Plasma-Wall Interactions in the Cesiated SNS H⁻ Ion Source

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Abstract. High-current H⁻ ion beams are needed to drive high-power accelerators as well as to heat future fusion reactors with neutral beams. The most productive H⁻ sources enhance the production of H⁻ ions with caesium. Cs lowers the work functions of the metal walls, which increases the probability of ions to capture a second electron when bouncing back from the metal plasma walls. However, caesium also causes voltage break downs that can be severe and cause significant downtime. SNS has developed a frugal caesium management, which uses a single injection of ~4 mg of caesium to produce ~50 mA of H⁻ beam without decay for up to 6 weeks. This paper presents calculations and experimental data, which suggest the persistence of the caesium enhanced H⁻ beams are due to 1) thermally limiting the Cs emission, and 2) conditioning for high purity hydrogen plasma, which eliminates the sputtering of Cs by non-hydrogen ions, and 3) hydrogen ions being too light to sputter Cs.

1. Introduction

High current beams of negative hydrogen ions are needed for producing neutral beams to heat the plasma in fusion reactors and in high-power proton accelerators with accumulator rings [1]. For example, SNS produces a 1 MW proton beam that impacts 60 times per second on a mercury target. Every pulse produces copious amounts of neutrons, which are used in neutron scattering experiments at the end of up to 16 neutron beam lines [2].

Briefly, to produce these neutrons, the ion source shown in figure 1 has to deliver ~50 mA of H⁻ ions for 1 ms at 60 Hz. The ion source voltage accelerates the beam to 65 kV. The two-lens electrostatic beam transport shown in figure 1 refocuses the beam into a radio frequency quadrupole, which accelerates the beam to 2.5 MeV. The medium energy beam transport refocuses the beam into the linear accelerator, which boosts the energy close to 1 GeV. A gentle bend filters the beam energy and brings the beam to the accumulator ring. As the H⁻ beam enters a bending magnet of the accumulator ring, a thin foil strips the 2 electrons and the stripped protons can join the trajectories of the already stored proton beam. Accumulating close to 1000 beamlets allows the ring to accumulate tens of amps of 1 GeV protons.

A chopper integrated into the second lens shown in figure 1 removes the beam for ~300 ns about every μs. These gaps accumulate in the accumulator ring and allow for a clean extraction of the beam. After accumulating for ~1 ms, the extraction kickers direct the accumulated beam onto the liquid mercury target.

This paper discusses the interactions between the walls and the plasma, which play crucial roles in the production of the H⁻ beam with the SNS ion source, its persistence and its lifetime.
2. The Production and Extraction of Negative Hydrogen Ions from Pure Hydrogen Plasma

The production of negative hydrogen ions is challenged by the mismatch between the ions' small electron affinity of 0.75 eV and the ~15 eV binding energies found in hydrogen atoms and molecules. The hydrogen’s limited atomic structure makes the capture of free electrons difficult, resulting in a cross section of $\sim 5 \times 10^{-22}$ cm$^2$ for the radiative capture. The increased complexity of molecules allows for negative hydrogen ions to be produced with a dissociative attachment in collisions with low-energy electrons ($E_e < 10$ eV) with a cross section of $\sim 10^{-20}$ cm$^2$ [3].

Accordingly, in 1977 it was a surprise when Bacal found large signals from negative ions in hydrogen plasma [4]. Extensive research has shown that negative hydrogen ions can be efficiently produced with a cross section of $\sim 3 \times 10^{-20}$ cm$^2$ when slow electrons ($E_e < 1$ eV) break up highly rovibrationally excited hydrogen molecules ($4 \leq \nu \leq 9$). However the efficient production of highly rovibrationally excited molecules with a cross section of $\sim 5 \times 10^{-18}$ cm$^2$ requires fast electrons with energies >15 eV. Unfortunately, such fast electrons destroy the negative hydrogen ions with a cross section of $\sim 3 \times 10^{-15}$ cm$^2$, severely limiting the lifetime and usability of the produced negative ions [4].

This dilemma was reduced with the introduction of “tandem type sources” like the SNS source shown in figure 1 [5]. It shows on the left the multicusp magnet lined plasma chamber containing a 2.5-turn porcelain-coated copper antenna. About 350 W of 13 MHz radio frequency generate continuous plasma. This dim plasma accelerates the breakdown produced by the 50-70 kW, 1 ms long pulses from a 2 MHz amplifier at 60 Hz. After the first 5 $\mu$s of each pulse, the frequency is up-shifted by $\sim 1\%$ to adjust the match for the increased plasma inductance [6]. The high-power RF produces a broad distribution of electron energies, which in turn excite numerous molecules. Near the open end of the antenna are filter magnets that generate a transverse dipole field of $\sim 250$ Gauss. This field returns energetic electrons towards the antenna, while it allows low-energy electrons to diffuse towards the outlet of the source. The exited molecules drift unimpeded through the filter field and produce negative hydrogen ions when colliding with low-energy electrons. The lower plasma temperature near the outlet improves the lifetime of the negative ions, which have more time to drift into the outlet where they are accelerated by the -65 kV applied to the ion source.

