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Design improvements to the SNS ion source and diagnostics

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Design improvements to the SNS ion source and diagnostics

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Abstract. The U.S. Spallation Neutron Source (SNS) is a state-of-the-art neutron scattering facility delivering the world's most intense pulsed-neutron beams to a wide array of instruments which are used to conduct investigations in many fields of science and engineering. The accelerator system is fed by an RF-driven, multicusp, H^- ion source which nominally provides pulsed beam currents of 50-60 mA (1ms, 60Hz). This report provides a discussion of ongoing design improvements to the SNS ion source and Low Energy Beam Transport (LEBT) as well as diagnostic upgrades undertaken since the previous ICIS conference. These improvements include (i) simple mechanical modifications to the source outlet aperture which resulted in dramatically increased extracted beam current and comparable or lower emittance at similar beam currents, (ii) design improvements to the LEBT chopper target which will enable full power beam-dumping during physics studies, (iii) refinement of the SNS Allison emittance scanner that has enabled the first reliable LEBT beam measurements at full beam power (65kV, 50-100mA, 1ms, 60Hz) on the SNS ion source test stand and (iv) the implementation of a thermal imaging camera for the monitoring the LEBT electrode temperatures. (v) The design of an advanced Cs system, capable of more efficient Cs utilization with significantly lower Cs losses from the source is also presented. Mechanical details, computational simulations and experimental results are discussed within the context of these improvements.

1. Introduction

The Spallation Neutron Source (SNS) is the highest-power pulsed neutron source currently operating worldwide and typically hosts ~1000 researchers per year. The accelerator system utilizes an RF-driven, multicusp, H^- ion source which nominally provides pulsed beam currents of 50-60 mA (1ms, 60Hz) [1]. Ions extracted from the source are then focused by a Low Energy Beam Transport (LEBT) into a Radio Frequency Quadrupole (RFQ) accelerator which, in turn injects a linear accelerator ultimately delivering beam to a neutron production target [2]. Fig. 1 shows details of the ion source and electrostatic LEBT. Presently, a beam current of ~35 mA is required out of the RFQ to support SNS operations for run periods of ~4 months with an availability >99.5% [3]. Future facility upgrades will likely require ~45 mA out of the RFQ with a similar run-period and availability [4]. Depending on the transmission of the RFQ, which has varied significantly in the past, additional beam current from the source is desired to provide sufficient margin to consistently meet these upgrade requirements [5]. This work presents design modifications to SNS ion source and LEBT which have been investigated at our facility since the last ICIS which include: (i) simple mechanical enlargement of the source outlet aperture which dramatically increased beam current (ii) modifications to the chopper target, shown in Fig. 1, to allow full-beam interception in the LEBT (iii) modifications to the Allison emittance scanner used on the test stand to allow emittance measurements at full beam power (up to 100 mA, 60 Hz, 1 ms). (iv) implementation of a thermal camera to monitor LEBT lens temperatures and (v) the design of a new high-efficiency, low loss Cs delivery system which should eliminate most of the problematic gas-phase transfer of Cs within the source.

