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Lecture 6
Part 1

Beam Delivery System and beam-beam effects

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ASTeC

Science & Technology Facilities Council

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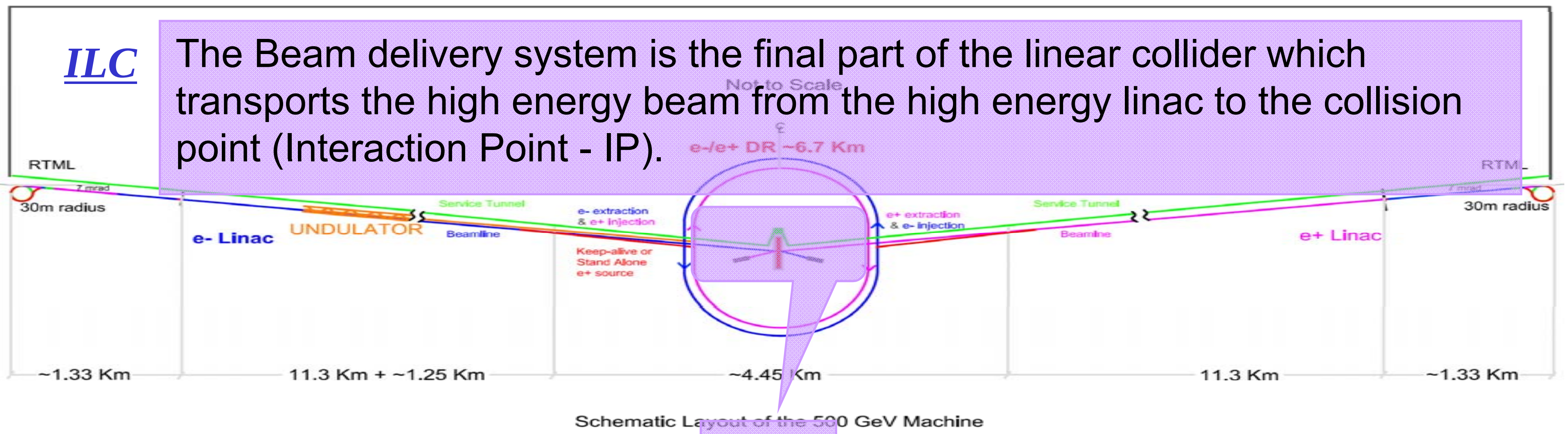
Introduction to the Beam Delivery System

Beam Delivery System

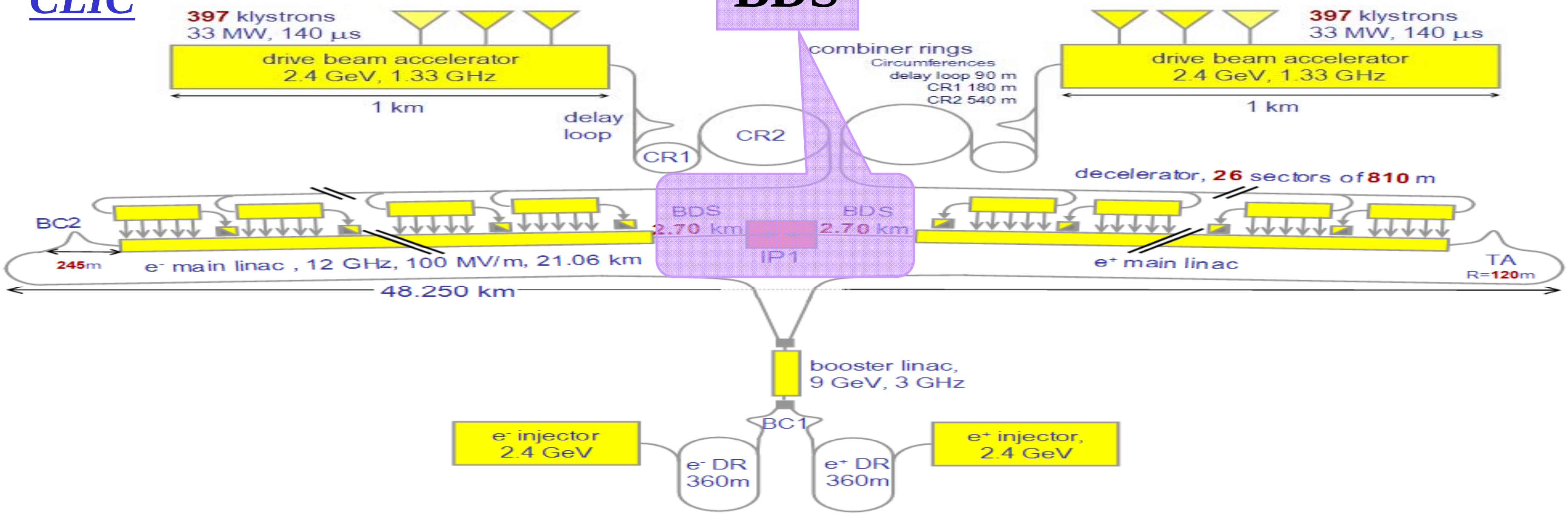
ILC

The Beam delivery system is the final part of the linear collider which transports the high energy beam from the high energy linac to the collision point (Interaction Point - IP).



Schematic Layout of the 500 GeV Machine

CLIC

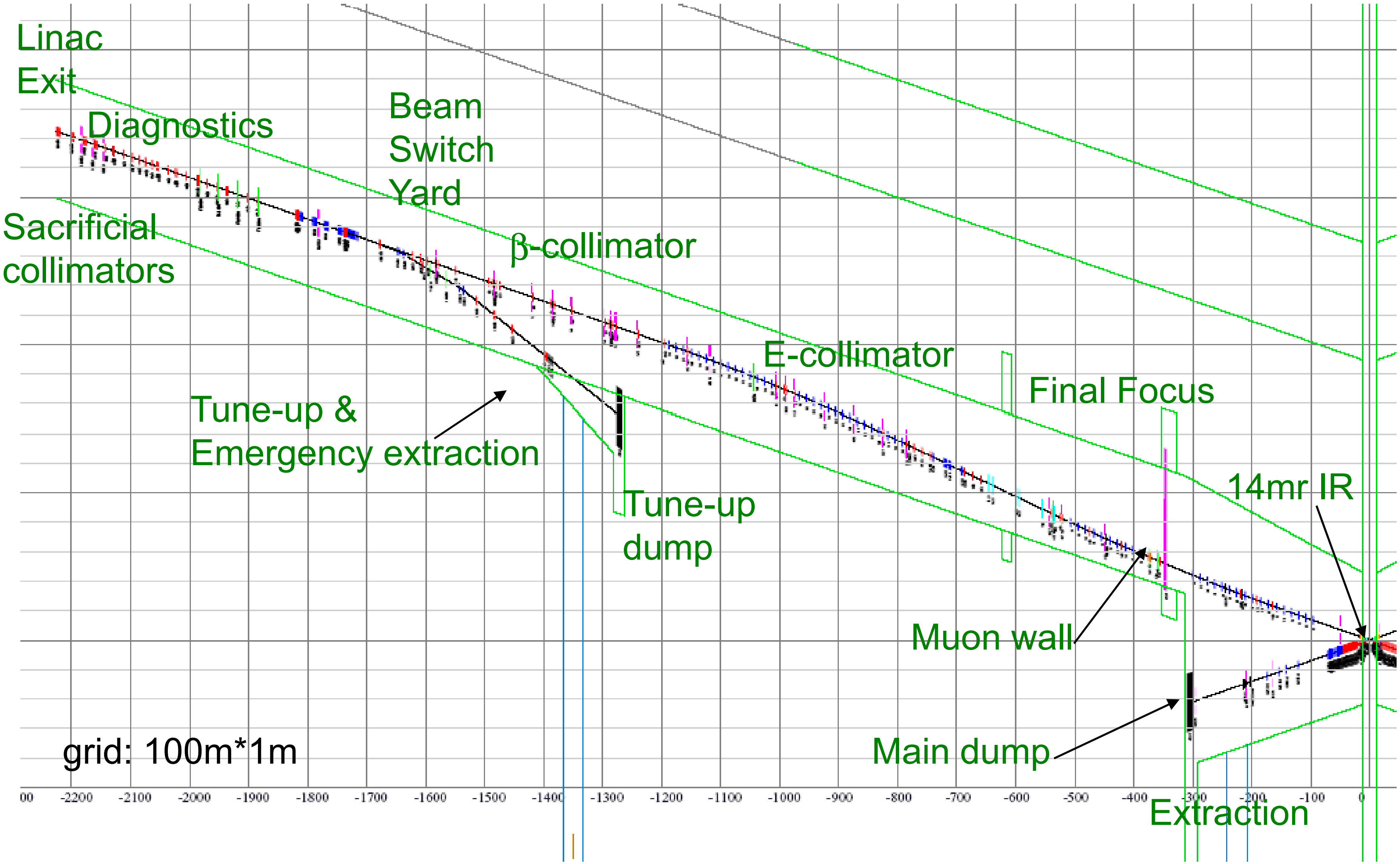


Beam Delivery System Functionality

The beam delivery systems perform the following essential functions:

- Focus the beams at the interaction point to achieve beam sizes to meet the linear collider luminosity goals.
- Remove any large amplitude particles (beam halo) from the upstream part of the accelerator to minimise the background in the detectors.
- Protect the beam line and detector against mis-steered beams from the linacs.
- Precise beam emittance measurement and coupling correction.
- Measure and monitor the key physics parameters such as energy and polarization.
- Ensure that the extremely small beams collide optimally at the IP.
- Safely extract the beams after collision to the high-power beam dumps.

ILC RDR BDS Layout



ILC BDS RDR Parameters

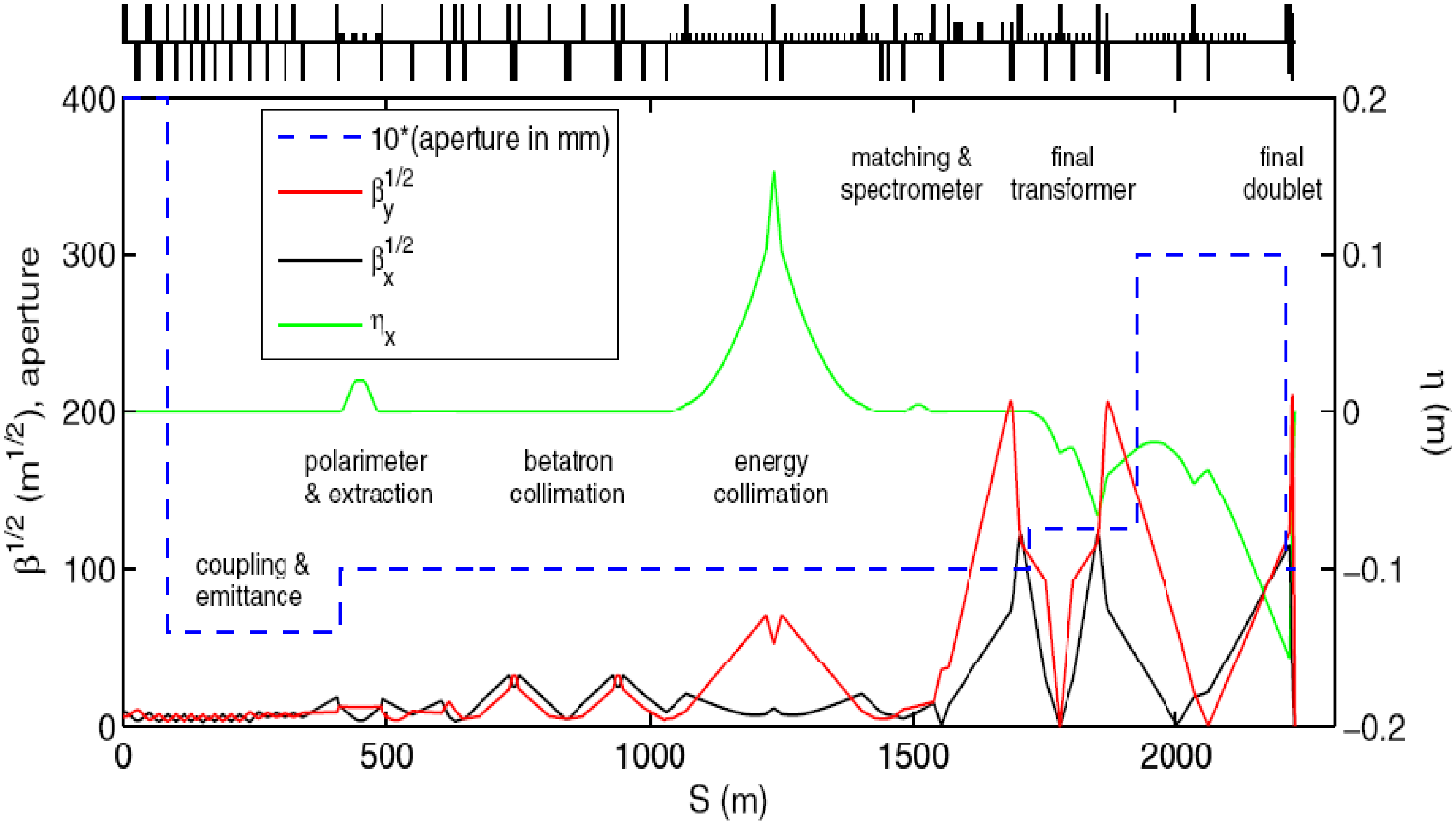
Length (linac exit to IP distance)/side	m	2226
Length of main (tune-up) extraction line	m	300 (467)
Max Energy/beam (with more magnets)	GeV	250 (500)
Distance from IP to first quad, L*	m	3.5-(4.5)
Crossing angle at the IP	mrad	14
Nominal beam size at IP, σ^*, x/y	nm	655/5.7
Nominal beam divergence at IP, θ^*, x/y	μrad	31/14
Nominal beta-function at IP, β^*, x/y	mm	21/0.4
Nominal bunch length, σ_z	μm	300
Nominal disruption parameters, x/y		0.162/18.5
Nominal bunch population, N		2×10^{10}
Max beam power at main and tune-up dumps	MW	18
Preferred entrance train to train jitter	σ	< 0.5
Preferred entrance bunch to bunch jitter	σ	< 0.1
Typical nominal collimation depth, x/y		8–10/60
Vacuum pressure level, near/far from IP	nTorr	1/50

CLIC BDS Parameters

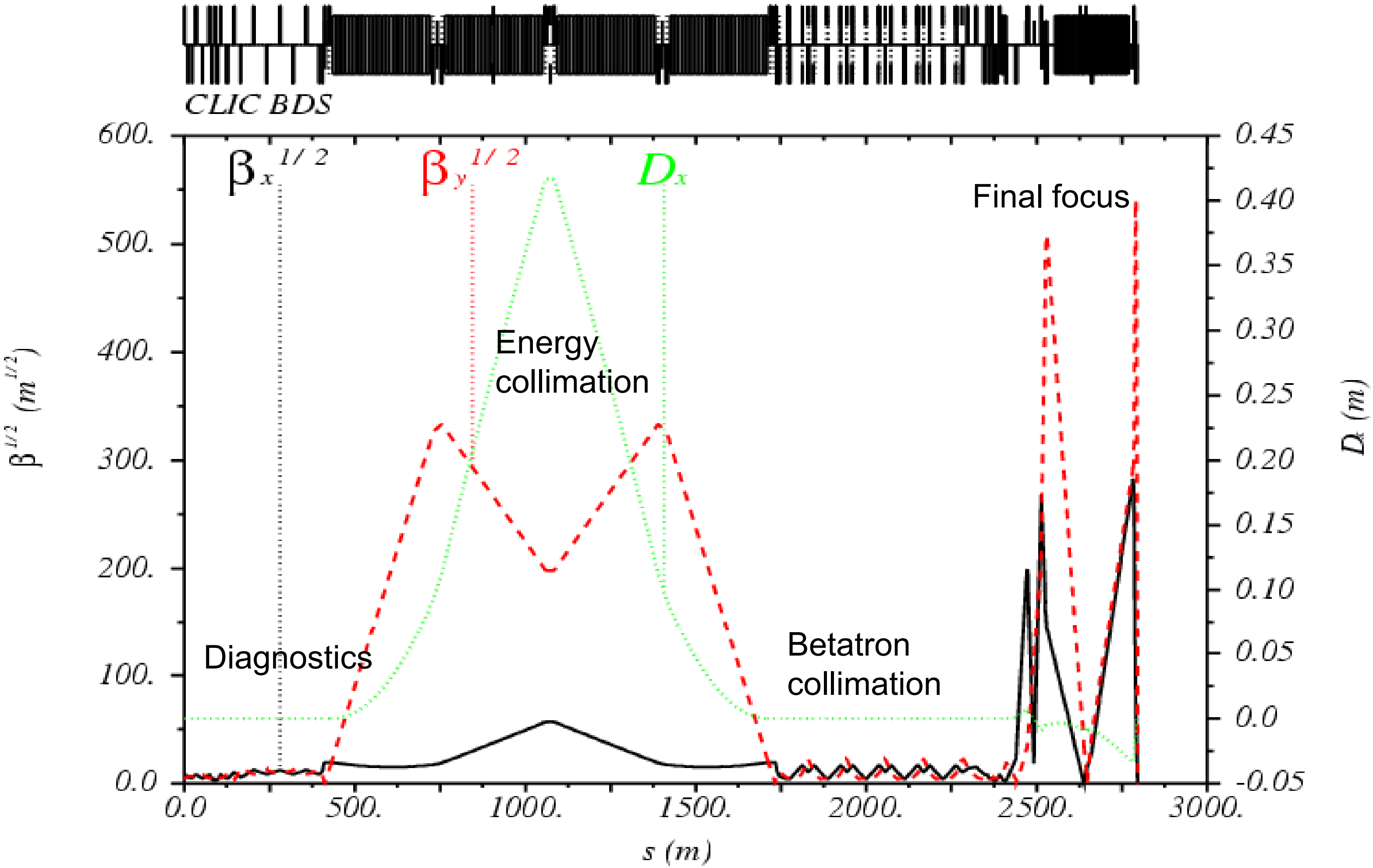
Maximum Energy/beam	1.5 TeV
Length (linac exit to IP distance)/side	2.75-2.84 Km
Distance from IP to first quad, L*	3.5-4.3 m
Nominal beam size at the IP, x/y	45 nm / 1 nm
Nominal beta function at IP, x/y	6.9 mm / 0.068 mm
Nominal bunch length	45 μm
Number of particles/bunch	$3.72\ 10^9$
Bunch separation	0.5 nsec
Bunch train length	156 nsec
Beam power	14 MW
Crossing angle at the IP	20 mrad
Jitter tolerance (FD) (for 2% L loss)	0.14-0.18 nm

CLIC draft parameter list
http://clic-meeting.web.cern.ch/clic-meeting/clictable2007.html

ILC BDS Optical Functions



CLIC BDS Optical Functions



Beam Transport Basics

Single Pass Beam Transport Optics

Particle trajectories are treated similar to the circular machine with the difference that they pass only once.

