DESIGN IMPROVEMENTS FOR THE SSC CCL

D. Raparia, C. R. Chang, D. Swenson, B. Turner, C. G. Yao and W. Funk
Superconducting Super Collider Laboratory*
2550 Beckleymeade Ave., Dallas, Texas 75237

Abstract

This paper describes the beam-dynamics changes in the SSC Coupled Cavity Linac (CCL). In the previous design [1] transverse emittance growth was 50%. This growth was due to the r-z coupling caused by rf defocusing. In the new design the r-z coupling is reduced by decreasing the beam size in the transverse and longitudinal direction. Beam size is reduced by (1) providing more transverse focusing, (2) removing the super-periodicity in the longitudinal plane and (3) reducing the number of cells per tank. The new design has only about 10% transverse emittance growth and uses one less klystron.

I. Introduction

The SSC coupled cavity linac (CCL) will be a side coupled structure operating at 1282.851 MHz to accelerate a nominal 25 mA H^- beam from 70 to 600 MeV. In designing the CCL the main consideration was the transverse emittance growth. Since CCL is least expensive per meter to fabricate, and it provides the highest accelerating gradient, the transition energy between drift tube linac (DTL) and CCL is chosen to be 70 MeV to minimize the cost. Other design considerations were reliability and ease of diagnosis. For achieving the reliability, large safety margins were kept, e.g. allowed peak surface field is 32 MV/m (1.0 E_K), beam to bore radius ratio is 0.5 without errors and with errors is 0.8. For diagnosis, there will be a diagnostic box after each tank.

II. Previous design and problems

In the previous design, the CCL consisted of ten modules, each module had six tanks which were resonantly coupled together by five bridge couplers. Each module powered by a 20 MW klystron connected to the central bridge couplers. There was one electromagnetic quadrupole after each tank to form a FODO array. There were two options to provide more space for the diagnostics between the modules: either make the magnetic lattice non-periodic, or keep the magnetic lattice periodic but make the first and last tank shorter in each module. We chose the magnetic lattice periodic, consequently the end tanks in both neighbouring modules had 20 cells and other tanks in the module had 22 cells. For ease of manufacturing, cell lengths within one tank were the same and equal to $\beta_{av}\lambda/2$. As far as periodicity tank to tank was concern, it was non-periodic in transverse as well as longitudinal plane. However, the lattice was still periodic from module to module, therefore it was possible to find a matched beam solution.

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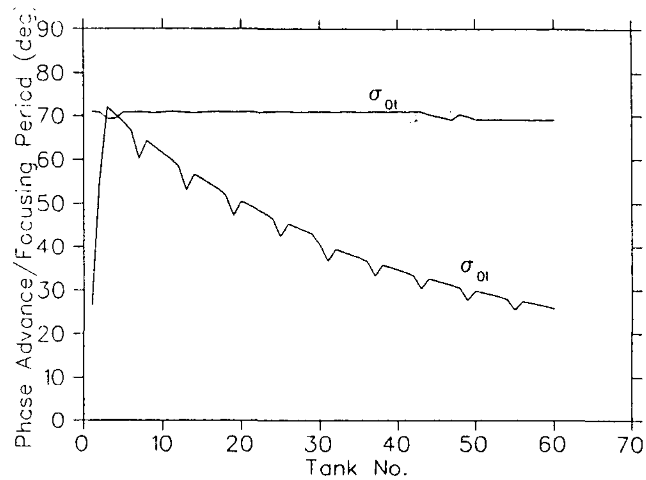

Figure 1: Zero-current transverse and longitudinal phase advances in the CCL as function of tank numbers.

The field gradient E_0T in the first two tanks of Module 1 was ramped 1 MV/m to 6.67 MV/m and then E_0T was kept constant throughout the CCL. Purpose of this ramp was to make the CCL performance current independent. The inter-tank spacing for the first five modules was $5/2\beta\lambda$ and for the last five module was $3/2\beta\lambda$. Inter-module spacing for first five modules was $9/2\beta\lambda$ and for the last five module was $7/2\beta\lambda$. The zero current transverse and longitudinal phase advances per focusing period are shown in Figure 1. Because of the beam size, bore radius for the first six modules was 1.25 cm and for the last four modules was 1.0 cm.

