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# DESIGN AND ANALYSIS OF THE COLD CATHODE ION SOURCE FOR 200 MeV SUPERCONDUCTING CYCLOTRON

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*Abstract*

SC200 is a superconducting isochronous cyclotron which generates 200 MeV, 400 nA proton beam for particle therapy. The cold-cathode-type Penning ion gauge (PIG) ion source for the internal ion source of SC200 has been selected as an alternative and preliminary designed. In this paper, design of ion source and test bench are demonstrated. Currently, the properties of ion source have been simulated for a variety of electric field and magnetic field distributions. The secondary electron emission in electromagnetic field has been simulated. It provides reference for the optimization design of arc chamber. In addition, the sample of cold-cathode-type ion source has been tested on the test bench and extracted beam intensity has been measured over 200 μA.

## INTRODUCTION

Per end of 2017 almost 200000 patients have been treated worldwide with particle radiotherapy, about 170500 with protons, about 25700 with C-ions and about 3500 with He, pions and other particles. Proton therapy is becoming an important means of tumor therapy. More and more research institutions have begun to develop proton therapy equipment. A 200 MeV superconducting proton cyclotron is being planned for building by the institute of plasma, Chinese academy of science (ASIPP), in collaboration with the joint institute for nuclear research (JINR) [1]. At present, the hot cathode ion source has been designed and tested. However, in order to further improve the lifetime of ion source, a cold cathode ion source is proposed to be used as an alternative during the operation of the accelerator. In the paper, the design of cold cathode source and experiment results are described.

## BASIC STRUCTURAL DESIGN OF COLD CATHODE ION SOURCE

The design of the cold cathode source is mostly based on the mechanical structure of the hot cathode source. The basic parameters of the cold cathode ion source are shown in the Table 1 below. The unusual combination of refractory properties with a low work function $\phi$ has led to the development of $LaB_6$ into useful cold cathode ion source. The structure diagram of cold cathode ion source is shown in Fig. 1. The arc chamber is grounded, the cathode and the anti-cathode are copotential, connected to negative high voltage. There is a resistance between the anode and the cathode, which as a voltage divider to protect the arc power supply during arc discharge. The cylindrical cathode is mounted on the cathode base, as shown in Fig. 2.

Table 1: Main Parameters of the Ion Source

| Parameters | Value |
|---|---|
| Cathode material | Lanthanum Hexaboride ($LaB_6$) |
| Arc chamber material | molybdenum |
| Inner diameter of arc chamber | 5 mm |
| Outer diameter of arc chamber | 7 mm |
| Plasma region length | 58 mm |

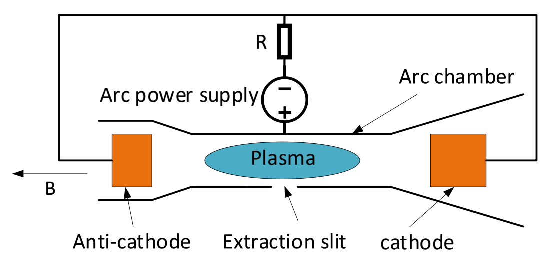


Figure 1: Structure diagram of cold cathode ion source.

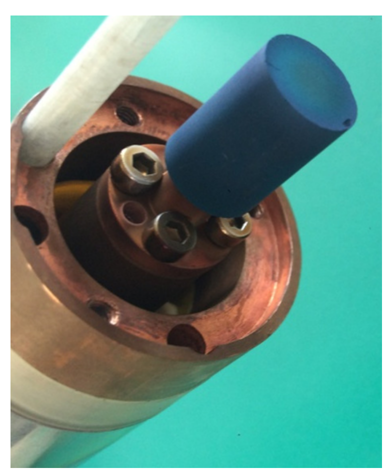

Figure 2: Installation of the cold cathode.

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## SIMULATIONS

Unlike the thermal emission electrons of the hot cathode, the initial electrons of the cold cathode come from the field emission and secondary emission of the cathode material. Due to the Schottky effect, the applied electric field can affect the electron emission current According to the formula of classical mechanics, the relation between the work function $\phi$ and the applied electric field $E$ is

$$\phi = \frac{e\sqrt{eE}}{\sqrt{4\pi\varepsilon_0}} \quad (1)$$

A wide range of values from 2.28 to 2.70 eV has been reported for work function of $LaB_6$. Assuming the work function of lanthanum hexaboride is 2.70 eV, it is calculated from Eq. (1) that the applied electric field needs to reach $5.1\times10^9$ V/m for electrons to be emitted across the potential barrier. But according to the tunneling effect of quantum mechanics, the applied electric field is mainly used to narrow the barrier, so that low-energy electrons have a certain chance to pass through the barrier.

