**Title**
State of H-Source Development

**Author**
Leung, K.N.

**Publication Date**
1991-05-01

LBL-30204

**Lawrence Berkeley Laboratory**
UNIVERSITY OF CALIFORNIA

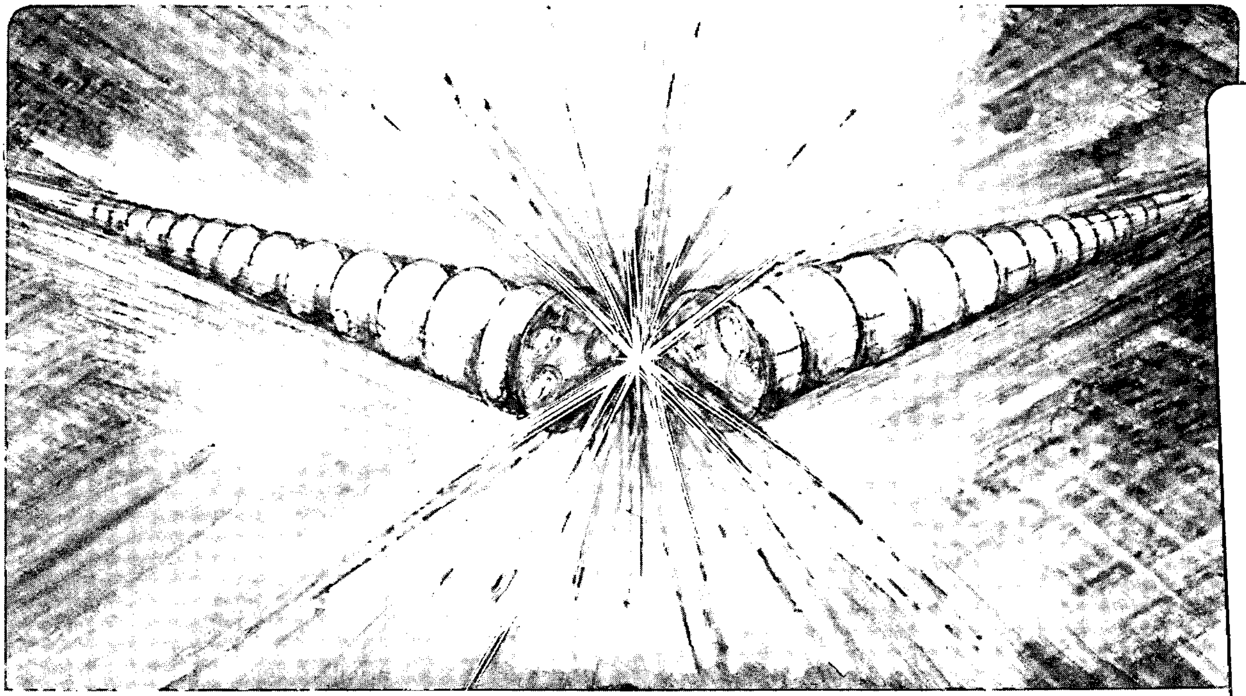
## Accelerator & Fusion Research Division

Presented at the IEEE Particle Accelerator Conference,
San Francisco, CA, May 6–9, 1991, and to be
published in the Proceedings

# State of H$^-$ Source Development

K.N. Leung

May 1991



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

# DISCLAIMER

LBL-30204

# STATE OF H⁻ SOURCE DEVELOPMENT

K. N. Leung

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Presented at the
IEEE Particle Accelerator Conference
San Franciscco, CA
May 6-9, 1991

This work is supported by the Director, Office of Energy Research, Office of Fusion Energy, Development and Technology Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

# STATE OF H$^-$ SOURCE DEVELOPMENT

K. N. Leung
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

## *Abstract*

The status of H$^-$ ion source development is reviewed. There are new and important advancement in both surface- and volume-production H$^-$ sources. It is shown that high brightness H$^-$ beams are generated by ion sources which utilize both surface and volume production processes.

