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DESIGN CONSTRAINTS FOR ELECTRON-POSITRON LINEAR COLLIDERS*

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Abstract

A prescription for examining the design constraints in the e^+-e^- linear collider will be presented. By specifying limits on certain key quantities, an allowed region of parameter space can be presented, hopefully clarifying some of the design options. The model starts with the parameters at the interaction point (IP), where the expressions for the luminosity, the disruption parameter, beamstrahlung, and average beam power constitute four relations among eleven IP parameters. By specifying the values of five of these quantities, and using these relationships, the unknown parameter space can be reduced to a two-dimensional space. Curves of constraint can be plotted in this space to define an allowed operating region. An accelerator model, based on a modified, scaled SLAC structure, can then be used to derive the corresponding parameter space including the constraints derived from power consumption and wake field effects. The results show that longer, lower gradient accelerators are advantageous.

Interaction Point

The interaction point may be characterized by eleven parameters: the number of particles per bunch (N), the particle energy (γmc^2), the bunch size (σ_x, σ_y, σ_z), the bunch repetition frequency (ν), the luminosity (L), the disruption parameter (D), the energy loss to beamstrahlung (δ_{BS}), the average beam power (P_b), and the Yokoya parameter ($A \equiv \sigma_z/\beta^*$). These parameters have been described by several authors.[1,2] Still more parameters are needed if the bunches have unequal intensities or if the collisions are offset. Such complications have been neglected here.

The four relationships between the IP parameters are as follows:

$$L = \frac{\nu N^2}{4\pi\sigma_y^2 R} H_D(D,R,A) \qquad (1)$$

$$D = \frac{2r_e N\sigma_z}{\gamma\sigma_y^2(1+R)} \qquad (2)$$

$$\delta_{BS} = \frac{2}{9}\frac{r_e^3 N^2\gamma}{R\sigma_y^2\sigma_z} H_b(D,R,A)H_\delta(\Upsilon) \qquad (3)$$

$$P_b = \nu N\gamma mc^2 \qquad (4)$$

where $R \equiv \sigma_x/\sigma_y$, Υ is the quantum beamstrahlung parameter, and r_e is the classical electron radius. The special functions H_D, H_δ and H_b are described in Amaldi's paper.[1] The beam-beam simulations by Yokoya[3] have been used to describe the pinch-enhancement factor.

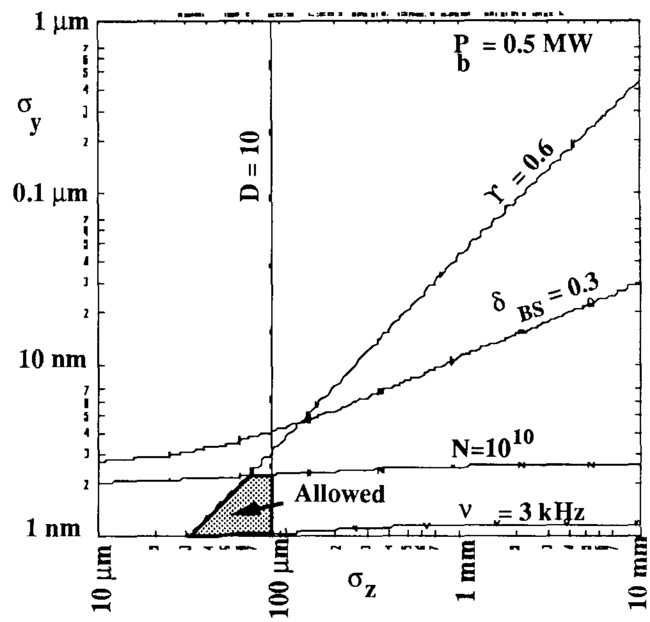

Fig.1 Interaction Point Parameter Space for a 1 TeV (CM) Collider with $L=2\times10^{37}$ m^{-2}-s^{-1}.

If γ, R, L, P_b, and A are specified in advance, then with Eq. (1) - (4) the unknown IP parameter space is reduced to two parameters (e.g. σ_y and σ_z) which may be visualized as a two-dimensional space. Curves of constraint may be plotted on this plane, as shown in Figure 1. For this figure the collider is assumed to be 1 TeV(CM), with $L=2\times10^{37}$ m^{-2}-s^{-1}, A=0.2, R=100, and P_b=0.5 MW.

