Experimental evidence of thermonuclear neutrons in a modified plasma focus

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The PF-1000 plasma focus was modified by adding the cathode disk 3 cm in front of the anode. This modification facilitated the evaluation of neutron energy spectra. Two neutron pulses were distinguishable. As regards the first neutron pulse, it lasted 40 ns during the plasma stagnation and it demonstrated high isotropy of neutron emission. A peak neutron energy detected upstream was 2.46 ± 0.02 MeV. The full width of neutron energy spectra of 90 ± 20 keV enabled to calculate an ion temperature of 1.2 keV. These parameters and a neutron yield of 10^9 corresponded to theoretical predictions for thermonuclear neutrons. © *2011 American Institute of Physics*. [doi:10.1063/1.3555447]

The search for thermonuclear neutrons in Z-pinches and plasma foci began in the 1950s. At the outset of controlled thermonuclear fusion research, compressional Z-pinches were found to produce a large number of neutrons which originated from D(d,n)^{3}He reactions; however, neutrons were not of thermonuclear origin.[1] The dominant fraction of beam-target neutrons and no direct evidence of thermonuclear neutrons were also reported in plasma focus studies in the 1970s and 1980s.[2] More recently, on a 10 MA current level, significant thermonuclear neutron yield has been simulated for deuterium gas puff Z-pinches on *Z*,[3,4] but insufficient experimental evidence has been provided. As for late plasma focus experiments,[5,6] the possibility of thermonuclear neutrons was identified during the pinch phase; however, the interpretation of results was not unambiguous. In this paper, we would like to provide more explicit experimental evidence of thermonuclear neutrons.

The experiments were carried out at the PF-1000 plasma focus (2.0 MA peak current, 24 kV charging voltage, 400 kJ stored energy).[7] The facility was equipped with Mather-type coaxial electrodes (48 cm length, 23 cm anode diameter). The cathode was composed of 12 stainless-steel rods distributed around a cylinder of 40 cm diameter. The initial pressure of a deuterium gas was between 160 and 240 Pa (i.e., relatively low for the sake of increasing an implosion velocity). In order to search for thermonuclear neutrons, the plasma focus was modified by placing a cathode disk 3 cm in front of the anode and by adding a copper plug into the hollow anode (see Fig. 1). The fixed length of a plasma column enabled to correlate plasma dynamics with neutron emission and to calculate an inductance and a power input during the radial phase more precisely. In addition to that, the shorter length caused a higher current during the pinch phase, a less significant zipper, and shorter neutron emission which facilitated the evaluation of neutron energy spectra.

Plasma dynamics was studied by means of a 16-frame laser interferometric system.[9] An illustrative example of analyzed interferograms[10] is shown in Fig. 2. Figure 3 then presents the neutron emission detected by a radial time-of-flight (TOF) detector[11] at 3 m. In shot 9006, a quite stable snowplough implosion was seen. The maximum implosion velocity v_{imp} exceeded 3.5×10^5 m/s. During a quiet phase at 10 ns, the first neutron peak was observed. The stagnation at about 15 mm diameter lasted 40 ns and then the second implosion with $m=0$ instabilities occurred. The main neutron emission started after the disruptive development of instabilities at 100 ns. Two neutron pulses were also observed in other mega-ampere plasma foci[12] and gas puff Z-pinches.[13,14] In what follows, we would like to deal with the question whether a fraction of neutrons in the first pulse may be explained by thermonuclear mechanism.

