OPTIMIZATION OF SURFACE PLASMA SOURCES FOR EFFICIENT PRODUCTION OF NEGATIVE IONS WITH HIGH EMISSION CURRENT DENSITY

J. Paul Farrell, V. Dudnikov, G. Dudnikova
Brookhaven Technology Group, Inc., Nesconset, NY 11667

Abstract

The main mechanism of negative ion formation in a Surface Plasma Source (SPS) is secondary emission of sputtered and scattered particles accompanied by capture of electrons from the electrodes. In the first, pulsed, versions of the SPS, adding a small amount of cesium increased the emission current density for light ions up to 3.7 A/cm^2 with a flat emitter and up to 8 A/cm^2 after optimization of geometrical focusing. Since this power density was too high for DC operation, LBL developed a large volume SPS with a hot cathode discharge, a large emitter-emission aperture gap and low emission current density. The LBL type of SPS was used for some accelerators and for heavy negative ion production with emission current density of 10 mA/cm^2.

Researchers at Budker Institute of Nuclear Physics (BINP) developed a small SPS optimized for long time DC operation. In the BINP source, DC H$^-$ current up to 2.5 mA and heavy ion current up to 1 mA have been extracted from a 1 mm diameter aperture using an improved SPS that employs a hollow cathode discharge and spherical focusing of negative ions toward the emission aperture. This paper describes further optimization of this type source for production of negative ion beam with a high emission current density.

1 INTRODUCTION

Negative ion beams are used for injection into tandems, ion lithography, and in cyclotrons. Some of these applications require very high brightness beams [1,2,3]. H$^-$ beams with very high brightness have been produced from pulsed Surface Plasma Sources (SPS) with charge exchange cooling of the ions [4]. For DC production of negative ion beam with a high emission current density, an SPS with hollow cathode discharge and spherical geometrical focusing of negative ions was developed [5]. An H$^-$ beam with intensity of 2.5 mA and heavy ions up to 1 mA have been extracted from a 1mm diameter aperture. The corresponding emission current density is 0.3 A/cm^2. Several variants of this type SPS were manufactured and tested.

An SPS with a separate Hollow Cathode Discharge (HCD) for DC beam production has been proposed. Computer simulations were used to optimize the beam formation and transport

2 SPS CONFIGURATIONS

The basic configuration of the SPS is shown in Fig.1a. Some modifications presented in Fig. 1b and 1c.

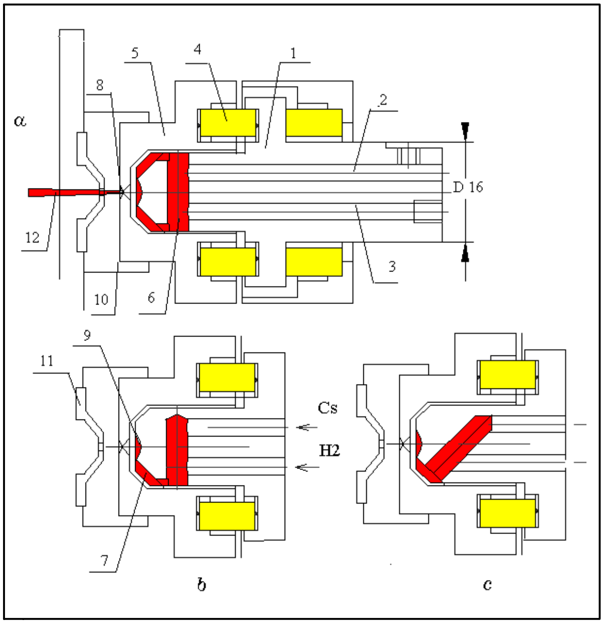

Fig.1 Modifications of Hollow Cathode Discharges in DC SPS. **a**- perpendicular channel through; **b**- perpendicular channel closed; **c**- 45 degree channel closed (discharge plasma is red).

