HIGHLY-PERSISTENT SNS H^- SOURCE FUELING 1-MW BEAMS WITH 7-9 kC SERVICE CYCLES*

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Abstract

Running routinely with ~40-mA, 1-MW beams, the SNS linac is fed from the ion source with ~1ms long, ~50-mA H^- beam pulses at 60 Hz. This requires the daily extraction of ~230 C of H^- ions, which exceeds the routine daily production of other H^- accelerator sources by almost an order of magnitude. The source service cycle has been extended from 2, to 3, to 4, and up to 5.6 weeks without age-related failures. The 7-9 kC of H^- ions delivered in single service cycles exceed the service cycle yields of other accelerator sources.

The paper discusses the findings as well as the issues and their mitigations, which enabled the simultaneous increase of the beam current, the duty factor, the availability, and the service cycle.

INTRODUCTION

Lawrence Berkeley National Laboratory (LBNL) developed the SNS baseline ion source and LEBT, shown schematically in Fig.1, as a part of the SNS Frontend [1].

Typically 300 W from a 600 W, 13 MHz amplifier generates continuous low power plasma. The high current beam pulses are generated by superimposing 40-70 kW from a pulsed 80 kW, 2 MHz amplifier.

Most of the H^- ions are produced on the conical Mo converter, which is attached to the Cs collar and surrounds the ion source outlet [2]. The converter is cesiated with ~3 mg of Cs at the beginning of the service cycle. Without adding more Cs, the H^- beam normally persists throughout the entire service cycle [3].

The two-lens electrostatic LEBT is 12 cm long and focuses the beam into the RFQ with the required Twiss parameters α = 1.79 and β = 0.0725 mm/mrad. The LEBT's compactness prohibits any beam characterization before it is accelerated to 2.5 MeV by the RFQ. The first beam current monitor is located near the exit of the RFQ.

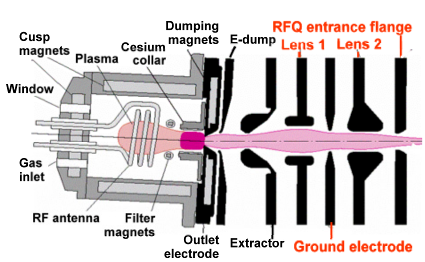

Figure 1: SNS baseline ion source and LEBT.

INITIAL PERFORMANCE

Starting out with low rep-rates, the short beam pulses easily exceeded the required 20 mA by tuning the 2 MHz for the highest beam current. The beam current, however, gradually decayed [2]. The decay was reversed by increasing the temperature of the Cs collar without having to replace the source during the entire run, as noted in Table I.

After an antenna failed with a water leak, a 2-week source replacement cycle was introduced, which created the opportunity to optimize and expedite source start-ups [2]. Without encountering age-related failures, the source service cycle was gradually increased and is now between 4 and 5.6 weeks as listed in Table 1.

Table 1: Performance and Issues of the SNS H^- Source.

