Study of D-D Reaction at the Plasma Focus Device

P. Kubes[1)], J. Kravarik[1)], D. Klir[1)], K. Rezac[1)], E. Litseva[1)], M. Scholz[2)], M. Paduch[2)], I. Ivanova-Stanik[2)], B. Bienkowska[2)], L. Karpinski[2)], M.J. Sadowski[3)], H. Schmidt[4)], K. Tomaszewski[5)]

[1)] *CTU Prague, Technicka 2, 166 27 Prague, Czech Republ; kubes@fel.cvut.cz)*
[2)]*Institute of Plasma Physics and Laser Microfusion, 23 Hery, 00-908 Warsaw, Poland*
[3)]*The Andrzej Soltan Institute of Nuclear Studies,05-400 Otwock- Swierk, Poland*
[4)]*ICDMP, 23 Hery, 00908 Warsaw, Poland*
[5)]*ACS Warsaw Hery 23, 01-497 Warsaw Poland*

Abstract. The plasma focus device PF-1000 at IPPLM Warsaw with neutron yields of 10^9– 10^{11} neutrons per shot is convenient for the determination of the axial neutron energy distribution in the fusion D-D reaction due to the horizontal position of a discharge axis and the distance of scintillation detectors up to 85 m from the neutron source in both axial (downstream and upstream) directions. In this paper the determination of the axial energy component of the fast deuterons producing neutrons is presented for the shot with a relative small neutron yield and nearly isotropic neutron energy distribution and the total energy of fast deuterons producing neutrons is estimated. We calculated, if the dense structure with the length of 2 cm and the density of $2x10^{25}$ m^{-3} could be the source of neutrons. We estimated the upper limit of energy of deuterons producing neutrons as 10-20 keV and their total number as 10^{18}. The deuterons with energies below 10-20 keV can't produce high number of neutrons due to the small cross-section of D-D reaction but they can be principally confined by magnetic field. We discuss the influence of magnetic field on the motion of deuterons.

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INTRODUCTION

Z-pinch and plasma-focus (PF) devices are very convenient tools for the study of neutron production from D-D reactions for several reasons. A comparatively high neutron yield (10^9– 10^{11} neutrons per shot) enables neutron detection at distances of several tens of meters. The duration of the neutron production in the range of 50-100 ns is sufficiently long to obtain precise temporal- resolution and its comparison with x-rays and frames. Further, the plasma densities at the pinch development (10^{18}–10^{20} cm^{-3}) are convenient for laser probing in the visible range. In spite of these circumstances and 50-years long research, the fusion reaction mechanisms as well as the acceleration mechanism of high-energy electrons and deuterons in Z-pinches are still under discussion. A detail research of fusion processes at the PF device was performed for example in Stuttgart [1], in France [2] and in Warsaw [3]. The idea of an influence of the magnetic field on the observed neutron yield was proposed in the paper [4]. The neutron spectra of a large DPF were measured by the time-of-flight methods in side-on direction in [5]. The idea of magnetized ions was supported theoretically with a so-called Gyrating Particle Model elaborated in the paper [6]. The magnetic field in the pinch was measured for example in paper [7] and its nature is described in [8]. Heating of the plasma by fast ions was shown firstly in publication [9].

In this paper we discuss the total number and energy distribution of deuterons producing observed neutrons. We mention an important role of internal magnetic fields in confinement of the fast deuterons and we evaluate crucial role of Coulomb ion-ion and electron-ion collisions for the heating and cooling of the plasma target.

EXPERIMENTS AND RESULTS

The measurements within the PF-1000 facility were performed at the maximum current of 1.5-1.8 MA, voltage of 27 kV and the deuterium filling pressure of 4 hPa. The radiation from the visible to hard x-ray range was measured with temporal-, spatial- and energy-resolution. We employed one soft x-ray microchannel-plate detector with 4 quadrants. The PIN-silicon diode detected XUV and soft x-ray radiation. Four optical frame cameras with a gating time of 1 ns imaged the emitting plasma in the visible spectral window. The visible streak camera had the slit perpendicularly to the z axis. The BCF 412 scintillator detected x-rays in the range above 4 keV. Fast electrons of energies in the range of 50-400 keV were registered with Cerenkov detectors (made of rutil crystals and shielded with 20-μm Al) located downstream (along the current sheath movement) and upstream as well as in the side-on direction. Seven scintillation probes BC 408 were used to perform the detailed time-resolved measurements of the hard x-ray (3 - 5 cm of steal or of lead was used as a filter) and the neutron emission. They were situated downstream (7.0 m, 16.3 m, 58.3 m, 84 m), upstream (at distances of 7.0 m, 16.3 m, 30.3 m, 44.2 m. 58.3 m, 84 m) and side-on (at the distance of 7.0 m). For estimation of the total neutron yield, the silver-activation counters were applied.

