A4 Beam Delivery System

1st day lectures

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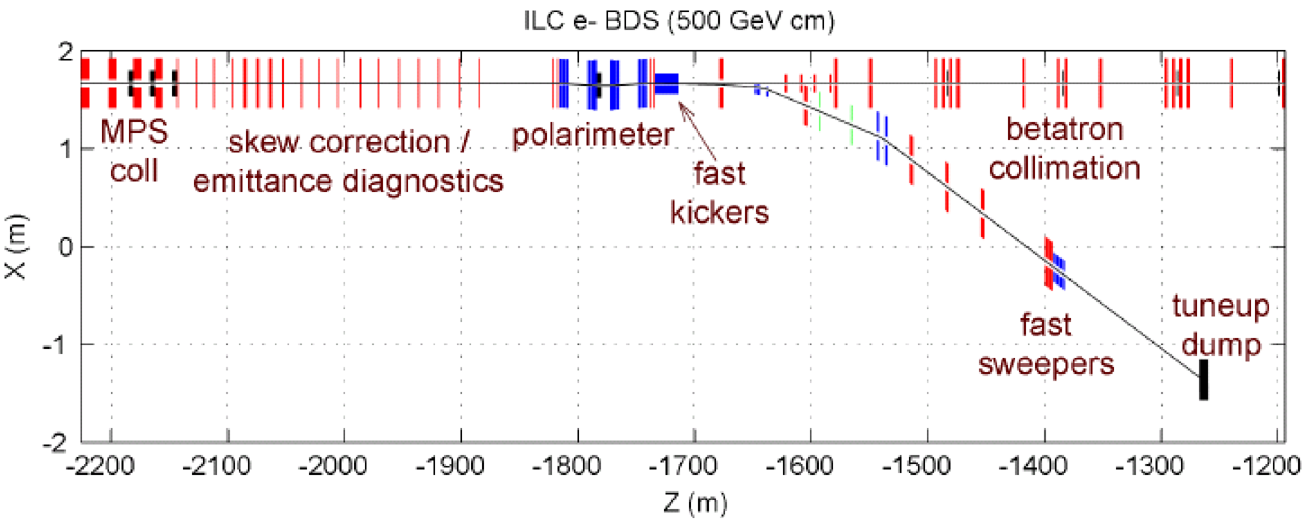
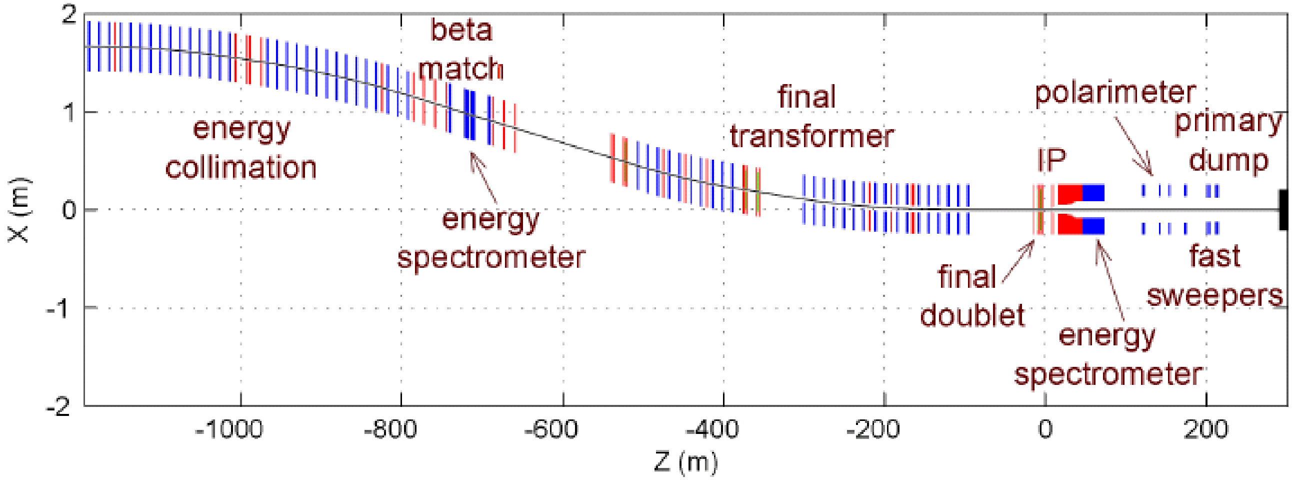
Overview of BDS (Beam Delivery System)

BDS is the beamline after main linac.





BDS consists of

- *beam diagnostic section.*
- *collimator system.*
- *final focus beam line.*
- *beam extraction line.*

Contents of the Lecture

Fundamental beam dynamics
IP parameter optimization
Optics design of final focus beamline for Linear Colliders
Beam size tuning of ILC final focus system
Beam collimation system for ILC
Optimization of ILC final doublet arrangement

ILC final focus beamline optics for various beam energy
Tolerance evaluation for ILC final focus system
Introduction of ATF2 (Test facility of ILC final focus system)
IP position feedback
ILC machine detector interface
ILC beam diagnostic section
ILC beam extraction line

Fundamental Beam Dynamics

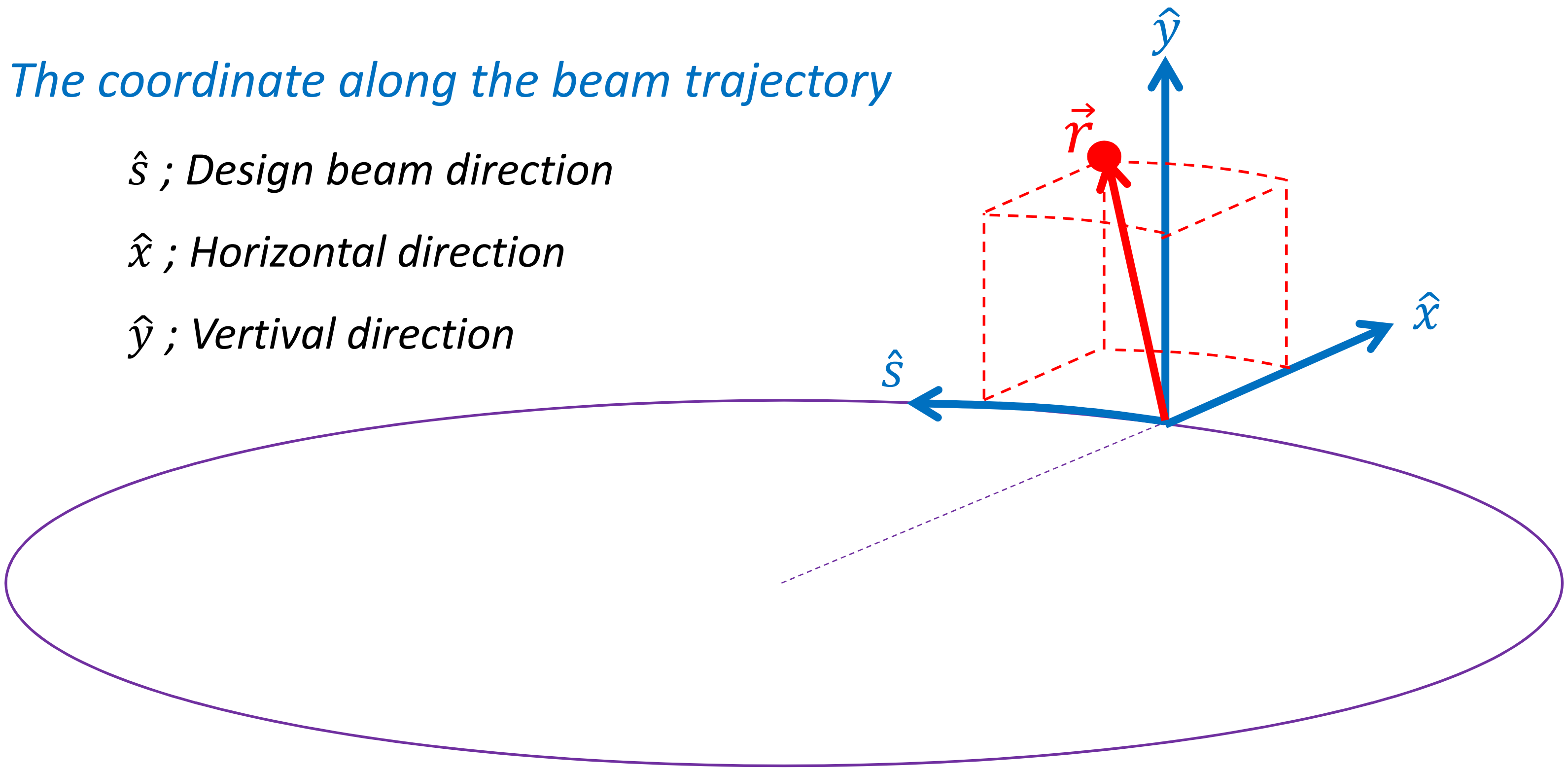
Frenet-Serret Coordinate

The coordinate along the beam trajectory

$\hat{s}$; *Design beam direction*

$\hat{x}$; *Horizontal direction*

$\hat{y}$; *Vertival direction*



Hamiltonian in Canonical Coordinate

$$H(x,y,z) = c\sqrt{m^2c^2 + \left(\vec{p} - q\vec{A}\right)^2} + q\Phi$$

Frenet-Serret Coordinate

$$H(x,y,s) = -\left(1 + \frac{x}{\rho_x} + \frac{y}{\rho_y}\right)\sqrt{(1+\delta)^2 - p_x^2 - p_y^2} - \frac{q}{p_0}A_s$$

