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OPERATING THE SNS RF H⁻ ION SOURCE WITH A 10% DUTY FACTOR*

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Abstract

The SNS (Spallation Neutron Source) (radio-frequency) RF-driven, H^- ion source injects ~50 mA of H^- beam into the SNS accelerator at 60 Hz with a 6% duty factor. It injects up to 7 A·hrs of H^- ions during its ~14-week service cycles, which is an unprecedented lifetime for small-emittance, high-current pulsed H^- ion sources. The SNS source also features unprecedented low cesium consumption and can be installed and started up in <10 h.

Presently, the LANSCE (Los Alamos Neutron Science CEnter) accelerator complex in Los Alamos is fed by a filament-driven, biased converter-type H^- source that operates with a high plasma duty factor of 10%. It needs to be replaced every 4 weeks with a ~4 day startup phase. The measured negative beam current of 16-18 mA falls below the desired 21 mA acceptance of LANSCE's accelerator especially since the beam contains several mA of electrons.

LANSCE and SNS are exploring the possibility of using the SNS RF H^- source at LANSCE to increase the H^- beam current and the ion source lifetime while decreasing the startup time. For this purpose, the SNS H^- source has been tested at a 10% duty factor by operating it at 120 Hz with 840 µs plasma pulses generated with ~30 kW of 2 MHz RF power, and extracting ~25 mA around-the-clock for 28 days. This, and additional tests and other considerations are discussed in this paper.

INTRODUCTION

The LANSCE (Los Alamos Neutron Science Center) 800-MeV accelerator was the world's most powerful accelerator when it was started up in 1972, and remains one of the most powerful accelerators today. In 1977 a pulsed spallation neutron source was commissioned [1]. In 1985, when the PSR (Proton Storage Ring) was started, the accelerator switched to negative H^- beams to efficiently accumulate protons in the ring. LANSCE has since served many tens of thousands of users with its five user facilities [1].

The required H^- ion source was developed and built at LBNL (Lawrence Berkeley National Laboratory) [2]. As shown in figure 1a, the source uses multicusp magnets for plasma confinement. The pulsed plasma is started by raising the hot filaments to a working temperature of ~2700 K [3], so that thermally emitted electrons generate hydrogen ions during the arc discharge pulse. The positive ions are attracted by the -300 V biased spherical converter electrode. Some of the ions convert to H^- ions and are pushed towards the outlet.

Some of the energetic ions sputter the work function reducing Cs atoms, which limits the beam output to 16-18 mA, with electrons contributing several mA. LANSCE compensates the beam current limit by operating with a 10% duty factor, the world's highest duty factor for pulsed high-current H^- accelerators. Also noticeable is the very small H_2 consumption of ~2.2 sccm (standard cubic centimeter per minute).

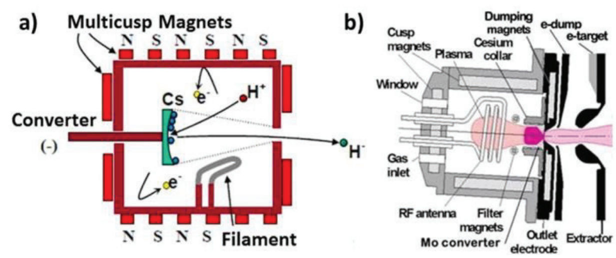

Figure 1: Schematics of **a)** the LANSCE filament-driven converter- and **b)** the SNS RF driven- H^- ion sources.

The SNS (Spallation Neutron Source) accelerator started up in 2006 and now is routinely operating at 1.4 MW making it the world's most powerful accelerator [4]. The incorporation of an accumulator ring in the design set the requirement for the use of negative ions. The H^- source was a part of the SNS Frontend, developed and built at LBNL, as a part of the six-laboratory collaboration that designed and built SNS [5].

While the H^- source worked well for commissioning the Frontend at LBNL [6] and then the multiyear low-duty-factor commissioning phase of the entire accelerator at ORNL (Oak Ridge National Laboratory), problems surfaced as soon as the duty factor was increased beyond 0.2% [7]. Fortunately, the past years of usage provided adequate opportunities to identify and correct deficiencies and weaknesses and to implement other improvements [8]. The most recent advances result from being able to show that the lifetime of the improved ion sources exceed the lifetime of the SNS targets, so that ion source replacement events are rare. This caused the typical H^- source availability to increase from ~99.5% to ~99.9%.