On the PF-1000 facility the total neutron yield reaches 10^{10} – 10^{11} per shot. The characteristics of neutron emission and the correlation of the x-rays with neutrons and frames were published in [3]. In this contribution we evaluate the energy distribution of the fast deuterons from the energy distribution of neutrons. As an example we chose shot No. 6573 with a modest neutron yield of $5x10^{10}$. The energy distribution of neutrons was calculated using adapted time-of-flight method and Monte Carlo reconstructions [10].

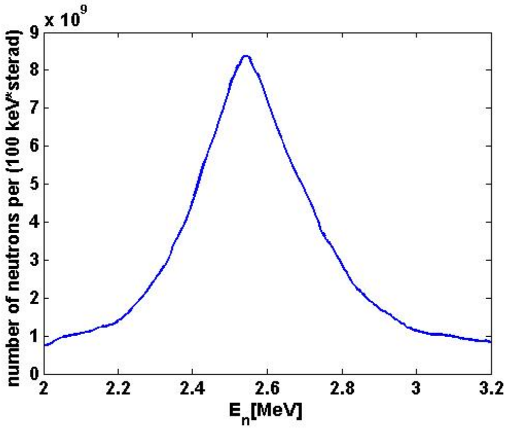

FIGURE 1. Energy distribution of neutrons downstream

In Fig. 1 we can see the energy distribution of all neutrons registered in this shot. It was reconstructed from all detectors in the downstream direction using time-of-flight method. The observed neutron energies belongs to the range of 2.1-3.0 MeV with the maximum of 2.55 MeV, i.e. 0.1 MeV above the mean value of 2.45 MeV for DD fusion neutrons in the centre of mass system. This difference is interpreted with the dominant deuteron velocity component in the direction downstream (from anode to cathode).

The energy distribution of deuterons producing neutrons was calculated using the equation of energy transformation of neutrons (E_d) to deuterons (E_n). From the energy distribution of neutrons shown in Fig.1, we can evaluate the axial component of deuteron energy. The obtained curves are shown in Fig. 2. The neutrons with energy above 2.45 MeV were produced by deuterons moving downstream (upper-curve) and the neutrons with energy below 2.45 were produced by deuterons moving upstream (down curve). This dependence is roughly $1/E_d^{-1}$.

For the determination of the total energy distribution of deuterons we need to know the radial neutron energy distribution as well. At the PF 1000 facility we had to disposal only one side-on detector, at the same distance of 7 m as the axial ones were. The differences between signals at the same distances are caused by the different energy distribution. But from the waveforms recorded by the detectors near the source, differences are not so substantial. The signals from shot No. 6573 are presented in Fig. 3.

These signals, and also signals in some other shots are very similar and differ from each other only partially. The side-on curve has its position between downstream and upstream curves and 90% of the side-on signal has common surface with downstream and upstream signals. This situation completely changed in shots with a higher neutron yield in which a considerably higher part of the