Beam transport uses

- Dipoles
- Quadrupoles
- Sextupoles (and higher orders in the final focus)

2X2 matrices describe the transverse motion of the particle

$$\begin{bmatrix} x_2 \\ x_2' \end{bmatrix} = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix} \begin{bmatrix} x_1 \\ x_1' \end{bmatrix}$$

The particle trajectories in single pass transport are not closed

$\Rightarrow$ initial lattice parameters ≠ final lattice parameters

Cannot use periodic conditions like in circular machines

$\Rightarrow$ final twiss parameters depend on initial twiss parameters

Beam Optics and Twiss parameters

The particle position and angular deviation are given by,

$$x(s) = \sqrt{\varepsilon\beta(s)}\cos[\psi(s)+\phi]$$

$$x'(s) = -\sqrt{\frac{\varepsilon}{\beta(s)}}[\alpha(s)\cos[\psi(s)+\phi]+\sin[\psi(s)+\phi]]$$

Where,

$$\psi(s) = \int_0^s \frac{d\tau}{\beta(\tau)}$$

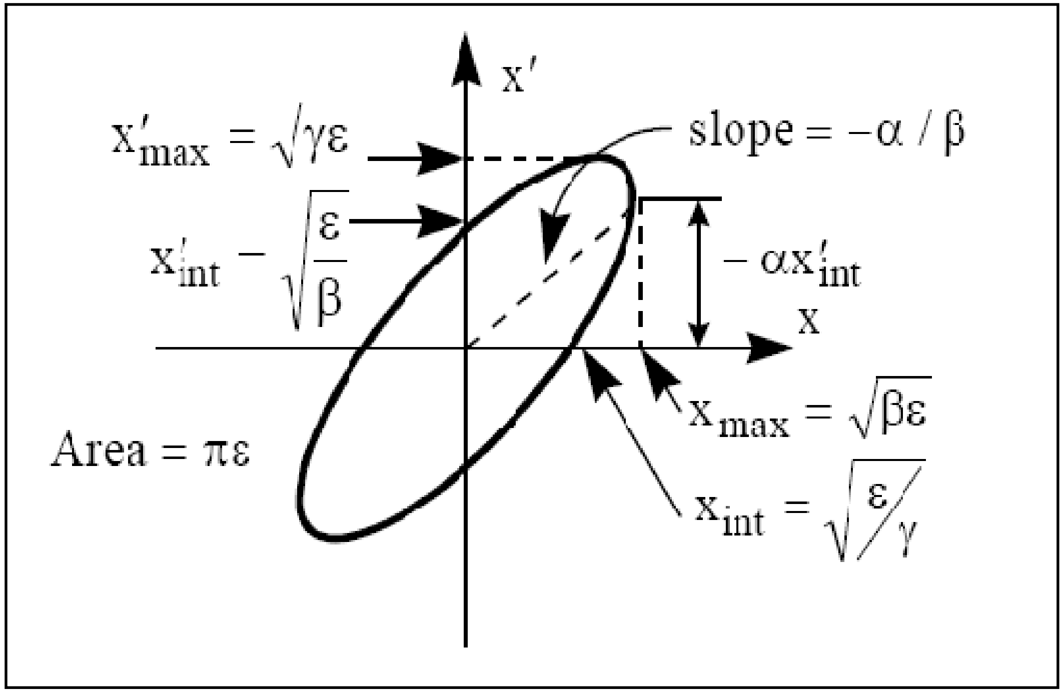
$$\alpha(s) = -\frac{\beta'(s)}{2}$$

$$\gamma(s) = \frac{1+\alpha^2(s)}{\beta(s)}$$

α, β, γ: Twiss parameters

The invariant emittance ellipse is given by,

$$\gamma(s)x^2 + 2\alpha(s)xx' + \beta(s)x'^2 = \varepsilon$$



Twiss Parameters Transform

The general form of the transfer matrix (1→2) written in terms of twiss parameters and the betatron phase advance :

$$\begin{bmatrix} x_2 \\ x_2' \end{bmatrix} = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos\Delta\psi + \alpha_1 \sin\Delta\psi) & \sqrt{\beta_1\beta_2}\sin\Delta\psi \\ -\frac{(\alpha_2-\alpha_1)\cos\Delta\psi + (1+\alpha_1\alpha_2)\sin\Delta\psi}{\sqrt{\beta_1\beta_2}} & \sqrt{\frac{\beta 1}{\beta_2}}[\cos\Delta\psi - \alpha_2 \sin\Delta\psi] \end{pmatrix} \begin{bmatrix} x_1 \\ x_1' \end{bmatrix} = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix} \begin{bmatrix} x_1 \\ x_1' \end{bmatrix}$$

While in a circular machine the optics functions are uniquely determined by the periodicity conditions, in a transfer line the optics functions are not uniquely given, but depend on their initial value at the entrance of the system.

$$\begin{pmatrix} \beta_2 \\ \alpha_2 \\ \gamma_2 \end{pmatrix} = \begin{pmatrix} R_{11}^2 & -2R_{11}R_{12} & R_{12}^2 \\ -R_{11}R_{21} & 1+2R_{12}R_{21} & -R_{12}R_{22} \\ R_{21}^2 & -2R_{21}R_{22} & R_{22}^2 \end{pmatrix} \begin{pmatrix} \beta_1 \\ \alpha_1 \\ \gamma_1 \end{pmatrix}$$

This expression allows the computation of the propagation of the optics function along the transfer lines, in terms of the matrices of the transfer line of each single element.

Higher Order Optics

In circular machines, chromaticity is defined as change of betatron tune with energy. In a single pass, based on TRANSPORT notations, the change of the co-ordinate vector is given by

$$x_i = \begin{pmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{pmatrix}$$

l : path length difference
$\delta = \Delta p/p$: fractional momentum deviation from the assumed central trajectory

$$x_i^{out} = R_{ij}\ x_j^{in} + T_{ijk}\ x_j^{in}\ x_k^{in} + U_{ijkn}\ x_j^{in}\ x_k^{in}\ x_n^{in} + \ldots \qquad \{j,k,n=1,6\}$$

All terms with one subscript equal to 6 are referred to as chromatic terms, since the effect depends on the momentum deviation of the particle.

All terms without subscript equal to 6 are referred as geometric terms, since the effect depends only on the central momentum.

Final Focus Systems

Luminosity Requirements

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

n_b is the number of bunches in a bunch train.

N is the number of particles in a single bunch.

f_{rep} is the machine pulse repetition rate.

σ_x^* and σ_y^* are the rms horizontal and vertical beam sizes at the IP.

H_D is the "enhancement factor“

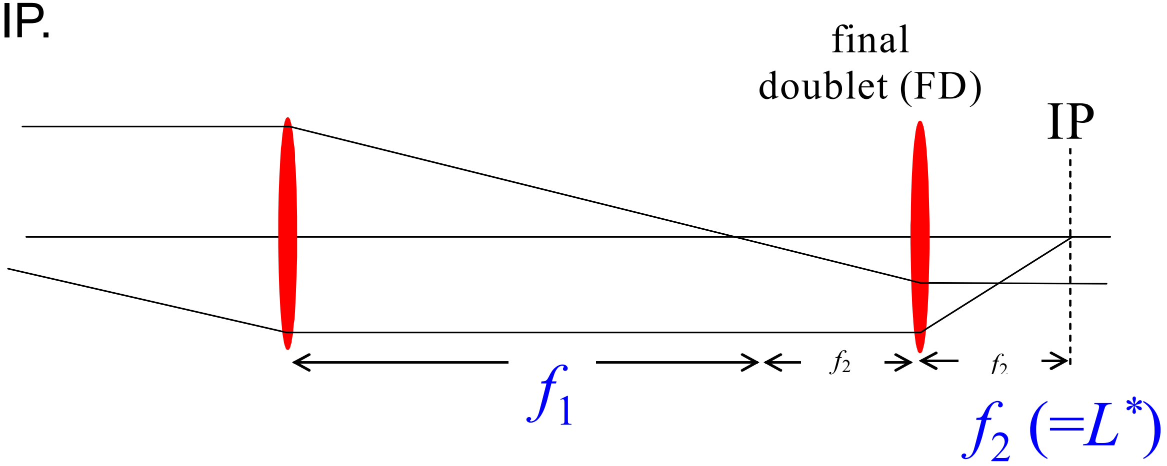
To achieve small transverse beam sizes, we need

Small emittances – Damping rings

Strong focusing (small beta functions) – BDS Final Focus

Optics Building Block: Telescope (1/2)

Essential part of final focus is Final Telescope.
It reduces (demagnifies) the incoming beam size to a smaller beam size required at the IP.



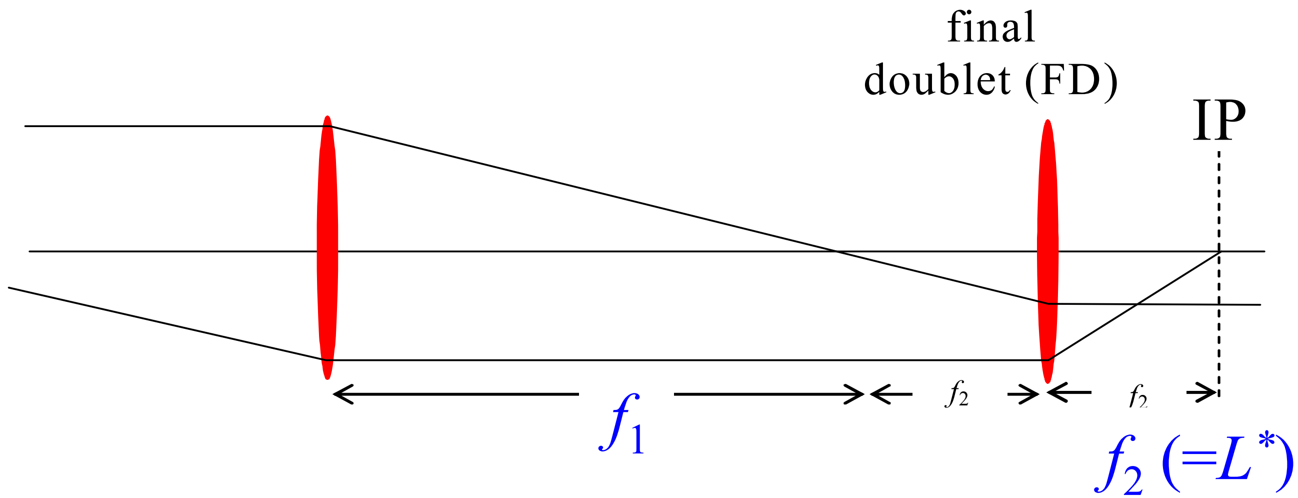
Matrix transformation of such telescope is diagonal :

$$R_{X,Y} = \begin{pmatrix} -1/M_{X,Y} & 0 \\ 0 & -M_{X,Y} \end{pmatrix}$$

A two dimensional telescopic system has four quadrupoles.

It has advantage that the demagnification of the beam transverse planes may either be same or different.

Optics Building Block: Telescope (2/2)



- Use telescope optics to demagnify beam size by factor $M = f1/f2 = f1/L^*$
- For ILC, β_{linac} = 40m, β_{IP} = 4.10^{-4}m

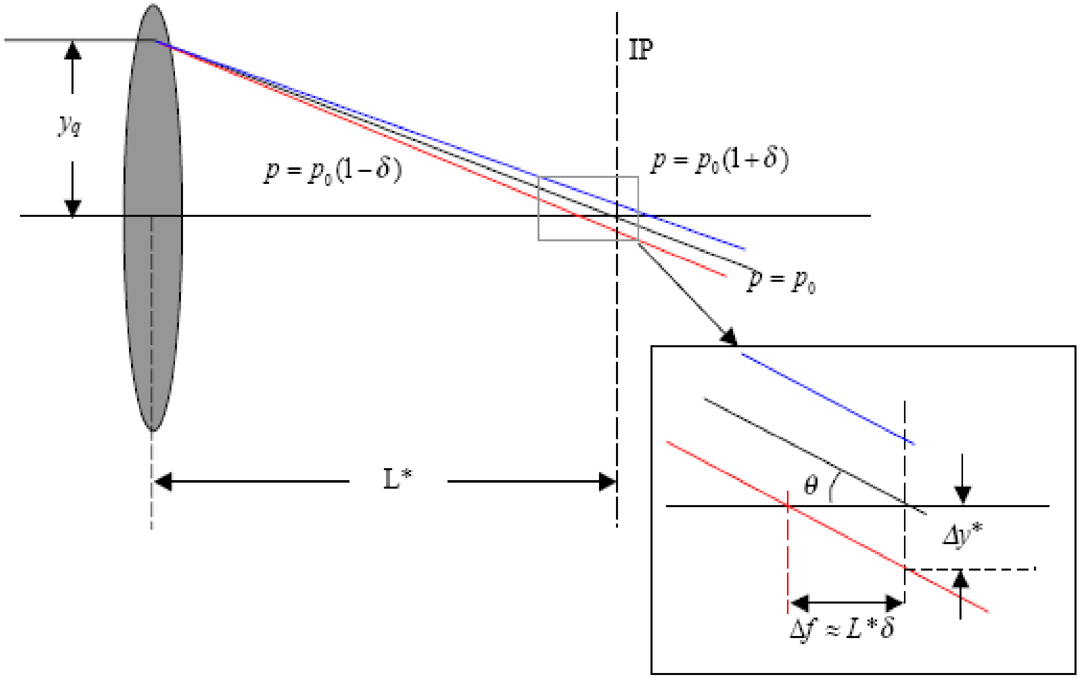
  $M = (\beta_{linac}/\beta_{IP})^{1/2} = 316$

  For $f2$ = 3 m $\Rightarrow$ $f1$ 🕔 948 m

- In reality, the final focus system is not strictly a simple telescope and same demagnifications can be obtained in shorter systems.

Final Focus Chromaticity

Short L* needs strong final quadrupoles $\Rightarrow$ high degree of chromatic aberration



$$\Delta f \approx L^* \delta$$

$$\Delta y^* \approx \Delta f \theta \approx L^* \delta\theta$$

Assuming that there is no initial correlation between energy and angle,

$$\frac{\Delta y^*_{rms}}{\sigma^*_y} \approx L^* \delta_{rms} \frac{\theta_{rms}}{\sigma^*_y}$$

$$\theta_{rms} = \sqrt{\varepsilon_y / \beta_y}$$

$$\sigma_y = \sqrt{\varepsilon_y \beta_y}$$

$$\frac{\Delta y^*_{rms}}{\sigma^*_y} \approx \frac{L^*}{\beta^*_y} \delta_{rms}$$

For L^*~4m, δ~0.01, β~0.1mm

$$\frac{\Delta y^*_{rms}}{\sigma^*_y} \approx 400 \longrightarrow$$

If uncorrected, chromatic aberration of FD would completely dominate the IP spot size! Need compensation scheme.

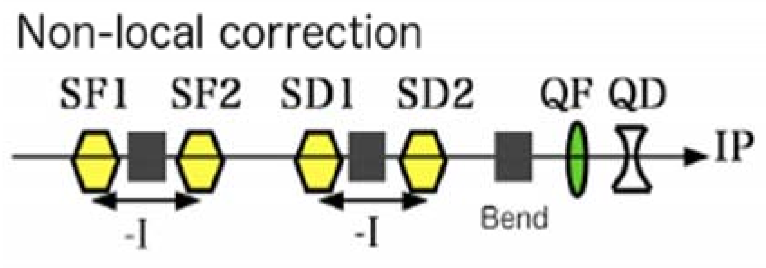
Chromaticity Correction Schemes

Conventional scheme with non-local correction :

Chromaticity is compensated in dedicated sections.

The design was used at Final Focus Test Beam (FFTB) at SLAC, where vertical beam size ~70nm was demonstrated.

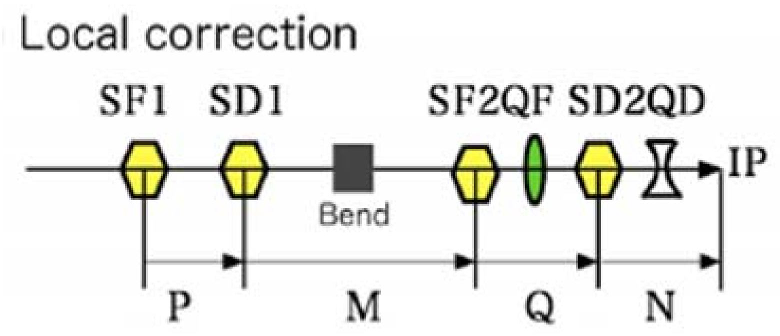
This design was used for earlier design versions of the future linear colliders.



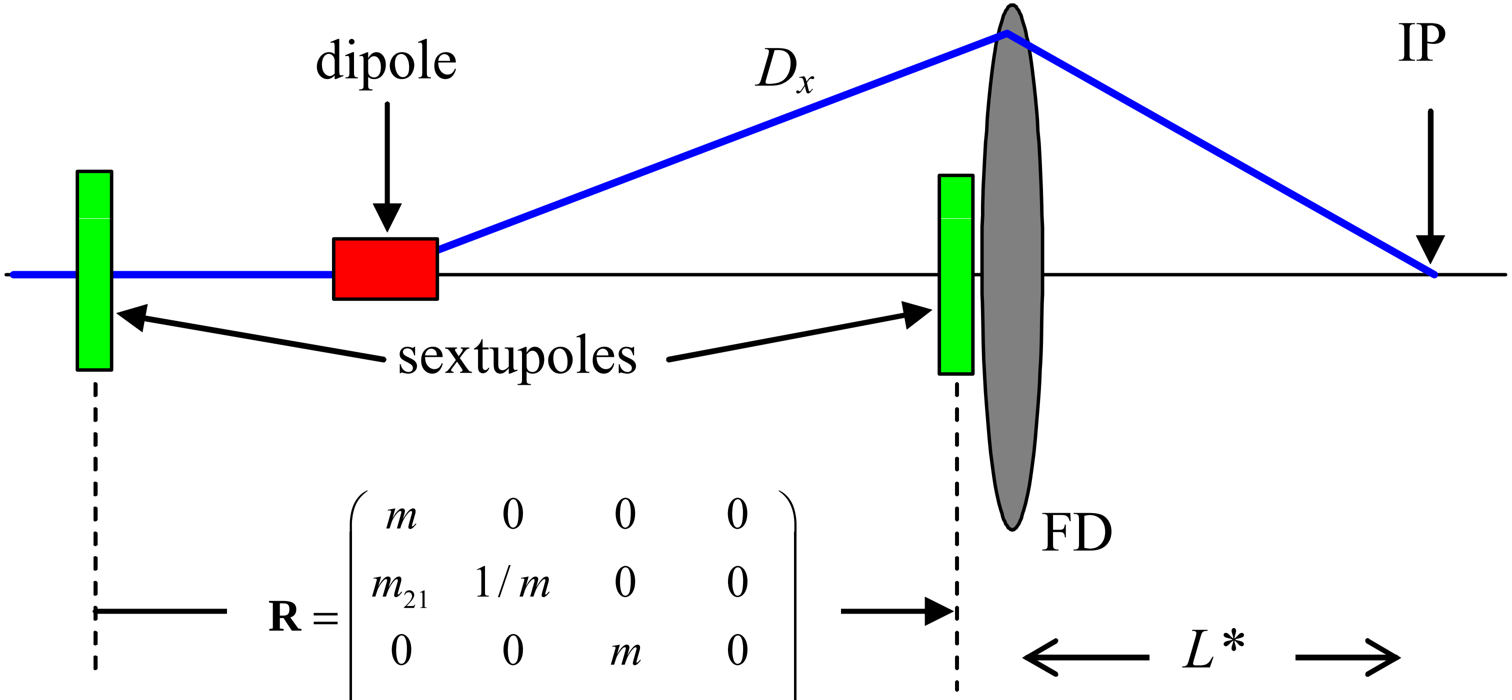
New scheme with local chromaticity correction :

Proposed by P. Raimondi and A. Seryi in 2000.

