# THE DEVELOPMENT OF HIGH-CURRENT AND HIGH DUTY-FACTOR $H^-$ INJECTORS

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*Abstract*

Increasing the ion beam current and/or the beam duty factor are normally the most cost-effective solutions for increasing the production rate of accelerator facilities. Accordingly, many accelerator laboratories have projects that involve an increase in ion beam current. Higher beam currents often come with an increase in the ion beam emittance. High-power accelerators, however, need to remain serviceable, which limits the acceptable beam losses throughout the high-energy part of the accelerator and often puts a limit on the acceptable emittance increase. This overview discusses the current status of some $H^-$ injectors, and the requirements of some upgrade projects, as well as how those requirements could be met.

## INTRODUCTION

Many existing and future accelerator facilities employ negative ion injectors to use the polarity-changing stripping process, either for beam stacking in accumulator rings or for further acceleration in Tandem accelerators. In a timeless quest for higher production yields, several facilities are studying and/or developing injectors that can deliver higher currents of negative hydrogen ions with higher duty cycles. Some of the projects are listed in Table 1. CERN is building a 3 MeV test stand, and planning "LINAC4", both requiring high $H^-$ beam currents with moderate pulse lengths, low repetition rates, and moderate emittances. The ultimate goal is the Superconducting Proton LINAC (SPL) with even more demanding requirements [1].

Table 1: Pulsed $H^-$ Injector Projects and Upgrade Goals.

| Project | Current (mA) | Pulse length (ms) | Rep Rate (Hz) | Norm. Emit. (rms) | Energy (keV) |
|---|---|---|---|---|---|
| CERN TS<br>"LINAC 4" | 40<br>80 | 0.4<br>0.7 | 1<br>2 | 0.25<br>(90%) | 95 |
| Fermilab A<br>Phase B | 15<br>45 | 3.2<br>1.2 | 2.5<br>10 | 0.25 | 50 |
| BSNS Ph I<br>Phase II | 20<br>40 | 0.4<br>to 0.6 | 25 | 0.2 | 75 |
| ISIS-FETS | 60 | 2 | 50 | - | ~65 |
| LANSCE | 25-30 | 1.0 | 120 | 0.13 | 80 |
| J-PARC | 50 | 0.5 | 25 | 0.2 | 50 |
| SNS 1.4 MW | 41 | 1.23 | 60 | 0.2 | 65 |
| SNS 3 MW | 67<br>to 95 | 1.23 | 60 | 0.2<br>to 0.35 | 65 |

To deliver up to 2 MW to a neutrino target, Fermilab is developing a multi-mission 8-GeV injector that requires initially 15 mA for over 3 ms, and later 45 mA for over 1 ms [2]. The Beijing Spallation Neutron Source requires similar pulse currents, but with a higher repetition rate [3]. ISIS is planning a RFQ test-stand with an ion source to explore requirements needed for a significant power upgrade [4]. LANSCE plans to double their pulse current without significantly increasing the emittance at their very high duty factor [5]. J-PARC is commissioning an accelerator complex that ultimately requires 50 mA with a low emittance. [6]. A high duty factor and a low $H^-$ beam emittance are required for 1.4 MW operations of the Spallation Neutron Source. Upgrading its power to 3 MW requires a significant increase in current without a drastic increase in beam emittance [7]. Supplying user facilities requires all these new injectors be reliable and have lifetimes that can support high availabilities.

## THE $H^-$ PRODUCTION CHALLENGE

The ion output of positive ion sources can be simply increased by increasing the power delivered to the plasma. This, however, does not necessarily apply for $H^-$ sources. The small electron affinity (binding energy) of 0.75 eV makes $H^-$ ions fragile and impedes their formation. At this low energy level, it is extremely rare that a free electron can dissipate its excess energy when colliding with a hydrogen atom ($\sim 5\cdot 10^{-22}cm^{-2}$). Multi-particle collisions, where the excess energy can be transferred to another particle, produce more $H^-$ ions, such as fast electrons colliding with hydrogen molecules ($\sim 10^{-20}cm^{-2}$). Inside the plasma the most likely production channel is a 2-step process: First a fast electron (>15 eV) excites an $H_2$ molecule into a high vibration state with $4\leq n\leq 12$ ($\sim 5\cdot 10^{-18}cm^{-2}$). When the excited molecules collide with slow electrons (<1 eV), there is a fair chance that the molecule breaks up and the slow electron gets trapped in the field of one of the atoms ($\sim 3\cdot 10^{-16}cm^{-2}$). The necessary ionization and excitation processes require high densities of fast electrons (>10 eV), which destroy the $H^-$ ions at a rapid rate ($\sim 3\cdot 10^{-15}cm^{-2}$). The destruction rate drops rapidly with the energy of the electrons and practically disappears below 1 eV, the range of energies needed for the described dissociative attachment process [8]. These contradicting requirements for the electron temperature can be spatially separated with a magnetic field in the range of 100-500 G.. For example, Fig. 1

