SNS LINAC RF SYSTEM OVERVIEW*

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Abstract

The Spallation Neutron Source (SNS) being built at Oak Ridge National Lab (ORNL) in Tennessee requires a linac with an output energy of 1 GeV and an average current during the pulse of approximately 18 mA (including the effects of chopping). The average beam power for the initial baseline is 1 MW (1 mA average at 1 GeV). The linac is followed by an accumulator ring and target/instrument facility [1]. The RF system for the 1 MW linac requires 52 each 805 MHz klystrons and 3 each 402.5 MHz klystrons. The 805 MHz klystrons are configured in pairs to drive one resonant structure. This uses the installed RF very efficiently and in addition is convenient for the upgrade to 4 MW which must be considered in the design. The RF must have the correct amplitude and phase in order to ensure complete acceleration along the linac and to minimize beam loss. Due to the configuration proposed for SNS, the LLRF controls must equalize each pair of klystrons to ensure proper operation. The high voltage system for the klystrons will be based on Insulated Gate Bipolar Transistor (IGBT) technology to provide the best possible operation at the least cost.

1 SYSTEM OVERVIEW

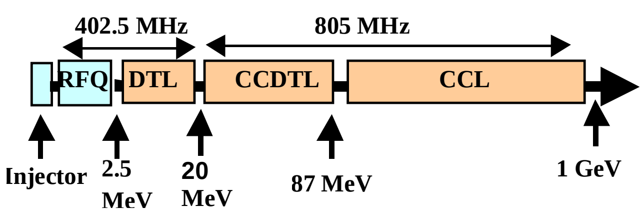

Figure 1: SNS Linac Block Diagram

The Linac is shown schematically in Figure 1. The RFQ (1 klystron) and Drift Tube Linac (DTL) (2 klystrons) operate at 402.5 MHz. The remainder of the Linac, which includes the Coupled Cavity Drift Tube Linac (CCDTL) and Coupled Cavity Linac (CCL) operates at 805 MHz. A total of 52 klystrons are needed for the 805 MHz portion of the Linac. An additional 805 MHz klystron is required for a bunch rotator located after the Linac, just before the ring injection point. The preliminary design activities started this year (FY-99), and the entire facility scheduled for completion in FY-05 with initial operation in FY-06.

Pertinent parameters for the Linac and RF systems are given in Table 1. In the definition of the system, an upgrade path is included that will ultimately provide 4 MW of average beam power. This is to be done through a combination of increased current from the front end (factor of 2) and the addition of a second front end which will be funneled into the CCDTL with the first front end (factor of 2). The Linac design has been done in an elegant and cost effective fashion [2,3] that accomplishes this upgrade by adding 1 klystron to each 2-klystron accelerator module. No additional structure power is needed for the upgrade, and only the additional beam loading must be provided by the additional RF power.

Table 1: Parameters of SNS Linac

H- Energy	1000 MeV
Beam Current	27.7 mA, peak
	1.04 mA avg.
Beam Power	1.04 MW, avg.
Pulse Width, (RF)	1.17 ms
Pulse Width, (beam)	1.04 ms
Repetition Rate	60 Hz
RF Duty Factor	7.02%
805 MHz power during pulse	97 MW
Total RF power during pulse	99 MW
Klystrons, 805 MHz, 2.5 MW pk.	53
Klystrons, 402.5 MHz, 1.25 MW pk.	3

1.1 Accelerator Module

A block diagram of one 805 MHz accelerator module is shown in Figure 2. Two klystrons are needed for each module, and they each drive the accelerator through a single RF/vacuum window and drive port. Each klystron is specified to deliver 2.5 MW peak at full saturated output. No circulators are planned for the initial installation. That should not present a problem as will be shown later, but circulators will most likely be required when the upgrade to 4 MW occurs.

The klystron specification includes the primary parameters of peak power, duty factor, pulse width, and gain. In addition we have specifications for phase and amplitude linearity, VSWR tolerance, heater hum limitations, and finally a specification that the tube must pass an extensive heat run (24 hours at full duty and 110% of nominal peak power). Table 2 lists many of the pertinent klystron parameters.