Production Run (CY)	Duty factor	Pulse length	mA required	mA in MEBT	RF [kW]	Random Antenna Failures^	%Availability#	Comments
2006-1		~.1 ms	20	28-20	~70	0	99.9	1 ion source, 1 cesiation, raise collar temp
2006-2	0.2%	~.25ms	20	30-16	~70	0	99.98	1 ion source, 1 cesiation + 24h @115°C
2007-1	0.8%	~0.4ms	20	20-10	60-80	1*(37)	70.6	Arcing LEBT; punctured antenna* after 37 days, start 2-week source cycles
2007-2	1.8%	~0.5ms	20	13-20	80	0	97.2	Modified lens-2; e-target failures; tune for long pulses
2007-3	3.0%	~0.6ms	25	25-30	35-50	0	99.65	**modified Cs collar (Mo outlet)**
2008-1	3.6%	~0.6ms	25/30	20-37	uncal	1 (6)	94.9	Restore matching network; new tube; Beam on LEBT gate valve
2008-2	4.0%	0.69ms	32	32-38	48-55	1 (9)	99.22	Start 3-week source cycles; Ramp up e-dump & collar temperature
2009-1	5.0%	0.8 ms	35	34-38	~50	$2^{\$}$ + 1 (8)	97.52	Start "Perfect Tune"; try external antenna$ source for 1st 8 weeks
2009-2	5.1%	0.85ms	38	42-26	~55	1 (1)	98.84	Start replacing LEBT, slim extractor; start 4-week cycles; RF system deteriorates
2010-1	5.4%	0.9 ms	38	39-30	~60	1*(11) +1(>4) +1(0)	96.80	Repair and tune-up RF; punctured antenna* to beam back in ~6 hours; lens-1 & e-dump breakdowns;
2010-2	5.7%	0.9 ms	38	46-36	<55	2(10) +1(3) +2(0)	~98.5	**three 5+-week cycles; inductance increased; grounded 2 MHz**
2011-1	5.7% 4.4%	0.9 ms 0.73 ms	38	38-30	~60	1(0) +2(2) +1(22)	<99%	2 antennas fail before the start of the run; duty factor lowered after 4th failure

^(lifetime of failed antenna); #past 2007 antenna failures each contributed ~0.2% unavailability per run

ACHIEVING PERSISTENCE

As the rep rate and the pulse length were increased, the beam current started to decay more rapidly. With a ~3% duty factor, the beam decayed in a matter of ~10 hours as shown in Fig. 2.

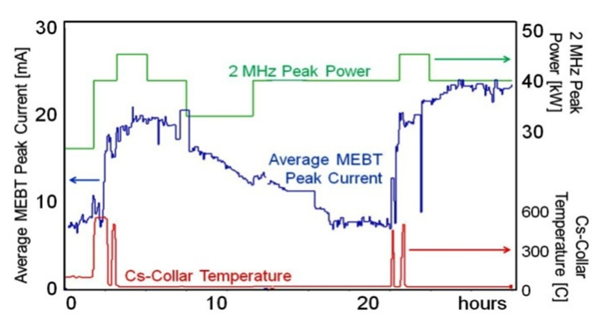

Figure 2: Initial decay of the beam current.

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However, the beam persisted after adding another dose of Cs the following morning. When the 6-7% plasma conditioning was extended to 2.5 hours, the beam persisted after the first cesiation [3]. It appears that Cs deposited on insufficiently plasma-conditioned surfaces is sputtered away, where Cs deposited on clean Mo surfaces persists in our H$^-$ source [4]. This persistence lasts the entire source service cycles, e.g. the 4-week cycle shown in Fig. 3 [5].

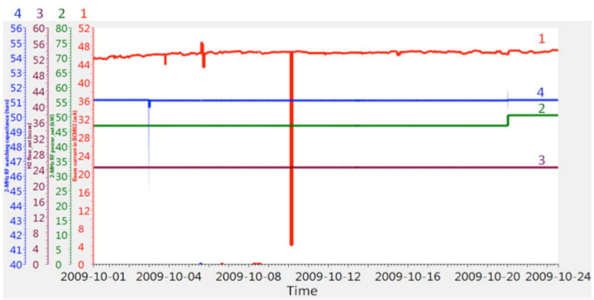

Figure 3: Beam current (1), tune (4), RF power (2) and gas flow (3) during a 4 week run.

ACHIEVING 38 mA WITH 5% DUTY FACTOR

For short beam pulses (<0.1 ms) high beam currents were obtained by maximizing the beam current while tuning the capacitance of the antenna circuit. When the pulse length was extended, the beam current dropped off after about 50 µs as seen in Fig. 4a. Increasing the tuning capacitor decreases the initial peak, while it increases the latter part of the pulse. This is due to gradually mismatching the breakdown conditions while improving the match in the presence of the plasma. For 50 kW the plasma lowers the ~0.4 µH inductance of the antenna by ~40% [5], which can be compensated by increasing the capacitance [2]. The improved tune restored the beam current to the required 20 mA.

