STATUS OF THE SPALLATION NEUTRON SOURCE *

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Abstract

The superconducting linac for the Spallation Neutron Source is being commissioned. Seventy seven of the eighty-one niobium cavities resonating at 805 MHz have been installed in the SNS tunnel in 11 medium beta (.61) cryomodules each containing 3 cavities and 11 (presently) high beta (.81) cryomodules each with 4 cavities. The niobium cavities and cryomodules were designed and assembled at Jefferson Lab to operate at 2.1 K. The Central Helium Liquefier has been tested to 2.1 K but is routinely operated at 4.2 K. At this temperature, all but four cavities have been tested, mostly at 10 pulses per second and at a full pulse length of 1.3 msec. Shorter periods of operation at 2.1 K have also been implemented, with results similar to those at 4.2 K. Beam commissioning is under way and operation with beam at both temperatures has been demonstrated. Negative hydrogen ion energies of 865 and 907 MeV have been reached at 4.2 K and 2.1 K respectively, even with a few cavities not being operated. Further beam commissioning is under way.

INTRODUCTION

The Spallation Neutron Source will start producing neutrons for materials science research in less than a year [1]. A central feature of the accelerator, designed to generate the 1 GeV protons for the spallation process, is the superconducting part of the H- linac. This section of the accelerator has accelerated the H ions from 187 MeV up to over 900 MeV, close to the design energy of 1 GeV, with two types of superconducting cavities, matched to β=.61 and .81 respectively. The use of superconducting elliptical cavities for particles at β<1 makes this accelerator a very important prototype for learning operating conditions of this type of cavities. Another important aspect of the superconducting linac is the fact that it is operated under pulsed conditions, for which only the Tesla Test Facility at DESY has extensive experience for electron acceleration [2].

By July 2005 all the installation and testing of the superconducting cavities, cryomodules, warm sections,

beam manipulation and diagnostics components was completed. In August and September 2005 beam commissioning has been accomplished, with successful transport and acceleration of a low power (up to 7.5 kW), high energy (up to 907 MeV) beam.

SPECIFICATIONS

The superconducting cavities for the SNS are built out of Niobium and have a design gradient of 10.1 and 15.6 MV/m for the medium and high beta cavities, respectively. Operation at 2.1 K should provide a Q_o of about $1.7x \, 10^{10}$, with the possibility of operating at a Q_o as low as $5x10^9$ under heavy field emission regime. The cryogenic system is designed for 2.4 kW of power at 2.1 K, which ensures a comfortable margin of operation over the static and dynamic losses of all the cavities in the present configuration [3] and also for a possible machine power upgrade which would include additional 36 high beta cavities (9 cryomodules).

Each of the 81 superconducting cavities is powered by a pulsed 550 kW klystron via a power coupler, previously processed in a test stand at JLab or at SNS [4], [5].

INSTALLATION

During the first six months of 2005 a large amount of installation work was completed in the superconducting linac at SNS [6]. As mechanical and electrical installation was being completed in a number of cryomodule zones, parallel work on installation of cryomodules, purging and cooldown of cryogenic lines and modules, diagnostics equipment and instrumentation assembly, warm section installation and vacuum connections progressed. Only one cryomodule, undergoing repairs, is not installed in the tunnel, but all the necessary equipment for beam transport through the superconducting linac has been in place since the end of June 2005.

The testing of cryomodules closely followed the high-paced installation activities. The high power testing was performed at nights and during weekends to avoid interference with the tight installation schedule.

WARM SECTION INSTALLATION AND TESTING

The warm sections between cryomodules contain focusing and steering magnets [7] as well as beam position monitors and laser beam profile monitor equipment. They are separated from the cryomodules by the gate valves at the end of each module. The cleaning

and assembly of the warm sections constituted a challenge for a new laboratory like SNS, where no facilities existed and had to be improvised. Even so, the quality of the temporary clean room facility is remarkably good and the beam pipe components cleaning procedures are state of the art [8]. The final connection of the warm beam pipes to the cryomodules has been carried out with strict procedures which have effectively preserved the integrity of the cryomodules and cavities themselves. The verification that the cleaning, assembly and connections were of excellent quality was carried out via an experiment designed to ascertain that all the above processes did not deteriorate the performance of the cavities in the cryomodules.

