Beam dynamics in the final focus section of the future linear collider

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LAL, CERN

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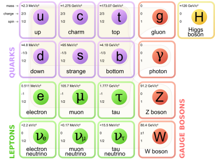
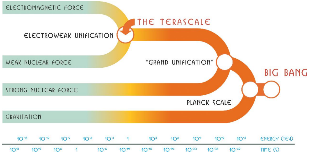
The need of colliders to explore particle physics

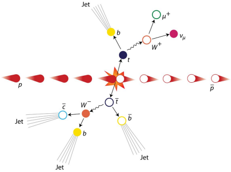
The Standard Model



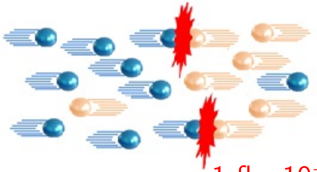
being explored at TeV scale (and beyond)



with enough interactions to measure particle properties



event!



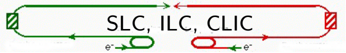
1 fb=10^{-39}cm^2

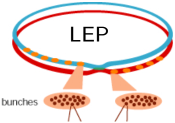
$$R = \sigma \mathbf{L}$$

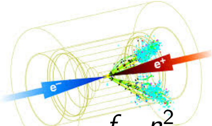
Rate of events **Luminosity**

Interaction Cross Section

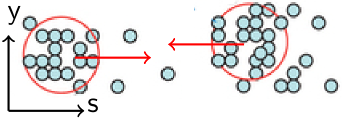
Luminosity







$$\mathbf{L} \propto \frac{f_{rep} n_b^2}{\sigma_x \sigma_y}$$



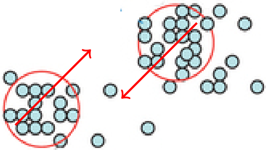
(@LHC, L is of the order of $10^{34}[\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}]$)

Symbol, [Unit]	LEP	SLC	ILC	CLIC 500 GeV	CLIC 3 TeV
E, [TeV]	0.1046	0.050	0.250	0.250	1.500
n_b	1.7×10^{11}	3.3×10^{10}	2×10^{10}	6.8×10^{9}	3.72×10^{9}
f_{rep}, [Hz]	11.2×10^{3}	120	5	50	50
σ_x/σ_y, [nm]	$(200/2.5) \times 10^{3}$	$(2.1/0.6) \times 10^{3}$	474/5.9	202/2.3	40/1
L, $[\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}]$	2.1×10^{31}	0.8×10^{30}	1.57×10^{34}	2.3×10^{34}	5.9×10^{34}

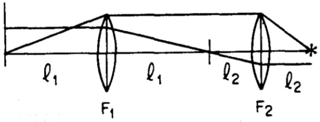
Linear colliders feature **nm beam size** to achieve 10^{34} luminosities.

Challenges for luminosity goals and nm beam size

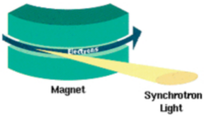
Beam-beam effects



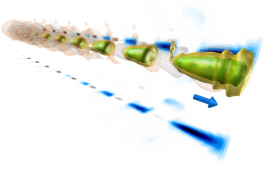
Demagnify the beam



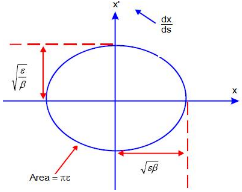
Synchrotron radiation



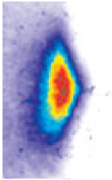
Beam positioning and stabilization



Small emittance beam generation and reduction



Small energy spread in the bunch

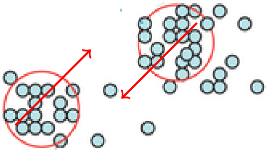


Challenges for luminosity goals and nm beam size

These are addressed in several sections of an accelerator.

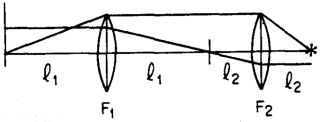
Beam-beam effects

IP Region



Demagnify the beam

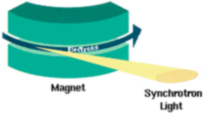
Final Focus Section (FFS)



Synchrotron radiation

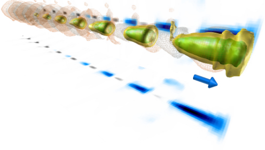
FFS, Damping Rings

IP Region



Beam positioning and stabilization

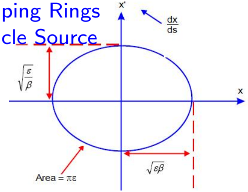
ALL



Small emittance beam generation and reduction

Damping Rings

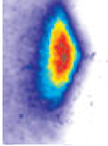
Particle Source



Small energy spread in the bunch

Particle Sources

LINACs



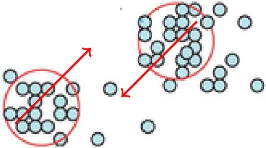
Challenges for luminosity goals and nm beam size

These are addressed in several sections of an accelerator.

Main contributions from this work to the FFS.

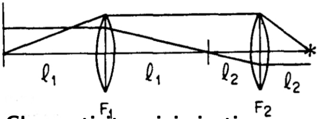
Beam-beam effects

IP Region



Demagnify the beam

Final Focus Section (FFS)



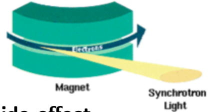
Chromaticity minimization

Chromaticity correction

Synchrotron radiation

FFS, Damping Rings

IP Region

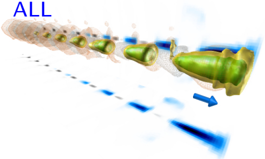


Oide effect

Rad. in bending magnets

Beam positioning and stabilization

ALL

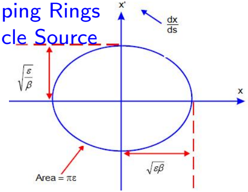


IP-BPMs @ ATF2

Small emittance beam generation and reduction

Damping Rings

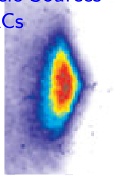
Particle Source



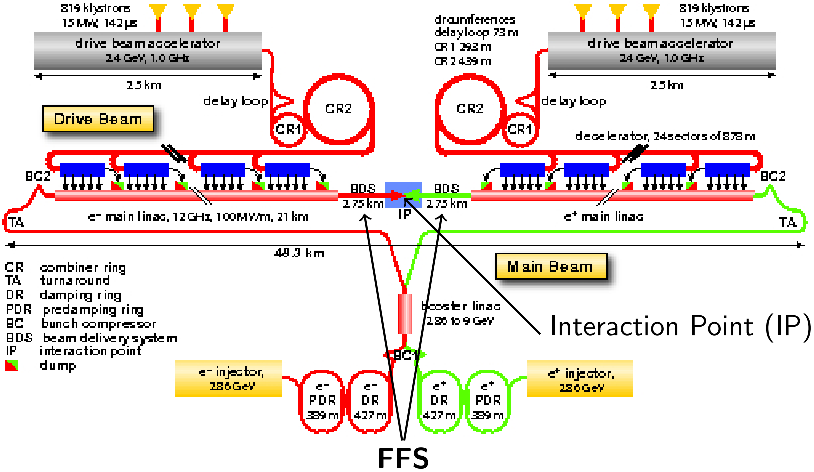
Small energy spread in the bunch

Particle Sources

LINACs

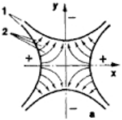


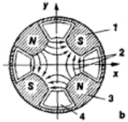
Sections of a Collider (CLIC 3 TeV as an example)

