Installation and Commissioning of the Ion Source Systems for the New SNS 2.5 MeV Injector

The SNS Ion Source Team and Robert Welton

ICIS 19 Lanzhou

• Why replace the existing Injector?
• Development of the new SNS injector on the Beam Test Facility (BTF) and Ion Source Test Stand (ISTS)
• Installation, commissioning and performance
ORNL hosts the world's most powerful accelerator-based neutron source. More than 1000 users per year conduct experiments in physics, chemistry, biology, material science, and engineering.

Currently the SNS operates near 1.4 MW with future plans to run at 2.8 MW to support a second target station.
The SNS accelerator system overview

Front-End:
Produce 1 ms long, H+ beam pulses at 60 Hz with ~300 ns chopped every ~1 μs

Accumulator Ring:
Compress 1 ms long pulse to ~700 ns

RFQ
IS
JTL
CCL
SRF, β=0.81
SRF, β=0.81

65 keV 2.5 MeV
~46 mA needed for 2.8 MW
~35 mA needed for 1.4 MW

~1 GeV

Current

Front-End:
~1 ms macropulse

Accumulator Ring:
~1 ms macropulse

Current

~1 ms
~1 ms

LEBT chopper system makes gaps

<1 μs

~35 A

~35A

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Why replace the original Berkeley Injector?

- The Berkeley RFQ (~17 years of service) has undergone a slow degradation of transmission which was making it increasingly difficult to meet SNS beam current requirements.
- Several unexplained detuning events and shifts in the RFQ field distribution have motivated us to procure a spare RFQ accelerator and build a dedicated off line facility to test it.
- Seized the opportunity to make multiple upgrades the ion source systems and tested them on the BTF and ISTS.
Operational history of the SNS ion source with the Berkeley RFQ

- Over the years we had had to increase source output to compensate for decreased RFQ transmission.
- Poor transmission results from not being able to run at full design field most likely caused by degradation in structural integrity either due to brazed joints shifting or surface coating / erosion. Also we found that the internal RFQ cooling system cannot maintain resonance under some conditions.
- Decision: Procure, commission and replace the RFQ by spring of 2018
The new RFQ accelerator

Manufactured by Research Instruments, GmbH

- Mechanical & RF structures were designed at ORNL using the Berkeley beam dynamic design
- Much better pumping: 4 additional turbos added
- No brazed joints (solid Cu) vacuum deformation: -18 vs -119 kHz/C
- Octagonal shape can provide better vacuum quality and mechanical strength
The Beam Test Facility

- Designed and built at ORNL to validate the new RFQ
- Currently serves as a stand alone 2.5 MeV research accelerator + diagnostic beam line employing the either RFQ
- Supports an extensive accelerator physics research program, worlds 1st 6D – phase space studies

All HV structures have a min of 6” gaps (2.5x FOS)

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The history of the BTF

- **2009** Decision to procure a 2nd RFQ for the SNS
- **2013** RFQ arrives at ORNL
- **2014** RFQ checked out with low power RF (acceptance test) / BTF construction largely complete
- **2016** Beam extraction and RFQ acceleration & transition to operations
- **2018** RFQ’s swapped with the SNS front end and both systems restarted
- **2019** BTF uses Berkeley RFQ (50 μs) and expands AP program adding new lines, etc.
The new SNS 2.5 MeV injector consists of components from the BTF and ISTS (ion source test facility)

- SNS ion sources
- BTF RFQ
- BTF LEBT enclosure
- ISTS new HV enclosure
- ISTS new On-ground H$_2$ gas system
- ISTS new 2 MHz matching network
- ISTS new Chopper target
- ISTS new LEBT gate valve
The SNS ion sources

- **SNS ion sources**: baseline source #2,3,4,5,6,7 & external antenna sources x2, x3, x4 can be installed interchangeably on the **SNS, BTF and Ion Source Test Stand (ISTS)**, they deliver persistent beams of **50-60 mA beams** through the LEBT.

- **Internal antenna source** – the workhorse of the SNS accelerator, originally designed and built at LBNL and modified by ORNL.