The FF system with local chromaticity correction is much shorter than the conventional one and has much better performance. This scheme has now been adopted to all the future linear collider final focus systems and will be experimentally verified at ATF2, KEK.



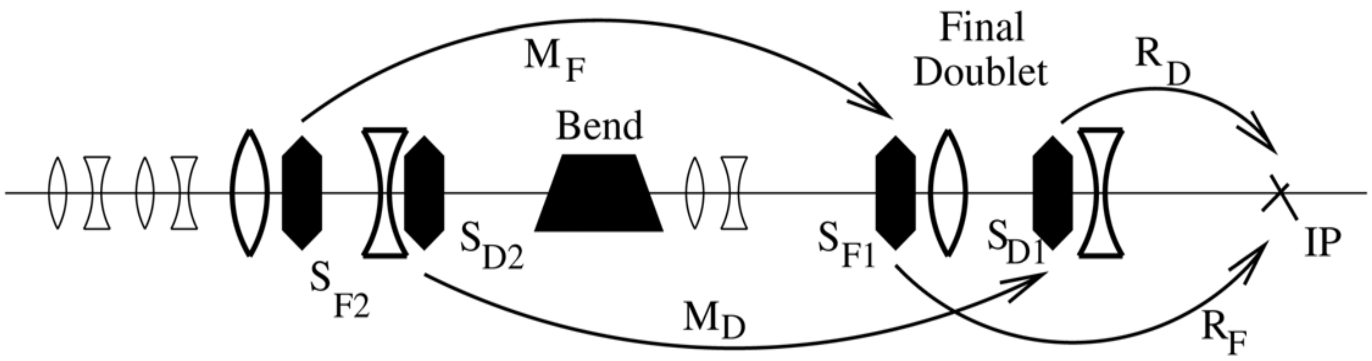
Novel Local Chromaticity Correction Scheme



$$\mathbf{R} = \begin{pmatrix} m & 0 & 0 & 0 \\ m_{21} & 1/m & 0 & 0 \\ 0 & 0 & m & 0 \\ 0 & 0 & m_{43} & 1/m \end{pmatrix}$$

P.Raimondi & A.Seryi, originally NLC FF and now adopted by all LC designs.

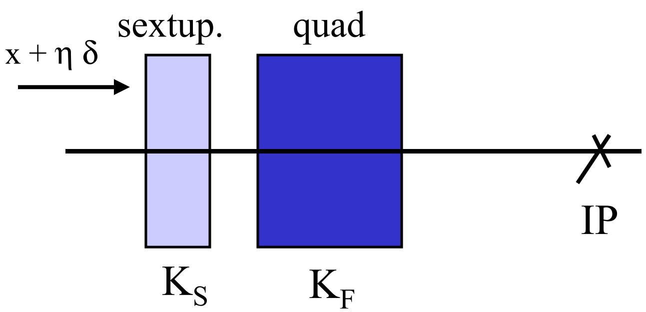
Final Focus with Local Chromatic Correction



Chromaticity is cancelled locally by two sextupoles interleaved with FD, a bend upstream generates dispersion across FD.

Geometric aberrations of the FD sextupoles are cancelled by two more sextupoles placed in phase with them and upstream of the bend.

Chromatic Correction in Final Doublet



- Straightforward in Y plane
- Bit tricky in X plane

Quadrupole: $\Delta x' = \frac{K_F}{(1+\delta)}(x+\eta\delta) \Rightarrow K_F(-\delta x - \eta\delta^2)$

chromaticity

Second order dispersion

Sextupole: $\Delta x' = \frac{K_S}{2}(x+\eta\delta)^2 \Rightarrow K_S\eta(\delta x + \frac{\eta\delta^2}{2})$

$$\Delta x' = \frac{K_F}{(1+\delta)}(x+\eta\delta) + \frac{K_{\beta\text{-match}}}{(1+\delta)}x \Rightarrow 2K_F(-\delta x - \frac{\eta\delta^2}{2})$$

$$K_{\beta\text{-match}} = K_F \qquad K_S = \frac{2K_F}{\eta}$$

If we require $K_S\eta = K_F$ to cancel FD chromaticity, then half of the **second order dispersion** remains.

Solution:
The β-matching section produces as much X chromaticity as the FD, so the X sextupoles run twice stronger and cancel the **second order dispersion** as well.

Synchrotron Radiation in Final Focus magnets

- Bends are needed for compensation of chromaticity
- Bends need to be long and weak, especially at high energy to keep the emittance growth due to synchrotron radiation small
- Synchrotron Radiation causes increase of energy spread which may perturb compensation of chromaticity
- Synchrotron radiation in final quadrupoles is harmful (Oide effect) and may limit the achievable beam size

Energy spread growth due to SR:

$$\frac{d\left(\left(\Delta E/E\right)^2\right)}{ds} = \frac{55}{24\sqrt{3}} \frac{r_e \lambda_e \gamma^5}{R^3}$$

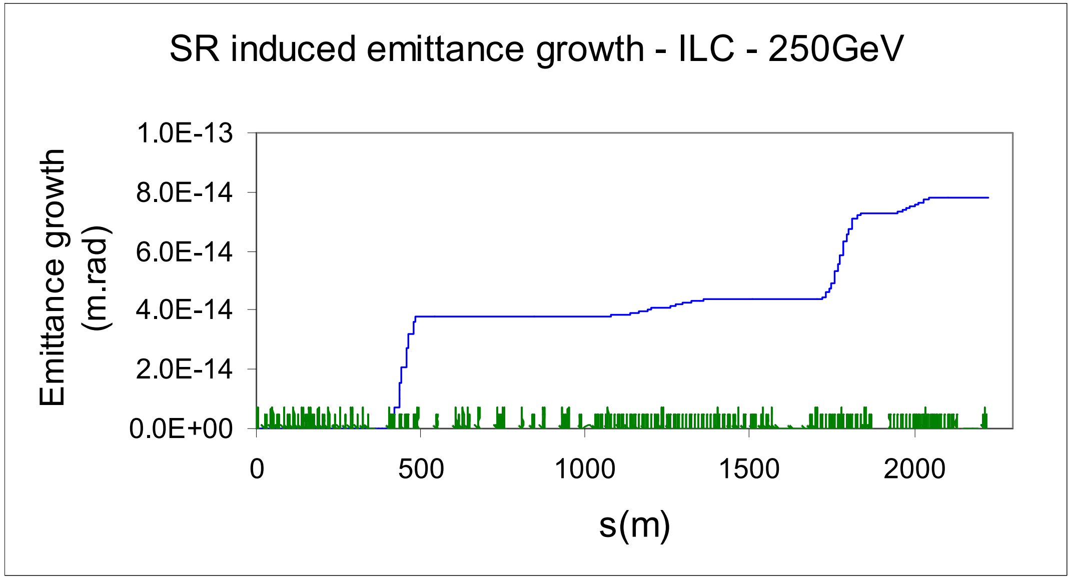
Emittance growth due to SR:

$$\frac{d\varepsilon_x}{ds} = \frac{\left(\eta^2 + \left(\beta_x \eta' - \beta'_x \eta /2\right)^2\right)}{\beta_x} \frac{55}{24\sqrt{3}} \frac{r_e \lambda_e \gamma^5}{R^3}$$

where $r_e = \frac{e^2}{mc^2}$ $\alpha = \frac{e^2}{\hbar c}$ $\lambda_e = \frac{r_e}{\alpha}$

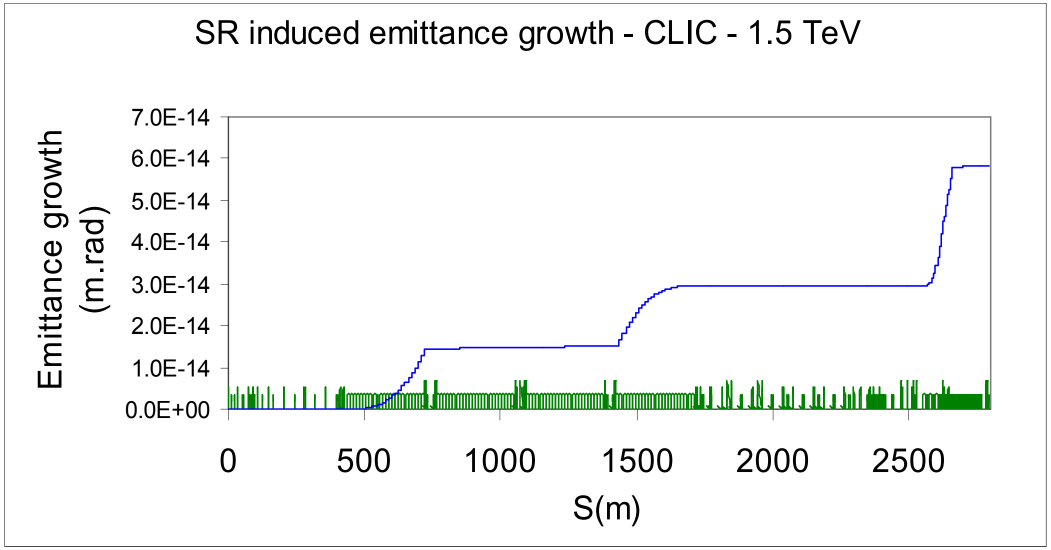
R is the bend radius; η, η’, β, β’ are the dispersion & twiss parameters in the bending magnets.

Emittance Growth due to Synchrotron Radiation



ILC 250 GeV

Design emittance : 2.044E-11 m
Emittance growth : 0.4%

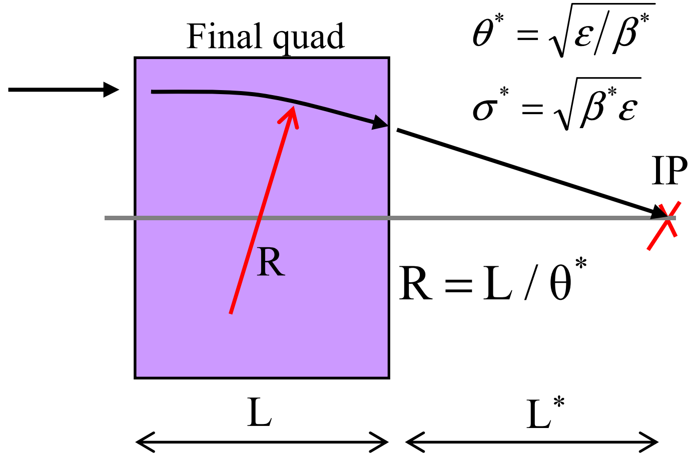


CLIC 1.5 TeV

Design emittance : 2.2484E-13 m
Emittance growth : 25 %

Final Focus : Fundamental Limits (Oide Effect)

At high beam energies: synchrotron radiation in the final focusing quadrupoles increases the beam size at the IP (Oide effect)



$$\theta^* = \sqrt{\varepsilon/\beta^*}$$

$$\sigma^* = \sqrt{\beta^* \varepsilon}$$

$$R = L/\theta^*$$

Energy spread obtained in the final quadrupole

$$\left(\frac{\Delta E}{E}\right)^2 \approx \frac{r_e\, \lambda_e\, \gamma^5\, L}{R^3}$$

Growth of the IP beam size

$$\sigma^2 \approx \sigma_0^2 + \left(L^*\, \theta^*\right)^2 \left(\frac{\Delta E}{E}\right)^2$$

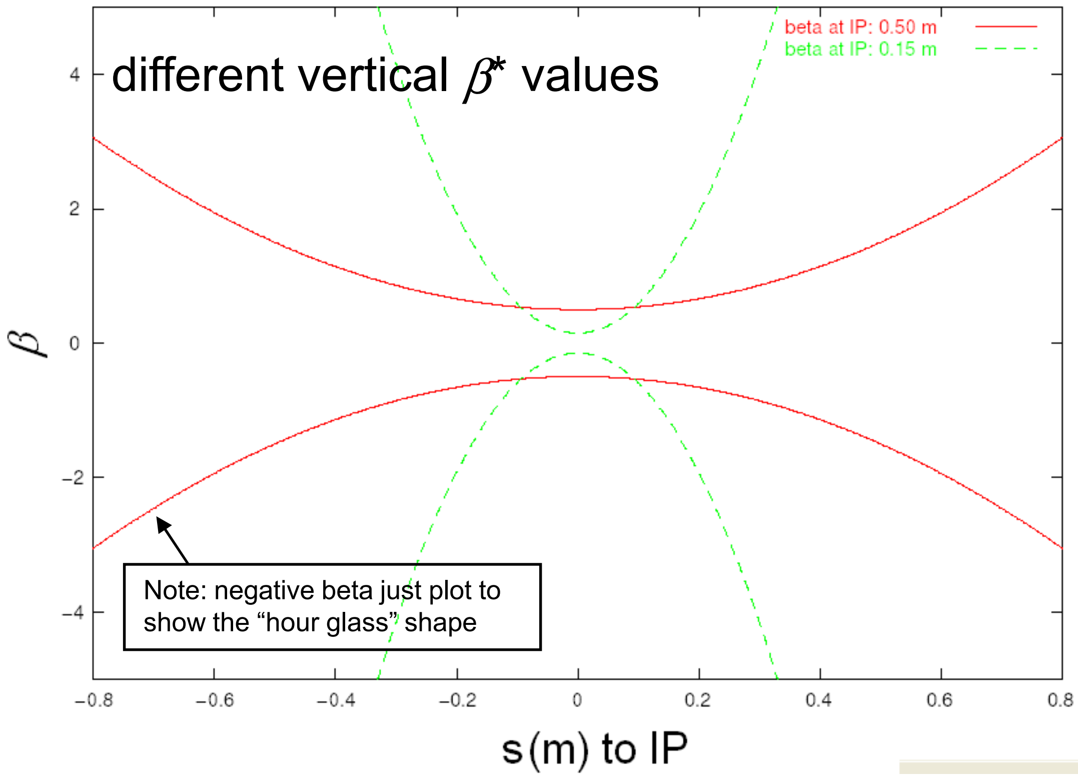
$$\sigma^2 \approx \varepsilon\beta^* + C_1 \left(\frac{L^*}{L}\right)^2 r_e\, \lambda_e\, \gamma^5 \left(\frac{\varepsilon}{\beta^*}\right)^{5/2}$$

(where C_1 is ~ 7 (depend on FD params.))

The achieved minimum beamsize: $\sigma_{min} \approx 1.35\, C_1^{1/7} \left(\frac{L^*}{L}\right)^{2/7} (r_e\, \lambda_e)^{1/7}\, (\gamma\varepsilon)^{5/7}$

When β* is: $\beta_{optimal} \approx 1.29\, C_1^{2/7} \left(\frac{L^*}{L}\right)^{4/7} (r_e\, \lambda_e)^{2/7}\, \gamma\, (\gamma\varepsilon)^{3/7}$

Final Focus : Fundamental Limits (hour glass effect)



Transverse beam sizes cannot be considered constant but vary with β near IP. Beta has quadratic dependence with distance s

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

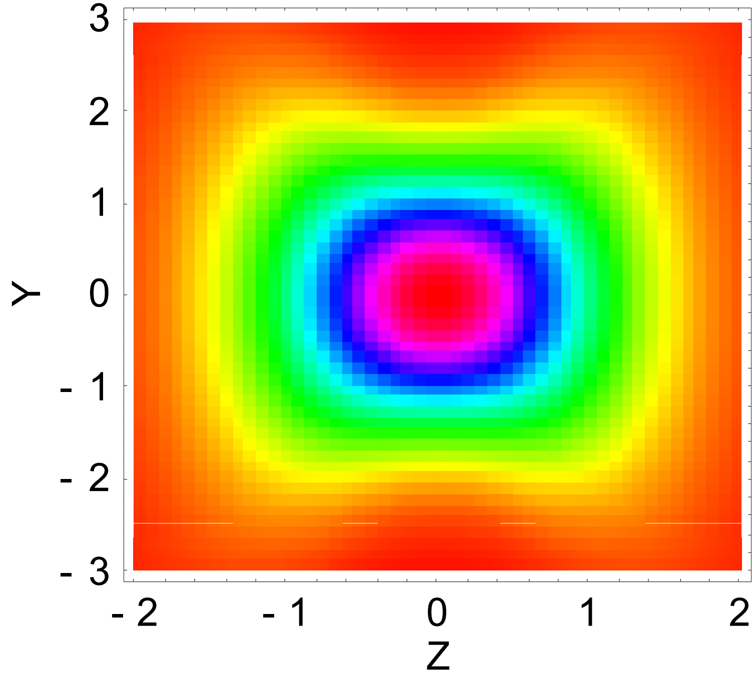
Beam sizes vary linearly with s at IP

$$\sigma_y(s) = \sqrt{\beta_y(s)\varepsilon_y}$$

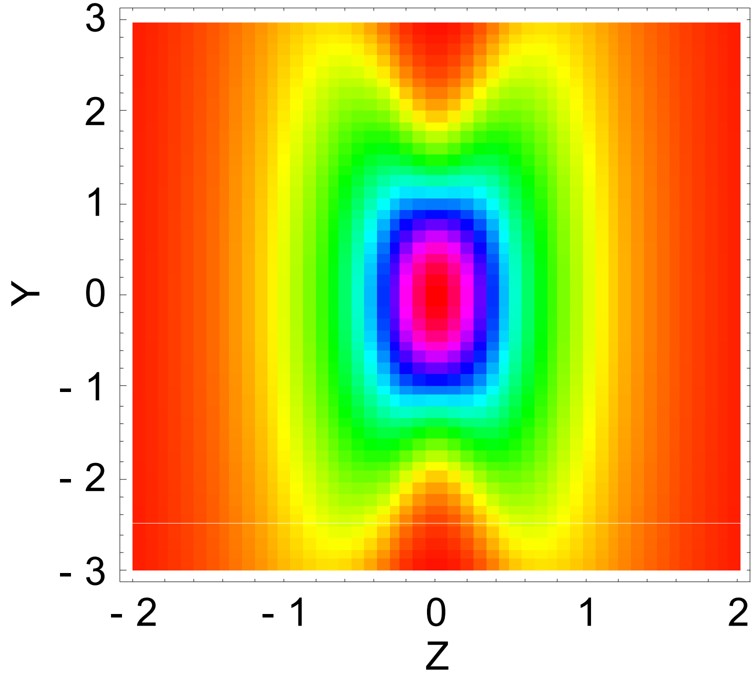
Important when $\beta_y \leq \sigma_z$ since not all particles collide at minimum of transverse beam size → reducing luminosity.

