Title
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Publication Date
1986-09-01

LBL-22034 c.2
Preprint

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UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Submitted to Review of Scientific Instruments

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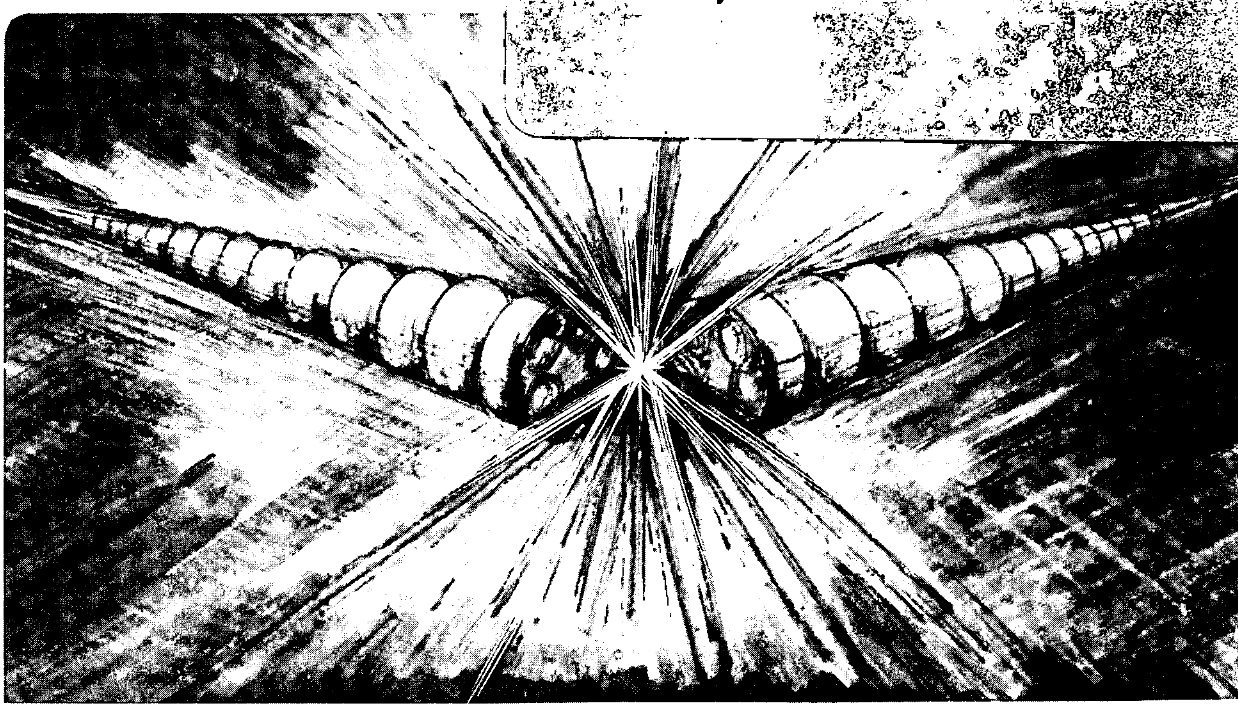
September 1986



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

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LBL-22034

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 low work function 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. Discharge current as high as 100 A has also been achieved for short pulse durations. 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.

* 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.

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. Figure 1 shows the arrangement of the electrodes which produces a Penning or what is commonly known as a PIG discharge. Electrons emitted from one of the cathodes are reflected back again by the opposite cathode. The axial magnetic field confines the electrons and prevents them from moving readily to the anode. As a result, the primary electrons make many transit paths and the probability of making ionizing collisions with the background gas in the plasma column is increased.

By operating with a hot cathode and a reflector, the Penning source was first studied and optimized by Ehlers[3] to generate steady-state beams of H^- ions for cyclotron operation. Discovery of H^- enhancement by introducing <u>cesium</u> 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]

Today, 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. The cesium on the cathode may have two functions: first, to provide a good electron emitter so that large discharge current can be obtained; second, to enhance the surface H^- yield by creating a low work function surface. 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" multicusp negative ion source 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 2 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 function as low as 2.3 eV.[9] Three different LaB_6 cathode arrangements have been tested. The complete cathode structure in Fig. 3(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. 3(b) and 3(c) respectively. (A detail drawing of this cathode arrangement is also shown in Fig. 2.).

The characteristics of LaB_6 when operated as directly heated cathodes in an ion source have been discussed in three previous papers.[10-12] In summary, LaB_6 has unusual physical properties, such as a high melting point, chemical inertness, low work function, and it resists erosion under ion bombardment. When heated to a temperature of 1600 K or higher, LaB_6 is a copious emitter of electrons. However, LaB_6 is very reactive with refractory metals, and must be separated from them by rhenium, graphite, or carburized tantalum. For this reason, the connector for the complete LaB_6 cathode of Fig. 3(a) is made of graphite. In the cathode arrangement of Fig. 3(c), a rhenium foil separates each LaB_6 insert from the molybdenum mounting.

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 us 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. 4 illustrate the arc current, the H^- beam current, and the arc voltage during a 700 us 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. Because of the strong magnetic field (~ 6 kG), the electrons have great difficulty in moving to the anode. Plasma oscillation can provide the mechanism to increase the flow to the anode.[13] Strong oscillatory electric fields in the plasma greatly enhance the rate of electrons and ions diffusion to the anode walls.

