SPALLATION NEUTRON SOURCE (SNS) HIGH PULSE REPETITION RATE CONSIDERATIONS*

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Abstract

Increasing the pulse repetition rate (PRR) of the SNS Linac to its designed maximum of 60 Hz to provide 1.4 MW of beam on target is in progress. Operation above 60 Hz to provide beam to a second target is also being considered in the future. Increasing the PRR to 80 Hz would allow the additional pulses to be diverted to a second target. This paper discusses the impact of increasing the PRR on the SNS infrastructure including Radio Frequency (RF) systems and structures, the ion source, cryogenics, controls and the target.

SNS 60 Hz OPERATIONAL GOALS

SNS is designed to deliver 1.4 MW of beam power on target (1 GeV x 1.4 mA average current). As of April 2007 SNS delivered 60 kW (Table 1) beam power on target during neutron production runs and a test run of 90 kW. The plan is to go from 60 kW to 1.0 MW by the end of 2008 and 1.4 MW in 2009. This entails increasing the PRR from 15 to 30 Hz in October 2007 and then to 60Hz by April 2008. Pulse length will gradually be increased from 500 µs to 1000 µs and concurrently peak beam current will be raised from 20mA to 38 mA between Oct 2008 and Oct 2009. Energy is assumed to be between 0.810 to 1.0 GeV as the cryo-cavities are optimized. Transport losses of about 8 – 10 % are part of the target power calculation.

Table 1: Beam Power Parameters

PRR (Hz)	Charge / Pulse	Energy (MV)	Power (kW)
15	2.9E13	887	60
15	4.2E13	887	90

Present Limitations to 60 Hz Operation

- Reliability of the ion source had initially been a problem. Operation at 20 mA pulse peak current is now routine. A great deal of development work [1] has resulted in an improved ion source with an external antenna and reduced Cesiation requirements. This combined with a 2-solenoid low-energy beam transport (LEBT) and robust chopper high-voltage switches presently in development show excellent promise for 60 Hz operation at 25 mA and above.
- New Radio Frequency Quadrapole (RFQ) input couplers have been developed and are being tested to improve reliability, power handling capability and field stability [2]. The total number of couplers will be reduced from eight to two with correspondingly higher individual fields that are above the multipacting range. The new couplers are more robust electrically and mechanically, each with 500 kW power handling capability (nominal operation is 340 kW each) and improved vacuum quality. The couplers will be located further downstream on the RFQ, away from the relatively higher vacuum pressure inherent near the ion-source.
- High voltage converter modulators (HVCMs) are power supplies that each drive sets of 11 (at 75kV) or 12 (at 69kV) superconducting linac (SCL) klystrons or 1 to 3 normal-conducting (NC) linac klystrons. These resonant units stress internal components such as coils and power transistors at their upper operating points [3]. All have been identically upgraded to run at 60 Hz at their designed voltage.
- The superconducting (SC) cavity structures are being driven at an average of 27% above design fields (Figure 1). Only 71 of 81 were in active operation before April 2007. Higher-order mode couplers have been coupling out fundamental power in some instances and some field emission with inter-cavity interaction has been seen. An aggressive program to remove and/or repair cryomodules is underway [4].

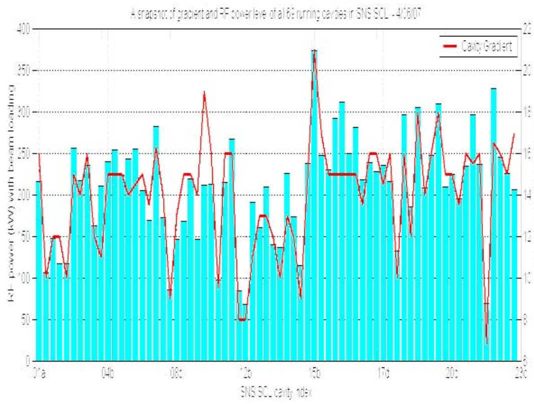

Figure 1: Cavity Field + RF Power vs Cavity position.

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This enhances the ability to reach higher energies. As of June 2007 seventy-five SCL cavities are on-line with one high-beta (HB) cryomodule out for repair.