"hour glass" effect from shape of β

Final Focus : Fundamental Limits (hour glass effect)



$\sigma_z = \beta_y$

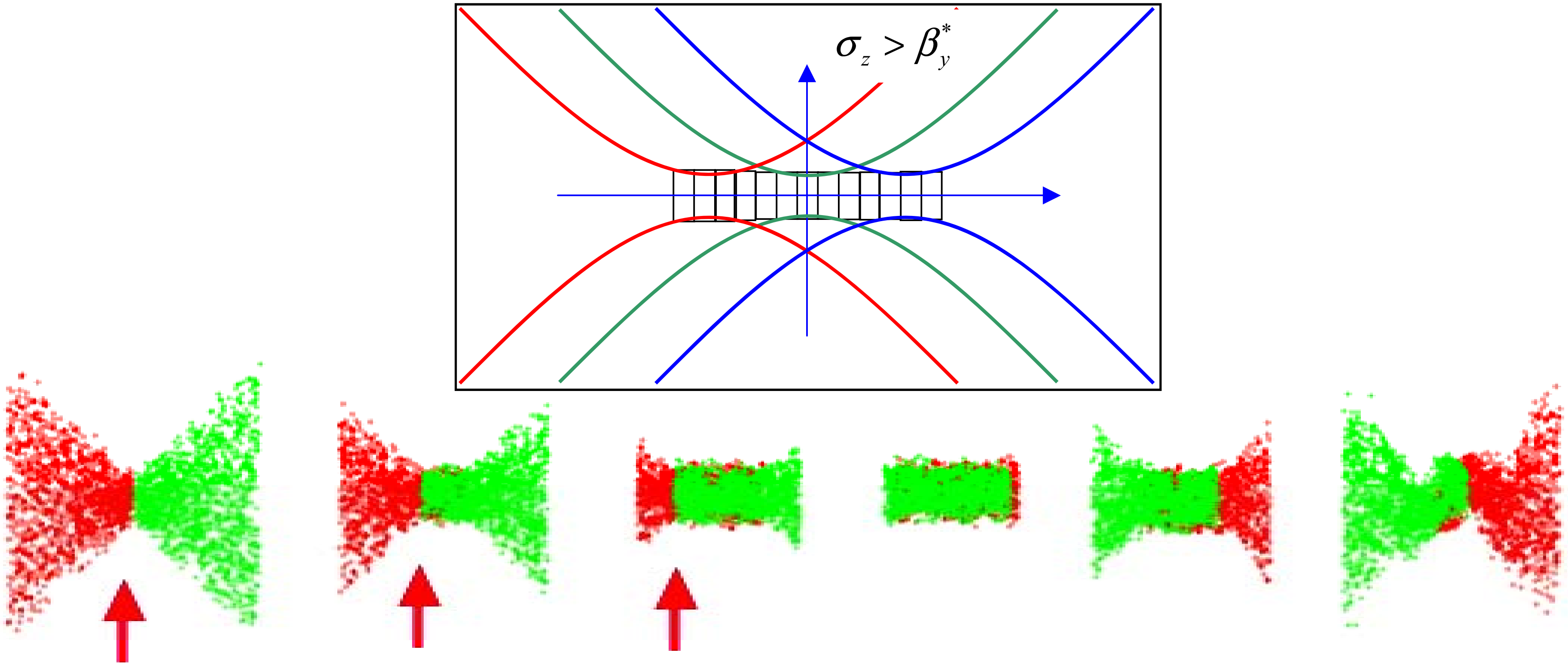


$\sigma_z = 3\beta_y$

Reduction of β_y below σ_z does not give further decrease of effective beam size.

Desirable to have $\sigma_z \leq \beta_y$

Beating the hour glass effect



Position of the focus point during collision

Travelling focus (V.Balakin) – idea is to use beam-beam forces for additional focusing of the beam – allows some gain of luminosity or overcome somewhat the hour-glass effect.

Collimation

Need for Collimation (1)

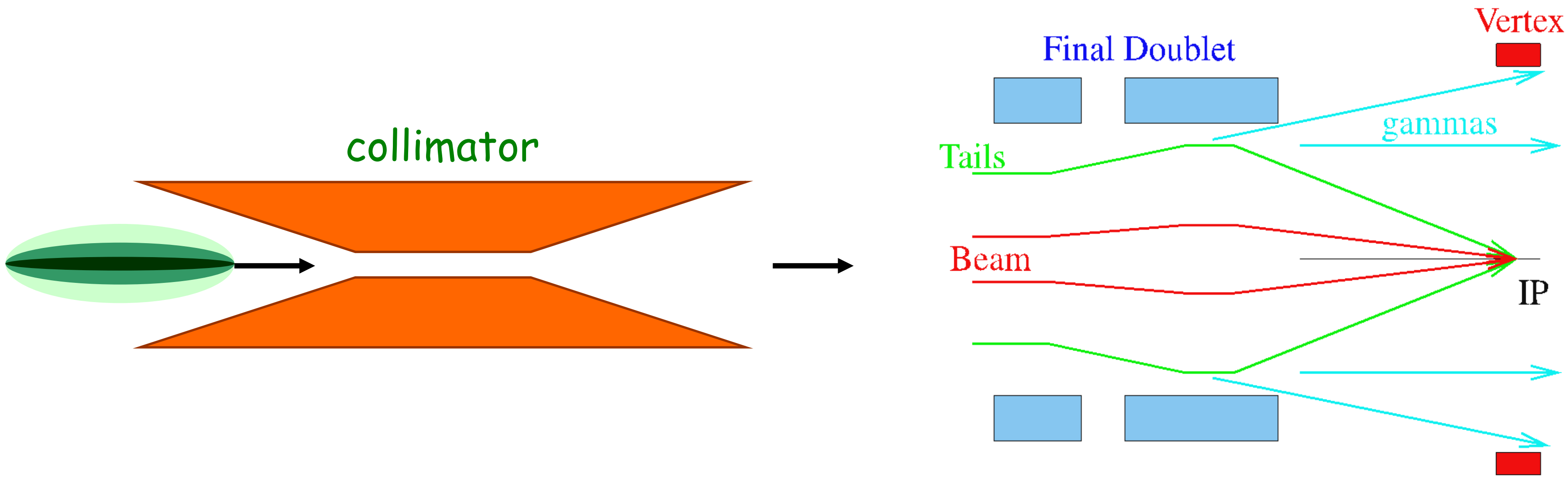
Beam collimation is mandatory at linear collider in order to

- reduce the backgrounds in the detectors to acceptable levels
- protect accelerator and detector components
- maintain operational reliability over the life of the machine
- provide acceptable hands-on maintenance conditions

> ‘Experience from the SLC indicates that collimation considerations must be dealt with early in the design of a linear collider’
>
> ***J. Seeman, SLAC-PUB-5607, 1991***

Need for collimation (2)

- Collimators need to be placed far from the interaction point to minimise the background in the detector.
- Beam halo must be collimated upstream in such a way that SR & halo e^+/e^- do not touch Vertex detector and the final doublet (or any other limiting apertures in the vicinity of IP).

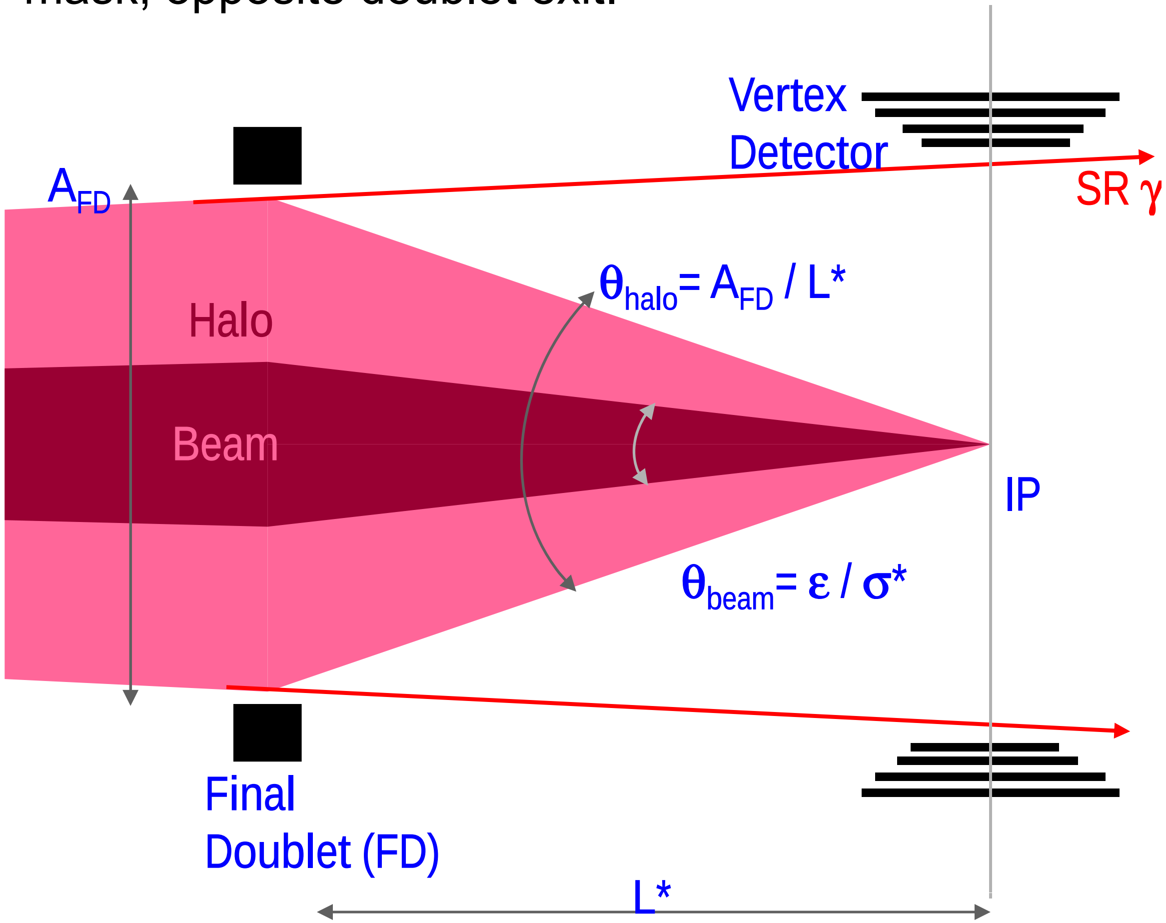


- In case of errant beam, not only beam halo but full errant beam (bunch/bunches or bunch train) would hit the collimator.

How much to collimate?

Synchrotron radiation generated in final doublet must pass cleanly through all apertures.

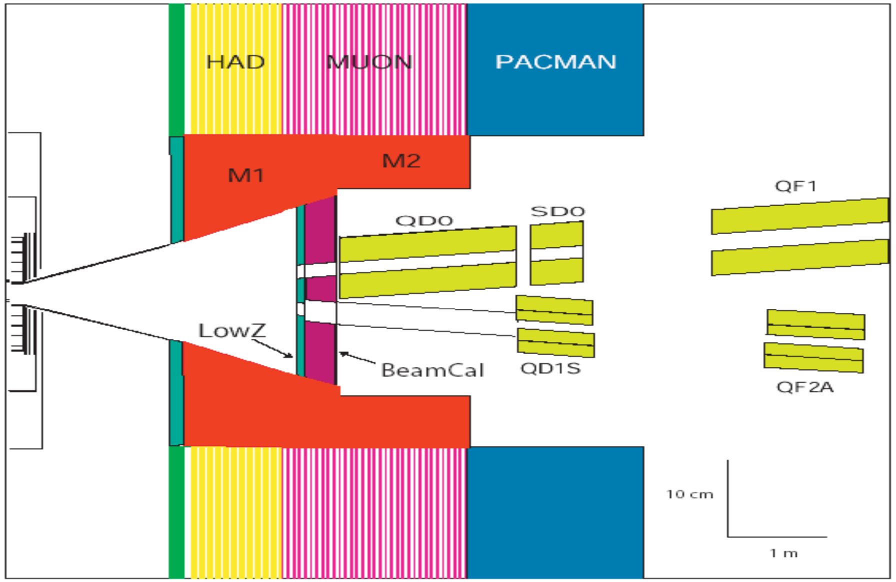
Potentially dangerous apertures are beam pipe at vertex detector, detector IR mask, opposite doublet exit.

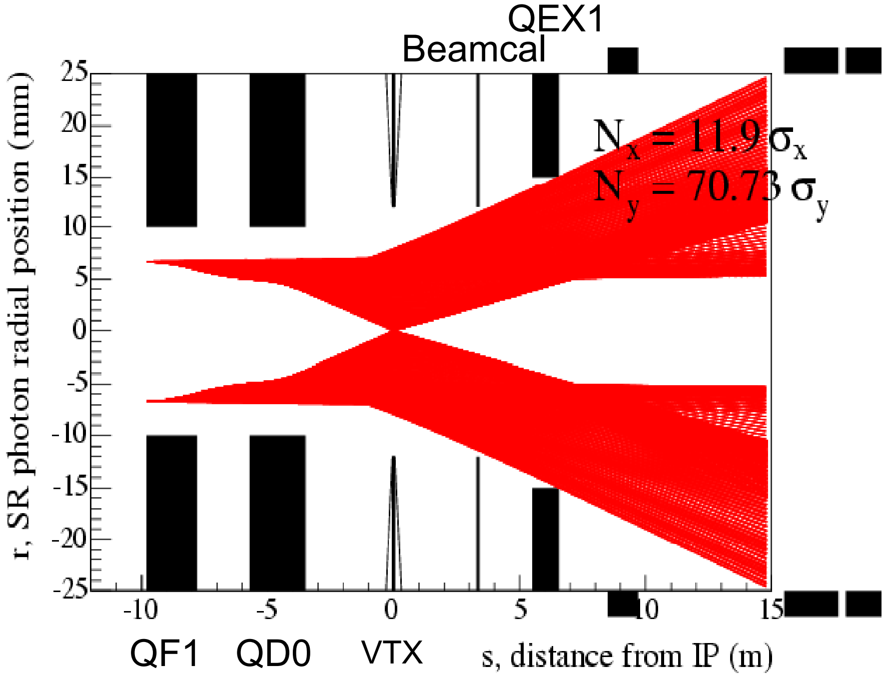


Beam convergence depend on beam parameters & final focus design. The halo convergence is fixed for given geometry.

Collimation depth is defined as $\theta_{halo}/\theta_{beam}$

Collimation Depths





Example of ILC RDR IR

Collimated halo size at FD entrance which allows SR clearance.

These collimation depths give spoiler full apertures of <1mm in vertical plane
→ wake fields an important issue

Beam Halo Prediction

Can we predict the beam halo size and distribution at end of linac?

Difficult problem as halo particles can arise from a number of sources

- Beam-gas scattering
- Ion or electron cloud effects
- Intrabeam scattering
- Synchrotron radiation
- Mismatch, coupling, dispersion
- Non-linearities
- Noise and vibration
- Dark currents
- Wake-fields
- Beam loading
- …………….

Is the beam halo distribution crucial or can we simply design for ‘worst case’ contingency?

0.1% of the beam

Collimator Wakefields

- The collimators in the BDS can be a significant source of wakefields and can reduce the luminosity significantly. The tapered geometry with low resistivity is chosen to reduce the wakefield effects.
- For each collimator a 'jitter amplification factor' is defined as

$$A_\beta = \frac{m}{n} = K \frac{\sigma_y}{\sigma_{y'}}$$

A beam offset of $n\sigma_y$ → angular deflection $m\sigma_{y'}$.

K is the collimator kick factor (kick angle per unit incident beam offset).

K has contributions from geometric and resistive wakefields. The geometric theory defines three regimes of collimator taper geometry : shallow or 'inductive', medium or 'intermediate' and steep or 'diffractive'.

Within each regime the kick factor depends on beam properties (charge, energy, bunch length) and collimator properties (taper angle, gap and width). The resistive kick is evaluated separately and added linearly.

- If jitter is a fixed fraction of beam size in all planes, and y & y' not correlated, the fractional incoming jitter increases by

$$\sqrt{1 + A_\beta{}^2}$$

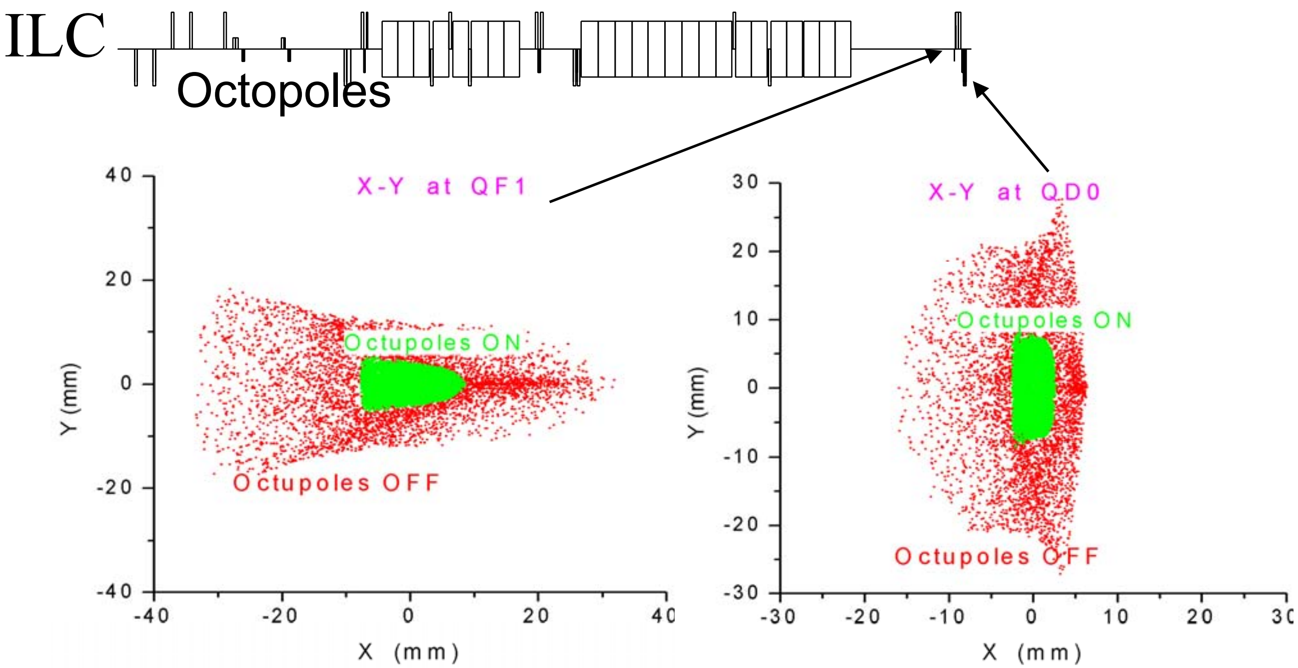
- Energy jitter can cause additional horizontal transverse jitter at $\eta \neq 0$.
- For given beam optics, the amplification factors for each collimator are evaluated and the total effect is calculated.

