

PROTON AND ION SOURCES FOR HIGH INTENSITY ACCELERATORS

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Abstract

Future high intensity ion accelerators, including the Spallation Neutron Source (SNS), the European Spallation Source (ESS), the Superconducting Proton Linac (SPL) etc, will require high current and high duty factor sources for protons and negative hydrogen ions. In order to achieve these goals, a comparison of the Electron Cyclotron Resonance, radio-frequency and Penning ion sources, among others, will be made. For each of these source types, the present operational sources will be compared to the state-of-the-art research devices with special attention given to reliability and availability. Finally, the future research and development aims will be discussed.

INTRODUCTION

Accelerators capable of delivering high average power beams (1 MW or more) have many applications. For ion sources, the most demanding projects use high duty factor linear accelerators accelerating the beam to final energies in the GeV range. In cases where the ion beam must be delivered in short pulses, a favoured technique requires charge-exchange injection into a compression ring, requiring the linac to accelerate a negative ion beam. A summary of the latest source specifications for accelerator projects are given in Table 1

The mixture of high current and high duty factors is a challenge for source engineers. The high beam powers require stable beam parameters, often with small emittances and delivered with very high reliability.

For high power proton beams, the Electron Cyclotron Resonance Ion Source (ECRIS) now deliver CW high beam currents (above 100 mA), with a high availability. Negative Hydrogen (H-) sources presently deliver high currents or high duty factors. However, average H-currents are presently below 10mA for accelerator use.

In this article, the different types of ion source promising high average currents will be compared, and the future plans discussed.

All emittances quoted in this report are 1 rms normalised. In the common case that a 90% emittance is

quoted, the conversion of $\epsilon_{90\%} = 4.6 \times \epsilon_{rms}$ is used.

PROTON SOURCES - ECR

For CW linear accelerators, the requirement for high currents and high reliability makes the Electron Cyclotron Resonance (ECR) proton source the only presently available choice. With a production efficiency of more than 100 mA/kW and no cathode, highly reliable 2.45 GHz sources have been demonstrated at CEA Saclay (SILHI) [7], INFN, Catania (TRIPS) [8] and at LANL for the LEDA study [10]. In all three cases, the average current and beam brightness required for the IPHI, TRASCO and LEDA accelerators have been achieved. The long lifetime has not been fully demonstrated, mostly due to the lack of an operational machine to which the beam can be delivered. However, all sources have demonstrated more than 100 hrs of operation without failure, with down-time less than 0.2% at CEA and INFN. At CEA the boron nitride window nearest the plasma would probably need changing every 6 months, a requirement probably common to all three sources. The beam proton fraction from the source is better than 80%.

Studies over the last few years have improved the sources and beam transport with the following:

1. Highly optimised multi-electrode extraction systems, allowing production of low emittance beams with minimal losses (especially in the high field extraction region).
2. Minimisation of emittance growth in the low energy beam transport, with controlled space-charge compensation by residual gas.
3. Highly electrical-noise-resistant controls near and on the source platform, with auto-restart procedures to minimise down-time when high voltage sparking occurs.
4. Demonstration that the optimal proton production occurs with the ECR surface on the surface of the boron- or aluminium-nitride windows, or the rear of the plasma electrode.

Furthermore, CEA Saclay have produced a 130mA D⁺ beam in pulsed mode (2ms, 1Hz) [7], the pulse length

Table 1. Ion Source parameters required for selected high power projects. † 1rms, normalised, in mm.mrad.

	Ion	Current (mA)	Pulse Length (ms)	Rep-Rate (Hz)	Duty Factor	Average Current (mA)	Emittance†
IPHI [1]	p+	100	CW	CW	100%	100	
TRASCO [2]	p+	30	CW	CW	100%	30	
SPL [3]	H-	30	2.8	50	14.0%	4.2	0.25
ESS [4]	H-	65	1.2	50	6.0%	3.9	0.3
SNS [5]	H-	50	1	60	6.0%	3	0.2
JKJ Project [6]	H-	30	0.5	50	2.50%	0.75	

being limited to avoid activating the source and beam line. Both institutes have designed permanent magnet sources, which are optimised in the CEA case for a lower intensity deuteron beam (5mA D⁺). INFN's design is aimed at producing a proton beam with no mains power on the high voltage platform (using an isolated 2.45GHz transfer and isolated gas tubing), but still with equal performance to the TRIPS source [9].

