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Ion Source Development for the Spallation Neutron Source

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SENIOR PROJECT - APPROVAL

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PROJECT TITLE: Ion Source Development for the Spallation Neutron Source

I have reviewed this completed senior honors thesis with this student and certify that it is a project commensurate with honors level undergraduate research in this field.

Signed: [Signature] (W. G. Blass), Faculty Mentor

Date: May 5, 2003

Comments (Optional):
Ion Source Development for the Spallation Neutron Source

Sonali J. Shukla
University Honors Program
Senior Honors Thesis
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Abstract

The ion source for the Spallation Neutron Source (SNS), initially developed at LBNL, is undergoing continuing development at ORNL. The ion source is a radio frequency (RF), multi-cusp, source designed to deliver 35-50 mA pulses of H+, 1 ms in length, at a repetition frequency of 60 Hz to the SNS accelerator. Short antenna lifetime has become a central issue in the continuing development of the SNS ion source. Under nominal operating conditions of high duty factor (6%) and high RF power (30 kW), antenna lifetimes have been measured to be on the order of several hours versus the SNS requirement of several hundred hours. Antenna failures have come as a result of “hot spots” or holes burned through the coating. Rather than continue to qualitatively “estimate” the material and geometrical parameters of a suitable coating, we have developed quantitative electrical, thermal, and mechanical models of the plasma interaction with the antenna coating and of the coating fabrication process. Similar models have been used in the past for selection of material and coating properties of plasma facing, RF antennas used for Ion Cyclotron Resonance heating (ICR) in fusion machines. This modeling allows determination of the desirable material and dimensional properties of the coating. We are working closely with the Metals and Ceramics division at ORNL and Cherokee Porcelain Inc. to develop a coating that fulfills the requirements determined by the modeling. Currently, a multi-layer TiO₂ free coating has run for 107 hours in the LBNL ion source.

Efficient H+ generation occurs when RF pulses with a frequency of 2 MHz and peak power of 20-50 kW are coupled into a low density plasma created by continuous application of approximately 100W of 13.6 MHz power. Coupling is achieved by a
plasma immersed RF antenna and a dedicated matching network. Large H\(^+\) beam currents can only be achieved by operating the 2 MHz RF power generator at high power levels (\(\sim 1\) mA / kW). Operating the RF generator at high power levels shortens the lifetime of the generator and associated RF components reducing the availability of the SNS accelerator. This experimental work presents a characterization of two competitive RF matching schemes: the traditional transformer-based matching network used in conjunction with a porcelain-coated helical antenna and a purely capacitive, lossless, matching network used with a similar antenna. In final form, both matching networks ran stability, sustaining plasma for long periods of time. Relative plasma density measurements by optical spectroscopy were performed as a function of source gas flow, RF power and network matching parameters. Under comparable operating conditions the capacitive network was found to be approximately twice as efficient as the traditional transformer-based network. Both networks required significant modification from their original form to achieve stable operation at full duty factor. From an operational point of view, this work represents the initial commissioning of the hot spare stand for the SNS ion source with plasma.
Introduction

Neutron sources have long been used to study the properties of matter, but present day neutron facilities do not adequately meet the needs of scientific and industrial researchers. The Spallation Neutron Source (SNS) is a new accelerator-based neutron scattering facility that will provide the world’s brightest pulsed neutron beam. Since the SNS will be a state of the art accelerator facility, each component of the SNS must be as robust and reliable as possible. The ion source for the SNS was developed at Lawrence Berkeley National Laboratory (LBNL). It is a multi-cusp, RF source designed to deliver 35-50 mA pulses of H-, 1ms in length, at a repetition frequency of 60 Hz to the SNS accelerator. About 100 W of 13.56 MHz RF power is continuously applied to a porcelain-coated helical antenna to create a low-density plasma followed by the application of high power RF pulses by a 2 MHz generator. This increases the density of the plasma and allows for the extraction of H- ions by a constant accelerating potential. A small amount of hydrogen gas is also released into the source chamber to facilitate H+ production (see Figure 1).

Figure 1: Cross section of ion source
**Background – Antenna Development**

The operational lifetime of a RF ion source is generally governed by the length of time the antenna survives during exposure to plasma. Coating the antenna with a thin layer of insulting material is a common means of extending the life of such ion source antennas. In many applications of low power and low duty factor RF excitation, antenna lifetimes are generally on the order of a few hundred hours. However, the SNS requires higher power (above 30 kW) and high duty factor (6%), significantly reducing the lifetime of the ion source. In order to create a suitable antenna, we performed a microanalysis of failed antennas from the SNS, developed a model of the damage mechanism based on plasma-insulator interactions and used the model to determine the properties of an ideal coating.