Occasionally, two discharge modes can appear in a single pulse. The oscilloscope trace in Fig. 5 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.

The oscilloscope traces in Fig. 6 demonstrate a 1-millisecond-long pulse for an arc power of 120 V, 27 A. In this case, an RC filter is added onto the input arc current and H^- current signal. The hydrogen gas flow is optimized at 36 sccm. The H^- current extracted from a 1-mm-diam aperture is 1.8 mA, corresponding to a current density of ~ 230 mA/cm^2. The extracted electron current is about a factor of 3 higher. 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 7 shows a plot of the extracted H^- current density versus the arc current. The data points have been accumulated for source operations with all the three LaB_6 cathode arrangements shown in Fig. 3. 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.

Thus far, H^- current density as high as 350 mA/cm^2 has been recorded for an arc current of 55 A. The decrease in the H^- current density for higher arc current operations (Fig. 7) is possibly due to poor beam optics because the available extraction voltage is limited to only 15 kV. Nevertheless, arc current as high as 100 A has been achieved for short pulse durations (< 1 ms). Other characteristics of the Dudnikov source when operated with LaB_6 cathodes are discussed in the following sections.

(a) Source operation without anode ribs

Figure 8(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. In this arrangement, 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 without the anode ribs has been investigated. Figure 8(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. 7) is reduced by a factor of 3 for the same source operating conditions. The reason for this drop in source efficiency is being investigated. It is conceivable that a large fraction of the H^- ions formed are destroyed by the primary electrons before they can be extracted from the source. The anode-rib width used in this experiment was optimized for the cesium-mode operation.[14] It is possible that a pure- hydrogen mode operation can have a different optimized rib geometry. If dissociative attachment only is operative, the transition from a two-region discharge to a single region discharge has been estimated to reduce the H^- yield by a factor of five.[15]

The anode ribs in the Dudnikov source generate a geometry quite similar to the relief region of the Penning source used by Ehlers[3] who discovered that extraction from a region somewhat isolated from the discharge region resulted not only in an increase in H^- ion current but a large reduction in the number of electrons extracted. It is for this same reason that a relief region between the plasma and the body of the source is incorporated in the magnetron H^- source.[16]

(b) B-field dependence of H^- current

It was found by Allison that 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. In this investigation, a large electromagnet is used to generate the B-field required for the source operation. Therefore, the magnitude of the B-field can be easily adjusted while the arc current and the gas flow rate are both maintained at constant values.

Figure 9 shows the extracted H^- current as a function of the B-field for three different discharge currents. In all cases, the H^- current increases monotonically with the B-field. As the B-field is increased from 2 to 7 kG, the H^- current increases by more than 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. The use of stronger B-field can 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.

III. Hybrid production of H^- ions

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[17] with a LaB_6 converter to generate both volume and surface produced H^- ions. A schematic of the experimental set-up is shown in Fig. 10. In this arrangement, the 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.

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. 11 shows that there are two groups of H^- ions. The tall narrow peak represents the H^- ions produced by volume processes. The second group are H^- ions emitted from the LaB_6 converter surface. It can be seen that in this cesium-free hydrogen discharge, the number of volume-produced H^- ions extracted from the source is larger than that of the surface-produced H^- ions.

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.

IV. Discussion

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.

The hybrid H^- production experiment discussed in Sec. III indicates that the majority of the H^- ions extracted from the Dudnikov source are produced directly from volume processes, possibly in the extraction region where very few energetic primary electrons are present. However, additional experiments must be performed in order to understand the H^- production mechanism when the source is operated with cesium. Experiments are also planned with the purpose of reducing the noise level and improving the arc and gas efficiency of the Dudnikov source. Results of these investigations will be reported in the near future.

Acknowledgment

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

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Figure Captions

Fig. 1 Schematic diagram of the Penning or PIG discharge geometry.

Fig. 2 Different components of the Dudnikov type Penning source: (1) extraction electrode; (2) anode housing with emission slit; (3) anode insert; (4) cathode; (5) boron-nitride insulator; (6) spacer; (7) cathode connector; (8) source mounting plate; (9) gas pipe. An enlarge view of the cathode with the LaB_6 inserts is also shown in the diagram.

Fig. 3 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.

Fig. 4 Oscilloscope traces showing the arc current, H^- beam current and arc voltage during a 700 μs pulse operation.

Fig. 5 Oscilloscope traces showing the two discharge modes which occur during the early part of a 600 μs pulse operation.

Fig. 6 Oscilloscope traces showing the arc current, H^- beam current and arc voltage for a 1 ms pulse operation. In this display, an RC filter is added onto the arc current and H^- current signal.

Fig. 7 Extracted H^- current density versus arc current. The five (Δ) data points are obtained without the anode ribs in the source assembly.

Fig. 8. Schematic diagram showing the discharge geometry (a) with and (b) without the ribs in the anode insert.

Fig. 9. H^- current density as a function of the applied magnetic field for three different arc currents.

Fig. 10. Schematic of the multicusp source equipped with a permanent magnet filter and a LaB_6 converter.

Fig. 11 Spectrometer output signal showing the extracted volume-produced H^- ions and the H^- ions formed on the LaB_6 converter surface.

