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Review of Negative Hydrogen Ion Sources*

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REVIEW OF NEGATIVE HYDROGEN ION SOURCES

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Abstract

In the early seventies, significant discoveries for H^- ion sources were made at Novosibirsk. These and many improvements which followed have led to useful accelerator sources. With these sources charge-exchange injection into circular accelerators has become desirable and routine. This paper reviews the major developments leading to practical H^- sources. Different types and variations of these sources with some basic physics and operation will be described. The operating parameters and beam characteristics of these sources will be given.

Introduction

The usefulness of negative hydrogen ions has been recognized for several decades for a variety of purposes. Early Tandem Van de Graaff Accelerators used proton sources followed by an attachment canal to produce several hundred microamps of H^- ions.[1] The H^- ions were accelerated to a high potential, stripped to protons and accelerated to ground, gaining an energy of twiee the potential.[2] Soon after, H^- ions were used with cyclotrons so extraction could be achieved by stripping to neutrals or protons. Penning type sources which fit within the Dees produced five milliamps of H^- current.[3]

Linear accelerators have long been used as proton injectors to synchrotrons. It was recognized early that H^- ions would be useful for charge-exchange injection into circular accelerators.[2] Intensity and reliability of H^- sources limited this possibility until the seventies when H^- injection was accomplished at the Argonne ZGS.[4] At that time H^- ions were achieved using a proton source with a charge-exchange cell.[5]

The next major step in H^- source development occurred in the Soviet Union at Novosibirsk. There, improved geometries and the addition of cesium produced intense sources with an output of several Amperes per square centimeter of aperture.[6] Geometries of both the Penning and magnetron forms were studied. These sources have become known as surface-plasma sources (SPS).

The Soviet work was adopted in the U.S. at Brookhaven to produce high current sources for neutral beam injectors for the confinement fusion program.[7] At Los Alamos the Penning geometry was studied to produce an accelerator source of high current and duty factor.[8] At Fermilab the research magnetron of the Brookhaven group was redesigned into an operational source for pulsed applications with good current and low duty factor.[9] Significant improvements to this source design at Fermilab [10] and Brookhaven [11] have made the magnetron a highly useful H^- source for many linacs used as synchrotron injectors.[10-13] The Penning sources have been useful in high-duty and high-brightness applications.[14,15]

While the magnetron and Penning sources were being pursued for accelerators, a large potentially d.c. multicusp surface-plasma source originated at Berkeley for the fusion program.[16] Modified versions of this source were studied and used for accelerators.[17,18]

Parallel to the SPS effort, a French group at Ecole Polytechnique near Paris vigorously pursued obtaining H^- ions from a hydrogen plasma.[19] This effort, which has led to the volume source, is being studied at several laboratories.[20,21]

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This paper will deal primarily with the modern surface-plasma and volume-process sources useful or anticipated for accelerators such as linacs. These sources can produce reliable pulsed H^- beams from ≈10 to 100 mA with normalized emittances of 0.2 to 2 π mm-mr for 90% of the beam.

Where emittances are in other than 90% values, the given emittance will be quoted and a value for 90%, assuming a Gaussian distribution, will be given in brackets for reference to other sources. [$\varepsilon_{(90)} / \varepsilon_{(rms)} = 4.6$, $\varepsilon_{(90)} / \varepsilon_{(95)} = 0.77$].

Basic Principles

Surface-Plasma Sources

The surface-plasma sources all produce H^- ions by the interaction of energetic plasma particles with a surface (Fig. 1). These particles, having energies of several tens to several hundred eV, are produced in a plasma near the surface. This surface is typically a cathode electrode. The incident particles may be protons, ionized hydrogen molecules, heaver positive ions, such as cesium, or energetic neutral atoms or molecules that may occur in the plasma. Upon striking the surface they may desorb hydrogen atoms which can leave the surface in several states, occasionally as an H^- ion. Also, protons or neutral hydrogen may reflect from the surface and acquire sufficient electrons to become an H^- ion. To improve the possibility that H^- ions will leave the surface and not lose electrons, cesium is added to the source to partially cover the surface and lower its work-function. As cesium covers the surface, typically tungsten or molybdenum, the work-function decreases from above 4.5 eV to ≈1.8 eV at 0.6 of a monolayer of cesium and then rises to about 2 eV for one monolayer or greater of cesium. To minimize the work-function and maximize the H^- yield the cesium feed is controlled. Cesium also ionizes easily to produce electrons and ions in the plasma improving the source stability. After formation the H^- ions pass through the plasma to the anode aperture and are extracted. Some ions incur collisions in the plasma and are lost or destroyed. Others may charge-exchange with neutral hydrogen atoms to form thermal H^- ions. These thermal ions are the basis for a brighter beam in some sources. Since the polarity is appropriate to extract negative ions, electrons are also extracted from the source and must be dealt with.