THE SNS CESIATED RF H⁻ ION SOURCE

Shown in figure 1b, about 30 sccm of H_2 gas is fed through the back of the stainless steel plasma chamber, which is embedded with water-cooled bar magnets arranged in cusp configurations. After launching ~300W of

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13.56 MHz through the 2½-turn, porcelain-coated copper antenna, the H_2 flow is raised to 100 sccm for 1 s, which breaks down the H_2 gas and forms a starter plasma. As seen in figure 2, the electrons in the starter plasma absorb the 45-65 kW, 2 MHz RF power when being pulsed for 1 ms at 60 Hz to form the intense plasma pulses needed for the high current H^- beam production. While the ~250-G filter field returns the energetic electrons to the hot plasma inside the antenna, the low-energy electrons and ions diffuse, and the excited molecules drift through the filter field towards the outlet of the source. Some of the excited molecules collide with electrons forming negative H^- ions, of which ~15 mA escape through the outlet.

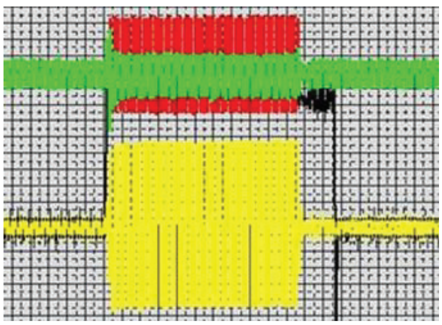

Figure 2: 2 ms of scope traces: the red forward 2 MHz RF amplitudes are significantly larger than the green reflected ones. The lower yellow trace is the antenna current measured with a transformer. The lower black trace is the 1 ms time signal that controls only the start of the 2 MHz RF pulse.

In addition, the plasma potential pushes the positive ions onto the Mo converter, which is treated with a fractional Cs layer when the source is started up [8]. Some of those ions add electrons to form H^-, which adds up to 50 mA of beam current depending on the 2 MHz RF plasma power and the temperature of the Mo converter.

While the SNS H^- source has very reliably and successfully supported the SNS accelerator, it remains to be proven that this source can also support the LANSCE accelerator system with its lower H^- current acceptance, its lower H_2 tolerance, its different LEBT (low-energy beam transport) configuration and its double repetition rate. Especially the combination of the higher repetition rate and the lower 2 MHz power (to preserve lifetime) may increase the risk of plasma outages that SNS has successfully resolved, but not fully understood.

THE 10% DUTY FACTOR EXPERIMENT

The SNS experience is essential to understanding the importance of this milestone experiment. In the early days, it was found that the SNS H^- source can be easily ignited with different schemes and sometimes self-ignites [9]. However, this turned out to be correct only for new sources, where high levels of impurities lower the breakdown voltage of the impure hydrogen gas [8]. It took a long time to understand that the plasma outages occurring after 3-4 weeks of continuous operations were the result of the breakdown voltage that had grown due to the vanishing impurities. Adding impurities is not an option for SNS because they would sputter away the performance-enhancing cesium atoms as was observed several times with accidental leaks [8]. However, such plasma outages were never observed beyond 4 weeks, and accordingly it seems that after ~4 weeks equilibria are reached where the breakdown voltage appears to be dominated by pure hydrogen.

The SNS can operate with any frequency between 0.1 and 60 Hz in steps of 0.1 Hz, but not beyond. To operate the source at 120 Hz, each of the 60 Hz timing signals triggered an additional DG535 which delivered an additional signal to the 2 MHz amplifier with an 8.33 ms delay. This can be seen in figure 3, which shows 40 ms of the 13 MHz RF amplitudes at the top: while the large forward amplitudes remain unchanged, the reflected amplitudes pop up every 8.33 ms when the 2 MHz plasma reflects the 13 MHz RF, all triggered by the 60 Hz timing pulses at the bottom.

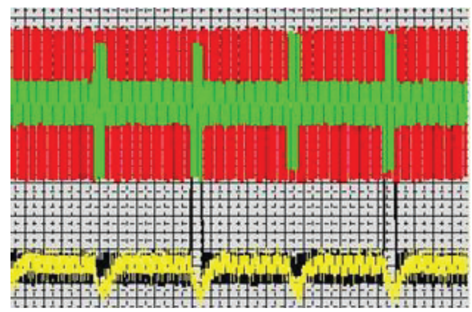

Figure 3: 40 ms of scope traces: the red forward 13 MHz RF amplitudes remain unchanged, while the green reflected amplitudes peak whenever 2 MHz is in the plasma at 120 Hz. At the bottom are the yellow co-extracted electrons and the black 1 ms timing signals at 60 Hz.

