Neutral beam start-up dynamics on TEXTOR measured by collective Thomson scattering (CTS)

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The understanding of fast ion dynamics is of great importance in optimising magnetic confined burning fusion plasmas. Especially, the confined part of the fast alpha particles is of interest, since these need to heat the bulk plasma in future fusion experiments such as ITER, but may drive unwanted instabilities that might react back on the fast ions and in the worst case expel them from the plasma [1]. Also in non-burning tokamaks the fast ion dynamics is of great interest, since any non-thermal fast ions may risk driving turbulence and hence reduce the performance of the plasma. Temporal measurements of the fast ion distribution function have previously been measured by collective Thomson scattering on TEXTOR in the phase during ion heating turn off, in good agreement with numerical simulations [2] . In this paper the temporal evolution of the fast ion velocity distribution in the neutral beam turn on phase is presented.

The CTS system on TEXTOR ($R = 1.75$ m, $a = 0.45$ m) uses a 110 GHz gyrotron operated at 100 kW to scatter off plasma fluctuations induced by the ion motion. A receiver beam collects part of the radiation from where the probe and receiver beam overlaps, referred to as the scattering volume. The wave vector and frequency of the resolved fluctuation is given by $(\omega^\delta, \mathbf{k}^\delta)$ = $(\omega^{\mathrm{s}}$ - $\omega^{\mathrm{i}}, \mathbf{k}^{\mathrm{s}} - \mathbf{k}^{\mathrm{i}})$, where superscripts i and s refer to incident and scattered, respectively. Extraction of ion information from Thomson scattering requires that the scattering is dominantly off collective fluctuations which implies $\alpha \equiv (|\mathbf{k}^\delta|\lambda_D)^{-1} > 1$. Here λ_D is the Debye length. In other words, fluctuation scale lengths longer than the Debye length are resolved by CTS. By using 110 GHz radiation as probing radiation on the TEXTOR CTS system, the resolved fluctuations are driven mainly by the ion motion. The frequency, ω^δ, of a particular wave vector component, $\mathbf{k}^\delta$, of the fluctuations driven by a particular ion is approximately given by $\omega^\delta = \mathbf{v}_{ion} \cdot \mathbf{k}^\delta$, where $\mathbf{v}_{ion}$ is the velocity of the ion setting up the fluctuation.

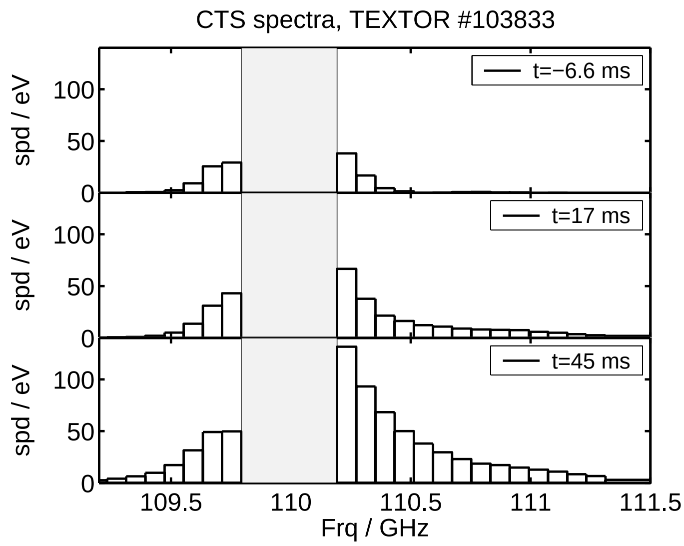

Figure 1: CTS spectra development for hydrogen beam injection. The gyrotron is centred at 109.95 GHz. The missing channels close to the gyrotron frequency represents the notch filters.

