Nuclear Instruments and Methods in Physics Research A 768 (2014) 146–150

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Gyrotron-driven high current ECR ion source for boron-neutron capture therapy neutron generator

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ARTICLE INFO

Article history:
Received 1 August 2014
Accepted 20 September 2014
Available online 30 September 2014

Keywords:
Neutron generator
High current ECR ion source
Boron neutron capture therapy
Ion beam formation

ABSTRACT

Boron-neutron capture therapy (BNCT) is a perspective treatment method for radiation resistant tumors. Unfortunately its development is strongly held back by a several physical and medical problems. Neutron sources for BNCT currently are limited to nuclear reactors and accelerators. For wide spread of BNCT investigations more compact and cheap neutron source would be much more preferable.

In present paper an approach for compact D–D neutron generator creation based on a high current ECR ion source is suggested.

Results on dense proton beams production are presented. A possibility of ion beams formation with current density up to 600 mA/cm^2 is demonstrated. Estimations based on obtained experimental results show that neutron target bombarded by such deuteron beams would theoretically yield a neutron flux density up to $6 \cdot 10^{10}$ cm^{-2}/s.

Thus, neutron generator based on a high-current deuteron ECR source with a powerful plasma heating by gyrotron radiation could fulfill the BNCT requirements significantly lower price, smaller size and ease of operation in comparison with existing reactors and accelerators.

1. Introduction

Radiation therapy is one of the main treatment methods of malignant neoplasms, necessary for at least 65–70% of cancer patients. Despite impressive progress in radiotherapy techniques and equipment development, which allow irradiating the tumor without damaging the surrounding normal tissue, there exists a group of tumors which are resistant to standard radiation types. A possible solution for this problem is boron neutron capture therapy (BNCT) [1–4]—one of the most promising options for radiation therapy nowadays.

The BNCT principle is the following. Stable boron isotope ^{10}B is injected into a patient and delivered to the cancer cells. There are several methods for selective delivery providing substantially (up to four times) higher content of ^{10}B in cancer cells compared with healthy ones. They include direct administering of ^{10}B to a tumor feeding vessel; conjugation of the isotope with antibodies specific for that neoplasm or with carriers selectively accumulated in the tumor tissue, and some others [3,5–8]. The patient is subsequently irradiated with a flux of epithermal neutrons (energy range within 0.5 eV < En < 30 keV). As a result of neutron capture by ^{10}B (cross-section of the process is about 3000 times higher for ^{10}B than for ^{12}C, ^{14}N, ^{16}O, H which form the basis of living tissue) and the following decay, energetic α-particle, ^{7}Li$^+$ ion and in 94% of cases γ-photon are generated. The new-born heavy particles are decelerated rapidly and release an energy of 2.3 MeV within a length of 10 μm, i.e. the cell size. Such energetic heavy particles cause DNA double-strand breaks in the nearest cancer cells with a high probability and prevent further cell division. Thus, boron neutron capture therapy could solve the problem posed by radiation resistant tumors.

BNCT advantages have been clearly demonstrated in test treatments of the most malignant and aggressive running brain tumor—multiform glioblastoma and melanoma metastasis, which are one of the most radiation resistant tumor types. Over the past ten years more than 1000 patients have been treated with BNCT.

All of the treatments were performed using neutron fluxes generated by powerful experimental nuclear reactors [9–15], which are currently the only devices capable of producing the desired thermal neutron flux density of 2–3 × 10^9 n/(cm^2 s) for effective therapy with appropriate collimation and therapeutic aperture size (~100 cm^2). Low availability and high cost (capital

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http://dx.doi.org/10.1016/j.nima.2014.09.058
0168-9002/

and operational) of nuclear reactors hinders further progress of BNCT severely. Thus, development of specialized neutron sources seems actual and necessary.

Specialized accelerators with the beam energy in the range of a few to several hundred MeV [16–19], which are able to produce neutron fluxes required for BNCT have been developed successfully. However, much more compact, technologically simpler, easier-to-operate and less expensive source of epithermal neutrons is required for wide spreading of BNCT to real clinics.

One of the ways to create a source fulfilling BNCT requirements could be a compact device, utilizing a nuclear reaction between two deuterium nuclei (D–D neutron generator), which could produce sufficient neutron output at comparably low particle energy (tens of keV). The nuclear reaction with 50% probability generates the ^{3}He isotope and neutron with energy of 2.5 MeV. Existing D–D neutron generators consist of deuterium ion (deuteron) source with extracted beam energy of 100–200 keV and deuterium saturated neutron production target. The deuteron beam is directed towards the target, provoking the nuclear reaction and neutron emission. However, state-of-the-art D–D generators based on conventional ion sources deliver only 1–10 mA/cm^2 deuteron current density to the target and do not provide necessary neutron flux density for BNCT (delivered flux is typically below 10^8 n/cm^2/s). Furthermore, the neutron flux resulting from the D–D reaction must be thermalized from 2.5 MeV to epithermal level and collimated for the medical application. Consequently the generated neutron flux would be additionally attenuated by one order of magnitude due to losses at these stages. Therefore, existing D–D neutron sources cannot meet the BNCT requirements.