In the basic SPS, a glow discharge is supported in a magnetic field due to the voltage between cathode, 1, and anode, 5, which are separated by the ceramic insulator, 4. In the source shown in Figure 1, the diameter of the cylindrical cathode body is 16 mm. The plasma discharge is localized in the cylindrical channel of a hollow cathode, 6. A working gas is delivered to the hollow cathode through the channels, 3, from the gas system. Cesium vapor is delivered through channel, 2, from a small oven filled by pellets made from a mixture of cesium chromate and titanium powder. After heating this mixture produces a pure cesium vapor. The plasma drifts in the crossed electro-magnetic field along the channel, 7, to the spherical surface of emitter, 9. The direction of the plasma drift is determined by the direction of the magnetic field. Positive ions and neutrals from the plasma bombard the emitter surface, 9. This causes secondary negative ions to be emitted. The negatives are accelerated in the electric field near the surface without space charge limitation and they are focused to the extraction aperture, 8. A high

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voltage applied between anode, 5 and extractor, 11 extracts the beam of negative ions, 12. A pair of permanent magnets between poles (10) provides the necessary magnetic field. The ion source is assembled in a simple vacuum chamber so there is no need for complicated vacuum seals. This design greatly simplifies the manufacture, assembly and maintenance of the ion source.

Operation of the SPS was examined in several different extraction and internal geometries. Both two and three electrode extraction optics were studied. In some experiments we used an electrostatic Einzel lens or solenoidal magnetic lens for focusing and for beam diagnostic we used a moving beam collector with electrical and magnetic suppression of secondary emission together with luminescent screens made from ruby ceramic, and magnetic and electrostatic deflectors. An emittance scanner was used for emittance measurement.

The first version of this type SPS examined was configuration ***b*** of Fig.1, which has a hollow cathode channel open from one side. The focusing radius of curvature was 4 mm. The discharge voltage with hydrogen gas was 0.4 - 0.5 kV. In this variant of the source there was significant sputtering and flake formation. After admixture of cesium, the discharge voltage dropped to less than 100 V. Stable DC operation was observed with optimized heating of the cesium oven. Up to 2.5 mA of H^- was extracted through an extraction aperture of 1 mm diameter with a discharge voltage 80 V and current 0.8 A.

Next, a second hollow cathode channel was drilled along the conical edge of the emitter transforming it to the configuration shown in **a.** The purpose was to decrease the gas density and provide a uniform thin plasma sheath in very close proximity around the working part of the cathode. Examination of this configuration was presented in reference [5]. This version of SPS was replicated and tested in TRIUMF by Bashkeev and Kupriyanov. The results of model ***a*** and ***b*** were very close. An emission current density j = 0.3 A/cm^2 was reached with an extraction aperture of 1 mm diameter and discharge power of ~ 65 W. The measured emittance (90%) of the H^- beam was ~ 26π mm mrad at 25 keV.

Transverse ion temperature on the extraction surface is T_i~3 eV. The effective brightness, $B = j/T_i = 0.1$ A/cm^2 eV is relatively high, but it is 10 times smaller, then the pulsed SPS [4]. Increase of gas density improves charge - exchange cooling and thus increases the brightness but electron stripping will also increase. In configuration ***a,*** a discharge can start from the top exit of the hollow cathode with a plasma drift in right, to the insulator, 4. This causes a loss of negative ion emission. This loss of emission phenomenon was a reason for returning to variant ***b***. Operation time of the ***b*** version of SPS was extended to 4 weeks. The volume of the cesium oven limited longer operation. For long time operation it is important to have a low discharge voltage (U_d < 90 V) and good Cs recycling. With an extraction aperture of 1 mm diameter, extraction of 2.5 mA of H^- was repeated

Fig. 2 shows dependence of the beam intensity vs. discharge current. With an extraction aperture of 0.4 mm diameter, H^- beam up to 0.9 mA was extracted (emission current density j=0.7 A/cm^2). The discharge voltage was 80 V and the discharge current 0.5 A. The efficiency of production of this current density, j/P = 17.5 A/cm^{2}kW, is much higher than for other sources [6]. With an admixture to the Hydrogen of some heavy gases such as O_2, NH_3 , C_2H_5OH and H_2O up to 1 mA of heavy negative ions have been extracted through the aperture of 1 mm of diameter. With an admixture of heavy gases, sputtering was stronger and source operation time was decreased to 3-4 days.