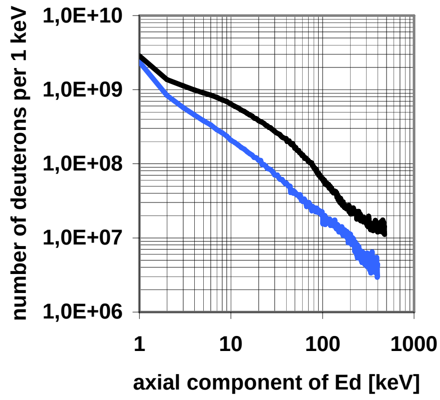

FIGURE 2: Number of deuterons producing neutrons detected in axial direction

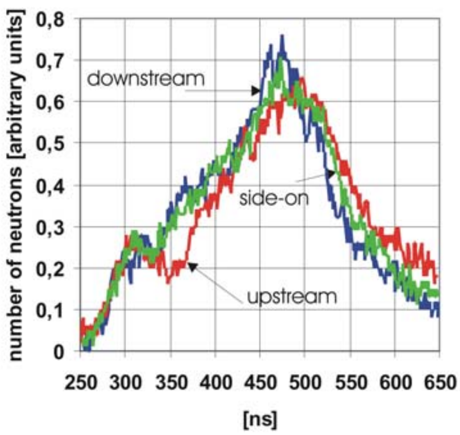

FIGURE. 3: Signals of neutrons registered in 7 m

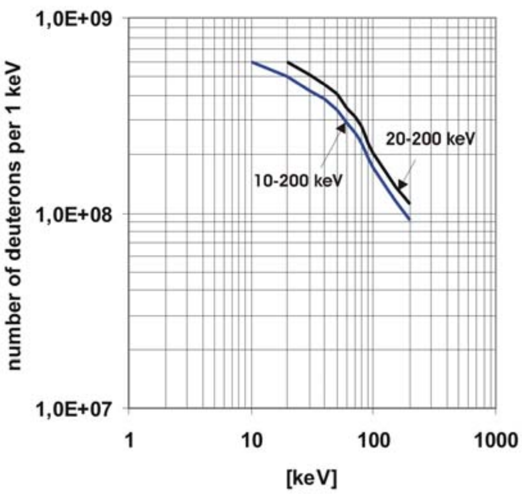

FIGURE 4: Spectral distribution of energy of deuterons produced observed neutrons

surface differs (up to 50%).

The neutron energy spectra at the PF devices usually show the radial symmetry distribution of energies. Therefore, the azimuthal symmetry and similarity between the axial and radial neutron signals in this shot enable to suppose roughly an isotropic distribution of deuteron energies (mainly for energies below 50-100 keV).

For the determination of the number of fast deuterons we need to know the lower and upper limits of energy of deuterons, which realize the fusion D-D reaction. In speculations done in this paper we took into account the upper limit of 200 keV and tree possibilities of the lower limit– namely 10, 20 and 30 keV. The distribution of the total energy imaged in Fig. 4 was chosen as the dependence imaged in Fig.2 multiplied by factor $(E_d)^{1/2}$. The total number of $5x10^{10}$ deuterons is equal to the number of detected neutrons.

For the estimation of the total number of fast deuterons we can estimate the mean free path of D-D reaction using the relation $\lambda_{DD} = 1/n_i\sigma\,(E_D)$ and the probability of D-D reaction $p_{DD} = l/\lambda_{DD}$ for the cross-section $\sigma(E_D)$ [11], the length l and the density n_i of the target (neutron source). The length of the neutron source about 10 cm was estimated experimentally for example in [1,12]. The ion density in the pinch and stagnation in the range of 10^{24}–10^{26} m^{-3} was measured by interferometric methods [1,2]. The deuteron density calculated from the observed neutron yield for the length of a few cm must have minimal value of 10^{25} m^{-3}. In following calculations we suppose, that the dense structures observed with visible frames (mean value of density of 2.10^{25} m^{-3} and length of 2 cm) are the neutron source.

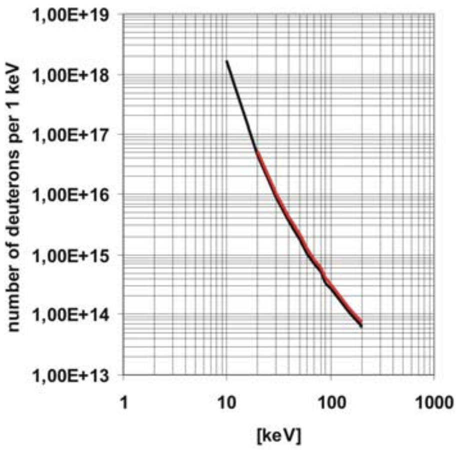

FIGURE 5: Distribution of fast deuterons

TABLE 1: Total values of fast deuterons

Ed [keV]	Number of deuterons	E_{total} [kJ]	I_{total} [kA]
10 - 200	$9x10^{18}$	17	170
20 - 200	$5x10^{17}$	3	140
30 - 200	$2.5x10^{17}$	1.7	70
1 - 10	10^{19}	2	350

