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First measurements of 14.7 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[5]. This diagnostic can measure high resolution 3 MeV protons and 1 MeV tritons energy spectra in discharges with all types of heating scenarii. A new experiment has been performed in which the 14.7 MeV protons produced in the fusion reaction:

$$d +^3 He \longrightarrow p(14681keV) + \alpha(3670keV) + Q \qquad (1)$$

are detected. 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 14.7 MeV protons are not confined. While they move out of the plasma towards the vessel walls they have a negligible probability to collide on plasma particles. Therefore, they reach the detector with their birth energy. Measurements are performed in deuterium plasmas containing fast ^3He ions. These fast helium ions are produced by means of ICRH heating (^3He minority heating) and ^3He neutral beam injection. In the case of a deuterium plasma with a Maxwellian deuterium population, the broadening, the shift and the shape of the spectrum are strongly influenced by the fast helium ions. Therefore the proton energy spectrum could be used to study the ^3He velocity distribution function [1]. The study can be subdivided in three different parts: The detection, the trajectories of the protons and the modelling of the proton source.

Detector and experimental setup: The fast charged particle detector has been described elsewhere [5]. PIPS silicon detectors are used. Silicon detectors of thickness of 500 μ were available for this experiment. They are normally used for 3 MeV protons and 1 MeV tritons detection. The slowing down of 14.7 MeV protons in silicon is calculated using the energy dependent stopping power function $\frac{dE}{dx}$. Values of this function are tabulated [6]. The 14.7 MeV protons lose about 4 MeV of their energy by passing trough 500 μ of silicon. A thin foil protects the detector against light and against particles and radiation of low energy. In this experiment an Aluminum foil of 800 μ was used to test the capability of the system to measure 14.7 MeV protons. The 14.7 MeV protons lose about 6 MeV in this Aluminum foil. Protons having an energy less than 11 MeV are totally absorbed by this foil whereas protons having an energy greater than 15 MeV will go through both foil and detector.

Proton trajectories and detection efficiency: The proton trajectory is simply determined by the magnetic field and the initial conditions because collisions and other forces can be neglected. The larmor radius is 25 cm, i.e. half the minor radius of TEXTOR. The proton only completes two or three larmor gyrations before hitting the wall. The trajectory is calculated numerically with the GOURDON code [4]. The next step is to compute several trajectories and look at those who are entering into the collimator. In such way, we can calculate the detection efficiency [2] which is defined as the ratio of the number of detected protons over the total number of emitted protons. The detection efficiency depends on the collimator and detector geometry and on the proton trajectories. Figure (1) shows the detection efficiency for detector 1. It is the distribution of detection efficiency as a function of the minor radius and the pitch angle. Distributions are sharply peaked in pitch angle. For the second detector we found a maximum of efficiency located at around 30 cm whereas for the first detector the maximum of detection efficiency occurs on a larger zone and nearer the centre (see figure 1).

Application of the diagnostic: Injection of a ^3He neutral beam or ^3He ICRF heating creates a population of 'suprathermal' helium particles. In the range of interest the cross section for $d(^3He,p)\alpha$ increases rapidly with the relative velocity of the reactants. A fast ^3He will therefore react with a higher probability than a thermal ^3He. It is possible to measure the high velocity tail of the ^3He velocity distribution function by measuring the energy spectrum of the 14.7 MeV protons.

Energy spectrum modelling: The energy of a fusion proton in the laboratory frame is given by:

$$E_{p,L} = \frac{1}{2}m_p s^2 + \frac{m_\alpha}{m_\alpha + m_p}(Q + E_{kin,S}) + scos\chi\sqrt{2\frac{m_p m_\alpha}{m_p + m_\alpha}(Q + E_{kin,S})} \tag{2}$$

In (2) s is the center of mass velocity, $E_{kin,S}$ is the relative kinetic energy and χ is the angle of emission of the proton in the center of mass frame, i.e. between the center of mass velocity direction and the proton velocity direction. The largest term in equation (2) is:

$$\frac{m_\alpha}{m_\alpha + m_p}(Q) = 14681keV \tag{3}$$

It is the proton energy for cold reactants or 'zero' energy. The second largest term in equation (2) is the last term containing the square root of Q. This term determines the broadening of the energy spectrum. The broadening is maximum when the center of mass velocity is the largest and when the cosine is equal to ± 1.

