Title

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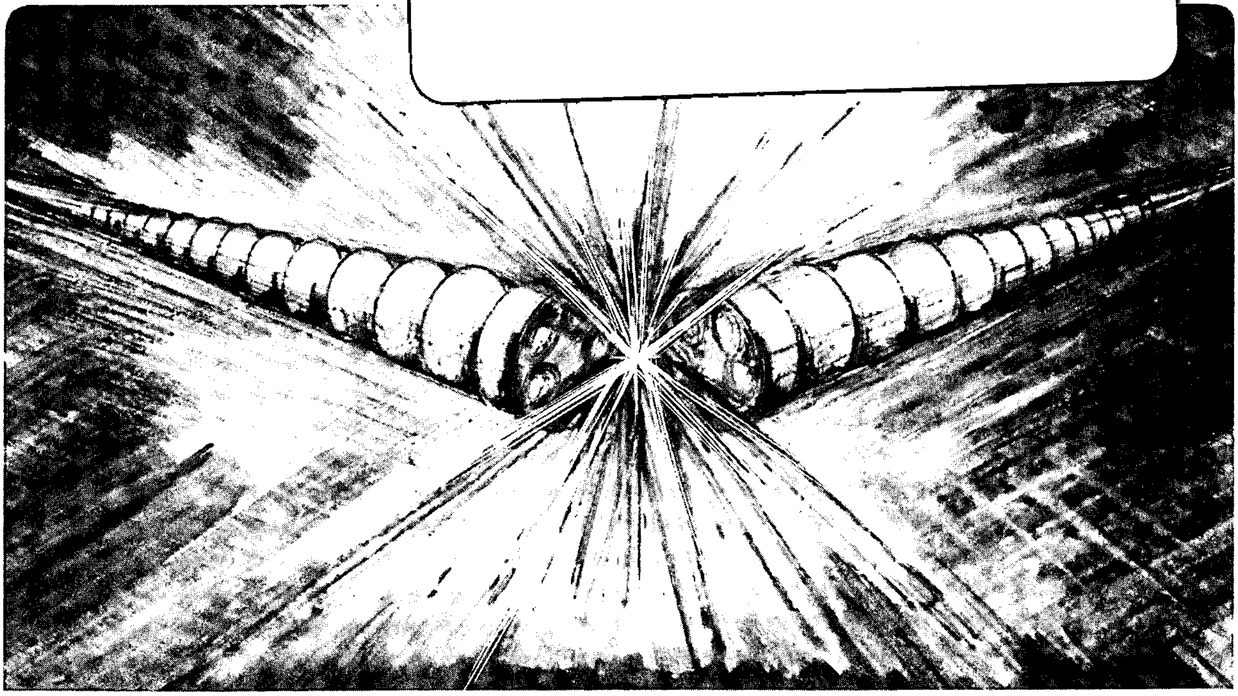

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Development of High Current and High Brightness Negative Hydrogen Ion Sources[*]

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Abstract

Negative hydrogen ions have found important applications in particle accelerators and in fusion research. These ions can be generated from two different types of ion sources - the surface conversion source and the volume production source. Recent experiments demonstrate that H^- current exceeding 1 A can be obtained from both types of ion sources. Because of the lower H^- ion temperature and the fact that they can be operated without cesium, volume H^- sources are highly desired. However, further technology must be developed on the control of electrons and the reduction of gas flow before this type of sources become practical units of a multiampere neutral beam injection system.

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I. Introduction

The use of H^- ions for accelerator applications was first proposed by Alvarez in 1951.[1] Since then, H^- have found important applications in cyclotrons and tandem accelerators, in fueling storage rings of high energy accelerators, and in generating energetic neutral beams ($E > 150$ keV) for heating and for current drive in fusion plasmas. Negative hydrogen ions can be formed by double charge exchange processes or by direct extraction from a negative ion source. In general, two distinct types of H^- ion sources can be identified: (1) surface conversion sources - in which the H^- ions are generated by particle collisions with low work function surfaces, and (2) volume production sources - in which the negative ions are produced by electron-molecule and electron-ion collision processes in the volume of a discharge plasma. Because of the smaller beam emittance and the fact that they can be operated without cesium, volume H^- sources are now being developed by various high energy and fusion laboratories in the world. This article reviews the development and some of the latest technology of these two types of negative ion sources. It can be seen that in just twenty years, H^- ion beams have been improved from several milli-ampere to more than 1 ampere.

II. Surface-produced H^- ion sources

There are two major types of surface conversion H^- ion sources. One type uses a Penning discharge geometry (for example the planotron source) or an E x B discharge configuration (for example the magnetron source). The second type employs the multicusp plasma generator as the discharge chamber. This source was originally developed at Lawrence Berkeley Laboratory for neutral beam application. Recently, it has been used as an H^-

source for particle accelerators at Los Alamos National Laboratory and at KEK in Japan.

In 1972, the Novosibirsk group discovered that the yield of H^- ions was increased from 5 to 20 mA by adding cesium to the hydrogen discharge in a planotron source. H^- current density greater than 3 A/cm^2 has been achieved in milli-second pulses.[2] The function of the cesium is twofold: first, it acts as a sputtering agent, and second, it lowers the work function of the target surface so as to enhance the negative ion formation.

In Novosibirsk, a multi-slit planotron source with one dimensional focusing was developed in 1979.[3] This source can produce pulsed beam of H^- ions with a current of 4 A. In 1981, Bel'chenko in Novosibirsk further developed a honeycomb multi-aperture source with focusing of H^- ions from spherical dimples on a cathode surface to the circular emission holes in the anode.[4] A total H^- current of 11 A was obtained at pulse lengths less than 800 us. A photograph of this multi-aperture honeycomb source is shown in Fig. 1.

