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Incremental Performance Improvements for a Surface-Conversion H^- Ion Source

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Abstract. We discuss some of the interventions on LANSCE's surface-conversion negative-hydrogen ion sources to increase reliability; lifetime and output without any major re-design of the machine. LANSCE's source presently delivers a baseline 16 mA, 60 Hz, 12% duty factor beam. We describe how better quality control and processing of tungsten filaments allow the comfortable completion of 28-day run cycles, how improved temperature control of the ion source body yields an increased H^- output, how higher input power through an additional filament allows operations at plasma densities while maintaining the filament lifetime and how adequate electrode biasing inside the source provide some control over the beam Twiss parameters on exit.

Keywords: surface conversion negative hydrogen ion source, cesium dynamics, tungsten filament driven.
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INTRODUCTION

Surface-conversion negative-hydrogen ion sources operate by the sputtering of H^- ions off a biased, low-work function surface (the converter) immersed in a cesiated, hydrogen plasma. Hydrogen atoms are adsorbed on the converter surface, whose low-work function favors their acquiring an additional electron. These H^- ions can be knocked off by energetic particle impingement. Since the converter has a negative bias, the impinging particles are positive ions collected from the plasma. Of particular effectiveness here are the cesium ions, whose mass makes them very capable of shaking the metallic substrate and sputter off H^- ions. Once ejected, the H^- ions traverse (or blend with) the plasma and exit the ion source.

Several different ion source configurations operate by these processes. The usual differences reside in the location of the converter surface, the cesium delivery mechanisms, and the ways to ignite the plasma. For example, the LANSCE accelerator at Los Alamos utilizes a H^- ion source that is driven by tungsten filaments, fed pure cesium, and has a converter that attempts to direct the H^- ions towards the exit aperture. In contrast, other designs favor plasma production through RF waves, converters close to the exit aperture while essentially point away from it, and get cesium through chemical compounds that when heated release elemental cesium. All these types are active and continue to be subject of study and re-design in other laboratories.

A filament-driven ion source such as LANSCE's, is characterized by its high output-current/input-power ratio and its low emittance, which makes this technology attractive in various contexts. The LANSCE accelerator facility in Los Alamos has operated such technology since its inception 30 years ago, delivering a baseline 16 mA, 60 Hz, 12% duty factor beam, but programmatic needs require improvements from this level. In the past few years, progress has been made in aspects such as materials quality control, filament lifetime and reliability, increased H^- output current as well as improved physics understanding, but with virtually no changes to our base design. In this paper these topics are discussed, each of which has yielded small but important improvements. Because of the improved understanding that these interventions provide, they set the stage for a more substantial re-design of the ion source, something that is left for a future report.

INCREMENTAL PERFORMANCE IMPROVEMENTS

We call "incremental" those changes in process (either in preparation or operation) that lead to small but important improvements in some aspect of the ion source performance such as lifetime, reliability or total output current, but that do not involve a substantial re-design of the ion source itself. In this report, improvements are described in: filament material quality control and processing, ion source temperature and its effect on cesium dynamics, improved repeller electrode biasing, and increased input power.

Tungsten Filament Management

Somewhat surprisingly, the operations and reliability of an accelerator facility with multiple user-programs can be brought down by the failure of a single component whose complexity is not far from that of a light bulb. In the past, operations at LANSCE were seriously affected by inadequate quality control of the material used to build the filaments and by the management of the filaments during operations.

After securing tungsten filaments with suitable purity, another important factor in the reproducibility of filament lifetime in production ion sources is their preparation or "conditioning" process. The main objective of this stage is to induce a re-crystallization of the tungsten, allowing the formation of larger grains, which provide higher mechanical strength. The conditioning also results in the ability of the filaments to yield higher arc currents. In brief, the process takes place in two similar stages. The first one takes approximately 20 hours and consists of an out-gassing stage, followed by the injection of hydrogen gas, and the slow increase of the driving current until roughly *2/3* of the production arc magnitude is reached. At this point, the system is turned off, let up to atmospheric pressure and opened up to have its internal surfaces cleaned. The second stage is identical but takes place in approximately 4 to 5 hours. After this, the source is deemed fit for production.