The electric field around cathode has been obtained with the CST-STUDIO-SUITE program. The simulation model is shown in Fig. 3. The distance between the cathode and the discharge region is an adjustable parameter, denoted by *d*. The cathode surface electric field at different voltages and distances is shown in Fig. 4. Considering the surface roughness of the cathode, the actual surface electric field is larger than the simulation results.

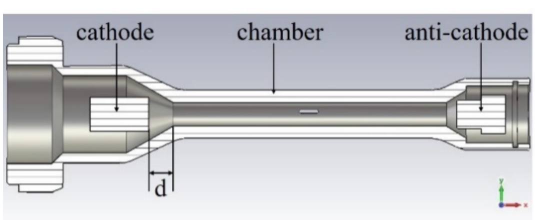


Figure 3: Cold cathode ion source model for simulation.

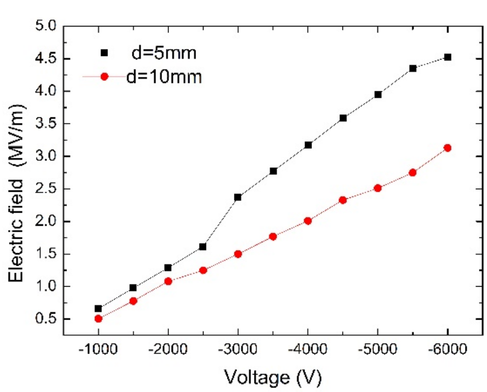


Figure 4: Cathode surface electric field vs. voltage applied to the cathode.

In addition, the results of secondary emission analysis are presented in Fig. 5. The initial number of electrons is set to 1500 and the magnetic field is 1 T. According to the material parameters setting, the secondary electron emission occurs on the internal surface of the arc chamber. Approximately 10% of electrons can be confined in the designed electromagnetic field while considering secondary electrons, as shown in Fig. 5. The electrons confined in the arc chamber are accelerated by an electric field and have enough energy to ionize hydrogen.

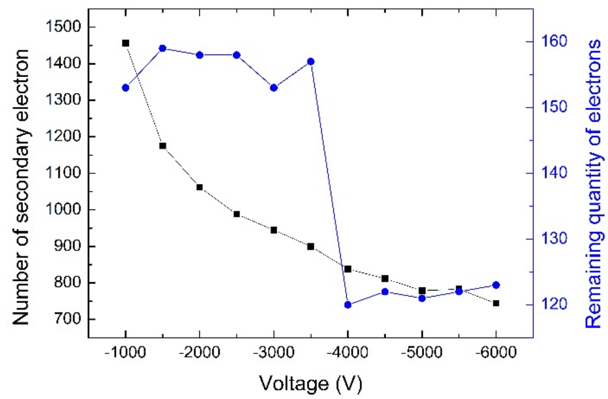


Figure 5: The results of secondary electron simulation.

## EXPERIMENTAL RESULTS AND DISCUSSION

The sample of the cold cathode ion source has been tested on the test bench. In the test, the arc voltage range was 1000 V to 1500 V. The arc current measured under different arc voltage is shown in Fig. 6. When the arc voltage is 1000 V, the oscillation range of arc current is about 5~45 mA. With the increase of arc pressure, the oscillation of arc current gradually becomes stable. When the arc voltage is 1500 V, the arc current is near 80mA with small amplitude and works smoothly.

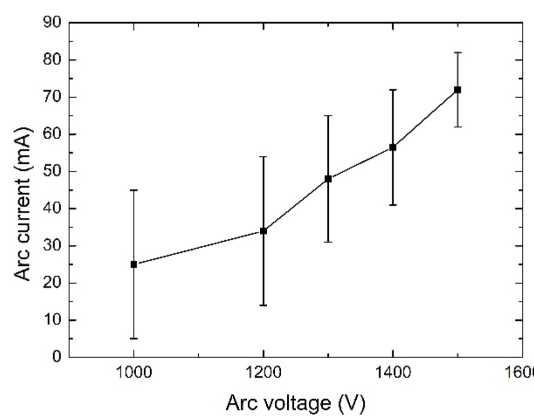


Figure 6: Arc current vs. arc voltage.