Vector Potential in Frenet-Serret Coordinate

Magnetic Field

$$B_x = \frac{1}{h}\left(\frac{\partial A_s}{\partial y} - \frac{\partial A_y}{\partial s}\right)$$

$$B_y = \frac{1}{h}\left(\frac{\partial A_x}{\partial s} - \frac{\partial A_s}{\partial x}\right)$$

$$B_s = \frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}$$

Vector Potential

$$h = 1 + \frac{x}{\rho_x} + \frac{y}{\rho_y}$$

Vector potential for bending magnet
- the coordinate is changing along the beam line

$$-\frac{q}{p_0}A_{s,0} = \frac{1}{2}\left(1 + \frac{x}{\rho_x} + \frac{y}{\rho_y}\right)^2$$

Vector potential for normal n-th multipole magnets

$$-\frac{q}{p_0}A_{s,nN} = \frac{k_{nN}r^{n+1}}{(n+1)!}\cos[(n+1)\theta] \Rightarrow$$

Normal quadrupole

$$-\frac{q}{p_0}A_{s,1N} = \frac{k_{1N}}{2}(x^2 - y^2)$$

Vector potential for skew n-th multipole magnets

$$-\frac{q}{p_0}A_{s,nS} = \frac{k_{nS}r^{n+1}}{(n+1)!}\sin[(n+1)\theta] \Rightarrow$$

Skew quadrupole

$$-\frac{q}{p_0}A_{s,1S} = k_{1S}xy$$

Equation of motion in Frenet-Serret Coordinate

Hamiltonian with dipole and normal quadrupole field

$$H = -\left(1+\frac{x}{\rho_x}+\frac{y}{\rho_y}\right)\sqrt{(1+\delta)^2-p_x^2-p_y^2}+\frac{1}{2}\left(1+\frac{x}{\rho_x}+\frac{y}{\rho_y}\right)^2+\frac{k_{1N}}{2}(x^2-y^2)$$

$$\approx -\frac{1}{2}-\delta\left(1+\frac{x}{\rho_x}+\frac{y}{\rho_y}\right)+\frac{1}{2}(p_x^2+p_y^2)+\frac{x^2}{2}\left(\frac{1}{\rho_x^2}+k_{1N}\right)+\frac{y^2}{2}\left(\frac{1}{\rho_y^2}-k_{1N}\right)$$

Equation of motion

$$\frac{d}{ds}\vec{q} = S\frac{\partial}{\partial\vec{q}}H(\vec{q}) \qquad \vec{q} = \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix} \qquad \mathrm{S} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

$$\frac{d^2x}{ds^2}+\left(\frac{1}{\rho_x^2}+k_{1N}\right)x = \frac{\delta}{\rho_x}$$

$$\frac{d^2y}{dy^2}+\left(\frac{1}{\rho_y^2}-k_{1N}\right)y = \frac{\delta}{\rho_y}$$

We can calculate the particle motion in Frenet-Serret Coordinate .

Equation of motion (continued)

Equation of motion

$$\frac{d^2 z}{ds^2} + k_z z = \frac{\delta}{\rho_z} \qquad (z = x, y)$$

The particle motion (z) is defined with on-momentum motion (z_0) and the motion difference, generated to on-momentum particle with momentum offset δ.

$$z = z_0 + \eta_z \delta$$

$$\left(\frac{d^2 z_0}{ds^2} + k_z z_0\right) + \delta\left(\frac{d^2 \eta_z}{ds^2} + k_z \eta_z - \frac{1}{\rho_z}\right) = 0$$

(1st term) $\Rightarrow$ *the equation of motion for on-momentum particle*

(2nd term) $\Rightarrow$ *the motion difference to on-momentum particle with momentum offset δ*

η is called to “dispersion function”.

Particle Motion for On-momentum Particle

Equation of motion for on-momentum particle ($\delta = 0$)

$$\frac{d^2 z}{ds^2} + k_z z = 0 \qquad (z = x, y)$$

$$k_x = \frac{1}{\rho_x^2} + k_{1N}$$

$$k_y = \frac{1}{\rho_y^2} - k_{1N}$$

We can express the particle transportation ($s_0 \rightarrow s_1$) in the uniform field as

$$\overrightarrow{q_1} = M \, \overrightarrow{q_0} \qquad M = \begin{pmatrix} \begin{matrix} & \\ & M_x \\ & \end{matrix} & \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} \\ \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \begin{matrix} & \\ & M_y \\ & \end{matrix} \end{pmatrix}$$

Transfer Matrix

$\circ \; k_z > 0 \qquad M_z = \begin{pmatrix} \cos\sqrt{k_z}L & \sin\sqrt{k_z}L/\sqrt{k_z} \\ -\sqrt{k_z}\sin\sqrt{k_z}L & \cos\sqrt{k_z}L \end{pmatrix}$

$\circ \; k_z = 0 \qquad M_z = \begin{pmatrix} 1 & L \\ 0 & 0 \end{pmatrix}$

$\circ \; k_z < 0 \qquad M_z = \begin{pmatrix} \cosh\sqrt{-k_z}L & \sinh\sqrt{-k_z}L/\sqrt{-k_z} \\ \sqrt{-k_z}\sinh\sqrt{-k_z}L & \cosh\sqrt{-k_z}L \end{pmatrix}$

Thin lens approximation

The approximation of $L \to 0$ by keeping $k_z L =$ (constant)

- $k_z > 0$

$$M_z = \begin{pmatrix} \cos\sqrt{k_z}L & \sin\sqrt{k_z}L/\sqrt{k_z} \\ -\sqrt{k_z}\sin\sqrt{k_z}L & \cos\sqrt{k_z}L \end{pmatrix}$$

$$\approx \begin{pmatrix} 1 - \dfrac{(k_z L)}{2}L & L \\ -(k_z L) & 1 - \dfrac{(k_z L)}{2}L \end{pmatrix} \xrightarrow{L\to 0} \begin{pmatrix} 1 & 0 \\ -K_z & 1 \end{pmatrix}$$

Integrated Field Strength

$$K_z = |k_z| L$$

- $k_z < 0$

$$M_z = \begin{pmatrix} \cosh\sqrt{-k_z}L & \sinh\sqrt{-k_z}L/\sqrt{-k_z} \\ \sqrt{-k_z}\sinh\sqrt{-k_z}L & \cosh\sqrt{-k_z}L \end{pmatrix}$$

$$\approx \begin{pmatrix} 1 + \dfrac{(|k_z| L)}{2}L & L \\ +(|k_z| L) & 1 + \dfrac{(|k_z| L)}{2}L \end{pmatrix} \xrightarrow{L\to 0} \begin{pmatrix} 1 & 0 \\ +K_z & 1 \end{pmatrix}$$

Thin lens approximation is useful for 1^{st} order optics evaluation.

