CLIC Beam Delivery System

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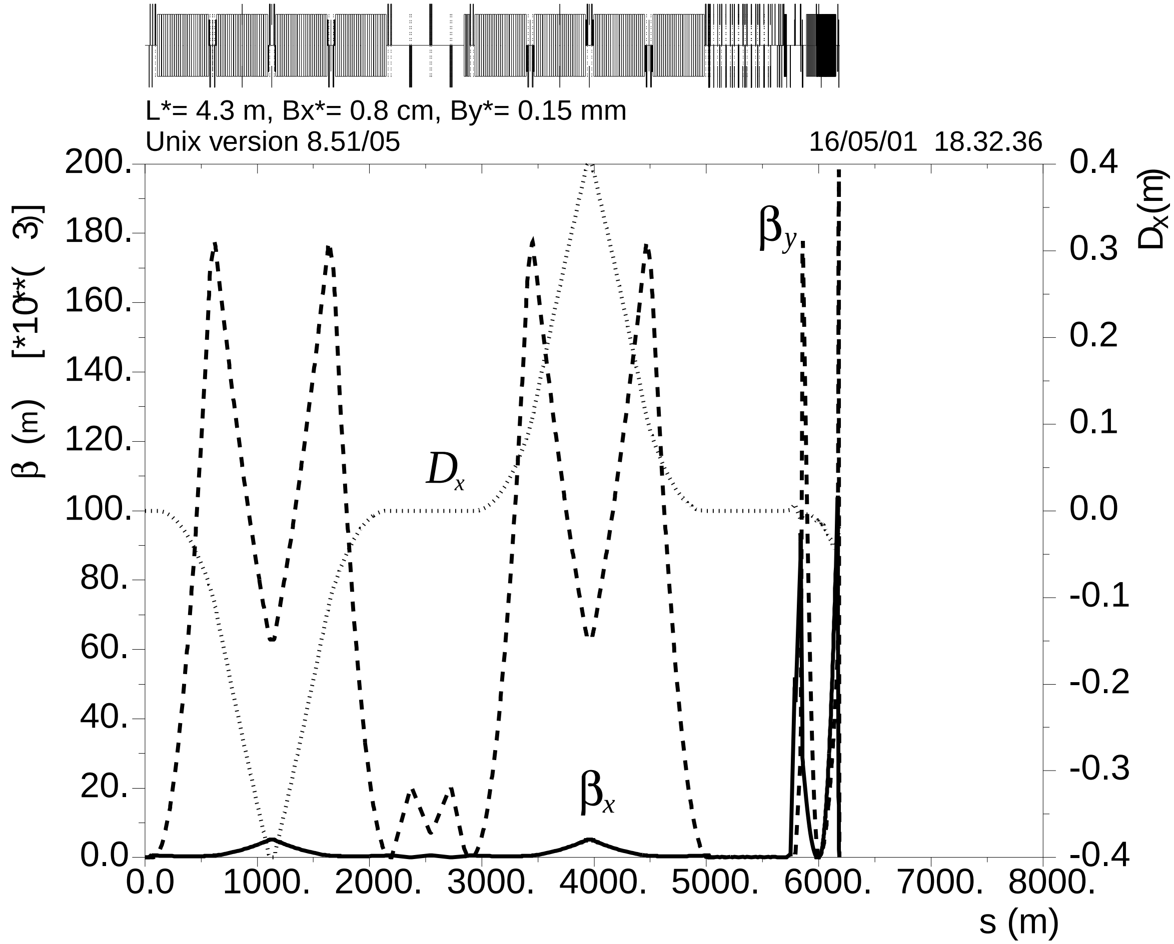
- parameters & layout
- optics & performance
- IR region
- collimation
- conclusion & open questions

parameter	symbol	3 TeV c.m.	500 GeV c.m.
final focus length [km]		0.5 (3.1)	0.5
collimation length [km]		2.0 (5.8)	2.0
total BDS length [km]		2.5 (8.9)	2.5
norm. emittance [μm]	$\gamma\epsilon_{x,y}$	0.68, 0.01 (0.02)	2.0, 0.01
IP beta functions [mm]	$\beta^*_{x,y}$	6.0, 0.07	3, 0.05
		(8, 0.15)	
rms spot sizes [nm]	$\sigma^*_{x,y}$	67, 2.1	180, 4.2
rms bunch length [μm]	σ^*_z	30	30
free length to IP	l^*	4.3 (2.0)	4.3
IP crossing angle [mrad]	θ_c	20	20
luminosity w/o pinch [10^{34} cm^{-2}s^{-1}]	L_0	4.0	1.9

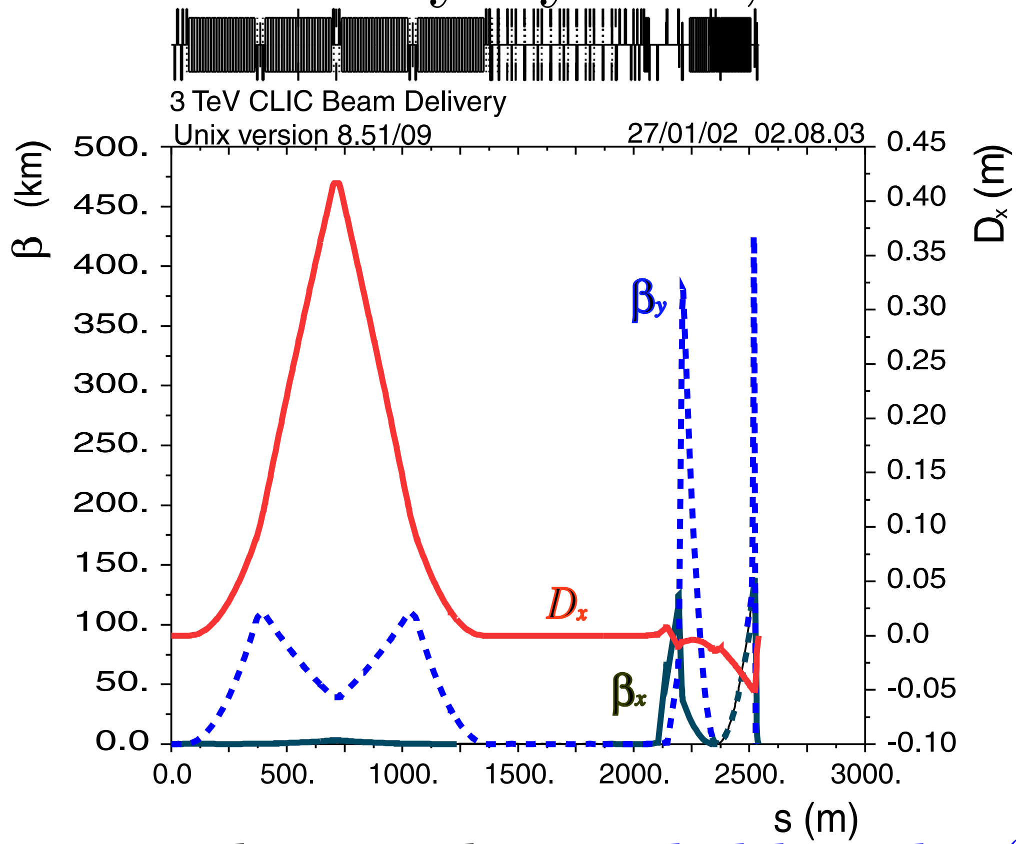
*2000 values in parentheses

3-TeV Beam Delivery System, June 2001



collimation system scaled from NLC (Tenenbaum), Raimondi compact final focus; IP beta functions: $\beta_x^* = 8$ mm, $\beta_y^* = 150$ μm; $l^* = 4.3$ m; $I_5 \approx 1.8 \times 10^{-20}$ m, $\Delta(\gamma\epsilon_x) \approx (4 \times 10^{-8}\ \mathrm{m}^2/\mathrm{GeV}^{-6}) E^6 I_5 \approx 9$ nm.

