ADVANCED RF-DRIVEN H⁻ ION SOURCES AT THE SNS

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Abstract

The US Spallation Neutron Source* (SNS), will require substantially higher average and pulse H⁻ beam current than can be produced from conventional H⁻ ion sources such as the baseline LBNL-SNS source. H⁻ currents of 70-100 mA with an RMS emittance of 0.20-0.35 π mm mrad and a ~7% duty-factor will be needed for the SNS power upgrade project in 2010. We are therefore investigating several advanced ion source concepts based on RF plasma excitation. First, a generalized discussion of our source development strategy is presented as well as the performance characteristics of a large-plasma-volume, external antenna source based on an Al_2O_3 plasma chamber. The design and results of computational modeling of a high-power version of this source featuring an AlN plasma chamber is subsequently discussed as well as a high-efficiency extraction system necessary for high-current operation.

INTRODUCTION

High-brightness H⁻ ion sources are widely used in large accelerator facilities which utilize charge-exchange injection into circular accelerators or storage rings [1]. One such facility, the U.S. Spallation Neutron Source (SNS)* [2,3,4] employs a Radio-Frequency (RF), multicusp ion source based on a porcelain-coated Cu antenna immersed in the plasma volume [5]. To date, the source has been utilized successfully in commissioning and early operations of the SNS accelerator, delivering 10 - 40 mA with duty-factors of ~0.1% for periods of many weeks with availability approaching ~100% during later runs. This success can be attributed in part to advances in antenna-coating technology [6].

Over the next several years the SNS will increase neutron production, providing 1.4 MW of beam power on target at the end of 2009 and 3-5 MW a few years afterwards. This will require the ion source to produce H⁻ beams of 40-50 mA, 1.2 ms in length with a repetition rate of 60 Hz (~7% duty factor) within an RMS emittance of 0.20-0.35 π mm mrad by 2009 and 70-100 mA thereafter. Currently, the ion source is operating at ~1% duty-factor and already internal antenna failures are becoming increasing frequent, hindering SNS operations.

Our source development strategy focuses on continuing development of the RF source because: (i) there are several existing, short-pulse, RF H⁻ sources producing 60-100 mA with Cs at 0.1% duty-factor, $\varepsilon_{n,rms} \sim 0.2$ π mm

mrad [7,8] (ii) multi-year lifetimes have been observed in short-pulse, RF, H⁻ sources using external antennas, with lifetimes much greater than competing filament-driven or Penning sources [9, 10] (iii) the SNS now has a considerable inventory of components, test equipment and experience related to the RF source and (iv) the baseline SNS source is highly modular, allowing development and testing of subsystems known to be weak.

Our approach is to first develop a stable ceramic plasma chamber supporting an external antenna capable of operation at full RF power and at 7% duty-factor. Once this is achieved we then plan to boost beam current to required levels by improving the ionization and extraction efficiency of the source, employing magnetic confinement schemes, plasma guns, improved Cs systems and advanced extraction systems [11]. Source emittance will be minimized by methodical computer design of the extraction system.

LARGE-VOLUME EXTERNAL ANTENNA SOURCE

Fig. 1 shows a cross-sectional view of the large-volume external antenna source as configured for these experiments.
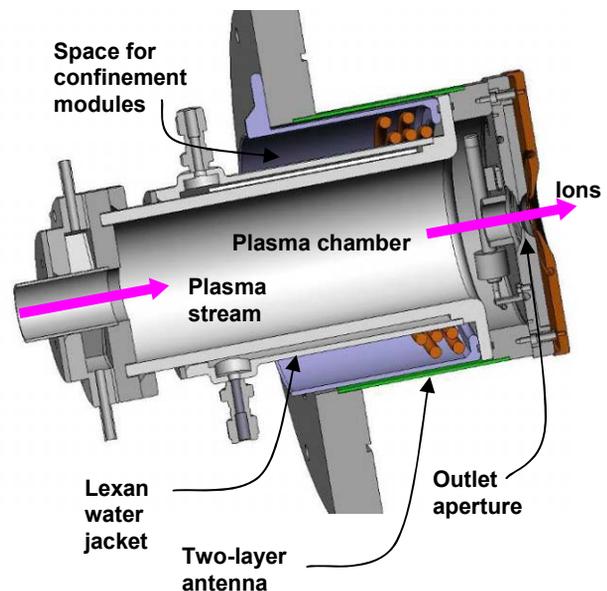
Figure 1: Large-Volume External Antenna Source.