Dispersion Function

The dispersion function of D_z, D'_z (Dispersion function for $\eta_z = \eta'_z = 0$ at $s = 0$)

$$\circ\ k_z > 0 \qquad D_z(s) = \frac{1 - \cos\sqrt{k_z}\,s}{\rho_z k_z} \qquad D'_z(s) = \frac{\sin\sqrt{k_z}\,s}{\rho_z\sqrt{k_z}}$$

$$\circ\ k_z = 0 \qquad D_z(s) = \frac{s^2}{2\rho_z} \qquad D'_z(s) = \frac{s}{\rho_z}$$

$$\circ\ k_z < 0 \qquad D_z(s) = \frac{\cosh\sqrt{-k_z}\,s - 1}{\rho_z k_z} \qquad D'_z(s) = \frac{\sinh\sqrt{-k_z}\,s}{\rho_z\sqrt{-k_z}}$$

The dispersion motion with finite values of η_z, η'_z at $s = 0$

$$\begin{pmatrix} \eta_z(s_1) \\ \eta'_z(s_1) \\ 1 \end{pmatrix} = \begin{pmatrix} M_z(s_0, s_1) & \begin{matrix} D_z(s_1 - s_0) \\ D'_z(s_1 - s_0) \end{matrix} \\ 0 \quad 0 & 1 \end{pmatrix} \begin{pmatrix} \eta_z(s_0) \\ \eta'_z(s_0) \\ 1 \end{pmatrix}$$

We can follow the dispersion function as linear motion.

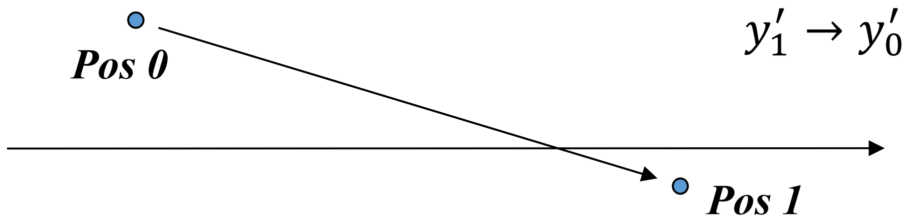
Single particle Dynamics

We can express the single particle motion by using "Transfer Matrix".

Free Space

$$x_1 \to x_0 + Lx_0' \qquad x_1' \to x_0' \quad \Rightarrow \quad \begin{pmatrix} x_1 \\ x_1' \end{pmatrix} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}$$

$$y_1 \to y_0 + Ly_0' \qquad y_1' \to y_0' \quad \Rightarrow \quad \begin{pmatrix} y_1 \\ y_1' \end{pmatrix} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} y_0 \\ y_0' \end{pmatrix}$$

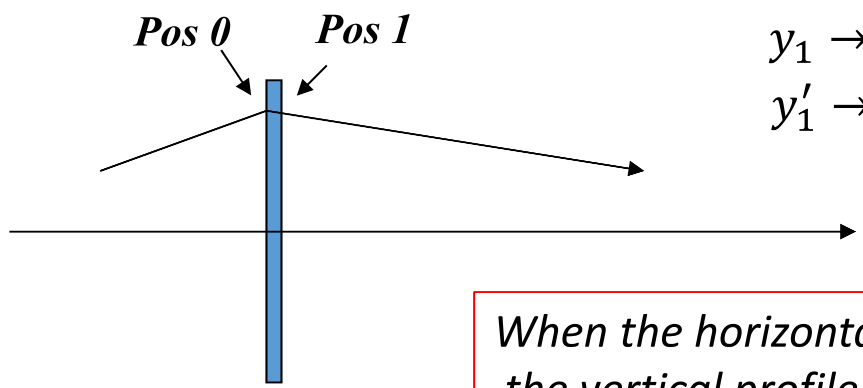


Transfer Matrix

Quadrupole Magnet

$$x_1 \to x_0 \qquad x_1' \to x_0' - Kx_0 \quad \Rightarrow \quad \begin{pmatrix} x_1 \\ x_1' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -K & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}$$

$$y_1 \to y_0 \qquad y_1' \to y_0' + Ky_0 \quad \Rightarrow \quad \begin{pmatrix} y_1 \\ y_1' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ +K & 1 \end{pmatrix} \begin{pmatrix} y_0 \\ y_0' \end{pmatrix}$$



When the horizontal profile is focused by quadrupole magnet, the vertical profile is defocused !

In generally speaking,
we can express the Transfer Matrix with mathematical parameters α, β and $\Delta\varphi$.

$$M(s_1, s_0) = \begin{pmatrix} \sqrt{\beta_1} & 0 \\ -\alpha_1/\sqrt{\beta_1} & 1/\sqrt{\beta_1} \end{pmatrix} \begin{pmatrix} \cos\Delta\varphi & \sin\Delta\varphi \\ -\sin\Delta\varphi & \cos\Delta\varphi \end{pmatrix} \begin{pmatrix} 1/\sqrt{\beta_0} & 0 \\ \alpha_0/\sqrt{\beta_0} & \sqrt{\beta_0} \end{pmatrix}$$

$$= T^{-1}(s_1) \begin{pmatrix} \cos\Delta\varphi & \sin\Delta\varphi \\ -\sin\Delta\varphi & \cos\Delta\varphi \end{pmatrix} T(s_0)$$

,where $T(s) \equiv \begin{pmatrix} 1/\sqrt{\beta} & 0 \\ \alpha/\sqrt{\beta} & \sqrt{\beta} \end{pmatrix}$

We can select any set of (α, β) in mathematically.
$\Delta\varphi$ is calculated for the (α, β).

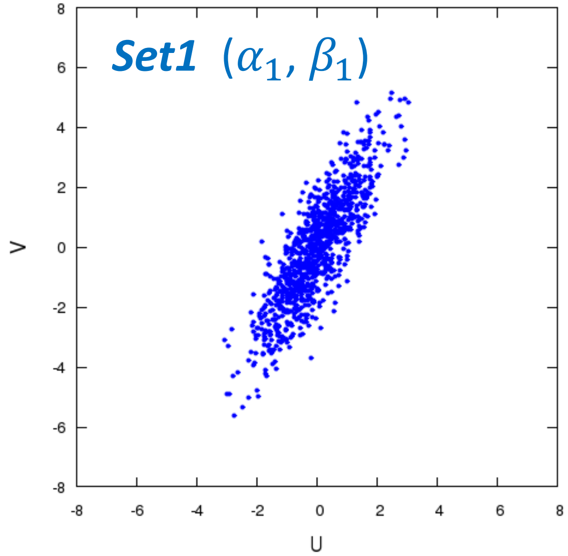
The parameters α, β are varied after Transfer Matrix by using the matrix components as

$$\begin{pmatrix} \beta_1 \\ \alpha_1 \\ \gamma_1 \end{pmatrix} = \begin{pmatrix} M_{11}^2 & -2M_{11}M_{12} & M_{12}^2 \\ -M_{11}M_{21} & 1 + 2M_{12}M_{21} & -M_{12}M_{22} \\ M_{21}^2 & -2M_{21}M_{22} & M_{22}^2 \end{pmatrix} \begin{pmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{pmatrix} \qquad \gamma = \frac{1 + \alpha^2}{\beta}$$

Once, we defined the parameters (α, β), the parameters will be propagated in the bamline.

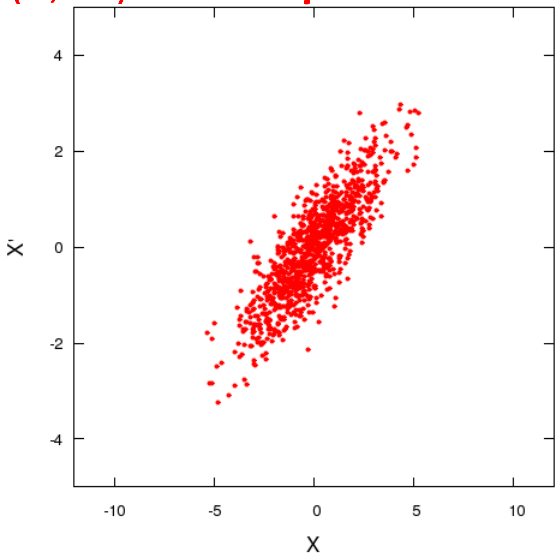
Phase Space Distribution

(u, v) ***Phase Space Distribution***



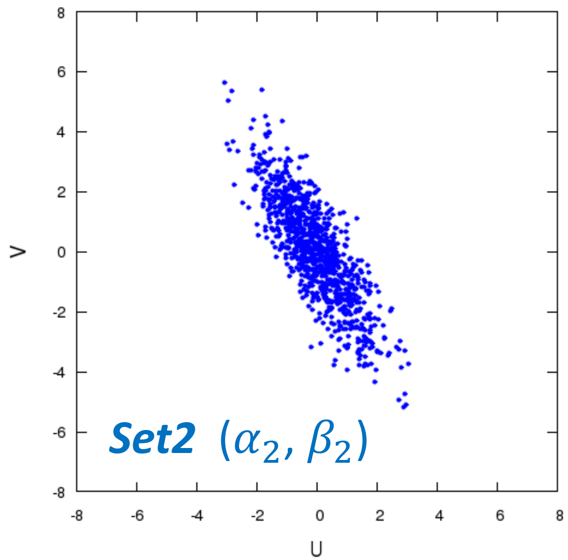
(α, β) are selected **arbitrary** in mathematically.

