ENERGY RECOVERY IN SUPERCONDUCTING COLLIDING LINACS WITHOUT PARTICLE RECOVERY

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ABSTRACT

A new type of electron-positron collider based on superconducting linacs is proposed. As in other schemes, the bunch energy is recovered by deceleration in the opposite linac, but the spent bunches are dumped after a single pass, thus avoiding many problems connected with their re-use. The needed low energy particles are produced by the monochromatic photons radiated coherently by the high energy bunches in a wiggler magnet before deceleration.

1. INTRODUCTION

At present, colliding linacs appear as the most economic means of producing electron-positron collisions at energies larger than about 2 × 150 GeV [1)]. In the energy recovery schemes[2),3)] an electron (positron) bunch is accelerated in one of the superconducting linacs and, after interacting with a positron (electron) bunch, is decelerated in the opposite linac (so that a large fraction of its energy is recovered) and re-used. The implementation of this idea requires complicated debunchers to reduce the energy spread of the decelerated bunches so that they can fit into the acceptance of the rings which damp the emittance of the bunches before re-use[4)]. Figure 1 shows the debunchers and the damping rings of the scheme proposed by Gerke and Steffen[5)]. Another complication of this use of superconducting colliding linacs arises from the need for continuously supplying new positrons as a consequence of the unavoidable losses[6)]. We here propose a new scheme that overcomes all these difficulties because it recovers the energy of the bunches after the interaction but uses the particles of each bunch only once. The principle is shown in Fig. 2: downstream of the interaction regions the electron (positron) bunches pass through a wiggler magnet in which they produce almost monochromatic photons by spending less than 1% of their energy. The low energy positrons (electrons) are produced by these photons in a thin target and, after suitable damping, are injected into the linacs.

In Section 2 we recapitulate the characteristics of the wiggler radiation and compute the positron yield N^+/N^- as a function of the beam energy E and of the other parameters of the wiggler. In Section 3 we define the parameters of a colliding linac that makes use of a wiggler magnet to produce positrons, recovers most of the beam energy and throws the spent bunches after a single pass.

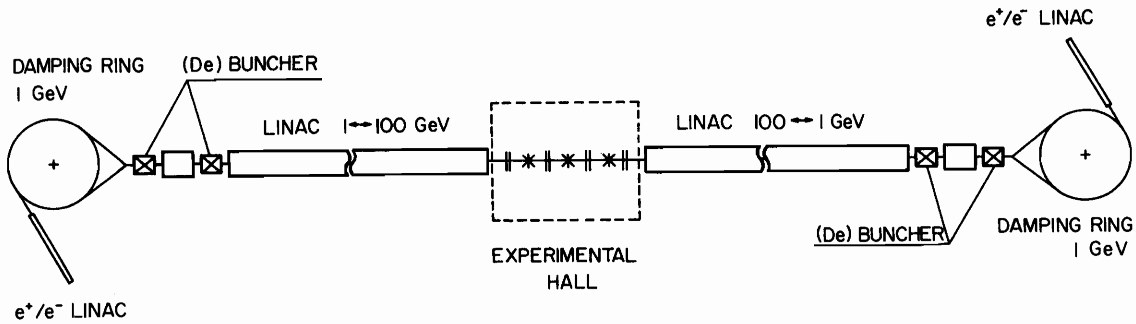

Fig. 1 Schematic layout of the scheme studied by Gerke and Steffen[5]. Note the debunchers, which are needed to reduce the energy spread of the decelerated bunches.

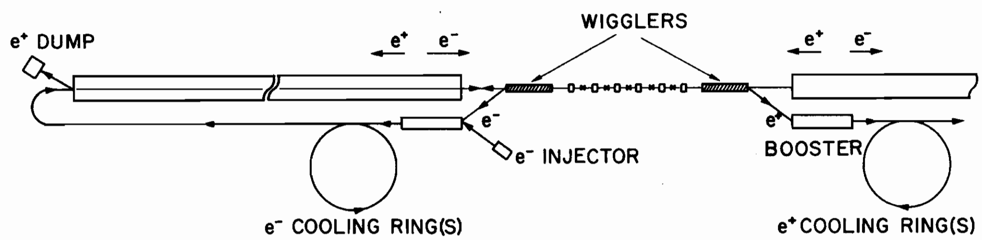

Fig. 2 The principle of the peloron which recovers the energy but not the particles. As discussed in Ref. 1), the many interaction regions have to be served in time sharing because of the emittance increase at an interaction point.

