DYNAMIC FOCUSING SCHEMES FOR LINEAR COLLIDERS*

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Abstract

By using the intense fields of a demagnified bunch as a final lens, one can greatly simplify and shorten the conventional final focus and collimation systems of linear colliders. In the dynamic focusing schemes described here, the lens bunches enter the interaction region through separate beamlines. Design details and constraint equations for such focusing schemes are developed for future high energy linear colliders.

1 INTRODUCTION

1.1 Motivation

This study was motivated by the observations that the beam delivery system for the next linear collider (NLC) [1], consisting of a final focus sytem, a big bend, and a collimation system, has a length one-half the length of the main accelerating system length, and that this beam delivery length will grow roughly as the center-of-mass energy to the 3/2 power. Since the length of linear colliders built on the crust of a round earth are limited in length to around 200 km, this scaling law becomes a serious obstacle to building linear colliders with greater than 5 TeV c.m. energy.

1.2 An ideal focusing system

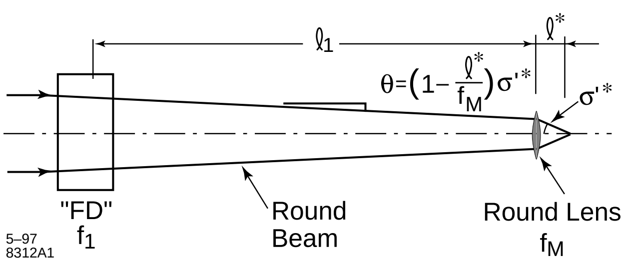

Figure 1. A schematic of an ideal final focus system. A very strong lens is placed 3 mm from the IP. The total length is about 2 m.

Figure 1 shows an ideal final focus system. FD labels a conventional final doublet where the beamsize is only modestly enlarged over its typcial vaues in the linac. The total length, from the final doublet to the IP, is a couple of meters. It is supposed that there is a very strong lens, not much larger than the beam, located a couple of millimeters from the IP. This has the advantage that the chromaticity, ℓ^* / β^* would be so small (about 20) that no chromatic correction is needed, and the sensitivity to errors would be small for similar reasons. Furthermore since the beam is not blown up, there is no need for a collimation system or a big bend. In other words the system of fig. 1 can replace an entire beam delivery system. The problem is how to manufacture the small powerful lens.

1.3 The Dynamic focusing idea

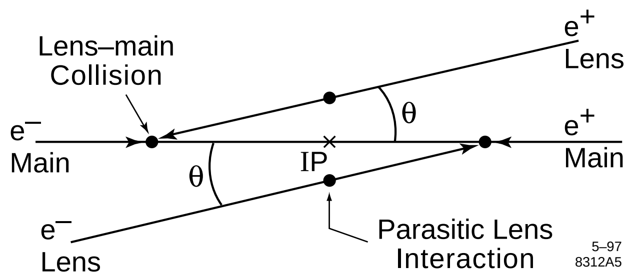

Figure 2. The dynamic focussing scheme for implementing the ideal final focus system.

Figure 2 shows a situation in which the small lens of fig. 1 is created by a secondary beam. The study of such a system will be the subject of this paper.

1.4 Relationship to superdisruption

The idea of using the strong fields of a particle bunch to focus beams has been attributed to D. Leith and discussed under the title superdisruption [2, 3]. These efforts were largely directed at achieving stronger focusing (smaller IP β functions), and implementation schemes were limited to consideration of two closely-spaced bunches traveling in the same beamline. With dynamic focusing the main intention is to simplify the beam delivery systems, and lens beams are imagined to have much lower energy and enter the interaction region through a second dedicated beamline.

2 LINEAR COLLIDER IP PARAMETERS

Any discussion of ideas for future linear colliders must pay attention to the constraints imposed by interaction point (IP) considerations.

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2.1 The main IP constraint equations

The three principal IP constraint equations are the luminosity equation, the disruption constraint, and the beamstrahlung constraint. We write the luminsoity equation as $F \equiv 4\pi \frac{L\,E_B}{P_B} = \frac{NH}{\sigma_x \sigma_y} = \frac{NH\varsigma}{\sigma_y\,(\sigma_x + \sigma_y)}$ where we have introduced a quantity F , a rationalized flux specified by luminosity, beam energy and beam power. H is the enhancement factor. $\varsigma = 1 + \frac{\sigma_y}{\sigma_x}$, has been introduced for convenience, and equals 1 for flat beams and 2 for round beams.

