ENERGY DISTRIBUTION FOR FUSION PLASMA NEUTRONS

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ABSTRACT

The determination of the energy distributions of fusion neutrons emerging from deuterium-deuterium or deuterium- tritium neutral beam heated plasmas, are shown to be useful for fusion plasma diagnostics. A three dimensions, (3-D), computer code has been developed, to model the fusion plasma neutrons, in the case of a single or several co-directed neutral beam. We have proved that the neutron spectra reflect the bulk plasma ion temperature and density. The Comparison of the calculated results of the fusion plasma neutron spectra, shows fair agreement with the available published results.

1- INTRODUCTION

Neutron generation rates due to deuterium-deuterium (D-D), or deuterium-tritium (D-T) fusion are abundant in recent and planned experiments. It is known that the energy of neutrons has a significant spread about the mean energies, 2.45 Mev and 14.1 Mev, for the D-D and D-T interactions respectively. It is now possible to apply neutron physics techniques in advanced fusion experiments, with the objective of deducing the optimum amount of information concerning the parameters of the reacting plasma.

From the measurements of the fusion neutrons spectral widths, a method is presented to calculate the ion plasma temperature, T_i. Absolute measurements of the neutron flux, further yield the density of the products n_D^2 (D-D) or n_D n_T (D-T), [1]. The interaction of two Maxwellians, with mutually different temperatures is also taken into account.

The present investigations is focused on the Tokamak, [2], which will always generate neutrons, although a similar discussion may be carried out for other neutral beam heated, fusion devices. We will use, in these calculations, the expected parameters of the Jet device, [3].

The number of parameters involved, makes necessary to develop a 3-D Monte Carlo like neutron spectrum code, MNSPEC, [4].

2- D-D and D-T reaction rates ,

In the case of the ions Maxwellian distribution, the reaction rates reactivity can be given by, [5]:

$$<\sigma\ v>_{DD} = 2.33\ 10^{-14} T_i^{2/3} \exp(-18.8 T_i^{1/3}) \mathrm{cm}^3/\mathrm{Sec} \quad (1)$$

$$<\sigma\ v>_{DT} = 3.68\ 10^{-12} T_i^{2/3} \exp(-19.9_i^{1/3}) \mathrm{cm}^3/\mathrm{Sec} \quad (2)$$

Where T_i is the ion temperature, the subscript D and T correspond to the deuterium and Tritium respectively. The corresponding reaction rate densities producing neutrons are, [5]:

$$R_{DD} = \sim 1/4\ n_D^2 <\sigma\ v>_{DD}\ \mathrm{cm}^3/\mathrm{Sec} \qquad (3)$$

$$R_{Dt} = n_D\ n_T <\sigma\ v>_{DT}\ \mathrm{cm}^3/\mathrm{Sec} \qquad (4)$$

The reaction rate densities are strongly dependent both on the ion temperature T_i (Kev), and the densities n_D and n_T (cm).

3- Neutron spectra characteristics.

There are four parameters of main interest with regard to the characterization of a neutron spectrum; the neutron flux ϕ, the neutron energy E_n° (zero temperature), the spectrum standard deviation σ_D, and the mean energy shift from the classical value S. The neutron flux ϕ is proportional to the densities of the two interacting media and to the reactivity $<\sigma v>$. The energy of a fusion neutron may be written as, [6]:

$$E_n = \frac{1}{2} m_n v_n^2 = \frac{1}{2} m_n V^2 + \frac{m_\alpha}{m_\alpha + m_n}(Q+K)$$

$$\cos\phi \, V \frac{\sqrt{2 m_n m_\alpha}}{(m_n + m_\alpha)} * (Q+K) \tag{5}$$

Where m_n is the neutron mass, v_n is the neutron velocity in the laboratory system, V is the center of mass velocity of colliding particles with reaction products of masses m_α and Q is the center of mass reaction energy, (3.27 Mev for D-D and 17.6 Mev for D-T), ϕ is the angle of the center of mass system, K is the relative kinetic energy defined as:

$$K = \frac{1}{2} \frac{m_1 m_2}{m_1 + m_2} (\overline{v_1} - \overline{v_2})^2 \tag{6}$$

