BEAM DELIVERY SYSTEMS FOR PEDESTRIANS

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Abstract

For the proposed e^+e^- linear colliders, the term 'beam delivery system' (BDS) refers to the beam transport system from the exit of the linac to the interaction point (IP). These beamlines are not one but in effect several beamline sections, each dedicated to a specific task. Of primary importance is the final focus section (FFS), whose task it is demagnify the transverse beams size to the required 'nanobeams' at the IP. In this paper, we briefly introduce the concepts and constraints on the designs of the BDS.

1 INTRODUCTION

The current proposals for a high-energy e^+e^- linear colliders all require nanometer-size beams (nanobeams) at the interaction point to achieve the required high luminosity (a few times 10^{34} cm^{-2}s^{-1}). Producing these tiny beams requires strongly demagnifying optics from the linac exit to the IP; factors of ~1000 reduction in beam size are typically required, with corresponding IP β-functions (β*) of hundreds of microns*.

The optical transport system responsible for the strong demagnification is referred to as the final focus system (FFS), and forms the last section of the linear collider beam delivery system (BDS). The BDS is the complete transport system from linac to IP, and provides the following functionality:

- strong demagnification of the beams at the IP (FFS);
- post-linac beam halo collimation to protect the detector from halo-driven backgrounds;
- beam phase space diagnostics (emittance measurement);
- IP beam phase space and luminosity tuning.

All four of these requirements put specific constraints on the optics design:

- The tiny value of β* drives very large β-functions (tens of kilometres) in the BDS itself, particularly in the FFS;
- the resulting large chromatic terms must be compensated, requiring the use of strong non-linear elements (sextupoles) and a need for a careful cancellation of the resulting geometric terms;
- design of the collimation system optics must take into account collimator jaw gap sizes and the corresponding wakefield effects; machine protection of spoilers with the extremely high beam powers is also a major design constraint;
- both the chromatic correction and (momentum) collimation sections generally require high dispersion functions (*i.e.* bending sections);
- Synchrotron radiation effects from bends and quadrupoles must be considered;
- purpose designed diagnostics sections *should* be included, where the optics allows the optimal measurement environment (beam conditions) for the beam parameter of interest.

Large β-functions and strong magnet strengths inevitably lead to very tight tolerances on field quality and alignment. Magnets in the BDS have some of the tightest alignment (vibration) tolerances of the entire machines, ranging from tens of nm to (ultimately) ~nm for the final strong focusing lens at the IP. It is impossible to achieve such levels of stability without the use of feedback systems, both mechanical (on the magnets themselves), and beam-based orbit correction feedback. A critical feedback system is the beam-beam position feedback at the IP, which is responsible for maintaining the nanobeams in collision; without this feedback, the beams would simply miss each other.

In the following sections, we will give a brief introduction to each sub-system of the BDS, placing emphasis on the current design solutions for each section, and the fundamental constraints which limit them.

2 FINAL FOCUS SYSTEM

The required demagnification is primarily achieved by a strong (short focal-length) lens close to the IP. Since $\beta^* << f$, the β-function at this lens is approximately given by

$$\beta \approx \frac{f^2}{\beta^*}$$

where f is the focal length of the lens (the distance from the lens to the IP, often referred to as L^*). Taking $f = 3$ m and $\beta^* = 0.1\,\text{mm}$ gives $\beta \approx 90\,\text{km}$; consequently the beam angles at the lens are very small and we have parallel-to-point focusing. In real systems, the final 'lens' is formed from a long quadrupole doublet (referred to as the final doublet, or FD), and β-functions in excess of 100 km are not unheard of.

The RMS chromatic aberration to the beam size at the IP from a thin final lens is approximated by

$$\Delta y_{\text{RMS}} \approx \left(\frac{\beta}{f}\right)\delta_{\text{RMS}}\sigma^*$$

* in the vertical plane. Since all linear colliders collide *flat* beams with $\sigma_x^*/\sigma_y^* \geq 100$, we will in general only refer to the vertical plane.

