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Ion beam source upgrade of the neutron source at IAP RAS

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The results of the ion source of the neutron generator upgrade, which makes it possible to operate in a CW mode, are presented. A magnetic trap consisting of permanent magnets (NdFeB) was developed. A 3-electrode extraction system equipped with a magnetic lens was used to extract the deuterium ion beam. Calculations are made for the formation of a deuterium ion beam with a current over 500 mA and an energy of 100 keV with practically no losses in the extraction system.

Keywords: extraction system, magnetic trap, neutron generator, ion beam.

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Introduction

Neutron sources are widely used in fundamental and applied studies [1]. There are different types of neutron sources (nuclear reactors [2], radioisotope sources [3], accelerator-based sources [4–12], etc.). They are in demand for various applications (neutronography, boron neutron capture therapy (BNCT), neutron tomography etc.).

In this paper, a neutron generator is discussed in the context of its application for BNCT. BNCT requires a flux of epithermal neutrons with a density of at least $10^9\,\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$ [13]. At present, a number of neutron sources based on proton accelerators are being developed and implemented in many countries of the world [14], which satisfy this requirement. These facilities are characterized by beam currents up to tens of mA, and the characteristic ion energy is few–tens of MeV. These sources include an ion injector, an accelerator, a target, and a moderator. The most advanced source of this type today is facility based on a tandem accelerator at the INP SB RAS. In this system the total neutron yield at the level of $5\cdot10^{12}\,\mathrm{s}^{-1}$, is achieved, and the necessary flux density sufficient for therapy is provided [15].

However, the number of neutron sources based on the proton accelerator is several dozen worldwide. Consequently, the development of BNCT technology is still limited by the lack of available neutron sources of sufficient intensity [16].

Among small-size neutron generators as compared to sources that include an accelerator, the portable and compact ones can be distinguished. Portable sources (for example, gas-filled or sealed neutron tubes produced by VNIIA [17]) have a peak neutron yield up to $10^{10}\,\mathrm{s}^{-1}$, which is not enough to be used in BNCT.

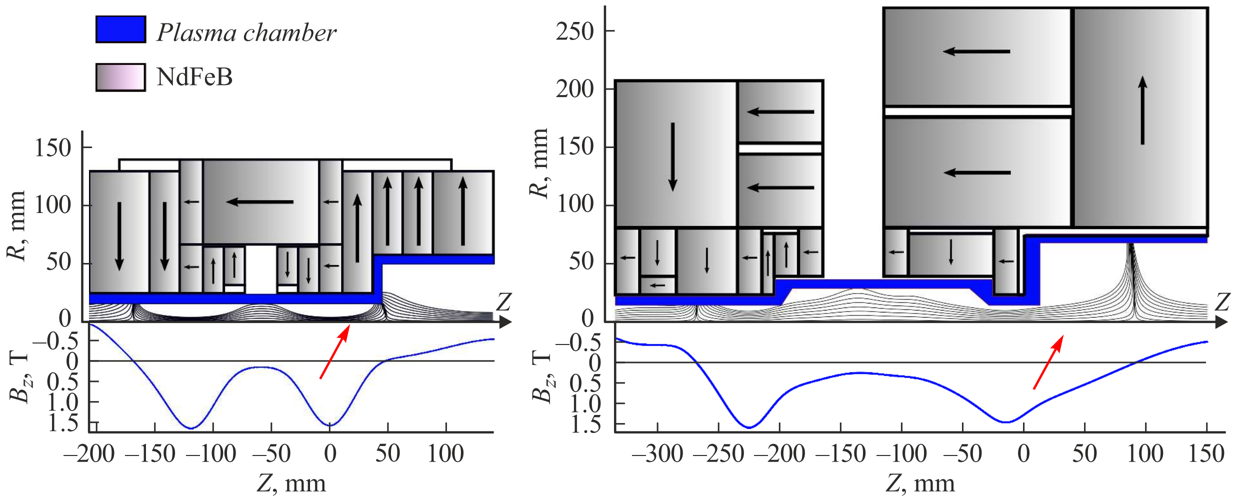
Compact neutron generators are considered in this work as sources based on accelerated ion beams extracted from plasma.. As an example, one can consider the following sources: Adelphi [18], Efremov NIIEFA [19], LBNL [20], Lanzhou University [21]. The typical beam energy is 100–300 keV at a current of a few–tens mA. Sources of this type can be considered for BNCT applications, but require significant modifications to achieve the required characteristics.

