CLIC Beam Delivery System

(1) Parameters & Perspective

(2) Final Focus

– Goal, Layout, Constraints, Options

(3) Collimation

– Requirements & Problems

(4) IP Region and Exit Line

– Spent Beam, Debris, Crossing Angle

(1) Parameters & Perspective

parameter	symbol	SLC	NLC	CLIC
c.m. energy [TeV]	E	**0.1**	1	**3**
luminosity [10^{34} cm^{-2} s^{-1}]	L	**0.0002**	1.3	**10**
repetition rate [Hz]	f_{rep}	120	120	100
bunch charge [10^{10}]	N_b	3.7	1	0.4
bunches/rf pulse	n_b	1	95	154
bunch separation [ns]	Δ_b	—	2.8/1.4	0.67
av. beam power [MW]	P_b	0.04	9	14.8

parameter	symbol	SLC	NLC	CLIC
IP hor. emittance [μm]	$\gamma\epsilon_x$	**50**	4.5	**0.68**
IP vert. emittance [μm]	$\gamma\epsilon_y$	**8**	0.1	**0.02**
hor. beta [mm]	β_x^*	2.8	12	8
vert. beta [mm]	β_y^*	1.5	0.15	0.15
hor. spot size [nm]	σ_x^*	**1700**†	235	**43**
vert. spot size [nm]	σ_y^*	**900**†	4	**1.0**
bunch length [mm]	σ_z	1	0.12	0.03
Upsilon	Υ	2×10^{-3}	0.3	**8.1**
pinch enhancement	H_D	2.0	1.45	2.24
beamstrahlung	δ_B [%]	**0.06**	10	**31**
photons per e^- (e^+)	N_γ	1	1.4	2.3