The most sensitive way to evaluate the possible contamination of a superconducting cavity is to determine whether the field emission threshold has been lowered by the emission of additional particulates during a specific beamline vacuum opening event. An ion chamber monitored the radiation generated by field emitted electrons near the first cell of the cavity adjacent to the gate valve connecting the cryomodule to the specific warm section. The field emission threshold was determined by positively detecting a radiation of a few mR/hr (in all cases at about 10 MV/m, consistent with the data collected at JLab during both vertical tests and cryomodule tests for the specific cavities). The radiation intensity was monitored during and after the gate valve opening for over half an hour. No decrease in field emission thresholds was observed for all of the warm section connections in the linac.

RF TESTING

The RF testing of the cavities in the SNS tunnel has been performed via the complete EPICS control system and by using the Low Level RF (LLRF) interface both for protection and measurements [9], [10].

In Figure 1, a sample of a LLRF screen is shown. Both amplitude and phase of the forward, reflected and transmitted signals are shown in a digitized form.

The forward, reflected, transmitted power through the field probe and the two HOM ports are monitored and used for protection and measurements.

Typical pulse measurements include calibrations with short pulses (optimized for maximum energy transfer between the incoming pulse and the stored energy in the cavity) and full pulse length (1.3 msec) open loop calibrations. Consistency between the fields determined via different ports and using logically independent measurement methods at the few-percent level is considered adequate for setting field levels in the cavity. Inconsistencies among ports with more than ±5 % are used to track improper calibrations or defective components in the RF network.

Interlock protection is implemented against arcing in the power coupler window, excessive power via any of the ports, especially the HOM couplers, thermal interlocks on cavity end groups, and window vacuum.

Once the system is calibrated, the limiting field in each cavity is determined by carefully increasing the incident power while observing both the evolution of power through all the ports and the specific interlock response.
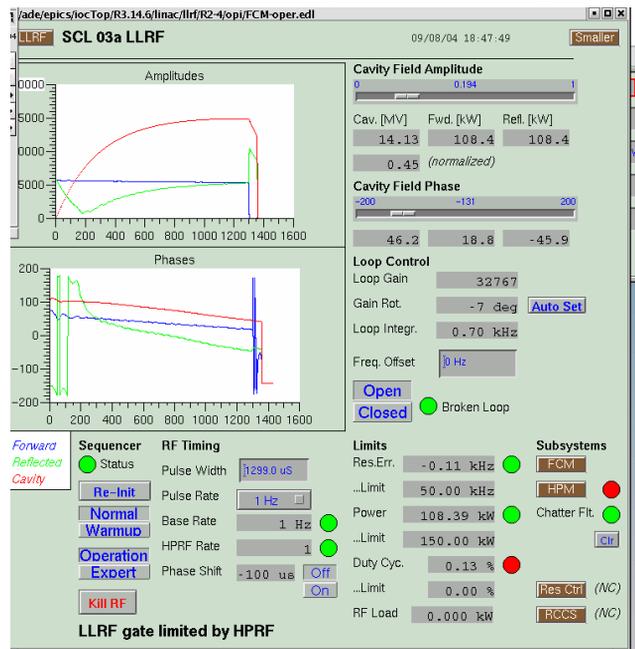

Figure 1. Low Level RF traces of forward (blue) reflected (green) and transmitted (red) amplitude (above) and phase (below) for a SNS superconducting cavity in open loop. Data acquisition terminates 50 μsec after the end of the RF pulse

TESTING AT 4.2 K AND 2.1 K

Due to unavoidable delays in the final assembly and commissioning of the 2.1 K cold compressors and cold box, a contingency plan was devised to partially test cryomodules at 4.2 K using local dewars in the tunnel or the main refrigerator complex run as a liquefier.

The analysis indicated that most of the functionalities of the cryomodule and some of those of the cavities could be verified ahead of time without being delayed by the commissioning of the 2.1 K cold box [11].

In particular, the Q_o of the cavities at 4.2 K is dominated by the BCS term which, at this frequency and for the SNS cavities, is of the order of 7×10^8. In principle, the gradients for the design values of SNS are well below the limits imposed by fundamental magnetic field limitations and whether the cavities are operated at 2.1 or 4.2 K should not make a difference. Small deviations from the design values of the temperature distributions in the cavities' end groups [12] were considered minimal in verifying the operability of the cryomodules and even a substantial degradation of the field performance was considered marginally important compared to the advantage of integrated testing of cryomodules in the tunnel. This analysis was done early in 2004 and by August 2004 the Central Helium Liquefier was capable of delivering liquid helium at atmospheric pressure to the first cryomodule installed in the tunnel and some tests

were performed in early September 2004, including the first simultaneous run of more than one cavity in an SNS cryomodule.

