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REPORT ON THE BNL H^- ION SOURCE DEVELOPMENT*

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ABSTRACT

This paper is a report on H^- ion source development at BNL over the past ten years, with most emphasis on the selected approach for the design of a steady state operating source. Sources of this kind will be used in neutral beam lines of future fusion devices, for plasma heating and toroidal current drive. In addition to the steady state operation, H^- ion sources for this application have to show very high gas and power efficiences.

INTRODUCTION

The work on H^- ion sources began at Brookhaven National Laboratory in 1972 with a proposal[1] to replace the existing proton injection into the Alternating Gradient Synchrotron with a more efficient H^- injection, via double electron stripping. Very soon afterwards it was realized that negative hydrogen ions could find an application in neutral beam lines for fusion devices and the BNL program began to receive the support from the Office for Magnetic Fusion Energy. Except at the very beginning of the program, all BNL ion source models have been based on surface production of negative hydrogen ions using cesiated molybdenum as the converter. Initial tests have been made with modifications of negative hydrogen ion sources previously developed in USSR, where a lot of pioneering work in this field has been done; later on new approaches have been studied at BNL, promising substantially improved devices.

The first source studied at BNL was a hollow discharge duoplasmatron; when operating with hydrogen gas only, the H^- yield was initially about 5 mA[2], later to be increased to 9 mA[3]. Injection of cesium through the center tube resulted in an increase of the yield to 18 mA. Subsequently a parametric study was done and the yield in the hydrogen-cesium mode increased to 60 mA[4] (current density in the extraction aperture: 1.27 A/cm^2). Energy analysis of extracted H^- ions has shown[5] that the large increase in H^- yield as a result of cesium injection is due to surface produced H^- ions, mostly from the center tube. The hollow discharge duoplasmatron has been running in pulses of less than 1 ms long, which would limit its application to pulsed accelerators.

A small magnetron source, similar to the one developed at Novosibirsk, was the next to be studied. The first model was very simple, but also very fragile. Still, an H^- yield of 7 mA was obtained from a device that had a volume of a few cm^3 only. The next versions were more rugged, with more slits, so that eventually up to 1A of H^- ions could be obtained in 10 ms pulses.[6] The first studies of electrode heating followed and scaling laws were established;

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however, it was determined that in order to match in a steady state the source performance when operating with pulses of 10 ms duration, removal of heat from electrodes at a rate of several kW/cm^2 would be necessary. A program was therefore initiated to study methods for efficient electrode cooling and up to 0.5 kW/cm^2 was removed from an electrode by nucleated boiling of water.

A similar performance was achieved with Penning sources. The basic design, two cathodes and the anode, was modified to include an independently biased converter[7], placed opposite the extraction slits. A maximum H$^-$ current of 0.44 A was obtained from slits with an area of 1 cm^2, in 3 ms pulses. As it was the case with the standard magnetron, steady state operation at an extracted current density of 0.1-0.2 A/cm^2 would require removal of several kW/cm^2 from the cathodes. A larger model was designed and fabricated[8], incorporating nucleated boiling of water as the method for heat removal. This source was tested with the discharge only; many problems have been encountered when cesium was injected (nonuniform coverage, breakdowns) and tests have been discontinued.

A real breakthrough in the design of H$^-$ sources was the introduction of geometrical focusing of surface produced negative ions[9-12] and widening of the electrode gap in the magnetron source.[12] In a pulsed mode of operation (10-25 ms), with 1 A of H$^-$ ions extracted[12], the gas efficiency was improved to 6% and power efficiency to 8 kW/A. Based on these very promising results, a larger magnetron was designed, fabricated and initially tested. Although its design value for the H$^-$ yield was 1 A in a steady state operation, not more than 0.12 A was achieved due to reasons to be described in more detail later. After initial tests, studies of this model were also discontinued.

