OVERVIEW OF HIGH-BRIGHTNESS H$^-$ ION SOURCES

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Abstract

High-brightness, H$^-$ ion sources are in widespread use in large accelerator facilities. New facilities dedicated to the production of neutrons, muons, neutrinos, and radioactive ion beams, as well as to the study of high-energy collisions, are being planned or constructed, which will require enhanced source performance. This report summarizes the current generation of H$^-$ ion sources that are in routine use at existing facilities. A basic description of the operating principles of each major type of source (magnetron, Penning, and multicusp) is provided. Performance characteristics such as pulse and average beam current, beam brightness, emittance, and source lifetime attained in routine operation are reviewed and compared with the requirements of new accelerator projects. A brief review of the performance of experimental H$^-$ sources reported at recent ion source workshops is also given. Specific attention is given to the RF-driven multicusp source developed at LBNL, which will inject the accelerator chain employed by the U.S. Spallation Neutron Source (SNS).

1 INTRODUCTION

Several new accelerator projects employing high-intensity/high-brightness H$^-$ beams are in the planning or construction stages [1]. These facilities are predicated on driver accelerators, which require ion sources of specified beam brightness, average and pulse beam current, and operational lifetime. The need to select or develop H$^-$ ion sources to meet these requirements has led to renewed interest in H$^-$ ion source technology [2, 3].

This report first provides a survey of H$^-$ ion sources that are in routine use at existing accelerator facilities or that have been extensively commissioned for such a purpose. Performance characteristics such as pulse current, average current, beam brightness, and operational lifetime are given and compared with the requirements of new accelerator projects. H$^-$ formation, as well as the operating principle of each major type of source, (Penning, magnetron, and multicusp) are discussed. A short summary of performance characteristics of "experimental" H$^-$ ion sources reported at recent symposiums is also given [2,3]. In the past, there have been several excellent reviews of high-brightness H$^-$ ion sources used for accelerator applications [4, 5, 6].

2 PHYSICS OF H$^-$ FORMATION

Two H$^-$ production mechanisms are now considered important in modern ion sources: surface and volume production. Surface production occurs when energetic particles strike a low work function surface and reflect from the surface or sputter eject adsorbed hydrogen on the surface. An ejected or reflected particle normally undergoes resonant neutralization at a distance of a few atomic units from the surface and therefore leaves the surface as a neutral. However, if the work function of the surface is small, the energy resonance between the Fermi sea and the ^{2}S bound state of H occurs at much larger distances and electron transfer to the surface is less probable. The probability of neutralization is decreased further if the particle is ejected with energies of ~1 eV or greater [7]. In many operational H$^-$ ion sources, low-work function surfaces are created by adsorption of a fractional monolayer of Cs on a metallic surface [8].

Surface production of H$^-$ can be approximated using the formulation of Rasser [9], which has been used successfully, to model H$^-$ production in large, fusion-type ion sources [10]. The equation has the form

$$\beta^- = (2/\pi)\exp(-1.2\pi(\phi - A)/\sqrt{E}). \qquad (1)$$

Here, β^- is the probability of an incoming H atom or ion being converted to an H$^-$ ion, ϕ is the effective work function of the cesiated surface ($\phi \sim 1.8$ eV at optimal coverage), A = 0.77 eV is the electron affinity of H, and E is the energy of the ejected H in eV. In cases where H$^+$ is reflected from the surface, this energy is roughly equal to the particles' incident energy, typically determined by the plasma sheath potential through which particles striking the surface must fall. In cases where the H$^-$ is formed through a sputter ejection process, E is usually much less than the energy of the incident particle, being on the same order as the bond energy between the adsorbed H and the surface. Ion sources based on surface production are termed plasma-surface sources and are discussed subsequently.

Several types of H$^-$ ion sources operate without low-work function surfaces; therefore, ionization must occur by different mechanisms. It is widely held, in these cases, that H$^-$ ions are produced mainly within the plasma volume. An excellent review of this process can be found

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[*] The Spallation Neutron Source (SNS) project is a partnership of six U.S. Department of Energy Laboratories: Argonne National Laboratory, Brookhaven National Laboratory, Thomas Jefferson National Accelerator Facility, Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, and Oak Ridge National Laboratory. SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.