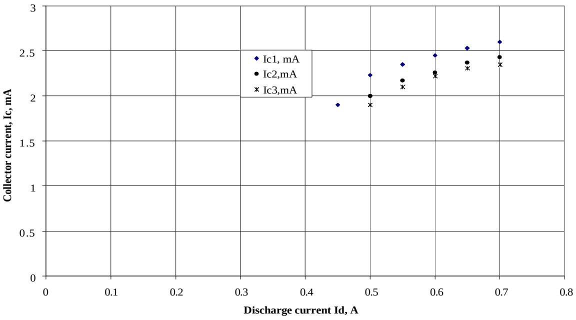

Figure.2. Collector current vs. discharge current for SPS **b** with extraction aperture of 1 mm diameter, U_{ex}=20 kV.

The next improvement was a transition to configuration SPS ***c.*** In ***c*** a hollow cathode channel is drilled normal to the conical part of the cathode surface and 45° to the axis. In variant, the distance for plasma drift to the emitter surface was minimized and the efficiency of negative ion generation was improved. Examples of collector current for different condition of SPS ***c*** operation are shown in Fig.3.

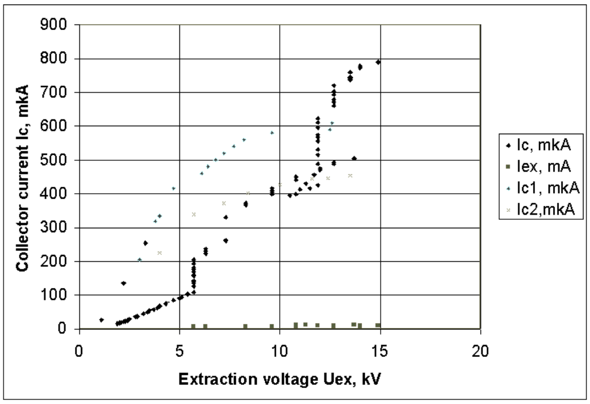

Figure 3 Optimization of a beam current for different extraction voltage for SPS c with extraction aperture of 0.4 mm diameter.

Signs of sputtering on the anode surface confirm there is good focusing of negative ions by spherical emitter. Movement of the focusing point relative to the extraction aperture could be the reason for observed variation of intensity. With a clean vacuum, increasing current consisting of electrons and ions was observed in the extractor gap independent of gas and discharge current. This current was suppressed by controlled leak of air. Conditions for extended long time operation without change of parameters was observed.

3 SPS FOR HEAVY NEGATIVE ION PRODUCTION

The versions of SPS discussed above are optimized for production of negative ions of hydrogen isotopes. When used to produce heavy negative ions, higher sputtering reduces the lifetime considerably. For heavy ion production we have designed a SPS with larger volume and somewhat larger gaps. The optimized radius of curvature of emitter for focusing is 1 to 1.5 cm. Projections of the SPS for heavy ion production is shown in Fig. 4.

