Negative hydrogen ion sources for particle accelerators: Sustainability issues and recent improvements in long-term operations

Robert Welton[1], Dan Bollinger[2], Morgan Dehnel[3], Ilija Draganic[4], Dan Faircloth[5], Baoxi Han[1], Jacques Lettry[6], Martin Stockli[1], Olli Tarvainen[5], Akira Ueno[7]

[1]Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[2]Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[3]D-Pace, Nelson, British Columbia, Canada
[4]Los Alamos Neutron Science Center, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[5]UKRI-STFC-ISIS Pulsed Spallation Neutron and Muon Facility, Rutherford Appleton Laboratory, Harwell, UK
[6]CERN, 1211 Geneva, Switzerland
[7]J-PARC Center, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan

Corresponding author: welton@ornl.gov

Abstract. High brightness, negative hydrogen ion sources are used extensively in scientific facilities operating worldwide. Negative hydrogen beams have become the preferred means of filling circular accelerators and storage rings as well as enabling efficient extraction from cyclotrons. Several well-known facilities now have considerable experience with operating a variety of sources such as RF-, filament-, magnetron- and Penning-type H^- ion sources. These facilities include the US Spallation Neutron Source (SNS), Japan Proton Accelerator Research Complex (J-PARC), Rutherford Appleton Laboratory (RAL-ISIS), Los Alamos Neutron Science Center (LANSCE), Fermi National Accelerator Laboratory (FNAL), Brookhaven National Laboratory (BNL), numerous installations of D-Pace (licenced by TRIUMF) ion sources used mainly on cyclotrons and, most recently, the CERN-LINAC-4 injector. This report first summarizes the current performance of these ion sources in routine, daily operations with attention toward source service-periods and availability metrics. Sustainability issues encountered at each facility are also reported and categorized to identify areas of common concern and key issues. Recent ion source improvements to address these issues are also discussed as well as plans for meeting future facility upgrade requirements.

1. Introduction

Large accelerator complexes have supported scientific user facilities which have had an enormous societal impact spanning many decades and enabling the work of 10's of thousands of scientific users worldwide [1]. Many of these facilities employ synchrotrons, storage rings, cyclotrons and tandem accelerators which depend on long-term operation with stable, highly available beams of negative hydrogen ions from high-brightness ion sources [2]. H^- ions are utilized because H^- and H^+ beams can be conveniently merged into a single beam by passage through an orthogonal magnetic field and, after merging, H^- can be converted efficiently into H^+ by charge exchange stripping. This ability makes H^- ideally suited to fill synchrotrons and storage rings by allowing both the injected beam and the circulating beam to pass through the same charge exchange device allowing injection with minimal emittance growth. Similarly, in cyclotrons, H^- ions can be extracted with near 100% using a stripping foil rather than using magnetic kickers and a septums which are employed in H^+ machines. In tandem accelerators, H^- can be converted to H^+ in a high voltage terminal thereby doubling the beam energy for a given terminal voltage. It should also be noted that H^- ions are capable of being simultaneously accelerated along with H^+ ions in linear RF accelerators by utilizing the 180 degree phase shift of the alternating direction of the applied RF electric field. Accelerated H^- ions can also efficiently form neutral beams for applications such as fusion energy but those ion sources tend to be much larger devices with multi-aperture extraction and are not included in this study.

The high brightness H^- ion sources which serve the facilities discussed here deliver beams from single apertures ranging in intensity from <1 to ~120 mA, pulse lengths of ~100 μs to Continuous (CW), repetition rates of <1 Hz to CW and generally have a normalized-RMS emittance of around 0.25 π mm mrad. Ion source service cycles range from a few weeks to many months of steady operation between maintenance interventions (source replacement / refurbishment). Generally, the length of each facilities service cycle has been optimized over time to deliver maximum source availability (minimum unplanned downtime). This report first summarizes the current performance of these ion sources in routine, daily operations with attention toward source service-periods and availability metrics. Sustainability issues encountered at each facility are also reported and categorized to identify areas of common concern and key issues. Recent ion source improvements to address these issues are also discussed as well as plans for meeting future facility upgrade requirements.

The facilities which participated in this study include Oak Ridge National Laboratory, the Spallation Neutron Source (SNS) which is a Megawatt (MW)-class, pulsed-neutron facility; Japanese Proton Accelerator Research Complex (J-PARC), a multi-purpose, MW-class, neutron, meson and neutrino facility; Fermi National Accelerator Laboratory (FNAL), a TeV-class, high energy physics and neutrino facility; Los Alamos National Laboratory, Neutron Science Center (LANSCE), a MW-class, multipurpose facility; Rutherford Appleton Laboratory, a Pulsed Spallation Neutron and Muon Facility (ISIS), a neutron and muon facility; the European Organization for Nuclear Research (CERN), LINAC-4 injector, a TeV-class high energy physics multipurpose laboratory; Brookhaven National Laboratory (BNL) and D-Pace, a company who provides their TRIUMF-licensed H^- source to many facilities worldwide. This list of participating facilities is by no means fully inclusive but should be largely representative of the field.

The following definitions will be used throughout this work; *Issues*: recent H^- ion source problems or concerns as defined by system experts in long-term facility operations or those anticipated in future facility upgrades; *Improvements:* recent developments, planned or implemented, which address sustainability issues; *Availability:* Beam time delivered by the source (in hours) / Beam time requested from source (in hours) per production run period, this definition only accounts for beam downtime attributed to the ion source.

2. The SNS Cs-enhanced, RF-driven, multicusp H^- ion source

The SNS RF ion source routinely produces ~55 mA H^- ion pulses, 1 ms in duration with a 60 Hz repetition rate [3]. Over time, this source and the Low Energy Beam Transport (LEBT) coupling it to an RFQ, have been improved to now have a >99.9% availability during a typical 4-month operational period [4]. Fig. 1 shows the operational SNS ion source. Some operational concerns reported include: (1) *Beam persistence*: sources have a slight beam decay months after the initial cesiation requiring minor adjustments to the time structure of the accelerated H^- beam filling the SNS storage ring to maintain full power on target. (2) *Consistency between ion sources*: presently only one of the four SNS production source bodies show minimal beam decay compared to that from the spare ion sources.