3. The Plasma assisted Production of Negative Ions on Metal Surfaces

Metals suitable for plasma chambers have work functions in the range of 4 to 5.6 eV, and those more loosely bound electrons are better matched for being captured by a hydrogen atom to form a negative ion. This fact motivated the successful development of compact surface plasma H$^-$ sources (magnetron and penning sources) [7] and surface converter H$^-$ sources [8]. The SNS source was
conceived as a hybrid source, where the large outlet boosts the output from the volume-produced $H^-$ ions, and a converter supplements surface-produced $H^-$ ions [5].

The 7 mm inner diameter source outlet is shown in detail in figure 2. On the plasma side of the outlet is the Mo converter, which is thermally attached to the Cs collar, which will be discussed later. During operation, positive hydrogen ions drifting into the plasma sheath are accelerated by the plasma potential. When the ions impact on the surface, they rapidly neutralize through auger transitions. Being energetic, most atoms will bounce back into the sheath, and there is a chance that a surface electron gets captured in the field of the fast atom. However, the chance is small because the 4.6 eV work function of Mo is much larger than the 0.75 eV electron affinity of the hydrogen atom. The electron capture probability increases with the velocity of the escaping atom [9]. The so produced negative ions initially tend to move away from the outlet, but diffusion, resonant charge transfer with hydrogen atoms, and the filter field allows for a fraction of the ions to reach the outlet. A fraction of the negative ions is lost due to associative detachment of the electron in collisions with energetic hydrogen atoms or due mutual neutralization in collisions with protons [3]. These losses are minimized by placing the converter surface as close as possible to the outlet and by using a cone with a 45° taper.

4. Increasing the Negative Ion Yield with Caesium

Around 1970 Novosibirsk was able to produce unprecedented currents of negative hydrogen ions by adding Cs to their magnetron source [7]. This started a large interest in the surface production of negative ions and the efficiency of various surfaces.

Briefly, alkali metals have lower work functions in the range of 2 to 3 eV due to their single, loosely bound electron in their outer shell. When being adsorbed on a substrate metal, the work function can be even lower than that of the bulk alkali metal. Figure 3 shows the work function of a

![Figure 2. Details of the outlet of the SNS $H^-$ ion source.](image)

![Figure 3. The work function of a Mo surface with adsorbed Cs.](image)
Mo surface as a function of the amount of adsorbed Cs in units of mono layers, meaning one 1-atom thick, dense layer. Without any Cs the work function starts out with 4.6 eV, the work function of the clean substrate Mo surface. Gradually adsorbing Cs slowly lowers the work function until reaching a minimum of 1.6 eV near 0.6 mono layers. Adding more Cs gradually increases the work function up to 2.1 eV, the work function of bulk Cs [10].

To demonstrate the effect of the changing work function on the production of negative hydrogen ions, the SNS ion source was equipped with an external Cs reservoir. After outgassing the Cs supply system and plasma-conditioning the plasma chamber, the Cs ampoule was cracked and a small Cs flow was started by heating the reservoir to ~110°C. As the Cs gradually adsorbed on the 55°C converter surface, the unanalyzed H⁻ beam current gradually grew from ~10 mA to over 40 mA as shown in figure 4. However, after about an hour the current started to gradually decay to 36 mA. This is consistent with the work function initially decreasing, passing through a minimum and then increasing after exceeding the optimal fraction of a monolayer [11].

![Figure 4. Beam current versus time when gradually applying Cs to the converter.](image)

This suggests that the minimum in the work function is relevant for the production of H⁻ with an ion source, even so it employs imperfect, technical surfaces rather than the perfectly structured surfaces that were used to measure such work function data.

Clearly the H⁻ production on surfaces benefits greatly from the addition of Cs. Lowering the work function also leads to larger electron emission from negatively charged surfaces such as the negative ion source itself, associated high-voltage electrodes like the E-dump, which collects the co-extracted electrons, and electrostatic lenses needed to focus the expanding beam as shown in figure 1. For example, the load current of the first electrostatic lens normally increases when Cs is released, which is a useful Cs indicator. However, excess Cs has led to many high voltage breakdowns and sometimes required extensive conditioning before the operational high voltages could be restored. For this reason some ion sources avoid Cs and settle for lower yields of H⁻ ions. The highly frugal Cs management developed with the SNS H⁻ source is a successful compromise [12].