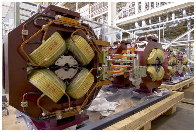


Beam demagnification, positioning and stabilization with low effect of radiation

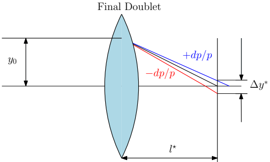
Final Focus Section (FFS)







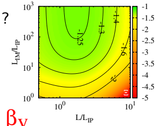
Focusing elements are magnets with 4 poles: quadrupoles

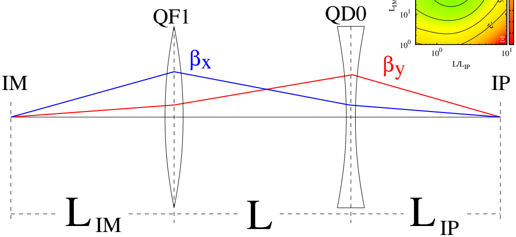


Quads behave as lenses: chromatic effect

The stronger set of lenses is the Final Doublet (FD): **QD0**, **QF1**

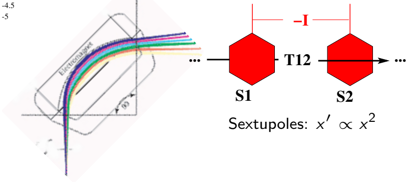
What are the distances to minimize the chromaticity ?





Correction of Chromatic effect

Bending magnets: $x = \eta_x \delta$

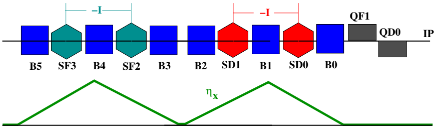


Sextupoles: $x' \propto x^2$

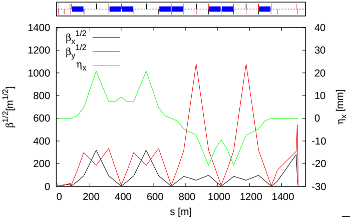
Chromaticity correction

Current **CLIC**, **ILC** and **ATF2** lines

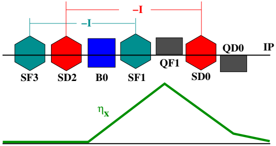
Local chromaticity correction (Brown, 1988)



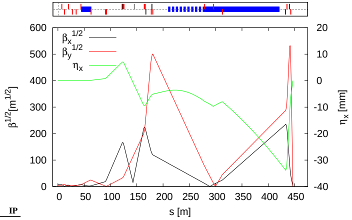
Easier to correct static errors, Longer line

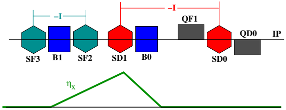


Local chromaticity correction (Raimondi, 2000)



More difficult to correct static errors, Shorter line



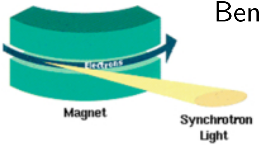


Recent proposal: The non-interleaved line (Tomas, Blanco, Bambade, 2014)

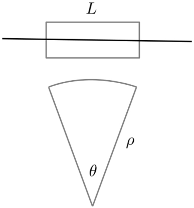
Final focus and small beam size

Radiation in bending magnets

Radiation effect in bending magnets



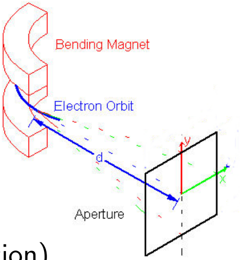
Bending magnets generate energy losses



$$\Delta E \propto \frac{E^4}{\rho m_0^4}$$

Energy loss is the principal limitation for circular lepton colliders.
The highest energy lepton collision, 209 GeV, have been reached with electron and positron coliding beams in LEP (circular tunnel of 27 km) at CERN.

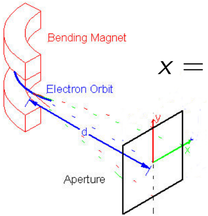
The effect on the beam size was calculated by Sands (SLAC/AP-47, Dec. 1985).



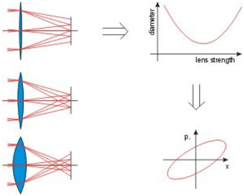
$$x = \sum_{i=1}^{N(T)} \Delta x_{i,total} - x_0$$

N: is the number of photons radiated (Poisson distribution)

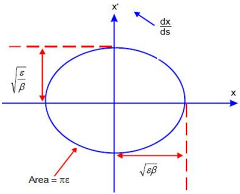
A generalization was required



$$x = \eta\delta$$



α



Sands expression was valid for $\alpha = 0$, $\eta = 0$.
During the design process not always the focus is perfect $\alpha = 0$, nor the η is perfectly corrected.

$$\sigma^2_{rad} \approx \int E^5 G^3(s) H(s) \cos^2(s) ds$$

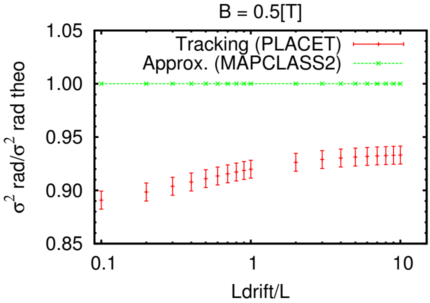
It becomes:

$$\sigma^2_{rad} \approx \int \frac{E^5}{\rho^3} \left\{ \sqrt{\frac{\beta_L}{\beta_s}} \left[\eta \cos\Delta\phi(s,L) + (\alpha\eta + \beta\eta')\sin\Delta\phi(s,L)\right] - \eta_L \right\}^2 ds$$

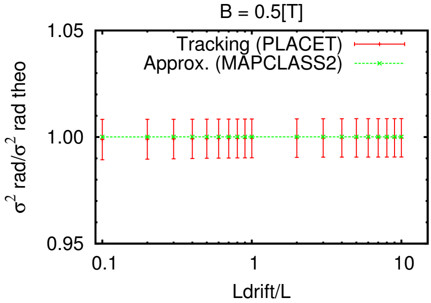
included in MAPCLASS2, lattice optimization code (published in CLIC-Note-1049).

Comparing theory with the tracking code PLACET

PLACET 0.99.01



PLACET 0.99.02

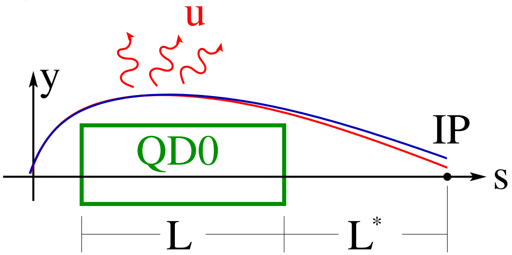


1) The lattice optimization of the line's optics now includes radiation!
2) This lead to an improvement in the tracking code calculations!

Oide effect

Oide effect

Radiation in a focusing magnet changes the energy of the particle and limits the focusing effect.



Designed particle trajectory, trajectory of a particle due to radiation in the quadrupole.

