High-Energy Muon Collider Workshop
Montauk 9/27 – 10/1 1999

10 – 100 – TeV (CoM) Collider Lattices

C. Johnstone
9/27/99

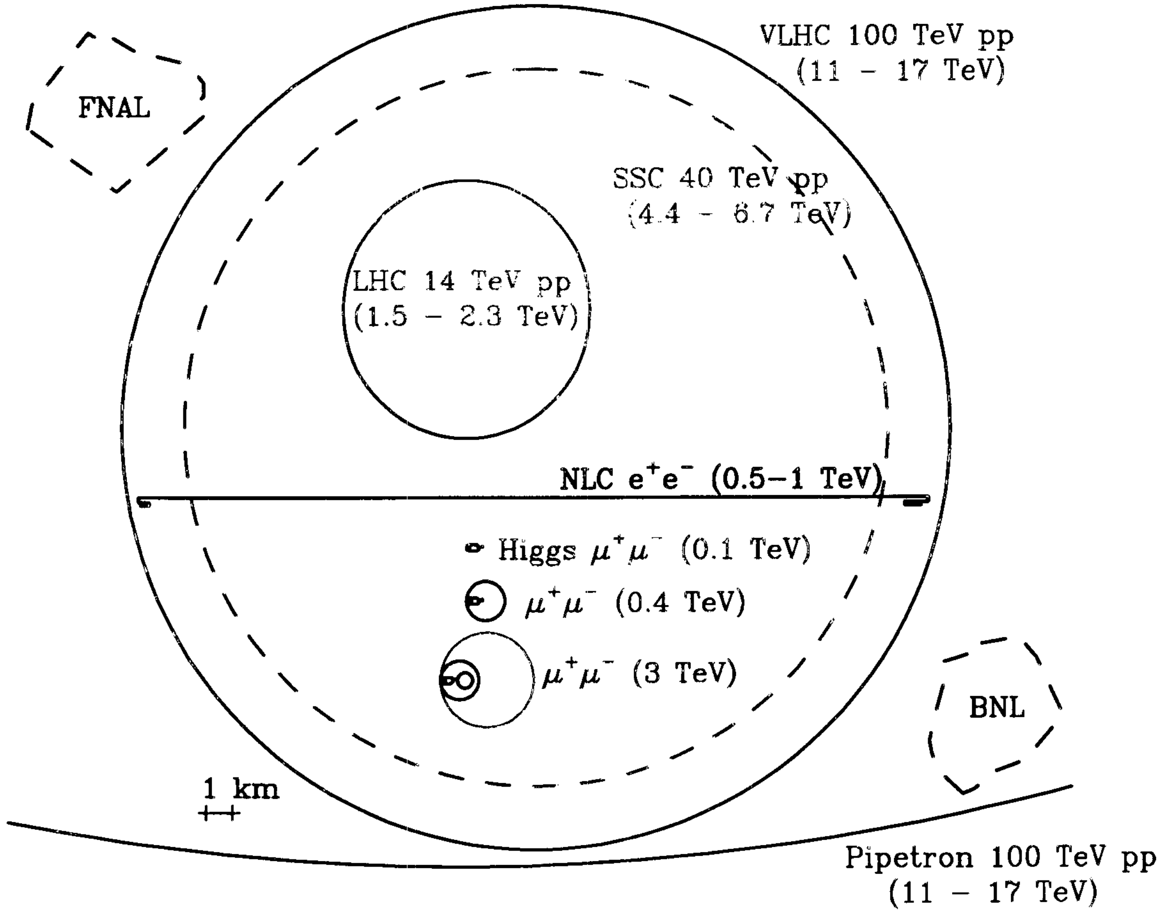


FIG. 1. Comparative sizes of various proposed high energy colliders compared with the FNAL and BNL sites. The energies in parentheses give for lepton colliders their CoM energies and for hadron colliders the approximate range of CoM energies attainable for hard parton-parton collisions.

producing a Higgs-like scalar particle in the s-channel (direct lepton-antilepton annihilation) is proportional to m^2, this extremely important process could be studied only at a muon collider and not at an e^+e^- collider [13]. Finally, the decaying muons will produce copious quantities of neutrinos. Even short straight sections in a muon-collider ring will result in neutrino beams several orders of magnitude higher in intensity than presently available, permitting greatly extended studies of neutrino oscillations, nucleon structure functions, the CKM matrix, and precise indirect measurements of the W-boson mass [14] (see section **II.I**).

