Experimental research of neutron yield and spectrum from deuterium gas-puff z-pinch on the GIT-12 generator at current above 2 MA

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Abstract. The Z-pinch experiments with deuterium gas-puff surrounded by an outer plasma shell were carried out on the GIT-12 generator (Tomsk, Russia) at currents of 2 MA. The plasma shell consisting of hydrogen and carbon ions was formed by 48 plasma guns. The deuterium gas-puff was created by a fast electromagnetic valve. This configuration provides an efficient mode of the neutron production in DD reaction, and the neutron yield reaches a value above 10^{12} neutrons per shot. Neutron diagnostics included scintillation TOF detectors for determination of the neutron energy spectrum, bubble detectors BD-PND, a silver activation detector, and several activation samples for determination of the neutron yield analysed by a Sodium Iodide (NaI) and a high-purity Germanium (HPGe) detectors. Using this neutron diagnostic complex, we measured the total neutron yield and amount of high-energy neutrons.

1. Introduction

A Z-pinch is a type of plasma confinement system that uses the electrical current to compress plasma magnetically to the axis. For half a century, Z-pinches have been studied as a source of neutron radiation [1].

We conducted experiments with different types of deuterium gas-puff loads [2]. Since 2013, we used a single-shell deuterium gas-puff surrounded by an outer plasma shell consisting of carbon and hydrogen ions. The outer plasma shell allows us to increase the efficiency of energy transfer from the current generator to the load and improve the stability of a pinch. This type of load was successfully used for neutron production in DD-reaction in our experiments. Neutron yield was increased by an order of magnitude (from 10^{11} to 10^{12}) at the peak current of 2.7 MA. Careful measurements of the neutron yield and neutron spectra are an essential and important part of the research. Since 2014, we have been started to use neutron activation analysis for the neutron measurements in addition to other diagnostic techniques.

This paper summarizes the experimental results on measurements of the neutron yield and the amount of high-energy neutrons with the help of neutron activation method.

2. Apparatus and diagnostic setup

The experimental sessions with deuterium gas-puff were carried on the GIT-12 generator at the Institute of High Current Electronics in Tomsk, Russia. The GIT-12 is a pulse current generator, which consists of 12 primary capacitive energy storage modules, an intermediate inductive storage, and a microsecond plasma opening switch (POS). At a 50 kV charging voltage, the generator stores an energy of 2.6 MJ. When the POS is applied, a load current reaches a value of about 2.5 MA with a 200 ns risetime and a rate of up to 20 kA/ns. Without the POS, the generator provides a load current of 4.7 MA with a rate of 3 kA/ns and a current rise time of 1.7 µs. In these experiments, the generator operation mode without the POS was used.

In the 2014-2015experimental sessions, the load was composed of a single shell deuterium gas-puff with an outer plasma shell of carbon and hydrogen ions. A fast electromagnetic valve was used to form the gas-puff. The diameter of the gas-puff was 80 mm, and the injected linear mass was from 60 µg/cm to 100 µg/cm. The outer plasma shell with a linear mass of about 5 µg/cm was generated by 48 plasma guns located at the diameter of 350 mm [2].

To determine the neutron yield and other parameters of neutron radiation, we used a neutron diagnostic complex containing various detectors. Time-of-flight detectors measured neutron energy. These detectors are composed of Bicron BC-408 scintillators and Hamamatsu H1949-51 photomultipliers. To prevent effect of hard x-rays, detectors were shielded by lead. In our experiments, four nToF detectors were located in the radial direction at distances of 1.5 or 2 m, 5.7 m, 10.1 m, and 25.8 m, and one detector was located in axial direction below cathode at a distance of 4.8 m. Using signals from these detectors, one can reconstruct neutron spectrum [3]. The total neutron yield was measured by a set of BTI bubble detectors, which were calibrated in situ. Five BTI detectors were placed at different angles and distance from the pinch, and the yield was determined as the average of the obtained values. A silver activation counter (SAC) was another diagnostics for the neutron yield measurements. SAC was located radially at a distance of 4.55 m from the pinch. SAC is assembled from polyethylene block (as moderator) and SBM-19 Geiger counter, which is covered by 1 mm silver foil. This technique is based on the activation of silver foil by neutrons from the pinch and subsequent registration of the radioactive decay intensity of silver isotopes. Initially, SAC was calibrated for distances, which are significantly less, than that used in our experiments. Therefore, it was cross-calibrated with the bubble-detectors.