## I. INTRODUCTION

H$^-$ ions have found important applications in fusion and in particle accelerators such as cyclotrons, tandem accelerators and proton storage rings. These ions can be formed by double charge exchange processes or by direct extraction from a negative ion source. In general, three distinct types of H$^-$ ion sources can be identified: (1) *surface conversion sources*, in which the H$^-$ ions are generated by particle interactions with low work function surfaces such as cesium-coated molybdenum. Surface-produced H$^-$ ions have a larger transverse energy and therefore a higher beam emittance; (2) *volume production sources*, in which the negative ions are produced by electron-molecule and electron-ion collisions in the volume of a hydrogen discharge plasma. Because of the lower H$^-$ ion temperature and the fact that they can be operated without cesium, volume H$^-$ sources are highly desired; and (3) *hybrid production sources*, in which the H$^-$ ions are formed by both volume and surface processes. Most hybrid sources are capable of producing high current densities of low temperature H$^-$ ions. This paper describes the latest development of these three types of H$^-$ ion sources.

## II. SURFACE-PRODUCTION H$^-$ SOURCES

In the early 1970s, several laboratories (BNL, LBL and ORNL) were developing H$^-$ sources which employed only surface conversion processes.[1] These sources were primarily used for neutral beam heating or for current drive in fusion reactors. In the surface conversion H$^-$ source, a water-cooled molybdenum converter is inserted into a plasma generator. By biasing the converter negatively respect to the plasma, positive ions are accelerated across the sheath and they impinge on the converter surface. Negative hydrogen 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 normally curved to geometrically focus the H$^-$ ions through the plasma to the exit aperture.

The advantages of the surface conversion H$^-$ sources are low source operating pressure (~ 1 mTorr) and very small electron content in the H$^-$ beam. These sources can be operated either in steady-state or pulsed mode. However, source operation always requires the presence of cesium which can cause voltage breakdown in the accelerator column. In addition, the transverse energy of the H$^-$ ions formed on the converter surface is large (>5 eV) and therefore the emittance of the accelerated beam is high. Nevertheless, multicusp surface-conversion H$^-$ sources have been operated in pulsed modes at LAMPF in Los Alamos and at KEK in Japan.

Barium is a metal which has a reasonably low work function and it has a much lower vapor pressure than cesium. Recent work at FOM in Amsterdam demonstrated that a pure barium metal surface can provide reasonable probabilities for H$^-$ ion formation.[2] Experimental results (Fig. 1) shows that the conversion efficiency (i.e. the ratio between the surface produced H$^-$ current density and the positive ion current density on the surface) can be as high as 8%.[3] By using a 2.5-cm-diam barium converter, van Os, Leung and Kunkel have obtained H$^-$ current higher than 20 mA in pulsed mode operation[4] (Fig. 2). Steady state beams of D$^-$ ions with current greater than 100 mA have also been achieved by

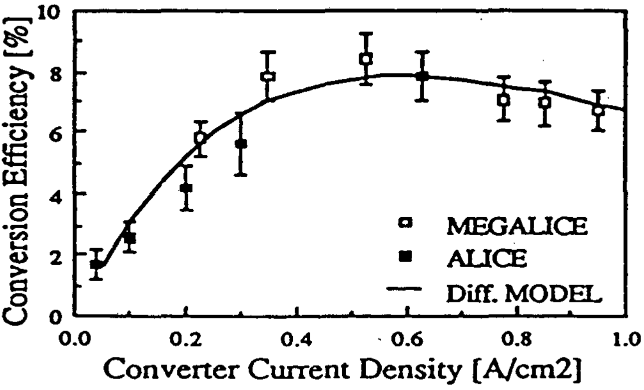


Fig. 1 The calculated and measured conversion efficiency for a barium surface as a function of the incident positive ion current density (from Ref. 3).

employing a larger 6-cm-diam barium converter at LBL.[5] Work is now in progress both at FOM and at LBL to develop large surface conversion $H^-$ sources with the use of barium metal for the production of multi-ampere $D^-$ beams for fusion application.