On the basis of analyzed interferograms and electric measurements, we were able to calculate important plasma parameters. To start with data from interferograms, we received a total number of deuterons of 4×10^{19} and a peak electron density of 10^{19} cm^{-3}. The implosion velocity of 3.5×10^5 m/s implied an ion temperature of 850 eV. This value was increased by adiabatic compression. In order to include this effect, we calculated the ion temperature from the energy input assuming that 80% of measured current is flowing inside the current sheath (this fraction corresponded to the observed implosion velocity). For the measured energy

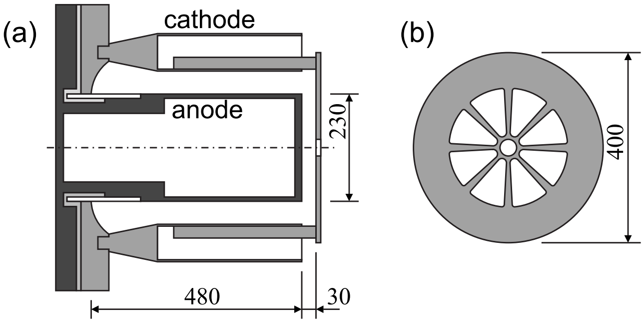

FIG. 1. (a) The side-on and (b) the end-on schematic of electrodes at a modified PF-1000 plasma focus (cf. with Ref. 8). Dimensions are in mm.

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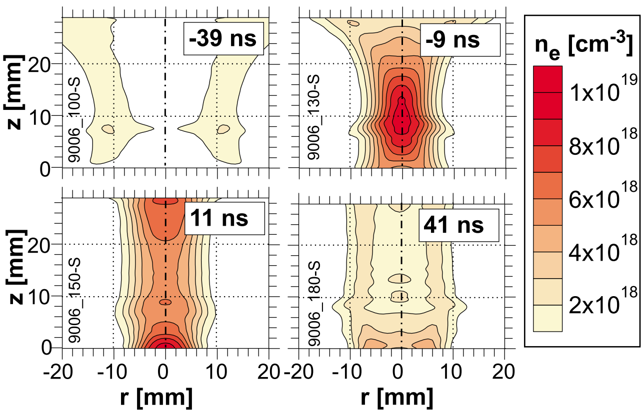

FIG. 2. (Color online) The sequence of electron density distributions in shot 9006.

input during the radial phase $W=\frac{1}{2}\int_{\text{rad}} dL/dt I^2 dt=13$ kJ, we received $k(T_i+T_e)=\frac{2}{3}W/N=1.3$ keV. Since the density is below 10^{19} cm^{-3}, the electron-ion temperature equilibration time is above 80 ns for $T_e \geq 300$ eV. Therefore, the lower estimate of the ion temperature during the stagnation is 1.0 keV. At this ion temperature, the ion-ion collision time of 8 ns is several times shorter than the duration of the pinch phase. Then, for the total ion density N of 4×10^{19}, the average density $\bar{n}_i$ of 8×10^{18} cm^{-3}, the confinement time τ of 40 ns and the D(d,n)^{3}He fusion reaction rate $\langle\sigma v\rangle_{1\ \text{keV}}$ of 0.75×10^{-22} cm^3, we obtain the thermonuclear yield $Y=\frac{1}{2}N\bar{n}_i\langle\sigma v\rangle_{1\ \text{keV}}\tau$ of 5×10^8. It is on the order of several percents of measured neutron yields.

Such a small fraction of neutrons is, however, difficult to observe. For this reason, neutron detectors should be placed on the axis in a so-called upstream direction.[15] In this direction, 2.45 MeV neutrons are one of the fastest and they could be distinguished from beam-target and scattered neutrons which are emitted during the second pulse. Downstream, on the contrary, it was not possible to observe the first neutron pulse at the distance of 16 m since it was concealed by the second pulse. Therefore, we placed one TOF detector side-on at 3 m, one detector downstream at 7 m, and four detectors upstream at 7, 24, 50, and 83.7 m. In Fig. 4(a), there are TOF signals which were recorded by the upstream detectors at 7 and 24 m in the shot described above. We chose this shot with a modest neutron yield because the first pulse of 6×10^8 neutrons was still clearly visible at these detectors and therefore neutron energies could be inferred.