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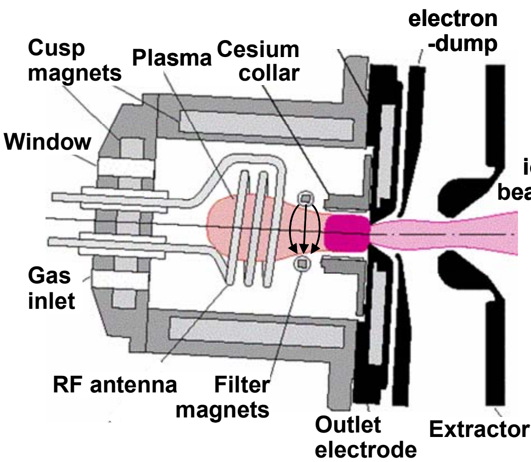


Figure 1: Schematic of an $H^-$ Volume source.

shows an RF-driven multicusp $H^-$ source [9], where the discharge power is coupled into the main plasma volume to generate fast electrons that maintain the ionization process and simultaneously excite $H_2$ molecules. The magnetic filter field reflects the fast electrons, but allows cold electrons and ions, as well as the excited neutrals, to diffuse from the power discharge volume into the space near the outlet aperture. In this cold plasma the slow electrons break up the exited molecules, frequently forming $H^-$ ions. Here, the main predators are the slow protons that readily recombine with the $H^-$ ions ($>10^{-14}cm^{-2}$) [8]. The highest $H^-$ extraction yields are achieved when the production occurs very close to the outlet aperture.

The described volume production can be complemented by surface production, where loosely bound surface electrons get trapped in the field of atoms that bounce off a surface. In most cases the interacting surface electron will return to the surface because its work function (~5 eV) is much more attractive than the electron affinity of the H atom (0.75 eV). Coating the metal surface with ~1 atomic layer of Cs lowers the work function to ~2 eV, which significantly increases the $H^-$ production yield [8].

The $H^-$ production yield further increases with increasing particle energy because the electron has less time to find the most attractive end state. Accordingly most surface produced $H^-$ ions originate from protons that are accelerated in the plasma sheath towards the surface, where they neutralize, elastically bounce back, and trap a second electron on their way back into the plasma. Therefore surface-produced $H^-$ ions feature a kinetic energy of about twice the energy gained in the plasma sheath, which can significantly increase the emittance of the extracted $H^-$ beam. However, when surface-produced $H^-$ ions collide with neutral atoms, there is a significant chance that the extra electron hops resonantly from the hot ion to the cold atom ($\sim10^{-14}cm^{-2}$) [8], thus forming the desired low-energy $H^-$ ions.

Increasing the temperature of the cesiated surface to several hundred degrees can further enhance the $H^-$ production yields [10] for several reasons. The elevated temperature shortens the lifetime of the cesium cover, which needs to be replenished more often.

Accordingly, the highest contributions of cold $H^-$ ions can be expected from surfaces that face the plasma; are near, but face away from the outlet aperture; and have a temperature of several hundred °C.

Surface $H^-$ sources, such as Magnetrons and Penning, are designed for optimal surface production and accordingly produce very little $H^-$ beam without cesium. Volume $H^-$ sources are designed to optimize the $H^-$ production inside the plasma, although their $H^-$ output can be increased by a large factor (>4) when adding cesium [11]. Adding cesium to an uncesiated source with a suitable outlet geometry promises an increased $H^-$ current output with a reduced beam emittance. It is therefore unlikely that all requirements listed in Table 1 can be met without cesium.