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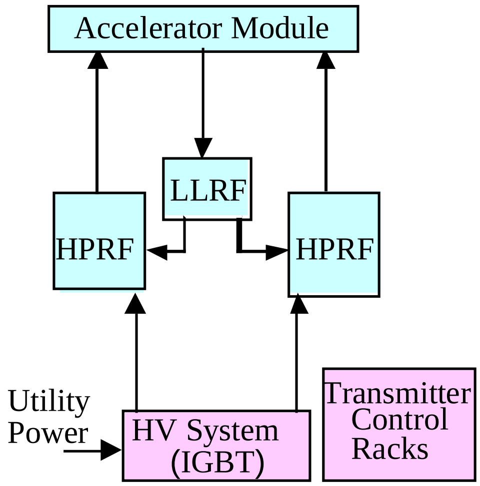

Figure 2: Layout of one Accelerator/RF Module

Two prototype 805 MHz klystrons have been ordered, one each from CPI and Litton. They are scheduled for delivery in June of this year. Both klystrons are modern designs with 5 fundamental and one-second harmonic cavitiy. Both klystrons are approximately 10 feet long.

Table 2: 805 MHz Klystron Specifications

Peak Power	2.5 MW
Repetition Rate	60 Hz
Duty Factor	10%
Gain at Saturation	≥45 dB
Efficiency at Saturation	≥55%
Gain Variation*	<1%
Phase Variation*	<0.5 degree
Allowable Load VSWR	1.5:1
Gain Variation due to Heater AC power phase	≤0.5 dB

*over range from 0.6 MW to 2.0 MW output

They are specified with a minimum efficiency of 55% at full output power and a minimum gain of 45 dB. [4] They have been ordered with a modulating anode to allow maximum flexibility in system design, detailed monitoring of performance, and to simplify testing at LANL in an existing modulator/HV system. The order for prototypes includes an option for a cathode-pulsed tube. The final klystrons for SNS will likely be cathode-pulsed klystrons. The HV system being designed for SNS is based on IGBT technology and will allow the use of cathode-pulsed tubes.

The waveguide layout for SNS is based on a similar layout done at LANSCE. This system has operated for over 25 years without circulators by carefully adjusting the waveguide length between the klystron output iris and the accelerator input iris. The length is adjusted to ensure that reflections from the accelerator due to loss of beam appear at the klystron as a low impedance.

Table 3: Expected Mismatch for SNS RF Module

Module 25, Output Energy=969 MeV		
Avg. Beam Power	1 MW	4 MW
Cavity Power	3.107 MW	3.107 MW
Beam Power	0.755 MW	3.020 MW
Total Power	3.863 MW	6.13 MW
Beam Loading	19.60%	49.30%
VSWR without Beam	1.27:1	2.10:1

Table 3 shows calculations for the mismatch for a typical accelerator module in the 1 MW case and the 4 MW case. We are specifying that the klystrons must be able to operate into a 1.5:1 mismatch at any phase, so the 1 MW case should not present a problem due to the low effective beam loading (less than 20%). In the 4 MW case the beam loading is much higher (approximately 50%). Loss of beam in the 4 MW case presents a much worse mismatch to the klystron (2.12:1). For this reason we believe circulators will be required when the upgrade is installed.

1.2 IGBT High Voltage System

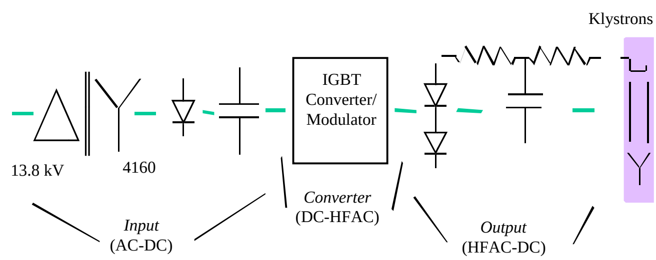

Figure 3: Block Diagram of IGBT-based HV System

We are developing a high voltage system based on IGBT's. [5] The design is shown in block diagram form in Figure 3. Each IGBT Converter-Modulator system will provide the power for 2 klystrons. There are a few features of particular interest. The first is that the system replaces both the HV components (HV supply and capacitor bank) as well as the modulating components (HV modulator or PFN). The IGBT section operates at low voltage (4160 V), and the circuit is a three-phase circuit with each half of each phase switching at 20 kHz. The IGBT's must be stacked to accommodate peak voltage potentials, so the total number of IGBT's needed for the 0.75 MW average system is 48. The output HV transformer is followed by 3-phase rectification and a small amount of filtering. Since the transformer is not required to operate for the full pulse width (1 ms), it can be made very compact. The output ripple frequency is 120 kHz and is expected to be <1%. Ripple can be made smaller by adding more stored energy in the output section, but this would also add to the available fault energy. The current design requires no crowbar. Droop over the 1 ms pulse is expected to be kept much less than 1% by pulse-width modulation of the IGBT's in the converter. In the case of a klystron arc the IGBT's are shut down. Backup protection comes from the saturation of the small high frequency HV transformer and ultimately from a fast vacuum interrupter on the input.

