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SNS Superconducting Linac

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Abstract

The Spallation Neutron Source (SNS) decided in early 2000 to use superconducting RF (SRF) in the linac at energies above 185 MeV. Since the SNS duty cycle is 6%, the SRF and normal conducting approaches have capital costs which are about the same, but operating costs and future upgradability are improved by using SRF. The current status of cavity and cryomodule development and procurement, including the basis for decisions made, is discussed. The current plan includes use of 805 MHz, 6-cell cavities with geometrical betas of 0.61 and 0.81. There are 33 medium beta and 60 high beta cavities in 11 and 15 cryomodules, respectively. Each cavity (except the 93rd) is powered by a 550 kW pulsed klystron. Issues addressed include choice of peak surface gradient, optimization of cavity shape, selection of a scaled KEK input power coupler, selection of scaled TESLA higher mode couplers, and control of the effects of higher order modes on the beam.

Introduction

The SNS management made the decision to build most of the linac using superconducting RF (SRF) for a number of reasons. Although, at the SNS's duty cycle of 6%, the capital cost of SRF and normal conducting RF (NCRF) are about the same, SRF has a lower operating cost and adds flexibility to operate with one cavity out of service. SRF also has a larger beam aperture, and offers upgrade potential as the technology advances further. In addition, the industrial base for manufacturing SRF cavities is beginning to exceed that for manufacturing NCRF cavities. The experience the SNS staff would acquire working with superconducting cavities would also be applicable to future accelerators.

Parameter Selection

The requirements for the SRF linac are that it accelerate H^- beam from 185.7 to 969 MeV, maintain longitudinal focussing matched to the output of the NCRF cavity coupled linac, limit the length of each cryomodule to accommodate the quadrupole doublet focussing, minimize jitter and beam emittance growth, control project costs, and meet a 4-year time schedule.

The first step in adopting SRF was to select a frequency and a number of cells. The first harmonic of the bunch frequency (402.5 MHz) was considered too low because such cavities are physically difficult to handle, the cost of Nb material is high (it was impractical to acquire thin film coating technology in the available time), the cavities would have a high susceptibility to microphonics, and the large surface area per cavity would limit the gradient, since gradient scales as $A^{-1/4}$, where A is the surface area.

The third (or higher) harmonic was adjudged undesirable because it would require an excessive number of cells per active meter, coupling the required power into the cavity would be more challenging, the aperture would be smaller, and the higher order mode (HOM) impedances would be higher.

Based on the above considerations, 805 MHz was adopted as the most desirable frequency.

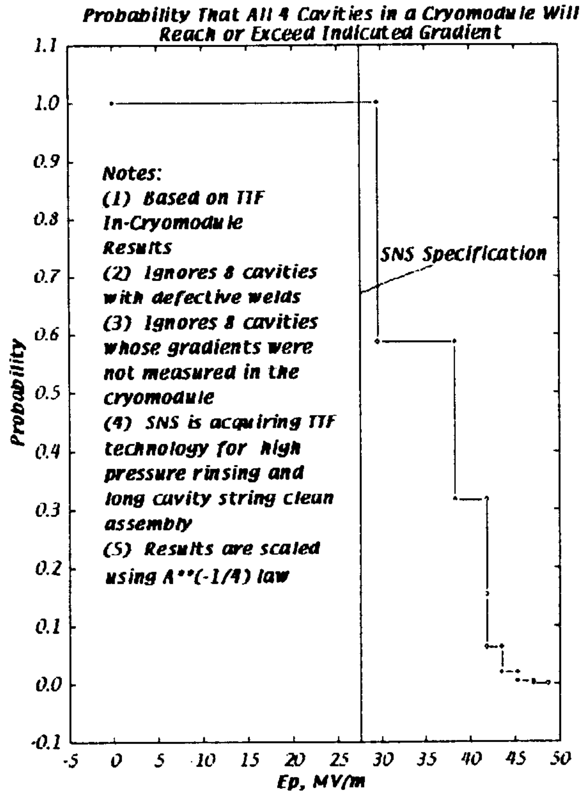
The next step was to optimize the number of cells. Drivers for a large number are improved real estate packing fraction, and minimized numbers of auxiliary components. Drivers for a small number are that the range of acceptable particle betas is larger, achieving and maintaining field flatness becomes less difficult, HOMs are less likely to be trapped, handling is less difficult, the surface area is smaller, and the power which needs to be transmitted through a single window and coupler is smaller. Based on these considerations, 6 cells was selected as the optimum number.