† 1998 average value

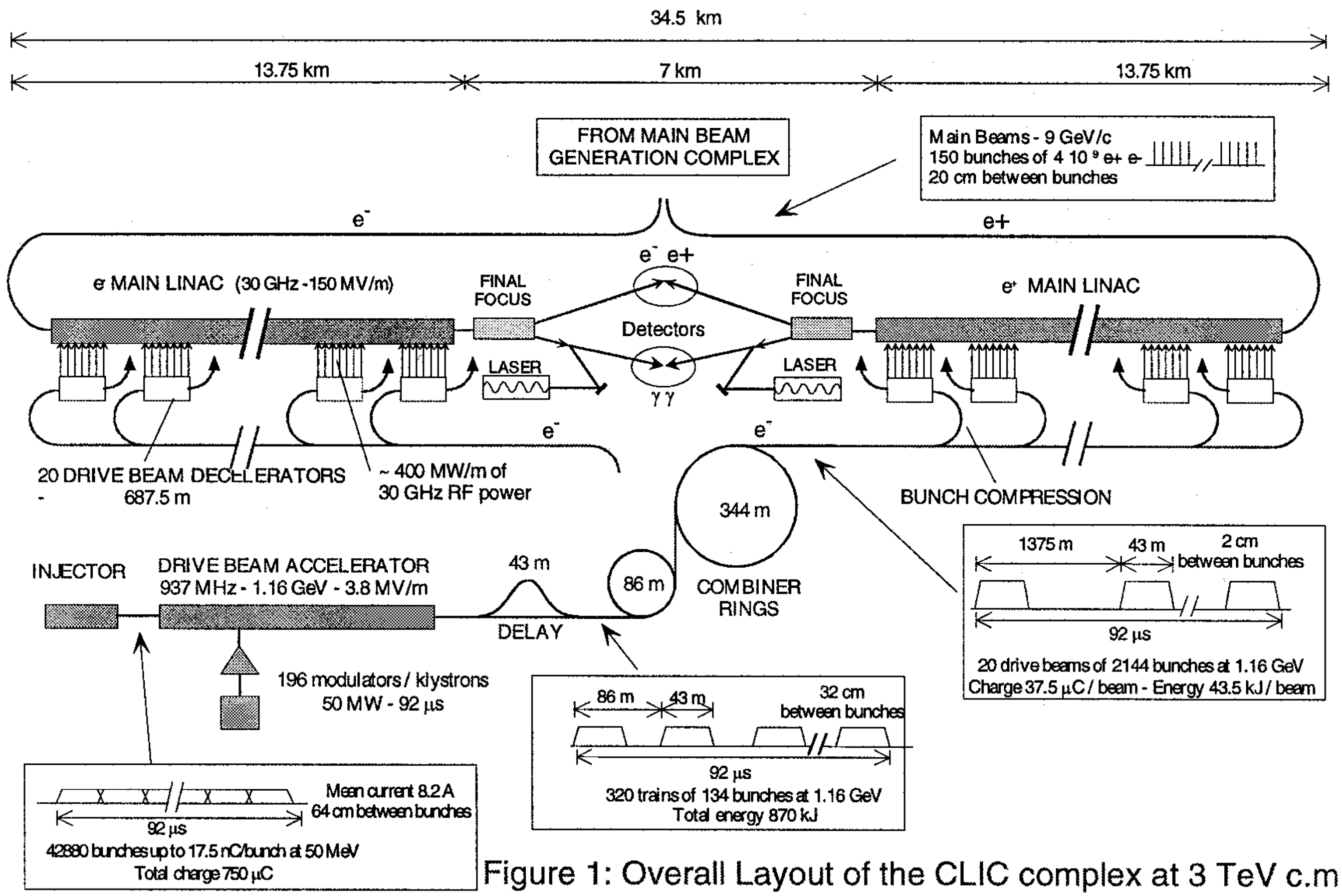
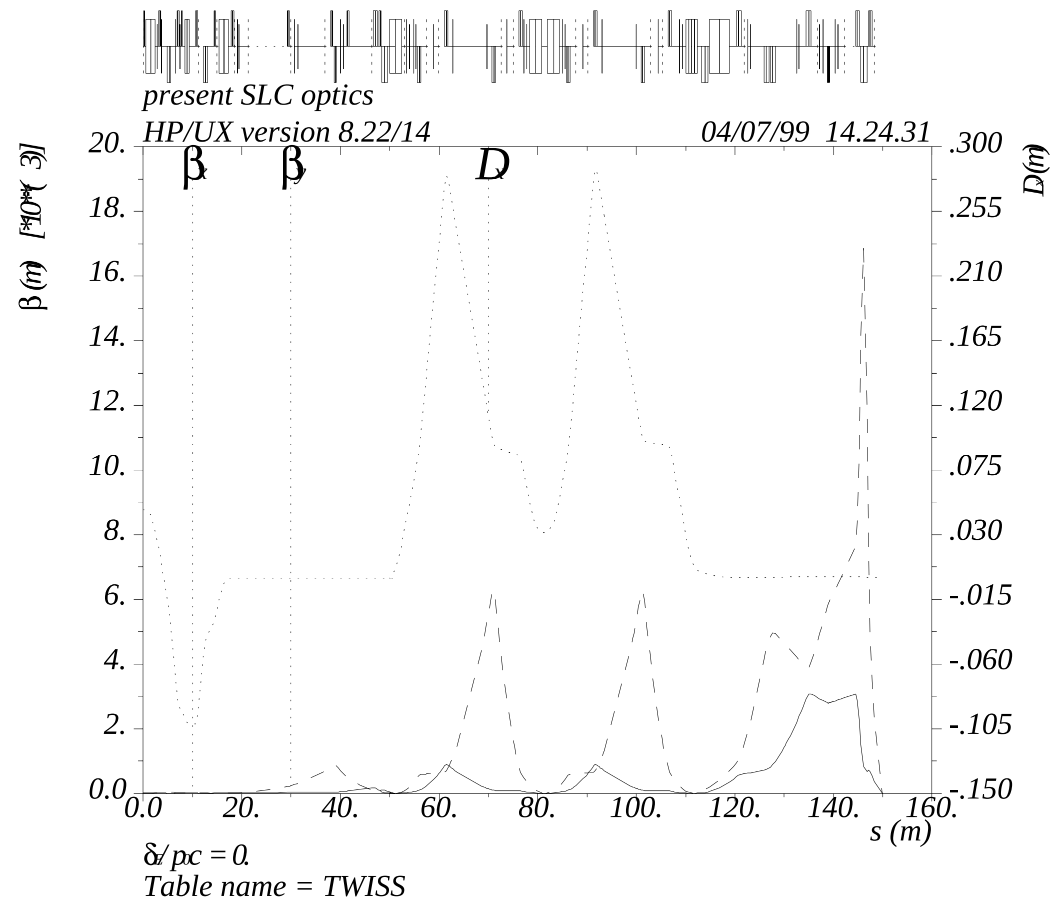
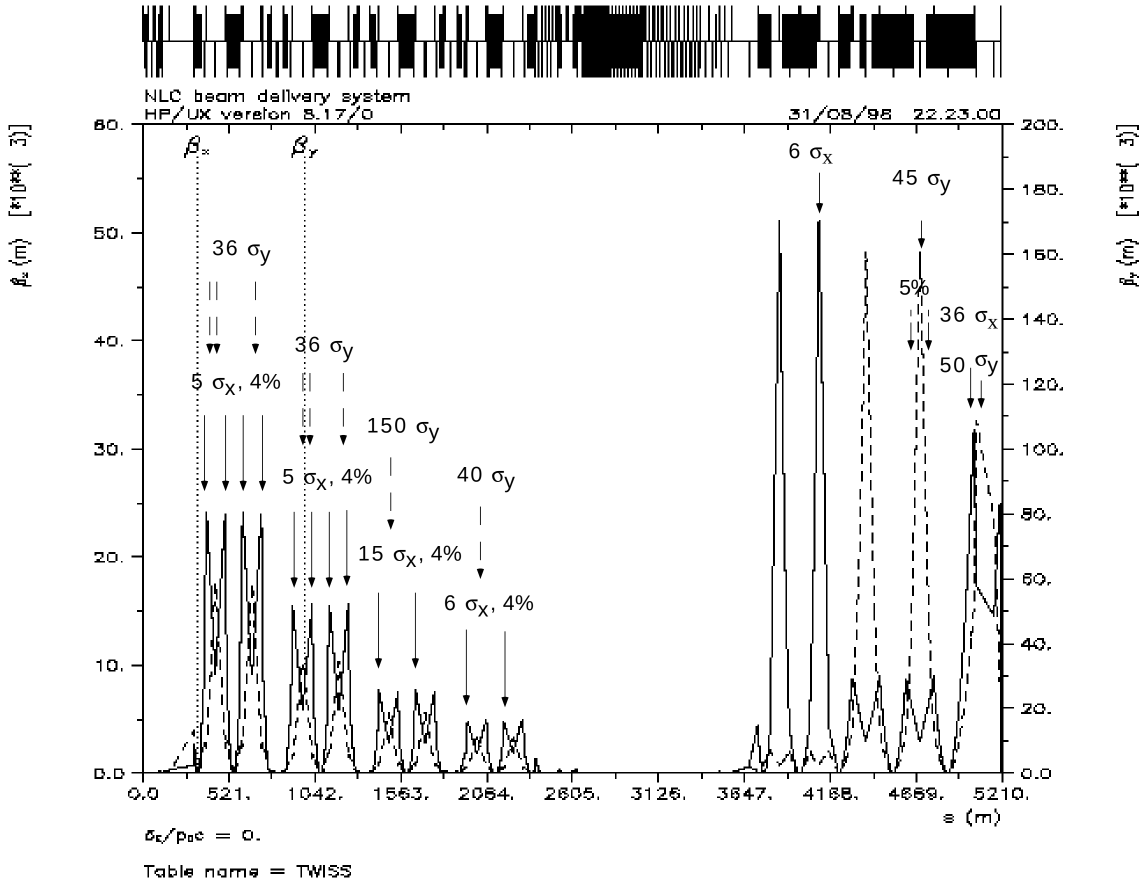


Figure 1: Overall Layout of the CLIC complex at 3 TeV c.m.

