*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-5.035 (2006)*

# Measurement of spatial distribution of D-D fusion neutron emission with the use of thermoluminescent dosimeters

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**Abstract** — Moderators of D-D fusion neutrons and thermoluminescent dosimeters (TLDs) as thermal neutron passive detectors were used for the measurement of spatial distribution of neutrons emitted by a Mather-type Plasma Focus Device PF-1000 at the Institute of Plasma Physics and Laser Microfusion, Warsaw. As the time-integrating dosimeters paired $^6$LiF:Mg,Cu,P (TLD-600H) and $^7$LiF:Mg,Cu,P (TLD-700H) chips were applied. The differences in readings between TLD-600H and TLD-700H, which are directly proportional to the number of thermal neutron, shown a cone-shaped anisotropy of neutron emission along the downstream axis.

## Introduction

High-current plasma focus discharges can emit neutrons during thermonuclear and ion beam–target type interactions of energetic deuterons. It is supposed that the emission of neutrons produced in plasma focus discharges consists of an isotropic component and an anisotropic one. Thus, the total yield is a sum of partial yields $Y = Y_{is} + Y_{anis}$. The anisotropy is experimentally characterised by a ratio of the total yields of neutrons $Y_0/Y_{90}$ measured in axial ($\vartheta=0°$) and radial directions ($\vartheta=90°$). The ratio $Y_0/Y_{90}$ ordinarily ranges from 1.4 to 3 [1]. Two principally different detectors can be employed for the yield measurement – time resolved detectors and time integrating ones. The last groups of detectors can be represented by track detectors, bubble detectors, and by TLDs.

In the neutron personnel dosimetry pairs of $^6$LiF:Mg,Ti (TLD-600) and $^7$LiF:Mg,Ti (TLD-700) chips have been successfully applied because of the possibility to estimate the $\gamma$-dose in mixed n-$\gamma$ fields [2,3]. On the basis of the content of $^6$Li in TLD-600 (95.6%) and

TLD-700 (0.007%) and differences in the macroscopic cross-sections, Σ, for $^{6}$Li(n,α)$^{3}$H, $^{6}$Li(n,γ), $^{7}$Li(n,γ) and $^{19}$F(n,γ) reactions, the TLD-700 is assumed to determine the γ-dose only. The difference between TLD-600 and TLD-700 signals indicates the net neutron response of the TLD-600 dosimeter. The response of TLD-600 and TLD-700 to a mixed neutron and gamma field can be described by $R^{n+\gamma}_{TLD600} = R^{n}_{TLD600} + R^{\gamma}_{TLD600}$ and by $R^{n+\gamma}_{TLD700} = R^{n}_{TLD700} + R^{\gamma}_{TLD700}$. The relationship between the gamma-response of these two TLD types can be expressed as $k = R^{\gamma}_{TLD600} / R^{\gamma}_{TLD700}$. Even if TLD-600 and TLD-700 dosimeters have almost equal sensitivities to gamma radiation, the parameter *k* must be determined experimentally, e.g. in γ-beams from $^{137}$Cs and/or $^{60}$Co sources. As at the thermal energies of neutrons the TLD-600 response is approximately three orders of magnitude greater than that of the TLD-700, the response equations can be combined to provide the net TLD-600 thermal neutron response: $R^{n}_{TLD600} = R^{n+\gamma}_{TLD600} - k\, R^{n+\gamma}_{TLD700}$.

This contribution is focused on the use of TLDs as a diagnostics tool of neutron emission from a plasma focus device PF-1000 operated at IPPLM, Warsaw [4].

## Experiments

High sensitive dosimeters $^{6}$LiF:Mg,Cu,P (TLD-600H) and $^{7}$LiF:Mg,Cu,P (TLD-700H) were employed to measure low neutron fluxes emitted by the PF-1000 device [5]. The lower sensitivity limit of the LiF:Mg,Cu,P dosimeters is 1 μGy. The dimensions of the dosimeters were 3.2 mm × 3.2 mm × 0.9 mm. TL responses were read-out at a heating ramp 10 °C/s from 160 °C to 300 °C in an $N_2$ atmosphere using a PC-aided Harshaw Model 3500 reader. The sensitivity of the TLD-600H dosimeters to neutrons was determined with the use of $^{252}$Cf neutrons, which were moderated by a polyethylene sphere containing the investigated TLDs. The parameter *k* equalising TLD-600H and TLD-700H responses to γ-rays was measured for $^{137}$Cs radiation.

Neutrons emitted from the PF-1000 device were scattered and moderated in paraffin spheres having a diameter of 10 inch. The paraffin sphere BS1 serving as a reference detector was placed 1 m below the electrode outlet. The other three Bonner spheres were positioned around the PF-1000 device, as Fig. 1 schematically shows. The paraffin spheres were positioned not only on the floor of the laboratory, as Fig. 1 shows, but also on pedestals to measure the emission in more directions. Their signals were recalculated to the solid angle corresponding to the reference BS1.

The plasma was generated in the PF-1000 device discharging energy of 600-650 kJ. The chamber's deuterium pressure was held at 3.5 Torr throughout the run. The recorded maximum neutron yield is ≈ $3.5\times10^{11}$ neutrons/shot [6]. The number of emitted neutrons per shot was also measured with 4 silver activation detectors located at different angles in *x-z* plane, see 4 boxes in the top of Fig. 1 [7].

