THE SNS SUPERCONDUCTING LINAC SYSTEM*

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Abstract

The SNS has adopted superconducting RF technology for the high-energy end of its linac. The design uses cavities of $\beta = 0.61$ and 0.81 to span the energy region from 186 MeV up to a maximum of 1.3 GeV. Thirty-three of the lower β cavities are contained in 11 cryomodules, and there could be as many as 21 additional cryomodules, each containing four of the higher β cavities, to reach the maximum energy. The design uses a peak surface gradient of 35 MV/m. Each cavity will be driven by a 550 kW klystron. Cryomodules will be connected to the refrigerator by a pair of "tee" shape transfer lines. The refrigerator will produce 120 g/sec of refrigeration at 2.1 K, 15 g/sec of liquefaction at 4.5 K, and 8,300 W of 50 K shield refrigeration.

1 BACKGROUND

The SNS line item project start was Oct-98. In the 4th quarter FY99, two workshops were held to explore the option of changing to a Superconducting Linac; this led to a CDR in Nov-99 [1]. The primary requirement for the 1 GeV Linac was a 52-months (later increased to 56-months) schedule including Research & Development, design, fabrication, installation, and checkout. SNS Accelerator Scientific Advisory Committee endorsed the change in Jan-00 and it was then formally reviewed and endorsed by DOE in Mar-00 at the Semi-Annual Review.

The primary advantages of the change are:

1) Reduces operating costs
2) Ultra-high vacuum from the cryogenic system creates less beam-gas scattering resulting in less beam loss
3) Large SRF cavity bore reduces Linac activation due to beam loss
4) Reduces schedule risk associated with the large amount of furnace brazing for a warm Linac
5) Increases flexibility for future upgrades, e.g., 1.3 GeV

The primary disadvantages of the change are:

1) Schedule risk associated with the changing technology two years into the project
2) Costs associated with redesign

A cavity workshop was held in Apr-00 which led to a successfully vertical dewar tested $\beta = 0.61$ cavity in Aug-00 (Figures 1 & 2) and a $\beta = 0.81$ cavity in Apr-01 (Figures 3 & 4).

LANL retained the responsibility for the Linac Accelerator physics design [2], as well as the RF system including the Low Level Radio Frequency. JLab accepted responsibility for the cryomodule, the refrigerator and transfer lines, beam pipes in the inter-cryomodule warm spaces, and a 5 cryomodule per year fabrication and repair facility.

JLab started a 24-month R&D program 1-Feb-00 with the help of the worldwide SRF community (Table 1) and in parallel started detailed designs and the procurement process.

Table 1: External Collaborations

SUBJECT	COLLABORATION
Cavity Design	INFN, Milan-C. Pagani, P. Pierini, D. Barni, G. Ciovati
Mechanical Modes, Lorentz Force Detuning	LANL-D. Schrage, K. Matsumoto, R. Mitchell,
Mechanical Tuning	JAERI-N. Ouchi
Fundamental Power Coupler	KEK-K. Saito, S. Noguchi, S. Mitsunobu,
Higher Order Modes	DESY-J. Sekutowicz,
HOM Coupler	DESY-J. Sekutowicz
Multipacting (Cavity)	INFN, Genoa-R. Parodi
Multipacting (Cavity, Coax Coupler)	R. Nevanlinna Institute, Univ. of Helsinki-P. Ylae-Oijala

Table 2: Cryogenic Time Line

09-Aug-99	First Workshop
16-Sep-99	Second Workshop
22-Nov-99	CDR complete
01-Feb-00	**Project starts**
17-Apr-00	Cavity Workshop
29-Jun-00	First five major procurements are placed
18-Aug-00	Cold compressor order placed
30-Aug-00	Nb $\beta = 0.61$ cavity complete
22-Dec-00	Last major refrigeration procurement placed
13-Apr-01	Nb $\beta = 0.81$ cavity complete
1-Jun-01	50% JLab effort costed or contracted
Jul-01	***Cavity procurement placed***

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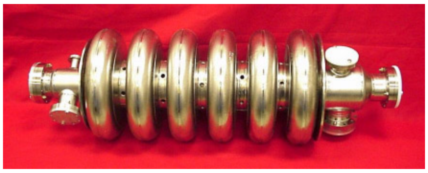