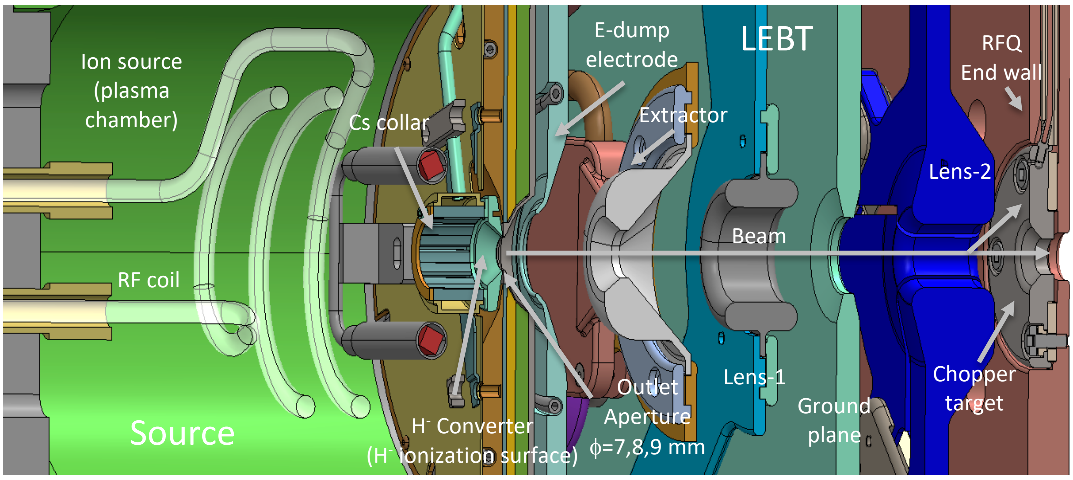

Figure 1. Central portion of the SNS ion source and LEBT: nominal bias: Source: -65kV, E-dump: -59kV, Extractor: 0kV, Lens-1: 40-45kV, Ground plane:0 kV, lens-2: 40-45 kV, Chopper target: 0kV

2. Increasing source outlet aperture size: theory and experiment

Recently, we have shown that small increases in the diameter of the outlet aperture, can significantly increase beam current without excessive emittance growth for comparable beam current [6]. We found the effect of simply drilling out the outlet aperture and H^- converter (shown in Fig. 1) from ϕ=7→8→9 mm achieved nearly a factor of 2 increase in beam current with up to 110 mA measured on the test stand [5]. See beam current data plotted in Fig. 2a (points). In addition, during testing on the SNS front end, ~60 mA was measured out of the RFQ with input current administratively limited to 75mA [5]. These experiments show that the additional beam current margin desired for facility upgrade projects can be met with the baseline SNS source with this simple modification. The slightly elevated H_2 gas consumption of the source was found not to be problematic to operation.

To further understand this effect, as well as determine applicability to other plasma-type ion sources, IBSIMU and PBGUNS plasma extraction simulations were performed. Only the former code will be discussed here for brevity. While these gun-type codes do not capture the full physics of beam formation, they have been proven useful in guiding the development of the SNS extraction and LEBT systems as well as many other ion sources worldwide [7,8,9]. Previous simulation input files used to successfully model the baseline SNS source (ϕ=7mm) were modified to include ϕ=8 and 9 mm outlet apertures while holding constant other input parameters [7,9]. Fig. 2a shows the calculated beam current (shown as lines) versus the H^- current density injected upstream into the simulation. In gun codes, the injected current density is considered a free parameter roughly proportional to the bulk plasma ion generation rates and is used to set the beam current of the simulation. Both data and simulation show the expected linear scaling of beam current with aperture size.

IBSIMU beam trajectory plots are shown in Fig. 2c for H^- ions (red) and coextracted electrons (yellow) for each of the three outlet aperture diameters investigated. Under nominal extraction conditions (ϕ=7mm) both codes show a strikingly convex plasma-beam meniscus which is calculated self-consistently and represents a balance between plasma pressure and the extraction field. The highly convex meniscus essentially forms the emission surface of a divergent beam which makes a dominant contribution to the downstream emittance. Fig. 2b shows the calculated emittance at the exit of the simulation (solid lines) while the dashed reference lines show the minor contribution ion temperature (T_i~1eV) makes to the emittance [9]. Fig. 2b also shows (points) the emittance measured on the test stand at the LEBT exit for each of the apertures under consideration. As can be seen in Fig. 2c, larger apertures effectively reduce the meniscus curvature (flatting it) for a given extracted beam current due to lower required plasma densities.

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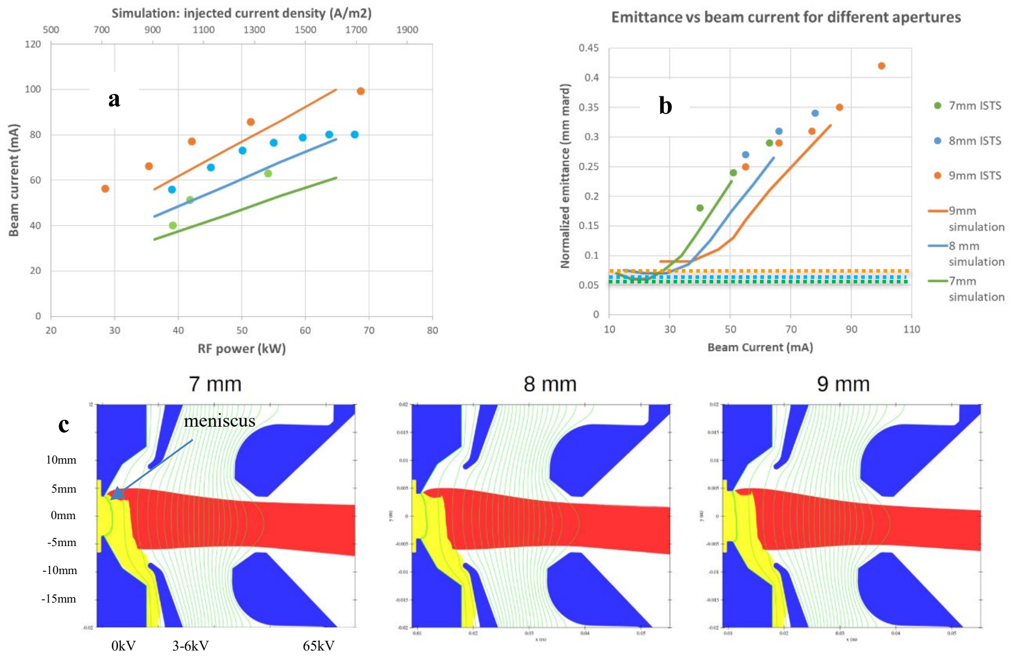

