Final Focus Systems for CLIC at $\sqrt{s} = 3$ TeV and $\sqrt{s} = 500$ GeV

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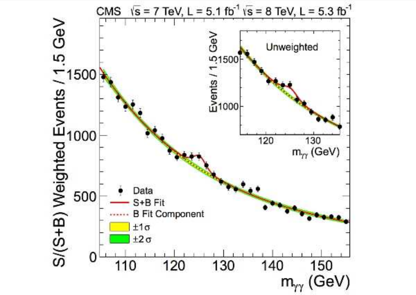
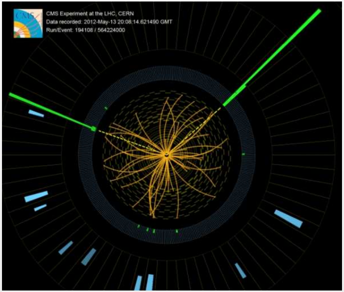
Outline

Why Linear Colliders

Higgs Milestone

The recent discovery at the LHC of the Higgs boson with a mass $m_H \approx 126$ GeV is one of the most important achievements of the recent history of science.





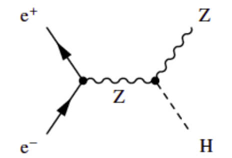
What's next?

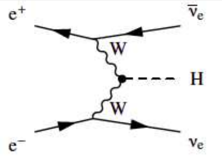
The next step in particle physics is to explore the real nature of the Higgs boson and knock on the door of New Phyiscs beyond the present Standard Model.

Why Linear Colliders

Precision studies

A very precise machine is required in order to reveal possible indirect contributions of New Physics via quantum corrections.





Why linear e^+e^- colliders

- Reduction of synchrotron radiation emission.
- QCD clean experimental environment.
- Background processes well calculated and measured.
- Ability to scan systematically in c.o.m. energy.
- High degree of e^- and e^+ polarization.
- Possibility for $\gamma\gamma$, e^-e^-, $e^-\gamma$ colliders

Linear Colliders

Nowadays, two main projects of linear colliders are ongoing: the International Linear Collider (ILC) and the Compact Linear Collider (CLIC).

ILC

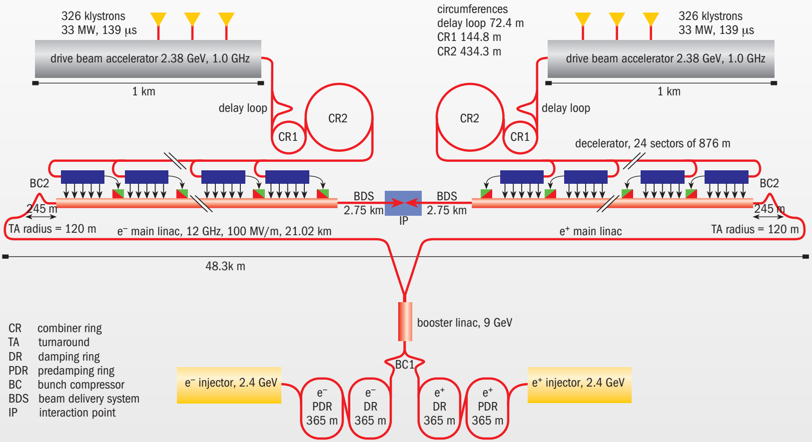
- International collaboration.
- Energy range: < 0.5 - 1 TeV c.o.m.
- Superconducting RF cavities (~ 35 MV/m).
- Japan did a first step for its construction.

CLIC

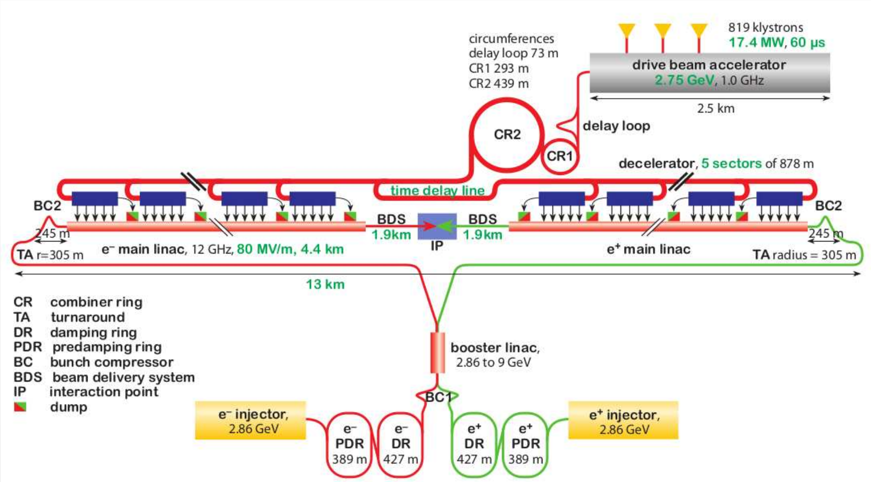
- Hosted at CERN.
- Energy range < 0.5 - 3 TeV c.o.m.
- Normal conducting cavities.
- Two beam acceleration scheme (~ 100 MV/m).

Both projects are in their design phase. The ILC presented in 2013 the Technical Design Report (TDR) and CLIC published its Conceptual Design Report (CDR) in 2012, where the basis of both projects are explained.

CLIC 3 TeV


326 klystrons
33 MW, 139 μs
drive beam accelerator 2.38 GeV, 1.0 GHz
1 km
delay loop
CR2
CR1
circumferences
delay loop 72.4 m
CR1 144.8 m
CR2 434.3 m
326 klystrons
33 MW, 139 μs
drive beam accelerator 2.38 GeV, 1.0 GHz
1 km
delay loop
CR2
CR1
decelerator, 24 sectors of 876 m
BC2
245 m
TA radius = 120 m
e⁻ main linac, 12 GHz, 100 MV/m, 21.02 km
BDS
2.75 km
IP
BDS
2.75 km
e⁺ main linac
BC2
245 m
TA radius = 120 m
48.3k m
booster linac, 9 GeV
BC1
e⁻ injector, 2.4 GeV
e⁻ PDR 365 m
e⁻ DR 365 m
e⁺ DR 365 m
e⁺ PDR 365 m
e⁺ injector, 2.4 GeV
CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point

CLIC 500 GeV



circumferences
delay loop 73 m
CR1 293 m
CR2 439 m
819 klystrons
17.4 MW, 60 μs
drive beam accelerator
2.75 GeV, 1.0 GHz
2.5 km
delay loop
CR2
CR1
decelerator, 5 sectors of 878 m
time delay line
BC2
BDS
1.9km
IP
BDS
1.9km
BC2
245 m
245 m
TA r=305 m
e⁻ main linac, 12 GHz, 80 MV/m, 4.4 km
e⁺ main linac
TA radius = 305 m
13 km
CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump
booster linac,
2.86 to 9 GeV
BC1
e⁻ injector,
2.86 GeV
e⁻ PDR 389 m
e⁻ DR 427 m
e⁺ DR 427 m
e⁺ PDR 389 m
e⁺ injector,
2.86 GeV

CLIC parameters

Parameter	**Units**	3 TeV	500 GeV
Center of mass energy E_{CM}	GeV	3000	500
Repetition rate f_{rep}	Hz	50	50
Bunch population N_e	10^9	3.72	6.8
Number of bunches n_b		312	354
Bunch separation Δt_b	ns	0.5	0.5
Accelerating gradient G	MV/m	100	80
Bunch length σ_z	μm	44	72
IP beam size σ_x^*/σ_y^*	nm	40/1	200/2.26
Normalized emittance (IP) ϵ_x/ϵ_y	nm	660/20	2400/25
Estimated power consumption P_{wall}	MW	589	272
Site length	km	48.3	13.0

Why such small beam sizes?