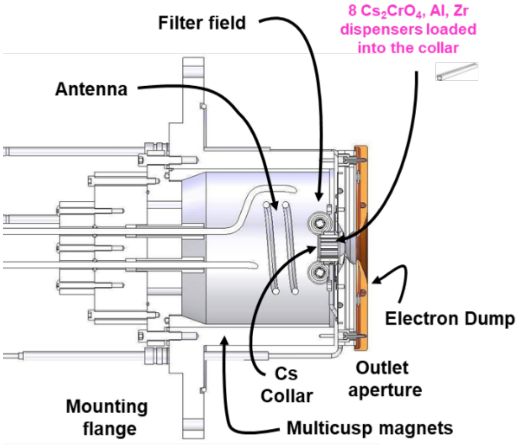


Figure 1. The operational internal-antenna SNS ion source

(3) *Co-extracted electron management*: the amount of these electrons can slowly grow over time which can cause the electron dump power supply to sag which can necessitate a second source cesiation. Cesiation is usually performed only once during startup by briefly heating the Cs-chromate dispensers. (4) *Beam intensity*: future SNS upgrade projects will require ~30% more beam out of the RFQ which the operational SNS ion source can provide if the RFQ performs as expected with an 80-90% transmission. More beam current, however, will be required if the RFQ underperforms this metric. (5) *Source lifetime*: the current internal-antenna source lifetime certainly exceeds the 4-month operational periods as it has not experienced an antenna failure in many years due to improved antenna manufacture and selection process [5]. We do, however, still recognize this as a risk since the antennas are manufactured by a single vender using a proprietary porcelain coating process [6].

Over the years, many improvements have been made to both the SNS internal [3] and external [7] antenna ion sources and are too extensive to discuss here. Looking forward, we are trying to minimize minor physical differences between the production ion source and spare sources. Towards this end, we hope to improve the thermal contact between the Cs-dispenser cartridges in the spare ion sources to be the same as that in the main SNS production source. We also plan to explore incremental improvements in beam intensity by testing slightly larger outlet apertures as well as improving electron management by implementing filter circuits and improved power supplies. Development of the external-antenna ion source also continues as a contingency source for the SNS should any issues with the internal antennas reemerge [7]. Development of this source now focuses on standardizing build quality of the source and improving the reliability of plasma ignition [4].

3. The J-PARC Cs-enhanced, RF-driven, multicusp H$^-$ ion source

The J-PARC RF ion source routinely produces ~60 mA H$^-$ ion pulses, 0.8 ms in duration with a 25 Hz repetition rate [8]. Fig. 2 shows the operational J-PARC ion source. Over time this source has been improved to now have near ~100 % availability as demonstrated during the last 5-month operational period [9]. Overall, the source operates well with the only reported operational issue being a couple of *antenna failures* in 2019 which have been attributed to degradation and issues with virtual and actual leaks in the forward O-ring on the plasma chamber and VCR vacuum seals on the gas feed line (see Fig. 2). The issues were resolved by replacing the VCR fitting with a welded structure, reducing the size of the O-ring groove and venting trapped air-pockets on the vacuum side of the seal [10]. Like many other facilities, J-PARC is also working towards achieving consistent performance across the available pool of ion source bodies [11]. From November 2020 to April 2021, the J-PARC RF-driven H$^-$ ion source (IS) successfully produced the H$^-$ beam of about 58 mA and 1.25 % duty-factor to J-PARC delivering a LINAC beam current of 50 mA with no ion source maintenance for ~152 operational days.

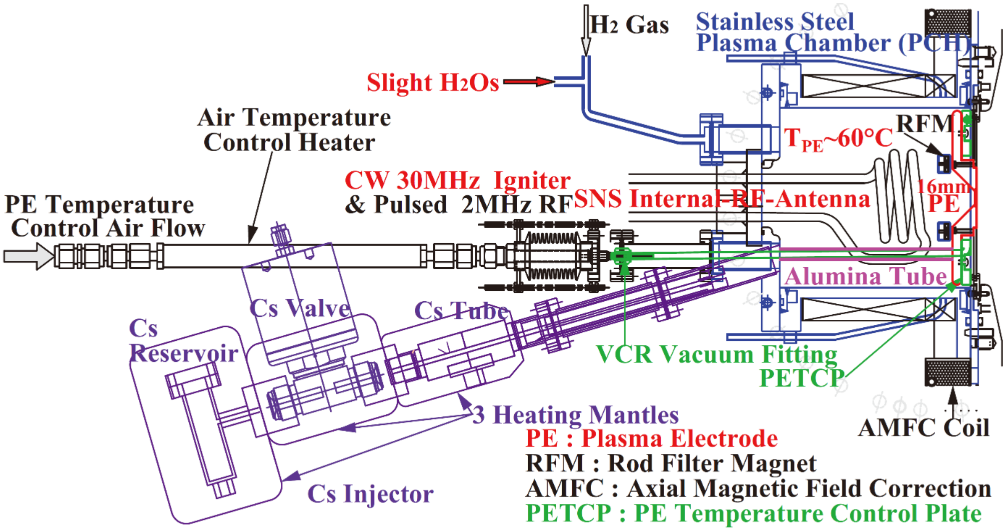


Figure 2. J-Parc operational internal-antenna source.

