Upgrading the LANSCE accelerator with a SNS RF-driven H\(^-\) ion source

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ABSTRACT
The LANSCE accelerator is currently powered by a filament-driven, biased converter-type H⁻ ion source that operates at 10%, the highest plasma duty factor for this type of source, using only ~2.2 SCCM of H₂. The ion source needs to be replaced every 4 weeks, which takes up to 4 days. The measured negative beam current of 12–16 mA falls below the desired 24 mA acceptance of the LANCSE accelerator. The SNS (Spallation Neutron Source) RF-driven, H⁻ ion source injects ~50 mA of H⁻ beam into the SNS accelerator at 60 Hz with a 6% duty factor and an availability of >99.5% but requires ~30 SCCM of H₂. Up to 7 A h of H⁻ have been produced during the 14-weeks-long source service cycles, which is unprecedented for small emittance, high-current, pulsed H⁻ ion sources. The emittance of the SNS source is slightly smaller than the emittance of the LANSCE source. The SNS source also features unrivaled low Cs consumption and can be installed and started up in <12 h. LANSCE and SNS are working toward the use of SNS H⁻ ion sources on the LANSCE accelerator because they could (a) fill the LANSCE accelerator to its capacity, (b) decrease the source replacement time by a factor of up to 7, and (c) increase source lifetime by a factor of about 4. This paper discusses some of the challenges that emerge when trying to match a different H⁻ source into an existing injector with significantly different characteristics and operating regimes.

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I. INTRODUCTION
In 1972, LANSCE (Los Alamos Neutron Science Center) started the world’s most powerful accelerator. Almost 50 years later, the 800-MeV accelerator still remains in the top ranks after having added many targets such as its spallation neutron source in 1977. Adding the PSR (Proton Storage Ring) in 1985, the accelerator switched to negative H⁻ beams to abundantly accumulate protons in the ring with charge exchange injection. LANSCE’s five user facilities provide unique research opportunities to tens of thousands of users.

Lawrence Berkeley National Laboratory (LBNL) developed and delivered the required H⁻ ion sources to LANSCE illustrated in Fig. 1(a). The plasma chamber is surrounded with bar magnets in cusp arrangements to confine the plasma. The pulsed power plasma is produced by raising the temperature of the hot filaments to 2700 K, with the thermally emitted electrons generating hydrogen ions during the pulsed arc discharge. Positive ions are pulled up to the ~350 V biased concave converter electrode, where some of them attach two electrons and then are pushed toward the beam extraction outlet. The positive ions are accelerated in the plasma sheath on to the converter electrode surface and sputter some of the work-function reducing, partial Cs layer during the arc discharge pulses of 0.84 ms. The partial Cs layer recovers between two plasma pulses for 7.5 ms because the dispenser tube injects Cs atoms directly and constantly from the ohmic heated oven at a working temperature...
of 170–190 °C. The converter surface ion source utilizes a process of peaking converter voltage and optimizing the Cs amount at the Mo converter electrode to maximize the H\textsuperscript{−} ion yield,\textsuperscript{1} which limits the extracted H\textsuperscript{−} beams to 12–16 mA.\textsuperscript{1} The H\textsuperscript{−} current limitation is partially compensated by operating with a plasma duty factor of 10\%, the highest for small, high-current H\textsuperscript{−} sources.\textsuperscript{2} Also striking for this type of source is the low H\textsubscript{2} consumption of 2.2 SCCM (standard cubic centimeters per minute) and the central position of the converter electrode over 12 cm from the repeller region and extraction aperture causing attenuation of the H\textsuperscript{−} ion beam inside the source.

The Spallation Neutron Source (SNS) started neutron production in 2006, and its power was gradually ramped up.\textsuperscript{6} Naturally, this included many R&D tests to explore the feasibility of planned upgrades, such as running 59 mA H\textsuperscript{−} into the medium-energy beam transport (MEBT) in 2008\textsuperscript{7} and accelerating 1 ms, 53 mA beam pulses with the 1 GeV linac at 1 Hz on August 5, 2018. The SNS became the world’s most powerful accelerator after routinely running at 1.4 MW in 2019.\textsuperscript{8} SNS was designed and built by a collaboration of six U.S. National Laboratories,\textsuperscript{9} with LBNL delivering the 2.5 MeV H\textsuperscript{−} injector. Its H\textsuperscript{−} source, shown in Fig. 1(b), worked well for commissioning the injector at LBNL\textsuperscript{10} and the low duty-factor accelerator commissioning at Oak Ridge National Laboratory (ORNL),\textsuperscript{11} but issues arose when the duty factor was raised beyond 0.3\%.\textsuperscript{12} The following years yielded many opportunities to identify and correct shortcomings.\textsuperscript{13,12} With becoming the world’s most productive and successful H\textsuperscript{−} injector, it became the standard for producing high duty factor H\textsuperscript{−} beams up to ∼60 mA.\textsuperscript{12} Being able to show that the H\textsuperscript{−} source lifetime can match the SNS target lifetime made ion source replacements rare events. This in turn increased the H\textsuperscript{−} ion source availability from ∼99.5\% to ∼99.9\%\textsuperscript{12} because downtimes of cesiated RF ion sources occur predominantly during their replacement, their startup, and the following week.