Even with the best results for the gas efficiency (6%), the gas flow from a scaled-up source could be prohibitively high. Late in 1979 it was felt that any substantial improvement in source performance would require radical changes in the design. Several options were considered and the hollow cathode discharge was chosen as the best candidate for a good H$^-$ source. The design was based on plasma generation by hollow cathode discharges and H$^-$ production on an independently biased converter with geometrical focusing. Many experiments have been performed with the objective to optimize the shape of the cathodes, configuration of the magnetic field, and creation and maintaining of the Cs layer on the surface of the converter. Up to 0.5 A of H$^-$ ions was achieved, with the source operating steady state and only extractor pulsed. Details of the design and experimental results will be described later in the paper, but the conclusion is that a steady state H$^-$ or D$^-$ source with an excellent gas efficiency can be designed, using hollow cathode discharges as a plasma source and a porous converter with liquid cesium transpiration for production of H$^-$ ions.

A STEADY STATE MAGNETRON SOURCE (MARK V)

Results with the improved design of a pulsed magnetron source were very encouraging and justified the decision to proceed with scaling-up of magnetrons to higher H$^-$ currents and steady state operation. Figure 1 shows the difference between the standard design (as basically developed at Novosibirsk) and the improved version[12] which incorporated the geometrical focusing and a larger anode-cathode gap. Comparison of the H$^-$ yield from the two geometries is shown on Figure 2; it is evident that the efficiency of H$^-$ ion production has been greatly increased. Also, it has been found that for the same H$^-$ current density the improved source geometry requires a much lower neutral gas pressure, which results in a higher gas efficiency. The improved power efficiency of the source has simplified the electrode cooling system: instead of nucleated boiling heat removal, standard water cooling became sufficient.

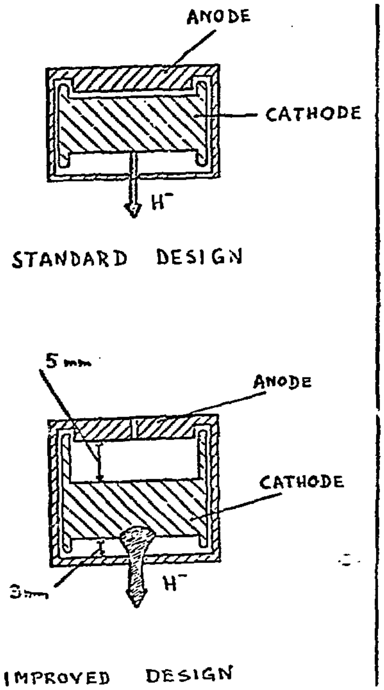

Fig. 1. Comparison between a standard magnetron and a magnetron with geometrical focusing and a wide chamber.

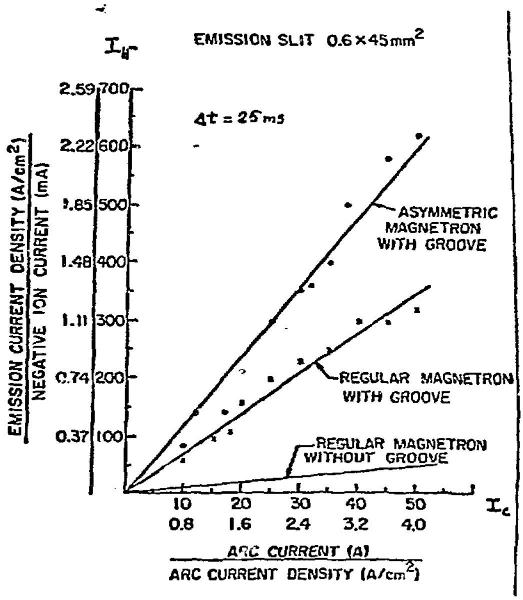

Fig. 2. H$^-$ yield for different magnetron source geometries.

Table I shows the design parameters of the water cooled, steady state operating, Mark V magnetron source, while Figure 3 shows a cross section of the source.[13] The source was first tested with hydrogen only and runs of several days duration have been achieved at power levels of 60% to 90% of the design value. The cooling system performed well during these tests. For the H$^-$ production tests a simple extractor was designed, with no cooling, so that the extractor voltage had to be pulsed (100 ms, 0.1 Hz). Maximum H$^-$ yield was not higher than 0.12 A (source operating steady state, extractor

TABLE I

Design Parameters of Mark V Magnetron

Basic geometry	5 grooves, 5 slits
Cathode surface area	50 cm^2
Cathode current density	0.8 A/cm^2
Cathode power density	100 W/cm^2
Extraction slit area	2 cm^2
Extracted H^- current	1 A
Extracted H^- current density (in slits)	0.5 A/cm^2
Average H^- current density	40 mA/cm^2
Power efficiency	8 kW/A
Gas efficiency	6%

