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Ion Temperature Determination from Atomic Fluxes above Neutral Beam Injection Energies in ASDEX Upgrade

H.-U. Fahrbach, A.V. Khudoleev[1], J.A. Heikkinen[2], A.G. Peeters, H. Meister, T. Kurki-Suonio[3], S.K. Sipilä[3], A. Stäbler, J. Stober, W. Ullrich and the ASDEX-Upgrade Team

Max-Planck-Institut für Plasma-Physik, EURATOM-Association, D-85748 Garching, Germany
[1]*A.F.Ioffe Physical-Technical Institute, 194021, St.Petersburg, Russia*
[2]*VTT Energy, Ass. Euratom-TEKES, P.O. Box 1604, FIN-02044 VTT, Finland*
[3]*Helsinki University of Technology, Ass. Euratom-TEKES, P.O. Box 2200, FIN-02015 HUT, Finland*

1 Introduction

Charge exchange atoms with energies up to one order of magnitude above the thermal energy are generally used for ion temperature determination by neutral particle diagnostics in magnetic confinement fusion experiments. For the case of Neutral Beam heated plasmas a second method was proposed [1,2], which is based on energies greater than injection energy: The ion distribution function of the injected particles is extended into this range due to collisions with thermal plasma background particles (High Energy Beam Tail: HEBT) and therefore the slope of the neutral particle spectrum is dependent on the ion temperature. This method has two advantages: Firstly, neutrals of this high energy can escape much better from the the central region of todays large and dense fusion plasmas. Secondly, it is the injected mass species, which is measured. It represents the majority species in most investigations, whereas the standard method, using the non-injected hydrogen isotope, often is handicapped by it's low concentration; normally the use of the injected mass species is prevented by severe spectral distortion due to slowing down particles.

2 Experiments

Diffusion of beam particles in velocity space takes always place in the plasma. But to produce experimentally measurable fluxes above injection energy, the ion temperature has to be sufficiently high, as in large Tokamaks (TFTR, JET, JT-60) and now in ASDEX Upgrade (AUG) improved H-Mode plasmas, where strongly peaked profiles of density and temperature with central T_i up to 15 keV were observed. As an example a hydrogen plasma with hydrogen beam injection is shown in Fig.1. The plasma contains about 10 % of deuterium, which allows to perform simultaneously classical neutral spectra analysis from maxwellian ion distribution function in addition to the evaluation of HEBT. This is possible due to three facts: A relatively low beam energy of 40 keV, low neutron and gamma background and the H^0 energy range of the neutral particle analyzer (NPA) being a factor 2 higher than for D^0. H^0 and D^0 spectra at the beginning and during the stationary phase of the discharge are shown in Fig.2. The flattening of the tail, which is a measure for the reciprocal ion temperature, $1/T_{eff} = -(d\ln(F)/dE)$, indicates the increase of ion temperature, as plasma reaches the plateau phase.

In this case ion temperature determination was possible with 3 independent methods: With charge exchange recombination spectroscopy (CXRS) diagnostics, with classical D^0, and with H^0 high energy tail spectra. The ion temperature profile from D^0 spectrum was reconstructed by simultaneous modelling of neutral density and ion temperature profile with the EIRENE

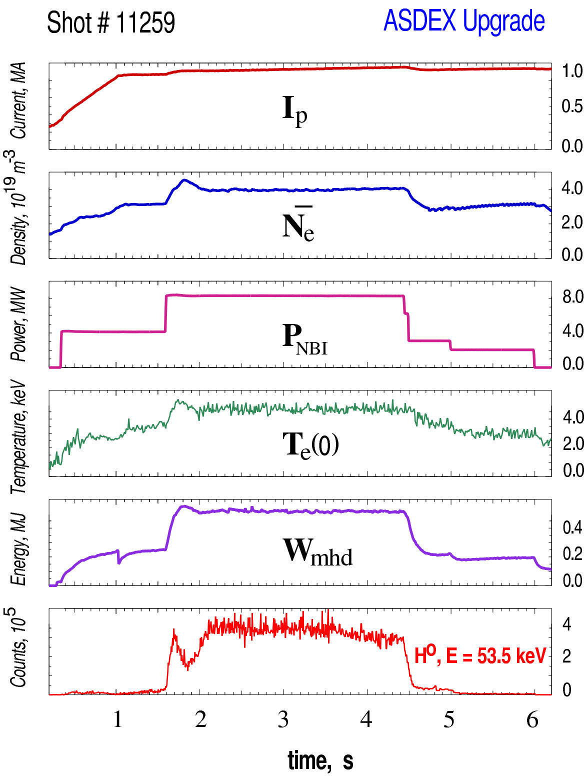

Figure 1: Improved H-Mode discharge in Hydrogen with 8.6 MW H^0 Beam Injection from 8 Sources.

