Title
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Publication Date
1986-10-01

LBL-22034 Rev.

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Accelerator & Fusion Research Division

Presented at the Fourth International Symposium
on the Production and Neutralization of
Negative Ions and Beams, BNL, Upton, NY,
October 27-31, 1986; and to be published
in Review of Scientific Instruments

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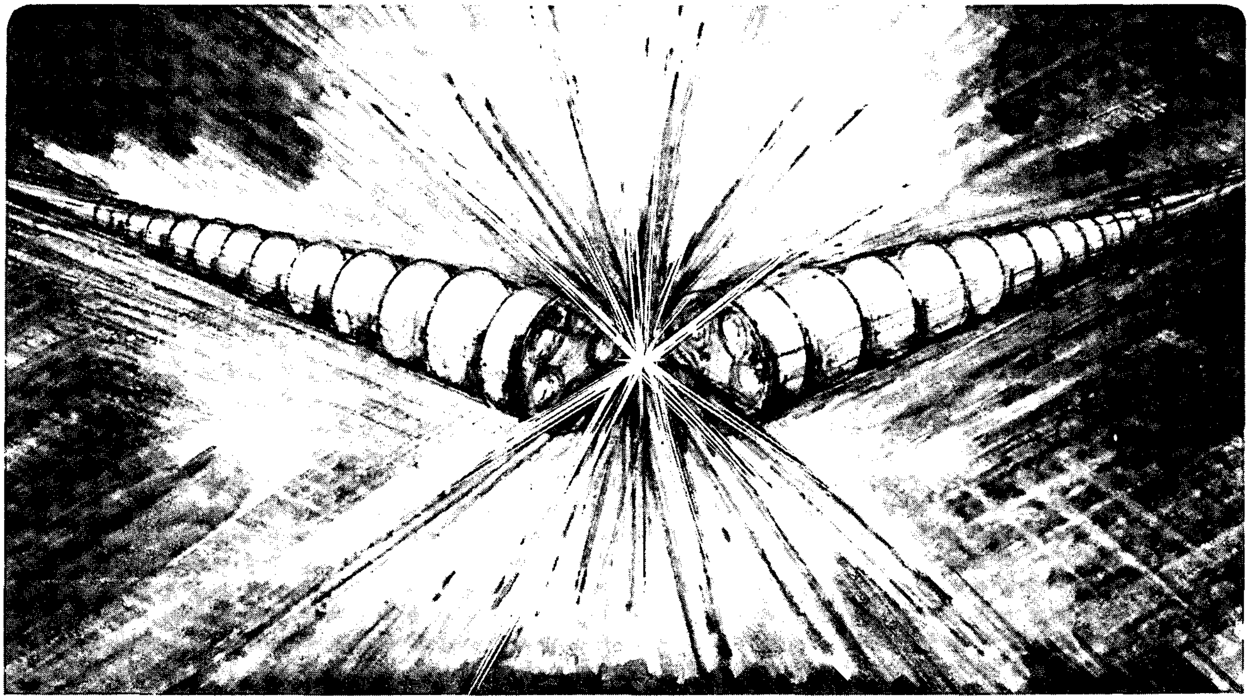
October 1986



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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OPERATION OF A DUDNIKOV TYPE PENNING SOURCE WITH LaB_6 CATHODES*

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ABSTRACT

The Dudnikov type Penning source has been operated successfully with LaB_6 cathodes in a cesium-free discharge. It is found that the extracted H^- current density is comparable to that of the cesium-mode operation and H^- current density of 350 mA/cm^2 have been obtained for an arc current of 55 A. The H^- yield is closely related to the source geometry and the applied magnetic field. Experimental results demonstrate that the majority of the H^- ions extracted are formed by volume processes in this type of source operation.

INTRODUCTION

The reflex discharge originated by Maxwell[1] and Penning[2] has found important applications as ion sources for generating positive ion, high charge state ion, or negative ion beams. By operating with a hot cathode and a reflector, the Penning or PIG source was first studied and optimized by Ehlers[3] to generate steady-state beams of H^- ions for cyclotron operation.

* This work is supported by the Air Force Weapons Lab. at Kirtland, the Air Force Office of Scientific Research and by the Director, Office of Energy Research, Office of Fusion Energy, Development and Technology Division, of the U.S. Dept. of Energy under Contract No. DE-AC03-76SF00098.