Figure 2. (a) Experimental (points) and calculated (lines) beam current versus RF power and injected current density, respectively, for the 3 apertures studied. (b) Normalized RMS emittance versus beam current. Dashed lines represent ion temperature contribution to total emittance. (c) IBSIMU simulation of the of the SNS source with 50 mA of H^- ions extracted (red) and 300 mA of electrons (yellow) for each aperture studied (ϕ=7,8,9 mm).

For a given beam current, say 50mA, Fig. 2b shows a significant decrease in calculated emittance as the aperture diameter is increased due to this flattening optical effect. The decrease in the measured emittance is not as pronounced likely due 3 factors: gun codes not capturing the full physics, emittance measurement location and significant uncertainties in emittance measurements [5]. Overall, however, meniscus shape plays a key role in understanding the effect of increasing the outlet aperture size and whether similar benefit could be expected in other ion sources. For example, increasing the outlet size will likely increase the emittance if the initial meniscus is flat or concave.

3. Improving the LEBT chopper target, emittance scanner and a new LEBT temperature diagnostic

This section describes several incremental but important upgrades to the SNS LEBT and test stand which could be of interest to the community. First, the chopper target, shown in Fig. 1, is being upgraded to accommodate the thermal load (~250W) of full beam interception which will prevent dumping beam into the RFQ during certain operational modes. The target itself is made from TZM and is electrically isolated with Al_2O_3 insulators. Modifications include increasing bolt number 5→8; adding stainless steel HeliCoils to the soft Cu RFQ end wall; applying maximum recommended torque to bolts and polishing all thermal contact surfaces. COMSOL thermal/mechanical modelling and a test of a prototype target on the test stand at full beam power (65kV, 60mA, 1ms, 60Hz) showed manageable target temperatures of 200ºC versus thermal run away of the unmodified target. A slight redesign will be necessary to accommodate in situ temperature measurement on the SNS accelerator. Similarly, the Allison emittance scanner used for these measurements on the test stand was also modified to handle the full beam power by adding bolt-on W front slits (3.2 mm thick) using 8 x 1/4 inch bolts mounted into a water-cooled Cu backing. Contact surfaces were polished, a Sigraflex 0.25 mm expanded graphite sheet was inserted into the interface and bolts were tightened to their specified torques. COMSOL thermal/mechanical simulations were also used to validate the modification and since implementation, >1 year ago, many emittance scans have been performed (up to 100mA, 1 ms, 60Hz) without any damage to the scanner. This approach was also taken by Fermilab [10] and avoids employing a costly and complex W-Cu braze. Lastly, a FLIR model A50 combined optical and thermal camera was installed on the test stand to monitor temperatures of LEBT lenses: extractor, lens-1 and the ground plane shown in Fig. 1 through a sapphire window atop the LEBT vacuum tank. These electrodes occasionally overheat during ion source start ups and can now be monitored as beam current is increased for future facility upgrades. The camera can resolve temperatures of ±2 ºC with 1-2mm of resolution. So far we learned that the max temperature in the LEBT occurs on the ground plane and is typically ~135 ºC near the aperture during normal operation. After nearly a year of operation on it seems to function well in the LEBTs x-ray environment.