First, several antennas that had failed in the LBNL source were analyzed. These antennas had a thin porcelain coating and tended to last for several hours. After being removed from the source, one observed several localized areas on the antenna where the plasma had burned through the porcelain coating to the copper. Once the plasma makes contact with the copper, the source no longer produces a high-density plasma, and the antenna must be replaced. With the assistance of the Metals and Ceramics department at ORNL, we prepared samples of the damaged regions of several antennas using standard metallographic techniques of cutting and polishing.

These samples revealed both damaged and undamaged regions of the antenna (see Figure). The damaged regions suggest that the enamel porcelain exceeded its melting point and became electrically conductive in the liquid state. Antenna failure occurs when a defect in the coating locally enhances the electric field in that region.
Figure 2: Cross section of damaged “hot spot” on antenna

Positive ions from the plasma accelerate into the antenna surface due to the negative cycle of the RF and cause sputtering and secondary electron emission. If adequate plasma sheath potential is present, this flux of ejected particles cause a “hot spot” on the surface of the antenna coating. This hot spot subsequently heats and causes further penetration into the antenna coating. Such destruction of the coating would not occur if the voltage drop across the RF plasma sheath were not sufficient enough to initiate and force the destruction. In order to reduce this type of failure, an analysis of the electrical properties of the antenna coating was performed. An ideal electrical coating would have the potential difference fall across the coating rather than the plasma sheath, thus reducing the appearance of hot spots on the antenna coating. Other optimizations were performed to create ideal thermal properties and mechanical properties for adhesion to the copper antenna. The results of the sheath-
insulator model are shown in the figures below. In order to reduce the plasma sheath potential, porcelain enamels must be approximately 1 mm thick. The dielectric constant should be less than 30 and the required electric resistivity should exceed $10^3 \Omega \cdot m$. (Figure 3 and 4). In a thermal analysis, it was shown that increasing the coating thickness to one millimeter would not affect conductivities (Figure 5).

In a mechanical analysis, an ideal coating should have a large thermal expansion coefficient to match that of copper, high compressive and tensile fracture strength, low elastic modulus, and a coating thickness greater than 200 microns (Figure 6).

$$\Delta T = \frac{q \Delta x}{k}$$

Figure 3: Electrical analysis
Figure 4: Results of electrical analysis

Figure 5: Results of thermal analysis
Background – RF coupling schemes

In order to comply with the requirements of the SNS, the ion source must effectively couple radio frequency (RF) power into the plasma. Since the impedance of the load, determined by the plasma density, is always changing, RF matching becomes a difficult issue to resolve. Only with a dedicated matching network can the impedance of the source be matched to the load allowing for maximum power transfer. At Lawrence Berkeley National Laboratory, two matching networks were developed to couple the RF power through the antenna to the plasma, the traditional transformer-based matching network and an experimental capacitive matching network. This research investigates two matching networks designed to couple the RF power to the plasma. By characterizing each matching network through spectroscopic analysis, one can note the relative efficiency of plasma coupling. With effective plasma coupling, the overall lifetime and stability of the ion source and supporting systems are increased.
**Experimental Apparatus and Methods**

The crux of this experiment was to compare and contrast the efficiencies of the two matching networks to couple the RF power of both the 13.56 MHz and 2 MHz pulsed generator to the plasma. In order to do so, both networks had to first be optimized. As no extraction system has been set up on the hot spare stand source to date, an optical spectrometer was used to directly view the plasma through a window on the plasma chamber. The plasma density gives the most direct indication of RF matching. Other measurable parameters, such as beam current, involve factors other than the RF power input. The intensity of the light emitted is directly proportional to the plasma density and was used to indicate effective power transfer in these studies. The antenna current, measured through a Pierson transformer on one of the antenna legs, is indicative of the amount of beam that can be extracted from the source. Thus plasma density and antenna current were the notable outputs in this experiment.

The traditional transformer-based matching network uses a ferrite transformer in series with an inductance. A variable capacitor is used to tune the resonance of the circuit to the changing load (see Figure 7).