The evolution of the fast ion distribution function has been monitored during the starting up phase of the co-current neutral beam. In figure 1 are shown 3 CTS spectra during the highly dynamical beam start up phase. The scattering geometry in this discharge is such that the scattering volume is located in the horizontal midplane at $R = 1.85$ m, close to the magnetic axis. The resolved fluctuation, $\mathbf{k}^{\delta}$ has an angle to the tokamak magnetic field of 135° degrees. The toroidal magnetic field is antiparallel to the plasma current. In the top graph in figure 1, the CTS spectrum at 7 ms prior to the beam turn on is shown. Here the spectrum of the scattered radiation is symmetric around the gyrotron frequency close to 110 GHz. The grey region represents the notch filters. In the middle plot the spectrum at 17 ms after the beam turn on, a clear asymmetry is seen in the spectrum. For this geometry the co-current beam ions are present in the spectrum at frequencies higher than the gyrotron frequency. At 45 ms after the beam turn on (bottom) a final spectrum is shown revealing even more fast ions.

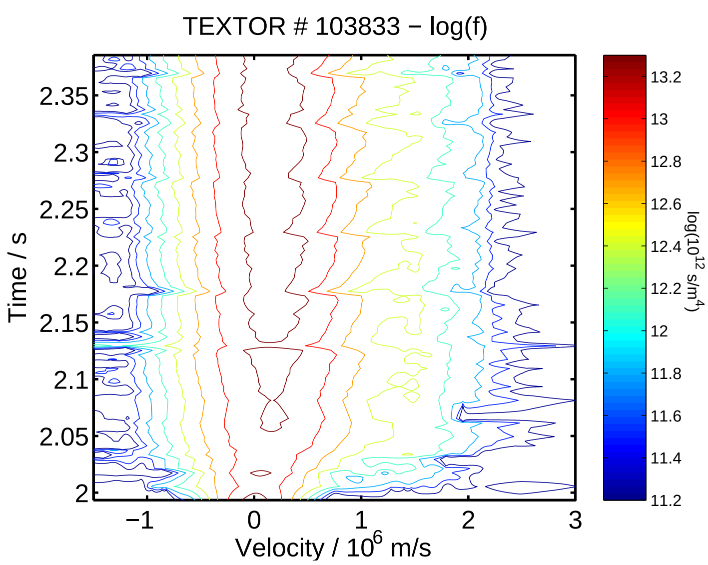

Figure 2: Inferred velocity distribution.

The velocity distribution is inferred by the use of a least squares fit with nuisance parameters (LSN) [4]. The forward model used in the inference is a fully electromagnetic model of CTS with magnetised thermal ions while the fast ions are treated as un-magnetised [3]. The inferred velocity distribution is shown in figure 2. The neutral beam injector is turned on at $t = 2$ s. A clear asymmetry is seen in velocity distribution after this time. The beam ions are born with a velocity of 3.1 10^6

m/s in the counter direction of the magnetic field. Since the measurements are a projection onto $\mathbf{k}^{\delta}$, the ions appear at positive velocities in the CTS projection for this geometry. Also the centre of the bulk ions is shifted to positive velocities indicating a bulk ion rotation build up.

A number of discharges have been performed studying the startup and the turn off of the NBI injecting deuterium into a deuterium plasma. The discharges have been done for different electron densities and temperatures giving different values of the slowing down time. These measurements were done in the horizontal midplane at a radial position of $R = 1.63$ m, slightly on the high field side (close to the NBI tangent radius), with a resolved fluctuation, $\mathbf{k}^{\delta}$, with an angle to the magnetic field of 113° degrees. In order to verify these measurements, a Fokker-Planck equation was solved for a homogeneous plasma using the Rosenbluth potentials to describe the slowing down and the velocity diffusion of the fast particles[5]. The measured electron density and temperature were used as input for the simulation. The beam deposition is calculated taking the ionisation rate of the neutrals to be proportional to the local density and integrating along the beam injection path. This gives rise to different deposition rates in the scattering volume for different electron density profiles.

In figure 3 (bottom) the logarithm of the measured fast ion distribution for # 89451 is shown. Again the fast ions are seen for positive velocities due to the scattering geometry. Figure 3 (top) shows the simulation of the velocity distribution. A good agreement between the two is seen.