2. POSITRON PRODUCTION FROM A WIGGLER MAGNET

Let the wiggler period be λ_W, the wiggler length $\ell = n\lambda_W$ and the wiggler magnetic field B_W. The wiggler parameter is defined as

$$k = \frac{eB_W\lambda_W}{2\pi mc} \tag{1}$$

and in most applications is taken to be of the order of one. In the wiggler the particle trajectory is either helical or sinusoidal and we assume the particle to move relativistically along the axis so that the peak transverse velocity is given by

$$\beta_t = \frac{k}{\gamma} << 1 \tag{2}$$

The particle moving in the wiggler will emit radiation in a cone of angle $1/\gamma$. This radiation is circularly polarized for a helical wiggler or lineraly polarized for a transverse wiggler. Assuming that $\beta_t < 1/\gamma$, or $k < 1$, most of this radiation is emitted in a line of wavelength

$$\lambda = \frac{\lambda_W}{2\gamma^2}(1 + k^2 + \gamma^2\theta^2) \tag{3}$$

where θ is the angle of observation. For a beam with a non-zero angular spread, this can be identified with θ. The line width $\Delta\lambda$ has contributions from the finite length $n\lambda_W$ of the wiggler ($\Delta\lambda/\lambda = 1/2n$), the beam energy spread ($\Delta\lambda/\lambda = 2\Delta\gamma/\gamma$) and the beam angular divergence ($\Delta\lambda/\lambda = \gamma^2\theta^2$). In our case the last contribution dominates and the total line width is $\sim 5\%$.

To estimate the number of photons, N_γ, emitted per electron, we assume that we use a wiggler with $k < 1$ and divide the total energy radiated per particle

$$E_T = \frac{8}{3}\pi^2 \frac{r_e n}{\lambda_W} \gamma^2 k^2 mc^2 \tag{4}$$

by the energy, E_γ, of a photon of wavelength given by (3) with $\gamma\theta << 1$. In this way we obtain

$$N_\gamma = \frac{2}{3}\pi\alpha n k^2 (1 + k^2) \tag{5}$$

where $\alpha = e^2/\hbar c = 1/137$. Notice that N_γ does not depend on the particle energy but only on the wiggler number of periods n. The photon energy depends on γ and can be written as

$$E_\gamma = 4\pi \frac{r_e mc^2\gamma^2}{\alpha\lambda_W(1 + k^2)} \approx \left[3.16 \times 10^{-4} E^2(\text{GeV})\right] \text{MeV} \tag{6}$$

where the numerical value is obtained for $k^2 = 0.5$, $\lambda_W = 2$ cm.

The positron source is schematically drawn in Fig. 3. It consists of a wiggler of length ℓ with n periods, a target of thickness t, a positron collecting system of acceptance $A = xx'$ and a three-magnet system to steer the electron around the target. (Electrons cannot be allowed to pass through the target because of the emittance blow-up due to multiple scattering.)

The wiggler must be optimized to have a positron yield N_+/N_- larger than one within the positron acceptance A. The yield takes the form

$$\frac{N_+}{N_-} \simeq N_\gamma \Sigma(E_\gamma) \frac{t}{X_o} \frac{\Delta E}{E_+} f(x,x') \tag{7}$$

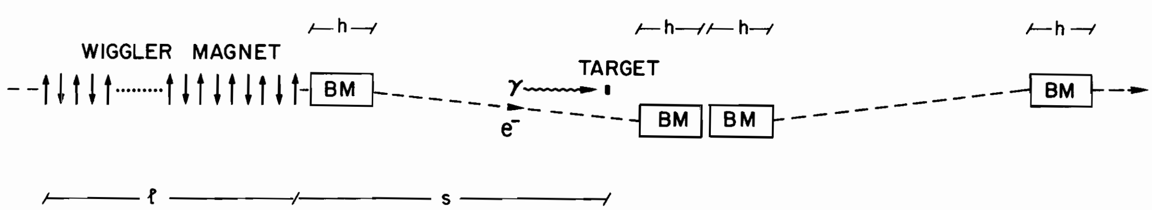

Fig. 3 Positron source based on a wiggler magnet. The four magnets BM steer the beam around the target. The figure defines the lengths ℓ, s and h used in the text.

