H^- ION SOURCES FOR HIGH INTENSITY PROTON DRIVERS*

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Abstract

Spallation neutron source user facilities require reliable, intense beams of protons. The technique of H^- charge exchange injection into a storage ring or synchrotron can provide the needed beam currents, but may be limited by the ion sources that have currents and reliability that do not meet future requirements and emittances that are too large for efficient acceleration. In this project we are developing an H^- source which will synthesize the most important developments in the field of negative ion sources to provide high current, small emittance, good lifetime, high reliability, and power efficiency. We describe planned modifications to the present external antenna source at SNS that involve: 1) replacing the present 2 MHz plasma-forming solenoid antenna with a 60 MHz saddle-type antenna and 2) replacing the permanent multicusp magnet with a weaker electro-magnet, in order to increase the plasma density near the outlet aperture. The SNS test stand will then be used to verify simulations of this approach that indicate significant improvements in H^- output current and efficiency, where lower RF power will allow higher duty factor, longer source lifetime, and/or better reliability.

INTRODUCTION

Today, new science projects, including spallation neutron sources (SNS) and proton drivers, commercial tandem accelerators and commercial cyclotrons need to have H^- beams with a higher intensity, duty factor (*df*) and brightness *B*. For these requirements, new research projects to improve H^- sources are underway at many Laboratories around the world. A partial list of these laboratories includes at least 20 institutions.

All these groups have made progress in improving H^- beam current, but other parameters including lifetime, power and gas efficiency, beam brightness and stability of operation also need improvement. Some of these organizations can be potential users of commercially available H^-/D^- sources with improved characteristics.

Programs and developments of several of these laboratories are discussed in recent reviews by J. Sherman, G.Rouleau [1], by M. Stockli [2], and by D. Moehs [3]. The most recent development in this field was presented at ICIS2007, EPAC2008 and in Cadarache at the International Symposium of Negative Ions, Sources, and Beams (ISNIS2008). For Spallation Neutron Sources and Proton Drivers, H^- beams are needed with pulsed current up to 70 mA, average current up to 6 mA (*df > 6%*), with normalized rms emittance < 0.25 π mm-mr. Lifetimes for high *df* operation should exceed 500 hrs (~3 A hrs). For high current tandem accelerators (BNCT, explosive and nuclear material detection, positron diagnostics) and for high current cyclotrons H^-/D^- beams with DC current > 10 mA, beam emittance < 0.2 π mm-mr and lifetime > 600 hrs (~6A hrs) are needed.

The primary application of the new source to be discussed in this report is the next upgrade of the Oak Ridge Spallation Neutron Source to higher beam power levels. The source would also be an essential component of a proton driver that might be used for muon colliders. In addition the source could be an upgrade path for all other existing and planned applications such as medical treatments (including cyclotrons with external injection for cancer therapy, and high current tandem accelerators for Boron Neutron Capture Therapy), and homeland defense (e.g. production of muons for cargo scanning or resonant gamma ray techniques to detect explosives).

We have proposed to upgrade one of the existing aluminum nitride (AlN) sources at SNS by 1) replacing the present 2 MHz plasma-forming solenoid antenna with a 60 MHz saddle-type helicon antenna and 2) replacing the permanent multicusp magnet with a weaker electromagnet, in order to increase the plasma density near the outlet aperture. The SNS test stand will then be used to verify simulations of this approach that indicate significant improvements in H^- output current and efficiency, where lower RF power could allow higher duty factor, longer source lifetime, and/or better reliability.

A1N EXTERNAL ANTENNA SOURCE

The ORNL Aluminum Nitride (AlN) external antenna source described here was based on the design of the Al_2O_3 external antenna source [4]. As shown in Fig. 1, the source consists of a flanged, high-purity, AlN ceramic plasma chamber with inside dimensions: diameter=6.8 cm; length: 18 cm; wall thickness: 0.7 cm. The outer surface of the AlN chamber is directly water-cooled by a Lexan serpentine jacket consisting of a single 3.3 x 9.6 mm water passage flowing 2.6 gal/min of de-ionized water (see Fig. 1).