(x, x') ***Phase Space Distribution***

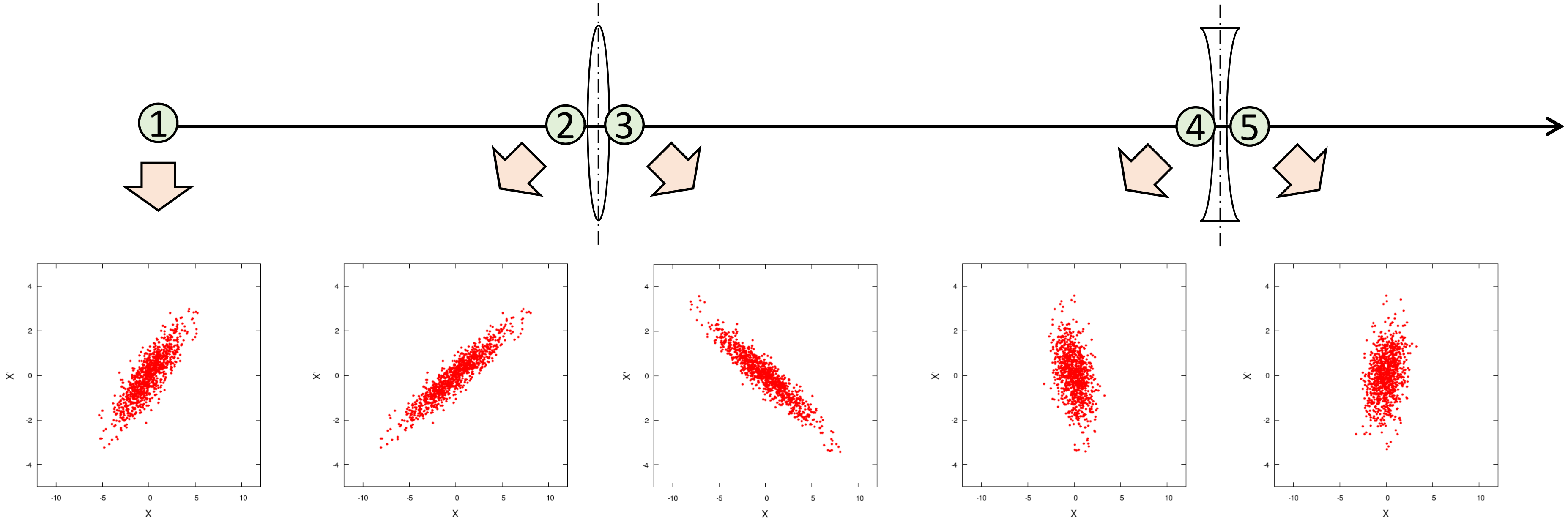


The phase space is transformed to the phase space V as

$$V = \begin{pmatrix} u \\ v \end{pmatrix} \equiv T \begin{pmatrix} x \\ x' \end{pmatrix}$$



Phase space propagation through the beamline



(x, x') ***Phase Space Distribution***

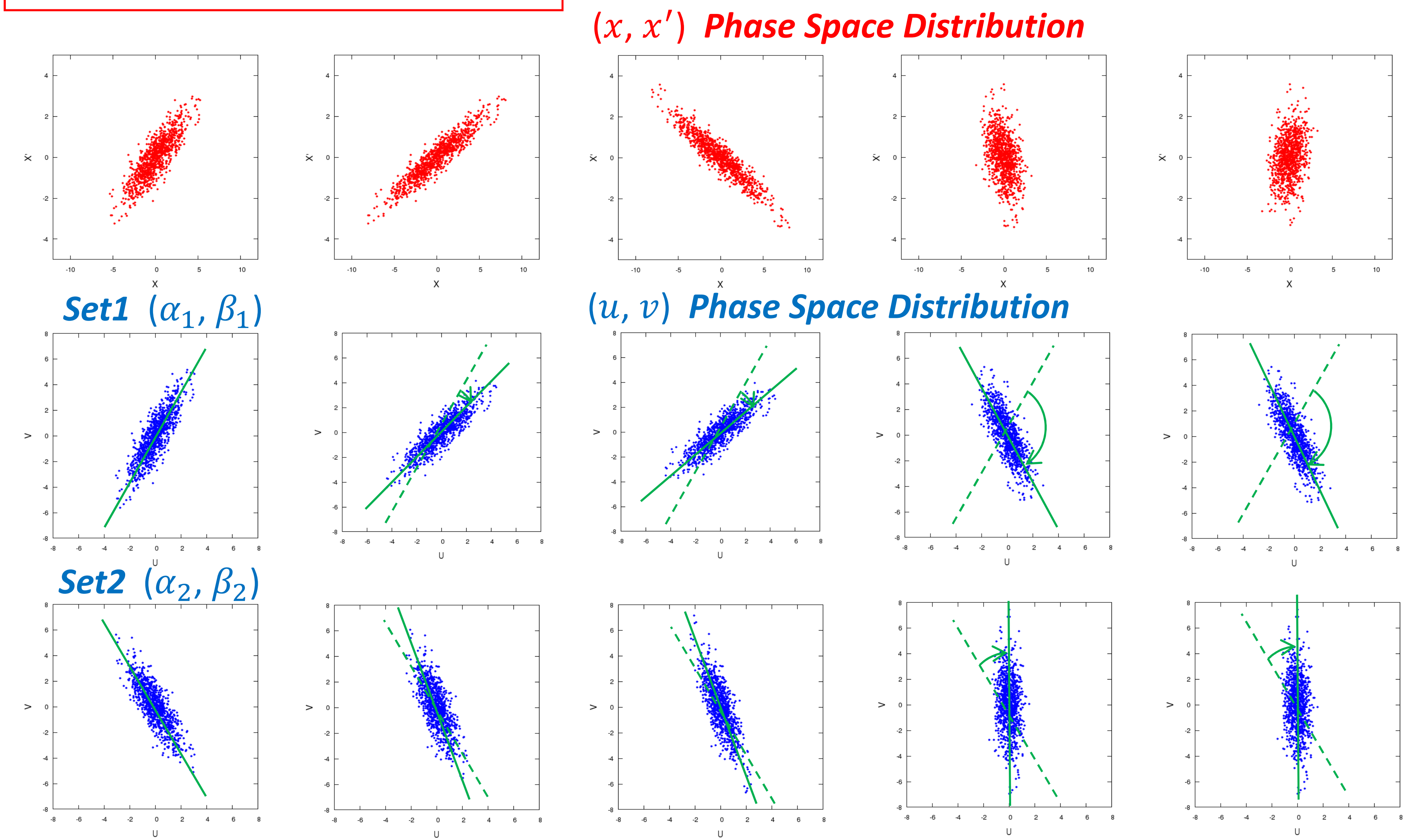
The shape of the distribution is changed in the beamline.

