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Conventional Collimation and Linac Protection

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Abstract

We describe linac protection and a conventional collimation system appropriate for a next linear collider. The linac accelerating structure can be protected from "worst credible failures" by a system of sacrificial spoilers. For the collimation system we consider the effects of transverse wakefields and the transmission, heating, mechanical stress, and edge-scattering properties of scrapers. We require local chromatic correction, scraper survival for two pulses of a mis-steered beam containing 0.5×10^{12} particles per pulse, average interception capability of 1% of the beam at any scraper, and zero particles incident on the final doublet in the final focus system. We describe emittance dependent limitations of this system and present formulae which determine scraper gaps. Conventional collimation systems appear adequate to collimate the beams of next generation 0.5 and 1.0 TeV c.m. linear colliders. Though we have combined functional units where possible to reduce total length, the length of our lattices for these systems are longer than 1 km per linac.

INTRODUCTION

There are many known sources of halo particles in electron linacs [Ref. 1], halos which: i) are present upon extraction from the damping ring, ii) are created in the bunch compressor, iii) are generated by wakefields within the linac, especially as a consequence of tails in bunch length, iv) are created by mismatches, misalignment and steering errors in the linac, v) result from injection jitter into the linac, vi) come from acceleration of dark current, and vii) are produced by hard Coulomb scattering within the linac. Sources i) through vi) can be ameliorated by a variety of strategies, whereas vii) places an irreducible lower limit on halos. An estimate of the fraction of particles scattered into a halo beyond "$n\sigma$" is [Ref. 2] $\Delta N/N \approx (5 \times 10^5)/n^2$ for a 5 km linac with gas pressure of 10^{-8} Torr. For $N = 0.5 \times 10^{12}$ and $n = 5$, $\Delta N \approx 10^6$. Since it may be true that even one particle hitting the final doublet can blind the detector [Ref 3], and substantial tails beyond $7\sigma_x$ or $35\sigma_y$ can cause synchrotron radiation incident on the final doublet, a collimation system for the next linear collider will be mandatory.

At the end of a 1 TeV/cm energy X-band linac the beam will have a $\sigma_x\sigma_y$ product of 5 μm^2 and each pulse will contain more than 0.5×10^{12} particles with an energy of 40 kJ. The time averaged power will be 8 MW [Ref 4]. One pulse of such a beam hitting any known solid material would vaporize and likely shatter it. Moreover, wakefields from jaws attempting to collimate micron-sized low-emittance beams could destroy the emittance. Potential radiation damage, absorber heat loads, detector backgrounds, and edge scattering further complicate this problem. We begin by describing the collimation system we propose, and then show how it meets projected operating requirements for an X-band linear collider.

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Conventional Collimation System

We symbolically represent a four-phase collimation system as follows:

IP phase:	mai..h/e.v.H/E__h/e.V.H/E..π/2..
FD phase:	h/e.v.H/E__h/e.V.H/E..π/2..
IP phase:	H/E.V__H/E.V..π/2..
FD phase:	H/E.V__H/E.V..mao

where IP (FD) phase indicates that particles in phase with the interaction point (final doublet) are being collimated. mai stands for the incoming match to the first phase of scraping, and mao stands for the match from the last FD phase into the next lattice section. "π/2" represents a lattice section which advances the phase of both the horizontal and vertical betatron motion by π/2. A long underline indicates that the joined symbols are part of a -I section. The small letters h,v, and e represent thin 0.25 radiation length (r.l.) pyrolytic carbon spoilers, which are designed to withstand a pulse or two of a mis-steered beam, while creating a divergent angle in the beam sufficiently large that downstream absorbers are not harmed. The large letters H, V, and E represent absorbers which are 20 r.l. long, made either of water-cooled copper where a large flux is expected, or a higher-Z material such as tungsten, in low flux situations.

The combination h/e or H/E indicates a position where energy and the horizontal plane are being collimated together. Two of these at -I with a symmetric dispersion function combine to collimate a triangle in (x,δ) space.

