H- Ion Source Requirements for the HINS R&D Program

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Objectives of the HINS R&D Program are summarized in Beams Document 2986.
http://beamdocs.fnal.gov/DocDB/0029/002986/002/HINS_Goals_Statement.doc

HINS operation beam will begin with protons, since a suitable H- ion source is not initially available. Many of the stated goals are achievable with a proton beam, but certain key objectives are possible only with H- ions.

HINS development is ultimately directed toward a high energy linac required to provide H- ions for multi-turn injection into a synchrotron. Space charge neutralization, different for proton and H- beams and particularly influential at low energies, can strongly affect beam quality and therefore machine performance. It is important to quantify HINS beam quality in the presence of this effect. Once superconducting spoke cavities are incorporated into HINS, cleanliness for the protection of the cavity surfaces is imperative; especially in this environment, beam diagnostics based on neutralization of H- ions are the preferred option as demonstrated at SNS. To these ends, an H- ion source is integral to the objectives of the HINS program.

The accelerated beam current, pulse length, and repetition rate supported by the HINS RF power system suggest an ion source with a capability approximately half that expected of the 6% duty cycle SNS ion source. This performance is far beyond that of any H- source available at Fermilab today (see Appendix 1) and beyond that required even for a Project X ion source. Important HINS objectives can be achieved with a source of considerably relaxed specifications.

Table 1 outlines specifications of a Project X H- ion source, an acceptable initial HINS H- source, and, for comparison, of the operational H- source serving the Fermilab linac.

The objective of H- ion source work for HINS shall be to deliver, at the earliest possible date, a source and accelerating column meeting the initial HINS specifications and physically compatible with the LEBT that serves the HINS proton source. The target date for delivery of this source shall be early 2009.

The initial approach shall be to pursue a source of the modified magnetron design. This approach shall be reconsidered should experimental evidence indicate that a source of this design is unlikely to achieve the initial HINS specs or at such time that Project X activities indicate that pursuing an ion source capable of Project X specs takes priority.

The HINS program M&S budget can support magnetron source development at a level of ~$25K in FY08. Current Project X R&D planning includes 3.3 FTE and $200K for ion source development spread over FY09-FY11.

Table 1. H- Ion Source Parameter Specifications

Parameter	**Project X**	**Initial HINS**	**Fermilab**	***Units***
Beam Energy	50	50	18	KeV
Energy Variation	± 5	± 5	± 5??	%
Beam Current (within specified emittance)	20	10	>50	mA
Transverse Emittance*	≤ 0.25 π rms x & y α = -1 to -3	≤ 0.25 π rms x & y α = -1 to -3	0.88 π 95% x 1.50 π 95% y	mm-mrad normalized
Beam Pulse Length	1000	1000**	60	μsec (max)
Beam Current Variation	≤ TBD ≤ TBD	≤ 15 ≤ 5	≤ 10 ?? ≤ 5 ??	% droop % rms in any10 μsec
Pulse Repetition Rate	5	10**	15	Hz (max)
Duty Cycle**	1.00	0.10**	0.090	% (max)

Notes:

* For simulations used to define HINS and Project X emittances, see “FNAL-LEBT Matching” by B. Mustapha available at:
http://tdweb.fnal.gov/HINS/MeetingMinutes/2007/20070111
and for Fermilab source, see “A 50-mA NEGATIVE HYDROGEN-ION SOURCE” by Charles W. Schmidt and Cyril D. Curtis available at:
http://accelconf.web.cern.ch/AccelConf/p79/PDF/PAC1979_4120.PDF

**On duty cycles:

- 5 Hz at 1 msec is present Project X specification
- 1 Hz at 1 msec establishes initial HINS duty cycle specification; higher repetition rates imply correspondingly shorter pulse lengths
- 15 Hz at 60 μsec sets the Fermilab source duty cycle

Appendix 1

H- Ion Source Considerations for the HINS / Project X Effort
Charles Schmidt   Nov. 21, 2007

The initial HINS beam studies will begin with protons from a conventional ion source that is available from the early days of Fermilab operation and projects. Assuming similar beam characteristics (which may not be the case going into the RFQ) proton beams are nearly as useful as H- beams, easier to come by, and more reliable from a source consideration. Still at some time (1-2 years) an H- source should be installed on the HINS or Project X prototype. H- sources of reasonable intensity and beam quality, high duty factor and pulse length, and decent reliability have only recently began to emerge or are under development for projects that are pushing the requirements for H- beams. HINS and Project X are at the lower boundary of this need, particularly for pulse length. At the November Workshop a concern over intensity from pulse-to-pulse and within a pulse was made. Because of the slowness in the vector modulator phase shifting, the beam intensity may need to be stable to +/- 1%. This is usually difficult to achieve.