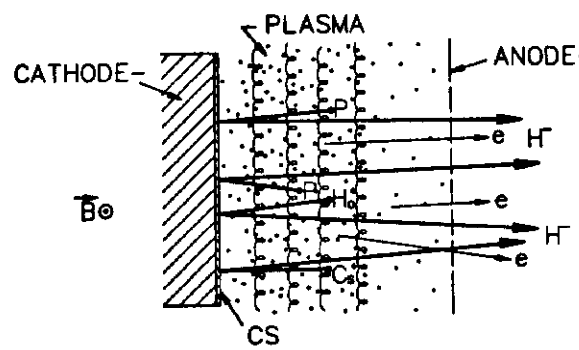

Fig. 1. Surface-plasma production of H^- ions.

Volume Sources

In volume sources, H^- ion formation relies on the greatly increased cross-section for the dissociative-attachment reaction when molecules are excited to high vibrational states. During collisions with walls or energetic electrons (>5 eV), hydrogen molecules are excited to high vibrational states (v">6). For such molecules the cross-section for the dissociative-attachment reaction, $e + H_2(v") \rightarrow H^- + H$, $e \leq 1$ eV, increases more than five decades for v"=6 and continues to rise for higher states.[22] Although the destruction reactions: neutralization ($H^- + H^+ \rightarrow H + H$), associative detachment ($H^- + H \rightarrow H_2 + e$), etc.; can be serious, the increased production due to high vibrational states can give a significant population of H^- ions in the plasma.

The source therefore takes on the geometry of a two region chamber [22] (Fig. 2). The first region contains a broad range of electrons emitted from hot cathodes or filaments. Here energetic electrons and wall collisions create high molecular vibrational states: $e + H_2(v"=0) \rightarrow e + H_2(v")$, $e > 5$ eV. The second region is separated from the first by a magnetic filter so only low energy electrons (≤ 1 eV) can pass along with molecular hydrogen in various states. In the second region H^- ions are more readily created than destroyed forming a significant fraction of the plasma from which they are extracted. To extract the H^- ions with minimum electrons, a magnetic filter is again used at the extraction region.

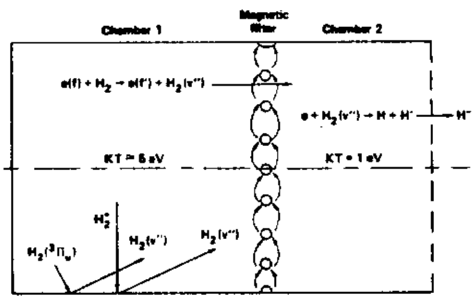

Fig. 2. Volume production of H^- ions.

Surface-Plasma Sources

Three basic geometries of H^- surface-plasma sources have been built for accelerators: magnetron, Penning and multicusp sources. The magnetron tends to be a low-duty-factor source and has been used with several linacs as injectors to synchrotrons. The Penning source can operate at much higher duty, possibly d.c. and tends to produce the brightest beam. It has been used on high duty-factor linacs and for stringent beam requirements. The multicusp source has its best application as a high-current, large-aperture d.c. source useful for neutral beam fusion injectors. It has been used on high duty-factor linacs. A discussion of these sources will show their typical operating characteristics and differences.

Magnetron H^- Source

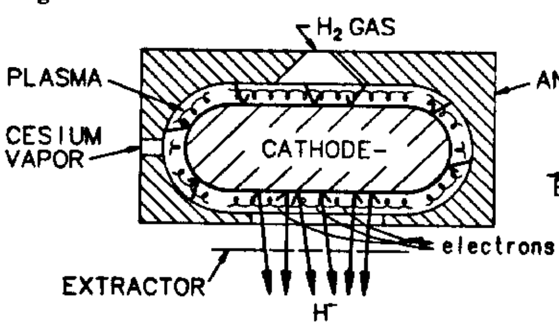

Fig. 3. Basic magnetron source configuration.