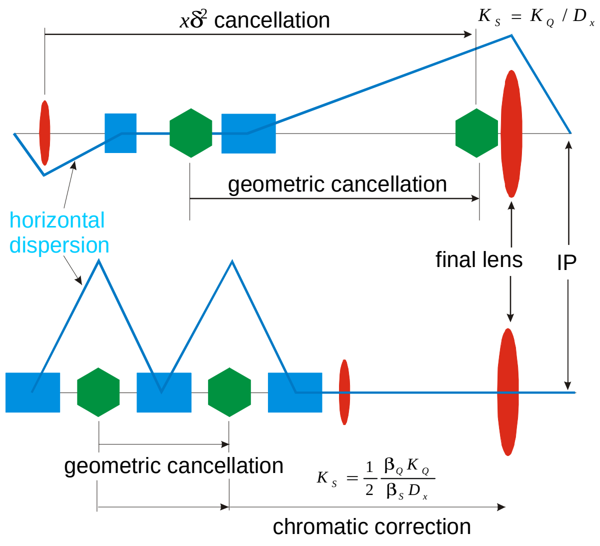

Fig. 1. Two FFS design concepts: (top) the compact local correction FFS and (bottom) the SLC/FFTB-style non-local correction system.

where δ_{RMS} is the RMS momentum spread of the beam, and σ^* is the *linear* RMS beam size at the IP. For our previous example $\beta / f = 3\times10^4$, and typical values for δ_{RMS} are on the order of 10^{-3}: hence the chromaticity of the FD would increase our 'nanobeams' by approximately a factor of 30 if left uncorrected.

The optics upstream of the FD have the following two requirements:

- they must produce the necessary 'parallel' beam (high β-function) at the FD; and
- supply the necessary chromatic correction.

Both requirements have a direct impact on the length of the FFS, which has cost implications (we would certainly like the FFS to be as short – and therefore as cheap – as possible). Chromatic correction is generally performed using sextupoles in a region of non-zero dispersion which requires dipole magnets; the tolerable bend angles are constrained by synchrotron radiation effects, especially at higher energies. Sextupoles introduce higher-order geometric and so-called chromo-geometric aberrations which must be delicately balanced by the lattice designer so as not to significantly increase the IP beam size.

Over the last fifteen years two approaches to the problem have been developed. They are shown conceptually in Fig. 1. The first proposal due to Brown [1] (Fig. 1 bottom) has been implemented in the SLAC Linear Collider (SLC) and later for the Final Focus Test Beam (FFTB) [2]. Demagnification is performed by a telescope system, which has point-to-point optics. Immediately upstream of the telescope is a dedicated chromatic correction section which consists of pairs of sextupoles so positioned that the linear phase space map between them is –*I*. Dipole magnets are then used to generate closed and symmetric high horizontal dispersion points at the sextupoles. The end result is an adding of the (required) chromatic terms and a cancelling of the (undesirable) geometric terms. The optics is so arranged that the sextupoles are at the same phase as the FD so that chromatic 'kick' they produce is exactly cancelled downstream by that of the FD. The required value of the integrated sextupole strengths[†] (K_{SX}) is approximately given by

$$K_{\text{SX}} \approx \frac{1}{2}\frac{\beta_{\text{FD}}}{\beta_{\text{SX}} D_x f_{\text{FD}}}$$

where β_{FD} and β_{SX} are the β-functions at the FD and sextupole respectively, D_x is the horizontal dispersion function at the sextupoles, and f_{FD} is the focal length of the FD. The factor of ½ comes from the fact that there are two sextupoles.

The advantages of the Brown approach lie in its modularity and ease of design. It is conceptually simple to understand and clear how the various aberrations cancel (at least the second-order terms). The very high degree of symmetry allows easy construction of *orthogonal* tuning knobs. In addition, it has been experimentally verified in two separate experiments.

Unfortunately, the concept suffers from several significant disadvantages:

- the separated functionality of the lattice (final telescope and dedicated chromatic correction sections) make the systems long (a few kilometres at centre-of-mass energies above a TeV);
- To keep the sextupole parameters reasonable, the chromatic correction sections also require relatively large β-functions and high dispersion functions, both of which increase the length of the system and result in tighter tolerances;
- the chromatic kick generated by the sextupoles must be transported over many quadrupoles before arriving at the FD where it is required; this *non-local* correction leads to the generation of high-order aberrations which ultimately limit the momentum acceptance (bandwidth) of the system.

