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Design and testing of an internal hot-cathode-type PIG ion source for superconducting cyclotron

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Abstract The superconducting cyclotron SC200 is intended to generate a 200 MeV, 400 nA proton beam for future particle therapy. The internal hot-cathode-type Penning ionization gauge (PIG) ion source for the SC200 is designed for the generation of hydrogen ions. A brief description of the design of ion source and test bench, which are used in SC200, is given in this paper. The ion source has been verified on the test bench, and the results indicated that the designed ion source meets the expected requirements. The lifetime of the filament exceeded 100 h in the test. In addition, the extraction voltage and the gas flow that influence the extracted ion current intensity have been tested in the experiment.

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1 Introduction

Proton therapy is a very promising treatment for cancer, compared with conventional therapies such as radiotherapy and chemotherapy. By the end of 2016, approximately 175,000 patients had been treated worldwide with particle radiotherapy, and close to 150,000 with protons. Approximately, 20,000 patients had been treated in 2016, nearly 10% of them being under the age of 20. A proton therapy facility is composed of a proton accelerator, an energy selection system, a beam transport system, a rotation gantry, a nozzle, a treatment couch, etc. The ion source is a key part of the proton accelerator. There are many types of ion sources. PIG ion sources are some of the best known ion sources and have been widely used with great success for the production of both heavy and light ions [1]. Ehlers et al. have designed a floating cathode PIG source for the Berkeley 88-inch isochronous cyclotron. The filament is cut from a 0.15-inch tantalum sheet. The ion exit slit is 1/2 inch in length and 1/32 inch in width [2]. The floating cathode PIG ion source for the IBA CYCLONE®230 cyclotron uses a tantalum filament, which needs to be replaced typically every 5–7 d [3]. Actually, the operating time of filament does not exceed 5 d.

The superconducting proton cyclotron SC200 is designed to contribute to proton therapy under the collaboration of the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) and the Joint Institute for Nuclear Research (JINR) [4]. The magnetic induction in the central region is 2.9 T, and the radio frequency (RF) electric potential applied on Dees is approximately 60 kV [5]. The hot cathode PIG internal ion source is applied in SC200 to produce protons that will be accelerated by RF system.

Filament lifetime is an important factor affecting the performance of the ion source. Improving filament lifetime and working stability is an important part of the design and development of the ion source. Although the Penning ion source has been developed for many years, its compact structure and working life have always been the focus of research as the internal source of cyclotron for proton therapy. In the paper, the PIG ion source designed for SC200 has an excellent working stability and the filament lifetime is longer than 100 h as per experimental verification. Several aspects are discussed in the paper, as follows: (1) the design of the ion source and the test bench, (2) the theoretical simulation and (3) the results of the experiment.

2 Design of ion source structure

On the basis of theory of Penning discharge [6, 7], the basic structure of the SC200 internal ion source consists of the following three parts: a cathode filament, an anti-cathode and an arc chamber with an extraction slit, as shown in Fig. 1.

The filament releases thermoelectrons when being heated to a certain temperature. The initial electrons do not have enough energy to ionize hydrogen. Electrons need to be accelerated by the electric field between the filament and the arc chamber. The electrons are also trapped in the arc chamber by an axial magnetic field [8, 9]. Electrons move back and forth in the discharge region under the effect of the electromagnetic field, colliding with hydrogen molecules. As a result, a plasma formation is obtained. Tantalum is selected for the filament owing its high heating temperature and excellent electron release performance. The size of the ion source is limited by the structure of the central region of the SC200 accelerator. The primary parameters of the ion source are listed in Table 1. In addition, the shape and size of the ion source slit play a decisive role in the performance of the extracted beam, which will be simulated in the next section.

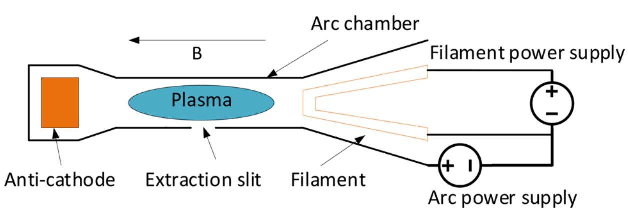

Fig. 1 Schematic of the SC200 internal ion source

Table 1 Main parameters of the ion source

Parameters	Value
Cathode material	Tantalum
Anti-cathode material	Tungsten
Arc chamber material	Molybdenum
Inner diameter of arc chamber (mm)	5
Outer diameter of arc chamber (mm)	7
Plasma region length (mm)	58
Extracted beam intensity (μA)	> 50