Another problem of negative ion sources is caused by the electrons that are simultaneously extracted with the negative ions. The electrons typically outnumber the ions by a factor of ~10 in uncesiated sources, but cesium can lower this factor to ~1 [12]. When extracting high ion currents with high extraction voltages, the created electron beam can acquire substantial power that needs to be dissipated, and can result in a significant X-ray hazard. The power can be reduced by intercepting the electron beam at an intermediate voltage level. For example, the SNS ion source shown in Fig. 1 features a 1.6 kG magnetic field across the extraction aperture that steers the electrons to the side, where most of them are intercepted by the electron dump that is ~5 kV positive with respect to the ion source body. The ion source tilt angle of 3° can be adjusted by ±3° to mitigate the small deflection encountered by the extracted $H^-$ ions [9].

## THE STATE OF $H^-$ INJECTORS

Table 2 lists some of the existing facilities that operate pulsed $H^-$ injectors, as well as some $H^-$ sources of interest.

DESY developed a cesium-free, multicusp $H^-$ source with an external RF antenna [13, 14]. Short pulses yield up to 60 mA and a 40 mA beam had a normalized 90% rms emittance of 0.25 $\pi$·mm·mrad [12]. A 72% larger value is reported 76 pages later in the same issue by the same DESY co-author [13]. 90% rms emittances ignore all signals below 10% of the measured peak current, and therefore those values need to be increased by 50-100% to be compared with 100% values [15]. Driven with an SNS RF amplifier, the source delivered up to 40 mA for 1.2 ms and 3 ms long pulses. The observed droop can partially be mitigated by stabilizing the drooping RF power.

At Fermilab one of their two $H^-$ injectors can be serviced while the other delivers beam. Their magnetron source ejects the ~20 keV beam into a dipole magnet that separates the electrons. A Cockcroft-Walton accelerates the beam to ~750 keV, where normalized rms emittances of 0.2 and 0.3$\pi$·mm·mrad are measured. ~60 mA are produced during the 0.1 ms long pulses at 15 Hz [12].

ISIS uses a Penning source with a similar dipole magnet, but injects the ~35 keV beam into their RFQ which replaced a Cockroft-Walton [16]. ISIS test stand measurements show the $H^-$ beam emerging from the dipole magnet to have a surprisingly large normalized rms emittance near 1 π·mm·mrad [17]. However, after losing about half of the beam, the emittance is much smaller at the RFQ output [16].

Table 2: The Physical Characteristics of some working H- injectors and H- Sources

| Facility | Source type | LEBT type | Cs | Curr-ent (mA) | Pulse length (ms) | Rep Rate (Hz) | Extract hole ∅(mm) | Normalized RMS Emittance (π·mm·mrad) | Reference | Emittance Location | Life-time (weeks) | Energy (keV) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DESY (RF) | Multicusp ext. RF | 2 solenoids | No | 40<br>30<br>40 | 0.15 | 8 | 6.5 | 0.25 (90%)<br>0.26 (90%)<br>0.43 (90%) | [12]<br>[13]<br>[13] | LEBT | >150 | 35 |
| Fermi | magnetron | Dipole | Yes | ~60 | 0.1 | 15 | 0.9x10 | 0.2/0.3 | [12] | 750 keV | ~30 | ~20 |
| BNL | magnetron | 2 solenoids | Yes | ~100 | 0.6 | 6.66<br>10 | 2 | ~0.4 | [18] | LEBT | ~30 | 35 |
| ISIS | Penning | Dipole | Yes | ~60<br>~35 | 0.5 | 50 | 0.6x10 | ~1<br>~0.12/0.17 | [17]<br>[16] | Dipole exit<br>665 keV | ~3 | 35 |
| LANSCE | Surface converter | 2 solenoids | Yes | ~18<br>{40} | 1 | 120 | 10<br>{8} | ~0.12 (98%)<br>{~0.23 (98%)} | [19]<br>[19] | LEBT | >4<br>- | 80 |
| J-PARC | Multicusp $LaB_6$ filam | 2 solenoids | No | 20<br>35 | 0.5 | 25 | 9 | 0.15/0.18 (9?%)<br>- | [20]<br>[20] | LEBT | >3 | 50 |
| SNS Frontend | Multicusp int. RF | 2 Einzel lenses | Yes | ~20<br>41 | < 1 | 1-5 | 7 | 0.12/0.14 (100%)<br>0.25/0.31 (100%) | [25]<br>[25] | Test LEBT exit | >11<br>- | 65 |
| SNS Teststand | Multicusp int. RF | 2 Einzel lenses | Yes | 33<br>41 | 1.23 | 60<br>10 | 7 | 0.18/0.26 (100%)<br>0.25/0.31 (100%) | [25]<br>[25] | Test LEBT exit | 2.3<br>- | 65 |
| JAERI | Multicusp W-filament | NA | Yes | 60<br>72 | 1 | 50 | 8 | ~0.21 (100%)<br>- | [26]<br>[11] | Source exit | ~0.5 | 70 |
| Sumy | Inverse magnetron | NA | No | ~50 | 0.1-1 | 1-10 | 5.4 | - | [28] | - | $<10^6$ p | 10-100 |