End-to-end beam simulation showed about 65% emittance growth in the CCL. Simulations have shown that the emittance growth was entirely due to the r-z coupling. Figure 2 shows rms normalized transverse and longitudinal emittance as a function of tank number. The source of this r-z coupling is the rf defocusing force which is given by

$$e(E_r - \beta c B_\theta) = \frac{1}{\gamma} E_0 I_1\left(\frac{\omega r}{\beta c \gamma}\right) \sin\phi$$

where $I_1(x) = \frac{x}{2} + \frac{x^3}{16} + \ldots$ is the bessel function of the first order, e is the electric charge, E_r is radial electric field, β, γ are relativistic parameters, c is velocity of the light,

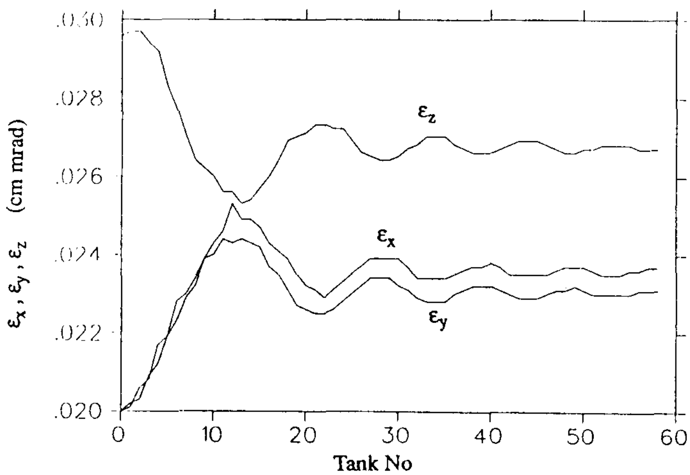

Figure 2: Normalized rms transverse (ϵ_x, ϵ_y) and longitudinal (ϵ_z) emittances as function of tank numbers.

E_0 is the accelerating field, ω is the angular frequency, r and ϕ are radial position and phase of the particles. There were three main contributor to this rf defocusing force. (1) Phase slip; the cell lengths within the tank are the same and equal to $\beta_{av}\lambda/2$. Therefore as the particle traverses the tank, it slips in the phase. It is common practice to design a tank such that particle phase at the entrance and at the exit of the tank is the same. This causes bunch motion in the bucket. Phase slip will be higher with higher number of cells in a tank. (2) Superperiodicity; superperiodicity in the previous design was another cause of higher r-z coupling. Simulations show that as a well matched beam propagates through the CCL, it oscillates longitudinally. (3) Transverse beam size; tanks with 22 or 20 cells were too long for the traverse beam size which was also adding to the rf defocusing. Because of the ramping, E_0T was very low in first two tanks of the Module 1. Power needed for this module was only 11 MW. Also most of the other module needed only 13 MW power. For klystrons that are capable of producing 20 MW power, this was very inefficient.

III. Improved new design

In the new design the r-z coupling is reduced by decreasing the beam size in the transverse and the longitudinal direction. Beam size is reduced by (1) providing more transverse focusing by making shorter tanks, (2) making lattice periodic in both traverse and longitudinal directions which reduces the longitudinal and transverse oscillations hence the beam size, and (3) reducing the number of cells per tank to 16 which reduces the phase slip. Shorter tanks have allowed stronger transverse focusing per unit length reducing transverse beam size. Smaller beam size has allowed us to reduce the bore radius to 1.0 cm throughout the CCL, which improves shunt impedance. Because of lowered longitudinal emittance resulting from removal of superperiodicity, and because of lower phase slip resulting from fewer cells per tank, it was possible to increase synchronous phase from -30 to -25 degrees resulting in still smaller phase slip and higher acceleration efficiency. With higher acceleration efficiency and better shunt impedance, it was possible to save one klystron. In the new design, only 9 klystrons instead of 10 are needed. Table 1 shows design comparison between the previous and the new design.

Parameter	Previous	New
Frequency (MHz)	1282.85	1282.85
Injection Energy (MeV)	70.0	70
Output Energy (MeV)	600.0	600.0
Number of tanks/module	60/10	72/9
Number of cell/tank	22/20	16
CCL Length (m)	115.33	112.41
Bore Radius (mm)	12.5	10.0
Inter-tanks space ($\beta\lambda$)	5/2-3/2	5/3-3/2
Inter-module space ($\beta\lambda$)	9/2-7/2	5/2-3/2
E_0T (MV/m)	1.0-6.67	7.2-6.6
ϕ_s(deg)	-30.0	-25.0
Ramp Gradient	yes	no
Magnetic lattice	FODO	FODO
σ_{0t} (deg)	70.	80.-60.
σ_{0l} (deg)	70-25	55-20
Current (mA)	25.0	25.0
Input ϵ_t (n,rms) (mm-mrad)	0.2	0.2
Output ϵ_t (n,rms) (mm-mrad)	0.295	0.215
Input ϵ_l (rms) (10^{-7} eV-s)	8.25	8.25
Output ϵ_l (rms) (10^{-7} eV-s)	7.75	8.00
Max. Beam Radius (mm)	10.0	6.3

Table 1: CCL Design Comparison.

In the new design, each module comprises eight tanks with 16 accelerating cells per tank. End-to-end simulations show that ramping the field has almost no effect on the current independency with our new design parameters, therefore ramping of E_0T is abandoned. The E_0T is 7.2 MV/m in the first module and thereafter it is slowly reduced to 6.55 MV/m. This makes the power dissipation in each module approximately the same (16 MW), which yields the maximum power efficiency.

