SLAC-PUB-5069
September 1989
(A)

EFFECTS OF RF DEFLECTIONS ON BEAM DYNAMICS IN LINEAR COLLIDERS*

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Abstract The beam dynamics effects caused by static RF deflections in accelerators of linear colliders are discussed including deflection, chromatic, and wakefield driven emittance enlargement from finite bunch lengths. These effects will impact the design and construction of the next linear collider.

INTRODUCTION

Transverse deflections of beams by RF accelerating structures have been under study for some time including attempts to reduce their effects.[1-3] For linear colliders the limits from RF deflections on-the stability of the amplitude and phase of klystrons due to wakefield and chromatic effects have been calculated.[4,5] The effect of RF deflections on trajectory correction has also been studied.[6] In this note the consequences of a finite bunch length and a non-uniform RF deflection over that length are calculated in terms of enlargement to the beam emittance. When the bunch length is much larger than the transverse beam size, RF deflections can cause beam tilts which cause dilution.[7]

DEFLECTION CHARACTERIZATION

A beam of Gaussian length σ_z is accelerated in a structure of length L and wavelength λ_{RF}. The maximum energy increase that a particle of energy E_0 receives when it passes through the structure at the peak phase (ϕ = 0) is E_{RF}. σ_z is assumed to be a nonnegligible fraction of λ_{RF} (see Fig. 1). The transverse position of a particle, say in the horizontal plane, is given by x and the angle by x'. The initial

Contributed to the XIV International Conference on High Energy Accelerators, Tsukuba, Japan, August 22–26, 1989.

⋆ Work supported by Department of Energy contract DE–AC03–76SF00515.

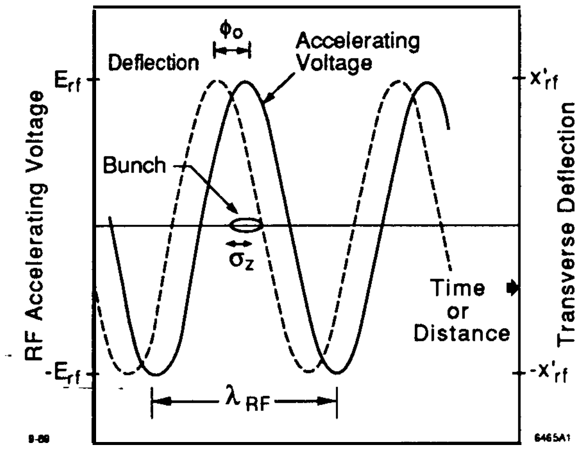

FIGURE 1 RF accelerating and deflecting fields as sampled by a bunch with a finite length.

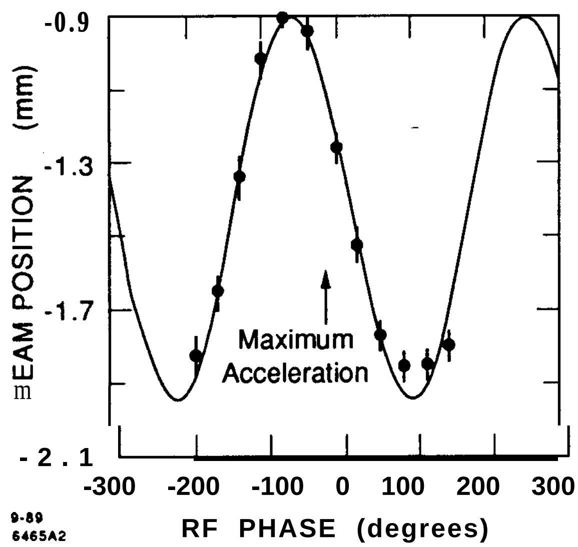

FIGURE 2 Measured RF deflection in the SLC linac.

transverse sizes of the beam are given by σ_{x_0} and $\sigma_{x'_0}$ at a lattice location described by Twiss parameters β_0, α_0, and γ_0 where $\beta_0 \gamma_0 = 1 + \alpha_0^2$. The emittance, ϵ_0, of the beam is

$$\epsilon_0 = \frac{\sigma_{x_0}^2}{\beta_0} = \frac{\sigma_{x'_0}^2}{\gamma_0} . \qquad (1)$$

