

Ion temperature measurements using the energy spectrum of escaping 3 MeV proton fusion products at TEXTOR-94:

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Introduction: A diagnostic for measuring fast charged particles escaping from the plasma is operational at TEXTOR-94. It is used to detect the protons produced in the fusion reaction:



where $Q = 4.032$ MeV is the energy outcome of the reaction. The total proton emission rate is up to 10^{14} s^{-1} at TEXTOR-94 and high resolution 3 MeV protons energy spectra can be measured. The energy resolution is very good, around 1 percent or even better. Two detectors are installed with a different line of sight to obtain spatial information. At TEXTOR, the plasma current is varied between 250kA and 600kA such that the 3 MeV protons and 1 MeV tritons are not confined. While they move out of the plasma towards the vessel walls they have a negligible probability to make a collision. They reach the detector with their initial energy.

In the case of an isotropic maxwellian velocity distribution function for the deuterium ions, the proton energy spectrum is [6],[7]

$$\frac{dN}{dE_p} \propto \langle \sigma g \rangle \exp\left(-\frac{2m_p}{kT}(v_p - v_0)^2\right) \quad (2)$$

with E_p, m_p, v_p energy, mass and velocity of the proton, $v_0 = \sqrt{\frac{3Q}{2m_p}}$ and $\langle \sigma g \rangle$ is:

$$\langle \sigma g \rangle = 4\pi \left(\frac{m_D}{4\pi kT}\right)^{\frac{3}{2}} \int_0^\infty \exp\left(-\frac{m_D g^2}{4kT}\right) g^3 \sigma(g) dg \quad (3)$$

The proton energy spectrum width is therefore a direct measurement of the plasma ion temperature. From equation(2), the full width at half maximum (FWHM) is

$$FWHM(keV) = 91.6\sqrt{T_i(keV)} \quad (4)$$

The numerical factor in this formula is very weakly temperature dependent[3]. A computer code, the LIPS code, similar to the JET code FPS[3] used in the neutron spectroscopy studies is now developed. This code simulates the fusion product spectrum

for entirely general ion velocity distribution and for any desired viewing angle. The simulation can be applied for example to the case of a plasma with a slowing down distribution of deuterium beam ions. The simulated spectrum is computed using the integral[3]:

$$\frac{dN}{d\Omega_p dE_{p,L}} = \int \int \int f_A(\vec{v}_A) f_B(\vec{v}_B) \frac{d\sigma}{d\Omega_p dE_p d\Omega_t dE_t} |\vec{v}_A - \vec{v}_B| d^3\vec{v}_A d^3\vec{v}_B d^3\vec{v}_t \quad (5)$$

where

$$\frac{d\sigma}{d\Omega_p dE_p d\Omega_t dE_t} = \frac{d\sigma}{d\Omega_p dE_p} \delta(E_p - E_p^*)$$

where E_p^* is the energy in the laboratory frame of the detected proton. In this case the spectrum width dependence on ion temperature is computed numerically. The formula (5) applies to a small plasma cell in which one assumes plasma parameters to be constant. Next a line integrated spectrum is calculated using plasma parameter profiles and radial distribution of detection efficiency [5] from the GOURDON code[4]. It is then finally compared with the measured data.

The fast charged particle detector has been presented elsewhere[8]. The measurements presented in this paper are performed simultaneously with one detector oriented quasi perpendicular to the direction of the toroidal magnetic field and one detector oriented quasi parallel to the magnetic field.