An alternative solution has been proposed by Raimondi and Seryie [3] which addresses these issues (Fig. 1 top). The basic idea is to perform the FD chromatic correction *locally*, by arranging to have non-zero horizontal dispersion at the FD. Care must be taken that the IP dispersion is zero[‡]. The correction sextupole(s) can now be placed directly at the FD. The sextupole strength is given by

$$K_{\text{SX}} \approx \frac{1}{D_x f_{FD}}$$

where D_x is now the dispersion at the FD. The pure geometric terms from the sextupole must still be cancelled, and this requires a second sextupole upstream

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[†] we define the sextupole strength here as $\left(\partial^2 B_y / \partial x^2\right) / B\rho$, where *l* is the sextupole length, and $B\rho$ is the magnetic rigidity of the beam.

[‡] But clearly *D'* is not – however this does not affect the IP beam size, only the divergence.

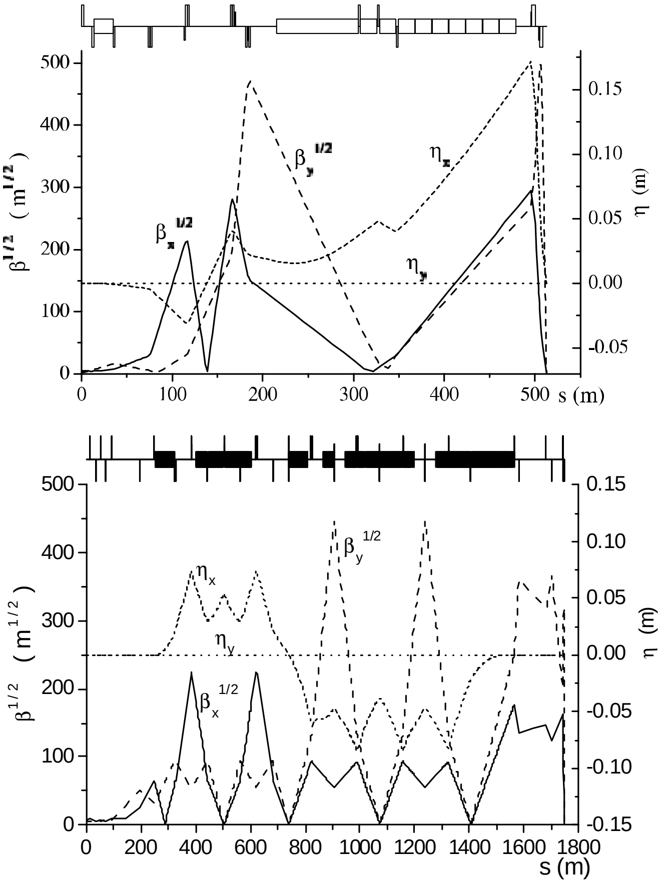

Fig 2. Examples of BDS lattices for the NLC: (top) the current compact local-correction design [3], and (bottom) the original SLC/FFTB-type non-local correction design[4]

at the same phase. The real trick to these systems is to cancel the second-order horizontal dispersion that is generated by the sextupole at the FD; this is generally achieved by careful placement of upstream quadrupoles in dispersive regions.

The primary advantage of the locally corrected system over the non-locally corrected one is its compactness. Fig. 2 shows the optics functions for original NLC SLC/FFTB-type system [4] and the new (current) compact system [3]. The length of the complete system was reduced from ~1750 m to little over 500 m. The second major advantage is bandwidth: the local correction of the FD chromaticity does not require the transport of the sextupole kicks and thus avoids the generation of the bandwidth limiting higher-order terms. As a result, the locally corrected system can accommodate (correct) a larger FD chromaticity, which allows us to increase the focal length and move the FD further out of the IR; this has many advantages for IR and detector design, including better detector background performance.