3-TeV Beam Delivery System, January 2002



collimation system shortened: rescaled lengths ($\times 0.625$), and bending angles θ_b ($\times 2.67$); omitted half of energy collimation (T.R.). Raimondi compact final focus; IP beta functions reduced: $\beta_x^* = 6$ mm, $\beta_y^* = 70$ μm; $l^* = 4.3$ m; $I_5 \approx 2 \times 10^{-19}$ m, $\Delta(\gamma\epsilon_x) \approx 90$ nm.

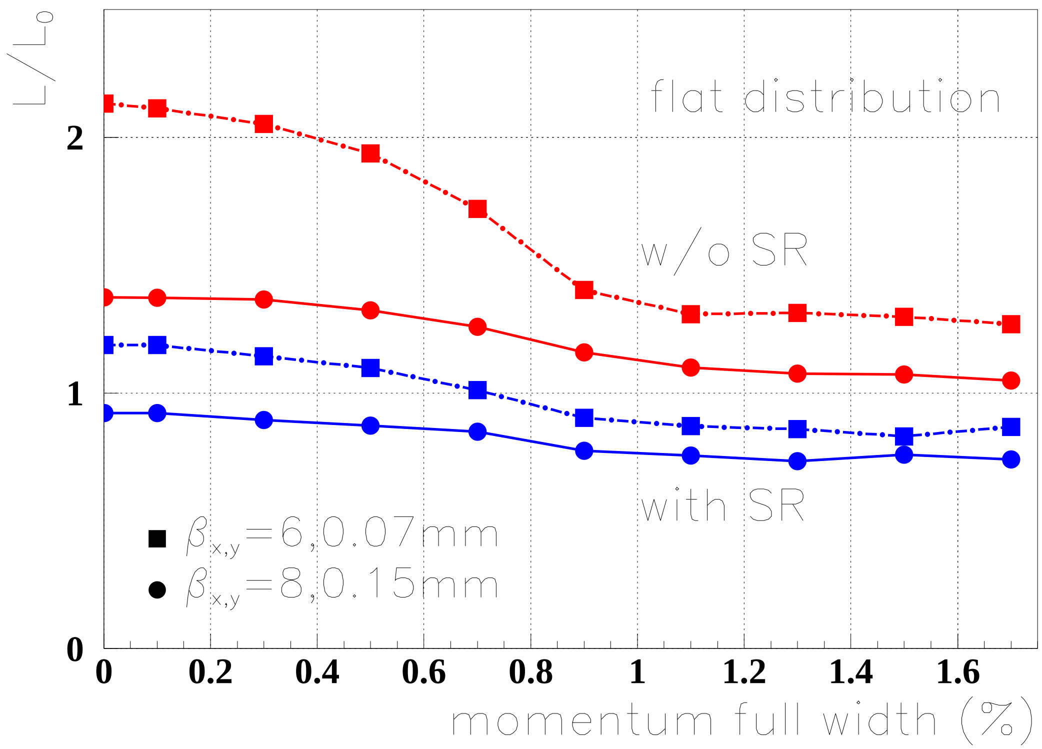
Is halving the energy collimation acceptable?
Which criteria apply? How do we balance?

- overall length
- tracked luminosity performance
- collimation efficiency (?)
- ...

lengths & luminosities for various systems

system	length [m]	luminosity w/o pinch [10^{34}] $cm^{-2}s^{-1}$]
present	2557	3.98
2× energy coll.	4325	3.80
increase length by 1.6 & reduce θ_b by 3/8	3356	3.76
2× energy coll. & incr. length & red. θ_b	6186	4.46

Performance of Compact 3-TeV BDS



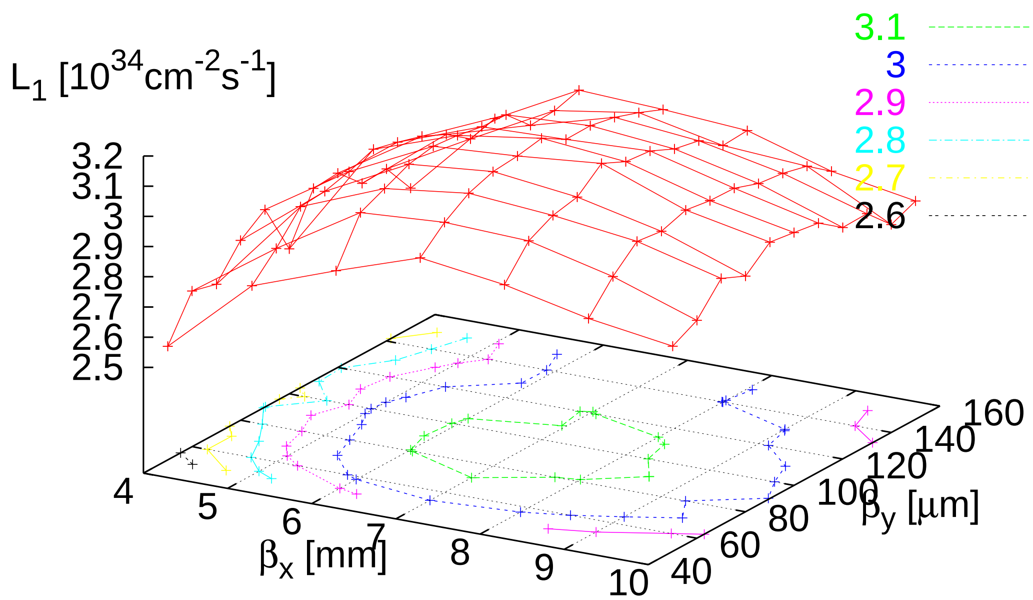
relative luminosity w/o pinch vs. FW momentum spread at 3 TeV as simulated by upgraded MAD (cross-checked with PTC), for two different values of $\beta^*_{x,y}$ and $\gamma\epsilon_y = 10$ nm ($L_0 = 4.6 \times 10^{34}$ cm^{-2}s^{-1})

Performance of Compact 3-TeV BDS Cont'd

Limitations:

