Spatially resolved and pitch angle resolved spectral analysis of 3 MeV fusion protons at TEXTOR-94 in auxiliary heated deuterium plasmas:

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Introduction: A diagnostic for measuring fast ions escaping from the plasma is operational at TEXTOR-94[1]. 3 MeV protons produced in the reaction:

$$D + D \longrightarrow p(3024keV) + T(1008keV) + Q \tag{1}$$

are detected. At TEXTOR, the plasma current is varied between 250kA and 600kA such that fast protons above energy of typically 500 keV are not confined. Two detectors are located inside the vacuum vessel just in front of the liner. The system has two sightlines through the plasma. The proton energy is measured with a resolution up to 15 keV. While protons travel out of the plasma they have a negligible probability to collide on plasma particles. Therefore, they reach the detector with their birth energy. In the case of a deuterium plasma with a fast deuteron population, the broadening, the shift and the shape of the measured proton energy distribution result from the fast ions velocity distribution. Infer directly the distribution function from the spectrum is a difficult task. In the present study we choose a model and we calculate the main parameters of the underlying distribution function. Finally we compare the predicted proton energy spectrum with the measured spectrum.

Experimental conditions and measurements: The collimator orientation with respect to the magnetic field γ defines the detector sightline. Two detector orientations are simultaneously used in these experiments. 1) γ=45^0: the detected protons come from the high field side (HFS) plasma region 2) γ=335^0: the detected protons come from the low field side (LFS) plasma region. Protons trajectories are calculated to determine the distribution of detection efficiency. The distribution of detection efficiency shows the space region where protons are born and shows their initial pitch angle. Proton trajectories are simply determined by the magnetic field and the initial conditions because collisions and other forces can be neglected. Proton trajectories are calculated numerically with the GOURDON code [2]. In the case considered here calculations show that the detection efficiency is maximum at around minor radius r=25 cm for the HFS detector and a little nearer the plasma edge for the LFS detector. Measurements are broadly resolved in space (of the order of the Larmor radius). In contrast the detected protons are well resolved in pitch angle [3].

Proton energy spectra have been measured in a set of deuterium plasma discharges with co-injection of a deuterium neutral beam. Typical plasma conditions in these discharges are as follows - central electron line averaged density between 2. and 5. 10^{+19} m^{-3}, central electron temperature $\simeq$1.5 keV , Ip = 400 kA and Bt =2.25 T. Typical measured spectra are shown in figure (1). Both spectra have approximately the same intensity but their width and position are different. The spectrum measured at the low field side is the narrowest. Its center is shifted towards lower energy because the detected protons are emitted backward and travel in the counter direction. The spectrum measured at the high field side is the largest. Its center is shifted towards higher energy because the detected protons are emitted forward and travel in the co direction. Measurements were mostly carried out at beam energy of 35 keV and 40 keV. The best data set, shown in figure (2), was obtained for a beam energy of 35 keV.

Measurements interpretation: For TEXTOR conditions and in high density deuterium plasmas heated with deuterium neutral beams the detected protons are predominantly produced in beam target reactions. The proton energy distribution is therefore mainly dependent upon the fast deuteron velocity distribution.

Energy spectrum modeling: The fusion proton energy in the laboratory frame is given by:

$$E_{p,L} = \frac{1}{2} m_p s^2 + \frac{m_p}{m_p + m_T}(Q + E_{kin,S}) + s cos\chi \sqrt{2 \frac{m_T m_p}{m_T + m_p}(Q + E_{kin,S})} \qquad (2)$$

In (2) s is the center of mass velocity, $E_{kin,S}$ is the relative kinetic energy and χ is the proton emission angle in the center of mass frame, i.e. between the center of mass velocity vector and the proton velocity vector. A Monte Carlo Code, LIPS[1] is used to compute proton energy spectra. The proton energy spectrum is computed for a small plasma volume with local plasma parameters as constants. The probability density function at point $\vec{r}$ of the proton per steradian and per unit of energy is given by the integral [4]:

$$\frac{dN}{d\Omega_{p,L} dE_{p,L}}(\vec{r}) = \int\int\int f_d(\vec{v_{d1}}) f_d(\vec{v_{d2}}) \frac{d\sigma}{d\Omega_{p,L} dE_{p,L} d\Omega_{T,L} dE_{T,L}} \mid \vec{v_{d2}} - \vec{v_{d1}} \mid d^3\vec{v_{d1}} d^3\vec{v_{d2}} d^3\vec{v_T} \qquad (3)$$

