RF-Plasma Coupling Schemes for the SNS Ion Source

R. F. Welton, M. P. Stockli, S. Shukla, Y. Kang

Accelerator Systems Division, Spallation Neutron Source
Oak Ridge National Laboratory, Oak Ridge, TN, 37830-6473

R. Keller

Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Abstract. The ion source for the Spallation Neutron Source (SNS) is a radio frequency, multi-cusp, source designed to deliver beams of 45 mA of H^- with a normalized rms emittance of 0.2 π mm mrad to the SNS accelerator. RF power with a frequency of 2 MHz is delivered to the ion source by an 80 kW pulsed power supply generating nominal pulses 1 ms in width with a 60 Hz repetition rate. The ion source, designed, constructed and commissioned at Lawrence Berkeley National Laboratory (LBNL), satisfies the basic requirements of commissioning and early operation of the SNS accelerator. In order to improve reliability of the ion source and consequently the availability of the SNS accelerator and to accommodate facility upgrade plans, we are developing optimal RF – plasma coupling systems at the Oak Ridge National Laboratory (ORNL). To date, our efforts have focused on design and development of internal and external ion source antennas having long operational lifetimes and the development and characterization of efficient RF matching networks.

INTRODUCTION

The Spallation Neutron Source (SNS) is a second generation pulsed neutron source dedicated to the study of the dynamics and structure of materials by neutron scattering and is currently under construction at Oak Ridge National Laboratory (ORNL) [1,2]. Neutrons will be produced by bombarding a liquid Hg target with a 1.4 MW, 1 GeV proton beam produced using a series of linear accelerators and an accumulator ring [3,4]. SNS performance upgrades are being discussed where 3-5 MW of beam power would be required.

In order to meet the 1.4 MW baseline requirement, the ion source must deliver ~45 mA of H^- within a 1-ms pulse (60 Hz) into a normalized rms emittance of 0.2 π mm mrad. This report discusses collaborative ion source development efforts undertaken between ORNL and LBNL, focusing specifically on the ion source RF – plasma coupling systems: antenna and matching network.

THE H⁻ MULTICUSP ION SOURCE

A schematic diagram of the H^- Ion Source is shown in Fig. 1. The source plasma is confined by a multi-cusp magnetic field created by a total of 20 samarium-cobalt magnets lining the cylindrical chamber wall and 4 rows of magnets lining the back plate. RF power (2 MHz, 20-50 kW) is applied to the antenna shown in the figure through a transformer-based impedance-matching network. A magnetic dipole (150-300 Gauss) filter separates the main plasma from a smaller H^- production region where low-energy electrons facilitate the production of large amounts of negative ions. A heated collar, equipped with eight cesium dispensers, each containing ~ 5 mg of Cs_2CrO_4, surrounds this H^- production volume. The RF antenna is made from copper tubing which is water cooled and coiled to 2 1/2 turns. A porcelain enamel layer insulates the plasma from the oscillating antenna potentials. More details of this source design can be found in reference 5.

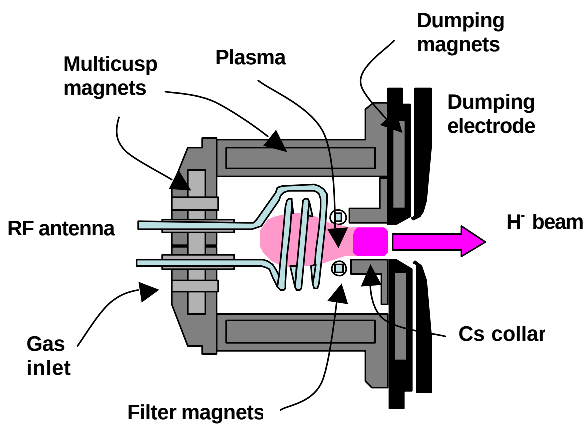


FIGURE 1. Schematic diagram of the SNS ion source.

RF ANTENNA DEVELOPMENT

The multicusp, RF-driven, positive/negative ion sources developed at LBNL have performed quite well in a wide variety of applications [6]. Most of these applications have involved low duty-factor, pulsed operation in which, thinly coated (100-200 um) porcelain enamel coatings were sufficient to guarantee long operational lifetimes. SNS operations at nominal parameters, on the other hand, require long pulses (1 ms) and high repetition rates (60 Hz) where these antennas tend to have a severely shortened lifetime, in some cases only several hours. In a collaboration between LBNL and ORNL we began improving the lifetime of this ion source component. Detailed accounts of this work can be found in an earlier report [7], and we will only summarize here.

