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DYNAMIC COLLIMATION FOR LINEAR COLLIDERS*

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Abstract

Experience with the SLC has indicated that backgrounds caused by the tails of the transverse beam distribution will be a serious problem for a next generation linear collider. Mechanical scrapers may not provide the best solution, because they may be damaged by the tiny, intense beams, and also because they may induce wakefield kicks large enough to cause emittance dilution.

In this paper, we present a possible solution, which uses several nonlinear lenses to drive the tails of the beam to large amplitudes where they can be more easily scraped mechanically. Simulations of several different schemes are presented and evaluated with respect to effectiveness, tolerances and wakefield effects.

Introduction

Experience with the SLC has indicated that backgrounds caused by the tails of the transverse beam distribution will be a fundamental problem of a next generation linear collider. Despite efforts to shield the detectors against beam caused backgrounds, particles in the tails of the beam distribution at times can produce unacceptably large backgrounds.

The mechanical scrapers, presently used in the SLC, will not necessarily provide the optimal solution for future colliders. First, in a next generation linear collider with beam energy between .25 and .5 TeV, and beam sizes of the order of a micron, the mechanical scrapers may be damaged if these tiny, intense beams hit them. A second problem originates from the wakefield kicks induced on the beam due to the collimators and is present in current as well as future machines. If the beam does not pass exactly through the middle of the scrapers, it gets a transverse deflection which varies longitudinally as the bunch density along the bunch [1]. If the variation of the transverse deflection is comparable to the angular divergence of the beam, the emittance will increase.

An expression for the kick of the beam due to two edges of a scraper has been derived analytically and verified numerically [1] under the assumptions that the scraper gap is small compared to the scraper length and the bunch length σ_z is not small compared to the scraper gap. This expression is given by

$$\Delta\theta = \left(\frac{2e^2 Z_0 c}{4\pi\sqrt{2\pi}}\right)\frac{2N}{E\sigma_z}\frac{\Delta x}{g} \quad , \qquad (1)$$

where Δx is the beam offset from the middle of the scraper, $2g$ is the scraper gap, N and E are the beam intensity and energy respectively, and Z_0 is the impedance of free space. Using typical parameters for the Next Linear Collider (NLC), namely $N = 1 \times 10^{10}$, $\sigma_z = 75\ \mu$m, $E = 250$ GeV we arrive at

$$\Delta\theta = 1.2 \times 10^{-6}\frac{\Delta x}{g} \quad \text{rad.} \qquad (2)$$

These kicks can lead to considerable emittance dilution. However if we drive the tail particles to large amplitudes, the required scraper gaps can be larger and hence the wakefield kicks are reduced.

In this paper we examine the possibility of collimating the transverse profiles of the beams in a dynamic (as opposed to mechanical) way. We first introduce the basic principle of dynamic collimation, which we then apply in the case of the NLC where beams are flat (emittance ratio $\epsilon_x/\epsilon_y \approx 100/1$) and the beam energy is 0.25 TeV. Next we address the question of wakefield kicks from scrapers and magnets, and we evaluate the tolerances of the proposed schemes. Finally, we present an alternative approach to dynamic collimation which uses decapole magnets. We conclude by giving a general overview and questions remaining to be answered. A detailed study of the proposed schemes can be found in Ref. [2].

Basic Principle of Dynamic Collimation

Dynamic collimation of beam profiles is a difficult problem. The difficulty lies in the fact that although the beam sizes are extremely small, we want to be able to penetrate them dynamically to affect particles with larger coordinates, while the core — which contributes to the luminosity of the machine — remains unaffected. To achieve this goal we must blow up the part of the beam we want to collimate so that mechanical scrapers can be used effectively without inducing significant wakefield kicks. Throughout this process the core must remain unaffected. This can be done with fields that provide a sharp edge at the right distance within the beam.

Linear optical magnification of the beam would not work because it would increase the sensitivity to the wakefield kicks. At a high beta point, the angular divergence of the beam is reduced by a factor of $1/\sqrt{\beta}$, ($\sigma' = \sqrt{\epsilon/\beta}$), while the wakefield kick remains the same since both Δx and g of Eq. (1) scale with the $\sqrt{\beta}$.

Higher order multipoles, on the other hand, such as decapoles, dodecapoles, etc. are not useful because they don't penetrate to the small distances necessary. However, for a TeV linear collider beam, sextupole and octupole fields placed at a relatively high beta, seem promising. We present results using both types of nonlinear lenses.

The proposed dynamic collimation scheme works as follows. The initial beam distribution goes through a nonlinear lens (sextupole or octupole) which is followed by a rotation in betatron phase by $\pi/2$. The long tails that have been developed are cut off by mechanical scrapers. However new unwanted tails still remain. There are two ways around this problem. The first method is to reduce the number of particles populating the new tails with the use of additional nonlinear elements. This method is analyzed later in this note.