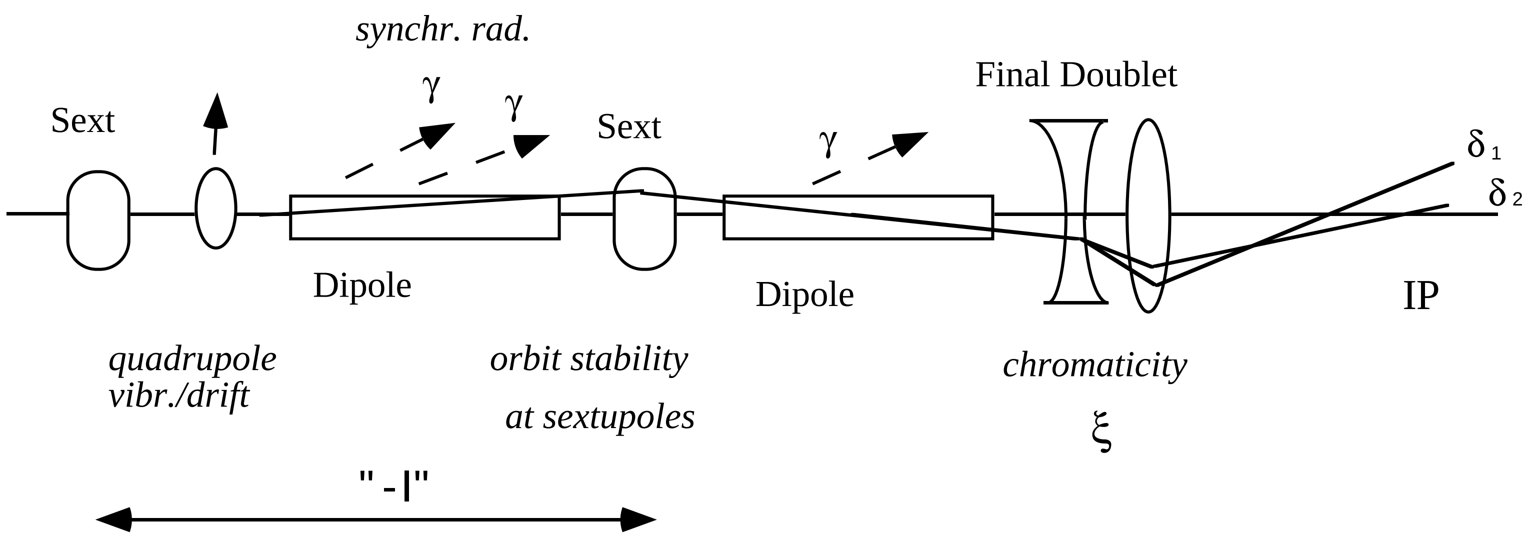


Optics of the SLC beam delivery system for 50-GeV beam energy. Total length (per side) is 150 m.



Optics of the NLC beam delivery system for 500-GeV maximum beam energy. Total length (per side) is 5 km.

(2) Final Focus



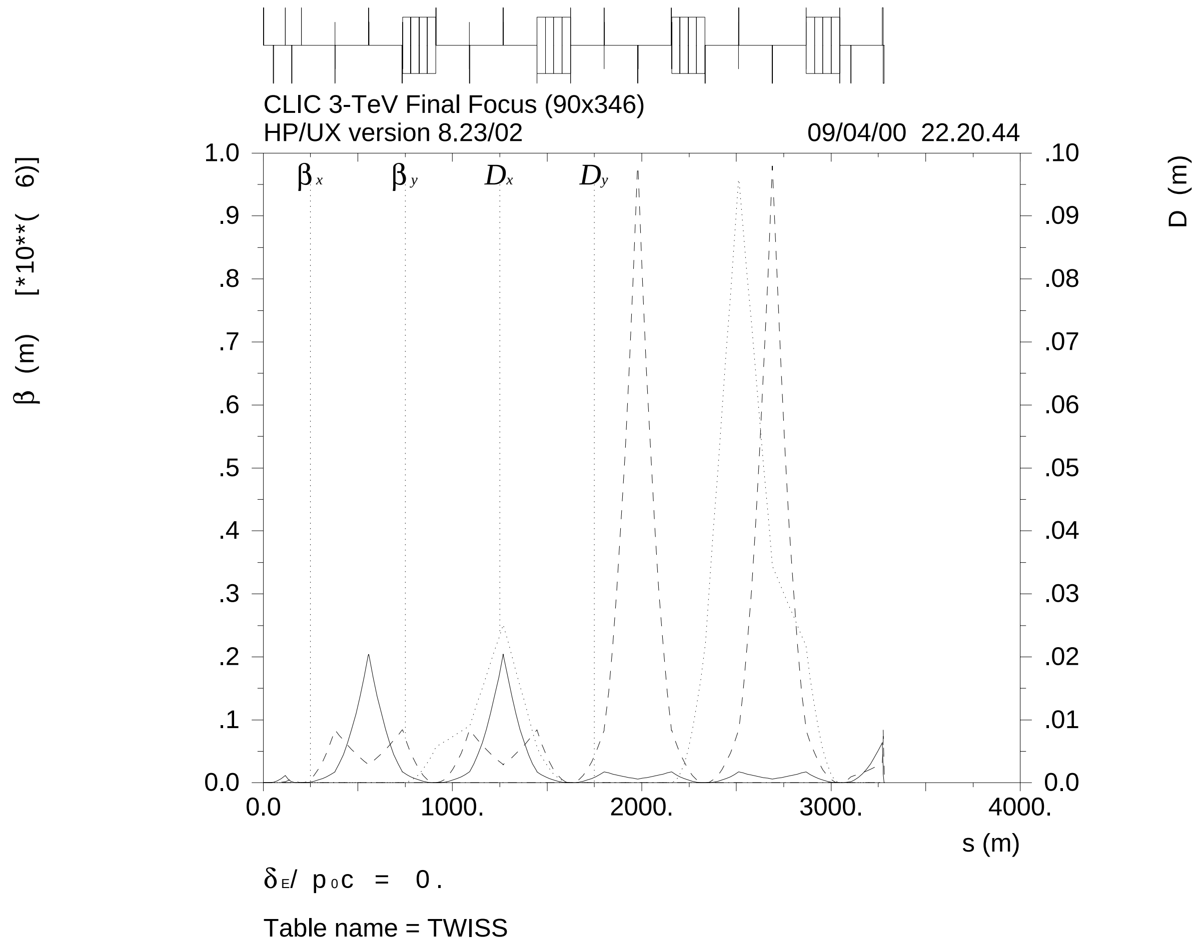
Schematic of a conventional final focus.

Approaches

- 4 sextupoles for chromatic correction; standard arrangement: SX1, SX2, SY1, SY2, with $-I$ transform between the two horizontal and the two vertical sextupoles.
- interleaved sextupoles (SLC): SX1, SY1, SX2, SY3; saves space, more aberrations.
- Oide's odd dispersion scheme: standard sequence, but η_x only at SX2 and SY2. Advantages: fewer bends and less aberrations.
- Brinkmann sextupoles, to compensate for the chromatic breakdown of the $-I$.
- Raimondi scheme: η'_x at the IP, and sextupoles near final doublet, extremly compact, tuning more difficult?
- rf quadrupoles: use correlation of energy and z within bunch; if addition to conventional scheme, rf dipoles are also needed, to bump the orbit across the sextupoles.