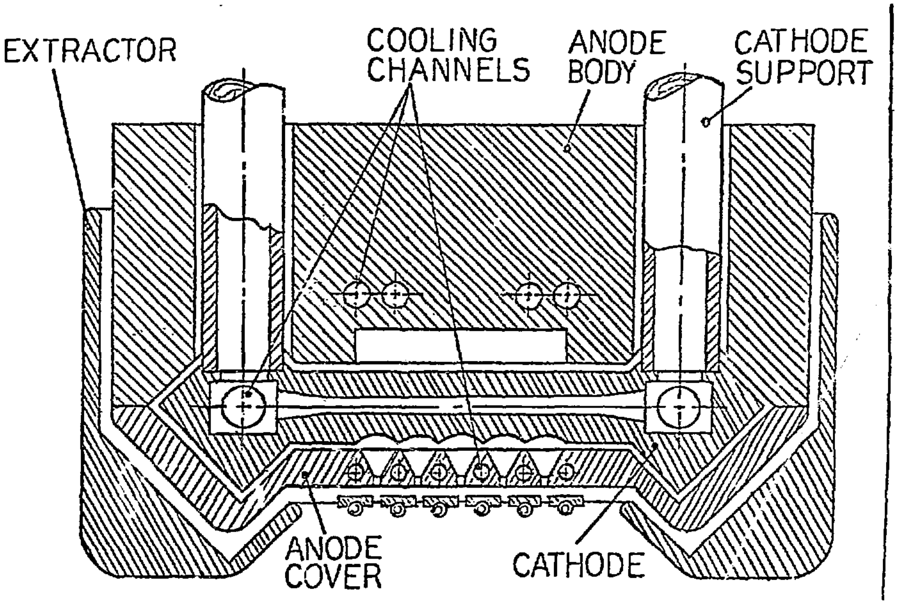

Figure 3. Cross section of a steady state magnetron source

voltage pulsed). Although the experiments with this source were discontinued, the main reason for the poor performance was found to be the nonuniformity of the cesium layer on the cathode. The channels for cesium injection were machined in the anode body of the source and cesium injected into the back part of the discharge chamber, away from the active surface of the cathode. For cesium it was very difficult to diffuse around the bends of the discharge chamber and produce the required layer on the front face of the cathode; instead, a much thicker layer would form on the anode (very efficiently cooled!) and on the back side of the cathode. This nonuniform distribution of cesium resulted in a nonuniform distribution of cathode current density, and eventually in the appearance of unstable operation and sparking. As the first step to ameliorate the situation, the cooling system was upgraded to operate at 150° C (pressurized water) in order to keep the surface temperature above this value. It was felt that in this way a higher density of cesium vapors would be achieved, condensation of cesium on anode wall reduced, and the uniformity of cesium layer on the cathode surface improved. Second, the focusing ratio (width of the groove to the width of the slit) was chosen too high, 10:1, and a large portion of H^- ions was hitting the anode wall in the vicinity of the slits. A value of 5:1 or even lower would be more appropriate, but the source operation was not studied after these modifications were incorporated.

A HOLLOW CATHODE DISCHARGE (HCD) SOURCE OF H^- IONS

Experience with all the models of H^- ion sources studied at BNL has been that they may operate very well with pulses even several tens of milliseconds long, but that problems would appear with longer pulses or in the steady state mode of operation. While a source may have yielded H^- ions with a current density of 1 A/cm^2 or more in pulses of 10 ms, not more than 0.2 A/cm^2 could be achieved with 100 ms pulses or only 0.06 A/cm^2 in the steady state. It has been also shown that the gas efficiency improves with the H^- current density in the extraction slits, indicating that it would not be easy to match the performance (≈6%) of a small model when scaled up for higher currents and steady state operation. In 1979, studies began with the objective to design a source that would approach as much as possible an ideal device. (An ideal H^- source, based on surface-plasma method, would have in the discharge chamber a pure plasma with no neutral gas; a plasma dense enough to supply the required current density on the converter and thin enough for a safe transport of H^- ions out of the source; an independently biased converter so that the production of H^- ions can be optimized; a converter surface without cesium, if possible; if cesium is required, then its coverage should be uniform over the surface and maintained constant in time.) For plasma generation the best candidate appeared to be a hollow cathode discharge, a device that can operate with many different gases (hydrogen, helium, argon, etc.), at very high values of the gas efficiency (approaching in some cases 90%) and producing plasmas with densities 10^{13}-10^{14} cm^{-3}. First tests with a 3 mm tantalum hollow cathode producing a steady state plasma and a cesium covered molybdenum converter[14] have shown that it is possible to produce H^- ions by this approach, with converter current densities as high or higher than in other sources, but at background gas pressures of 10^{-3} torr or lower.