in Ref. 8. Briefly, slow electrons colliding with H_2 induce a Frank-Condon transition from the ground state of the molecule to an auto-dissociating state of H_2^-, forming H^- upon dissociation:

$$e(slow) + H_2(\nu'') \rightarrow H_2^- \rightarrow H^- + H \ . \tag{2}$$

It has been shown that the cross section for this reaction can be increased by more than five orders of magnitude if H_2 is in a heightened state of vibrational excitation ν'' [11]. The cross sections for H^- formation in Eq. 2 achieve a maximum of $\sim 10^{-16}$ cm^2 colliding with excited H_2 ($\nu''>5$) at relative energies of ~1 eV. Several volume and surface mechanisms have been identified that contribute to the population of vibrationally excited H_2. It is commonly held that one of the most important excitation mechanisms is electron impact excitation,

$$e(fast) + H_2(\nu''=0) \rightarrow H_2^* + e \rightarrow H_2(\nu'') + e \ , \tag{3}$$

which undergoes a maximum at impacting electron energies of ~40 eV, producing H_2 ($\nu'' > 1$) [12]. Ion sources that employ this H^- production mechanism are broadly termed volume sources and are also discussed in the following.

3 SURVEY OF OPERATIONAL ION SOURCES

In this section, the only ion sources considered are those that have either demonstrated a high degree of reliability through extended use on an accelerator or that have been extensively commissioned off-line. Table I contains a sufficiently large representative sampling of the current generation of ion sources to allow a conservative assessment of source capabilities and reasonable comparison with the requirements of new accelerator projects. The parameters quoted represent a set of operating conditions, which can be sustained for the quoted maintenance periods. The table shows three types of sources: magnetron, Penning, and Multicusp (RF driven, filament driven, and surface conversion).

The following conventions are held in this report: **Pulse beam current**—average of the H^- current extracted from the source during the extraction pulse. **Average beam current**—time averaged H^- beam current extracted from the source. **Repetition rate and pulse length**—frequency and length of pulses extracted from the ion source. **Maintenance interval**—time interval of continuous source operation during a nominal run period, generally smaller than the mean time between source failures. **Emittance**—area in 2D phase space that is enclosed by an equal intensity contour line enclosing 90% of the total beam current, $\beta\gamma$ normalized. Measurements were taken as close to the source as possible under operational conditions. In some cases, raw data from the laboratory were analyzed using a common analysis algorithm [13]. In most cases, analyzed data were found to be very close to Gaussian, making $\varepsilon_n(90\%) = 4.6\,\varepsilon_n(\mathrm{rms})$ a good approximation. Two listed values mean individual x and y scans. **Brightness**—pulse beam current divided by square of emittance as define previously [mA/(mm mrad)^2]. **Power efficiency**—pulse current divided by the total power applied to the source during the pulse (mA/kW).

3.1 Magnetron Sources

Magnetron sources were first developed at the Budker Institute in Novosibirsk in the early 1970s where they were called planotrons [14]. This technology was transferred to FNAL, BNL, ANL, and DESY, where ion sources continue to operate today (see references in Table I). Taking the BNL source as an example, pulse beam currents as high as ~100 mA are attainable with excellent reliability for ~25 weeks and with a modest average beam current of ~0.5 mA and brightness of ~3 mA/(mm mrad)^2.

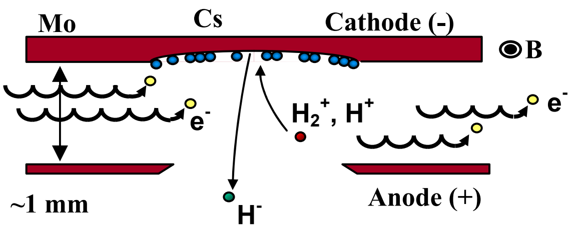

Figure 1: Simplified schematic of the magnetron H^- ion source with grooved cathode.

Fig. 1 shows a simplified schematic of the ionization region of the source. A voltage of ~150 V is normally applied between the anode and cathode and is allowed to draw a discharge current of tens of amperes provided by a pulsed DC supply. A strong magnetic field (normal to the page) of ~1 kG is applied to efficiently confine electrons to an ExB drift in the gap between the anode and cathode. Not shown in the figure is a "racetrack" geometry, which allows drifting electrons, exiting the right of the figure to actually drift through the structure and reenter from the left of the figure. H^- ions are formed when positive ions from the discharge, accelerated through the cathode sheath, strike the cesiated surface and eject H^- ions through the process described in Section 2. H_2 gas is fed into the source at the rate of a ~2 SCCMs (standard cubic centimeters per minute) using a piezoelectric valve while Cs vapor is delivered to the source at a rate of ~0.5 mg/h by heating an external reservoir containing liquid Cs. Both slit and circular extraction systems are used that employ a grooved cathode to enhance yield. The emittance of this source is generally considered the highest of the operational sources because the energy-angular distributions of the sputter ejected H^- are folded into the beam emittance since they are directly extracted from the source.