Measurements in H → D NBI heated discharges: 3 MeV proton energy spectra have been obtained in about 50 discharges with ohmic heating and NBI hydrogen neutral beam heating. In such heating scenarios the following assumptions are reasonable. The ion velocity distribution is nearly maxwellian. The measured 3 MeV proton spectrum therefore has a gaussian shape. The superposition of the spectra along the detector line of sight does not affect strongly the spectrum shape and its broadening. Because the fusion proton emission is generally the highest at the center, the contribution to the line integrated spectrum comes therefore mostly from the center. This question has been investigated in details in [2]. With a central temperature $T_i < 0.9keV$ the line integrated spectrum is steeper than a gaussian profile so that a simulated spectrum must be fitted to the experimental one. For higher temperature the line integrated spectrum is well approximated by a gaussian spectrum. Corrections depending on the temperature profile can be applied to obtain the central temperature. These corrections are modest compared to the overall uncertainty. The temperature is obtained simply by fitting a gaussian curve to the measured proton spectrum. After corrections for energy straggling and noise broadening[2] the spectrum width is put in the relation (4) to find the temperature. The experimental results are plotted at fig.1 as a function of the central electron temperature. Due to the energy equipartition time there should not be large deviation from the central electron temperature. The spectra are time-integrated over 3s which is the duration of the neutral beam heating phase in these discharges. Data from the argon Xray spectroscopy measurements are shown for comparison. There are no large discrepancies. Most of the results are in agreement within the error bars. However the proton data are slightly higher in absolute value. Some data points from the ion temperature measurement by the charge exchange diagnostic are also shown. The central line averaged density range for

these measurements is 2 to 4 10^{13} cm^{-3} . With the second detector 3 MeV proton spectra are measured from plasma region with minor radius $r > 25\text{cm}$. For ohmic plasmas the 3 MeV proton energy spectrum broadening is smaller than the broadening from the central measurement. An ion temperature can be deduced. In the case of NBI H \rightarrow D injection the 3 MeV proton energy spectrum broadening is found larger than the central value up to a factor of two. This may be due to a small amount ($\leq 10^{-2}$) of deuterium in the hydrogen beam which causes parasitic 'beam-thermal' reactions. These reactions may considerably broaden the spectrum as it can be seen from the LIPS code simulations.

Measurements in NBI D \rightarrow D heated discharges: 3 MeV proton energy spectra from deuterium plasmas heated by deuterium neutral beam injection are about a factor of two broader than the spectra measured with hydrogen injection. For a given injection geometry (tangential at TEXTOR-94) and a given detector viewing angle, the 3 MeV proton 'beam-thermal' spectrum broadening depends mostly on the deuterium beam ion velocity, the ion temperature and the electron temperature. The 3 MeV proton emission profile in these plasmas is depending on the beam ions deposition profile. The emission profile is generally broader than the thermal emission profile. The effect on the line integrated spectrum is therefore important. An appropriate ion velocity distribution function describing the beam ions is used in this model[9]:

$$f_b(v, \xi) = \frac{S^0 \tau_s}{v^3 + v_c^3} \sum_{l=0}^{\infty} \frac{2l+1}{2} P_l(\xi_b) P_l(\xi) \left(\frac{v^3}{v_b^3}\right) \left(\frac{v_b^3 + v_c^3}{v^3 + v_c^3}\right)^{\frac{1}{6}(l+1)Z_2} U(v_b - v) \quad (6)$$

where v_b is the beam velocity, ξ_b is the injection angle, $U(v_b - v)$ is a step function, v_c the critical velocity and τ_s is the Spitzer slowing-down time. The beam ion distribution function (6) is introduced in the integral (5) which is calculated with the Monte Carlo code LIPS. A calculation of the spectrum width has been done for fixed beam injection at 40 keV for different ion temperatures for 1 keV electron temperature and Z_{eff} of 1. The results are shown at the fig.2. The largest width are observed for the parallel viewing but both show a significant variation of the width with temperature. When going below 1 keV the shape of the spectrum is rapidly changing from a near-gaussian shape to a characteristic two-lobe shape. The two-lobe is characteristic from a beam-thermal spectrum when the plasma temperature is going to zero. This has been demonstrated analytically [1]. At the fig.3 two proton spectra have been taken in two consecutive discharges both at 40 keV injection voltage and with respective ion temperature $T_{i0} = 1.28$ and 1.52 keV measured by charge exchange spectroscopy. The prediction of the LIPS code is shown at the fig.4 for shot 77828. The line integrated spectrum is computed with the measured density profile, ion temperature, electron temperature and calculated beam ion deposition profile. The proton distribution of detection efficiency is calculated from the GOURDON code. The ion temperature profile is taken from the charge exchange measurements. The agreement between measured and calculated spectrum is rather good as it can be seen at the fig.4. A better agreement is obtained with a slightly narrower ion temperature profile and a higher n_d/n_e deuterium to electron density ratio.

