CONCEPTUAL DESIGN FOR REPLACEMENT OF THE DTL AND CCL WITH SUPERCONDUCTING RF CAVITIES IN THE SPALLATION NEUTRON SOURCE LINAC

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Abstract

The Spallation Neutron Source Linac utilizes normal conducting RF cavities in the low energy section from 2.5 MeV to 186 MeV. Six Drift Tube Linac (DTL) structures accelerate the beam to 87 MeV, and four Coupled Cavity Linac (CCL) structures provide further acceleration to 186 MeV. The remainder of the Linac is comprised of 81 superconducting cavities packaged in 23 cryomodules to provide final beam energy of approximately 1 GeV. The superconducting Linac has proven to be substantially more reliable than the normal conducting Linac despite the greater number of stations and the complexity associated with the cryogenic plant and distribution. A conceptual design has been initiated on a replacement of the DTL and CCL with superconducting RF cavities. The motivation, constraints, and conceptual design are presented.

INTRODUCTION

The Spallation Neutron Source (SNS) Linac utilizes traditional normal-conducting Drift Tube Linac (DTL) and Coupled Cavity Linac (CCL) structures to accelerate a H- ion beam from 2.5 MeV to 186 MeV. Representative photographs of the DTL and CCL are shown in Fig. 1 and Fig. 2, respectively. The Linac operates at 60 Hz with a macro pulse width of 1 ms and an average macro pulse current of 26 mA [1].

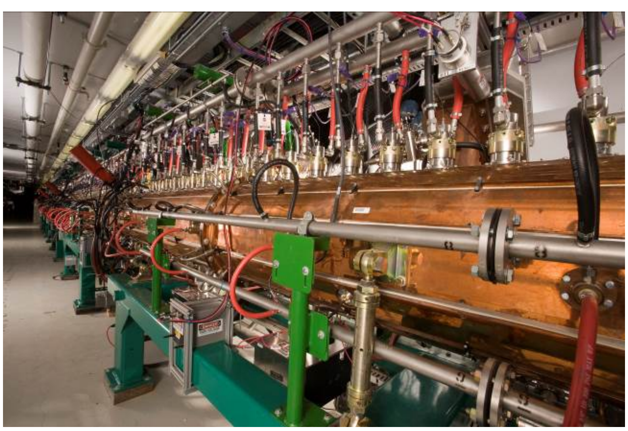

Figure 1: The SNS Drift Tube Linac.

The six DTL and four CCL structures are powered individually by 402.5 MHz, 2.5 MW klystrons and 805 MHz, 5 MW klystrons, respectively. The structures are water cooled via individual Resonance Control Cooling Systems (RCCS) that remove heat and maintain the operating frequency. The RF power is delivered to the structures via rectangular waveguide. The DTL structures feature a single RF power coupler comprised of a RF vacuum window, a waveguide taper, and a coupling iris, whereas the CCL structures feature dual RF power couplers, each comprised of a RF vacuum window, a waveguide section, and a coupling iris.

The remainder of the Linac is comprised of 81 superconducting RF cavities packaged in 23 cryomodules. Thirty-three medium-beta (β=0.61) cavities and 48 high-beta (β=0.81) cavities are installed in 11 and 12 cryomodules, respectively. These cavities are individually powered by 805 MHz, 550 kW klystrons.

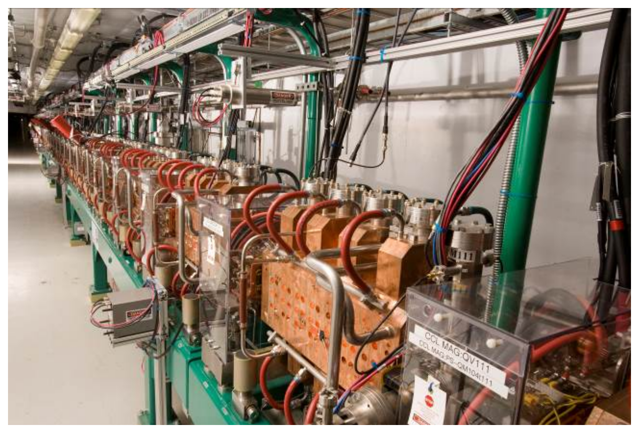

Figure 2: The SNS Coupled-Cavity Linac.

Motivation

The motivation to investigate replacement of the DTL and CCL (hereafter referred to as the Normal Conducting Linac) with superconducting cavities is based largely on reliability concerns and experience with contemporary Linac designs.