The β-functions must be large at the scrapers so that: i) the beam, if mis-steered, is sufficiently large when in hits the spoiler, and ii) the beam and collimator gap are large enough to make the wakefields small. Chromaticity is created because of the large β-functions. A large dispersion function is required for energy collimation, and this can be used in conjunction with sextupole pairs at -I for chromaticity correction. Sextupole pairs have been placed at all spoilers and absorbers represented above. Lattice functions for a 3-phase collimation system are shown in Fig. 1. Overall system length could likely be reduced by redesigning the third and fourth phases, since these have no requirements based on spoiler survival, and absorbers will receive far less flux.

We have not attended to the ultimate fate of all secondary particles created at the spoilers. Absorbers other than those specifically called out will certainly be required.

Because of the large dispersion function and large β–functions, the whole system must be protected against beams that are very badly mis-steered or are far off-energy. We propose to accomplish this with sacrificial tungsten spoilers at the entrance to the collimation system set at 35 σ_x and 280 σ_y.

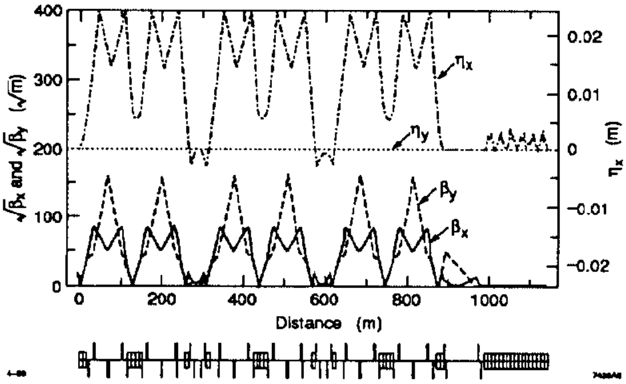

Figure 1. Lattice functions for three-phase collimation systems.

Limitations of Conventional Collimation Systems

To minimize wakefields, scrapers must be tapered. The optimum taper angle is given by:

$$\Theta_T^{opt} = 1.6\,(\lambda\sigma_z/g^2)^{1/4}$$

where g is the scraper gap, λ is the skin depth, and σ_z is the rms bunch length [Ref 5]. Taken together, the wake from the taper, which prefers a small gap, and the resistive wall wake which requires a large gap, yield the following condition [Ref 6]:

$$2\,u^3 - 3\,a\,u^2 + 1 \le 0$$

where $u = (g/g_1)^{1/2}$ and $a = (n/n_{min})^2$, where

$$g1 \approx 0.9\,(\Sigma n_i L_{Fi} \lambda_i^{1/2})^{2/3}\,\sigma_z^{1/6} \,/\, (\Sigma n_i\,\lambda_i^{1/4})^{2/3}$$

and

$$n_{min}^2 \approx 0.8\; t/t'\; N r_e/(\varepsilon_N \sigma_z)\,(\Sigma n_i L_{Fi} \lambda_i^{1/2})^{1/3}\,(\Sigma n_i\,\lambda_i^{1/4})^{2/3}\,\sigma_z^{1/3}$$

Here, n_i is the number of scrapers at the phase being considered with length L_{Fi} and resistive skin depth λ_i. ε_N is the normalized emittance, N is the number of particles per bunch, and r_e is the classical electron radius. In other words, for a = 1, which occurs at $n = n_{min}$, where n is the number of sigmas being collimated, the cubic equation has one positive root at u = 1 ($g = g_1$). Corresponding to this gap and n we have a β-function $\beta_1 = g_1^2/(n_{min}^2\varepsilon)$. The jitter amplification deemed acceptable is t′/t. The outgoing jitter strength t′ is perpendicular in phase space to the incoming jitter strength.

For $n > n_{min}$ the cubic equation has two positive roots and any u between the roots satisfies the equation. For $n/n_{min} = 1.1$ the roots are u =0.66 and u=1.6, hence g may take any value in the range $0.37g_1 < g < 2.6g_1$, and β can take any value in the range $0.16\beta_1 < \beta < 5.6\beta_1$. For $n/n_{min} = 5/3$ the roots are u = 0.5 and u = 2.4. Hence g may take any value in the range $0.25g_1 < g < 5.8g_1$, and β can take any value in the range $0.02\beta_1 < \beta < 12\beta_1$. We see that n_{min} is tightly set by the equation, but that for n only slightly larger than n_{min}, rather broad ranges of g and β are possible.