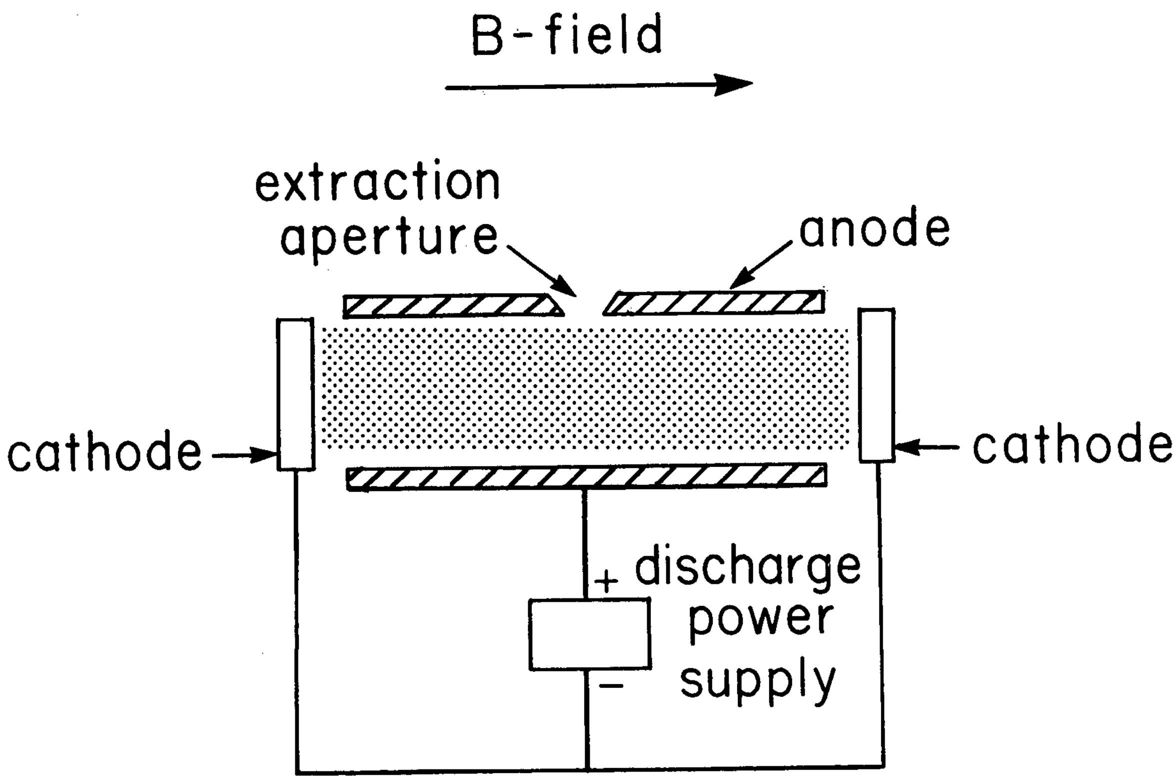

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Fig. 1

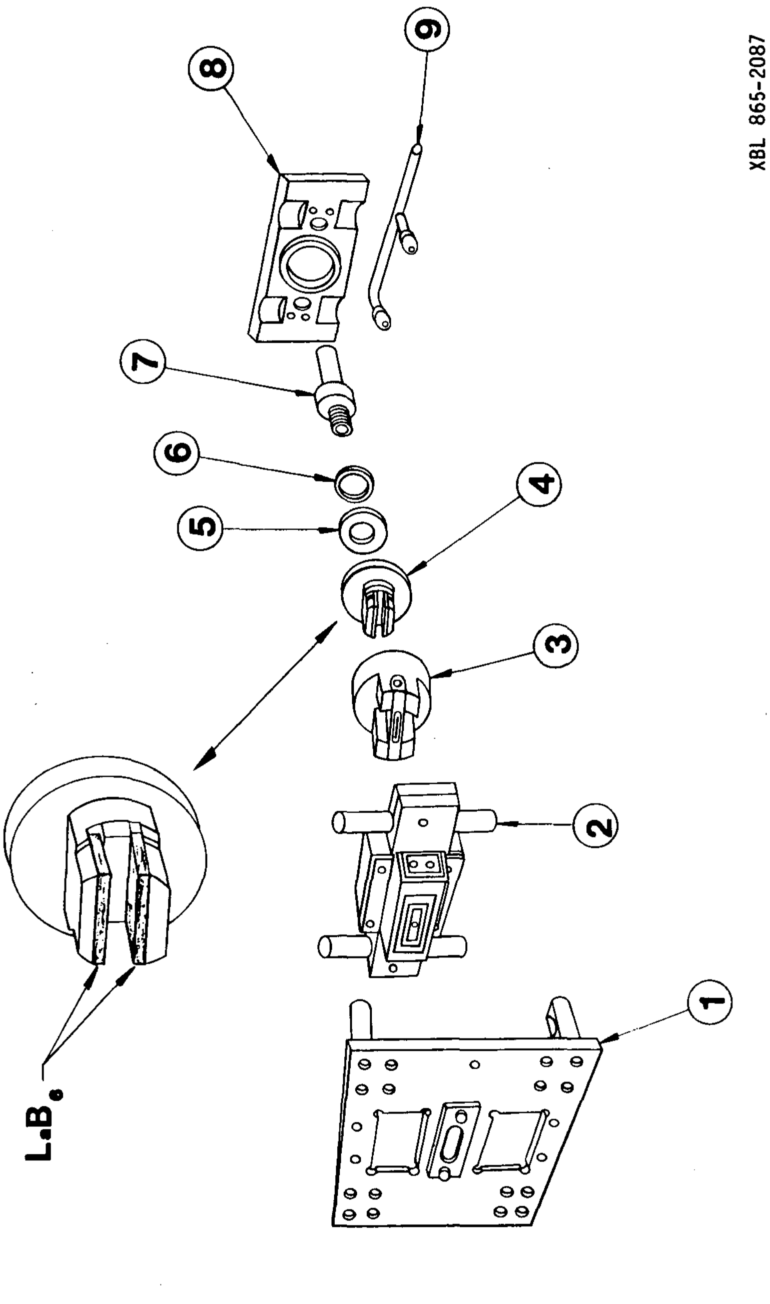

Fig. 2

(a) (b) (c)