when $\Sigma(E_\gamma)$ is the number of pairs produced by the incident photon of energy E_γ in one radiation length X_o, ΔE is the HWHM energy acceptance of the collecting system and E_+ is the positron energy taken to be $E_\gamma/2$. The function $f(x,x')$ is unity if, for a given angular spread θ_+ of the positrons, the effective source width

$$x = \sqrt{a^2 + t^2\theta_+^2} \tag{8}$$

is smaller than A/θ_+. In Eq. (8) $\underline{a}$ is the radius of the photon spot at the target and the second term is due to the depth of field effect. The spot radius receives contributions from the angular spread and the radius of the electron beam of normalized emittance ε, and from the $1/\gamma$ opening angle of the radiation. For its minimum value we obtain

$$a = \frac{(\ell + 2s)}{2\gamma}\left[1 + \frac{4\gamma\varepsilon}{\pi(\ell + 2s)}\right]^{\frac{1}{2}} \tag{9}$$

where ε is the normalized beam emittance <u>after</u> the collision defined as $\varepsilon = \pi x x'\gamma$. This value of $\underline{a}$ is obtained by choosing a β-function inside the wiggler equal to its optimum value $\beta = \ell/2$.

It was shown in Ref. 1) that, after the collision of two bunches containing N particles each, the emittance is approximately given by the relation

$$\varepsilon \simeq \pi r_e N \tag{10}$$

In the following we shall assume $N \simeq 8 \cdot 10^{10}$ particles/bunch, a value that gives the requested luminosity of $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, as shown in Section 3.

To determine the value of the target thickness t appearing in Eq. (7) we use the condition $x\theta_+ = A$ (i.e., $f(x,\theta_+) = 1$) and Eqs (8) and (9). For θ_+ we use the expression for the multiple scattering angle

$$\theta_+ \simeq \frac{E_o}{E_+}\sqrt{\frac{t}{X_o}} \qquad (E_o = 15\ \mathrm{MeV}) \tag{11}$$

In the case $a \ll t\theta_+$ the target thickness turns out to be

$$\left(\frac{t}{X_o}\right)^* = \frac{E_+}{E_o}\left(\frac{A}{X_o}\right)^{\frac{1}{2}} \tag{12}$$

In the more general case, but with $a \lesssim t\theta_+$, we obtain

$$\left(\frac{t}{X_o}\right) = \left(\frac{t}{X_o}\right)^* \left[1 - \frac{\left(\frac{t}{X_o}\right)^* \left(\frac{aE_o}{2AE_+}\right)^2}{1 + \left(\frac{t}{X_o}\right)^* \left(\frac{aE_o}{2AE_+}\right)^2}\right] \tag{13}$$

The previous formulae have been used to compute the positron yield N_+/N_- which can be obtained for a given wiggler and a given positron collecting system. We choose

$$\lambda_W = 2\ \text{cm} \qquad k^2 = 0.5 \qquad \ell = 100\ \text{m}$$

$$s = 10\ \text{m} \qquad A = 5 \cdot 10^{-4}\ \text{m} \qquad \Delta E = 5\ \text{MeV} \tag{14}$$

$$E_+ = E_\gamma/2 \qquad X_o = 6\ \text{mm}$$

In Table 1 results are given for different electron energies in the range 100 to 400 GeV. At all energies the number of photons produced is 57 (Eq. (5)). One can see that for the given wiggler and positron acceptance we produce too many positrons ($N_+/N_- > 1$) at all energies above 170 GeV. Hence we could either reduce the wiggler length or the positron acceptance or the target thickness. The target thickness needed to have $N_+/N_- = 1$ with a wiggler of fixed length is plotted in Fig. 4.