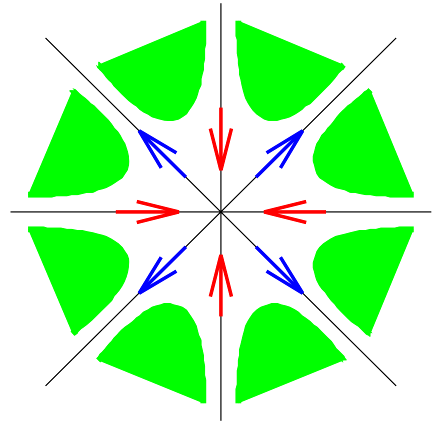
Octupole Tail-folding

Using octupoles one can focus beam tails without changing the core of the beam

Octupole doublets can provide non-linear tail folding, which can relax the collimation requirements.

For this to work, beam should have small angles.





Single octupole focuses in planes and defocuses on diagonals.

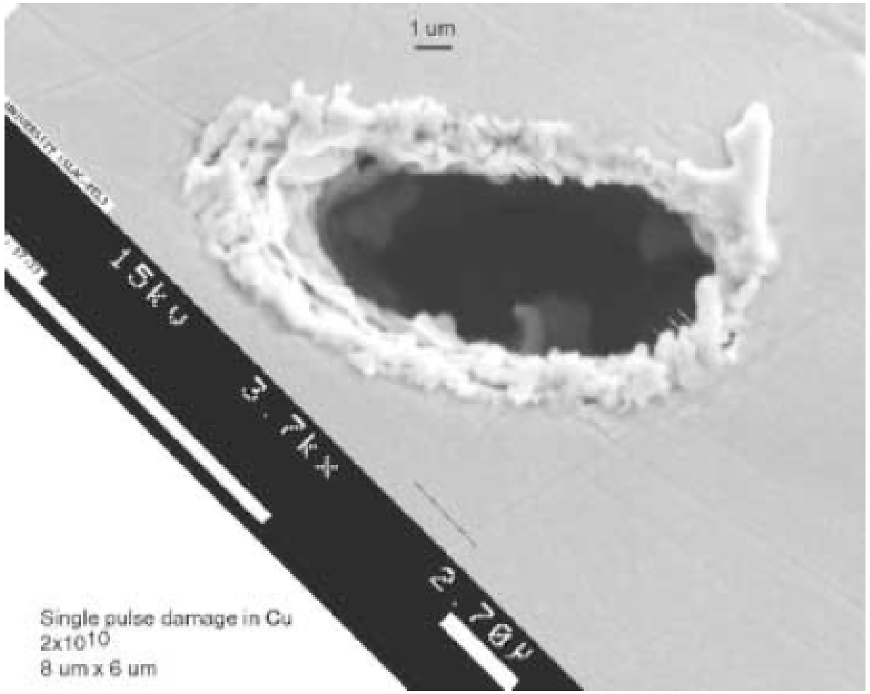
Several non-linear elements need to be combined to provide focusing in all directions.

Two octupole doublets give tail folding by ~ 4 times in terms of beam size in FD

Machine Protection

The beam sizes at the collimators are usually very small, spoiler damage or survival is an important issue. Need for MPS (Machine Protection System).

- Damage may be due to
  - electromagnetic shower (need several radiation lengths to develop)
  - direct ionization loss
- Mitigation of collimator damage
  - using spoiler-absorber pairs
    - thin (0.5-1 χ_0) spoiler followed by thick (~20-30 χ_0) absorber
  - increase of beam size at spoilers
  - MPS diverts the beam to emergency extraction as soon as possible (ILC)



Picture from beam damage experiment at FFTB. The beam was 30GeV, 3-20x10^9 e-, 1mm bunch length, σ~45-200um^2. Test sample is Cu, 1.4mm thick. Damage was observed for densities > 7x10^{14}e-/cm^2. Picture is for 6x10^{15}e-/cm^2

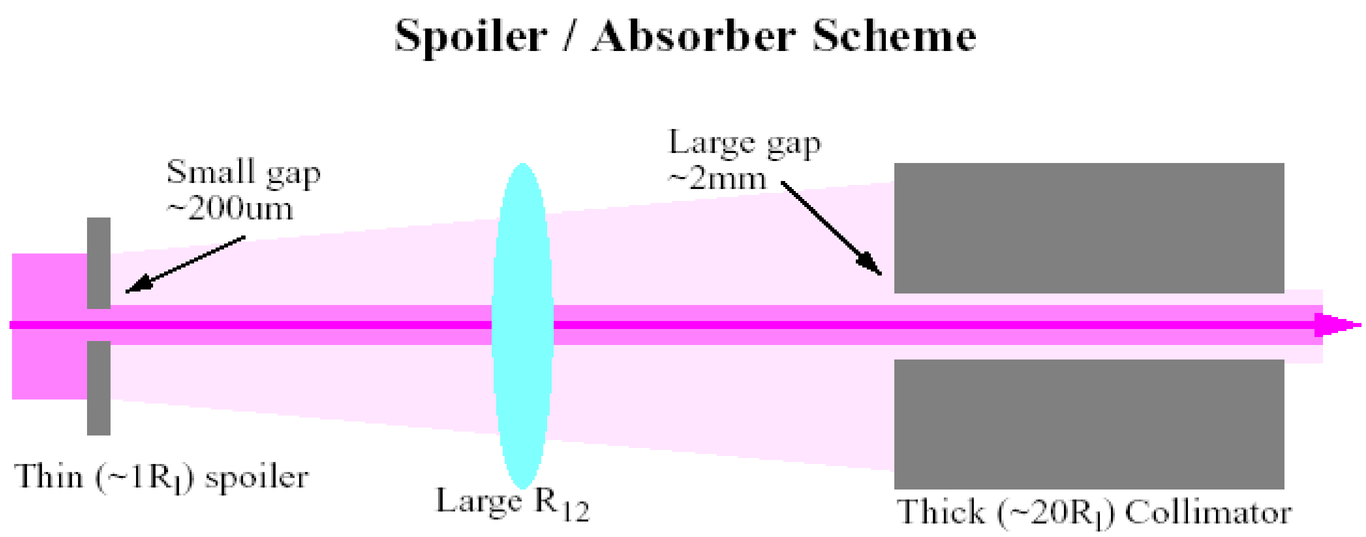
Survivable and Consumable Spoilers

- For ILC, the bunch separation within bunch train is ~300nsec, which allows machine protection system to pass one (500 GeV) bunch or two (250 GeV) bunches through the spoiler before the rest of the train is diverted (fast extracted) to the beam dump.
- For CLIC, the bunch separation within a train is 0.5 nsec and the machine protection scheme like ILC cannot be used. The spoilers need to absorb full bunch train (312 bunches), when MPS could stop the next train.
- If it is practical to increase the beam spot size at spoilers so that spoilers survive more number of bunches, then they are survivable. Such schemes using non-linear lenses (octupoles, skew sextupoles) were earlier proposed for TESLA design and CLIC design.
- If the optics and MPS does not permit survivable spoilers, spoilers must be consumable or renewable.

Spoiler-Absorber Design

Two stage collimation approach

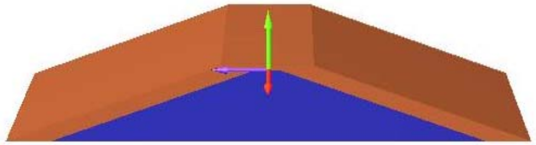
Thin (0.5-1 radiation length) spoiler followed by a thick (~20 radiation length) absorber at the appropriate phase advance in the lattice.



Thin spoiler increases beam divergence and size at the thick absorber already sufficiently large. Absorber is away from the beam and contributes much less to wakefields.

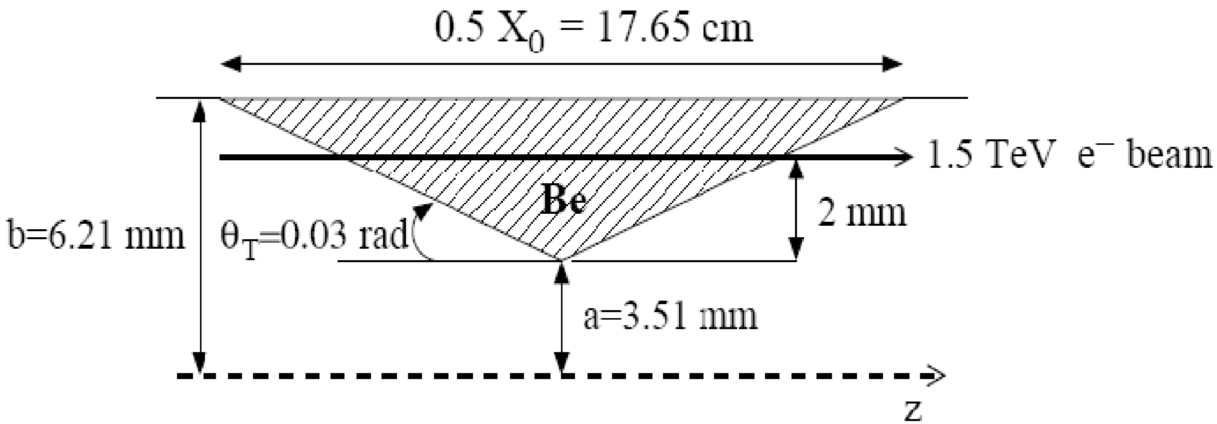
Spoiler Design

- Long, shallow tapers (~20mrad?), reduce short range transverse wakes, reduce longitudinal extent of the spoiler.
- High conductivity surface coatings
- Robust material for actual beam spoiling



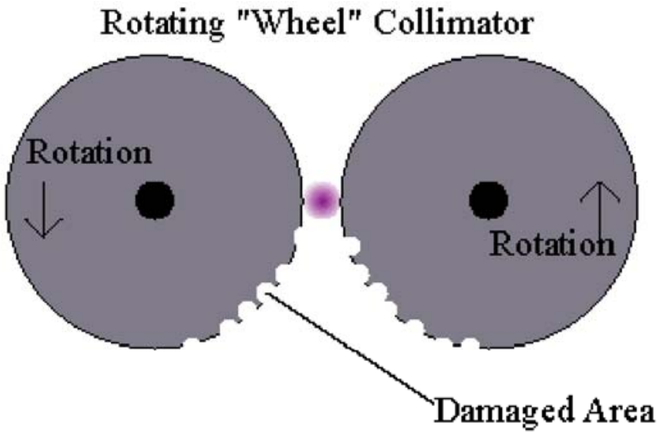
ILC : 0.6χ_0 of Ti tapers with graphite survives at least 2 (1) bunches at 250 (500) GeV

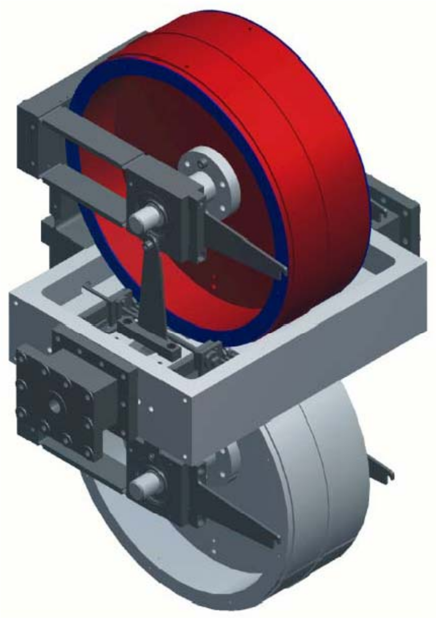
- Long path length for errant beams striking spoilers
  - Large χ_0 materials (beryllium, graphite,…)



CLIC : Be spoiler survives full bunch train (312 bunches) but reaches fracture temperatures

Renewable Spoilers





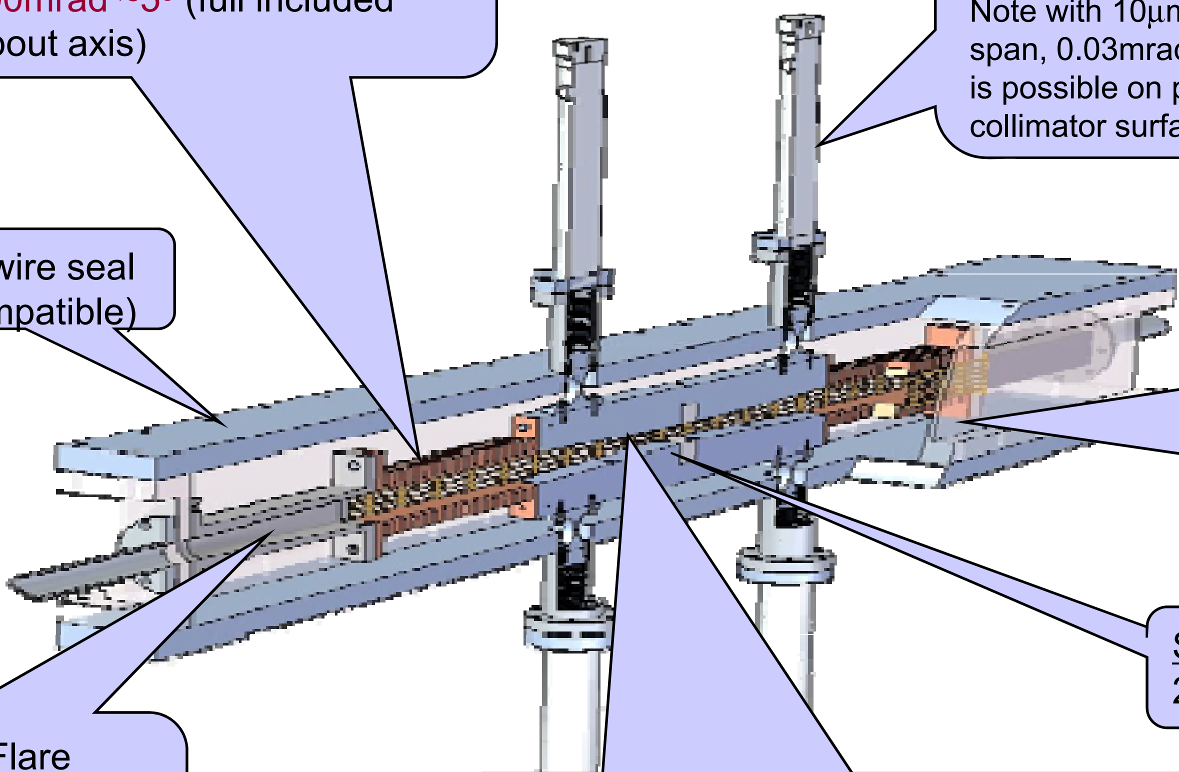
This design of renewable spoiler was proposed for NLC, where short inter-bunch spacing made it impractical to use survivable spoilers.

ILC Spoiler Design

Flexural Section (wakefield taper) Peripheral cooling sufficient? Angle varies from 0 at max aperture opening to 90mrad ~5^{o} (full included angle (or ±20mrad about axis)

Precision encoded actuators with bi directional repeatability to <10µm (<5µm possible?). Note with 10µm over 300mm span, 0.03mrad angle control is possible on pitch of collimator surfaces

Vessel (wire seal UHV compatible)



Vented Side Grill for Wakefield continuity and pumping

Spoiler Block
21mm width Ti

EntranceTransition Flare
From 20mm diameter to 30(h)x40(w)mm rectangular section.

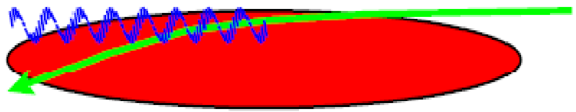
Inclined Wakefield Collimator Block
Bulk Material – Be, semi-transparent to 500GeV electrons. Converging in 2 steps of opening angle 65mrad (3.7^{o}) & 40mrad (2.3^{o}) nearer the spoiler block (note: opening angle = ± 32.5mrad & ±20mrad about central axis respectively) then diverges at same angular rate downstream of the spoiler block

First draft design - Daresbury

Beam-Beam Effects

Beam-Beam Interactions

- The beam-beam interaction in the linear collider differs from the circular collider due to very strong interaction within single collision.
- The single pass nature allows very large bunch deformations.
- Extremely high charge densities at the interaction point lead to very intense fields; hence quantum behaviour becomes important.



- Strong mutual focusing of beams (pinch) gives rise to luminosity enhancement $H_{D.}$
- As electrons/positrons pass through intense field of opposite beam, they radiate hard photons 'beamstrahlung' and loose energy.
- Interaction of 'beamstrahlung photons' with intense field causes e^+e^- pair production, which causes background.