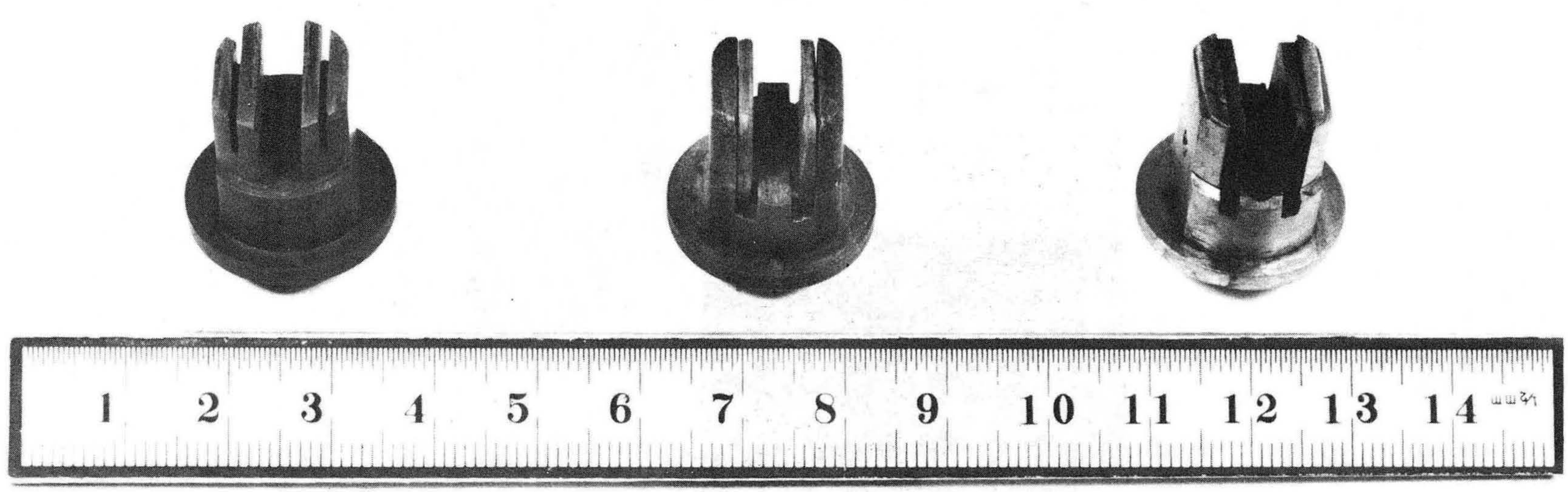

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Fig. 3

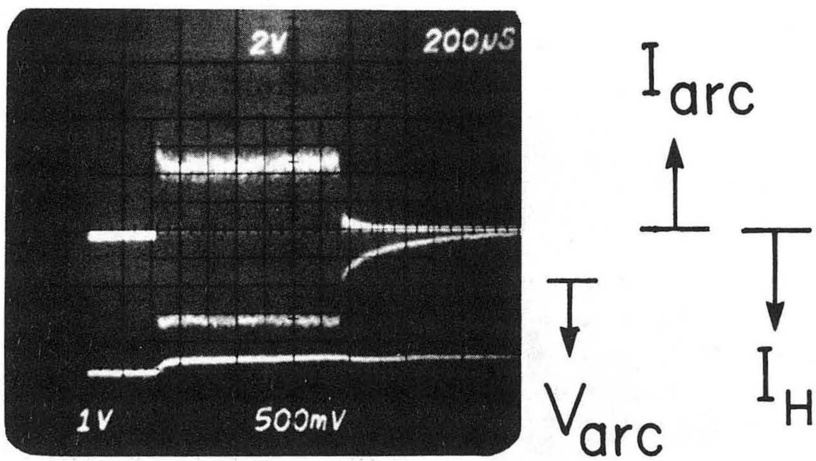

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Fig. 4