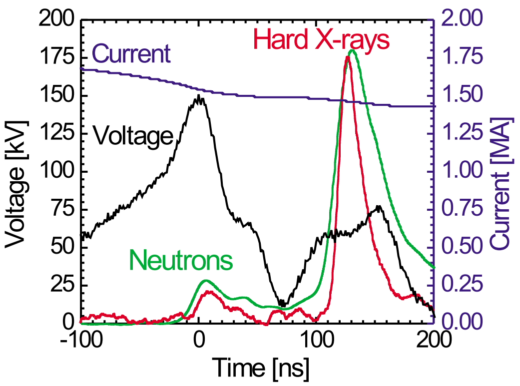

FIG. 3. (Color online) Waveforms of current, $V-LdI/dt$ voltage, hard x-rays, and radial neutrons at 3 m. Neutrons were shifted by TOF of 2.45 MeV neutrons. The time $t=0$ corresponds to the voltage peak. Shot 9006, 190 Pa D_2 pressure, 2×10^{10} neutron yield.

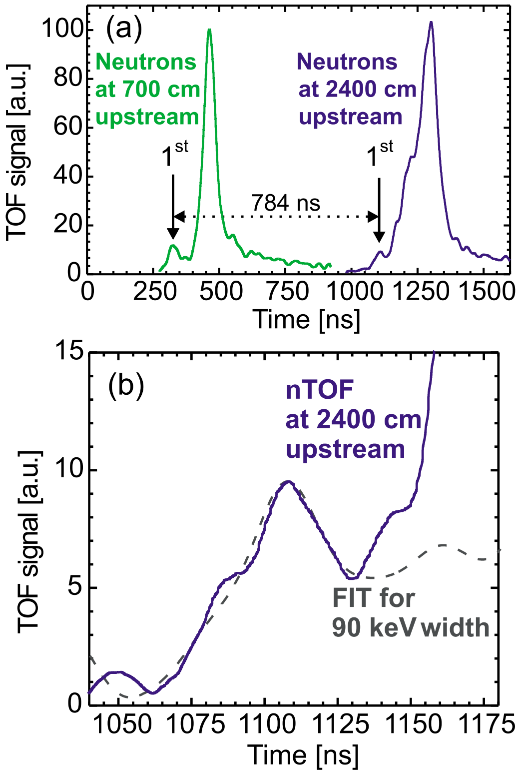

FIG. 4. (Color online) (a) Neutron signals detected upstream at 7 and 24 m in shot 9006. 784 ns corresponds to 2.46 MeV neutrons. (b) The first neutron pulse at 24 m and the fit for the energy spectrum with the 2.46 MeV peak and 90 keV width.

From the time-of-flight of the first peak at 7 and 24 m, it was possible to find with precision that these neutrons were emitted during the stagnation and their peak energy was 2.46 ± 0.02 MeV. This is a very important finding because most of beam-target mechanisms are based on axially accelerated deuterons which produce lower energetic neutrons in the upstream direction.[1] Nevertheless, the thermonuclear mechanism is not the only one which could provide a 2.45 MeV peak in the axial direction. Such a peak could be produced, for instance, by deuterons accelerated in the radial direction by the gyroreflecting mechanism.[16] Therefore, more unambiguous support for the thermonuclear mechanism here should be the measurement of a width of neutron energy spectra. For that purpose, we used the Monte Carlo method and we simulated TOF signals at 7 and 24 m for the instant neutron source with the Gaussian energy spectrum with 2.46 MeV peak and various widths. Then, the simulated TOF signal at 24 m was deconvoluted by the response at 7 m. Finally, the obtained response was convoluted with the measured neutron signal at 7 m and the result was compared with the signal at 24 m. In shot 9006, the best fit of the neutron TOF signal at 24 m was found for a 90 keV width [see Fig. 4(b)].