The magnetron source (Fig. 3) consists of a central oval cathode, the active surface, surrounded by an anode. A magnetic field passes through the source parallel to the cathode axis, perpendicular to the anode-cathode electrical field. This ExB configuration is highly efficient at confining electrons and producing dense plasmas. Ions and energetic particles from the plasma strike the cathode and reflect or desorb hydrogen atoms producing H^- ions. The H^- ions go through the plasma to the anode gaining energy and where possible pass through the anode aperture to be accelerated through the extractor. In this source the anode-cathode gap is small, typically 1 mm, to avoid significant destruction of the H^- ions while traveling through the plasma. Nevertheless, some ions are lost or charge-exchange with neutral thermal atoms: $H^-(\text{fast}) + H(\text{slow}) \rightarrow H(\text{fast}) + H^-(\text{slow})$. These thermal ions can be extracted to form a beam of greater brightness. In the magnetron, energetic ions are extracted at low pressure (≈400 mTorr) where the source normally operates. At high pressure, low-energy ions dominate, but the gas consumption is large.

Hydrogen gas is introduced in the rear of the source by a closely connected pulsed gas valve. Since these sources are small and operate at low duty factor, the small volume allows the gas to be pulsed into the source to minimize vacuum requirements.[23] Cesium is obtained by heating metallic cesium in an oven at 150-200°C.[23] All parts of the cesium supply system must be maintained above the oven temperature to prevent condensation of the cesium. The vapors enter the source and coat the cathode surface. The cesium usage is <1 mg/hr. In operation the source operates at 350 to 450°C for good surface conditioning and sufficient cesium ions in the plasma. Heating of the source comes from the plasma arc power plus a small external heater if needed.[10] The plasma power, passive cooling and permissible source temperature limit this source to low-duty operation.

To increase the ions passing through the anode aperture, the cathode is curved to give focusing from the cathode to the anode.[24] With slit apertures the curving is a groove on the cathode parallel to the aperture. In the newer magnetrons circular apertures and extraction geometries are used and the cathode is dimpled behind the anode aperture.[11] These changes have reduced the arc current, increased the beam current and improved the beam optics.

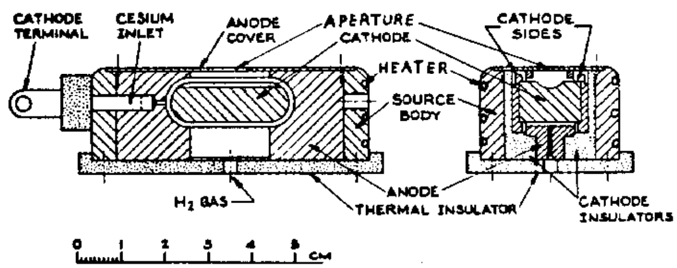

Fig. 4. The Fermilab H^- magnetron source.

Operating magnetron sources produce a beam current of ≥50 mA. In the Fermilab source [9] (Fig. 4) the beam is extracted at an energy of 18 keV from a 1-mm x 10-mm aperture. This large asymmetry creates a stronger space charge force in the narrow or perpendicular direction to the slit than in the parallel direction. To compensate for this difference and obtain a nearly circular beam, a 90°-bending magnet with a radius of 8 cm and a gradient index, $n = -rdB/Bdr \approx 1$, is used after the extractor. This magnet has pole extensions to provide the source field. Following the bending magnet, the beam enters the primary accelerating column and is accelerated to 750 keV (Fig. 5). At 750 keV the normalized emittance for 90% of the beam is $\varepsilon_{n\,\text{horz}\,(90)} = 0.9\ \pi$ mm-mr, $\varepsilon_{n\,\text{vert}\,(90)} = 1.5\ \pi$ mm-mr.

The Brookhaven source operates with a circular extraction geometry sized to produce >50 mA and extracts at 35 keV.[11] There is no bending magnet following the source. This arrangement produces a circular beam with emittance in both planes of $\varepsilon_{n\,(90)} = 1.1\ \pi$ mm-mr. The circular beam is matched to an RFQ by a 2-meter magnetic-focusing line (Fig. 6). The RFQ accelerates the beam to 750 keV.