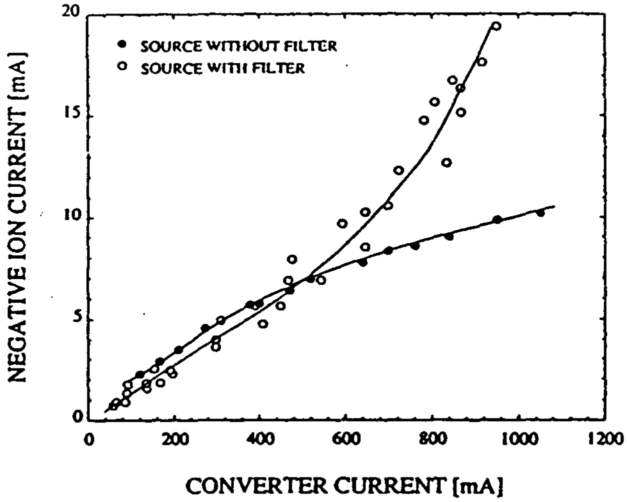


Fig. 2 Total $H^-$ output as a function of the barium converter current (from Ref. 4).

## III. VOLUME-PRODUCTION $H^-$ SOURCES

A hydrogen plasma contains not only positive ions ($H^+$, $H_2{}^+$, $H_3{}^+$) and electrons but also $H^-$ ions. These $H^-$ ions are generally believed to be formed via the dissociative attachment process and so their average energy could be less than 1 eV. As a result, the $H^-$ beam extracted from a "volume" source will have a lower emittance than those produced by surface-conversion sources.

In the past, attempts have been made to extract $H^-$ 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 1960s. In 1983, a novel method of extracting volume-produced $H^-$ directly from a multicusp source was reported by Leung et al.[6] In this $H^-$ source, a permanent magnet filter is included and it divides the source chamber into a discharge and an extraction region. The filter provides a limited region of transverse magnetic field which is strong enough to prevent energetic primary electrons from entering the extraction zone. Excitation and ionization of the gas molecules are performed by primaries in the discharge region. In the extraction region, the low electron temperature makes it favorable for the production and survival of $H^-$ ions.

It was demonstrated in 1984 that the filter-equipped multicusp source could provide high quality $H^-$ beams with current densities ≈ 38 mA/cm$^2$.[7] By employing a 3-cm-diam extraction aperture, $H^-$ current higher than 100 mA has been obtained from a similar source in steady-state operation.[8] In addition, emittance measurements performed at TRIUMF, LBL and other laboratories show that the effective $H^-$ ion temperature is typically less than 1.5 eV.[8,9] Recent laser diagnostic measurements further confirm that the temperature of volume-produced $H^-$ ions is indeed very cold.[10]

Several methods to improve the efficiency of the multicusp $H^-$ source have been investigated. In 1988, a small 7.5-cm-diam filtered-multicusp source has been operated successfully to generate $H^-$ ions in a pulsed mode.[11] From this compact volume source, an $H^-$ current density greater than 250 mA/cm$^2$ has been extracted. However, the source operating pressure is high (>50 mTorr) and the electron to $H^-$ ratio in the accelerated beam is larger than 100.

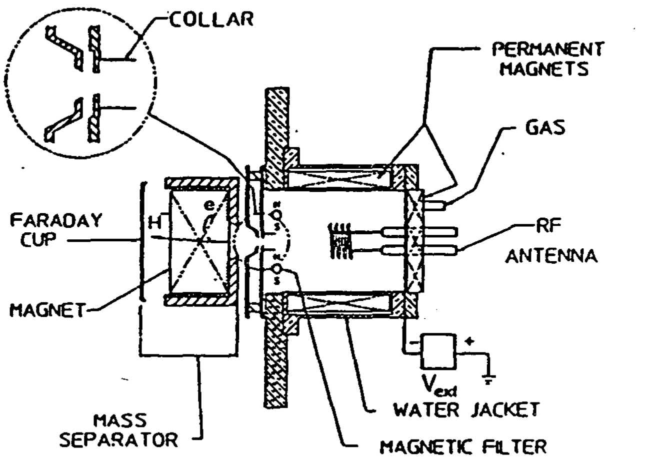


Fig. 3 The LBL rf driven multicusp $H^-$ source (from Ref. 12).