The concept of muon colliders was introduced by G. I. Budker [2,3], and developed further by A. N. Skrinsky *et al.* [15–22] and D. Neuffer [13,23–25]. They pointed out the significant challenges in designing an accelerator complex that can make, accelerate, and collide μ^+ and μ^- bunches all within the muon lifetime of $2.2\,\mu$s ($c\tau$ = 659 m). A concerted study of a muon collider design has been underway in the U.S. since 1992 [26–42]. By the Sausalito workshop [30] in 1995 it was realized that with new ideas and modern technology, it may be feasible to make muon bunches containing a few times 10^{12} muons, compress their phase space and accelerate them up to the multi-TeV energy scale before more than about 3/4 of them have decayed. With careful design of the collider ring and shielding it appears possible to reduce to acceptable levels the backgrounds within the detector that arise from the very large flux of electrons produced in muon decays. These realizations led to an intense activity, which resulted in the muon-collider feasibility study report [43,44] prepared for the 1996 DPF/DPB Summer Study on High-Energy Physics (the Snowmass'96 workshop). Since then, the physics prospects at a muon collider have been studied extensively [45–47], and the potential physics program at a muon collider facility has been explored in workshops [39] and conferences [40].

Encouraged by further progress in developing the muon-collider concept, together with the growing interest and involvement of the high-energy-physics community, the *Muon Collider Collaboration* became a formal entity in May of 1997. The collaboration is led by an executive board with members from Brookhaven National Laboratory (BNL),

WHEN COMPARED TO PREVIOUS COLLIDERS,
multi TeV high luminosity
THE NLC beam PARAMETERS AND

TOLERANCES ENTER A DISTINCTLY NEW

REGIME

Zeroth-Order Design Report for the

Next Linear Collider, Vol II, pg. 661

STRINGENT TOLERANCES, ULTRA SENSITIVITY TO ERRORS

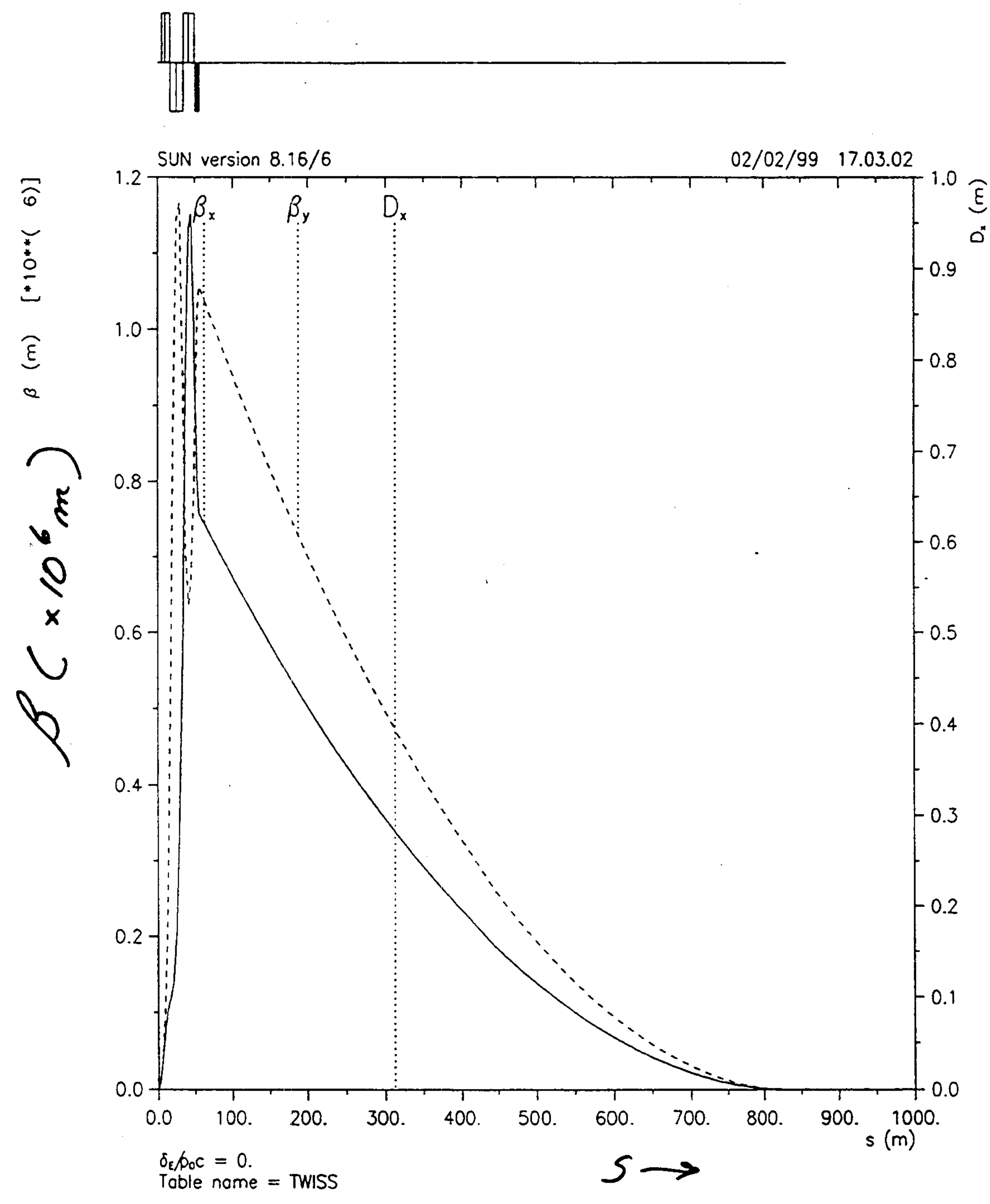
→ Small Spot Sizes @ IP : FINITE MOMENTUM widths