A compact pulsed neutron generator [22] based on the ECR of ion source SMIS (Simple Mirror Ion Source) with a gasdynamic confinement mode [23] was previously developed at the Institute of Applied Physics of the Russian Academy of Sciences. Plasma is created using microwave radiation of the gyrotron [24,25] at a frequency of 37.5 GHz with a power of up to 100 kW and a pulse width of 1 ms. Neutrons were generated through $D-D$-reaction with the yield of fast neutrons (2.5 MeV) $1.2\cdot10^{10}\,\mathrm{s}^{-1}$ at the beam current 50 mA and energy 75 keV in pulsed mode with pulse width of about 1 ms [26]. This neutron generator is considered not only for BNCT applications [22,27], but also for neutron tomography [28–30,26].

The developments of Phoenix Nuclear Labs are the closest analogue of the IAP RAS source [31]. The main difference of our facility is a significantly higher design current of the ion beam, combined with its high quality. Also, in the developments of the IAP RAS both a solid-state and a gas targets are considered, while Phoenix Nuclear Labs focuses on large-volume gas targets only, which leads to a decrease in the maximum available neutron flux density on the sample.

The aim of further developments of the IAP RAS source is to increase the neutron yield to $10^{11}\,\mathrm{s}^{-1}$ by increasing the beam energy and current. It is also necessary to switch to a CW mode and develop a neutron beam shaping assembly for use in BNCT.

At this stage the modernization of the neutron generator includes the development of the following components: a magnetic system for plasma confinement, an ion beam formation system, a cooled plasma chamber, a cooled target,



GISMO

Neutron generator

Figure 1. Comparison of magnetic traps for the GISMO facility (left) and neutron source (right). The Figures show permanent magnets (the direction of magnetization is indicated by arrows), and the section of the plasma chamber is shown. The force lines of the magnetic field and its profile on the Z axis are plotted. In both cases, microwave radiation propagates from the left side, and the neutral gas is injected, while the ion beam is extracted from the right side. The arrow indicates the approximate location of the extraction system. Schemes of magnetic systems are given in the same scale.

and a moderator. The first two problems are considered in this work.

Thus, the aim of the paper is to develop a magnetic system and an ion beam extraction system that allow one to form a beam of deuterium ions with current over 500 mA and energy of up to 100 keV. When the indicated beam parameters are reached, the design value of the neutron yield is $10^{11}\,\mathrm{s}^{-1}$.

1. New magnetic system

The basis for the magnetic trap of the modified source is the magnetic system of the GISMO facility (Gasdynamic Ion Source for Multipurpose Operation) [32,33]. It consists of a set of permanent magnets with radial and axial magnetization, which are rings that form an open magnetic trap in the mirror mirror configuration. The magnetic trap also has an inner diameter expansion on the ion beam extraction side for more convenient placement of the extraction system. The current plasma chamber does not allow its full use for intense compact neutron source because the extraction system must be placed in a narrow part (Fig. 1). The GISMO facility trap has the following parameters: the magnetic field in the injection side plug $B_{\mathrm{inj}} = 1.61\,\mathrm{T}$, the minimum field on the axis $B_{\mathrm{min}} = 0.26\,\mathrm{T}$, the field in the extraction side plug $B_{\mathrm{ext}} = 1.61\,\mathrm{T}$, weight of magnets $M = 132\,\mathrm{kg}$, plasma volume $V_{\mathrm{plasma}} = 36\,\mathrm{cm}^3$, maximum cross-sectional area of the plasma tube $S_{\mathrm{plasma}} = 8\,\mathrm{cm}^2$, distance between plugs $L = 120\,\mathrm{mm}$.