The sustainability of the J-PARC source was realized by successive improvements of the RF efficiency and transverse emittances and the reduction of impurities in the plasma. By the superior RF efficiency of about 2.6 mA/kW (making 72 mA H^- beam with only 28 kW of 2 MHz RF power) [12], the longer lifetime of the internal-RF-antenna, which was developed by the SNS [5], is expected. Also, the excellent transverse emittances suitable for the J-PARC RFQ, which were measured on the test stand, enabled the excellent J-PARC RFQ transmission efficiency of 94.3% (67.9 mA acceleration for the injected 72 mA H^- beam) [12]. This source performance was enabled by the following improvements [8]; (1) 45 ° tapered Plasma Electrode (PE) with 16 mm thickness to significantly increase I_{H-}, (2) continuous-wave igniter plasma driven by 50 W, 30 MHz RF to reduce hydrogen pressure in plasma-chamber by 50 % and beam loss in the Low Energy Beam-Transport (LEBT) by 12 % compared with that by popularly used 300 W 13.56 MHz-RF, (3) operation with low PE temperature of ~60 ºC to significantly reduce the transverse normalized rms emittances ($\varepsilon_{95\%}$) and (4) slight water (H_2O) feed in hydrogen line to avoid $\varepsilon_{95\%}$ growth and divergence angle expansion. It should also be noted that during beam development periods on the J-PARC accelerator and on the test stand the ion source was shown to be capable of meeting the near-term, J-PARC RCS upgrade LINAC beam current requirement of ~60mA, 0.6 ms, 25 Hz for 1.44 MW of beam power on target.

4. The FNAL cesiated magnetron H^- ion source

Overall, the ion source runs very well and routinely produces ~60 mA H^- ion pulses, 0.2 ms in duration, with a 15 Hz repetition rate. Fig. 3 shows a simplified schematic and installation view of the FNAL ion source. FNAL had been using Magnetron ion sources to supply the LINAC with H^- ions since 1997. From then until 2012 Cockcroft-Walton (C-W) accelerators were used as the injector accelerator. During this time the magnetron sources had a lifetime of ~3 months. In 2012 the C-W injectors were replaced with a Radio Frequency Quadrupole (RFQ) accelerator. At the same time the magnetrons were changed to a design used by Brookhaven National Lab (BNL). The lifetime of the sources is now greater than 9 months with a ~99.8% availability as demonstrated during the last 9-month operational period [13].

Some of the current operational issues for the FNAL sources come in 3 categories: *functional, procedural and equipment*.

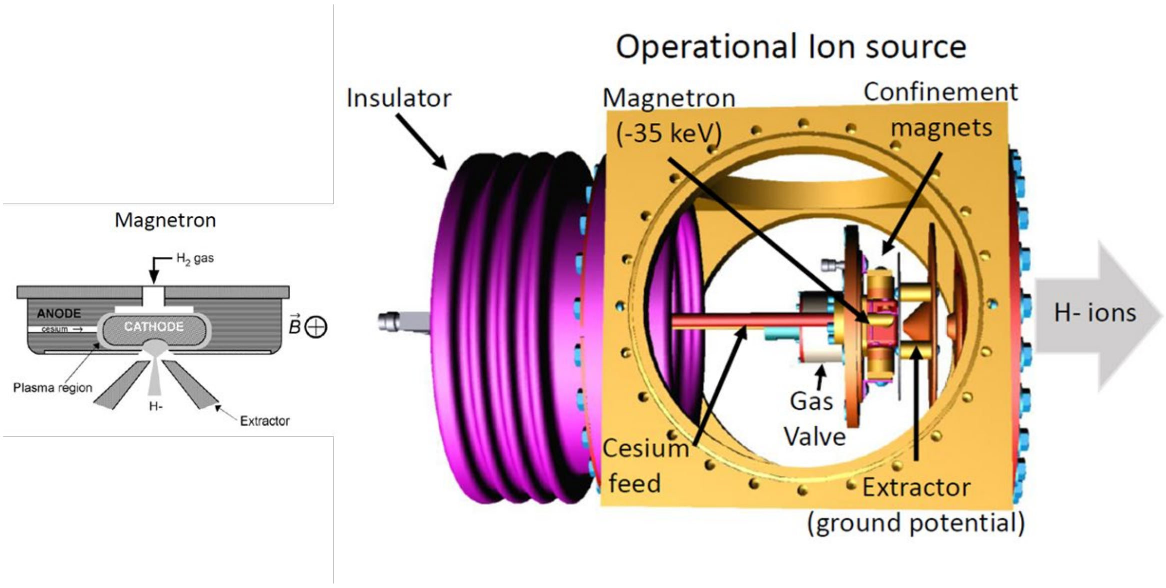


Figure 3. FNAL H^- ion source schematic (left) and actual installation (right).

The major issues are maintaining the required beam intensity and quality over the run cycle time of 9 months. We do have Proportional–Integral–Derivative (PID) loops to keep the gas pressure and cesium oven temperature mostly constant, but there is still frequent adjustment of source parameters to keep the sources running well. The major procedural issue is the annual ion source refurbishment and rebuild consistency. Finally, equipment issues include the arc pulser not terminating the end of the arc pulse when the source impedance is too high, inconsistent pulsed solenoid (electromagnetic) gas valves, and extractor pulser cables which fail twice per run on average.

The future of the FNAL complex will use the Proton Improvement Plan II (PIPII) super conducting LINAC. The front end of that accelerator was built as a test stand to test equipment that will be used in the final installation. The source used was a 10 mA DC H^- source (D-Pace) with a pulsed extractor. With a lifetime of around 300 hours, the source is not ideal for accelerator operations. FNAL have been studying a magnetron source and will soon be studying a Penning ion source to meet the initial PIP II parameters [14]. To date, the magnetron source seems capable of meeting the current and duty-factor requirements (~2mA, 550µs, 20 Hz in the LINAC), but beam quality studies still need to be performed.

5. The LANL surface converter H^- ion source

Over the past three decades at LANSCE, the negative ion beams supplied to our various user programs have been generated using the surface-converter negative ion source. The source now routinely produces ~16 mA H^- ion pulses, 0.84 ms in duration with a 120 Hz repetition rate, ~98.5% availability and ~4-week service period. Fig. 4 shows a side-view photograph of the interior of the source with the major components labeled. In the past several years and under high duty-factors of 5% and 10% (60/120 Hz x 840 µs), several issues with the converter ion source were observed and attempts made to resolve them. The issues included: (1) modest H^- current in range 12 – 14 mA (no electrons), (2) limited source lifetimes, i.e., 4 weeks or shorter with filaments failures, (3) long rise-time of the arc discharge (<180 µs) that reduces the usable H^- pulse length, (3) beam instability associated with frequent 80 kV arc downs (every few minutes), (4) larger-than-expected transverse, normalized, RMS emittances, > 0.2 π mm mrad, (5) 4 days of beam downtime for a source exchange, full Cs transfer to achieve production beam-intensity levels, (6) excessive high energy (voltage) droops over the beam pulse (~1-2 keV), (7) significant equipment failures due to numerous HV arc breakdowns, (8) low beam stability and low charge per pulse to all H^- user facilities.