Where m_1, m_2 and $\overline{V_1}, \overline{v_2}$ are the masses and velocities of the reacting particles. As can be seen from Eq. 5, the true mean neutron energy is actually shifted slightly upwards in energy. Due to isotropy in the center of mass system, the shift may be written as:

$$S = \frac{1}{2} m_n, <V^2> = \frac{m_\alpha}{m_\alpha + m_n} <K> \tag{7}$$

Analytical calculation, [7, 8], yields p-p reaction in the shape of Gaussians in normalized form given by:

$$f(E_n) = \left(\frac{4\pi m_n T <E_n>}{m_n + m_\alpha} \right)^{-1/2} * \exp$$
$$-(E_n - <e_n>)^2 / \left(\frac{4 m_n T <E_n>}{m_n + m_\alpha} \right) \tag{8}$$

With the following fwhms (full width at half-maximum):

$\Delta E_n = 82.5 \sqrt{T_i}$, for D-D reaction and $\Delta E_n = 177 \sqrt{T_i}$ for D-T reaction.

Code results are well fitted by:

$$\sigma_d = \begin{array}{l} 34.5 Ti^{0.5} + 0.06 T_i^{1.5} \text{Kev}, \text{for D-D} \\ 73.0 T_i^{0.5 \text{ Kev, for D-T}} \end{array} \tag{9}$$

The collimator neutron flux from a plasma volume V_p (D-D), may be written, [4],:

$$\Phi = V_p \, \omega * 0.5 * n_D^2 < \sigma v > \tag{10}$$

Where Φ is the solid angle occupied by the collimator aperture, $\Phi = 7.34 \; 10^{-8}$ and $V_p = 0.0527$ m^3, which are a Jet like parameters, [3].

Throughout this calculations we have used the Duane fusion cross sections, [9], with the ion temperature T_i in Kev, the results are fitted by, [3]:

$$S = \frac{3}{8} T_i + 3.1 \, T_i^{0.84} \quad \text{Kev for D-D}$$

$$S = \frac{3}{10} T_i + 3.8 \, T_i^{0.78} \quad \text{Kev for D-D} \tag{11}$$

4- THE COMPUTER CODE STRUCTURE

The 3-D computer code NNSPEC calculates neutron spectra from two interacting ion velocity and pitch angle distributions f_i (θ, v) and f_2 (θ, v) [10].

We first define the device geometry and dimensions and a line of sight. The plasma is divided into appropriate sections along the line of sight. At each section a representative neutron spectrum is computed. Monte Carlo methods are used for generating the distributional velocities $\overline{v_1}$ and $\overline{v_2}$ as well as Maxwellian plasma. The only spatially varying parameters of interest are T_i (r,z), n_i (r,z) which are the plasma ion temperature and density respectively, r and z are the usual cylinder coordinates. The statistics has been 30000 events per spectrum. There are situations when neutrons associated with the interaction of two maxwellians with different temperature T_{i1} and T_{i2} are produced. In this code this case is treated in the D-D case.

5- RESULTS AND discussion

A comparison of normalized code neutron spectrum with analytically calculated one, [2], is shown in Figure (1). For D-D plasma at T_i = 10 Kev, the shift (Eq. 10) is : s = 25.2 Kev, while for D-T plasma at T_i = 5 Kev, the shift is: s = 14.8 Kev; which are quite moderate.

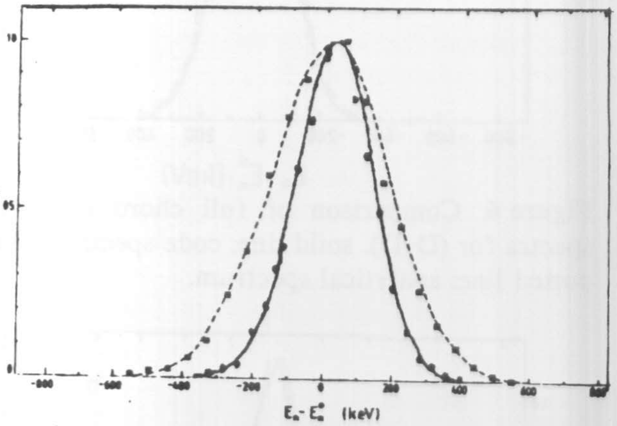

Figure 1. Comparison of normalized code neutron spectra, with analytically calculated spectra:
D-D analytically D-T analytically,
D-D code - - - D-T code.