BNL extracts ~100 mA $H^-$ beam from their magnetron source, which is refocused with a 2-solenoid LEBT before being injected into the RFQ. Despite the high current, lifetime is not an issue with the 0.6 ms long pulses at 10 Hz [18].

The LANSCE source features a very small emittance at low beam currents. The injector is very reliable despite its demanding duty cycle. A high current source was tested but not implemented due to unacceptable emittance [19].

JPARC developed a filament driven source that delivers 20 mA without cesium for commissioning [20].

Brightness comparisons among sources are notoriously inaccurate because emittances are measured in different locations for a different fraction of the original beam with different emittance scanners measuring different distributions that are often thresholded, and often without mentioning the threshold level.

## THE STATE OF THE SNS $H^-$ INJECTOR

For the commissioning and for the initial low-power operational phase of the SNS accelerator, the ion source delivers the required currents of 15-41 mA during the 0.2 to 1 ms long pulses at 1-5 Hz. The source normally lasts the 5-10 week long runs, after which it is replaced with a reconditioned source [21]. At low rep rates short pulses of 50 mA have been measured exiting the RFQ [22].

Reliable, high-power operations, scheduled for 2009, are being explored on the SNS test stand. It was found that no more than ~40 mA can be produced for 1.23 ms long pulses. At 60 Hz, after optimising all ion source parameters, which are well below the maximum limits, no more than ~33 mA can be produced for 1.23 ms long pulses [23], which is sufficient for operations at 1 MW.

We believe that small modifications of the geometry and the procedures will eventually produce the 41 mA at 60 Hz and 1.23 ms required for 1.4 MW operations.

The SNS LEBT is only 12 cm long and features two electrostatic lenses. The 2nd lens is partitioned into four quarters to impose a transverse steering field and to chop the beam [9]. After completion of a 2.3 week long lifetime test with 33 mA at full duty cycle, the 2nd lens disintegrated into two halves, most likely due to overheating of the glue joints. A beam dynamics study suggested no losses for beam currents up to 70 mA [24]. An ORNL R&D program has started to test and improve lens 2. Again, we believe that small modifications, better alignment, and more careful tuning will allow the SNS LEBT to properly operate with 41 mA beams.

The emittance of the beam emerging from the ion source is nearly elliptical, as seen in Fig. 1. Its value increases significantly when increasing the RF-power to increase the $H^-$ beam output.

The non-linear space charge force and the aberrations of the 2-einzel-lens LEBT distort the ellipse, as evidenced by the S-shaped emittance distribution measured at the LEBT output shown in Fig. 3. This distortion increases the rms emittance and lowers the RFQ transmission.

Figure 4 shows the SNS LEBT output current as a function of the measured beam emittance. The 33 mA values were measured at LBNL before the LEBT was mounted on the RFQ [9]. They are consistent with the 22, 30 and 40 mA values measured on the SNS test stand [25]. The larger horizontal emittance is likely caused by the magnetic field in the outlet aperture. The emittances are slightly larger than the 0.2 π·mm·mrad requirement for the baseline system.