During the operation of a multi-filament source, experience suggests that one important guiding principle during operations is the equilibration of the operating temperature of the filaments. In this way, the arc current is presumably equally distributed as is the temperature damage induced during every pulse. This helps minimize the maximum operating temperature for a given discharge current.

In a similar spirit, ion source filaments at LANSCE are managed by continually trying to maintain parity between the values of their resistance values. For instance, if for a given driving current one filament displays a slight increase in resistance, this can be interpreted as a region of the filament that is operating at a higher temperature and is thus more susceptible to damage. With the policy of equilibrating the resistance values, the current to this filament would be slightly decreased (which would result in a lower arc current), while the current to the other filament would be increased to pick up the drop in arc current. This practice has consistently allowed filament lifetimes to comfortably surpass the scheduled 28-day cycle used in the operations at LANSCE. As an example, Figure 1 shows how the relative resistance change of the filaments is maintained in unison during the whole run cycle until failure.

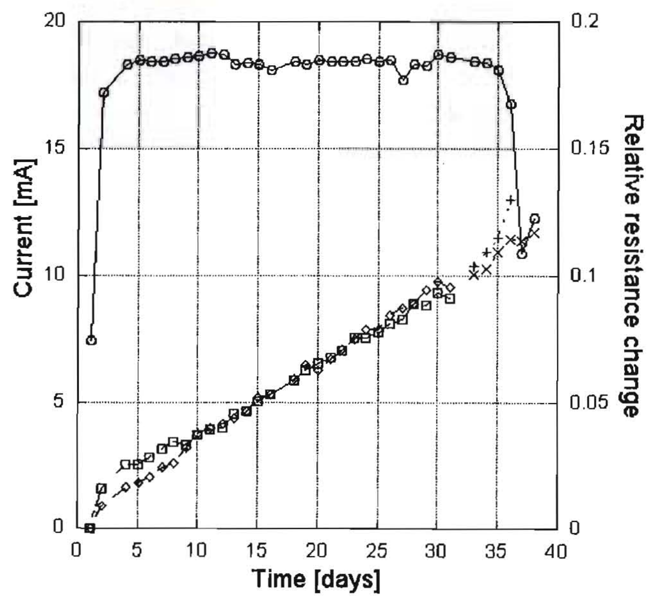

FIGURE 1. Bottom: relative change of the filament resistance with respect to its initial value. The two data sets represent the two filaments inside the source. The objective during operations is to match the resistance of both filaments. Resistance is here a proxy for the filament operation temperature. Top: corresponding H^- output current.

Ion Source Body Temperature

The main effect of the ion source body temperature is to alter the balance of the cesium dynamics inside the ion source. Details of our research on this topic were presented before [1]. In brief, cesium coverage is an important factor that determines the H^- yield of the converter surface since it determines the value of the surface's work function and thus its ability to lend electrons to the adsorbed hydrogen atoms.

The cesium balance on the converter surface is determined by two opposing effects. On the one hand, evaporation and sputtering of *Cs* atoms during the arc discharge decreases the *Cs* atom coverage. Sputtering is strongly influenced by the voltage bias on the converter, as energetic particles are more able to sputter off *Cs* atoms. On the other hand, the surface is constantly being replenished by the deposition of *Cs* atoms that flow freely into it from the *Cs* gas atmosphere (thus proportional to the *Cs* gas pressure) and become adsorbed.

As an example, if one makes the hypothetical change in the operation duty factor from 6% to 12%, this change would be accompanied by an increased depletion rate of the adsorbed *Cs* atoms, all other things being equal. To counteract this effect, the standard measure would be some combination of an increase of the *Cs* gas pressure by rising the temperature of the cesium reservoir and a lowering of the converter voltage bias to reduce the sputtering.