In late June 2005 the subatmospheric part of the Central Helium Liquefier was reliable enough that final tests of the cavities could be carried out at 2.1 K. However, the power consumption at the lower temperature is nearly 2 MW higher than for operation at 4.2 K, and the system is more easily maintained at this higher temperature.

RF TEST RESULTS

Cavity performance

The September 2004 run gave encouraging results, as it was verified that all the functional characteristics of the integrated SNS cryomodule system were indeed met. Three cavities were run for the first time simultaneously and reached in open and closed loop gradients in excess of 10 MV/m with a full pulse length of 1.3 msec and at 30 pulses per second (limit imposed by the present average power configuration of the High Voltage Converter Modulator). This result was considered remarkable, because it demonstrated the possibility of performing meaning full measurements on cavities designed for 2.1 K operation at 4.2 K, as well as proving that it was possible to operate large systems at SNS with success comparable to that of the sister laboratories from which all the equipment was obtained. It was also clear that the coupler conditioning performed ahead of time had paid off, as coupler power came up almost instantly, largely limited by prudence rather than by physical phenomena: in general that has been true for all the couplers tested since.

A three-month hiatus to improve the CHL operability led to the beginning of an uninterrupted cold testing of cryomodules since late December. At that time several cryomodules were tested simultaneously and since then installation and testing went hand in hand at a sustained pace. A total of 77cavities have been tested and as many as 76 have been run simultaneously.

After a considerable time spent in understanding the performance of the system as a whole (caution was necessary, given the large number of untested systems and the fact that the tests were being performed at 4.2 K) we embarked in a systematic recalibration of all the RF system and into a campaign of determining the limiting fields of the cavities at the operating temperature of 4.2 K. From March, through June, 2005 a substantial set of measurements were performed. Most of the initial measurements were performed in open loop, with full 1.3 msec pulse length but at a repetition rate of 10 pulses per second.

The main results are as following:

- Medium beta cavities (32 out 33) have an average maximum gradient of 17.6 MV/m (to be compared with the design value of 10.1 MV/m). A substantial fraction of the tested cavities is limited by incidental factors, such as protection limits for the LLRF board, and not by fundamental limits.

- The high beta cavities (44 out of 48) have an average maximum gradient of 18.0 MV/m, compared to the design value of 15.6 MV/m. Again a number of them are limited by non binding factors at this time.
- The JLab testing [13] indicates an average maximum field of 18.3 MV/m for all cavities (32 out of 81).
- Preliminary measurements indicate that Lorentz force detuning is not a problem in the high beta cavities, and it is more prevalent in the medium beta ones.
- The results are very similar to JLab's measurements both at 2.1 K and at 4.2 K.

At the end of June 2005 and for two weeks the system was run at 2.1 K and all the measurements repeated at that temperature.

LIMITS AND LIMITATIONS

Among the physical phenomena which limit cavity gradients there are some which are fundamental and other which are accessory. For instance, in a number of cases the HOM power transmitted by the filter at the fundamental mode exceeds values safe for RF feedthroughs and the fields are prevented from reaching their natural limit by the excessive power going through those ports. During testing at JLab two cryomodules were vented due to failures of HOM feedthroughs subjected to excessive power, so at SNS the power is monitored and a limit imposed on the transmitted power. Better knowledge of the behavior of the feedthroughs may eventually lead us to allow higher power and field levels.

Physical limits of a more fundamental nature (although not necessarily insurmountable) are the quenches observed as the field is pushed to higher and higher limits.

Quench behavior

Figure 2 shows a trace of the reflected power during a quench: the measured loaded Q_L for all the cavities tested under quench has a value of about 3×10^5, indicating a localized quench and not global transition to normal niobium. The corresponding unloaded Q_o is of the order of 4.5×10^5, down from 7×10^8 in the superconducting state at 4.2K. The same phenomena are observed in operation at 2.1 K.