In the case of a non Maxwellian ion velocity distribution as well as complicated detector viewing geometry numerical methods are used to compute the proton energy spectrum. A Monte Carlo Code has been developed to simulate fusion product energy spectra. The LIPS[1] code is able to compute the fusion product energy spectrum for any ion energy distribution and any detector viewing angle. 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 [3]:

[1] Line Integrated Proton Spectrum

$$\frac{dN}{d\Omega_{p,L}dE_{p,L}}(\vec{r}) = \int\int\int f_d(\vec{v_d})f_{^3He}(\vec{v_{^3He}})\frac{d\sigma}{d\Omega_{p,L}dE_{p,L}d\Omega_{\alpha,L}dE_{\alpha,L}}|\vec{v_d}-\vec{v_{^3He}}|\,d^3\vec{v_d}d^3\vec{v_{^3He}}d^3\vec{v_\alpha} \tag{4}$$

where

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

in which $E^*_{p,L}$ is the proton energy in the laboratory frame corresponding to given $\vec{v_d}$ and $\vec{v_{^3He}}$ (2). The ion velocity distribution functions are given as input to the calculations. They depend generally on the position $\vec{r}$. Therefore the integral (4) must be further integrated in space along the line of sight of the detector. Up to now two cases have been treated.

Case of a deuterium plasma heated by ^3He neutral beam: The ^3He neutral beam is injected nearly tangentially in the TEXTOR tokamak. The velocity distribution function of ^3He ions is calculated with a Fokker Planck code [7]. We take a maxwellian distribution function for the deuterium ion velocity distribution function. Using the formula (4), we can compute the corresponding proton energy spectrum for different detector lines of sight. The largest broadening is obtained for the case of the detector observing in the direction parallel to the magnetic field.

Case of a deuterium plasma heated by ^3He neutral beam and ICRF: The velocity distribution function of ^3He ions is shown in figure (2). We take a maxwellian distribution function for the deuterium ion velocity distribution function. The resulting simulated proton energy spectrum is shown in figure (3). The three different spectra correspond to different detector viewing angles, respectively 90^0,i.e. perpendicular to the magnetic field, 45^0 and 0^0, i.e. parallel to the magnetic field.

Measurements: Figure(4) shows a premilinary measurement in a discharge with injection of a ^3He neutral beam (coinjection), injection of a deuterium neutral beam (counter injection) and ICRH heating. The spectrum is measured over the whole discharge. The observation angle with respect to the magnetic field is 45 and co-circulating protons are detected. The detection efficiency is shown in figure (1). The 14.7 MeV protons are clearly seen on this spectrum. The spectrum is free of background and parasitic lines. It is much broader than the theoretical spectrum. When analyzing the different contributions to the broadening of the energy spectrum the largest one comes from the aluminum foil. The scatter of the proton energy due to the aluminum foil inhomogeneity is of the order of 800 keV whereas the theoretical spectrum broadening is of the order of 200 keV. The shape is due to the non linear response of the detector to the incident proton energy.

Conclusions: First measurements of 14.7 MeV protons have been performed at the TEXTOR tokamak. Spectra with energy resolution up to 60 keV are obtained. The observed spectrum broadening is due to the 800μ aluminum foil and the shape is due to the non linear response of the current detection system. A thicker detector (thicker than 1.4 mm) will be used for future energy spectrum measurements. We performed modelling of energy spectra in the case of a deuterium plasma heated by a ^3He neutral beam and in the case of combined beam and ICRH heating. In both cases we find rather different spectrum shapes, different broadenings and shifts of the spectrum as a function of the detector line of sight. The excellent resolution in velocity space (or pitch angle) makes this diagnostic a powerfull tool to study the velocity distribution of the fast ^3He ions.