Neutron diagnostics for Jet, [3], are capable of measuring shifts of this magnitude.

The spectrum standard deviation σ_d, for D-D and D-T reactions are shown in Figure (2). For a Gaussian distribution we have the relation: fwhm = $\sqrt{8 \ln 2} * \sigma_d$, [4]. From the curve we find: σ_d = 111.1 Kev for D-D and σ_d = 166.4 Kev for D-T reaction. The large spectral broadning in Figures. (1), (2) provides a means for ion temperature diagnostic. The broadening is due to the fact that cos ϕ, in Eq. 5, which is random in the interval (-1,1), is multiplied by V, which goes as $\sqrt{T_i}$ according to Eqs. 7, and 10, and $\sqrt{Q}$ in the last term of Eq. 5.

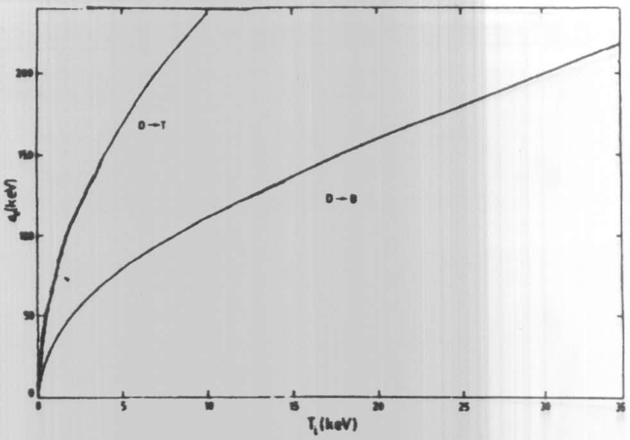

Figure 2. Spectrum standard deviation σ_d.

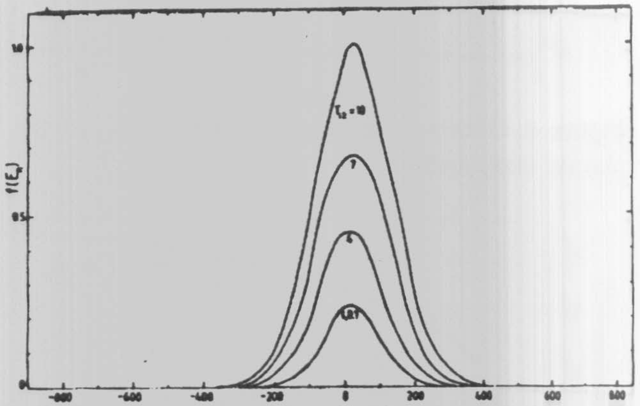

Figure 3. D–D spectra from interacting Maxwellians with different temperatures.

In Figure (3), neutron spectra from two interacting D-Maxwellians with T_{i1} = 10 Kev and T_{i2} = 10,7,4,1, and 0.1 Kev, respectively are shown. The spectra for T_{i2} = 1, 10.1 Kev practically coincide indicating that the hottest Maxwellian largely determines s and σ_d

(Eq. 7, and 9). Reactivities and fluxes for different plasma temperatures are shown in Figures (4), and (5) respectively, the neutron flux is that into a collimator from a cater plasma volume of 0.053 m^3.

An experimentally determined fusion neutron spectrum contains the integrated contributions along a chord through the plasma. To model this experiment computed spectra have been summed from a discrete number of volumes along the chord, taking the radial profiles into account.

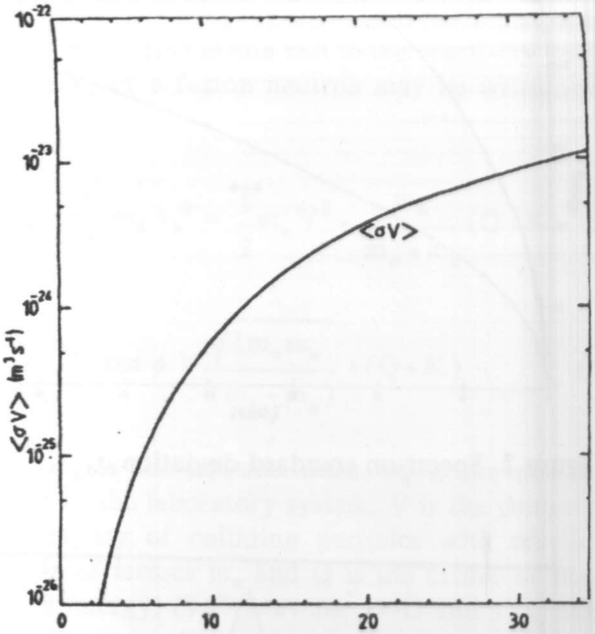

Figure 4. Obtained reactivity as a function of the plasma temperature.