A schematic diagram of the Berkeley type surface-conversion H^- source is illustrated in Fig. 2.[5] The source is essentially a multicusp plasma generator. To produce H^- ions, a water-cooled, concave, molybdenum converter is inserted into the plasma. By biasing the converter negatively (~200 V) with respect to the plasma, positive ions from the plasma are accelerated across the sheath and strike the converter surface. Negative ions that are formed at the converter are then accelerated back through the sheath by the same potential. The bias voltage on the converter thus becomes the negative ion extraction potential. The converter surface is curved to geometrically direct the negative ions through the plasma to a position at the exit aperture which is located between two ceramic magnet columns. The B-field in the exit region is strong enough to reflect energetic primary electrons but it produces only a small lateral displacement on the trajectories of the H^- ions.

In normal operation, cesium is introduced into the discharge so as to lower the work function of the converter and consequently enhance the H^- yield. This multicusp surface-conversion source has been operated successfully to generate a steady-state H^- beam of current greater than 1 A. By employing an electrostatic accelerator, the "self-extracted" H^- beam can subsequently be accelerated to a higher energy.[5,6] Since the H^- output is proportional to the surface area of the converter, higher H^- beam current can be achieved by using a larger converter.

Measurements of the negative ion energy spectrum showed that the H^- ions are made both by the desorption and the reflection processes on the converter surface.[7] For optimum cesium coverage, the energy spectrum in Fig. 3 shows that desorption becomes the dominant H^- production process. For reasons not yet understood, molybdenum seems to be the best converter material for H^- production.

Multicusp surface-conversion sources have also been operated in a pulse mode in Los Alamos and in KEK. An H^- current of 21 mA has been accelerated to 750 keV at the LAMPF facility in the Los Alamos National Laboratory with a normalized emittance value of 0.081 cm-mrad.[8] By employing LaB_6 filament cathodes, a similar H^- source at KEK can be operated continuously for more than 2600 hours.[9]

III. Volume-Produced H^- Ion Sources

A hydrogen plasma contains not only positive ions (H^+, H_2^+, H_3^+) and electrons but also negative hydrogen ions. By using the photodetachment technique, Bacal et al. have measured large concentrations of H^- ions in a dc hydrogen discharge plasma.[10] In the past, attempts have been made to extract these H^- ions from the plasma of a duoplasmatron, a magnetron, or a Penning-type discharge source. Considerable progress has been made in increasing the extractable H^- current of these sources since the early 1960's.

In 1972, a magnetron negative ion source, shown schematically in Fig. 4 was developed in Novosibirsk by Bel'chenko et al.[2] In this source, the discharge chamber has the shape of a race track and plasma is kept circulating in the narrow space by the E x B drift motion. The H^- ions are extracted from the plasma through a slit in the anode, elongated perpendicularly to the magnetic field. A pulsed beam of H^- ions with a current up to 22 mA and a high emission density of 220 mA/cm^2 was obtained with discharge currents as high as 100 A and an arc voltage of 500 V. The accompanying electron current was less than 100 mA and the source pressure was estimated to be about 1 Torr.

In 1963, Ehlers et al. in Berkeley developed a direct extraction negative ion source which could be easily adapted for use in a cyclotron.[11] This source is operated with a hot cathode Penning-type gas discharge. A D^- ion beam of 2 mA has been extracted from the arc in a direction normal to the magnetic field, with a discharge voltage of 300 V and a discharge current of 5 A. Subsequently, this source was modified with a recess in the arc chamber where the extraction slit was located. With this new geometry, continuous H^- beam with current in excess of 5 mA ($J^- \sim 40$ mA/cm^2) was obtained.

In 1982, the Ehlers' type Penning Source was again modified in Berkeley so that the anode was divided into two sections: a top anode part and a wall anode part. By applying the appropriate bias voltage between these two anodes, 9.7 mA ($J^- \sim 100$ mA/cm^2) of H^- and 4.1 mA ($J^- \sim 42$ mA/cm^2) of D^- current were obtained in a dc operating mode.[12] The increase in negative ion yield was attributed to the enhancement of anomalous plasma diffusion.

Recently, a Dudnikov type of Penning source (which requires cesium in normal operation) has been operated successfully in a pure hydrogen mode by using a low work fundtion LaB_6 cathode.[13] It is found that the extracted H^- current density was comparable to that of the cesium-mode operation; an H^- current density of 350 mA/cm^2 has been obtained for an arc current of 55 A. Expreimental results also demonstrated that the majority of the H^- ions extracted are formed by volume processes in this type of LaB_6 cathode source operation.

In 1983, a novel method of extracting volume-produced H^- ions directly from a multicusp source was reported by Leung et al.[14] The multicusp plasma generator has demonstrated its ability to produce large volumes of uniform and quiescent plasmas with good gas and electrical efficiency.[15] A schematic diagram of the apparatus is shown in Fig. 5. The source chamber (20 cm diam by 24 cm long) is surrounded externally by 10 columns of samarium-cobalt magnets which form a longitudinal line-cusp configuration for primary electron and plasma confinement. A steady-state hydrogen plasma is produced by primary electrons emitted from tungsten filaments and the entire chamber wall served as the anode for the discharge.

When operated as a H^- ion source, a water-cooled permanent magnet filter is included and it divides the entire source chamber into an arc discharge and an extraction region. This filter provides a limited region of transverse magnetic field which is strong enough to prevent the energetic primary electrons from entering the extraction zone. Excitation and ionization of the gas molecules are performed efficiently by the primaries in the discharge region. Both positive and negative ions, together with cold electrons, are able to penetrate the filter and they form a plasma with very low electron temperature in the extraction region. H^- ions are then produced in the extraction chamber and filter region via processes such as the dissociative attachment of vibrationally excited H_2 molecules[16], or the dissociative recombination of H_2^+ and H_3^+ ions.[17,18] Initial results show that this filtered multicusp geometry will not only enhance the H^- ion yield but sizably reduce the extracted electron component.