When developing the new magnetic system, the following goals were pursued: moving the magnetic trap mirror closer to the expander (in order to place the extractor directly in the expanded part), as well as increasing the plasma cross section (to increase the maximum available current of the beam that can be extracted). It is necessary to increase the linear dimensions of the plasma tube approximately by 2 times. In this case, the values B_{inj}, B_{min}, B_{ext} of the new trap should be approximately equal to the values for the GISMO magnetic trap (with an accuracy of 10%) with the minimum possible weight of magnets. Magnetic field calculations were performed using COMSOL Multiphysics.

To reduce the weight of the magnetic material, a plasma chamber with a variable cross-section is used (Fig. 1), which has a wide part in the region of the space between the magnetic mirrors and thus resembles the shape of the plasma tube. The magnet consists of two parts, which is determined by the shape of the plasma chamber. An additional advantage of this configuration is the possibility of placing ports for direct plasma diagnostics in the space between the magnets.

The magnetic trap is unambiguously specified by the geometric parameters of its constituent parts (inner diameter, thickness, outer diameter of each of the rings) (Fig. 2). Some of the parameters ($r_1 = 25\,\mathrm{mm}$, $r_2 = 40\,\mathrm{mm}$, $r_4 = 80\,\mathrm{mm}$, $l_{11} = 50\,\mathrm{mm}$, $l_9 + l_{10} = 150\,\mathrm{mm}$) are determined by external factors (for example, restrictions on expander parameters imposed by the extractor). The remaining parameters varied to obtain the magnetic trap with the required characteristics.

According to the calculation results, the magnetic trap has the following parameters: the magnetic field in the injection side plug $B_{\mathrm{inj}} = 1.6\,\mathrm{T}$, $B_{\mathrm{min}} = 0.26\,\mathrm{T}$, $B_{\mathrm{ext}} = 1.49\,\mathrm{T}$, total weight of magnets $M = 550\,\mathrm{kg}$, $V_{\mathrm{plasma}} = 288\,\mathrm{cm}^3$, $S_{\mathrm{plasma}} = 30\,\mathrm{cm}^2$, $L = 210\,\mathrm{mm}$. To heat the plasma in a

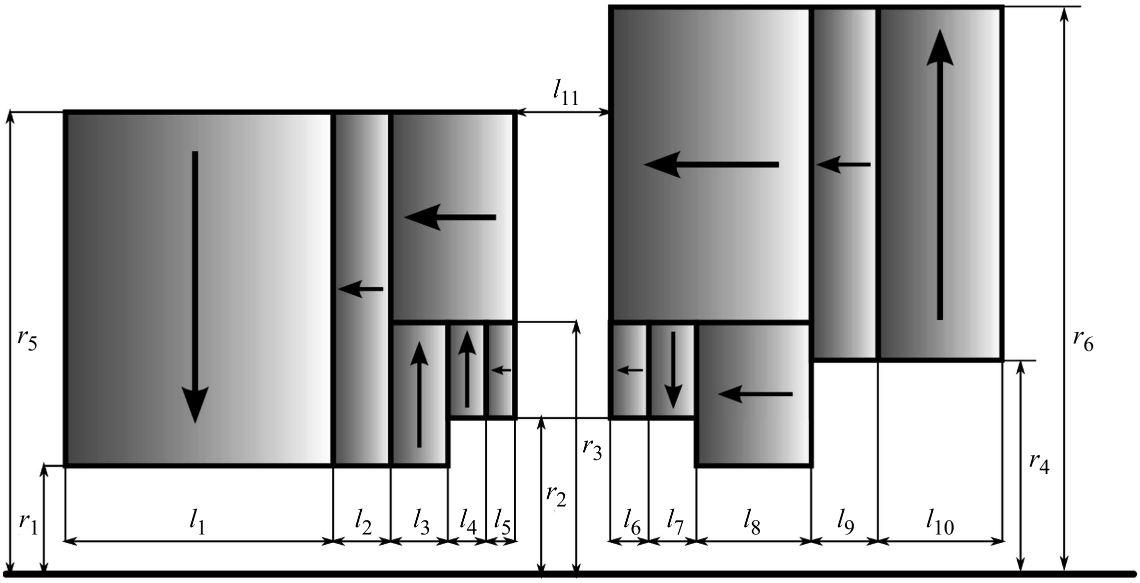


Figure 2. Cross section of the magnetic system and its geometrical parameters. The arrows indicate the direction of the magnetization vector. The bottom horizontal line is the axis of symmetry. Microwave radiation is fed into the plasma chamber from the left, and the ion beam is extracted from the right.