4. Design of a direct-transfer Cs system

Fig. 1 shows the baseline Cs collar (nominal T: 175-225 ºC) which houses 8 Cs_2CrO_4 dispensers and is attached to a conical Mo H^- ionization surface (T~350 ºC) surrounding the outlet aperture. The system has been described previously [1,3] and overall performs quite well but does have a few disadvantages: (i) It is limited to only 2-3 cesiations (accomplished by briefly heating collar to ~500 ºC), (ii) can fail to maintain an optimal Cs coating on the ionization surface leading to slight beam decay and electron loading of power supplies over a run period and (iii) can occasionally cause LEBT sparking due to over cesiation. To improve this, we first set out to design a supplemental rear-feed, elemental Cs system, as is commonly employed in other H^- facilities [11]. Fig. 3a shows the mechanical design which features 2 commercially available heaters to provide an increasing temperature gradient from the Cs reservoir (50-200 ºC) to the plasma chamber injection point (~350 ºC). COMSOL software was used to validate this thermal/mechanical design and the molecular and transitional flow modules were then employed to simulate gas-phase Cs transport through a constant ~3 Pa of H_2 gas in the plasma chamber using the Monte Carlo routine. Here the Cs-H_2 total cross section taken from Ref. 12 and trajectories are plotted in Fig. 3c for the plasma-off condition (94% of the time). It is clear from this simplistic analysis that ~100% of the Cs is diverted to the water-cooled plasma chamber walls (50 ºC) where Cs will accumulate far away from the outlet aperture only to be re-evaporated at rates governed by Cs vapor pressures and other surface reactions [13]. This represents a significant Cs loss channel since it is widely held that nearly all the surface produced H^- contributing to the beam is produced on the H^- converter due to the short mean free path of H^- in the source volume and proximity to the outlet aperture [14,15]. The simulation also shows that ~30% of the small amount of the useable Cs delivered by a rear-feed system is lost to the LEBT through the outlet aperture. Similar modelling of the baseline SNS Cs_2CrO_4 system shows an overall higher Cs utilization efficiency but at the cost of larger losses to the LEBT. Alternatively, we are now investigating an approach which replaces the baseline Cs collar and converter with the integrated assembly shown in Fig. 3b. Cs-dispersers are now placed directly behind a porous frit-type converter (Mo, Re, Ni or Pt) thereby eliminating most of the lossy, gas-phase Cs transfer. The frit can have micropores (e.g. supplied by Heatwave Labs Inc.) or machined with tiny holes. Advantages include: (i) eliminates most Cs volume transport losses (ii) protects dispensers from direct plasma bombardment (iii) better temperature control of converter, T<350 ºC which would be in line with other H^- sources and (iv) lower Cs losses to the LEBT. For example, quantitatively at 175 ºC, 8 Cs-dispensers will release only ~10^6 Cs atoms/s [15] which should approximately supply the amount needed to maintain a ~1/2-monolayer on the converter at the same temperature [13]. In contrast, the baseline converter (T ~350 ºC) requires ~10^{11} Cs/s to maintain a half-monolayer resulting in much more Cs lost to the LEBT. In related work, a 1983 experiment showed significantly more H^- production from a porous versus solid converter [16]. Going forward we plan to test this configuration in the near future.

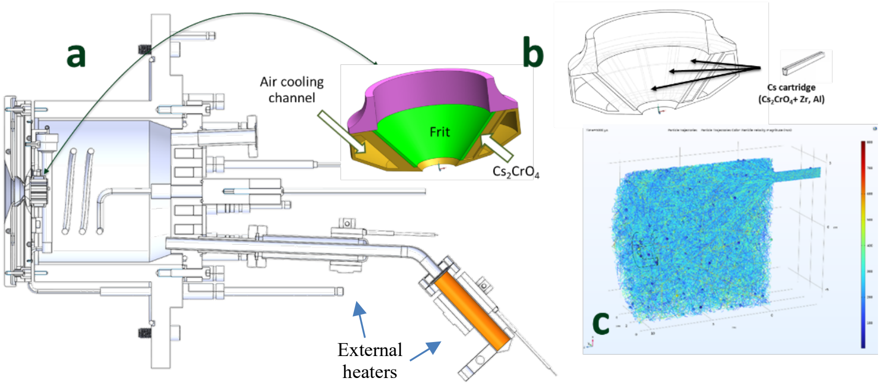

Figure 3. (a) The Baseline SNS source shown with the proposed rear-feed elemental Cs system. (b) enlarged view of the proposed direct-transfer Cs collar (replaces existing) and (c) COMSOL Cs flow simulation of the proposed rear-feed Cs system.

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