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High yield neutron generator based on a high-current gasdynamic electron cyclotron resonance ion source

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In present paper, an approach for high yield compact D-D neutron generator based on a high current gasdynamic electron cyclotron resonance ion source is suggested. Results on dense pulsed deuteron beam production with current up to 500 mA and current density up to 750 mA/cm^2 are demonstrated. Neutron yield from D_2O and TiD_2 targets was measured in case of its bombardment by pulsed 300 mA D^+ beam with 45 keV energy. Neutron yield density at target surface of 10^9 s^{-1} cm^{-2} was detected with a system of two ^{3}He proportional counters. Estimations based on obtained experimental results show that neutron yield from a high quality TiD_2 target bombarded by D^+ beam demonstrated in present work accelerated to 100 keV could reach 6×10^{10} s^{-1} cm^{-2}. It is discussed that compact neutron generator with such characteristics could be perspective for a number of applications like boron neutron capture therapy, security systems based on neutron scanning, and neutronography. *© 2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4929955]

INTRODUCTION

Neutron sources are widely used in fundamental and applied research. Manifold applications require neutron fluxes of various intensities, energy spectra, and degrees of collimation. Several types of neutron sources have been developed for the purpose including nuclear reactors,[1–7] radioisotope sources,[8,9] D-D and D-T generators,[10,11] plasma pinch machines,[12–14] accelerators,[15–19] etc. Each neutron source type occupies a niche fulfilling the parameters desired in a given application. Accelerator-based generators are capable of tuning the output neutron flux energy spectrum and direction by changing the energy of the beam incident on the target. Other types of generators are using moderators to conform the energy spectrum of neutrons to fulfill the application requirements, especially when low energy neutrons are needed, as, e.g., D-D fusion yields neutrons with 2.49 Mev energy (14.6 Mev for D-T fusion).

The present article presents the results of recent investigations devoted to development of a new generation of compact D-D (D-T) neutron generators capable to generate neutron fluxes that surpass the state-of-the-art devices by an order of magnitude. The neutron generator consists of the following main parts: plasma source, electrostatic extraction system for deuterium beam formation/acceleration, and the neutron-generating target containing deuterium or tritium. Improving the performance of each of these subsystems increases the total neutron flux. Ion flux density from the plasma source determines the maximum ion beam current density. The beam extraction and formation system affects the total beam current and current density as well as the final energy of the D+ beam, on which D-D and D-T fusion cross-sections depend strongly.[20] The density of deuterium or tritium in the target material as well as the ion beam current contribute directly to the total neutron yield.

The technique of D- or T-containing target manufacture is well-developed; certain metals, i.e., titanium, zirconium, and tantalum effectively absorb up to 1.8 atoms of hydrogen and/or its isotopes per single metallic atom.[21,22] The most challenging part of the target technology is to provide adequate cooling as there is no known material which binds hydrogen at temperatures above 800–1000 °C, whereas typical target materials like titanium desorb hydrogen at temperatures above 100–400 °C.

Methods to design and construct beam extraction and formation systems are well-developed; computational ion-optics tools are capable of modeling complex systems taking into account space charge effects affecting the beam extraction and transport.[23–26] Various diode and multi-electrode systems, equipped with compensating electrodes for high current density beam formation, have been developed. Such ion extraction and beam formation systems are well-optimized and widely used in different types of modern ion sources.[27–30]

The only foreseeable method to improve the yield of a D-D (D-T) neutron generator is a significant increase of the ion beam intensity. This, in turn, could be done by increasing the plasma density in the ion source. Various types of discharges have been studied earlier for the purpose: RF,[31–33] Penning,[34,35] vacuum arc,[36] laser,[37] and ECR.[38] Existing state-of-the-art ion sources are able to deliver deuterium beams with the current density up to 100 mA/cm^2.

