Study on a cold-cathode H PIG-type ion source Postprint

Authors: LONG Jidong, YANG Zhen, DONG Pan, HE Xiaozhong, ZHANG Kaizhi

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Abstract

A cold-cathode Penning Ion Gauge (PIG) type ion source as the internal ion source of an 11 MeV cyclotron is designed and tested at Institute of Fluid Physics. The design considerations and some testings are presented. Experimental results of Balmer-line-Emission show that the discharge characteristic, which is mainly determined by gas-flow rate, is not very sensitive to arc current and magnetic field in the operation ranges of the cyclotron. The arc power decreases and ascends while the gas-flow rate goes up from 0.5 SCCM to 20 SCCM. By improving the sealing design and reducing the machine tolerance of the source, the minimum power consumption reduces from 9 SCCM to 4 SCCM, thus having better energy efficiency and benefiting for the pumping system. Preliminary DC extractions show that H-microampere current ranges from several tens to hundreds under different operation conditions. Some problems during the experiments and future plan are discussed in the end.

Full Text

Study on a Cold-Cathode H^- PIG-Type Ion Source

Jidong Long, Zhen Yang*, Pan Dong, Xiaozhong He, Kaizhi Zhang
Institute of Fluid Physics, China Academy of Engineering Physics, Mianyang 621900, China

Abstract

A cold-cathode Penning Ion Gauge (PIG) type ion source has been designed and tested at the Institute of Fluid Physics as the internal ion source for an 11 MeV cyclotron. This paper presents the design considerations and experimental results. Balmer-line-emission measurements show that the discharge characteristics, which are primarily determined by gas flow rate, are not highly sensitive

to arc current or magnetic field within the cyclotron' s operational ranges. As the hydrogen flow rate increases from 0.5 SCCM to 20 SCCM, the arc power initially decreases then subsequently increases. By improving the sealing design and reducing machining tolerances, the minimum power consumption was reduced from 9 SCCM to 4 SCCM, resulting in improved energy efficiency and reduced burden on the pumping system.

Preliminary DC extraction experiments demonstrate that H^- currents ranging from several tens to hundreds of microamperes can be obtained under various operating conditions. The paper concludes with a discussion of experimental challenges and future plans.

Keywords: PIG-type ion source, Cyclotron, Balmer-line-emission, H^- current

Introduction

A compact cyclotron currently under construction and testing at the Institute of Fluid Physics (IFP) is designed to accelerate H^- ions to 11 MeV. For the production of short-lived medical isotopes, H^+ beams are generated by stripping two electrons from H^- using a carbon foil. This extraction method offers very high efficiency and compact dimensions. The cyclotron therefore requires an H^- source, and a radially inserted internal source is necessary due to beam dynamics in the central region and the compact design. The PIG-type ion source is an excellent candidate because of its compact size, low cost, long lifetime, minimal contamination of the cyclotron cavity, and proven performance in high magnetic field environments [**?**].

This paper presents preliminary work on the source design and testing performed both on a dedicated test-stand and on the cyclotron itself.

Design Outline of the Source

The source height is less than 53 mm and its width less than 45 mm, as shown in Fig. 1. The cathode and anti-cathode feature a symmetric structure with separate power feeding, allowing the discharge parameters of the two cathodes to be controlled independently. Water cooling is implemented due to the source' s high power consumption.

Fig. 1 Schematic cutaway view of the head of the ion source.

The water channels are embedded within the top and bottom covers, providing a more compact design and better cooling efficiency than externally attached copper pipes. The anode is constructed from copper alloy with a varying inner radius. The extraction slit measures 6 mm × 0.4 mm with a wall thickness of 0.13–0.16 mm.

Two gas feeding configurations were designed. In the first, gas inlets near the extraction slit enhance H^- yield but increase gas loading. In the second, inlets located farthest from the slit require H_2 gas to pass through the hot cathode pole first, pre-warming the gas and reducing gas loading. Comparative experiments between these two approaches have not yet been conducted.

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Corresponding author. E-mail address: yangzh2004@gmail.com

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Experimental Setup

Most testing was conducted on a dedicated test-stand that simulated the cyclotron environment before the cyclotron itself was available. Recently, some experiments have been completed with high-frequency power feeding into the cyclotron cavity.

The test-stand consists primarily of a dipole magnet with a vacuum cavity in its gap. To save cost and time, a refurbished electromagnet provides a maximum magnetic field of 0.7 T, approximately half the field strength inside the actual cyclotron. Since the electron gyro radius in the source is on the micrometer level at fields above 0.1 T—smaller than the source dimensions—the difference in magnetic field magnitude between the test-stand and cyclotron does not significantly affect source discharge characteristics.

Diagnostic measurements of the source emission spectrum and DC voltage ion extraction have been performed on the test-stand, as shown in Fig. 2. During spectroscopic measurements, the slit faces the quartz window directly without the extractor and collector installed inside the cavity.

After cyclotron magnetic field calibration and radio frequency power feeding into the cavity, the installed source was used for beam tuning. The operating magnetic field is 1.2 T, the radio frequency is 72 MHz, and the vacuum level is 10^{-4} Pa. The designed extraction voltage amplitude is 37 kV, though the actual voltage can reach 45 kV.