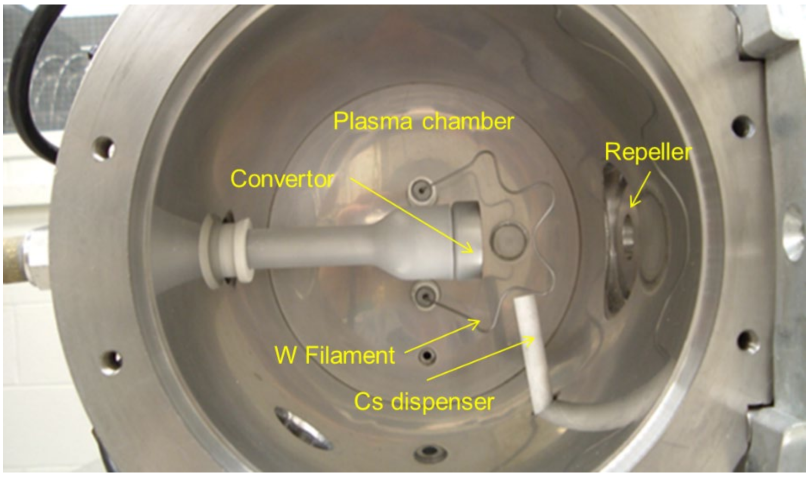


Figure 4. LANL surface conversion source.

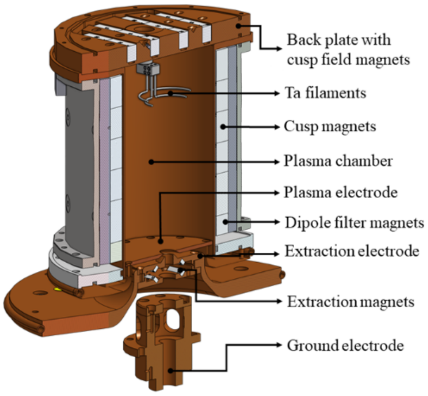
In recent beam production cycles, however, incremental *performance improvements* were achieved for the negative ion injector, linear accelerator, and proton storage ring including: (1) average production currents now range from 15 - 16.7 mA, (2) Extracted peak beam currents in the range 17 - 18.5 mA during beam development times, (3) demonstrated W-filament lifetimes of 5 weeks (DF=10%) and 6 weeks (DF=5%), (4) Improved H^- beam stability with 3-5 hours between 80 kV arc downs, (5) reduced high voltage droops now < 500V over the full macro pulse, (6) average current injected into PSR over <120 µA, (7) no major equipment failures due to reduced HV breakdowns.

Several critical *ion source preparation improvements* were also made that enhanced the negative ion source performance. These included: (1) improved converter-head cooling, (2) installation of a new 80 kV high voltage regulator, (3) improved converter electrode alignment, (4) improved processing of the Cs reservoir, valve cleaning and Cs loading procedures, (5) adoption of a lower vacuum leak rate of ion source vacuum assembly at processing stand and in the H^- dome, (6) implementing a new method of filament outgassing and preparation with monitoring outgassed molecules, (7) use of converter quartz insulation tube with rougher surfaces, and (8) careful HV column electrode assembly and using SF_6 gas in Plexiglas jacket.

Further improved beam performance was realized by employing a new ion source *operational tuning procedure*. This procedure was applied in recent beam production cycles and features:

1) Lower arc voltage 160 - 170 V, which reduces plasma sputtering, increases filament lifetime, and improves arc discharge rise time
2) Higher arc discharge currents of 40-55 A to increase the extracted H^- beam currents to the range of 16-18 mA
3) Lower Cs oven temperature <180 C, which reduces plasma sputtering of the hot filaments, increases filament lifetime, minimize number of HV breakdowns, but increases arc discharge rise time over 180 µsec
4) Convertor voltage peak centered at ~ -250 V: Peaking a source at lower voltage (up to -200 V) will lower extracted-beam transverse emittances thereby reducing spill along LINAC and beam lines
5) Optimized H_2 gas flow (in the range from 2 - 3 sccm): The right amount of injected gas will increase beam output, decrease arc time response, and reduce number of HV arcs.

Finally, to dramatically improve beam performance for the H^- users and overcome the modest output current limitation of our present H^- ion source, a collaboration between SNS-ORNL and LANSCE-LBNL to build and install an SNS RF negative ion source at LANSCE is in progress [15].



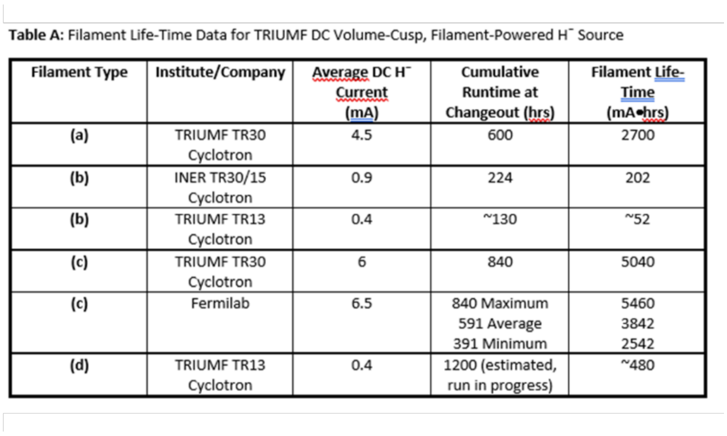


Table A: Filament Life-Time Data for TRIUMF DC Volume-Cusp, Filament-Powered H^- Source

Filament Type	**Institute/Company**	**Average DC H^- Current (mA)**	**Cumulative Runtime at Changeout (hrs)**	**Filament Life-Time (mA•hrs)**
(a)	TRIUMF TR30 Cyclotron	4.5	600	2700
(b)	INER TR30/15 Cyclotron	0.9	224	202
(b)	TRIUMF TR13 Cyclotron	0.4	~130	~52
(c)	TRIUMF TR30 Cyclotron	6	840	5040
(c)	Fermilab	6.5	840 Maximum 591 Average 391 Minimum	5460 3842 2542
(d)	TRIUMF TR13 Cyclotron	0.4	1200 (estimated, run in progress)	~480

Figure 5. The D-Pace (TRIUMF) filament-driven, multicusp source shown with the 4x semi-circular Tantalum filament (φ = 1.6 mm) structure (c). The table contains filament lifetime data for various structural filament types (a,b,c,d), see text. [21-27].