Here, the authors demonstrate neutron production using a high-current quasi-gasdynamic ECR ion source, which utilizes a powerful gyrotron radiation of mm-waveband for plasma creation and heating.[39–41] Such ion sources are capable to form ion beams with record current densities of

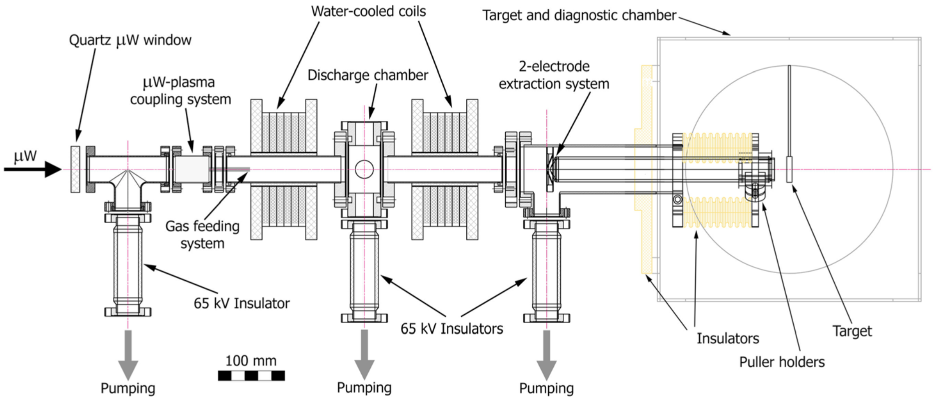

FIG. 1. Schematic view of SMIS 37 experimental facility.

1 eA/cm^2 and low emittance.[42,43] The reported current density is more than an order of magnitude greater in comparison to rivaling technologies. Accordingly, the use of quasi-gasdynamic ion source is expected to increase the density of the neutron flux from the target by a corresponding factor.

HIGH-CURRENT QUASI-GASDYNAMIC ECR ION SOURCES

Using powerful mm-waveband radiation allows to increase the plasma density in the discharge significantly (proportional to the square of the radiation frequency[38–41]) in comparison to conventional ECRISs, which utilize microwave radiation with frequencies on the order of 10 GHz.[38] In experiments with 37.5 GHz and 75 GHz gyrotrons, the plasma density reaches values of 10^{13}–10^{14} cm^{-3}.[42,44] Significant increase of the plasma density leads to a change of the confinement mode. A so-called quasi-gasdynamic confinement[45,46] was realized in the presented experiments instead of the collisionless one,[47] which is common for modern ECRISs. The transition from collisionless to quasi-gasdynamic confinement occurs when the plasma density is high enough for the scattering rate of electrons into the loss-cone to be more than the maximum possible electron loss rate caused by the ion-sound flux through the magnetic mirrors.[45] In such a situation, the loss-cone in velocity space is populated, and the plasma lifetime does not depend on the collisional electron scattering rate into the loss-cone, i.e., on the plasma density, but is determined by the trap size, magnetic field structure, and ion sound velocity.[45] The plasma lifetime, which is much shorter than in conventional classical ECRIS, can be expressed as

$$\tau = \frac{L \cdot R}{2V_{is}},$$

where L—magnetic trap length, R—trap mirror ratio (ratio between magnetic field in the magnetic mirror and in the trap center), and V_{is}—ion sound velocity. Short plasma lifetime provides high plasma flux density from the trap. The flux is proportional to the plasma density and ion lifetime, i.e., $I \sim N/\tau$, where N—plasma density. Due to the high plasma density, the confinement parameter $Ne{\cdot}\tau$, which determines the ionization degree and average ion charge, can be as high as 10^8–10^9 s cm^{-3}, which is enough for almost 100% ionization of hydrogen and deuterium in 10^{-5}–10^{-3} Torr pressure. Under our experimental conditions, typical plasma lifetime is on the order of 10 μs. The described peculiarities of quasi-gasdynamic ECR discharge sustained by mm-waveband radiation, namely, short lifetime and high density, provide unprecedented plasma flux densities of several eA/cm^2.