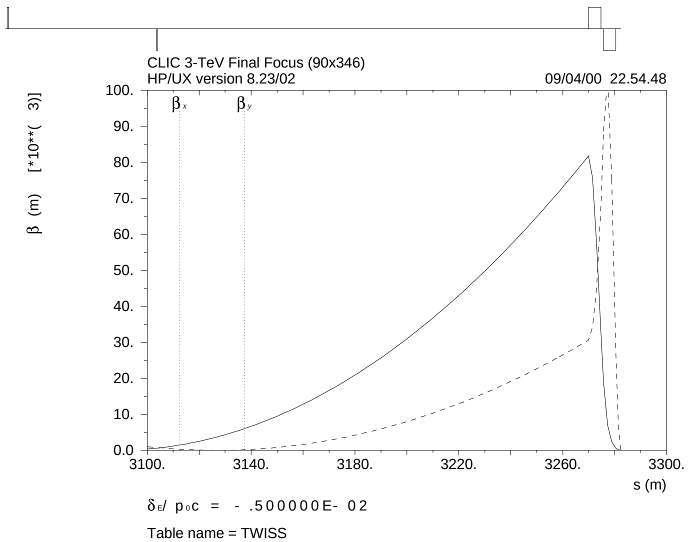
Draft Optics

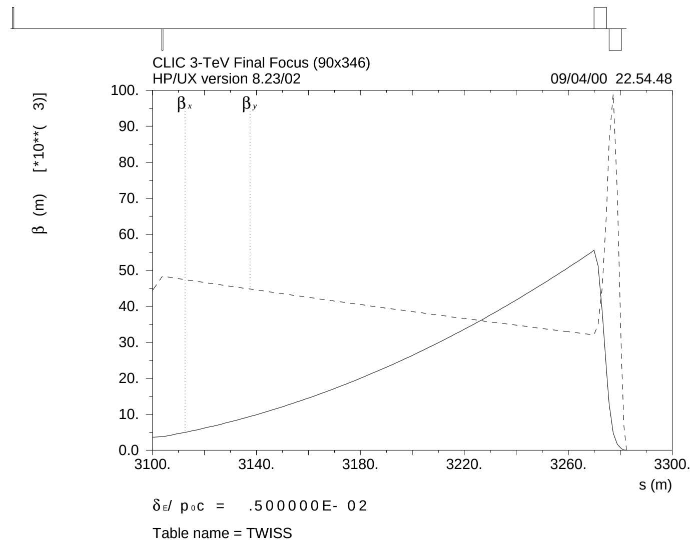
- baseline design, aided by FFADA code and O. Napoly
- beta match, chromatic correction (CCX, CCY) and final transformer, total demagnification factor 90/346, initial $\beta_{x,y} \sim 65,\ 18$ m
- odd-dispersion scheme à la Oide → fewer dipoles, larger bandwidth
- final-quadrupole gradient: 450 T/m, extrapolating from LHC magnet design: 320 T/m & 35 mm 1/2 inner radius
- trade-off between Oide effect (→ large ξ_x) and chromatic bandwidth (→ small ξ_x)
- vary bending/drift lengths, ratio vertical/horizontal bending angle, strength of final-doublet quadrupoles, Brinkmann sextupoles,... for optimum luminosity with 1% flat energy spread



Final-focus optics: beta functions and (odd) dispersion.

Chromatics: $d\beta/d\delta$



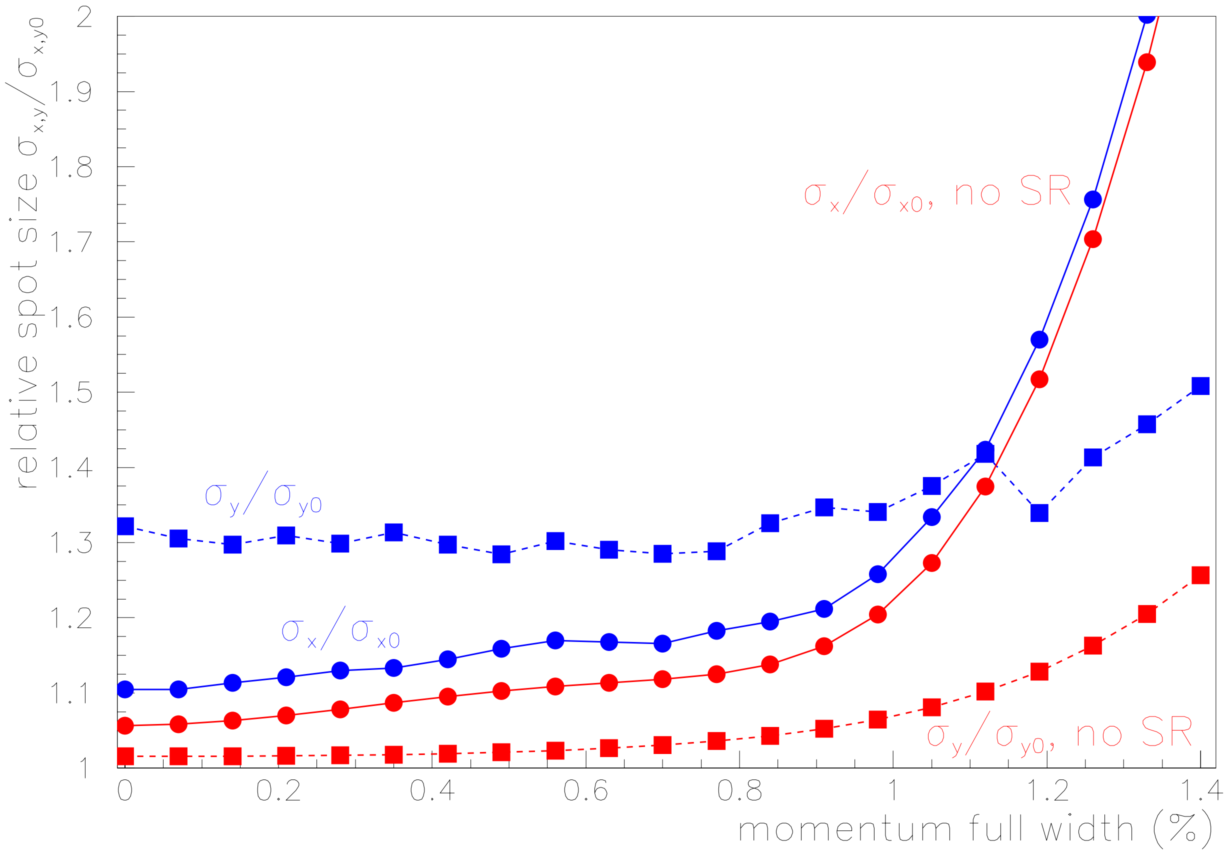


Final-telescope optics for energy offsets of -0.5% and $+0.5\%$.