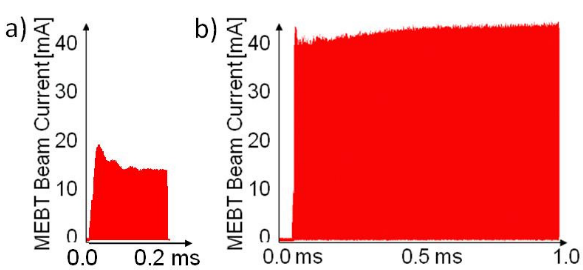

Figure 4: Beam current in 2007(a) and 2009 (b).

Replacing the 1 mm thick stainless steel ion converter with a 4 mm thick Mo converter increased the beam current by over 50% [2]. Increasing the e-dump voltage and retuning the LEBT increased the beam current by another 15% [3]. Lowering the LEBT pressure decreased the losses by~5%. A beam current of ~38 mA (Fig. 4b) was reached in 2009 [3] and became routine in 2010 by gradually increasing the RF power while improving the matching network.

MATCHING NETWORK OPTIMIZATION

Early in 2008 the plasma extinguished every time the tune was increased to increase the beam production. The situation improved after lowering the inductance, likely by avoiding high voltage discharges in the matching network. After robustifying the network, and pushing the RF power to 55 kW, plasma outages started to occur 1-2 weeks after starting up a refurbished source, with the problem getting worse with the age of the source as well as with the age of the run [5]. Plasma outages can be reduced by improving the breakdown conditions: Increasing the RF powers, increasing the gas pressure, and/or decreasing the tune. Towards the end of run 2009-2, having reached the limit of reliable RF power and the upper hydrogen flow acceptable to the RFQ, detuning became a necessity. This drastically reduced the beam current, as shown in Fig. 5 [5].

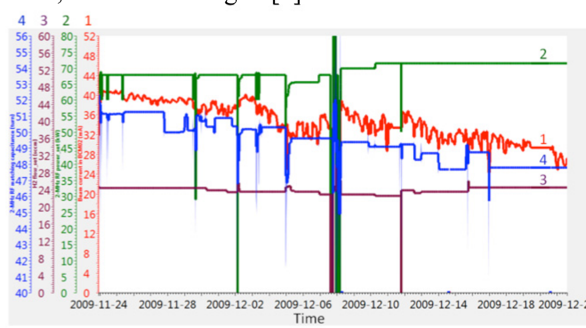

Figure 5: Beam current (1), RF power (2), H2 flow (3), and the tune of the matching net work (4) late in 2009.

The rate of plasma outages appeared to correlate with the decreasing pressures of the electron-rich residual gases, which can increase the breakdown voltage. During run 2010-1 the plasma outages were successfully lowered by increasing the inductance of the original matching network from 1.1 to 1.6 µH (Fig 6a).

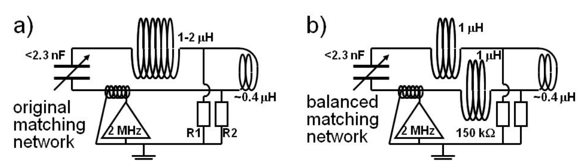

Figure 6: a) Original; b) balanced matching network.

However, ~4 month into the 4.5 month run 2010-1, plasma outages again required detuning, which reduced the performance. As mitigation the matching network was symmetrised with two 1 µH inductors, which allowed for running 4.5 month without detuning for reducing plasma outages. Since 2011 the high power RF pulse is started with 1.97 MHz to ease the breakdown, apparently eliminating the need for compromise tunes.

RESTORING AVAILABILITY WHILE RAMPING UP THE DUTY FACTOR

Ramping up the duty factor has revealed several issues that compromised the availability of the ion source and

LEBT. The first major issue occurred when the duty factor was raised to 0.4%, which heated up lens-2. The unshielded glued ceramics started to arc excessively, which caused frequent failures of the capacitively coupled chopper electronics. Changing to a glue-free assembly and shielding the ceramics eliminated the problem [2].

