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HIGH RELIABILITY, LONG LIFETIME, CONTINUOUS WAVE H- ION SOURCE

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Abstract

Phoenix Nuclear Labs (PNL) is developing a high-current, long-lifetime negative hydrogen (H-) ion source in partnership with Fermilab as part of an ion beam injector for future Intensity Frontier particle accelerators. In this application, continuous output with long lifetime and high reliability and efficiency are critical. Existing ion sources at Fermilab rely on plasma-facing electrodes and are limited to lifetimes of a few hundred hours, while requiring relatively high gas loads on downstream components. PNL's H- ion source uses an electrodeless microwave plasma generator which has been extensively developed in PNL's positive ion source systems, demonstrating 1000+ hours of operation and >99

INTRODUCTION

Ion sources are critical for a wide range of applications including basic science research, medical applications, and semiconductor production. In many cases, the performance and reliability of very large, complex, and expensive systems is limited by the performance and reliability of the ion source, which often represents a relatively small part of the total system in terms of size and cost. Thus, advances in ion source technologies can lead to drastic improvements in system performance relatively quickly. However, ion sources are complex devices that often suffer from reliability issues when pushed to high currents, as is often demanded by the rest of the system.

Lifetime and reliability issues can be troublesome for ion sources, and this can be especially true for negative hydrogen (H-) sources. Nonetheless, negative ion sources are still commonly used across a broad range of applications due to the fact that, for many applications, downstream system components require negative rather than positive ions. In this project, a new type of ion source that can produce high DC current output (up to 15 mA) and has a long lifetime (up to several months) has been designed. It is understood that the near term DoE need for such a source is to serve as an ion beam injector into future Intensity Frontier particle accelerators that are under development at Fermi National Lab and other DoE labs.

Intensity Frontier accelerators are next generation basic science research accelerators which include GeV-scale linacs able to operate at higher current levels than have ever been achieved at this energy level.

The leading H- ion source candidate that is currently under consideration by the Fermilab design team has a lifetime of a few hundred hours. This lifetime decreases further when operated at full power (15 mA). Furthermore, the source has high power requirements (15 kW) and high gas load

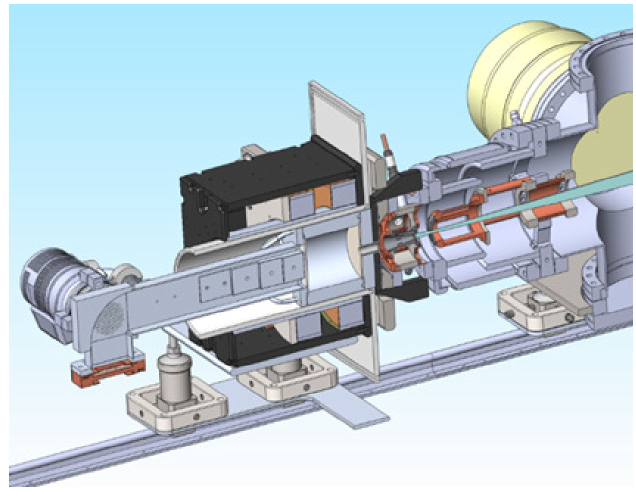

Figure 1: Cross-sectional view of negative ion source beamline.

(18-20 SCCM) on the downstream vacuum components. Though ion sources are cheap on the scale of large research accelerators, if a more reliable H- source is not developed the results of the entire project could be in jeopardy.

In this project, a modified 2.45 GHz microwave proton source has been evaluated as a generator of atomic hydrogen that will be used for surface production of H- ions. A cesiated surface converter is located between the proton source and the H- extraction region. In the extraction region, electrostatic lenses produce a low energy H- ion beam. Diagnostics developed in this work monitor neutral atomic hydrogen particle energy and flux, along with electron temperature and density near the extractor. A design for H- beam formation in a reduced plasma density environment has been developed. It is particularly important to reduce high temperature electron density in the converter region. Thus, the two ion source chambers (neutral production and H- conversion) are separated by a tunable magnetic dipole field.

DESCRIPTION

Phoenix Nuclear Labs (PNL) has developed a design for a negative hydrogen ion source. The device is driven by a plasma chamber that produces energetic electrons, positive hydrogen ions, and neutral hydrogen atoms. The particles generated by the plasma are filtered by a transverse magnetic field, which preferentially removes energetic electrons while allowing fast neutrals to pass. These neutrals are directed to a surface converter and produce the desired negative hydrogen ions, which are then extracted into a low energy beam using

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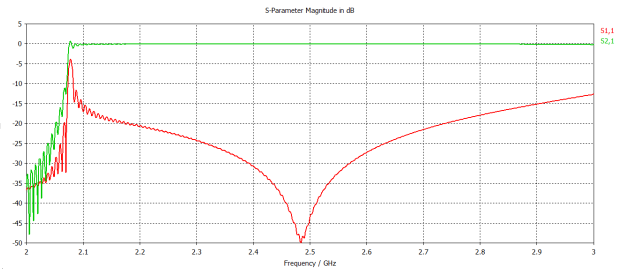

Figure 2: Simulated S-parameters for the DC waveguide break. At 2.45 GHz, >99.98% of incident microwave power is transmitted across the air gap.

electrostatic lenses. A cross-sectional view of this system is shown in Fig. 1.