Fig. 2 Experimental schematic of the ion source on the test-stand.

Experimental Results and Analysis

The H^- source operates in an arc discharge state, which is primarily determined by its structure, electrode materials, and three external conditions: power supply, magnetic field, and H_2 feeding. Studying the effects of these parameters on source discharge characteristics helps in physically understanding and optimizing the source performance.

Effect of Gas Flow on Discharge

Balmer lines Hα, Hβ, and Hγ were recorded using a PI (Princeton Instruments) SP2756A spectrometer with a resolution of approximately 0.06 nm in the 200-1050 nm range. The intensity of emitted light is proportional to the number of excited particles [?]. With a constant arc current of 1.34 A and magnetic field of 0.46 T, the emission intensity of the ion source was recorded as a function of hydrogen flow rate, as shown in Fig. 3.

Fig. 3 Relative intensity of line emission versus gas flow rate.

The line emission intensity increases with gas flow rate. In principle, two competing effects occur simultaneously. As electron collision frequency with neutral atoms increases, the number of excited atoms grows, emitting more light. However, as the electron mean free path decreases, the adverse effect on electron kinetic energy reduces the cross-section for excitation or ionization processes. As gas flow rate increases, these two effects compete, potentially resulting in a peak emission intensity corresponding to maximum excited atom production.

Experimental data do not show this maximum point in the H_2 flow range of 0-20 SCCM (standard cubic centimetres per minute at standard temperature and pressure), but they do reveal a minimum in source power consumption. As shown in Fig. 4, as gas flow rate increases, power consumption decreases to a minimum point then rises again. By improving the source sealing design and reducing machining tolerances, the minimum power consumption was reduced from 9 SCCM to 4 SCCM, achieving higher power efficiency and better vacuum levels. Further reduction of the minimum power consumption is possible with our current design.

Fig. 4 Arc power with respect to the gas flow rate.

Effects of Magnetic Field on Discharge

Generally, Penning sources operate in moderate magnetic fields of several hundred Gauss. However, this negative hydrogen Penning source operates in a stronger magnetic field. The electron gyro radius is smaller than the source dimensions, as shown in Fig. 5, which demonstrates that the discharge state remains nearly stable when the magnetic field varies between 0.3-0.7 T. Additionally, the source discharge state does not change significantly when transitioning from the test-stand to the cyclotron, indicating that cyclotron performance can be reliably predicted from most test-stand experiments.

One phenomenon requiring attention is that magnetic field does affect H^- extraction within the tested range. More detailed investigation is planned for future studies.

Fig. 5 Relative intensity of the emission spectrum with respect to the magnetic field.

V-I Characteristic of the Ion Source

To obtain sufficient H^- current, the source operates in an arc discharge state of several amperes, whereas most Penning sources operate in a glow discharge state [?]. The V-I curve of the source was measured on the cyclotron using a 1 SCCM H_2 feeding rate and 1.2 T field. The curve (Fig. 6) shows that the source can operate at any point by adjusting the power supply current. During V-I characterization, the power supply was modified several times to improve load-matching effects.

The arc ignition process is controllable. Future work will also investigate cathode erosion monitoring and lifetime extension, in addition to V-I characteristics.

Fig. 6 Arc voltage of ion source with respect to the arc current.

Preliminary Ion Extraction Experiments

H^- extraction experiments have been conducted on both the test-stand and the cyclotron [?]. On the test-stand, the applied DC voltage between the source and extractor could reach 40 kV when the source was not operating. However, as soon as the source discharged in either glow or arc state, the DC voltage could not exceed 2 kV. Above this value, corona discharge occurred on the extractor, and the collected negative charge signal increased rapidly to several mA, with most of the signal contributed by electrons. The extracted H^- current was approximately 200 A at this voltage.

On the cyclotron, the extraction voltage of the RF field could reach 40 kV. Peak currents exceeding 80 A of 11 MeV H^- have been obtained at the cyclotron target zone, surpassing the design goal of 50 A. However, significant efforts are still needed to increase the average H^- yield and improve operational lifetime and stability in the next development stage. By inverting the polarity and slightly decreasing the magnetic field, over 160 A of proton peak current was obtained at the target, thereby verifying the correctness of the cyclotron' s physical design.

Discussion

The characteristics of the negative hydrogen Penning source have been preliminarily studied, and its prototype has already met the basic engineering requirements of the cyclotron, including size constraints, heat dissipation, gas load, and adjustable positioning. The successful acceleration of 11 MeV H^- and H^+ beams confirms that the physical design of the IFP cyclotron is correct. However, the H^- yield and source lifetime remain lower than expected.

Due to space and experimental time limitations, the cyclotron test-stand is more suitable for studying source physics. Currently, the most significant problem is that the extraction DC voltage cannot be adjusted above 2 kV. This is likely because charges carried by the H_2 gas flow substantially reduce the insulation level of the vacuum cavity. Several attempted measurements failed to increase the voltage level. We plan to adopt pulsed voltage extraction and further investigate the physical processes inside the chamber. The H^- yield can be enhanced at relatively low cost.

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