Upgrading a mature accelerator with a novel, better performing ion source sounds simple, but one needs to realize that ion sources are small components of complex injectors that are designed to match the ion source output into the first stage accelerator and therefore can vary greatly. Table I shows that replacing the LANSCE ion source with a SNS ion source can undoubtedly increase the H\textsuperscript{−} beam current up to the acceptance limit of the LANSCE accelerator. The LANSCE injector requires the SNS ion source to be operated at a higher voltage and a significantly higher duty factor. Increasing the duty-factor decreases inversely proportional its lifetime. Requiring a lower H\textsuperscript{−} output requires less RF power, which increases the lifetime inversely proportional. The net effect suggests a lifetime that slightly exceeds the SNS lifetime. The required 30–35 kW of 2 MHz RF is less than what is needed at SNS, but it demands more plasma power than what is currently used in the LANSCE injector, likely requiring an electrical power upgrade.

The LANSCE low-energy beam transport (LEBT) pumping system also needs to be upgraded to handle the higher gas load of the SNS H\textsuperscript{−} source. One advantage of RF sources is the rapid buildup of its plasma, and accordingly in the future, LANSCE could opt to increase the beam pulse length without increasing the plasma duty factor and compromising the source lifetime.

The integrated H\textsuperscript{−} charge per source cycle is an estimate because it depends on the efficiency of the H\textsuperscript{−} production that can only be determined from operational data.\textsuperscript{12} The low-energy beam transport (LEBT) is obviously so different that their adaptation will be discussed in a separate paragraph at the end of this paper.

II. THE SNS Cs-ENHANCED, RF-DRIVEN H\textsuperscript{−} ION SOURCE

The SNS H\textsuperscript{−} ion source, shown in Fig. 1(b), obtains ∼30 SCCM H\textsubscript{2} gas through the back of the stainless steel plasma chamber. The chamber wall is stuffed with water-cooled bar magnets ordered in cusp configurations to contain any plasma emerging in the chamber. Launching ∼300 W of 13 MHz RF through the 2 1/2 turn, porcelain-coated antenna and raising the H\textsubscript{2} flow to 100 SCCM for 1 s is the most reliable way to breakdown the low-pressure hydrogen gas.\textsuperscript{11} With the matching network properly tuned, the source reflects only ∼20 W of 13 MHz power as seen in the center of Fig. 2(a), which shows the outputs of a 13 MHz dual directional coupler.

This low-density “starter” plasma can easily absorb the 2 MHz RF\textsuperscript{2} when being launched with 60 Hz onto the same antenna as seen from the outputs of a 2 MHz dual directional coupler shown in Fig. 2(b). The reflected power is initially high but drops within tens of microseconds to the minimum, to which the matcher is tuned when the full plasma inductance is present.