The RF-coupling antenna shown in Fig. 1 is located in the air space surrounding the Lexan cooling jacket and is constructed from 4.8 mm diameter Cu tubing which is water-cooled and covered with layers of Teflon and polyolefin shrink wrap for RF voltage isolation. The antenna is resonated in series with a variable capacitor driven by a 2 MHz (0-80kW) RF generator. The antenna is coiled in a 4 ½ double-layer 'stacked' geometry, with a 2.4 mm thick Teflon ring separating the inner- from the

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outer layer. The ring had to be upgraded with a T-shaped cross section to eliminate frequent antenna failures.

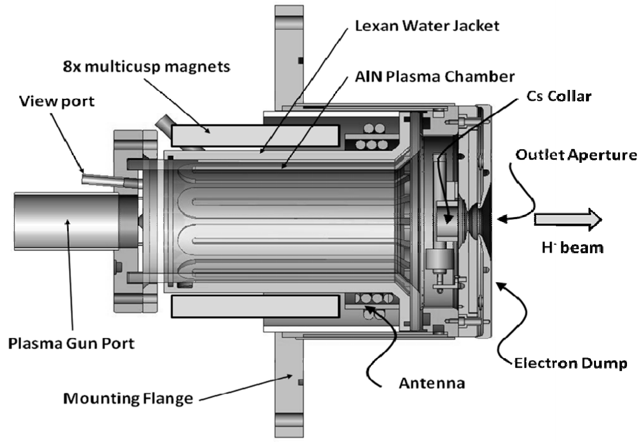

Figure 1: Cross-sectional view of the AlN source configured as tested. The AlN chamber is shown as transparent to allow viewing of the Lexan cooling jacket.

Experimental runs on the test stand varied in length from less than 1 day to ~3 weeks. Over an approximately year-long testing period, the maximum beam current attained from different source configurations on the test stand has increased from ~45 mA to ~95 mA and a sustained multi-day operation at >60 mA has also been demonstrated. On the SNS Frontend, the source was able to produce the required 35 mA Linac beam current, but its use had to be suspended after experiencing 5 failures that required a source replacement within 25 days. A reimplementation is expected after finding and adequately testing an appropriate plasma starter.

SADDLE-TYPE HELICON DESIGN

For efficient H^-/D^- generation in surface plasma sources for accelerators, it is necessary to have plasma particles flow to a small surface around the emission aperture. Unfortunately, in all previously tested versions of RF and filament discharge negative ion sources, the plasma flux is distributed almost uniformly throughout the volume of the plasma chamber, and only a very small part of the plasma is used for negative ion generation. A large part of the plasma is spent on the surfaces of the plasma chamber, which causes deactivation of catalytic properties that are important for surface plasma generation of negative ions. The efficiency of this type of large volume plasma source is ~1 mA H^- current per 1kW of discharge power or less. In contrast, in a well designed compact surface plasma source, the efficiency is up to 60 mA/kW, the emission current density is up to 1-2 A/cm^2 and a typical H^- beam intensity is ~100 mA.

Configurations of plasma generators with an ordinary solenoid antenna and with a saddle-type antenna are shown in Figures 2a and 2b.

In this proposal, we suggest improving the performance of negative ion sources by generating the plasma in an RF discharge with a saddle type antenna in the presence of a DC longitudinal magnetic field. Features of this saddle type of helicon discharge system include [5]: high efficiency of plasma generation using a resonance in a weak magnetic field, low gas density (1 to 5 mTorr), strong separation of plasma from the chamber wall, low flux of plasma particles to the discharge chamber wall, and flexible control of the plasma flux distribution by magnetic field adjustment.

