

Neutral Beam Injection Induced Anisotropy of the Electron Velocity Distribution on ASDEX Upgrade

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1. Introduction

Thomson scattering is used on nearly all fusion devices as a standard diagnostic for measuring electron temperature T_e and density n_e robustly and routinely. For the evaluation of the measured scattering spectrum a Maxwellian velocity distribution is assumed for the electrons, which is normally a sufficiently good approximation.

In some H-mode discharges with early application of Neutral Beam Injection (NBI) discrepancies in the derived electron densities and temperatures, measured at the same position with two different Thomson scattering systems, are found. This indicates that in these cases the assumption of a Maxwellian velocity distribution for the electrons fails.

2. Diagnostics

On ASDEX Upgrade two different Thomson scattering diagnostics are now available: With the “Vertical Thomson Scattering” (VTS) system (fig. 1a) constructed for 90° -scattering

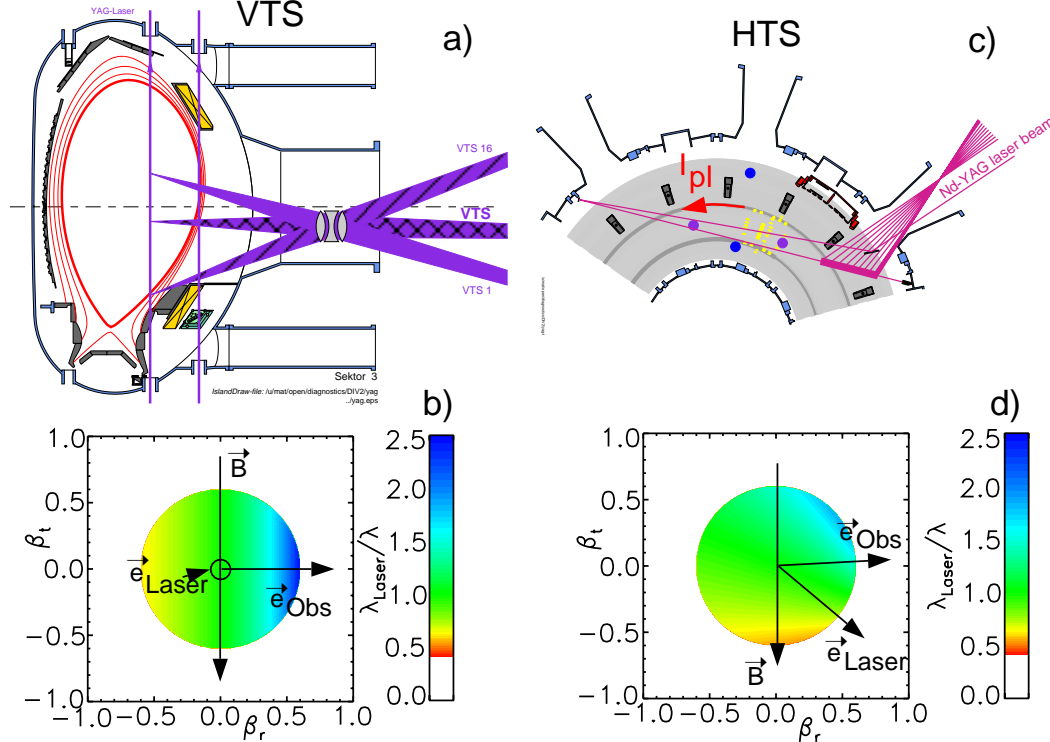


Figure 1: Scattering geometries and Doppler shifts for the VTS and HTS systems. The direction of the plasma current I_{pl} is indicated in c). β_r , β_t are the radial and toroidal electron velocities normalized to the speed of light. \vec{e}_{Laser} , \vec{e}_{Obs} indicate the directions of the laser beam and of the observation of the scattered light, and \vec{B} is the toroidal magnetic field. λ_{Laser} and λ are the wavelengths of the laser and of the scattered light.

and the laser beam aligned perpendicular to the toroidal magnetic field the poloidal-radial velocities of the electrons give the strongest Doppler shift (fig. 1b). So with this system

the mean perpendicular energy of the electrons is measured. In contrast to this the newly installed “Horizontal Thomson Scattering” (HTS) system (fig. 1c) with approximately 45° -scattering and the laser beam enclosing with the toroidal magnetic field an angle of about 45° produces a strong blue-shift of the scattered photons for electron velocities enclosing with the toroidal magnetic field an angle of 45° , and a strong red-shift for the velocities in the direction of the inductively driven electron current (fig. 1d).