	NLC (> 1 TeV)	10-TeV	100-TeV
spot size vertical	200-250 nm	1.3 μm	.21 μm
spot size horizontal	3-5 nm	1.3 μm	.21 μm
dp/p (rms)	.3 %	.6 %	.1 %
Demag-nification	3×10^4	2×10^4	3×10^5

PRESENT-day accelerators (LHC/TEVATRON) have demagnifications $\sim 10^2$, tolerances 10^{-3} m, .1% field quality

→ 10-TeV μ COLLIDER is comprable to the NLC ; 100-TeV ~ order of magnitude more difficult.

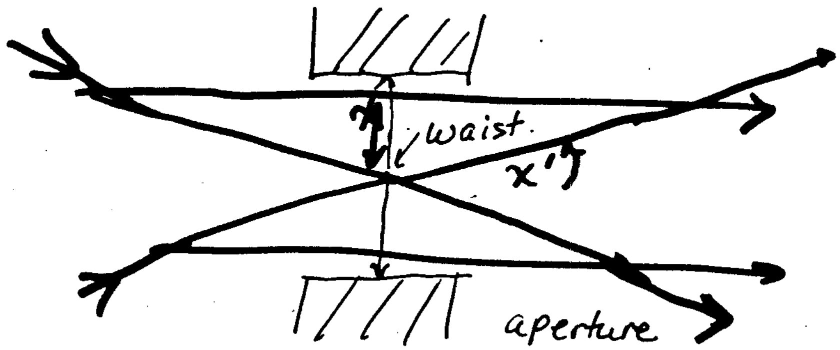
NLC tolerances: $10^{-4} - 10^{-5}$

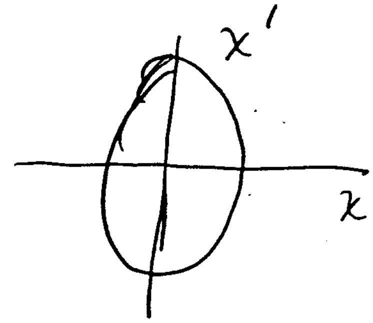


SUN version 8.16/6
02/02/99 17.03.02
β (m) [*10**(6)]
β (× 10⁶ m)
D_x (m)
β_x
β_y
D_x
s (m)
S →
δ_E/p_0c = 0.
Table name = TWISS

BEAM DISTRIBUTION, MAGNETIC OPTICS

→ certain beam acceptance characteristic of magnetic optics which is preserved as the particles propagate through the lattice





describe a beam distribution x, x', y, y'
their product is the phase space area or emittance

Propagation of the beam, the linear transformation, is independent of x, x', y, y' OR phase space area.