Discovery of H$^-$ enhancement by introducing cesium into the discharge has led Dudnikov to modify the original Penning source, by changing the dimensions and adding cesium vapor.[4] Since then, there have been extensive studies at Brookhaven and Los Alamos to optimize the source performance and the H$^-$ yield. It has been demonstrated by Allison that high intensity H$^-$ beams ($J^- > 2$ A/cm^2) can be extracted from the Dudnikov type Penning source if the proper amount of cesium is present.[5]

It is generally believed that H$^-$ ions in the Dudnikov source are first formed on the cesiated cathode surface, either by desorption or backscattering.[6] Some of these ions undergo resonance charge exchange with the neutral hydrogen atoms near the emission slit.[7] The low energy H$^-$ ions formed are then extracted from the source. However, a recent investigation shows that H$^-$ ions formed by volume processes can play an important role in this type of Penning discharge.[8] These volume-produced H$^-$ ions can also account for the high negative ion output current if sufficient plasma density is present in the discharge volume.

Instead of employing cesium, we have operated the Dudnikov source equipped with a LaB_6 cathode of similar low work-function. It is found that the extracted H$^-$ current density in this cesium-free operation is comparable to that of the cesium-mode operation, and discharge current as high as 100 A can be obtained for short pulse durations. These results together with the measurements obtained from a "hybrid" production of H$^-$ ions indicate that the majority of the H$^-$ ions extracted from the Dudnikov source, when it is operated with LaB_6 cathodes, are formed directly by volume processes. Additional experimental investigation is required in order to understand the H$^-$ production process when the Dudnikov source is operated with cesium.

I. EXPERIMENTAL SET-UP

A general description of the Dudnikov type Penning source has been discussed previously by Allison.[5] Figure 1 illustrates the different components of the Dudnikov source. The cathode, anode insert, extractor and emission slit are normally made of molybdenum while the anode housing is constructed from stainless steel. In this experiment, the original molybdenum cathode is replaced by LaB_6 material which can provide a work

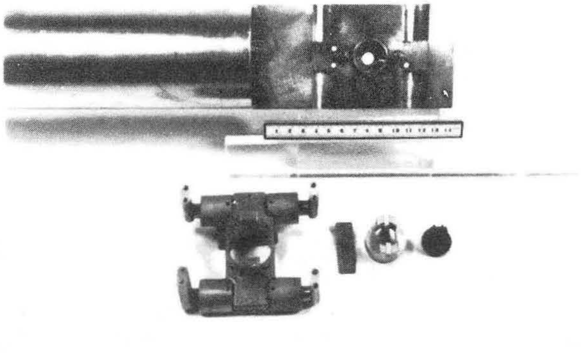

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Fig 1. Different components of the Dudnikov type Penning source.

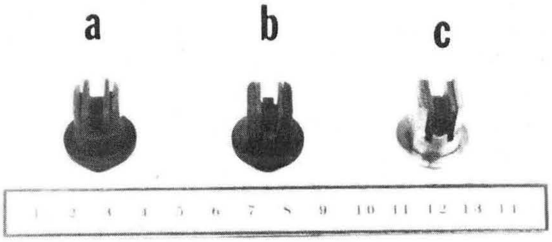

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Fig. 2 The three different cathode arrangements: (a) a complete LaB_6 cathode; (b) a graphite cathode with two LaB_6 inserts; and (c) a molybdenum cathode with two LaB_6 inserts.

function as low as 2.3 eV.[9] Three different LaB_6 cathode arrangements have been tested. The complete cathode structure in Fig. 2(a) was fabricated from LaB_6. Only two planar LaB_6 inserts (13 mm x 12mm x 1.5mm) were installed on either a graphite or a molybdenum mounting in Figs. 2(b) and 2(c) respectively. Since LaB_6 is very reactive with refractory metals, it is separated from the molybdenum mounting by a rhenium foil.

The ion source is mounted on a water-cooled copper block. Hydrogen gas is introduced into the source chamber from three small holes located in the anode insert. The gas flow rate can be adjusted and is monitored by a digital mass flow meter. The magnetic field required for the source operation is generated by a pair of large electromagnets which can provide a uniform B-field as high as 7 KG. The ion source assembly is placed inside a 50 cm x 25 cm x 152 cm vacuum chamber which in turn is installed in the gap between the two magnet pole faces.

A 2 kV, 1 A power supply is used to start the discharge in a dc mode, and a 700 V, 400 A transistor pulser is used for pulsed operation. The ion source and its electronics are at high potential. H^- ion beams are extracted from the arc column through a 1-mm-diam aperture. The maximum extraction voltage available from the high voltage power supply is approximately 15 kV. The H^- ion beam is collected in a Faraday cup and is measured across a 1 kΩ resistor. Both the arc voltage and arc current are measured with an oscilloscope via fiber-optic analog telemetry. Due to the E x B drift motion, electrons extracted from the source drift side-ways in the extraction gap and are collected at the chamber wall.

