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SNS SUPERCONDUCTING CAVITY BETA STUDIES

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SNS Superconducting Cavity Beta Studies

The SNS super-conducting RF linac design must meet several requirements. First, the output energy should be ≥ 800 MeV in order to produce at least a 1 MW pulsed beam. Sometime after the initial commissioning, with the benefit of additional cavity processing the linac is expected to produce a 1300 MeV beam,. So there is a range of operational energies the linac needs to perform well in. Additional considerations guiding the choice of cavity beta include the maximum phase slip, and the minimum transit time factor (TTF) of the first cavity at the transition between the high and low beta sections. If the transit time factor is too small (or the phase slip too large) there is a danger of not being able to accelerate the beam should the accelerating gradient be lower than expected. Or part of a finite bunch length beam could be lost. Finally, the choice of cavity beta needs to match the energy out of the present CCL structure at 185 MeV. The schedule for the SNS project permits development of only two cavity beta families. Two super-conducting beta families is adequate for reasonably efficient acceleration from the 185 MeV CCL exit energy to the required final energy. This starting energy of the first super-conducting section is determined by a break point in the CCL based on RF partitioning.

A previous study [1] indicated that in order to maximize the real-estate gradient, use of a constant accelerating gradient is preferable over a constant RF power per cavity and that the use of 6 cells per cavity is optimum. Here we investigate the choice of the cryo-module beta, and the number of high and medium beta cryo-modules. Unless indicated otherwise, assumptions used in this study are listed in Table 1. The cavity phase law show in this table attempts to smoothly match the longitudinal focussing strength per unit length.

Choice of Cavity Beta

The super-conducting cavity geometric beta (β_g) is picked to maximize the beam acceleration for the conditions expected to be achieved in the SNS. This optimization is influenced by the incoming beam energy, the cavity accelerating gradients, and the number of cryo-modules for each cavity beta type. For SNS the beam energy at the entrance to the Superconducting section is 185 MeV, and we initially consider the case for 11 medium beta cryo-modules with 3 cavities each, and 17 high beta cryo-modules with 4 cavities each. Additionally the linac tunnel is sized to accommodate 4 more high beta cryo-modules (for a total of 21 high beta cryo-modules).

Figure 1 shows the beam energy for various β_g values calculated using the reference peak surface field of 27.5 MV/m. The choice of medium beta cryo-module β_g has only a small influence on the beam acceleration. The previous choice of $\beta_g = 0.61$ is retained for the medium beta cryo-modules. The choice of β_g for the high beta cryomodule is more sensitive. Using $\beta_g = 0.81$ instead of $\beta_g = 0.76$ offers an additional 52 MeV acceleration for the nominal conditions.

Table 1. Partial list of assumptions used in the SNS cavity beta studies.

Phase law	• Starting phase of the medium beta cryo-module family = 22°, with a bilinear ramp to the final phase (2/3 phase change occurs in first 1/3 of family) • Phase of the high beta cryo-module = 26.5° • Ending phase of the medium beta cryo-module is solved to give constant E_0 T sin(ϕ) β_g.
Peak surface field (E_{peak})	27.5 MV/m
E_{peak} / E_0 (1)	$1 / \left(-0.4814 + 2.244 b_g + 1.1129 b_b^2\right)$
Number of cells/cavity	6
Cavities/ cryo-module	• 3 for medium beta cryo-module • 4 for medium beta cryo-module
Linac architecture	• Two β_g families • Constant gradient / cavity

(1) – this is a fit of Superfish output of three similarly optimized cavities: β_g= 0.45 with E_{peak} / E_0 = 3.3, : β_g= 0.61 with E_{peak} / E_0 = 2.11, : β_g= 0.81 with E_{peak} / E_0 = 1.65