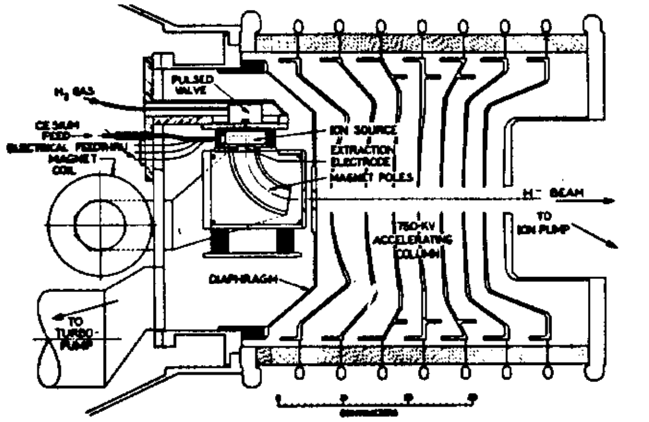

Fig. 5. The Fermilab H⁻ 750-keV preaccelerator.

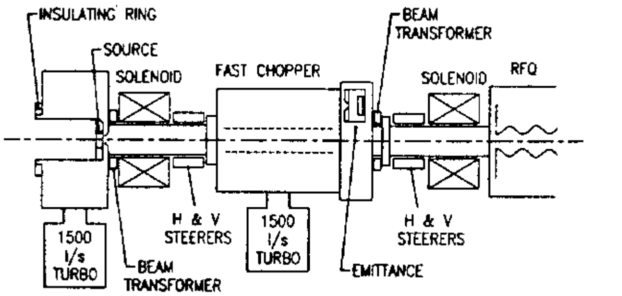

Fig. 6. The Brookhaven H⁻ source and transport line.

The magnetron source has been only used for pulsed operation at low duty factor. At Fermilab the beam-pulse width is up to 66 μs at a repetition rate of 15 Hz.[10] Brookhaven uses a 600-μs beam pulsed at 5 Hz [25] and Argonne operates at 30 Hz with 90-μs pulse width.[12] DESY uses even lower duty for the HERA injector [13] and pulses the source arc between beam pulses to maintain source temperature.

Lifetimes for the source range from four to six months at Fermilab to about one year between changes at Argonne. Failures occur due to erosion of the cathode and the buildup of erosion products in the source. The piezoelectric pulsed gas valve is an occasional cause of early breakdown. Auto fuel injectors have recently been used for gas valves with good success.[26]

The magnetron, originally developed by the Novosibirsk group, is referred to as the planotron source in Soviet literature. A modification has produced the semiplanotron. The semiplanotron [27] (Fig. 7) is similar to the planotron but uses only the front portion where the plasma is produced.

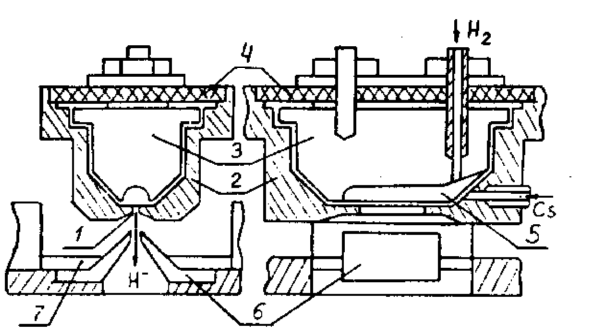

Fig. 7. The semiplanotron source. 1. emission slit, 2. anode, 3. cathode, 4. insulator, 5. groove, 6. extractor, 7. steel inserts.

Penning H⁻ Source

The Penning source geometry (Fig. 8) resembles a right circular cylinder as an anode with isolated caps at each end of the cylinder which are the cathodes. A magnetic field passes through the source parallel to the anode axis. In this arrangement the electric and magnetic fields are parallel. Electrons created in the source oscillate from cathode to cathode, trapped in the magnetic field lines, to produce a dense plasma. Positive ions from the plasma are accelerated into the cathode and, as in the magnetron, produce primary H⁻ ions coming from the cathode surfaces. Cesium is added to the source to lower the surface work-function and increase the H⁻ yield.

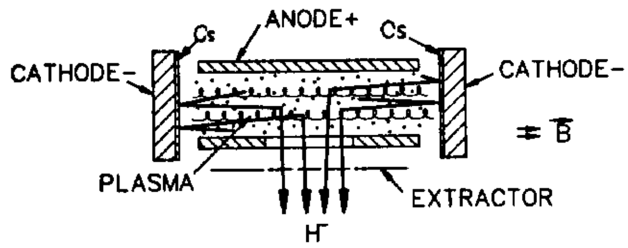

Fig. 8. Basic Penning source geometry.