The vertical disruption constraint equation is crucial because if the beam is not charge compensated there is a kink instability which limits the disruption to about 15, and for charge-compensated beams there is an instability in the charge separation which limits the disruption to about the same value. It is interesting that these two constraint conditions already determine σ_z.

By introducing appropriate variables, the beam-strahlung equation can be solved analytically to give $N/(\sigma_x + \sigma_y)$ as a function of γ/σ_z. The result can be written

$$\frac{25\,\alpha\, r_e}{12\, n_\gamma} \frac{N}{(\sigma_x + \sigma_y)} = \eta \left(\frac{2\, n_\gamma\, \bar{\lambda}_e}{5\alpha} \frac{\gamma}{\sigma_z} \right)^{1/2}$$

where η is a factor greater than 1 which goes to 1 rapidly for large γ/σ_z. Even with charge compensation, which will be valid only to some fractional extent, one must heed a beamstrahlung constraint equation.

One can now solve for σ_y and N.

$$\frac{1}{\sigma_y} = \frac{1}{c_1\,\eta} \left(\frac{D_y\, F}{n_\gamma^3\, H\, \varsigma} \right)^{1/2} \quad \text{and} \quad N = \frac{\eta^2\, c_1^2\, n_\gamma^3\, \varsigma}{D_y} \frac{\sigma_x}{\sigma_y}$$

where c_1 is a constant about equal to 8000. The only free parameter is the aspect ratio at the IP. The Oide condition can be used to determine the required normalized emittance. The β^* thusly determined is fairly constant with energy and has a value near 100 μm.

3 DYNAMIC FOCUSING PARAMETERS

3.1 Cromaticity condition

The chromticity $\xi_y = \frac{\ell^*}{\beta_y^*}$ of the lens-beam lens is chosen to be about 20, so for β^*=150 μm, ℓ^*= 3 mm. The chromaticity is also the demagnification from the lens-beam lens to the IP.

3.2 Lens beam charge per bunch

For a charge $\overline{N}_Q$ in a uniform disk of radius R_Q $\frac{1}{\ell^*} = \frac{2\,\overline{N}_Q\, r_e}{\gamma_M\, R_Q^2}$. This condition yields

$$\overline{N}_Q = N_{Q_0} \frac{R_Q^2}{2\,\sigma_M^2} \quad \text{where} \quad N_{Q_0} = \frac{(\gamma\,\varepsilon_M)}{r_e} \xi_y$$

The fraction of the main beam not incident on the uniform disk will be $\exp(-\frac{R_Q^2}{2\,\sigma_M^2})$. To limit this quantity to 2%, the exponent would have to be about -4. Furthermore, if one assumes that 50% of the beam is outside the uniform disk, then the total charge in the lens will be about 6 times $N_{Q0.}$ For the NLC emittance, the total charge comes out to be a workable 4 10^9.

3.2 Uniform lens distributions

Concerning the production of uniform bunches we remark that there exists a phase-space density function, $\rho \propto 1/\sqrt{R^2 - r^2}$ where $r^2 = x^2 + x'^2 + y^2 + y'^2$, which produces a uniform distribution This is hollowed-out in the center and singular at R=r. Nevertheless one can try to approximate this distribution at low energy. Nonlinear elements in the lens-beam final focus system can shape the distribution at the IP phase.

3.3 Pinch effect

Figure 3 shows the lens beam colliding with the main beam. Each beam focuses the other. The ratio of the focal lengths can be detemined to be a power ratio:

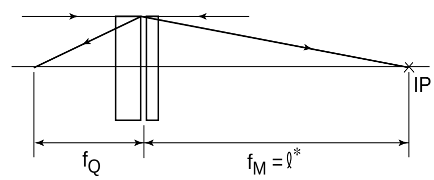

Figure 3. The lens beam, moving to the left, is pinched by the main beam moving to the right..

$\frac{f_M}{f_Q} = \frac{\gamma_M\, N_M}{\gamma_Q\, N_{Q_0}}$. The luminosity loss due to the change in focal length will be about $\frac{\Delta L}{L} \approx \frac{2}{15} \left(\frac{f_M}{f_Q} \frac{\sigma_z}{\beta_M^*} \right)^2$. To have a low-power lens beam, one must have a very short main-beam bunch length.