II. EXPERIMENTAL RESULTS

A discharge in the source is initiated by first increasing the dc "keep-alive" power supply to about 500 V. Since the LaB_6 is cold, electrons are emitted from the cathode (approximately 20 - 50 mA) mainly due to secondary emission. As the arc current gradually increases to about 200 mA, the arc voltage decreases to 200 V. At this stage, the transistor pulser is switched on and the arc is operated in short pulses with a repetition rate of 5 - 20 Hz. The 200 V, 200 mA dc discharge is maintained during the time between pulses.

For new LaB_6 cathodes, the source requires some initial conditioning, therefore the pulse duration is kept below 100 μs so that source damage is minimized. Once conditioned, the pulse length can be gradually increased to several milli-seconds. The temperature of the LaB_6 cathode rises with the pulse length and the repetition rate. As the LaB_6 becomes sufficiently hot, electrons can be emitted thermionically.

The oscilloscope traces in Fig. 3 illustrate the arc current, the H^- beam current, and the arc voltage during a 700 μs pulse operation. The arc current and voltage and the H^- beam current stay constant during the time of the pulse. The noise level of the arc current is approximately 25% peak-to-peak.

Occasionally, two discharge modes can appear in a single pulse. The oscilloscope trace in Fig. 4 shows that during the early part of the pulse, the arc current oscillates between two discharge modes; a high current and a low current mode. It then settles to the higher current mode in the later part of the pulse. This type of two mode operation eventually disappears as the LaB_6 cathode temperature increases or conditioning occurs. For arc current below 40 A, uniform pulses longer than 5 ms have been recorded. As the arc current increases, the pulse length is reduced in order to prevent possibility of damaging the LaB_6 cathode.

Figure 5 shows a plot of the extracted H^- current density versus the arc current. The data points have been

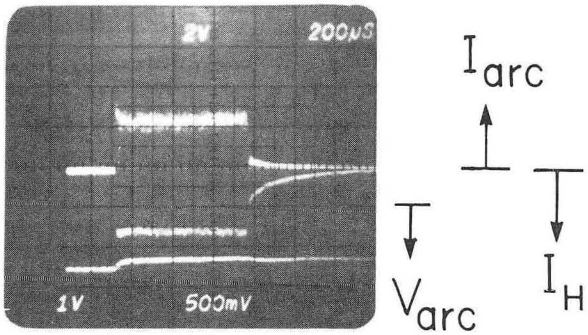

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Fig. 3 Oscilloscope traces showing the arc current, H^- beam current and arc voltage during a 700 μs pulse operation.

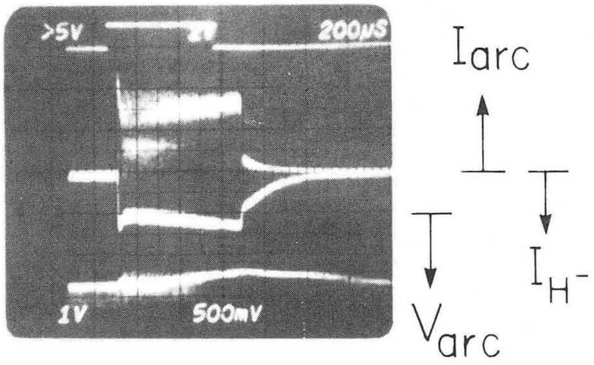

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Fig. 4 Oscilloscope traces showing the two discharge modes which occur during the early part of a 600 μs pulse operation.

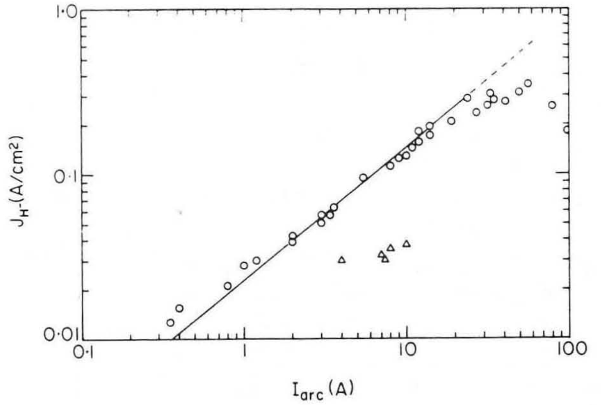

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Fig. 5 Extracted H^- current density versus arc current The five (Δ) data points are obtained without the anode ribs in the source assembly.