The Normal Conducting (NC) Linac is a significant source of down time at the SNS primarily due to the long thermal time constants of the structures. The turn-on time after a fault requires up to 30 minutes due to the need to warm up the structure and achieve phase-locked RF control at exactly 402.5 or 805 MHz. In contrast, the superconducting cavities can be turned on in a few minutes or less. Additional motivating factors are listed as follows:

- RF power levels are high in the CCL and will be further increased as the beam power on target is increased towards 1.4 MW. Beam loading will increase as the average macro pulse current increases from 26 to 42 mA. The klystrons in this section require cathode voltages up to 135 kV.

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- The high voltage converter modulators in the NC Linac section operate at the highest voltages and power levels and tend to require more maintenance than those in the SC Linac.
- RF vacuum windows have been somewhat problematic throughout the NC Linac. Several failures have occurred and caused uncontrolled venting of the structures and/or leakage of deionized water into the structures.
- The DTL structures utilize many elastomer O-rings for vacuum and water sealing. The lifetime of these seals is uncertain, and poorly understood gas releases sometimes occur when the RF power is switched off in preparation for Linac maintenance.
- The DTL structures contain many water-cooled drift tubes (max of 59 drift tubes in DTL1). There is a risk of water leaks due to erosion and/or corrosion as the structures age.
- Many water circuits and flow meters are utilized in the NC Linac. Flow balancing and maintenance of these circuits requires significant resources; instrumentation failures are not infrequent and are a source of down time.
- The gas load caused by operation of the NC Linac is non-negligible. Nearly all of the ion pumps on the CCL had to be replaced in 2012 due to saturation, and a major upgrade of the NC Linac vacuum system is being planned.

The SNS Linac commissioning was completed in 2006. A variety of H- and heavy ion Linacs have been designed since then, and a common theme is widespread adoption of superconducting RF cavities throughout the Linac. For example, Project X at Fermilab calls for the first superconducting cavity to accept H- beam at just 2.1 MeV, the beam energy at the exit of the Radio Frequency Quadrupole [2]. Another example is the FRIB Linac planned for construction at Michigan State University, where the first superconducting cavity accepts heavy ions at 0.5 MeV/u [3]. Finally, the European Spallation Source plans to utilize superconducting cavities beginning at 78 MeV [4]. It is probable that the SNS Linac would contain more superconducting cavities if it were to be designed today.

CONSTRAINTS

There are a number of significant constraints that must be accommodated in developing a plan to replace the existing NC Linac with a SC Linac. Primary constraints include: linear and transverse space in the Linac tunnel; beam dynamics lattice requirements; waveguide chases to the klystron gallery; and sufficient cryogenic plant capacity.

Space

The linear space occupied by the existing DTL and CCL is fixed, so any upgrade of the accelerating structures must fit within the existing footprint. The DTL and CCL have lengths of 36.6 m and 55.1 m, respectively. The Linac tunnel has a width of 4.27 m, a height of 3.05 m, and readily accommodates the existing SC Linac cryomodules. The distance from the beam axis to the walls is 1.68 m on the back side and 2.59 m on the aisle side.

Beam Dynamics

The beam energy at the entrances of the DTL and CCL is 2.5 and 87 MeV, respectively. The average macro pulse current ranges from 26 to 42 mA dependent on the required beam power on target. The beam pulse length is 1 ms maximum at a repetition rate of 60 Hz.

The existing medium-beta section of the SC Linac has a lattice period of 5.3 m.

Beam loss in the Linac must be controlled to less than 1 W/m.

Waveguide Chases

The NC Linac structures are serviced by 17 chases linking the Linac tunnel to the klystron gallery. Twelve of these chases contain RF waveguide (four chases for DTL3-6 and eight chases for CCL1-4). The chases contain water pipes and a variety of cables in addition to RF waveguide. The DTL and CCL chases have diameters of 0.91 m and 0.61 m, respectively, and lengths of 6.86 m. Typical DTL and CCL chases are shown in Fig. 3 and Fig. 4, respectively.

Figure 3: Typical DTL waveguide chases as viewed from the klystron gallery. The chase diameter is 0.91 m, and the waveguide size is WR2100.

Cryogenic Plant Capacity

The existing cryogenic plant distributes helium to the Linac tunnel at 4.5 K and 40 K for cooling of the superconducting cavities, the RF power couplers and the thermal shields. Operation at 2 K is achieved via four-stage cold compressors. The cryogenic transfer lines enter the Linac tunnel at the middle of the SC Linac (between cryomodules 16 and 17). The transfer lines extend upstream to the first cryomodule and downstream beyond the final cryomodule to the end of the energy upgrade region, which includes nine additional slots for high-beta cryomodules. The transfer lines do not pass through the NC Linac. The cryogenic plant capacity is 125 g/s at 2 K, 8500 W at 40 K, and 15 g/s at 5 K for the coupler cooling. The existing cryogenic capacity at the SNS is sufficient to support the DTL/CCL replacements and the nine energy-upgrade cryomodules.