In order to achieve high current densities, volume $H^-$ sources require high discharge power. For this reason, the lifetime of filament cathodes is normally short for steady-state or high repetition rate pulse operation. To address this problem, a radio-frequency (rf) driven volume $H^-$ source (Fig. 3) has been developed at LBL for use in a calibration beam system and possibly in the injector unit of the Superconducting Super Collider (SSC).[12] This rf driven $H^-$ source has almost no lifetime limitation and a clean plasma can be maintained for a long period of opertion. To date, it has been proven that 30 mA of $H^-$ current can be extracted from this source with a 5.4-mm-diam aperture.[13] Beam emittance is found to be about the same as dc filament discharge.[14]

Since future fusion reactors require energetic neutral beams for driving current, large area volume $H^-/D^-$ sources are now being investigated in various laboratories to generte high currents of $H^-$ beams with multi-aperture extraction systems. Figure 4 shows a large filtered multicusp source developed at JAERI in Japan. This volume source can produce 3 A of $H^-$

current and it is equipped with an extraction system which can eliminate most of the electrons in the accelerator column.[15]

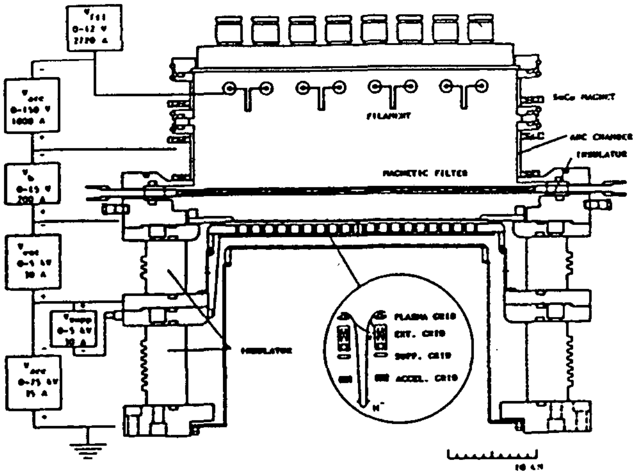


Fig. 4 Cross-sectional view of the JAERI large volume H⁻ source together with the extraction systems (from Ref. 15).

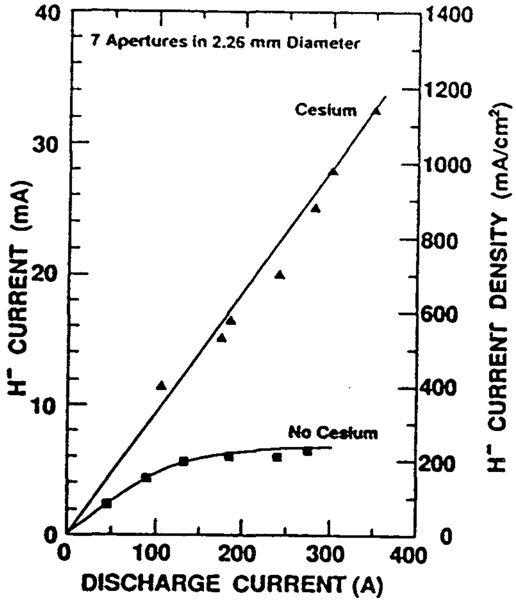


Fig. 5 A graph of the extracted H⁻ ion current and current density versus discharge current when the LBL multicusp source is operated with and without cesium (from Ref. 17).

## IV. HYBRID-PRODUCTION H⁻ SOURCES

Previous work on cesiated H⁻ ion sources has been concentrated on surface production type ion sources. Surprisingly, a recent experimental study at LBL on a small multicusp volume-production source indicates a large increase in H⁻ output when cesium vapor is added to a hydrogen discharge.[16,17] Figure 5 is a plot of the extracted H⁻ current density as a function of discharge current. When some cesium is added to the source, the H⁻ current density is about double that of a pure hydrogen discharge. Further addition of cesium results in an overall improvement of H⁻ output by a factor of 5 and H⁻ current densities exceeding 1 A/cm$^2$ are obtained. It is also found that the improvement in H⁻ yield is accompanied by a large reduction in the extracted electron current as well as the optimum source operating pressure. Similar results have now been observed in other volume H⁻ sources developed at JAERI, KEK, Los Alamos, Grumman Corporation, Brookhaven and Culham Laboratory. In fact, Kojima et al. have succeeded to produce a total H⁻ current of 10 A by adding cesium vapor into the large multi-aperture volume source (Fig. 6).[18]

The H⁻ beam emittance before and after the addition of cesium has been investigated at both Grumman Corporation and LBL.[19] Results of the measurement indicate that there is very small change in the beam emittance. Consequently, the brightness of the H⁻ beam can be much improved by seeding the volume H⁻ sources with cesium.