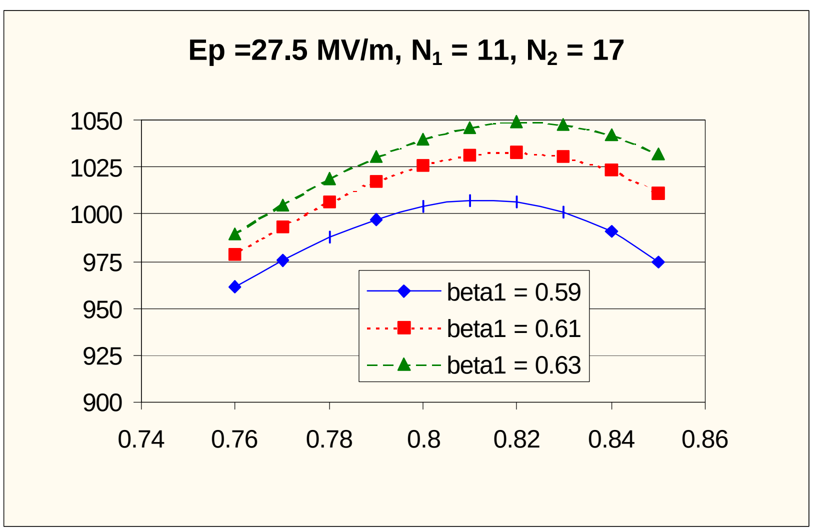

Figure 1. Final beam energy vs. the high beta cryomodule β_g, for three different medium beta cryomodule β_g values. The reference peak surface field of 27.5 MV/m is used here.

Figure 2 shows the attainable beam energy under conditions of reduced attainable accelerating gradient, with the peak surface field is limited to 25 MV/m. With 17 high beta cryo-modules, the attainable beam energy is 940 MeV, and with 21 cryo-modules the beam energy is about 1100 MeV. Providing the tunnel space for 21 high beta cryo-modules permits attaining greater than 1000 MeV even in the unlikely event of only achieving 25 MV/m. Also, use of β_g = 0.81 tends to maximize the beam energy with a reduced accelerating gradient.

Improved performance using β_g =0.81 for the second section, instead of β_g =0.76, is more pronounced if higher accelerating fields are assumed. For example, for the case of a peak surface field of 30 MV/m and use of 21 high beta cryo-modules, the final beam energy vs. β_g is shown in figure 3. In this scenario, operation near 1300 MeV is achieved for β_g = 0.81, whereas only 1180 MeV is attained for β_g = 0.76.

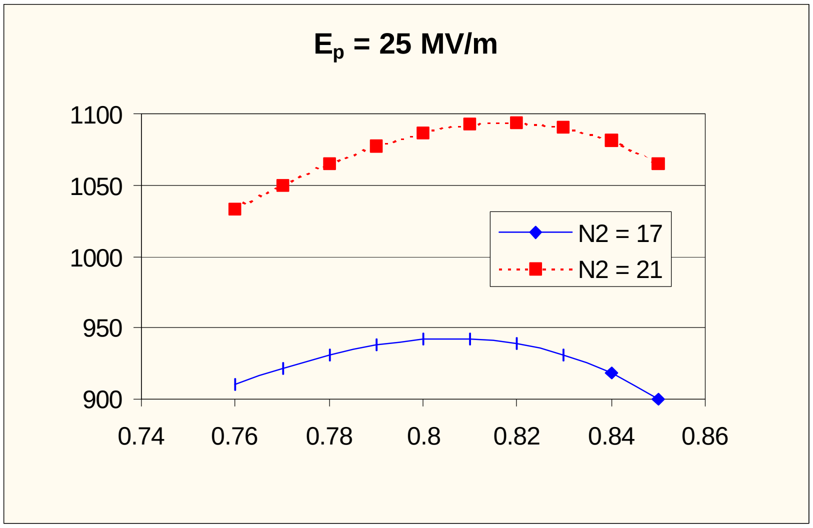

Figure 2. Final beam energy vs. the high beta cryomodule β_g, for 17 and 21 high beta cryo modules. 11 Medium beta cryo-modules with β_g = 0.61 and a lower peak surface field of 25 MV/m is used here.

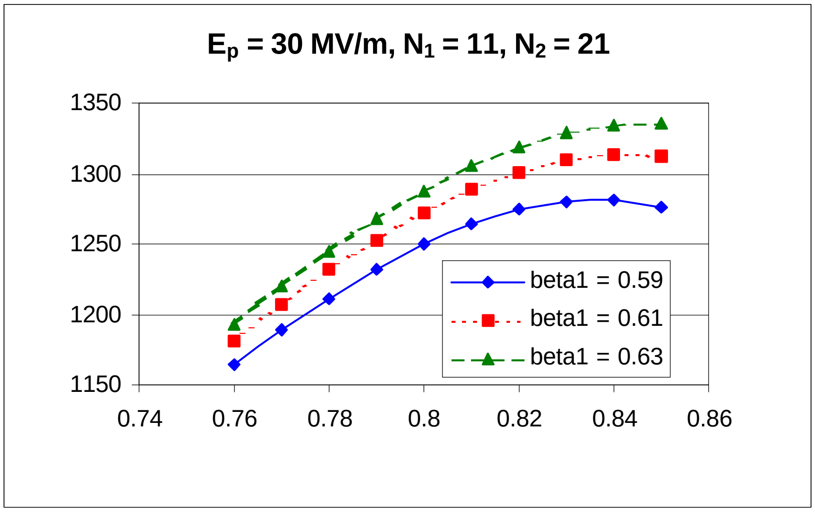

Figure 3. Final beam energy vs the high beta cryomodule β_g, for three different medium beta cryomodule β_g values. A peak surface field of 30 MV/m is used here.