In both diagnostics only the blue-shifted spectra are analyzed by four (VTS) and three (HTS) spectral channels. Suprathermal electrons generated in the inductively driven toroidal electric field appear in the red-shifted spectrum and therefore cannot be observed.

3. Experimental Findings

In H-mode discharges with NBI as the only additional heating source, switched on in the current ramp up phase, or shortly after it, and followed by a density plateau phase, differences in the electron densities and temperatures, derived with the VTS and HTS systems, develop, which are assigned to an anisotropic distribution function. In a typical discharge of this kind where NBI was switched on at $t = 1$ s the anisotropy develops with a relaxation time constant of about 3 s (fig. 2). The anisotropy in the temperature has its maximum in the

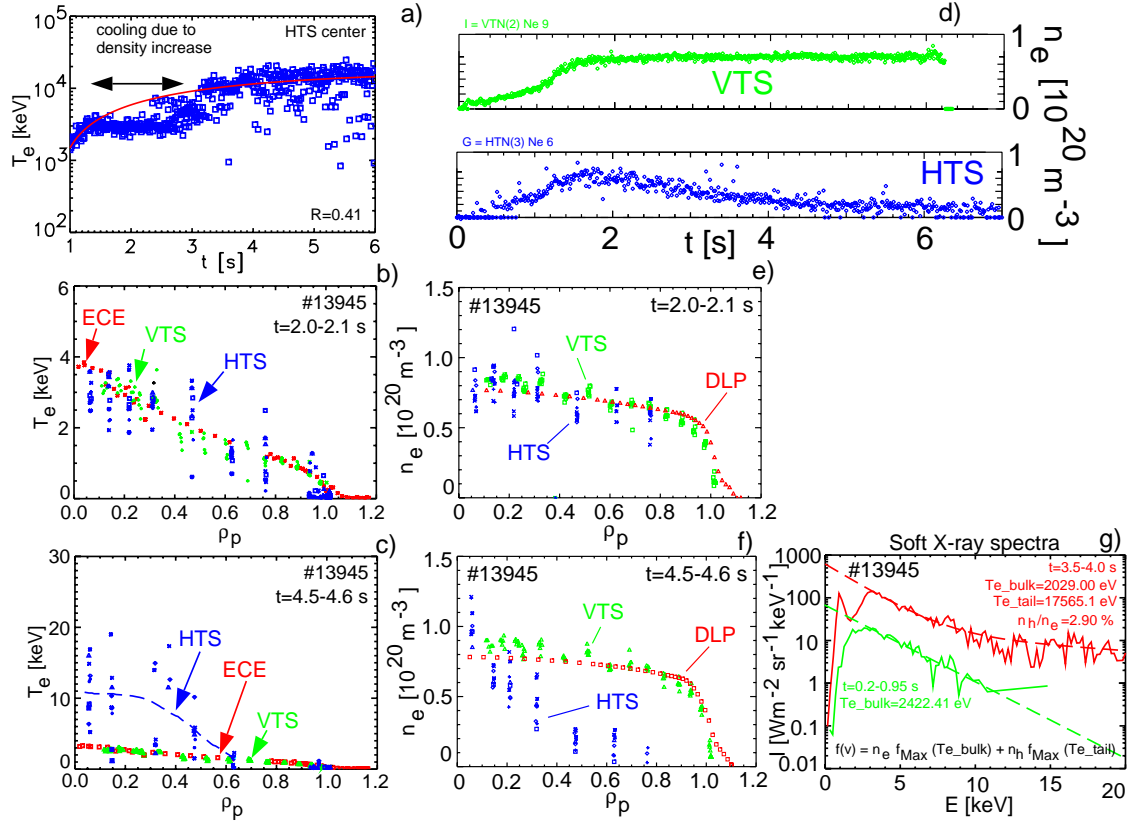


Figure 2: Anisotropies in the electron density and temperature. The density profiles determined from a deconvolution of interferometric signals and the Li-beam diagnostic are indicated by DLP.

plasma center and decreases towards the plasma edge (fig. 2 c). The effect of the anisotropic distribution function on the derived density is most strongly pronounced in the plasma edge and decreases towards the plasma center where it practically vanishes (fig. 2 f). In the Soft X-ray spectra obtained for a line of sight through the plasma center a high energy tail develops with time, which is fitted by a Maxwellian distribution of a temperature of 18 keV (fig. 2 g), confirming the high electron temperatures of about 12 keV measured with the HTS system in the plasma center. The electron temperatures determined from X mode Electron

Cyclotron Emission (ECE) agree with the temperatures measured with the VTS system, because both diagnostics are sensitive to the electron velocity distribution perpendicular to the magnetic field.