It was demonstrated in 1984 that the filter-equipped multicusp source could provide high quality H^- beams with current densities as high as 38 mA/cm^2.[19] The beam emittance increases approximately as the square root of beam current and thus the beam brightness is essentially constant with increasing current density. By comparison, the brightness of this ion source (at the 8% threshold level) is 0.58 A/cm^{2}mrad^2 at a current density of 38 mA/cm^2 which is 2.4 times as bright as the 0.24 A/cm^{2}mrad^2 value obtained for a multicusp surface production source operating at 16 mA/cm^2.

Several methods to improve the efficiency of the multicusp H^- source have been investigated. By optimizing the extraction chamber length, a substantial improvement in the output has been achieved.[20] Experimental results have demonstrated that the H^- yield can be enhanced by choosing aluminum or copper as the chamber wall material[21] or by mixing hydrogen and xenon gases in the source discharge.[22] A substantial improvement in H^- yield also occurs when very low energy electrons ($E \sim 1$ eV) are added into the filter or extraction regions.[23]

Most recently, a small version of the filtered-multicusp source (Fig. 6) has been operated successfully to generate volume-produced H^- ions.[24] From this new source H^- current density greater than 250 mA/cm^2 has been extracted from a 1-mm-diam aperture for a discharge voltage of 150 V and a discharge current of 450 A. However, the large electron to H^- current ratio, as well as the high operating source pressure indicate that further development is needed in order to make this small negative ion source practical for producing high brightness H^- beams for long pulse or steady-state operations.

Multicusp volume-produced H^- sources and extraction systems are now being developed in various laboratories (Berkeley, Brookhaven, CERN, Culham, JAERI, KEK, Los Alamos and TRIUMF) to achieve the best electron suppression with no degradation of ion optics. Since future fusion reactors may require energetic neutral beams for heating or for current drive, large area multicusp sources equipped with permanent magnet filters are now being tested to generate high currents of H^- ion with multi-aperture extraction systems.

It has been reported by Okumura et al.[25] that H^- ion beams of 1.26 A were extracted at 21 keV for 0.2 s from the large multicusp source shown in Fig. 7. The extractor consists of four grids, each having 209 apertures of 9 mm diameter within a rectangular area of 12 x 26 cm^2. Small permanent magnets are installed in the second electrode so that a large fraction of the extracted electrons are deflected and captured by this electrode before they are accelerated to full energy. These results indicate that one might soon operate large area plasma sources to provide multi-ampere H^- beams in much the same manner as is now done to provide positive hydrogen ions for neutral beam systems.

Acknowledgment

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References

1. L. W. Alvarez, Rev. Sci. Instrum. 22, 705 (1951).
2. Yu. I. Bel'chenko, G. I. Dimov and V. G. Dudnikov. Investiya of USSR Academy of Science Ser. Fix. 37, 2573 (1973).
3. Yu. I. Bel'chenko, V. G. Dudnikov, Journal de Physique, Colloque C7, 40, 501 (1979).
4. Yu. I. Bel'chenko and V. G. Dudnikov, Proc. of the XVth International Conf. on Phenomena in Ionized Gases, Minsk (1981).
5. K. N. Leung and K. W. Ehlers, Rev. Sci. Instrum. 53, 803 (1982).
6. J. W. Kwan, G. D. Ackerman, O. A. Anderson, C. F. Chan, W. S. Cooper, G. J. deVries, A. F. Lietzke, L. Soroka, and W. F. Steele, Rev. Sci. Instrum. 57, 831 (1986).
7. K. N. Leung and K. W. Ehlers, J. Vac. Sci. Techno. A3, 1240 (1985).
8. R. L. York (private communication).
9. Y. Mori, A. Takagi, K. Ikegami and S. Fukumoto, Proc. of the 4th International Symposium on the Production and Neutralization of Negative Ions and Beams, Upton, NY (1986).
10. M. Bacal and G. W. Hamilton, Phys. Rev. Lett. 42, 1538 (1979).
11. K. W. Ehlers, B. F. Gavin, and E. L. Hubbard, Nucl. Instrum. Meth. 22, 87 (1963).
12. K. Jimbo, K. W. Ehlers, K. N. Leung, and R. V. Pyle, Nucl Instrum. Meth. A248, 282 (1986).
13. K. N. Leung et al., Rev. Sci. Instrum. 58, 235 (1987).
14. K. N. Leung, K. W. Ehlers, and M. Bacal, Rev. Sci. Instrum. 54, 56 (1983).
15. R. Limpaecher and K. R. MacKenzie, Rev. Sci. Instrum. 44, 726 (1973).

16. M. Allen and S. F. Wong, Phys. Rev. Lett. 41, 1795 (1978).
17. B. Peart and K. T. Dolder, J. Phys. B8, 1570 (1975).
18. B. Peart, R. A. Forrest, and K. Dolder, J. Phys. B12, 3441 (1979).
19. R. L. York, Ralph R. Stevens, Jr., K. N. Leung, and K. W. Ehlers, Rev. Sci. Instrum. 55, 681 (1984).
20. K. N. Leung, K. W. Ehlers, and R. V. Pyle, Rev. Sci. Instrum. 56, 364 (1985).
21. K. N. Leung, K. W. Ehlers, and R. V. Pyle, Rev. Sci. Instrum. 47, 227 (1985).
22. K. N. Leung, K. W. Ehlers, and R. V. Pyle, Rev. Sci. Instrum. 56, 2097 (1985).
23. K. N. Leung, K. W. Ehlers, and R. V. Pyle, Rev. Sci. Instrum. 57, 321 (1986).
24. K. N. Leung, K. W. Ehlers, C. A. Hauck, W. B. Kunkel, and A. F. Lietzke, Rev. Sci. Instrum. 59, 453 (1988).
25. Y. Okumura, H Horiike, T. Inoue, T. Kurashima, S. Matsuda, Y. Ohara, and S. Tanaka, Proc. of the 4th International Symposium on the Production and Neutralization of Negative Ions and Beams, Upton, NY (1986).