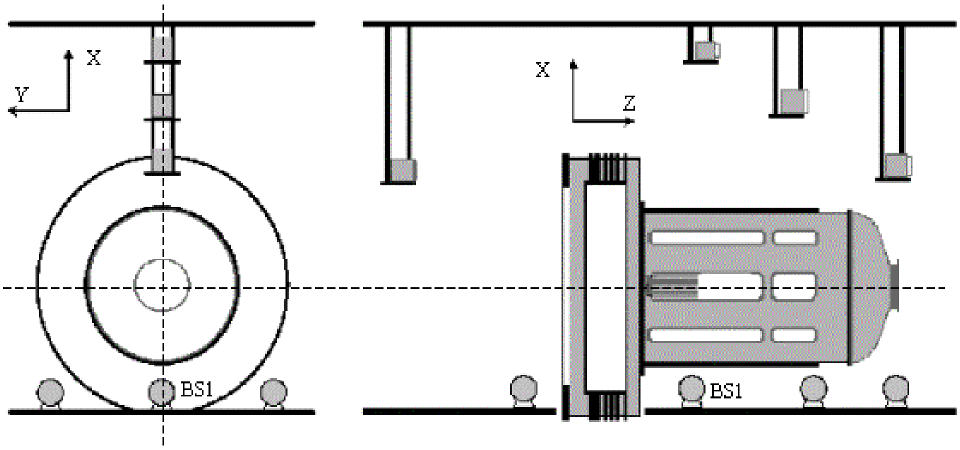

*Fig. 1 Experimental arrangement of the Bonner spheres (BS) containing dosimeters TLD 700H and TLD 600H. The reference BS1 positioned at 1-m distance below the electrode outlet was able to record a neutron yield higher than ≈$5\times10^{9}$ neutrons/shot.*

The neutron emission by plasma focus devices shows in particular an anisotropy, which can be adjusted by a Gaussian function superposed on a constant representing the isotropic part of the emission: $Y(\vartheta) = \text{const} + G(\vartheta)$ [8]. In contrast to measurements presented elsewhere [8], our result shows two peaks in the angular distribution, as Fig. 2 demonstrates. The solid line is a fit of a function of $Y(\vartheta) = \text{const} + G_1(\vartheta) + G_2(\vartheta)$ to measured data. The neutron emission reached two maximums at $\vartheta_1 \approx 15°$ and $\vartheta_2 \approx 345°$. The anisotropic emission dominates in ranges from 0° to ±30°. Due to the axial symmetry of both peaks we can suppose that the anisotropic component of the neutron emission is cone-shaped along the downstream (head-on) axis at 15°. The ratio $Y(15°) / Y(90°) = 1.82$, while the ratio $Y(0°) / Y(90°) = 1.24$. The emission measured in the *x-y* plane crossing the electrode outlet but measured only at six angles can be considered as isotropic.

The detailed background information on the anisotropy of the neutron emission could be obtained analysing time-resolved signals of neutron detectors, which detect neutrons in different angles $Y(t,\vartheta)$. Signals from scintillation detectors show that the PF-1000 device usually emits neutrons in two main pulses [9]. The second pulse, which contains the predominant number of all neutrons produced, is emitted with a delay of 120 ns to 200 ns. The major part of the neutrons in each pulse has asymmetry energy distribution. A small part of neutrons producing at the last part of neutron pulses has isotropic distribution. The origin of neutrons seems to be of a beam-target mechanism.

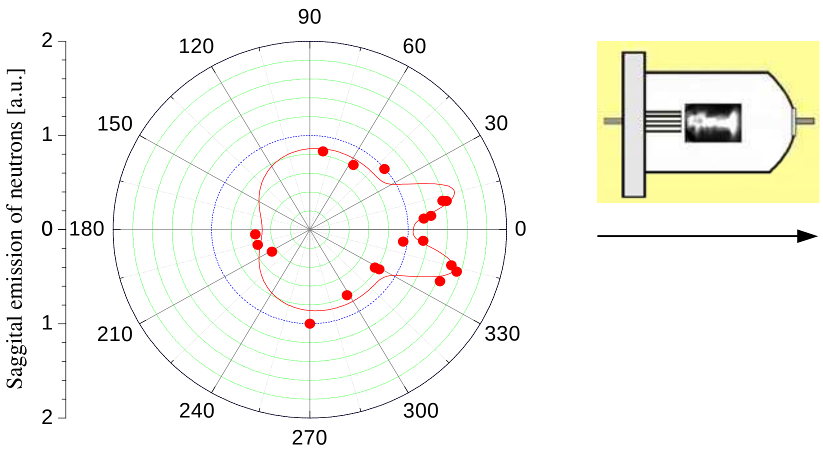

*Fig. 2 Emission of DD neutrons in x-z plane (see Fig. 1) measured with pairs of TLD 700H and TLD 600H. The TL signals of the TLDs were related to TL response of the dosimeters positioned into BS1. The PF 1000 facility was operated at the energy of 600-650 kJ. The $D_2$ pressure was 3.5 Torr.*

## Conclusions

The time-integrated measurement of neutron pulses with TLDs indicates a cone-shaped anisotropy of neutron emission along head-on axis with a maximum at $\vartheta \approx 15°$. It is evident that the measurement with high angular resolution is needed. Moreover, theoretical neutron transport calculations are necessary to complete the description of the anisotropy of the neutron emission. Distinguishing between the beam–target and bulk plasma motion processes for the different discharge conditions will be the subject of further investigation.

**Acknowledgment -** This work was partly supported by The Czech Ministry of Education in the frame of the grant 1P2004 LA235, INGO, by IAEA CRP grants no 11940, 11941 and the grant of the European Commission G4MA-CT-2002-04037, which is acknowledged.

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