Number of Cryo-modules

The above analysis indicates that the choice of the medium beta cryomodule β_g is insensitive and that β_g = 0.61 is a good choice. Also the β_g for the high beta cryo-module should be ~ 0.81. Here we investigate the impact of the number of medium and high beta cryo-modules. Figure 4 shows the attainable energy vs. the number of medium beta cryo-modules for three different values of the high beta cryo-module β_g. The total number of cryo-modules is held fixed at 28[1], so this represents a trade-off between high beta and medium beta cryo-modules. As seen previously the high beta cryo-module β_g value to increase is beneficial, although there is a diminishing benefit as β_g = 0.81 is approached. Also going to fewer medium beta cryo-modules improves the energy gain of the linac.

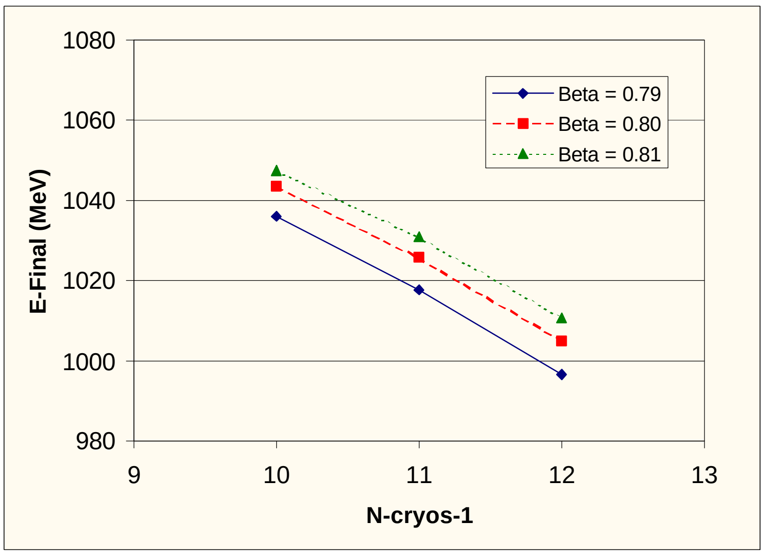

Figure 4. Final energy vs. the number of medium beta cryo-modules. The total number of cryo-odules is held fixed at 28, and the medium beta cryo-module β_g is 0.61.

However, additional considerations influence the choice of the number of medium and high beta cryo-modules. Figure 5 shows the maximum phase slip and minimum cavity transit time factor (TTF) for these cases. Both of these extremes occur at the first cavity in the high beta cryo-module section. The conditions that maximize the energy gain from the linac also to small TTF and large phase slip in the first high beta cavity. The low TTF level at fewer medium beta cryo-modules indicates that the transition energy is approaching the value below which, the high beta cavity will no longer accelerate the beam. While the simple synchronous particle model used here favors a fewer number of cryo-module to obtain the maximum energy gain, some allowance needs to be made for effects not included here. These additional effects include: (1) the phase spread of a real

[1] This is 1 fewer cryo-module than assumed in the baseline design presented at the March 14 DOE review, which used 8 medium beta cryo-modules at β_g = 0.61 and 21 high beta cryo-modules at β_g = 0.81.

bunch, (2) machine imperfections, (3) operation with failed cavities, and (4) the possibility that the peak surface fields will be lower than the 27.5 MV/m assumed here.

Due to these considerations, SNS uses 11 medium beta cryo-modules with $\beta_g = 0.61$and 17 high beta cryo-modules with $\beta_g = 0.81$. This choice of parameters provides the 1000 MeV capability with an adequate margin in the phase slip and TTF at the transition from the medium beta to high beta family.