HIGH INTENSITY D+ BEAM FORMATION WITH THE SMIS 37 GASDYNAMIC ION SOURCE

The first experiments on neutron production with an ion source utilizing mm-band radiation were conducted at SMIS 37 facility, schematically depicted in Fig. 1. The plasma was created and sustained inside a d = 4 cm vacuum chamber (placed in a magnetic trap) by pulsed (1.5 ms) 37.5 GHz linearly polarized radiation with power up to 100 kW and generated by a gyrotron. The simple mirror magnetic trap was created by pulsed solenoids, positioned at a distance of 15 cm from each other, providing a mirror ratio of 5. The magnetic field strength was varied in a range of 1–4 T at mirror plugs, whereas the resonant field strength is 1.34 T for 37.5 GHz. Microwave radiation was guided into the chamber quasi-optically through a quartz window and a special coupling system, which protects the window from the plasma flux. The pulsed gas feed line was incorporated into the coupling system, i.e., the neutral gas was injected axially.

The ion extraction and beam formation were realized by a two-electrode (diode) system consisting of a plasma electrode and puller. The electrodes are shown in Fig. 2. The distance between the extraction system and the magnetic plug at the center of the solenoid magnet was designed to be

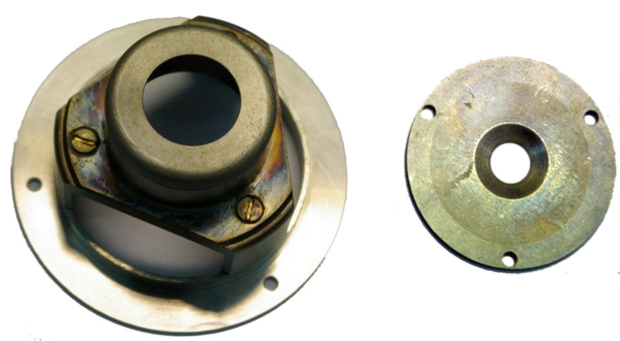

FIG. 2. Puller (on the left), aperture diameter 24 mm; plasma electrode (on the right), aperture diameter 10 mm.

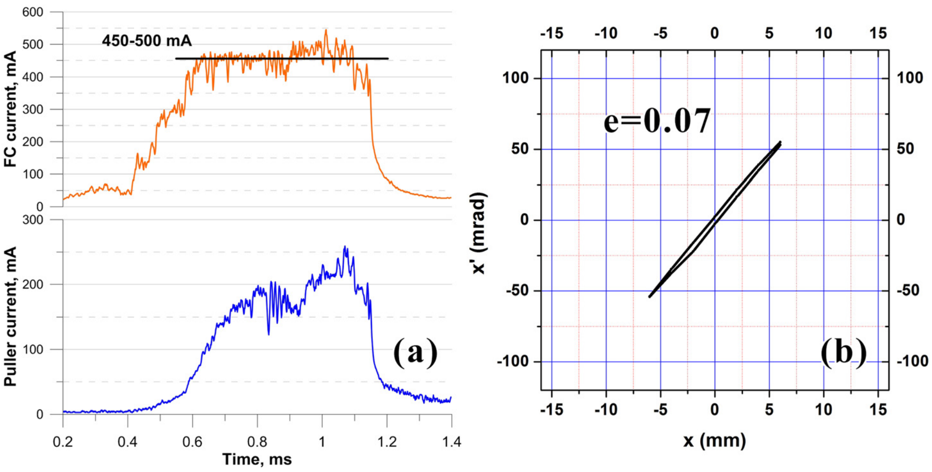

FIG. 3. (a) The Faraday cup and puller current waveforms of a single pulse. (b) Corresponding emittance diagram measured with the "pepper-pot" method. Extraction voltage is 45 kV.

variable, which allows tuning the plasma flux density at the plasma electrode. The maximum applied extraction voltage was 45 kV, which was an absolute maximum for the used power supply. A Faraday cup with an aperture of 85 mm was placed right behind the puller (grounded hollow electrode) for capturing the whole ion beam. The cup is equipped with an electrostatic secondary electron suppression. A magnetostatic mass-to-charge analyzer with 42° bending angle was installed downstream in the beam line for measuring the species fraction (D+/D2+) of the extracted beam. The plasma flux density was measured with a Langmuir probe.