where

$$\frac{d\sigma}{d\Omega_{p,L} dE_{p,L} d\Omega_{T,L} dE_{T,l}} = \frac{d\sigma}{d\Omega_{p,L} dE_{p,L}} \delta(E_{p,L} - E^*_{p,L})$$

in which $E^*_{p,L}$ is the proton energy in the laboratory frame corresponding to given $\vec{v_{d1}}$ and $\vec{v_{d2}}$ (2). The ion velocity distribution functions are given as input to the calculations. They depend generally on the position $\vec{r}$. Therefore the integral (3) must be further integrated in space along the detector sightline.

[1] Line Integrated Proton Spectrum

Model with spatial dependence(r): In past experiments with deuterium neutral beam heating proton energy spectra were first measured at the plasma center([3]). In that case a velocity distribution function such as given in Gaffey([5] is taken for the modeling. It is put in integral(3) and the spectrum is computed. The calculated and the measured spectra can be satisfactorily compared[3].

Model with spatial dependence(r,R): The previous model fails when applied to the measurements considered here. This model predicts energy spectra with nearly same widths for high field side and low field side. Therefore it cannot explain the large differences observed between HFS and LFS energy spectra. We apply now a more sophisticated model which takes account of the spatial dependence in major radius R of the fast ions pitch angle distribution. As a first step only fast deuterons near the injection speed are considered. Fast deuterons with $v \leq 0.8 v_b$ are neglected. Fast deuterons above this velocity produce around 80% of the fusion protons. These mostly slow down on electrons and their deflections can be neglected. They move around the torus along passing orbits. While moving alternatively from LFS to HFS the fast ion pitch angle is changed because the magnetic moment remains constant. This pitch angle variation along the injected deuterons trajectories must be taken into account in the proton energy spectrum computation. Deuterium beams are injected tangentially into the torus at the TEXTOR-94 tokamak. An example of calculated beam deposition profile is presented in figure (3). The number of deuterons deposited per cubic meter and per solid angle unit is shown as a function of the minor radius and the pitch angle at which they cross the plane R=R0. The deposition maximum is found at a pitch angle of about χ=30^0. The term 'tangential injection' is somewhat misleading because the deposition maximum is not at an ion velocity vector parallel to the magnetic field (pitch angle χ=0^0). In figure (4), the pitch angle corresponding to the deposition maximum is plotted as a function of the minor radius. It ranges between 20^0 at the plasma center and 40^0 at the plasma edge.

Comparison of modeled spectra with experiment: The fast deuterons mean pitch angle is taken from beam deposition profile calculation. It is the pitch angle at the maximum value of beam deposition profile (see figure 4). A proton spectrum is then calculated for HFS (at R0=1.45 m, z=0) and for LFS (at R0=2.05 m, z=0). Figure (5) and (6) show comparisons between measured spectra and calculated spectra. Spectra widths and positions are in good agreements with experiments. Modeled spectra have a double humped shape.

Conclusions: Proton energy spectra measured in plasmas heated with deuterium neutral beam show significant differences between HFS and LFS. The pitch angle distribution of injected fast ions is spatially dependent on the major radius R due to the toroidal magnetic field spatial dependence. We have demonstrated that this effect has a strong influence on both measured and calculated proton energy spectra. Our model predicts correctly the spectra widths and position. In the next step effects due to spectrum integration along the detector sightline will be investigated.

References

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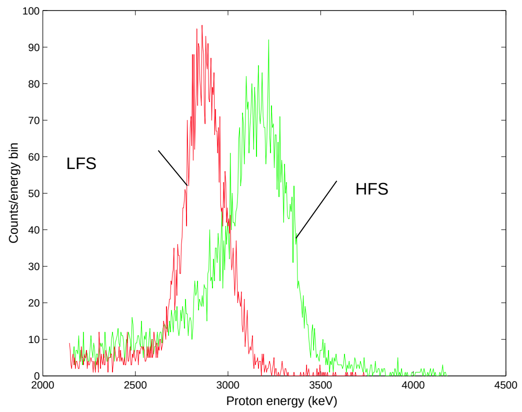

Fig.1: Comparison between energy spectra measured at HFS and LFS. Injection energy Eb = 40 keV.

