RF H⁻ ION SOURCE WITH SADDLE ANTENNA*

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Abstract

In this project we are developing an RF H^- surface plasma source (SPS) which will synthesize the most important developments in the field of negative ion sources to provide high pulsed and average current, higher brightness, longer lifetime and higher reliability by improving a power efficiency. Several versions of new plasma generators with different antennas and magnetic field configurations were tested in a small AlN test chamber in the SNS ion source Test Stand. Then a prototype saddle antenna was installed in the Test Stand with a larger, normal-sized SNS AlN chamber that achieved a peak current of 67 mA and an apparent efficiency of 1.6 mA/kW. These values are comparable to those of the present SNS sources and can be expected to be improved when the prototype is developed into an operational version in the next phase of the project.

INTRODUCTION

Typical RF sources for H^- generation have a coil antenna, which creates an RF magnetic field along the axis of the source. The upgraded SNS H^- source with internal coil RF antenna can deliver pulsed average beam currents of up to 56 mA into the Medium Energy Beam Transfer (MEBT) line, with an estimated efficiency of >1.3 mA/kW [1]. Occasional failures of the internal antenna limit the source service cycle to >700 hours, and the availability of the source to 99.8% when operating with 50-65 kW of RF power.

To increase the service cycle, and to increase the availability to >99.9%, SNS developed an external antenna source, which yielded unanalyzed average beam currents up to 95 mA with efficiencies up to 1.8 mA/kW [2]. A recent version of the RF SPS with external antenna and AlN discharge chamber is shown in Fig. 1, and has about the same efficiency of ion beam generation. The necessary RF power is high, which can create problems for very long-term SPS operation [3].

These problems are being addressed by development of new RF plasma generators with higher plasma generation efficiency and more useful flux onto the internal surfaces of the collar around the emission aperture at lower RF power [4]. In this project, we use a saddle antenna, which has its RF magnetic field transverse to the source axis, combined with an axial DC field, to concentrate the plasma on the collar where the ions are formed [5].

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EXTERNAL ANTENNA SOURCE

The total efficiency of the surface-produced fraction of the H^- beam is a product of the coefficient of secondary emission of H^- caused by plasma bombardment of the collar surface around the emission aperture, the probability of extraction of emitted H^-, and the efficiency of generation of plasma flux bombarding the working surface of the collar. The coefficient of secondary emission of H^- is determined by surface properties (proper cesiation) and the spectrum of the plasma particles bombarding the collar surface around the emission aperture. The SNS cesiation was improved recently [1] and appears to be nearly optimal (however, improving of cesiation is always important). The probability of extraction of H^- emitted from the collar surface is dependent on the surface collar shape [1,2,4-6], which was optimized recently to improve H^- emission [1].

The strong transverse magnetic field (up to 1.6 kG) created in the collar emission aperture by permanent damping magnets (in Fig. 1) should be enough to filter out the fast electrons from the discharge plasma and to decrease the number of escaping co-extracted electrons. The gas density in the discharge plasma should be low to minimize the recombination of the H^- ions with the positive ions and to minimize electron stripping of the extracted H^- ions. This critical gas density is inversely proportional to the emission aperture dimension. The gas density in the extraction-acceleration region was decreased by improving the gas pumping but a further decrease is desirable to reduce the ~7% stripping losses in the SNS low energy beam transport section. One possibility to decrease the necessary RF power is to enhance the generation efficiency of the plasma flux bombarding the internal collar surface (see Cs collar in Fig. 1).

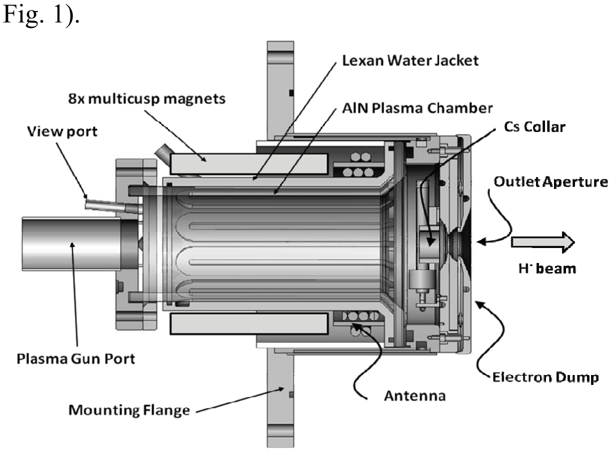

Fig.1: SNS RF SPS with external antenna plasma generation and with multicusp plasma confinement (AlN ceramic chamber).

RF PLASMA GENERATORS

Several versions of new plasma generators with different antennas and magnetic field configurations were fabricated and tested in the test stand with useful plasma flux generation improvements up to 5 times by increasing the DC magnetic field.

Small RF Plasma generators

Discharges in a small (30 mm ID) AlN ceramic discharge chamber with coil and saddle antennas were studied in pulsed mode. An RF generator with frequency f=13.56 MHz, output power up to P=1.2 kW, pulse 3 ms, 5 Hz was used. The ion current extracted through a small (2 mm diameter) emission aperture with extraction voltage -3kV was measured as a function of H_2 gas flow and RF power.