The one pass configuration of the linear colliders requires very small beam sizes in order to compensate the very high frequency of circular colliders.

Luminosity

Luminosity is defined as the overlapping integral of the two bunch density distributions:

$$\mathcal{L} = f_{\text{rep}} n_b N^2 H_D \int \rho_{e^+}(x,y)\rho_{e^-}(x,y)dxdy$$

for Gaussian distributed beams:

$$\mathcal{L} = \frac{N_e^2 f_{\text{rep}} n_b}{4\pi\sigma_x^*\sigma_y^*} H_D$$

Event rate:

$$R = \mathcal{L}\sigma$$

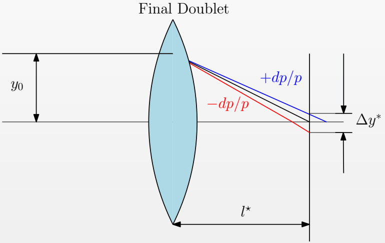
Dismounting luminosity:

$$\mathcal{L} = \frac{N_e^2 f_{\text{rep}} n_b}{4\pi\sigma_x^*\sigma_y^*} H_D = \frac{1}{4\pi}\left(\frac{N_e}{\sigma_x^*}\right) N_e f_{\text{rep}} n_b \frac{1}{\sigma_y^*} H_D$$

Luminosities of the order of $10^{34}\text{cm}^{-2}s^{-1}$ will require nanometer beam sizes.

Chromaticity in linear colliders

- Such small beam sizes are achieved by a very strong focalization.
- Due to small changes in the energy of the particles, the focal strength is different and they are focalized to different points.



Quadrupole chromaticity:

$$\xi_{x,y} = \int \beta_{x,y}(s) K_q(s) ds \quad \Rightarrow \quad \xi_{x,y} \sim \frac{l^*}{\beta^*_{x,y}}$$

Beam size dilution:

$$\sigma^*_y \approx \sigma^*_{y,0}\sqrt{1+\xi_y^2\sigma_\delta^2} \quad \Rightarrow \quad \sigma^*_{y,0} = \sqrt{\epsilon_y \beta^*_y}$$

Final Focus System function

- The resulting beam size increase due to chromaticity, even for small $\Delta p/p$, could be more than a factor 100 higher than the nominal beam size.
- Therefore, a compensation of the chromaticity is necessary.
- The Final Focus System (FFS) has the task to focalize the beam size to the nanometer level and to correct the aberrations introduced by such strong focalization.

Circular colliders style

- Chromatic compensation is usually carried out by sextupoles located in the arcs.
- Benefit from dispersion generated by the bending sections.
- LEP, LHC, DaΦne...

Linear colliders style

- Chromatic compensation is compensated in dedicated sections where we put sextupoles.
- One needs to create dispersion "artificially" at the sextupole locations.
- SLC, FFTB, CLIC, ILC, SuperKEKb, TLEP...

Schemes

There are two main schemes to focalize the beam and to compensate the chromaticity. The dedicated correction scheme and the local correction scheme

Chromaticity correction using Hamiltonian formalism

Chromaticity is corrected by means of sextupoles placed on high dispersive and high-β regions.

Quadrupole chromaticity

$$H_q = \frac{1}{2} k_q (1-\delta_p)(x^2 - y^2)$$

$$H_q = \frac{1}{2} k_q (x^2 - y^2) - \frac{1}{2} k_q \delta_p (x^2 - y^2)$$

Sextupole chromaticity

$$H_s = \frac{k_s}{3!}(x^3 - 3xy^2)$$

$$x \rightarrow x + \eta_x \delta_p$$

$$H_s = \frac{k_s}{3!}((x+\eta_x\delta_p)^3 - 3(x+\eta_x\delta_p)y^2)$$

$$H_s = \frac{1}{3!} k_s (x^3 - 3xy^2) + \frac{1}{2} k_s \eta_x \delta_p (x^2 - y^2) + \frac{1}{2} \eta_x^2 \delta_p^2 x + \frac{1}{3!} \eta_x^3 \delta_p^3$$

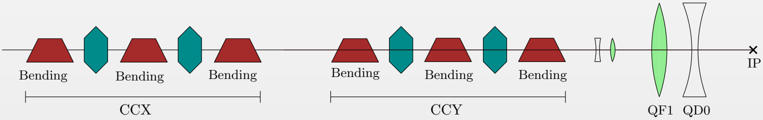
$$k_q y_q = k_s \eta_x y_s \Rightarrow \beta_y^q k_q = \beta_y^s k_s \eta_x \Rightarrow \xi_y^q = \xi_y^s$$

Remaining terms

- Geometrical sextupolar aberration: It is canceled by putting sextupoles in pairs with a $n\pi$ phase advance between them.
- Second order dispersion
- Purely chromatic term: It does not affect the dynamics of the system.

Dedicated correction scheme

- The first scheme proposed is the Dedicated (or Traditional) Final Focus Scheme.
- The chromaticity is corrected in two separated sections, one for horizontal correction and a second one for vertical correction.
- In each section there are bending magnets to create the required dispersion for correction.
- At the high dispersion and high β-function regions we place sextupoles in pairs ($-\mathcal{I}$ transformation).
- Dispersion D_x and its derivative D_x' are zero at the IP.



Stanford Linear Collider (SLC)

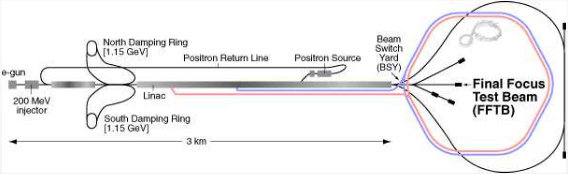
This chromatic correction system was used to reduce the beam size to 2.07 μm and 1.67 μm in the horizontal and vertical plane respectively where $\beta^*_{x,y} = 5$ mm.

Final Focus Test Beam (FFTB)

In 1995, minimum vertical spot size: $\sigma_y^* = 70$ nm with $\beta_y^* =$

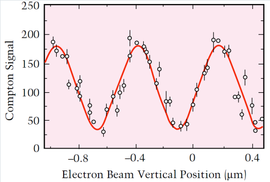
Test facilities: FFTB

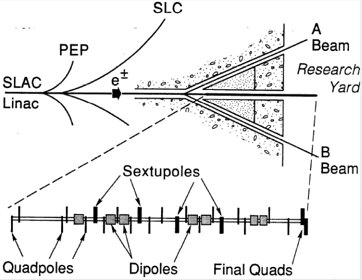
The Final Focus Test Beam (FFTB) was the first test facility of a prototype for the final focus system of the future linear colliders.



Results

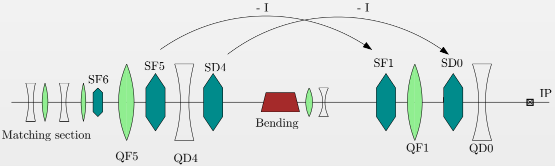
In 1995, a minimum spot size of 70 nm was achieved using a Laser Compton Beam Size Monitor.