Phase space propagation through the beamline

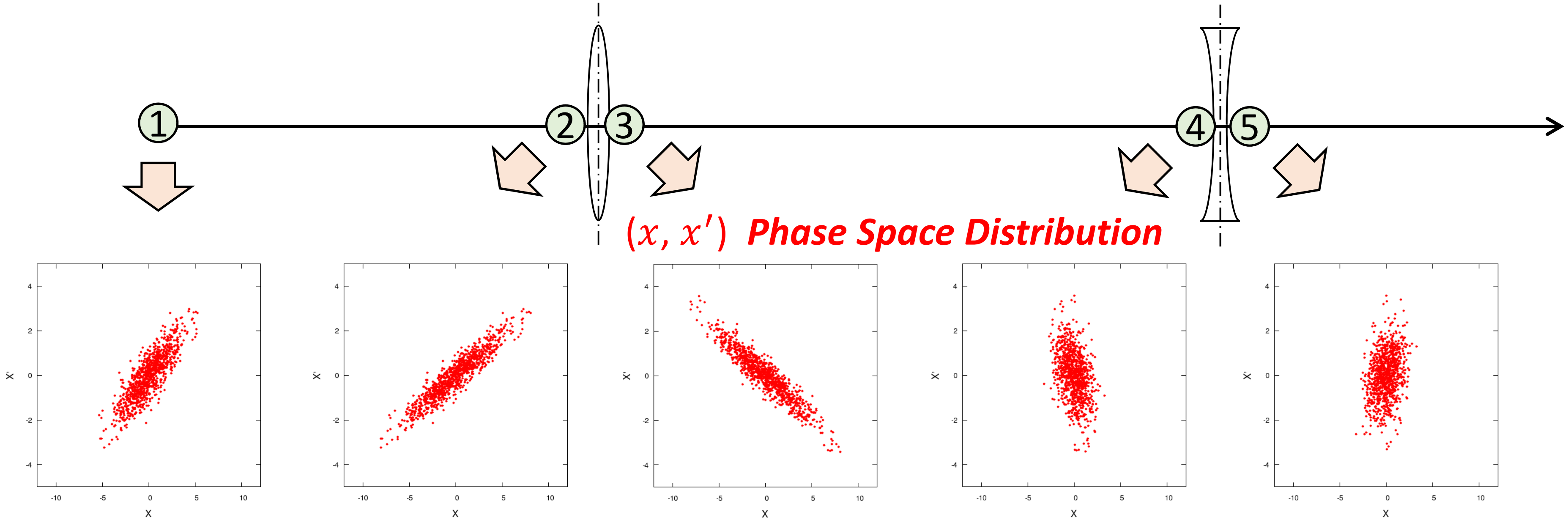
$$\begin{pmatrix} u_1 \\ v_1 \end{pmatrix} = \begin{pmatrix} \cos\Delta\varphi & \sin\Delta\varphi \\ -\sin\Delta\varphi & \cos\Delta\varphi \end{pmatrix} \begin{pmatrix} u_0 \\ v_0 \end{pmatrix}$$

All particles rotate same angle.

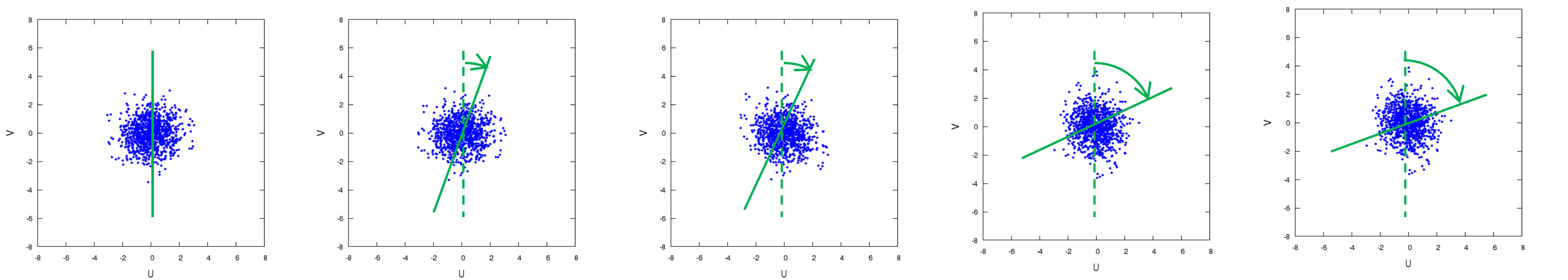
- *The shape is different for the initial setting of* (α, β).
- *Rotation angle is different for the initial setting.*
- *But, the shape will be kept through beamline.*



Phase space propagation through the beamline



When we select the parameter (α, β) to make the distribution round shape, the distribution in the phase space V is not changed through the beamline.



The area of the V phase space distribution is called to "emittance".

$$\langle u^2 \rangle = \langle v^2 \rangle = \varepsilon$$ **Beam quality parameter**

Phase space propagation through the beamline

Twiss parameters (Beam envelope parameters)

Beam size

$$\langle x^2 \rangle = \beta \langle u^2 \rangle = \beta \varepsilon$$

$x - x'$ correlation

$$\langle x x' \rangle = \langle uv \rangle - \alpha \langle u^2 \rangle = -\alpha \varepsilon$$

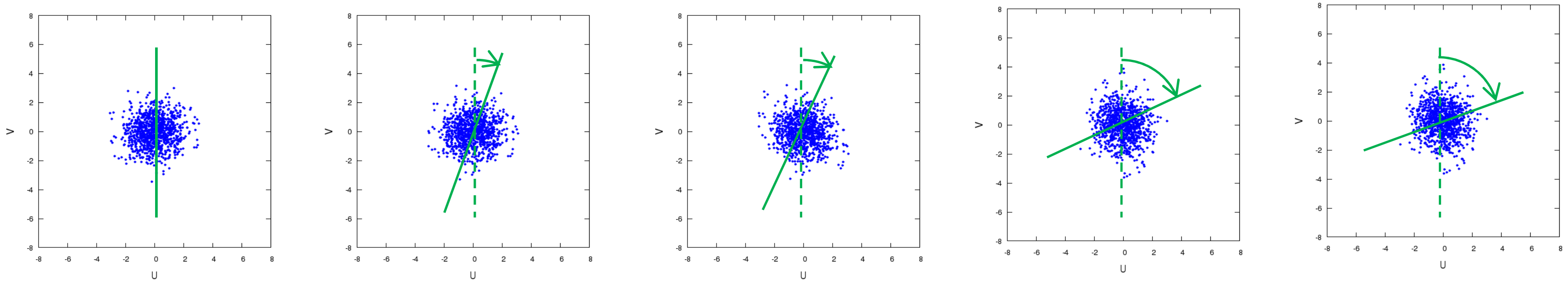
Beam divergence

$$\langle x'^2 \rangle = \frac{\langle v^2 \rangle - 2\alpha \langle uv \rangle + \alpha^2 \langle u^2 \rangle}{\beta} = \frac{1 + \alpha^2}{\beta} \varepsilon = \gamma \varepsilon$$

When we selected the (α, β) to make V space distribution round shape,

α, β and γ will be the physics parameters.

(u, v) ***Phase Space Distribution*** ***Phase Advance***

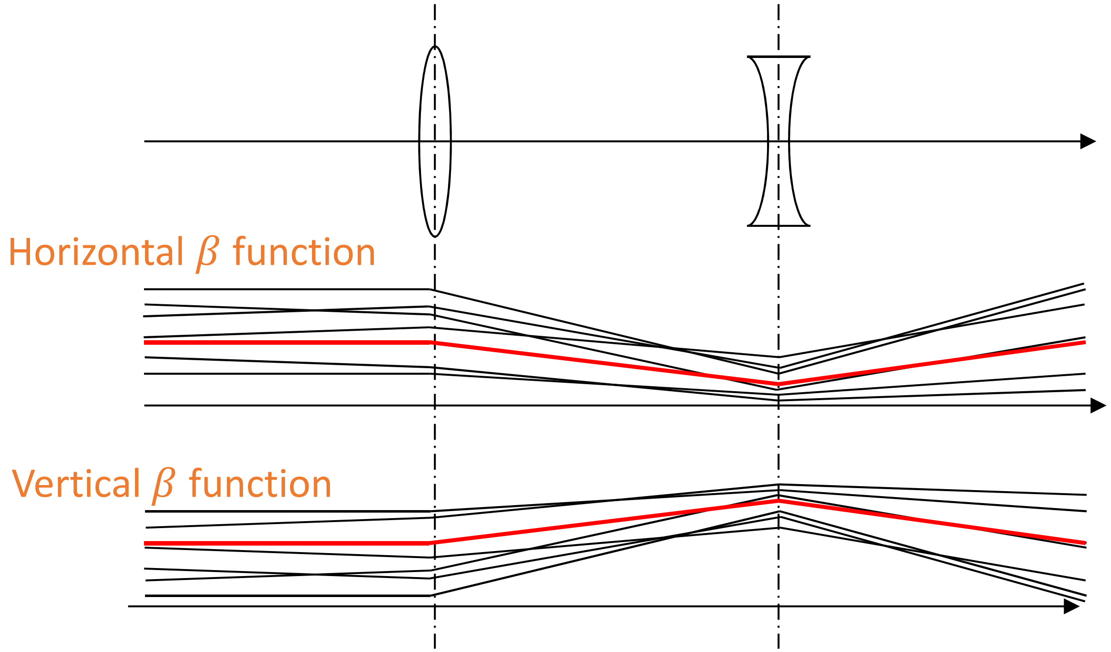


The area of the V phase space distribution is called to "emittance".

$$\langle u^2 \rangle = \langle v^2 \rangle = \varepsilon$$ **Beam quality parameter**

Collective particle motion as a "BEAM"

By selecting the parameter (α, β) to make V space distribution round shape,
we can calculate the beam size through the beamline as a "BEAM".