The surface gradient was chosen to approach, but not exceed, the state-of-the-art. TESLA TTF in-cryomodule cavity performance was used as the standard for the state-of-the-art. At the time the specification was set, three TTF eight-cavity cryomodules existed. One had manufacturing defects which yielded reduced gradients, and was ignored. Another had cavities whose properties in the cryomodule had not been measured, so no data was available. The third showed cryomodule success probability dropping abruptly above E_p = 29.6 MV/m ($A^{-1/4}$ adjusted).

Two potential performance limitations are a high peak surface electric field, E_p, which produces field emission, and a high peak surface magnetic field, H_p, which causes quenches. For typical shapes and the current state-of-the-art, E_p is the predominant limitation.

The E_p specification adopted for SNS is $E_p = 27.5 \pm 2.5$ MV/m. A lower specification would cause SRF to be less competitive at the SNS duty cycle. A higher specification would cause technical, cost, and schedule risk to be excessive. The variation in gradients is accommodated by keeping the RF slope at the bunch equilibrium phase a smoothly varying function from cavity to cavity.

The probability of achieving a particular E_p gradient in a 4-cavity cryomodule is shown in the following figure, along with the SNS specification.



The next step was to select the cavity cell shape. Desirable attributes include a low ratio of peak electric to accelerating field (E_p/E_a), a low ratio of peak magnetic to accelerating field (H_p/E_a), large intercell coupling and aperture, avoidance of persistent multipacting, high cell stiffness, easy manufacturability, easy cleanability, and a $5 * \pi / 6$ mode which avoids the injection notch sideband. Achieving a low E_p/E_a ratio is in opposition to large intercell coupling and aperture, and to high cell stiffness. This was addressed by imposing boundary conditions on the latter factors, and then minimizing the E_p/E_a ratio. This minimization was performed separately for the beta = 0.61 and 0.81 cavities. The resultant design has en elliptical iris with a minor to major axis ratio of 0.59, which spreads the highest electric field over a large area. A 1.5% intercell coupling was adopted, as was a 7° end wall slope. Persistent multipacting was avoided. No unusually small radii, inaccessible welds, etc., occurred in the design. All regions of the cavity are accessible to high pressure rinsing, and all surfaces drain when the cavity is in the vertical position. The 5 * π / 6 mode overlap with the accumulator ring injection notch is avoided for all realistic linac output energies. End cell shapes are optimized separately to obtain a flat field profile and to accomplish the above objectives.

Auxiliary Devices

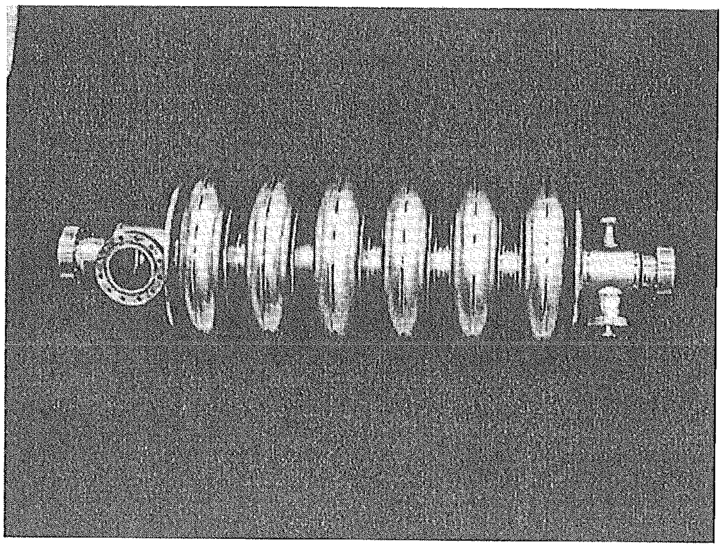
The proven KEK-B fundamental power coupler was adapted to the SNS design by scaling the frequency to preserve the RF properties. The scaled average power handling capability is more than adequate.