5. Managing a Fractional Monolayer of Caesium

Creating a ~0.6 monolayer of Cs on a Mo substrate and maintaining it under plasma condition is a challenging task and took many optimizations to find a reliable process. This is complicated by the fact that Cs likes to stick to metal surfaces and therefore much Cs needs to be deployed before the partial monolayer is formed on the desired surface. For example, the SNS source requires ~4 mg of Cs to reliably and consistently apply a partial monolayer on the Mo converter, which accounts for only ~0.1 µg of Cs. This initial 4 mg dose produces a persistent H⁻ beam current for up to 6 weeks,
apparently consuming less than 0.12 mg per day or less than 2 mg per plasma-day when normalized to the plasma duty factor.

Other cesiated H\(^+\) sources use significantly more Cs, like a converter H\(^+\) source, which consumes ~1 g per day [13] or ~8 g per plasma-day. Low duty factor H\(^+\) sources consume much less Cs, such as 0.7 mg per day achieved with a frugally managed magnetron source [14], although that adds up to 37 g per plasma-day. Apparently, SNS operates its H\(^+\) source without a significant consumption of Cs.

Cs can be lost through sputtering by ions from the plasma, which will be discussed later. Thermal emission is the other loss mechanism, which normally can be described by with an exponential decay with an exponent \(-\frac{E_{\text{Cs}}}{kT}\), where \(E_{\text{Cs}}\) is the bond energy of the adsorbed Cs atom, \(k\) the Boltzmann constant, and \(T\) the absolute temperature in °K [15]. Such an exponential decay could be used to depopulate the surface until reaching the desired fractional monolayer and then drastically lowering the temperature to prevent further losses.

However, Cs behaves quite differently because its binding energy decreases with the amount of Cs that is adsorbed on the surface as seen figure 5 for a polycrystalline Mo surface (Kaminsky) [16] and a 110 Mo surface (Hansen) [17]. This unique behaviour appears to be caused by the ionic radius of Cs, which is significantly larger than the metallic radius of most metals except for some alkali and alkaline earth metals [18].

As thermal emission depopulates the Cs, the increasing binding energy drastically reduces the thermal emission. The resulting loss rate and remaining layer can be calculated by integrating the time it takes to lose a certain fraction [11]. Using the Hansen approximation, and starting with one monolayer, figure 6 shows the results for nine different temperatures of the Mo substrate [11].
Because logarithmic time scales are unusual, figure 7a shows the same data for three different temperatures for the first 5 hours and figure 7b for the first five weeks [12]. Figure 7a shows all drastic changes to happen in the first few minutes, and some noticeable changes over the first two days before the system stabilizes. Figure 7b shows that small changes could be noted over the first 1-2 weeks before the system stabilizes. These calculations show how the temperature of the substrate can be used to rapidly obtain a desired monolayer, and that no adjustment is needed to maintain this monolayer within a narrow range.

The SNS Cs collar is normally set to \( \sim 170^\circ C \) without further adjustments. The H beam normally grows for a few days before it becomes persistent and remains at this value for the remainder of the source service cycle.

![Figure 7](image)

**Figure 7.** As figure 6 but with linear time scales for the first a) 5 hours and b) 5 weeks.

### 6. Achieving and Loosing the Persistence of the H Beam

Mono layers are fragile and therefore it was no surprise when initially the H beam kept decaying every time after applying a dose of Cs [19]. The surprise came about a year later when it was noticed that decay slowed down with every cesiation as shown in figure 5 [20]. The figure also shows that the H beam became persistent after applying a dose of Cs the following morning.

![Figure 8](image)

**Figure 8.** The beam current and lens-1 load current during a 2007 source start up.

In 2008, the full-power plasma conditioning was extended from 30 to 150 minutes, which started to produce persistent beams after the first cesiation. Apparently, the plasma sputter-cleaned the surface and the Cs strongly bonded to the Mo surface and resisted sputtering. Without thorough sputter cleaning, the Cs is adsorbed on water and other adsorbates forming much weaker bonds.
Conditioning for about three hours yielded persistent beams until a ~1% beam loss per hour was encountered in June of 2011 [20]. RGA data showed about 1 ppm NH₃, which disappeared when the plasma was switched off. A post-service leak check revealed a E-10 scc/s leak in a widow. Apparently, the heat from the plasma enlarged the air leak to E-6 scc/s, which contaminated the hydrogen plasma with about 1 ppm of products from air.