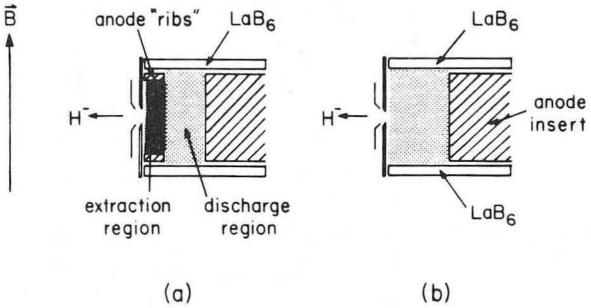

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Fig. 6. Schematic diagram showing the discharge geometry (a) with and (b) without the ribs in the anode insert.

accumulated for source operations with all the three LaB_6 cathode arrangements shown in Fig. 2. The result demonstrates that there is essentially no difference in the H^- output between the three different LaB_6 cathode geometries, and a wide range of arc current can be easily obtained from them. Overall, the extracted H^- current densities are comparable to those obtained when the source is operated with cesium,[5] except that both the optimized gas flow rate (36 sccm) and the applied magnetic field (7 kG) are higher.

Figure 6(a) is a cross-sectional view of the Dudnikov Penning source showing the LaB_6 cathode, the anode insert with the "ribs", and the plasma column. The two anode ribs essentially divide the source chamber into two regions; the discharge and the extraction region. In the first or discharge region, primary electrons emitted from the two LaB_6 cathode surfaces oscillate back and forth along the field lines. They ionize or vibrationally excite the background gas, forming a dense hydrogen plasma. Both the anode ribs and the applied B-field serve to keep the energetic primary electrons out from the second or extraction region. However, both ions and plasma electrons can cross the magnetic field and they form a plasma in the extraction region that is colder than the plasma in the discharge region. It is very likely that the majority of the H^- ions extracted are formed in this part of the source by volume processes, either by electron collision with the H_2^+ or H_3^+ ions or by dissociative attachment of very low energy electrons to vibrationally excited H_2 molecules.

The effect on the H^- yield by operating the Dudnikov source <u>without</u> the anode ribs has been investigated. Figure 6(b) is a cross-sectional view of this particular source arrangement. With the shadowing effect of the anode ribs removed, primary electrons emitted from the LaB_6 cathode now exist throughout the entire chamber. The extracted H^- current density (as shown by the five (Δ) data points in Fig. 5) is reduced by a factor of 3 for the same source operating conditions. The reason for this drop in source efficiency is being investigated.

When the Dudnikov source was operated with cesium, the extracted H^- current saturated when the applied B-field reached about 2 - 3 kG.[5] The B-field dependence of the H^- current when the Dudnikov source is operated with the LaB_6 cathodes has also been studied. For a given arc current, the H^- current increases monotonically with the B-field. As the B-field is increased from 2 to 6 kG, the extracted H^- current (Fig. 7) increases by about a factor of two. It is observed that the increase in B-field is accompanied by an increase in the arc voltage in order to maintain a constant arc current. As a result, the arc power used for the discharge is increased, producing a higher plasma density. A stronger B-field can also provide better plasma confinement which in turn will contribute to the increase in the plasma density of the source. Since the H^- ion production rate is proportional to the density of the source plasma, the increase in B-field will result in a higher H^- output current.

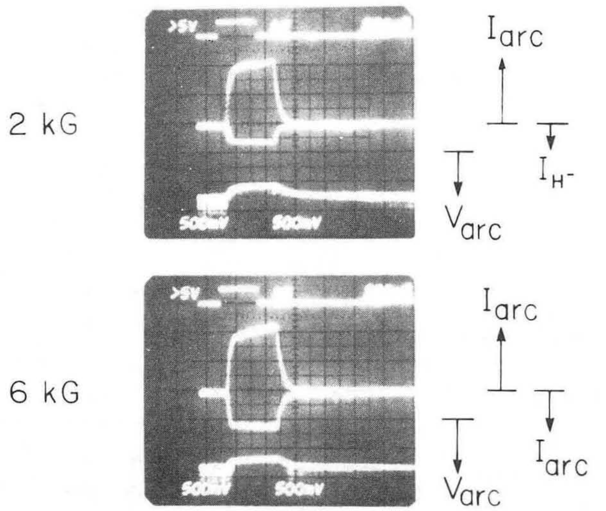

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Fig. 7 Oscilloscope traces showings the arc current, H^- current and arc voltage for two different applied B-field.