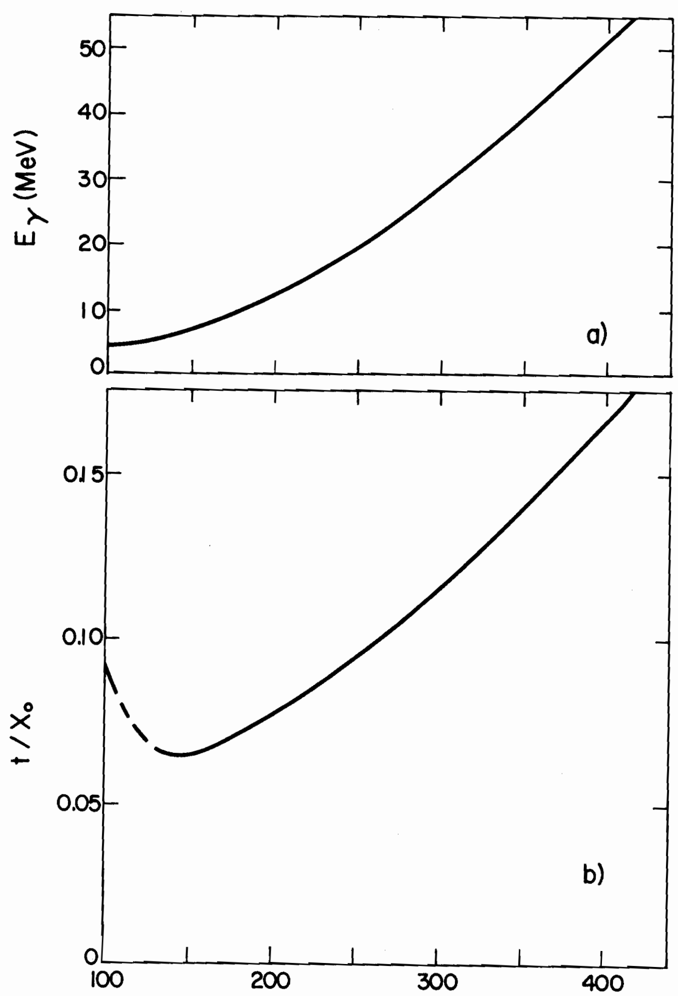

Fig. 4 a) Energy of the photons radiated by electrons or positrons of energy E. The parameters of the wiggler are given in Eqs (14).

b) Target thickness (expressed in radiation length) as a function of the beam energy.

Table 1

Positron yield for a system with the parameters of Eqs (14)

E (GeV)	E_γ (MeV)	$\Sigma(E_\gamma)$	t ($10^{-2}X_o$)	x (mm)	θ_+ (rad)	N_+/N_-
100	3.17	0.12	0.02	0.50	1.29	0.24
150	7.12	0.19	0.06	0.51	1.02	0.90
200	12.7	0.29	0.11	0.62	0.79	1.47
250	19.8	0.38	0.18	0.76	0.65	2.02
300	28.5	0.43	0.26	0.89	0.54	2.31
350	38.8	0.49	0.36	1.05	0.47	2.64
400	50.6	0.53	0.48	1.20	0.41	2.89

Table 2 gives the characteristics of the magnets steering the electron beam around the target, the electron energy loss in the steering magnets $(\Delta E/E)_S$ and in the wiggler $(\Delta E/E)_W$. The energy loss in the magnet was calculated for a case of a total magnet length of (2 × 4 m) = 8 m. The total energy loss is ∿ 0.6% at 350 GeV, still small enough not to reduce appreciably the overall efficiency of energy recovery.

Note that in the scheme of Fig. 2 each beam crosses both wigglers, so that the fractional energy lost is twice $(\Delta E/E)_{TOT}$. To avoid this, the less symmetric scheme of Fig. 5 has to be preferred: here the electrons are injected directly into the cooling ring and only the positrons are produced in the wiggler.

In conclusion, for energy larger than ∿ 150 GeV a 100 m long wiggler is a very suitable positron source. The wiggler field is only B_W = 0.37T (Eq. (1)) and might be supplied by small permanent magnets.