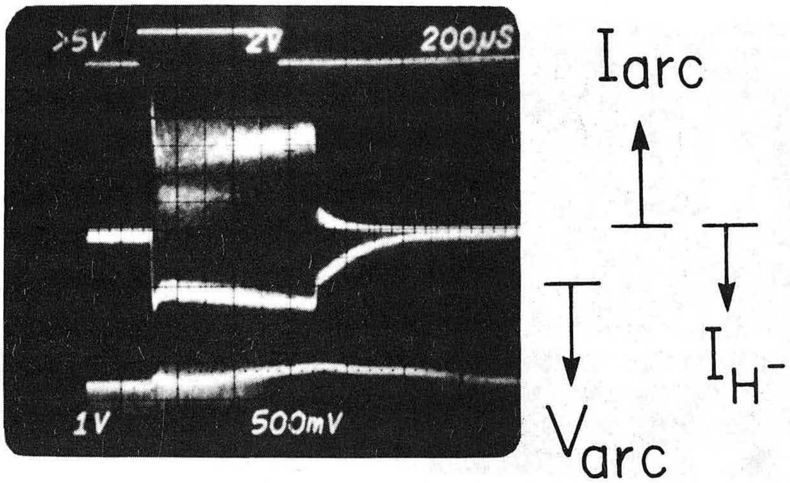

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Fig. 5

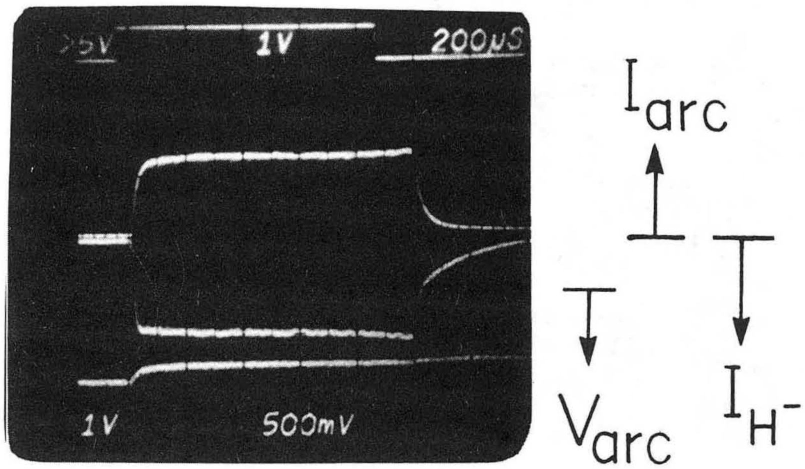

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Fig. 6