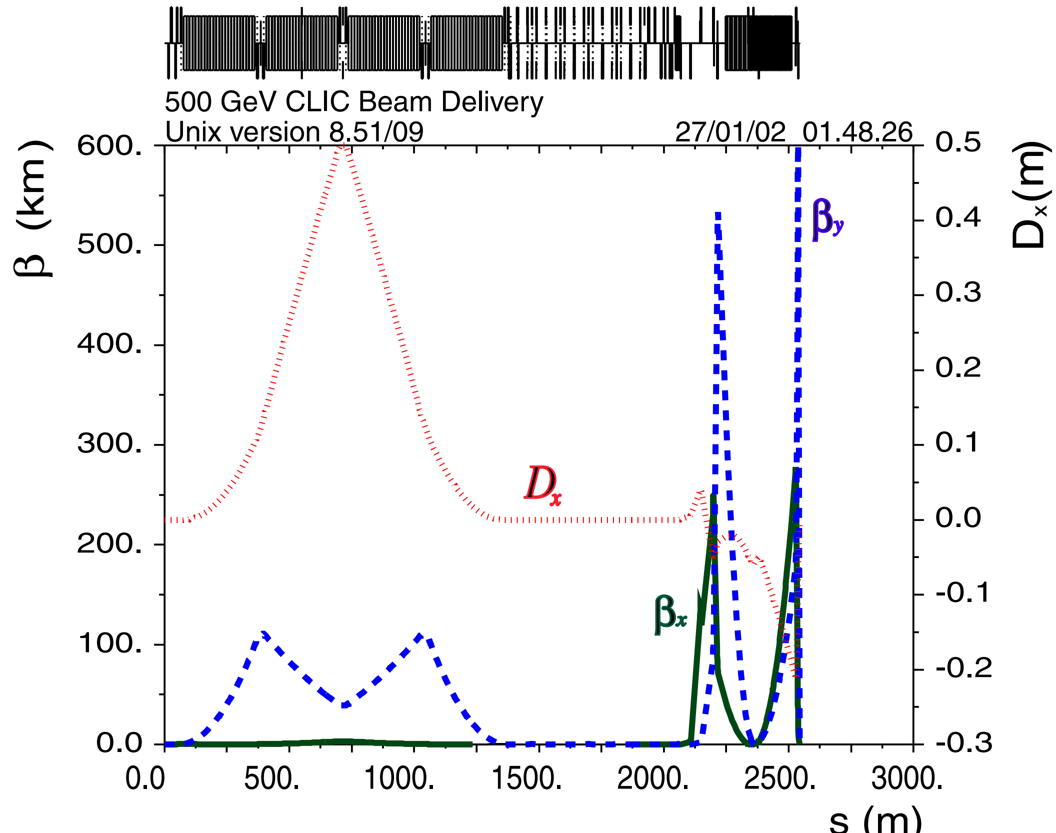
- synchrotron radiation in bends: $\sim$ factor 2 luminosity loss
- momentum spread of the beam: $\sim 30\%$ loss
- synchrotron radiation in final quadrupoles: $\sim 10\%$ loss

Performance of Compact 3-TeV BDS Cont'd



3-TeV luminosity L_1 ($E_{cm} > 99\% E_0$) with pinch, beamstrahlung and pair production vs. β_x^* & β_y^*, as determined by integrated simulations using Guinea-Pig (courtesy D. Schulte)

500-GeV Beam Delivery System



modifications to 3-TeV system: same total length, increase FF bend angles by 4.25 (and reduce sextupoles); increase bending angles in coll. system by 20%; larger squeeze of IP $\beta^*_{x,y}$ possible, down to $\beta^*_x = 3$ mm, $\beta^*_y = 50\ \mu$m (plot)

Performance Improvement: β Squeeze at 500 GeV (at 3 TeV it is less effective)

ϵ_y [nm]	β_y^* [μm]	β_x^* [mm]	σ_x [nm]	σ_y [nm]	L [10^{33} cm^{-2} s^{-1}]
20	150	10	209	2.65	7.3
10	150	10	209	1.88	10.2
10	110	10	209	1.69	11.5
10	70	10	209	1.55	13.6
10	50	10	209	1.56	15.0
10	50	8	189	1.77	16.0
10	50	6	169	2.17	17.2
10	50	4	160	3.12	18.1
10	50	3	178	4.07	18.5

squeeze only β_y to preserve quality of lum. spectrum

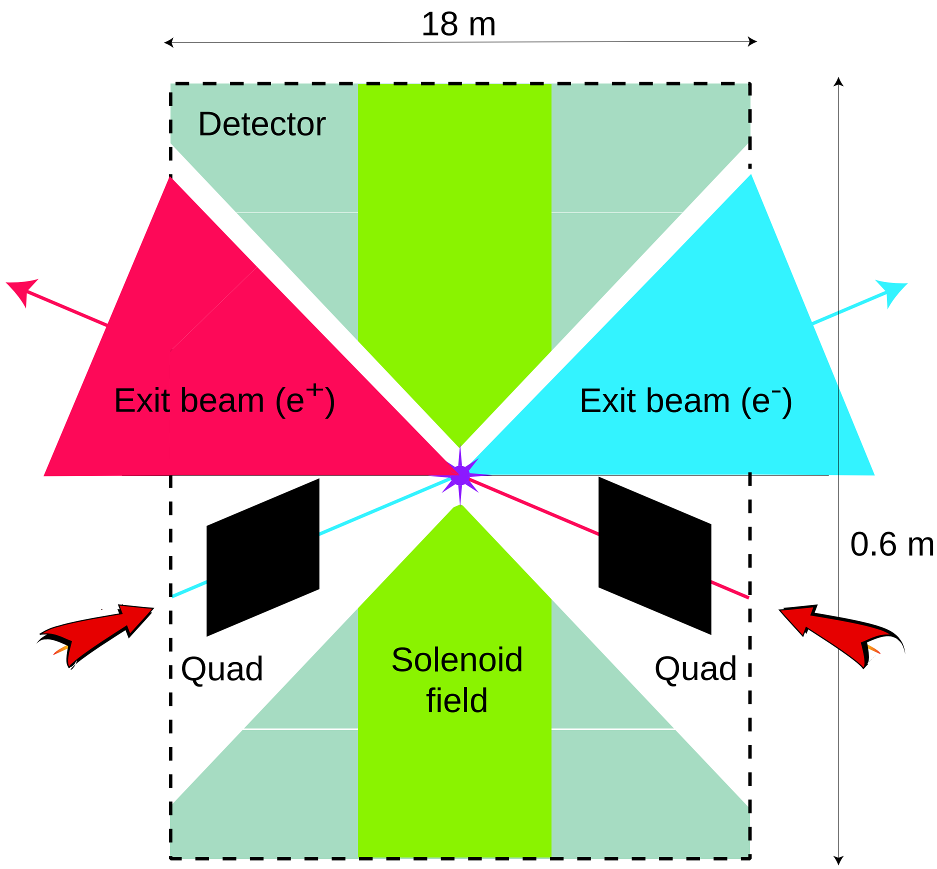
Comments on β Squeeze

- yields higher luminosity;
- facilitated by Raimondi final focus (wide bandwidth, little chromatic aberrations);
- makes optimum use of short bunch length
- also makes use of decreased vertical emittance
- rms spot sizes become less meaningful
- effective beam size from Gaussian fit (S. R.) or beam-beam simulation (D. S.)

Let's Design a Raimondi Final Focus!

my draft recipe (for discussion), software tools?