Local Correction scheme

- An alternative was proposed in 2001 by P.Raimondi and A.Seryi.
- The correction is carried out locally thanks to a pair of interleaved sextupoles in the FD.
- A bending magnet creates dispersion in the FD region.
- A second pair of sextupoles is placed upstream of the bending section ($-\mathcal{I}$ transformation).
- Dispersion D_x is zero at the IP but its derivative D'_x is not.
- Shorter system and improved momentum bandwidth.



CLIC and ILC

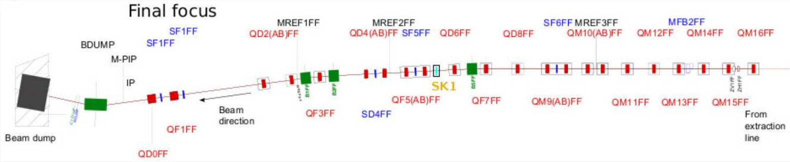
This is the current design in the linear collider baseline.

Accelerator Test Facility 2 (ATF2)

In 2013, the FFTB record was beaten achieving a vertical spot size of $\sigma_y^* = 60$ nm.

Test facilities: ATF2

The Accelerator Test Facility 2 is a prototype final focus system based on the local chromaticity correction scheme.



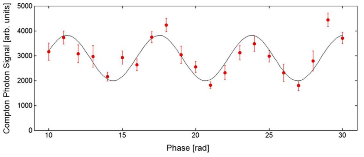
	ILC (500 GeV)	CLIC (3 TeV)	ATF2 (Nom.)	ATF2 (UL)
L^* [m]	3.5/4.5	3.5	1.0	1.0
ϵ_y [pm rad]	0.07	0.003	12	12
$\xi_y \sim (L^*/\beta_y^*)$	7300/9400	50000	10000	40000
$\sigma_\delta(\%)$	0.07/0.012	0.3	0.08	0.08
$\Delta\sigma_y/\sigma_y$	5/9, 7/11	150	8	32
σ_y [nm]	5.9	1.0	37	23
β_x^* [mm]	11	4.0	4.0	4.0
β_y^* [nm]	0.048	0.07	0.1	0.025

Test facilities: ATF2 Goals

The experimental validation of the local chromatic correction scheme relies on two main goals, beam size and stabilization.

Goal 1: Beam size

Last year, the minimum vertical beam size ever was achieved after long periods of beam tuning. The final beam size of 60 nm was reached several times during different runs.



Results are published in PRL **112** 034802 (2014).

Goal 2: Orbit Stabilization

- In order to keep constant luminosity in future linear colliders, not only the small beam size must be kept but also the stabilization of the beam at the IP.
- A ~ 2 nm beam size stabilization is required.
- A precise control of beam jitter sources and good feedback systems is crucial.

Beam-beam effects

When bunches cross each other, particles within the bunch experiment a very strong magnetic fields from the opposite beam.

Pinch effect

e^+ beam and e^- beam attract to each other. This effect enhances luminosity. Factor H_D in luminosity.

Disruption

Beams are strongly affected by the collision.

$$D_{x,y} \equiv \frac{\sigma_z}{f_{x,y}} = \frac{2Nr_e\sigma_z}{\gamma\sigma^*_{x,y}(\sigma^*_x + \sigma^*_y)}$$

Beamstrahlung emission

Photon emission due to the field of the opposite beam.

- Loose of energy.
- Luminosity spectrum.
- Flat beams

$$\Upsilon = \frac{2\hbar\omega_c}{3E} \approx \frac{5}{6}\frac{\gamma r_e^2 N}{\alpha\sigma_z(\sigma_x + \sigma_y)}$$

Beam induced background

- Coherent and Incoherent e^+e^- production.
- Hadronic jets, muons...

Hourglass effect and crossing angle

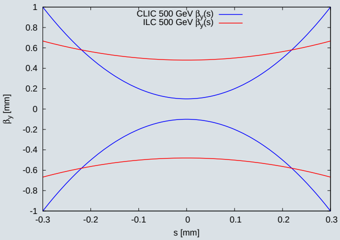
Apart from the beam-beam limitations, there exist some optical limitations.

Hourglass effect

Beam size is not constant in s.

$$\beta(s) = \beta_y^* \left(1 + \left(\frac{s}{\beta_y^*}\right)^2\right)$$

- Notably when $\beta_y^* \approx \sigma_z$.
- Natural limit on $\min(\beta_y^*)$



Crossing angle

Colliding beams with a certain crossing angle θ_c reduces luminosity.

$$\mathcal{L} \approx \mathcal{L}_{\text{head on}} \frac{1}{\sqrt{1+\Theta}}$$

Pivinsky angle:

$$\Theta \equiv \frac{\tan(\theta_c/2)\sigma_z}{\sigma_x}$$

Luminosity can be recovered using Crab Cavities.

In order to design and optimize the Final Focus System one has to take into account all these effects.

Final Focus System Design

Final Focus Design

During the last three years, I designed Final Focus Systems for CLIC and I compared its performance with the local chromatic correction FFS already designed as the baseline.

Motivation

The local chromaticity correction scheme presents a very complex and delicate tuning process. The traditional correction scheme could be much more easy to tune thanks to its simpler optics.

FFADA

The Final Focus Automatic Design and Analysis is a FORTRAN based code that generates the optics of a Final Focus System given a series of initial inputs like, beam parameters at the IP and some general constraints on the optics.

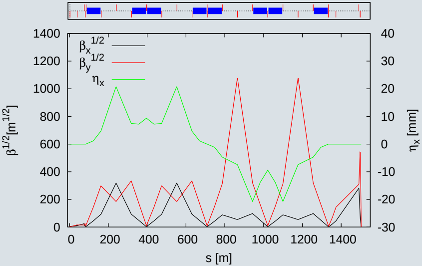
Objective

Design a competitive traditional FFS and apply tuning simulations in order to compare the final performance for CLIC at 3 TeV and 500 GeV c.o.m. energy.

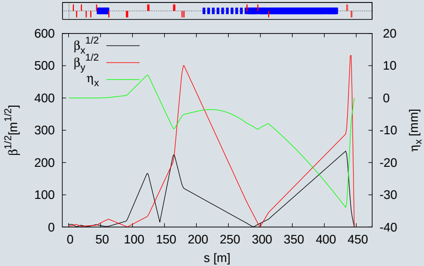
Final Focus System at $\sqrt{s} = 3$ TeV

Linear optics

Traditional scheme



Local scheme



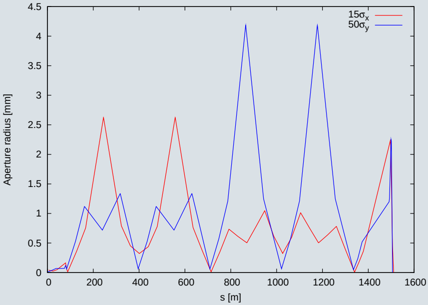
$$L^* = 3.5\text{m}$$
$$L_{\text{QD0}} = 2.67\text{m}$$
$$L_{\text{QF1}} = 3.27\text{m}$$
$$\beta^*_{x,y} = 7/0.07\text{mm}$$

$$L^* = 3.5\text{m}$$
$$L_{\text{QD0}} = 2.73\text{m}$$
$$L_{\text{QF1}} = 3.26\text{m}$$
$$\beta^*_{x,y} = 7/0.07\text{mm}$$

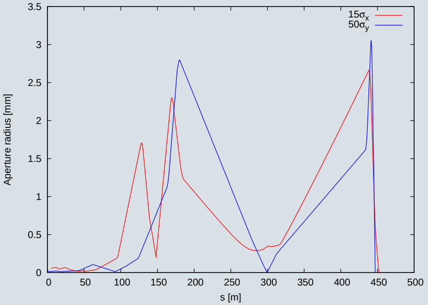
Apertures

Apertures are calculated taking into account: $15\sigma_x$ and $50\sigma_y$.