6. The D-Pace (TRIUMF) filament-driven, multicusp H^- Ion Source

D-Pace licensed the 15 mA TRIUMF Direct Current (DC), volume-cusp, filament-powered, H^- source in 2001 [16]. A cross sectional model of the source is shown in Fig. 5. This source technology is primarily used in three areas:

a) Commercial axial injection type cyclotrons for medical radioisotope production by way of companies/institutes such as IBA, SHI, THALES, ACSI, KAERI, INER [17]
b) Boron Neutron Capture Therapy (BNCT) applications for the case of tandem accelerators or cyclotrons in companies/institutes such as TAE, SHI, CNEA, KIRAMS, BINP [18,19]
c) National laboratories for various applications i.e., TRIUMF, Fermilab, KIRAMS, KAERI, CNEA, INER, BINP.

Since these sources are often used by end-clients in confidential business environments, it has been difficult to garner sustainability information that would be useful for the ion source community. For example, filament lifetime data, the key sustainability issue for the TRIUMF DC H^-/D^- source utilized in commercial and research environments is sparse. The authors of this paper are thankful for contributors [21-27] for the table in Fig. 5 containing lifetime data for the following filament configurations: (a) 1 Tungsten arch-shaped filament segment (φ = 2.4 mm), (b) 2 semi-circular Tantalum filament segments (φ = 2 mm), (c) 4 semi-circular Tantalum filament segments (φ = 1.6 mm), and (d) 1 pigtail Tungsten alloy filament segment (φ = 3 mm) [20]. Recent source improvements include implementing single machined Ta filament holder which was superior to earlier Elkonite structures which could fail after months of service [26]. Efforts to develop and RF driven version of this source are ongoing.

7. The CERN-LINAC-4 RF H^- ion source

The IS03b H^- source is shown in Fig. 6 and is the first element of CERN's new 160 MeV injector (LINAC-4) that started operation in September 2020. The ion source provides 35 mA H^- pulses of 0.8 ms duration at 0.83 Hz, and LINAC 4 delivers 0.6 ms, 27 mA pulses at 160 MeV which is sufficient to produce all CERN beams. To date the source has operated with >99.9% availability on LINAC-4 for ~6 months experiencing only minor preventive maintenance of the gas pulsing valve (see below). The design of all ion source components aims at utmost sustainability via systematic testing, preventive maintenance and identifying source components which could be potentially lifetime limiting. Three fully tested

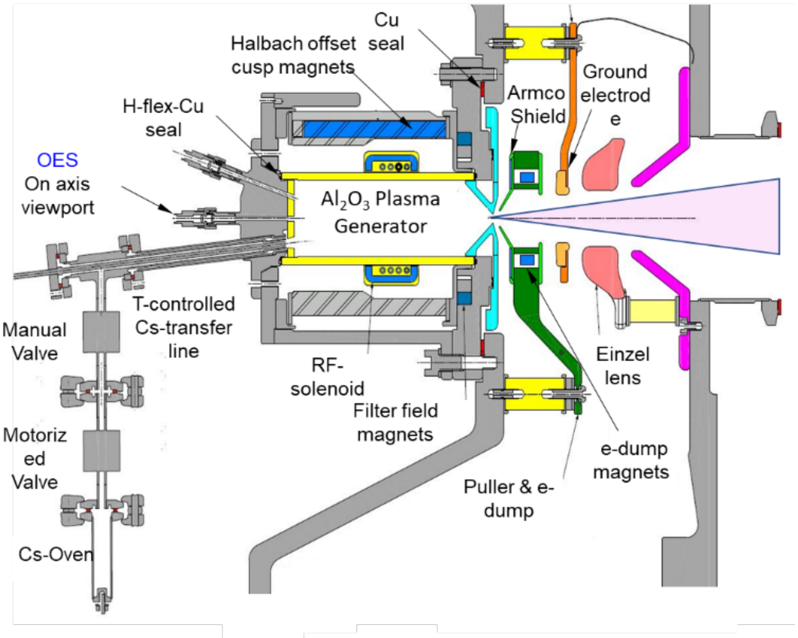


Figure 6. The CERN-LINAC-4 RF H^- ion source.

spare ion sources are ready to be installed in the event of operational source hardware failure, in addition the test stand's source front end can be used as a spare. HV-sparks induced damages are related to capacitive stored energy; therefore, the HV-system is designed to minimize HV-cable length, plasma and puller electrodes are connected to the secondary of standardized and stabilized 700 µs pulse generators equipped with protection resistors and current detection monitoring [28]. Currently, plasma- or puller- electrodes do not show signs of wear and their voltage stability is within the specified 1% [28].

Vacuum is an important aspect of the sustainability of all ion sources and, therefore minimizing the presence of impurities to protect the very reactive Cesium layer deposited on the Mo-plasma electrode is essential. Therefore, all components of the ion source and LEBT are UHV compatible featuring bakeable metallic seals eliminating the need for O-rings and their associated gas permeation issues. Dedicated Helicoflex / Cu seals surround the cylindric Al_2O_3 plasma chamber with Ti rings brazed on the ceramic to ensure tightness. The large Al_2O_3 main insulator is brazed, equipped with a bellows and employs Al seals which are made at CERN. And all other seals are standard con-flat Cu rings.

