OPERATIONAL EXPERIENCES AND UPGRADE OF CSNS ION SOURCE

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Abstract

The CSNS ion source has been in operation over 10 years since 2015. It has provided a stable beam current, progressing from an initial beam commissioning power of 10 kW to the current 180 kW. The CSNS ion source is responsible for delivering 30-40 mA H^- at 50 kV. During CSNS phase I, a Penning surface negative ion source was used, based on the ISIS ion source prototype. It met the operational requirement of 100 kW beam power of CSNS phase I. However, due to its short lifetime, typically requiring replacement every month, and its relatively large emittance, it faced significant challenges as the beam power for CSNS phase II is raised to 500 kW. To address this, an RF ion source was proposed and its development began in 2016. This volume ion source has been successful used in SNS and JPAC and offer some advantages such as a longer lifetime, lower emittance, lower cesium consumption. Unlike the internal antenna design used by SNS and JPAC, an external antenna RF ion source was successful developed and put into operation in September 2021. This paper will discuss the extensive operational experience and upgrade of CSNS ion source.

INTRODUCTION

The China Spallation Neutron Source (CSNS) is an accelerator-based high power project with multipurpose currently under operation with an on-target beam power of 100 kW[1,2]. The accelerator complex consists of an 80 MeV H− linear accelerator as the injector and a 1.6 GeV rapid cycling proton synchrotron (RCS). The linear accelerator consists of a 50 keV H− Penning surface plasma ion source (IS), a low energy beam transport line (LEBT), a 3.0 MeV RFQ accelerator, a medium energy beam transport line (MEBT), an 80 MeV drift tube linear accelerator (DTL) and a high energy beam transport line (HEBT). The beam power is 100 kW. For the CSNS upgrade (CSNS-II), the injection energy is increased from 80 MeV to 300 MeV . The beam power is increased up to 500 kW. Since the operation of CSNS, the performance of the ion source has been critically important, as it directly affects the beam condition of the RCS. Even minor fluctuations may lead to an increase in beam loss in the RCS ring. For CSNS phase I, the front end should provide a stable H− beam with energy of 3.0 MeV, a maximum pulsed current up to 15 mA, at a repetition of 25 Hz and beam pulse width of 400 ms before chopping. For CSNS phase II, beam power is up to 500 kW and H− bema current with 40 mA at the RFQ exit before chopping is required. Therefore, higher beam current intensity and lower beam emittance are required from ion source.

PENNING ION SOURCE

The installation of CSNS front end was completed in 2015. A Penning surface plasma source is used to serve CSNS, which is also applied to ISIS [3]. This ion source is characterized by its high emission current density, simple operation, rapid replacement and relatively low cost. The ion source consists of a discharge chamber, an extraction electrode, an analyzing magnet, a -50 kV isolation ceramic insulator, an accelerating electrode and a large vacuum chamber with two turbo molecular pumps [2]. Cesium is used to increase the H^- ion production efficiency. The discharge chamber consists of a molybdenum anode, cathode and aperture plate, where the plasms arc is confined. A transverse magnetic Penning field is applied across the discharge chamber. Hydrogen and cesium are fed into the discharge chamber via holes in the anode. The detail design and operational parameters find reference [4,5].

The CSNS beam supply efficiency is shown in Fig. 1. Starting from 2018, beam commissioning of the accelerator was carried out, and the designed target of 100 kW was achieved in 2019. Penning ion source was installed in 2015, and replaced by RF ion source in 2021. For the discharge chamber of a Penning ion source, its service life is typically one month.

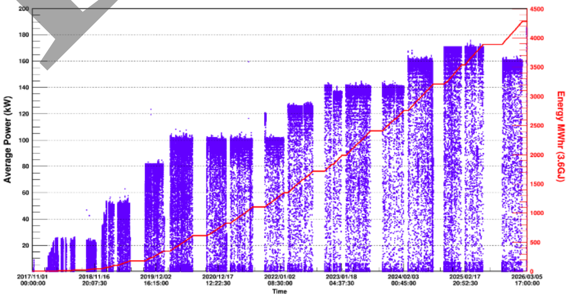

Figure 1: Beam Power from 2018 to 2026.