It consists of a flanged high-purity Al_2O_3 plasma chamber with the dimensions: inside diameter = 7.6 cm; length=20 cm; and wall thickness = 0.6 cm. It is surrounded by a Lexan serpentine water cooling jacket consisting of two parallel 3x25 mm water passages in contact with the ceramic. The antenna is constructed from ϕ=4.8 mm Cu tubing which is water-cooled and covered with two layers of polyolefin shrink wrap. It is coiled in a five turn 'stacked' configuration consisting of 3 inner and 2 outer turns, with the inner and outer layers separated by a 1.3 mm thick Teflon ring. The antenna has been placed in the downstream-most position to enhance plasma density near the outlet aperture as well as allow clearance for the addition of future magnetic confinement modules. This source body design was originally described in Ref. 12, which included an internal multicusp magnetic configuration which also served as a faraday shield. Experiments have shown that this configuration could not produce stable plasma so the multicusp magnet array was removed and replaced with a water-cooled backflange. The backflange mechanically supports a second-generation glow-discharge plasma gun which will be described in a subsequent publication (the first generation gun is described in Ref.13). The elemental Cs system employed here is very similar to the one described in Ref. 14 with the addition of air cooling of the Cs collar injector and a tantalum Cs vapor transfer line to support high duty-factor operation. The source also employs the baseline-LBNL outlet aperture assembly, shown in Fig. 1, which includes an electron dumping electrode and magnets as well as the filter magnetic field [5].
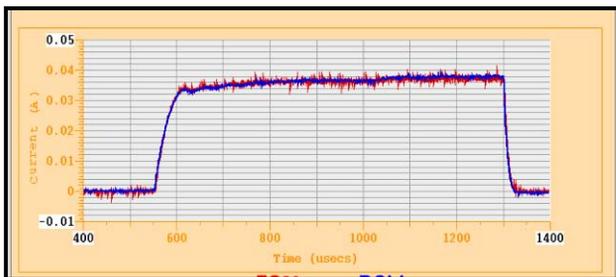
Figure 2: Extracted H⁻ beam pulse.

Fig. 2 shows a cesiated H⁻ beam pulse of parameters employed in the current SNS production run: 750 μs, 30Hz. Beam extraction measurements were performed on the SNS ion source test stand [15] employing the electrostatic Low Energy Beam Transport (LEBT) [11]. The red trace in the figure is a Faraday cup signal and the blue trace is from a toroidal Beam Current Monitor (BCM) both located at the LEBT exit. Fig. 3 shows the extracted, pulse-averaged, H⁻ beam current dependence on applied RF power for the large volume external antenna source (diamond points) with a pulse width of 750 μs and repetition rate of 30 Hz. For comparison, the square points in the figure also show the performance of the smaller SNS prototype external antenna source (plasma
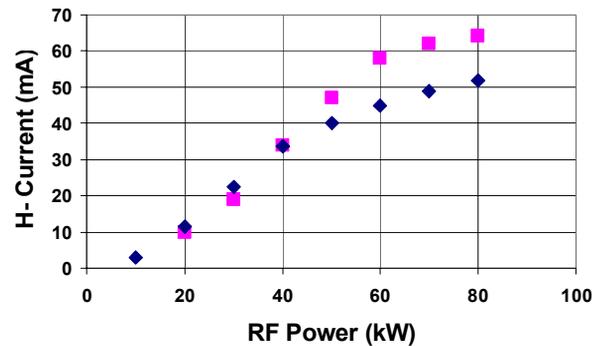
Figure 3: H⁻ beam current as a function of applied RF power pulse for both the source shown in Fig. 1 (diamonds) and the smaller prototype source in Ref. 11 (squares).

chamber: ϕ=4.8 cm x l=10 cm; Antenna: 6-turns) described in Ref. 11 and 16 when operated with Cs. Currently, both sources employ no magnetic confinement. Although the smaller prototype source had a better power efficiency than the larger source, it suffered from excessive pulse droop (30-50%) which could only be corrected by using the larger plasma chamber - a phenomena likely related to neutral starvation effects within the plasma. As seen in Fig. 2, the larger source produced pulses with essentially no droop and ~50 μs rise-times.