Figure 4: Typical CCL waveguide chases as viewed from the klystron gallery. The chase diameter is 0.61 m, and the waveguide size is WR1150.

CONCEPTUAL DESIGN

In this phase of the design study we are considering only the replacement of the CCL structures with superconducting cavities. In this region, where the H- beam is accelerated from approximately 87 to 186 MeV, the logical choice of accelerating structure is an elliptical multi-cell 805 MHz cavity with a geometric beta in the range 0.4 to 0.55. This structure choice takes advantage of the existing SNS cryomodule design and experience and offers a significantly increased beam aperture compared to 30 mm in the existing CCL. The proposed cavity type is also compatible with the SRF infrastructure at SNS.

Initial studies indicate that a six-cell elliptical cavity with β=0.45 is approximately optimal with respect to transit time factor (Fig. 5). The prototype cavity is illustrated in Fig. 6, and its parameters are listed in Table 1. The proposed accelerating gradient is 9 MV/m, which corresponds to peak surface electric and magnetic fields of 31.3 MV/m and 63.9 mT, respectively.

We propose a low-beta Linac configuration of nine cryomodules, each containing three β=0.45 cavities, for a total of 27 cavities. Adjacent cryomodules will be connected via warm sections that contain magnetic focusing and diagnostics (as in the existing SC Linac). At this stage we have maintained the same physical layout as for the β=0.61 Linac for simplicity, i.e., the new cryomodules would have the same length as the existing β=0.61 cryomodules. The total length for nine cryomodules and the interleaved warm sections is 48 m, which is a reduction of 7 m compared to the existing CCL. The additional space could be utilized for a longer matching section, enhanced differential pumping between the NC Linac and the SC Linac, additional diagnostics, or perhaps an additional β=0.45 cryomodule.

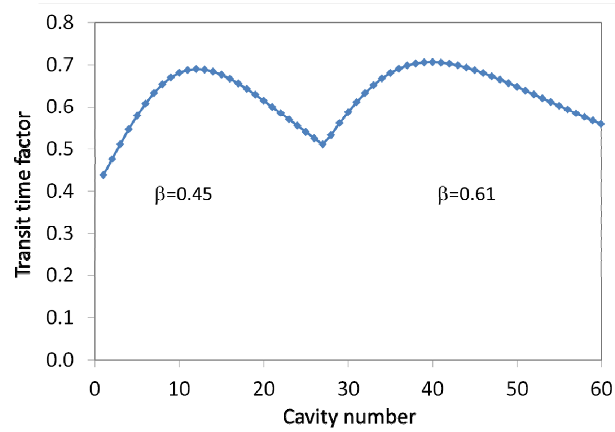

Figure 5: Transit time factor for the β=0.45 and β=0.61 sections of the SC Linac.

Beam dynamics for the proposed configuration was checked at beam currents of zero and 42 mA using Trace 3D. The emittance parameters of the injected beam are based on measured emittances in the SNS Linac [5-7]. The results of the simulations indicate the design is adequate from a beam dynamics perspective. The 42 mA case is depicted in Fig. 7.

The existing medium-beta Linac operates at an output energy of 425 MeV with 32 (of 33) cavities in service. The design of the SNS Linac specifies 386 MeV at this location, but the medium-beta cavities are operated at higher-than-design gradients. Based on the average operating gradient of the medium-beta Linac and the proposed operating gradient for the low-beta Linac, the energy gain per cavity has been calculated as shown in Fig. 8. In this case, the output energy of the medium-beta Linac would be 440 MeV.

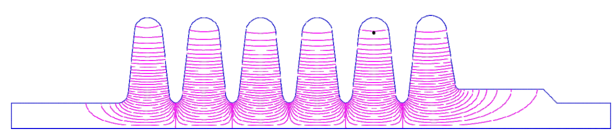

Figure 6: Geometry for proposed six-cell, β=0.45 cavity.

The SC Linac at the SNS is very flexible due to its topology of one cavity per RF station. Individual cavities can be switched off or operated at different gradients with minimal impact on overall Linac performance. Entire cryomodules may be removed and the remainder of the Linac can be re-tuned to maintain neutron production, albeit at a reduced beam energy. The proposed low-beta Linac is similarly robust, and calculations indicate the overall Linac would be operable with a low-beta cryomodule offline. Further studies are needed to validate this assertion, especially for the case of the first cryomodule being inoperable.