1.3 Low Level RF (LLRF) Controls

A block diagram of the LLRF system is shown in Figure 4. In addition to standard field control, the LLRF design must include the RF reference and distribution, resonance control of the accelerator cavities, and klystron control. Since each accelerator cavity is powered by 2 klystrons, the system must accommodate variations in the tube performance. A feedback loop is used around each klystron to equalize their performance. Field control of the accelerator will include feedback and, most likely, feedforward control.

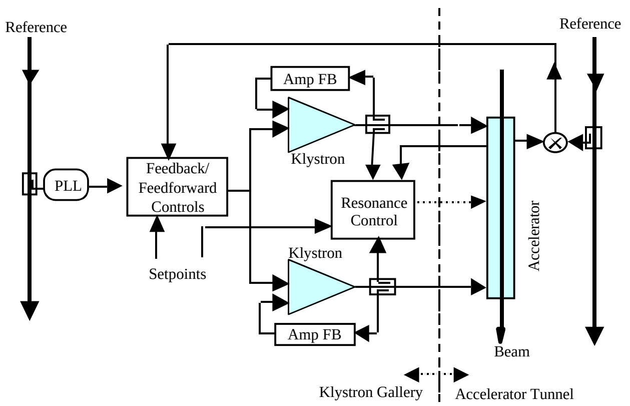

Figure 4: Block Diagram of Feedback control System

We have specified the system to allow the accelerator physics designers a maximum of 2.0 MW per klystron at the accelerator. Since each module consists of 2 klystrons, this provides a maximum of 4.0 MW per module. The extra power (0.5 MW per klyston) is needed for many purposes. There are losses in the RF transport (estimated at 7% of the output from the klystron). These losses come from resistive losses in the waveguide and mismatch losses at flanges, bends, and other discontinuities. In addition there are coupling losses at the module due to imperfect beam amplitude and phase and coupling losses due to klystron inequalities (since there are two klystrons driving each module). Finally, excess power is needed for drive margin to allow the feedback/ feedforward system to operate effectively.

The drive margin is needed because of the saturation characteristics of the klystron. As a klystron is operated closer and closer to peak output the effective gain (Pout/Pin) approaches zero. This gain is a key element in the forward path of the control circuit. Hence, reduced klystron gain translates to reduced control loop gain. In a typical saturation curve, the klystron may have 3 dB less gain at 75% output and 6 dB less gain at 90% output than it has at 50% output. Of course at saturation, the effective gain is zero. The effectiveness of the feedback control system is reduced more and more as the system operates closer to saturation. This system will likely need excellent control (±0.5% amplitude, ±0.5° phase), so the control margin is very important to maintain. We are adapting the model we are currently using for the Accelerator for Production of Tritium (APT) for the SNS application. [6] A sample result is shown in Figure 5. This modeling work will be used to estimate the amplitude and phase control limits in the presence of errors and noise, particularly from the beam and the klystron HV system. In addition, the modeling will be used as the basis for the control system design, determining whether feedforward is needed, etc.

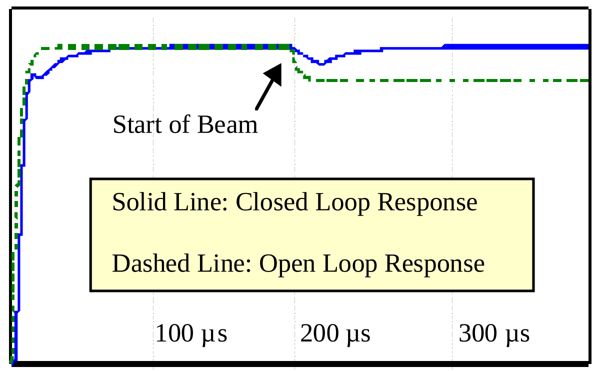

Figure 5: Modeling result of SNS RF transient response

2 SUMMARY

The SNS linac is an exciting program. To meet the program schedule and budget, we have been very selective in the technologies we are developing. The developments must be necessary to achieve the SNS operating parameters, or they must promise significant payback in cost or schedule. In addition, wherever possible, we are borrowing from developments we have achieved in other recent or existing programs.

3 REFERENCES

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