LaB_6 is a low work function material ($\phi_W \approx 2.3$ eV). If it is used as a converter in a surface production type negative ion source, the surface- produced H^- ions should be enhanced as in the case of a cesium-coated molybdenum surface ($\phi_W \approx 2$ eV). We have operated a filtered multicusp source[10] with a LaB_6 converter to generate both volume and surface produced H^- ions.[11] A mass spectrometer detects the H^- ions leaving the source and therefore can provide a comparison between the volume produced H^- ions extracted near the filter region (extraction voltage = 700 V) and the "self-extracted" H^- ions formed on the LaB_6 converter surface.

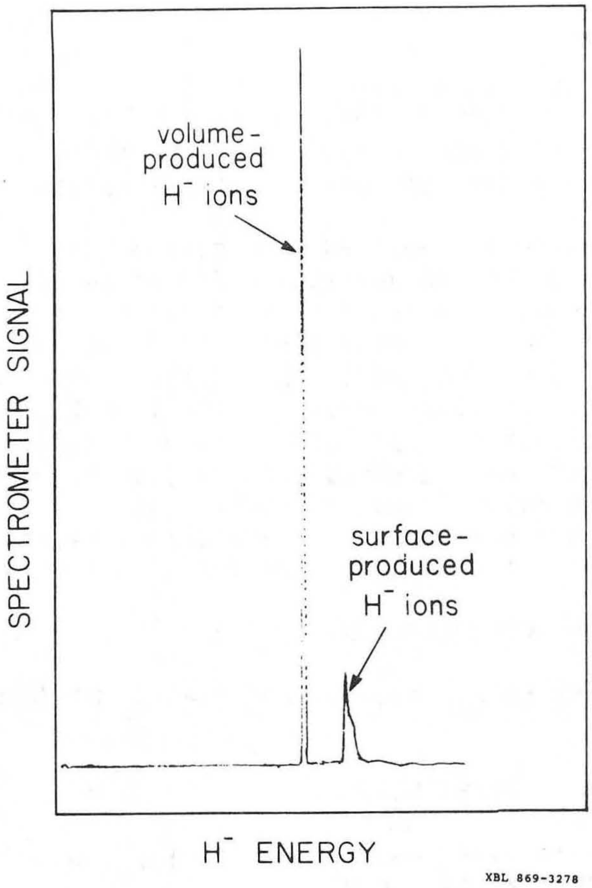

Fig. 8 Spectrometer output signal showing the extracted volume-produced H^- ions and the H^- ions formed on the LaB_6 converter surfaces.

In this test, a background hydrogen plasma is generated by dc discharge (80 V, 3 A) between the filament and the anode chamber wall. The converter is biased at -200 V with respect to the anode. Thus, positive hydrogen ions are impinging on the LaB_6 converter surface with an energy appropriate to this bias potential and H^- ions are formed both by desorption and backscattering processes. The spectrometer output signal in Fig. 8 shows that the number of volume-produced H^- ions extracted from the source is larger than that of the H^- ions emitted from the LaB_6 converter.

In the Dudnikov source, fast H^- ions emitted from the cathode surface cannot reach the emission slit. In order to be extracted, they must undergo resonant charge exchange with the background H^0 atoms, forming low energy H^- ions, which are then extracted from the source.[7] Since the result of this experiment shows that the H^- generated from a LaB_6 surface is lower than those formed directly by volume processes, it is unlikely that this two-step process (surface production followed by resonant charge exchange) can account for the high H^- ion current observed in the Dudnikov source when operated with the LaB_6 cathodes.

CONCLUSION

The results of this experiment demonstrate that H^- current densities as large as 350 mA/cm^2 can be obtained from a Dudnikov Penning source when it is operated with LaB_6 cathodes in a cesium-free hydrogen discharge. When the arc current is less than 40 A, pulse length of several milli-second have been achieved. For higher arc current, source operation is limited to short pulses of several hundred micro-seconds. In order to extend the pulse length and duty factor, source cooling must be improved; in addition, a feed-back circuit must be employed to stablize the arc current so that uniform H^- current can be maintained.

When the Dudnikov source is operated with cesium, the life-time of the source is limited due to the formation of a deep hole on the molybdenum cathode, arising from positive ion sputtering. Further, cesium vapor migrating out of the source can cause voltage break-down problems in the accelerator column. In the pure hydrogen mode operation however, the life-time of the Dudnikov source is expected to be much improved because of the absence of massive Cs^+ ions in the discharge together with the lower LaB_6 sputtering rate. However, additional experiments must be performed in order to understand the H^- production mechanism when the source is operated with cesium.

ACKNOWLEDGMENT

We would like to thank D. Moussa, C. Hauck and S. Wilde for technical assistance.

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