In general, for each set of discharge chamber, the ion source can produce up to 40 mA H^- ion beam with a beam duty factor about 1.25% (500 µs and 25 Hz) and a normalized rms emittance about 0.8 πmm.mrad. Although the emittance is much larger than the acceptance of RFQ (0.2 πmm.mrad), the H^- ion beam current is still larger than 20 mA within the acceptance of RFQ, which satisfies the current requirement of CSNS phase I. For 100 kW beam power operation, a routine beam current from ion source of about 30 mA is enough. The average expected lifetime of CSNS Penning ion source, mainly limited by the discharge chamber, is about 1 month. The instability of ion source

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mainly comes from the electrode damage. Electrode sputtering could lead to discharge shorten, which is the limitation of discharge chamber, shown in Fig. 2. In each operation period, shorten faults of the discharge chamber occur once or twice. In such case, the beam must be shut down and the discharge chamber was replaced, which reduces the operational efficiency. In addition, plasma slit plate blockage occurred once in 2021, causing a sharp drop in the extracted beam current. This fault requires breaking the vacuum and replacing the discharge chamber. Moreover, instability of the ion source is also manifested in the extracted beam current. The ion source consumes a large amount of cesium, and the operating temperature of the cesium oven exceeds 130 °C. Although a cold trap is installed at the ion source outlet to trap cesium vapor, cesium deposited on the cold trap surface easily triggers severe sparking with the discharge chamber. Such beam instability usually appears at the end of the ion source service life. Excessive cesium deposition readily induces sparking between discharge chamber and cold box and leads to severe beam fluctuation. To address this problem, cesium temperature is strictly controlled on one hand; on the other hand, a dual-extraction pulsed beam scheme is designed, seen in Fig. 3. One pulse adopts 8 kV high voltage for beam extraction to clean cesium deposits on the surface of the extraction electrode. This beam travels along an abnormal orbit inside the bending magnet and is lost in the LEBT, producing no impact on the normal beam. The other pulse serves as the normal extracted beam, which passes through the LEBT and finally enters the RFQ. This power supply eliminates sparking faults caused by cesium deposition under low duty factor, greatly improving operational stability.

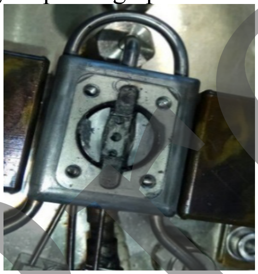

Figure 2: Sputtered Metal Covers the Discharge Chamber.

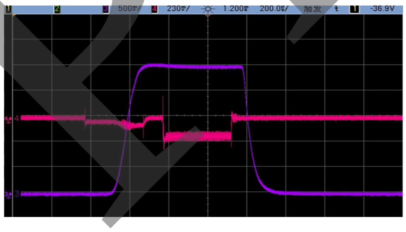

Figure 3: Dual-extraction pulse. Two beams (red curve) are extracted with the power supply: one pulse for the normal operation (right) and another pulse for the cesium cleaning (left). Another curve stands for the arc current.