Traditional scheme



Local scheme



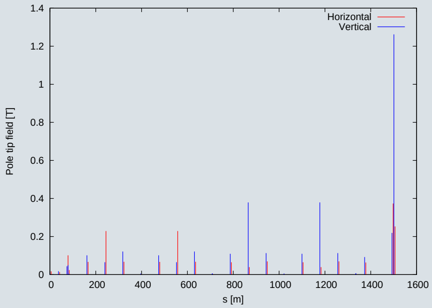
Max aperture: ~ 4 mm.

Max aperture: ~ 3 mm.

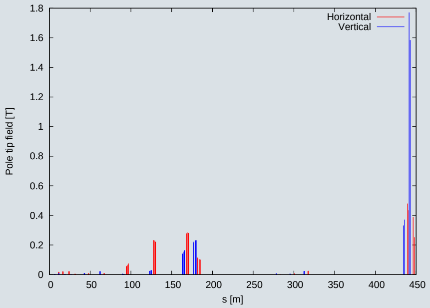
Quadrupole Pole tip Field

Pole tip fields are calculated at the aperture radius, i.e.: $15\sigma_x$ and $50\sigma_y$.

Traditional scheme



Local scheme



Max field: ~ 1.2 T.

Max field: ~ 1.7 T.

The Final Doublet magnets are the strongest and the ones that must be designed more carefully.

Chromaticity

Taylor map:

$$z_f = \sum_{jklmn} X_{z,jklmn} x_0^j p_{x0}^k y_0^l p_{y0}^m \delta_0^n$$

Chromaticity:

$$\xi_y^2 = \frac{1}{12\beta_y^*}\left(X_{y,00101}^2 \beta_{y0} + X_{y,00011}^2 \frac{1}{\beta_{y0}}\right)$$

Beam size dilution:

$$\sigma_y^* \approx \sigma_{y,0}^* \sqrt{1 + \xi_y^2 \sigma_\delta^2} \quad \Rightarrow \quad \sigma_{y,0}^* = \sqrt{\epsilon_y \beta_y^*}$$

Scheme	Energy [GeV]	L_{FFS} [m]	ξ_y	$\sigma_y^*/\sigma_{y,0}^*$
Local	3000	450	23005	229.7
Traditional	3000	1500	32242	327.1

The traditional chromatic correction scheme is more chromatic due to the high-β functions at the sextupoles.

Nonlinear optimization

After sextupole optimization, the effects of chromatic aberrations are reduced.

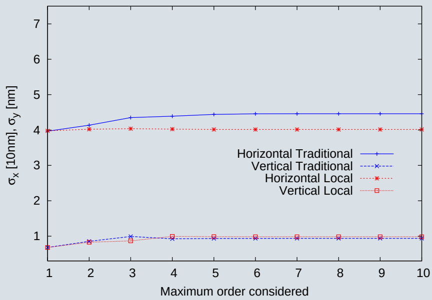
MAPCLASS

Allows the computation of the beam size at different orders.

$$z_f = \sum_{jklmn} X_{z,jklmn} x_0^j p_{x0}^k y_0^l p_{y0}^m \delta_0^n$$

$$\langle x_f^2 \rangle = \sum_{\substack{jklmn \\ j'k'l'm'n'}} X_{z,jklmn} X_{z,j'k'l'm'n'} \times$$

$$\int x_0^{j+j'} p_{x0}^{k+k'} y_0^{l+l'} p_{y0}^{m+m'} \delta_0^{n+n'} \rho_0 dv_0$$



Local: $\sigma_x^*(10) = 40.1\,\mathrm{nm}, \sigma_y^*(10) = 0.98\,\mathrm{nm}$
New tradtional: $\sigma_x^*(10) = 42.1\,\mathrm{nm}, \sigma_y^*(10) = 0.84\,\mathrm{nm}$

Luminosity

- In the end, the performance of the FFS and the accelerator is given by the luminosity it delivers.
- Luminosity is calculated with GuineaPig after a beam tracking in Placet including SR effects.
- Peak luminosity is the luminosity delivered by those particles with energy ≥ 0.99 of the nominal energy (Luminosity spectrum due to Beamstrahlung).

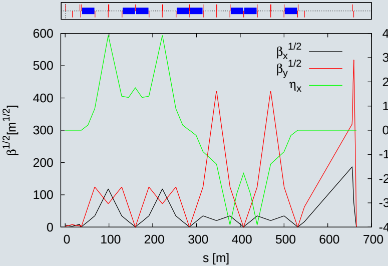
Scheme	Energy [GeV]	$\mathcal{L}_{\mathrm{T}}$ $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$\mathcal{L}_{1\%}$ $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$\mathcal{L}_{1\%}/\mathcal{L}_{1\%}^{(\mathrm{w/o\ SR})}$
Local	3000	7.8	2.4	0.79
Traditional	3000	7.5	2.4	0.76

The Local and the Traditional deliver approximately the same total luminosity and the same peak luminosity.

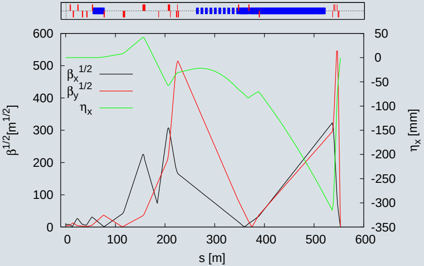
Final Focus System at $\sqrt{s} = 500$ GeV

Linear optics

Traditional scheme



Local scheme

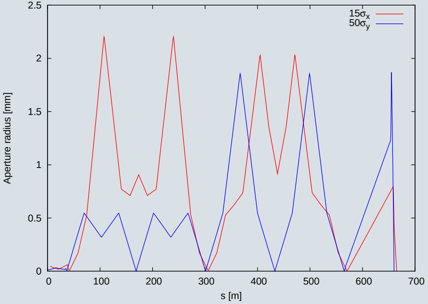


$$L^* = 4.3\text{m}$$
$$L_{\text{QD0}} = 1.26\text{m}$$
$$L_{\text{QF1}} = 0.88\text{m}$$
$$\beta^*_{x,y} = 8/0.1\text{mm}$$

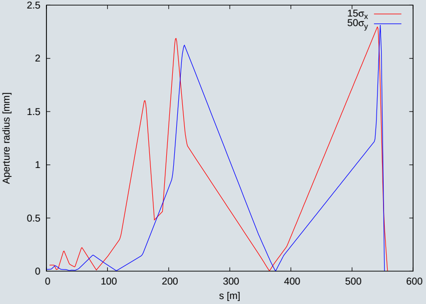
$$L^* = 4.3\text{m}$$
$$L_{\text{QD0}} = 3.35\text{m}$$
$$L_{\text{QF1}} = 4.0\text{m}$$
$$\beta^*_{x,y} = 8/0.1\text{mm}$$

Apertures and Pole tip Field

Traditional scheme



Local scheme

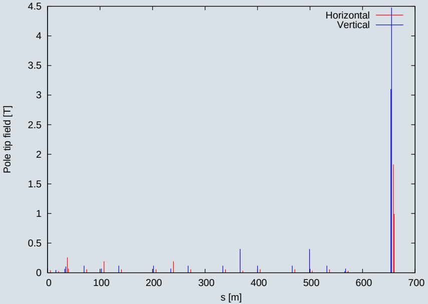


Maximum aperture $\sim$ 2.2 mm.