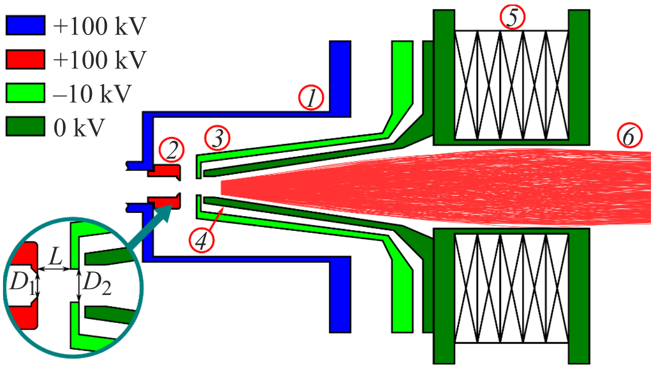


Figure 3. Image of the extraction system, which includes the plasma electrode *2* with the plasma chamber *1*, the puller *3*, the grounded electrode *4*, the solenoid *5*. The trajectories of the ion beam *6* are also indicated. The extraction system with its geometric parameters is shown enlarged.

CW mode, it is proposed to use a technological gyrotron with frequency of 28 GHz and power of up to 10 kW [34]. The plasma chamber with forced water cooling will also be designed.

2. Beam forming system

In the formation of the ion beam with current of several hundred mA, its own space charge plays an important role. For the effective formation of this ion beam, it is necessary to achieve a high compensation degree of the beam space charge. The two-electrode beam extraction system, which has the simplest design, does not provide the necessary degree of compensation. The reason for this is that the electrons compensating the space charge are lost from the beam under the action of the electric field accelerating the ions. To eliminate this electron loss channel, a three-electrode system is used, consisting of a plasma electrode, an extraction electrode (puller), and a grounded electrode. Similar systems (for example, such extractors are described in the monograph edited by J. Braun [35]) are widely used in ion sources [36,37]. The puller has a negative potential and creates a potential barrier for electrons compensating the space charge of the beam. The use of electrostatic lenses to control the beam shape is unacceptable, since in this case the compensation of the space charge is locally violated. Therefore, the extraction system is equipped with a magnetic lens, which forms a weakly divergent ion beam (Fig. 3). Let us introduce the following extractor parameters: D_1 — diameter of the plasma electrode hole in [mm], L — interelectrode distance in [mm], D_2 — diameter of the puller hole in [mm].

For the calculation the package of libraries for numerical simulation IBSimu is used [38]. It is necessary to know the following characteristics of the plasma flow from which the ion beam is formed: ion temperature ($T_i = 1\,\text{eV}$, which is a characteristic value for ECR of ion sources), electron temperature ($T_e = 50\,\text{eV}$ — value corresponding to experimental results [39]), longitudinal energy of ions ($E_0 = 50\,\text{eV}$, which corresponds to Bohm's criterion [40]), plasma potential ($U_{\text{plasma}} = 50\,\text{V}$ — the numerical value is chosen equal to the electron temperature as an estimate of the value). For simplicity, the ion beam is assumed consisting entirely of deuterium ions. It is assumed in the calculations that the space charge compensation degree the beam is 90%, which is a characteristic value for beams