- The Low Level Radio Frequency (LLRF) cavity field feed-forward control system is presently limited to 20 Hz by computationally-intensive operations between pulses performed in software. Ideally the feed-forward should be updated every pulse rather than every third pulse. However, typical beam operation is sufficiently stable for 20 Hz feed forward control at a 60 Hz PRR [5]. A dedicated buss between the cavity Frequency Control Module (FCM) [6] and VME CPU is being considered to reduce processing time as well as more extensive digital signal processing (DSP) integrated hardware upgrades.
- Target studies show that short beam pulses at low repetition rates damage the mercury target vessel surface through cavitation and pitting [7] more so than at high repetition rates. The same energy per pulse deposited into the target at higher rep rates (60 Hz) should improve vessel lifetime; bubbles formed in the liquid mercury can still be present when the next pulse arrives and serve to cushion the shock.

System Interdependence

The SC cavities have a variance in field performance. The average (taken 4/2007) operational field differs from the design value (table 2), with a significant standard deviation. Some cavities are pushed moderately above their design fields [8] and require more power. At 60 Hz the operating field must be lowered somewhat because the higher heating contributes to field emission. The SNS SCL architecture [9] provides one klystron per SC cavity in eleven three-cavity medium-beta cryomodules and twelve four-cavity high-beta cryomodules. The klystrons driven at higher power require higher voltage from their respective HVCM. Since each HVCM operates a dozen klystrons in parallel it must provide the higher voltage to all of them, even if only a few require higher voltage.

Table 2: Superconducting Cavity Designed Field

	#	Design MV/m	Avg MV/m	σ
Beta 0.61	33	10.1	13.9	2.48
Beta 0.81	48	15.8	13.7	2.39

This load on the HVCM causes the voltage to droop across the pulse width and some 3-phase 20 kHz ripple to be superimposed upon the output. Klystron output power is proportional to $V^{5/2}$. As such, the ripple and droop are superimposed upon the RF power to the cavity fields. A low level RF (LLRF) field control system provides feedback (BW ~ 100 kHz) to the input of the klystron to negate these and other influences (such as beam loading) and maintain the proper cavity field. The high-loaded Q (~ $7*10^5$) SC cavities have a three τ fill time ($\tau = 2Q_L/\omega_{cav}$) of ~ 834 µs. Beam loading compensation requires a field that is higher than the nominal accelerating field. To decrease the rise time of the field, the LLRF must use higher-than-nominal RF power and start the RF field as far ahead of beam arrival as possible, and that in turn requires the HVCM pulse to operate at a higher voltage for longer (1.35 – 1.5 ms) duration, which exacerbates the HV droop issue. The first four HVCMs that drive twelve klystrons each provide a maximum of 69 kV, limiting the klystron output power to ~350kW. Figure 2 shows the RF power applied at full power to fill the cavity. The reflected power drops as the cavity fills. The cavity field rises exponentially. The square bump in the RF power and field near the end of the pulse is to compensate for beam loading. Eventually this "bump" will extend (~1ms) for the entire pulse after the cavity is filled.