3 Simulation in the PIG ion source

Plasma generation requires the collision of electrons with hydrogen. Whether electrons can be effectively confined in an electromagnetic field is the primary factor in the operation of an ion source. In order to examine the electron constraint efficiency in the arc chamber, a simulation has been carried out under the calculated electromagnetic field distributions. The magnetic field in the ion source has been obtained with a CST magnetostatic solver. The direction of the axial magnetic field of the accelerator is the same as the direction of the z-axis as shown in Fig. 2. The electrostatic field distribution in the PIG ion source has been obtained with the CST electrostatic solver. The mesh is set to hexahedral, and the number of hexahedra is approximately thirty million. The mesh is refined in the area around the slit to ensure the reliability of the simulation results and minimize the amount of calculation. The arc chamber potential was set to 160 V, and the potential distribution is shown in Fig. 2a. The initial electrons uniformly distribute

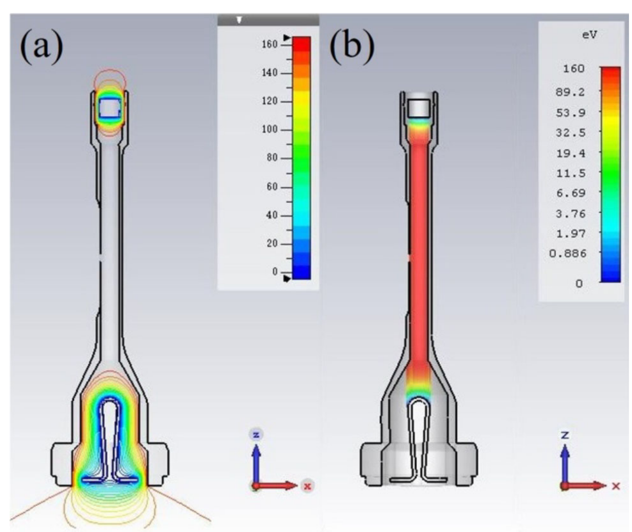

Fig. 2 (Color online) Simulation results of the distribution of potential (**a**) and electrons energy (**b**)

on the surface of the top part of the filament, and the number of electrons is ~ 5000. The trajectories of the electrons are shown in Fig. 2b. Moreover, the emission of secondary electrons is an important parameter in determining the behavior and the efficiency of plasma generation [10]. CST utilizes a secondary electron emission model based on the empirical formula of Vaughan [11]. According to the material parameter definition in CST, secondary electrons are only produced on the undersurface of the anti-cathode. The arc voltage ranges from 100 to 1000 V, and the magnetic field is 0.1, 1 and 3 T. The simulation result for the number of remaining electrons is shown in Fig. 3. Approximately, 37% of electrons can be confined in the designed electromagnetic field after 30 ns while considering secondary electrons. The electron beam from the cathode surface is well confined in the arc chamber and has enough energy to ionize the hydrogen gas. Figure 4 shows the number of secondary electrons for various arc voltages and magnetic field levels. Electrons have already been well constrained with the 1-T magnetic field, which is shown in Fig. 4.

Some simulation results on beam trajectory for various shapes and sizes of the slit are shown in Fig. 5. The first drawing in Fig. 5 shows the cross section of the arc chamber. In the diagram, s represents the width of the ion source slit, d represents the thickness of the slit, and θ represents the chamfer angle of the slit. In the simulation, the extraction voltage is 8 kV and the distance between the electrode and the source is 2 mm. The magnetic field level is 1 T, which is consistent with the magnetic field of the test bench. The extracted beam will diverge more as the extraction slit width gets larger. In addition, as the chamfer angle increases, the beam can be extracted more readily, but its divergence increases. The position of the extraction electrode and the extraction voltage also needs to be adjusted to reduce the loss of the beam on the extraction electrode [12].