The system is not without its disadvantages however. Close examination of Fig. 2 shows the compactness and performance has been gained at the expense of the symmetry of the system. Generally speaking, the delicate balance of higher-order terms appears harder to achieve in the new system, and obtaining the necessary performance requires a great deal of skill (*and* experience) on the part of the lattice designer. In addition, unlike the non-locally corrected system, the compact system has not been experimentally demonstrated, although the need for such demonstrations is debatable. Despite these points, the advantages of the compact system over the non-local system seem so overwhelming, that the former has now replaced the latter as the system of choice for all linear collider designs (for an example, see [5]).

3 HALO COLLIMATION

The BDS also contains the post-linac beam halo collimation system. It is the job of the collimation system to remove that part of the beam halo which would otherwise cause intolerable detector backgrounds. This is achieved by physically intercepting the halo using mechanical ‘spoilers’, which are some fraction of a radiation length of material. Thick (>20 radiation lengths) absorbers judiciously placed downstream of the spoiler(s) collect the debris generated. Several sets of such ‘collimator’ systems are generally required. A primary system (so-called because it intercepts the primary high-energy halo particles) is located upstream of the FFS, while secondary ‘clean-up’ collimators are usually located in the FFS itself.

The optics design of the collimation system has many constraints:

- the apertures of the spoilers must be correctly chosen to optically ‘shadow’ the relevant apertures in the detector; the absolute value of the aperture depends on the local β-function at that point;
- the choice of aperture is also constrained by resistive wall and geometric wakefield effects, which can impact the core of the beam and therefore the luminosity
- the optics of the system should not adversely affect the bandwidth of the system for the core beam;
- spoilers and absorbers should be protected from a direct hit by the beam (machine protection issues).

These often conflicting constraints complicate the design of the system. The machine protection issue is a severe constraint on the design, especially when you consider that the typical instantaneous beam power densities are many GW/mm^2! For a spoiler to survive a direct hit from the beam, the beam sizes should be made large so that the spoiler material can survive. This generally requires β-functions of many kilometers, which make the systems long (cost!) and tend to drive tight tolerances on the magnet alignment. Large β-functions also tend to increase the transverse wakefield effects [6]. Such passively protected systems have so far proven untenable, and alternative (pragmatic) solutions such as the ‘consumable collimator’ approach currently proposed by the NLC [7] are being favoured. Work on non-linear collimation systems is also underway [8,9].

How tight the collimation has to be (i.e. how close to the core of the beam the apertures must be set) is determined by the geometry of the IR and the quads close to the IR (particularly the FD). The guiding principle is based on synchrotron radiation photons generated by the beam halo in the final quads: all photons generated by the *remaining* halo particles should pass cleanly through the IR[§]. This criterion defines a maximum allowed amplitude of particles at the entrance to the FD, which is referred to as the *collimation depth.* In terms on the nominal (design) core beam size, typical collimation depths are ~10σ_x by 40–80σ_y. If the beam transport system was purely linear, then it would be possible to set the apertures of the upstream spoilers (at the FD phase[**]) to the same gaps relative to the local linear beam sizes. However, non-linear effects (both chromatic and geometric) – which may have no influence on the core of the beam – can cause these relatively high-amplitude particles to re-populate the phase space outside of the collimation aperture. Edge scattering from the collimators themselves also reduces their efficiency. For these reasons, it is generally required to collimate tighter than the collimation depth[††].

To arrive at an optimal collimation system design requires many iterations between optics design and simulation. For the latter, ray tracing codes which include all the non-linear effects are needed for halo tracking. In addition, tools which include the material interaction (scattering and shower generation) are also required. A further set of tools for the study of muons generated by these interactions is also mandatory. In the past, most of these various aspects of the same design problem were dealt with by different simulation tools to various degrees of sophistication. There are now new tools becoming available which take an integrated approach (such as those codes based on GEANT4), which should allow far more sophisticated studies to be made. Two particular areas of simulation work that require attention are background tuning, and the effects of accelerator errors on the collimator efficiency; these important problems are only now just beginning to be addressed, and there is still much work to done.

For examples of current collimation system designs see [11,12,13].

4 STABILITY ISSUES

Maintaining 'nanobeams' in collision is a major technical challenge of these systems [14]. As with any *precision instrument*, care must be taken to stabilise the components or control the beam (or both) to acceptable levels. For the BDS (indeed for the entire collider), the worst case is that of the strong FD; here the parallel-to-point focusing immediately gives us a one-to-one correspondence between a transverse displacement of the quadrupoles and the offset of the beam at the IP. Hence the 'tolerance' on the FD motion (vibration) is on the order of a nanometer or less (in the vertical plane).