Maximum aperture $\sim$ 2.4 mm.

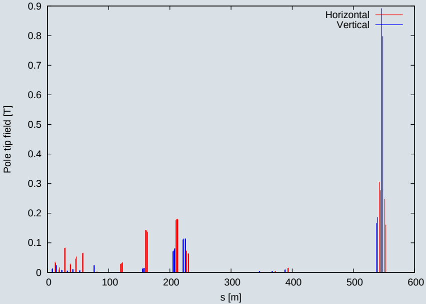
Apertures and Pole tip Field

Traditional scheme



Maximum field ∼ 4.5 T. Optimization will require longer FD magnets.

Local scheme



Maximum field ∼ 0.9 mm.

Chromaticity

Taylor map:

$$z_f = \sum_{jklmn} X_{z,jklmn} x_0^j p_{x0}^k y_0^l p_{y0}^m \delta_0^n$$

Chromaticity:

$$\xi_y^2 = \frac{1}{12\beta_y^*}\left(X_{y,00101}^2 \beta_{y0} + X_{y,00011}^2 \frac{1}{\beta_{y0}}\right)$$

Beam size dilution:

$$\sigma_y^* \approx \sigma_{y,0}^* \sqrt{1 + \xi_y^2 \sigma_\delta^2} \quad \Rightarrow \quad \sigma_{y,0}^* = \sqrt{\epsilon_y \beta_y^*}$$

Scheme	Energy [GeV]	L_{FFS} [m]	ξ_y	$\sigma_y^*/\sigma_{y,0}^*$
Local	500	553	19231	197.8
Traditional	500	660	22186	227.9

Nonlinear optimization

After sextupole optimization, the effects of chromatic aberrations are reduced.

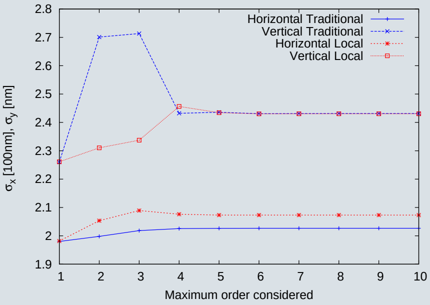
MAPCLASS

Allows the computation of the beam size at different orders.

$$z_f = \sum_{jklmn} X_{z,jklmn} x_0^j p_{x0}^k y_0^l p_{y0}^m \delta_0^n$$

$$\langle x_f^2 \rangle = \sum_{\substack{jklmn \\ j'k'l'm'n'}} X_{z,jklmn} X_{z,j'k'l'm'n'} \times$$

$$\int x_0^{j+j'} p_{x0}^{k+k'} y_0^{l+l'} p_{y0}^{m+m'} \delta_0^{n+n'} \rho_0 dv_0$$



Local: $\sigma_x^*(10) = 207\,\mathrm{nm}, \sigma_y^*(10) = 2.43\,\mathrm{nm}$
Traditional: $\sigma_x^*(10) = 203\,\mathrm{nm}, \sigma_y^*(10) = 2.43\,\mathrm{nm}$

Luminosity

- In the end, the performance of the FFS and the accelerator is given by the luminosity it delivers.
- Luminosity is calculated with GuineaPig after a beam tracking in Placet including SR effects.
- Peak luminosity is the luminosity delivered by those particles with energy ≥ 0.99 of the nominal energy (Luminosity spectrum due to Beamstrahlung).

Scheme	Energy [GeV]	$\mathcal{L}_T$ [10^{34}cm^{-2}s^{-1}]	$\mathcal{L}_{1\%}$ [10^{34}cm^{-2}s^{-1}]	$\mathcal{L}_{1\%}/\mathcal{L}_{1\%}^{(\text{w/o SR})}$
Local	500	2.3	1.4	0.99
Traditional	500	2.2	1.3	0.94

- In this case, the performance is even more similar than in the 3 TeV case.

Partial conclusion

- From the point of view of the optics design and luminosity performance, both, traditional and local chromatic correction schemes, are similar.

Tuning

Tuning simulation

- When we consider realistic imperfections, the machine performance decreases and luminosity drops dramatically.
- Luminosity can drop from 10^{34} cm^{-2}s^{-1} to 10^{28} cm^{-2}s^{-1}
- Some tuning techniques to recover the nominal performance are required.
- Here we apply BBA+Knobs techniques.

Tuning set up

- 100 randomly misaligned machines (seeds).
- Initial misalignment: 10 μm RMS (x, y) for all elements.
- BPM resolution: 10 nm.
- Dipole correctors: BPM+Quad+Corrector.
- Placet for tracking and GuineaPig for luminosity measurement.
- Four lattices: Traditional and local at $\sqrt{s} = 3$ TeV and $\sqrt{s} = 500$ GeV.

Alignment algorithm

The alignment algorithm is based on sequential applications of orbit correction and knobs based on sextupole positions.

- Multipoles OFF:
  - 1:1 correction

$$\begin{pmatrix} b_x \\ b_y \end{pmatrix} = \begin{pmatrix} R_{xx} & 0 \\ 0 & R_{yy} \end{pmatrix} \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix}$$

  - DFS

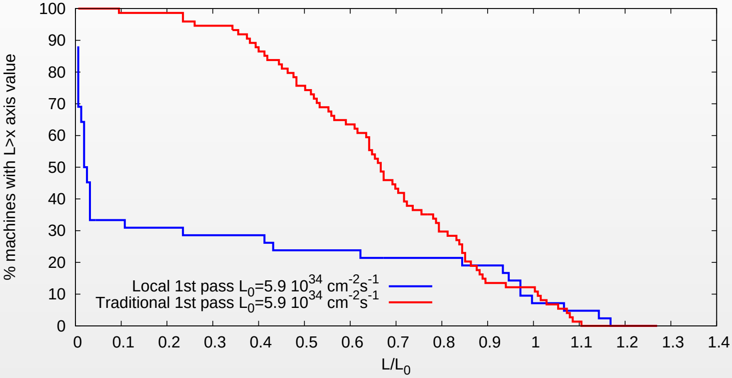
$$\begin{pmatrix} b \\ \omega_1(\eta - \eta_0) \\ 0 \end{pmatrix} = \begin{pmatrix} R \\ \omega_1 D \\ \beta I \end{pmatrix} \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix}$$

- Multipole Knobs
- Multipoles ON:
  - DFS

$$\begin{pmatrix} b \\ \omega_1(\eta - \eta_0) \\ 0 \end{pmatrix} = \begin{pmatrix} R \\ \omega_2 D \\ \beta I \end{pmatrix} \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix}$$

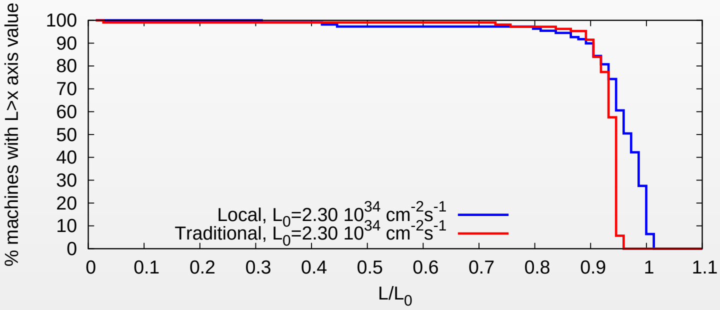
  - Multipole Knobs

Tuning simulation results 3 TeV



- The first observation is that the tuning simulation after just one pass is not satisfactory in any case.
- But, although the local scheme presents more luminosity, it seems that the traditional scheme is easier to tune.
- In both cases something more iterations of the algorithm are required and a Simplex optimization on top has demonstrated to work fine.