Figure Caption

Fig. 1 Multi-aperture honeycomb source.

Fig. 2 Schematic diagram of the LBL surface-conversion H^- source.

Fig. 3 The energy spectrum of the H^- ions produced by a Mo converter. For no cesium, the second and the third peaks are H^- ions formed by backscattered H_3^+ and H_2^+ ions respectively.

Fig. 4 The magnetron H^- ion source.

Fig. 5 Schematic drawing of the multicusp negative ion source with a magnetic filter.

Fig. 6 Schematic drawing of the small multicusp H^- ion source.

Fig. 7 Cross-sectional view of the JAERI large volume H^- ion source together with the extraction system.

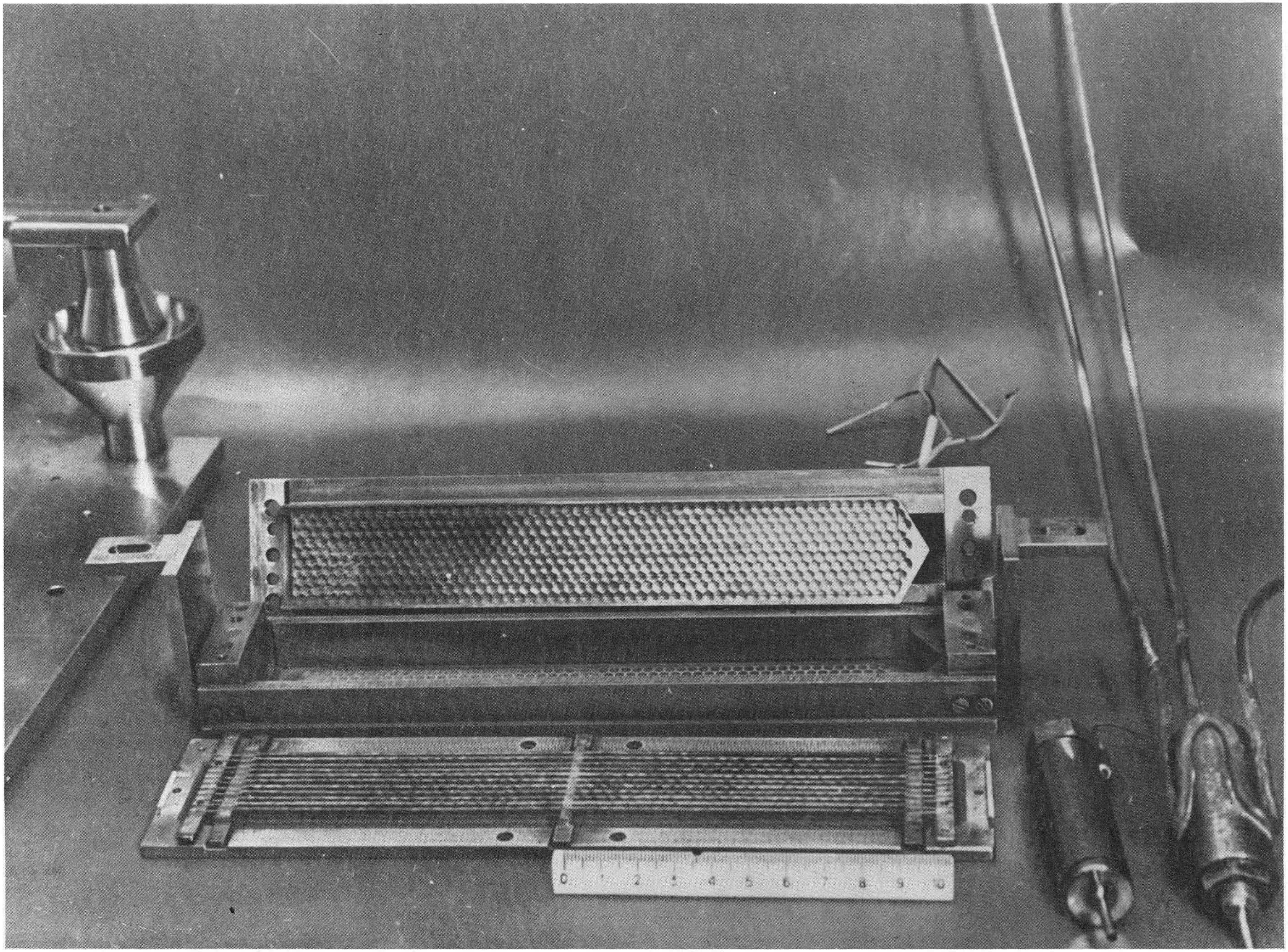

Fig. 1

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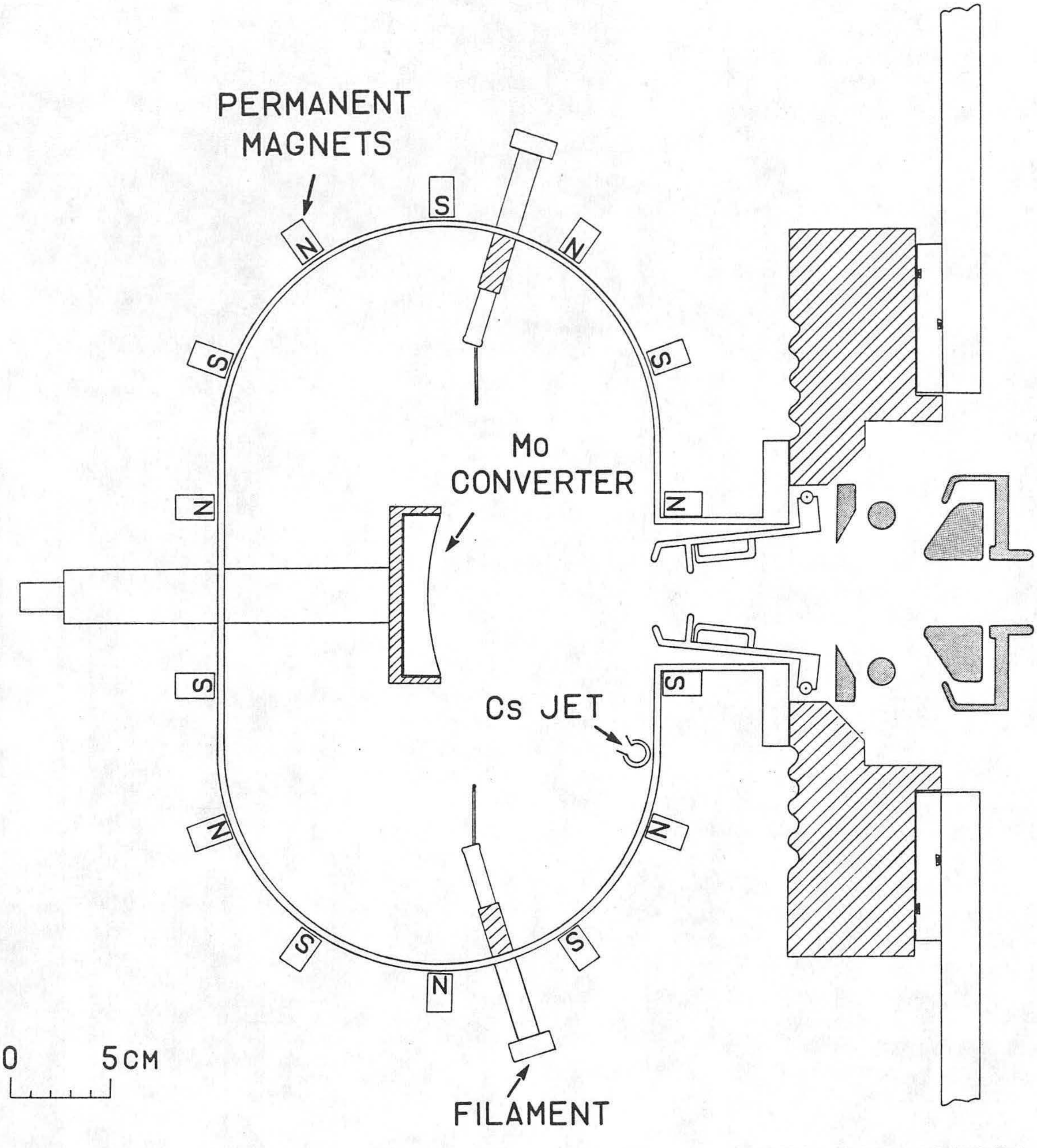
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Fig. 2

