TESTING OF THE SNS SUPERCONDUCTING CAVITIES AND CRYOMODULES *

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Abstract

The superconducting linac for the Spallation Neutron Source is in the process of being commissioned. Eighty-one niobium cavities resonating at 805 MHz are being installed in the SNS tunnel in 11 medium beta (.61) cryomodules each containing 3 cavities and 12 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, 70 of the 81 cavities have been tested, mostly in open loop at 10 pulses per second and at a full pulse length of 1.3 msec. The results indicate that high gradients can be reached even at 4.2 K (average value of 17.8 MV/m) and that operation of the superconducting linac at that temperature may be possible.

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 will accelerate the H ions from 187 MeV up to 1 GeV with two types of superconducting cavities, matched to β=.61 and .81 respectively. The use of superconducting elliptical cavities for particles at $\beta<1$ 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 the end of July 2005 beam operation is set to start in the superconducting linac. By then all the installation and testing of the superconducting cavities, cryomodules, warm sections, beam manipulation and diagnostics components will have been completed. Here we report the present status and the results of the tests conducted so far.

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SPECIFICATIONS

The superconducting niobium 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 last six months an increasingly accelerating amount of installation work has been occurring 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 have progressed. At the time of writing only two cryomodules undergoing repairs are not installed in the tunnel, but all the necessary equipment for beam transport through the superconducting linac is ready for final connections. All equipment will be in place before the end of June 2005.

The testing of cryomodules has been closely following the high-paced installation activities. The high power testing has been 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 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. Two warm sections were connected to the first three cryomodules which were operational in January 2005. 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. A total of four valves in two warm sections facing three cryomodules were sequentially opened and closed. No decrease in field emission thresholds was observed and the procedures for cleaning, assembling and installing the warm sections were declared adequate.

RF TESTING

The RF testing of the cavities in the SNS tunnel is 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.

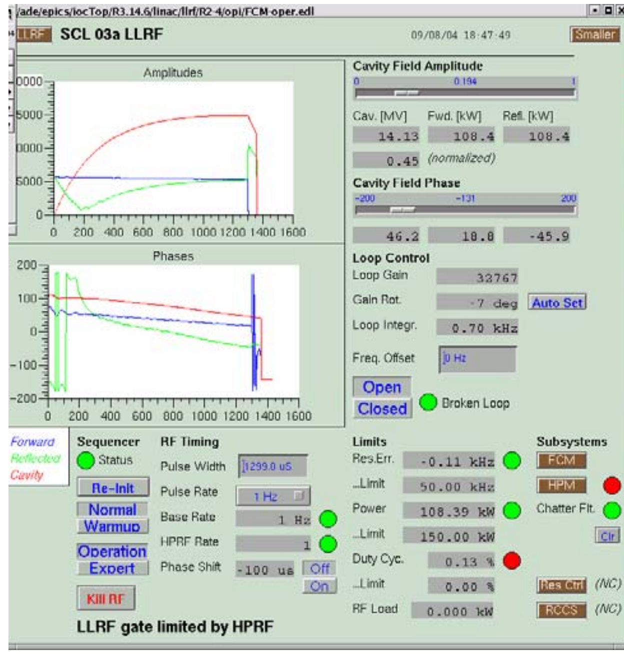

Figure 1: Low Level RF traces of forward (blue), reflected (green) and transmitted (red) amplitude (above) and phase (below) for a SNS superconducting cavity.

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.

4.2 K TESTING

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 $7x10^8$. 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

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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. The results of the tests are described next.

RF TEST RESULTS

Differences between JLab tests and SNS tests

The main differences in the tests at JLab and SNS are the following [13]:

- At JLab only one cavity at a time in each cryomodule could be tested, at SNS all available cavities are tested simultaneously
- At JLab a local test system is used, whereas at SNS the full control and LLRF systems are included in the test
- At JLab a local refrigerator is used only for the test cave, whereas at SNS the full 2.4 kW, 2.1K CHL is employed
- At JLab a maximum field is reached and then the a cavity is tested for one hour before being declared suitable, whereas at SNS cavities are run for extended periods of time and their limits increased as time goes on.
- At JLab the tests are conducted at 2.1 K, whereas so far the SNS tests have been run at 4.2 K

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 have been going hand in hand at a sustained pace. A total of 70cavities have been tested and as many as 65 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 are 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. In March, April and May, 2005 a substantial set of measurements were performed. Those measurements are still going on. Most of the initial measurements are 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 (28 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 (37 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).
- The results are very similar to JLab's measurements.
- It should be noted that the JLab results are achieved at 2.1 K and the SNS ones at 4.2 K.

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 $3x10^5$, indicating a localized quench and not global transition to normal niobium. The corresponding unloaded Q_o is of the order of $4.5x10^5$, down from $7x10^8$ in the superconducting state at 4.2K.

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.