Bunch-to-bunch and pulse-to-pulse energy jitter can also be a problem. However, because of the symmetric dispersion function in the -I sections, the wakes from scrapers at -I will have opposite polarity and could be designed to cancel one another.

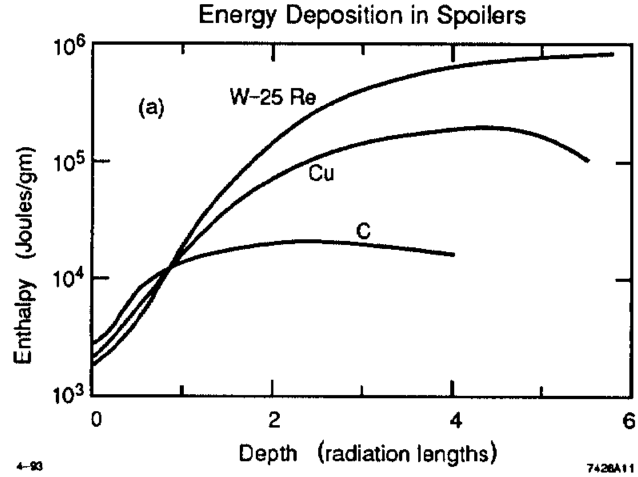

Figure 2. The energy deposited in several materials by a 500 GeV beam of 10^{12} particles incident with a $\sigma x \sigma y$ product equal to 2000 μm^2.

Required Collimation Cuts

The transverse collimation cut is determined by the final focus design together with the maximum divergent angle expected at the IP. The final doublet apertures are primarily determined by wakefield criteria. We take $6\sigma_x$ and $35\sigma_y$ as acceptable collimation cuts to avoid any particle hitting the final doublet and to minimize synchrotron radiation flux incident on the doublet.

The acceptable energy cut is determined by the bandwidth of the transport system from the collimation system to the final doublet. Studies show that the bandwidth is about 5.5%, so we have taken 4% as an acceptable energy cut.

Spoiler Survival

Within the constraints dictated by the beam dynamics described above, the β–functions must be large enough that the energy density deposited by a full beam pulse incident on a spoiler will not destroy it. The spoiler should withstand two beam pulses to allow for data acquisition in puzzling circumstances. Figure 2 shows the energy deposited per gram for three materials for $\sigma_x\sigma_y$ = 2000 μm^2 and $Nn_B = 10^{12}$ particles per bunch. Energy density can be translated into temperature rise using enthalp vs. temperature data for the material. Carbon is thermally very rugged. It may be coated and plated to reduce resistive wall wakefields.

Post-Spoiler Particle Distributions

Figure 3 shows the angular distribution of particles exiting the spoilers. Each curve represents particles in a 1 GeV bin at energies indicated. These show that angular distributions are independent of energy. At the scrapers, $\sigma_x' \approx 30$ nr so the scattering angles represent $10^3\sigma$ horizontally. The great majority of these particles will be intercepted by absorbers in the same-phase beamline section where they were produced. Those with very small angles, $\le 35\ \sigma_x$, about 1μr at the spoiler, will be

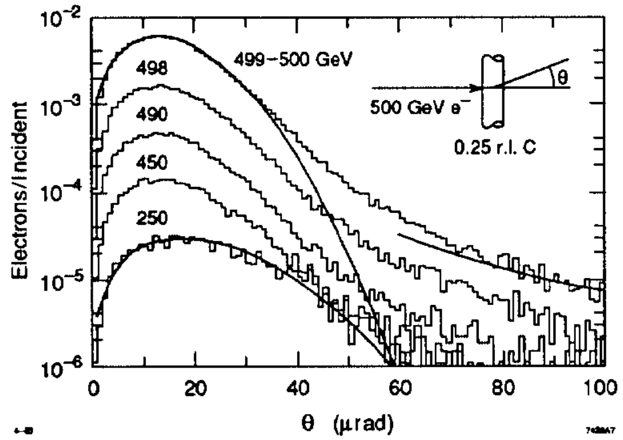

Figure 3. The angular distribution for particles exiting a 0.25 r.l. pyrolytic carbon spoiler. Solid lines correspond to a single scattering ansatz.