In most cases the following sequence of events is observed:

1. Some heating of beam pipe and coupler flange is detected
2. For those cavities instrumented with x-ray detectors, x-rays appear around 10 MV/m, consistent with the observations at JLab.
3. Sudden quenches accompanied by excessive HOM power and arc trips occur, indicating large amount of sudden field emission energy. When cavities at the high energy end of the cryomodule quench, the downstream ion pump also trips, triggered by the radiation pulse.

4. A drop in liquid helium level follows, with a large time hysteresis, indicating that the source of heat is not in contact with the bath.

5. A subsequent similar quench occurs at a fraction of an MV/m higher, with several cycles for some cavities, as the field emission sites are being destroyed.

6. Eventually a true final quench is reached, limited by the insufficient cooling of some component in the end groups.
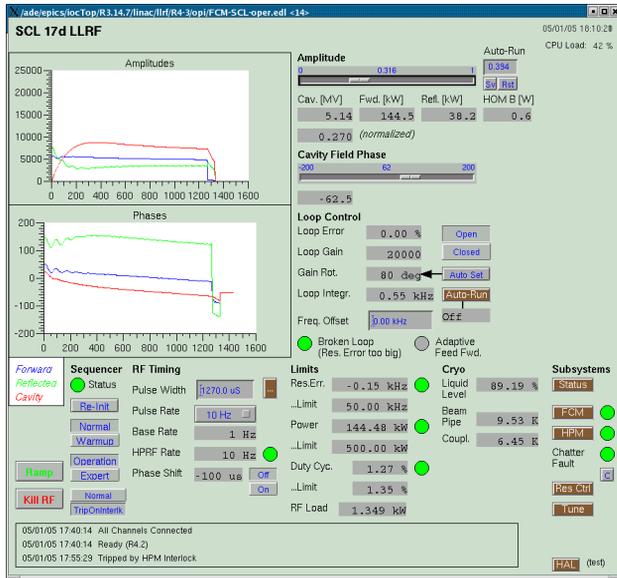

Figure 2. Low Level RF screen showing the RF amplitudes (Forward blue, transmitted red, reflected green) during a quench event for an SNS superconducting cavity. During the quench the loaded Q drops to about $3x10^5$ and the unloaded Q_o to $4x10^5$.

A good fraction of the cavities reached and exceed fields of 20 MV/m, up to 25 MV/m (Figure 3). The cavity that exceeded 25 MV/m has a forward power of 510 kW peak, a value never before achieved in a coupler connected to a superconducting cavity in a full cryomodule under real operating conditions.

Many cavities are limited by excessive fundamental power being extracted by the HOM couplers, although some of them may be pushed to higher levels as the operation of the machine is better understood. Better end group cooling would most likely allow one to reach higher gradients.

The distributions in Figure 3 are a combination of real physical limitations, such as the field emission induced thermal quench, of incidental protection limits, such as the HOM power and of control system noise levels which in some case prevent stable operation close to the physical limits. In general, it is observed that high beta cavities have a broader distribution than the medium beta, spanning the lowest and highest field limits, but with about the same average values. The limits do not seem to be different at 4.2 or 2.1 K, as discussed in the following paragraph.

Other incidental limitations that will be corrected shortly are:

- Six cavities cannot reach operating frequency at 4.2 K and the tuners will have to be reset (four of them reach frequency at 2.1 K)
- Eight cryomodules have helium leaks from the process circuit to the insulating vacuum and need continuous or periodic pumping. Additionally, four leaking cryomodules have been repaired at SNS and put back online
- One high beta cryomodule has a leak from the primary helium circuit to the insulating vacuum. It has been repaired but was not in place in time for the initial beam run.
- One cavity in the medium cryomodule that was vented during testing at JLab is inoperable due to excessive HOM power going through a detuned filter and has a limiting multipacting level at .5 MV/m
- The high beta cryomodule that was vented at JLab during testing has extremely high levels of field emission-induced radiation, together with degradation of limiting fields with respect to the values measured at JLab and must be operated at a gradient well below 2/3 of its design value.
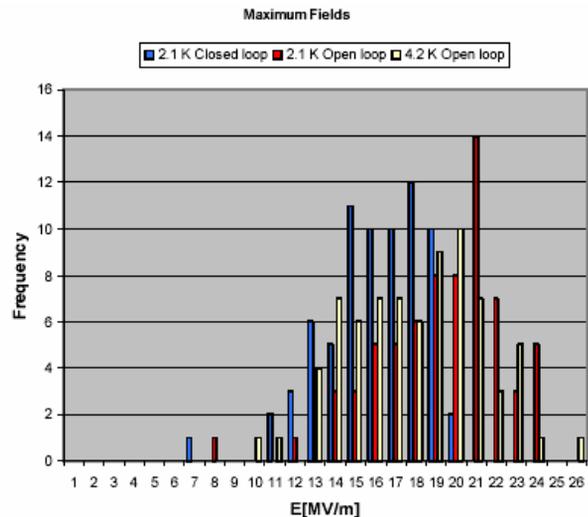