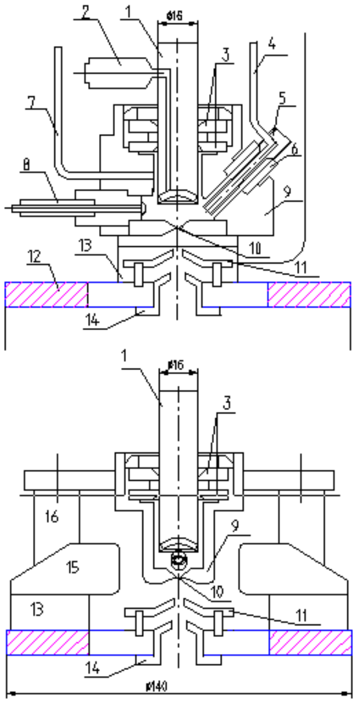

Figure 4. Schematic projections of SPS for heavy negative ion production (HNISPS)

Referring to Fig. 4, the emitter- target 1 has a concave spherical surface on the end close to the extraction aperture, 10. This surface is made from a special material, optimized for each particular negative ion species. (Materials for emitters are discussed below). The emitter, 1, is electrically separated from the anode, 9, by a ceramic insulator, 3. The plasma flux is generated by a hollow cathode discharge HCD assembly, 5. The HCD assembly is inserted into the insulator, 6, and has an angle of 45° relative to the emitter axis. A transverse magnetic field is created by permanent magnets, 13 and shaped by poles, 15. A magnetic base plate, 12, serves as return yoke for the magnet system. A central nonmagnetic insert connected to the ion source can have a small rotation around the axis parallel to the magnetic field for compensation of the ion beam deflection by the magnetic field. Plasma from the HCD, 5, drifts in the crossed field to the spherical surface of the emitter, 1. The emitter is biased negative (U_d= 0.1- 1 kV) relative to the anode, 9 and the plasma. Positive ions extracted from the plasma, accelerate in the near cathode layer of space charge and bombard the emitter's surface with an energy eU_d. This bombardment induces secondary emission of sputtered and reflected negative ions from the emitter surface. These ions accelerate in the near surface layer of potential drop and are focused by the spherical surface to the extraction aperture, 10.

For cathode materials for the HNISPS we have designed lanthanum hexaboride emitters with concave spherical surface of radius 8 and 13 mm, respectively. For very efficient production of Au^- and some other ions, it is possible to use emitter targets made from compounds such as CsAu, GdAu, SmPt, SmAg, SmCu, SmPd and others. High efficiency of negative ion formation with these targets was first observed by an IBM group in 1977.

The efficiency of negative ion formation on the surface is high if the work function φ is close to the electron affinity, A (φ - A < 1 eV). The work function of LaB_6, φ=2.6 eV, is good for efficient formation of many negative ions with affinity A > 2 eV. This includes Au (2.3 eV), Se (2 eV), Pt (2.13 eV), S (2 eV), At (2.9 eV), F (3.4eV), Cl (3.6 eV), Br (3.36 eV), I (3 eV), and many molecular negative ions such as BO_2 (4.1 eV), BO (2.79 eV), and UF_5 (4 eV).

Cesium vapor, or other catalyst will be delivered to the emitter surface from the oven, 2, through a channel in the emitter rod and slit in the emitter support. The vacuum arc discharge system, 8, can be used for deposition of a solid material film such as Au, U, Bi, etc. on the emission surface. The arc discharge will operate in pulsed mode with a low repetition rate.

4 COMPUTER SIMULATIONS OF INNER SOURCE

The purpose of the computer simulations was to optimize the inner geometry and the extraction geometry by maximizing current and minimizing beam emittance. Mass species including boron, iodine, gold and uranium were simulated in a geometry that takes into consideration the basic approach of this SPS, which is that negative ion production is concentrated near the cathode surface and the emitter to anode gap should be small to reduce destruction of negative ions.

The program, PBGUNS [7], was used to carryout computer simulations. The program uses relaxation techniques to solve the Poisson equation for electron and positive and negative ion beams. Based on input parameters, the program can calculate ion beam formation, plasma boundary effects, current distribution, emittance and transmission in the presence of space charge. The possibility to have low aberrations with a high current density have been demonstrated.

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