Instead a lattice is described in an independent set of coordinates:

$\beta_x, \alpha_x, \beta_y, \alpha_y$ + COURANT-Snyder parameters
which give linear beam properties at ANY point in the lattice for ANY emittance

CONVENTIONAL IR DESIGN

TO ACHIEVE A SPECIFIED LUMINOSITY (given the INCOMING BEAM emittance & # PARTICLES) means fixing the spot size or β^*

The entire IR design revolves around the choice of β^* — at least with conventional magnets.

Two types of IR telescopes

~ pt. to parallel

pt. to pt.

with focussing done by the "high-β" quadrupoles; their focussing strength ultimately being determined by technology (poletip fields) and the beam divergence (x', y') which goes as $\sqrt{\epsilon/\beta^*}$.

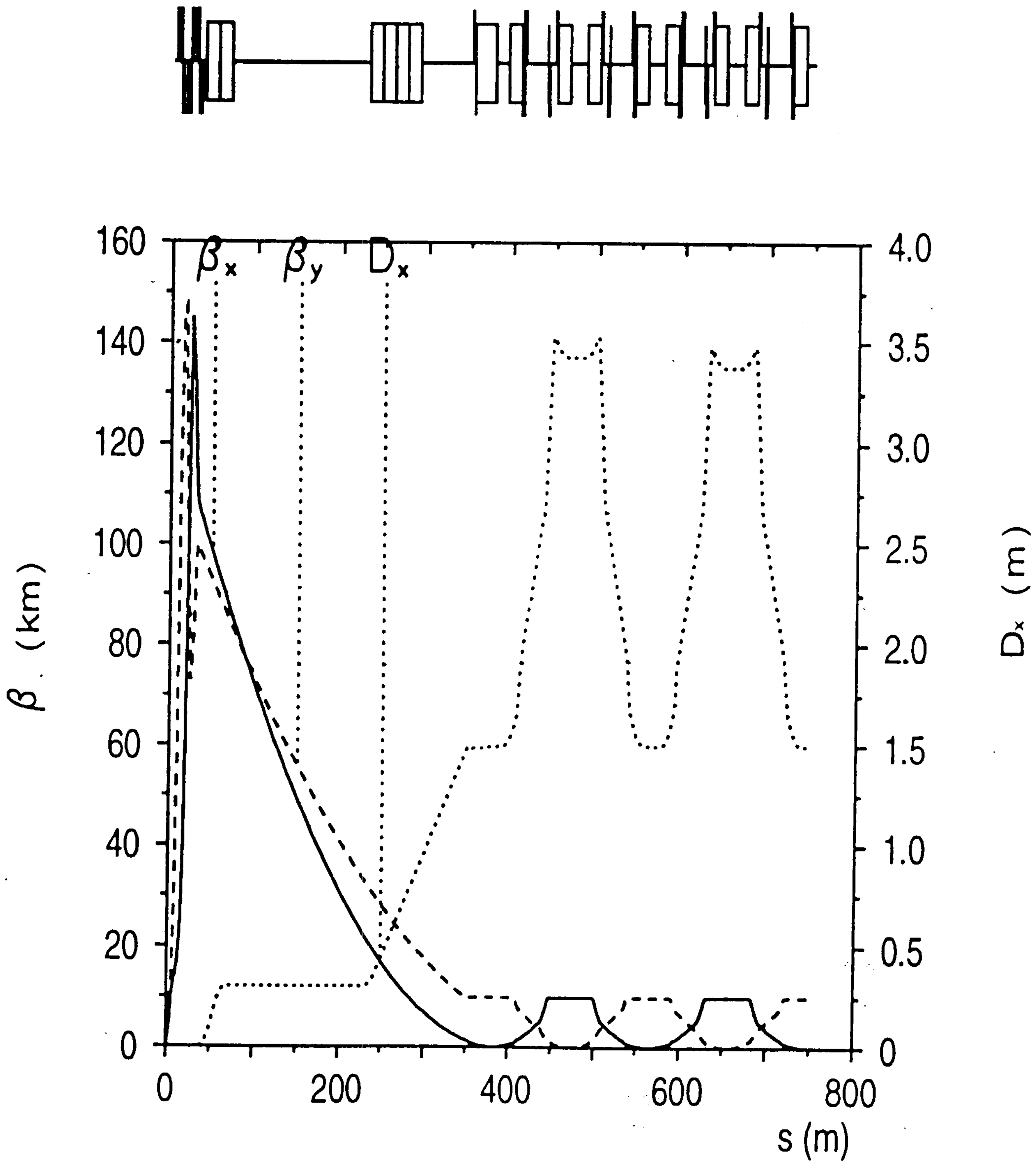


Figure 1: 3-TeV IR and Chromatic Correction

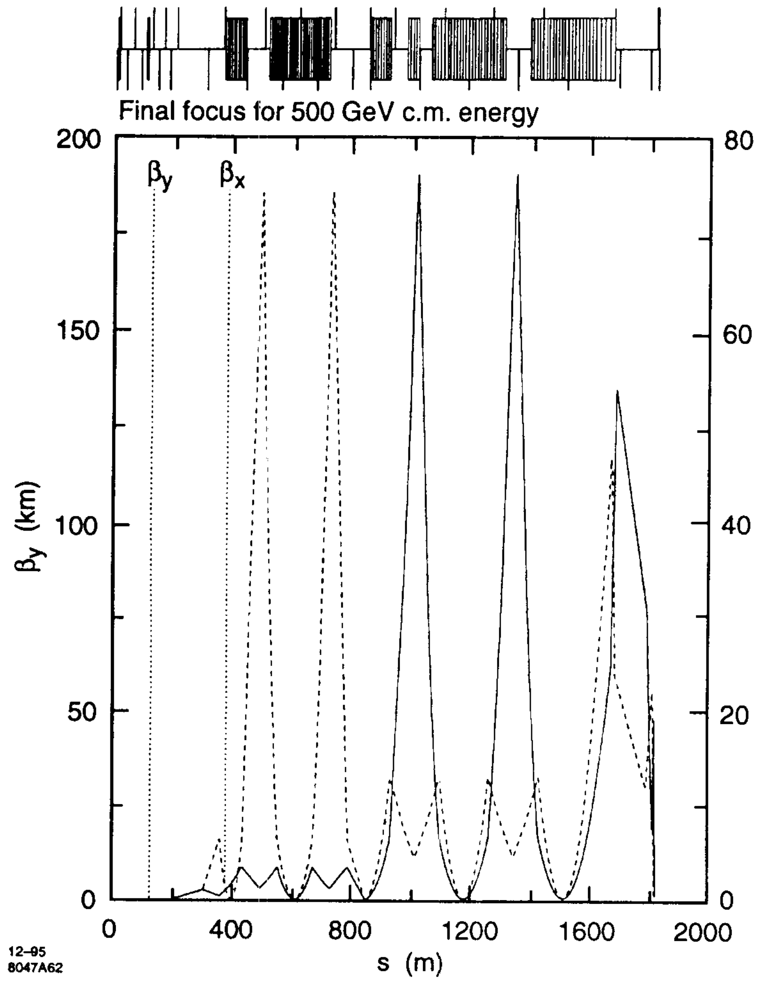


Figure 11-8. *Horizontal and vertical beta functions from BMS to IP, for the 500-GeV final focus.*

to allow matching of the betatron phase advance between the collimator section and the IP. These two new quadrupoles and the accompanying minor optics change of the BMS are not included in the following discussion.

The optics at 1-TeV-c.m. energy is almost the same as that for 500 GeV. Again assuming the parameters of Table 11-4 (Case IIa), the peak values of horizontal and vertical beta functions at the CCX sextupoles are 60 km and 190 km, respectively.

The upper part of Figure 11-8 indicates that more than half of the final focus is occupied by about 100 bending magnets. These magnets generate the dispersion required for chromatic correction. Their maximum field at 1-TeV-c.m. energy is only 160 G, in order to restrict the emittance growth due to synchrotron radiation. The length of the entire system, the maximum beta functions, and the maximum dispersion (hence the bending angles) were optimized for the original design parameters, not only with regard to the effect of synchrotron radiation, but also with regard to nonlinear aberrations, magnet-vibration and field-ripple tolerances. The optimization procedure is discussed in the next section, and in [Zimmermann 1995].

WHY are low β^* IRs so difficult?

* Beams are not monochromatic
  — focal length changes as a function of momentum ⊕ other chromatic aberrations which blur and move the IP beam spot.

Off-momentum behavior of the IR is characterized, to lowest order, by a term called chromaticity

$$\Delta\nu = \xi \, dp/p$$

↑ phase advance change

A change in phase advance always implies a deviation in the path of the particle.