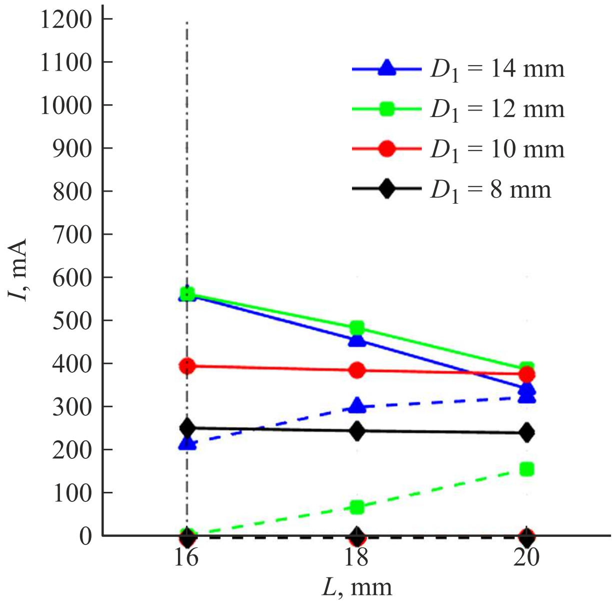


Figure 4. Beam current at the extractor output (solid line) and the current to the grounded electrode (dashed line) vs. interelectrode distance for different plasma electrode apertures. The vertical bar indicates the estimate of the minimum allowable distance between the electrodes.

of light ions with energy of about 100 keV and current of hundreds of mA [41,42]. The potential of the plasma electrode is equal to $\varphi_{\text{pl}} = +100\,\text{kV}$, of the puller — $\varphi_{\text{pu}} = -10\,\text{kV}$. The magnetic field formed by the solenoid is 0.5 T at its center. The calculation assumes that the density of the ion flux extracted from the plasma is $500\,\text{mA} \cdot \text{cm}^{-2}$. The indicated flux density of deuterium ions is assumed to be achievable, since it was experimentally shown in the GISMO facility that the emissivity of hydrogen plasma exceeds $1\,\text{A} \cdot \text{cm}^{-2}$ [{] 43}.

The main difficulty in constructing the beam formation system for accelerating voltages of about 100 kV — is the taking into account of the electrical breakdown of the space between the plasma electrode and the puller. For a particular extraction system, it is possible to determine the frequency of breakdown occurrence only experimentally due to the presence of the ion beam and an external magnetic field in the interelectrode space. However, there is an estimate of the minimum distance between flat electrodes at which breakdowns do not occur (Kilpatrick's criterion) [44]:

$$L = 0.01414\,U^{3/2},$$

where L — electrode spacing in [mm], and U — extraction voltage in [kV]. For the used voltage $U = \varphi_{\text{pl}} - \varphi_{\text{pu}} = 110\,\text{kV}$ the minimum interelectrode distance is $L = 16\,\text{mm}$, which gives the limitation of the minimal parameter value.

To determine the optimal parameters of the extractor, we will calculate the beam formation for various values (D_1, L, D_2). It is important to obtain the maximum beam current at the extractor output with its minimum losses. On Fig. 4. the dependences of beam currents at the extractor output and the current to the grounded electrode are shown. In this case, the beam current to the puller is equal to zero in all cases.

For the values of the plasma electrode aperture $D_1 = 8$ and 10 mm the formed ion beam has no losses, but its total current is less than the required value. In the considered range of interelectrode distances ($L \geq 16\,\text{mm}$) the ion beam at the output has approximately the same current for extractors with $D_1 = 12$ and 14 mm, i.e. increase in the aperture did not lead to increase in the current at the output, and additional ions settled on the grounded