A 5-turn solenoid of silver-coated 4 mm diameter Cu-tube capacitively (for ignition) and inductively (after plasma formation) couples RF power into the ion source plasma. 3D printed epoxy spacers, vacuum molded around the solenoid are used to prevent arcing of the antenna structure by equalizing turn spacing and reducing the possibility of air ionization. Multicusp magnetic plasma confinement is well known to improve plasma densities in small laboratory plasmas for a given amount of input power. However, in our case, simulation and experiment showed that our external antenna inductive coupling is more than twice as efficient without cusp [29,30]. Therefore, the source is now operated without the cusp which halves the RF-power and avoids the e-loss lines that were visible on the inner surface of the ceramic plasma chamber.

Automated operations were necessary to adjust cesiation, hydrogen injection, RF pulse shape and frequency [31] to follow changes in the surface production yield from the source. A fail-safe control system ensures a constant, very low flux of cesium that stabilizes operational parameters while keeping the oven at low temperature (60°C). The source now operates under cesium loss compensation [30] and a simple RF-driven, H^- current regulation feedback control system ensures the required stability over time. Every beam interruption is recorded, its origin identified and attributed to sub-systems;

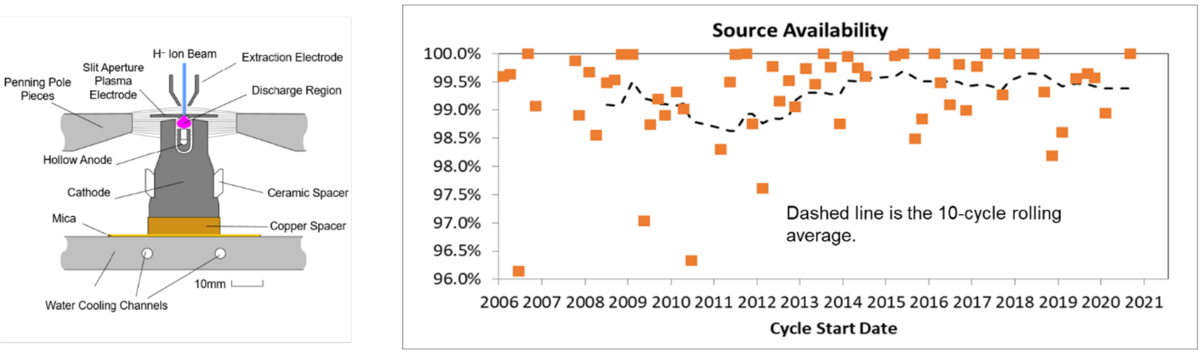


Figure 7. Schematic diagram of the ICIS H^- ion source and the 15-year source availability data.

the analysis of these failure statistics is the key to prioritize improvement. This led to studying insertion of a manual valve between the source and electromagnetic pulsed hydrogen valve, which is known to evolve and would occasionally fail, allowing the source to remain under vacuum during valve replacement. This would dramatically reduce the H_2 valve replacement time [32]. H^- pulse of 35 mA extracted from the source require typically 20 kW of RF-power while the RF system was tested up to 90 kW. Under cesium loss compensation the electron to ion ratio remains below 4, the co-extracted electrons current is below 150 mA while the e-dump was tested to 3A; these considerable operating margins will provide room for the improvement required to meet LINAC4's 45 mA out of the RFQ goal set by the High-Luminosity LHC project [33]. Preliminary test stand results from a new extraction system and an RFQ mask suggest that modified extraction optics may meet this requirement at similar duty-factor [34]. Beam sustainability (availability and reliability) are essential to respect the impressive investment of the 14000 physicists' experiments on CERN site.

8. The ISIS Penning H^- ion source

The ISIS Penning Surface Plasma Source, shown in Fig. 7, is a pulsed DC discharge surface plasma source, which produces 48-55 mA of H^- current pulsed at 50 Hz repetition rate [35]. The discharge pulse length is typically set to 700 µs (3.5 % plasma duty factor) and the extraction pulse length is modulated from 220 to 270 µs (1.1-1.35 % beam duty factor) to compensate for beam variations while injecting a constant charge per pulse into a rapid cycling synchrotron. The source lifetime varies between 5 and 40 days, with scheduled changes often taking place at 14-21 days and requiring a fleet of ten nominally identical sources to serve ISIS.

The main factor limiting the source lifetime is electrode sputtering by cesium ions and formation of macroscopic molybdenum debris electrical shorting the anode and cathode or causing a partial blockage of the outlet aperture. Most of the sputtering damage is believed to occur during the first 100-200 µs of the discharge pulse when so-called breakdown oscillations result in drastic fluctuations of the discharge voltage and current. The breakdown oscillations can be suppressed by improving the discharge power supply and its auxiliary circuits, which presumably leads to reduced sputtering damage [36]. The formation of the macroscopic flakes is thought to be related to the thermal cycling of the cathode and hydrogen embrittlement of the metal. The surface temperature of the cathode varies by approximately 100 C during each discharge pulse, which causes a strong local temperature gradient within the cathode material [37] and exposes it to the formation of stress layers. Maintaining a favorable cesium balance on the cathode surfaces is only possible in a certain temperature window, which prevents mitigating the flake formation by more aggressive cooling of the cathode.

Another sustainability issue of the ISIS Penning ion source is the gradual increase of the co-extracted electron current as the source ages with the fastest increase occurring in the first 5 days of operation. To counter-act the electron current drift and to avoid operating the extraction power supply at its limit the source is tuned throughout its lifetime by very slowly adjusting the cesium oven temperature, hydrogen flow rate and air cooling.