The existing Mark V magnetron structure was subsequently modified for tests with the HCD approach (Figure 4). The active part of the converter electrode has five grooves for geometrical focusing of H^- ions into the anode slits (focusing factor 5:1); the area of this part of the converter is 5 x 5 = 25 cm^2. Many different shapes of the cathode were studied and, finally, two rectangular cathodes (inside dimensions approximately 9 mm x 0.75 mm) were chosen to produce

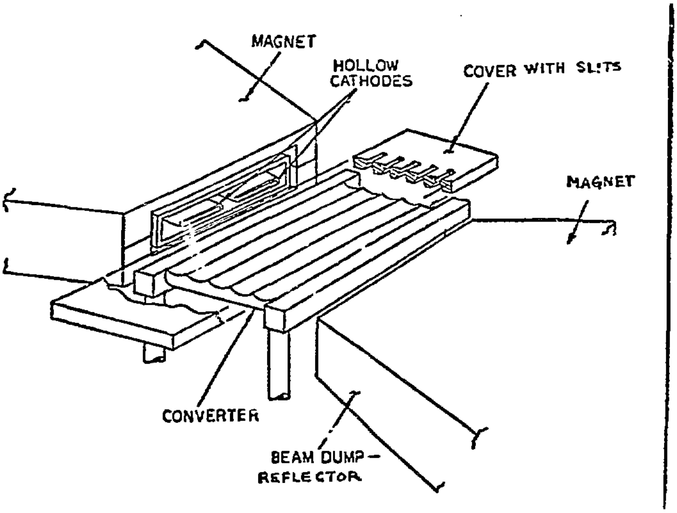

Figure 4. Cross section of the HCD source.

a flat plasma sheet in the vicinity of the converter. Magnetic field (100-200 G), required for the operation of hollow cathodes, was produced between the poles of an electromagnet. The initiation of the discharge was done by producing a Penning discharge first between the cathode and a hot tantalum filament,[15] placed in the vicinity of the opposite pole; after the discharge transferred from the Penning mode into the HCD mode (usually after less than one minute), the filament can be switched off. Plasma studies have shown that the density is uniform within 10% (Figure 5), high enough to reach a primary, positive ion current density on the converter of 0.5 A/cm^2, with a neutral background gas pressure of (1-2) x 10^{-3} torr. The required gas flow depends on the shape of the magnetic field and, as a general rule, with air-core systems the background pressure can be reduced to below 5 x 10^{-4} torr. Steady state operation was achieved (3-4 days continuous running), limited by factors not related to the cathode itself (Figure 6).

The converter was fabricated from solid molybdenum, with channels for water cooling. This was the simplest design, but it also limited the options for cesium injection. The highest H^- yield was obtained when cesium was injected into the discharge from one or two heated perforated tubes, placed along the surface of the converter. Cesium injection through the hollow cathode itself, as an admixture to hydrogen gas, was also tried, resulting first in a lower arc voltage, but the H^- yield was not as high as with the former method. The extractor was not cooled (solid tungsten wires) and its voltage