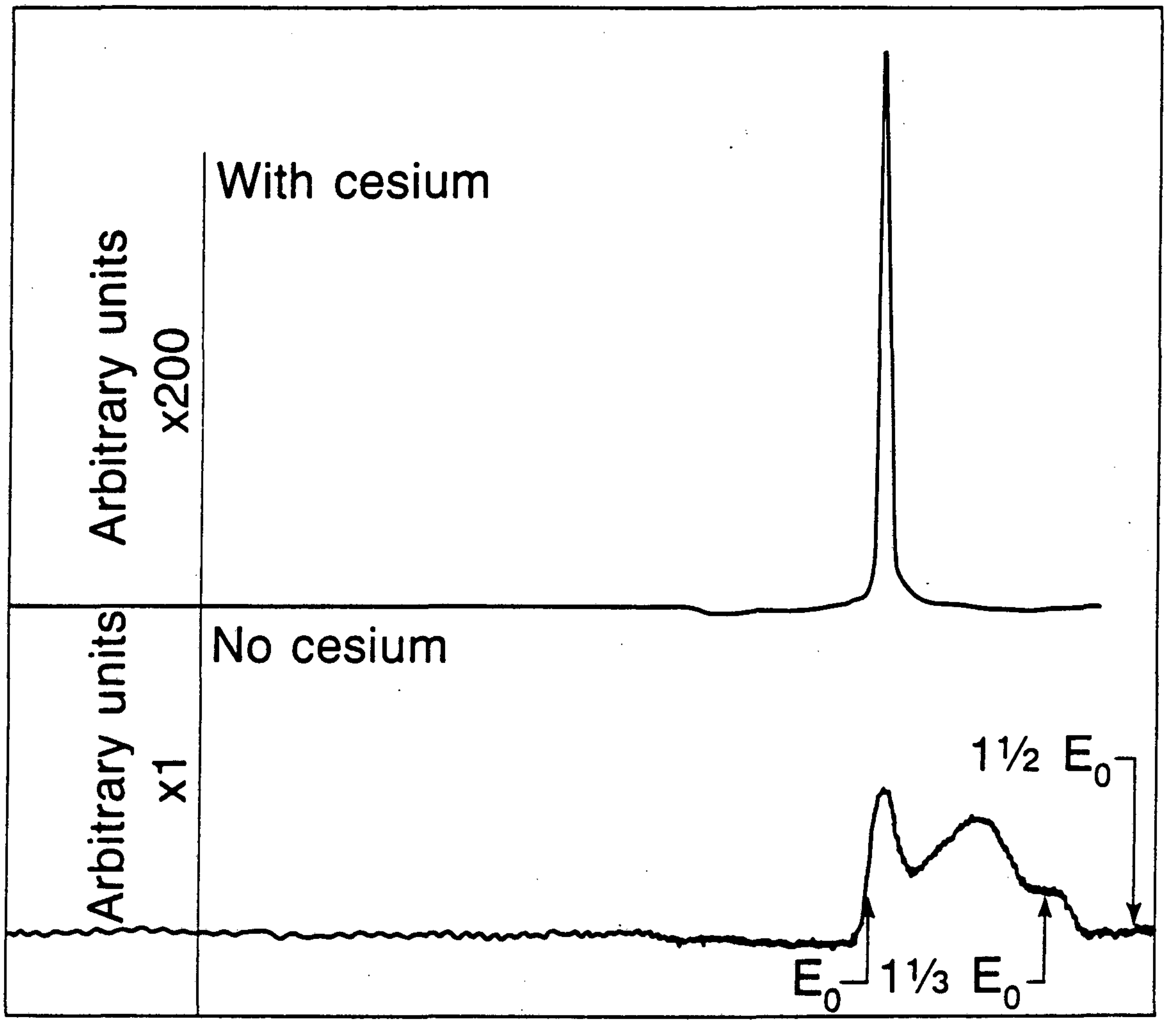

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Fig. 3

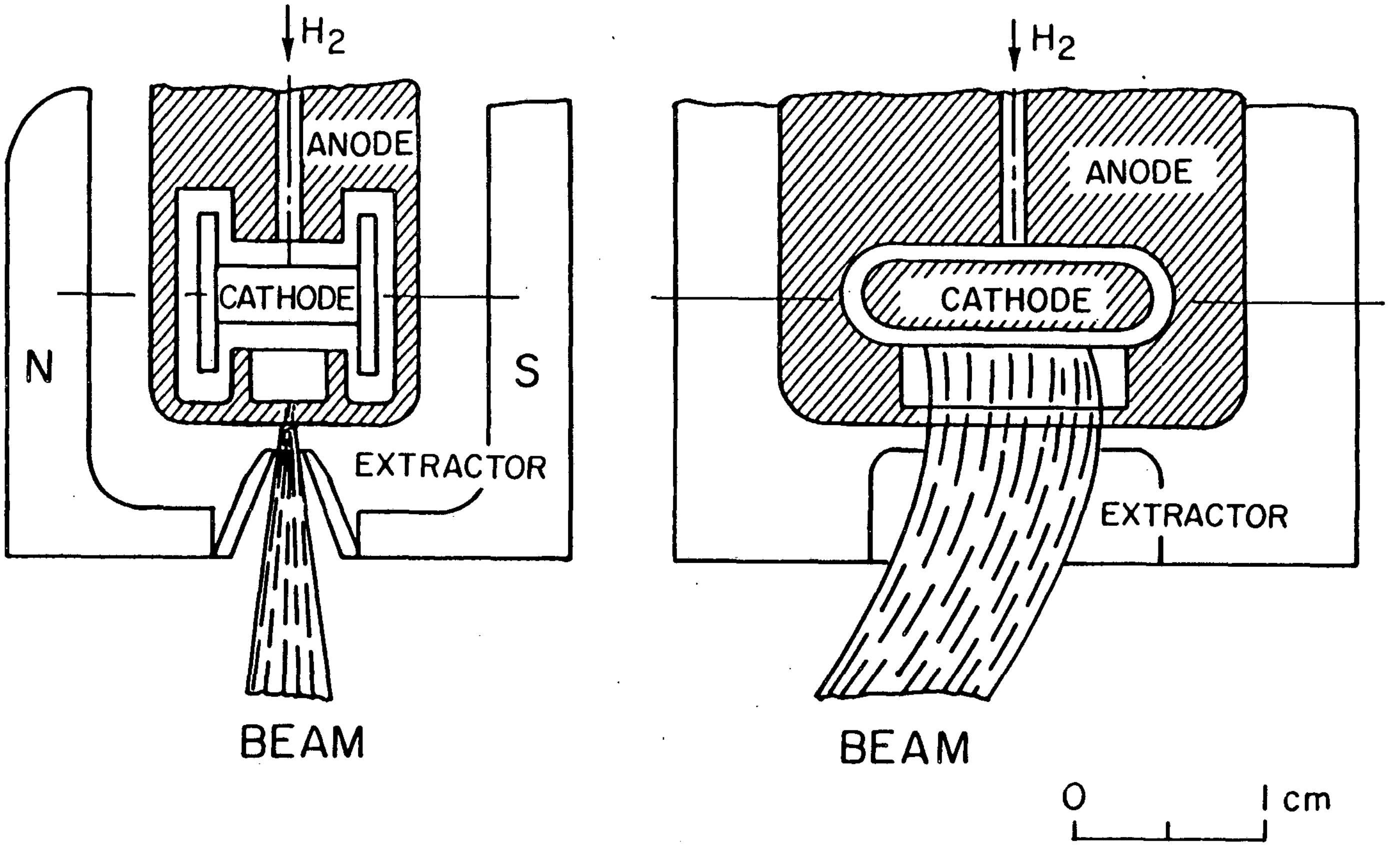

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Fig. 4