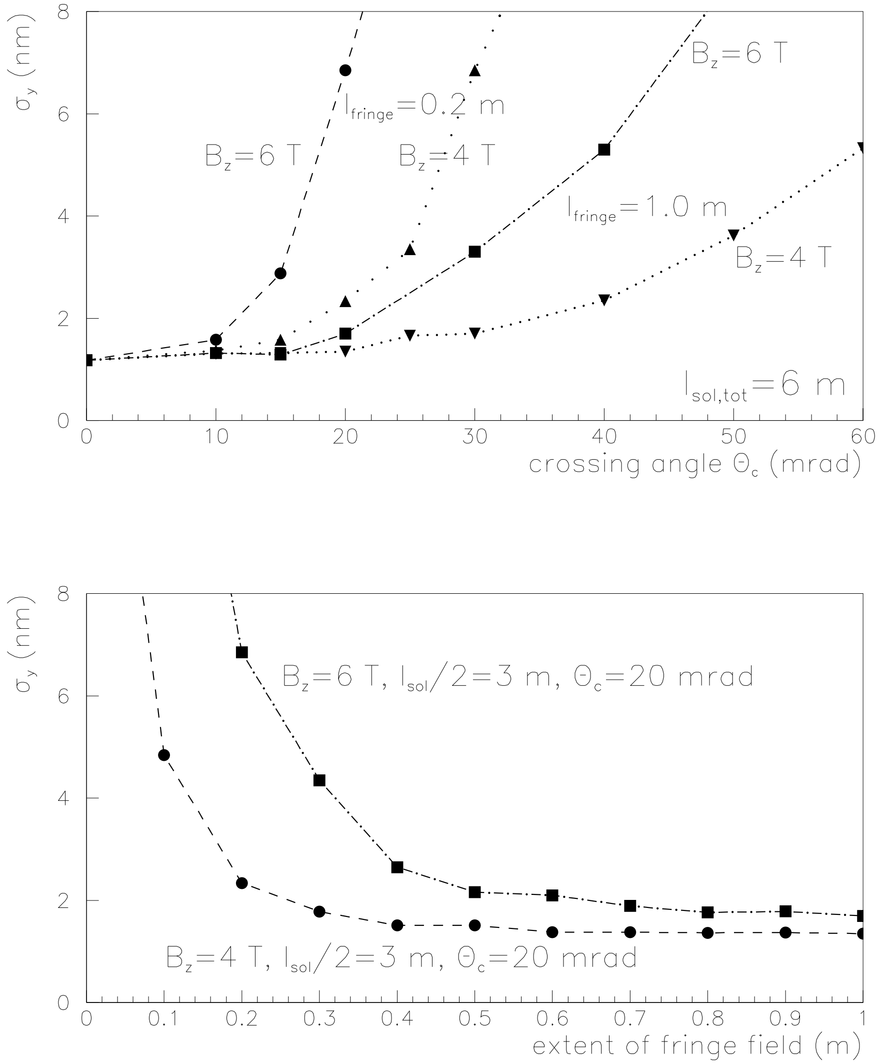
- design a linear system
- add 2 FD sextupoles, correct ξ_y and T_{166}
- adjust the linear optics (x) to cancel ξ_x as well
- add 2–3 geometric sextupoles, and cancel T_{122} and T_{144}
- treat higher order aberrations by fine-tuning of $\alpha_{x,y}$ and phase advances, adding octupoles, fine-tune dispersion,...



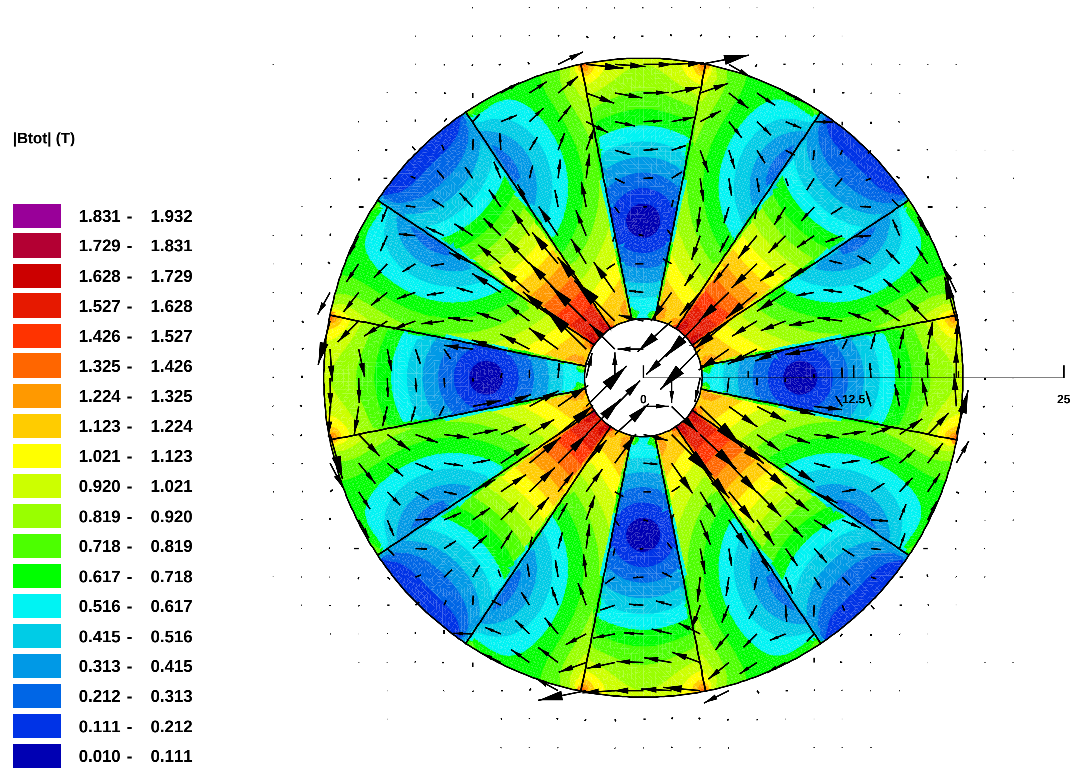
Top view of the CLIC IP region with the detector, the colliding beams, and the final quadrupoles at 3 TeV. Scales are indicated. The transverse size of the detector is about 17 m [Courtesy Ralph Assmann] Crab cavity: $\hat{V}_{crab} \approx 1$ MV at 30 GHz ($\hat{V}_{crab} \propto \lambda_{\rm rf}$); $\Delta\phi_{lr} \leq 0.1^\circ$ ($\propto 1/\lambda_{\rm rf}$)

Choice of Crossing Angle

- $\theta_c \geq 20$ mrad for spent beam (D. Schulte, PAC99)
- $\theta_c \geq 20$ mrad for multi-bunch kink instability, including effect of coherent pairs (O. Napoly CERN-SL-99-054-AP, D. Schulte, CLIC Note 484)
- $\theta_c \leq 20$ mrad for vertical spot size increase due to synchrotron radiation in solenoid (fringe) field and vertical dispersion (D. Schulte & F.Z., CLIC Note 484, 2001)



Vertical spot size σ_y^* vs. θ_c (left) and vs. length of fringe field (right), considering solenoid fields of 4 and 6 T. [D. Schulte & F.Z., CLIC Note 484, 2001]



Cross section of a final focusing quadrupole with gradient 468 T/m for the permanent magnet material VACOMAX 225HR Sm_2Co_{17}, as computed for a 16-sector magnet by ROXIE [M. Aleksa, S. Russenschuck, CLIC Note 506] (note: optics 'only' requires 388 T/m at 3 TeV)

$$\Delta T = 1 \text{ K } (9 \ \tfrac{\text{kJ}}{\text{m}}) \rightarrow \Delta y = 286 \text{ nm! Limit: } 6 \ \tfrac{\text{J}}{\text{m}} \ (< 1 \text{ mK!})$$

