SUPERCONDUCTING LINAC UPGRADE PLAN FOR THE SECOND TARGET STATION PROJECT AT SNS*

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Abstract

The beam power of the Linac for the Second Target Station (STS) at the Spallation Neutron Source (SNS) will be doubled to 2.8 MW. For the energy upgrade, seven additional cryomodules will be installed in the reserved space at the end of the linac tunnel to produce linac output energy of 1.3 GeV. The cryomodules for STS will have the same physical length but will incorporate some design changes based on the lessons learned from operational experience over the last 10 years and from the high beta spare cryomodule developed in house. The average macro-pulse beam current for the STS will be 38 mA which is about a 40 % increase from the present beam current for 1.4 MW operation. Plans for the new cryomodules and for the existing cryomodules to support higher beam current for the STS are presented in this paper.

INTRODUCTION

The proposed Second Target Station (STS) concept is based on a short pulse configuration by 10-Hz, 470 kW proton beam, which is optimized for cold neutrons with high peak brightness [1]. In order to provide required beam to the First Target Station (FTS) and STS, the plan for the SNS accelerator upgrade is to increase the linac output energy from 940 MeV to 1 GeV and to increase average macro pulse beam current from 26 mA to 38 mA. The total beam repetition rate will be the same at 60 Hz; 50 Hz for the FTS and 10 Hz for the STS. As a result the accelerator capacity will be doubled in terms of beam power from 1.4 MW to 2.8 MW.

The original SNS Power Upgrade Project (PUP) plan [2] was to upgrade the SNS linac to 3-MW capability by increasing the linac beam energy to 1.3 GeV with nine additional high beta cryomodules and by increasing the average macro pulse beam current to 42 mA. There are empty slots at the end of the linac tunnel for nine additional high beta cryomodules, and space for the high power RF and control racks in the klystron gallery that were prepared during the original construction. The design accelerating gradient of the new SRF cavities for the PUP was 14 MV/m mainly due to two concerns; 1) the average accelerating gradient of existing high beta SRF cavities are lower than the original design gradient that is 15.8 MV/m, 2) The klystron power at saturation for the upgrade will provide 700 kW that limits the accelerating gradient at 15 MV/m for the 42-mA beam loading.

The spare high beta cryomodule was developed and commissioned in 2012 and has been in service in the tunnel for the neutron production since then [3, 4]. All cavities in this cryomodule are running at 16 MV/m stably limited by the available RF power. The existing high power RF system provides 550 kW. The average macro pulse beam current is 38 mA that is about 10 % less than the beam current for the PUP. For the STS, these two factors are basis for the design accelerating gradient of the new SRF cavities at 16 MV/m. Thus, seven additional high beta cryomodules are required for the STS. Installing seven cryomodules in the nine available slots helps the practical issues. Currently some of the chases for the upgrade section between the klystron gallery and the tunnel have been already filled with cables. Removing these cables will affect the machine operation and will generate additional cost.

The optimum geometric beta of the cavities for STS is higher than that of the original high-beta cavities but the module length and accordingly cavity geometric beta will be kept same due to economic reasons. All helium transfer lines are already installed during the SNS project with bayonets for the high beta cryomodules. Waveguides penetrations from the klystron gallery to the linac tunnel were also installed for the length of the high beta cryomodules. Some changes, that do not require changes of overall layout, will be made based on the lessons learned from operational experiences over the last 10 years and the pressure-vessel compliance issue. Table 1 summarizes the design changes between the original SNS high beta cryomodule and the high beta cryomodule for the STS.

Table 1: Cryomodule Design Changes for the STS

Parameters	**Original**	**STS**
E_{acc} at β=0.81 (MV/m)	15.8	16.0
Fundamental power coupler rating, peak/average (kW)	550/48	700/65
End group Nb	Reactor grade	High RRR
Fast tuner	Piezo	none
HOM coupler per cavity	2	none
Pressure vessel	Good Engineering Practice	Code Stamp required

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SCL STRATEGY FOR THE STS

For the current operation at the SNS, each cavity is set at a maximum gradient based on the collective limit of gradients achieved through a series of SRF cavity/cryomodule performance tests at SNS [5], rather than setting uniform gradients as designed. As seen in Fig. 1 the accelerating gradients of low performing cavities are increased for the STS. At SNS, in-situ processing in the tunnel has been identified as an important area of research to improve the SRF cavity performance while minimizing the machine operational impact and reducing cost for the improvements. The R&D for the in-situ processing using plasma is actively ongoing at SNS and the results are very promising to increase accelerating gradient [6, 7]. The accelerating gradient of the existing cavities for the STS is an example of gradients after plasma processing for both medium and high beta cavities. In addition, cavity 5a (cavity number 13 in Fig. 1) and 11a (cavity number 31) that exhibit known problems are also assumed to be fixed for the operation. The linac output energy with this scenario will be between 1,340 MeV and 1,360 MeV for 22 degree and 18 degree beam phase respectively, which corresponds that at least three cavities can be used for the energy reserve. If performance improvements after repair or in-situ plasma processing are less than expected, the linac output energy will still be 1.3 GeV, but with reduced energy margin.