Similar to the surface-conversion source, Walther et al. discovered that the addition of barium to a multicusp volume source also enhances the H⁻ output current.[20] Experimental investigation shows that H⁻ ions generated on the anode surfaces are responsible for the large enhancement of the H⁻ current when barium is added to a multicusp source.[21] Operating the volume source with a barium washer insert, it is further demonstrated that the area around the extraction aperture is the most effective area for converting low energy positive hydrogen ions into extractable H⁻ ions.[22] Experiments performed at KEK, JAERI and BNL provide additional evidence that in a cesiated-volume source, the enhanced H⁻ ions are also originated from the surface of the plasma electrode.[23-25] Thus, "volume" H⁻ sources become "hybrid-production" H⁻ sources once cesium or barium is added to the discharge. In this type of source opertion, the energy of the surface-generated H⁻ ions can be minimized by adjusting the bias potential on the plasma electrode. For this reason, the cesium or barium-seeded volume sources can be used to provide large currents of low-emittance H⁻ beams.

Following the above development, one can conclude that in other types of sources (such as the magnetron source, the Penning source, or the Planotron source developed at Novosibirsk[26]) where cesium is used in the discharge, H⁻ ions can be formed in three different places; in the plasma volume, and on the cathode and the anode surfaces (a combination of volume and surface H⁻ production). As a result, three distinct groups of H⁻ ions can be identified. The distribution of these groups of H⁻ ions in the extracted beam will depend on the source configuration, the source pressure and the amount of cesium or barium in the discharge. In order to achieve low beam emittance, H⁻ ions formed in the plasma volume (including those produced by charge exchange) and on the anode surfaces are more desirable. Recent emittance measurements performed at Los Alamos reveal that the H⁻ ion temperature in the Penning source is indeed very low (<1 eV).[27] Therefore, to generate high current and high brightness H⁻ beams, either the cesium or barium-seeded filtered multicusp source or the Penning source should be employed.

This work is supported by the Director, Office of Energy Research, Office of Fusion Energy, Development and Technology Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

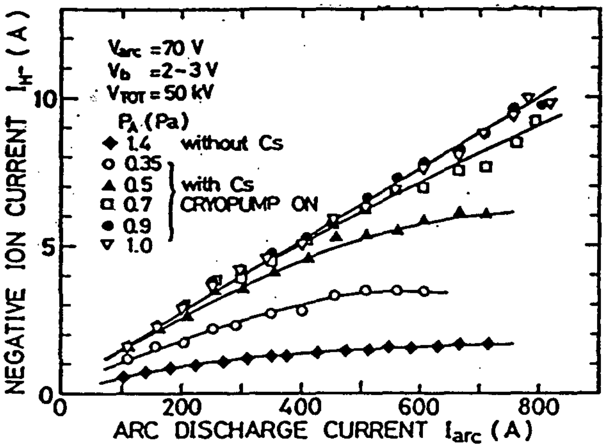


Fig. 6 The dependence of H⁻ current on the arc discharge current for operation of the JAERI large volume source with and wothout cesium (from Ref. 18).