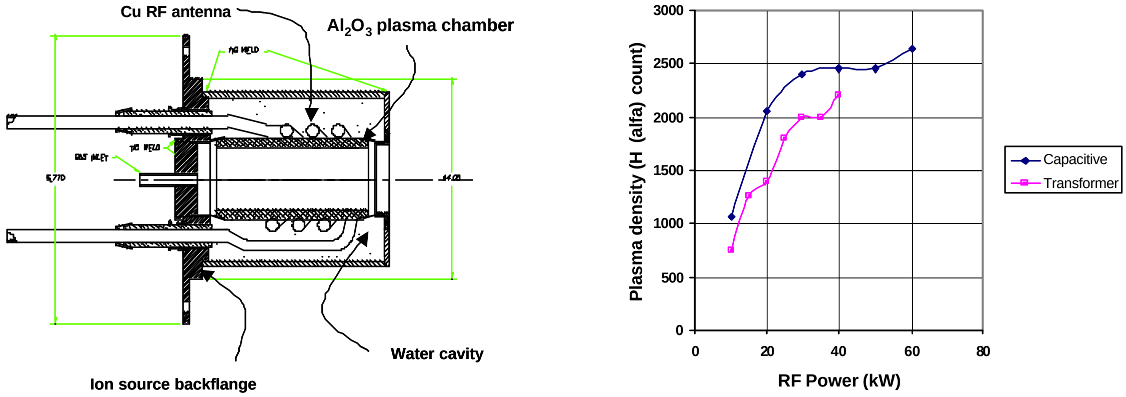
Electromagnetic modeling has shown that a 1-2 kV RF potential develops across the length of the antenna due to its inductance. Large RF electric fields can develop between different parts of the antenna and between the antenna and the plasma chamber, since one leg of the antenna is grounded to the plasma chamber through a small resistor. If the antenna coating is not sufficiently thick or has too large a dielectric constant the majority of this electric field will exist within the plasma sheath as opposed to within the insulating coating. Large electric fields in the plasma sheath accelerate charged plasma particles into the coated antenna, causing sputter ejection of the coating materials as well as vaporization of the coating material from localized heating. Eventually, a thin spot in the coating develops which enhances the electric field, driving the process until a hole is burnt through the coating. Once bare conductor of the antenna is exposed to the plasma, the plasma itself can conduct a significant portion of the RF current normally carried by the antenna and thereby greatly reduce the inductive power coupling to the plasma.

Quantitative models have been developed and applied to fusion plasmas to determine the fraction of a given electric field which exists within the plasma sheath, versus the field inside a dielectric wall material [8]. Using the plasma parameters of the SNS source and material properties of the porcelain enamel coating it has been shown that essentially all of the electric field within the plasma sheath can be eliminated provided the following two conditions are met [7]. First, the coating is sufficiently thick, greater than 0.5 mm, several times the thickness of the original coating. Second, the dielectric constant of the porcelain is reduced by removal of the TiO_2 (K=86) component from the porcelain mixture.

Based on these calculations, a local company [9] developed a multi-layer coating technique to achieve the specified coating thickness and composition. Since TiO_2 is added to porcelain enamel mixtures purely as a color pigment with no structural importance, it was easily eliminated from the mixture resulting in a coating that appears clear. This approach has yielded coatings as thick as 1 mm which was achieved through the successive application of ~10 enamel layers.

To date antennas fabricated in this fashion have allowed the successful commissioning of the front end of the SNS at LBNL (~500 hours of operation) and again at ORNL (~1000 hours of operation) [10]. In addition to these accelerator-commissioning activities, which have generally required low duty-factor operation, we have also performed several high duty-factor lifetime tests. On one occasion, the source operated continuously for 107 hours with ~25 kW of applied RF power at the full 6% duty factor with no visible damage to the antenna observed. During the last few hours of the test a ~25 mA beam was extracted from the source. Another such test also occurred at LBNL on the front end system where the source was operated for 125 hours at 2-3% duty factor, again producing ~25 mA with no antenna damage visible.