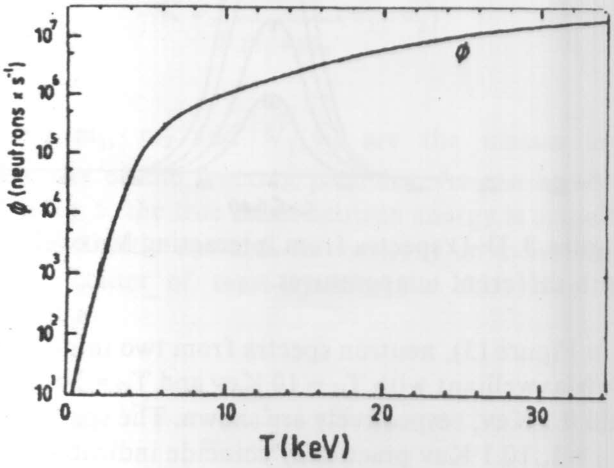

Figure 5. Neutron flux into the collimator.

Results from D–D (T_i = 10 Kev) and D–T (T = 5 Kev) plasmas, are shown in Figures (6) and (7); for computation reasons only three volumes are used here. The spectra calculated by Elevent, [5], are also inserted in the Figures. Consequently, without much error, the plasma ion temperature T_i may be directly estimated with Eq. 9, from the chord spectrum. The error in this example, for the D–D spectrum is about 1 Kev and for the D–T spectrum about 0.4 Kev. For D–D spectrum, fwhm is about 150 Kev and the shift of the order 20 Kev, while for D–T spectrum, fwhm is about 250 Kev and the shift of the order of 15 Kev. The code shows reasonable agreement with the available published results.

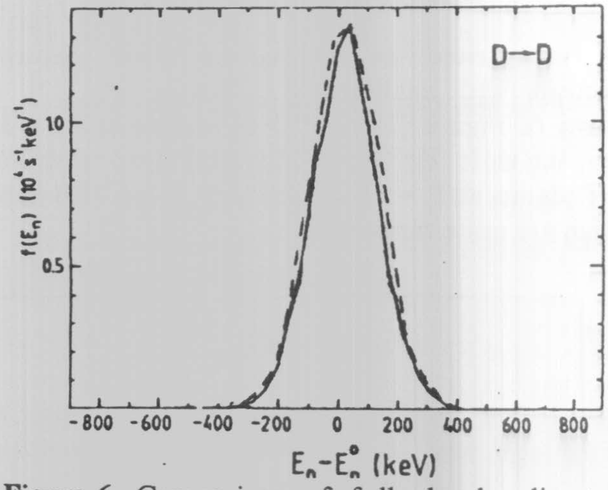

Figure 6. Comparison of full chord colimator spectra for (D–D). soild line: code spectrum, and dotted line: analytical spectrum.

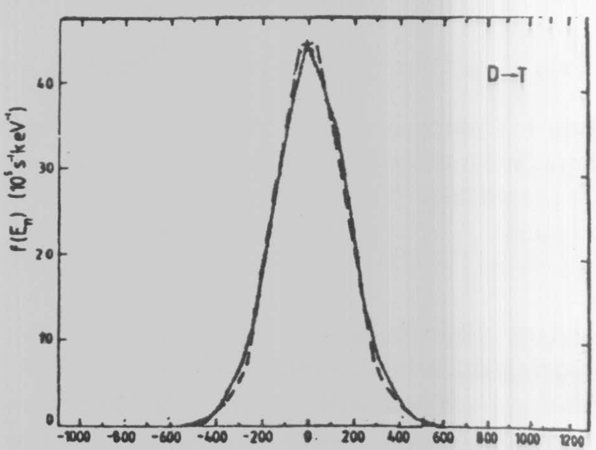

Figure 7. Same as in Fig. 6, for (D–T) reaction.

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