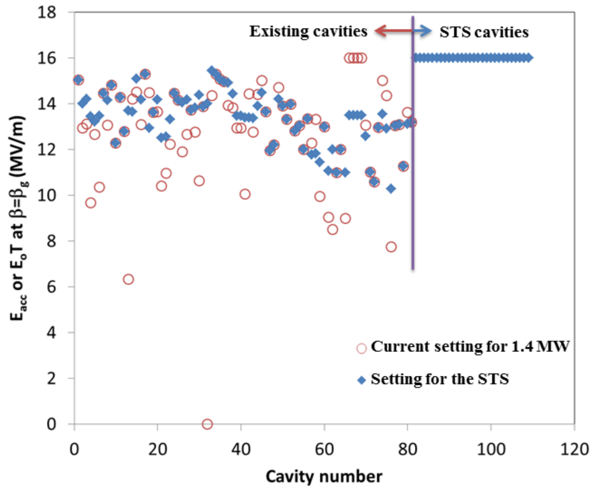

Figure 1: SCL accelerating gradient scenario for the STS compared with the current operating accelerating gradients.

The high power RF (HPRF) systems for the existing cavities will be kept as same for economic reason. Since the output power at saturation of the existing HPRF systems is 550 kW, accelerating gradients of high performing high beta cavities need to be lowered for the STS beam loading as can be seen in Fig. 1.

Figure 2 shows the required RF power for the SCL accelerating gradient scenario in Fig. 1 that includes 15% control margin. The measured Q_{ex} and dynamic detuning are used for calculation of existing cavities. Three new high voltage converter modulators (HVCM) are planned for the STS. As beam energy goes higher the required RF power for the STS cavities is getting smaller due to transit time factor. Thus the last HVCM will feed nine klystrons, which results in reduced available RF power by 10 %. The cavities fed by 8-pack klystrons per HVCM could run up to 17 MV/m depending on cavity performances.

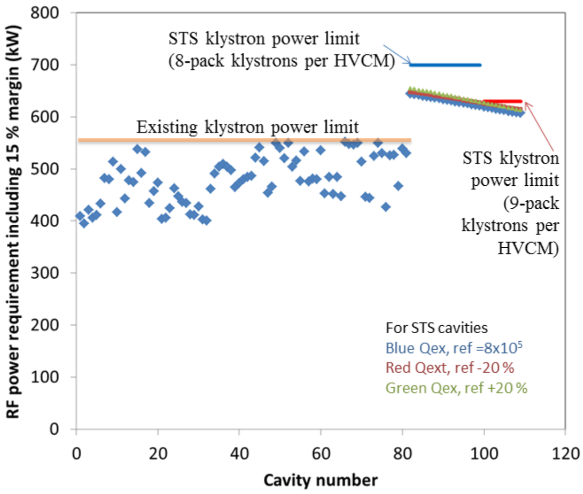

Figure 2: RF power requirement for the STS.

CHANGES FOR THE STS

Cavity

All cavities in the spare high beta cryomodule exceed the design accelerating gradient for the STS. These cavities were electro-polished and were commissioned up to 17 MV/m or higher in the test cave. Only one cavity shows minor x-rays in the tunnel starting at 15 MV/m. For the STS electro-polishing is selected for the final chemical processing.

One identified issue of all existing SNS cavities was that the end group surfaces are very rough due to high aspect ratio deep drawing and the additional heat treatments. These end groups were fabricated from reactor grade niobium and not high purity or high RRR material as an attempt to reduce the material costs of the cavities. The reactor grade material was then heat treated in a vacuum furnace to improve its thermal conductivity. The high aspect ratio deep drawing will not be used for STS cavity fabrication.