TESLA TTF couplers were adopted. They provide strong coupling over large bandwidth, and have a notch at the fundamental power frequency.

TESLA tuners were adopted because they provide good resolution and negligible backlash.

CEBAF 12 GeV upgrade cryostat designs were used. These include helium vessels welded to the cavities, and use strongbacks to permit clean assembly of a cavity string followed by insertion into the vacuum tank.

The following photographs show a beta 0.61 Nb cavity and a beta 0.81 Cu cavity.



Beta 0.61 Nb Cavity

Beta 0.81 Cu Cavity

Key Parameters of Cavities Resulting from Design Effort

Parameter	Beta 0.61	Beta 0.81	Units
R/Q	295	484.8	Ohms
E_p/E_a	2.69	2.19	-
B_p/E_a	5.64	4.75	mT/(MV/m)
E_a	10.223	12.557	MV/m
Q_{ext}	$7.3*10^5$	$7.0*10^5$	-
Q_o	$5*10^9$	$5*10^9$	minimum

Other Issues and their Resolution

The expected microphonic amplitude of 6 σ = 100 Hz is well within the cavity bandwidth of 1103 Hz.

Lorentz force detuning of ~ 390 Hz is accommodated by centering this swing on the resonance, making it well within the cavity bandwidth. Achieving this small a Lorentz effect requires stiffeners between cavity cells and an overall cavity length constraint.

Transverse HOM effects have been simulated in detail. A transverse instability can occur at any frequency because the transverse phase shift between consecutive bunches is unconstrained. A special case occurs on the edge of beam spectral lines, where any transverse position errors are magnified by the RF. It was found that instabilities are avoided and the magnification is negligible with $Q \leq 10^8$ and with at least 20% of the expected manufacturing frequency spread, which is of the order of 0.1% of the frequency difference from the fundamental mode.

Longitudinal HOM effects were also explored by detailed simulation. A longitudinal instability can occur at any frequency because the phase error advance from one bunch to the next is unconstrained. Output energy errors and timing errors occur near beam harmonics. Some have proposed that high Qs be relied on to avoid HOM problems; the argument is that the probability of landing on a high Q resonance is small. However, HOM frequencies vary with time because of He pressure, He depth, thermal cycling, and intentional detuning from resonance. In addition, beam harmonic frequencies change when the beam energy is changed. Reactive energy exchange with the beam is a problem anywhere near a beam harmonic at high Q. In addition, the cavities are not guaranteed to have extremely high Qs because some damping is provided by the fundamental power coupler and by the copper plated bellows along the beamline.

The fundamental power deposited in a cavity depends on the Q achieved for the associated mode. This power can be as high as 473 watts with a Q of 10^8, but this power is reduced to 0.11 watts with a Q of 10^3. The achievable Qs are being explored. The achieved Qs will determine where the power needs to be dissipated.