NEGATIVE HYDROGEN IONS (H⁻)

Beams of negative hydrogen ions are favoured for many accelerator applications, in particular because of the possibility to use charge-exchange injection into synchrotrons, or extraction from cyclotrons.

The operating principles of the different volume and surface sources are well explained by Welton[11], Dudnikov[12], and Sherman and Rouleau[13], while excellent reviews of the upgrade history have been reported by Peters [14]. More in depth discussion can be found in books by Forrester[15] and Zang [16].

Recently, Dudnikov[17] has proposed that the volume production method may not contribute a significant fraction to most H⁻ sources, and that in well optimised sources the principle production method is from the source electrode surfaces.

Filament Multi-Cusp H⁻ Sources

Using a multi-cusp magnetic arrangement, a plasma can be produced by a discharge from a cathode or a filament to the chamber wall. The H⁻ ions are either produced both from the chamber surfaces or in the plasma volume. Most sources report the H⁻ current increasing proportional to the discharge power.

The highest performance accelerator source of this type was built by IAP, Frankfurt [20] in anticipation of the European Spallation Source project. Running at the same 6% duty factor as the SNS project source, this filament multi-cusp source has demonstrated higher average currents (120mA pulsed, leading to an average current of 7.2mA). This current is achieved with cesium seeding of the plasma by an oven, which delivers cesium into the outlet aperture region of the source. The controlled release of the cesium is required every 10–18 hours. The H⁻ output current has been demonstrated to vary almost linearly with arc discharge power up to 50 kW. No saturation of this has yet been seen, so higher currents appear not to be limited by fundamental processes in this source, but rather the arc power supply and the cathode lifetime. This source has not been in use since 1998 and there are presently no plans to put it back into operation.

Full CW operation, without cesium, is achieved for the cyclotrons at TRIUMF[21] and the University of Jyväskylä, Finland[22], albeit with 6 and 1.5 mA respectively. A pulsed low duty factor source is also in operation for the Joint KEK JAERI (JKJ) project, producing 38mA of H⁻ at less than 1% duty factor.

The production efficiency of the non cesiated sources is 1.1-1.4 mA/kW, while the pulsed IAP source, with cesium, has a factor 2 greater efficiency.

Lifetimes of the sources range from 200 to 600 hrs due to erosion of the filaments by ions falling through the cathode sheath potential. The JKJ source uses LaB₆ cathodes [23], but its lifetime is less than the tungsten and filament driven sources. The IAP source uses multiple filaments of 1.8mm diameter tungsten wire, and has been run for 190 hours operation at 6% duty factor. The tungsten erosion suggests that the lifetime of the source would be approximately 14 days before the filaments require changing.

At LANSCE, the filament multi-cusp source includes a cesium coated molybdenum converter, to produce H⁻ ions by surface conversion. 18 mA of H⁻ ions are extracted radially into an emittance of 0.13 mm.mrad at 12% duty factor. The source tungsten filaments have to be replaced every 28 days [24].

To upgrade the LANSCE source beam current to 40 mA, LBNL developed a surface converter source using six filaments and an 8 - 10 kW pulsed discharge. Results show saturation in the H⁻ current for discharge powers greater than 8 kW, suggesting that more discharge power must be accompanied by a larger converter surface. The emittance of the beam (0.35 mm.mrad) is larger than specifications, with simulation suggesting this may be due to two modes of H⁻ production, i.e. surface and volume. As the surface produced ion are created on a surface negative biased by ~250V with respect to the rest of the source, these two distinct components of H⁻ ions form their own phase-space after extraction, causing a larger emittance[24]. An improvement of the emittance to 0.13 mm.mrad is required before the source will be installed on the accelerator.