Beam Matrix

$$\Sigma = \varepsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

$$\Sigma_1 = M\,\Sigma_0 M^{-1}$$

equivalent

$$\begin{pmatrix} \beta_1 \\ \alpha_1 \\ \gamma_1 \end{pmatrix} = \begin{pmatrix} M_{11}^2 & -2M_{11}M_{12} & M_{12}^2 \\ -M_{11}M_{21} & 1+2M_{12}M_{21} & -M_{12}M_{22} \\ M_{21}^2 & -2M_{21}M_{22} & M_{22}^2 \end{pmatrix} \begin{pmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{pmatrix}$$

"Twiss parameters" expressed the envelopes of beam along the beamline .

Summary of linear optics parameters

The particle motion in accelerator is defined by using ***Frenet-Serret Coordinate*****.**

Transfer Matrix *is denotes a single particle motion in phase space.*

Dispersion function *denotes the difference to on-momentum particle with the momentum offset δ.*

*When we treat the corrective motion of many particles as a "**BEAM**", the following parameters are useful.*

- ***Emittance (ε)*** *; Beam quality parameter*
- ***Twiss parameters (α, β and γ)*** *; Beam envelop parameters*
- ***Phase advance (θ)*** *; Rotation angle in (u, v) phase space*

Fundamental Notation of Accelerator Physics

IP Parameter Optimization

Most simple notation of luminosity

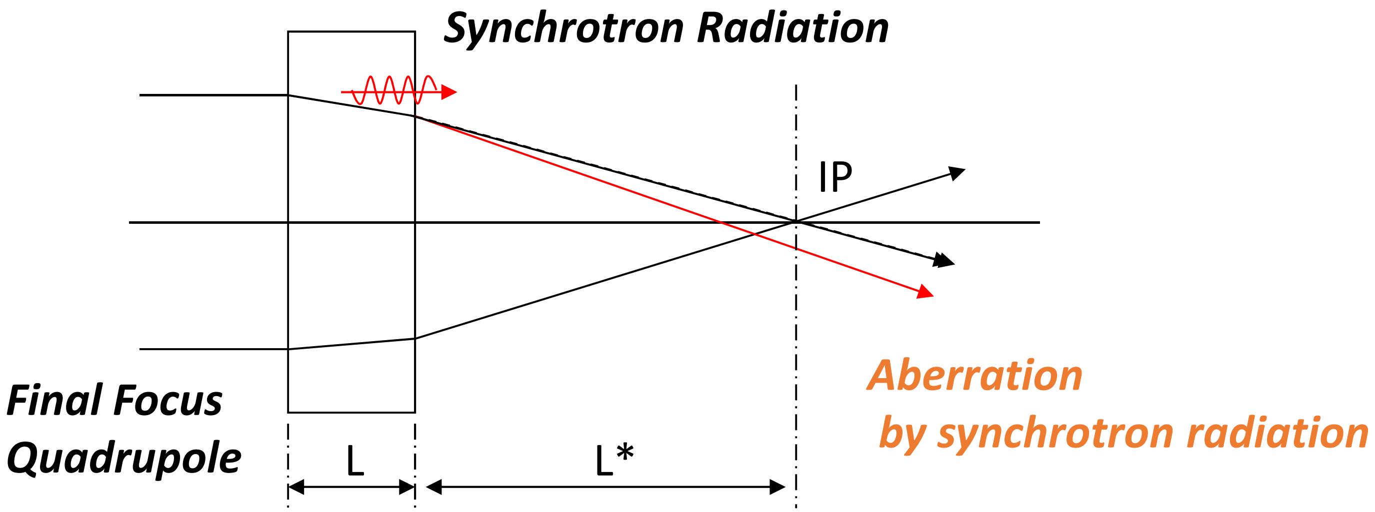
$$\mathcal{L} = \frac{N^2}{4\pi\sigma_x^*\sigma_y^*}$$

It is better to focus the beam as small as possible to have higher luminosity.

What is the limit of IP beam size ???

Oide Limit (Theoretical Limit of IP Beam Size)

The theoretical limit of minimum beam size at IP is determined by the aberration by synchrotron radiation at final focus quadrupole.



Since the beam distribution itself is deformed by the synchrotron radiation, we cannot compensate the effect by optics correction.

Oide Limit (continued)

Beam Size Defined by Linear Optics
(smaller for smaller IP β function)

IP beam size growth by synchrotron radiation

- larger for larger β at quadrupole
- larger for smaller IP β function.

$$\sigma_y^2 \cong \sigma_y^{*2} + (L^* \sigma_{y'}^*)^2 \left\langle \frac{\Delta E}{E} \right\rangle^2$$

$$\cong \varepsilon_y \beta_y^* + C_1 \gamma^5 r_e \lambda_e \left(\frac{L^*}{L} \right)^2 \left(\frac{\varepsilon_y}{\beta_y^*} \right)^{\frac{5}{2}}$$

The theoretical minimum IP beam size was determined by making the balance of two beam sizes as

$$\beta_{y,\min}^* \cong 1.29\gamma \left\{ C_1^2 r_e^2 \lambda_e^2 (\gamma \varepsilon_y)^3 \left(\frac{L^*}{L} \right)^4 \right\}^{\frac{1}{7}}$$

$$\sigma_{y,\min}^* \cong 1.35 \left\{ C_1 r_e \lambda_e (\gamma \varepsilon_y)^5 \left(\frac{L^*}{L} \right)^2 \right\}^{\frac{1}{7}}$$

$$\cong 1.19 \sqrt{\varepsilon_y \beta_{y,\min}^*}$$

E_{CM}	500 GeV	1 TeV
$\beta_{y,\min}^*$	32 μm	65 μm
$\sigma_{y,\min}^*$	1.8 nm	1.8 nm

ILC IP parameters

E_{CM}		500 GeV	1 TeV
ILC design	β_y^*	410 μm	225 μm
Oide limit	$\beta_{y,\min}^*$	32 μm	65 μm
	$\sigma_{y,\min}^*$	1.8 nm	1.8 nm

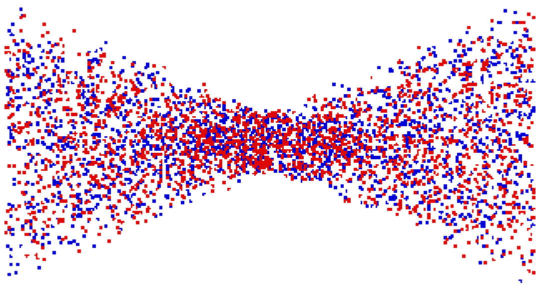
The ILC IP parameter is not determined by the theoretical beam size limit "Oide Limit".

How to design the IP parameters ??

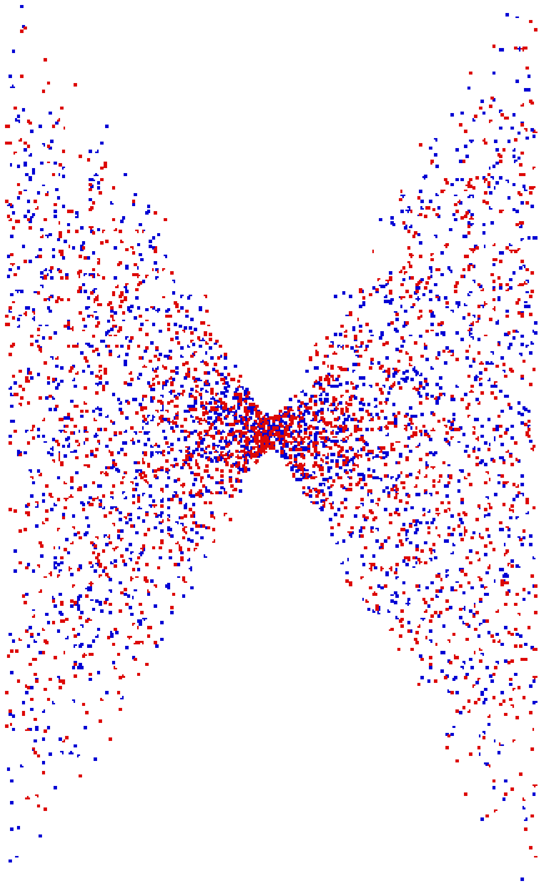
- *Hour-glass effect*
- *The effect of the crossing angle*
- *Beam-beam effect*

Hour-glass Effect

When we set to make the IP β function smaller than the bunch length, the effective beam size at head/tail of bunch is larger than that at center.