- **External antenna source** – the workhorse of the BTF, the plasma ignition gun has not yet been perfected sufficiently to use this source on the SNS but we have built a test bench to characterize the guns without source.
The ion source HV enclosure for the new SNS injector

- Greatly improved routing of HV source cables and water lines. Increased all HV gaps to >6 inches, external sparks are now rarely observed!

- Uses helical HV water breaks developed previously on the FE & BTF

- Removed the ‘golden 2 MHz matcher’ replaced with an open external matching network

- On ground H₂ gas system installed, feeding the source through a 12 cm ceramic break at 5-10 psig. Easy bottle exchange

- Installed new chopper target design allowing maintenance during routine LEBT electrode replacements
New 2 MHz matching network

- Electrical circuit is electrically identical to LBNL golden matcher
- New design, however, offers much larger voltage gaps and full visibility
- RF antenna reference resistors had to be upgraded to a 8W array to better handle charge accumulation
- Configuration extensively tested on ISTS and similar on the BTF

\[ L \frac{C}{N^2} = 1 \]

- Matching transformer
- Matching capacitor
- G-10 isolation shaft
- Match motor on ground
In 2018 the new SNS 2.5 MeV SNS injector was installed.
Injector beam commissioning went smoothly

- Vacuum and water testing done late March
- Conducted HV and RF testing early April
- Beam extraction began in late April after Readiness Review
- Measured LEBT and MEBT beam current, beam emittance, HV stability with beam & noted beam persistence
- On May 7 we installed source #2 and neutron production begins
LEBT / MEBT beam current measurements
MEBT emittance scans

- RMS normalized (0.6% threshold)
- MEBT scans: 2-slit method (50 μs)
- Very similar to emittance from Berkeley RFQ

- Phase scans of the 1st 2 RF bunchers in MEBT:
- The energy after RFQ was found in the range 2.5 ± 0.05 MeV or 50 kV
RFQ transmission measurements

<table>
<thead>
<tr>
<th>Ion source RF antenna current rms (arb. unit)</th>
<th>QEI delivered RF power (kW)</th>
<th>LEBT output/RFQ input current (mA)</th>
<th>RFQ output current (mA)</th>
<th>RFQ amplitude setpoint</th>
<th>RFQ transmission (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.94</td>
<td>40.1-3.6=36.5</td>
<td>33</td>
<td>30</td>
<td>0.440</td>
<td>91.0</td>
</tr>
<tr>
<td>2.08</td>
<td>45.3-3.5=41.8</td>
<td>38</td>
<td>35</td>
<td>0.440</td>
<td>93.1</td>
</tr>
<tr>
<td>2.18</td>
<td>47.8-1.5=46.3</td>
<td>43</td>
<td>40</td>
<td>0.440</td>
<td>92.5</td>
</tr>
<tr>
<td>2.36</td>
<td>56.2-1.6=54.6</td>
<td>49</td>
<td>45</td>
<td>0.440</td>
<td>91.8</td>
</tr>
<tr>
<td>2.61</td>
<td>68.5-0.7=67.8</td>
<td>53</td>
<td>50</td>
<td>0.440</td>
<td>94.3</td>
</tr>
<tr>
<td>2.61</td>
<td>68.0-0.9=67.1</td>
<td>53</td>
<td>50</td>
<td>0.440</td>
<td>94.3</td>
</tr>
</tbody>
</table>

Source #6
Measured and calculated RFQ transmission

- Nominal input current: ~40 mA
- Nominal input emittance: ~0.2 \( \pi \) mm mrad
- Parmteq calculated RFQ transmission: ~90%
- Nominal measured RFQ transmission: ~90%
- Transmission now close to design
Historical RFQ transmission measurements

The RFQ transmission has been restored to design values!
Summary and conclusion

- The major components of the new injector have been developed and tested at ORNL’s the Beam Test Facility (BTF) and Ion Source Test Stand (ISTS).

- The basic injector configuration ran on the BTF for **over 4100 hours** allowing considerable operational experience with the new RFQ while supporting the accelerator physics program mostly using the External Antenna source.

- In 2018 the new injector was **installed and commissioned** on the SNS front end. Beam current, beam persistence, transverse emittance, energy and energy spread were all measured and found to **meet and exceed the SNS requirement**.

