RF Steering in the CEBAF CW Superconducting Linac

R. C. York*, CEBAF, 12070 Jefferson Avenue, Newport News, VA 23606
C. Reece**, Laboratory of Nuclear Studies, Newman Laboratory,
Cornell University, Ithaca, New York 14853

Introduction

There exists a transverse gradient of the electric field parallel to the beam axis in the fundamental rf power coupler for the superconducting, five-cell cavity to be used in the CEBAF 0.5–4.0 GeV, cw, electron accelerator. This electric field gradient results in a tranverse deflection of the electrons the magnitude of which varies during the passage of a microbunch, causing a dilution of the transverse emittance. This paper describes the estimate of the transverse deflection and the simulations performed to evaluate the magnitude of the emittance dilution caused by this deflection. The results of these simulations and the method used to reduce this effect are discussed.

RF Beam Steering

There is a magnetic dipole field in the fundamental rf power coupler to be used for the CEBAF linac accelerating sections from or caused by a gradient transverse to the beam direction in the longitudinal electric field. (Any contribution from electric fields transverse to the beam direction have been neglected.)

Estimates of the transverse kick to the electron beam caused by the longitudinal electric field gradient appropriate to the CEBAF geometry have been made.[1] The transverse kick per cavity for an electron with phase ϕ is given by

$$\Delta p_T = -\frac{\Delta z}{k}\frac{\partial E_z}{\partial y}\sin(\phi + \Delta),$$

where

- Δp_T = transverse momentum imparted
- Δz = coupler width = 0.0254 m
- $k = 2\pi/\lambda = 31.4\ \mathrm{m}^{-1}$
- $\Delta = +\ 147.2°$ for coupler downstream of cavity
- $\Delta = -\ 147.2°$ for coupler upstream of cavity

The value of Δ is given by the rf phase advance as an electron moves from the center of the accelerating cell adjacent to the center of the fundamental power coupler over a distance of 8.18 cm. The value of $\frac{\partial E_z}{\partial y}$ was deduced from bead-pull measurements performed on a copper model of the Cornell LE5 cavity. The frequency perturbations produced by the dielectric bead are proportional to $\mathbf{E}^2$, and these data were used to determine the value of $\frac{\partial E_z}{\partial y}$. Based upon these analyses, the estimated value of the transverse kick produced by the rf power coupler for a CEBAF cavity operating at an accelerating gradient of 5 Mev/m is

$$\Delta p_T = (1.5 \pm 1.2)10^{-5}\ \mathrm{rad} - \mathrm{GeV/c}$$

The CEBAF cavities are to be joined in pairs with the fundamental rf couplers placed at the center of each cavity pair. Therefore, within a pair there will be an rf feed downstream of an accelerating cavity followed by an rf feed upstream of an accelerating cavity. A result of the kick caused by the fundamental rf power coupler is a movement of the microbunch centroid that may be corrected in a manner similar to that used to correct magnetic element misalignments. However, due to the finite length of a microbunch, there will be a differential movement of the head relative to the tail of the microbunch, which will result in a dilution of the transverse emittance, the subject of this paper.

Simulation

The effect of the rf coupler induced dipole field on the beam was simulated using a CEBAF modified version of DIMAD,[2] which modeled the accelerating structure as a first-order matrix. A value representing the largest estimated dipole field was conservatively taken for the simulations. As discussed in a paper on the CEBAF injector in these proceedings,[3] a value of $\phi = \pm 0.5°$ was taken for the bunch length. The coupler magnetic field effect was simulated by an impulse kick at the position of the fundamental rf power coupler of magnitude:

$$\Delta\theta = \frac{1.1\times 10^{-2}\Delta E \sin(\Delta + \phi)}{p}\ \text{radians},$$

where

- ΔE = Energy gain per 5-cell cavity
- ϕ = Half Microbunch length
- p = Momentum of electron at fundamental power coupler

Simulations were performed using optics for the linacs as specified in a paper on the CEBAF machine optics in these proceedings[4] where the two 0.5 GeV linac segments were assumed contiguous with a first pass beam phase advance of 120° per FODO cell with a quadrupole to quadrupole spacing of 9.4 m. The simulations were approximate only in that matrices representing the accelerating sections and the quadrupole focusing lattice used were always based upon the assumption that all cavities were run at a gradient of 5 MeV/m. The rf steering kicks were, however, calculated assuming a random powering of the cavities as discussed below. The emittance dilution was evaluated by tracking three particles representing the head, centroid, and tail of a microbunch. The output of a preceding pass was mapped by the appropriate optics[4] before tracking was done on the succeeding pass.