Conclusions: Energy spectra of fast tritons and fast protons with an energy resolution up to 25 keV are measured. In thermal plasmas the ion temperature can be measured with good accuracy. The central ion temperatures obtained from independent measurements are in agreement within the errorbar with the value derived from the 3 MeV proton energy spectrum. These temperatures however are somewhat higher than the temperatures

measured by Argon Xray spectroscopy. Further measurements with better accuracy in the proton data would be useful to confirm this. In plasmas with neutral beam deuterium injection, the LIPS code is able to predict the 3 MeV proton spectrum. Taking the ion temperature profile from the charge exchange measurement the predicted spectrum agrees with the measured data. It is possible to find the ion temperature from the width of the measured beam-thermal 3 MeV proton energy spectrum using our numerical modelling for TEXTOR conditions.

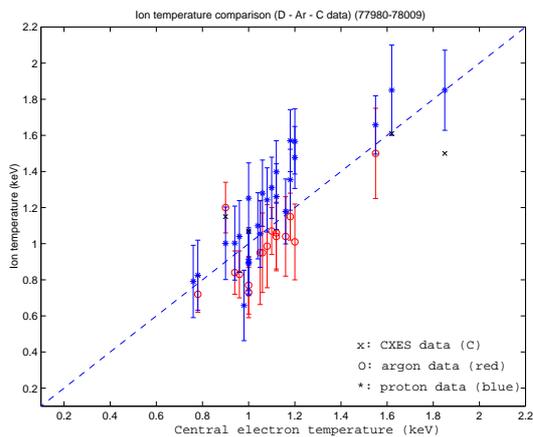


Fig.1: Ion temperature data in NBI H -> D discharges

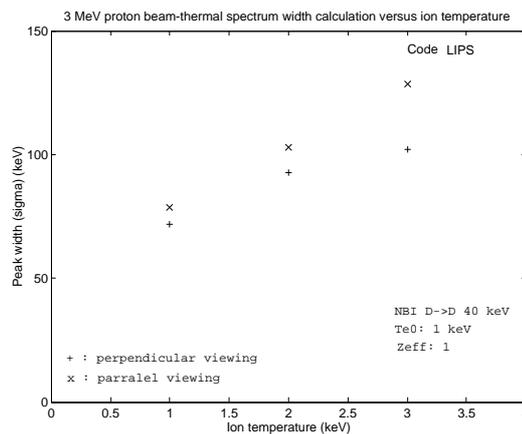


Fig.2: Calculation of spectrum width as a function of the ion temperature

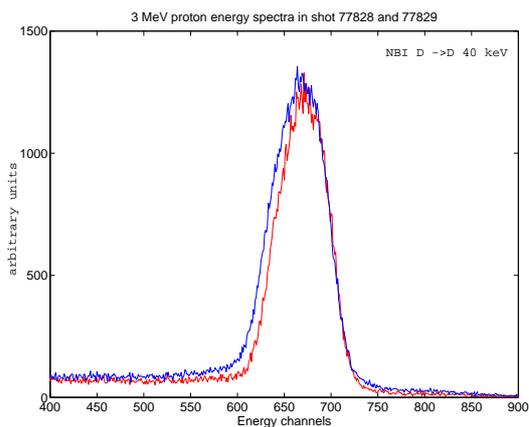


Fig.3: Proton spectra:Ti0(CXES)=1.28 and 1.52 keV

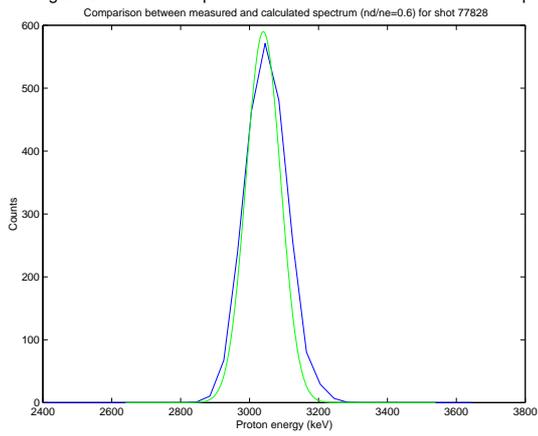


Fig.4: Comparison between experiment and calculated spectrum (Code LIPS)

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