On the SNS ion source test stand, the H^- ions are extracted with 65 kV. The strong dumping magnets embedded in the outlet electrode steer most of the co-extracted electrons onto the e-dump, which are seen in figure 3, and only a small fraction ends up on the grounded e-target. The H^- beam is transported through a two-lens electrostatic LEBT before being measured by a beam current toroid, which also picks up some erroneous charges as the upper trace in figure 4 shows. The shielded and suppressed Faraday cup is placed further away and yields more reliable signals as can be seen from the lower trace in figure 4.

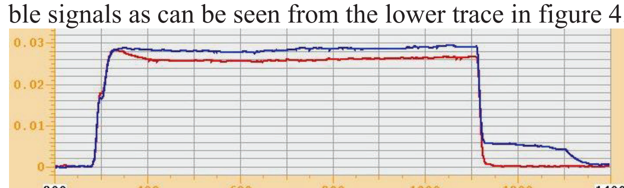

Figure 4: The extracted H^- beam current measured with the Faraday cup (lower trace) and with a beam current toroid at the exit of the LEBT, which picks up some erroneous charges (upper trace).

To avoid plasma outages during pretesting, the H^- source required elevated H_2 flow, but that settled down. Within less than 2 days of starting the run on the ion source test stand, the H_2 flow could be reduced to the

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nominal 30 sccm as the lowest trace in figure 5 shows. Also seen in figure 5, after a few hours near 36 kW to make the beam current grow to an average of 24 mA, the 2 MHz could be lowered to ~30 kW to maintain the H$^-$ current level. Over the next several days, the beam grew by ~1 mA, but then very slowly started to decay. This was occasionally corrected with very small increases in RF power. 24 mA were maintained mainly with ~32 kW until an unnoticed decay started on the last weekend. To add insult to injury, on Sunday uninformed operators shut down the system because the misleading control setup made them believe the plasma was out. Next morning, as soon as a system expert became available, the system was restarted without any difficulty. Obtaining 25 mA with 34 kW it was run for another 24 hours to make up for the lost night.

Figure 5: The ion source high voltage (green top trace), the H$^-$ beam current (blue 2nd from top trace), the RF power (red 3rd from top), and the H_2 flow (pink bottom trace) during the 29 day long run of the SNS source with a 10% duty factor.

The successful conclusion of this 4-week test proved the long run capability of the SNS H$^-$ source under low-power RF conditions and at a 10% duty factor without excessively burdening the mission of the SNS ion source test stand. In addition, it guarantees a 4-week lifetime, the absolute minimum that still guarantees a significant benefit to LANSCE due to the shorter startup.

ADDITIONAL EXPERIMENTS

After the 4-week test was concluded the source was run for 72 hours at 36 kW of 2 MHz power at the same 10% duty factor, yielding 29 mA without any decay. This assures a range of operability conditions and was selected because it is the same thermal load the source endures under SNS conditions without any issues for over six years now.

Furthermore, it was determined that at the end of the run the H_2 flow could be lowered to 22 sccm before plasma outages started to appear. While this is a step in the right direction, there is no doubt that a successful implementation has to include a significant increase of the pumping speed in the LANSCE LEBT.

In addition, the H$^-$ beam current was measured as a function of the ion source voltage, while the e-dump and the two lens voltages were scaled proportionally. The plasma was operated with 30 sccm of H_2 flow and 32 kW of 2 MHz power. The results are seen in figure 6. Most remarkable, there was no change in beam current detected between 60 and 70 kV, consistent with an ion-density limited extraction. This is welcome news for the LANSCE LEBT that is designed for an ion source voltage of 80 kV, and implies that it should be able to accept the SNS H$^-$ source with an accordingly increased high voltage.

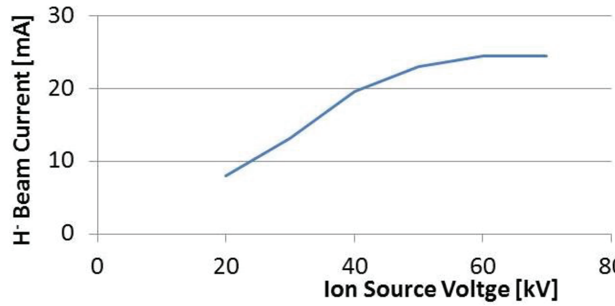

Figure 6: The H$^-$ beam current vs. the ion source voltage.

CONCLUSIONS

The successful completion of the described tests are very encouraging for upgrading the LANSCE accelerator with a Cs-enhanced, RF-driven H$^-$ ion source, resulting in increased LANSCE beam current, lengthened source lifetime and reduced source startup time. One of the main remaining open questions is the size and its control of the H$^-$ beam emerging from the SNS H$^-$ ion source, which will be addressed in the near future.

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