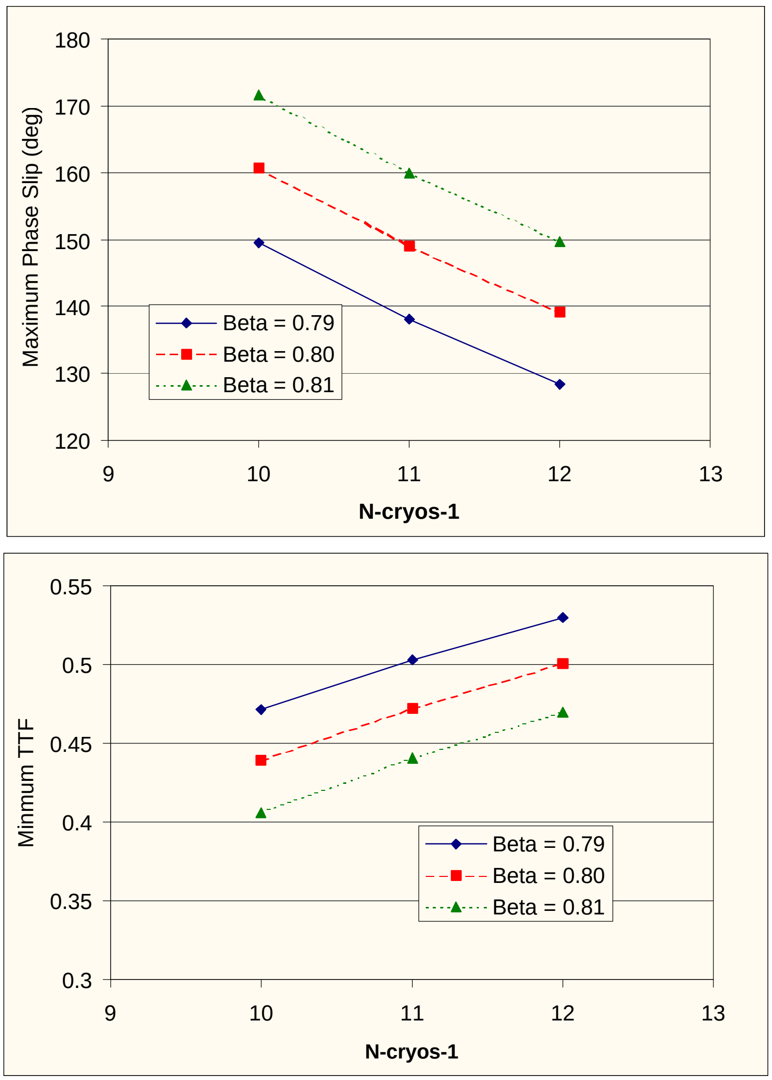

Figure 5. Maximum phase slip and minimum transit time factor (TTF), which occur in the first high beta cavity.

Comparison with the Previous Baseline

A comparison of parameters between the previous baseline and the new case is shown in Table 2. For each case, parameters are shown for the initial operation with 27.5 MV/m cavity peak surface field, and for later enhanced performance with (1) a peak surface field of 30 MV/m and (2) additional high beta cavities. The new case achieves higher energy, with fewer cavities than the previous baseline. This additional capability is due to (1) the more optimized cavity beta , (2) higher accelerating fields due to more optimized cavity shapes, and (3) to a small extent a more favorable phase ramping law. The impact on the enhanced performance is even more dramatic. Roughly 100 additional MeV is attained for the 30 MV/m operation with the new proposed cavity beta, using about the same number of cavities.

Reference

[1] John Galambos, Jeff Holmes, Dong-o Jeon, and David Olsen , Synchronous Particle Scoping Studies for an SNS SC Linac, ORNL SNS Accelerator Physics Internal Memo, 9/14/99.

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Table 2. Comparison of parameters of the previous baseline and parameters from a linac with the proposed new cavity beta.

	Previous Baseline[1]		Proposed Baseline	
	E_p = 27.5 MV/m	E_p = 30 MV/m	E_p = 27.5 MV/m	E_p = 30 MV/m
CCL-β_1 transition energy (MeV)	185	←	185	←
β_1-β_2 transition energy (MeV)	310	322	374	387
Section 1 cavity β_g	0.61	←	←	←
Section 1 cavity β_g	0.76	←	0.81	←
TTF(β_2) at transition	0.45	0.49	0.44	0.47
Max phase slip (deg.)	158	145	160	150
Output Energy (MeV)	1001	1143	1031	1246
Number of cavities ($\beta_1 + \beta_2$)	24 + 84 = 108	24+92 = 116	33 + 68 = 101	33 + 84 = 117
SC Linac length (m)	208	224	199	223

1 – The previous baseline assumed a phase ramp from -25^o to -30^o in the first beta section and a phase of -26.5^o in the second cavity section. Also, the previous baseline assumed $E_{peak} / E_{0\text{-interior}}$ = 2.33 for the $\beta_1$section and 1.82 for the $\beta_2$section