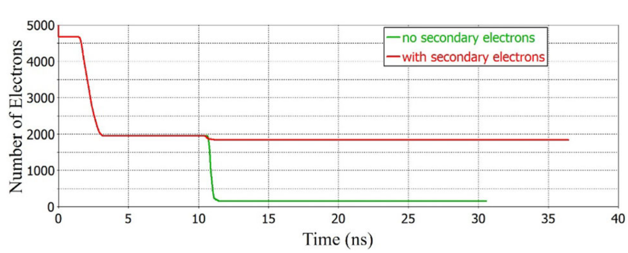

Fig. 3 (Color online) Simulation results of the remaining quantity of electrons

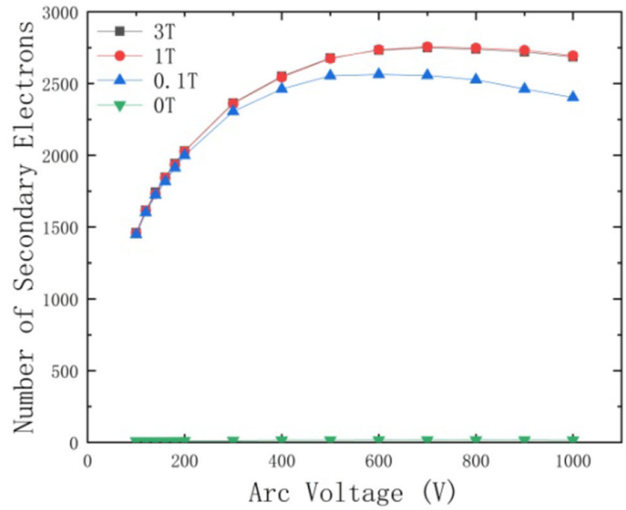

Fig. 4 Number of secondary electrons in the magnetic field versus voltage applied to the arc chamber

4 Ion source test bench

To verify whether the designed ion source can work properly in the cyclotron, a test bench was built in 2017, which can provide all the conditions required for the operation of the ion source. The test bench is composed of a vacuum system, a power system, a water-cooling system, a gas injection system and a magnet system, as presented in Fig. 6 [4]. The magnet system can generate a 0.5–1-T tunable axial magnet field in the vacuum chamber. The ion source was inserted into the vacuum cavity along the magnetic field direction. The beam extraction electrode was fixed outside the ion source by ceramic insulation, and the gap between the electrode and the ion source is kept at approximately 2 mm. The extraction electrode slit size is 4.3 mm × 1 mm with a 1-mm thickness.

5 Experimental test and discussion

Like most of SC200 components, the method and effect of design and implementation need to be verified by experiments [13, 14]. Based on the results of the simulation analysis, the shape of the ion source slit shown in Fig. 5e was selected for testing. The source slit was designed to be 0.5 × 2 mm^2 with a thickness of 0.1 mm. The extraction beam intensity was measured under various experimental conditions, such as extraction voltage and gas flow. The beam extraction experiments were carried out with low dc voltage up to 11 kV, and the adjustment range of gas flow was 1–4 sccm.

The measured results of the extracted beam intensity under various extraction voltages are shown in Fig. 7. The