4 MAIN CONCERNS

4.1 Parasitic crossing effects

The most challenging situation can be seen in the multibunch geometry of fig. 4, where the beams are separated by a distance $\ell^*\,\delta\theta$. The parasitic kick can be expanded into multipoles. The dipole kick can be corrected by steering, and the quadrupole kick by adjusment of matching into the interaction region. Even the sextupole term could be compensated. But suppose we take it as uncompensated and let it define a limit on the beam separation. The resulting equation is

$\delta\theta \geq \frac{5}{9}\frac{N_Q}{N_{Q_0}}\frac{\gamma_M}{\gamma_Q}\sigma_M^{*'}$. At the NLC, with a divergent angle of about 30 μr, the limit on $\delta\theta$ is about 1 mr. The parasitic crossing is not a limiting problem.

4.2 Motion of lens

Again referring to the geometry of fig. 4, if θ_L is small, then the focal points as the lens beam travels through the main beam will lie along a vertical line. This is exactly what is required to crab the main beam. If θ_L is non-zero, it must be small compared to the diagonal angle of the main beam. As pointed out in the pinch effect, the main beam must be very short, so the diagonal angles are quite large. Lens motion should not be a problem.

4.3 Multibunch instability

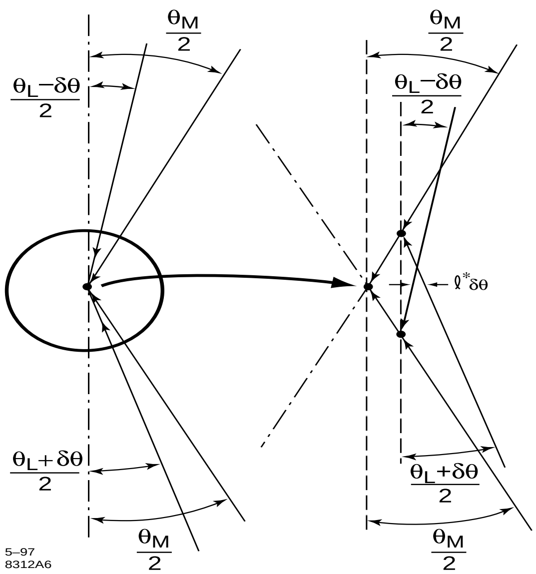

Figure 4. The incoming beam geometry required for multiple-bunch beams.

To facilitate multiple-bunch beams we must have both the main beams and the lens beams enter and exit in separate beam lines with a crossing angle. The required geometry is shown in fig. 4. Because the energy of the lens beam is contemplated to be smaller, one obtains a limit

$\frac{\theta_M + \theta_L}{2} \geq \sqrt{\frac{\gamma_M}{\gamma_L}}\,\bar{\theta}_M$ where $\bar{\theta}_M$ is the usual lower limit on θ_M arising from multibunch considerations. This limit establishes the bound on γ_L/γ_M. $\bar{\theta}_M$ depends weakly on energy.

4.4 Jitter

The jitter of the lens beam is a serious problem, because the lens determines the focal point for the main beam. With the demagnifications assumed, the lens beam jitter would have to be less than 1%. If in fact such a small jitter were achieved, one could contemplate a head on $\delta\theta=0$ operation. Then the head-on lens-lens collision would align the main-main collision if the focal length of the lens-lens collision is twice ℓ^*. The jitter limit in this case comes from distortion due to the misaligned lens-lens collision. See ref. [2]. The jitter limit for this case is about 6%.

5 EXOTICA

It is interesting to contemplate whether one can bypass the Oide limit with dynamic focusing. For the geometries we have described the Oide limit is not changed. But one can contemplate long-bunch lens beam schemes which approach the adiabatic focusing scheme [5]. It seems that appropriate lens beams could be prepared, but the effects of the parasitic crossing reappear and have not been fully analyzed.

6 SUMMARY

For energies greater than 10 TeV cm, beam delivery system lengths become unmanageable. Dynamic focusing is an alternative solution if micron length bunches can be produced and accelerated. Lens beam jitter must be held to a few percent. IP parameters are improved from the ability to have round beams at the IP. For NLC parameters one could achieve $\sigma_y = \sigma_x = 20$ nm, $\gamma\varepsilon = 10^{-6}$ rad-meter, and $N = 5\ 10^9$. Furthermore the collimation system, the big bend and the final focus system are all but eliminated. For $\sigma_z = 2$ μm the lens beam to main beam power ratio is 1/30. An energy ratio of 25 is permitted by the multibunch instability.

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