Table I: Operational H^- ion sources. Reference chosen to provide best description of source not the most recent.

	Facility	**Pulse beam current (mA)**	**Ave. beam current (mA)**	**Rep. rate (Hz)**	**Pulse length (ms)**	**Duty factor (%)**	**Extr. pot. (kV)**	**Main-tenance interval (weeks)**	**Emit. 90% x/y (norm) (π mm mrad)**	**Bright-ness**	**Power efficiency (mA/kW)**	**Ref.**
Magnetron	**DESY-HERA**	**60**	**0.03**	**5**	**0.1**	**0.05**	**18**	**~ 52**	**1**	**6**	**~ 8**	**6, 15**
	BNL-AGS	**95**	**0.5**	**7.5**	**0.7**	**0.5**	**35**	**~ 26**	**1.8**	**3**	**~ 67**	**16**
	ANL-IPNS	**48**	**0.1**	**30**	**0.07**	**0.2**	**20**	**~ 16**	**0.9 /1.4**	**4**	**~ 9**	**17**
	FNAL	**75**	**0.08**	**15**	**0.07**	**0.1**	**20**	**~ 16**	**0.9 /1.5**	**4**	**~ 2.5**	**18**
Multicusp - RF	**DESY-HERA**	**40**	**0.05**	**8**	**0.15**	**0.12**	**36**	**~ 150**	**0.43**	**22**	**~2**	**19**
	SSC	**60**	**0.06**	**10**	**0.1**	**0.1**	**35**	**~ 1**	**0.9**	**8**	**~ 2.1**	**20**
Penning	**RAL-ISIS**	**35**	**0.35**	**50**	**0.2**	**1.0**	**18**	**~ 4**	**0.7 / 1.1**	**5**	**~ 6**	**21**
	INR-MMF	**50**	**1.0**	**100**	**0.2**	**2.0**	**20**		**0.6 / 1.2**	**7**	**~ 8**	**22**
Multicusp - sur. con.	**KEK-KENS**	**18**	**0.07**	**20**	**0.2**	**0.4**		**~ 14**	**2**	**0.5**	**~ 4.5**	**23**
	LANL-LANSCE	**20**	**2.4**	**120**	**1**	**12**	**80**	**~ 4**	**0.6**	**6**	**~1.6**	**24**
Multicusp - filament	**TRIUMF**	**8**	**8**	**cw**	**cw**	**1**	**25**	**~ 6**	**0.5**	**3.2**	**~ 3**	**25**
	Jyvaskyla	**3**	**3**	**cw**	**cw**	**1**	**5.8**	**~ 6**	**0.6**	**1**	**~ 3**	**26**

3.2 Penning Sources

Penning source ions were also developed at the Budker Institute in the mid 1970s [27]. This technology is currently in use at RAL-ISIS and INR—Meson factory (see references in Table I). Taking the INR source as an example, somewhat smaller pulse beam currents are available, ~40 mA, but with much higher average currents, ~1 mA, as well as higher maintenance requirements, ~4 weeks (RAL). Beam brightness is generally better since sputter-formed H^- is prevented from being directly extracted from the source.

Fig. 2 shows the operating principles of the Penning ion source. Like the magnetron source, a pulsed DC supply is used to establish a discharge between an anode and cathode (~150V, ~50A). Plasma electrons are constrained to spiral trajectories around a strong, externally imposed ~1-kG magnetic field, with field lines extending from cathode to cathode. Electrons are efficiently confined by reflection from the cathode surfaces. Cs vapor is effused into the source using the same method employed by the magnetron source. This creates a low-work function surface, which enhances the plasma density by improving the emission characteristics of the cold cathode surface as well as creating an ionization surface for H^-. As before, H^- is formed by positive ions falling through the cathode sheath and striking the cathode surface, ejecting H^- ions. Fig. 2 also shows small shields, which prevent direct extraction of the surface-produced H^-.

It is believed that the extracted H^- results from resonant charge exchange with the neutral H component of the plasma, leading to thermal starting energies of the H^- ions, explaining the low beam emittance observed in this type of source [8]. H_2 gas is introduced into the source also using a piezoelectric valve gated slightly before the discharge pulse the ion source. Cs consumption is greater than in the magnetron source, ~5 mg/h because of the higher average current (duty factor).