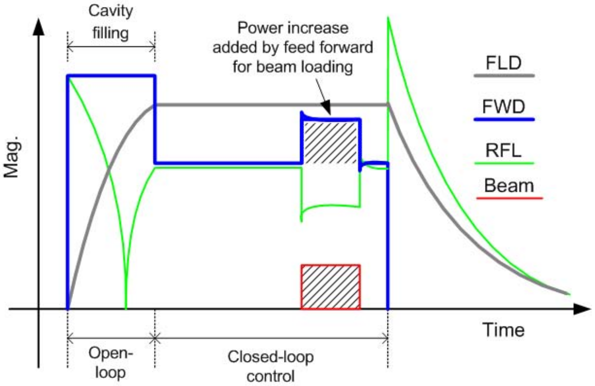

Figure 2: Cavity Field Levels and Timing

There is evidence of increasing target vessel damage with decreasing PRR for given-incident beam pulse on target. The mechanism for cavitation originates with the abrupt pressure rise associated with deposited energy from short beam pulses. Less pitting has been observed at higher PRR in a non-beam test and this was attributed to the survival of cavitation bubbles from one pulse to the next. Residual bubbles may act as dampers against subsequent imposed pulses. If the trend from the non-beam test data holds true for the SNS target, the damage per pulse at 60 Hz would be 70% of that at 15 Hz for the same deposited energy on target. Much more important is the evidence for damage erosion rate dependence on incident proton intensity (protons per unit area) that suggests power law dependency with exponents perhaps as large as 4 [10]. For a given *time-averaged beam power*, proton energy and profile on target, the damage rate should be reduced by more than 300 times by increasing the PRR from 15 to 60 Hz.

Thermal Considerations

Each SCL HVCM delivers about 15 kJ per pulse (75 kV x 11.5 A x 1.5 ms x 11 klystrons) at 85% efficiency, clearly illustrating the increasing power dissipation with pulse rate. The total of all RF systems at 60 Hz exceeds 14.5 MW average. The water cooling capacity for the modulator, klystrons and waveguide components presently is 5775 gpm. However, as characteristic of centrifugal pumps, the output pressure drops with increasing flow. That relegates flow to about 85% of maximum to maintain adequate pressure with a maximum input temperature of 87°F. This equates to a still acceptable average cooling water temperature rise of ~ 11.2°F overall, with local exceptions.

The cryogenic heat load is directly proportional to the RF duty cycle, effectively doubling between 30 and 60 Hz. Each cryomodule dissipates approximately 16 - 28 W (MB - HB) at 60 Hz on top of the static heat load., for which the refrigeration units are properly sized [11]. Changing from the present 4 K operation to 2 K will lower the dissipated power per cryomodule by virtue of lower cavity wall resistance at the expense of increased power consumption in the SNS cryo-plant.

System Control Response

As the time between pulses shortens with higher rep rate the SNS Control system must ensure all systems, clocks and communications have responded appropriately before the next pulse. Data has to be saved and displayed, diagnostic instruments must be re-zeroed, interlocks checked and user inquiries addressed. Using present data acquisition rates and algorithms, the upper limit of 60 Hz for the pulse repetition rate is limited by beam instrumentation waveform processing times. A reduced set of processing tasks and higher-speed networks will allow a higher but presently undetermined rate.

SECOND TARGET STATION CONSIDERATIONS

A second target station (T2) has always been part of the SNS plan. Siphoning beam from the existing target (T1) for T2 most efficiently utilizes the existing infrastructure [12]. The construction of a long-wavelength (1 ms pulse length) second target station will enable SNS to be optimized for experiments such as small-angle neutron scattering, reflectivity, and high-resolution inelastic neutron scattering and diffraction.

Using 1ms pulses "stolen" from the existing pulse train as it traverses between the linac and the ring would meet requirements for a long pulse second target station application. The ring is bypassed for T2 so rather than "seeing" a single 660 ns pulse of $1.4^{E}14$ protons as T1, it receives 1060 mini-pulses of 660 ns, each consisting of 265 micro-pulses of ~ $5.0^{E}8$ protons at 1GeV. A kicker magnet at the end of the linac would selectively "kick" pulses to T2 up to a maximum pulse repetition rate of 20 Hz, and be adjustable to much lower rates as needed. Ideally, if SNS were to operate at 80 Hz and every 4th pulse was stolen, then T1 would see 60 PPS and T2 would see 20 PPS. The period of the T1 pulses would be 12.5 ms with a gap of 25ms between bursts of three pulses. It would require pre-ring kickers to operate up to 20Hz. Another scenario, considering the previous equipment limitations, is using a linac PRR of 60Hz with every fourth pulse to T2 resulting in 45 Hz T1 and 15 Hz T2 operation. 120Hz operation has the advantage of line synchronization but stresses the HVCM, shortens processing time and doubles the thermal load.

Conclusion

SNS has a viable plan in place to achieve 60 Hz operation by April 2008 with full-power operation in 2009. There is time to weigh the second target timing options and much to be learned before key decisions are made.

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