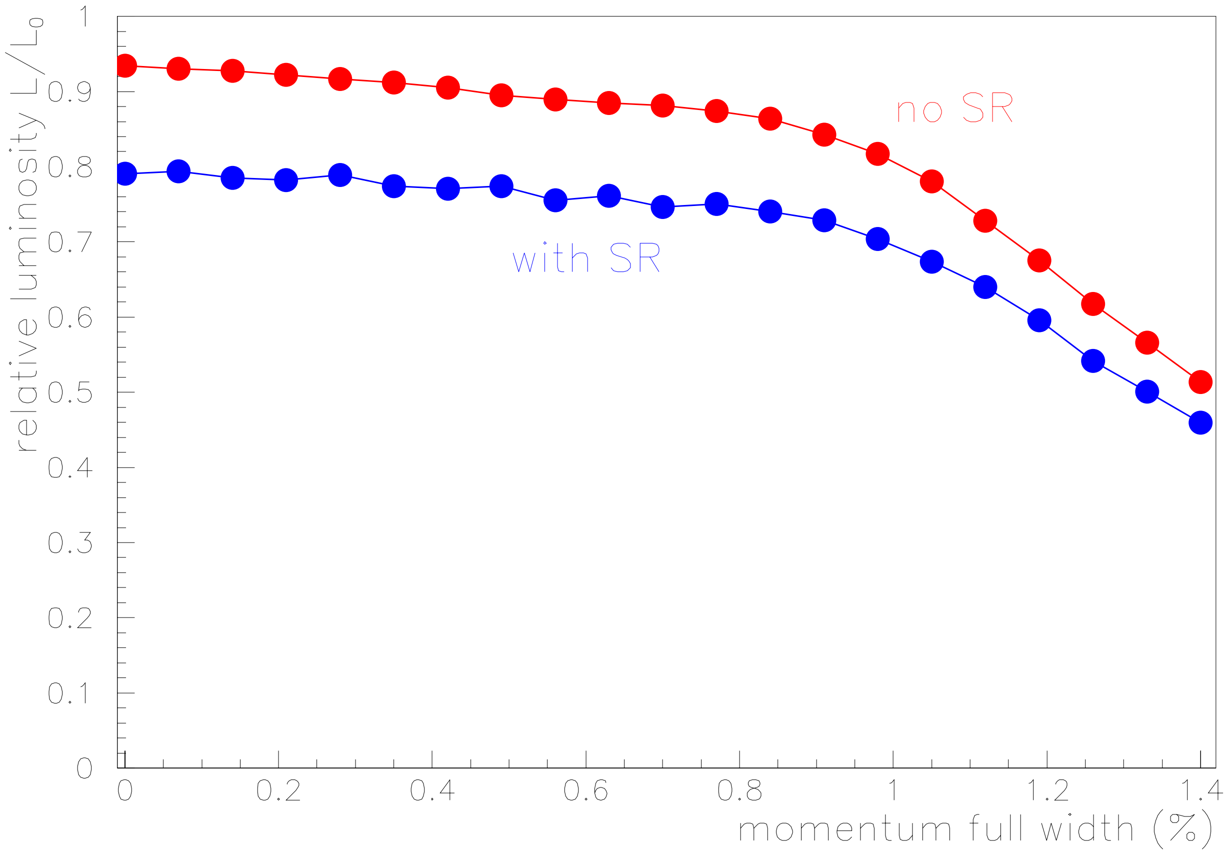
Final-focus characteristics

total length (per side)	3282 m
demagnification factor $M_{x,y}$	90, 346
IP beta functions $\beta^*_{x,y}$	8, 0.15 mm
FT chromaticity $\xi_{x,y}$	6900, 27000†
bending length	4×176 m
angle per dipole section	63, 230 μrad
final quadrupole gradient	450 T/m
beta function $\hat{\beta}_y$ at CCY sextupoles	1000 km†
peak dispersion η_x in CCY	0.1 m†
beta functions $\beta_{x,y}$ at entrance to final quad	15, 88 km

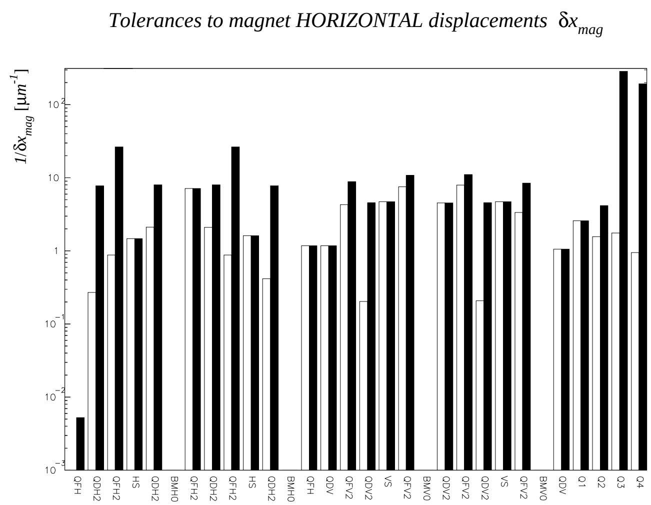
† NLC: $\xi_x \approx 7000$, $\xi_y \approx 30000$, $\hat{\beta}_y \approx 200$ km, $\eta_x \approx 0.1$ m

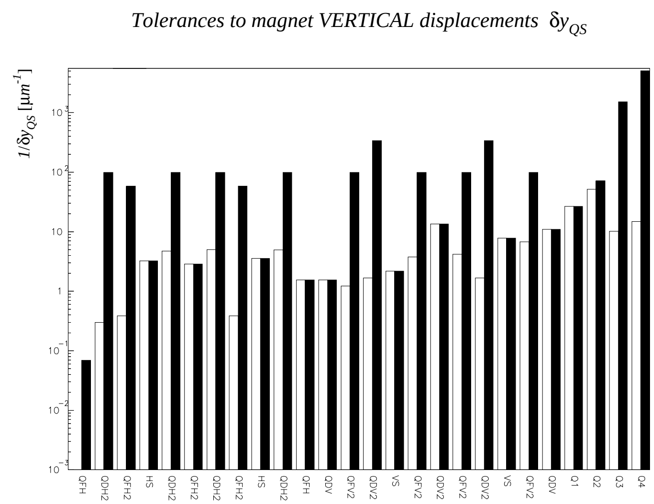


Relative rms spot sizes versus the full energy spread for a flat distribution. Design spot sizes: $\sigma_{x0} = 43$ nm, $\sigma_{y0} = 1.0$ nm.

