other plasma components. Fig. 2(b) shows the theoretical fast ion velocity distribution and the fast ion velocity distribution inferred from the measured CTS spectra. In the experimental data both the asymmetry induced by the neutral beams and the decrease in signal strength and fast ion density when one beam is turned off can be clearly seen and are outside the error bars in both figures. However, although the spectral shape of the experimental data is well reproduced by the synthetic data some disagreement can be seen in the overall signal strength. The significance and origin of the disagreement is a subject of ongoing investigation. In this respect it may be noted that the simulated spectra shown in Fig. 2(a) do not account for uncertainties in the parameters used to generate them. This includes an overall



(a) Measured and simulated spectra.

(b) Measured and simulated fast ion velocity distributions

Figure 2: (*a*) Comparison of measured and simulated spectra. The two heating regimes are shown respectively in blue (one beam) and red (two beams).−− NUBEAM, ○ - measurement, ··· - gyrotron frequency. (*b*) Comparison of measured and simulated fast ion velocity distributions along $\mathbf{k}^{\delta}$. The measured distribution is restricted to the range outside twice the thermal velocity: $2 \cdot v_T \sim 10^6$ m/s.

scaling factor which is poorly known. Such uncertainties are, however, taken into account by the Bayesian method used to infer the fast ion velocity distribution shown in Fig. 2(b).

Conclusion

We have performed CTS measurements to diagnose the fast ion velocity distribution for an H-mode discharge with different NBI configurations. The results demonstrate the ability of the CTS system to detect fast ions from neutral beam injection and to distinguish between the different heating regimes. The experimental results were compared to theoretical expectations for the fast ion velocity distribution based on TRANSP/NUBEAM calculations. Within the uncertainties of both theory and experiment this first comparison show a reasonable level of agreement.

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