Final-Quadrupole Parameters

length	4.75 m	3.5 m
field gradient	468 T/m	388 T/m
inner radius	3.3 mm	3.8 mm
outer radius	20 mm	43 mm
weight	50 kg	150 kg

p.m. material Sm_2Co_{17}, radiation hardness $\Delta B/B \leq 0.4\%$ at 2 MGy, no damage from neutrons up to 10^{18} n cm^{-2}, temperature stability 3×10^{-4} K^{-1}

Final-Doublet Issues

- multipole errors of p.m. quadrupole

$$\frac{\Delta\sigma_y^*}{\sigma_{y0}^*} = (n-1)\sqrt{(2n-5)!!}\frac{GL_Q b_n}{(B\rho) r_0^{n-2}} \beta_{Q,x}^{(n-2)/2}\epsilon_x^{(n-2)/2}\beta_{Q,y}$$

blow up from b_4 less than 0.06%

- resistive-wall wake

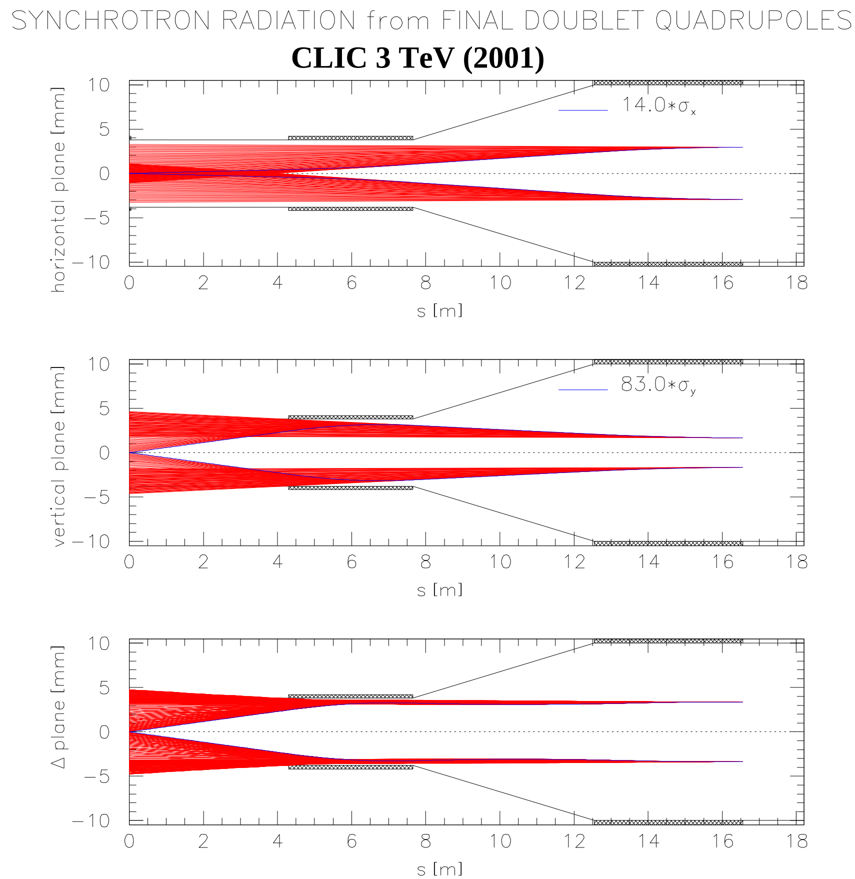
$$\frac{< \Delta y' > /\sigma_{y'}}{< y > /\sigma_y} \equiv K = 0.3\frac{2}{\pi}\frac{r_e N_b L}{a^3\gamma}\left(\frac{c}{\sigma\sigma_z}\right)^{1/2} \beta_y$$

example: $\sigma = 5.4 \times 10^{17}$ s^{-1} (Cu), $a = 3.3$ mm, $E = 1.5$ TeV, $N = 4 \times 10^9$, $\sigma_z = 30$ μm, $L = 10$ m, $\beta_y = 400$ km $\rightarrow$ $K = 0.31$ (5% enhancement if y and y' motion uncorrelated)

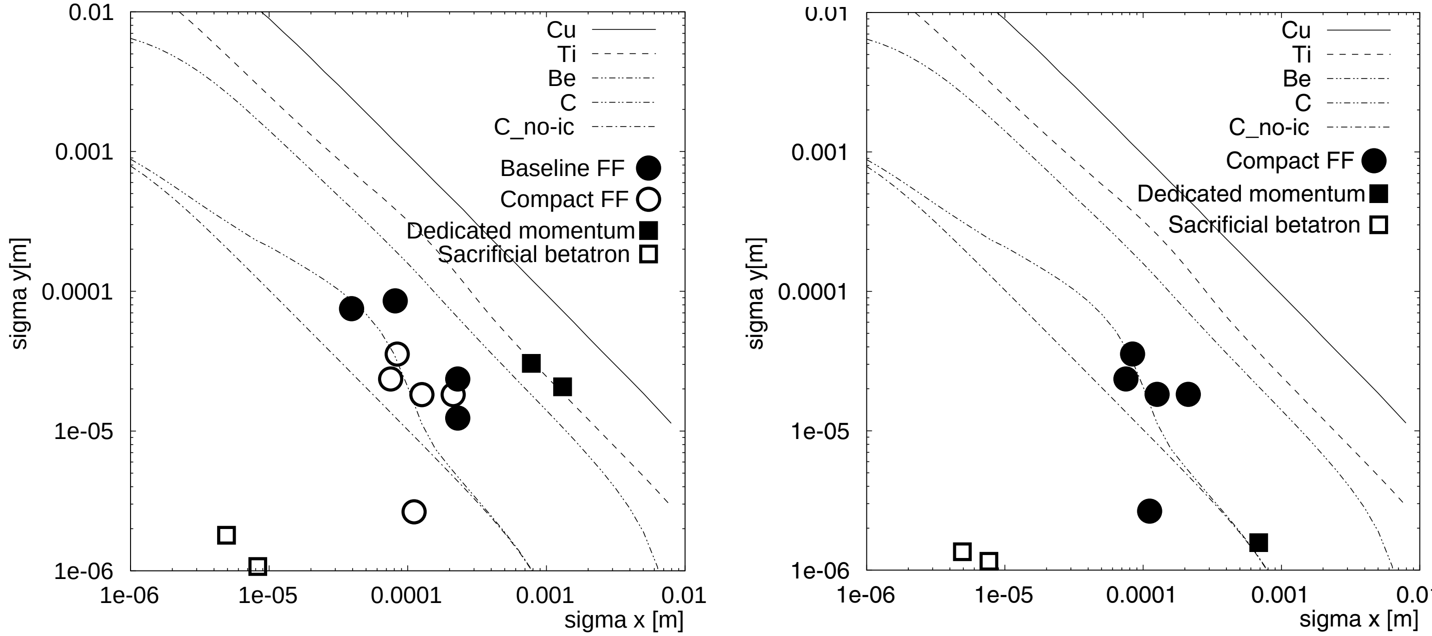
- vacuum: local pumping via (1) segmented magnets, (2) slitted magnets, (3) coating with getter material. At 10 nTorr & 5 m, bremsstrahlung $\rightarrow$ 0.6 events / train.
- jitter tolerances (S.R.)