The change of arc discharge mode was also observed during the experiment. As shown in Fig. 7, under 1500 V arc voltage, the arc current increases after 60 s arc discharge, and the value changes to about 3-4 times of the previous working state. But when the arc current suddenly increases, the discharge cannot last. When the arc voltage is

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reduced to 1400 V, the increase amplitude of the arc current is reduced, which is about twice as large as before, and the steady working state can be maintained after the arc current increases, as shown in Fig. 8. With the further decrease of arc voltage, the phenomenon of arc current increasing disappeared, and the arc current is relatively stable when discharging. The phenomenon of arc current increasing after the discharge is maintained for a period of time is believed to be caused by the change of arc discharge mode. In the first mode, arc current is relatively low. The cathode is cold and the electron emission is principally field emission and secondary emission. As the ions continue to bombard the cathode, the cathode temperature slowly rises. At some point, thermionic emission of electrons from the cathode becomes greater than the secondary emission and field emission, driving the ion source into a second mode. In this second mode, ion production accelerates and arc current increases.

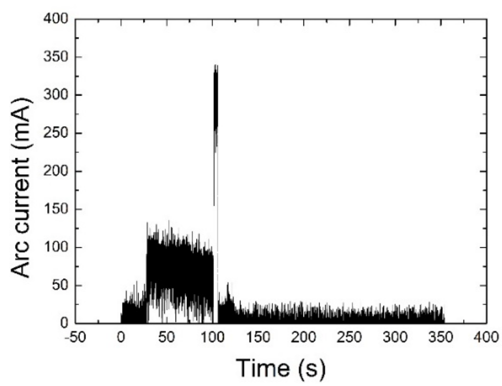

Figure 7: Arc current waveform under 1500V arc voltage.

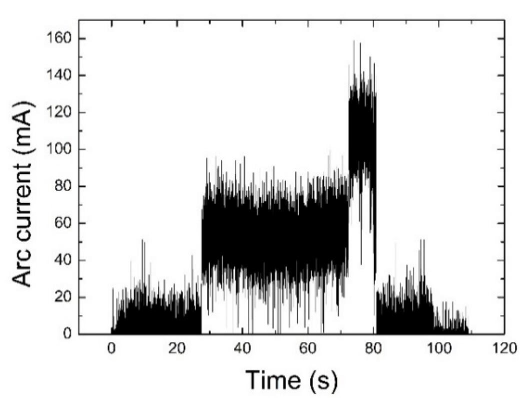

Figure 8: Arc current waveform under 1400V arc voltage.

The measured results of the extracted beam intensity under various arc voltages are shown in Fig. 9. The other general conditions were: gas flow 2 sccm, magnetic field 1 T, and extraction voltage 2 kV. The beam extraction strength exceeds 200 μA when the arc voltage is set to 1500 V.

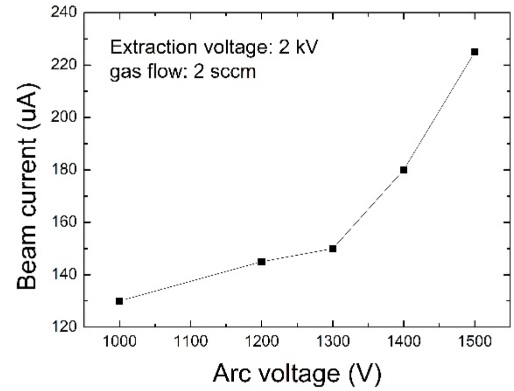

Figure 9: Extracted beam current vs. arc voltage.

## CONCLUSION AND FUTURE WORK

The basic structures of the designed cold cathode ion source has been introduced. The results of computer simulation and measurements on the test bench confirms that the cold cathode ion source for SC200 could produce the plasma needed for the cyclotron. The extracted beam intensity is greater than 200 μA. In the near future, the cold cathode ion source will continue to be optimized and taken lifetime test on the test bench.

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