Table 2

Fractional energy losses in the magnet system (S) and in the wiggler (W)

E (GeV)	Bh (Tesla m)	$(\Delta E/E)_S$	$(\Delta E/E)_W$	$(\Delta E/E)_{TOT}$
100	0.17	3.6×10^{-6}	1.6×10^{-3}	1.6×10^{-3}
150	0.25	1.2×10^{-5}	2.4×10^{-3}	2.4×10^{-3}
200	0.41	4.2×10^{-5}	3.2×10^{-3}	3.2×10^{-3}
250	0.63	1.3×10^{-4}	4.0×10^{-3}	4.1×10^{-3}
300	0.88	3.0×10^{-4}	4.8×10^{-3}	5.1×10^{-3}
350	1.21	6.5×10^{-4}	5.6×10^{-3}	6.3×10^{-3}
400	1.58	1.3×10^{-3}	6.4×10^{-3}	7.7×10^{-3}

3. A PELORON WITHOUT PARTICLE RECOVERY

In the scheme we propose (Fig. 5) the positrons are produced in a wiggler system like the one drawn in Fig. 3, accelerated to about 1 GeV and their emittance damped in the ring, where each bunch circulates for a few ms before being extracted and transported to the input of the positron linac. As in other schemes, after the interaction point, the particles are slowed down in the opposite linac where a large fraction of their energy is coherently recovered. However, in this case the spent positron (and electron) bunches are dumped after only one pass, thus avoiding many of the complications inherent in the particle recovery schemes previously proposed.

The parameters of a colliding linac scheme and the equations that relate them are discussed in Ref. 1). By using them we arrive at the parameter list of a (350 + 350) GeV collider, reported in Table 3.

Table 3

Parameter list of an electron-positron linear collider

Quantity	Symbol	Value
Energy	2E	(350 + 350) GeV
Luminosity	L	10^{33} cm^{-2} s^{-1}
Number of particle/bunch	N	7.1×10^{10}
Bunch/s	f	2.5×10^{4} Hz
Bunch length	d	10 mm
Power in the two beams	P	200 MW
Bunch transverse radius at the interaction point	σ	1.0 µm
Normalized emittance (with $\beta^* = 5$ cm)	ε	$1.4 \times 10^{-5}\pi$m

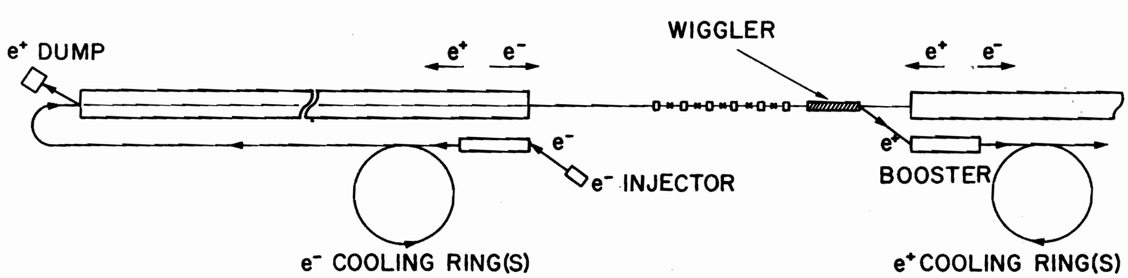

Fig. 5 An asymmetric scheme, such as the one shown in the figure, is advantageous with respect to the scheme of Fig. 2 because the losses by radiation are smaller.

During the bunch-bunch collision the average radiated power ΔU is such that the bremsstrahlung parameter $\delta = \Delta U/P$ takes the value[1)]

$$\delta \simeq \frac{2}{3}\ r_e^3\ \frac{\gamma N^2}{d\sigma^2} \simeq 5 \times 10^{-3} \tag{15}$$

where we have assumed a bunch length d = 10 mm. The disruption parameter turns out to be

$$D = \frac{r_e dN}{2\gamma\sigma^2} \simeq 1.4 \quad , \tag{16}$$

close to what is considered to be the maximum value $D \simeq 2$ [7)].

This example shows the interesting features of a peloron in which a large fraction of the 350 MW beam power can be recovered without need of reusing the degraded bunches. The bunch time separation is long enough that each bunch can spend 4 ms in the damping ring if 100 bunches can fit into it. If this should be a problem, one can use multiple rings as proposed by Gerke and Steffen[5)].

