THE SPALLATION NEUTRON SOURCE NORMAL CONDUCTING LINAC RF SYSTEM DESIGN FOR THE PROTON POWER UPGRADE PROJECT*

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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.

Table 1: Cavity RF Power for 1.4 MW

Cavity	Forward Power
DTL-1	590 kW
DTL-2	1680 kW
DTL-3	1800 kW
DTL-4	1940 kW
DTL-5	1640 kW
DTL-6	1570 kW
CCL-1	2480 kW
CCL-2	3030 kW
CCL-3	2900 kW
CCL-4	2890 kW

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).

$$Pg = V_a^2 \frac{(1+\beta)}{8\beta} \frac{1}{r_L} \left[\left(1 + \frac{I_g r_L}{V_a} \cos\theta\right)^2 + \left(\tan\varphi + \frac{I_g r_L}{V_a} \sin\varphi\right)^2 \right] \quad (1)$$

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where:

$$
\begin{aligned}
&V_a = V_0 T\\
&\beta = Q_0/Q_{ext}\\
&r_L = r_e/(1+\beta)\\
&r_e = r_{sh}/2\\
&\theta = synchronous\ phase\\
&\varphi = detuning\ angle\\
&I_g = 2 * I_b
\end{aligned}
$$

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.

$$
Power\ Margin\ (\%) = \left(\frac{Psat-Prf}{Prf}\right) * 100\%\ , \qquad (2)
$$

where:

$$
\begin{aligned}
&P_{sat} = RF\ system\ saturated\ power\\
&P_{rf} = RF\ power\ required\ for\ acceleration
\end{aligned}
$$

The results for each cavity are shown in Table 2.

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

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

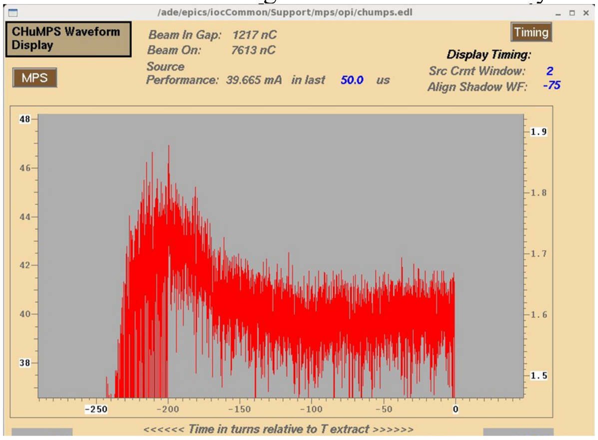
Preliminary Design

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.


/ade/epics/iocCommon/Support/mps/opi/chumps.edl

Beam In Gap: 1217 nC
Beam On: 7613 nC
Source Performance: 39.665 mA in last 50.0 us

Display Timing:
Src Crnt Window: 2
Align Shadow WF: -75

Figure 1: 38 mA H- beam.

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.

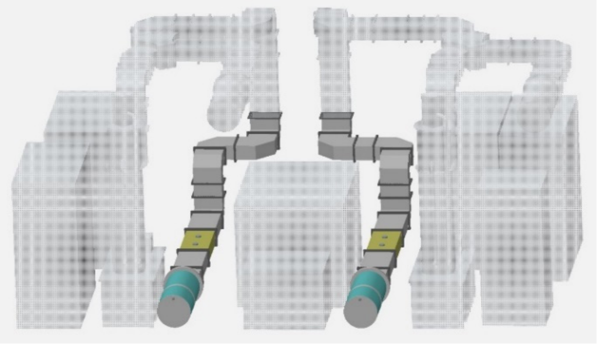


Figure 2: DTL saturated power testing waveguide design.

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.

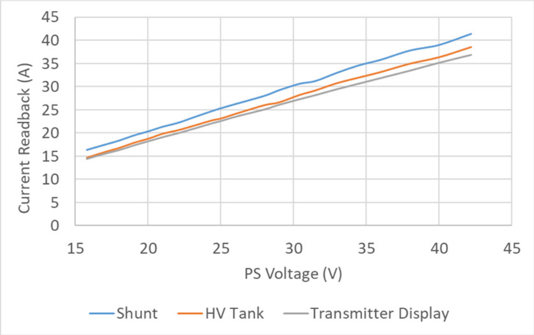


Figure 3: Cathode current calibration data.

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.

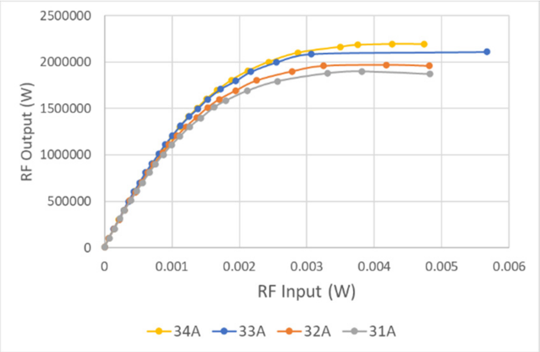


Figure 4: Gain curves.

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 3: Power Margin Results

Cavity	Measured P_{rf}	Measured P_{sat}	PM
DTL-2	1847 kW	2194 kW	19%
DTL-3	2038 kW	2300 kW	13%
DTL-4	2336 kW	2370 kW	1%
DTL-5	2215 kW	2310 kW	4%
DTL-6	1770 kW	2513 kW	42%
CCL-3	3324 kW	4699 kW	41%

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.

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