Because of their mass, *Cs* ions are particularly effective in sputtering H^- ions from the converter surface. For this reason, an increase in the *Cs* gas pressure translates into increased H^- output current. To rely exclusively on the delivery rate from the cesium reservoir to increase the *Cs* particle density is inefficient, since a substantial number of *Cs* ions are simply deposited on the cold source chamber walls; in addition the lifetime of the ion source could be impaired. In contrast, to attain an increase in the *Cs* gas pressure, a change in the temperature of the chamber walls is easily achievable.

For a given input power on the filaments, the equilibrium temperature is determined by the water cooling system, whose action depends of course on two main parameters, the water temperature and the flow rate. Given the specific configuration of our ion source cooling system, varying the input water temperature was explored. As a result, it was confirmed that the H^- output current would increase linearly at a rate of 0.11 to 0.14 mA/K in a 60 Hz operation mode and at a rate of 0.06 to 0.08 mA/K at 120 Hz. The higher duty factor is directly opposes the increased deposition rate achieved with the higher *Cs* gas pressure.

An important result was that, within the range of temperatures explored, in which the beam current increased from 14.0 to 18.3 mA, the emittance (1-RMS normalized) stayed constant at 0.022 π cm·mrad.

Effects of the Repeller Electrode Voltage Bias

After leaving the converter, the H^- ions propagate within the source as a compensated beam due to the presence of the plasma. This quality of being a directed beam is what makes this type of ion source configuration different from others where the converter is located close to the exit aperture. In this second case, the path of the H^- ions is more indirect: the ions need to collide and blend with other ions in the plasma volume before being extracted. In our case, in contrast, it is essentially the ions that did not get deflected that can exit the ion source.

While necessary, the plasma region that compensates the beam is not extended all the way until the exit aperture. The result would be an unacceptably large amount of electrons on exit. In order to regulate the flow of electrons, the LANSCE source uses an element denominated the "repeller" electrode. This is a water-cooled structure that contains a permanent magnet setup, and that can be raised to some positive potential up approximately 20V. Previously other magnetic configurations have been tested, which have involved a trade-off between the electron-to-H^- ratio on exit and the total amount of H^- current [2]. The present magnet configuration produces a line cusp right on the beam path.

The repeller affects the electron flow in two ways: by the shape of the magnetic field lines and by an electric bias. Figure 2 shows a schematic of the locations of these elements produced by a particle-in-cell simulation.