Figure 1: β = 0.61 cavity

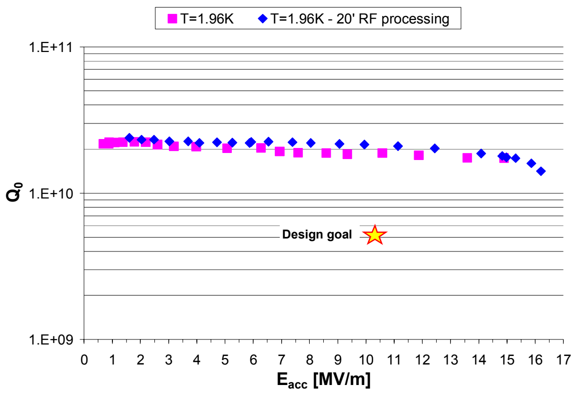

Figure 2: β = 0.61 cavity performance

Figure 3: β = 0.81 cavity

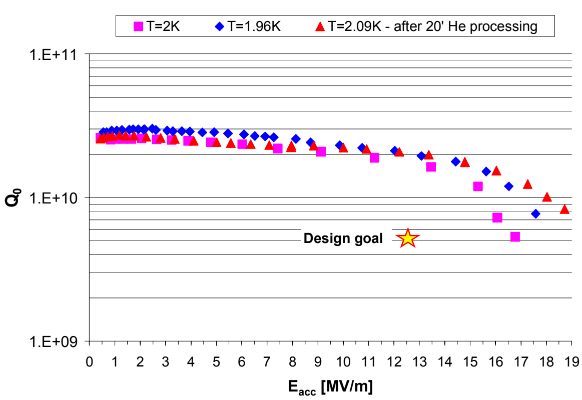

Figure 4: β = 0.81 cavity performance

Table 3: Linac parameters

Cavity β	Medium 0.61	High 0.81
Energy In	186 MeV	379 MeV
Energy Out	379 MeV	0.84→1.3 GeV
Number of CM	11	12 plus 9 slots
Cavities per CM	3	4
E_{acc}	10.1 MV/m	12.5→15.9 MV/m
Slot length	5.839 m	7.891 m
CM length (bore tube)	4.239 m	6.291 m
RF power	550 kW	550 kW

2 PHYSICAL LAYOUT

SNS requires 23 short Cryomodules (CM) plus 9 empty slots for a total length of 228.34 m vs. the 42.25 units at 9.6 m each required for CEBAF. Figure 5 shows the tunnel cross-section including CM and related piping.

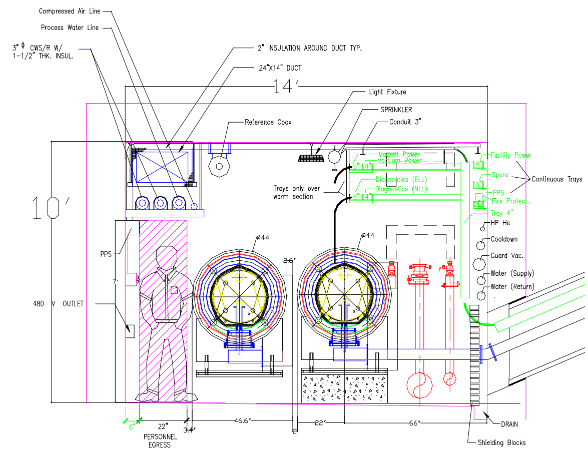

Figure 5: SNS tunnel cross section

3 CAVITY DESIGN

The cavity design maximizes E_{acc} assuming E_{peak} = 27.5 MV/m, and uses four dies to prevent higher fields in the end cells [3]. We chose a six-cell design to limit the RF power loading in the Fundamental Power Coupler.

Table 4: Cavity parameters

Cavity β	0.61	0.81
Frequency [MHz]	805.000	805.000
E_{peak}/E_{acc}	2.71	2.19
B_{peak}/E_{acc} [mT/(MV/m)]	5.72	4.72
R/Q [Ω]	279	483
G (=R_sQ_0) [Ω]	179	260
Cell-to-cell k [%]	1.53	1.52
K_L [Hz/(MV/m)^2]	−2.07	−0.43

During the last year 2 JLab Upgrade and 1 TESLA multi-cell cavities have been Electro-Polished with the help of KEK. All three had similar excellent results; Figure 6 shows a typical before and after result. It should be noted that the 19 MV/m was not the limit of the cavity but the RF system.