Transverse deflections are caused by a small coupling of the longitudinal accelerating field into the transverse. There are many possible sources of the coupled fields.[2,3] The resulting transverse fields have a fixed phase relationship to the accelerating fields but need not be in phase (see Fig. 1). The phase displacement is denoted by ϕ_0. A measurement of such a deflection was made at the SLAC Linear Collider (SLC) and is shown in Fig. 2, where the RF deflection of a 1 GeV beam was observed in a magnetic-free region downstream of an accelerating structure driven by a single klystron.[3] Note the 45° retardation. The integrated change in transverse angle x'_{RF} given to a particle traversing the structure with phase ϕ relative to the peak acceleration is:

$$x'_{RF} = g \frac{E_{RF}}{E_0} \cos(\phi - \phi_0) . \qquad (2)$$

Here g is a measure of the coupled fields and, typically, has a distribution[3] centered on zero with a FWHM of about 0.001.

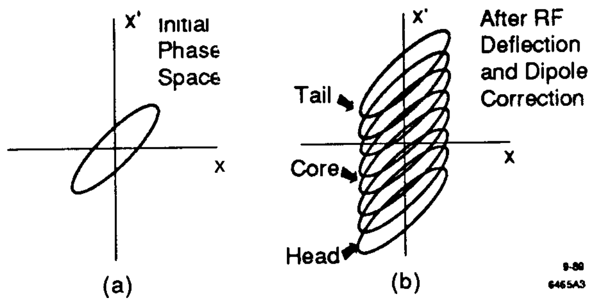

FIGURE 3 An example of the dilution of angular phase space from an RF deflection.

INSTANTANEOUS EMITTANCE GROWTH

The change in the RF deflection over the bunch length will dilute angular phase space as is shown in Fig. 3. The direct effect on emittance can be calculated integrating over the distorted phase space. The unperturbed density distribution $\rho(x, x')$ of the particles in the x-x' plane is a correlated Gaussian.

$$\rho(x,\ x') \ = \ [\ 2\pi\ \epsilon_0]^{-1} \ \exp \left\{ -\frac{\gamma_0\, x^2 + 2\alpha_0\, x x' + \beta_0\, x'^2}{2\epsilon_0} \right\} \ . \qquad (3)$$

The longitudinal particle distribution in the z direction is

$$p(z) \ = \ [\ 27r\ \sigma_z^2\ ]^{-1/2} \quad e \ x \left\{ , \ \frac{z^2}{24} \right\} \ . \qquad (4)$$

The x' variable changes with z by the RF deflection, and is included by replacing x' by $(x' - x'_{RF})$ in Eq. 3. The effective angular beam size is determined by examining the second moment.

$$\sigma^2_{x'eff} \ = \ \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x'^2\ p(z)\ \rho\,[x,\ (x' - x'_{RF})]\ dz\ dx\ dx' \ . \qquad (5)$$

The effective phase space area and shape of the beam have changed, giving new effective Twiss parameters and emittance: β, α, γ, and ϵ. Letting $B = \sigma_{x'eff}/\sigma_{x'_0}$, the angular enlargement factor,

$$\epsilon\beta \ = \ \epsilon_0\ \beta_0\ , \qquad \text{and} \qquad \epsilon\gamma \ = \ B^2\ \epsilon_0\,\gamma_0\ . \qquad (6)$$

For α_0 = 0 at the deflection source, ϵ and β are easily determined.

$$\beta = \frac{\beta_0}{B} \quad , \qquad \text{and} \qquad \epsilon = B\,\epsilon_0 \quad . \tag{7}$$

The most sensitive accelerator in a linear collider is the bunch length compressor early in the machine where the relatively long bunches from the damping rings extend over a large fraction of λ_{RF}. Several numerical examples determining acceptable g values for bunch length compressors for the SLC and a potential Intermediate -Linear Collider' (ILC) are given in Table I. Emittance dilution from direct RF deflection is within measured limits for the present SLC, but is a moderate concern for an ILC or the SLC operating with vertically flat beams. Pre-installation screening tests for the structures will most likely be needed. The main linac of these colliders will also produce deflections which can be calculated as above and added over the various accelerating segments along the linac.

TABLE I Several examples of limits on RF deflections in linear collider bunch length compression accelerators. The two ILC cases are for the expected two compression sections. β = 5 m. $\phi_0 = \pi/2$.