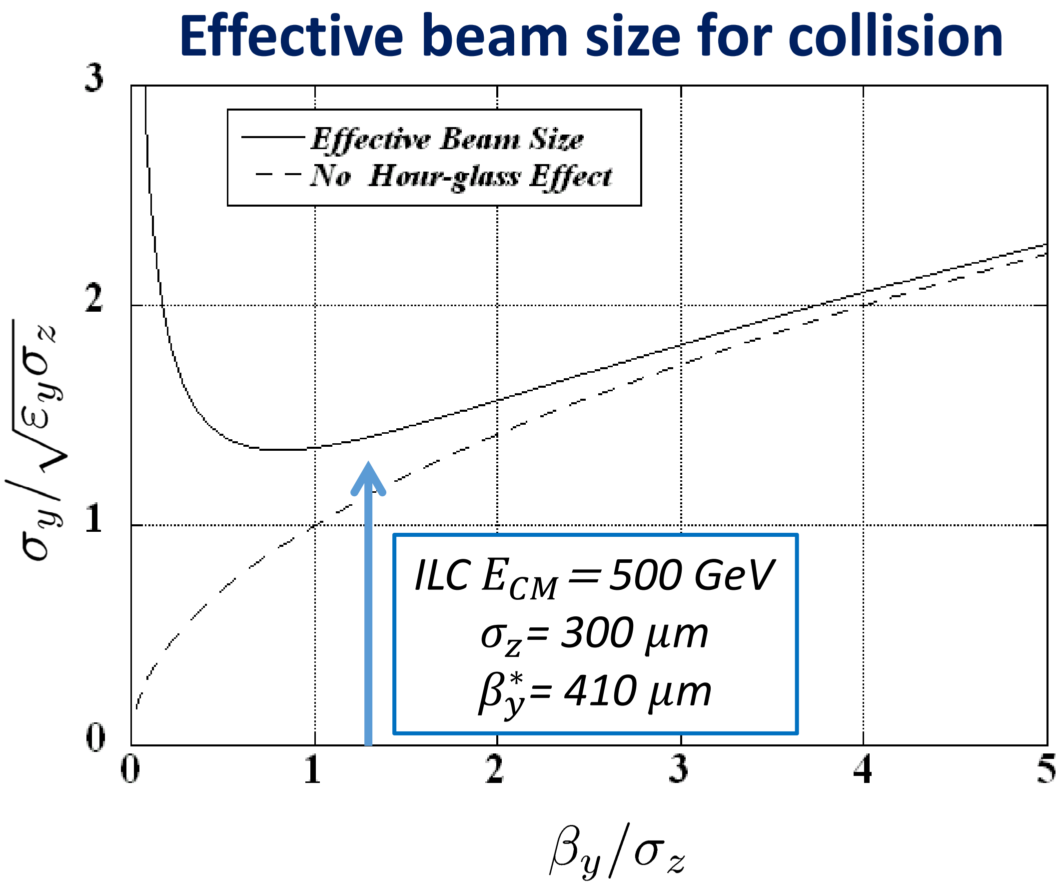


Long focal depth



Short focal depth

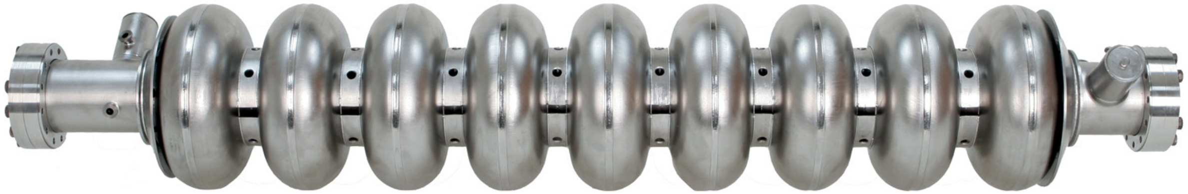
ILC IP beta function



IP beam size is limited by the bunch length too.

Bunch Length of ILC and CLIC

ILC superconducting RF cavities

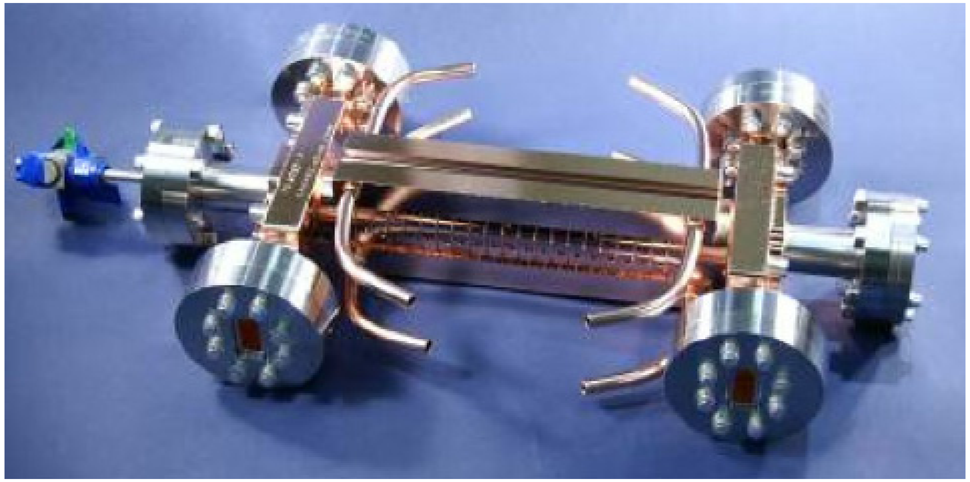


RF frequency 1.3 GHz
Wavelength 230 mm
(640 μm/degree)

$\Downarrow$

Bunch Length
$\sigma_z = 300\ \mu m$ *for* $E_{CM} = 500\ GeV$
$\sigma_z = 250\ \mu m$ *for* $E_{CM} = 1\ TeV$

CLIC RF cavities



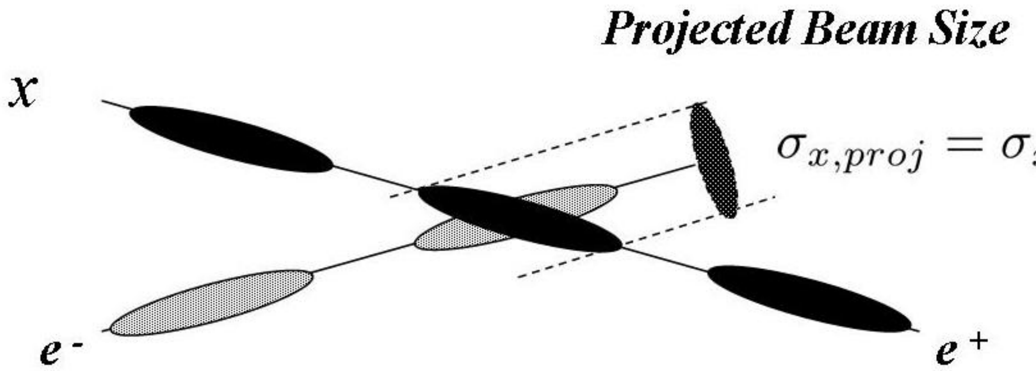
RF frequency 12GHz
Wavelength 25mm
(69 μm/degree)

$\Downarrow$

Bunch Length
$\sigma_z = 72\ \mu m$ *for* $E_{CM} = 500\ GeV$
$\sigma_z = 44\ \mu m$ *for* $E_{CM} = 3\ TeV$