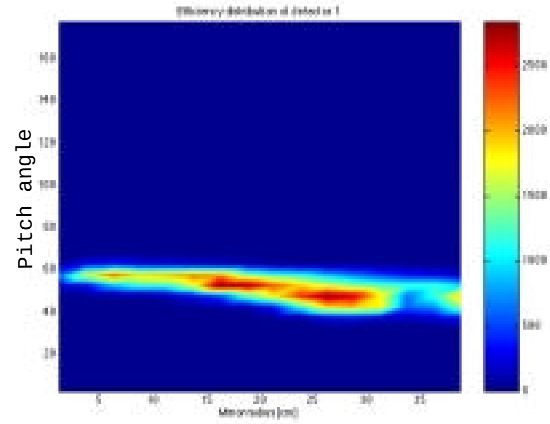

Fig 1: Detection efficiency for the first detector.

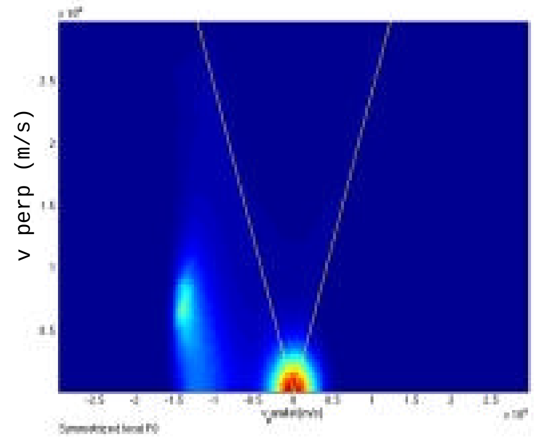

Fig 2: He3 velocity distribution for a plasma heated by ICRF and a He3 neutral beam.

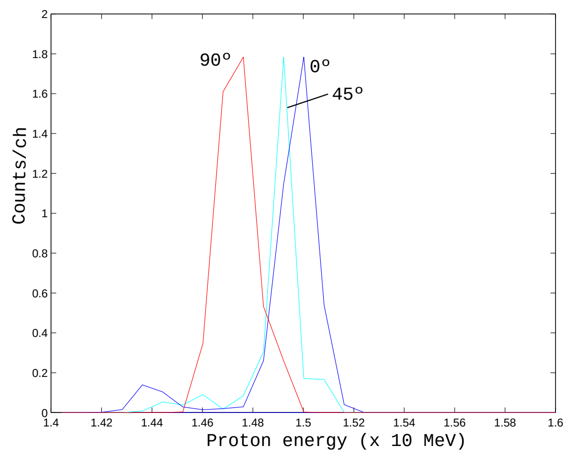

Fig 3: Theoretical proton spectrum

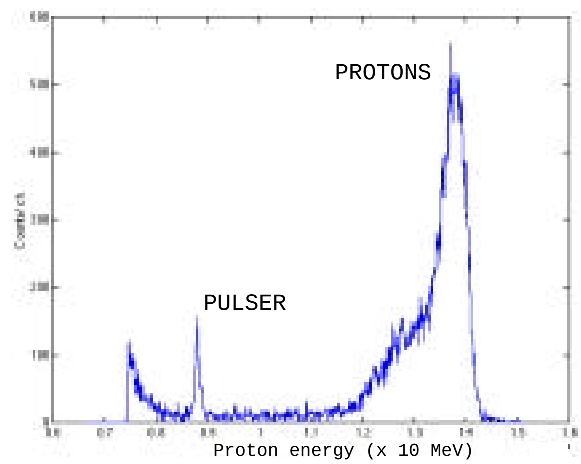

Fig 4: Measured proton spectrum

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