The RRR of niobium for the end group of the existing cavities is about 70 after heat treatment and the end group is cooled by indirect conduction to the helium circuit. The thermal processes of the end group are, more or less, slow since the surface magnetic fields are relatively small and the cooling relies on conduction. In terms of thermal stability, the end group can allow a fairly large material defect size since the field is low. But the end group is sensitive to heating from broad range thermal loads such as field emission, multipacting and thermal radiation from the inner conductor of the Fundamental Power Coupler (FPC), because of the long conduction path to the thermal sink. Most of the existing cavities show electron activities, which is the major limiting condition by electron loading, leading to end group heating, gas bursts and cavity quench. The analysis indicates that the end group is not stable with an additional localized external thermal load of 0.2 to 2 W depending on the magnetic field for the RRR=70 case, while it is still stable with five times larger additional thermal loads for the RRR=150 case. The end groups for the STS cavities will be made of high RRR niobium. It was considered to use the existing twenty high beta spare cavities produced during the SNS project in STS. Currently, a study is in progress where the end groups were replaced on two spare cavities. For these test cavities, the new end groups were constructed of high RRR niobium, the HOM cans were removed from the design, and high aspect ratio deep drawing was not used for manufacturing of parts (Fig. 3). These cavities were delivered from the vendor and chemical polishing has been completed. Testing of the cavities is scheduled in near future.

Figure 3: End group modification for the STS.

The other thermally weak location in the original cryomodules is the cavity end group of the field probe side at the warm to cold transitions. At normal operating conditions the temperature at this location is about 7-8 K. When there are electron activities, other external thermal loads such as beam halo or a combination of these around this warm to cold transition, the local temperature easily goes to hydrogen evaporation temperature. This can result in a large vacuum burst which interacts with the RF field. Sometimes, a vacuum burst changes the cavity condition drastically and cavities require serious conditioning or reduction of gradient. For the high beta spare cryomodule a thermal cooling block cooled by 5-K supercritical helium was installed at each end. This design addition will be deployed to the STS cavities.

Higher Order Mode (HOM) Coupler

As reported the SNS HOM couplers showed issues. Observations and physical conditions near the HOM couplers imply that HOM coupler failures and/or degradations seem to be resulted from electron activities originated by combinations of multiple causes such as electromagnetic field at the HOM coupler, multipacting, field emission, and even a gas discharge with fundamental mode. A few cavities were inoperable due to large coupling with the fundamental accelerating mode. In 2007, the SNS re-evaluated the HOM characteristics including dangerous HOM modes measurement for all installed cavities. It was concluded that HOM couplers are not needed for SNS and it was decided to remove HOM couplers when cryomodules are taken out of the tunnel for repairs. Four cryomodules were taken out of the tunnel so far and leaks were detected from half of the HOM feedthroughs. Thus, the STS cavities will not have HOM couplers.

Dynamic Detuning Compensation

Observed dynamic detuning of the original SNS high beta cavities due to the Lorentz force is in the range of 1-2 Hz/(MV/m)^2 during the whole pulse. The dynamic detuning during the RF flattop is less than 0.5 Hz/(MV/m)^2. Since the cavity bandwidth is relatively large (~500 Hz) or external Q is relatively low (<10^6) due to the high beam loading, the additional RF power needed to compensate the dynamic detuning is minor. This amount of detuning is well managed by the adaptive feed forward. Fast piezo tuners were installed on the original cavities to mitigate any unexpected mechanical resonance conditions, but these fast tuners have never been used at t SNS. The piezo tuner design has proved to be mechanically unreliable and will not be part of tuner for the STS.

Fundamental Power Coupler (FPC)

The original FPCs were tested up to 2-MW peak for the full travelling wave condition in the test stand and over 550 kW peak power in real cavity operation at various standing wave ratios (SWR) limited by the operational envelope. The FPC for the STS cavities must be able to transfer up to 700 kW peak power over a 1.3 ms RF pulse width at a repetition rate of 60 Hz at various SWRs. Based on the testing and operational experience, the RF performances of the original FPC satisfies the STS requirements. But the thermal radiation from the inner conductor will be higher due to the increased average RF power. A thicker inner conductor will be sufficient for the STS requirement, which would be the simplest solution. Active cooling for the inner conductor was also taken into account if the passive enhancement of cooling with the thicker inner conductor is not enough. Active cooling will require a more complex design configuration and may result in operational difficulties at an upset condition. The temperatures are calculated for various inner conductor thicknesses at both full travelling and standing wave conditions. During the pulsed operation, the actual condition in the FPC is between full standing and full travelling wave condition. Figure 4 shows comparisons of inner conductor tip temperatures. With a 7-mm thick inner conductor, the inner conductor tip temperature at the STS condition can be kept below that of the FPCs presently operating at SNS. The prototype FPC for STS with increased wall thickness was manufactured by the vendor who provided the original FPCs, installed in a horizontal test apparatus (HTA) and successfully tested. Except thicker wall thickness of the inner conductor all other designs are exactly same for the STS.