RESULTS AND ANALYSIS

Microwave Source Plasma Chamber

The ion source design presented here is driven by electron cyclotron resonance (ECR) heating. The 2.45 GHz microwaves used require an 875 G magnetic field to satisfy the resonance condition. A pair of solenoid magnets surrounding the plasma chamber provide this field and allow the source to be finely tuned while the beam is extracted in order to maximize performance. Models and experimental results at PNL with similar systems have shown that optimal performance is achieved when this resonant region is located at the exit aperture from the driver chamber.

Additionally, this electrode-less design provides much longer service lifetimes compared to those which rely on filaments. Similar ion sources at PNL have demonstrated lifetimes of several months or greater.

In order to electrostatically extract and accelerate the beam, a potential difference of -30 kV must exist between the plasma source and the target. To improve reliability and reduce complexity, it is desirable to locate as much equipment at ground voltage as possible. To allow microwave generation at ground, a DC waveguide break was developed which transports microwave power from the grounded magnetron to the plasma chamber, which is floating at the extraction voltage of -30 kV.

This device consists of multiple plates, similar to a choke flange, separated by an air gap capable of sufficient high voltage standoff. High-frequency electromagnetic modeling software was used to design this system and optimize the geometry to minimize reflected and radiated power. The calculated S-parameters for this device are shown in Fig. 2. This DC waveguide break design has been implemented successfully on multiple systems at PNL.

Filtering Magnet Region

Considering the very high electron temperatures observed in the microwave source, a magnetic filter will be required to reduce the electron temperature and minimize electron-

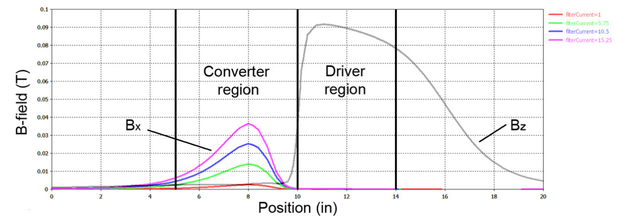

Figure 3: Plot of transverse and axial components of the magnetic field for various filter solenoid currents.

detachment disassociation of the desired H- ions before extraction. Fast electrons are preferentially removed while slow electrons and positive ions pass through the filter by mechanisms discussed below. The neutral atomic hydrogen passes unaffected through the dipole magnetic filter field. This flux strikes the conversion surface and leads to H- formation with yield determined by the surface conversion efficiency.

A system of magnetic shunts was designed to provide the required magnetic profiles. 3-D magnetic models of the combined ECR and filter fields were performed to verify the design. These show that the required 875 G axial field can be produced at the ends of the plasma chamber while being highly attenuated outside of this region. Minimizing stray axial fields outside of the source is important for the performance of the magnetic filter, which relies on a highly transverse field. Using these models, it was confirmed that the fields in these adjacent regions are decoupled, allowing better optimization. The modeled magnetic field components along the axis are plotted in Fig. 3.

Cesium Enhanced Surface Conversion

The energetic atomic hydrogen which passes through the magnetic filtering region is directed to a surface converter to produce H- ions. This reaction requires the transfer of an electron to the incident hydrogen atom, making the work function of the surface critical. Tungsten offers a low work function which can withstand the plasma environment. The work function of this material can further be reduced with a sub-monolayer coating of cesium.

The converter is conical to maximize surface area and flux collection. The converter must be located as close to the plasma driver as possibleto maximize efficiency. Due to the relatively large destruction cross-sections for H- ions, the converter must also be positioned close to the high-voltage extraction aperture to maximize the ions available to the beam. To aid in these processes, the collar can be biased to repel newly created H- ions and reduce sputtering losses of ionized cesium.