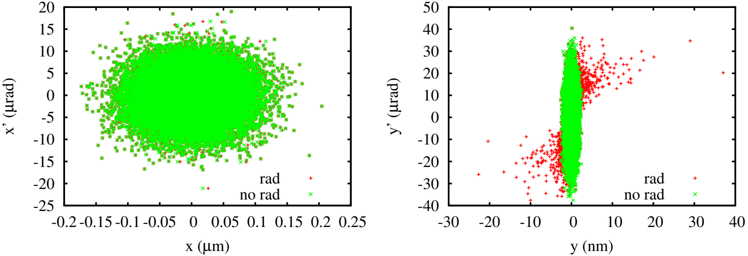
Oide limit

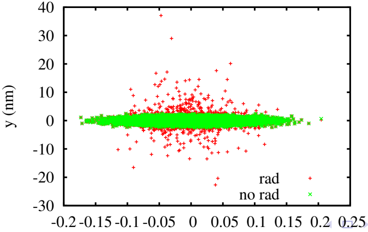
The minimum beam size is independent of energy (PhysRevLett.61.1713, 1988).

$$\sigma^*_{y\ \mathrm{min}} = c_2 \left[F(\sqrt{K}L, \sqrt{K}L^*) \right]^{\frac{1}{7}} (\epsilon_{Ny})^{\frac{5}{7}}$$

Lattice	ϵ_N (nm)	γ (10^3)	σ_0 (nm)	k (m^{-2})	L (m)	L^* (m)	F	σ_{oide} (nm)	σ (nm)	σ_{min} (nm)
CLIC 3 TeV	20	2935.0	0.70	0.116	2.73	3.5	4.086	0.85	1.10	1.00
CLIC 500 GeV	25	489.2	2.3	0.077	3.35	4.3	4.115	0.08	2.3	1.17
ILC 500 GeV	40	489.2	5.7	0.170	2.20	4.3	9.567	0.04	5.7	1.85

Oide in CLIC 3TeV

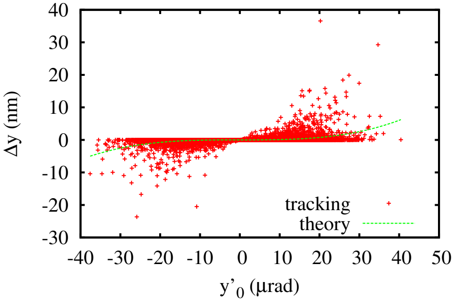




Δy due to radiation

Oide averages over u, s, y, y', obtaining $\langle \Delta y \rangle = 0$.
But this result hides a correlation between $\Delta y, y'$:

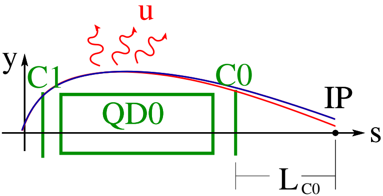
$$\langle \Delta y(y_0') \rangle = \frac{2}{3} r_e \gamma^3 G(\sqrt{K}L, \sqrt{K}L^*)(y_0')^3$$



For CLIC 3 TeV parameters it is possible to substract 10% of the Oide effect.

Corrector

A pair of correctors is added to the strong focusing in order to mitigate the radiation effect.



nominal trajectory: the kick in C1 must cancel the kick in C0.
all particles that radiate: the difference in kicks should cancel Δy.

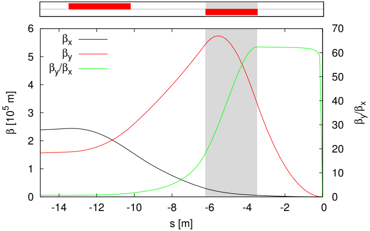
Result

A 4% of beam size reduction was possible for CLIC 3 TeV (6%∼7% of Oide effect reduction).

Why it was not possible to reduce the correlation even more ?

	OD1		OD0		σ_x	σ_y	L_{tot}	L_{peak}
	l [m]	k_3 [m^{-4}]	l [m]	k_3 [m^{-4}]	[nm]	[nm]	[10^{34}cm$^{-2}\cdot$ s^{-1}]	
NO RAD	0.01	0	0.01	0	47.45	0.69	7.7	2.9
RAD	0.01	0	0.01	0	47.45	1.18	7.5	2.7
RAD	0.01	0	0.01	-3900	47.45	1.13	7.4	2.7
RAD	0.01	1502	0.01	-3900	47.45	1.17	7.1	2.7

(to be submitted to PRST-AB next week).



(β_y/β_x) ratio needs to be equal for both correctors.

The phase advance between correctors.

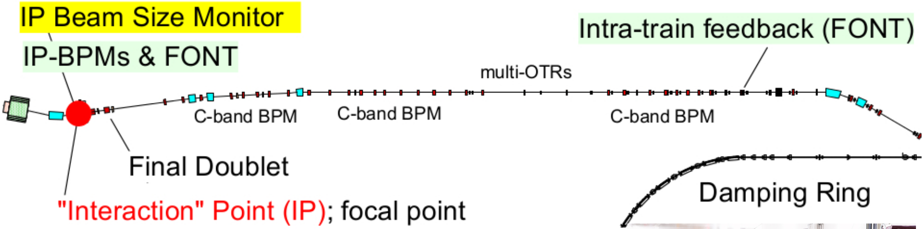
Beam positioning and stabilization

ATF2 line

ATF2 is an extension of ATF (Accelerator Test Facility Test) to be used for the linear colliders R&D.

The FFS in ILC ($\sim$ 700 m) was scale down to $\sim$ 38 m

Beam of e^- at 1.3 GeV



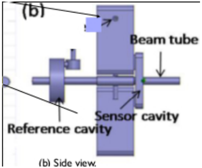
Goal 1: 37 nm of vertical beam size at the IP

Goal 2: beam stabilization at the nm level

We need to measure with nm resolution close to the IP

A vertical beam size of 44 nm was achieved by systematic tuning.

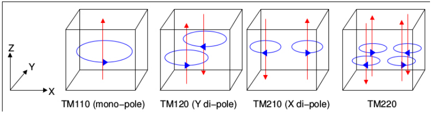
Cavity for 1 nm resolution



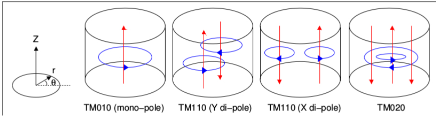
Sensitivity

X: 2.2 μV/nm/nC, Y: 3.7 μV/nm/nC, Ref: 3.27 V/nC

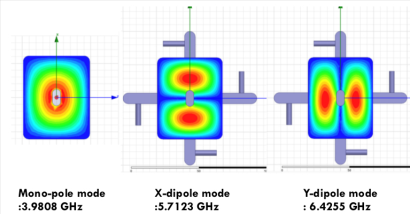
Cavity for Beam Position Measurement (BPM)