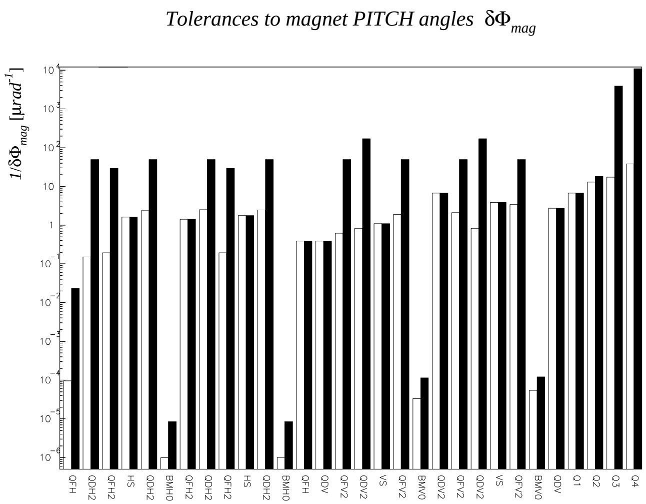


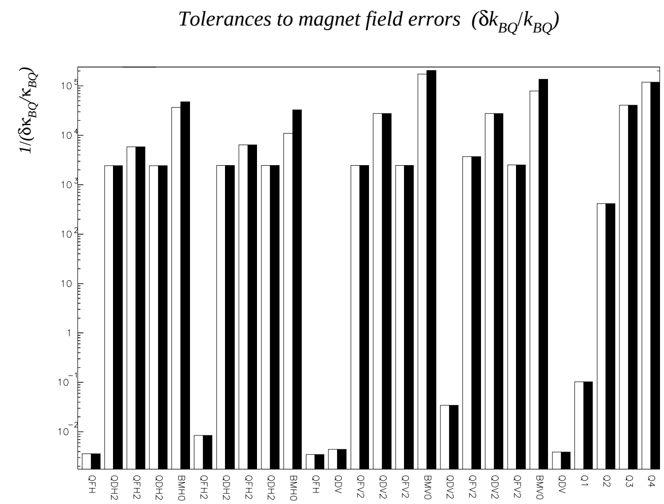
Relative luminosity (from tracking & convolving) vs. energy spread.
Ideal luminosity w/o pinch: $L_0 = 4.6 \times 10^{34}$ cm^{-2}s^{-1}.





Displacement sensitivities for 2% luminosity loss, calc. with FFADA.
The tightest jitter tolerances are about 3 nm (x) and 0.2 nm (y).
Drift tolerances are of the order of 100 nm.





Sensitivities to pitch angle (left) and relative field change $\Delta k_{BQ}/k_{BQ}$ (right), again calculated with FFADA. The tightest pitch angle tolerance is 0.1 nrad for the final quadrupole. Field stability tolerances are about 10^{-5}.

(3) Collimation System

2 functions: halo removal & machine protection

major problem: collimator survival for bunch train impact

$$\sigma_{UTS} > \frac{\alpha E}{C_p} \frac{d\mathcal{E}}{dm}$$

with σ_{UTS} ultimate tensile strength, α linear thermal expansion coefficient, C heat capacity, E elastic modulus, $d\mathcal{E}/dm$ energy loss per g material. Rewrite this as

$$\sigma_x \sigma_y > \frac{\alpha E}{\sigma_{UTS} C_p} \frac{d\mathcal{E}}{dx} \left(\frac{n_b N_b}{2\pi} \right)$$

E.g., copper, $\alpha = 1.7 \times 10^{-5}$ K^{-1}, $E = 120$ GPa, $C_p = 0.385$ Jg^{-1}K^{-1}, $d\mathcal{E}/dx \approx 1.44$ MeV cm^2/g, $\sigma_{UTS} = 300$ MPa:

$$(\sigma_x \sigma_y)^{1/2} > 200\ \mu\text{m} \quad \text{or} \quad \beta_{x,y} \geq 1000\ \text{km}$$

Collimator Materials

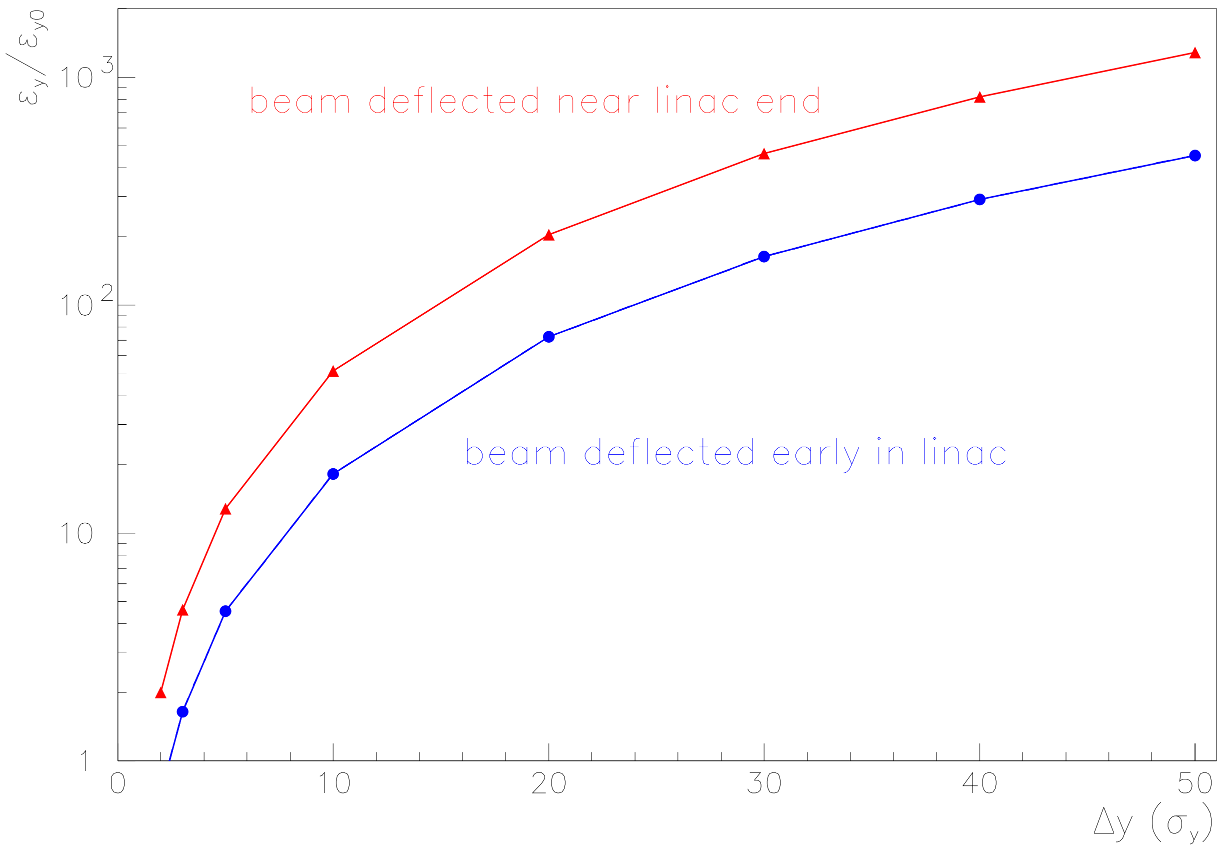
material	α	E	C_p	c_p	K	σ	σ_{min}
	[1/K]	[GPa]	$[\frac{\mathrm{J}}{\mathrm{gK}}]$	$[\frac{\mathrm{MJ}}{\mathrm{m^3K}}]$	$[\frac{\mathrm{W}}{\mathrm{Km}}]$	$[\Omega^{-1}\mathrm{m}^{-1}]$	[μm]
Cu	16.5	120	0.385	3.4	390	6×10^7	200
Ti	8.5	110	0.52	2.4	17	2×10^6	100
W	4.4	411	0.132	6.8	200	2×10^7	84

Other parameters $dE/dx \approx 1.14 - 1.51$ MeV cm^2/g and $\sigma_{\mathrm{UTS}} \approx 300 - 400$ MPa.