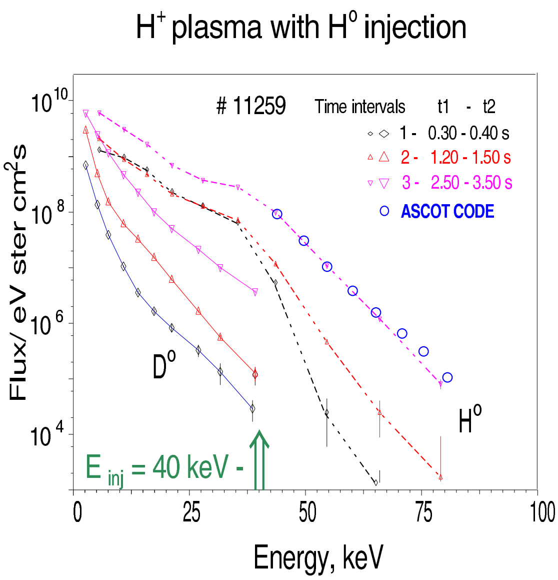

Figure 2: Spectra of H^0 (dashed) and D^0 (full) from three different time intervals.

Monte-Carlo code [3]. The high energy tail was evaluated, as described in [1], with the formula

$$T_i = T_{eff} + (T_{eff} - T_e)(E/E_{crit})^{1.5}. \tag{1}$$

T_{eff} is the ion temperature corresponding to the high energy spectral slope, E_{crit} is the critical energy, above which the beam power goes predominantly to the electrons, here for unity ion charge:

$$E_{crit} = A_b A_i^{-1/3} 14.8 T_e, \tag{2}$$

In the experiments described here, the NPA viewed the central plasma region roughly horizontally from the outside. The angle in the horizontal plane can be varied between 0 and 18 degrees with respect to AUG major radius. The angle between neutral beam injection (NBI) and major radius is about 35 degrees near the plasma axis. The four sources of each beamline inject particles with slightly different pitch angles. Moreover those particles, which reach the NPA observation line, are deflected by a relatively small pitch angle. Under these circumstances it is not obvious, that the diffusive tail above injection energy is formed well enough to allow application of formula (1) for the relation between slope of HEBT and plasma temperature. Also the beam ions at the high energies have significant excursions from the magnetic surfaces.

3 Numerical Simulations of the High Energy Tail

To take these factors into account and to assess the scale of necessary correction we performed numerical modelling of experimental data. For calculation of the ion distribution function the

ASCOT code [4] was applied. The code is based on Monte Carlo techniques. It follows guiding center trajectories of test particles in the real AUG tokamak magnetic topology. The collisions of the test particles with the background plasma are simulated using binomially distributed Monte Carlo operators derived from Fokker-Planck equation. The calculations were performed in 10 radial slots and for 8 energy groups of test particles. To describe the background plasma the experimentally measured relevant plasma parameters such as temperatures and density were used. The emitted neutral flux spectra were calculated on the basis of the ion distribution function from ASCOT and the modelled neutral profile in the plasma from EIRENE. This allows to compare directly experimental and model results [5].