RF Feed Geometries

The magnitude of the effect is correlated with the rf feed geometry, and therefore, several feed geometries were investigated to determine a geometry that was technically acceptable and that would minimize the emittance dilution. Because of the significant forces that would be incurred during the transition of the cyromodule contents from room temperature to 2 K, the alternation of rf feed directions within a cavity pair was precluded. Therefore, only cases where each cavity within a cavity pair was fed from the same direction were evaluated. It was determined that an rf feed pattern of ↑↑↓↓↓↓↑↑ provided the least emittance degradation while, not surprisingly, a feed geometry of ↑↑↑↑↑↑↑↑ provided the greatest emittance degradation, where the arrows show the direction of the rf feed to the fundamental power coupler for each of the eight accelerating cavities per cryomodule. The preferable geometry of ↑↑↓↓↓↓↑↑ may be understood as nothing more than an $\alpha,-2\alpha,\ \alpha$ bend system providing significant cancellation of the effect.

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Differential Powering of the Accelerating Cavities

To take maximum advantage of the capabilities of each accelerating structure, it is necessary to have the ability to power each cavity up to its own individual field limit independent of the other cavities of the machine, and therefore, the CEBAF design provides for individual klystrons for each accelerating section. In addition, there will be instances when some fraction of the cavities may not be powered. In the circumstance where there is an unequal powering of the accelerating structures, there will be a reduction in the cancellation effect provided by the rf feed geometry of ↑↑↓↓↓↓↑↑. Several possible situations were simulated. Typical examples are given below.

- An rf feed pattern of ↑↑↓↓↓↓↑↑.
- 380 of the 400 0.5 m accelerating sections were randomly powered assuming a four sigma ($\sigma_{\Delta E}$ = 2 MeV) Gaussian distribution centered about an energy gain per cavity of 2.5 MeV with all powered cavities providing an energy gain of 0.4 MeV $\leq \Delta E \leq$ 7.5 Mev. (The lower limit is fixed by the minimum field required for appropriate phase and amplitude detection, and the upper limit is set by an assumed likely maximal field value.)
- 20 of the 400 cavities were randomly chosen to be off-line and detuned, and therefore, providing no deflection.

The emittance envelopes generated under these conditions are shown in Figs. 1 through 4 for the case where the rf feeds were assumed to be in the horizontal plane. Similar results were found when the rf feeds in the same case were assumed to be in the vertical plane, equivalent to reversing the quadrupole polarities and horizontal rf feeds. For comparison, the emittance envelopes generated under the same circumstances but with an rf feed pattern of ↑↑↑↑↑↑↑↑ are shown in Figs. 5 through 8 for rf feeds in the horizontal plane. The figures show the phase space at the end of the second linac segment after each pass. Compatible with the design emittance of 2.0×10^{-9} mrad at 1 GeV, emittances were taken as 2.0, 1.0, 0.66, and 0.50 $\times 10^{-9}$ mrad for the first, second, third, and fourth pass beams at this position, respectively. The solid ellipses represent the microbunch centroid, and the broken curve ellipses represent the head and tail of the microbunch.

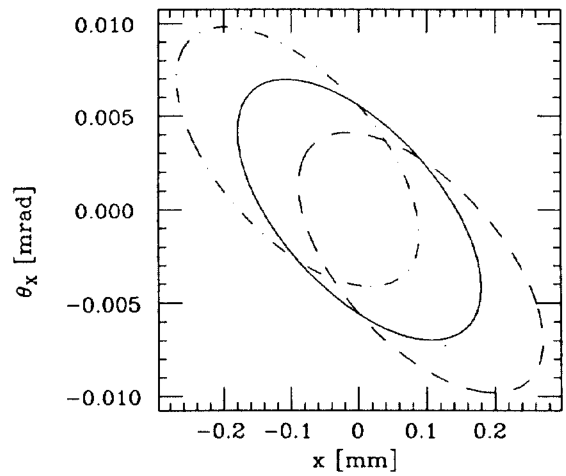

Figure 2. Second pass horizontal transverse phase space.