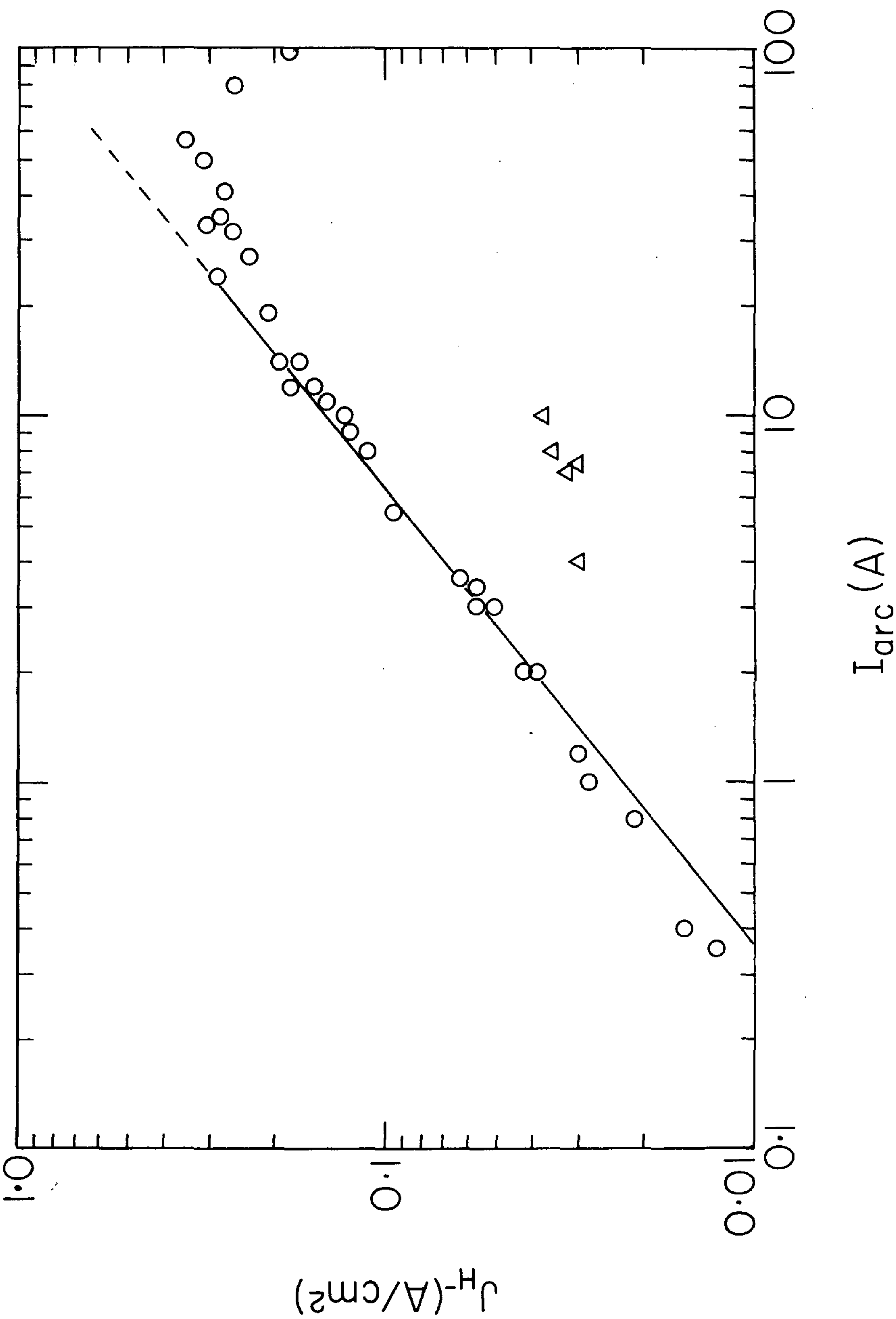

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Fig. 7

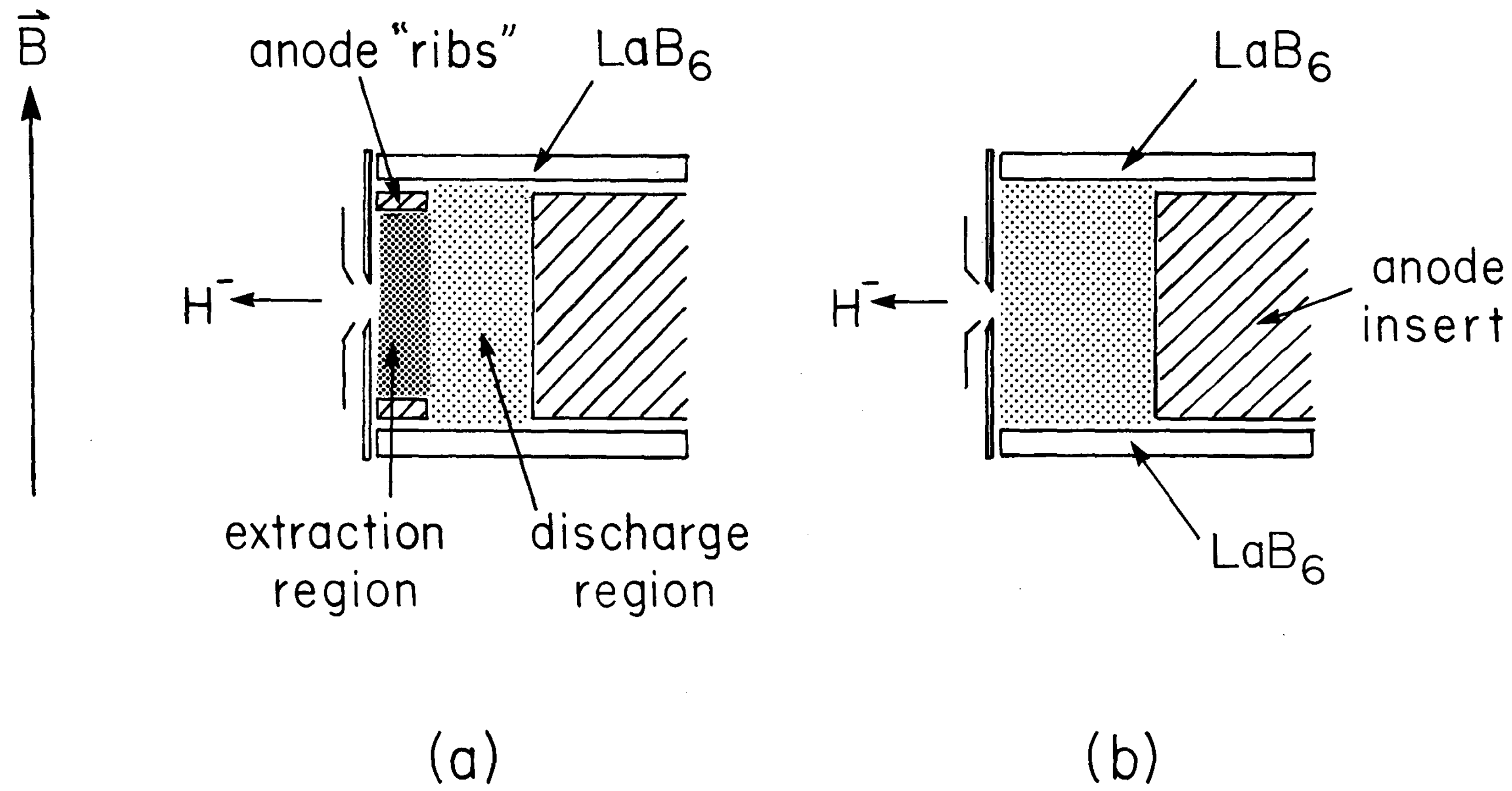

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Fig. 8