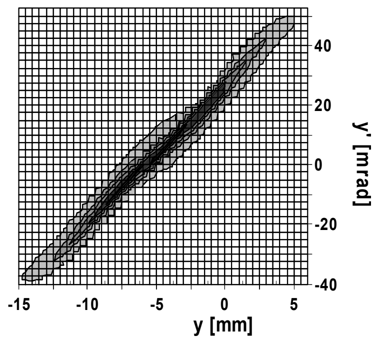


Figure 2: SNS ion source output emittance.

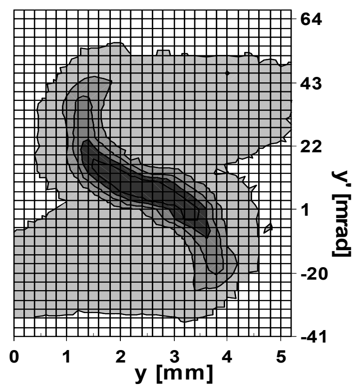


Figure 3: SNS LEBT output emittance.

## THE SNS POWER UPGRADE CHALLENGE

Some of the existing H⁻ injectors appear to meet the initial requirements of many of the H⁻ injector projects, although there are some questions regarding the RFQ acceptance based on Gaussian distributed beams and the typical S-shaped emittance distribution measured at the output of the typical LEBT.

Upgrading the SNS power to 3 MW requires an RFQ output current of 59 mA [7]. Figure 4 shows required RFQ input (=LEBT output) beam current as a function of its emittance when taking into account the RFQ beam losses predicted by PARMTEQ for Gaussian beams. Losses predicted for the SNS LINAC exclude emittances in excess of 0.35π·mm·mrad. Figure 4 shows clearly that the SNS baseline H⁻ injector cannot meet any of these requirements. Table 2 shows that no existing H⁻ injector meets the beam current and emittance requirements needed for the SNS 3 MW upgrade.

Accordingly, the SNS 3MW upgrade requirements have to be met by combining a very bright H⁻ ion source with a robust LEBT that inflicts minimal emittance growth. Both of those components have been technically demonstrated, but not specifically in the required configuration and not all components under stringent operational requirements.

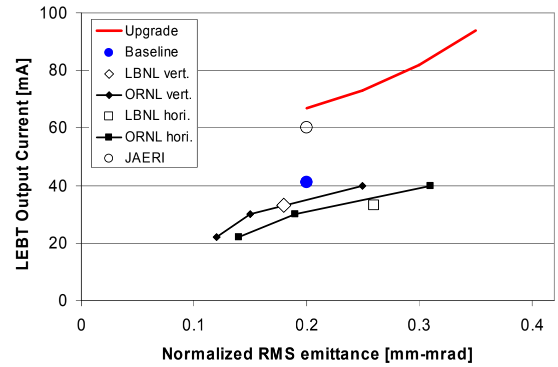


Figure 4: SNS LEBT output current requirements.

## THE QUEST FOR BRIGHT H⁻ SOURCES

Several years ago, JAERI developed a filament-driven, multicup H⁻ source, which ejects a 60 mA beam with an elliptical emittance and a normalized rms value of only 0.13/0.15 π·mm·mrad when thresholded at ~7% [11]. A threshold-free analysis yielded a normalized rms emittance of 0.21 π·mm·mrad for 100% of the 60 mA beam [26], clearly the record brightness of H⁻ sources. This is very close to the SNS 3 MW requirement shown in Fig. 4. The source delivered as much as 72 mA, which would actually meet the SNS 3 MW requirements if the rms emittance increases linearly with beam current. However, being a filament-driven discharge, the source lifetime is limited to ~4 days at 60 mA. Reconditioning typically requires removing most of the sputtered filament material, a tedious and time-consuming process, which is neither appealing nor cost-effective.

One goal of the SNS ion source R&D program is to understand the characteristics that make the JEARI source so bright for high-current beams. If understood, it may allow for integrating those features into other H⁻ sources that have a considerably longer lifetime and a higher reliability, such as the high-power, external-antenna H⁻ sources being developed at SNS [27].