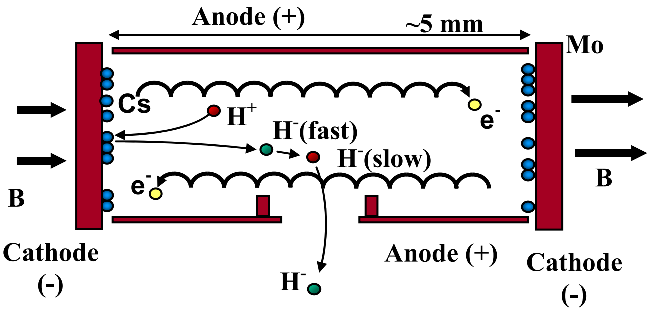

Figure 2: A simplified schematic diagram of a Penning H-ion source. A rectangular anode chamber is capped by two electrically isolated cathodes.

3.3 Multicusp Sources

This broad category of ion sources typically employs both radial and axial multicusp magnets to form a magnetic bucket confining the plasma. Plasma can be created by RF excitation or by using a hot filament. Multicusp sources have been developed based on volume, surface, or both methods of H^- production. Sources surveyed are capable of producing high average beam currents, ~8 mA of D^- injected routinely into the TRIUMF cyclotron or high pulse currents; 35 mA (at low duty factor) was used to commission the front end of the SSC. Later by adding Cs [25] vapor to these sources, 60-80 mA were routinely extracted from the SSC source at low duty factor [28], while the TRIUMF source has produced ~25 mA of H^- at 100% duty factor. In all cases, emittance from this type of source is excellent, making it possible to extract very bright beams in the case of the DESY source: ~22 mA/(mm mrad)^2 even without the use of Cs. It is worth noting that the DESY multicusp source delivered ~80 mA of H^- using an internal antenna and biased Ta collar to the HERA injector [6].

The principle of operation is straightforward: plasma is created inside a discharge chamber. The chamber is surrounded by a bucket configuration of “cusp” magnets: many alternating N and S poles face the plasma chamber. This causes reflection of electrons, creating a high degree of plasma confinement. Fig. 3 shows a conceptual illustration of a multicusp source equipped with a H^- formation (converter) electrode similar to the sources used at LANL-LANSCE and KEK.

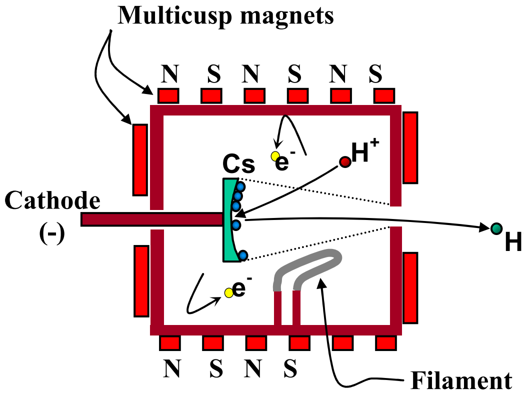

Figure 3: A multicusp source featuring a H^- formation electrode biased negatively with respect to the plasma chamber.

Here the converter surface is negatively biased with respect to the plasma chamber by ~300 V causing positive ions within the plasma to ejected H^- ions from the surface. The geometrical shape, location, and negative bias of the converter surface directs the H^- ions towards the extraction opening. Plasma and neutral densities in this source must be kept at modest values to prevent excessive charge exchange losses of the ejected H^- species.

Another embodiment of the multicusp source has been realized at DESY in an operationally proven source: an external helical RF antenna replaces the filament for plasma production and there is no converter electrode. Since this source operates without Cs, there are no low-work function surfaces within the source and ionization occurs through volume processes. In this case, hot electrons within the helical antenna excite vibrational states of H_2 through the process shown in Eq. 3. The extraction region of the source is “filtered” by an externally applied transverse magnetic field of ~150 G, deflecting hot electrons from the plasma core and allowing cool, collisional electrons to pass through. The excited H_2 is neutral and therefore drifts freely through the filter field. The combination of vibrationally excited H_2 and cold electrons in the extraction region creates conditions for substantial H^- volume production through the process shown in Eq. 2.