Beam Parameters at Collision

Parameter	Unit	ILC nominal	CLIC
E_{CM}	GeV	500	3000
N	10^9	20	3.72
σ_x^*	nm	639	45
σ_y^*	nm	5.7	1
σ_z	μm	300	45
n_b		2820	312
f_{rep}	Hz	5	50
Δt	nsec	340	0.5
L_{Total}	$10^{34} cm^2 s^{-1}$	2.0	5.9
θ_c	mrad	14	20
δ_{BS}	%	2	29
n_γ		1.3	2.2

Electric field from a relativistic flat beam

The electric field can be computed with Gauss law in a closed form. Basetti-Erskine formula gives electric field for flat beams with $\sigma_x > \sigma_y$:

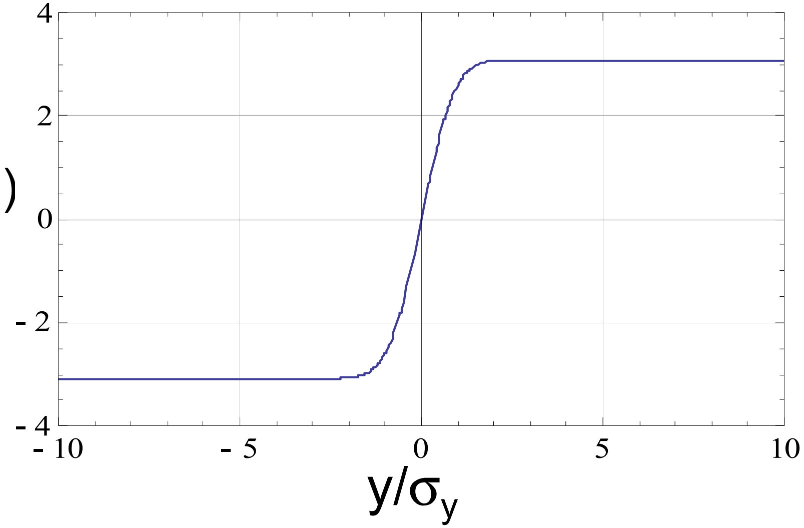
$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \frac{Ne}{2\varepsilon_0 \varsigma} \begin{bmatrix} \mathrm{Im} \\ \mathrm{Re} \end{bmatrix} \left[W\left(\frac{x+iy}{\varsigma}\right) - e^{-\left(\frac{x^2}{2\sigma_x^2}+\frac{y^2}{2\sigma_y^2}\right)} W\left[\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\varsigma}\right]\right] \frac{e^{-\left(\frac{(z-ct)^2}{2\sigma_z^2}\right)}}{\sqrt{2\pi}\sigma_z}$$

Where $\varsigma = \sqrt{2(\sigma_x^2 - \sigma_y^2)}$ and W is the complex error function

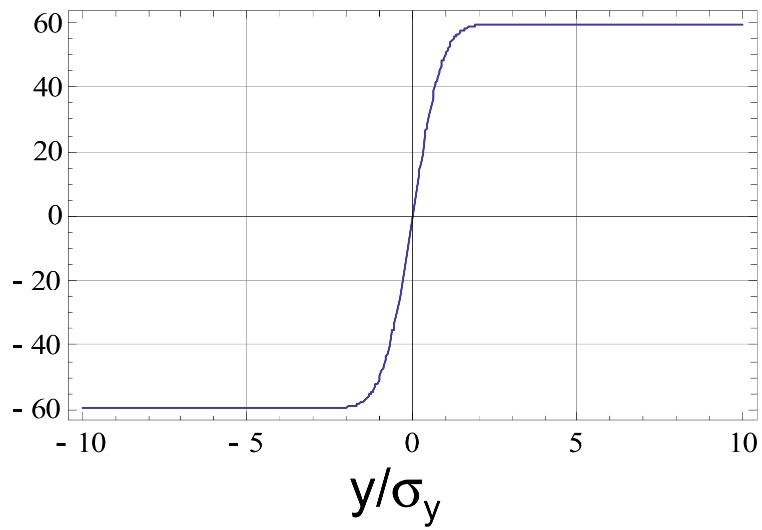
For flat beam, $\sigma_x >> \sigma_y$, assuming infinitely wide beam with constant density per unit length in x and Gaussian distribution in y:

2xE_y (GV/cm) plotted at peak of longitudinal density z=0

ILC 250 GeV Nominal



CLIC 1.5 TeV



Disruption parameter

For Gaussian transverse beam distribution, and for particle near the axis, the beam kick results in the final particle angle:

$$\Delta x' = \frac{dx}{dz} = -\frac{2Nr_e}{\gamma\sigma_x(\sigma_x+\sigma_y)}x \qquad \Delta y' = \frac{dy}{dz} = -\frac{2Nr_e}{\gamma\sigma_y(\sigma_x+\sigma_y)}y$$

The bunch behaves like a focusing lens for a particle travelling in the opposite direction and is equivalent to a lens with focal lengths

$$\frac{1}{f_{x,y}} = \frac{2Nr_e}{\gamma\sigma_{x,y}(\sigma_x+\sigma_y)}$$

'Disruption parameter' $D_{x,y} = \frac{\sigma_z}{f_{x,y}}$ characterises the focusing strength of the field of the bunch

$$D_x = \frac{2Nr_e\sigma_z}{\gamma\sigma_x(\sigma_x+\sigma_y)} \qquad D_y = \frac{2Nr_e\sigma_z}{\gamma\sigma_y(\sigma_x+\sigma_y)}$$

D<<1 => beam acts as a thin lens on other beam
D>>1 =>particle oscillates in the field of other beam

In linear colliders, usually D_x<<1 and D_y>>1
Since particles in both beams start to oscillate, analytical estimates become tedious. Use computer codes GUINEAPIG(Schulte et al), CAIN (Yokoya et al)

Pinch Enhancement

During collision, the bunches focus each other (self-focusing or pinching) leading to an increase in luminosity

Luminosity enhancement factor : $$H_D = \frac{L}{L_0} = \frac{\sigma_{x0}\sigma_{y0}}{\sigma_x \sigma_y}$$

Very few analytical results exist on this parameter.

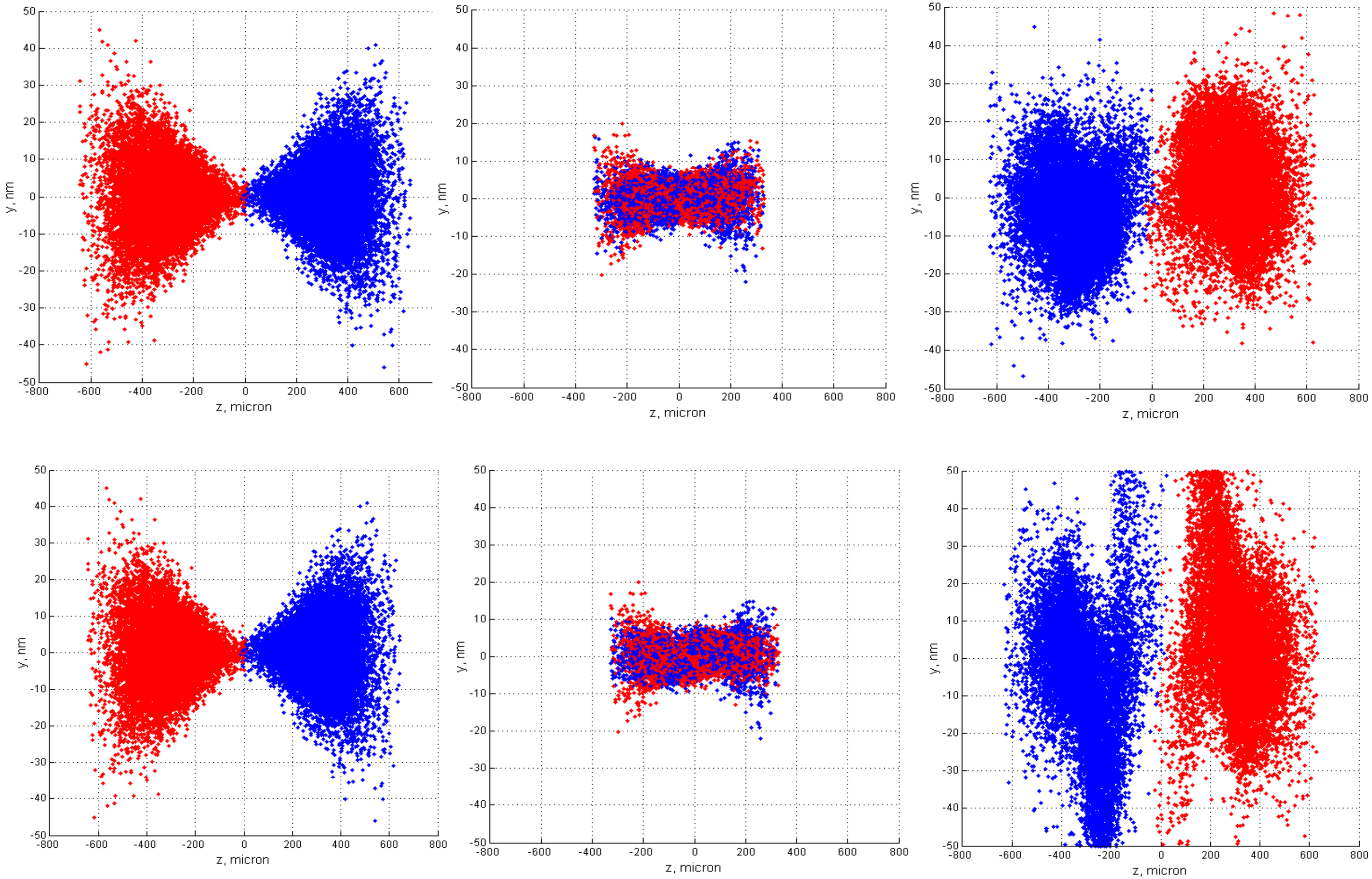
Empirical fit to beam-beam simulation results gives

$$H_{D_{x,y}} = 1 + D_{x,y}^{1/4}\left(\frac{D_{x,y}^3}{1+D_{x,y}^3}\right)\left(\ln\left(\sqrt{D_{x,y}}+1\right) + 2\ln\left(\frac{0.8\beta_{x,y}}{\sigma_z}\right)\right)$$

Only a function of disruption parameter $D_{x,y}$

Hour glass effect

Beam-Beam Simulations

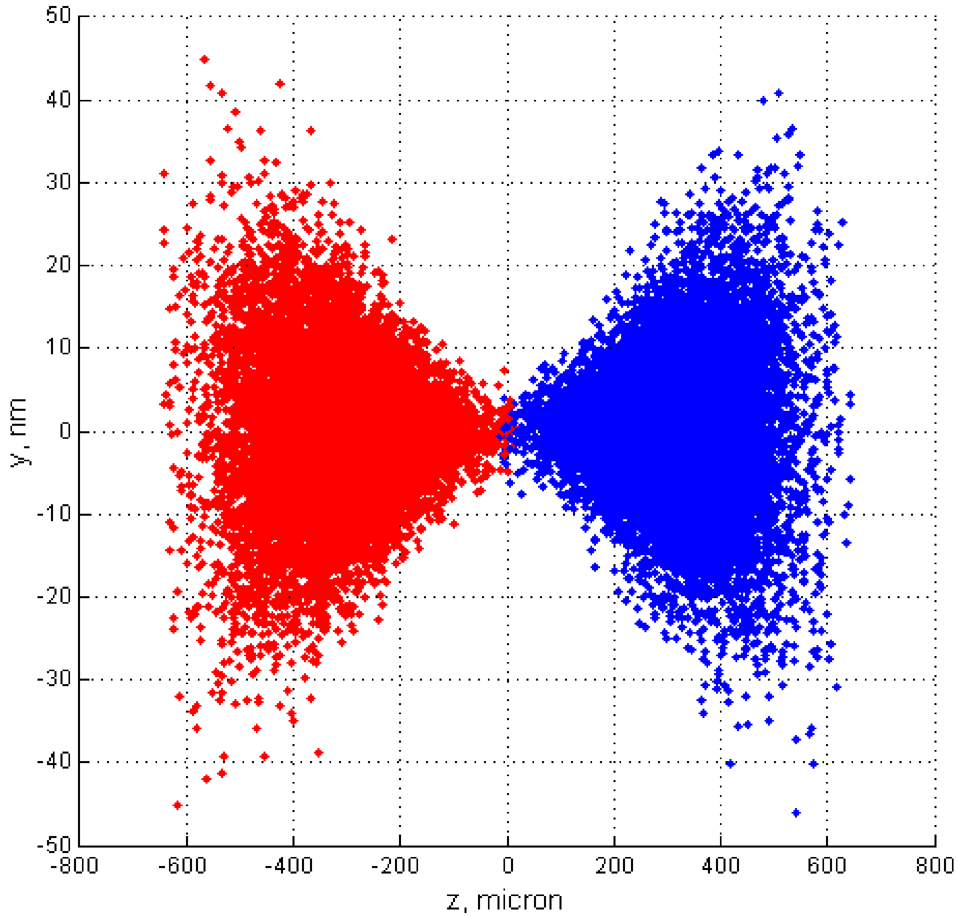


D_y~12

Nx2
D_y~24

Animations produced by A. Seryi using the **GUINEAPIG** beam-beam simulation code (D. Schulte).

Beam-Beam Simulations



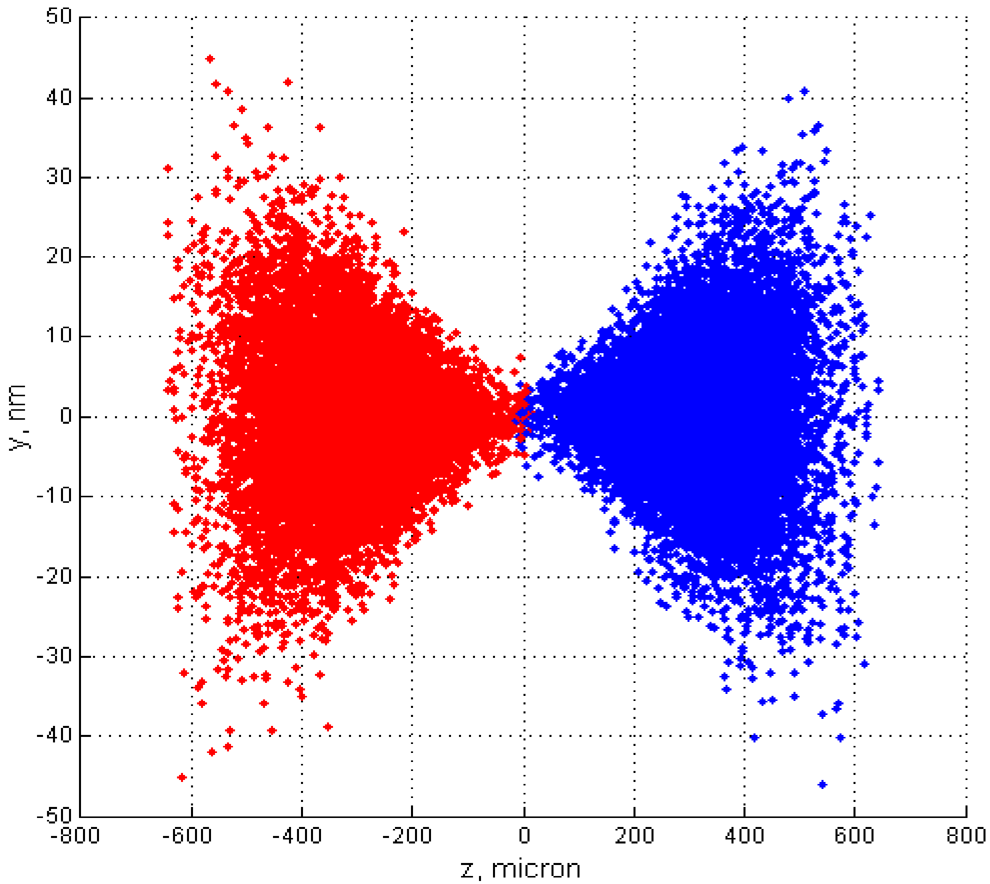
LC parameters
D_y~12

Luminosity enhancement
H_D ~ 1.4

Not much of an instability.

Animations produced by A. Seryi using the **GUINEAPIG** beam-beam simulation code (D. Schulte).

Beam-Beam Simulations



Nx2
D_y~24

Beam-beam instability is clearly pronounced.

Luminosity enhancement is compromised by higher sensitivity to initial offsets.

Animations produced by A. Seryi using the **GUINEAPIG** beam-beam simulation code (D. Schulte).

Disruption Angle

The disruption angle after the collision is characterised by nominal deflecting angle

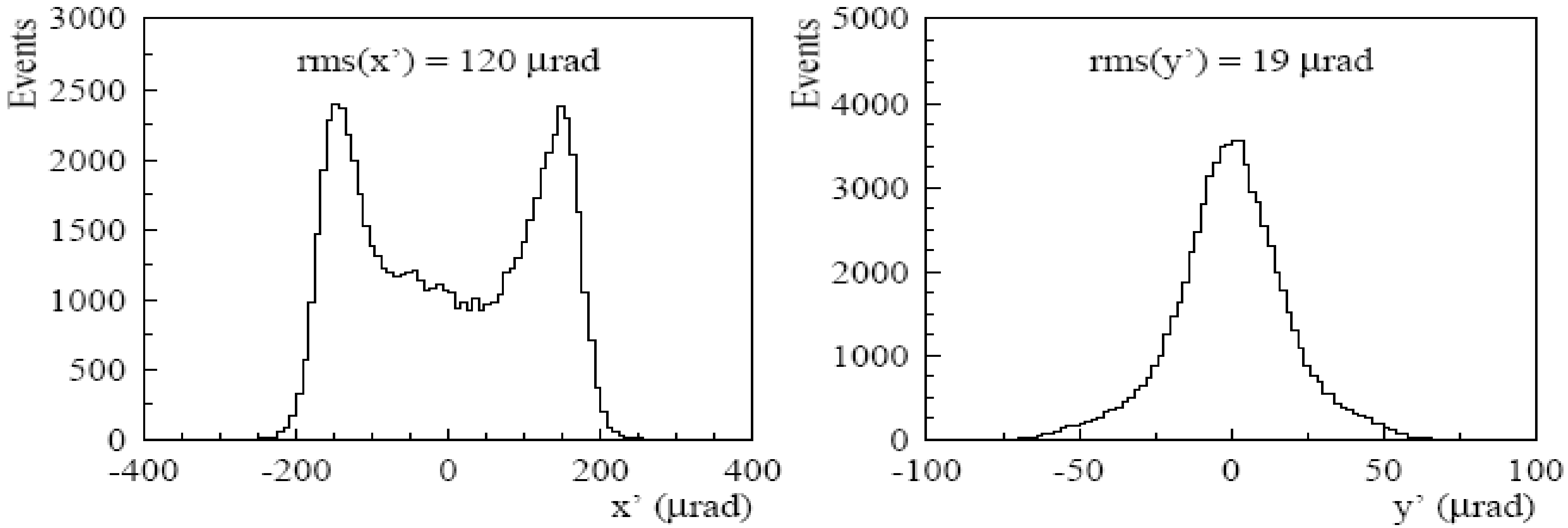
$$\theta_0 \equiv \frac{D_x \sigma_x}{\sigma_z} = \frac{D_y \sigma_y}{\sigma_z} = \frac{2Nr_e}{\gamma(\sigma_x + \sigma_y)} \approx \frac{2Nr_e}{\gamma \sigma_x}$$

The maximum and rms disruption angles obtained from computer simulations scaling laws for flat beams and in the limit $A_y \equiv \sigma_z / \beta_y \to 0$

$$\theta_{y,rms} \sim \frac{0.55\,\theta_0}{\left[1 + (0.5 D_y)^5\right]^{1/6}}$$

$$\theta_{y,\max} \sim 2.5\,\theta_{y,rms}$$

Disruption angle : simulations for CLIC



Important in designing the beam extraction after collision.

Beamstrahlung

Electrons of one bunch radiate against the coherent field of the other bunch- synchrotron radiation – called ‘Beamstrahlung’.

Peak magnetic field of a bunch

$$B_{max} = \frac{2E_{max}}{c} = \frac{qN}{2\pi\varepsilon_0 c\sigma_x\sigma_z}$$

Beamstrahlung opening cone angle is ~ 1/γ

Synchrotron radiation is characterised by the critical energy : $\omega_c = \frac{3}{2}\frac{\gamma^3 c}{\rho}$

Beamstrahlung is fully characterised using the beamstrahlung parameter Υ :

$$\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{E_0}$$

The average value for Gaussian beams :

$$\langle\Upsilon\rangle = \frac{5}{6}\frac{N r_e^2 \gamma}{\alpha(\sigma_x + \sigma_y)\sigma_z}$$

α is fine structure constant

Beamstrahlung Numbers

The average value for Gaussian beams : $\langle \Upsilon \rangle = \frac{5}{6} \frac{N r_e^2 \gamma}{\alpha (\sigma_x + \sigma_y) \sigma_z}$

$$\Upsilon_{\max} \approx 2.4 \langle \Upsilon \rangle$$

Photons per electron : $n_\gamma \approx 2.54 \left[\frac{\alpha \sigma_z}{\lambda_e \gamma} \right] \frac{\langle \Upsilon \rangle}{\sqrt{1 + \langle \Upsilon \rangle^{2/3}}}$

Average energy loss : $\delta_{BS} = \left\langle -\frac{\Delta E}{E} \right\rangle \approx 1.24 \left[\frac{\alpha \sigma_z}{\lambda_e \gamma} \right] \frac{\langle \Upsilon \rangle^2}{\left[1 + (1.5 \langle \Upsilon \rangle)^{2/3}\right]^2}$

$$\lambda_e = r_e / \alpha$$

δ_{BS} and n_γ (and hence Υ) directly relate to luminosity spectrum and backgrounds

GUNEAPIG simulations for CLIC

	CLIC 3000	ILC 500
Υ	5.4	0.05
n_γ	2.2	1.3
δ_{BS} [%]	29	2

Luminosity and Beamstrahlung

Beamstrahlung causes a spread in the center of mass energy of $e^- e^+$. This effect is characterized by the parameter δ_{BS}.