Deposition of the cesium coating is accomplished using commercially available dispenser cartridges located in close proximity to the conversion surface. This process utilizes a temperature-driven reduction reaction of a cesium-containing compound such as cesium chromate. Careful thermal management of these parts is therefore necessary to

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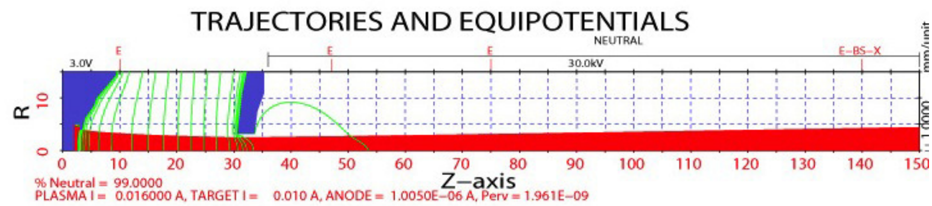

Figure 4: Trajectories and equipotentials output from the PBGUNS ion beam simulation program. Distances are in mm.

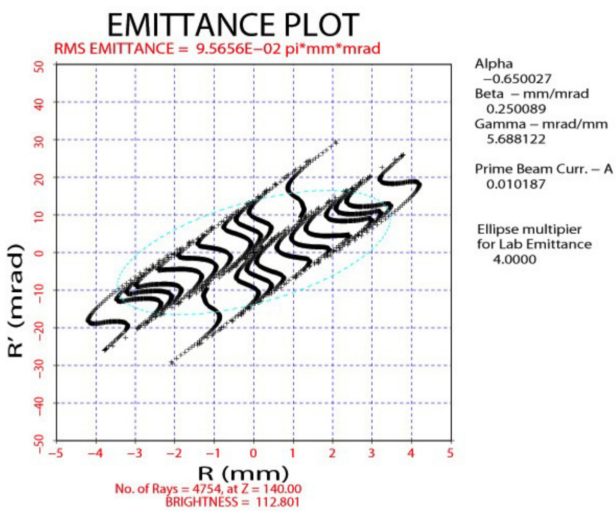

Figure 5: Emittance plot for the 10 mA H- beam calculated from PBGUNS at z = 140 mm.

accurately control deposition. A system of channels carrying water are integrated into the dispenser and conversion surface to provide independent temperature control of the two sections. The thermal performance of this system was modeled with finite element analysis software to ensure the required temperature profiles could be reached.

Negative Hydrogen Extraction

H- ions produced by the surface converter are extracted into a low energy beam using a set of electrostatic lenses. PBGUNS simulations were completed for 30 kV H- ion extraction with a 10 mA beam using an 8 mm diameter emission aperture and transported to a distance of z = 140 mm. The extraction gap is 27.2 mm, and the extraction electrode is 6.4 mm in diameter.

An H- ion temperature of 1 eV is used for these simulations. Under these conditions, the predicted rms emittance is 0.0956 pi-mm-mrad, which is more than a factor of 2 less than the Fermilab requirement of 0.2 pi-mm-mrad. This simple two-electrode extraction system gives predictions consistent with the beam current and emittance requirements. The predicted trajectories and equipotentials for this beam are shown in Fig. 4, while the phase space plot at the target calorimeter (z = 140 mm) is shown in Fig. 5.

In this extraction model, the co-extracted electrons are accelerated to 30 kV. A bending magnet will be used to separate co-extracted electrons and direct them into a beam dump.

Diagnostics

A number of diagnostic systems will be implemented during the commissioning of the ion source. These measurements will provide validation of the real-world performance of the various sub-systems. The electron temperature profile along the axis of the device is critical for the efficient production of H-. Specifically, the magnetic filter must significantly reduce the temperature of electrons reaching the conversion region. A Langmuir probe will be used to directly measure the temperature and density of the electrons and ions along the axis of the source. This device can be inserted axially through the source to provide spatially resolved measurements of these parameters and confirm suitable performance of the magnetic filter.

Broadband optical spectra of the plasma can also be used to determine its chemical composition from known spectral lines during operation. The evolution of cesium within the converter and the presence of impurities within the system can be monitored.

An electrically isolated aperture will allow for detection and measurement of charged particles located outside of the intended beam envelope. Such particles could be due to an improperly focused beam or halo due to secondary ionization with the background gas.

A Faraday cup will be used as the target for the H- beam. This will allow the beam current to be directly monitored via electrical measurements. A negatively biased ring provides electron suppression for the target. As the Faraday cup is water cooled, colorimetric measurements can also be performed.

CONCLUSIONS

Phoenix Nuclear Labs has begun assembly of a CW negative hydrogen ion source that will exceed the requirements of proposed Intensity Frontier particle accelerator injectors. The design pairs proven microwave ion source technology as a source of hyperthermal neutral hydrogen atoms and a cesium converter for negative hydrogen ion production similar to that which is used at the Spallation Neutron Source. The anticipated result will be a CW negative hydrogen ion source capable of generating a low emittance beam of at least 10 mA of H- ions with a source lifetime that should be at least several months, if not longer.