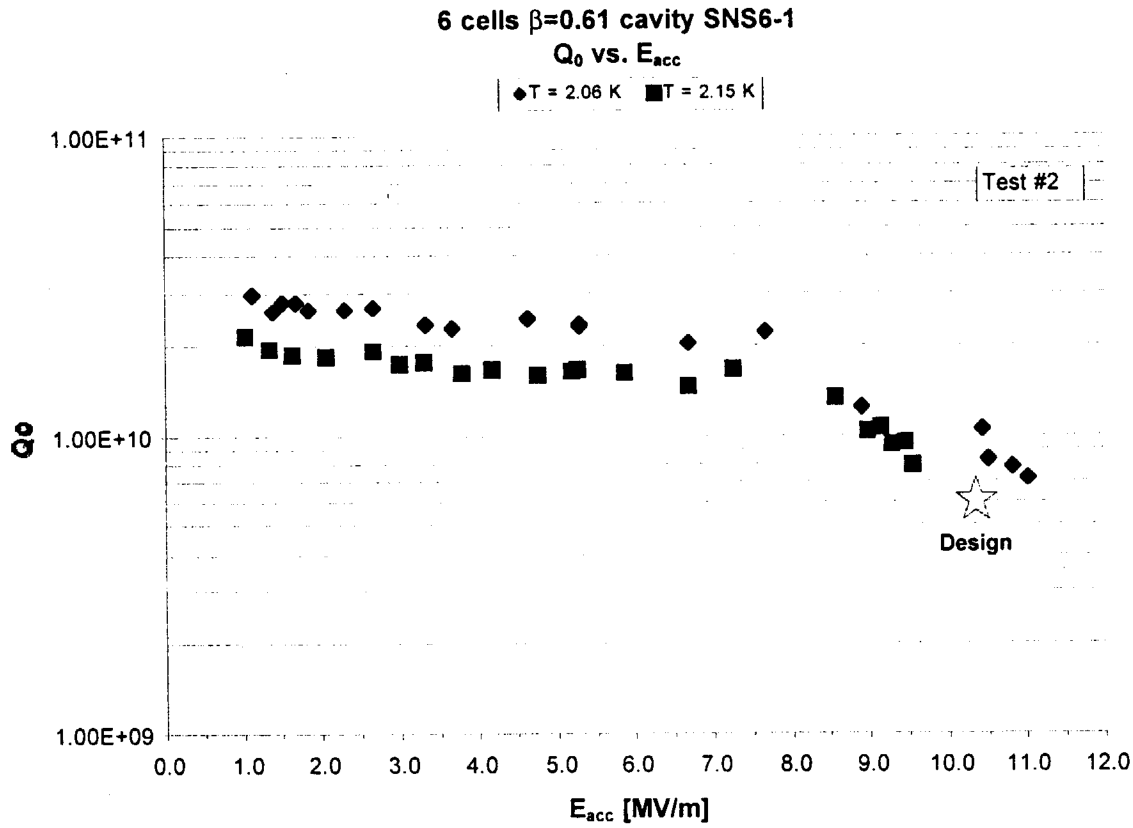
R&D Scope (FY 2000 - FY 2002)

The R&D scope includes the following:

- o Beta 0.61
  - One tested cryomodule containing 3 pre-tested Nb cavities
  - One additional Nb cavity, tested
  - One copper cavity for model measurements
  - One single-cell cavity for multipacting measurements
  - One procurement package
- o Beta 0.81
  - Two tested Nb cavities
  - One cryomodule design
  - One procurement package
- o Additional fundamental power couplers for testing

Results to Date

In addition to the design and fabrication work completed, the first beta 0.61 cavity has been tested for the first time. This cavity met its gradient and Q requirements. The results are shown below.



Construction Scope (FY 2000 - FY 2004)

The construction scope for the SRF linac (excluding the RF source and controls) includes:

- o Beta 0.61
  - Eleven three-cavity cryomodules, installed and commissioned
- o Beta 0.81
  - Fifteen four-cavity cryomodules, installed and commissioned
- o Vacuum system interconnecting cryomodules
- o One 2.1 K refrigerator, installed and commissioned
- o Transfer lines and U-tubes, installed and commissioned
- o One SRF facility, 5 cryomodules/year rework capacity

Conclusion

The superconducting linac design parameters have been optimized for the SNS. Prototyping is well under way. No show-stoppers have been encountered. A new phenomenon for heavy particle linacs, cumulative longitudinal instability, has been recognized, confirmed by simulation, and controlled by Q limitations and cavity-to-cavity frequency spreads. Design work and procurements for construction are on schedule.