In the Penning source, ions are extracted from an opening in the anode wall. Because of the aperture orientation it is difficult for the primary H⁻ ions to pass favorably through the opening. To obtain a useful beam, primary H⁻ ions must charge-exchange with thermal hydrogen atoms, H⁻(fast) + H(slow) → H(fast) + H⁻(slow), to form slow H⁻ ions which can migrate to the aperture and be extracted. As in the magnetron, slit apertures of large asymmetry are used for the Penning source and strong-focusing bending magnets are used to handle the beam forces. Circular apertures are also being used with minimum bending to give higher quality beams.[28]

Beam currents of 50 to 100 mA is typical for Penning sources in operation or under study. Since the cathodes are accessible they can be cooled or rotated to produce sources of high duty factor and possibly d.c. operation. Because the ions leaving the source originate from thermal atoms their transverse energy is low and small emittance is typical of the Penning source. The Los Alamos sources [28] (Fig. 9) produce bright beams to 100 mA with a normalized rms emittance at ≈29 keV of $\varepsilon_{n\,(rms)} \approx 0.05\,\pi$ mm-mr, [$\varepsilon_{n\,(90)} \approx 0.23\,\pi$ mm-mr].

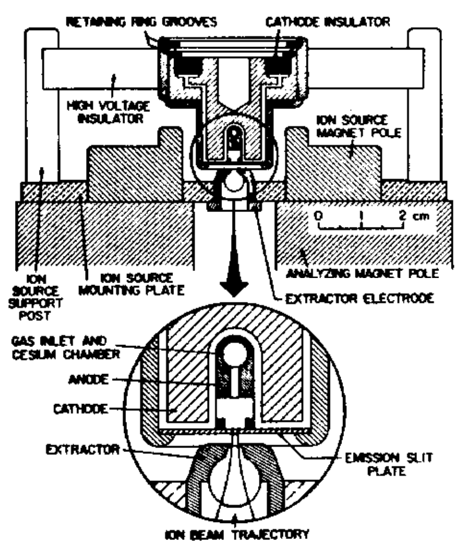

Fig. 9. A Los Alamos H⁻ Penning source.

Multicusp Surface-plasma Source

The multicusp surface-plasma source [16] (Fig. 10) is a large-volume low-pressure source that can operate at high duty factor. The source chamber is typically a cylinder of large diameter (≈20 cm) with alternating polarity magnetic dipoles on the outer surface to produce cusp magnetic fields inside. The chamber, usually the end plates, contain feedthrus for filaments in the source. Near the center of the chamber is the H^- production surface or converter. Opposite the converter surface is an opening in the chamber wall for extracting the H^- ions. In operation the filaments supply electrons to ionize the gas (pressure ≈1 mTorr) and create a plasma. The cusp field minimizes the electron loss to the walls and confines the plasma to the center of the chamber near the converter. Ions created in the plasma strike the converter surface which is biased negative with respect to the plasma. H^- ions formed on the converter surface are accelerated through the plasma region and into the extractor. As in other SPS, cesium is injected into the source to lower the converter surface work-function and increase the H^- yield. Negative ions reaching the extractor leave the source for further acceleration. Most electrons which would accompany the ions through the extractor are repelled by a magnetic filter made of dipole permanent magnets at the extraction aperture.

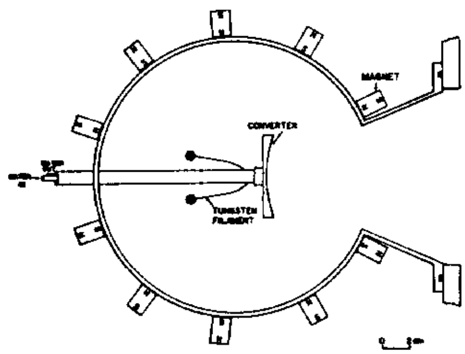

Fig. 10. Basic multicusp surface-plasma source.