![Figure 7: Circuit diagram of transformer-based matching network](image-url)
Significant modifications had to be made to Berkeley’s design in order to transmit 2 MHz RF power into the plasma. By varying the number of turns in the secondary windings of the transformer, a maximum plasma density was achieved. The matching network currently at the front end has six windings in its secondary loop. However, for the hot spare stand, four windings produced the optimum plasma density. The number of turns in the series inductor was also varied, again to find the maximum output of plasma density (see Figure 8).

![Figure 8: Optimization of transformer-based matching network](image)

An experimental capacitive matching network was also developed at LBNL, although development was discontinued because stability was never reached. The network consists of a capacitive voltage divider in series with a large inductor. The series inductor is large compared to the antenna equivalent series inductance, which changes plasma conditions, and stabilizes the resonant frequency of the network (see Figure 9).
Both capacitors for the 2 MHz channel of the matching network were varied until an optimum combined capacitance was found (see Figure 10). Significant modifications had to be made in order to use the matching network with a thick-coated antenna as opposed to the traditional thin-coated antenna (see Figure 11). The water-cooling system was also rerouted to avoid overheating that occurred at the high duty.
factor. In both matching networks, the 13.56 MHz matching networks did not need significant modifications or tuning after the initial lighting of the plasma.

![Graph showing Plasma Density vs Capacitor Settings](image)

**Figure 11:** Optimization of the capacitive network with thick-coated antenna

**Results and Discussion**

After each network was optimized for maximum plasma density, a series of tests were performed varying the input 2 MHz RF power and hydrogen gas flow. For each forward power level (kW) and gas flow (sccm) the plasma density and antenna current were noted (see Figure 12 and 13). Both the plasma density and antenna current were found to be greater in the capacitive matching network. Overall, the capacitive network produced ~20% higher plasma density and ~50% higher antenna current than the transformer based network.
Figure 12: Capacitive matching network
Figure 13: Transformer-based matching network

All of the power and pressure variance tests were performed at 100 microseconds pulse width and 10 Hz pulse repetition rate. When the ion source is producing beam for the SNS, it will be running at 6% duty factor, 1 millisecond pulse width and 60 Hz pulse repetition rate. Both networks ran stably at high duty factor and forward power of ~25 kW. The capacitive matching network ran on the order of 20 hours, at power levels of both 25 kW and 34 kW. The transformer-based network was tested for ~10 hours at 25 kW (see Figure 14). Both networks required modification, mainly in cooling networks, before they were operational at the high duty factor. Neither network failed completely; rather each endurance test was prematurely ended in the interest of time.
In addition to testing the stability, robustness, and capability of the matching networks, this research project also tested several types of RF antennas developed at ORNL. The RF antenna for the SNS ion source has traditionally been a helical copper coil coated with a thin insulating layer of porcelain. The antenna coated by an Oakland company in Berkeley lasted only about 10 hours in the source and was not tested at the high duty cycle. A Knoxville-based company, Cherokee Porcelain, produced a thick-coated antenna that had ~ten layers developed from the analysis outlined above. On the thick antenna, "machinable" Al$_2$O$_3$ antenna leg holders were tested. The holders cracked under stress, evaporating material into the ion source. This deposited a layer of material on the thick-coated antenna but did not destroy it. This antenna lasted over 30 hours in the source and is still in usable condition. A new transverse antenna design was also tested. Studies show that the transverse design would lower the electric field on critical portions of the antenna where damage most often occurred (Welton 2002). However, the transverse antenna was 5 mm from the nearest plasma chamber structure whereas the
typical helical antenna had an 11 mm gap. This caused the transverse antenna to arc to the chamber wall, but still stably produced plasma.

Conclusion

For the first time, the RF/plasma systems of the ion source hot spare stand were brought to an operational state using both alternative coupling schemes. The capacitive network was more stable at higher RF powers (60 kW versus 40 kW), producing a ~20% higher plasma density and ~50% higher antenna current. At constant power 40 kW and gas flow of 30 sccm, the capacitive network produced ~10% higher plasma density and ~20% higher antenna current. The thin-coated Oakland antenna proved vulnerable to start-up conditions failing after a few hours. The thick-coated antennas, from Cherokee Porcelain in Knoxville, were not damaged in the experiments and are still in usable condition.
**Selected References**


“Ion source antenna development for the Spallation Neutron Source”, Welton et al., RSI 73 (2002) 1008

