EFFECT OF TRANSIENTS ON THE BEAM IN THE SUPERCONDUCTING SUPERCOLLIDER (SSC) COUPLED-CAVITY LINAC*

L. M. Young and S. Nath

Accelerator Technology Division, Los Alamos National Laboratory

Los Alamos, New Mexico 87545, USA

Abstract

Each module of the Superconducting Super Collider (SSC) Coupled-Cavity Linac (CCL) consists of eight tanks (16 accelerating cells each) coupled with bridge couplers. The radio frequency (rf) power drive is in the center of the module at the bridge coupler between the fourth and fifth tanks. In this simulation of the beam dynamics, the rf power is turned on 10 μs before the beam is turned on. This time lapse allows the fields to build up and stabilize before they are required by the beam. When the beam is turned on, the beam loading causes the fields to change. This transient state of the fields together with their effect on the beam is presented. A model has been developed to calculate the field distribution throughout the module as a function of time. Beam dynamics simulations were run with the results of this model at several times during the beam pulse. An estimate of the effect of the transients is given by the results of these simulations.

Introduction

The steady state of a coupled-cavity linac has been well documented by the coupled resonator model (1, 2, 3). The transient response of a chain of coupled resonators was also analyzed many years ago (4, 5, 6). The model used in this analysis is basically the same as that used in Ref. 5.

Theory

The CCL is modeled as a chain of $N+1$ loss less coupled resonators that have modes $q = 0...N$ and field distributions described by eigenfunctions $X(q,n)$, where n is the cavity number $n = 0...N$. In this model the accelerating field $\overline{E}(n,t)$ in cavity n at time t is represented as a sum over all the eigenfunctions. $\overline{E}(n,t)$ is a complex number representing the amplitude and phase of the accelerating field.

$$\overline{E}(n,t) = \Sigma_q \, \overline{a}(q,t) X(q,n) \exp(j\omega t) \tag{1}$$

where $\overline{a}(q,t)$ is a complex number representing amplitude and phase of the qth eigenmode. $X(q,n)$ is a real number, and ω is the angular frequency of the radio frequency power source. In a singly periodic chain of coupled resonators, the eigenfuctions are

$$X(q,n) = (\text{const}) \cos(\pi q n / N), \tag{2}$$

and the frequencies are

$$\omega(q) = \omega_o / \sqrt{(1 + k \, \cos(\pi q / N))}. \tag{3}$$

where ω_o is the resonance frequency of a cell and k is the nearest neighbor coupling.

If the fields in the accelerator are zero when $t = 0$ then $\overline{a}(q,0) = 0$. The value of $\overline{a}(q,t)$ can be determined by numerical integration by setting

$$\overline{a}(q,t + \partial t) = \overline{a}(q,t) \exp\left[\left(-\frac{1}{2}\omega(q)/Q(q) + j(\omega(q) - \omega)\right)\partial t\right]$$
$$+ \left(\overline{kickp}(q) + \overline{kickb}(q)\right)\partial t \tag{4}$$

where ∂t is a small increment in time and other parameters are described below.

The factors that affect $\overline{a}(q,t)$ are (1) the losses in the cavity that cause an exponential decay in the fields $\left(\exp\left[\left(-\frac{1}{2}\omega(q)/Q(q)\right)\partial t\right]\right)$, where $\omega(q)$ is the angular frequency of the qth mode and $Q(q)$ is the unloaded quality factor of the qth mode; (2) the angular frequency of the qth mode that causes the phase of the qth mode to change with respect to the rf drive phase $\left(\exp\left[j(\omega(q) - \omega)\partial t\right]\right)$; (3) the external rf drive; and (4) the beam loading. Let $\overline{pf}$ be the complex amplitude of the rf drive and $\overline{pt}$ be the complex amplitude of the rf power transmitted out of the accelerator through the wave guide coupling. Then

$$\overline{pt} = \Sigma_q \frac{1}{2}(\omega(q)/Q(q))\overline{a}(q,t)X(q,nd)\sqrt{\beta(q)} \tag{5}$$

where $X^2(q,nd)\beta(q)$ is the coupling of the qth mode to the wave guide at cell number (nd). For the calculations in this paper, $\beta(q) = 1$. Then

$$\overline{kickp}(q) = \left(2\overline{pf} - \overline{pt}\right)X(q,nd)\sqrt{\beta(q)}/\left(\Sigma_n X^2(q,n)\right) \tag{6}$$

Note that the forward power $= |pf|^2$, and the reflected power $= |\overline{pf} - \overline{pt}|^2$. Let $\overline{beam}(n)$ be the complex amplitude of the beam current integrated over the volume of cell (n).

$$\overline{beam}(n) = C \int \overline{I}(x) E(x) dx / \int E(x) \, dx \tag{7}$$

where $\overline{I}(x)$ is the beam current at $x, E(x)$ is the accelerating field in cell (n), and C is a constant. Then

$$\overline{kickb}(q) = \Sigma_n \overline{beam}(n) X(q,n)/\left(\Sigma_n X^2(q,n)\right) \tag{8}$$

For simple periodic structures the eigenfuctions $X(q,n)$ are known (1). For complicated structures such as the CCL for the SSC, the eigenfuctions and frequencies can be calculated with the program LOOP (3).