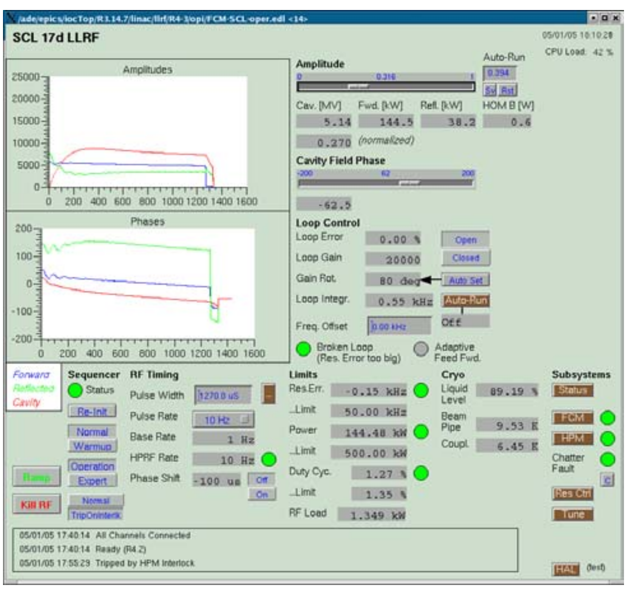

Figure 2: Low Level RF screen showing the RF amplitudes (Forward blue, transmitted red, reflected green) during a quench event for an SNS superconducting cavity. During the quench the loaded Q drops to about $3x10^5$ and the unloaded Q_o to $4x10^5$.

A good fraction of the cavities reached and exceed fields of 20 MV/m, up to 25 MV/m (Figure 4). 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 under real operating conditions.

Many cavities are limited by excessive HOM power, 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.

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 would 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, three 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 and another one from the shield circuit. They are being repaired and will not be used 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 will have to be operated at a gradient well below 2/3 of its design value.

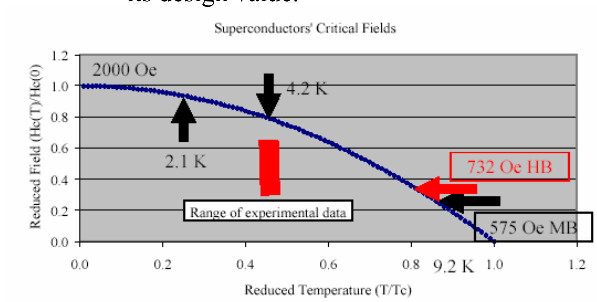

Figure 3: Theoretical magnetic field limits for a superconductor as a function of temperature. The operating values for SNS are well below the theoretical limits (blue curve).

ON THE PULSE OPERATION OF SUPERCONDUCTING CAVITIES

Figure 3 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

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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.

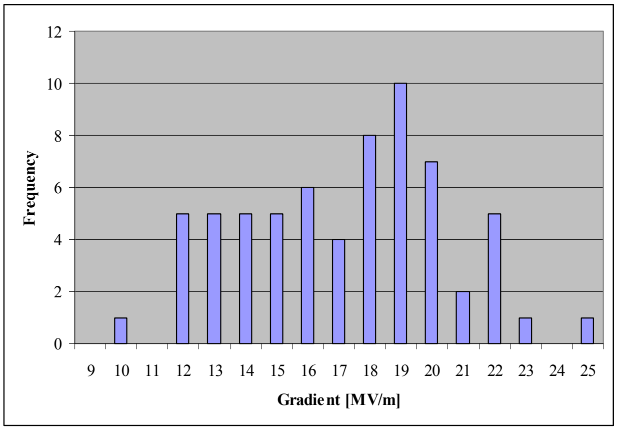

Figure 4: Distribution of maximum gradients achieved in the SNS superconducting cavities so far (65 out of 81) at 4.2 K in open loop at 1.3 msec pulse length at 10 pps. The overall average value is 17.8 MV/m.

PREPARATION FOR BEAM COMMISSIONING

Beam will be injected into the superconducting linac starting the end of July 2005. Full tests of the superconducting cavities will be conducted in June 2005 using gradients derived from the measurements being conducted at present. At that time it will be determine if the operation at 4.2 K can be sustained even for beam commissioning.

Improvements in the cryogenics systems configuration have resulted in pressure fluctuations levels 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 make testing of the accelerator with beam at 4.2 K a distinct possibility.

Without two high beta cryomodules, the gradients of all the cavities will have to be pushed to near the established limits during operations. It is estimated that if the installed cavities can be used at a gradient of 80% of the established limits, then the final linac energy would exceed about 850 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].

CONCLUSIONS

The SNS superconducting linac is only months away from beam commissioning. The cavities have been performing well beyond expectations, especially since all the testing so far has been conducted at 4.2 K. The testing of all the cryomodules has proceeded at the same pace as the installation with all the systems working according to specifications from the very beginning.

ACKNOWLEDGEMNTS

The work presented here is the result of the efforts of hundreds of people in the Laboratories that contributed to the SNS construction. In particular, the remarkable results of the performance of the superconducting cavities have been possible thanks to the work of the personnel at Jefferson Lab. The testing of the cryomodules at SNS is the culmination of the work of all the people of the Accelerator Systems Division, whose dedication made the above results possible.

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