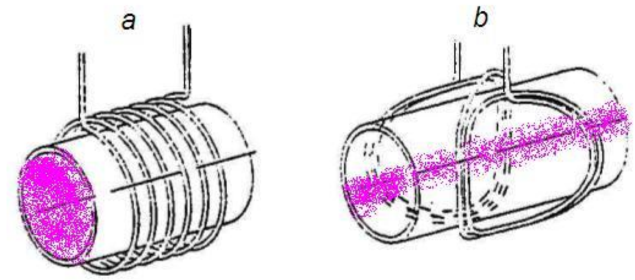

Figure 2: RF plasma generator antennas, a- ordinary solenoid antenna; b- saddle type antenna. An external magnetic field is along the axis of the cylindrical discharge chamber.

Resonant plasma generation has been observed in previous investigations of RF ion sources with an RF field with frequency of ~10 MHz and magnetic fields ~100 G. In an RF field with frequency f, the dependence of the plasma density on magnetic field has a resonant peak at a magnetic field $B_{res\parallel} = 4\ B_c$ for a magnetic field parallel to the RF coil axis, and at $B_{res\perp} \sim 2\ B_c$ for magnetic field perpendicular RF coil axis. Here $B_c = 2\pi f(mc/e)$ is the magnetic field of cyclotron resonance for electrons.

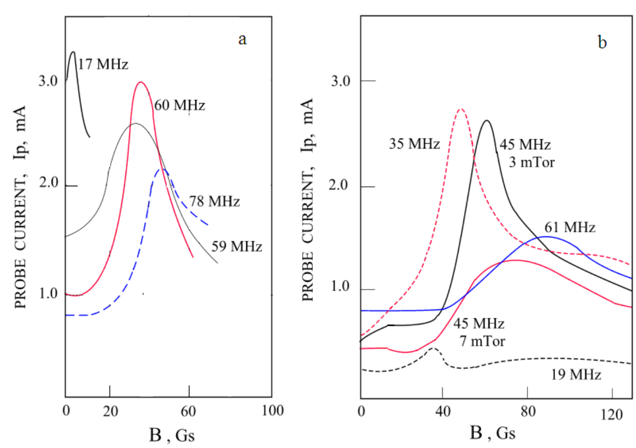

Figure 3: Resonance dependences of plasma density (probe current) on transverse (a) and axial (b) magnetic field for different RF frequencies.

The plasma density in a resonant field condition is up to 3-4 times higher than in a non-resonant field. Examples of these resonances are shown in Fig. 3a for transverse magnetic field and in Fig. 3b for axial (longitudinal) magnetic field.

Configurations of plasma generators with an ordinary solenoid antenna and with a saddle type antenna are shown in Fig. 2 (a, b). An external DC magnetic field is oriented along the axis of the cylindrical discharge chamber. Ion flux distributions at the plasma electrode (the electrode at the end of the cylindrical discharge chamber) for solenoid and saddle type antennas are shown in figure 4 (for solenoid antenna - left and for saddle type antenna- right).

As seen from Fig. 4 the saddle-type antenna increases the plasma flux density compared to the solenoid antenna up to 5 times from 140 mA/cm2 to 750 mA/cm2 with 14 MHz RF frequency, power of 2.7 kW and magnetic field of 70 Gauss. (To get this density with a solenoid antenna would take 40 to 50 kW of power).

With the saddle-type antenna, the plasma column is concentrated near the axis. The plasma flux on the chamber wall is reduced significantly, and the pure hydrogen radiation from the plasma column can be seen to be brighter in the comparison photographs in Fig. 5. This big difference in plasma density distribution is because the plasma generation with the solenoid antenna takes place largely near the chamber wall whereas the saddle type antenna generates plasma largely on the axis where the electric field is largest.