The SSC CCL

The code TRAN6 uses the equations in the preceding section to calculate the amplitude and phase of the rf in the first module of the SSC CCL. The best guess of the parameters for this module was used as input to the program LOOP, with the exception of Q. Because this code requires the eigenfunctions for the lossless case, a very large value was used for the Q in the input to LOOP. A control program was used to run LOOP for all the modes, and the

values of $X(q,n)$ and $\omega(q)$ were written to files. TRAN6 used the data in these files for $X(q,n)$ and $\omega(q)$.

The code TRAN6 calculates the field amplitude and phase of all the cells versus time. The code displays a moving picture (two frames of which are shown in Figs. 1 and 2) of the amplitude of all the cells plus a history of the forward power, the average amplitude of all the accelerating cells, and the reflected power. The amplitude of each accelerating cell and coupling cell is shown by the small *'s. The scale for the amplitude is shown on the left side of the plots, and the scale for the forward and reflected power is on the right side. The time scale is on the top of the plots. The scale on the bottom shows the cell number for the plot of amplitude versus cell number at the current time, displayed at the top. The amplitude of the accelerating field in all the cells is about 100%. The amplitude in the bridge coupler power cells is about 50% (not shown on this scale) and the amplitude in the coupling cells ranges from 15% in the cells nearest the rf drive to 0% near the ends of the module. Cell no. 0 is the drive cell in the center of the module, and cell No. 148 is the accelerating cell at the ends of the module. Because the module is driven at the center and is symmetric about the drive in this model, only half the module has been plotted. The amplitude and phase of each tank are listed in the upper right corner of the plot. The label "tank 4-5" represents the fourth and fifth tank in the module (nearest the rf drive, cell numbers 4 to 34). The tank label "tank 1-8" represents the first and last tank in the module (farthest from the rf drive) and the label "pwflwdrop" represents the difference in the amplitude and phase of cell No. 4 and cell No. 148. The label "refpow phase" represents the phase of the reflected power.

In Fig. 1 the time has advanced to 9.95 μs. The scale for the amplitude of the accelerating cells is 1% per division with a depressed zero. The amplitude scale for the coupling cells and for the histogram of the average amplitude is 20% per division. Note the tilt in the amplitude from cell to cell in each tank. The average amplitude in each tank has been adjusted to be nearly 100% by adjustment of the value of the nearest neighbor coupling constant between one of the coupling cavities between one of the tanks and the bridge coupler. This has been done in three places (six places for the whole module).
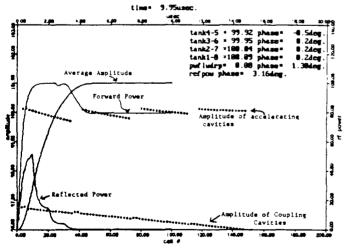

Fig. 1 TRAN6 Display at time = 9.95μs.

In Fig. 2 the time has advanced to 10.75 μs. The beam was turned on at 10 μs. The amplitude in the tanks has dropped 1% to 2%. The rf power has increased because the feedback system is requiring more power to compensate for the beam loading. The rf power scale on the right side of the plot means percent of maximum klystron power. The simulation has proportional, integral, and differential (PID) feedback built into the code. This PID feedback on the rf

power simulates a nearly ideal PID feedback control system; however, no feedforward that may be used on the SSC CCL rf control system is included.
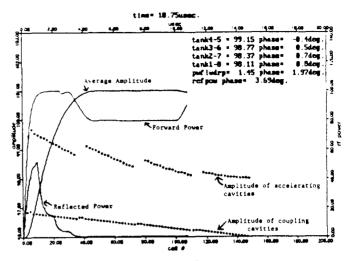

Fig. 2 TRAN6 Display at time = 10.75 μs.

Beam Dynamics

For beam dynamics simulation, we renormalize the design values E_d of the accelerating electric field in any given tank by the ratio of the transient field amplitude levels E_t in the tanks, and the steady state values E_s just before $t = 10$ μs. Table 1 shows these field amplitudes E_0 in the tanks within a module. The beam loading is assumed to be 12%, an average for the nine modules for a beam current of 25 mA. In the simulation, we ignored the very small field amplitude tilt from cell to cell within a tank and took the average value as the field amplitude for the entire tank. Particle simulation runs were made for 1000 macroparticles transported through the entire CCL at several t values, before and after $t = 10$ μs. Results are summarized in Table 2. Figures 3 and 4 show the energy and phase profiles at $t = 9.95, 10.5, 10.75, 11.00,$ and 12.00 μs respectively.

TABLE I
Field Amplitude E_0 in Tanks 1 Through 8 vs Time.