A single aperture extraction system with a plasma electrode aperture of 10 mm was used in this work. The aperture sizes of both electrodes, the distance between the plasma electrode and the mirror point of the magnetic trap and the gap between the electrodes, were optimized during the experiments in order to maximize the total beam current. The optimal distance from the mirror point to the plasma electrode was 12 cm, and the gap between electrodes—16 mm. The Faraday cup and puller current waveforms of a single pulse are shown in Fig. 3(a). The maximum Faraday cup current was 450 meA, which corresponds to a current density of 600 meA/cm^2 at the plasma electrode. To our knowledge, this is a record for ECR ion sources. An emittance diagram measured with the same extraction system configuration and the "pepper-pot" method[48] is shown in Fig. 3(b). The RMS emittance for 450 meA beam is 0.07 pi-mm-mrad.

The dependence of the total extracted beam current on the extraction voltage is shown in Fig. 4. The current increases linearly with the voltage, which enables further improvement with higher voltage, thus enhancing the neutron yield as discussed later.

The D+/D2+ species fraction of the ion beam is shown in Fig. 5. The ratio of molecular D_2^+ ions is less than 6% of the total current, which according to our knowledge surpasses the best results achieved ion sources of any type. Lower ratio of molecular ions in the beam increases the neutron yield of the target at the same level of thermal load.

Plasma flux density at the mirror of the trap excess 5 eA/cm^2, while the total plasma flux across the chamber dimension was estimated to be approximately 50 eA. The radial distribution of the plasma density is shown in Fig. 6. It

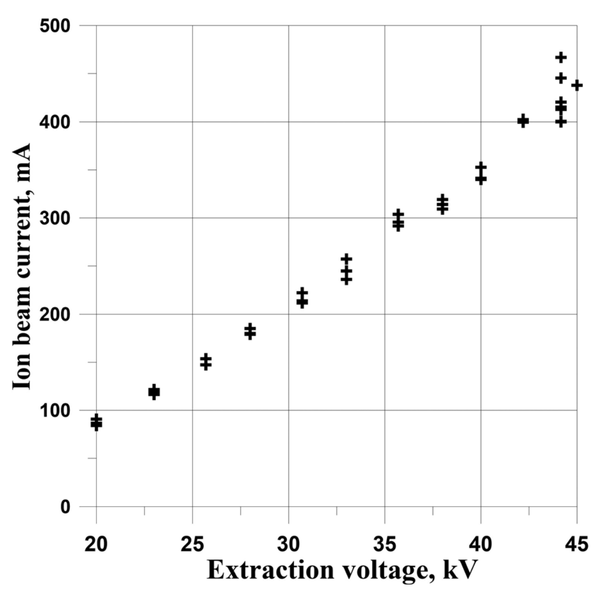

FIG. 4. Ion beam current versus extraction voltage.

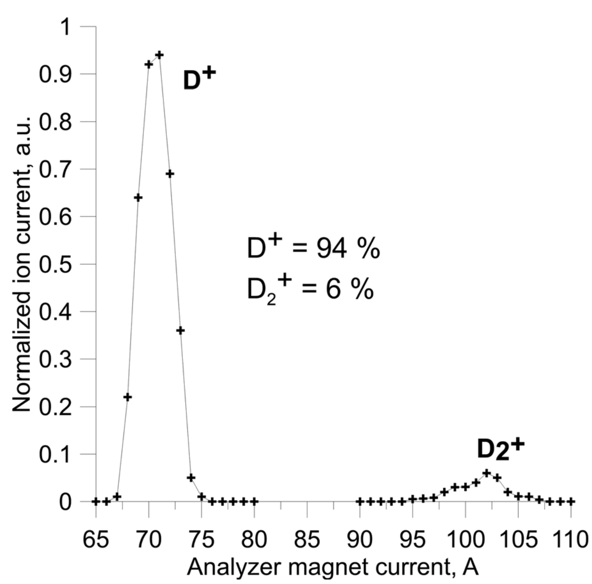

FIG. 5. Ion spectrum of the extracted beam normalized to the total deuterium beam current.