As regards average values from seven shots, we received the neutron yield of 7×10^8 and the width ΔE_n of 90 ± 20 keV. On the one hand, such a narrow spectrum is inconsistent with proposed beam-target models. On the other hand, this spectrum and the observed neutron yield could be easily explained by thermonuclear plasma. According to the relation $\Delta E_n(\text{keV})=82.5\sqrt{kT_i[\text{keV}]}$, the ion temperature T_i

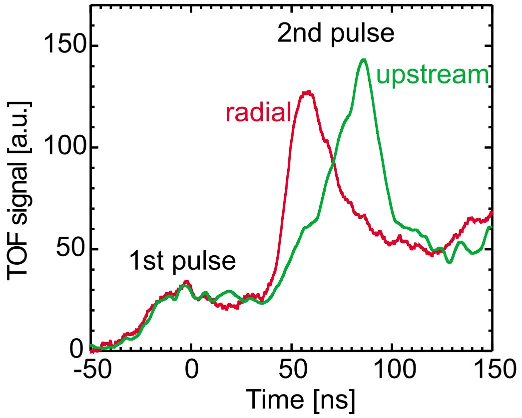

FIG. 5. (Color online) Neutron signals at the radial and upstream TOF detectors. Neutrons are shifted by TOF of 2.45 MeV neutrons. Shot 9008, 190 Pa D_2 pressure, 3×10^{10} neutron yield.

was 1.2 keV. It is for the first time when the ion temperature of thermonuclear Z-pinch plasma is calculated from the width of neutron energy spectrum.

Up to this point, the results from the upstream detectors were presented. The final issue that should be discussed here is neutron emission isotropy.

As far as the neutron energy spectrum is concerned, it was highly isotropic since the peak energy of the first pulse was ≈2.45 MeV in the axial as well as in the radial direction. In several shots, a fraction of the first neutron pulse (up to 30%) seemed to be anisotropic with the downstream energy above 2.45 MeV. Although the shift could be explained mostly by a plasma moving downstream with $\approx 10^5$ m/s fluid velocity, a small contribution of beam-target neutrons cannot be ruled out.

As for the neutron flux anisotropy, results from indium samples demonstrated a relatively high isotropy in the case of the modified plasma focus. However, this time-integrated technique is not a deciding factor since only the small fraction of the total neutron yield was produced during the first pulse. Therefore, it is useful to compare the ratio of the first and the second neutron pulses at the radial and axial detectors. In shot 9008 with a high ratio between the first and the second pulses (see Fig. 5), the ratio at the radial detector was about 1.2 times higher than at the upstream detector (the sensitivity of a scintillator on neutrons with different energies was taken into account). Such a result could be influenced by the anisotropy of the second pulse which is most likely produced by axially accelerated deuterons. In any case, the neutron flux anisotropy during the first pulse was low and it was possible to exclude the acceleration of >10 keV deuteron beams only in the radial direction. Nevertheless, it was still possible to think that some neutrons were produced by head-on collisions of deuterons interacting with $2v_{\mathrm{imp}}$ relative velocity near the axis. However, since the product of the fusion cross-section and the velocity $\sigma(2v_{\mathrm{imp}})\cdot v_{\mathrm{imp}}$ is for $2v_{\mathrm{imp}} = 7 \times 10^5$ m/s by two orders of magnitude smaller than the reaction rate $\langle \sigma v \rangle_T$ of 1 keV thermalized plasma, this contribution to the neutron yield can be neglected.

In conclusion, from the facts presented above, it is possible to summarize that (i) the time, (ii) the energy spectrum, (iii) the emission isotropy, and (iv) the yield during the first neutron pulse corresponded to the theoretical predictions for thermonuclear neutrons. The thermonuclear yield of 7×10^8 was achieved in shots with the modest total neutron yield of 2×10^{10} which were suitable for data processing. Since some thermonuclear neutrons could be expected also after the first neutron pulse,[17] we estimate the fraction of thermonuclear neutrons on the order of 5%. On higher current machines such as *Z*, this fraction should be more significant.[4]

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