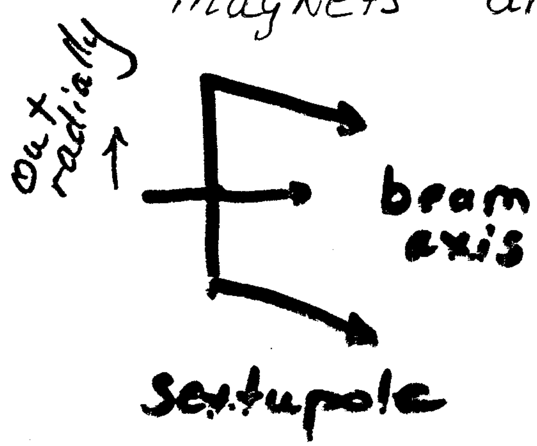
CONTROLLING path deviations ~~from~~ relative to the fixed point or central trajectory is the art of IR design.

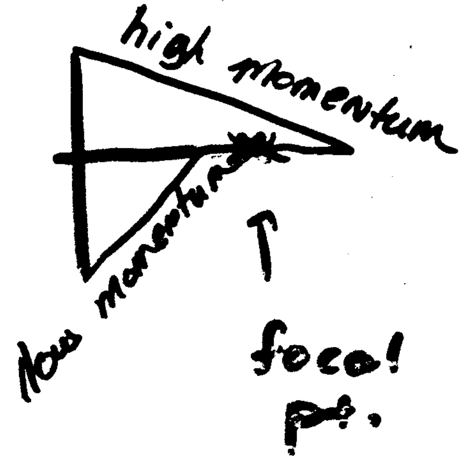
(biggest source are the strong-focussing high-β telescope quads.)

CHROMATIC CORRECTION

Chromatic correction is achieved by increasing the focussing at high momentum and decreasing it for low momentum

To do this one first disperses momenta in the radial direction using bend magnets and then, at the high dispersion points, sextupole magnets are introduced.



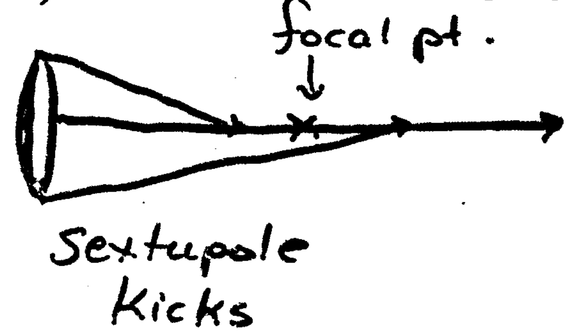


Standard chromatic corrections are usually distributed globally about the ring. - These intenge local sources of chromaticity must be corrected immediately using a special chromatic correction section appended to the IR.

Rule of Lattice Design:

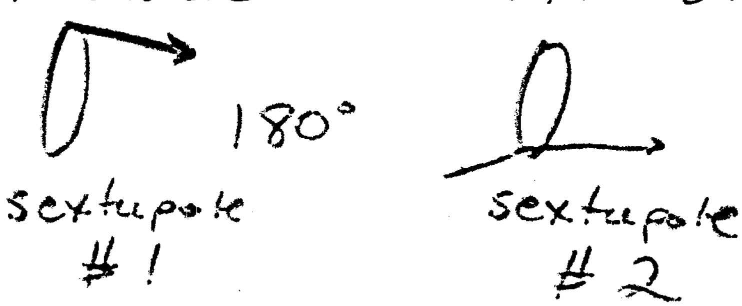
Corrections ~~Create~~ Beget More Correction

Beams have finite transverse sizes, ⇒ kicking on-momentum particle, for example, is inevitable



this is known as — tuneshift with amplitude
(proportional to β & sextupole stren

Now, (to 1st & 2nd order) sextupoles can be paired at 180° phase advance to eliminate tuneshifts with amplitude



Cancellation works only over a limited range — strong nonlinear terms (large emittances OR large deviations in momentum) change the phase advance. Conclusion is that these lattices will require a dedicated tuneshift with amplitude correction section

SAMPLING OF special SECTIONS needed to support an IR with high chromaticities
→ stealing NLC nomenclatu[re]

Skew Quadrupole Correction System

— measure + correct anomalous cross-plane coupling

Diagnostics Section

— emittance measurements to specify the match into final focus

Geometry Adjusting Section

— steering for proper collision

Beta and Phase Matching Section

— precise match of beam into final focus

(*) **Tuneshift with Amplitude + other High-Order Corrections**

Horizontal and Vertical Chromatic Correction

Final Focus Telescope

IP finally

? For large divergences, kinematical correction section?