Tuning simulation results 500 GeV



- Unlike the 3 TeV case, both systems seems to be equal from the point of view of the tuning.
- Simplex algorithm has been applied on top of this results improving the results even more.

Tuning results

- The number of luminosity measurements per pass is ~ 1200.
- We consider that fast luminosity measurement takes approximately 1 second.
- Therefore, the tuning time is about $20 - 30$ minutes per pass.
- The results show a clear better performance of the traditional FFS at high energies. At low energies both perform similarly.

Summary and Conclusions

Summary

- We have designed two Final Focus Systems based on the Traditional Chromatic Corrections for CLIC at 3 TeV and 500 GeV center of mass energy.
- We have carried out tuning simulations based on BBA and knobs based on sextupole positions for all the systems at different energies.

Conclusions

- Traditional Final Focus Systems perform as well as the Local chromaticity correction systems in terms of luminosity.
- At high energies the Traditional system is about 3 times longer than the local system but they are comparable in length for low energies (500 GeV).
- Tuning simulations reveal that Traditional system are much easier to tune than the local scheme at high energies.
- Reconsider the FFS baseline for CLIC at high energies in order to introduce the Traditional Chromatic Correction scheme?

Thank you!

Backup

CLIC 500 GeV β_x^* reduction

Motivation

- Flat beams are required to avoid big beamstrahlung photon emission.
- Therefore we set $\sigma_x^* >> \sigma_y^*$. This is achieved normally using $\beta_x^* >> \beta_y^*$.
- But running at low energies (500 GeV), the impact of such radiation is lower.

- Idea: Reduce β_x^* until the limit imposed by physics requirements.

Why?

- It implies a luminosity gain.
- Keeping the same luminosity, reduction of the bunch charge and, probably, a cost reduction.
- Some luminosity recovery if lower energies are considered.

Why not?

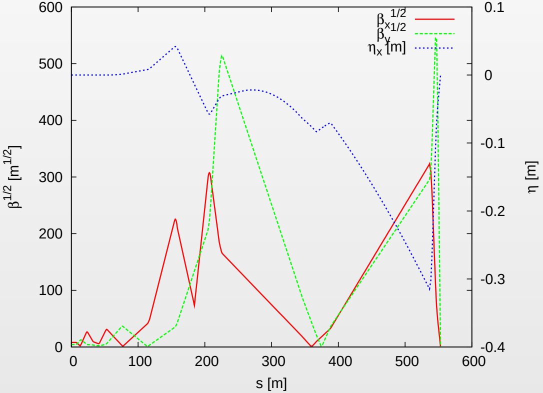
- It reduces the $\mathcal{L}_{1\%}/\mathcal{L}_T$ ratio, because ...
- ... it increases the beam induced background due to beamstrahlung. Experiments affected.

CLIC 500 GeV CDR parameters

Parameter	**Units**	CLIC500
Beam energy E_0	GeV	250
Bunches per beam n_b		354
$e^{\pm}$ per bunch N	10^9	6.8
Repetition rate f_{rep}	Hz	50
Hor. emittance ϵ_x^N	nm	2400
Vert. emittance ϵ_y^N	nm	25
Hor. beta β_x	mm	8.0
Vert. beta β_y	mm	0.1
Hor. beam size σ_x^*	nm	200
Vert. beam size σ_y^*	nm	2.26
Bunch length σ_z	μm	72
Energy spread δ_E	%	1.0
Luminosity $\mathcal{L}_T$	$10^{34} \cdot \text{cm}^{-2}\text{s}^{-1}$	2.3
Peak Luminosity $\mathcal{L}_{1\%}$	$10^{34} \cdot \text{cm}^{-2}\text{s}^{-1}$	1.4

CLIC 500 GeV FFS CDR

The lattice with CDR parameters fulfills the luminosity requirements but with no margin of error.



Placet+GuineaPig

$$\beta_x^* = 8\text{mm}$$

$$\beta_y^* = 0.1\text{mm}$$

$$\sigma_x^* = 210.4\,\text{nm}$$

$$\sigma_y^* = 2.51\,\text{nm}$$

$$\mathcal{L}_T = 2.31\,\text{s}^{-1}\text{cm}^{-2}$$

$$\mathcal{L}_{1\%} = 1.40\,\text{s}^{-1}\text{cm}^{-2}$$

$$\Upsilon = 0.61$$

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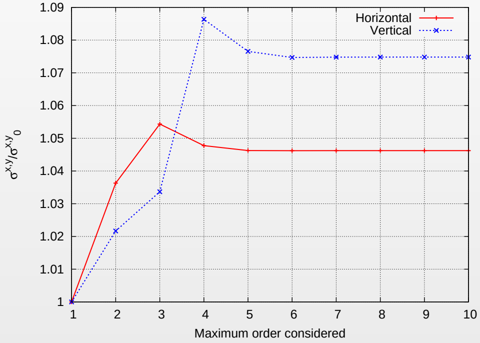

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$$\Upsilon = 0.61 \rightarrow n_\gamma = 1.32$$

Beyond Standard Parameters?

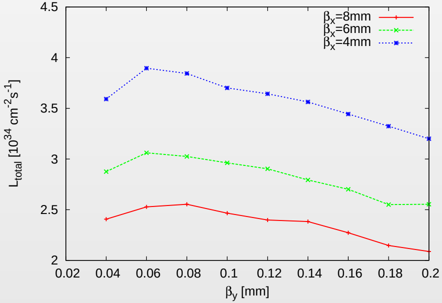
As in any optimization problem one question arises: Can we push the limits of β_x^* and β_y^* and make them even smaller?

Reducing β_y^* and β_x^* in CLIC 500 GeV FFS

Let's start using ideal distributions at the IP...

β_y^*

The nominal value for β_y^* is 0.1 mm. We scan a wide range of β_y^* to find the optimal value that maximizes both $\mathcal{L}_{1\%}$ and $\mathcal{L}_T$.



β_x^*

The nominal value for β_x^* is 8 mm. Reducing β_x^* we can increase the total luminosity while keeping the ration $\mathcal{L}_{1\%}/\mathcal{L}_T$ in a reasonable value.

- Is there any natural limit on $\min(\beta_x^*)$ in the system design?
- What is the minimum value for $\mathcal{L}_{1\%}/\mathcal{L}_T$ we can consider?