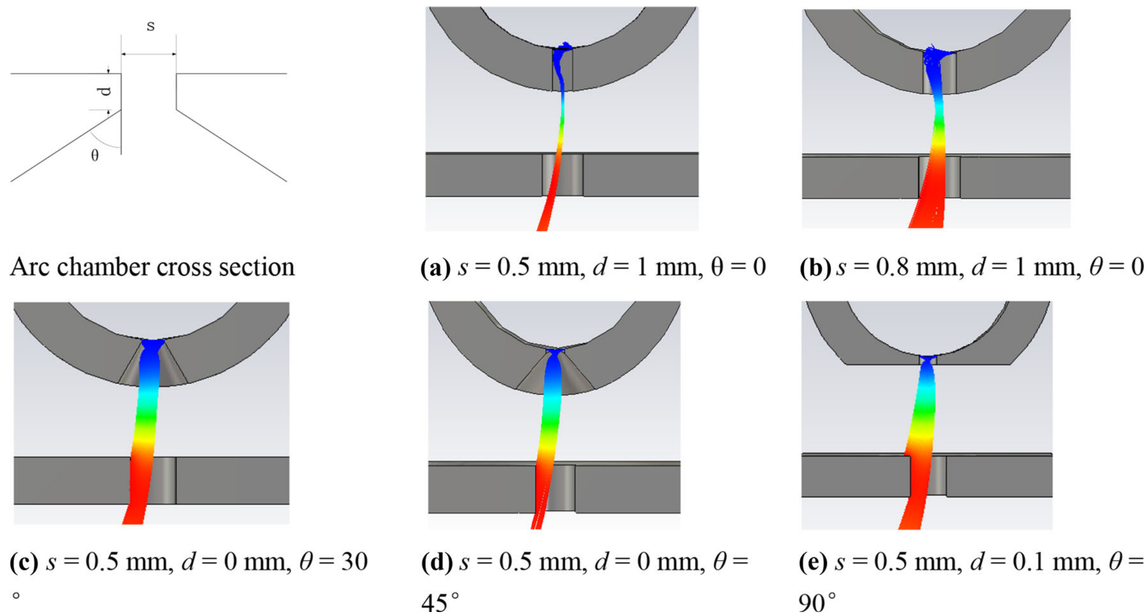

Fig. 5 (Color online) Beam trajectory under various shapes and sizes of the slit

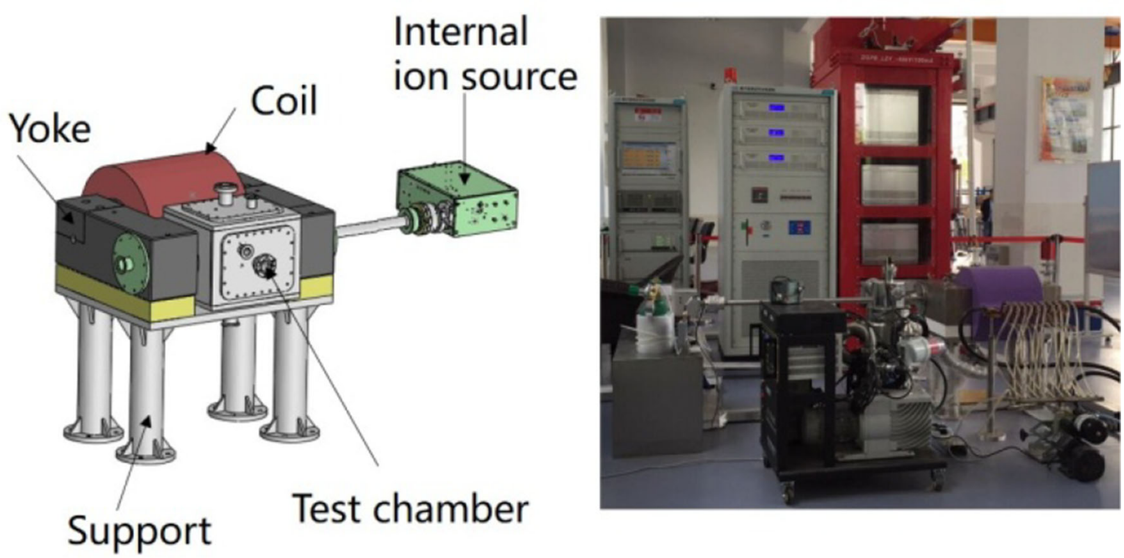

Fig. 6 (Color online) Ion source test bench

other general conditions were: gas flow 2 sccm, magnetic field 1 T, filament current 170 A and arc voltage 160 V.

The extracted beam intensity at various gas flow rates was measured under a magnetic field of 1 T, a filament current of 170 A, an arc voltage of 160 V and an extracted voltage of 6 kV. The results are shown in Fig. 8.

The extracted beam intensity is optimum at 2 sccm. Moreover, an excessive amount of intake gas will increase the risks of spark between the electrodes and waste the working gas. According to the design requirements, a 1–3-sccm hydrogen flow is enough for the SC200 ion source working condition.

A long pulse discharge test was performed to verify the stability of the designed ion source. Figure 9 shows the values of the five parameters measured in the experiment. From top to bottom, the five parameters are the coil current, the filament current, the arc voltage, the arc current and the extraction beam current. Figure 9 shows that the discharge is extremely stable for 1 h and the beam extraction for 0.5 h. And the beam extraction strength exceeds the design requirement of 50 μA. According to the experimental test results, the thickness of the main electron emission area of the filament is slightly reduced after more than 100 h of