A second method is to reabsorb the tails in the core of the distribution [3]. This is easily done by adding to the above lattice section its mirror image. This technique is well known. Two nonlinear elements of the same or opposite polarity (depending on their multipolarity), π apart in phase advance, amount to the identity transformation (up to a $\pm$ sign).

Next we present two different schemes that can be employed in an actual machine. They are both variations of the idea just described. Since in a real machine it is not clear whether position or angle tails cause most of the background problems, one would like to clean up the beam profiles in both directions (say x and x'). The following schemes take this into account.

Both schemes include two lattice sections each of which consists of two nonlinear elements π apart; thus, collimation in both directions is possible. In the first scheme the two lattice sections are next to each other separated by a phase advance of $\pi/2$. This variation will be called the "Serial collimation" scheme. Fig. 1 is a schematic representation of it.

In the second variation the two basic lattice sections are within each other. This scheme will be referred to as the "Nested collimation" scheme. Fig. 2 is its schematic representation. This scheme has the advantage over the serial one of occupying less space. How-

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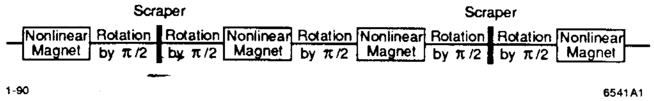

Figure 1: Schematic representation of the serial scheme.

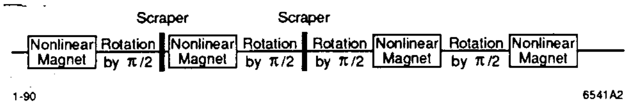

Figure 2: Schematic representation of the nested scheme.

ever it suffers from more serious geometric aberrations.

Dynamic Collimation for TeV Linear Colliders

In this section we present three alternative solutions for dynamic collimation in a next generation linear collider. The first is a serial scheme using sextupole magnets and it is examined in detail. The second is a serial scheme using octupoles and the third is the nested scheme with octupoles. These two cases will be examined briefly and final results will be presented. In designing the collimation section of a TeV linear collider we assume that beams are flat with a ratio of horizontal to vertical emittance equal to 100 to 1. The incoming beam to the collimation section has $(\sigma_x, \sigma_y) = (8, 0.8)\mu$m, at beta functions $(\beta_x, \beta_y) = (20, 20)$m. The beam energy is 250 GeV.

A. Serial Scheme with Sextupoles

We start by collimating the beam in the horizontal plane first. This is fairly straightforward dynamically because the horizontal beam size is 10 times larger than the vertical size. The serial configuration is used with normal sextupoles. Both sextupole magnets and scrapers are placed at high horizontal and low vertical beta points ($\beta_x = 200$ m, $\beta_y = 20$ m). Thus the beam is blown up horizontally to facilitate the collimation. It is important that the vertical size of the beam is small, so coupling effects are small.

Collimation in the vertical plane takes place immediately after the horizontal collimation. Skew sextupoles are needed for this plane. They are placed at high vertical and low horizontal beta points ($\beta_x = 20$ m, $\beta_y = 2{,}000$ m). The beam again is blown up in the plane we want to collimate. At the same time the horizontal divergence of the beam is large compared to the vertical, so the horizontal plane stays unaffected. Here the vertical scrapers are placed at a point of $\beta_y = 100$ m. This is important in controlling the wakefield effects from the scrapers, as explained in the Introduction.

Simulation Studies: Two degree of freedom simulation studies have been performed to examine the effectiveness of this scheme. Initial conditions consist, in both planes, of a gaussian core extended to 2σ and uniform tails from 2σ to 20σ. Figs 3a and 3b are the normalized phase space plots of the initial beam distribution in the horizontal and vertical plane, respectively, plotted at a point of $\beta_x = 20$ m and $\beta_y = 2{,}000$ m. The beam sizes are $(\sigma_x, \sigma_y) = (8\,\mu$m, $8\,\mu$m).

For the purpose of tracking we have populated the core with 2,000 particles and the tails with 20,000 particles. Both core and tail particles have been tracked through the horizontal and subsequently through the vertical collimation sections. The sextupole magnets have pole-tip field equal to 1 Tesla, length of 0.1 meter and pole-tip radius of 1 mm. The scraper half gap is $300\,\mu$m both in the horizontal and vertical plane.

The final horizontal and vertical phase space plots are shown in Figs 3c and 3d. They are plotted at a point where $\beta_x = 20$ m and $\beta_y = 2{,}000$ m. The phase space boundary is the intersection of the image of the two scrapers (parabolas) through the collimation optics line. It is worth noticing that in the above simulation study the emittance of the core of the distributions changed by a negligible amount.