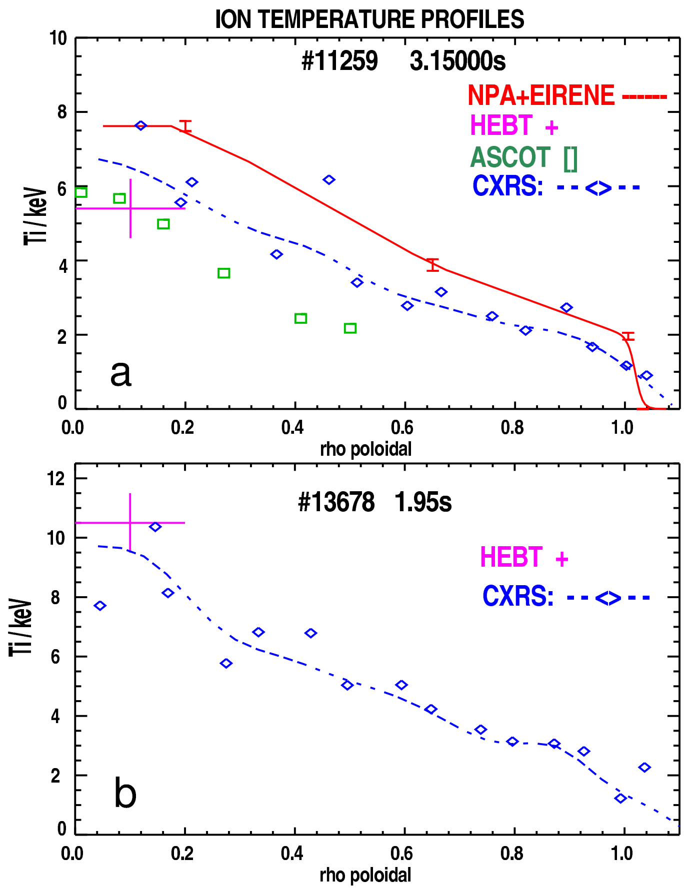

Figure 3 a,b: Ion temperatures from ASCOT Simulations, CXRS, classical and HEBT neutral spectra.

The full code run was made for shot #11259. The results of ASCOT with experimental input data are presented as circles in Fig.2. As seen the results are in the good agreement with measured flux. In Fig.3a three ion temperature profiles are shown. One from CXRS measurements, another is from NPA-EIRENE processing of D^0 minority spectra. The third is the reverse transformation of ASCOT results using formula (1). This profile is in plasma center about $10 - 20\%$ lower than the former two and the ratio increases towards larger radius.
One possible reason for the underestimate of ion temperature from HEBT with the simple formula (1) is that the angular scattering of HEBT particles is not sufficiently strong, to reach this analyzer with the viewing line at toroidal angle 0 degrees (perpendicular to plasma axis). The spectra from Fig.4. are from deuterium shots ##13677-78 with more "tangential" injection and higher beam energy (68 keV), where the analyzer was tilted against beam injection direction to the smallest toroidal angle (-7 degrees) possible in the present setup. Under these conditions

the HEBT ions must be deflected by an angle of about 20 degrees to be detected by NPA. Evaluation of central ion temperature from HEBT is in the good agreement with the spectroscopic data (Fig.3b). This indicates, that our present experimental layout allows to come to the limit, where the asymptotic formula (1) is applicable. Variation of the viewing line angle between -7 and +12 degrees shows the general tendency, that the closer the analyzer views against the beam injection direction, the flatter the HEBT becomes, and the more the ion temperature from HEBT approaches that from CXRS.

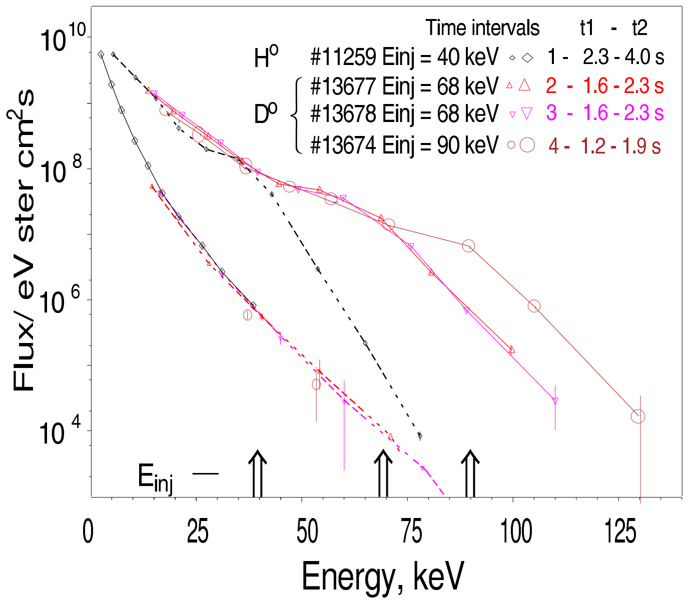

Figure 4: H^0 and D^0 fluxes from discharges with 40, 68, and 90 keV beam injection energy.

The measurements of HEBT were performed for the complete energy range of NBI. In Fig.4 the neutral spectra for NBI energies = 40, 68, 90 keV are shown. The higher the injection energy is, the higher is the required plasma temperature to give statistically valuable data.

4 Conclusion

It is possible to infer ion temperature from the high energy tail of injected particles in AUG experimental layout and for presently attainable high plasma temperatures.
Comparison with the other methods - CXRS and T_i from maxwellian part of distribution function - shows reasonable agreement.
Monte Carlo simulation of Fokker-Planck equation for beam ions with the ASCOT code were successfully started. Measured neutral spectra could well be reproduced.
Plasma rotation does not significantly affect high energy spectra.
Experimental limitations can be overcome by increasing the energy range and resolution, the sensitivity of the NPA and by optimization of the sightline.
The method may be advantageously applied in the next generation of tokamaks, provided they will use NBI for plasma heating. For detailed assessment further numerical simulations are required.

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