A new independent technique, which was employed for neutron measurements in our experiments, was the neutron activation analysis. The method is based on activation of a sample by a neutron flux [4]. The sample is bombarded by neutrons, causing the elements to form radioactive isotopes. The radioactive emissions and radioactive decay paths for each element are known. Using special diagnostic equipment, it is possible to study spectra of the emissions from the activated sample and determine the concentrations of the radioactive isotope within it. Knowing the number of target and produced nuclei, one can calculate the amount of neutrons passing through the sample. In our experimental sessions, we used Canberra GC 1020 high-purity Germanium (HpGe) detector and Sodium-Iodide (NaI) gamma-spectrometer with special software for registration of gamma rays. Both detectors were calibrated by radioactive samples before every experimental campaign.

We can calculate the amount of activated particles as

$$N_p = N_t \cdot \sigma_{aver} \cdot \Phi \qquad (1)$$

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where N_p is a number of the activated (produced) nuclei in the sample, N_t is number of the target particles in the detector, σ_{aver} is the average cross section of the reaction, Φ is the neutron flux through the sample.

Thereby, we can calculate neutron fluence as

$$\Phi = \frac{N_p}{N_t \cdot \sigma_{aver}} = \frac{Se^{\lambda t}A}{\varepsilon I N_A mk(1-e^{-\lambda\Delta t})\sigma_{aver}} \tag{2}$$

where S is the area of the gamma rays peak, λ is the decay constant of radioactive material, t is the time between the beginning of activation and start of measurement, A is the atomic mass of the target isotope, ε is the detection efficiency of the gamma-spectrometer for a certain energy of gamma rays, I is the gamma ray emission probability, N_A is the Avogadro constant, m is the mass of the sample, k is the abundance of target isotope in the sample, Δt is the time of measurement. For neutron yield calculation, we should multiple the neutron fluence on the geometry factor $4\pi R^2$, where R is the distance from the pinch (neutron source) to the activation sample in radial direction. All data about nuclei and properties of nuclear reactions we can found in the IAEA databases [5][6]. The average cross-section of the reaction was calculated, using neutron spectra, reconstructed from nToF-detectors signals.

Selecting samples for activation, we were guided by the following considerations: availability, purity (lower impurity content), high concentrations of the desired isotope in the element, high cross-section of reaction (> 100 mbarn). An isotope that appears as a result of the activation should have a half-life in the interval from 2 minutes to 5 hours (otherwise gamma rays intensity will be very low for the detectors used).

Activation measurements were conducted with indium and copper samples. Determination of the total neutron yield was carried out with the help of indium samples. In 2014, the measurements were based on ^{115}In(n,γ)^{116m}In neutron radiative capture reaction, but this reaction is sensitive to scattered neutrons. Therefore, ^{115}In(n,n')^{115m}In nuclear excitation reaction with 2 MeV energy threshold was used in 2015. The number of high-energy neutrons (with energy > 12 MeV) was measured by ^{63}Cu(n,2n)^{62}Cu reaction.

3. Experimental results

Conducting neutron activation measurements during the experimental sessions in 2014 and 2015, we pursued the following goals: first, to master the activation technique and analysis routine; second, to obtain the data on the total neutron yield with the help of an independent diagnostic method; third, to determine the part of high-energy neutrons in the full spectrum. In subsequent experiments, it is planned to expand the application of the activation method for the study of neutron production from deuterium gas-puff z-pinch, for instance, to characterize the anisotropy of neutron radiation and to obtain quantitative data on the neutron yield in different ranges of energy spectrum.