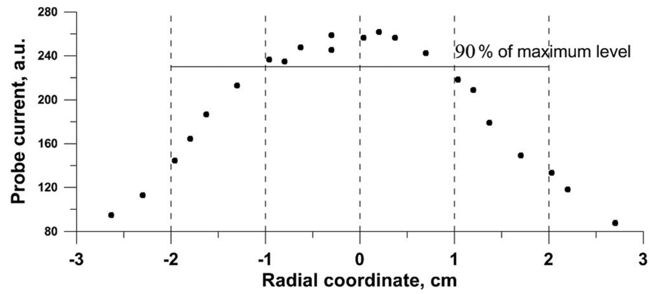

FIG. 6. Radial distribution of the plasma density in 10 cm behind the magnetic mirror.

is rather uniform near the source axis, i.e., >90% of the maximum across d = 2 cm and slowly decreases towards the boundaries. This would allow one to use a multi-aperture extraction system if necessary to increase the total beam current. The possibility of multi-aperture extraction was previously demonstrated in Ref. 49.

NEUTRON PRODUCTION

Two types of neutron-generating targets were used in experiments: D_2O target made of "heavy ice" and conventional titanium deuteride target on a tungsten substrate. The D_2O target was created by heavy water vapor being frozen on a copper plate cooled by liquid nitrogen flow, directly in the vacuum vessel. The content of D_2O in the vapor was approximately 80% the rest being regular water. The target is shown in Fig. 7.

The titanium deuteride target used in the experiments was a tungsten plate covered with thin titanium layer saturated with D_2. The target (after D+ bombardment; the beam spot can be seen) and a secondary ion mass spectroscopy (SIMS) analysis result of the surface composition are shown in Fig. 8. Deuterons with 45 keV energy penetrate the target to a depth less than 1 μm. This surface layer is highly susceptible to factors reducing the content of D_2 (oxidation mainly), and thus it is important to know the exact content of D_2 in the target for further neutron production efficiency analysis and scaling towards higher ion beam currents and energies. The SIMS analysis shows the relative abundances of deuterium and oxygen on the target surface (tungsten and titanium signals were used as a reference signals for depth calibration, as the 10 μm thickness of titanium layer is well-known). It can be seen from Fig. 8 that there is a thin oxidised layer on the surface of the target with reduced content of deuterium, which decreases the efficiency of the target.

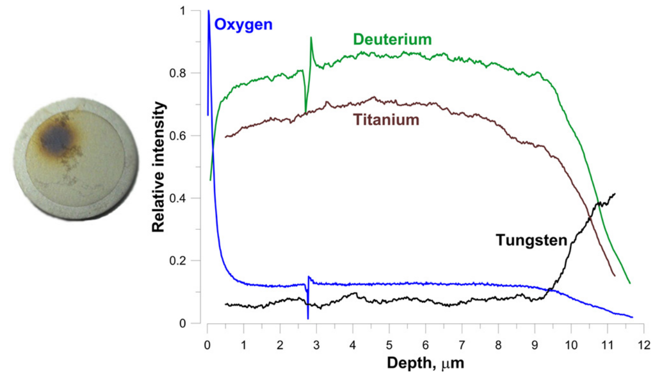

FIG. 8. TiD_2 target with 2 cm diameter and the result of its SIMS analysis.

The neutron detection system consisted of two proportional neutron counters filled with ^{3}He. The counters had different amplitude spectra, which were used as verification that signals were generated by neutrons, not plasma X-Rays or electric noise. The counters were surrounded by two vessels filled with water, acting as neutron moderators (thermalizers) for enhancing the detection sensitivity. This method is very effective as the capture cross-section of ^{3}He is several orders of magnitude higher for thermal neutrons than for 2.5 Mev neutrons.[50] The absolute system sensitivity was pre-calibrated with a ^{252}Cf reference neutron source positioned at the place of the target and using the same water moderators. The reference source had a neutron yield of 1200 n/s with the average energy of 2.12 Mev, which is close to D-D fusion. The overall system sensitivity was approximately 5%, i.e., one out of 20 neutrons incident on ^{3}He was detected.