We have just demonstrated that the above lattice provides scraping of the beam tails from 20σ to about 5σ in the horizontal plane and from 20σ to about 10σ in the vertical plane. In the rest of the simulation studies for a TeV linear collider we are going to assume that collimation in the horizontal plane has taken place already and the initial horizontal beam distribution will extend only to 5σ. So we shall concentrate on the scraping of the vertical plane.

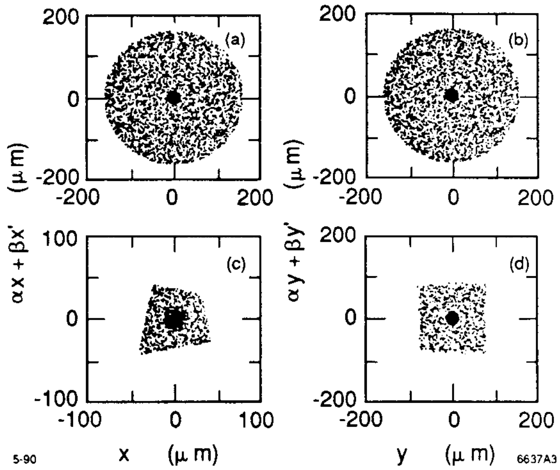

Figure 3: Dynamic collimation in the NLC.

Wakefield Kicks from Magnets and Scrapers: Let us now calculate the wakefield kicks from the sextupole magnets and the scrapers for the case considered above. For an offset equal to 1σ of the beam, sextupole magnets with pole-tip radius of 1 mm induce wakefield kicks equal to about twice the angular divergence of the beam.

The wakefield kick from the scrapers, for 1 σ offset, is comparable to the divergence of the beam.

One can reduce the magnitude of the wakefield kicks by tapering the beam pipe at the magnets and the scrapers. For a bunch length comparable to the scraper gap and large taper angles, it has been estimated numerically [1] that the transverse kick from a scraper is reduced by a factor of $(2\theta_{\rm tap}/\pi)^{1/2}$ where $\theta_{\rm tap}$ is the taper angle (θ being $\pi/2$ for a step scraper). For small angles there are indications that the dependence on the taper angle is linear [4]. Hence, tapering the scrapers by .01 rad – which can be easily achieved if the scraper's vertical extent is 5 mm and its total longitudinal extent is about 1 m – reduces the transverse kick by a factor of approximately 40.

Once the transverse kicks are under control, one may further reduce the scraper gap to achieve better scraping efficiency. For example, for sextupole magnets, reduction of the scraper gap by a factor of four results in a phase space boundary reduced by a factor of two.

Let us now discuss the effect of wakefield kicks on the beam emittance. In the presence of a transverse kick of the form

$$\Delta x' = \theta_{\rm max} \frac{\Delta x}{g} e^{-\frac{z^2}{2\sigma_z^2}} \tag{3}$$

the final emittance of the beam is given by [2]

$$\epsilon = \left[\frac{\sigma^4}{\beta^2} + \frac{(2-\sqrt{3})}{2\sqrt{3}} \sigma^2 \theta_{\rm max}^2 \left(\frac{\Delta x}{g} \right)^2 \right]^{1/2} . \tag{4}$$

Thus a kick of $1/5\,\sigma'$ will cause an emittance dilution of 0.15%.

Tolerances: The tolerance required for sextupole offsets depends upon the acceptable emittance dilution. For an emittance blow up of 10%, the tolerance on random misalignments is about 1 μm. Strictly speaking this requirement is not on absolute alignment but rather on beam to sextupole center offsets. This would require accurate beam positioning rather than tight absolute alignment. In addition, one may use skew quadrupoles downstream of the collimation section to take out the sextupole offset effects, and thus relax these tolerances.

B. Serial Scheme with Octupoles

In this section we are going to restrict our discussion to the vertical plane only. To achieve the same scraping efficiency as before, we now need much stronger magnets. So we use octupoles with pole-tip field 1.2 Tesla and length 1 meter. The collimators are placed at a beta of 100 m as before, and their half-gap is 100 μm. The initial horizontal phase space assumed in the simulations extends to 5σ, while the initial vertical one extends to 20σ as before.

At the end of the collimation section the vertical phase space looks like Fig. 4.