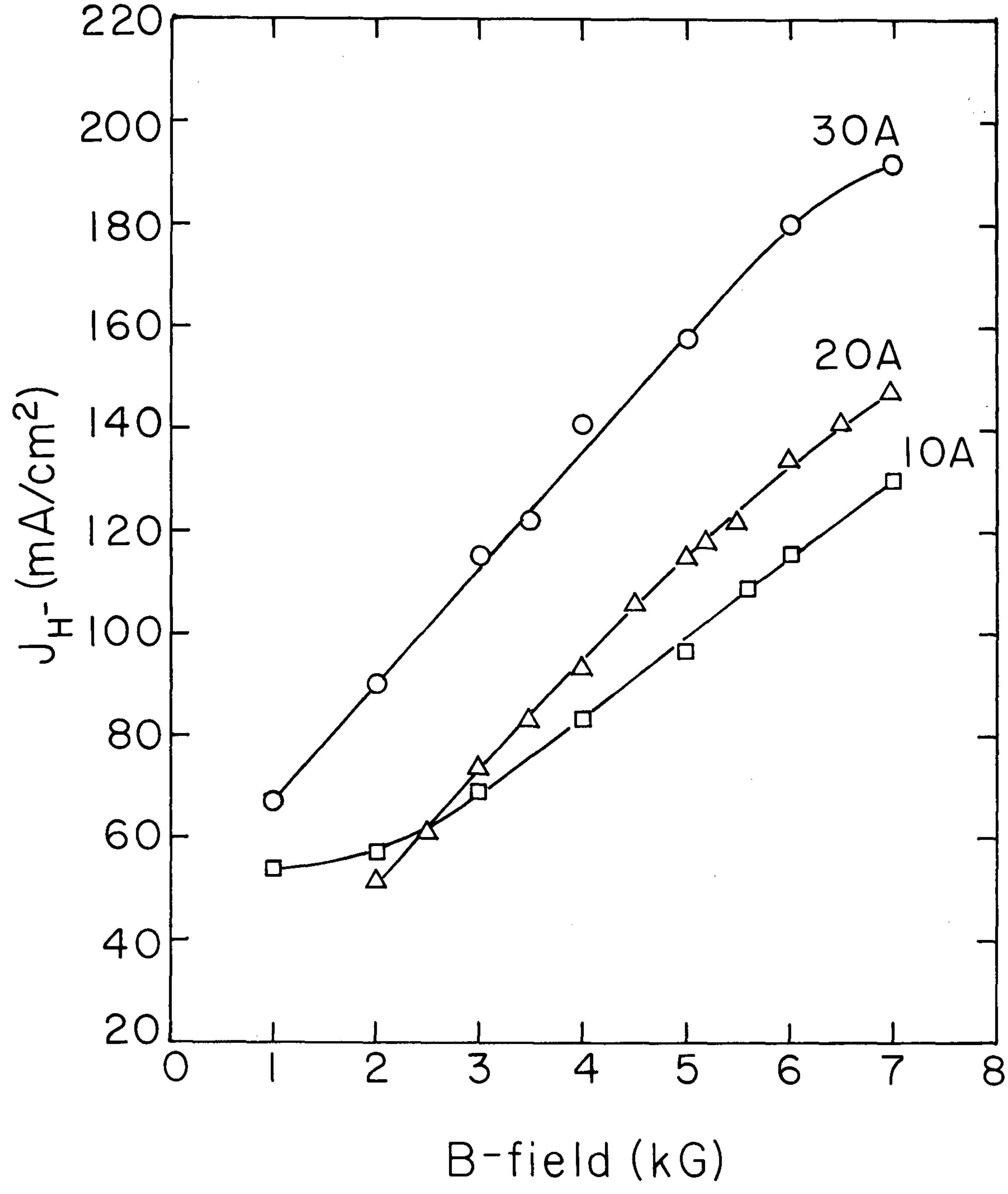

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Fig. 9

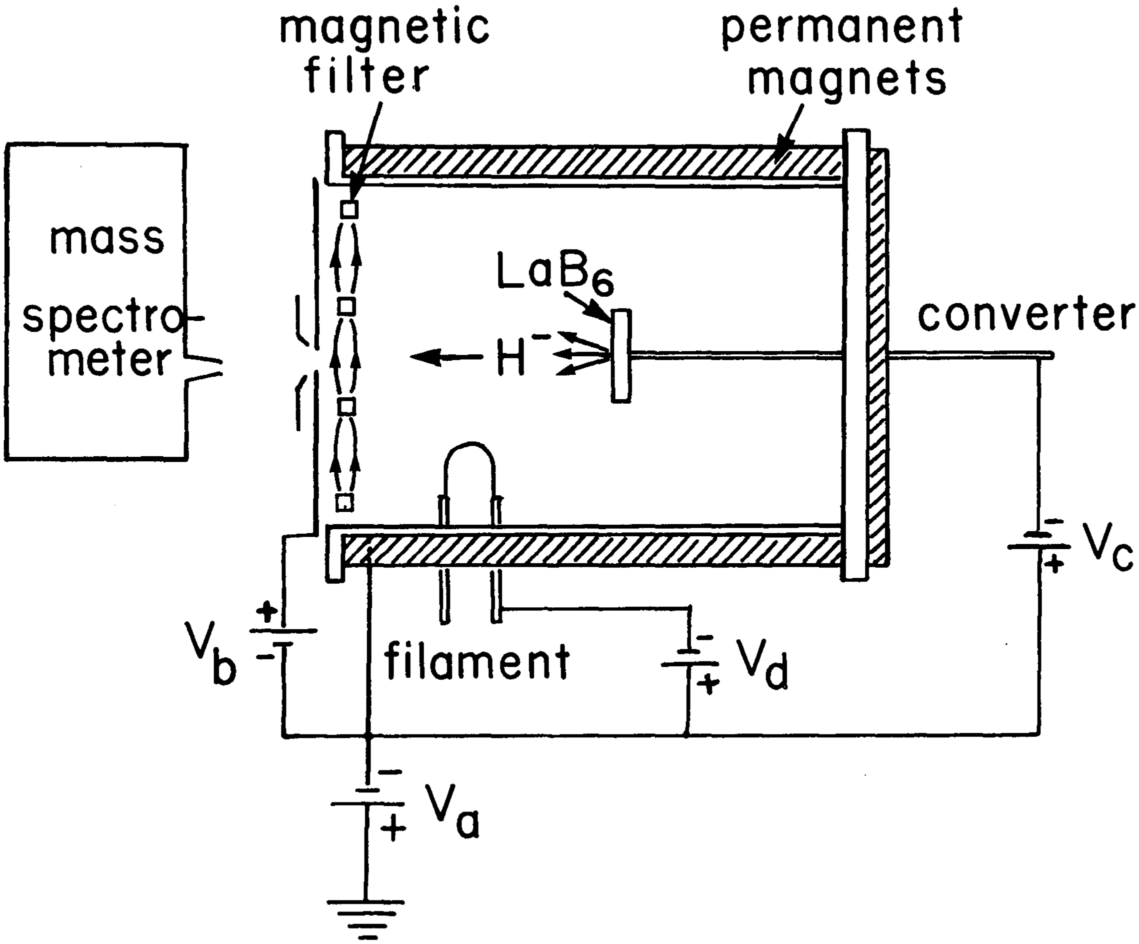