Collimation System Functions

- remove beam halo to reduce detector background
- provide a distance between collimators and IP for muon suppression
- ensure collimator survival and machine protection
- not amplify incoming trajectory fluctuations via the collimator wake fields



synchrotron radiation fans at 3 TeV with beam envelopes of $14\sigma_x$ and $83\sigma_y$. [Courtesy O. Napoly & CLIC Note 476] $\rightarrow$ betatron collimation amplitude



Vertical vs. horizontal beam sizes required for spoiler survival [S. Fartoukh, J.B. Jeanneret, J. Pancin, CLIC Note 477] and values at spoiler locations. Left: baseline & compact FF, long collimation optics; right: compact FF and shorter collimation section

Collimation Depth at 3 TeV

- β_x: from SR fan in final quadrupole $\rightarrow$ about $\pm 12\ \sigma_x$ ($2\sigma_x$ margin) [O. Napoly, CLIC Note 476]
- β_y: from SR fan in final quadrupole $\rightarrow$ about $\pm 80\ \sigma_y$ ($3\sigma_y$ margin) [O. Napoly, CLIC Note 476]
- energy: from linac failure modes (see separate talk, D. Schulte & F.Z., CLIC Note 492) $\rightarrow$ about $\pm 1.5\%$

Collimator Parameters

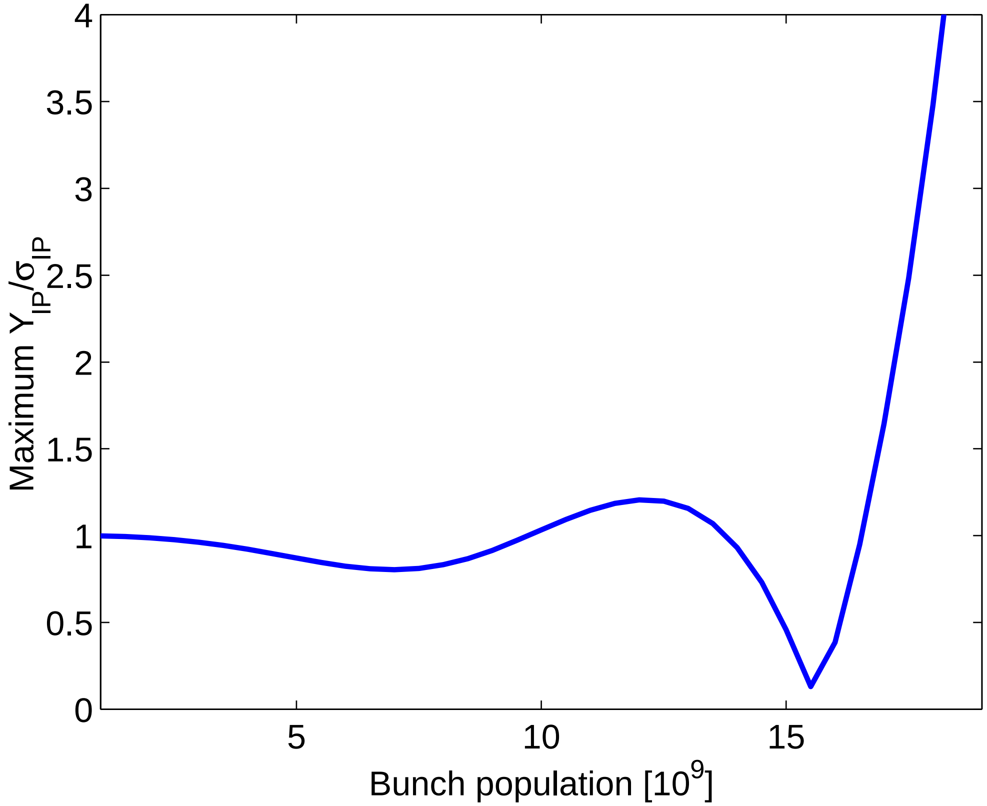
cm energy	3 TeV	500 GeV
energy spoiler gap	± 4 mm	± 4.8 mm
β_x spoiler gap	$\pm 95\ \mu m$ ($12\ \sigma_x$)	$\pm 300\ \mu m$ ($9\ \sigma_x$)
β_y spoiler gap	$\pm 104\ \mu m$ ($80\ \sigma_y$)	$\pm 215\ \mu m$ ($69\ \sigma_y$
spoiler material	Be (or C)	Be (or C)
spoiler length	177 mm (0.5 r.l. Be)	177 mm (0.5 r.l. B
	or 144 mm (0.5 r.l. C)	or 144 mm (0.5 r.l.
absorber material	Ti (Cu coated)	Ti (Cu coated)
absorber length	712 mm (20 r.l.)	712 mm (20 r.l.)
number of energy spoilers	1	1
number of $\beta_{x,y}$ spoilers	4, 4	4, 4

Wake Field Effects

Centroid deflection by tapered circular collimator [K. Yokoya]:

$$\Delta y' = \frac{2N_b r_e}{\gamma \sigma_z} \left[\frac{(4\lambda\sigma_z)^{1/4}}{g^{3/2}} + \frac{L_F (\lambda\sigma_z)^{1/2}}{2\sqrt{\pi} g^3} \right] y$$

where y is the offset from the center of the chamber, $\lambda[\mathrm{m}] = \rho[\Omega\mathrm{m}]\ /(120\pi)$, L_F the length of the collimator flat part, and g the half gap. The taper angle is assumed to be optimally chosen as $\theta_{\mathrm{opt}} \approx 1.1(\lambda\sigma_z/g^2)^{1/4}$ [J. Irwin]