In present final-focus design, maximum spot sizes are $\sqrt{\sigma_x\sigma_y} \approx 45\mu$m at the first three sextupoles, $\sqrt{\sigma_x\sigma_y} \approx 76\mu$m for the last one.

emittance growth of mis-steered beam

(PLACET, D. Schulte)



Fundamental Questions:

- how much halo do we expect?
- how many muons per bunch train are acceptable for the detector?
- which are the failure modes in the linac that can missteer the beam? what is the emittance increase as a function of linac steering error?

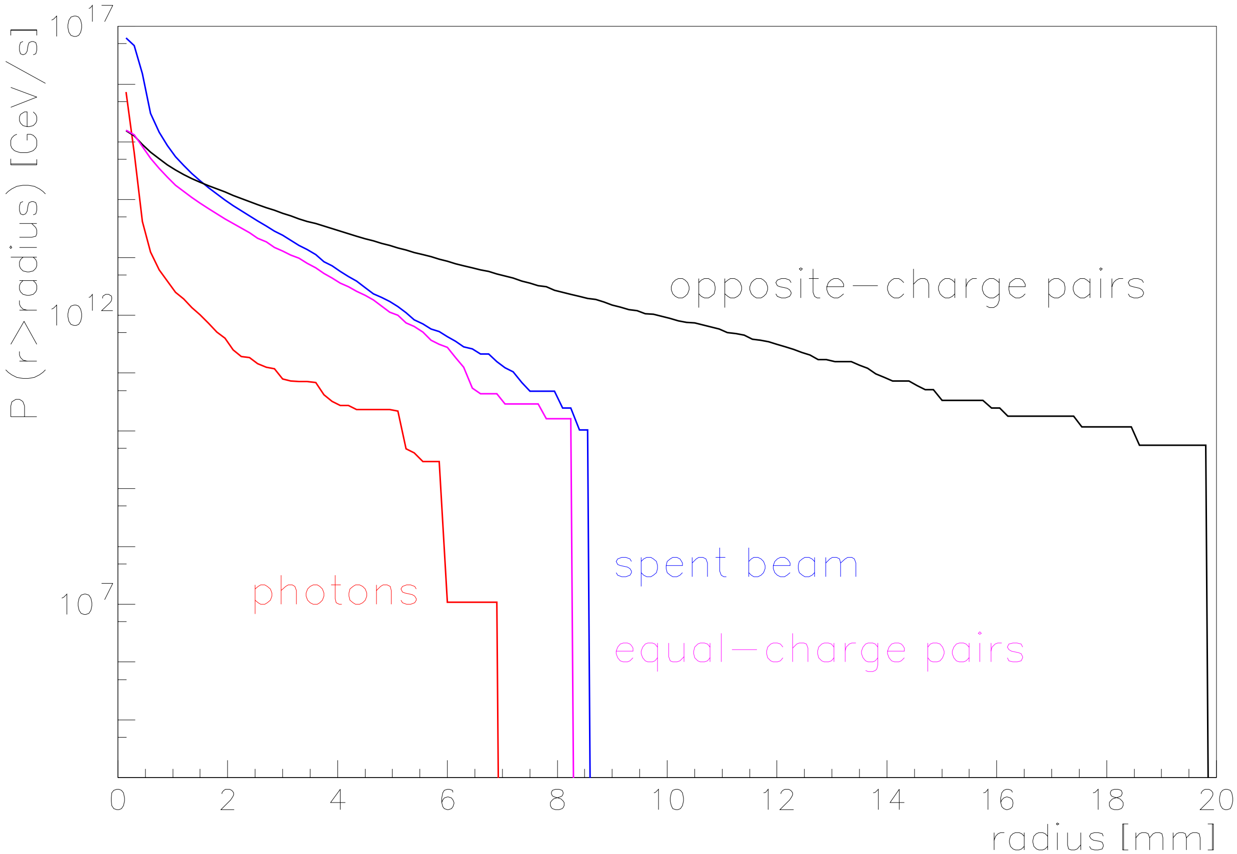
We hope that collimation only in the final focus will be sufficient, and that we do not need beta function as large as naively estimated.

(4) IP and Exit Line Issues

- *background from coherent pairs and beamstrahlung*; at 3 TeV there are about as many pairs as beam particles!
- *extraction of spent beam with* $\Delta E/E \approx 100\%$, photons and pairs, layout of final quadrupole
- suppression of *thermal shock waves* (J.B. Jeanneret)
- exit line diagnostic, luminosity monitors, tuning
- effects of solenoid field, multibunch kink instability, crab crossing (O. Napoly)
- *off-center collisions in the high-*Υ *regime:* angular divergence, beamstrahlung, defl. scans (Napoly)

spent beam & debris 2 meters from IP:
power at $r > a$

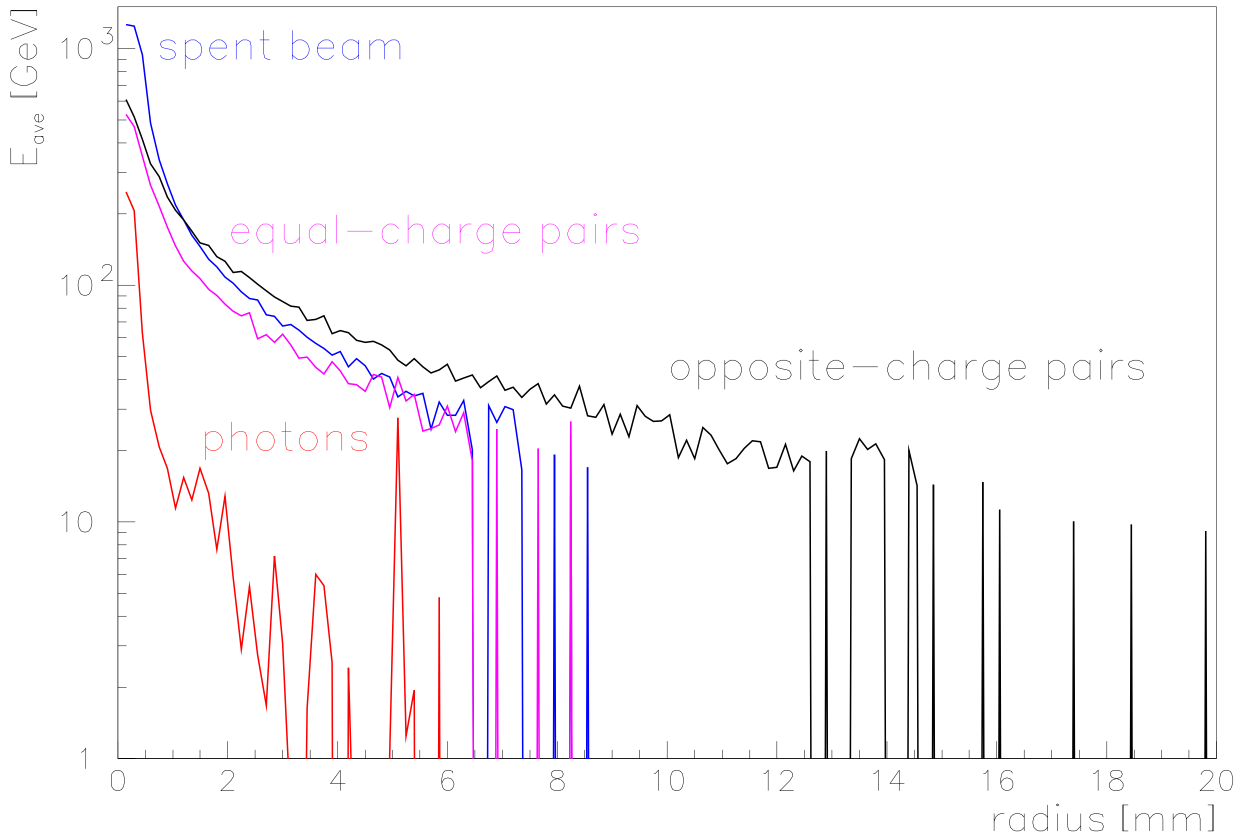
(D. Schulte, Guinea-Pig)