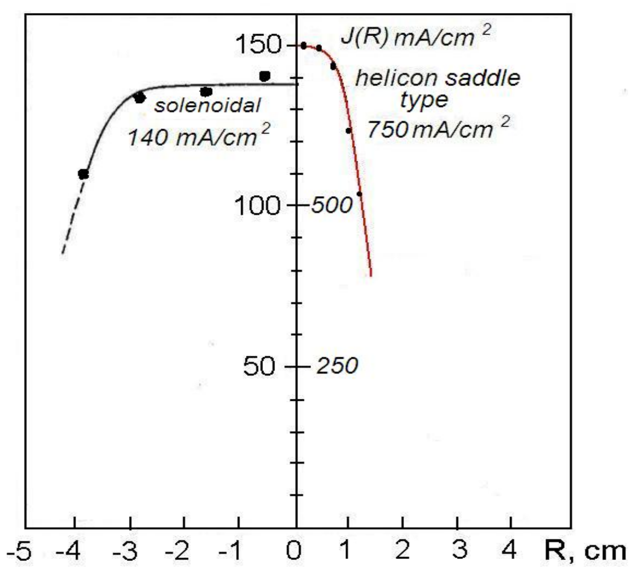

Figure 4: Radial ion flux density distribution measured by ion extraction through plurality of small apertures in the plasma electrode. Left: with a solenoid antenna shown in Fig. 2a, without magnetic field; right: with a saddle type antenna shown in Fig. 2b with magnetic field 70 G.

PROPOSED MODIFICATIONS

We have proposed an SBIR-STTR project to replace the solenoid antenna in the AlN (or Al_2O_3) SNS ion source shown in Fig. 1 with a saddle-type antenna and to replace the multicusp permanent magnetic with a small electromagnet for generation of a variable longitudinal magnetic field up to 200 Gauss.

These modifications should enhance the concentration of plasma density on the axis several times as shown in figure 4 and improve the efficiency of H^- generation. With a saddle-type antenna with frequency ~60MHz a resonant magnetic field for improved plasma generation is about 50 Gauss as shown in Fig. 2a. The proposed assembly is shown below in Fig. 6.

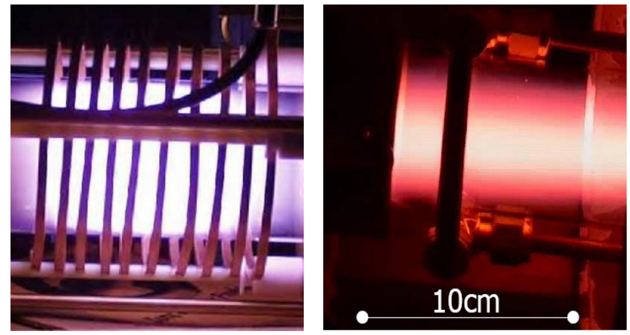

Figure 5: Photographs of plasma discharges. [LEFT] with a solenoid antenna, [RIGHT] with a saddle-type antenna.

The project described here, if approved, would be a first step in an aggressive program to improve H^- sources for the next generation proton drivers needed for several new accelerators.

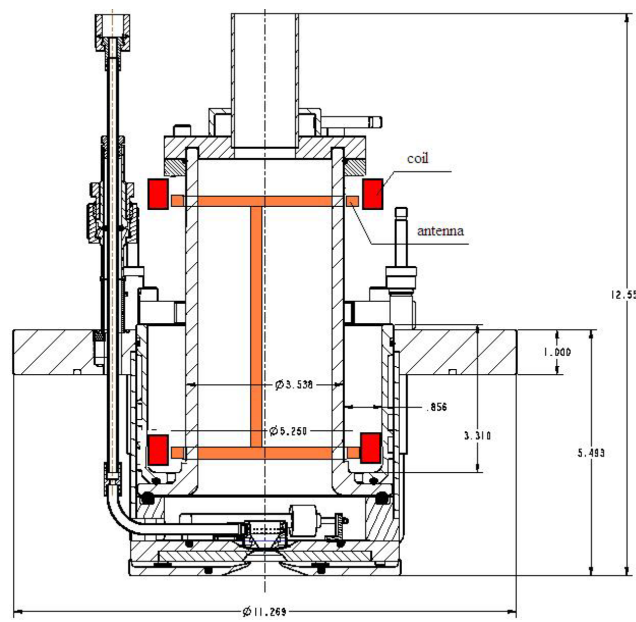

Figure 6: Drawing of the SNS Al_2O_3 H^- source with the (red) proposed saddle-type antenna and the solenoid coils in place.

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