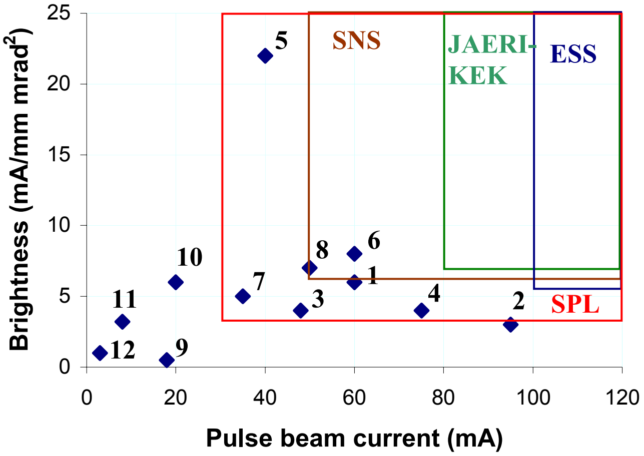

Figure 4: Beam brightness and pulse current of operational ion sources (points) and new facility requirements (rectangles). Magnetron sources: 1-DESY, 2-BNL, 3-ANL, 4-FNAL. Multicusp RF sources: 5-DESY, 6-SSC. Penning sources: 7-RAL and 8-INR. Multicusp surface conversion sources: 9-KEK and 10-LANL. Multicusp filament sources: 11-TRIUMF and 12-Jyvaskyla.

3.4 Performance Summary

Figs. 4 and 5 show the performance of each source surveyed. The ability of each source, under routine operating conditions, to simultaneously achieve high beam brightness and pulse current, as well as high average and pulse current, can be visualized using plots of this type. Performance required by new accelerator facilities are shown as rectangles in these plots where the lower left corner of each rectangle represents the minimum acceptable requirement for each project and all interior points of the rectangle meet or exceed the specified performance. Accelerator projects include **ESS**—European Spallation Source, **JKJ**—Joint KEK-JAERI project, **SPL**—Superconducting Proton Linac at CERN (phase 2), and **SNS**—U.S. Spallation Neutron Source. The figures show that under normal operational conditions, no ion source can simultaneously meet all requirements.

4 EXPERIMENTAL ION SOURCES

There has been an ongoing worldwide effort to develop ion sources that can meet these criteria. A few selected examples are given here that were discussed in recent ion source workshops [2,3].

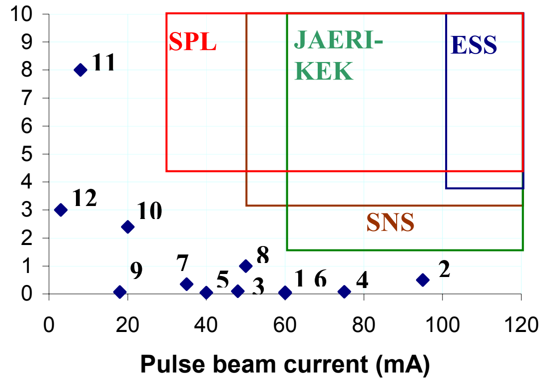

Figure 5: Average and pulse beam current of operational ion sources (points) and new facility requirements (rectangles). Source numbering is given in the caption for Fig. 4.

The JAERI-KEK group has developed a multicusp, filament-driven source with good initial results: 72 mA pulse, 1.8 mA average current, and 15 mA/(mm mrad)^2 beam brightness. Efforts are under way to improve lifetimes [29]. Frankfurt University has also developed a multicusp, filament-driven source with good reported results: H^- currents of 120 mA pulse and 7.2 mA average current were extracted from the source for ~eight days of continuous operation [30]. LANL has developed and tested a large Penning source with four times the dimensions of the original Penning source from Novosibirsk. This source was tested for ~two days of continuous operation in 1987 and produced 250 mA pulse and 1.2 mA average current [31].

LBNL has developed a multicusp, RF-driven source that employs antennas developed at ORNL [32]. The source has demonstrated operation at 52 mA pulse, 3 mA average current, with a brightness of 6 mA/(mm mrad)^2 for a short period of time. The source was also used successfully to commission the SNS front end at LBNL, delivering 30-55 mA pulse currents at very low average current for several weeks. Two lifetime tests were performed at ~25 mA pulse, 0.6 mA average current for ~100 hours: both tests were intentionally stopped because of time constraints.

5 CONCLUSION

The present generation of H^- ion sources has evolved into very reliable accelerator subsystems providing continuous operation for many weeks. Unfortunately, when operated under nominal conditions, with known source lifetimes, none of these proven sources simultaneously meets each requirement of new accelerator facilities. Fig. 5 suggests that achieving, simultaneously, high pulse and average current may be the most significant challenge of future source development. Experimental sources described in Sect. 4 do meet many of these requirements, but lifetime remains a considerable uncertainty, possibly to the point of excluding some from consideration. Perhaps the most developed source in Sect. 4 is the SNS source, which has passed several lifetime tests, commissioned the SNS front end, and demonstrated brief operation at the full project requirement.

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