Applying another dose of Cs would restore the H⁺ beam current, but the decay continued at the same rate. The unchanging decay rate means that the Cs keeps bonding to the surface with the same bond energy, which one would expect if the Cs is being sputtered while the surface remains unchanged. This suggests that ions from ammonia sputter Cs, while ions from hydrogen do not.

7. The Sputtering of Caesium

Sputtering plays an important role in ion sources. Its thresholds and yields are governed by the adsorbate mass \( m_a \) and surface bond energy \( E_a \), and the ion mass \( m_i \), and ion energy \( E_i \), which is normally dominated by the plasma potential. The threshold \( E_{th} \) was approximated as [21]:

\[
E_{th} \approx 8 E_a (m_i/m_a)^{2/5} \quad \text{for} \quad m_i > 0.3 m_a \quad \text{(1a)}
\]

\[
E_{th} \approx E_a / (\gamma (1-\gamma)) \quad \text{with} \quad \gamma = 4 m_i m_a / (m_i + m_a)^2 \quad \text{for} \quad m_i \leq 0.3 m_a \quad \text{(1b)}
\]

The ratio of these approximate thresholds divided by the bond energy for Cs is plotted in figure 10 versus the square root of the ion mass \( m_i \). It clearly shows the hydrogen ions to have a much higher threshold than nitrogen or any heavier ions. Using the 2 eV bond energy shown in figure 2 suggests that the plasma potential exceeds 14 V to provide nitrogen ions with enough energy to sputter Cs. On the other hand, the normal persistence of the beam suggests the plasma potential to be less than 24 V to inhibit the hydrogen ions from sputtering the Cs.
8. The Sputtering of the RF Antenna

There were significant concerns that plasma ions bombarding the RF antenna limit the lifetime of RF sources with antennas immersed in the plasma [22]. Optical spectroscopy was implemented on the SNS H source to monitor the plasma for impurities. The spectrometer features two gratings, one optimized for short wavelengths and the other for long wavelengths [23]. Figure 11 shows the spectra emitted from a SNS H source shortly after deploying Cs. It is dominated by the Balmer lines of hydrogen and two bands from hydrogen molecules. There are no significant traces of oxygen or OH, while the Cs I line is clearly visible at 852 nm. The intense line at 589 nm is a superposition of the Na I line and a line from the molecular hydrogen band. The porcelain coating of the RF antenna is the only significant source of Na.

Figure 12 shows the time evolution of selected lines starting about 30 minutes after starting up the source. The start up procedure uses 50 kW RF power, but after deploying Cs the power had to be reduced to avoid plasma outages, most likely caused by discharges. The shown hydrogen delta line at 410 nm is a good indicator of the injected RF power. The bands from molecular hydrogen grow with time during the first ten hours or so as it can be seen by comparing the line at 582 nm with the delta
line. Oxygen at 777 nm, a fragment of water, is rapidly conditioned away and disappears when Cs is introduced. The Cs at 852 nm spikes during the 12-minute cesiation period and falls to a more moderate level. It then gradually falls to the background level over the next few hours. The data between 17 and 23 hours show the hydrogen molecular lines at 582 nm and 589 nm to be of equal strength. Accordingly, the difference between the 589 nm line and the 582 nm line is due to Na. This suggests that Na is present in the plasma during conditioning and for about 15 hours after cesiation. Raising the RF power and/or retuning the source briefly returns Na into the plasma. This coincides with the time periods when heavy impurities are in the plasma, namely water during conditioning and Cs after cesiation and retuning.

![Figure 12. H-δ, Cs I, O I, Na I and H₂ line emissions during the first day of a source.](image)

The sputter approximation of formula 1 predicts Na to be more likely sputtered by hydrogen ions than heavy ions such as H₂O and Cs. Apparently, Na sputters not as single atoms but as a cluster of several atoms, making its effective mass much heavier.

![Figure 13. Na sputtering threshold divided by the surface bond energy for different ion masses](image)
9. Summary

The interaction between the hydrogen plasma and the caesiated Mo converter contributes a large fraction of the produced H− ion beam and therefore is critical to the success of SNS. Spectroscopic data show significant impurities in the plasma during the start up of the source and those impurities appear to sputter the caesium as well as the antenna. However, these impurities disappear before or about at the same time as the Cs disappear from the plasma. Because all impurities become negligible within a day and hydrogen is too light to sputter the caesium and the antenna, sputtering does not appear to limit the lifetime of the SNS H− sources.

10. References

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