For the total neutron yield measurement, indium samples were placed for activation outside the experimental chamber at the distance of 37 cm from the pinch in the radial direction. The neutron yield determined with the help of two different neutron activation reactions is shown in Figure 1. The data obtained by the SAC and the bubble detectors are shown for each shot for comparison. In principle, the neutron yield determined by both reactions correlates well with the data obtained by other diagnostics. However, the results of measurements carried out with the help of neutron radiative capture reaction ^{115}In(n,γ)^{116m}In is systematically higher, than the total neutron yield measured by the mean of the SAC and the bubble detectors. The most likely reason for this discrepancy is a high reaction cross section in the region of neutron energies below 2 MeV and, therefore, sensitivity of this reaction to the scattered neutrons. From our point of view, the measurements performed with the help of ^{115}In(n,n')^{115m}In nuclear excitation reaction with 2 MeV energy threshold provide more accurate data on the total neutron yield.

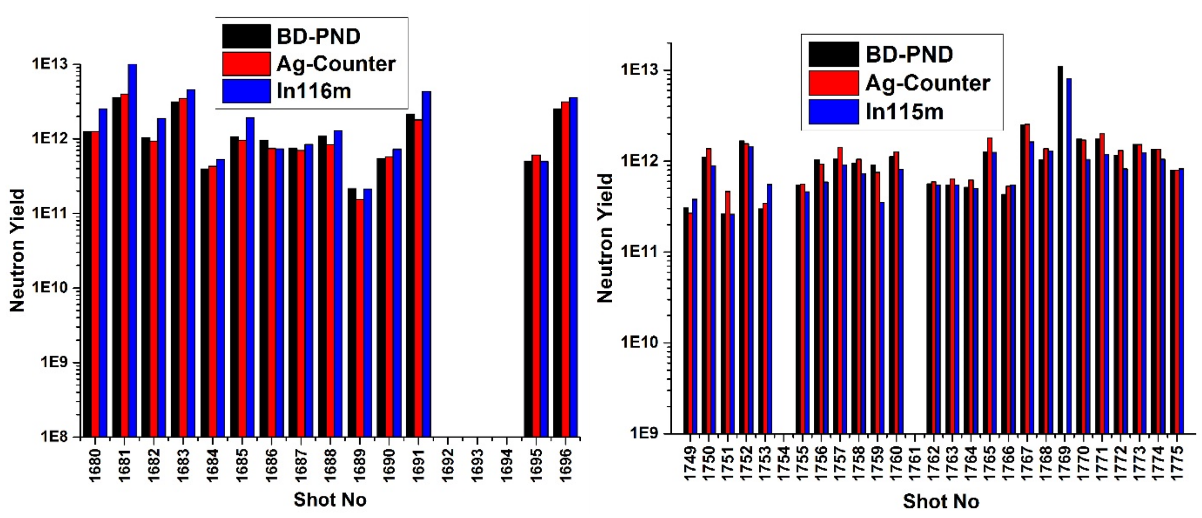

Figure 1. Neutron yields measured by activation of indium samples in comparison with the data obtained by means of the bubble detectors and silver activation counter

In the early experiments with triple shell deuterium gas-puff, the high energy tail of the neutron spectrum reached the energies up to 6 MeV. In the experiments with a single-shell deuterium gas-puff surrounded by an outer plasma shell, the neutron spectrum was significantly broader, and the energy of neutrons exceeded 12 MeV. In order to determine the amount of high-energy neutrons, the activation of the copper samples was employed. The reaction used in activation analysis has a high energy threshold (11.9 MeV), and that makes it possible to cut off the low-energy neutrons. The measured amount of high-energy neutrons was about 10^9 neutrons/shot in a typical shot with the total neutron yield above 10^{12} neutrons/shot. The fraction of the high-energy particles in the total neutron yield (≤0.5 %) is consistent with the neutron spectrum data obtained with the help of nToF diagnostics.

4. Conclusion

The neutron production from the single-shell deuterium gas puff with the outer plasma shell was studied in the experiments on the GIT-12 generator. The neutron activation method has been employed during two experimental campaigns. The neutron yields determined with the help of activation method and by other diagnostics are in good agreement. The measured amount of the high-energy neutrons is 10^9 neutron/shot. The part of high-energy neutrons in the neutron spectra determined by the activation method is consistent with the results obtained by means of the nToF diagnostics.

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