The power consumption can be estimated by summing the passive heat load, due to the unavoidable losses of the cryogenic system, and the power G^2/ZQ dissipated in the walls, where G is the gradient in V/m, Z is the RF specific impedance (we take Z = 3000 Ω/m) and Q is the Q-value of the cavity, for which we assume $Q = 5 \cdot 10^9$. As a realistic estimate of the passive heat load we take 2W/m [1)]. By using the approximate formula of Ref. 1), the higher mode losses due to each of the beam are estimated to be ∿ 30W/m at a cavity frequency of 3GHz. Recent calculations[8)] show that, if the bunch spectrum and the cavity mode spectrum do not overlap, the modes do not absorb energy, so that in a superconducting cavity there are no higher order mode losses. Thus if the resonant condition can be avoided for all cavity modes, the computed 30W/m should not worry us. Otherwise, an extraction efficiency larger than 99% will make them negligible with respect to the assumed passive heat load of 2W/m. For the cryogenic efficiency we take the value $\eta = 2.5 \cdot 10^{-3}$.

Figure 6 shows the dependence of the total power consumption versus the gradient G in the linacs. In computing the power it has been assumed that 0.5% of the beam energy is lost by bremsstrahlung (Eq. (15)) and 0.63% in the wiggler system (Table 2). It is seen that from the point of view of power, low gradients are favoured. On the other hand, the length of the collider is proportional to 1/G (broken line) and the number of points n along each linac where the beams have to be electrostatically separated also decreases with G (dotted line)[1),9)]. By combining the above arguments, we conclude that the optimum gradient is in the range 10 - 20 MV/m. The actual value depends upon the assumed power cost and the number of running hours per year.

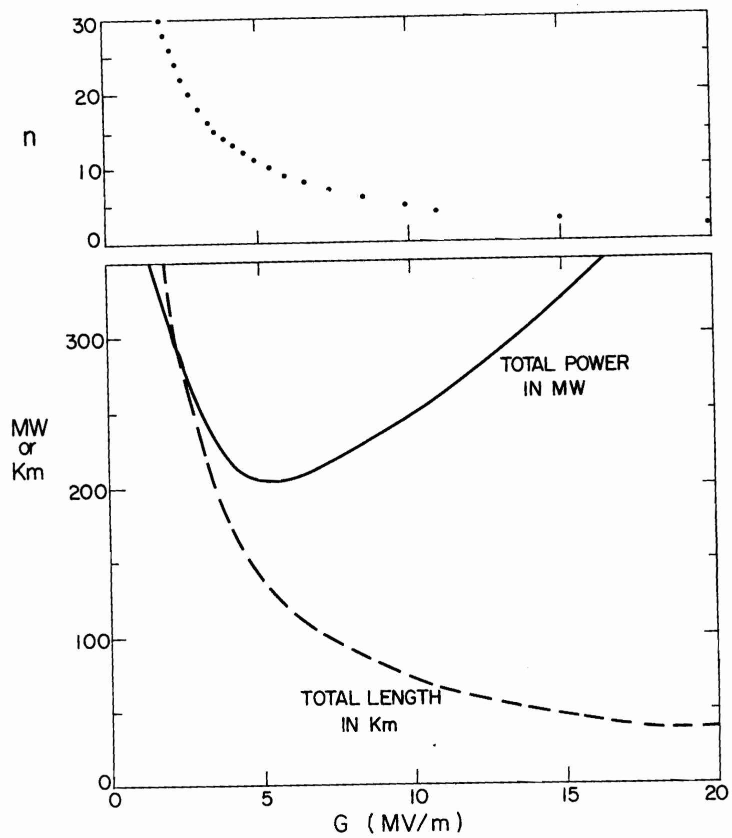

Fig. 6 The upper part of the figure shows the gradient dependence of the number of points n at which the beams have to be separated in each linac. The solid and broken lines represent the total power and the length of the two superconducting linacs as a function of the electric gradient in MV/m.

We are very grateful to the members of the electron-positron group of the Second ICFA Workshop for many stimulating discussions. At the workshop we learned that the Novosibirsk group had independently proposed the use of wigglers to produce polarized positrons to be used in a 100 × 100 GeV conventional collider without energy recovery[10]. In their case the main advantage with respect to the use of a thick target, previously foreseen, is connected with the availability of partially polarized electrons and positrons. On the other hand, our work was motivated by the difficulty posed by particle recovery in a superconducting linac scheme.

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9) As pointed out by E. Keil, Eq. (14) of Ref. 1) contains an error and should read $n + 1 \simeq 2Ef/ceG$, when n is the number of points in which the bunch cross in each linac. To avoid undue increase of the emittance in each of these points (Eq. (10)) the beams have to be electrostatically separated by at least ten times their width.

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