Measurement of the produced neutron flux was performed by bombarding the target with 300 meA D^+ beam accelerated to 45 keV energy. An example of neutron counter signal is presented in Fig. 9(a) and the corresponding amplitude spectrum (collected over 100 pulses) in Fig. 9(b). The amplitude spectrum of the acquired signals matches the reference one, proving that the signals are generated by neutrons, not X-rays or electrical noise. The D_2O target yield was 10^9 n/s, whereas the titanium deuteride target yield was 6×10^8 n/s. Lower yield in the case of the metallic target is explained by the fact that the surface of the target had been contaminated with oxygen, which was confirmed by the SIMS analysis (see Fig. 8). It is worth noting that the area of the target was about 1 cm^2, which corresponds to a neutron flux density of about 10^9 cm^{-2} s^{-1} at the target.

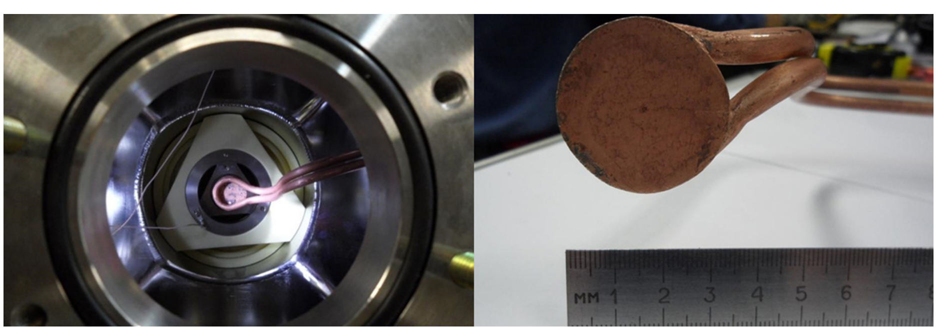

FIG. 7. Copper plate with nitrogen cooling for D_2O target.

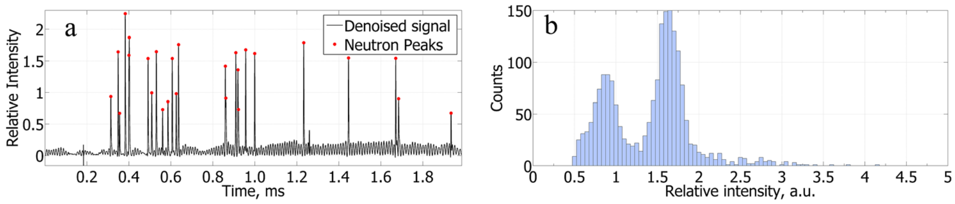

FIG. 9. (a) Single pulse waveform from neutron counters. Each peak corresponds to a single detected neutron. (b) Amplitude spectrum of the neutron signals collected over 100 pulses. Two peaks on the spectrum correspond to different counters.

PROSPECTS OF A NEUTRON GENERATOR BASED ON HIGH-CURRENT ECR ION SOURCE

Finally, we discuss the prospects of D-D neutron generator development using deuterium ion source based on quasi-gasdynamic ECR discharge, sustained by powerful gyrotron radiation.

First, we note again that a single aperture extraction system with voltages up to 45 kV was used in the experiments. Such configuration does not allow realizing the full potential of the ion source—the extraction system was moved 12 cm downstream from the magnetic mirror point to reduce the plasma flux density down to the level matching the optics of the 45 kV extraction voltage (as a maximum). The D-D reaction cross-section increases with the energy up to 1 Mev (Ref. 20), and hence the neutron yield could be enhanced by increasing the beam energy. However, increasing the extraction voltage above 100 kV is apparently impractical as it would lead to a significant increase of complexity, including high-voltage platforms, dry air, etc., which would make the generator difficult to use in real-world conditions and increase the cost significantly. Cross-section of D-D reaction for 45 kV is about 5×10^{-3} barns and for 100 kV is 2.5×10^{-2} barns. Therefore, the authors find it desirable to increase the extraction voltage to the level of 100 kV together with employing a multi-aperture extraction system. These modifications would greatly increase the total beam current as demonstrated in Ref. 42. It had not been done in described experiments because power supply technology capable of handling 1 A/100 kV is challenging on its own, and therefore these proof of principle experiments were performed with a more conservative choice of 45 kV.