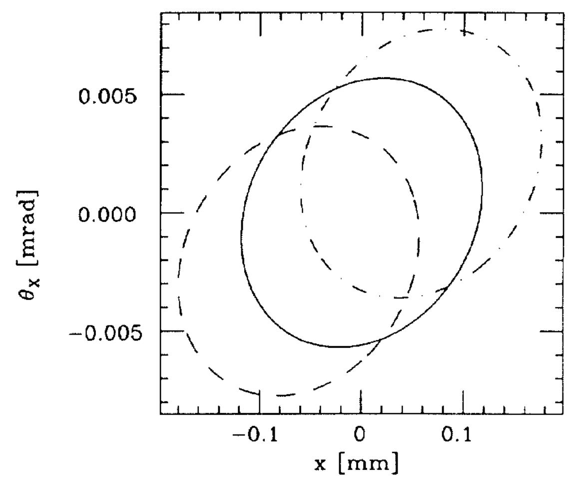

Figure 3. Third pass horizontal transverse phase space.

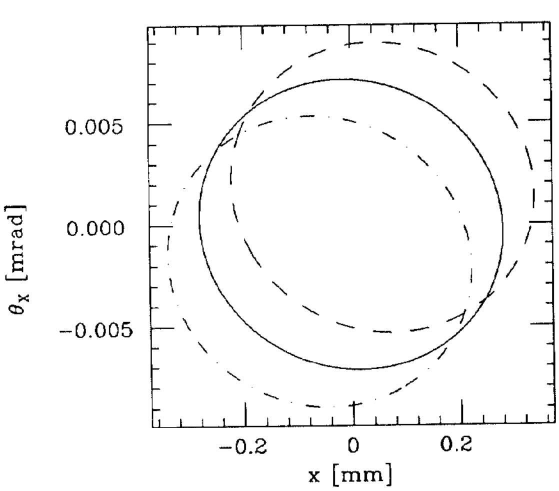

Figure 1. First pass horizontal transverse phase space.

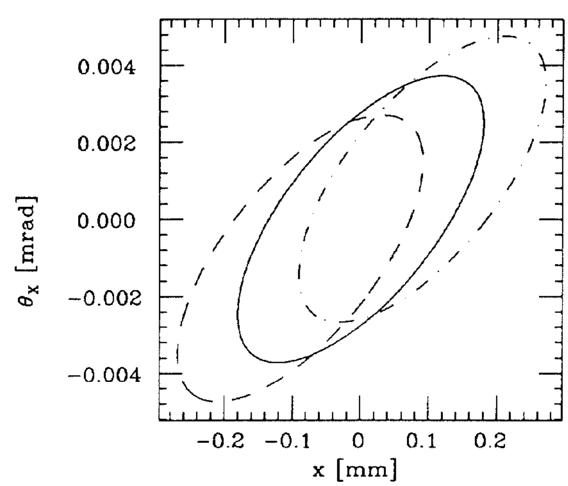

Figure 4. Fourth pass horizontal transverse phase space.

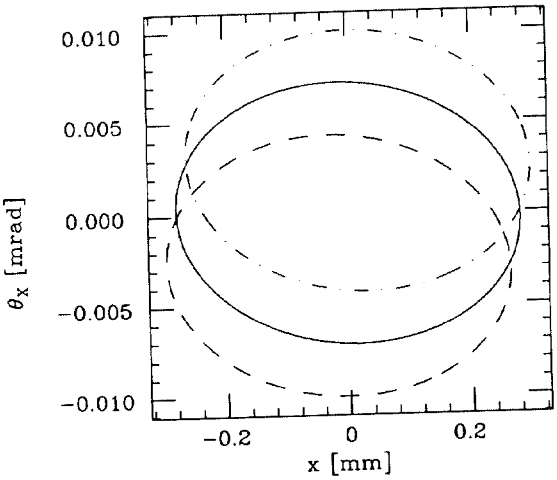

Figure 5. First pass horizontal transverse phase space.