A potential Achilles heel of the SNS H\textsuperscript{−} source in its current configuration\textsuperscript{1} is the fact that the dense 2 MHz plasma reflects the
TABLE I. A comparison of the parameters and characteristics of the LANSCE and the SNS low-energy injectors, as well as the projections for equipping the LANSCE injector with a SNS RF-driven ion source.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LANSCE Cockcroft Injector</th>
<th>SNS RFQ Injector</th>
<th>LANSCE injector with SNS source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ions</td>
<td>H⁻</td>
<td>H⁻</td>
<td>H⁻</td>
</tr>
<tr>
<td>Injector output beam energy (keV)</td>
<td>80</td>
<td>65</td>
<td>80</td>
</tr>
<tr>
<td>Injector output beam current (mA)</td>
<td>12–16</td>
<td>50–60</td>
<td>≤24</td>
</tr>
<tr>
<td>Pulsed plasma power (kW)</td>
<td>7.2</td>
<td>50–60</td>
<td>30–35</td>
</tr>
<tr>
<td>H₂ consumption (SCCM)</td>
<td>2.2</td>
<td>~30</td>
<td>≤30</td>
</tr>
<tr>
<td>Output emittance (π cm mrad) (rms)</td>
<td>0.02</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Plasma pulse length (μs)</td>
<td>840</td>
<td>1000</td>
<td>840</td>
</tr>
<tr>
<td>Beam pulse length (μs)</td>
<td>630</td>
<td>990</td>
<td>≥630</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>120</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>Duty factor (%)</td>
<td>10.02</td>
<td>6</td>
<td>10.02</td>
</tr>
<tr>
<td>Ion source cycle or lifetime (weeks)</td>
<td>4</td>
<td>≥14</td>
<td>≥15</td>
</tr>
<tr>
<td>Integrated H⁻ charge per cycle (A h)</td>
<td>0.8–1.0</td>
<td>≥7</td>
<td>~7</td>
</tr>
<tr>
<td>Ion source replacement</td>
<td>1–4 days</td>
<td>12 h</td>
<td>~12 h</td>
</tr>
<tr>
<td>Low-energy beam transport</td>
<td>Magnetic</td>
<td>Electrostatic</td>
<td>Magnetic</td>
</tr>
<tr>
<td>LEBT length (cm)</td>
<td>312</td>
<td>10</td>
<td>~312</td>
</tr>
<tr>
<td>Beam diameter in 1st lens</td>
<td>24 mm</td>
<td>14 mm</td>
<td>24 mm</td>
</tr>
</tbody>
</table>

13 MHz RF. This is seen in Fig. 2(a) as two bursts of reflected amplitudes accompanied by coextracted electrons whenever a pulse of 2 MHz (unseen) is launched. Whenever the 2 MHz power is turned off and the 2 MHz plasma decays, the 13 MHz plasma has to reestablish itself before the 2 MHz plasma decays completely, an issue that caused mysterious plasma outages at low H₂ pressures.\(^{12,13}\) It took significant efforts to understand the issue and find a solution for operating the source reliably at lower H₂ flows (\(~30\) SCCM),\(^{14}\) which is important because lower flows can deliver higher H⁻ output currents. However, the specific solution, or even the existence of a solution, likely depends on the RF power, and the desire to operate the SNS H⁻ source at lower RF powers for LANSCE elevated this to a major issue that will be addressed in the next paragraph.

The filter magnets shown in Fig. 1(b) return hot electrons to the core of the hot plasma within the antenna, whereas low-energy electrons, ions, and excited molecules drift through the filter-field toward the outlet of the source. Some of the excited molecules collide with the low-energy electrons near the outlet, forming H⁻ ions and escaping through the outlet, accounting for \(~10\) mA H⁻ beam with 35 kW of 2 MHz plasma.\(^{15}\)

In addition, the plasma potential pushes the positive ions onto the Mo converter, also shown in Fig. 1(b), which is treated with a fractional Cs layer whenever a source is started up.\(^{6,12}\) Just like in the LANSCE source, some of those ions pick up two electrons and return to the plasma as H⁺ ions. Some of those make it through the outlet to complete the extracted H⁻ beam current.

On the SNS source, the coextracted electrons are dumped in an \(E \times B\) field in the outlet, with a small fraction being intercepted by the water-cooled e-target on the extractor shown in Fig. 1(b). On the SNS ion source test stand, the extracted H⁻ beam is transported through a 10 cm long, 2-lens electrostatic LEBT before being measured with a beam current toroid, which according to Fig. 3 also picks up some secondary charges, before being dumped in the

**FIG. 2.** (a) 20 ms of scope traces of 13 MHz forward amplitudes in red, reflected amplitudes in green, and the coextracted electrons observed after an RC filter in yellow in arbitrary units; (b) 1.2 ms of scope traces with 2 MHz forward amplitudes in red, reflected amplitudes in green, the 60 Hz timing signals in black, and the current transformer signal from the antenna in yellow.

**FIG. 3.** 840 μs long H⁻ beam pulses measured at the LEBT output with a beam current toroid (upper, blue trace) and the downstream Faraday cup (lower, red trace).
downstream, deep, suppressed Faraday cup, which yields more reliable signals.