The resulting energy distribution of deuterons in three variants mentioned above is imaged in Fig. 5 and Table I. The number of fast deuterons monotonically decreases with increasing deuteron energy as the function $(E_d)^{-(2-4)}$. The deuterons with energy below 10-20 keV did not produce high number of neutrons due to small cross-sections. For the limit of 20 keV, the total number of deuterons is roughly $5x10^{17}$, total energy 3 kJ and total current 140 kA. For the lower limit of 10 keV we need the total number of deuterons roughly 10^{19} and total kinetic energy 17 kJ; the values are in the boundary of the parameters obtained at PF-1000. The total number of particles in the pinch column was estimated as 10^{20}- 10^{21}. Therefore, we can estimate an upper boundary of the number of deuterons accelerated in the pinch to the energy below 10keV (10^{19}) in the last row of the TABLE 1. This limit is restricted with the total energy and current of these deuterons.

DISCUSSION AND CONCLUSION

The number of deuterons and their energy spectrum presented in Fig. 5 and Table I was calculated by 3 suppositions: (i) isotropic distribution of the velocities of fast deuterons, (ii) estimation of lower limit of deuteron energy producing fusion neutrons and (iii) estimation of the number of target deuterons.

The radial distribution of deuteron energy was estimated from the comparison of the signals registered at 7 m, i.e. near the neutron source, where the energy distribution is imaged poorly. Recently, we have installed one side-on detector at the distance of 50 m, which makes possible to determine more exactly the distribution of the deuteron energy as well as the lower fusion limit. Also the dimensions and densities of the dense localities will be measured using new installation of laser interferometric diagnostics.

In Fig. 5 and Table I we can see, that energy of deuterons of 10-20 keV is the most probable lower limit for production of fusion neutrons. The fraction of fast deuterons above this limit reaches 1% of ions in the pinch. The total energy of a few kJ carrying by fast deuterons is lower then the energy of 10 – 20 keV which is to disposal in the pinch.

We do not know the number of deuterons with energy in the range below 20 keV. The number of 10^{19} estimated in Table 1 represents roughly a few % of the particles in the pinch and 10% of the total kinetic energy. These deuterons can be confined by internal magnetic field of the dense structures for the longer time. This fact considerably influenced trajectories of deuterons and thus the energy loss due to Coulomb interactions.

The magnetic field of 20 T produced by the MA current in the plasma column with radius 1 cm can influence the direction of the motion of the fast deuterons with energies up to 100 keV.

The relaxation time of Coulomb interaction for deuteron-deuteron collisions given by formula $\tau_{ii} = 2.3\text{x}10^{13}(T(\text{eV})^{3/2}/n.\ln\Lambda)$ and the relaxation time of Coulomb interaction for deuteron-deuteron collisions has the value of 10-40 ns (for $n_i = 10^{25}$ and E_d =(1-2) keV), while the time of equilibrium between electrons and ions in these conditions given by Coulomb interaction $\tau_{ei} = \tau_{ii}\,(\text{m/M})^{1/2}(\text{Ei/Te})^{3/2}$ is effective for electron temperature below 0.1 keV [13]. Fast ions can produce an additional heating of deuterons and electrons [14,15] of the target.

For effective heating of the target to thermonuclear temperature of a few keV it is necessary to have to disposal enough of deuterons with energies up to 20-50 keV and the target surface density above 10^{24} m^{-2}.

Neutrons generated in PF discharges on the MA current level are produced by 10^{18} deuterons with energies above 10-20 keV in the localities with density above 10^{25} cm^{-3}. The internal magnetic field can partially confine fast deuterons with energies up to

100 keV and increase their path in the dense plasma. The energy of deuterons in the range up to 10 keV is insufficient for neutron production but these deuterons can be confined by magnetic field for the longer time and can heat deuterons in the dense plasma due to Coulomb interaction to the temperature of a few keV.

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