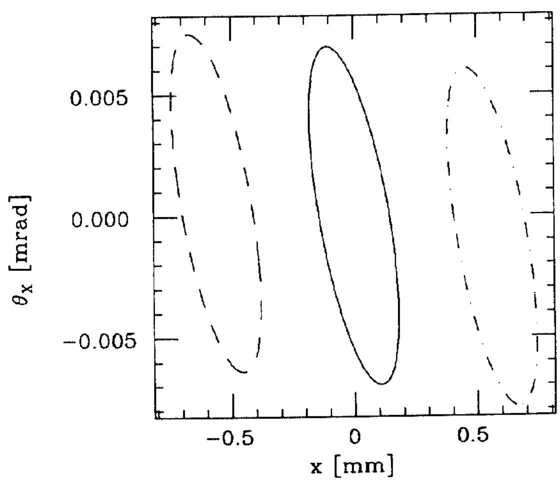

Figure 6. Second pass horizontal transverse phase space.

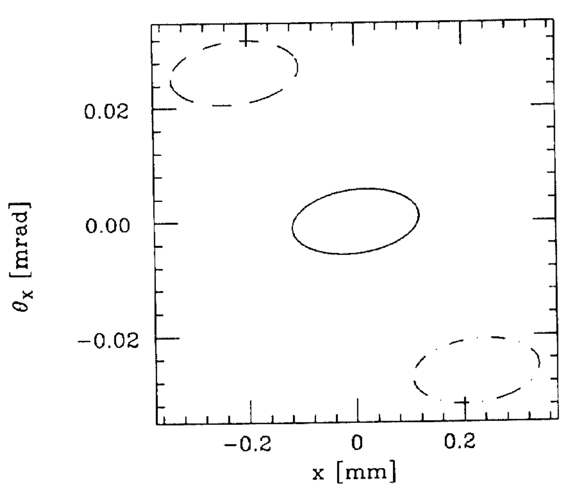

Figure 7. Third pass horizontal transverse phase space.

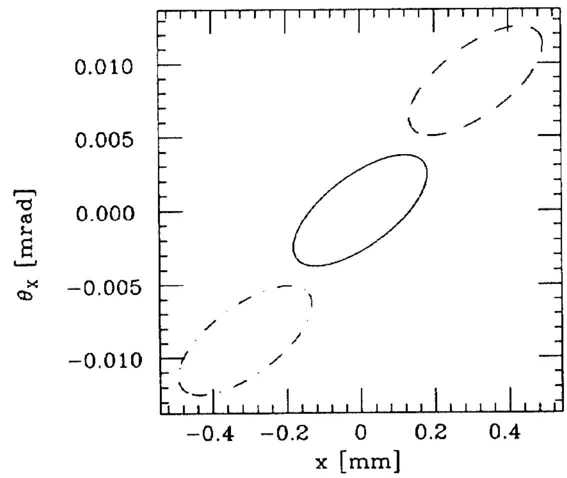

Figure 8. Fourth pass horizontal transverse phase space.

Operational Compensation

Since the transverse kicks imparted to the beam by any one cavity are compensated by many others, an operational algorithm was evaluated that by slight adjustment of the accelerating gradient of all cavities would reduce the emittance dilution of the output beams. To demonstrate the utility of such a procedure, a coefficient matrix was constructed describing the effect of each cavity on the transverse coordinate of each output beam. By adjusting all cavity gradients by amounts proportional to these coefficients and of order $\pm 3\%$, reductions of the emittance dilution have been achieved in simulation simultaneously for all four passes by two orders of magnitude.

Conclusions

The rf feed geomtry of ↑↑↓↓↓↓↑↑ clearly reduces the emittance dilution over that generated from an rf feed geometry of ↑↑↑↑↑↑↑↑. The emittance dilution with the ↑↑↓↓↓↓↑↑ feed geomtry, even assuming a somewhat pessimistic distribution of cavity gradients and an extreme value for the estimated $\frac{\partial E_s}{\partial y}$, is only $\approx$ a factor of 2. Furthermore, an algorithm has been demonstrated that, by small adjustments (≤ 3 %) of the accelerating gradients in each cavity, reduces the emittance dilution by two orders of magnitude, virtually eliminating the effect. Therefore, it is concluded that with an rf feed geometry of ↑↑↓↓↓↓↑↑ presently incorporated in the machine design, acceptable performance will be realized for the CEBAF accelerator.

References

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