Limiting the beamstrahlung emission is of great concern for the design of the interaction region.

Low energy regime, $\Upsilon \rightarrow 0$

$$\delta_{BS} \approx 0.86 \frac{e r_e^3}{2 m_0 c^2} \left[\frac{E_{CM}}{\sigma_z} \right] \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

Luminosity : $\mathcal{L} = \dfrac{n_b N^2 f_{rep}}{4 \pi \sigma_x \sigma_y} H_D$

we would like to make $\sigma_x \sigma_y$ small to maximise Luminosity.

BUT keep $(\sigma_x + \sigma_y)$ large to reduce δ_{SB}.

Using flat beams $\sigma_x >> \sigma_y$; $\quad \delta_{BS} \propto \left[\dfrac{E_{CM}}{\sigma_z} \right] \dfrac{N^2}{\sigma_x^2}$

Set σ_x to fix δ_{SB}, and make σ_y as small as possible to achieve high luminosity.

Pair production

Beamstrahlung photons, particles of beams or virtual photons interact, and create $e^+ e^-$ pairs.

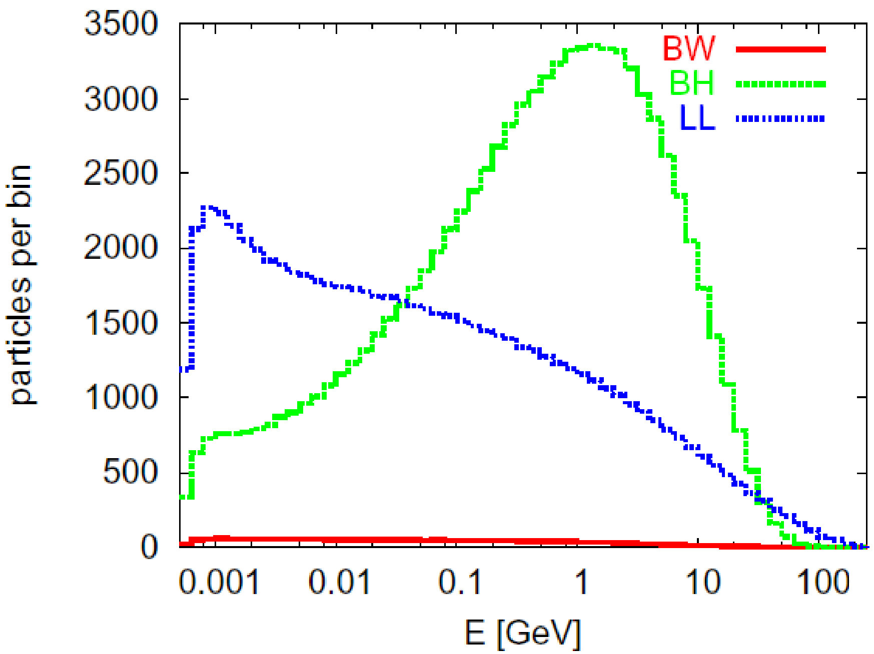
Three processes are important for incoherent pair production (Υ<0.6):

Breit-Wheeler process ($\gamma\gamma \rightarrow e^+e^-$)

Bethe-Heitler process ($e^\pm\gamma \rightarrow e^\pm e^+e^-$)

Landau-Lifshitz process ($e^+e^- \rightarrow e^+e^-e^+e^-$)

Spectrum of pairs

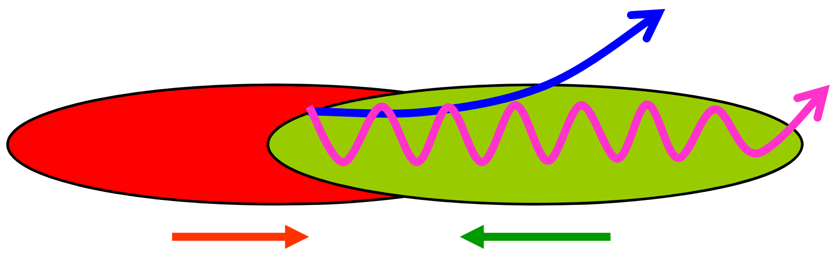


Coherent $e^+ e^-$ pairs (0.6<Υ<100)are generated by a photon in a strong electromagnetic field.

⇒ Rate of pairs is small for centre of mass energies below 1 TeV

⇒ In CLIC, rate is substantial

Pair production



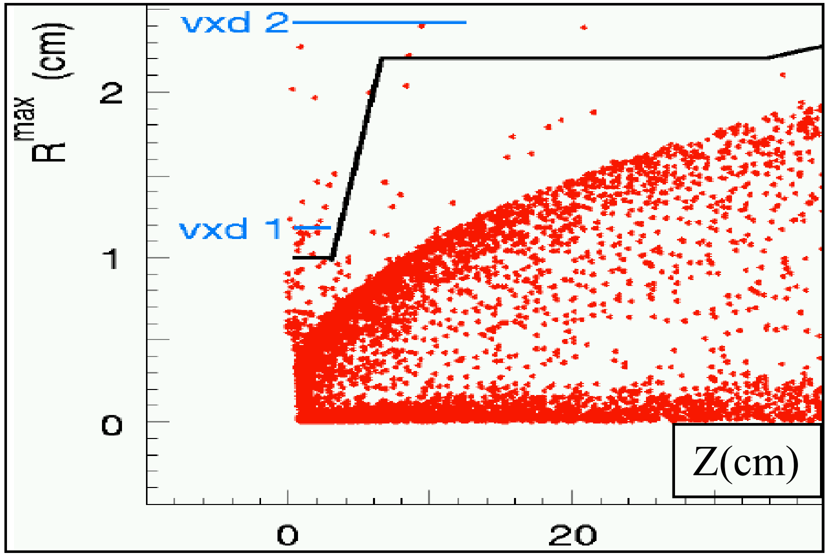
Pairs are potential source of background.

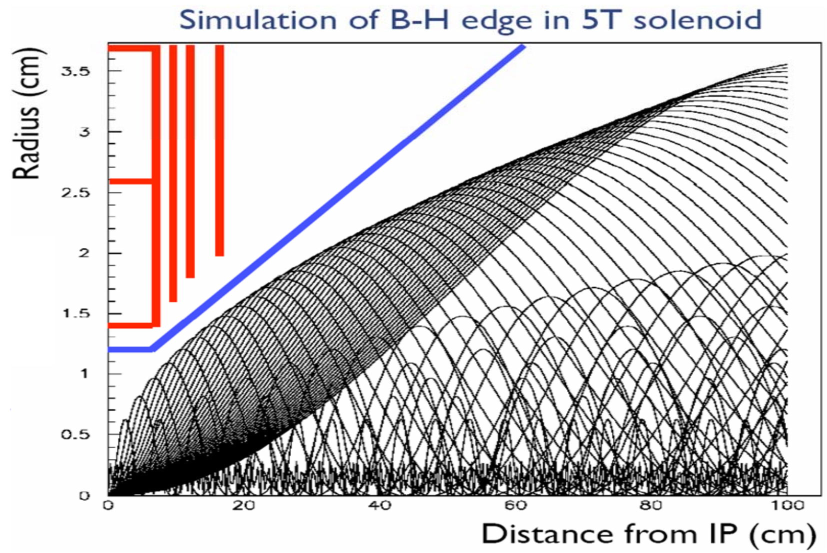
Pairs are affected by the beam (focused or defocused)

Most important: angle with beam axis (θ) and transverse momentum P_T.

Pairs are curled by the solenoid field of detector.

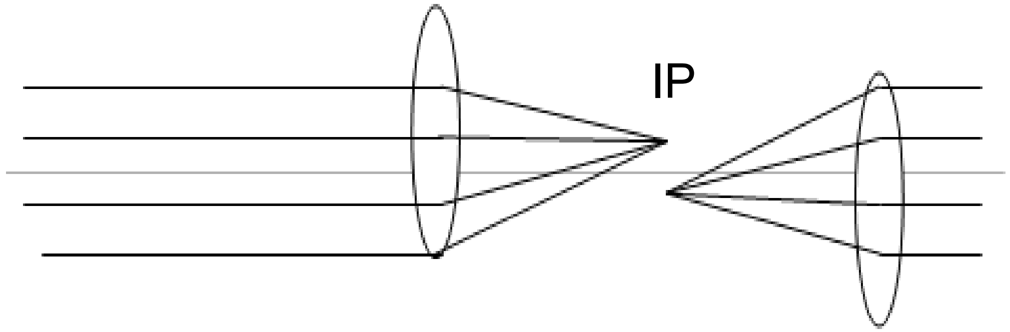
Geometry of vertex detector and vacuum chamber chosen in such a way that most of pairs do not hit the apertures.





Luminosity Optimisation
&
Physics measurements

Stability and Feedback



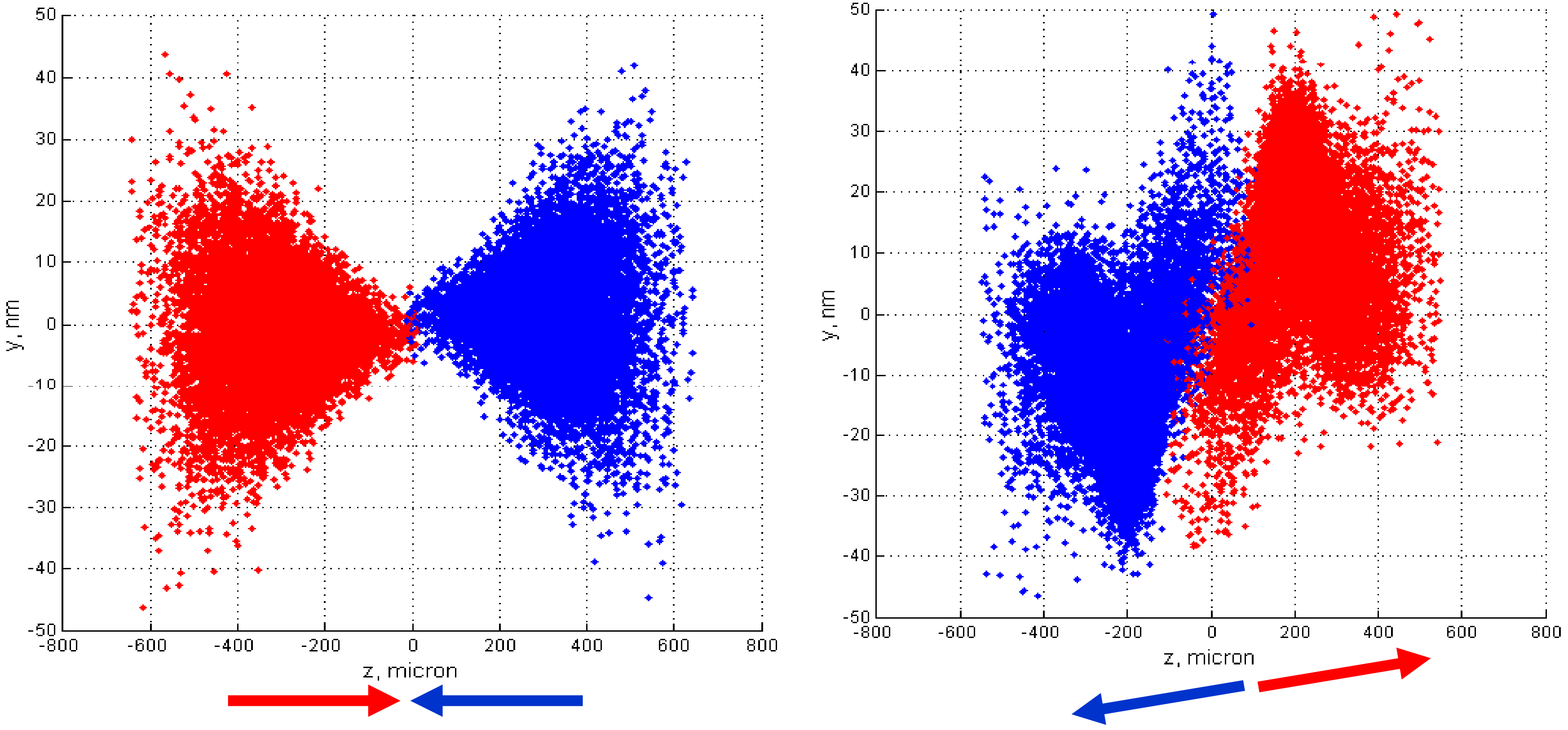
- Due to parallel to point focusing of FD, the offset of the FD causes the same offset at the IP.
- Stability of FD need to be maintained with a fraction of nanometer accuracy.
- Beam size at the IP is very sensitive to orbit of the beam through FD, the sextupoles and other higher strong optical elements of the BDS.
- Misalignments and ground motion affect the beam offsets.
- Beam offset due to slow motion can be compensated by feedback $\Rightarrow$ may result only in beam emittance growth.
- Beam offset due to fast motion cannot be corrected by a pulse-to-pulse feedback operating at the F_{rep} $\Rightarrow$ causes beam offsets at the IP.
- Understanding of ground motion and vibration spectrum important.

Beam beam deflection

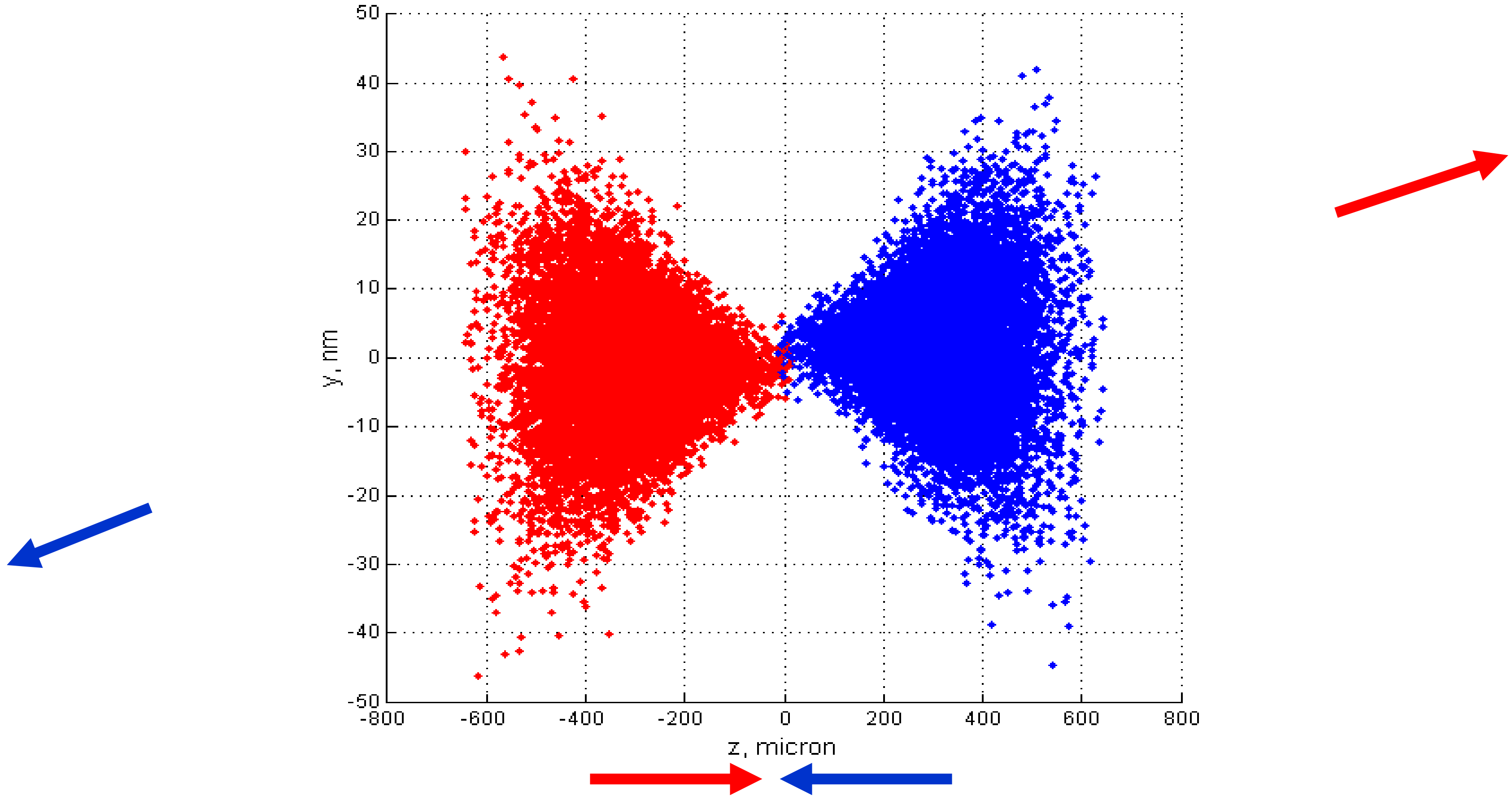
Colliding with offset e^+ and e^- beams deflect each other – sub nm offsets at IP cause large offsets of the beam a few meter downstream.

Deflection is measured by BPMs.

Feedback corrects next pulses to zero deflection.

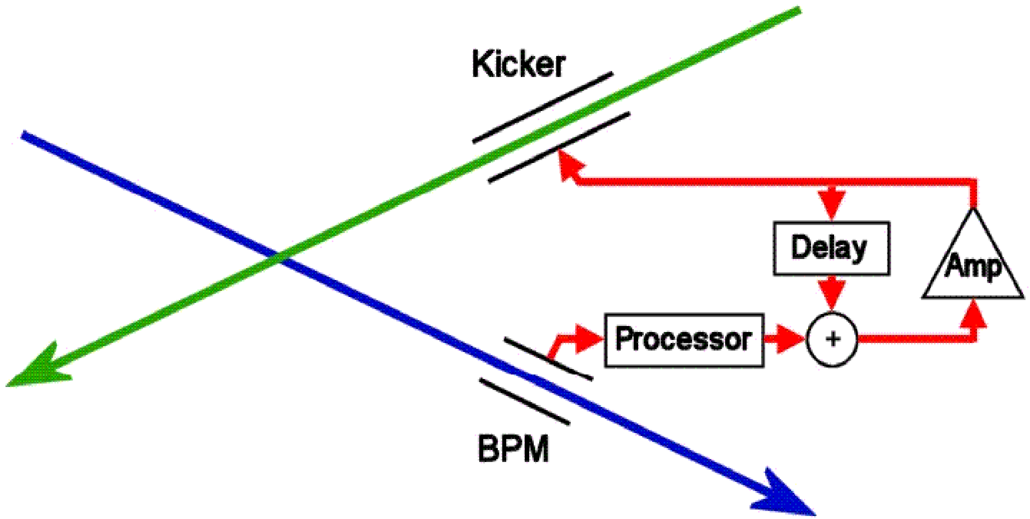


Beam-beam deflection allow to control collisions



Animations produced by A. Seryi using the **GUINEAPIG** beam-beam simulation code (D. Schulte).