JLab proposed a $1.9 M, 2.5 year (01-Feb-01 to 01-Aug-93) R&D program with the goal of achieving a linac output of 1 GeV with fewer cavities by using electro-polishing techniques to raise the gradient in the 48 high-β cavities. The program has two phases:

1) Set up an Electro-Polish facility at JLab and develop parameters for SNS cavities
2) Develop procedures for maintaining improved vertical dewar performance during CM assembly

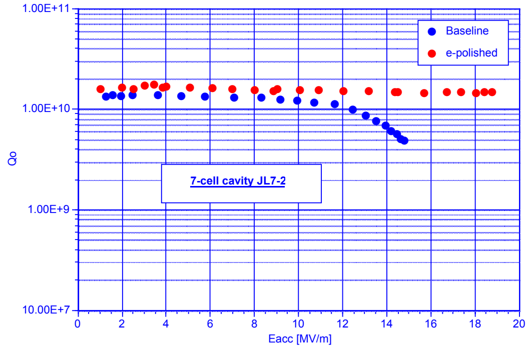

Figure 6: Electropolishing of 7 – cell cavity

The 11 medium–β cryomodules to be assembled between October 2002 and July 2003 will be used in Phase 2 to establish cryomodule assembly procedures that preserve good cavity performance. SNS has adopted this higher gradient as the baseline and started to fund the R&D program. The revised baseline was formally reviewed and endorsed by the May-01 DOE Semi-Annual Review.

The 805 MHz fundamental power coupler was scaled from the KEK 508 MHz coupler, that successfully coupled 320 kW to a beam. It uses 4.5 K liquefaction flow to cool the outer conductor; the inner conductor is conduction cooled to a water-cooling loop outside the vacuum system [4,5]. The first pair was successfully warm tested up to 550 kW at LANL [6,7]. The HOM couplers are scaled TESLA couplers. The medium-β HOM coupler testing is complete and the high-β coupler testing should be complete within a month [8].

4 He VESSEL

The cavity is surrounded by ~150 liters of 2.1 K superfluid in a 61 cm diameter He vessel [9]. The vessel is 5 bar rated, built with titanium and niobium-titanium dished heads on the cavity. The field probe end has a titanium bellows and a TESLA-style tuner. The vessel is supported by double-X pattern nitronic rods.

Table 5: Cryomodule parameters

Cavity β	**Medium 0.61**	**High 0.81**
CM diameter	0.991 m	0.991 m
2 K static heat load per CM (inc. TL)	25 W	28 W
2 K dynamic heat load per CM	10 W	33 W
Shield heat load per CM (inc. TL)	170 W	200 W
Control valves per CM	5	5
Bayonets per CM	4	4
Radiation hardness	10^8 rads	10^8 rads
Pressure rating::		
2 K system – warm	3 Bar	3 Bar
2 K system – cold	5 Bar	5 Bar
shield & 4.5 K system	20 Bar	20 Bar

5 CRYOMODULE DESIGN

The SNS Cryomodule is based on the CEBAF Cryomodule with improvements borrowed from LHC, TESLA, and JLab 12 GeV Upgrade and uses the frequency scaled KEK fundamental power coupler. Figure 7 is a 3D section of the medium-β CM, while Figure 8 is the schematic of the high-β CM helium circuit. The primary Cryomodule parameters are given below [10,11].

The co-axial fundamental power coupler requires a 4.5 K lead flow to cool the outer conductor; therefore we use the LHC concept of producing the 2K in the CM rather than in the refrigerator. The refrigerator produces a 3 Bar 4.5 K stream which feeds two CM cooling loops in parallel: 1) The first heat exchanges with the return stream through a small subcooler in the CM and then JT's to cool the cavity, 2) The second feeds the power coupler outer conductor.

The 50 K CM shield is cooled by a 4 Bar 35 K stream which first cools the supply transfer line (TL) shield, then the CM shield, and finally the return TL shield before returning to the refrigerator at 55 K.

The bayonet design permits replacement of a Cryomodule in less than a day, if needed, without warming up. In the eight years since initial CEBAF cooldown, the Linacs have never been warmed up and only four CM's have been replaced during scheduled accelerator shutdowns.