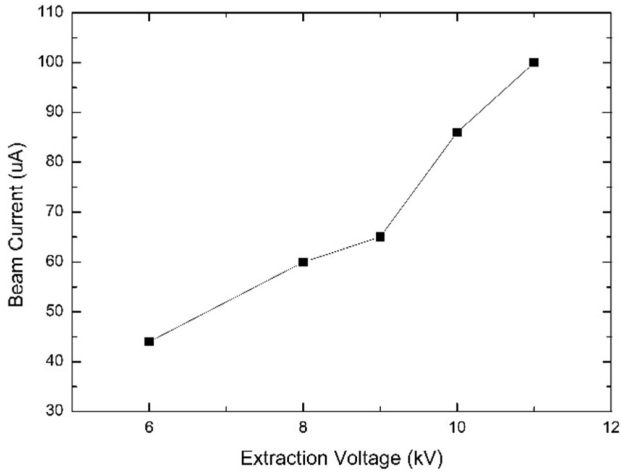

Fig. 7 Results of beam extraction experiments: beam current versus dc extraction voltage

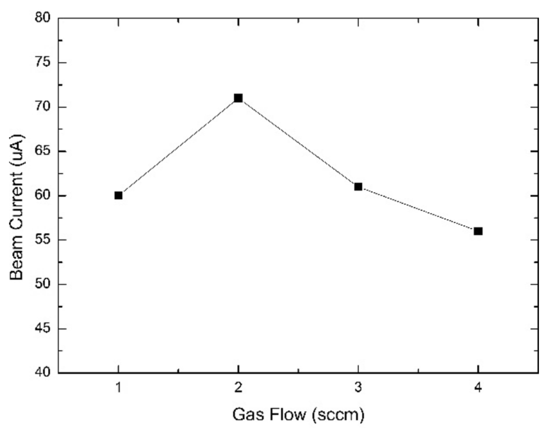

Fig. 8 Extracted beam intensity measured as a function of gas flow

cumulative operation, but the continued use of the filament is not affected.

During the arc discharge test, it was found that the cathode material evaporates into a layer of black matter on the arc chamber after a prolonged operation under large filament current, as shown in Fig. 10, resulting in a short circuit between the arc chamber and the filament. 97% of the black substance was identified as cathode material. Because tantalum is a metal that is easily oxidized, it will indeed be oxidized if the vacuum situation gets worse. This shows that during the operation of the ion source, it is necessary to maintain a certain degree of vacuum and periodically cleans the arc inner wall to ensure the normal operation of the ion source.

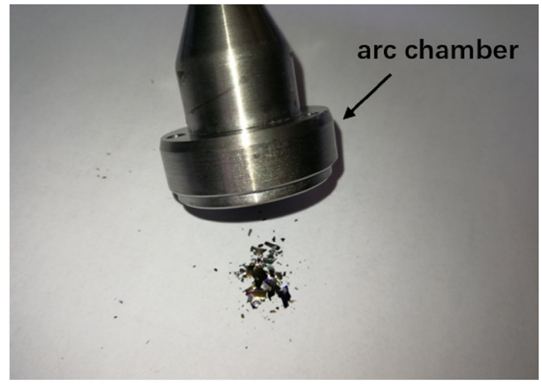

Fig. 10 Black substance

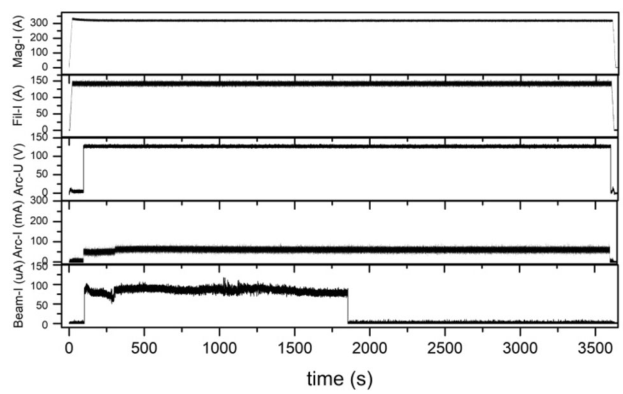

Fig. 9 Waveform of an ion source discharge

6 Conclusion

The basic structures of the designed PIG ion source and the proposed test bench have been introduced. The results of computer simulation and measurements on the test bench confirm that the performance of the ion source for SC200 could meet the design requirements. The extracted beam intensity is greater than 50 μA, and the operating lifetime of the cathode is longer than 100 h. In the near future, the hot-cathode-type PIG ion source will be assembled in the SC200 cyclotron for beam extraction with RF and superconducting magnet systems.

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