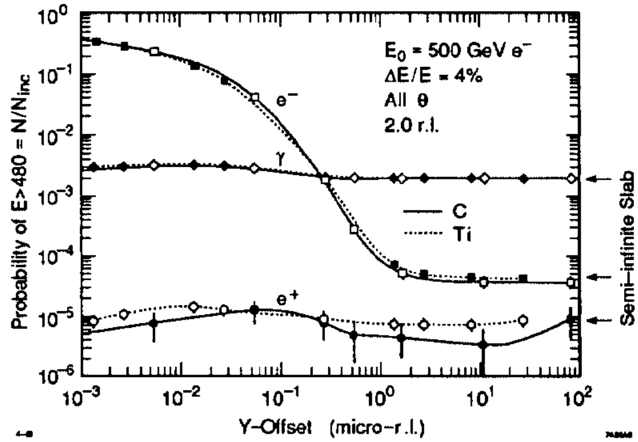

Figure 4. The probability of rescattering into the beam with energy degradation less than 4% as a function of initial position from the scraper edge.

transported to the next-phase beamline. This fraction is about 2×10^{-3}. Hence one would expect about 1 particle in 10^4 to hit the next spoiler within 1 σ of the edge of the scraper.

Edge Scattering

After the two collimation phases with thin carbon spoilers, the re-population of the beam halo comes from edge scattering. The angular distribution for these particles is similar to that shown in Fig. 3. Figure 4shows the number that reenter the halo with energies above the 4% cut. Ten percent of those particles hitting within 0.3 μm from the edge will re-emerge in the beam. For incident particles spread over a width of 1 $\sigma \approx 700$ μm, 0.5×10^{-4} re-emerge in the beam. The number of edge-scattered particles in the beam after the third phase of collimation will be at least 10^{-8} of those incident on the first carbon spoiler. These will be intercepted in the final FD phase collimation.

Tail Repopulation

There is about a kilometer of beam-line from the last collimator to the IP, including a possible "big fork" to allow switching between two detectors, a 200-m long "big bend" for muon protection (and to accommodate two detectors and a crossing angle independent of linac orientation), and the final focus system. In order to insure that less than one particle per beam-pulse impacts the final doublet as a result of being hard scattered by a gas nucleus, it is necessary to have gas pressures of 10^{-9} Torr in the "big fork" and "big bend" [Ref 6]. Collimators should be placed in the final focus system at the first large β-function location.

Linac Protection System Issues

A badly mis-steered beam in the linac could destroy a long length of accelerator by destroying the edge of an iris, executing a betatron oscillation, destroying the edge of another iris, and so on down the machine. The destructive capability of an 8 MW beam having a cross-sectional area of a few square microns is awesome.

The worst credible failure that we have identified is a simultaneous short in the windings of two poles of a quadrupole. We assume that a system designed to detect magnet problems failed, and that continuous beam-position monitor (BPM) analysis also failed to identify the errant beam. While the resultant field on the quadrupole axis is not large enough that the beam will hit the accelerator structure before the next quad, it can hit the structure in the accelerator section after that [Ref 6].

Our proposal for protecting the linac from this and similar failures is to insert a "sacrificial spoiler" immediately before each quadrupole. The word "sacrificial" indicates that we expect to have to replace this element if ever the full beam is incident upon it. The inner radius of the "sacrificial spoiler" must be such that a mis-steered beam passing through it cannot hit the accelerating irises before reaching the next quadrupole. For a structure iris radius of 4.4 mm, the spoiler radius must be about 1 mm. The wakefield induced emittance growth from a linac filled with such spoilers is acceptably small ([Ref 6]).

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