Another promising option is the cesiation of existing high current H⁻ sources that have not yet been tested with cesium. A prime example is the Sumy inverse magnetron H⁻ source where a magnetron-produced plasma is expanded into a volume where the negative ions form. Without cesium it produced 50 mA during 1 ms long, 10 Hz pulses [28], but with an emittance comparable to a magnetron source. SNS is collaborating with Sumy to cesiate this source and see whether the addition of cesium and later controlling the temperature of the outlet aperture can lower the emittance and increase the current to meet the 3 MW requirements.

It is possible that the significantly larger emittance of the DESY source compared to the SNS source is simply due to the absence of cesium. At this time only one DESY source exists, which is needed as a backup for HERA operation and therefore cannot be tested with cesium. The opportunity will likely arise after CERN has implemented a copy of the DESY source for their test stand project [1].

The ion temperature could be another brightness limiting factor. Helicon waves have a better plasma penetration and therefore allow for achieving required plasma densities with lower RF power levels, yielding lower plasma temperatures. SNS is collaborating with the ORNL Fusion Energy Division on the development of a helicon plasma driver for an $H^-$ source [29].

## A ROBUST, HIGH AVAILABILITY, EMITTANCE-CONSERVING LEBT

Electrostatic LEBTs are normally very cost-effective. However, their vulnerability to losses from high-power, high-duty-factor beams raises questions regarding their application in user facilities. The more common magnetic LEBTs are robust because uncontrolled beam losses are spread over the large area of the vacuum envelope, which is cooled by ambient air. The physical nature of high power magnets causes magnetic LEBTs to be much longer than our baseline electrostatic LEBT. During the start of the pulse the large space charge force in high-current, small-emittance beams causes the beam to blow up and generate significant losses. Due to the inefficiency of negative ion sources, especially volume sources, the LEBT pressure is normally in the $10^{-6}$ to $10^{-4}$ Torr range. In this range, the $H^-$ beam produces a significant rate of $H_2^+$ and $H^+$ ions from collision with the residual gas. Applying a positive potential barrier at both ends of the LEBT traps those ions in the space charge potential of the $H^-$ beam until it is neutralized. BNL observes neutralization in less than 0.1 ms at a pressure of $\sim 10^{-6}$ Torr [30]. Beam neutralization allows for transporting the beam with a small radius, thus minimizing the effects of aberrations in lenses.

2-solenoid LEBTs have proven to be robust and transport beams with minimal emittance growth. We are designing a 2-source LEBT to mitigate the risk of short lifetimes and increased failure rate that may be coupled with the challenging ion source requirements. While such systems are common in accelerator systems, they are normally not subjected to such high-current, low emittance beams and our stringent requirements. A prototype will be built and serve as a test stand for bright ion sources as well as to study the $H^-$ beam transport as a part of the R&D program for the SNS power upgrade.

## CONCLUSIONS

High-current $H^-$ injectors with small emittances are in demand. The emittance requirements appear challenging, because existing small-emittance $H^-$ sources yield emittances that grow rapidly with $H^-$ current. However, a normalized emittance of 0.2 $\pi$·mm·mrad has been demonstrated with a 60 mA $H^-$ beam. Understanding the difference between this unusually bright high-current $H^-$ source and other high-current $H^-$ sources will likely allow for reducing the emittance of some of the other sources. This should lead to a high-current $H^-$ source with a small emittance and a long lifetime.

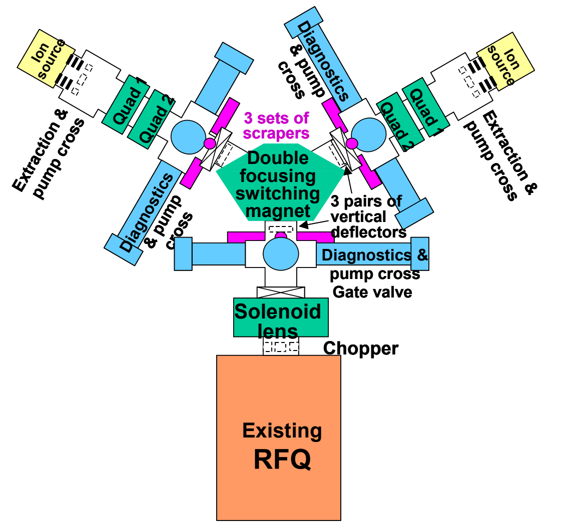


Figure 5: 2-source LEBT for the SNS 3 MW upgrade.

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