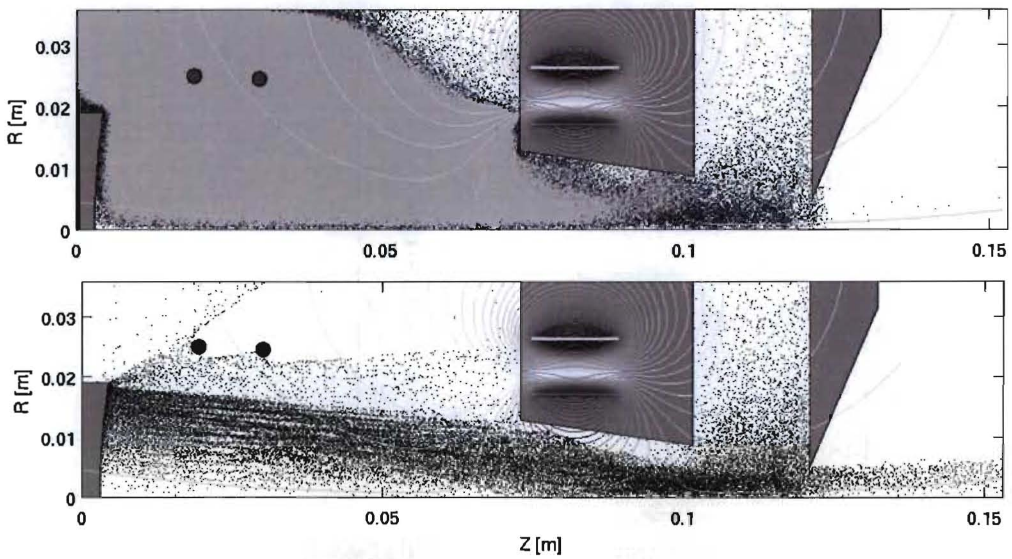

FIGURE 2. Snapshot from an RZ, particle-in-cell simulation depicting some prominent components of the ion source: the converter (left), the plasma region, the "repeller" housing a ring magnet (middle), and the exit aperture (right). The top figure shows the configuration of electrons (light) and positive ions (dark), the bottom shows the negative hydrogen ions.

The simulation makes evident that once the plasma region is disrupted, there are various mechanisms at play which affect the beam behavior. For instance, gradients in the particle density of electrons and ions affect the degree of compensation that the H^- beam experiences. This in turn affects the beam propagation inside the source and thus the losses, as the beam can be intercepted by metal surfaces.

With the source's present setup, decreasing relations are observed between the H^- ouput current and the electron/H^- ratio vs the repeller voltage (see Figure 3). When analyzing the effects on the Twiss or Courant-Snyder parameters of the beam exiting the source, another clear dependence is noted, an increasing beam divergence as the repeller voltage increases (see Figure 4). This is significant because the output current also drops with the repeller voltage. It is know that the increased divergence is not the result of increased beam space charge outside of the source (note also that the space charge reduction by the co-moving electrons is negligible as their relativistic γ differs from unity by only 1%). The above supports the tracing of the increase in the beam divergence to processes inside the ion source. In this case, the positive ion density in the region between the repeller and the exit aperture is affected by the electron population, and thus, so is the capability to compensate the beam before it exits the ion source. The result is an increase in the divergence of the beam inside the source, coupled with higher beam losses when the wider beam intercepts the exit aperture. This larger divergence is can detect downstream from the source.

In the future, this situation might make possible the treatment of the beam inside the source in more conventional terms, like the introduction of a stronger focusing element to increase the capture at the exit aperture plane.

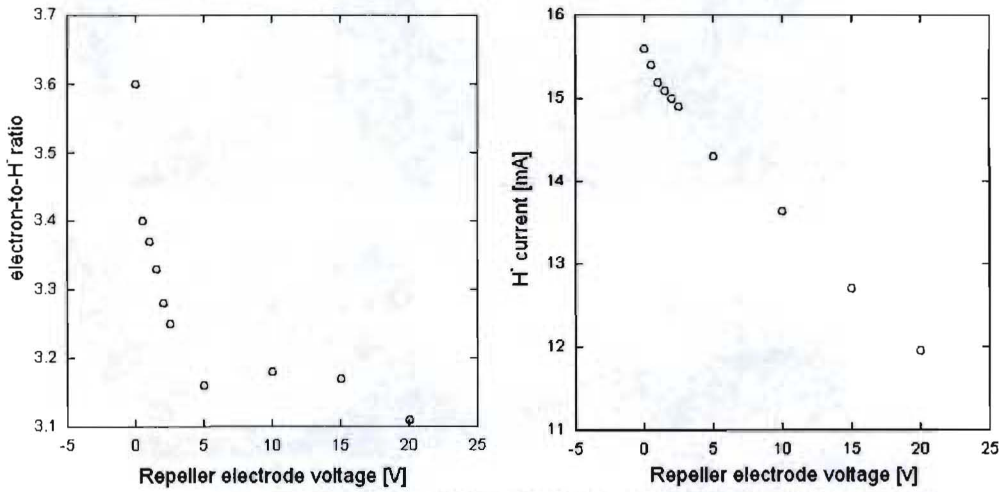

FIGURE 3. (a) e^-/H^- ratio vs. repeller electrode voltage. (b) Negative hydrogen ion current vs. repeller electrode voltage. Arc discharge of 37 A.