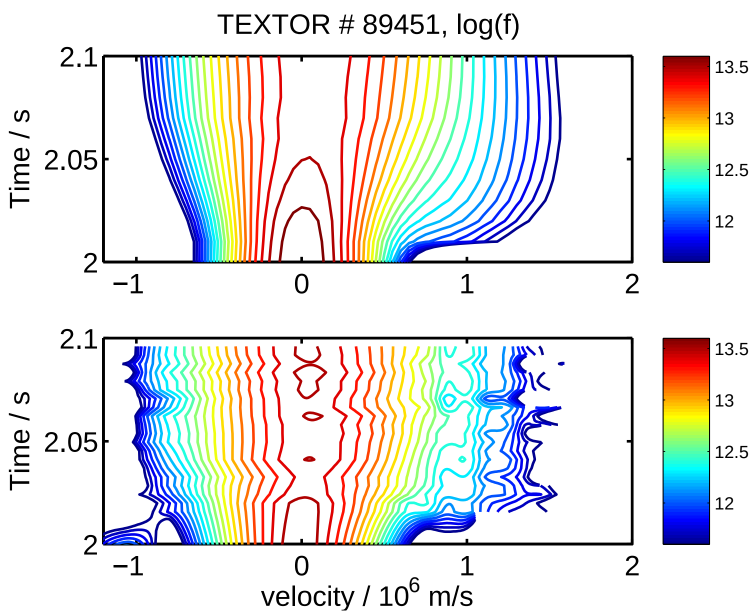

Figure 3: Bottom: measured fast ion velocity distribution for beam injected applied from $t = 2$ s. Top: simulated fat ion velocity distribution of measured distribution.

Due to limited gyrotron probe time, the turn off phase of the neutral beam was measured in a different discharge. The beam injection timing was advanced to make the beam turn off match the CTS time window. The electron density and temperature profiles of the two discharges are similar and a simulation of the entire 200 ms beam injection time was preformed by taking the first part of the heating phase to match discharges #89451 while the second part was set to match #89461.

Figure 4 (left) shows the measured velocity distributions for the two discharges together with

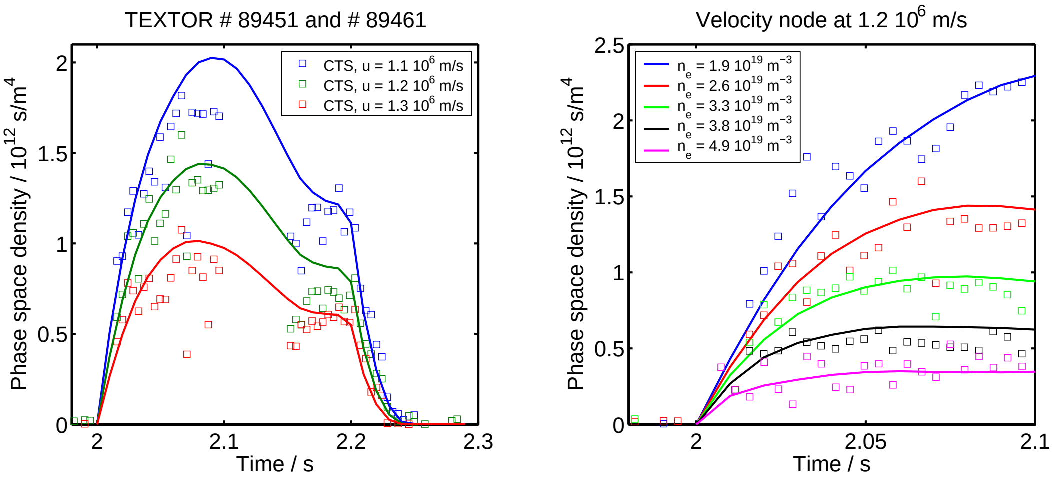

Figure 4: Time trace of 3 super–thermal velocity nodes of discharge #89451 and #89561. The solid lines show the corresponding velocity nodes of the simulated distribution.

the simulation of the two plotted as solid lines. In this combined discharge the beam injection is started at $t = 2$ s and turned off at $t = 2.2$ s. Again good agreement is seen between measurements and simulation. To the right in figure 4 a single super–thermal velocity node of 1.2 10^6 m/s is shown during the beam startup phase for a number of discharges with different electron density. All discharges have the scattering geometry of #89451. The simulations are plotted in the solid lines.

In conclusion, we have shown measurements of the temporal evolution of fast ion velocity distributions obtained by collective Thomson scattering (CTS) during the neutral beam startup phase for different densities and for different scattering geometries. The discharges with resolved velocity component close to v_{perp} is compared to Fokker-Planck simulation and the measurements are in good agreement with simulation.

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