- In Nov 2018 the RFQ experienced an operational end wall c-seal, failure which is currently being addressed by regular inspection / replacement and should be solved by seal redesign.

- For about a year and half now, the new injector has operated reliably for neutron production with an ion source / LEBT reliability of **> 99.5%**.

- Overall this upgrade increased the available SNS beam current by **~20%**, dramatically reducing the challenge of meeting the 1.4 MW SNS beam current requirement.

- The higher beam current requirements of major SNS upgrade projects can **now be routinely achieved!**
An Artist's conception of the 6D physics experiments on BTF

By Jill Hemmon
Back up slides
## Operational history since installation of new injector

<table>
<thead>
<tr>
<th>Ion source</th>
<th>Length of service</th>
<th>Beam power required</th>
<th>RFQ</th>
<th>Beam current delivered (BCM02)</th>
<th>Issues</th>
</tr>
</thead>
</table>
| #6         | 11 days 4/26/2018-5/7/2018 | New RFQ  
Set point: 0.44 | 30-50 mA | Source was used for commissioning of the new injector, 30 mA / 40 kW, 35 mA / 45 kW, 40 mA/49 kW, 45 mA/55 kW, 50 mA/68 kW |        |
| #2         | 91 days 5/7/2018-8/6/2018 | 1.3 MW  
New RFQ  
Set point: 0.44 | ~43 mA / ~45 kW | the first source run for production with the new front-end, no failure or degradation, 55 mA / 62 kW was demonstrated during beam studies |        |
| #4         | 4 days 8/17/2018-8/21/2018 | A popped out LEBT thermocouple wire caused 65 kV arc and disabled the source operation |        |
| #6         | 87 days 8/21/2018-11/16/2018 | 1.4 MW  
New RFQ  
Set point: 0.44 | ~43 mA / ~55 kW | Poorly referenced 13-MHz matcher box caused plasma outages, LEBT extractor loose screw caused misalignment of the beam, both problems were fixed/mitigated, the source served for production until the run was ended prematurely due to RFQ C-seal issue |        |
| C-seal failure | #2 | 46 days 12/27/2018-2/11/2019 | 40-35 mA / ~52 kW | A popped out LEBT thermocouple wire was removed without compromising the already cesiated source by flowing dry nitrogen while the flange for the thermocouple feedthrough was removed, e-dump insulator failure necessitated reducing the e-dump voltage to 2.7 kV; after ~3 weeks with lowered e-dump, decision was made to change out the source |        |
| #4         | 43 days 2/11/2018-3/26/2019 | 1.4 MW  
New RFQ  
Set point: 0.385 | ~40 mA / ~55 kW | there were slight decay of beam current and droop in e-dump voltage, Cs collar temperature was raised two times to make up the beam, the source served for production until the run was ended prematurely due to target mercury loop issue |        |
| RFQ Disassemble/reassemble (preventive maintenance) | #2 | 47 days 4/17/2019-6/3/2019 | ~40 mA / 52 kW | The source worked well, idled waiting for the SNS target mercury loop repair and a new run to start. It was changed out because management decided to start the new production run with a new source |        |
| #4         | 63 days 6/6/2019-8/8/2019 | 1.4 MW-0.75 MW  
New RFQ  
Set point: 0.367-0.364 | 39-31 mA/53 kW | Beam decay and e-dump voltage drooping, Target CMS issues |        |
| #2         | 1 day 8/9/2019-8/10/2019 | New RFQ  
Set point: 0.364 | E-dump failure due to stuck filter field magnet assembly issue |        |
| #6         | 8/10/2019-Present | New RFQ  
Set point: 0.364 | 38 mA/51 kW | No issue with the source so far, SNS target issues |        |
The history of the BTF

- **2013** Design and acquisition work begins in earnest for the Ion Source / LEBT systems (weekly meetings)
- **2014** RFQ assembled and checked out with low power RF (acceptance test) / BTF construction largely complete
- **2015** RFQ fully conditioned to 1ms, 60Hz, 550kW & 1\textsuperscript{st} plasma and HV source operation source platform
- **2016** Beam extraction and RFQ acceleration & transition to operations
- **2017** Extensive operation with external antenna ion sources and many 6D beam physics studies conducted
- **2018** RFQ’s swapped with the SNS front end and both systems restarted
- **2019** a ~6 m photo lattice beam line was installed on the BTF and external antenna ion source and accelerator physics experiments continue
The ion source systems of the BTF

Designed and built at ORNL: BTF has the same operational functionality as the SNS front end (no chopping) as well as similar personal & equipment safety features.