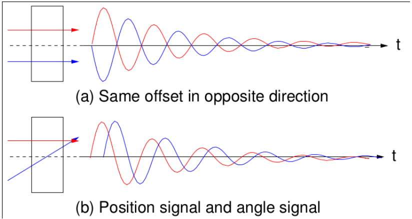
Reference Cavity



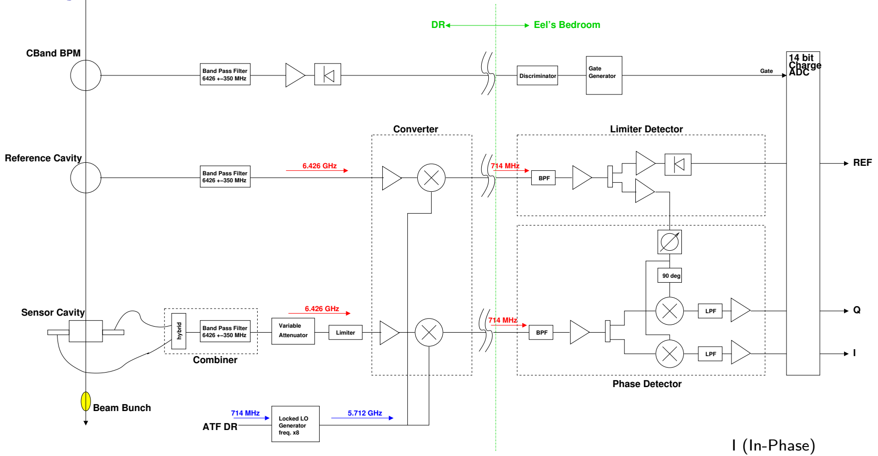
Separation of resonant frequencies



Position and angle



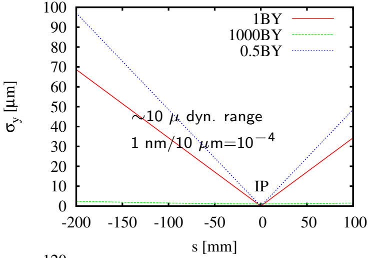
Cavity Electronics

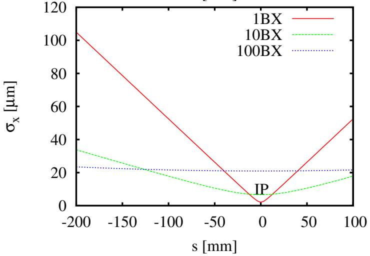


Beam passes through the cavities → 1st stage of downconversion → 2st stage of downconversion → I (In-Phase), Q (Quadrature-Phase), Ref (Reference)

To measure and stabilize

Fluctuations in the beam position are (10∼ 20%) of the beam size!

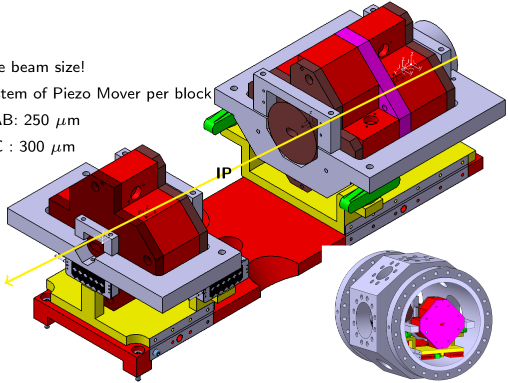


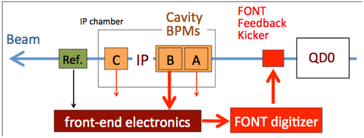


System of Piezo Mover per block

IPAB: 250 μm

IPC : 300 μm





Measure one packet of particles and kick the second

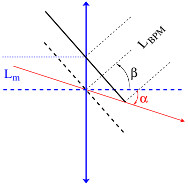
IPBPMs alignment

The alignment goal is:

1. to keep calibration constants within $10^{-3} \sim 10^{-4}$ relative precision.
2. to put the three BPMs inside the **electronics** dynamic range with lowest possible attenuation.

$$I' = L_{BPM}$$
$$Q' \propto 3.2\mu\text{m}/\text{mrad}(\alpha + \beta) + \text{bunch tilt?} + \text{monopole-like modes?}$$

$$A = \sqrt{I' + Q'} < \text{elect. dyn. range(e.g. } 0.3{\sim}0.6\mu\text{m @0dB@}10^{10} \text{ particles)}$$



Movers axis, BPM, beam

Signal Acquisition and Analysis

3 BPMs × 2 planes (x,y) × 2 signals (I,Q) + 2 Ref (x,y)=14 signals

SIS3316

16 channels, 14 bits, 238 MS/s, 2V or 5V dynamic range, parallel acquisition

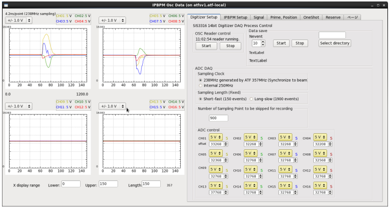
To sample within the 20 ns of signal decay

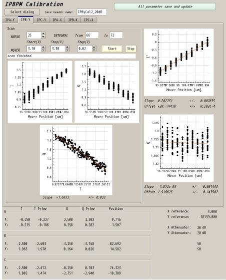
$2^{13} = 8192, 2^{14} = 16384$

$1/238$ MHz $= 4.2$ ns

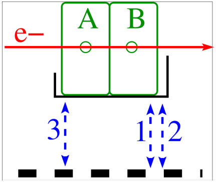
Calibration = Signal/**Displacement**

Waveform and jitter analysis



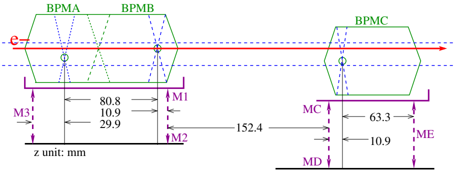


Systematic change of movers 1,2,3 while the beam is running



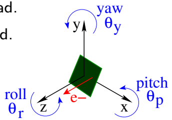
Progress toward the integration with the ATF tuning instrumentation

Displacing the blocks (piezo-movers)

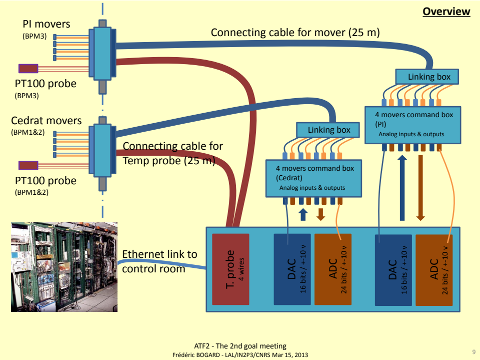


IPAB: $\pm 250\ \mu$m, ± 1 mrad.

IPC : $\pm 300\ \mu$m, ± 2 mrad.



Movers can change vertical and horizontal position, or pitch.



Laptop running NI VI.

DACs 16 bits/ADC 24 bits→Step resolution.

Control Boxes (PI, Cedrat)→Feedback.

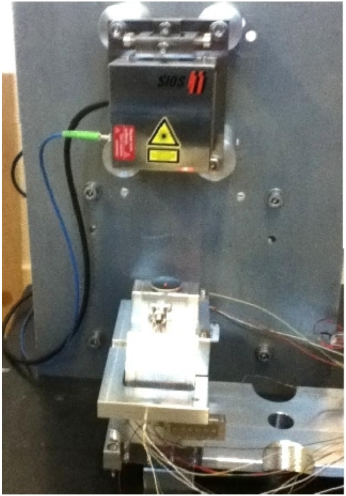
Two PT100 temperature probes→Thermal expansion.

3 vertical/1 horizontal movers per block→Alignment.

