Abstract

The Proton Power Upgrade (PPU) project at the Spallation Neutron Source (SNS) will double the available H- beam power from 1.4 to 2.8 MW by increasing the beam energy from 1.0 to 1.3 GeV and the beam current from 26 to 38 mA [1]. The increase in beam current resulted in the need to redesign parts of the existing normal-conducting Linac (NCL) RF Systems. High-power testing of the existing NCL RF Systems configured to accelerate PPU-level beam provided the data used to make the final design decisions. This paper describes the development and execution of those in-situ tests and the subsequent results.

INTRODUCTION

The SNS NCL consists of six drift-tube Linac (DTL) and four coupled-cavity Linac (CCL) type structures resonating at 402.5 and 805 MHz, respectively. The 26 mA H- beam enters the first DTL cavity with an energy of 2.5 MeV and exits the last CCL with an energy of 186 MeV. The cavities are held on resonance using deionized water to maintain their temperature and they are powered using klystron-based RF transmitters. Table 1 shows the current RF power requirements for the NCL cavities to support the pre-PPU 1.4 MW beam power.

The PPU requires a nearly 50 percent H- beam current increase from 26 to 38 mA. It was of interest to the project to ensure that the existing NCL RF Systems could provide the forward power needed to accelerate the higher current beam and, if not, what components required upgrade. The PPU RF systems team chartered a task force to formalize the NCL design criteria and subsequently guide the data collection and analysis needed to finalize the design.

NCL DESIGN PROCESS

Design Criteria

The design criteria for the NCL RF Systems consisted of two main parts. First, and most obviously, the systems needed to be able to provide the power needed to transport the 38 mA H- beam. In addition, the RF systems needed to maintain the SNS-mandated power, or control margin, of 25 percent [2].

The 25 percent power margin requirement ensured that the new systems did not deviate from the design requirements of the original SNS project. The power margin also provided for system-to-system variations in component performance. Most importantly, this level of margin allows the RF systems to operate in the linear or “early” compression regions of their gain curves. The systems can more efficiently adjust to changes in the H-beam that require momentary increases in forward power. Saturated operation would not allow for these types of adjustments, adversely affecting accelerator reliability which is the key metric used to measure the SNS performance.

Conceptual Design

The conceptual design for the NCL RF systems first estimated the RF power needed to propagate the higher current H- beam using Eq. (1).

$$P_g = V_o^2 \left(1 + \frac{\ell_n}{\ell_p} \cos \theta \right)^2 \left(1 + \frac{\ell_n}{\ell_p} \sin \phi \right)^2$$

(1)
where:

\[ V_0 = V_0T \]
\[ \beta = Q_0/Q_{ext} \]
\[ r_\ell = r_e/(1 + \beta) \]
\[ r_e = r_{sh}/2 \]
\[ \theta = \text{synchronous phase} \]
\[ \varphi = \text{detuning angle} \]
\[ I_b = 2 \times I_b \]

Using values measured during the original installation of the SNS and an \( I_b \) of 38 mA, the estimated total power required was calculated for each cavity. Those results were compared to measured power values scaled up from 26 mA operation for verification. Once verified, the scaled power values were then used to calculate the conceptual power margin using Eq. (2) and the rated system saturated power levels of 2.5 MW for the DTLs and 5.0 MW for the CCLs.

\[
\text{Power Margin (\%)} = \left( \frac{P_{sat} - P_{rf}}{P_{rf}} \right) \times 100\% , \quad (2)
\]

where:

\[ P_{sat} = \text{RF system saturated power} \]
\[ P_{rf} = \text{RF power required for acceleration} \]

The results for each cavity are shown in Table 2.

### Table 2: Conceptual RF Power Requirements and Power Margin [3]

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Estimated ( P_{rf} )</th>
<th>Scaled ( P_{rf} )</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTL-1</td>
<td>555 kW</td>
<td>636 kW</td>
<td>293%</td>
</tr>
<tr>
<td>DTL-2</td>
<td>1710 kW</td>
<td>1983 kW</td>
<td>26%</td>
</tr>
<tr>
<td>DTL-3</td>
<td>2003 kW</td>
<td>2141 kW</td>
<td>17%</td>
</tr>
<tr>
<td>DTL-4</td>
<td>2133 kW</td>
<td>2282 kW</td>
<td>10%</td>
</tr>
<tr>
<td>DTL-5</td>
<td>2136 kW</td>
<td>2306 kW</td>
<td>8%</td>
</tr>
<tr>
<td>DTL-6</td>
<td>1954 kW</td>
<td>2109 kW</td>
<td>19%</td>
</tr>
<tr>
<td>CCL-1</td>
<td>3205 kW</td>
<td>3747 kW</td>
<td>33%</td>
</tr>
<tr>
<td>CCL-2</td>
<td>3487 kW</td>
<td>4065 kW</td>
<td>23%</td>
</tr>
<tr>
<td>CCL-3</td>
<td>3667 kW</td>
<td>4176 kW</td>
<td>20%</td>
</tr>
<tr>
<td>CCL-4</td>
<td>3727 kW</td>
<td>4105 kW</td>
<td>22%</td>
</tr>
</tbody>
</table>

**Preliminary Design**

The conceptual design results indicated that DTLs 3 through 6 fell short of the 25% power margin requirement as well as CCLs 2 through 4. To further refine the design past a conceptual state, the task force decided that more precise measurements of actual RF system output were needed. First, the RF power needed to transport a 38 mA H- beam through the NCL was measured using a series of studies on the operational SNS accelerator.