Metallic targets made of substrate covered with titanium deuteride are widely used in neutron generators. Commercially available targets of that type are capable of generating up to $10^8\,s^{-1}$ neutrons per 1 meA of deuterium beam bombarding the target with 100 keV energy. In case of target bombardment with the beam current demonstrated (current density from 500 to 700 mA/cm^2) in the present work and accelerated up to 100 keV energy, the neutron flux density could reach the level of $6 \times 10^{10}\,s^{-1}\,cm^{-2}$.

The described experiments were performed in pulsed mode. Many applications, however, require continuous (CW) flux of neutrons. Therefore, we discuss the parameters of a CW D-D neutron generator using deuterium ion source based on CW ECR discharge, sustained by a 24–28 GHz/several tens of kW gyrotron. The plasma density in an ECR discharge, sustained by 28 GHz radiation, can reach values close to $10^{13}\,cm^{-3}$. The transverse size of the discharge is determined by the magnetic trap size and plasma energy losses. Estimates based on previously developed models[51] show that the plasma flux density in 15 kW 28 GHz CW discharge could reach the value of 1 eA/cm^2 with a total flux up to 100 eA. Combined with 100 kV extraction voltage, the estimated ion beam current would be enough to produce high neutron yield across a total cross-section of 100 cm^2. However, such scheme would require development of a specialized target capable of dissipating the total thermal load of 100 kW. This task is challenging, yet technically feasible.

One of the most interesting and important applications of high yield neutron generators discussed above is boron-neutron capture therapy (BNCT) of oncologic diseases.[52–55] The main problem hindering the development of BNCT is the necessity of neutron fluxes over $10^9\,s^{-1}\,cm^{-2}$. The only machines able to produce the required neutron flux are nuclear reactors and large-scale accelerators plagued by tremendous price and strict safety rules for protecting the staff and patients. The D-D neutron generator scheme discussed here is free of those shortcomings as it does not use radioactive isotopes including tritium and/or high energy particles, thus not requiring heavy X-Ray shielding. Moreover, the device has a compact size allowing it to be installed in literally any existing clinic and has significantly lower price in comparison to the aforementioned technologies. In summary, a neutron generator based on high-current quasi-gasdynamic ECR ion (deuterium) source with plasma heating by powerful gyrotron radiation would fulfill all requirements of BNCT.

Another application of neutron generators is related to security systems based on neutron scanning. Unlike X-Ray scanners, neutron-based systems are capable of detecting light elements,[56,57] which is of great importance while searching for explosives and/or drugs. Detection of contraband substances is based on the analysis of characteristic nuclear gamma-ray emission stimulated by the irradiation of the screened object by fast neutrons. Such systems are of interest for use in contactless inspection of suspicious objects in public locations, luggage, and cargo scans at transportation hubs, to counter terrorism, at customs processing of cargo containers to prevent smuggling of prohibited goods. The use of neutron irradiation screening is emerging worldwide, and modern analysis methods have been already developed, i.e., so-called method of marked neutrons[58] designed at JINR (Dubna, Russia). However, even the state-of-the-art neutron scanning systems use low-yield generators (neutron flux up to 10^8 n/s). The use of generators with higher yield would significantly shorten the scanning time and increase the resolution. This would be important for the inspection of large scale cargo containers, as it takes up to 1 h to perform the scan with the current systems with mass detection threshold above 5 kg. Both parameters (scanning time and resolution) must be greatly improved for wide and effective use of the technology, which can be achieved through the development of high-yield and compact neutron generator.

Last but not least, another application of high density neutron fluxes is neutronography,[59,60] one of the most important achievements of nuclear physics over the past decades. It provides great opportunities in micro-analysis of not only physical but also chemical and biological entities. Structural neutronography is a well-developed and widely used method of crystal structure analysis. The emergence in recent years of high neutron flux nuclear reactors, computer-controlled automatic neutron diffractometers, and specialized data processing software have greatly expanded the possibilities of structural neutronography and have led to a sharp increase of interest in it by physicists, chemists, biologists, metallurgists, etc. The development of a compact high yield neutron generator could facilitate further developments of neutronography methods in laboratory conditions, previously available at nuclear reactors and large-scale accelerator facilities, thus greatly increasing the accessibility of this analysis method. Also pulsed neutron generators with high yield could be very perspective for the such kind of applications.

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