The ISIS Penning source availability for each user cycle for the last 15 years is shown in Fig. 7. The dashed black line is a 10-cycle rolling average. The average source availability for that period was 99.3%. As the ISIS ion source is fundamentally lifetime-limited by electrode damage and requires a specific operational window to run trouble-free, the ISIS Low Energy Beams Group has started a project to replace the Penning source with a cesium-free, RF ion source aiming to produce 28-30 mA H^- pulses. The reduction of the beam current is enabled by simultaneous improvements to the LEBT and matching of the beam into the drift tube linac by constructing a new medium energy beam transport section. The commissioning progress of the RF ion source is reported elsewhere in these proceedings [38]. The long-term (> 10 years) plan of ISIS is to upgrade the existing facility into a MW-level spallation neutron source. The requirements for the ion source depend on the accelerator design, which has not been completed. It is expected that the injector will need to deliver 57-120 mA of H^- out of the RFQ in 600–1000 μs pulses at 50 Hz with 0.15-0.25 π mm mrad rms-emittance. Both, the Penning source and the (cesiated) RF source are being considered for now.

9. The BNL Magnetron H^- ion source

Recently the BNL-RHIC-LINAC injector was upgraded to include 3 ion sources (2 magnetron and 1 optically polarized source). In normal accelerator operation an H^- magnetron ion source routinely produces ~120 mA H^- ion pulses, 0.65 ms in duration with a 7 Hz repetition rate for ~3-month service periods with excellent availability achieved after the upgrade [39]. In this configuration, one source delivers beam while the others remain in standby should a source fail minimizing injector downtime. The recent injector upgrade involved several sustainability improvements to the ion source systems which were incorporated into the last BNL production run:

a) Improved heating system for the source and Cs supply to ensure steady Cs flow and minimum consumption while keeping the source body 160-180C range (unable to be heated by arc power alone)
b) Improved power supplies reducing footprint and achieving better arc stability with reduced noise.
c) Improved ceramic supports for the ion optics: reducing Cs and W deposition on insulators and consequent spark frequencies.
d) Significant improvements were also made to the pulsed gas valve

Due to the high gas and pulsed power efficiency (~100mA/kW) of this source, work is ongoing to increase the pulse length to 1 ms to support the BNL isotope program with encouraging initial results. Also encouraging is the low co-extracted electron current and low average operating power of the source (e.g. ~100W at 50Hz, 1 ms) [40].

Source Function	SNS	J-PARC	FNAL	LANSCE	D-Pace	CERN	ISIS	Impact Score
Beam persistence (long-term drifts in current, emittance)	x		x					**2**
Beam Intensity (beam current, transmission and margin)	x			x		x		**3**
Beam stability (arc events, pulse ignition)			x	x			x	**3**
Intrinsic Source Lifetime (cathodes, filaments and antenna)			x	x	x		x	**4**
Electron management	x					x	x	**3**
Build/source consistency	x	x	x					**3**

Cs System	SNS	J-PARC	FNAL	LANSCE	D-Pace	CERN	ISIS	Impact Score
Cs system	x		x	x				**3**
RF system	x	x						**2**
Gas feed system			x			x		**2**
DC power sources	x							**1**
Pulsed power sources			x					**1**
Cathode / filament structure			x	x	x		x	**4**
Ion /electron extraction structure	x						x	**2**

Table I. Operational & anticipated issues reported: grouped by source function and components.

10. Summary and Outlook

Overall, H$^-$ ion sources for accelerators operate very well with most having an availability > 99% with service cycles ranging from a few weeks to greater than 9 months. The high availabilities have resulted from numerous and continuous source improvements and judicious selection of ion source service periods. These efforts have enabled decades of high-impact science which have advanced the frontier of human knowledge considerably in many areas. Now, many of these facilities are looking toward upgrade projects which will require higher beam current / duty-factors and most seem well-positioned to meet their near-term upgrade goals.

Ion source experts from each facility also shared their 'behind the scenes' concerns and detailed recent improvements which were summarized in the previous sections. Table I, provides a quick reference to issues reported which are grouped by source function and source component to help identify key and common areas of concern. Not surprisingly, issues associated with filaments and cathodes were still most notable in the survey results with most of these facilities now actively pursuing the development alternative RF sources which have simultaneous high-availability, long-service cycles and proven scalability to higher duty-factors. Concerns about co-extracted electrons and Cs management were also clearly voiced in the survey.

Acknowledgements

A special thank you to Anatoli Zelenski who contributed information about the BNL ion source on short notice and Kiersten Ruisard for serving as a technical reviewer on this and other publications. This manuscript has been co-authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). This research was supported by the DOE Office of

Science, Basic Energy Science, Scientific User Facilities. The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan)