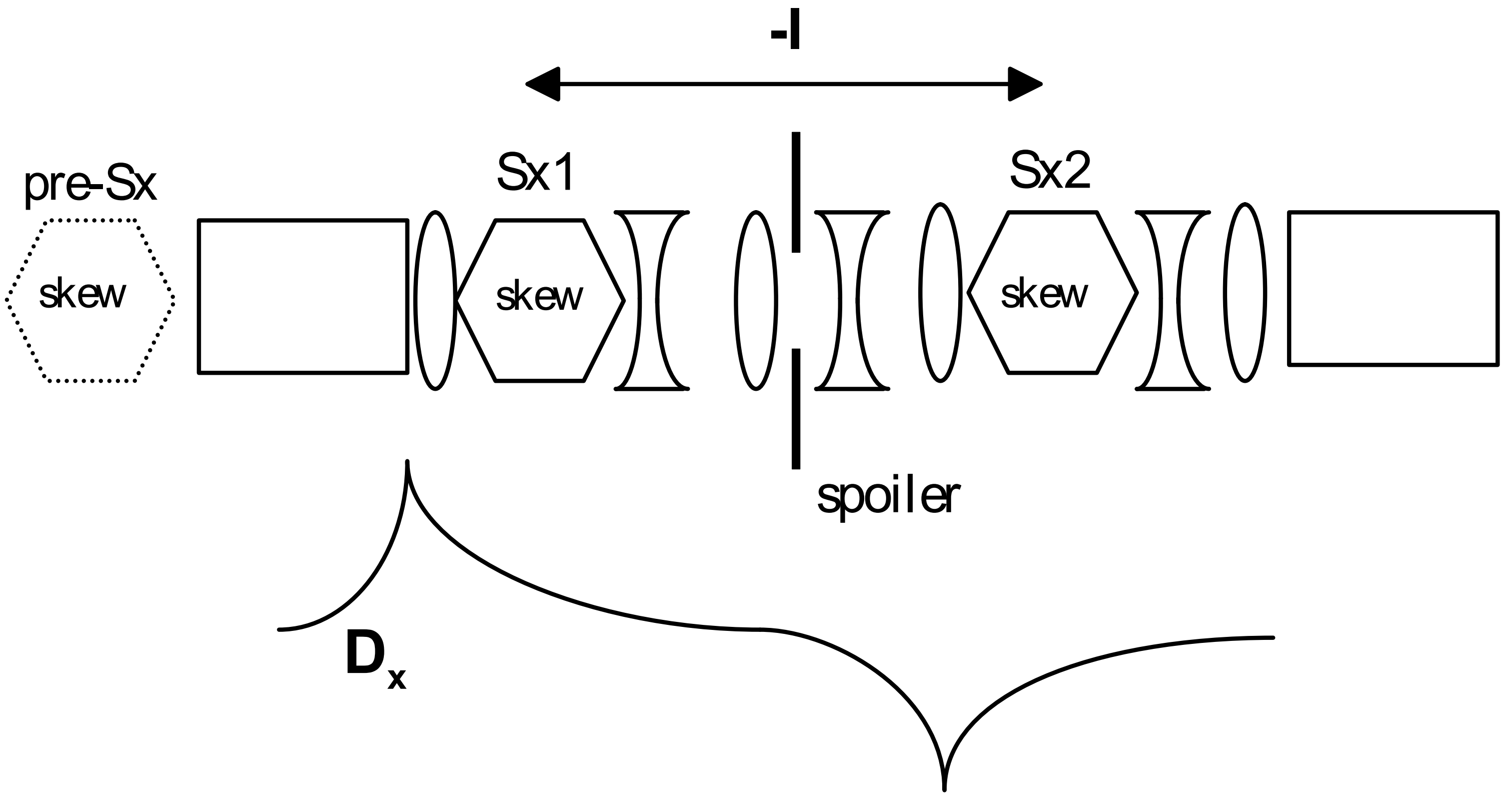


'Maximum' IP orbit displacement for a 1σ change in incoming beam trajectory as a function of bunch population N_b, at 3 TeV.
[S. Redaelli, CLIC Note 493]

$$(\beta \Delta y'/y)_{500\mathrm{GeV}} \approx 0.8 (\beta \Delta y'/y)_{3\mathrm{TeV}}$$

Alternative Nonlinear Collimation System

basic scheme



Alternative Nonlinear Collimation System Cont'd

- even shorter (?)
- use skew sextupole → increase σ_y at spoiler
- skew sextupole amplifies δ & x_β oscillations → spoiler at larger amplitude (smaller wake effect)
- (possibly) $D_x = 0$ at spoiler avoids $\Delta E \rightarrow x_\beta$ coupling
- 2nd skew sextupole cancels aberration
- single spoiler only (compact, less wake)
- 3rd weak skew sextupole for other phase
- comfortable spot size at absorber behind spoiler
- emittance growth from SR

Effect of Skew Sextupole

$$K_s = \frac{2 B_T l_s}{(B\rho) a_s^2}.$$

deflection:

$$\Delta x' = -\frac{\partial H_s}{\partial x} = K_s (D\delta + x) y$$

$$\Delta y' = -\frac{\partial H_s}{\partial y} = -\frac{1}{2} K_s (y^2 - x^2 - D^2\delta^2 - 2D\delta x).$$

position at downstream spoiler

$$x_{\rm spoiler} = x_{0,\rm spoiler} + R_{12} \Delta x'$$

$$y_{\rm spoiler} = y_{0,\rm spoiler} + R_{34} \Delta y'$$

$$\sigma_x \approx (\beta_{x,\mathrm{spoiler}}\epsilon_x)^{1/2}, \quad \sigma_y \approx \sqrt{\frac{9}{5}}\ \frac{1}{2}\ |R_{34}K_s|\ D^2\delta_{\mathrm{rms}}^2.$$

$$\sigma_x\sigma_y \approx \frac{9}{5}|R_{34}K_s|D^2\delta_{\mathrm{rms}}^2\sqrt{\beta_{x,\mathrm{spoiler}}\epsilon_x} \geq \sigma_{r,\mathrm{min}}^2 \qquad (1)$$

simultaneous δ and y collimation:

$$\beta_{x,\mathrm{sextupole}} = \frac{D^2\Delta^2}{\epsilon_x n_x^2}, \quad \beta_{y,\mathrm{sextupole}} = \frac{K_s^2 R_{34}^2 D^4\Delta^4}{\epsilon_y n_y^2} \qquad (2)$$

emittance growth from synchrotron radiation:

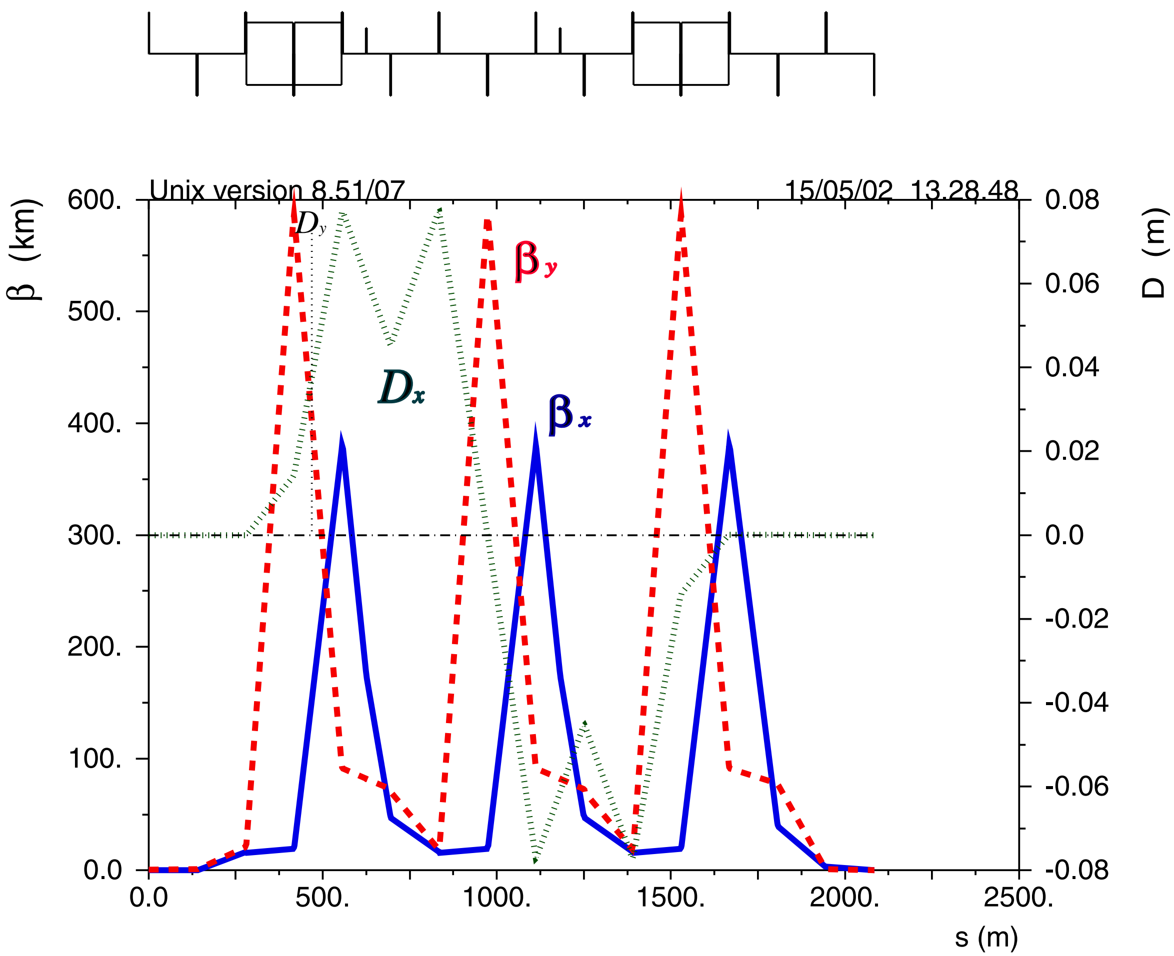
$$\Delta(\gamma\epsilon_x) \approx (4\times 10^{-8}\ \mathrm{m}^2\mathrm{GeV}^{-6})\ E^6 I_5 \ll \epsilon_x \qquad (3)$$