RF Driven Multi-Cusp H⁻ Sources

RF sources use a few turn helical or plane antenna to drive a plasma confined in a multi-cusp magnet arrangement. Driven at low RF frequencies – 2MHz is the most common – a dense plasma is formed which can contain a high abundance of excited hydrogen molecules. Towards the extraction area, a filter dipole removes the high energy electrons, and conditions are optimized for the production of negative ions. A collar around this low electron temperature region (containing cesium on the SNS source) increases the H⁻ yield.

At DESY, Germany; LBNL, California (for SNS) and Seoul National University (SNU) development of RF sources has continued for the production of low to full duty factor beams.

The lifetime of RF sources is limited by sputtering of the antenna surface, as it is exposed to the plasma. For several years, different metal materials were tried for the conducting antenna (which typically is hollow for water cooling) and different surface treatments with insulating materials. The most promising, using less than a milli-

meter of porcelain, produced average operational lifetimes of 1000 hours at DESY.

Although in the later part of the 1990's the SNS and DESY source designs were very similar, DESY has since made a break-through in reliability, by isolating the antenna from the plasma with a thick Al_2O_3 cylinder [26]. This external antenna source has now delivered 40mA, 150us length pulses of H- at 8 Hz for 25,000 hours, without cesium enhancement, using an RF power of 20kW. A thin film of metal appears on the inside of the ceramic cylinder, which does not reduce the performance of the source. The performance of the source is presently limited for current, pulse length and duty factor by the RF power supply.

The SNS source also uses up to 50 kW, 2 MHz RF coupled to the plasma with a porcelain enamel coated antenna. Continuous, low power RF at 13.56 MHz is supplied to facilitate ignition of the plasma. With cesium enhancement – provided by cesium chromate inside a heated collar – the source has produced 50mA beams with a duty factor of 6%, but is still in testing stage to produce this beam in an operational manner and with high reliability [5]. Without cesium, the source has produced 15mA of H-. The source is presently providing beams for the commissioning of the SNS RFQ, with operation at low duty factor from 2006. In the future, a design with an external antenna will be tried for high duty factors.

The source designed by Seoul University uses RF at 13.56 MHz delivered with an antenna behind a quartz or alumina window, allowing the antenna to be completely separated from the plasma. Used in CW operation, the source manages to deliver 0.2 mA of H- at 20 kV with no cesium. Previously higher currents were claimed[25] but measurements appear not to have fully suppressed the electron current.

H- Production efficiencies are highly variable with values of 2, 1 and 0.13 mA/kW for the DESY, SNS and SNU sources, suggesting that the configurations of the SNU and even SNS source could still be improved.

The variation of source performance with frequencies in the range from 1.65 to 8 MHz, was recently investigated at DESY [14]. The multi-cusp field configuration was kept constant, but the number of antenna windings was varied, using 6.5, 20 and 40 turns. The results are consistent with 2MHz and 6.5 windings providing the highest ion current. In the future, measurements will be made of the H- ion distribution in the plasma using the photo-detachment method.

Magnetron H- Source

Magnetron ion sources consist of a central cathode surrounded by an anode, which is immersed in a magnetic field along the cathode axis. The negative ions are produced from the cesiated cathode surface, and are accelerated through the cathode sheath potential. Charge exchange with neutral hydrogen in the plasma can lead production of a lower energy component of H- ions in the plasma, which lead to a larger beam emittance.

Magnetrons are used for H- production of beams with 0.5% duty factor or less at Argonne, Brookhaven, and Fermilab in the US, and at DESY, Germany. Between them the magnetron has more than 80 years operational experience. In all cases the magnetron sources were able to satisfy the requirements of the accelerators, and in most cases ran at the space-charge limit for extraction. All sources manage to provide beams for 6-9 months per year before requiring dismounting and cleaning, usually being shutdown rather than failing. Failure of the source is usually attributed to:

1. Build up of Cesium Hydride near the Cs inlet, or on the pulsed gas valves.
2. Flaking of the cathode material, either shorting the anode and cathode, or blocking the source outlet.
3. Cesium oven heater failure.
4. Extraction sparking, possibly caused by cesium leakage.
5. Pitting of the cathode surface.
6. Contamination.