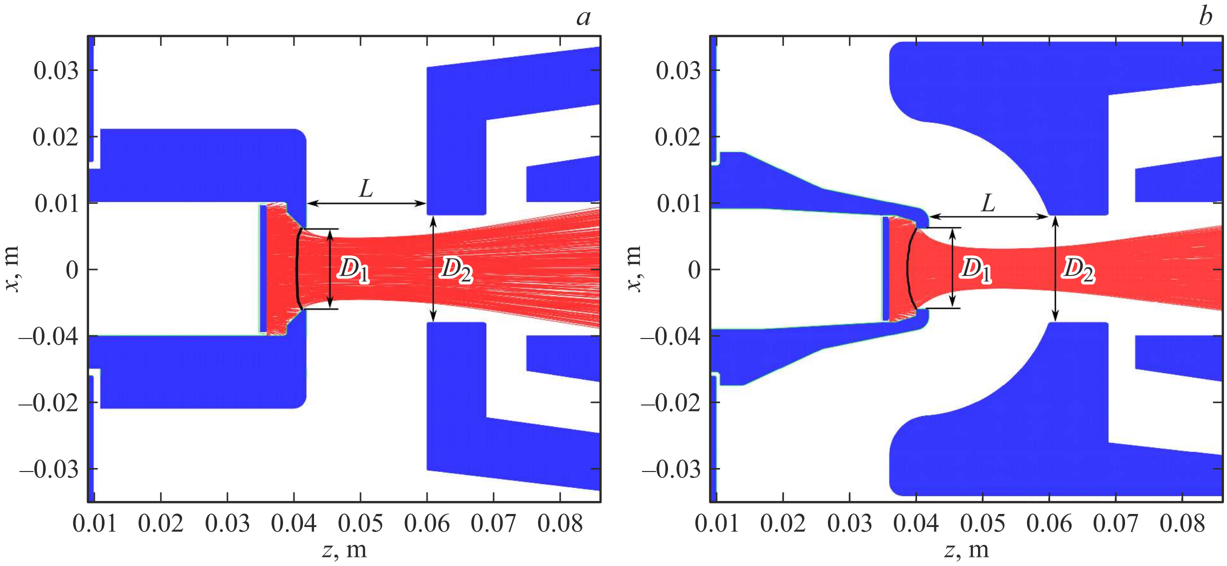


Figure 5. Comparison of beam formation systems: flat (a) and systems with inhomogeneous field (b). The blue color (in the online version) indicates the electrodes, the red color (in the online version) — ion trajectories. The black line represents the plasma meniscus.

electrode. Thus, the optimal parameters of the extraction system are $D_1 = 12$ mm and $L = 16$ mm. The total ion current at the extractor output is 560ṁA, and the beam loss is about 5ṁA, which is a negligible value from the point of view of the efficiency of the beam formation system. In this case the ion beam will settle on the grounded electrode, and thermal power of about 500 W will be continuously released on it. Forced water cooling will be organized to ensure heat dissipation.

Consider another possible option of the extraction system. It is proposed to use a beam formation system with inhomogeneous electric field [45,46] (Fig. 5).

A distinctive feature of this extractor is the shape of the plasma electrode with narrow tip, which provides the electric field increasing near the plasma meniscus. This makes it possible to form the ion beam with higher current density compared to a flat extractor. Also, the electric field redistribution in the accelerating gap leads to field decreasing on the puller surface, which reduces the probability of breakdowns. The last factor is important in this case. Fig. 5 compares the formation of ion beam for extractors with parameters $D_1 = 12$ mm, $L = 18$ mm and $D_2 = 16$ mm for cases of flat geometry and the extractor with a inhomogeneous field. It can be seen that for the latter case the meniscus is more concave, which indicates a smaller beam space charge in this region. For the flat geometry in this configuration, the beam losses are 70 mA, and for the extractor with inhomogeneous field, — 5 mA. The smaller losses are consequence of the smaller divergence of the ion beam at the exit from the accelerating gap. The large beam divergence in the flat case is due to the action of the space charge.

Conclusion

In this paper the development of magnetic system and beam formation system in the ion source of the neutron generator was carried out. The main goal is to switch the neutron generator to CW mode of operation and to achieve the necessary margin of electrical breakdown strength to achieve accelerating voltage of about 100 kV. The parameters of the extraction system were determined to make it possible to form the beam of deuterium ions with current over 500 mA and low losses in the extractor. It is also proposed to use the extractor with inhomogeneous field, which with the same efficiency of beam extraction provides a significantly higher electrical breakdown strength of the accelerating gap. In the future, it will be necessary to manufacture and test the extraction system in order to make sure that there are no breakdowns in the interelectrode space.

The next stage in the development of the compact CW mode source is the design of neutron generating target capable of operating in a continuous mode. The power of the thermal load on the target from the hit of a beam with current of 500 mA and energy of 100 keV is 50 kW in the CW mode, so the main problem in the implementation of the intense compact neutron source is to remove heat from the target.

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Conflict of interest

The authors declare that they have no conflict of interest.

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