Beam-Beam Orbit Feedback

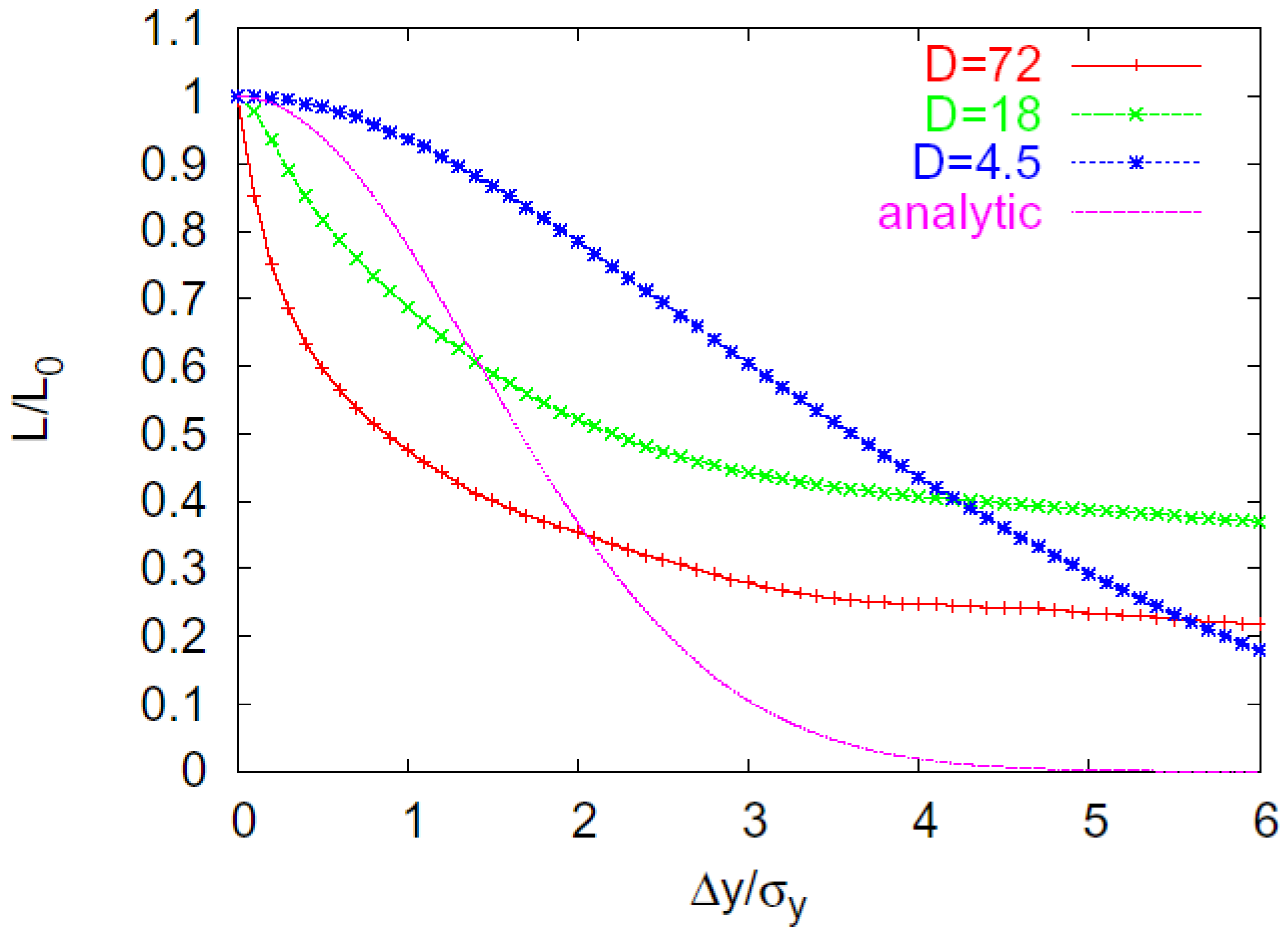


Beam-beam orbit feedback uses strong beam-beam kick to keep beams colliding.

ILC
- Intra-train feedback is within 1 ms bunch train
- No active mechanical stabilization of final doublet is required
- Final doublet jitter tolerance is ~ 100 nm

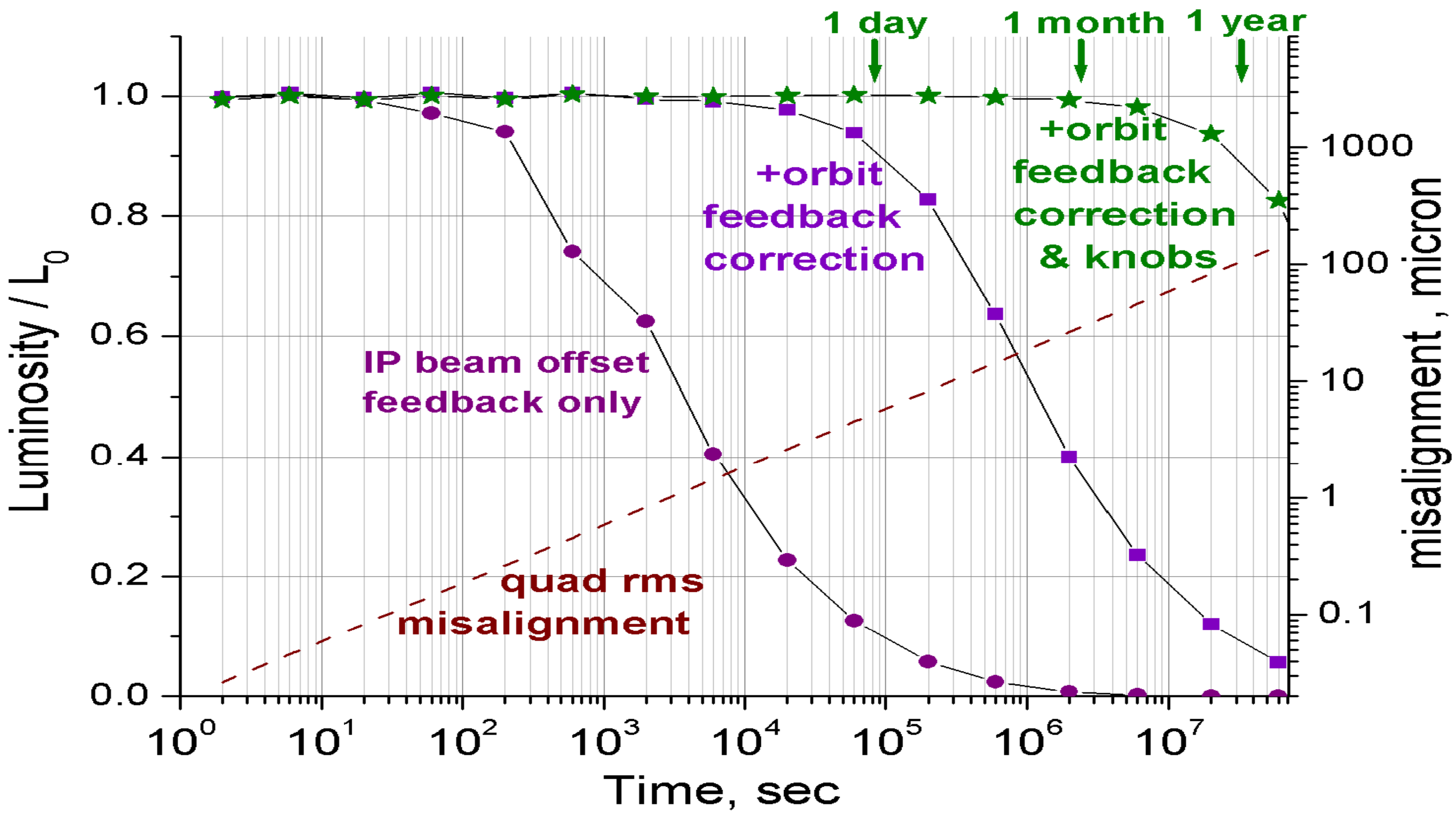
CLIC
- Final doublet jitter tolerance is fraction of nanometer
- Bunch train is 150 nsec
- The reduction of jitter is dominated by feedback latency (achieved so far 23 nm@FONT3)

Luminosity as a function of beam offset



Luminosity (normalised) versus offset at IP for different disruption parameters. Large disruption parameters are more sensitive to beam offsets.

Luminosity recovery through feedbacks



IP feedback combined with other feedbacks can recover the luminosity loss caused by ground

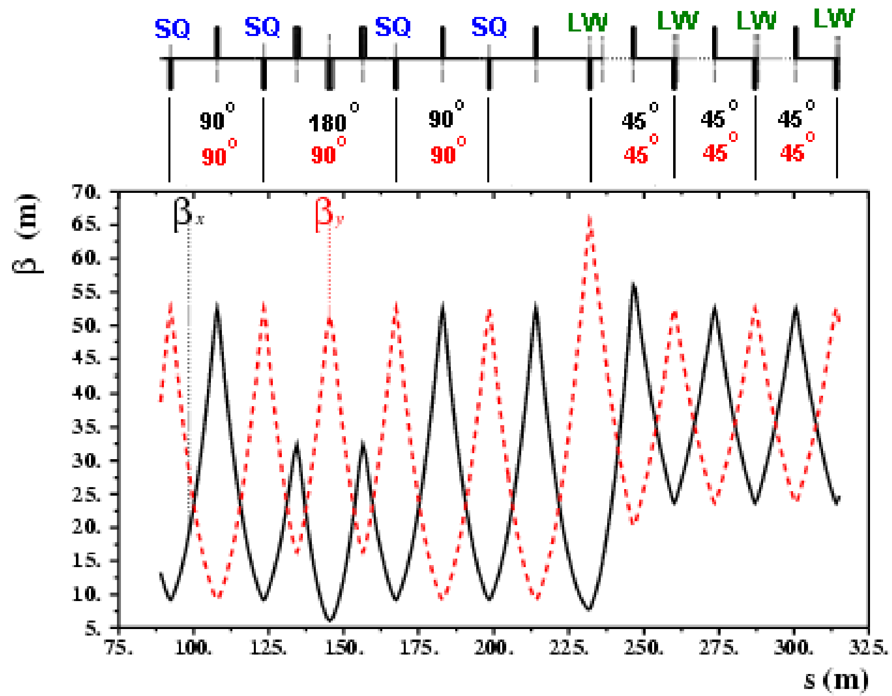
Coupling Correction and Emittance Measurement

- Correction of cross-plane coupling is important in order to minimize the vertical emittance to maintain the luminosity.

- Skew correction section contains 4 orthonormal skew quadrupoles which provide complete and independent control of 4 betatron coupling terms (<xy>,<x'y'>,<x'y>, <xy'>).

- Emittance diagnostics section contains 4 laser wires which are capable of measuring horizontal and vertical beam sizes to ~1μm.

- The wires separated by 45° betatron phase advance allows measurement of projected horizontal and vertical emittances.



Skew correction and 2D emittance measurement section proposed for ILC.

Similar diagnostics section is also proposed for CLIC.

Final Focus Tuning Knobs

- First order tuning knobs :
  offsets of sextupoles (symmetrical or anti-symmetrical in X or Y) to correct the waist shift, coupling, dispersion at the IP.

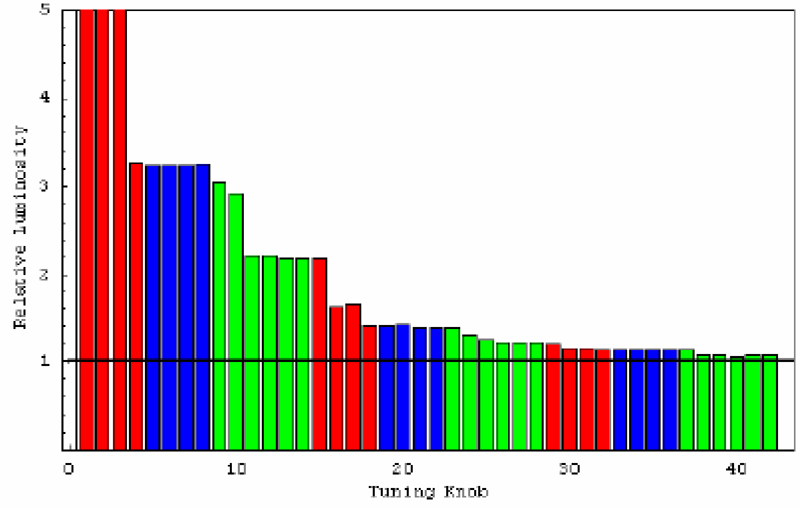
- Second order tuning knobs :
  sextupole rotations and field strengths

The final focus sextupoles need to be on the movers.

The effectiveness of the knobs depends on the set of random machine errors which cause the IP aberrations. Tracking of many sets of errors required to decide the effectiveness of the knobs.

BDS alignment tolerances

	Δx (μm)	Δy (μm)	ΔΨ (mrad)	ΔK/K
Quadrupole	30	30	0.1	10^{-6}
Sextupole	30	30	0.1	10^{-6}

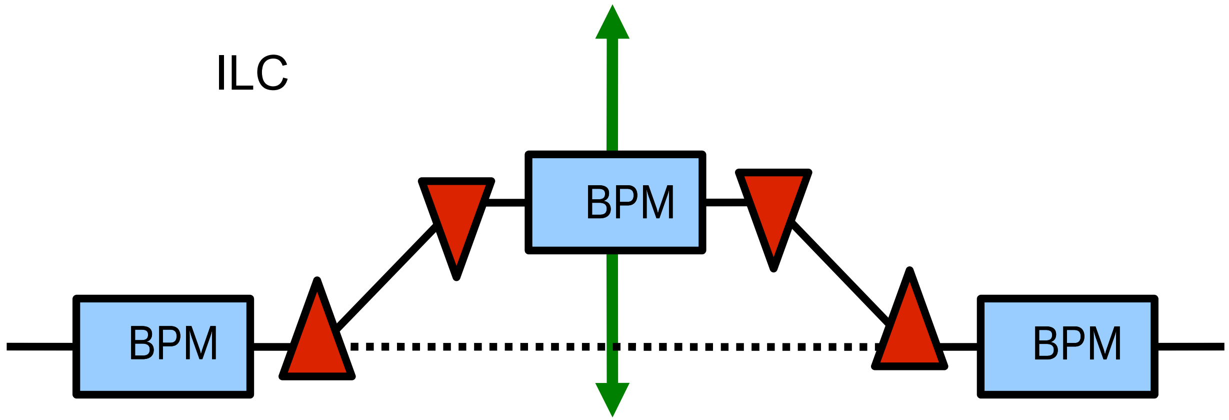


Inverse relative luminosity vs tuning knob.
First order, coupling, second order

rms sextupole changes

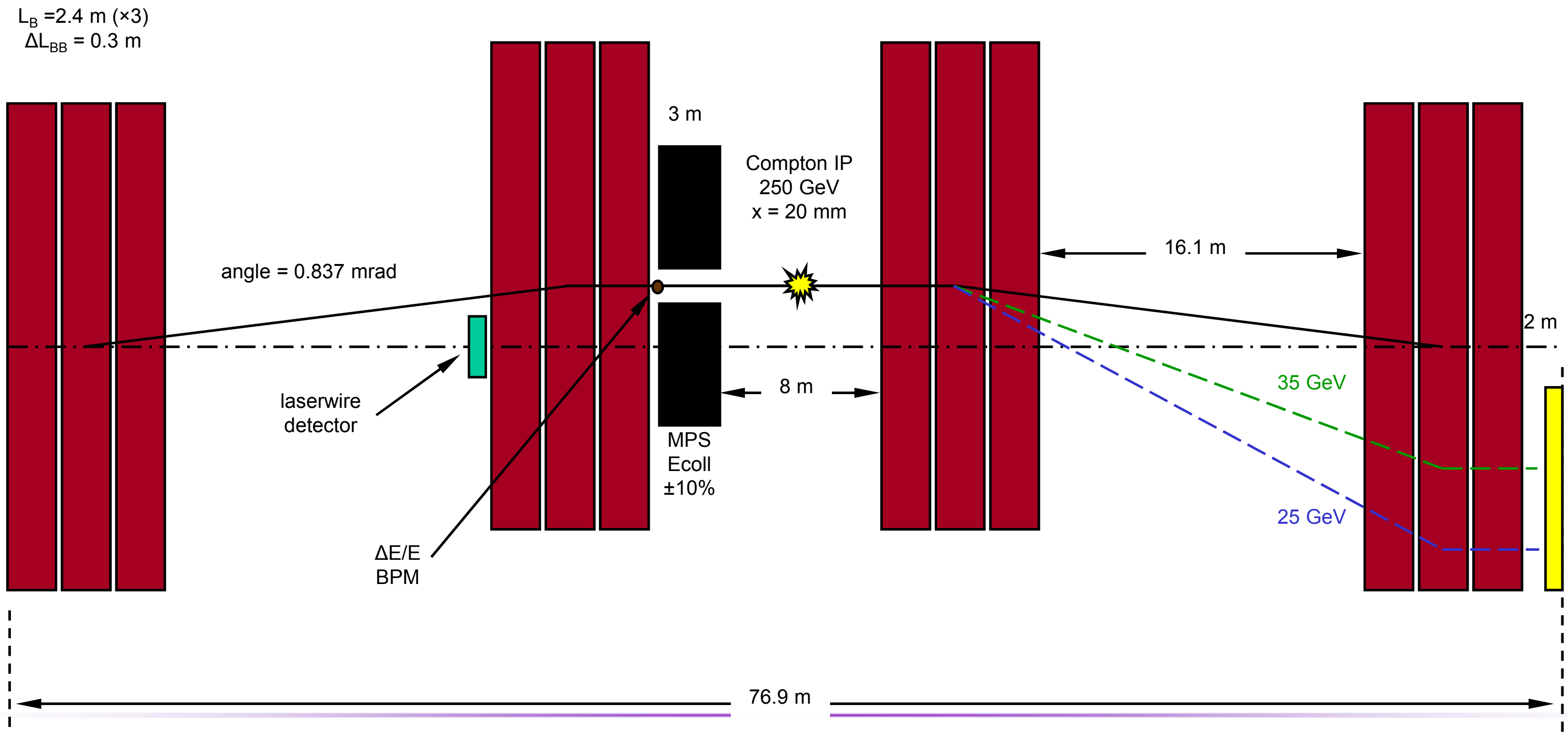
	Δx (μm)	Δy (μm)	ΔΨ (mrad)	ΔK/K (%)
Sextupole	342	61	0.77	7.4

Upstream energy and polarisation measurements



Precision measurements of energy, polarisation and luminosity necessary to reach physics goals.

Beam energy ~ dE/E ~10^{-4}
Polarization ~dp/p~0.25%



End of Part 1