RF-DRIVEN ION SOURCE

To meet the beam requirements of the CSNS upgrade and further improve the operational efficiency of the front-end system, an RF ion source with an external antenna has been developed. The configuration of the RF-driven H− ion source is shown in Fig. 4 [6,7]. The cylindrical plasma chamber is made of silicon nitride ceramic. It has high thermal-shock resistance (above 700 K) and mechanical strength. A 4.5-turn antenna is made of a copper tube with a square cross section. The antenna is wound tightly around the plasma chamber. To increase the withstand voltage, each turn of the antenna is separated by a screw thread machined on the ceramic chamber. The tail part surface of the chamber is surrounded with segmented copper blocks, which are bound tightly to the chamber. The end sides of the copper blocks are brazed together with a water channel. A water cooled square copper tube is attached on the other end of the chamber to make sure the chamber is homogeneously cooled. As a result, the plasma chamber is cooled by three parts, the antenna, the copper block, and the copper tube. All of these parts are put into a stainless cover and filled with epoxy. To synchronized the plasma pulse with the timing of the whole accelerator, a glow discharge igniter is used to trigger the main plasma on time. The igniter operates at a repetition rate of 25Hz and pulse width of 200 ms，the pulse starts ahead of the RF power but has an overlap of 50 µs.

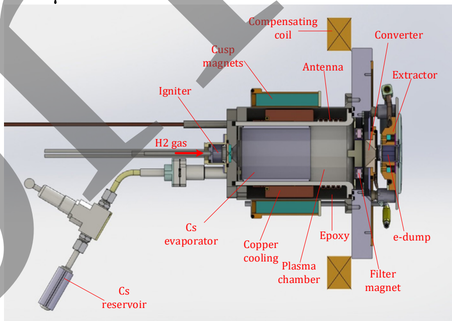

Figure 4: The Configuration of RF Ion Source.

The RF ion source was put into operation in September 2021, replacing the Penning ion source. To better monitor the operating state of the ion source, online monitoring of the ion source plasma emission spectrum is adopted, with the main functions as follows: Firstly, to monitor the oxygen content in the plasma. The relative content of oxygen in the discharge chamber can be determined from the oxygen spectrum. Excess oxygen will consume cesium and cause fluctuations in the extracted beam current. A hydrogen purifier is installed before hydrogen enters the chamber to filter impurities. Since the purifier has a limited service life of approximately half a year, monitoring the oxygen emission spectrum enables evaluation of the remaining service life of the hydrogen purifier and determines whether replacement is necessary. The oxygen emission spectrum is intense at the initial stage of ion source operation and gradually stabilizes to a steady value as the operation continues. Secondly, to monitor the cesium spectrum and determine the cesium content. A negative hydrogen ion source relies on cesium to improve the production yield of negative hydrogen particles, therefore, cesium monitoring is particularly important during long-term operation. The relative content of cesium in the discharge chamber is assessed by monitoring the cesium-to-hydrogen spectral ratio. The cesium consumption is recorded, and concentration measurement inside the discharge chamber are conducted during each maintenance shutdown. About 0.5g cesium is used in one operational period (around 310 days). The cesium oven temperature was raised from 85 gradually to 120 in an operational period.

Since the RF ion source was put into operation, no major maintenance failures have occurred. During the annual summer accelerator shutdown maintenance, the discharge chamber is disassembled and cleaned, the cesium vapor system is replaced, and the entire vacuum chamber is wiped and cleaned with alcohol. Residual cesium vapor, once exposed to the atmosphere, tends to induce high-voltage sparking inside the vacuum chamber. Figure 5 shows the output beam current stability at the exit of ion source in the operational period of 2024.10-2025.07.

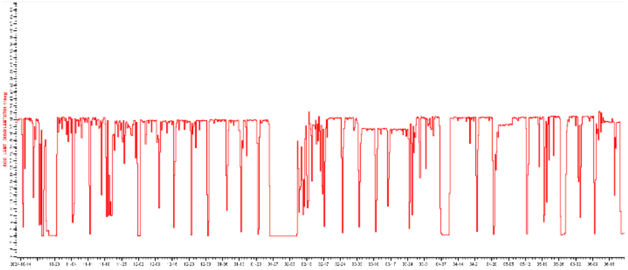

Figure 5: The H- current from 2024.10 to 2025.07.

To meet the beam current requirements of CSNS-II, a duplicate RF ion source and LEBT test platform has been built in the laboratory. Research including optimization and upgrading of the ion source and LEBT can be carried out on this platform. Using this test bench, a negative hydrogen beam current of 60 mA was achieved for the RF ion source, with an emittance of 0.22 πmm·mrad. This beam current satisfies the beam demand for 500 kW operation.