Figure 3. Distribution of maximum gradients achieved in the SNS superconducting cavities so far at 4.2 K in open loop (yellow bars) at 2.1K in open loop (red bars) and at 2.1K in closed loop (blue bars). All data are for 1.3 msec pulse length at 10 pps. The overall average values are 17-18 MV/m.

ON THE PULSE OPERATION OF SUPERCONDUCTING CAVITIES

Figure 4 represents the fundamental limits of a superconductor, showing also the small difference in operating conditions between 2.1 and 4.2 K. Until a few

months ago it was far from certain that its applicability would be successfully demonstrated at SNS. This result demonstrates that superconducting cavities behave substantially differently in a pulse mode than in CW, a fact that in principle has been known for years [14]. The present results prove that complex systems which include auxiliary components and cryomodules can be effectively operated in a pulse mode at temperatures different from those below the helium's lambda point. In fact, depending on the cavity frequency and fields required by a specific application, there may always be an optimum temperature of operation, other than 2.1 K, which may optimize a particular system. Operation at temperatures higher than 2.1 K may turn out to be more stable and reliable and certainly less expensive than those under superfluid helium conditions.
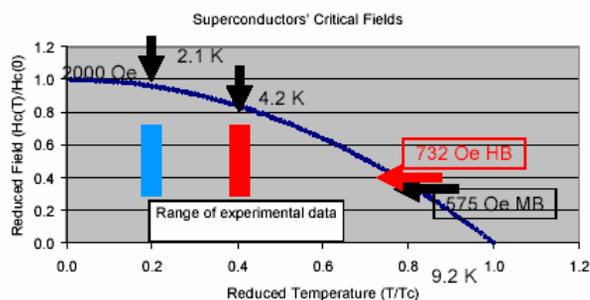

Figure 4. Theoretical magnetic field limits for a superconductor as a function of temperature. The operating values for SNS are well below the theoretical limits (blue curve). Experimental maximum field ranges are essentially identical at 4.2 K (red bar) and at 2.1 K (blue bar).

BEAM COMMISSIONING

Beam was injected into the superconducting linac starting at the beginning of August, 2005. Operation with beam and with the cavities at 4.2 K has been successfully demonstrated. Most cavities have been operated at about 80% of the maximum field determined both at 4.2 K and 2.1 K.

Improvements in the cryogenics systems configuration have resulted in pressure fluctuations levels at 4.2 K down to .1-.3 torr, which correspond to typical frequency modulations of 10-30 Hz, well within the control range of the LLRF system. These results made testing of the accelerator with beam at 4.2 K a distinct possibility.

Without one high beta cryomodule and several inoperable cavities, the gradients of all the other cavities were pushed to about 80% of the established limits. Under those conditions, the simulations produced estimated beam energies somewhere between 850 and 900 MeV [15].

Given the large distribution of gradients and the uncertainty of the actual values for operation, algorithms have been developed to set up the machine for optimum utilization of the superconducting cavities [16].

Using the techniques mentioned, the superconducting linac was set up for operation at 4.2 K and within days it was possible to accelerate a beam of a few kW up to 865 MeV, an energy well above the estimated minimum acceptance energy (780 MeV) for the ring, which will be commissioned within a few months. This was achieved with 69 of the 81 cavities running.

At the end of August 2005 and once the beam was reliably established, the CHL was set up to operate at 2.1 K and a few more cavities became available. Almost immediately a higher energy of about 907 MeV was achieved, with 72 of 81 cavities operational.

CONCLUSIONS

The SNS superconducting linac has been successfully commissioned with low power, full energy beam. The cavities have been performing well beyond expectations, and it has been established that beam operation can be supported both at 4.2 K and 2.1 K.

ACKNOWLEDGEMNTS

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