To insure an adequate ion source lifetime at the nominal SNS beam current and duty factor, in the absence of specific lifetime tests, we have developed a contingency strategy for coupling RF power into the source: use of an external antenna. This approach is similar to that employed at DESY for their very low duty factor application [11]. To date, thermal and mechanical finite element analysis has been performed on an Al_2O_3 plasma chamber to determine an optimal design. One such design, shown in Fig. 2, was developed in conjunction with designers at ISI Corporation. The design features an alternative ion source backflange where the helical antenna is submerged in de-ionized water surrounding an Al_2O_3 plasma chamber. This system is currently under consideration for development.



a. **b.**

FIGURE 2. (a) Initial design of the SNS external RF antenna and (b) Comparison of the optimal RF coupling which could be achieved by each matching network (see text).

RF MATCHING NETWORKS

Efficient power transfer between the RF generator and ion source antenna is extremely important since the extracted H^- current is, to first order, directly proportional to the RF power coupled to the plasma [6]. We have investigated two alternative schemes to accomplish this coupling: (i) a transformer based matching network and (ii) a simple capacitive voltage divider circuit. Both matching networks were developed at LBNL and described in detail in reference 12 but have not yet been critically evaluated for plasma generation efficiency at power levels required by the SNS ion source.

Briefly, the transformer-based network (i) directly excites the primary windings of a ferrite transformer (6 turn). The secondary winding (1 turn) is attached to a series LC circuit which includes the ion source antenna (inductance) and a variable vacuum capacitor (50-2300 pF) which is adjusted to allow the circuit to resonate at 2 MHz. The impedance matching is accomplished by varying the turn number of the ferrite transformer. The other matching network, (ii) consists of a parallel LC circuit where a vacuum capacitor (1100-2500 pF) is resonated with an inductance, which includes the ion source antenna. The impedance of the RF generator is matched to that of the parallel LC circuit by a second vacuum variable capacitor (50-2300 pF) which is connected between the generator and LC circuit.

Figure 2b shows a comparison between the relative plasma densities that could be achieved using each individually optimized matching network. Each network was electrically tuned for optimum power transfer and the H_2 flow was held at 15 SCCMs as required for optimal H^- production. Water-cooling was added to several components of the capacitive voltage divider matching network to allow operation at high power levels. The relative plasma density was monitored by observing the Balmer-α line emitted from the plasma by using an optical spectrometer. Fig. 2b clearly shows the capacitive network is capable of more efficient coupling to the source and is also stable at higher total RF powers. At a nominal operating power of 30 kW the capacitive network produced a ~20% denser plasma than the transformer-based network currently employed. Based on these findings we will consider the benefit of ultimately switching to the lower-loss capacitive system.

REFERENCES

1. SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.
2. SNS is a collaboration of six US National Laboratories: Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Thomas Jefferson National Accelerator Facility (TJNAF), Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), and Oak Ridge National Laboratory (ORNL). SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.
3. Holtkamp, N., et al., "The SNS Linac and Storage Ring: Challenges and Progress Towards Meeting Them", *Proceedings of the European Particle Accelerator Conference*, EPAC'02, Paris, France, ID: 191 - TUZGB002.
4. White, M., "The Spallation Neutron Source (SNS)", *Proceedings of the Linear Accelerator Conference*, LINAC '02, Gyeongju, Korea, ID: MO101
5. Keller, R., et al., "Ion-source and LEBT Issues with the Front-End Systems for the Spallation Neutron Source", *Rev. Sci. Intrum.* **73**, 914 (2002)
6. Leung K.N., "The Application and Status of the Radio Frequency Multicusp Source", *Rev. Sci. Intrum.* **71,** 1064 (2000)
7. Welton, R.F., et al., "Ion Source Antenna Development for the Spallation Neutron Source", *Rev. Sci. Intrum.* **73,** 1008 (2002)
8. J.R. Myra et al., J. Nucl. Mater. 249 (1997) 190
9. Cherokee Porcelain Enamel Corporation, 2717 Independence Lane, Knoxville, TN 37914
10. A. Aleksandrov, "Commissioning of SNS Front End Systems at ORNL", PAC 2003.
11. J. Peters, "Internal versus External RF Coupling into a Volume Source", EPAC'02, Paris, France, ID: 710 – THPRI025.
12. J. Staples, "High-Efficiency Matching Network for RF-Driven Ion Sources", *Proceedings of the Particle Accelerator Conference*, PAC '01, Chicago, USA, ID: WPAH014