The observed maximum apparent temperature anisotropy is in the range $[T_e(\text{HTS}) - T_e(\text{VTS})]/[T_e(\text{HTS}) + T_e(\text{VTS})] = 0.55 - 0.8$. The parameter range for which these anisotropies appeared so far are $3.2 \leq \bar{n}_e [10^{19} \text{ m}^{-3}] \leq 7.5$ (line density), $0.43 \leq I_p [\text{MA}] \leq 1.06$ (plasma current), $5.1 \leq P_{\text{NBI}} [\text{MW}] \leq 9.8$ (power of NBI), $E_{b1} = 60 \text{ keV}$ (beam energy of NBI box 1), $68 \leq E_{b2} [\text{keV}] \leq 93$ (beam energy of NBI box 2).

A reconstruction of the electron velocity distribution function is possible by a series expansion into Legendre polynomials, $f(v, \mu) = f_M(v, T_e) \left[1 + 3\mu(n_b/n_e) \left(v_b v / v_{Te}^2 \right) \right] + \alpha f_M(v, T_{e2}) \left(3\mu^2 - 1 \right) / 2$, with v : electron velocity, μ : cosine of pitch angle, n_b : ion beam density, v_b : ion beam velocity. The temperatures T_e , T_{e2} in the Maxwellian distributions f_M and the parameter α are adjusted for best agreement between the scattering spectra belonging to the temperatures observed with the VTS and HTS systems and the scattering spectra calculated with the distribution function. The NBI current drive term $\propto \mu v$ [1] does not change the distribution function significantly for the realistic beam densities of $n_b = (10^{17} - 10^{18}) \text{ m}^{-3}$. For the case of maximum anisotropy the parameters $T_e = 4.5 \text{ keV}$, $T_{e2} = 13 \text{ keV}$ and $\alpha = 2.2$ are found (fig. 3) where T_e is also the mean energy of the electrons.

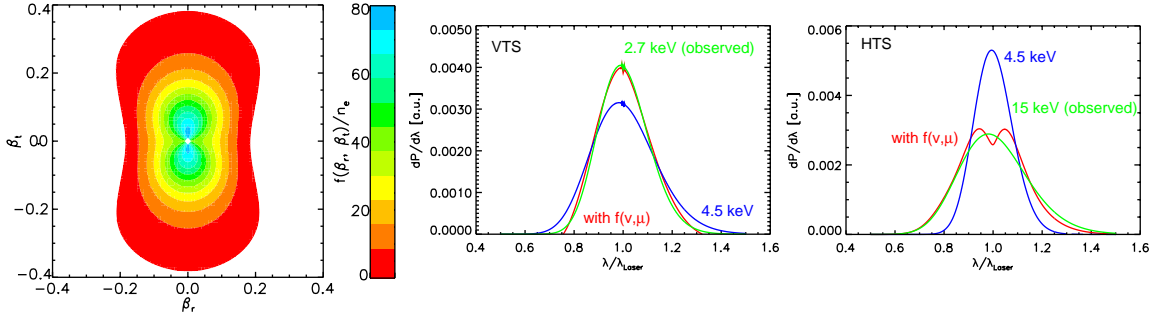


Figure 3: Reconstructed electron velocity distribution function

4. Comparison to Theory

In the plasma center where there are no magnetic mirrors and where the magnetic field enforces axial symmetry, the dynamics of the electrons interacting with the thermal and beam ions is determined by the conservation laws of energy, of the momentum along the magnetic field and of the angular momentum resulting from the gyromotion. For the discharge discussed above the energy transfer times [2] of the beam ion energy to the electrons for the electron density $n_e = 3 \times 10^{19} \text{ m}^{-3}$ and the temperature $T_e = 3 \text{ keV}$, are $\tau_{tr1} = 0.15 \text{ s}$ and $\tau_{tr2} = 0.21 \text{ s}$ for the beam energies $E_{b1} = 60 \text{ keV}$ and $E_{b2} = 93 \text{ keV}$ respectively. Since the beam energies E_{b1} , E_{b2} are above the critical energy [2], $W_c = 44 \text{ keV}$, these energy transfer times are mainly determined by ion-electron collisions.