The large source shown in Fig. 1 was then subjected to a 3-week lifetime test where it consistently delivered beam currents of 25-35 mA (750 μs, 30 Hz) using an RF power of 40-50 kW and Cs oven temperatures of 100-130 C. The beam emittance was not measured due to lack of an operational emittance scanner. It is, however, expected to be similar to the baseline source (~0.2 π mm mrad RMS normalized at ~35 mA) since it employs the same outlet aperture assembly and the plasma ion temperature is expected to be the same or less than that of the baseline internal antenna source. Unfortunately, due to the lack of an internal water-cooled Faraday shield as proposed in the original design [11], the plasma chamber could not withstand more than 3.25 kW of average RF power (pulse RF power x duty-factor). The chamber cracked as a result of thermal stress near the antenna. The smaller prototype source in Ref. 11 also failed twice at ~2.4 kW of average RF power using air-cooling.

FULL-POWER VERSION

Fig. 4 shows the design of a full-power version of the source shown in Fig. 1. This source design is similar to the earlier version with the exceptions that: the plasma chamber is constructed from AlN; water cooling is present throughout the source body; and the Lexan water-cooling gallery is a more efficient design. The configuration shown in Fig. 4 has been extensively modeled using coupled computational fluid dynamic, heat transfer, and thermal stress simulations utilizing finite element analysis
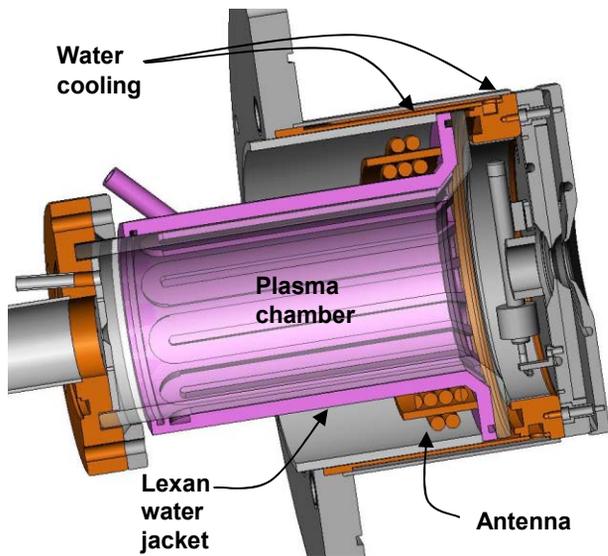
Figure 4: Full-power version of the Large Volume External Antenna Source shown in Fig. 1.

(FEA) [17].   The simulations were first used to successfully model the failures of the Al_2O_3 sources and then applied to the new design.   The AlN source shown above was found to be capable of withstanding 100kW at 7% duty factor while maintaining a thermal-stress-safety-margin of ~2x, easily meeting our requirements.

HIGH-EFFICIENCY EXTRACTION SYSTEM

In order to ensure we can meet the SNS facility beam current and emittance requirements, the baseline extraction system must be improved. Previous analysis has shown that having a high electric and low transverse magnetic field at the outlet aperture of the source is required for efficient extraction [11]. Fig. 5 shows the current extraction system design which has evolved from a collaborative effort [18] to reduce the emittance of the system proposed in Ref. 11. The current design was developed using the software listed in Ref. 17 and features the following improvements over the baseline-LBNL extraction system: ~3x higher electric field at the outlet aperture; elimination of the transverse dumping magnetic field at the outlet; and ~50% less emittance growth calculated at 80mA compared to the baseline system calculated at 40 mA. Both systems dump the co-extracted electron beam at the same energy and employ an electron-dumping power supply tied to source potential. The plasma meniscus shape calculated in PBGUNS (2D) is imported into the 3D Lorentz code and both electrons and ions are flown in the presence of their mutual space charge. The Lorentz code is also used to design the inhomogeneous, transverse, electron-dumping magnetic field (~400G) in order to spread electron bombardment over a larger surface area. The heat loads are then imported into the Cosmos software which is used to determine the cooling requirements [17].
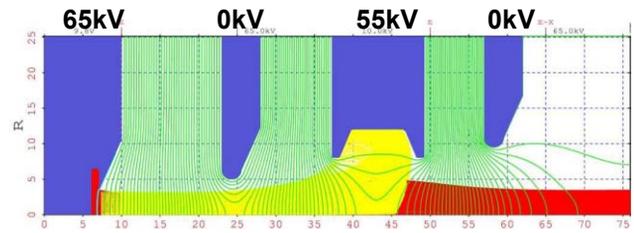
Figure 5: 2D PBGUNS simulation of the proposed extraction system. Red trajectories are H⁻ ions and yellow are electron beam (quasi 3D).

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