Use of a small permanent ring magnet 12 cm from the extraction aperture was tested with small coil and saddle antennas. The ring magnetic field increased the plasma density and decreased significantly (up to 20 times) the gas density necessary for discharge triggering (self-triggering without external plasma generator).

The emission current density to the collector was as high as $J_c \sim 60$ mA/cm^2 at $P_{rf} \sim 1$ kW, which is up to 5 times higher than without the ring magnetic field. These plasma sources can be used for pulsed discharge triggering at very low gas density.

Large RF Plasma generators

The schematic of a large RF plasma generator with the AlN ceramic discharge chamber, prototype saddle antenna, and DC magnetic coil is shown in Fig. 2. The chamber has an ID=6.8 cm. The saddle antenna in this prototype plasma source was made from Litz wire, with inductance L=2.7 µH.

The plasma density distribution was measured by a system of collectors of ion beam current extracted through small emission apertures in the end plate attached to the discharge chamber (Fig. 2). The end plate had seven 2 mm diameter emission apertures so that the gas consumption is about half that of the SNS source with a 7 mm diameter outlet.

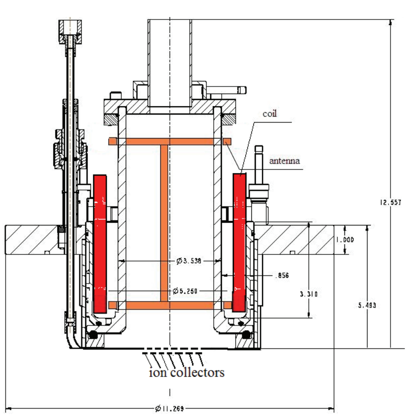

Fig. 2: Schematic of discharge chamber with end plate and collectors showing the saddle antenna (orange) and DC magnetic coil (red).

The DC magnetic field was created by a magnetic coil wound from a copper tube of 4-mm OD in two layers with 25 turns per layer.

Experimental Results

Oscilloscope traces of collector currents at high magnetic field are shown in Fig. 3. The collector current increased up to 5 times, from 12 mA/cm^2 to 60 mA/cm^2, as the magnetic field increased from 0 to 250 G.

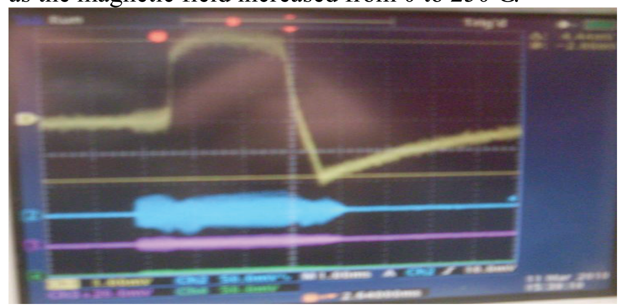

Fig. 3: Oscilloscope trace of collector current I_c at high magnetic field (I_m=70A).

The ion current density distributions for different magnetic fields are shown in Fig. 4. For low magnetic field (I_m up to 20A) the radial distribution of plasma density is flat. For higher magnetic fields, the plasma density inside 2 cm radius is much higher.

The same increase of ion current density on the axis with increasing magnetic field was observed in saddle antenna discharges at f=5 MHz.

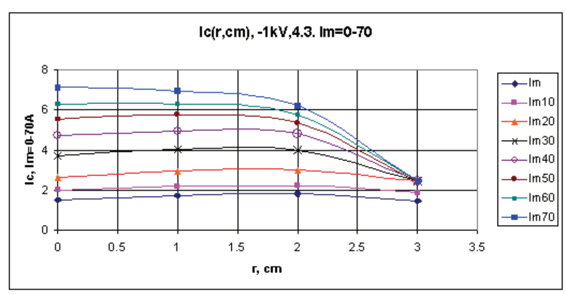

Fig.4: Radial distribution of current density of extracted positive ions for different magnetic fields (coil current I_m), as determined from the 7 collectors.

SA RF SPS IN THE TEST STAND

The prototype of the saddle antenna RF H^- SPS (SA RF SPS) was tested in the SNS test stand as shown in Fig. 5. The first tests used a plasma plate with a molybdenum conical collar with a 300 G magnetic filter and a 1.6 kG electron dumping magnet. The DC magnetic coil was excited by a manually regulated current supply (I_m =0 to 74 A) and was cooled by water flow. A plasma gun with DC glow discharge was used for the pulsed RF discharge triggering at low gas density.

A pulsed RF (2 MHz) discharge with duration 0.3 ms, 10Hz and power up to 56 kW was used. Stable, reproducible generation of H^- beam was reached. An example of an H^- beam current pulse is shown in Fig. 6. The pulse shape depends on gas flow, magnetic field, and RF matching network tuning.