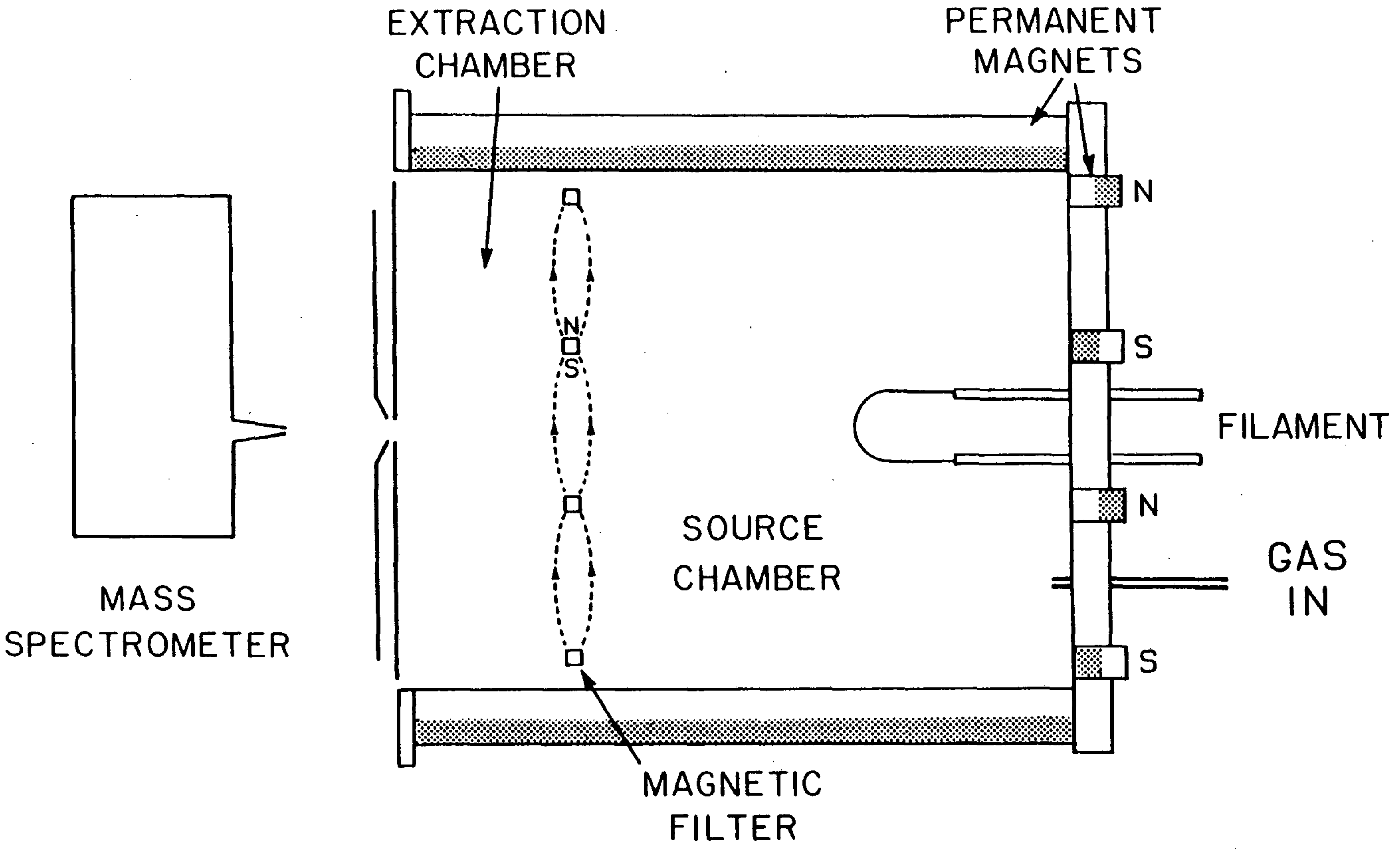

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Fig. 5

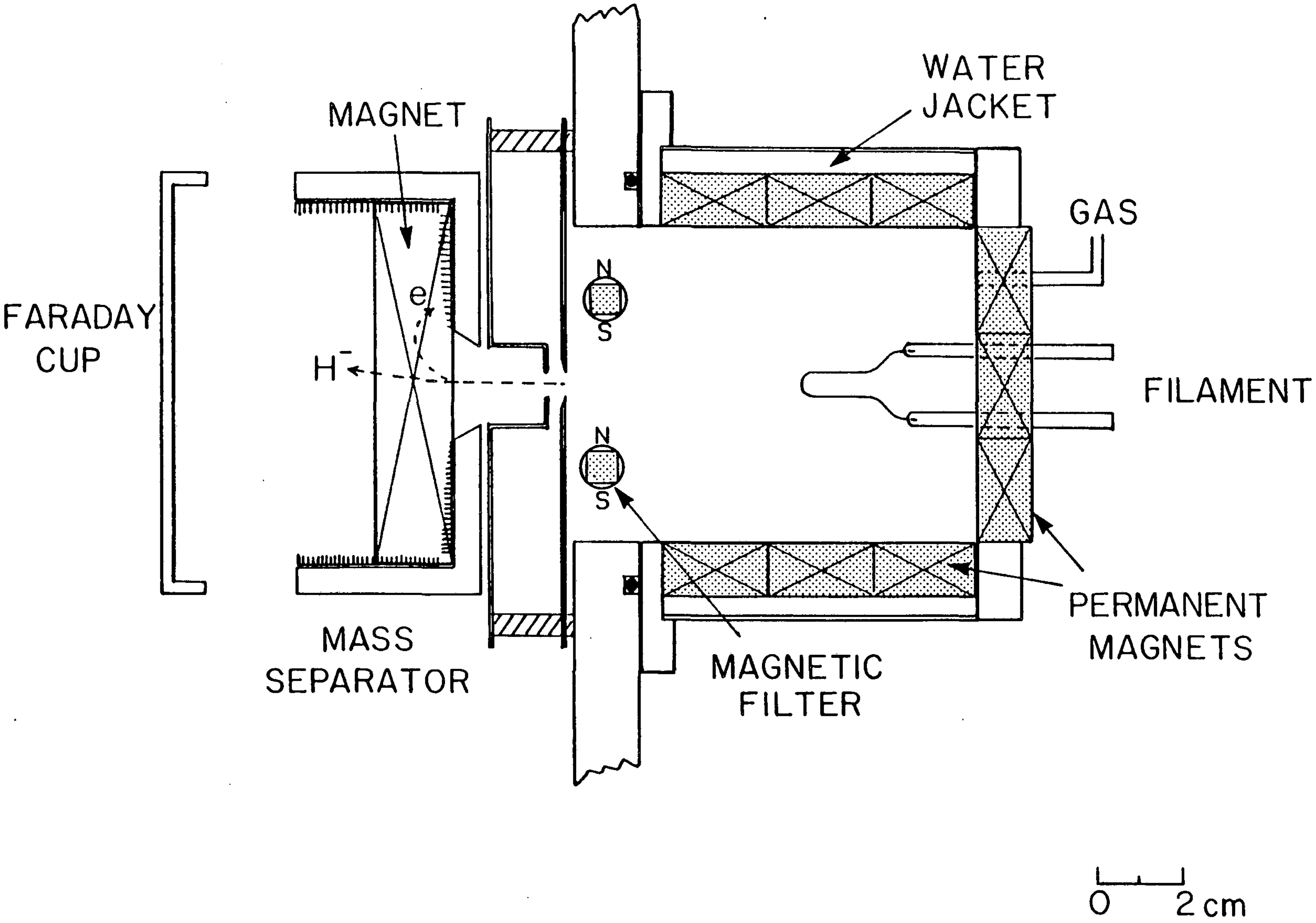