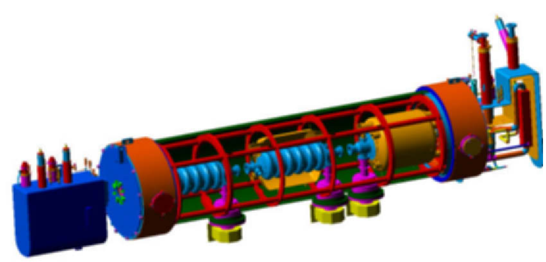

Figure 7: Medium-β cryomodule (β = 0.61)

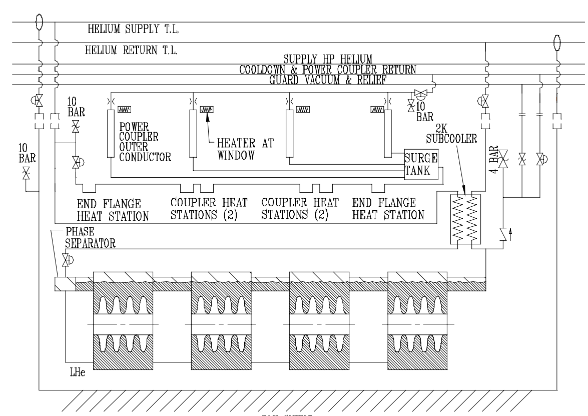

Figure 8: Cryomodule flow schematic

6 REFRIGERATION SYSTEM DESIGN

SNS requires a cryogenic system with a capacity of about half that of the CEBAF system. The CEBAF design can be adapted with very minor modifications. Since SNS uses a lower frequency, 805 vs. 1500 MHz, its optimum temperature is just below Lambda [12]. We have specified 2.10 K for the refrigerator, which then provides a large margin of 0.07 K for pressure drops in the return of the transfer line and cryomodule (0.005,7 Bar).

Table 6: Refrigeration parameters

32 Cryomodules	**Primary**	**Secondary**	**Shield**
Temperature	2.10 K	5.0 K	35-55K
Pressure	0.041,3 Bar	3.0 Bar	4.0-3.0 Bar
Static load	850 W	5.0 g/sec	6125 W
Dynamic load	600 W	2.5 g/sec	0 W
Capacity	2,850 W	15 g/sec	8300 W
Margin	100%	100%	35%

Figure 9 is the block diagram of the refrigeration system. The system consists of two pairs of warm compressors with an installed spare pair for the SNS high availability requirements. Each of the six skids has a three-stage 100 ppm oil removal system. This is followed

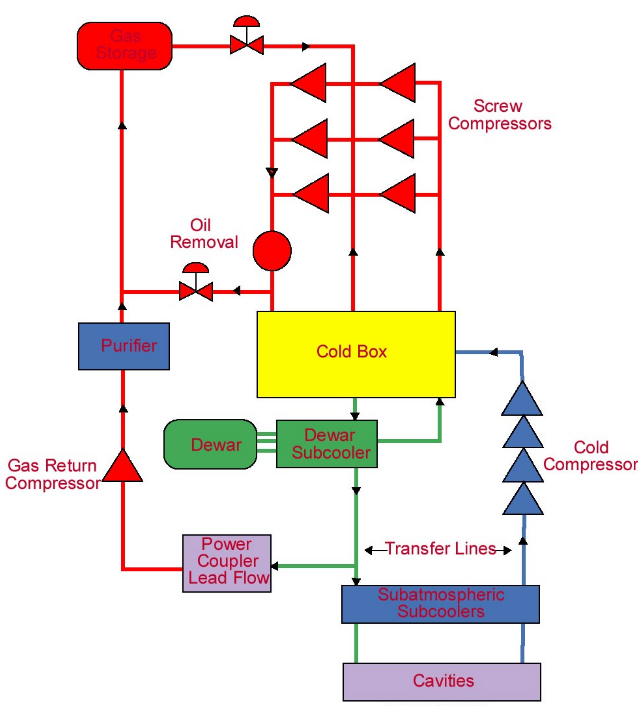

Figure 9: Block diagram

by three stages of coalescer-demisters and a final charcoal bed with final particulate filter. This supplies a 4.5 K coldbox, which uses a standard liquefier cycle to produce a 3 Bar 4.5 K supply stream. This feeds up to 32 cryomodules through quick disconnect U-tubes in parallel. At each cryomodule there are two JT valves: 1) 4.5 K fundamental power coupler lead flow supply and, 2) 2.1 K 0.041 Bar cavity cooling. The cavity cooling boil off is returned to a set of four cold compressors. They recompress the stream to 1.05 Bar at about 30 K where it is used to provide counter-flow cooling in the 4.5 K coldbox.

This is very similar to the CEBAF system at JLab [13]. The primary difference is that the final 4.5 to 2.1 K heat exchanger is in the cryomodule rather than in the cold compressor coldbox, Figure 8. This change was driven by the need for 4.5 K fundamental power coupler lead flow. The other option of adding an additional transfer line pipe and extra U-tubes was quickly rejected. The supply transfer line is at 4.5 K while the return is at 4.0 K in the cryomodules. This had the secondary benefit of higher system efficiency since the transfer line and u-tube heat leaks are absorbed at a higher temperature.