The current measured by the Faraday cup I_{fc} increased by a factor of ten as the longitudinal magnetic field B was increased from 0 to 250 G. The plasma gun operated as the gas flow was decreased down to Q=8.8 sccm (standard cm^3/minute), while the H^- current increased up to 15 mA at P_{rf}=15 kW (H^- generation efficiency I_{fc}/P_{rf} = 1 mA/kW before cesiation).

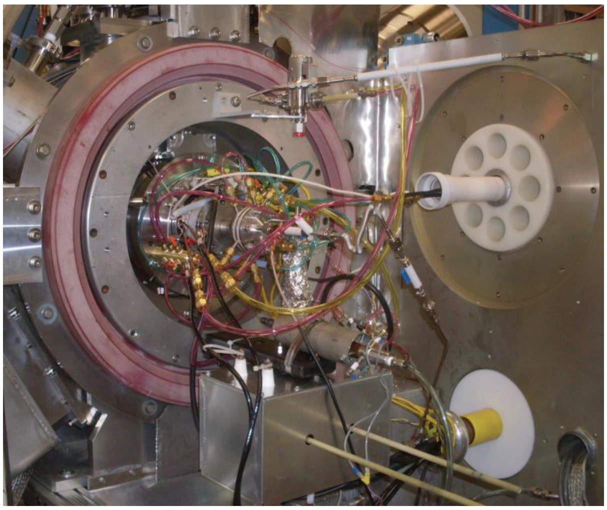

Fig.5: RF SPS saddle antenna, magnetic coil, and external Cs source attached to the test stand.

The magnetic field from the DC coil is below 50 G at the emission aperture and does not change the suppression and deflection of co-extracted electrons by the dumping magnetic field at B_d=1.6 kG

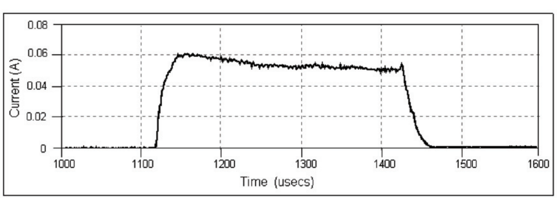

Fig. 6: Example of the H^- current pulse (10mA/div) as measured by the Faraday cup.

After a "partial" cesiation by cracking the Cs ampoule, I_{fc} increased by about 50% instead of the expected typical increase of a factor of 3 or 4.

In the next experiments, the magnetic filter was removed and a ferromagnetic ring was located around the collar to improve the concentration of plasma flux into the collar. After starting the RF discharge with P_{rf}=25 kW the initial beam current I_{fc}=12 mA started growing and increased up to 42 mA over 4 hours without cracking the cesium ampoule, mostly likely due to residual Cs from the previous experiment. Stable operation of the prototype of RF H^- SPS with the saddle antenna and longitudinal magnetic field was successfully demonstrated up to RF power 56 kW, 0.3 ms, 10 Hz.

The dependence of beam current versus RF power is shown in Fig. 7. Without cracking the cesium ampoule, but likely with Cs from the previous experiment, the efficiency ratio achieved I_{fc}/P_{rf} ~ 1.6 mA/kW, which is comparable with SNS RF discharges in similar conditions. We believe that perfect cesiation was produced (without additional Cs) by the collection and trapping of traces of cesium remnants from SPS surfaces. Long conditioning is necessary because cesium is only slowly recovered from remnants. This slow accumulation demonstrates that the lifetime of these catalytic impurities in the collar can be very long. Nanograms of impurities are enough for enhancement of secondary emission of negative ions from the collar surface. This process efficiently works for other impurities with low ionization potentials such as K, Na, Ba, and La [6,7]. This cesiation from contamination was so perfect that H^- generation efficiency could not be improved significantly by cesiation after cracking of the cesium ampoule. A small contamination of ceramic such as 0.01% of K_2O can dominate "volume" surface plasma generator RF sources [8].

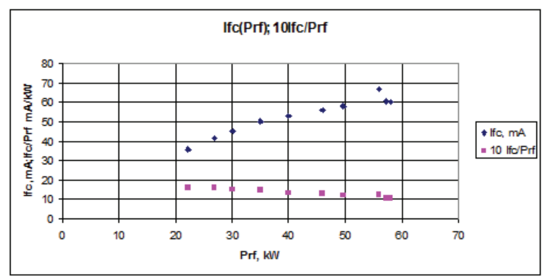

Fig.7: Evolution of the Faraday cup current I_{fc} and ratio I_{fc}/P_{rf} as function of P_{rf} during cesiation. The efficiency of I_{fc} generation increased with decreased gas flow Q from 20 sccm to 17.2 sccm.

The beam intensity increased significantly with decreased gas flow Q below 9 sccm, but the plasma gun discharge became unstable for Q<19 sccm. For operation at lower Q it is possible to use the small RF plasma generator described above for triggering. All measurements of beam intensity and RF power reported here were collected under the same conditions as for recent measurements with other SNS RF SPS for correct efficiency comparisons. Further design and operation optimization of the SARF SPS will improve its efficiency.

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