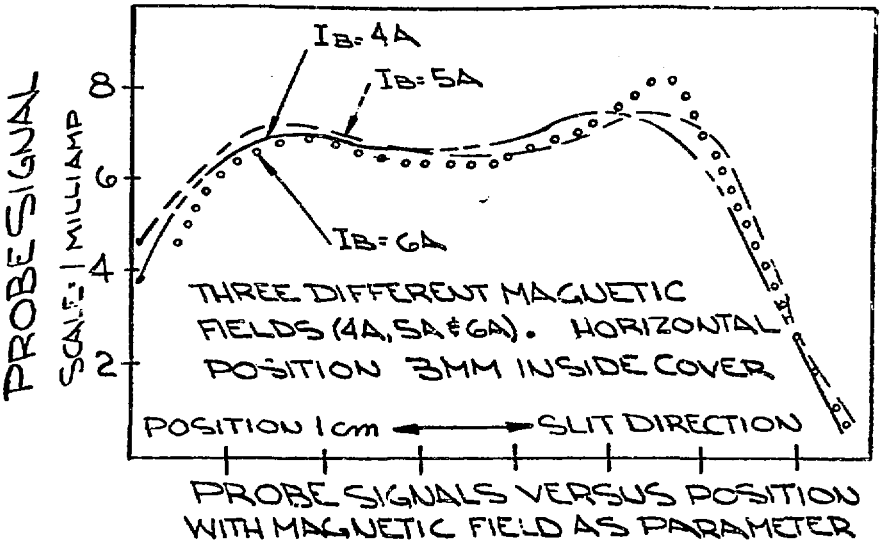

Figure 5. Plasma density distribution in the HCD source.

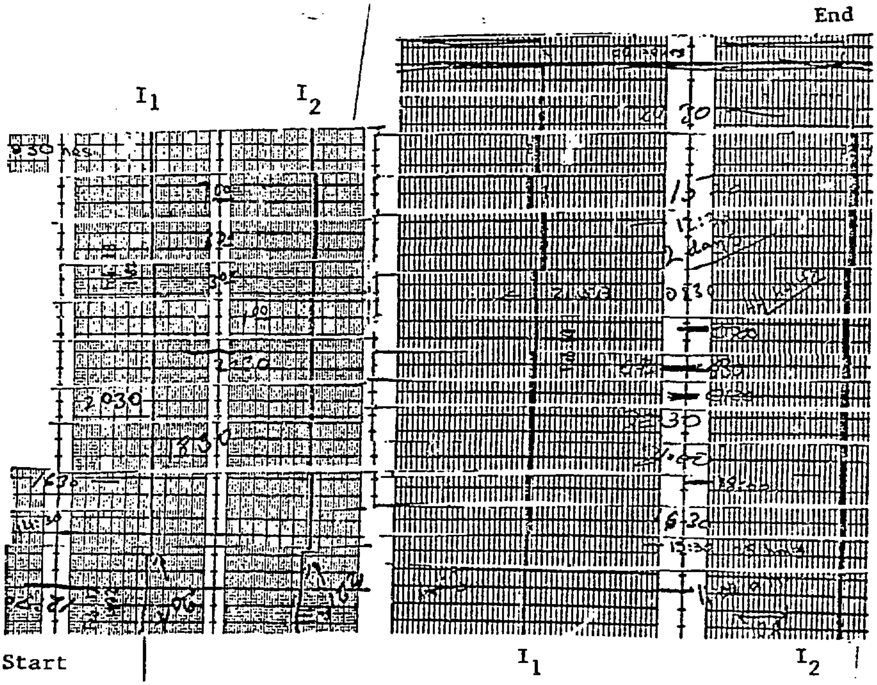

Figure 6. Chart recording of the HCD current.

had to be pulsed in order to avoid the overheating (pulse duration up to 1 s). With the plasma generator and converter operating steady state (converter bias: −100 to −150 V) and 7.5 kV extraction voltage pulsed, stable H^- currents of 0.2-0.3 A have been maintained over periods of several hours (Figure 7) with shorter peaks up to

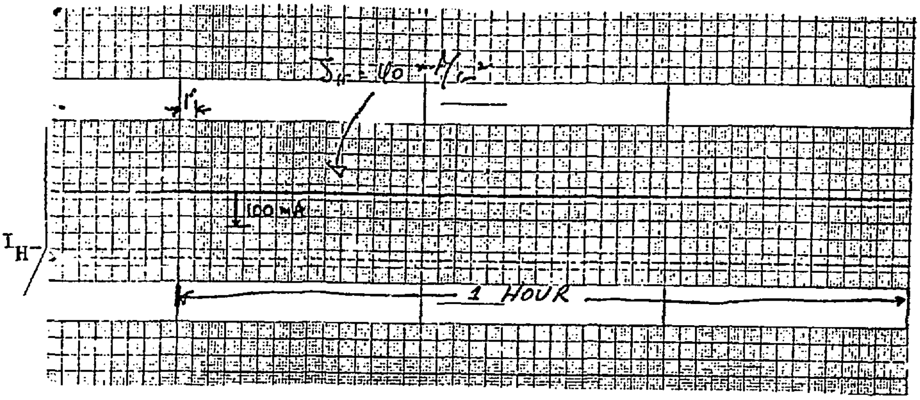

Figure 7. Chart recording of the extracted H^- current from the HCD source.