A squirt tube for cooling the extractor failed at 1.8%. The cooler was redesigned with a single-pass water loop.

At 5.4% duty factor, uncontrolled beam losses and discharge-triggered corona discharges started to occasionally heat up lens-1 until becoming inoperable. The successful mitigation included limiting the corona current by limiting the lens-1 load current.

The water-cooled, 2.5-turn, internal antennas, coated with 4-7 layers of Ti-free porcelain, [6] appeared reliable for up to ~40 kW and/or ~3% duty factors. After 2007, ~1 antenna failed per run, reducing the ion source availability to 99.7%. However, when the power was raised to ~55 kW and duty factor to 5.7%, up to 50% of the antenna started to fail, reducing the ion source availability to 99%. Most antennas failed within a few days, consistent with infant mortality. Records show that most failures occur on the transitions, which taper the 65 mm diameter loops to the 25 mm gap between the feedthroughs as seen in Fig. 7a. Because these transitions penetrate into the central space, the rotating plasma appears to heat the porcelain excessively. As shown in Fig. 7b, the antennas have been redesigned with 57 mm between the feedthroughs, which appears to have mitigated the problem.

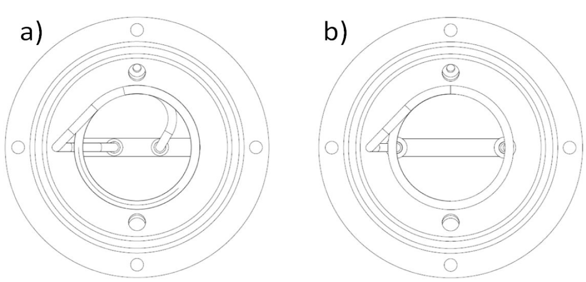

Figure 7: Flange with original (a) & wide-leg antenna.

IMPROVING CONSISTENCY

Initially the source could be installed and started up several days before the run, which allowed for reaching the requirements with a gradual tune up of the source. To prevent perceived old age issues, fixed length source service cycles were introduced in 2007, which put a premium on rapid startups. After a while pump downs were expedited with plasma desorption, thus starting the plasma as soon as possible. The Cs enhancement became significantly more consistent after the Cs cartridges were actively degassed with heat [2]. In addition the consistency was enhanced with improved control over the position of the Cs collar as well as the position of all Cs cartridges [2]. The effort to improve the control of the Cs continues [4].

The consistency appears to also be limited by the accuracy of the alignment. The various LEBT electrodes are aligned on a bench using tight fitting gauges. Every run, a new LEBT is installed and aligned to the RFQ. Every new source is started up and then aligned with respect to the LEBT by maximizing the beam exiting the RFQ. However, it appears that the beam parameters change over the first one to several days. Alignment on the second day is often more successful, but not always an option. In 2009 the beam could be enhanced by changing the source tilt angle from 3° to 0°, most likely benefitting from minor LEBT misalignments. This effect could not be reproduced in 2011.

BEAM CURRENT UPGRADE

While the source is normally operated to produce 38 mA linac peak current, there is a continuous effort to explore higher current capabilities. Recently 50 mA linac beam current has been transported through the entire linac. The demonstration of 50 mA is not an uncommon occurrence when testing sources in preparation for a new run [5]. In one case 59 mA peak current were demonstrated at the end of a run [7] as shown in Fig.8. This meets the requirement for the SNS power upgrade to 2-3 MW. However, it still has to be learned how to achieve this performance routinely.

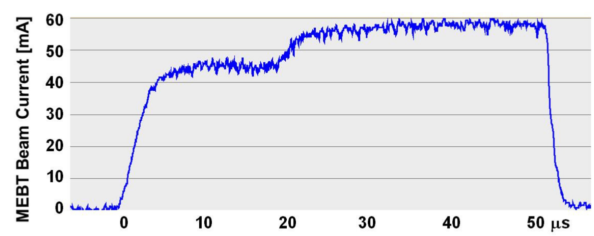

Figure 8: A 50 µs slice accelerated by the RFQ yielding 59 mA peak current.

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