All HV structures have a min of 6” gaps (2.5x FOS)

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To reduce the RF seal issues of the new RFQ, the power has been lowered, lowering the transmission from ~90 to ~70%.

Since middle of 2016 only 1 source is used per ~14 week long ion source runs. However, since 2018, the source is sometimes replaced to improve stability.

To reduce the RF seal issues of the new RFQ, the power has been lowered, lowering the transmission from ~90 to ~70%.

151 refurbished H\textsuperscript{-} sources have been started up for n-production!
Characterization of the new injector on the SNS

- LEBT current measurements at 65kV
- MEBT current measurements at 2.5 MeV
- Beam persistence
- Transverse Emittance: Slit-Slit scans
- Energy spread measurement (rebunchers not shown)

RFQ transmission measurements
The ion source HV enclosure for the Berkeley injector

Source Cage  2MHz Matching Network  HV & GND Conduits
The on-ground H$_2$ system

- Removed H$_2$ bottles from BBB high voltage which greatly simplifies bottle exchange and monitoring
- A rack with valve panel and diffuser has been constructed outside the building 8100 radiation safety fence.
The new LEBT Gate Valve

- Unidirectional valve
- Extensively tested on ISTS, vacuum shop and FE-worked quite well
- Interlocks: whenever valve moves off of the fully open position 65kV and Lens-2 are disabled via hard wire.
- If air flow drops below 20 SCFH (read on FE) valve closes to protect the RFQ
- Other soft and hard interlock associated with valve
The new LEBT chopper target

- New chopper target now replaceable from the LEBT side
- Used to intercept chopped beam and measure LEBT beam current
- Full beam power in LEBT: ~200W
- Beam power deflected to target (normal chopping): ~60 W
- Beam power on target during foil conditioning: ~100 W
### The ion source and LEBT availability are normally >99.5% and improving!

However, every 2-3 years, some complex problem or failure piles up downtime!

The key is finding the root causes!