Multicusp accelerator sources (Fig. 11) have been built at LAMPF and KEK. LAMPF developed a 20-mA source that is capable of long term operation at 10% duty factor (800-µs pulses at 120 Hz).[17] The normalized emittance for 95% of the beam is $\varepsilon_{n\,(95)} = 0.8\ \pi$ mm-mr, [$\varepsilon_{n\,(90)} \approx 0.6\ \pi$ mm-mr]. At KEK a multicusp source has operated on the 12-GeV synchrotron.[18] The source produced 15-20 mA of H^- beam with pulses of 200 µs at 20 Hz. The normalized emittance after acceleration to 750 keV is $\varepsilon_{n\,(90)} = 1.8 - 2.1\ \pi$ mm-mr. This source used lanthanum hexaboride (LaB_6) cathodes that ran cooler and survived longer than tungsten filaments. As a result the cesium consumption was lower, operation was more stable and lifetime much longer (>2500 hours) than previous sources.

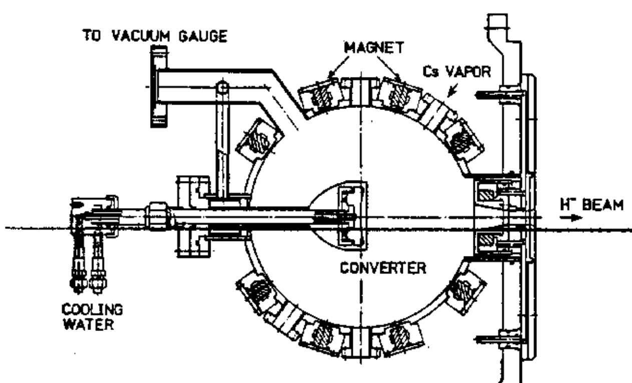

Fig. 11. The H^- multicusp source.

Volume Source

The volume source (Fig. 12) is another "large" source similar to the multicusp. The plasma is usually contained in a cylindrical chamber surrounded with permanent dipole magnets that form cusps and fields to confine the electrons of different energies. The rear or outer regions of the chamber contain filaments biased to create electrons of sufficient energy (E>5 ev) to excite hydrogen molecules to high vibrational states. The second region, separated from the first by a magnetic field, is located near the extraction aperture. This field prevents energetic electrons (E>1 ev) from entering the second region and destroying the H^- ions once produced. In this region the collision of slow electrons with excited hydrogen molecules produces H^- ions. Good operation is very sensitive to the dimensions and conditions in this region. At the extraction aperture another magnetic filter passes the H^- ions and hopefully excludes the electrons.

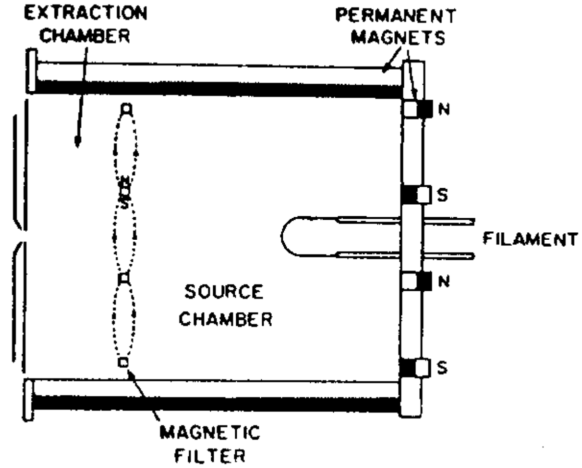

Fig. 12. Basic H^- volume source.

Several volume sources are in use or under study. TRIUMF uses a low-current (≈1 mA) volume source.[29] The normalized emittance is $\varepsilon_{n\,(90)} = 0.15\ \pi$ mm-mr. The source has good electron suppression with e/H^- as low as one.

Brookhaven has achieved 30 mA of H^- with 750 mA of electrons from a 1-cm^2-aperture volume source [30] (Fig. 13). With higher arc current the source pressure increases from 5 to 15 mTorr for optimum output. For a 21-mA beam the normalized emittance at 90% is $\varepsilon_{n\,(90)} \approx 0.94\ \pi$ mm-mr. Considerable work is still being done on the source.

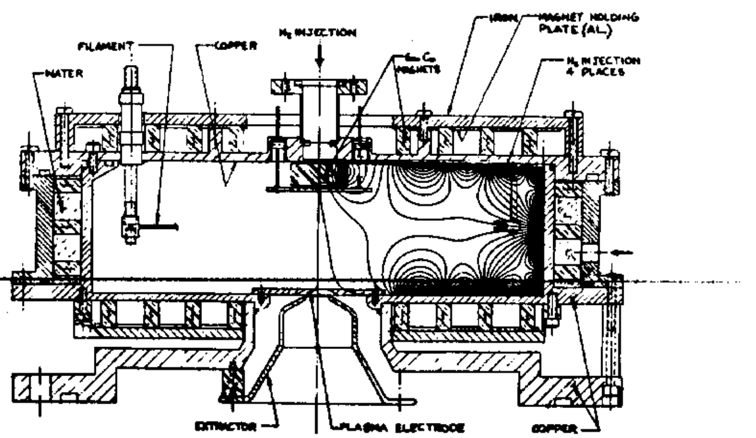

Fig. 13. The Brookhaven H^- volume source.