Increasing the current density of deuterium ion beams bombarding the target is one of the obvious ways to amplify the neutron yield in D–D generators. Higher current density can be accomplished by increasing the plasma density inside the magnetic trap of the ion source. A new type of high current ion source based on a dense plasma supported by millimeter wave radiation (with frequency up to 100 GHz) of high power gyrotrons under the electron cyclotron resonance condition in open magnetic trap was suggested in [20,21]. Plasma with unique parameters can be generated in such devices (density above 10^{14} cm^{-3}, several tens of eV electron temperature) due to the high frequency of microwave radiation. As a result the plasma flux density from such a source reaches record values for ECRIS (up to 10 A/cm^2) [21]. A possibility to apply the described high current ECR ion source as the driver of a compact D–D neutron generator for BNCT is discussed in the present paper.

2. Experimental setup

The experimental research presented in this work was carried out on the SMIS 37 shown schematically in Fig. 1 [22]. A gyrotron generating a Gaussian beam of linearly polarized radiation at the frequency of 37.5 GHz, with the power up to 100 kW, and pulse duration up to 1.5 ms was used as a source of pulsed microwave radiation. The microwave radiation is launched into the plasma chamber through a quasi-optical system consisting of 2 mirrors, quartz vacuum window and a special μW-to-plasma coupling system shown on the left in Fig. 1. The facility has been designed for efficient transport of the plasma heating microwave radiation and, at the same time, avoiding parasitic resonances and plasma flux impinging the quartz window. A simple mirror trap was used for plasma confinement. The magnetic field in the trap was produced by means of pulsed solenoids, spaced 15 cm apart. The current pulse with the shape close to half period of a sinusoid had the duration of 11 ms with the magnetic field variation during the microwave pulse being less than 3%. Magnetic field in the mirror was varied from 1.4 to 4 T (ECR for 37.5 GHz is 1.34 T). Ratio of the maximum and minimum magnetic fields of the trap was equal to 5 (i.e. Bmax/Bmin). Hydrogen was used as a working gas to reduce experimental expenses. Difference between hydrogen and deuterium is negligible in terms of ionization processes in plasmas and optimal extraction voltage is only 25% higher for heavier gas. The hydrogen inlet into the source was realized through an opening incorporated with the microwave coupling system. The delay between hydrogen injection and subsequent microwave pulse (300–3000 μs) as well as the gas pulse duration (about 5 ms) were adjusted for each experimental condition in order to maximize the beam current and optimize the temporal shape of the extracted current pulse.

The ion extraction and beam formation were realized by two-electrode, i.e. single gap plasma electrode—puller electrode system. Holes in plasma electrode and puller were 10 mm and 22 mm respectively. Both electrodes are shown in Fig. 2. The plasma electrode was placed 10 cm downstream from the magnetic mirror to limit the extracted ion flux as described in [23], which helps improving the beam transport through the puller.

The maximum available extraction voltage was 45 kV. A Faraday cup was placed immediately behind the puller electrode to measure the total beam current passing through the extractor. A conventional bending magnet analyzer (placed 1 m from the extraction) and another Faraday cup located at the end of the beam line (1 m downstream from the magnet) were used for studying the species

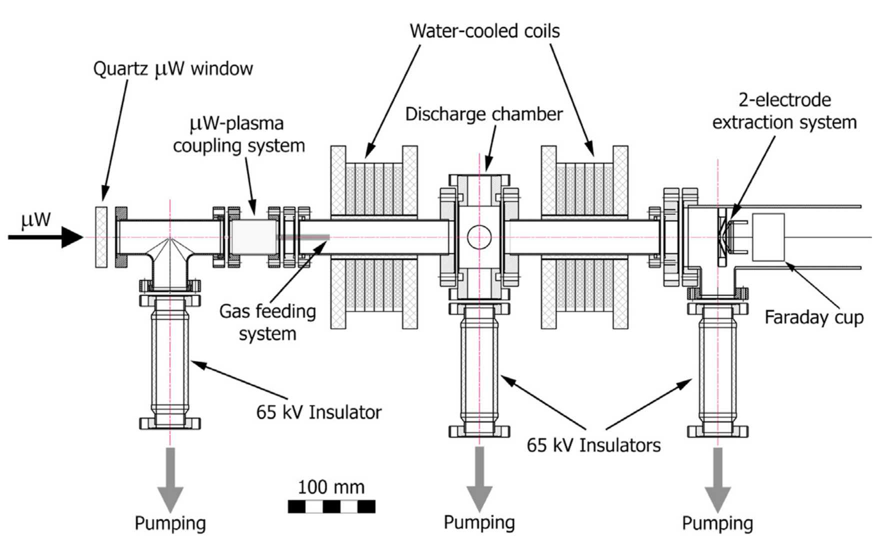

Fig. 1. SMIS 37 experimental setup.