It is generally recognised that source of vibration (natural ground motion, accelerator sources etc.) are a major challenge to linear collider performance. There has been a great deal of effort over the last several years to characterise and model the effects of ground motion (see for example [15]). There are basically four approaches to dealing with the problem:

- passive mechanical stabilisation of components by clever design of supports;
- active damping of mechanical vibration using feedback;
- beam-based feedback to correct the resulting beam 'jitter';
- careful choice of site.

It is expected that a combination of some or all of the above will be required. The extensive use of beam-based feedback systems (orbit correction) is absolutely necessary (see for example [16]), particularly at the IP where a system using the strong beam-beam kick will be used to maintain the beams in collision [17,18]. When discussing feedback systems and their usefulness, it is necessary to discuss the frequency spectrum of the noise source and the response of the feedback system. In general, beam-based feedback systems strongly attenuate all frequencies below a certain cut-off f_{co}, a rule of thumb for which is $f_{co} \approx f_{rep}/10$, where f_{rep} is the repetition rate of the machine (the 'sampling' rate). This is particularly important when considering ground motion, which tends to have a power spectrum that falls of as f^{-4}; hence it is advantageous to have a high repetition rate. High-frequency (C and X band) collider designs all have $f_{rep} \approx 100-200\,\text{Hz}$, and so they effectively damp frequencies below 10–20 Hz[‡‡]. Even with the use of these feedback systems, the remaining RMS 'jitter' (with frequencies above f_{co}) may still be excessive, and mechanical stabilisation of the magnets will also be required. Stabilisation of the FD quadrupoles in a realistic 'detector' environment is an ongoing R&D program [19].

5 SUMMARY

The BDS of a linear collider serves several functions, the most important being (i) strong demagnification of the transverse beam sizes to produce the desired 'nanobeams' at the IP, and (ii) beam halo collimation. Strong demagnification is performed by the FFS and requires a careful lattice design where all second-order aberrations are cancelled, and the effects of third- and higher-order aberrations are minimised by careful choice of magnet placement (phase advance). Two design concepts for the

[§] see for example [10]

[**] The FD phase is the primary phase of interest. Collimation in the orthogonal phase is generally looser, but is still required.

[††] the non-linear collimation discussed in [8] actually allows the jaws to be opened wider than the collimation depth.

[‡‡] The TESLA proposal uses superconducting L band RF with a low repetition rate of 5 Hz. However, the bunch train is very long (~3000 bunches in ~1 ms) and beam based feedback can be performed within each train [15].

FFS exist: the older SLC/FFTB-type system which used separate dedicated chromatic corrections upstream of the final telescope providing a non-local chromaticity correction; and the newer compact system which utilises dispersion at the FD to make a local correction. The latter system is now the preferred solution, due to its compact length and significantly improved bandwidth properties, although the system appears more difficult to design and optimise than its predecessor.

The collimation systems are equally challenging. Collimation system design is a balance between several conflicting constraints (wakefield effects, system length, magnet tolerances and non-linear optical effects). Spoiler jaws must also be suitably protected from direct hit from the beam (or use of novel ideas such as 'consumable collimators' must be adopted). Design of the collimator systems relies heavily on complex simulations of the beam halo and its interaction with the apertures (spoilers). Modern software tools are now just becoming available to perform integrated studies of collimation performance, particular in the presence of machine errors and tuning.

Stability issues are at the very heart of the technical challenge for the BDS. Maintaining collisions between nanometer beams at the IP in the presence of magnet vibration (driven by both ground motion and mechanical systems) requires extensive use of state-of-the-art stabilisation techniques and beam-based feedback systems. Stabilisation of the worst-case FD to less than a nanometer above ~10 Hz will be required; achieving this in a realistic detector environment is the subject of several ongoing R&D programs.

Although in many ways the designs of BDS for the next generation of linear colliders are mature, there is certainly still room for improvement and new ideas. No doubt R&D in this technically challenging area will continue on all fronts for a few years to come.

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