At Los Alamos, a volume source [20] has produced 10 mA with a normalized rms emittance of $\varepsilon_{n\,(rms)} = 0.08\ \pi$ mm-mr, [$\varepsilon_{n\,(90)} \approx 0.37\ \pi$ mm-mr]. The aperture was 6.3-mm diameter and the source operated at pressures of 2 to 20 mTorr.

At Berkeley, cesium has been added to a volume source with significant improvement.[31] At high currents the H^- output increased fivefold exceeding current densities of 250 mA/cm^2 with reduced e/H^- ratios. At high cesium levels, where extraction breakdowns occurred, the output exceeded 1 A/cm^2. Using an extractor of seven apertures (each 0.7 mm diam inside a 2.26 mm diam circle), 33 mA of H^- was extracted with an e/H^- of 20. At present the tungsten filaments limit the source lifetime. LaB_6 filaments should be a great improvement. To remove the filaments and improve the lifetime, the Berkeley group has been developing an rf driven volume source.[32]

Summary

H^- ion sources are still very new and there is much research and improvement to be done in this area. Each application has a unique set of requirements for the source and among the existing sources a great many applications can be met. Typically the accelerator usage has stressed duty factor, reliability, lifetime, gas consumption, intensity and emittance. Most modern sources have the intensity for linear accelerators (20 to 100 mA). For emittance or brightness the Penning or possibly the volume source is best with the magnetron being acceptable for general uses. The magnetron is presently good only for low duty-factor operation (<0.3%) in contrast to the other sources which have high duty factor capability and may achieve continuous operation. Lifetime is often dependent on the duty factor of the source and for low-duty usage the lifetime can be many months to a year as witnessed by operating magnetrons. The multicusp SPS has achieved many thousand hours running at high duty-factor operation using LaB_6 cathodes. The Penning source does operate many days at high duty factor and may do better with cathode improvements. Presently the largest operational experience has been with the magnetron and its reliability is very good. The multicusp SPS has also shown reliable operation. The other sources have not had the same operational experience.

For small sources the gas consumption depends on the operation. At low duty-factor operation the gas can be pulsed into the source so the consumption per a pulse is simply the volume times the pressure. Fortunately in these sources the volume is small since the pressure is relatively high (<2 cc, >100 mTorr). For larger and high duty factor or d.c. operation the pressure and anode aperture determine the gas flow. For the multicusp SPS and the volume source the aperture is large but the pressure is low (≈1 cm^2, 0.1-10 mTorr).

Cesium usage is typically about one milligram per hour or less for the cesium sources. Even though these sources may exist just before high voltage-gradient devices, additional sparking has not been a problem. In some cases refrigerated surfaces have been used before the accelerator while in others there has been little more than a meter or less transport line to minimize cesium contamination.

Many ideas look good and work fine on the test bench even under simulated operational conditions but the real operational proof for lifetime, reliability and other qualities can be determined only under running conditions. In operation, the daily fine adjustments done on a test bench are often not possible, and less then experienced operators must be able to keep it running. This is the real test of an ion source. Of course, the reliability of a source is not just the device from which the ions emerge. There are many support devices - vacuum, gas, cesium and cooling systems, power supplies, monitoring, controls, etc.- all which must operate reliably in the source environment.

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In addition to the references cited, the Proceedings of the International Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams contain much detailed information on H^- ion sources. Five symposia have been held at Brookhaven. These Proceedings are published as:
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Second Symposium (1980) BNL 51304,
Third Symposium (1983) AIP Conf. Proc. 111,
Fourth Symposium (1986) AIP Conf. Proc. 158,
Fifth Symposium (1989) AIP Conf. Proc. 210, in print.
Likewise the book by A. T. Forrester, *Large Ion Beams*, (Wiley-Interscience, New York, 1988) has an excellent chapter on H^- sources.

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