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Fig. 10

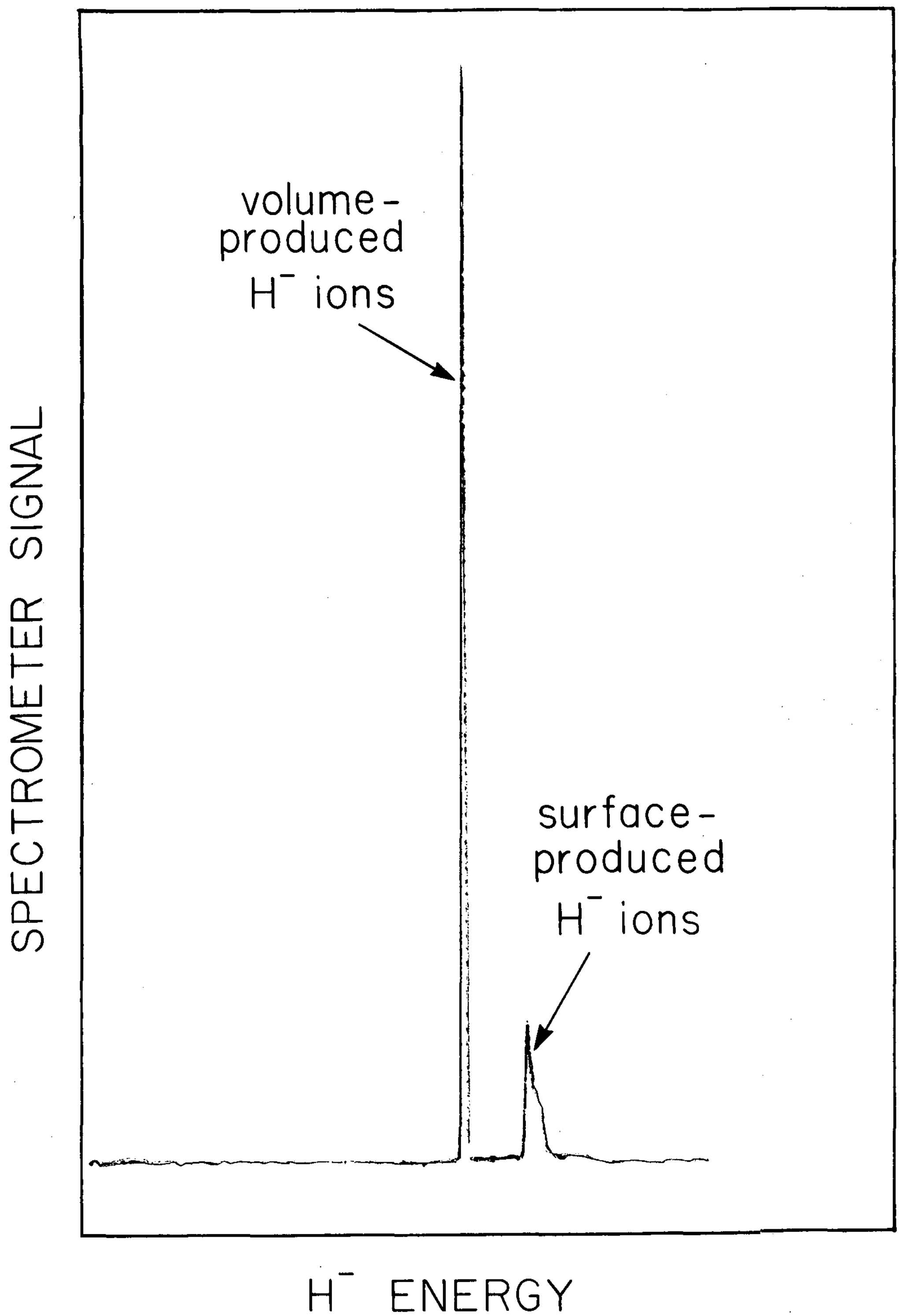

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Fig. 11

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