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Fig. 6

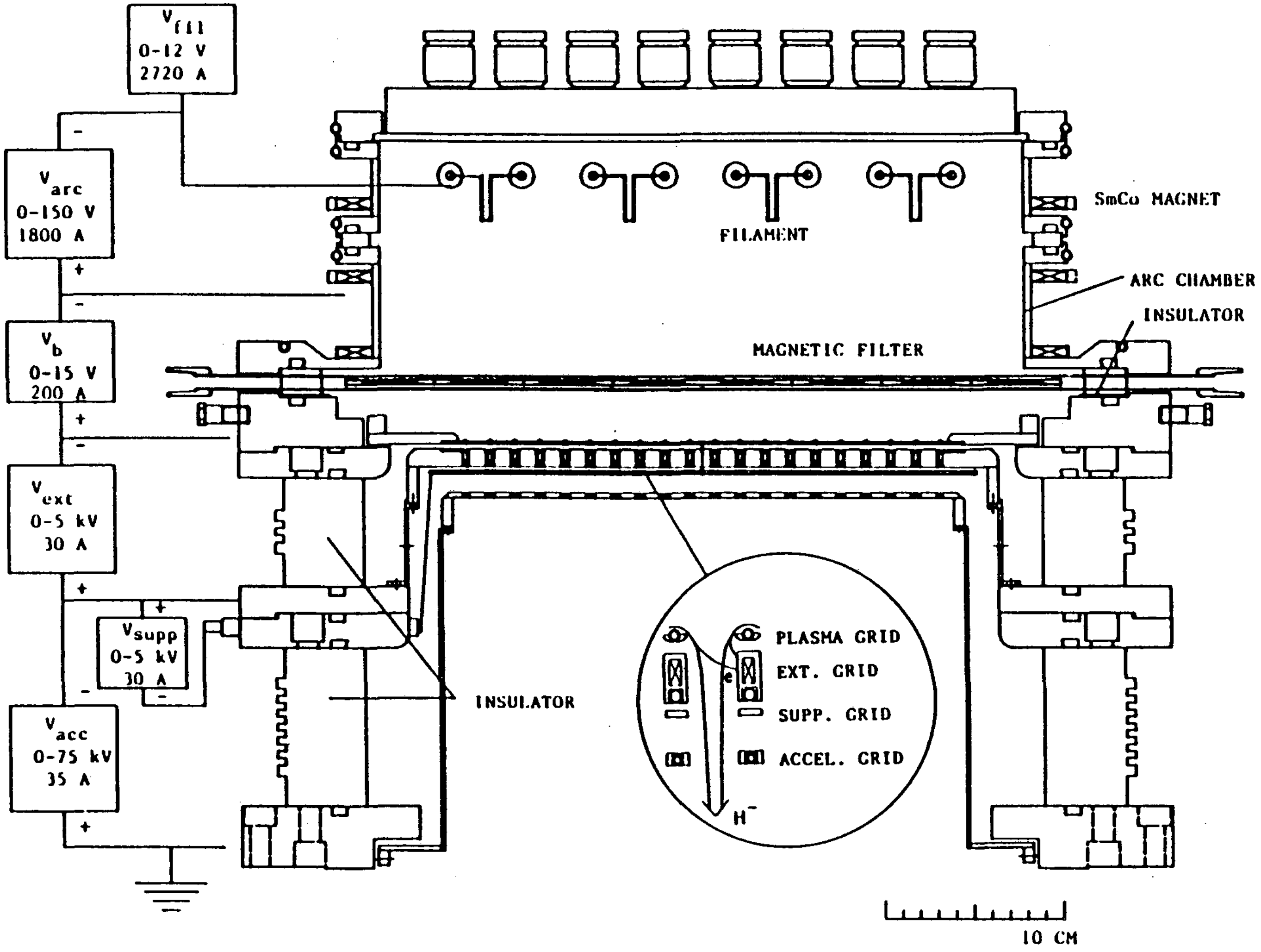

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Fig. 7

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