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Table 1: β=0.45 Cavity and Cryomodule Parameters

Geometric beta, β	0.45
Accelerating gradient, Eacc	9 MV/m
Ep/Eacc	3.48
Bp/Eacc	7.1 mT/MV/m
Effective acceleration length	504 mm
r/Q (at design β)	142 Ohm
Rs*Q	130 Ohm
Cell-to-cell coupling	1.5 %
Beam pipe diameter	76 mm
External Q	7e5
Cavities per cryomodule	3
Number of cryomodules	9
Input energy	86 MeV
Output energy	193 MeV

A design option under consideration would change the number of low-beta cryomodules to eight and replace the 9th cryomodule with an additional medium-beta cryomodule. In this case the output energy of the medium-beta Linac would be 447 MeV (given the assumptions applied in generating Fig. 8). The robustness of the SC Linac would be unchanged with respect to operability with missing cavities.

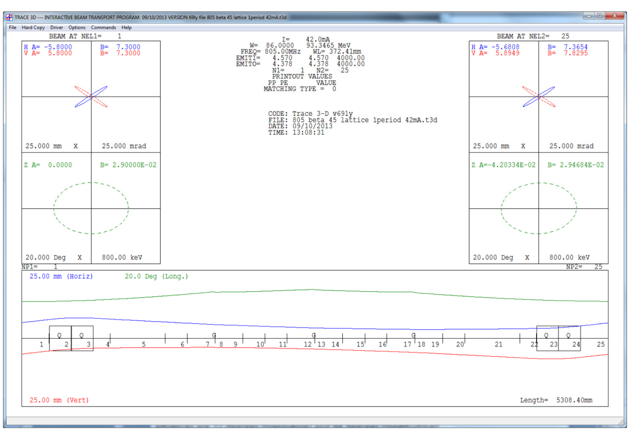

Figure 7: Trace 3D results for an input beam energy of 86 MeV and 42 mA beam current. Period tuned with RF phases at -20 degrees and quadrupole focusing strength of 3.2 T/m. Phase advances are 72 degrees (transverse) and 94 degrees (longitudinal).

CONCLUSION

This study demonstrates the feasibility of replacing the existing CCL structures with superconducting cavities. The next steps in the development of this upgrade include:

- Beam matching studies between the DTL and the upgraded SC Linac
- Multi-particle beam dynamics simulations
- Studies on the impact of inoperable cavities and cryomodules
- Mechanical design and analysis of the beta=0.45 cavity and cryomodule
- Physical layout of the upgrade to ensure compatibility with the existing Linac components and infrastructure

The replacement of the DTL with superconducting cavities has not been addressed in this study and will be investigated in the future.

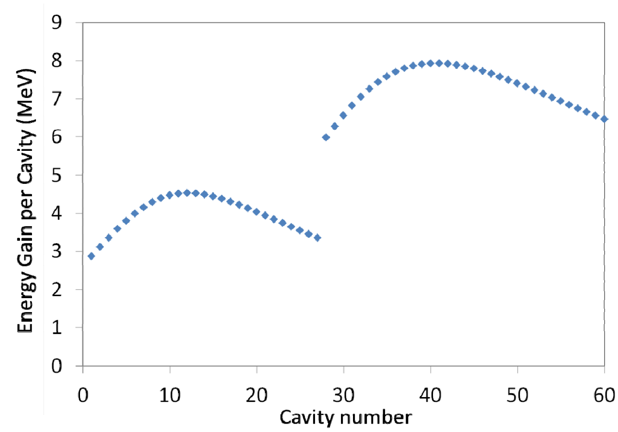

Figure 8: Energy gain per cavity along the low-beta and medium-beta sections of the proposed Linac.

ACKNOWLEDGEMENTS

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REFERENCES

[1] SNS Parameters List, SNS-100000000-PL0001-R13, ORNL, Oak Ridge, June 2005.

[2] Project X Reference Design Report, Fermilab, Batavia, June 2013.

[3] J. Wei et al, “The FRIB Project – Accelerator Challenges and Progress,” MOB01, HIAT2012, Chicago (2012).

[4] ESS Technical Design Report, European Spallation Source, Lund, April 2013.

[5] A. Shishlo and A. Aleksandrov, “Noninterceptive method to measure longitudinal Twiss parameters of a beam in a hadron linear accelerator using beam position monitors,” PRSTAB 16, 062801 (2013).

[6] Y. Zhang, “Experience and Lessons with the SNS Superconducting Linac,” Proceedings of IPAC10, Kyoto (2010)

[7] S. Shishlo, “SCL Laser Wire Measurements,” internal seminar, ORNL, Oak Ridge, March 2012.