Luminosity and Beamstrahlung

$$\mathcal{L} = \frac{N^2 f_{\text{rep}} n_b}{4\pi\sigma_x^*\sigma_y^*} H_D, \quad \Upsilon = \frac{N^2 e\gamma}{\sigma_z(\sigma_x^* + \sigma_y^*)}$$

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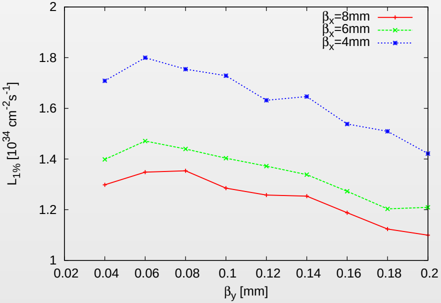

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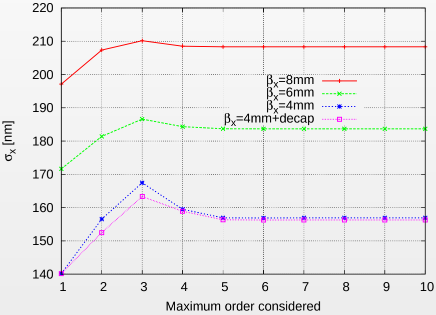
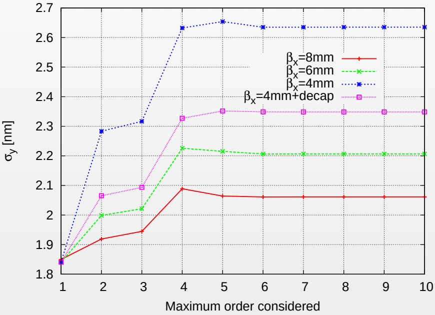
Reducing β_x^*

One expects that some aberrations due to the β_x^* reduction will dilute the beam size in both planes due to uncorrected aberrations. Can we deal with them?





When we reduce β_x^*, we see that σ_x^* does not suffer from severe degradation due to aberrations. This is not the case for σ_y^* where we see that making β_x^* half of its nominal value sends the vertical aberrations to a 44% of the linear vertical beam size.

CLIC $\sqrt{s} = 500$ GeV optimization

We take $\beta_y^* = 0.065$ mm as the optimal value and we scan β_x^*.

β_x^* [mm]	σ_x^* [nm]	σ_y^* [nm]	$\mathcal{L}_T$ [10^{34}cm^{-2}s^{-1}]	$\mathcal{L}_{1\%}$	$\mathcal{L}_{1\%}/\mathcal{L}_T$	n_γ
[1] 8	210.1	2.51	2.31	1.40	0.61	1.32
8	213.3	2.20	2.34	1.45	0.62	1.30
6	189.2	2.36	2.70	1.56	0.58	1.47
4	163.6	2.84	3.12	1.61	0.52	1.74
4+decap	162.8	2.56	3.20	1.65	0.52	1.74

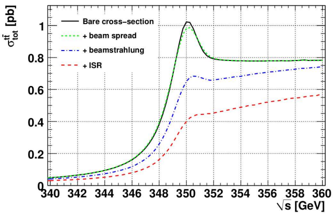
We observe an important luminosity gain in absolute terms but as long as we reduce β_x^* the ratio between peak and total luminosity decreases mainly due to the photon emission.

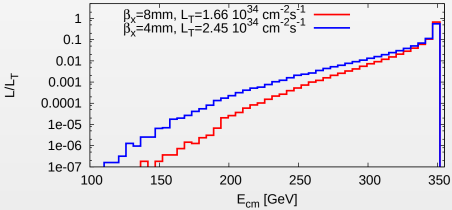
- What is the minimum β_x we can reach? 8mm, 4mm, 2mm?
- What is the minimum luminosity ratio required for physics experiments?

[1] CDR lattice with $\beta_y^* = 0.1$ mm

Luminosity spectrum

As we have seen, the smaller the horizontal beam size, the more photons due to Beamstrahlung emission are produced. This effect may reduce the ratio $L_T/L_{1\%}$ creating a long tail in the luminosity spectrum.





Top quark threshold

Precision measurements of the top quark mass at the threshold are mainly limited by Beamstrahlung emission. Although a β_x^* reduction could yield to a higher luminosity, the measurement can be suffer from the luminosity quality.

Charge scaling

Luminosity:

$$\mathcal{L} = \frac{N^2 f_{\text{rep}} n_b}{4\pi\sigma_x^*\sigma_y^*} H_D = \frac{N}{\sigma_x^*}\frac{\eta P_{\text{wall}}}{4\pi\sigma_y^*} H_D$$

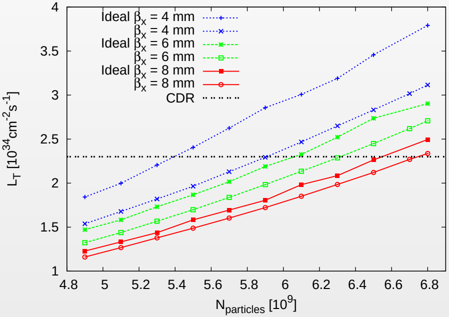
Options

- Bunch population reduction:

$$\beta_x^* \downarrow \Rightarrow N \downarrow \Rightarrow \frac{N}{\sigma_x^*} = \text{const.} \Rightarrow \mathcal{L} = \text{const.}$$

- Luminosity increase:

$$\beta_x^* \downarrow \Rightarrow N = \text{const.} \Rightarrow \frac{N}{\sigma_x^*} \uparrow \Rightarrow \mathcal{L} \uparrow$$



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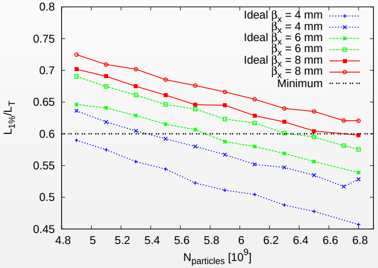
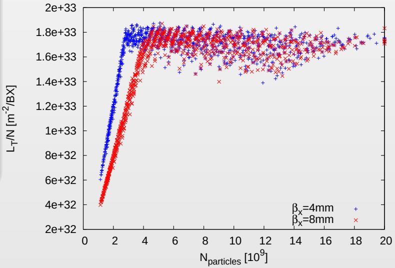
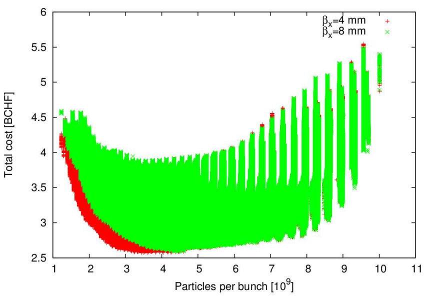
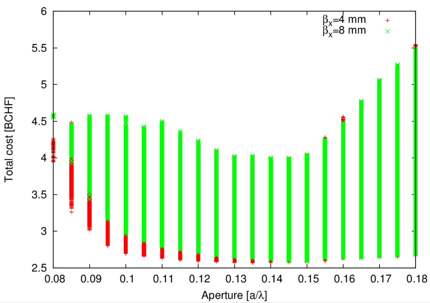




Cost optimization





- Some cost gain is seen for low bunch charges, but it does not imply a big impact.
- Luminosity for this cases would be very small even with lower β_x^*

Running at lower energies (250 GeV and 350 GeV)

To be able to reduce β_x^* a factor 2 is very convenient in case of running at lower energies.

- Due to linac considerations, the number of particles per bunch N is proportional to the energy of the beam E.
- Since luminosity $\mathcal{L}$ is proportional to N^2, from 350 GeV to 250 GeV this implies a luminosity reduction factor of 2.7.
- If we keep the ratio N/σ_x^* constant, the luminosity reduction factor is only 1.7, a 60% less.
- Therefore, the β_x^* reduction can partially mitigate the effect of the energy reduction.