There are two, possibly three, phases that may be necessary two meet the full operating needs of a commissioned Project X.

1. An initial H- source that produces modest intensity, pulse length and beam quality with low duty factor. For example, 35-mA pulsed current at 1-ms pulse length having low emittance suitable for injecting into the RFQ. This is basically the expectation for the present HINS project. Because this is a prototype machine the concerns for reliability and lifetime are not as critical as for an operational system.
2. A good H- source producing 15 – 20 mA with a 1-ms pulse having the desired emittance for injecting into the RFQ and suitable for the initial Project X testing and operation with the ILC superconducting cavities. This source should be stable and reliable. Source lifetime may still be questionable.
3. Finally for the fully commissioned and operational Project X, the source should fully meat the needs of the program with good lifetime and minimal downtime. Phases 2 and 3 may happen together.

Phase 1. HINS initial H- source:

At Fermilab, Doug Moehs began studying this problem by using a low duty factor H- magnetron ion source that has been in use at Fermilab for 30 years and for a similar period at other accelerator laboratories. This has culminated in a prototyping effort that has had H- beam pulses of ten to fifteen milliamperes of 30-millisecond pulse length on our source test bench. Still, this is for many reasons far from a reliable operating source (if it would make it that far). This effort has come to a standstill due to manpower, funds and Doug's initiative.

An H- source for this purpose probably requires collaborating with another laboratory that has developed H- sources in this range. Berkeley (LBL) is a likely choice. They were responsible for the present SNS and LASL sources. Although both labs are considering improvements to their present source, these sources were state-of-the-art accelerator sources when they were built. They may either have a source available or have drawings they could build from. Another possibility is an old LAMPF source from LASL, if they are still around and one doesn't expect too much for this phase.

Phase 2. Project X prototype H- source:

As HINS becomes an initial front-end prototype for Project X a more appropriate H-source may be necessary to better match the RFQ and downstream cavities. CERN is planning to copy and develop the DESY RF-volume H- source which appears to be an excellent source but has only been studied under limited conditions without cesium enhancement. Presently, the source comes on quickly and easily, has good intensity, operation and stability with low maintenance and emittance. It sounds good but only one has been built from "sketches" and it has had limited low duty-factor operation. It needs a second study that will show its possibilities. About two years ago Doug (Fermilab) and others from the SNS and DESY did a short study to increase the pulse length to three milliseconds. The results were encouraging. If all goes well it could be the source for Phase 2 and 3 depending on the development time.

Phase 3. Project X operating H- source:

Project X is planned to require a source H- beam of ~15 mA, with a 1-ms pulse length, at ~15-Hz repetition rate, with low emittance. Further more it should also be reliable, stable, have good lifetime (0.5 - 1 year) and low maintenance. Together these are a formidable set of requirements. The lower beam current of 15 mA for Project X gives Fermilab a big edge up for achieving these requirements since these higher power source can always be turned down producing even more favorable all-around operation.

While CERN is studying the DESY source, SNS should be developing a significantly higher power H- source and transport to the RFQ to meet its near term requirement and the long term requirement of multi-megawatt beam on target. Fermilab could be a collaborator to this work.

Similarly, the Beijing SHS, ISIS, LANSCE, and J-PARC will need high-power H-sources. (See a first page reproduction of Martin Stockli's paper from Linac 2006, below, or the full PDF version from the Conference proceedings.)

One of these high-power sources could be of interest for an operational Project X and should fit its time scale.

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 "LINAC 4"	40 80	0.4 0.7	1 2	0.25 (90%)	95
Fermilab A Phase B	15 45	3.2 1.2	2.5 10	0.25	50
BSNS Ph I Phase II	20 40	0.4 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 to 95	1.23	60	0.2 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 $4 \le n \le 12$ ($\sim 5\cdot 10^{-18} cm^{-2}$). 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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