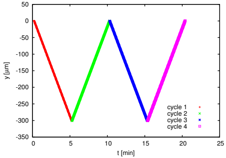
Measurements

Movers calibration

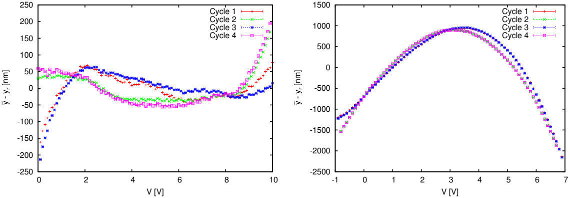
Interferometer better than 1 nm resolution



Four cycles over the entire range of vertical movers



Residual after linear fitting for IPC (left) and IPAB (right)



Cal=(30.002±0.007) μm/V

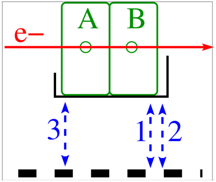
Stability∼1 nm

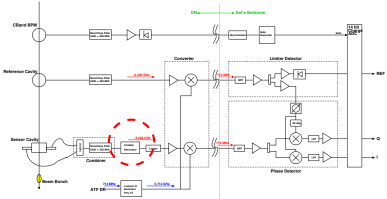
Cal=(31.0015±0.012) μm/V

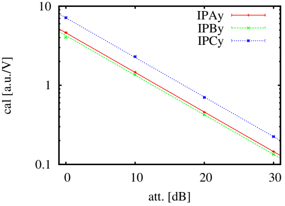
Stability∼1 nm

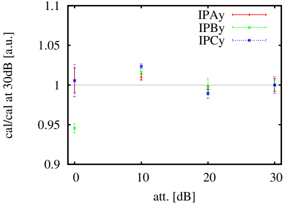
Cavity calibration

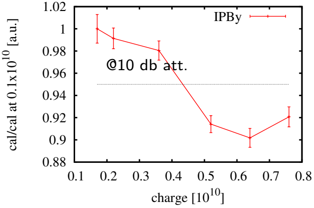
The block position is systematically **changed in steps** to obtain signal/displacement ratio per attenuations.







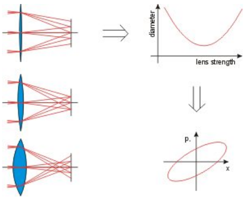


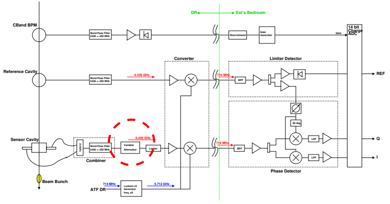


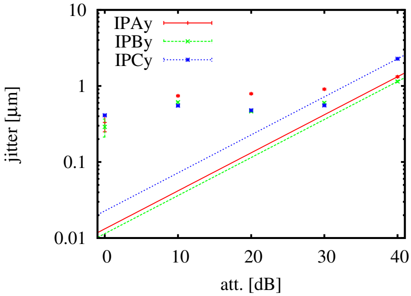
IPBy shows saturation and it is used to determine the dynamic range (10μm@10 dB att.@0.4x10^{10}).

Resolution (noise floor)

The block position is **fixed** and the beam position is measured using the calibrations.



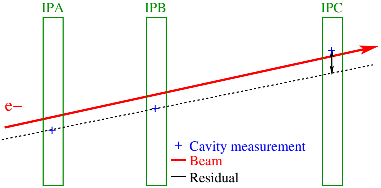


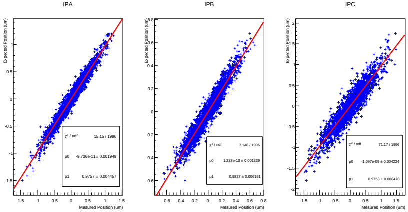


Electronics Noise imposes a limit on resolution.
IPA,IPB: 10 nm.
IPC: 20 nm ?!

Resolution (3 BPMs)

The block position is **fixed** and the beam position is measured using the calibrations.



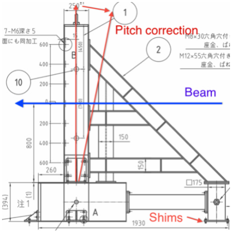


Parameter	IPAy	IPBy	IPCy
Jitter [μm]	0.437	0.216	0.498
Slope	0.9757 ± 0.0044	0.9827 ± 0.0062	0.9753 ± 0.0085
Correlation	0.9798	0.9626	0.9322
Geometrical factor	0.5457	0.7988	0.2531
R [nm]	87.2 ± 1.4	59.7 ± 1.0	185.3 ± 2.9
Resolution [nm]	47.6 ± 0.8	47.7 ± 0.8	46.9 ± 0.7

Resolution $\sim$ 47 nm.

Alignment

The initial installation was corrected by tilting the optical table (S. Jang, IPAC14)



After a second installation the alignment results have been:

Vertical	IPA	IPB	IPC
Y [μm]	-7	+79	-
θ_p [mrad]	0.024	1.0	-

Status of the IP-BPMs

PARAMETER	REQUIREMENT	STATUS	Comments
Resolution	$\sim$nm@1×10^{10}	$<$50nm@$0.4 \sim 0.5 \times 10^{10}$	Calibration factors within 5% linearity BPM/Electronics noise : 10 nm per cavity IPC sensitivity and/or gain : +20nm X to Y coupling is still unexplored
Dynamic Range	$\sim 10\mu$m+extra@0 dB att.	$9 \sim 11\mu$m@10 dB att.	Cavity response is linear within 5% Electronics starts to saturate at 0.4×10^{10}@10 dB att. IPBy Q' signal saturates at 0 dB
Compatibility	IPBSM, EPICS	In progress	Calibration Software : Initial version released and i quires comparison with offline results. Jitter analysis Software : Initial version released and quires comparison with offline analysis. IP-BSM, requires study of resolution vs low char 0.5×10^{10}
Feedback	Operative	Tested	Jitter reduction to 67 nm. Limited by BPM resolution.

Conclusions

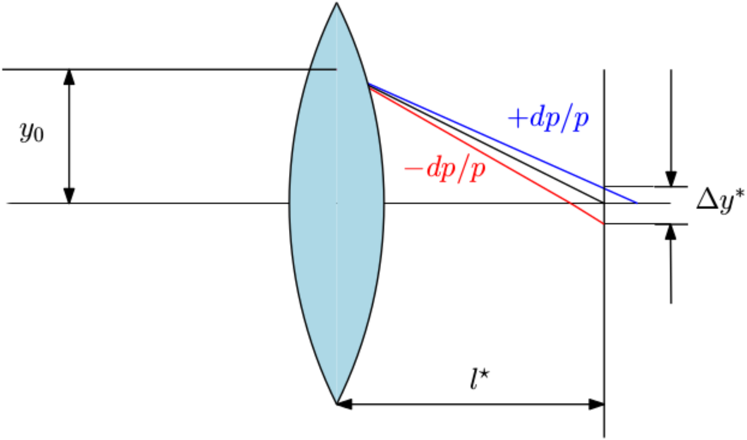
- Three theoretical and computational contributions have been given to the FFS design and optimization at 3 TeV
  - chromaticity minimization: distance between QD0 and QF1 between 1$\sim$2 times L_{IP}
  - Oide effect: Oide beam size contribution reduced by (6$\sim$7)%
  - Radiation in Bending Magnets: Generalization of theoretical formula for lattice design including radiation effects, and an improvement in the tracking code PLACET.
- One new chromaticity correction method has been proposed and initially studied.
- The experimental work reached 50 nm resolution of the IP-BPMs. The system characterization points to upgrade the electronics to reach better resolution.
- This work is relevant for high energy colliders in the TeV energy scale and beyond.

Thank you, I felt welcome at LAL, CERN and ATF.

Extra slides

Telescope Design

Chromaticity

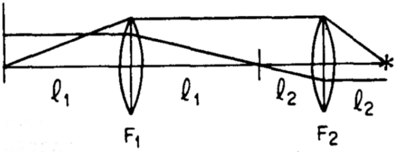


The focal point changes as a function of the energy.

This generates an increase of the beam size.

Why a telescope ?