Collider	σ_z (mm)	ϵ_0 (nm-rad)	λ_{RF} (mm)	E_0 (GeV)	E_{RF} (GeV)	Allowed j (B = 1.1)
SLC Round	8	7.1	105	1.2	0.03	1.6 x 10^{-3}
SLC Flat	8	0.2	105	1.2	0.03	2.7 x 10^{-4}
ILC First	5	0.006	105	1.8	0.05	6.4 x 10^{-5}
ILC Second	0.5	0.0006	17.6	18.	1.00	1.6 x 10^{-5}

CHROMATIC EMITTANCE ENLARGEMENT

As the above distorted beam is transported down the remaining portion of the linac, centroid and shape oscillations will occur. The centroid oscillations can be fixed by dipole steering. The shape oscillations will cause further filamentation of the emittance because of a finite energy spectrum. For full filamentation, the effective beta function of the bunch becomes that of the matched lattice and the final emittance ϵ_f becomes[9]

$$\epsilon_f \approx \frac{B}{2}\epsilon_0\left(\frac{\beta_0}{\beta} + \frac{\beta}{\beta_0}\right) = \epsilon_0\frac{1+\beta^2}{2} \quad , \qquad \text{for} \qquad \alpha_0 = 0 \quad . \tag{8}$$

Beta matching through quadrupole changes near the offending accelerator will reduce this additional emittance growth.

TRANSVERSE WAKEFIELD EMITTANCE ENLARGEMENT

The finite bunch length, combined with a nonuniform RF deflection, will launch the bunch with a tilt such that the head, core, and tail of the bunch will not follow the same trajectory down the linac. This situation leads directly to transverse wakefield effects, as all longitudinal sections of the beam cannot be aligned on the accelerating structure center line. Various tilts are possible given a deflection, as can be seen in Fig. 4. To minimize wakefield effects, the desired orientation is that shown in Fig. 4(d),where the head of the bunch is just over the axis from the core. This arrangement will move the core slowly to the axis via wakefields encountered downstream; however, the concern here is of the effect of the off-axis core on the beam tail. If transverse wakefield damping is used,[7] this effect will be small. In regions without this damping, for example between the two compressors in the ILC or downstream of where the damping is effective, wakefield growth occurs. A two-particle model can be used to calculate a limit on the magnitude of the allowed deflections.[6,10] The difference of the tail position x_t from the core position x_c grows linearly downstream of the deflection.

$$(x_t - x_c) = x'_{c0}\, \beta_0\, C\, z\, \sin\,(kpz) \quad , \tag{9}$$

where x'_{c0} is the initial core angle; k_β is the betatron wave number; and C = $eQW/4Ek_\beta$, the wakefield coefficient. Q is the charge of the core, e is the electron charge, W is the transverse wakefield for this particle spacing, and E is the beam energy. Acceleration is neglected here. Requiring that the final tail offset relative to the core be smaller than beam size, a limit on the deflection angle difference between the head and core can be calculated using Eq. (2).

$$g < \frac{\sigma_{xf} E_0}{E_{RF}\, \beta_0\, C\, z_f\, \sin\,(k_\beta z_f)\, [\cos\,(\phi_{core} - \phi_0) - \cos\,(\phi_{\mathrm{head}} - \phi_0)]} \quad . \tag{10}$$

The subscript j refers to the parameter values at the end of the linac. As an example, for the linac between the first and second compressors for the ILC, the head and core are separated by σ_z, Q = 5 x 10^9, k_β = 0.28, z_f = 700 m, C = 6.7 x 10^{-4} m^{-1},

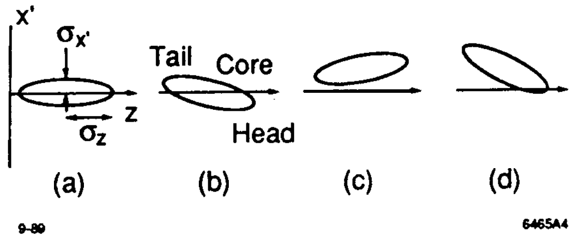

FIGURE 4 Possible longitudinal beam tilts from RF deflections. The initial beam (a) can have several orientations after deflection, e.g., (b), (c), or (d); orientation (d) is best for transverse wakefields and can be achieved by dipole correction from any orientation.

and the parameters in Table I are used. In this case, the resulting g must be less than 3 x 10^{-4}, which is comparable to, but not as restrictive as, the value in Table I. A full particle tracking simulation should be used to verify this simplified result.

ACKNOWLEDGMENTS

Many thanks are given to K. Johnston, D. Land, and to the staff of the SLAC Publications Department for their help in preparing this document.

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