<table>
<thead>
<tr>
<th>Product Run (CY)</th>
<th>Duty cycle %</th>
<th>Pulse length ms</th>
<th>mA Desired</th>
<th>MEBT mA delivered</th>
<th>RF [kW]</th>
<th>tilt deg</th>
<th>Antenna Failures (days)</th>
<th>% Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006-1</td>
<td>-1</td>
<td>20</td>
<td>28-20</td>
<td>~70</td>
<td>3</td>
<td>0</td>
<td>99.9</td>
<td>1 ion source, 1 cesiation, raise collar temp</td>
</tr>
<tr>
<td>2006-2</td>
<td>0.2</td>
<td>25</td>
<td>30-16</td>
<td>~70</td>
<td>3</td>
<td>0</td>
<td>99.98</td>
<td>1 ion source, 1 cesiation + 24@115°C</td>
</tr>
<tr>
<td>2007-1</td>
<td>0.8</td>
<td>-0.4</td>
<td>20-10</td>
<td>60-80</td>
<td>3</td>
<td>1(37)</td>
<td>70.6</td>
<td>Lens-2 arcing; 2-week source cycles after ant fails</td>
</tr>
<tr>
<td>2007-2</td>
<td>1.8</td>
<td>-0.5</td>
<td>13-20</td>
<td>80</td>
<td>3</td>
<td>0</td>
<td>97.2</td>
<td>Modified lens; 5-target failures; long pulse tuning</td>
</tr>
<tr>
<td>2007-3</td>
<td>3.0</td>
<td>-0.6</td>
<td>25</td>
<td>35-50</td>
<td>3</td>
<td>0</td>
<td>99.65</td>
<td>modified Cs coll (Mo converter); new LEBT</td>
</tr>
<tr>
<td>2008-1</td>
<td>3.6</td>
<td>-0.6</td>
<td>25/30</td>
<td>20-37</td>
<td>uncal</td>
<td>3</td>
<td>1(6)</td>
<td>Restore matching network; new tube; Beam on LEBT gate valve</td>
</tr>
<tr>
<td>2008-2</td>
<td>4.0</td>
<td>0.69</td>
<td>32</td>
<td>32-38</td>
<td>48-55</td>
<td>3</td>
<td>1(9)</td>
<td>Start 3-week source cycles; Ramp up e-dump &amp; coll temp temperature</td>
</tr>
<tr>
<td>2009-1</td>
<td>5.0</td>
<td>0.8</td>
<td>35</td>
<td>34-38</td>
<td>~50</td>
<td>3</td>
<td>2 ExAn 1(8)</td>
<td>Start &quot;Perfect Tune&quot;: use external antenna source for 1st 8 weeks; start 7.2% conditioning</td>
</tr>
<tr>
<td>2009-2</td>
<td>5.1</td>
<td>0.85</td>
<td>38</td>
<td>42-26</td>
<td>~55</td>
<td>0</td>
<td>1(1)</td>
<td>Start replacing LEBT, slim extractor; start 4-week cycles; 2 MHz degrades; plasma outages at end</td>
</tr>
<tr>
<td>2010-1</td>
<td>5.4</td>
<td>0.9</td>
<td>38</td>
<td>39-30</td>
<td>~60</td>
<td>0</td>
<td>1*(11)+1(4)+1(0)</td>
<td>Repair &amp; tune-up RF; punctured antenna* to beam back in ~6 hours; lens1 &amp; e-dump breakdowns;</td>
</tr>
<tr>
<td>2010-2</td>
<td>5.4</td>
<td>0.9</td>
<td>38</td>
<td>46-36</td>
<td>&lt;55</td>
<td>0</td>
<td>2(10)+1(3)+2(0)</td>
<td>Replace 1.6 µH with two 1 µH inductors; start 2 MHz on ground</td>
</tr>
<tr>
<td>2011-1</td>
<td>5.4</td>
<td>0.9</td>
<td>38</td>
<td>38-30</td>
<td>~60</td>
<td>1.5</td>
<td>1(22)+1(6)+1(12)</td>
<td>Double LEBT pumping; start frequency hopping; source leaks by electric arc &amp; by plasma heating; start 6% conditioning</td>
</tr>
<tr>
<td>2011-2</td>
<td>4.4</td>
<td>0.9</td>
<td>38</td>
<td>38-30</td>
<td>~55</td>
<td>0</td>
<td>1*(&gt;5)+1(9)</td>
<td>*Start of run; contamination of #2 &amp; 4; 6 week #3 run; start rigorous antenna selection &amp; DC% conditioning</td>
</tr>
<tr>
<td>2012-1</td>
<td>4.3</td>
<td>0.88</td>
<td>38</td>
<td>38/34</td>
<td>~60</td>
<td>3</td>
<td>99.3</td>
<td>6/2 week cycles with source 3 &amp; 4</td>
</tr>
<tr>
<td>2012-2</td>
<td>5.3</td>
<td>0.88</td>
<td>30-34</td>