It is not clear if higher duty factors would significantly increase these failure rates. If higher duty factors increase the cesium consumption, this may decrease the time between these failure modes.

All four source examples use an extraction voltage of 35kV or less, so the higher field gaps required for future accelerators may be an issue. Although extraction through a slit aperture is common, Brookhaven has used a circular aperture since 1989, and this has increased the H- production efficiency from 6.7 to 67 mA/kW (although it presently runs at 36 mA/kW). In today's configuration, the source uses only 7.8W average power and no cooling is required [18]. To increase the duty factor (by a factor 10 or more) would have implications not only for the heat load, but for the pulsed gas injection and the cesium coverage of the cathode.

Presently, the cesium coverage is probably maintained by condensation during the off cycle, while the atoms are sputtered away by incoming Cs^+ ions during the discharge. A porous cathode could allow cesium to seep through the cathode body to the surface, as demonstrated by Alessi *et al* in 1984 [19].

However, there is presently little active research on increasing the duty factor magnetrons.

Penning H- Source

The Penning H- Ion source uses a discharge with a hollow cylindrical anode capped with cathodes at each end, along the magnetic field. Extraction of the ions is through a slit in the anode. As for magnetrons, a cesium layer on the cathode is bombarded by H^+ ions and can emit H- ions. In contrast to the magnetron source, these ions are not directly aimed at the extraction aperture, therefore the additional electron must be charge exchanged to a neutral H atom which may then be extracted. Therefore, the energy distribution of the H- ions is from the plasma and without a direct contribution

from the cathode surface, which results in a lower emittance beam when compared to magnetron sources.

Existing sources running with high currents and medium to full duty factors are used at ISIS, Rutherford (35mA, 1%) [27] and a CW prototype source for medical beams (8mA, 100%) [28]. The ISIS penning source is based on a Los Alamos design, and is able to make runs of 50 days at 1% duty factor before the source is changed. The INP medical source runs during working hours for 3 weeks before more cesium must be added, equating to approximately 150 hours.

Penning sources with slit extraction have a negative ion production efficiency (H- current per unit discharge power) of 8 – 12 mA/kW, which primarily heats the small surface area of the cathode and anode. Extending the performance of the to higher duty factors with high currents, involves solving three main issues: Reducing the power per unit area incident on the source electrodes; sufficiently cooling the electrodes; and maintaining a coating of cesium on the cathodes.

At LANL, sources were designed and constructed applying plasma scaling laws and increasing two of the source dimensions by a factor 4 (the 4X source), which reduced the cathode power load from 16.7 to 2.24 kW/cm², while increasing the H- current from 160 to 250 mA [29] and [30].

The emittance product $\epsilon_x \epsilon_y$ increased by a factor 4, but the increase was not distributed to the x and y emittances with the same ratio as the increase in outlet slit apertures, with the y emittance being slightly larger than the value demanded for most high power accelerators. It is further suggested that this 4X source could run at 5% duty factor

and 105mA H- current, while keeping the source lifetime to about 2 months operation. In tests, the discharge was successfully maintained at 6% duty factor without extraction. Ion current measurements with a circular aperture result in an appreciable decrease in the average current density

Rutherford have available a full development rig, and hope in the near future to improve the source cooling and upgrade the power supplies to provide 1.2 or 2.5 ms pulses with a higher extraction voltage. This development is pursued within an EU Framework 6 programme[31].

LNAL developed an 8X source with hot water cooling of the cathode and anode close to the discharge surfaces, based on the same scaling as the 4X source. Initial pulsed operation is reported in [32], however full CW operation was never achieved due to funding limitations.

ECR H- Source

With the success of CW proton beam sources using 2.45 GHz ECR plasma heating, development of these sources for H- production of great interest. With dense plasma available at lower input powers, highly reliability for CW beams may be attained.