Second, the saturated power of select systems was measured by disconnecting the klystron output from the cavity and driving it into a matched load. The results from these tests provided a more precise power margin.

**High Current Beam Measurements** The first of three high current beam studies occurred in February 2017. The second study took place in April 2017 and the final study was completed in July of 2018.

For the final study, the H- beam was pulsed at 1 Hz with a width of 250 µs, a peak value of over 46 mA and an average value of 38 mA, as shown in Fig. 1.

The RF power data was recorded during the high current tests using installed, operational RF system equipment. These same components, essentially consisting of a waveguide directional coupler and the SNS low-level RF control system (LLRF), were used in the subsequent saturated power measurements and became the common reference for the remaining data collection and analysis.

**Saturated Power Measurements** Using the results of the high H- current studies, the task force selected six RF systems – DTL-2 through 6 and CCL-3 – for saturated power measurements. The measurement process consisted of several steps.

First, the saturated power had to be measured in-situ on each operating system at full duty factor. To do that, the waveguide had to be disconnected from the accelerating cavity and connected to a matched waveguide load in the SNS Klystron Gallery. Care was taken to design temporary waveguide runs for each system to avoid interferences with existing equipment. An example of that design effort is shown in Fig. 2.

![Figure 1: 38 mA H- beam.](image1.png)

![Figure 2: DTL saturated power testing waveguide design.](image2.png)
Second, the testing required that no klystron be driven over its individual datasheet cathode current rating. It was key that klystrons were not operated above their normal range to achieve higher gain, as this would skew the power margin results. The cathode current monitors for each RF system were calibrated to ensure accuracy and provide a common reference for the high H- current and saturated power measurements. The calibration system consisted of a pulsed current source and a high-frequency shunt. Current measurements were taken at the shunt, the test point on each klystron oil tank, and at the user interface. Sample calibration data is shown in Fig. 3.

![Figure 3: Cathode current calibration data.](image)

After completion of the cathode current calibration, saturated power data was taken at four different cathode current values. RF power measurements were made using a high-directivity (28 dB) waveguide coupler along with a standard-directivity (23 dB) waveguide coupler and individual power meters as a comparison to the measurements made by the operational SNS LLRF system. As mentioned earlier, the LLRF measurements served as the common reference between the high H- current and the saturated power studies. Representative gain curves are shown in Fig. 4.

![Figure 4: Gain curves.](image)

**Power Margin Results** The results of the studies, shown in Table 3 [4], confirmed that RF stations DTL-3 through DTL-5 did not meet the 25% power margin requirement when accelerating 38 mA H- beam. DTL-2 also did not meet the 25% requirement. However, there is an ongoing effort to upgrade the high voltage power supply for DTL-2, which will increase the available power margin to acceptable levels. Stations DTL-6 and CCL-3 met the minimum requirements, and no further design work was necessary.

**Final Design**

Based on the power margin measurements, the final design effort focused on systems DTL-3 through DTL-5. A new 3 MW peak-power klystron, designed to operate in the existing infrastructure, was procured and will be installed in the affected RF systems in 2023. Other existing components considered included the waveguide circulator, circulator load, vacuum window, and the cavity couplers. The data taken at 38 mA indicates that these components will not exceed their existing peak RF power ratings. Subsequent computer models of the circulator confirmed that no upgrade is needed for that component [5]. In addition, the final design takes credit for existing equipment protection that will ensure no existing components operate outside of their capabilities.

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Measured $P_{rf}$</th>
<th>Measured $P_{sat}$</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTL-2</td>
<td>1847 kW</td>
<td>2194 kW</td>
<td>19%</td>
</tr>
<tr>
<td>DTL-3</td>
<td>2038 kW</td>
<td>2300 kW</td>
<td>13%</td>
</tr>
<tr>
<td>DTL-4</td>
<td>2336 kW</td>
<td>2370 kW</td>
<td>1%</td>
</tr>
<tr>
<td>DTL-5</td>
<td>2215 kW</td>
<td>2310 kW</td>
<td>4%</td>
</tr>
<tr>
<td>DTL-6</td>
<td>1770 kW</td>
<td>2513 kW</td>
<td>42%</td>
</tr>
<tr>
<td>CCL-3</td>
<td>3324 kW</td>
<td>4699 kW</td>
<td>41%</td>
</tr>
</tbody>
</table>

**CONCLUSION**

The PPU NCL RF system design followed a thorough and complete engineering process that used a combination of calculations and field measurements to finalize engineering choices. The design process led to value-engineering decisions that enabled the use of existing components at higher power levels by taking credit for existing engineered protection. Further, designing the new components, such as the upgraded klystrons, to operate under the constraints of the existing mechanical and electrical infrastructure keep these same value engineering principles in mind.

**ACKNOWLEDGEMENTS**

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REFERENCES