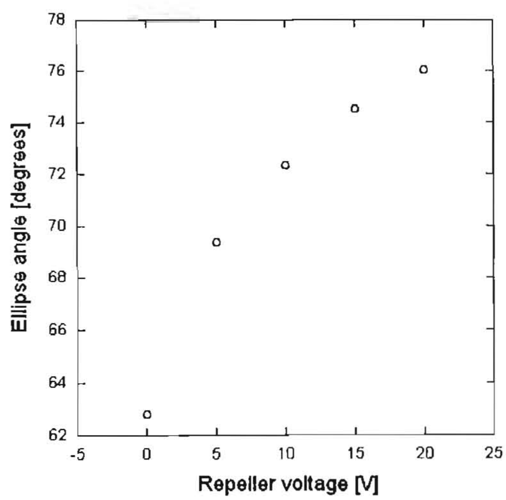

FIGURE 4. Ellipse tilt angle (more specifically arctan(- α/β)). Arc discharge of 37 A.

Increased Input Power

An output current vs. input power curve for LANSCE's H^- production sources is shown in Figure 5. In the range shown, the linear dependence is evident. For a discharge voltage of 180 V the H^- output beam current per unit of input power is between 3.6 and 1.8 mA/kW, with a decreasing efficiency as input power increases. A direct increase in the input power to the existing filaments as a means to attain higher currents would be penalized by a shortened filament lifetime, which obviously is not desirable. The alternative is to increase the electron emission area from the filaments. This can be attained in several ways: increasing the filament diameter [3], or increasing the emissive length.

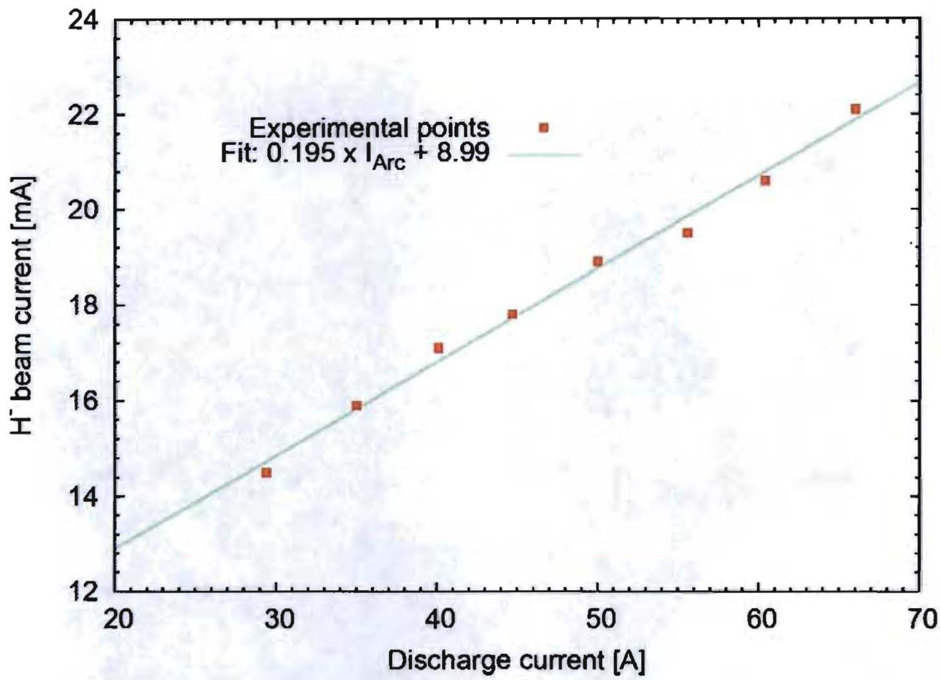

FIGURE 5. Extracted H^- beam current as a function of arc discharge current. The normal range of operations for LANSCE's source is 35-45 A.

It is assumed that the same behavior represented by Figure 5 can be achieved regardless of the source of the arc current. For this reason, a decision has been made to increase the emissive length by adding a third filament to the ion source.