CEA Saclay[7] (1.4mA, 2% duty factor), ANL (4-5mA, CW[33]) and TRIUMF (2mA, CW[34]) have all produced beams. CEA and ANL both used 2 solenoid field configurations, while TRIUMF used a multi-cusp arrangement with some magnets inverted to produce a magnetic filter, and reached a production efficiency of 4 mA/kW. This multi-cusp source has run continuously for 1 month with only vacuum gauge failure.

CERN continues to test the multi-cusp field arrangement

Table 2. Parameters of selected sources. Op: Operational on an accelerator. a) Average over pulse length and time average current values; b) Radial source with converter; c) Axial source with converter not yet in operation, d) 20mA available at higher discharge power, e) 1rms normalised in mm.mrad, f) Estimated from optical measurements [20].

	Op	Type	Ion	Current ^a (mA)	Duty Factor	Discharge Power (kW)	Emittance ^e	Cesium (mg/day)	Lifetime (hrs)
CEA		2.45GHz ECR	p+	130	CW	0.8	0.15	N/A	336
LEDA		2.45GHz ECR	p+	117	CW	0.8	0.2	N/A	168
TRIPS		2.45GHz ECR	p+	60	CW	1.0	0.18	N/A	142
IAP		Arc Multi-Cusp	H-	120 / 7.2	6.0%	47.5	0.07 ^f	50	190
TRIUMF	✓	Arc Multi-cusp	H-	6 ^d	CW	5.0	0.16, 0.16	-	600
Jyväskylä	✓	Arc Multi-cusp	H-	1.5	CW	1.1		-	200
JKJ		Arc Multi-cusp	H-	38 / 0.34	0.90%	35	0.1	-	>100
LANSCe	✓	Filament Multi-Cusp ^b	H-	18 / 2.2	12%		0.13	110	700
LANSCe		Filament Multi-Cusp ^c	H-	40 / 4.8	12%	10	0.35		
SNS		RF Multi-cusp - 2MHz	H-	50 / 4	7.8%	50	0.17	<<1	~100
SNU		RF Multi-Cusp - 13.56 MHz	H-	0.2	CW	1.5		-	
DESY	✓	RF Multi-cusp 2 MHz	H-	40 / 0.025	0.05%	20	0.18, 0.16	-	25000
BNL	✓	Magnetron	H-	90 / 0.48	0.53%	2.5	0.27, 0.27	12	4000
INP		Penning	H-	8	CW	0.63	0.3	40	140
ISIS	✓	Penning	H-	35 / 0.35	1.00%	4.0	0.12, 0.17	0.1	1200
LANL		Penning - 1X - Slit	H-	160 / 0.8	0.50%	18	0.17		
LANL		Penning - 4X - Slit	H-	170 / 0.9	0.50%	19.8	0.29		

and couples the microwaves with an antenna. The scaling of the ion current with microwave power to higher power levels, and the frequency scaling are yet to be made.

Summary

Direct current proton sources using 2.45GHz ECR plasma heating, delivering stable beams with high availability and small emittances are now available as injectors for accelerators, with proton currents greater than 100 mA, but have not yet ran in an operational regime of several months due to the lack of a beam user.

The same beam parameters for H- ion sources are not yet realised. DC beams (and pulsed average currents) up to 8mA are delivered from filament discharge multi-cusp and Penning sources, but with operational lifetimes of 100 to 600 hours. Although RF multi-cusp sources with an external antenna have extremely long lifetimes at low-duty cycles, the SNS RF source at 8% duty factor and an internal antenna is still limited in the 100 hour's range. The implementation of an external antenna at a high duty factor is eagerly awaited. The surface plasma sources (Penning and Magnetron) still require development to achieve a few percent duty factor at high currents, with a few months between maintenance. The high production efficiency of the BNL source should probably be further investigated to high repetition rates.

Research in most of these areas is highly active due to the construction of SNS and the physics potential of high power beams.

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