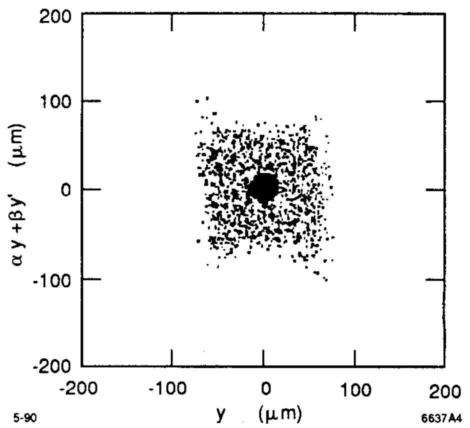

Figure 4: Vertical phase space of the scraped distribution - Serial scheme with octupoles.

The core emittance changed by .05%. Out of 20,000 tail particles, 16,200 were scraped. Notice that the scraping is equally efficient as before, but not as "clean," due to the geometric aberrations caused by the stronger magnets. For an emittance blow up of 10%, the tolerance on octupole offsets is $\pm 3\mu$m.

C. Nested Scheme with Octupoles

We now consider dynamic collimation in the NLC with the nested scheme. It is expected that this scheme will induce stronger geometric aberrations. In order to be able to compare the nested scheme with the serial one, we performed simulation studies using identical conditions. Fig. 5 displays the final vertical phase space.

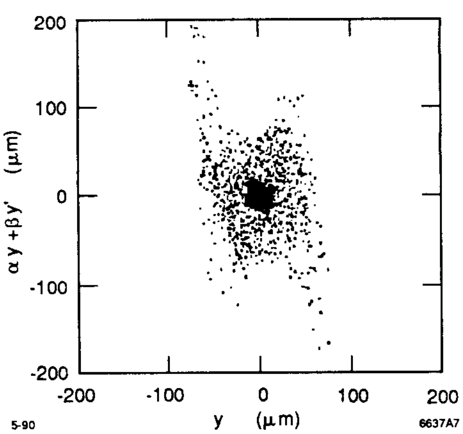

Figure 5: Vertical phase space of a scraped distribution - Nested scheme with octupoles.

Notice that the scraping is not symmetric in the y and y' dimensions. This is because one dimension is essentially scraped after one octupole while the other is scraped after two. The strong aberrations give rise to long y'-tails.

An Alternative Approach: Collimation with Decapoles

The basic idea in this section is the same as in the previous section; nonlinear lenses are used to stretch the beam tails to large amplitudes where they can be more easily scraped mechanically. The beam is directed through two nonlinear magnets 90^0 apart in betatron phase. Scrapers are then used to cut off the stretched particles.

The difference from the previous approaches is that here we don't use a $-I$ section to reabsorb the tails into the core. Instead we add another two nonlinear lenses, 90^0 apart, to the above configuration. The last two magnets must be of *weaker* strength. The first two create a 'dynamic aperture' which 'scrapes' the beam. The weaker ones create a bigger dynamic aperture which acts only on the tail particles but leaves the core unaffected. Hence the tail population is reduced. Simulation studies show that although the tail population can be reduced significantly it will not disappear completely. In order to avoid strong coupling effects and not to disturb the core of the distribution, decapole magnets were used. Fig. 6 illustrates the vertical phase space after collimation with decapoles. The initial phase space extends, as usual to 20σ.

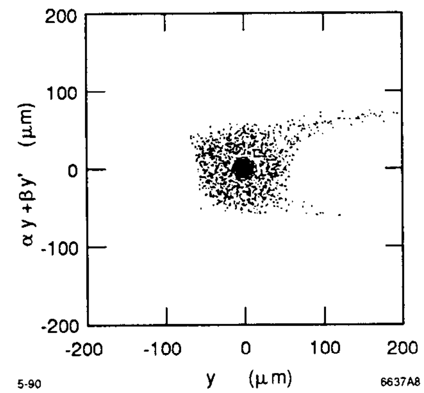

Figure 6: Collimation with decapoles.

The initial horizontal phase space was assumed to be extending to 3σ. Out of 20,000 particles populating the tails of the beam distribution, 18,068 were scraped.

Tolerances in this scheme are relatively loose. Six micron offsets in both planes, simultaneously applied to all four magnets give rise to 17% emittance change. The major problem with this method is that the magnets required have a very small pole tip radius (0.5 mm) and may be difficult to construct.

Conclusions

We have illustrated several different collimation schemes for a TeV linear collider. Mechanical scrapers probably can not be used alone because they may be damaged by the small beams. Furthermore scraping of the extremely small NLC beams requires equally small scraper gaps which in turn induce large wakefield kicks. Linear optical magnification defeats the purpose because it magnifies the wakefield effects.

However, nonlinear fields, in particular sextupole and octupole fields can be used to stretch the tails of the distributions to large amplitudes without affecting the core. By tapering scrapers and magnets one can achieve acceptable wakefield kicks.

The tolerances on the magnet offsets appear tight, however a further study may lead to a more optimized design.

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