This is an accelerator physicists dream machine, but is it a workhorse?

(*) NOT NEEDED IN A LINEAR COLLIDER

CHROMATICITIES −1500 ÷ −2000 → −6500 ÷ −10,200

JUST BASED ON CHROMATICITIES
(providing a CCS can be efficiently designed)

DA ~ 1 σ about the

central momentum using a conventional IR design

WHAT CAN WE DO?

→ Lithium lenses (perfect if can take the beam)

→ Dynamical focussing using particle beams (Irwin, Chen)

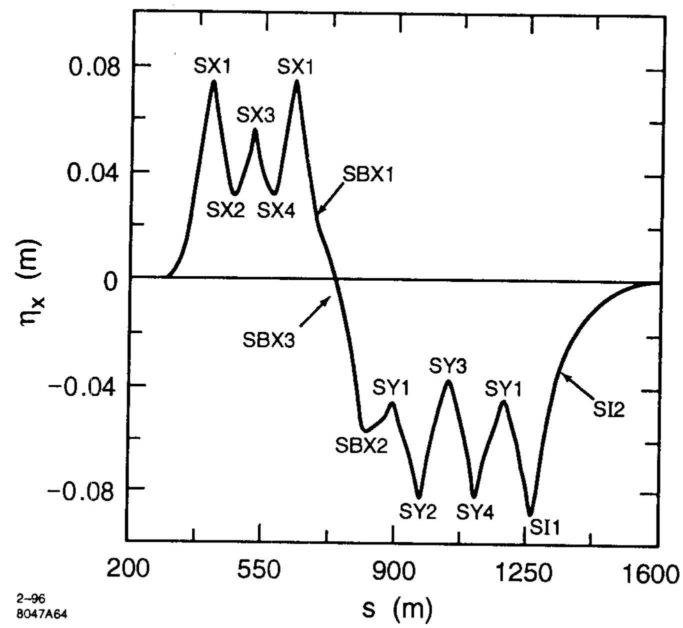


Figure 11-11. *Sextupole locations and dispersion for the 1-TeV design.*

The 44 quadrupoles between the BMS and IP are typically 0.5-m long, and, for 1-TeV-c.m. energy, their pole-tip field is 3–5 kGauss. A few magnets, with larger apertures, require pole-tip fields of about 8 kGauss. The final focus also comprises between seven and 16 sextupoles which cancel chromatic aberrations. First, there are two conventional $-I$ sextupole pairs located in the chromatic correction sections. These are used to compensate the first-order chromaticity of the system. In addition, between three and 12 weaker sextupoles are interspersed in the GAS, CCX, BX, CCY, and FT; all at positions with nonzero dispersion. The sextupole locations and the dispersion function for the 1-TeV final focus are illustrated in Figure 11-11.

The sextupole strengths are determined from tracking to optimize the momentum bandwidth of the system. This application of sextupoles for bandwidth-optimization was first proposed by Brinkmann at DESY [Brinkmann 1990]. Similar to Brinkmann's early results, the momentum bandwidth of the NLC final focus is at least doubled by means of the additional sextupoles. This beneficial effect of Brinkmann-sextupoles is explained by a reduced chromatic breakdown of the $-I$ sections between the main sextupoles and also of the FT: a Taylor-map analysis of the final-focus optics reveals a significant reduction of fifth-order chromo-geometric aberrations due to the additional sextupoles (Section 11.5.3).

Optimization

The length of the 1.5-TeV final-focus system was originally optimized with regard to nonlinear aberrations, such as third-order horizontal and vertical chromaticity, and chromo-geometric terms with generator $x'^2 y'^2 \delta$, and also with regard to the effect of synchrotron radiation in the bending magnets, octupole-like aberrations from long sextupoles, magnet vibration tolerances inside the CCY, and power-supply ripple. A general optimization procedure is described in [Zimmermann 1995], and is a modified version of an earlier proposal by Irwin [Irwin 1991]. Some specific side-constraints for the actual design are not included in this optimization

Working Group Subjects

General Interest

* radiation → site selection

Lattice Design topics (no particular order)

general high-order correction section *
isochronicity
fringe fields → large aperture magnets
scraping / extraction
beam dynamical parameters - constraints
on Δp, x', y', x, y?
image points of IP
diagnostic
error tolerances
kinematical corrections

Nonconventional final focus techniques → designs

* implications for cooling scenarios