Time	E_0			
(μs)	Tanks 4&5	Tanks 3&6	Tanks 2&7	Tanks 1&8
9.95	99.92	99.95	100.04	100.09
10.25	99.18	99.09	99.15	99.19
10.50	99.04	98.70	98.46	98.38
10.75	99.15	98.77	98.37	98.11
11.00	99.09	98.94	98.83	98.77
11.50	99.51	99.70	99.89	100.02
12.00	100.00	100.07	100.12	100.15

TABLE 2
Effect of Transient Field on the Beam

Time (μs)	Transverse Emittance growth(%)	Longitudinal Emittance growth (%)	ΔW_c^* (keV)	$\Delta \Phi_c^*$ (degree)
9.95	12.9	-7.7	+27	+0.10
10.25	6.2	2.9	-111	+0.96
10.50	14.4	-6.2	-394	+0.85
10.75	15.7	-5.2	-559	+0.51
11.00	7.7	1.5	-270	+1.15
11.50	8.9	-2.0	+72	-0.34
12.00	14.2	-9.1	+38	+0.06

*Deviation of the mean from the synchronous value.

As expected, the transverse root-mean-square beam (not shown) size during the transient stage does not change when compared with the same in the steady state. However, the transient fluctuation in E_0 sets in phase-energy oscillations in the longitudinal phase-space, as evidenced in Figs. 3 and 4. The mean energy W_C of the output distribution deviates significantly from the steady state value within the first microsecond after $t = 10.0$ μs. At t = 10.75 μs, the mean energy deviation is = 559 keV. At $t = 11.50$ μs, the phase energy oscillation starts to damp out and at $t = 12.00$ μs the conditions are virtually the same as in the steady state. No particles are lost at any time due to the transient effect. There is also no statistically meaningful emittance growth during the transient stage. The deviation in the Phase $\Delta\Phi_C$ is not significant.
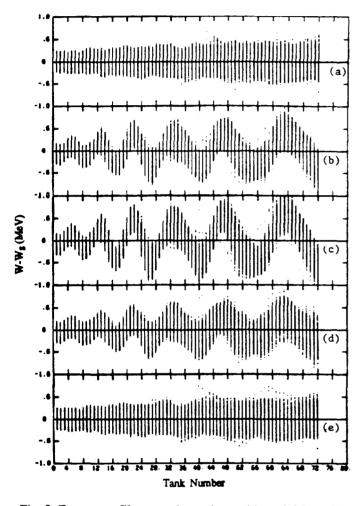

Fig. 3 Energy profile vs. tank number at (a) t = 9.95 μs, (b) t = 10.5 μs, (c) t = 10.75 μs, (d) t = 11.0 μs and (e) t = 12.0 μs.
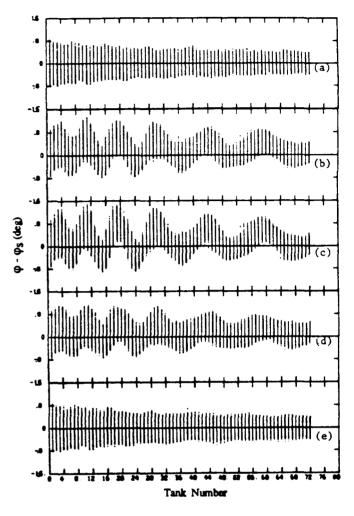

Fig. 4 Phase profile vs. tank number at (a) t = 9.95 μs, (b) t = 10.5 μs, (c) t = 10.75 μs, (d) t = 11.0 μs and (e) t = 12.0 μs.

References

[1] P. M. Lapostolle and A. L. Septier, eds., *Linear Accelerators*, Elsevier North-Holland Pub. Co. , The Netherlands, 1970, pp. 601–616 (E. A. Knapp), 665–709 (G. Dome), and 809–826 (T. Nishikawa).

[2] G. R. Swain, "Circuit Analog Techniques for Analysis of Resonantly-Coupled Linear Accelerator Structures", Proc. of the 1966 Lin. Acc. Conf., Los Alamos, NM, Oct. 3–7, 1966, LANL report LA-3609, pp. 125–131.

[3] S. O. Schriber, "Exact Equilibrium Current Solutions for a Set of LC Coupled Loop Circuits with Second Neighbor Coupling", Proc. of the 1972 Proton Linear Acc. Conf., Los Alamos, NM, Oct. 10–13, 1972, LANL report LA-5115, pp. 407–410.

[4] E. A. Knapp, "Resonantly Coupled Standing Wave Accelerator Structures for Electron and Proton Linac Applications", *IEEE Transactions on Nuclear Science* NS-16, 329–337 (June 1969).

[5] T. Nishikawa, "Beam Loading Effects in Standing Wave Linacs", Proc. of the 1966 Linear Acc. Conf., Los Alamos, NM, Oct. 3–7, 1966, LANL report LA-3609, pp. 294–302.

[6] G. R. Swain and L. D. Scott, "Calculation of the Transient Response of Long Chains of Slightly Lossy Coupled Resonators", *IEEE Transactions on Nuclear Science* NS-17, 10–13 (Aug. 1970).