## REFERENCES

1. K. N. Leung, Proc. of the 10th Symposium on Fusion Engineering, Philadelphia, Pa (Dec. 1983).
2. C. F. A. van Os, P. W. van Amersfoort and J. Los, J. Appl. Phys. 64, 3863 (1988).
3. C. F. A. van Os, C. Leguijt, R. M. A. Heeren, J. Los and A. W. Kleyn, SPIE Proceedings, 1061, 568 (1989).
4. C. F. A. van Os, K. N. Leung and W. B. Kunkel, Appl. Phys. Lett., 57, 861 (1990).
5. C. F. A van Os, J. W. Stearns, A. F. Lietzke, K. N. Leung, and W. B. Kunkel, Bull. Am. Phys. Soc. 35, 2099 (1990).
6. K. N. Leung, K. W. Ehlers and M. Bacal, Rev. Sci. Instrum., 54, 56 (1983).
7. R. L. York, Ralph R. Stevens, Jr., K. N. Leung, and K. W. Ehlers, Rev. Sci. Instrum., 55, 681 (1984).
8. J. W. Kwan et al., Rev. Sci. Instrum., 61, 369 (1990).
9. K. R. Kendall, M. McDonald, D. R. Mosscrop, P. W. Schmor, and D. Yuan, Rev. Sci. Instrum., 57, 1277 (1986).
10. M. Bacal, C. Courteile, P. Devynck, Y. D. Jones, R. Leroy and R. A. Stern, SPIE's OE/LASE 91, Los Angeles, Ca. (Jan 1991) Proc. No. 1407-64.
11. K. N. Leung, K. W. Ehlers, C. A. Hauck, W. B. Kunkel, and A. F. Lietzke, Rev. Sci. Instrum., 59, 453 (1988).
12. K. N. Leung, G. J. DeVries, W. F. DiVergilio, R. W. Hamm, C. A. Hauck, W. B. Kunkel, D. S. McDonald, and M. D. Williams, Rev. Sci. Instrum., 62, 100 (1991).
13. K. N. Leung, W. F. DiVergilio, C. A. Hauck, W. B. Kunkel and D. S. McDonald, Proc. 1991 IEEE Particle Accelerator Conference, San Francisco, CA (May 1991).
14. G. Gammel et al., Proc. 1991 IEEE Particle Accelerator Conference, San Francisco, CA (May 1991).
15. Y. Okumura, H. Horiike, T. Inoue, T. Kurashima, S. Matsuda, Y. Ohara and S. Tanaka, Proc. 4th Int. Symp. on the Production and Neutralization of Negative Ions and Beams, Upton, NY (1986).
16. S. R. Walther, K. N. Leung and W. B. Kunkel, J. Appl. Phys. 64, 3424 (1988).
17. K. N. Leung, C. A. Hauck, W. B. Kunkel and S. R. Walther, Rev. Sci. Instrum, 60, 531 (1989).
18. H. Kojima et al. Proc. 13th Symposium on Ion Sources and Ion-Assisted Technology, Tokyo, (June 1990).
19. T. W. Debiak, L. Solensten, Y. C. Ng, and J. J. Sredniawski, Bull. Am. Phys. Soc., 35, 957 (1990); J. W. Kwan, Rev. Sci. Instrum. (to be published).
20. S. R. Walther, K. N. Leung and W. B. Kunkel, Appl. Phys. Lett., 54, 210 (1989).
21. K. N. Leung, S. R. Walther and W. B. Kunkel, Phys. Rev. Lett.,62, 764 (1989).
22. K. N. Leung, C. F. A. van Os, and W. B. Kunkel, Appl. Phys. Lett. 58, 1467 (1991).
23. Y. Mori, T. Okuyama, A. Takagi and D. Yuan, KEK Preprint 90-64 (July 1990).
24. Y. Okumura, M. Hanada, T. Inoue, H. Kojima, Y. Matsuda and K. Watanabe, Proc. 13th Symposium on Ion Sources and Ion-Assisted Technology, Tokyo (June 1990).
25. J. G. Alessi and K. Prelec, Proc. 1990 Linac Conf., Albuquerque, NM. (Sept 1990); also J. G. Alessi and K. Prelec, Proc. EPAC-90 Particle Accelerator Conference, Acropolis, Nice, France (1990).
26. Yu. I. Bel'chenko, G. I. Dimov, V. G. Dudnikov, Nucl. Fusion 14, 113 (1974).
27. J. D. Sherman, H. V. Smith, C. Grisik, and P. Allison, Proc. 1991 IEEE Particle Acclerator Conference, San Francisco, Ca (May 1991).

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
INFORMATION RESOURCES DEPARTMENT
BERKELEY, CALIFORNIA 94720