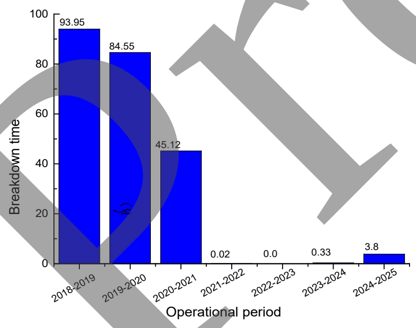

Figure 6: Breakdown Time of CSNS Ion Source from 2018.09 to 2025.07.

In Fig. 6, the breakdown time since the commissioning of the ion source are listed. The RF ion source has greatly improved the operational efficiency of the ion source. Since RF ion source operation, the main fault of the RF ion source was oxidation-induced short-circuit at the terminal of the extraction electrode after long-term service. This fault occurred in 2025 at the atmospheric side of the connector. The connector adopts an SHV high-voltage resistant connector, through which an extraction voltage of approximately 10 kV is fed into the electrode inside the vacuum vessel. After long term operation, surface metal oxidation degrades the insulation performance and eventually causes a short circuit. Maintenance personnel quickly replaced the faulty cable with a spare high-voltage line and restored operation. This fault resulted in a beam shutdown of 3.8 hours (the actual fault time was mainly spent on tunnel access, ventilation and tunnel closure). This incident is classified as an aging failure. The new connector terminals are gold-plated on the surface to prevent oxidation during long-term operation.

CONCLUSION

The CSNS ion source has evolved from a Penning ion source to an RF-driven ion source, which further improves the beam efficiency of the front-end system and provides adequate preparation for the CSNS upgrade.

Since the beam extracted from the RF ion source features rotational symmetry, the number of solenoids in the LEBT has been reduced from three to two, and the LEBT length has been further shortened. A shorter LEBT can effectively mitigate the space charge effect during transmission, which is beneficial to the subsequent acceleration and transport of high-intensity beams. The new LEBT has completed design and fabrication, and is scheduled to replace the original one in the summer. Meanwhile, the RFQ cavity has been redesigned, and a new RFQ dedicated for high-intensity beam operation is also about to be commissioned.

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REFERENCES

[1] Hesheng Chen, Xun-Li Wang, "China's first pulsed neutron source", *Nature Materials,* Vol. 15, pp. 689, 2016. doi:10.1038/nmat4655

[2] Hesheng Chen *et al.*, "Design and construction of China spallation neutron source", *Nucl. Instrum. Methods Phys. Res. A*, Vol. 1078, pp. 170431, 2025. doi:10.1016/J.nima.2025.170431

[3] D.C. Faircloth *et al.,* "Thermal modelling of ISIS H- ion source", *Rev. Sci. Instrum.,* Vol. 75, pp. 1738, 2004. doi:10.1063/1.1695615

[4] Sheng-jin Liu *et al.*, "Status of CSNS H- ion source", *Chinese Phys. C,* Vol. 39, pp. 057008, 2015. doi:10.1088/1674-1137/39/5/057008

[5] H. Ouyang *et al.*, "The operation and improvement of CSNS front end". *Radiation Detection Technology and Methods,* Vol. 4, pp. 110-115, 2020. doi:10.1007/s41605-019-00159-8

[6] W. Chen *et al.*, "Operation of RF-driven negative hydrogen ion source in China Spallation Neutron Source", *Rev. Sci. Instrum.*, Vol. 90, pp. 113320, 2019. doi:10.1063/1.5128553

[7] W. Chen *et al.,* "Over 7200 hours commissioning of RF-driven negative hydrogen ion source developed at CSNS", *J. Instrum.*, Vol. 18, pp. 04030, 2023. doi:10.1088/1748-0221/18/04/P04030