Demagnify the beam with minimal chromaticity generation



$_k + \cdots \qquad x_i \in x, x', y, y', \tau, \delta$

$$R = \begin{pmatrix} M_x & 0 & 0 & 0 \\ 0 & 1/M_x & 0 & 0 \\ 0 & 0 & M_y & 0 \\ 0 & 0 & 0 & 1/M_y \end{pmatrix}$$

A Conceptual Design of Final Focus Systems for Linear Colliders

$\ldots R_{12}(0) = 0$, $T_{116} = 0 \ldots$

$$\beta(\delta)\beta_0 = R_{11}^2\beta_0^2 + \mathbf{2[0]\delta} + [2R_{11}U_{1166}\beta_0^2 + T_{126}^2]\delta^2 + \cdots$$

So for telescopic systems ... the derivative with respect to δ vanishes...

The problem

A Conceptual Design of Final Focus Systems for Linear Colliders

. . .

The principal problem in designing Final Focusing Systems (FFS) for linear colliders is the elimination or minimization of the chromatic distortions introduced by the final lens system nearest to the interaction point (I.P.).

. . .

There are several possible approaches ...

3. Sextupoles can be introduced into the optical design to cancel the principal second-order chromatic aberrations ...

4. Alternatively one might choose to 'live with' the small residual second-order chromatic aberrations

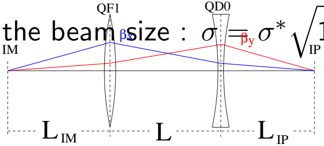
. . .

Karl L. Brown (SLAC-PUB-4159)

Chromaticity minimization

$$\xi_x = \frac{1}{\beta_x^*}\left(\cancelto{0}{T_{116}^2}\beta_{x0} + T_{126}^2\frac{1}{\beta_{x0}}\right) \qquad \xi_y = \frac{1}{\beta_y^*}\left(\cancelto{0}{T_{336}^2}\beta_{y0} + T_{346}^2\frac{1}{\beta_{y0}}\right)$$

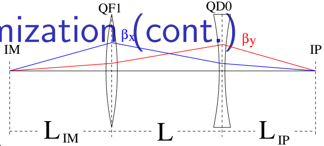
Chromaticity increases the beam size : $\sigma = \sigma^* \sqrt{1 + \xi^2\sigma_\delta^2}$



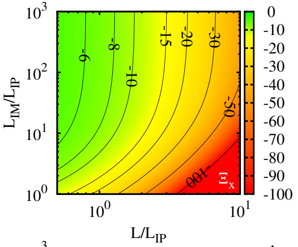
$$\xi_{\substack{x\\y}} = \mp\frac{1}{4\pi}\int \beta_{\substack{x\\y}} k dl = \mp\frac{1}{4\pi}\left(\beta_{\substack{x\\y}1} k_1 l_1 - \beta_{\substack{x\\y}0} k_0 l_0\right) = \frac{1}{4\pi}\frac{L_{IP}}{\beta_{\substack{x\\y}}^*}\Xi_{\substack{x\\y}}(r, r_{im})$$

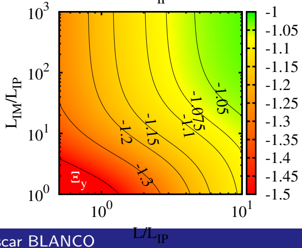
with

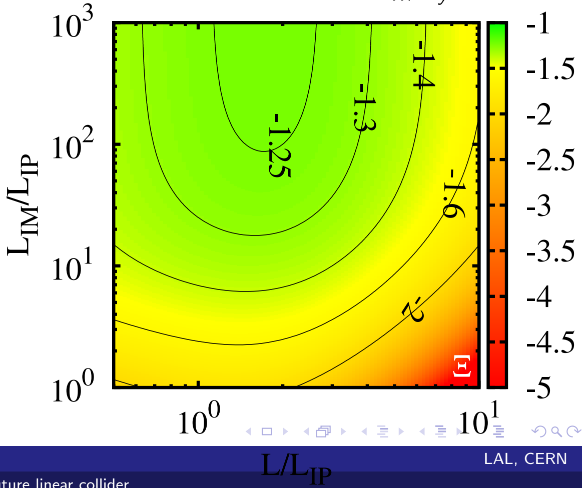
Chromaticity minimization (cont.)



$$\Xi = \frac{\Xi_x}{\beta_x^*/\beta_y^*} + \Xi_y$$





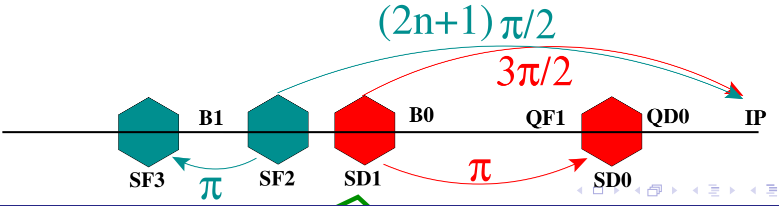


Chromaticity correction

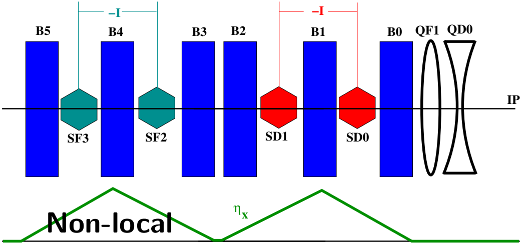
Second order terms reduction

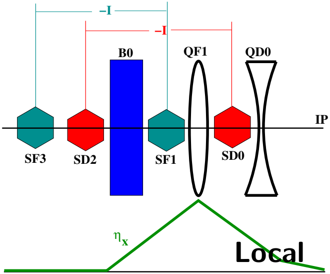
Quadrupoles generate chromaticity ($k_1\delta x, k_1\delta y$) and in dispersive regions also generate second order dispersion ($k_1\eta_x\delta^2$).
One of the paired sextupoles is in a horizontal dispersive region ($\eta_x \neq 0$).
This will correct second order dispersion ($\eta_x^2\delta^2$), twice the h. chromaticity ($\eta_x\delta x_1$) and the total v. chromaticity ($\eta_x\delta y$).
The sextupoles in non-dispersive regions ($\eta_x = 0$) will correct the geometrical components from sextupoles (x^2, y^2, xy).

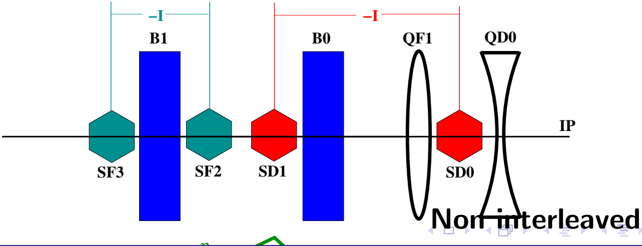
$$
\begin{aligned}
x_2' &= \frac{k_2}{2}(x_1+\eta_x\delta)^2 - y_1^2 = \frac{k_2}{2}(x_1^2 + 2x_1\eta_x\delta + \eta_x^2\delta^2 - y_1^2) \\
y_2' &= k_2(x_1+\eta_x\delta)y = k_2(x_1y_1 + \eta_x\delta y_1)
\end{aligned}
$$