Due to collisions the angular momentum contained in the gyromotion of the beam ions, $L_b^B = -(n_b m_b / eB) E_b$ is transferred to the angular momentum of the electrons' gyromotion, $L_e^B = (n_e m_e / eB) T_{e\perp}$ and is thus being reduced with the time constant [3] $\tau_{ie\perp} [\text{s}] = T_e^{1/2} [\text{eV}] E_b [\text{eV}] (m_b / m_p) / (3.2 \times 10^{-9} n_e [\text{cm}^{-3}] Z^2 \lambda_{ie})$. Since the

energy $2T_{e\perp} + T_{e\parallel} = \text{const.}$ is conserved on the timescale of $\tau_{ie\perp} = 4.9 \text{ s} > \tau_{tr1,2}$ ($T_e = 3000 \text{ eV}$, $n_e = 3 \times 10^{13} \text{ cm}^{-3}$, Coulomb logarithm $\lambda_{ie} = 15$), perpendicular energy must be transferred to parallel energy. The anisotropic perpendicular energy distribution is being isotropized by collisions of the electrons with the thermal ions with a time constant of the order of [3] $\tau_{ei}^T [\text{s}] = (m_D/m_e) T_e^{3/2} [\text{eV}] / (8.2 \times 10^{-7} n_e [\text{cm}^{-3}] \lambda_{ie})$ which is $\tau_{ei}^T = 1.6 \text{ s}$ for the above mentioned parameters. The resulting differential equation $dL_e^B/dt = L_e^B/\tau_{ie\perp} + (n_e m_e/eB)(T_{e\perp} - T_{e\parallel})/\tau_{ei}^T$ has the solution $T_{e\parallel} - T_{e\perp} = (n_b m_b/n_e m_e) (\tau_{ei}^T/\tau_{ie\perp}) E_b [1 - \exp(-3t/\tau_{ei}^T)]$. The temperature anisotropy relaxes with the time constant $\tau_{ei}^T/3$ to a stationary value. For the observed final temperature anisotropy of $T_{e\parallel} - T_{e\perp} \approx T_e(\text{HTS}) - T_e(\text{VTS}) = 9 \text{ keV}$ a beam density of $n_b = 0.1 \times n_e$ for $T_e = 4.5 \text{ keV}$ is needed. For a center density of $n_e = 8 \times 10^{19} \text{ m}^{-3}$ the beam density is $n_b = 8 \times 10^{18} \text{ m}^{-3}$. This compares well to the mean beam density, determined from the injected NBI power, $\langle n_b \rangle = [P_{\text{NBI1}}/(E_{b1} \tau_{tr1}) + P_{\text{NBI2}}/(E_{b2} \tau_{tr2})]/V_{\text{pl}}$, which is $\langle n_b \rangle = 7 \times 10^{18} \text{ m}^{-3}$ for $P_{\text{NBI1}} = 2.5 \text{ MW}$, $P_{\text{NBI2}} = 5 \text{ MW}$ and the ASDEX Upgrade plasma volume $V_{\text{pl}} = 10 \text{ m}^3$.

The shape of the anisotropic electron velocity distribution function is investigated by the solution of the time dependent 2 D Fokker-Planck equation including collisions between the electrons and the beam ions and the thermal ions and electron-electron collisions. The anisotropic distribution function is expanded by Legendre polynomials $P_j(\mu)$ around a Maxwellian distribution, $f(v, \mu) = f_M(v, T_e) + \sum_{j=0}^{\infty} f_j(v) P_j(\mu)$. With the evolution in time the leading terms are $f_2(v)$, describing the anisotropy between parallel and perpendicular energy as observed in the experiment, and $f_1(v)$ describing the NBI current drive [1] (fig. 4).

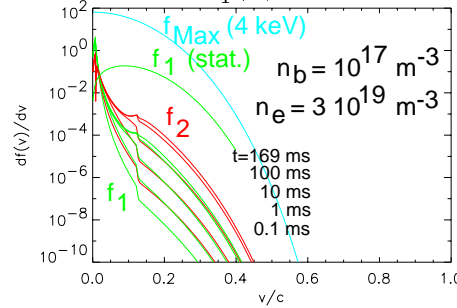


Figure 4: Time evolution of $f_1(v)$ and $f_2(v)$ up to 169 ms.

5. Conclusion

The electron temperature anisotropy observed in the center of the plasma, during NBI heating, can be explained by the beam ions transferring angular momentum to the electrons. The observed long timescales are due to the ion-electron and electron-ion collisions involved.

References

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