References

[1] Vladimir Shiltsev, "Particle beams behind physics discoveries", Physics Today 73, Issue 4, 32 (2020)
[2] D. Faircloth and S. Lawie, "An overview of negative ion sources for accelerators", New J. Phys. 20, 025007 (2018)
[3] M.P. Stockli, R.F. Welton, and B.X. Han, "Record productions establish RF-driven sources as the standard for generating high-duty-factor, high-current H^- beams for accelerators", in Rev. Sci. Instrum. 89, 052202 (2018).
[4] B. Han, M. Stockli, R. Welton, C. Piller, S. Murray Jr., T. Pennisi, C. Stinson, and S. Kim, "H-ion source operational performance and latest development at the Spallation Neutron Source", these proceedings.
[5] R. Welton, V. Dudnikov, B. Han, S. Murray, T. Pennisi, C. Pillar, M. Santana, M. Stockli, and M. Turvey, "Improvements to the internal and external antenna H^- ion sorces at the SNS", Rev. Sci. Instrum. 85, 02B135 (2014)
[6] Cherokee Porcelain Enamel Corporation, 2717 Independence Lane, Knoxville, TN 37914, USA.
[7] R. F. Welton, M. P. Stockli, B. X. Han, S. N. Murray, T. R. Pennisi, C. Stinson, A. Aleksandrov, C. Piller, Y. Kang, O. Tarvainen,, "H^- ion source research and development at the Oak Ridge National Laboratory" in AIP Conf. Proc. 2373, 070004 (2021).
[8] A. Ueno, "Cesiated surface H^- ion source: optimization studies", New J. Phys. 19 015004 (2017)
[9] T. Shibata, K. Ohkoshi, K. Shinto, K. Nanmo, K. Ikegami and H. Oguri, "Emittance measurement of J-PARC RF ion source after 5-month continuous operation", these procedings
[10] A. Ueno, K. Ohkoshi, K. Ikegami, A. Takagi and H. Oguri, "Emittance Improvements of cesiated RF-driven H^- ion source to enable 60 mA operation of high-energy and high-intensity LINACs by plasma impurity controls", AIP Conf. Proc. 1869, 030011 (2017).
[11] A. Ueno, K. Ohkoshi, K. Ikegami and H. Oguri, "Impurities reduction conditioning to Recover Best Beam Quality of J-PARC Cesiated RF-Driven H^- Ion Source with New Parts Exposed to Plasma", these procedings.
[12] A. Ueno, "J-PARC H^- ion source and space-charge neutralized LEBT for 100-mA high energy and high duty factor LINACs", Rev. Sci. Instrum. 91, 033312 (2020)
[13] D. Bollinger, "Installation and commissioning of the new Fermi National Accelerator Laboratory H^- Magnetron", Rev. Sci. Instrum. 85, 02B121 (2014)
[14] S. Holmes, P. Derwent, V. Lebedev, S. Mishra, D. Mitchell, V. Yakovlev, "PIP-II status and stratagy", 6th Internaitonal Particle Accelerator Conference, Richmond, VA, USA, THPF116 (2015)
[15] M. Stockli, B. Han, M. Clemmer, S. Cousineau, A. Justice, Y. Kang, S. Murray Jr., T. Pennisi, C. Piller, C. Stinson, R. Welton, I. Draganic, Y. Batygin, R. Garnett, D. Kleinjan, J. Medina, J. Montross, G. Rouleau, V. Dudnikov, "Upgrading the LANSCE Accelerator with a SNS RF-driven H^- Ion Source", Review Scientific Instruments 91, 013321(2020)
[16] T. Kuo et al., "On the development of a 15 mA direct current H^- multicusp source", Rev. Sci. Instrum 67 1314 (1996)
[17] M. Dehnel et al. "An ion source upgrade for an axial injection based commercial cyclotron", NIMB, 241, Issues 1-4, 896 (2005)
[18] J. Ma, "Tandem electrostatic accelerators for BNCT", 13th Int'l. Conf. on App. of Accel. in

Research and Industry, Denton, 201 (1994)
[19] T. Mitsumoto et al, “Cyclotron-based neutron source for BNCT”, AIP Conf. Proc. Vol. 1525 (1), 319 (2013)
[20] D. Prevost et al. “New ion source filament for prolonged ion source operation on a medical cyclotron”, Instruments 3, 5 (2019)
[21] B. Milton et al. “Commissioning and first operation of a 500 μA, 30 MeV, H^- cyclotron: The TR30”, Particle Accelerator Conference (PAC), San Francisco, 67 (1991)
[22] T. Duh, INER, Private Communication, August 2021.
[23] D. Prevost, TRIUMF, Private Communication, August 2021.
[24] G. Cojocaru and J. Lofvendahl, “Operational experience at the intensity limit in compact cyclotrons”, Proc. of the 20th Int’l Conf. on Cyclotrons and their Applications, Vancouver, 432, (2013)
[25] L.R. Prost, Fermilab, Private Communication, July 2021.
[26] M. Bacal, K. Maeshiro, S. Masaki, M. Wada, “Performance of tantalum as plasma electrode material in negative hydrogen ion sources”, Plasma Sources Sci. Technol. 30, 075014 (2021)
[27] T. Stewart, D-Pace, Private Communication, July 2021.
[28] D. Aguglia, “Design of a System of High Voltage Pulsed Power Converters for CERN’s Linac4 H^- Ion Source”, CERN-ACC-2014-0345 (2014).
[29] S. Briefi, S. Mattei, J. Lettry, and U. Fantz, “Influence of the cusp field on the plasma parameters of the Linac4 H^- ion source”, NIBS-2016, Oxford, NIBS Oxford, AIP conference proceedings 1869, 030016 (2016)
[30] J. Lettry, S. Bertolo, U. Fantz, R. Guida, K. Kapusniak, F. Di Lorenzo, C. Machado, C. Mastrostefano, T. Minea, M. O’Neil, H. Neupert, D. Noll, D. Steyaert, and N. Thaus, Linac4 $H-$ source R&D: “Cusp free ICP and magnetron discharge”, AIP Conference Proceedings 2052, 050008 (2018)
[31] G. Voulgarakis, J. Lettry, B. Lefort and V. J. Correia Costa, “Autopilot regulation for the Linac4 H^- Ion source”, NIBS-2016, Oxford, AIP conference proceedings 1869, 030012 (2016)
[32] C. Mastrostefano, S. Bertolo, M. O’Neil and F. di Lorenzo, CERN, Private Comminucaiton, August 2021
[33] High-Luminosity LHC | CERN (home.cern)
[34] F. Wenander, “CERN hadron sources: status and innovation overview”, these proceedings
[35] R. Sidlow, P. Barratt, A. Letchford, M. Perkins and C. Planner, Proc., “Operational experience of penning H^- ion sources at ISIS”, EPAC'96, THP084L, 1525, (1996), jacow.org
[36] O. Tarvainen, R. Abel, S. Lawrie, D. Faircloth, J. Macgregor, T. Sarmento and T. Wood, “Breakdown oscillations of the ISIS $H-$ Penning ion-source hydrogen–cesium discharge”, IEEE Transactions on Plasma Science, 47, 11, (2019).
[37] D. Faircloth, S. Lawrie, H. Pereira Da Costa, and V. Dudnikov, “Operational and theoretical temperature considerations in a Penning surface plasma source”, AIP Conf. Proc. 1655, 030013 (2015).
[38] S. R. Lawrie, “External RF-coil H^- ion source plasma commissioning”, in these proceedings.
[39] A. Zelenski, G. Atoian, T. Lehn, D. Raparia and J. Ritter, “High-intensity polarized and un-polarized sources and injector developments at BNL linac”, AIP Conference Proceedings 2373, 070003 (2021)
[40] A. Zelenski, a private communication 2021