0.5 A. This corresponds to the extracted current density in the slits of 0.04 to 0.1 A/cm^2. As it was the case with Mark V magnetron source, the cesium coverage of the converter surface was not uniform and close to the required optimum.

There are two ways to try to improve the performance of the converter, either by developing a low work function surface that does not require cesium or by diffusing cesium through pores in the converter. The first approach was tried with some success[14] by using a cesium doped LaB_6 converter; no further tests have been done since then. In order to test the second method, several small-scale experiments have been done[16] at BNL. In the first, H^- yields from a solid and from a porous molybdenum surface were compared; in the latter case the yield was reduced by less than 20%. The second test was even more important; it is shown schematically on Figure 8. In front of a molybdenum piece, which could be either solid or porous, a sheet of plasma was produced using a hollow cathode. Negative hydrogen ions, formed on the surface of the negatively biased converter, were bent 90° in the magnetic field to reach a Faraday cup. No signal was observed on the cup in pure hydrogen or argon plasma nor in the cesium-hydrogen mode unless the converter bias (i.e., the energy of H^- ions) and the magnetic field were adjusted for the 90° bend. As a reference, solid molybdenum converter was used with the standard way of cesium supply through the discharge. The best value of the H^- current, collected on the cup, was 5 mA with the solid converter. With the porous converter, but no discharge and no pressure on the liquid cesium in the chamber, there was no cesium on the surface as determined by the absence of the photoelectric current

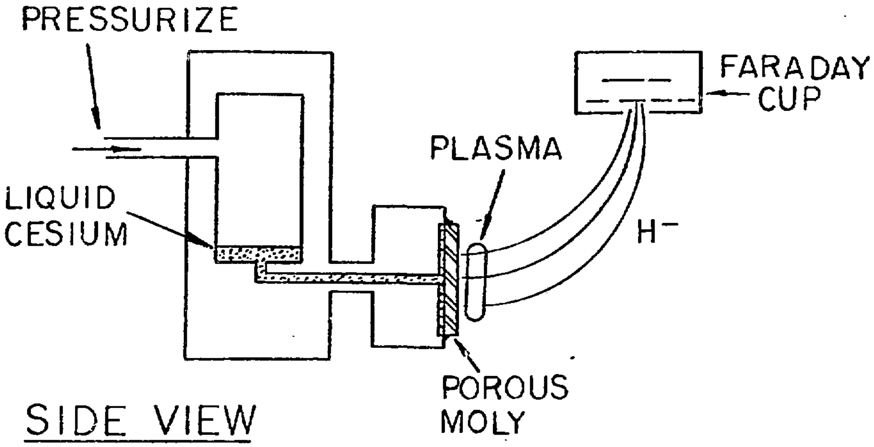

Figure 8. Experiment to compare the H^- yield for different methods of cesium supply.

under He-Ne laser illumination. Once the pressure on cesium was increased and plasma in front of the converter established, the H^- signal on the cup increased to 25 mA. This unexpected result can be explained by the fact that the cesium layer created by transpiration on the surface of the porous converter suffers much less sputtering of Cs^+ ions and, therefore, can be maintained closer to optimum conditions, than the layer that has to be maintained by deposition of cesium particles (Cs^0,Cs^+) from the discharge.

CONCLUSION

Experiments with hollow cathode discharges have shown that they can be used as steady state plasma generators with parameters as required for applications in H^- ion sources (plasma density, uniformity). For the converter, transpiration of liquid cesium through porous molybdenum seems to be the best choice at present, eliminating the need for cesium in the discharge. These features and very low values of the background gas pressure (10^{-4} to 10^{-3} torr) promise that an H^- source could eventually be developed with a performance equal to that of the best positive ion sources. Such a source could be scaled up to currents required for neutral beam lines as well as adapted easily to different types of accelerators.

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