Detail

$$N \sim G \sim E, \qquad \mathcal{L} \sim \frac{N^2}{\sigma_x^* \sigma_y^*}, \qquad \sigma_{x,y}^* \sim \gamma^{-1/2}$$

$$\mathcal{L} \sim N^2 \gamma \sim E^3$$

$$\text{Keep: } \; N/\sigma_x^* = \text{const.}$$

$$\mathcal{L} \sim \frac{N}{\sigma_x^*} N \gamma^{1/2} \sim E^{3/2}$$

Conclusions and future prospects

Conclusions

- We have designed a lattice with half of the nominal β_x^*.
- It could imply a luminosity gain of $> 30\%$.
- It can be used to reduce bunch charge keeping the same luminosity.
- The reduction of the cost is not very large.
- The β_x^* reduction could be very useful for lower energy options.

Future prospects

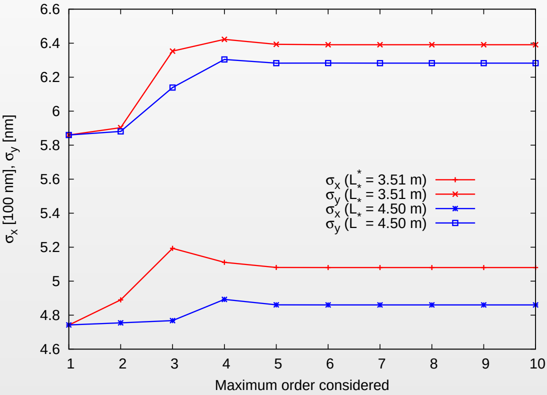
- Study the impact of such aggressive lattice on the physics.
- Study in detail lower energies: Higgs peak production and top threshold (250 and 350 GeV).

ILC Final Focus System

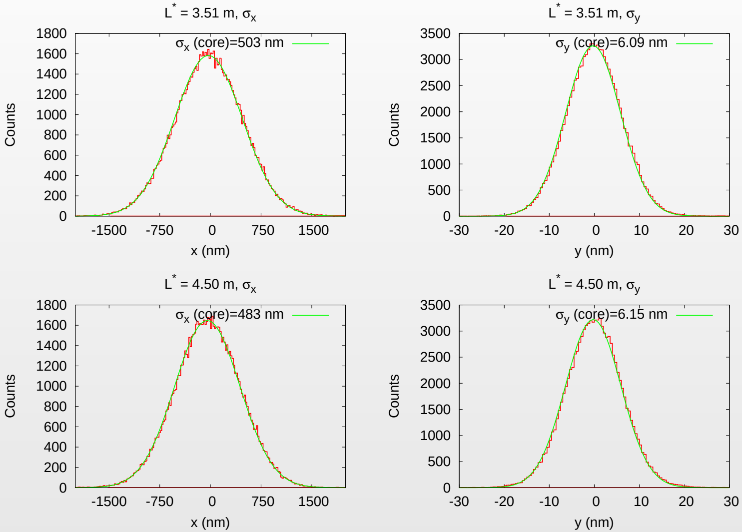
ILC Final Focus System optimization

Parameter	**Units**	CLIC500	ILC500
Beam energy E_0	GeV	250	250
Bunches per beam n_b		354	1314
$e^{\pm}$ per bunch N	10^9	6.8	20
Repetition rate $f_{\rm rep}$	Hz	50	5
Hor. emittance ϵ_x^N	μm	2.4	10.0
Vert. emittance ϵ_y^N	nm	25	35
Hor. beta β_x^*	mm	8.0	11.0
Vert. beta β_y^*	mm	0.1	0.48
Hor. beam size σ_x^*	nm	200	474
Vert. beam size σ_y^*	nm	2.26	6.0
Bunch length σ_z	μm	72	300
Energy spread δ_E	%	1.0	0.125
Main tunnel length	km	48.3	13.2
Luminosity $\mathcal{L}_T$	$10^{34} \cdot {\rm cm}^{-2}{\rm s}^{-1}$	2.3	1.47

Nonlinear optimization



ILC tracking



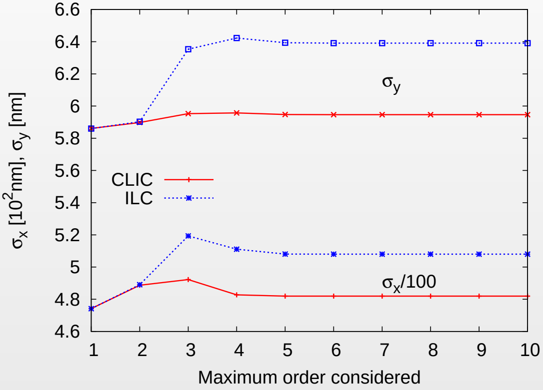
ILC luminosity

L^*	3.51 m	4.50 m
$\mathcal{L}_T[10^{34}\mathrm{cm}^{-2}s^{-1}]$	1.38	1.54
$\mathcal{L}_{1\%}[10^{34}\mathrm{cm}^{-2}s^{-1}]$	0.867	0.934

CLIC as ILC Final Focus System

QD0	L^*	L_{quad}	β_x	β_y	$KL_{\mathrm{quad}}[\mathrm{m}^{-1}]$
ILC	3.51	2.2	2247	37776	-0.167
ILC	4.50	2.2	3285	56318	-0.152
CLIC	4.30	3.35	9387	62914	-0.129
QF1					
ILC	3.51	2.0	37583	16156	0.072
ILC	4.50	2.0	32017	26206	0.080
CLIC	4.30	4.0	69747	20642	0.054

CLIC as ILC Final Focus System



CLIC as ILC Final Focus System

Parameter	ILC	CLIC-based
Length [m]	735	553
β_x^*/β_y^* [mm]	11/0.48	11/0.48
$\sigma_x^{\rm core}$ [nm]	503.0	483.7
$\sigma_y^{\rm core}$ [nm]	6.09	5.89
$\mathcal{L}_T$ [$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1.38	1.47
$\mathcal{L}_{1\%}$ [$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	0.86	0.89

ILC travelign focus

ATF2 studies

ATF2 studies

TLEP chromatic correction

TLEP Chromatic correction

Cancellation of geometric aberrations

$$H_s = \frac{k_s}{3!}((x + \eta\bar{\delta})^3 - 3(x + \eta\bar{\delta})y^2) =$$

$$= \frac{k_s}{3!}(x^3 - 3xy^2) + \frac{k_s}{2}\eta\bar{\delta}(x^2 - y^2) + \frac{k_s}{2}\eta^2\bar{\delta}^2 x + \frac{k_s}{3!}\eta^3\bar{\delta}^3$$

$$e^{:H_{\text{ccs}}:} = e^{:H_c:}e^{:H_g:}(-\mathcal{I})e^{:H_g:}e^{:H_c:} =$$

$$= (-\mathcal{I})e^{:H_c:}(e^{:-H_g:}e^{:H_g:})e^{:H_c:} =$$

$$= (-\mathcal{I})e^{:2H_c:}$$

Synchrotron radiation effects

Table: Synchrotron radiation contribution due to bending magnets and quadrupole magnets effect in % of the RMS beam size.

Scheme	E_{cm} [GeV]	$\Delta\sigma_x/\sigma_{x0}$ (Bend) [%]	$\Delta\sigma_y/\sigma_{y0}$ (Quads) [%]
Local	3000	15.0	110
Traditional	3000	10.2	78.8
Local	500	0.2	1.6
Traditional	500	0.1	47.7