In the new design, the inter-tank spacing is the same as inter-module spacing. This makes the focusing system completely periodic. For the first two modules, inter-tank spacing is 5/2 $\beta\lambda$ and for the last 7 modules, 3/2 $\beta\lambda$. The minimum inter-tank space available for the diagnostic devices is $\geq$ 30cm. All quadrupole magnets are shifted towards the low energy side so the extra space can used for beam diagnostic devices. In contrast to the previous design where diagnostic devices only exist after each module, in the new design there is one diagnostic box after each tank.

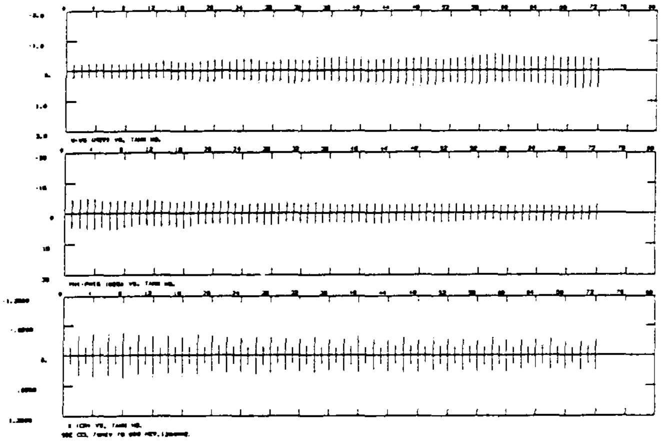

Figure 3: Beam size, phase and energy profiles as the beam traverses the CCL.

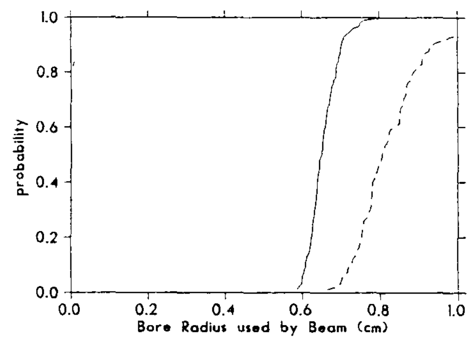

Figure 4: Probability distribution of the bore radius used by the beam for a combination of random errors given in Table 3. Graph shows the probability that the beam radius will be at or below the plotted value.

All quadrupoles are dc and have fixed gradient of 31 T/m except the last four quadrupoles in Module 2 where the transition in inter-tank space occurs.

IV. SIMULATION RESULTS

Simulation studies were carried out for the new CCL design discussed above using CCLDYN. Typical CCLDYN runs were made with 1000 macro-particles uniformly filling a six-dimensional hyperellipsoid in the input phase-space. Figure 3 shows the beam size, phase and energy profiles as the beam traverses the CCL. Other runs were made using the input phase space distribution from the DTL-CCL Matching section [2]. Emittance results are shown in Table 2. CCLTRACE [3] calculations were done for the errors listed in Table 3. These are not rms errors but are uniformly distributed over the tolerance limits. Figure 5 shows that the beam only fills two-third of the bore radius of the CCL. The dotted curve shows the bore radius used by the beam when errors were twice as large as given in Table 3; in this case there is a 8% probability that the beam size will exceed the bore radius.

Table 2: Normalized rms ϵ_x, ϵ_y(π mm-mrad) and ϵ_z (MeV deg) .

Input Dist.	I mA	INPUT			OUTPUT		
		ϵ_x	ϵ_y	ϵ_z	ϵ_x	ϵ_y	ϵ_z
6-D uni-	10.	.194	.188	.378	.201	.199	.376
	25.	.194	.188	.371	.199	.216	.350
	50.	.234	.228	.418	.240	.260	.434
From DTL	10.	.192	.197	.447	.206	.222	.411
	25.	.198	.192	.438	.220	.240	.432
	50.	.246	.228	.438	.248	.275	.456

Table 3: Tolerance Budget for the SSC CCL.

Error	
Tank disp	±0.1 mm
Quad disp	±0.1 mm
Quad Pitch and Yaw	±1.0 deg
Quad Roll	±0.5 deg
Quad Strength	±0.15%
Tank Field	±0.5%
Tank phase	±0.5 deg
Cell-to-Cell Field	±1.0%
Klystron Field	±0.5%
Klystrom Phase	±0.5 deg

V. SUMMARY

The new design of the SSC CCL is a well-optimized conservative design for acceleration from 70 to 600 MeV with an output beam of the required quality. It also saves one klystron rf station which yields over one million dollars in savings. There is essentially low ($\leq$ 10%) emittance growth in the absence of fabrication error and the beam occupies only half of the bore size for a uniform input beam.

VI. REFERENCES

[1] C. R. Chang, *et al*,"Design Studies of SSC Coupled Cavity Linac," 1991 IEEE Particle Accelerator Conference, San Francisco, CA, May 1991, p2993.

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[3] K. R. Crandell, Private communication.