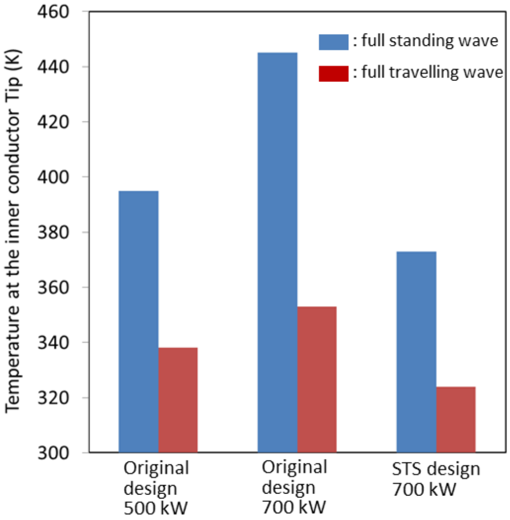

Figure 4: Comparisons of inner conductor tip temperature. The inner conductor thickness of the original design is 3 mm. 8 % RF duty factor is used for the calculation.

Cryomodule

The relevant parameters for the mechanical design of the original high beta cryomodules will remain same for the new STS cryomodules such as the slot length, cryomodule length, cold mass assembly, number of bayonets, number of control valves and FPC positions. The spare high beta cryomodule developed in 2012 [3] serves as the baseline design for the STS cryomodules. For the spare cryomodule, it was required to meet the pressure requirements put forth in 10 CFR 851; Worker Safety and Health Program. The most significant engineering change was applying Section VIII of the ASME Boiler and Pressure Vessel Code to the vacuum vessel of this cryomodule instead of the traditional designs where the helium circuit is the pressure boundary. Applying the pressure code to the helium circuit within the cryomodule was considered. However, it was determined to be schedule prohibitive because it required a code case for the niobium materials which are not currently covered by the code. Good engineering practice however, was applied to the internal components to verify the quality and integrity of the entire cryomodule. By moving the pressure vessel boundary to the vacuum vessel there are some benefits and also challenges. Benefits are; 1) pressure testing of the completed helium circuit is not required, 2) pressure boundary will never reach cryogenic temperature during a failure, 3) material of vacuum vessel for the SNS case is stainless steel that has good performance at cold temperatures and is a ASME listed material, 4) pressure stamp can be applied to sub components, which increases quality assurance and documentation of fabrication/materials and 5) internal components are not required to follow ASME code. Challenges are that assembly will be more difficult between vacuum vessel and end plates and between vacuum vessel and end cans. For example, removal of the bridging ring complicated assembly in the warm to cold transition region necessitating design changes to this region of the cryomodule. This also affected the flexibility of alignment of the string to the warm beam line flange. Therefore modelling of the string within the vacuum vessel had to be very precise because the movement of the warm to cold transition in the old design was eliminated. The alignment during the spare high beta cryomodule assembly was performed with a laser tracker and the modelling was successful such that the string aligned with the warm valve within the specification limit of 1 mm. Figure 5 shows the schematics of warm-to-cold transition.

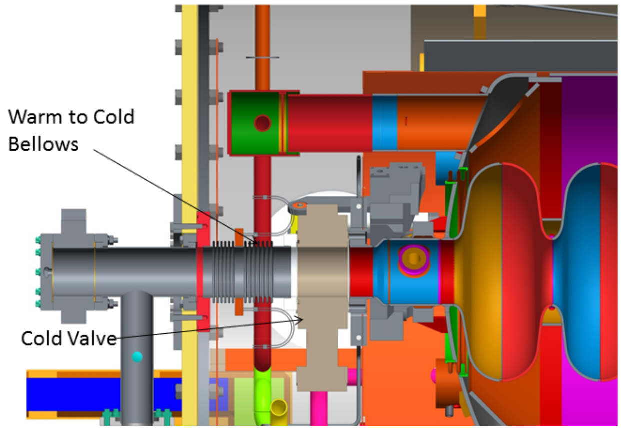

Figure 5: Schematics of warm-to-cold transition region for the spare high beta cryomodule. The same scheme will be used for the STS cryomodules.

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