solve Eqs. (1), (2), (3) by optimizing length, optics, and positions;

strength of additional ‘pre’ skew sextupole:

$$K_s^{\mathrm{pre}} = \frac{2}{{n_y^{\mathrm{IP}}}^2\beta_y^{\mathrm{pre}}\epsilon_y}\left(\frac{2a_{y,\mathrm{spoiler}}}{K_s R_{34}}\right)^{1/2}\frac{1}{R_{34}^{\mathrm{pre}}}$$

Example Optics for 3 TeV (A. Faus-Golfe, F.Z.)



beam size at spoiler: $\sigma_r = 120\ \mu$m; spoiler half gap: $a = 16.7$ mm; $I_5 \approx 10^{-19}$ m $\rightarrow$ $\Delta(\gamma\epsilon_x) \approx 0.05\ \mu$m (7%); blow up from pre-sextupole $\rightarrow$ 6% increase in IP divergence; so far system does not include chromatic correction *parameters for main skew sextupoles and for spoiler*

variable	value
length	2.07 km
beta functions (x, y) at skew sext.	175, 82 km
dispersion at skew sext.	61 mm
skew sextupole pole-tip field, radius, length	1.4 T, 4 mm, 3 m
skew sextupole strength K_s	104 m^{-2}
R_{12}, R_{34} from sext. to spoiler	110, 307 m
beta functions (x, y) at spoiler	20.5, 586 km
dispersion at spoiler	$\sim$0 m
rms spot size (x, y) at spoiler	69, 209 μm
vertical spoiler half gap $a_{y,\mathrm{sp}}$	16.7 mm

parameters for 'pre' skew sextupole

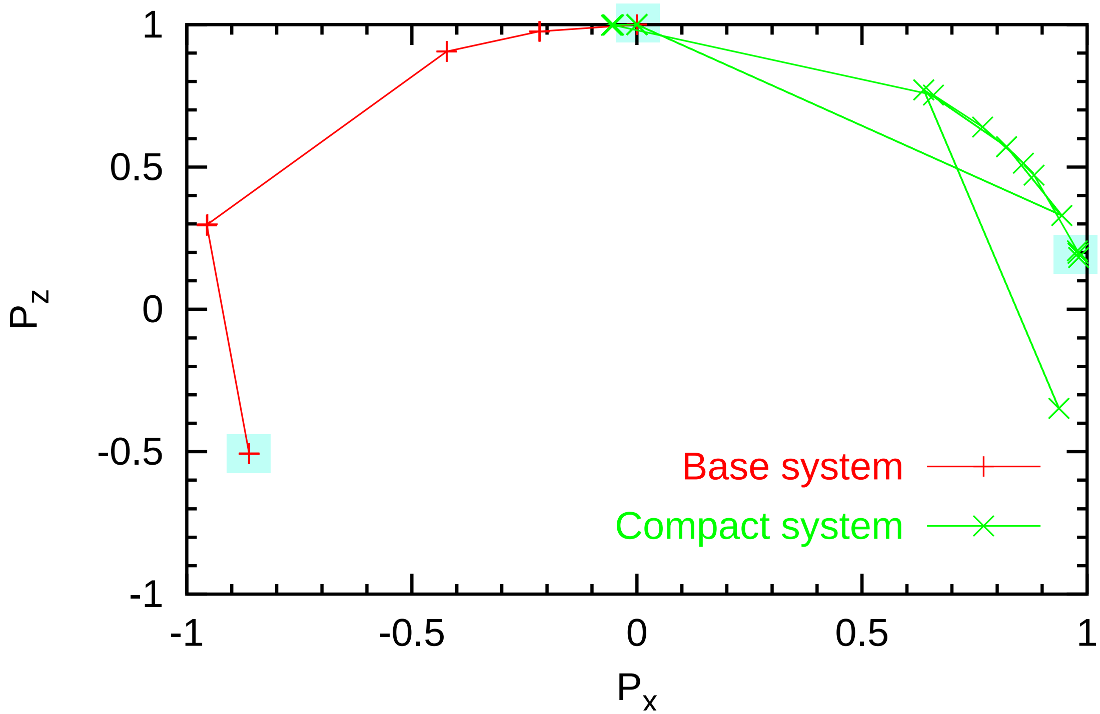
variable	value
hor. beta function at pre skew sext.	5.4 km
vert. beta function at pre skew sext.	19.5 km
pre-skew sextupole pole-tip field, radius, length	23 mT, 20 mm, 3 m
pre-skew sextupole strength $K_s^{\rm pre}$	0.068 $\rm m^{-2}$
R_{12} from pre-sext. to sext.	290 m
R_{34} from pre-sext. to sext.	113 m

Spin Transport and Depolarization
Thomas-BMT Equation

$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m}\vec{S} \times \left[(1 + a\gamma)\vec{B}_{\perp} + (1 + a)\vec{B}_{||}\right]$$

where $a = (g - 2)/2 = 0.00115966$

Possibly more spin rotation at higher energy!



Rotation of the polarization vector in the x-z plane in the short and base CLIC final-focus system. The initial $(P_x = 0, P_z = 1)$ and final polarization values are indicated by underlaid boxes. $\rightarrow$ Initial polarization vector must be 'matched' into the BDS! [R. Assmann & F.Z., CLIC Note 501]

Conclusions

- CLIC BDS performs well at both 3 TeV and 500 GeV ; ideal system exceeds the target luminosity by factor 1.5 at 500 GeV, close to target value at 3 TeV
- several small and subtle effects
- alternative nonlinear collimation system is being finalized (A. F.-G.)
- can we come up with a concise clear recipe or with a 'MAD engine' for designing a compact final focus?
- how do we balance between length and performance?