The electron current from an emissive filament is not uniform along the filament's length, but rather it is determined by the filament's temperature profile during the arc discharge. The latter is in turn determined by the combined effects of the DC current that drives the filament, and the current pulse that drives the discharge. The current pulse enters the filament through one terminal, but since the discharge circuit closes with the ion source chamber, this current is not present at the other end of the filament. This results in a relatively small segment of the filament delivering a disproportionately large fraction of the discharge current. Evidence for this mechanism is frequently found in the failure modes of the filaments. In general, these will consistently exhibit a similar breaking point location: always on the negative side of the filament, but at sufficient distance from the holding post so that cooling by conduction is not important. A visual inspection confirms that this region is eroded more strongly than the corresponding location on the opposite end of the filament. These observations suggest that further increases in filament lifetime can be achieved by a periodic (in the scale of days) flipping of the filament polarity.

Because of the above, a filament of substantially smaller length was designed for testing, with a single hairpin bend (see Figure 6). It has been confirmed that this configuration is able to deliver as much arc current as the longer, standard filaments. In this way, the total input power in the discharge can be increased while maintaining the ion source lifetime.

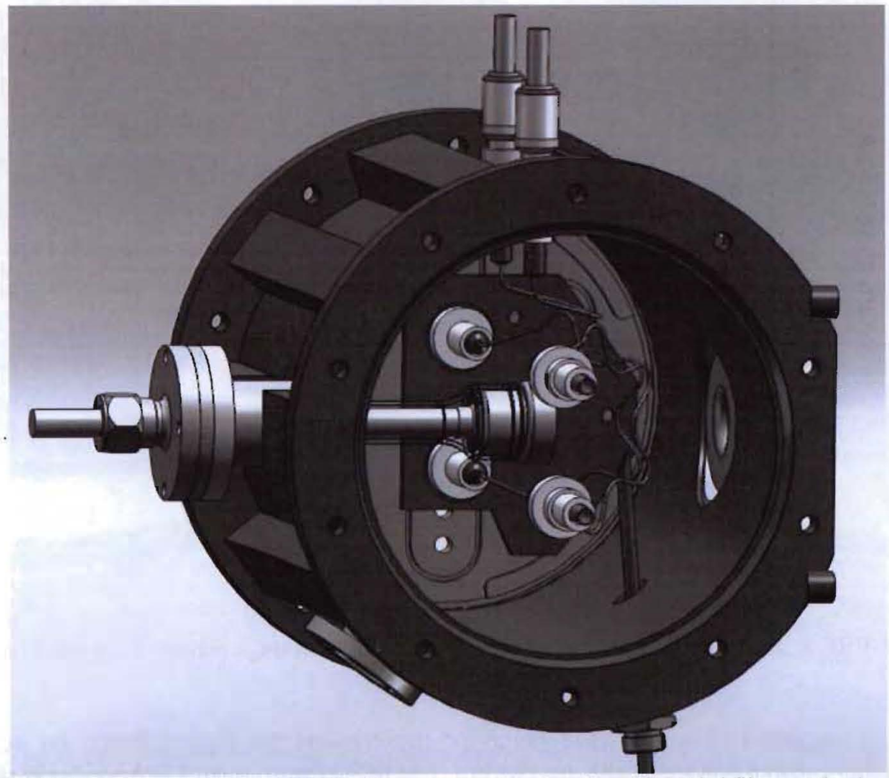

FIGURE 6. Model of the LANSCE H^- ion source showing the added third filament (top).

Preliminary tests have pointed out the importance of the location of the emissive segment. While the design intent was to have this segment (the hairpin bend) as close as possible to a low-magnetic field region (i.e. the center of the chamber), manual fabrication difficulties resulted in a suboptimal positioning closer to the wall which favored a too-direct flow of electrons from the filament to the ion source chamber wall. This was identified by observing an unusually hot region on the source chamber wall, close to the hairpin bend. Cesiation was not attempted with this configuration so presently is not possible to report if this condition adversely affects the achievable plasma density.

ACKNOWLEDGMENTS

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