<td>30-35</td>
<td>60-65</td>
<td>3</td>
<td>99.7</td>
<td>LEBT &amp; converter TCs; 2 targets fail</td>
</tr>
<tr>
<td>2013-1</td>
<td>5.3</td>
<td>0.88</td>
<td>30-34</td>
<td>30-35</td>
<td>~60</td>
<td>0/1.5</td>
<td>1(11)</td>
<td>99.5</td>
</tr>
<tr>
<td>2013-2</td>
<td>5.3</td>
<td>0.88</td>
<td>30-34</td>
<td>34-36</td>
<td>~55</td>
<td>0</td>
<td>99.4</td>
<td>46 days #4; then 26 days #3 for ≥ 850 kW</td>
</tr>
<tr>
<td>2014-1</td>
<td>≤6 ≤1.0</td>
<td>30-35</td>
<td>≤6 ≤1.0</td>
<td>35-38</td>
<td>~55</td>
<td>0</td>
<td>99.7</td>
<td>1-1.4 MW; start ½-hour HV delay after cesiations; ignition frequency increased from 1.96 to 1.985 MHz</td>
</tr>
<tr>
<td>2014-2</td>
<td>≤6 ≤1.0</td>
<td>30-35</td>
<td>~55</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>98.2</td>
<td>12h 2-MHz repair; e-dump, target &amp; MEBT fail; plasma outages</td>
</tr>
<tr>
<td>2015-1</td>
<td>≤6 ≤1.0</td>
<td>34-36</td>
<td>~55</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>99.6</td>
<td>Bad Di water damages resistor, antenna; 65 arcing; 48 day run</td>
</tr>
<tr>
<td>2015-2</td>
<td>6.0</td>
<td>1.0</td>
<td>35</td>
<td>35-38</td>
<td>~55</td>
<td>0</td>
<td>99.2</td>
<td>Modify CX600; detune 13 MHz; 51 day run; e-dump failures</td>
</tr>
<tr>
<td>2016-1</td>
<td>6.0</td>
<td>1.0</td>
<td>35</td>
<td>35-36</td>
<td>~60</td>
<td>0</td>
<td>99.5</td>
<td>2 sources: 71k/48 days, 5.5 Ah (5KV extraction, 6.7 kV e-dump)</td>
</tr>
<tr>
<td>2016-2</td>
<td>6.0</td>
<td>1.0</td>
<td>35</td>
<td>34-36</td>
<td>~60</td>
<td>0</td>
<td>99.4</td>
<td>2 sources: 99/75 days, 65/7 Ah; 5KV extraction, 6.7 kV e-dump</td>
</tr>
<tr>
<td>2017-1</td>
<td>6.0</td>
<td>1.0</td>
<td>35</td>
<td>33-37</td>
<td>~60</td>
<td>0</td>
<td>97.9</td>
<td>E-dump fails after w, lens-1 fails after 6 d, start 1H HV delay</td>
</tr>
<tr>
<td>2017-2</td>
<td>6.0</td>
<td>1.0</td>
<td>35</td>
<td>32-30</td>
<td>68</td>
<td>0</td>
<td>100.0</td>
<td>1 source 99, wide-leg antenna, beam decay after 8 weeks</td>
</tr>
<tr>
<td>2017-3</td>
<td>6.0</td>
<td>1.0</td>
<td>35</td>
<td>37-35</td>
<td>~55</td>
<td>0</td>
<td>99.9</td>
<td>1 source 66 days; last week e-dump unstable</td>
</tr>
<tr>
<td>2018-1</td>
<td>6.0</td>
<td>1.0</td>
<td>35</td>
<td>44</td>
<td>~45</td>
<td>3</td>
<td>99.8</td>
<td>new RFQ: 1 source 91 days</td>
</tr>
<tr>
<td>2018-2</td>
<td>6.0</td>
<td>1.0</td>
<td>35</td>
<td>43</td>
<td>~55</td>
<td>3</td>
<td>98.5</td>
<td>13 MHz grounding issue; source #6 87 days</td>
</tr>
<tr>
<td>2019-1</td>
<td>6.0</td>
<td>1.0</td>
<td>35</td>
<td>41</td>
<td>~53</td>
<td>3</td>
<td>99.6</td>
<td>e-dump fails source change after 46 d, 2 min. Cs, 3h HV delay</td>
</tr>
<tr>
<td>2019-2</td>
<td>6.0</td>
<td>1.0</td>
<td>35</td>
<td>~36</td>
<td>~55</td>
<td>3</td>
<td>99.6</td>
<td>RFQ power lowered;</td>
</tr>
<tr>
<td>Product Run (CY)</td>
<td>Duty cycle %</td>
<td>Pulse length ms</td>
<td>mA desired</td>
<td>MEBT mA delivered</td>
<td>RF [kW]</td>
<td>tilt deg</td>
<td>Antenna Failures (days)</td>
<td>% Availability</td>
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<tr>
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