Local, Non-local and Non-interleaved correction

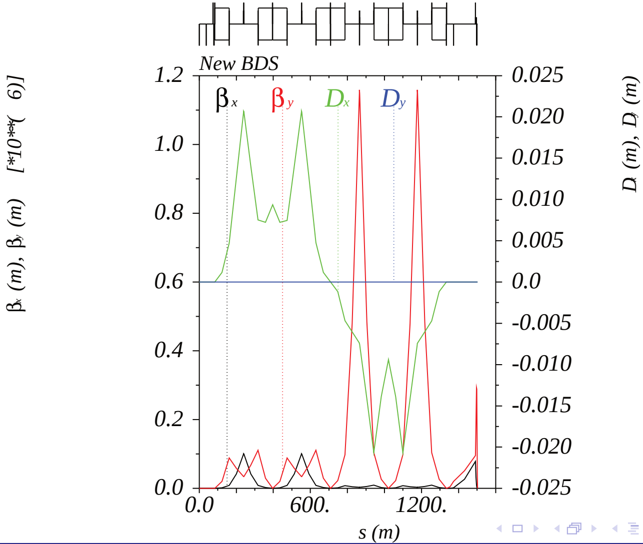




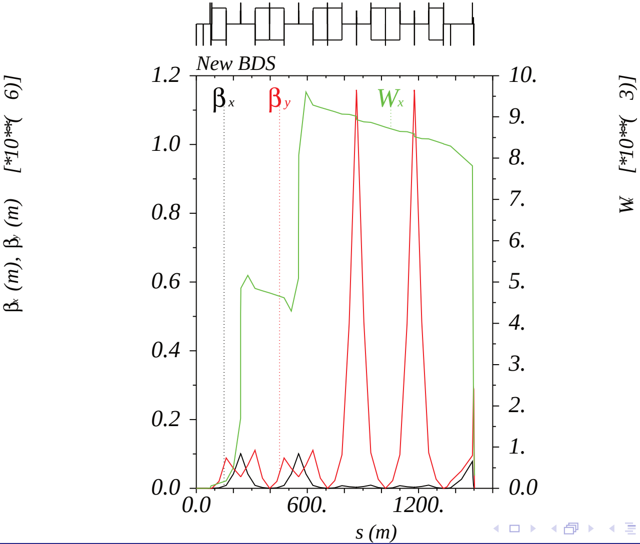


CLIC 3TeV Non-local (trad)

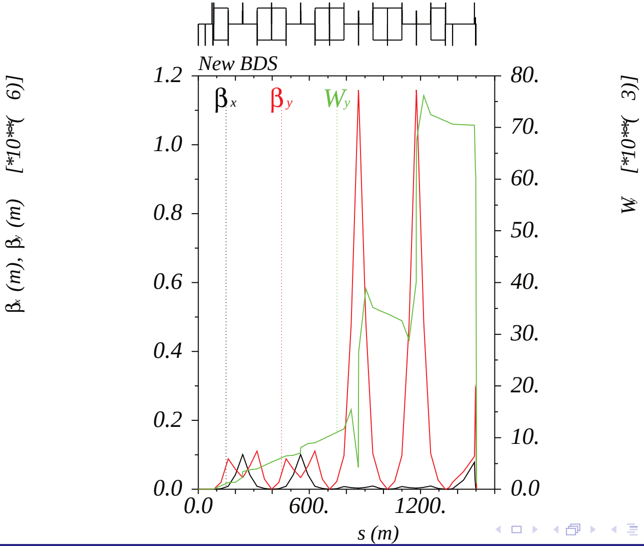
CLIC 3TeV Non-local (trad)



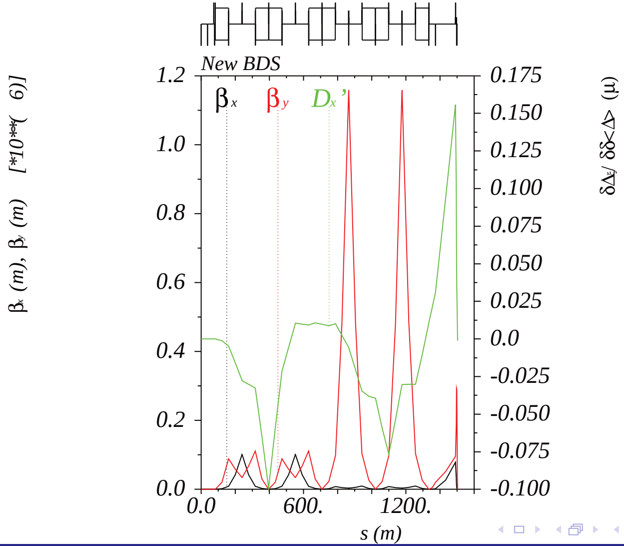
CLIC 3TeV Non-local (trad)



CLIC 3TeV Non-local (trad)

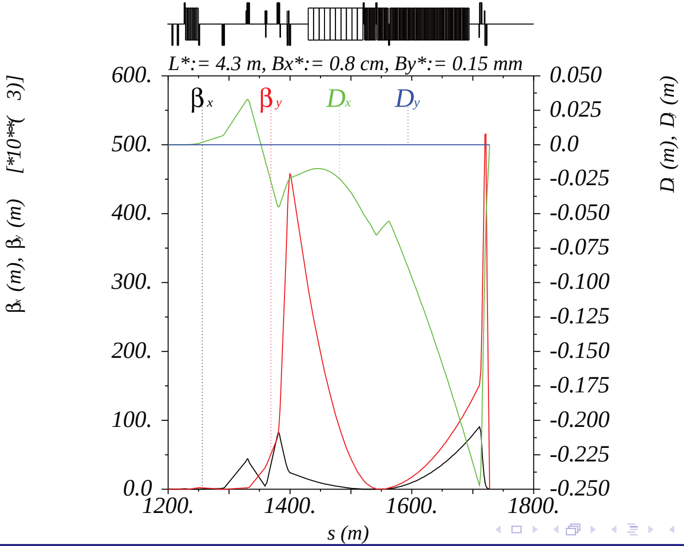


CLIC 3TeV Non-local (trad)

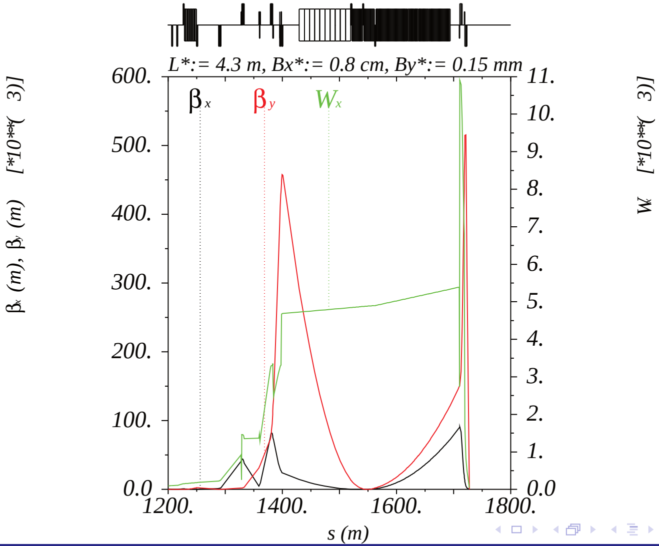


ILC 500 GeV

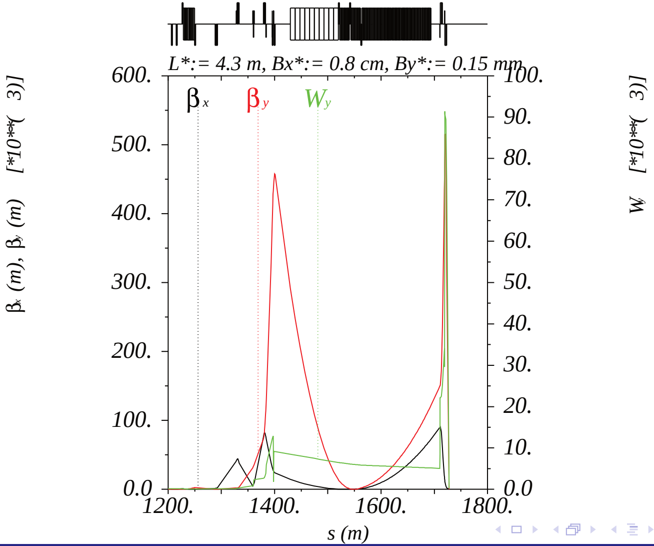
ILC 500 GeV (Local)