The constraint curves used in the figure represent "soft limits" on IP quantities. The allowed region on the figure corresponds to a parameter set where $N \le 10^{10}$, $D \le 10$, $\delta_{BS} \le 0.3$, $\nu \le 3$ kHz, and

$\Upsilon \leq 0.6$. The limit on D arises from the sensitivity of the luminosity to offset collisions at large D, while the need to limit coherent pair production sets the constraint on Υ.[4]

Accelerator Model

The accelerator model utilizes a SLAC-type RF linac with an enlarged iris, $a/\lambda=0.2$, to reduce wake-field effects. The structure is scaled linearly with the RF wavelength λ in all dimensions. SLAC wake fields, scaled in both iris aperture and RF frequency, are used. The transverse wake field is derated by up to a factor 4 from the scaled-SLAC value to take account of the effect of procedures to de-Q the long-range beam-breakup (BBU) instability. It is assumed that the BBU mode has been reduced to $Q \approx 10$-20, so that multi-bunch wake-field effects can be ignored.

The total AC-to-RF conversion efficiency, including pulse compression, has been assumed to be 29% at all RF frequencies. The structure efficiency, i.e. the ratio of incident RF energy per pulse to the energy stored in the structure, has been assumed to be 60%. The single-bunch beam efficiency, i.e. the ratio of the energy acquired by the beam to the stored RF energy, is $\eta_b=NeE_a/w_s$, where E_a is the average accelerating gradient, and $w_s=E_0^2/4k_1$ is the RF energy stored per unit length. E_0 is the electric field at the peak of the RF wave and k_1 is the longitudinal wake-field loss factor for the accelerating mode. The calculations presented below assume that there are 10 bunches per RF pulse.

If the center of the bunch is advanced from the peak of the RF wave, the longitudinal wake field can be used to offset the energy spread which results from the finite bunch length on the RF wave. This procedure leads to a minimum energy spread at some phase advance θ_0. With this procedure the average accelerating gradient and the energy spread are given by

$$E_a = E_0\left[e^{-\theta_z^2/2}\cos(\theta_0) - \frac{Nek_L}{E_0}\right] \qquad (5)$$

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{E_0}{E_a}\right)^2 \left\{\frac{1}{2}\left[1+e^{-2\theta_z^2}\cos(2\theta_0)\right] + \left(\frac{Ne}{E_0}\right)^2 I_T - \left(\frac{2Ne}{E_0}\right)\left[I_c\cos\theta_0 - I_s\sin\theta_0\right]\right\} - 1 \qquad (6)$$

where k_L is the total longitudinal loss factor and $\theta_z \equiv 2\pi\sigma_z/\lambda$. The coefficients, I_T, I_c and I_s have been defined in an earlier publication.[5]

Single-bunch transverse wake-field effects, including both energy spread and acceleration have been studied previously,[6] and expressions have been derived for the ratio of the transverse displacement to the initial displacement, x/x_0, as functions of distance s along the accelerator, distance ζ measured backward from the bunch head, head-to-tail energy spread ε, and a parameter

$$\alpha \equiv \left[\frac{Ne^2W_1(\ell_b)}{\gamma_0 mc^2 k_{\beta 0}^2}\right]^{1/2} \qquad (7)$$

where $W_1(\ell_b)$ is the dipole wake field at the end of the bunch, and γ_0 is the beam energy at the location where the betatron wavenumber is $k_{\beta 0}$. For large s there is an asymptotic regime where the transverse displacement oscillates without growth as

$$\frac{x}{x_0} \approx \left[I_0(u) + \frac{2\varepsilon\zeta}{u}I_1(u)\right]\frac{\cos(r_\varepsilon s)}{(1+\varepsilon\zeta)} - \frac{1}{s}\left\{\frac{2\alpha}{\zeta^{1/2}(2\varepsilon)^{3/2}} J_1\left(\frac{u}{(1+\varepsilon\zeta)^{1/2}}\right)\sin(s) - \frac{\alpha^2 r_\varepsilon}{2\varepsilon^2}(1+\varepsilon\zeta)^2\left[I_0(u) + \frac{2\varepsilon\zeta}{u}I_1(u)\right]\sin(r_\varepsilon s)\right\} \qquad (8)$$

to order $O(1/s^2)$, where $r_\varepsilon \equiv [(1-\varepsilon\zeta)/(1+\varepsilon\zeta)]^{1/2}$ and $u \equiv 2\alpha[\zeta(1+\varepsilon\zeta)/2\varepsilon]^{1/2}$. The functions $I_0(x)$, $I_1(x)$ and $J_1(x)$ are Bessel Functions.