spent beam & debris 2 meters from IP:

average energy

(D. Schulte, Guinea-Pig)



CERN

Crossing Angle

Constraints

- loss in luminosity (w/o crab): $L/L_0 \approx 1/(\sqrt{1+\left(\frac{\phi_c}{2\phi_d}\right)^2})$ where $\phi_d = \sigma_x/\sigma_z \approx 1.4$ mrad, e.g., $L/L_0 = 28\%$ for $\phi_c = 10$ mrad, and 14% for $\phi_c = 20$ mrad.

- multi-bunch kink instability:
$\phi_c \geq \sqrt{D_x m_b}(3D_y)^{1/4}\phi_d \approx 12$ mrad, with $m_b = 154$ no. of bunches; $D_x = 2N_b r_e \sigma_z/(\gamma(\sigma_x+\sigma_y)\sigma_x) = 0.12$, $D_y = 5.2$; simulations indicate that 10 mrad would be ok (O. Napoly).

- space for spent beam & collisions debris, in particular for opposite-charge pairs (D. Schulte).

Crab Crossing

Crab cavity produces z-dependent displacement at IP:

$$\frac{\partial x^*}{\partial z} = \frac{\phi_c}{2}$$

or

$$\frac{\phi_c}{2} = R_{12} \frac{e V_{\rm max} k_{\rm rf}}{E}$$

where $R_{12} \approx 23$ m; $\rightarrow V_{\rm max} = 1$ MV at 30 GHz.

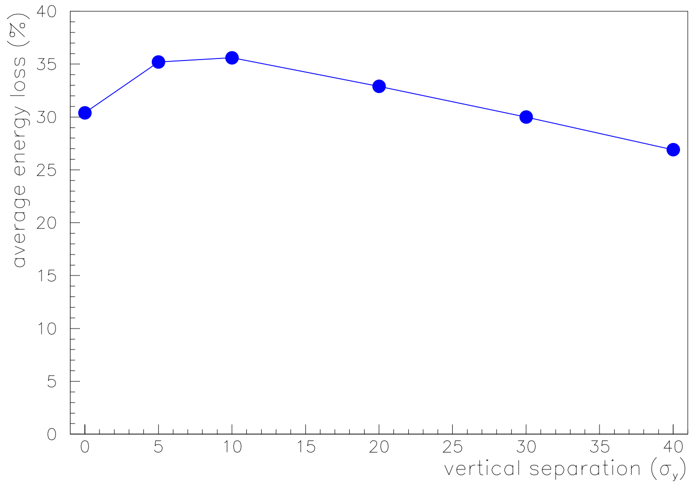
If relative phase of crav cavities jitters, the collision will not be head-on. Tolerance for 2% luminosity loss:

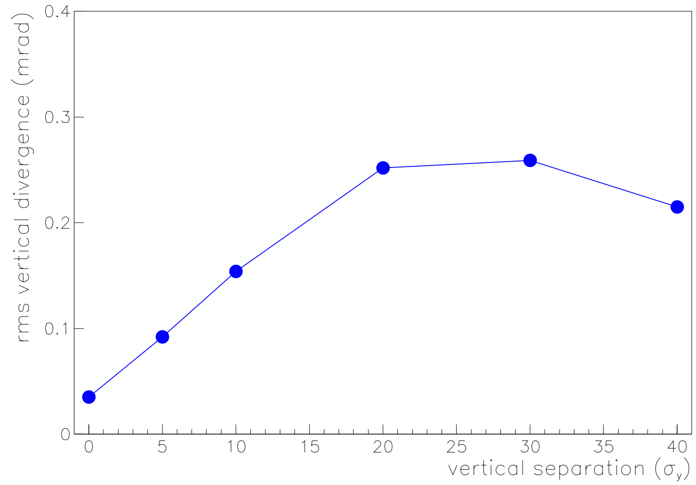
$$\Delta z \leq \frac{4}{5} \frac{\sigma_x}{\phi_c} \quad \text{or} \quad \Delta \phi_{\rm rf} \leq k_{\rm rf} \frac{4}{5} \frac{\sigma_x}{\phi_c} \approx 0.06^\circ$$

at 30 GHz. Tighter at lower frequencies.

For comparison: KEKB crab cavities, 500 MHz, $\phi_c = 11$ mrad, $\sigma_x = 200$ μm: $\Delta \phi_{\rm rf} \leq 8^\circ$, much relaxed.

Off-Center Collisions at High-Υ





Average relative energy loss (left) and rms divergence of spent beam (right) vs. vertical beam-beam separation, as simulated with GUINEA-PIG. Incoming divergences: $\theta^*_{x,y} \approx 5-7\ \mu$rad, characteristic deflection angle: $\theta_d = 2N_b r_e/(\gamma(\sigma_x+\sigma_y)) \approx 170\ \mu$rad.

Exit line acceptance should suffice for off-center collisions!

(5) Summary

- 3-km long baseline final-focus optics exists; $L/L_0 \approx 70-80\%$ with $\Delta E/E|_{FW} \approx 1\%$; compromise between SR in last quadrupole and higher-order chromatics; now exploring shorter alternatives
- jitter tolerance of $Q1$: $\Delta y < 0.2$ nm, determined by σ_y^*
- collimation profits from increased emittance of missteered beam; integrated in FF; det. requirements?
- crossing angle $\phi_c \geq 20$ mrad, $\Delta\phi_{\rm rf} < 0.06^\circ$ at 30 GHz.
- spent-beam disposal & extraction line diagnostics: still to be studied