To meet the initial SNS schedule of 1 GeV beam in 4th quarter FY04, the CM installation schedule required Linac cooldown 1-Nov-03; this in turn made the refrigerator and TL procurements the critical path. The similarity to the CEBAF system permitted us to get a quick start on this with the first major contracts being awarded in Apr-00 and the last one 22-Dec-00; the last component, 4.5 K coldbox, is scheduled to be delivered Jul-02. The current projected cooldown date is 1-Apr-04, which is driven by the BOD dates of the Linac tunnel and CHL building. The primary refrigeration design elements are given below [14].

Table 7: Refrigeration parameter

Warm Compressor System:	two stages of two (plus installed spare) 321 mm screw compressors 10 PPM oil removal on each compressor
4.5 K Coldbox:	LN2 precooling five turbines dual 80 K absorbers single 20 K absorber 4.5 K subcooler
2.1 K Coldbox	four stages of cold compressors compression ratio of 25 for 2.10 K Note: 2 K subcooler is removed to the Cryomodules
Auxiliary equipment:	15,000 Gal LHe Dewar 20,000 Gal LN2 Dewar eight 30,000 Gal GHe storage tanks dual external 50 g/sec purifier local control room

The CEBAF transfer line (TL) system consists of two tee shaped 240 m Linac feeds each capable of supplying a maximum capacity of 5 kW at 2.0 K. SNS will use the same design for one Linac (228.34 m) with only the Cryomodule spacing changed. The supply TL is a 6 IPS (168 mm OD) with an 1 IPS (30 mm ID) primary supply and eccentric 35K shield. The return TL is a 12 IPS (324 mm OD) with an 6 IPS (163 mm ID) primary subatmospheric return and eccentric 55K shield. Figure 10 shows the transfer line cross sections, while Figure 11 shows the 15 m tunnel installation modules.

The 40m long branch supply to the center of the SC Linac has the same cross section as the tunnel transfer lines, with only the 1 IPS replaced with a 1.25 IPS (39 mm ID). The branch return is a 16 IPS (406 mm OD) with an 8 IPS (214 mm ID) primary subatmospheric return.

In addition there are three He gas headers:

1 IPS	3.00 Bar	warm gas supply for bayonets & coupler
3 IPS	1.05 Bar	cooldown and coupler return
4 IPS	0.01 Bar	guard vacuum and relief

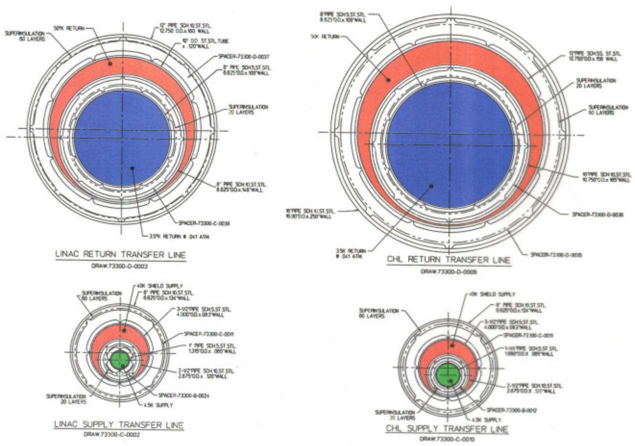

Figure 10: Transfer line cross section

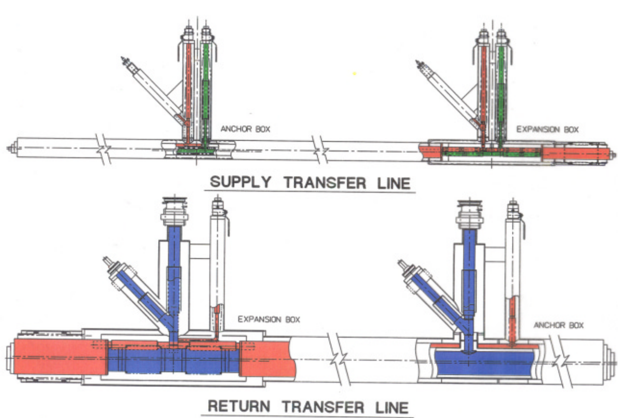

Figure 11: Transfer line module

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