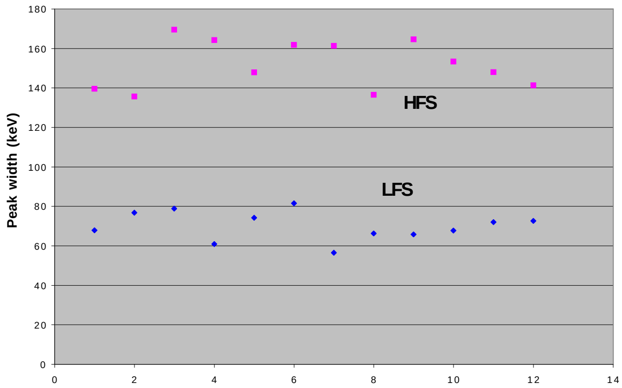

Fig.2: Measured peak widths from a serie of discharges with injection of deuterium beam at 35 keV.

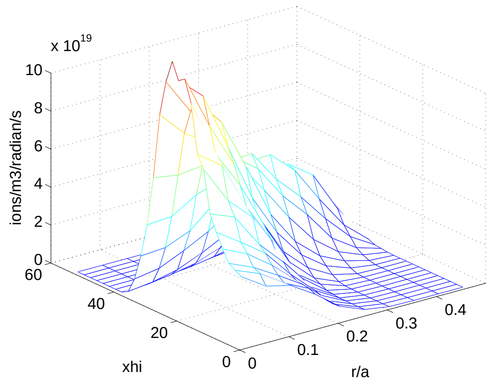

Fig.3: Beam particle deposition as a function of minor radius and pitch angle.

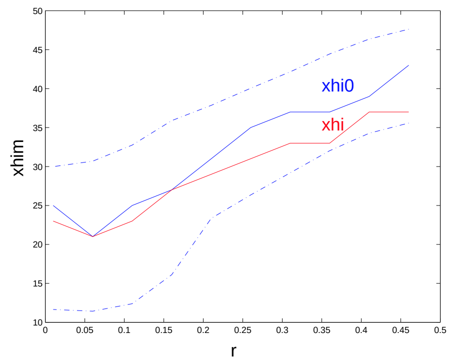

Fig.4: Pitch angle corresponding to the deposition maximum as a function of r (red: at ionization point, blue: at R=R0, dashed lines give the distribution width.)

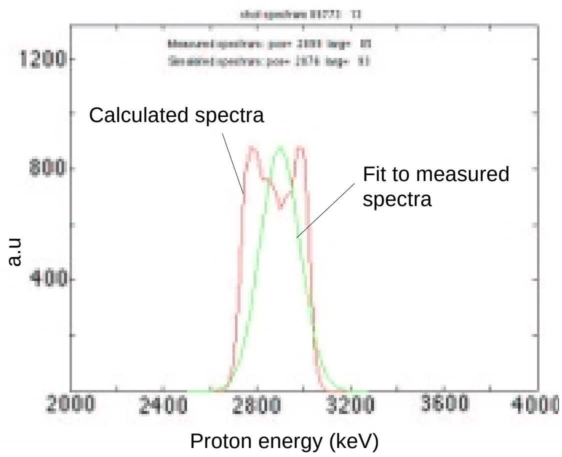

Fig.5: LFS: Comparison between measured and calculated spectra.

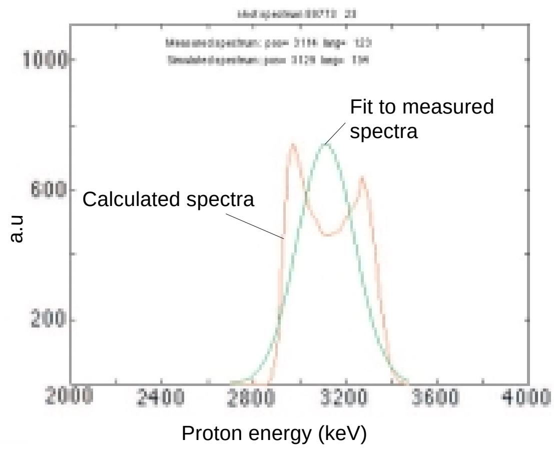

Fig.6: HFS : Comparison between measured and calculated spectra.