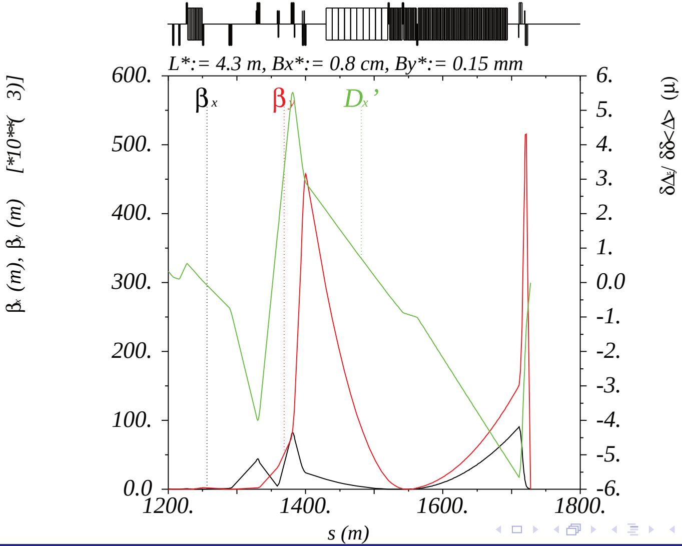
ILC 500 GeV (Local)



ILC 500 GeV (Local)



ILC 500 GeV (Local)

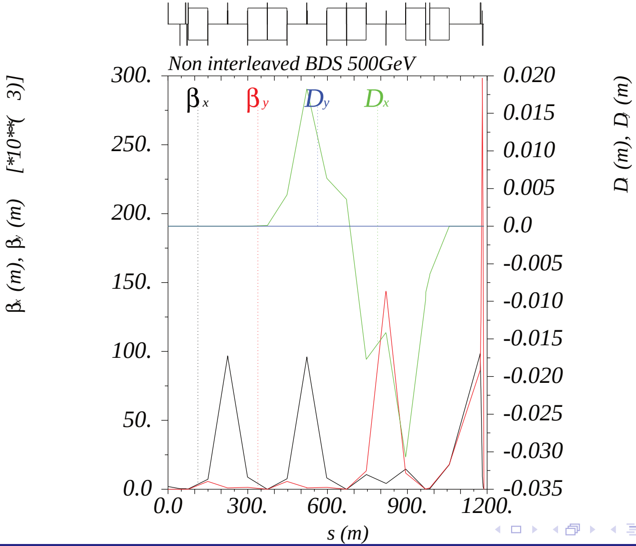


CLIC 500 GeV Non-interleaved Lattice

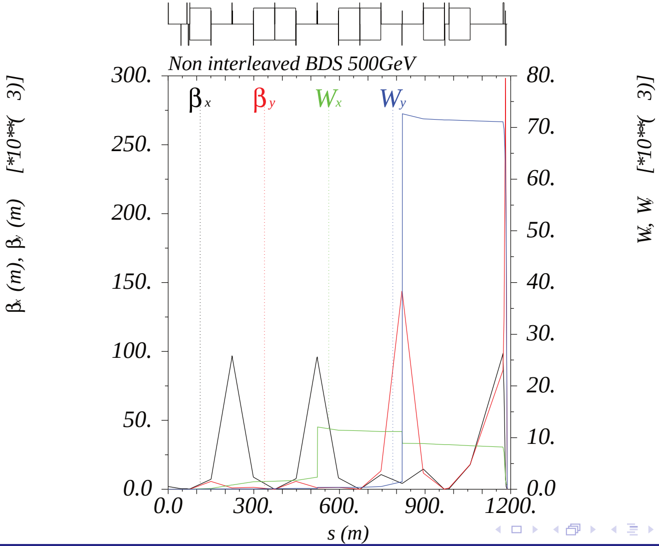
Current 500 GeV Lattice Parameters (from CDR)

Parameter [Units]	Value
Length (linac exit to IP distance/side [m])	1750
Maximum energy/beam [TeV]	0.25
Distance from IP to first quad, L^* [m]	4.3
Crossing angle at the IP [mrad]	18.6
Nominal core beam size at IP, σ^*, x/y [nm]	202/2.3
Nominal beam divergence at IP, θ^*, x/y [μrad]	25/23
Nominal beta-function at IP, β^*, x/y [mm]	8/0.1
Nominal bunch length, σ_z [μm]	72
Nominal disruption parameters, D, x/y	0.1/12
Nominal bunch population, N	6.8×10^9
Beam power in each beam [MW]	4.9
Preferred entrance train to train jitter [σ]	< 0.2
Typical nominal collimation aperture, x/y [σ_x/σ_y]	10/55
Vacuum pressure level, near/far from IP [10^{-9} mbar]	100/10

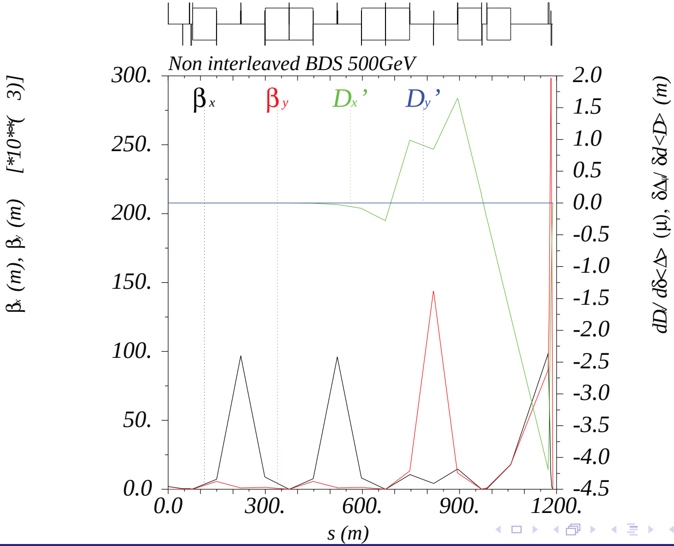
CLIC 500GeV Non-interleaved Lattice



CLIC 500GeV Non-interleaved Lattice



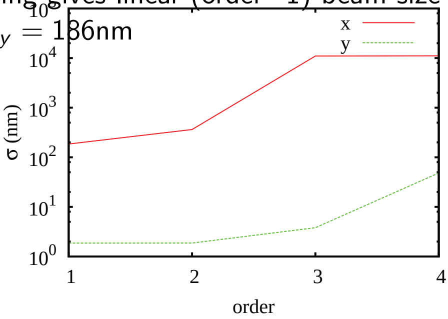
CLIC 500GeV Non-interleaved Lattice



Non-interleaved CLIC 500 GeV (cont.)

The lattice desing gives linear (order=1) beam size of :

$\sigma_x = 1.9\text{nm}$, $\sigma_y = 186\text{nm}$



$\sigma_{bends} = 0.2\text{nm}$

The third order terms U_{1166} and U_{3466} increase the beam size due to second order dispersion at the sextupole inside the Final doublet.

Second order dispersion needs to be corrected before the FD (not only at