The accelerator model has been reduced to the parameter plane, (E_0,λ), where curves of constraint are plotted. Figures 2 and 3 show the results of these calculations for the collider having its IP parameters as shown in Figure 1. The IP parameters are specified at the largest (σ_y,σ_z) in the allowed region on Figure 1; $\sigma_y \approx 2.2$ nm and $\sigma_z \approx 90$ µm; $N=10^{10}$ and $D=10$. The allowed region in Figure 2 corresponds to an accelerator having $\sigma_E/E \leq 0.5\%$, $x/x_0 \leq 1.2$, average AC power less than 55 MW/linac, peak RF power per feed less than 400 MW, and accelerator length less than 6 km/linac. The x/x_0 constraint corresponds to approximately a 25% increase in the normalized beam emittance during acceleration. The transverse wake field in these calculations is one-quarter of the scaled SLAC value, corresponding to an assumed wake-field reduction due to measures to control the multi-bunch BBU mode. Without this assumption there is no allowed region (without using BNS damping[7]). These results indicate that BNS damping may not be needed in a structure which has been modified to reduce the long-range dipole modes.

Figure 2 shows that under these assumptions there is an operating window for RF frequencies in the range 11.5 GHz - 20 GHz. For higher frequencies the transverse wake fields will cause greater than 25% emittance growth. For lower frequencies the peak RF power will exceed 400 MW/feed for ≤6 km/linac. Of course, the frequency range can be expanded to lower frequencies by allowing longer linacs.

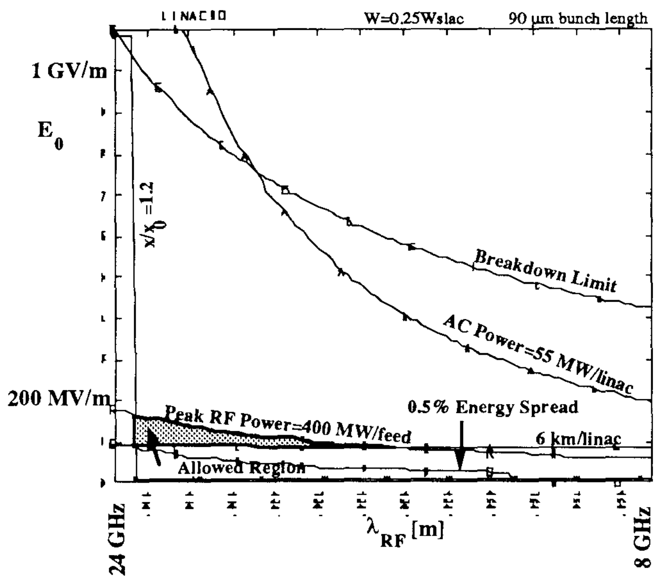

Fig. 2 Accelerator Parameter Space Using Largest Allowed (σ_y-σ_z) From Fig. 1.

Using twice σ_z (180 µm) leads to basically the same allowed range of frequencies, except that in this case the high frequency cut-off is set by the energy spread constraint ($\sigma_E/E \leq 0.5\%$) rather than by emittance growth.

It is interesting that as σ_z is decreased, the average transverse wake field over the bunch gets weaker while the average longitudinal wake field gets stronger. But, transverse wake-field effects are effectively damped by energy spread, and shorter bunches have far lower energy spread than long bunches. The net result, as seen in Figure 3, is that shorter bunches can suffer larger emittance growth due to transverse wake fields than long bunches.

Figure 3 shows the result obtained using half σ_z (45 µm), with all other parameters the same as those used for Figure 2. In this case the constraint curve for $x/x_0=1.2$ shifts to longer wavelengths, effectively shrinking the operating window in Figure 2 to a single point.

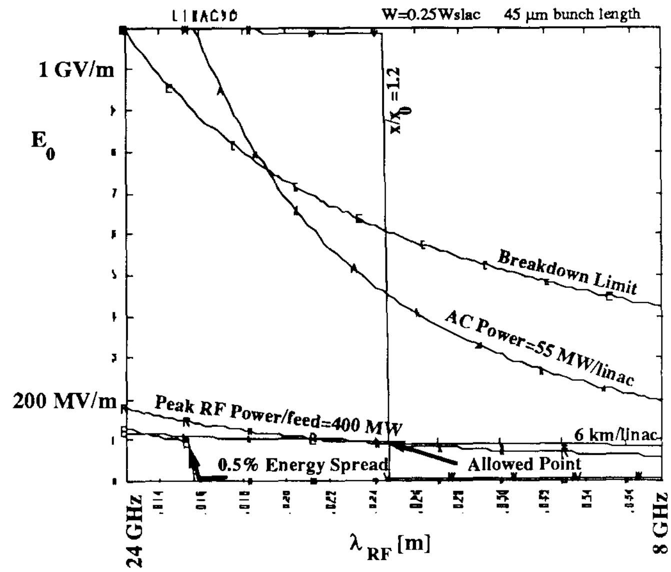

Fig. 3 Same Parameters As Fig. 2, Except σ_z Has Been Reduced By Half.

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