III. THE 4-WEEK, 120 Hz, 10% PLASMA DUTY-FACTOR EXPERIMENT

The first mysterious plasma outages were encountered late in the 2nd run of 2009 after the ion source cycles were increased from 3 weeks to 4 weeks. Apparently, lingering impurities lower the electrical breakdown strength of the H$_2$ gas in the first few weeks and so cause the breakdown strength to grow as they fade away. When the electrical breakdown strength exceeds the induced electrical fields, plasma outages start to occur.\textsuperscript{12,13} They are recovered by restarting the starter plasma and operating with a higher H$_2$ gas flow normally resulting in a lower H$^-$ output. Adding impurities would sputter Cs and result in decaying H$^-$ beams.\textsuperscript{16} It took years to correctly identify the root cause, and several measures were implemented that mitigated but not completely eliminated the plasma outages. However, no plasma outage ever started beyond 4 weeks despite running for up to 14 weeks.\textsuperscript{12} Accordingly, a 4-week experiment is most likely to find or rule out plasma outages caused by excessively pure hydrogen gas. In addition, 4-weeks is the minimum acceptable lifetime for upgrading the LANSCE injector as the upgrade would still benefit from the increased H$^-$ beam current and the faster source replacement times. There was a previous report on this 4-week experiment,\textsuperscript{17} but it is recounted here in more details due to its fundamental importance.

The SNS timing system was designed for frequencies of 0.1–60 Hz in steps of 0.1 Hz and nothing beyond. Accordingly, it was set up that each 1 ms long timing signal generated a 840 $\mu$s long 2 MHz signal and simultaneously triggered a 8.33 ms delay for another 840 $\mu$s long 2 MHz signal, producing the 120 Hz, 10% duty-factor 2 MHz plasma indicated by the reflected 13 MHz RF, and the coextracted electrons seen in Fig. 4.

As seen in Fig. 5, the experiment had to be started with 38 SCCM H$_2$ gas, but it could be lowered to 30 SCCM within 2 days and remained there during the rest of the 4-week experiment. Also, it took a few hours of 36 kW of 2 MHz to make the H$^-$ output grow to 24 mA, after which the power was lowered to ~30 kW. After ~2 weeks, the RF power needed to be increased twice by 1 kW to maintain the 24 mA output. Without being noticed or understood, the beam started to decay at the start of the last weekend. The unusual and misleading control display of the 60 Hz/120 Hz hybrid setup caused an operator to believe that the plasma was out, and therefore, the experiment was switched off out of equipment safety concerns as seen in Fig. 5. On Monday morning, a system expert arriving for work restarted the experiment without any difficulty, yielding 25 mA H$^-$ beam with 34 kW of 2 MHz for another day.

IV. ADDITIONAL EXPERIMENTS

Operating with 32 kW of 2 MHz and the 10% plasma duty factor, the H$^-$ beam current output was measured as a function of the source voltage while scaling the e-dump and the two lens voltages. With the extraction optimized for 65 kV,\textsuperscript{6} it is not surprising that no change in beam current was observed between 60 kV and 70 kV. However, this also suggests that increasing the SNS source voltage to 80 kV for operation on the LANSCE injector will not yield substantial changes after proper adjustments to the extraction geometry are made.

Then, the H$_2$ gas flow was lowered to 22 SCCM without encountering plasma outages. This confirmed that 4-week conditioning apparently made the source more robust against plasma outages, a common observation with the SNS source during its routine operation. Here, it should be noted that at ~30 kW, the 2 MHz plasma is less dense and reflects the 13 MHz less completely, a fact that should work in favor of low-power RF operations although a significant upgrade of the LANSCE LEBT vacuum system remains essential.

At the end of these experiments, the source was operated with 36 kW at the 10% plasma duty factor for 3 days outputting about 29 mA of H$^-$ without any sign of decay as seen in Fig. 6. This test assured a range of operability conditions within the typical thermal load normally encountered at the SNS source over many years.
V. ADAPTING THE SNS ION SOURCE TO THE LANSCE LEBT

With optimal extraction, the H− beam from the SNS RF source emerges nearly parallel from its extractor. It is the space charge in the electrostatic LEBT that increases the beam diameter to the nearly optimal value of ∼14 mm in the first lens ∼30 mm downstream. If the beam emerging from the SNS extractor is injected into the LANSCE magnetic LEBT, the beam diameter would only grow to ∼10 mm in the first magnetic lens 263 mm downstream due to the ∼94% neutralization of the beam. This is far below the required diameter of 26 mm for a proper transport in the LANSCE LEBT. While the problem could be addressed with a slight focus in the extraction, one would have to give up the benefits of parallel extractions. An alternative is to transport the beam from 65 kV to 80 kV without space charge compensation and let the space charge expand the beam to the desired diameter. Naturally, the length of this expansion acceleration depends on the beam current and therefore needs to be adjustable. Results are pending.

VI. CONCLUSIONS

The investigations and experiments so far have been highly encouraging that the LANSCE injector can be upgraded with a Cs-enhanced, RF-driven SNS H− ion source to significantly increase the LANSCE beam current and user hours, while reducing the required ion source maintenance.

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