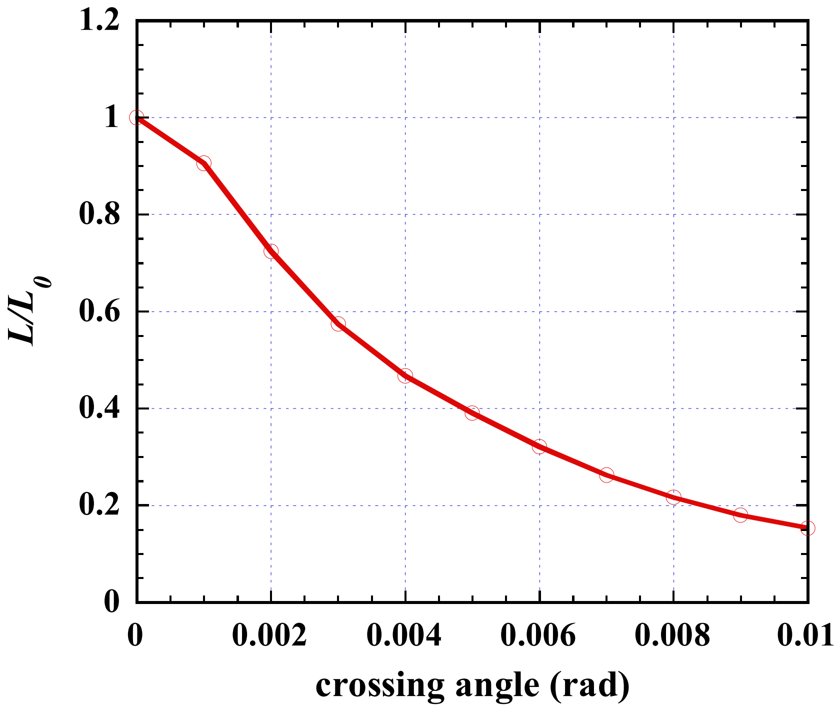
Shorter bunch length $\Rightarrow$ Larger beam loading $\Rightarrow$ energy spread larger

Effect of crossing angle



$$\sigma_{x,proj} = \sigma_{x0} \sqrt{1 + \left(\frac{\sigma_z \sin\phi}{2\ \sigma_{x0}} \right)^2}$$

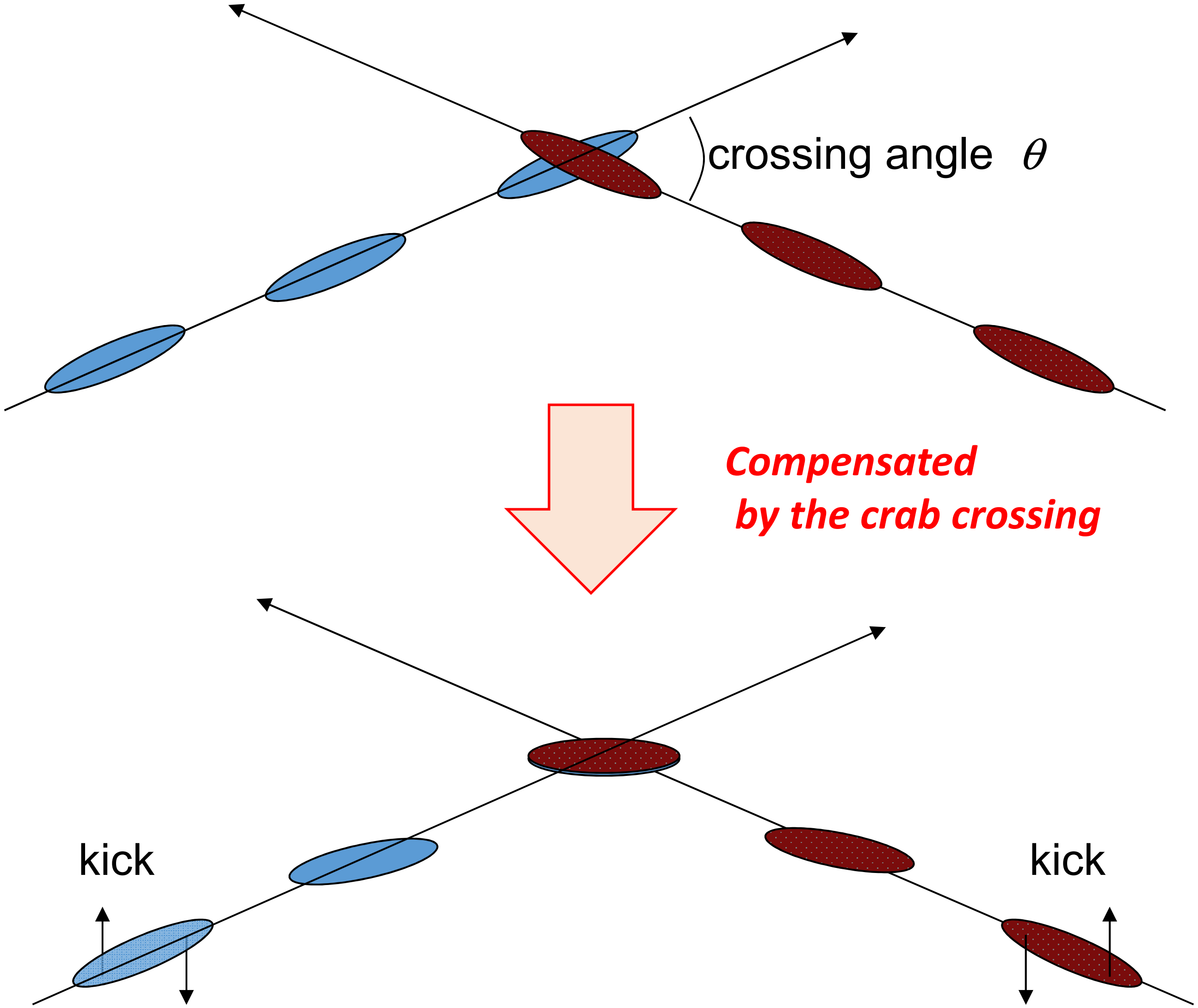
ILC RDR parameter, by CAIN simulation

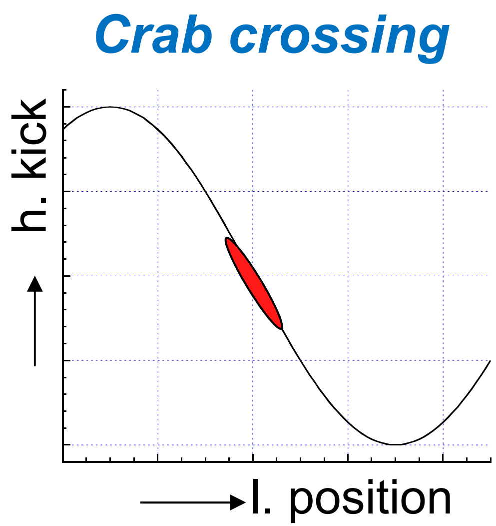


The large crossing angle is good to separate the injection/extraction beams.
(ILC design is 14 mrad)

But, when we set the large crossing , the luminosity is reduced.

Crab crossing (crossing angle compensation)

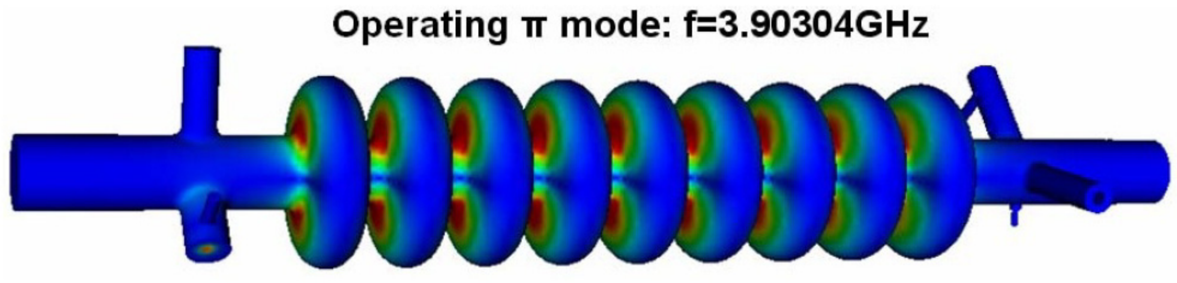


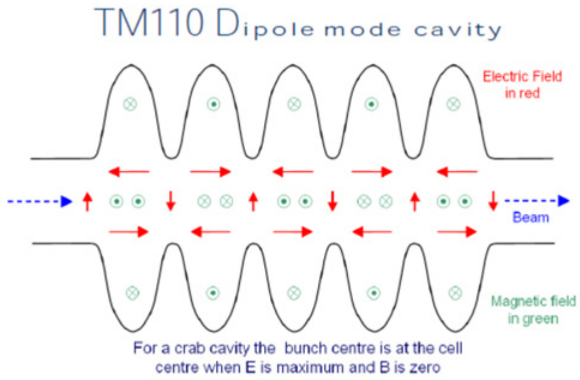


Crab Cavity Design & Prototyping

Design & prototypes been done by UK-FNAL-SLAC collaboration.

Prototype of crab cavity was built at FNAL.

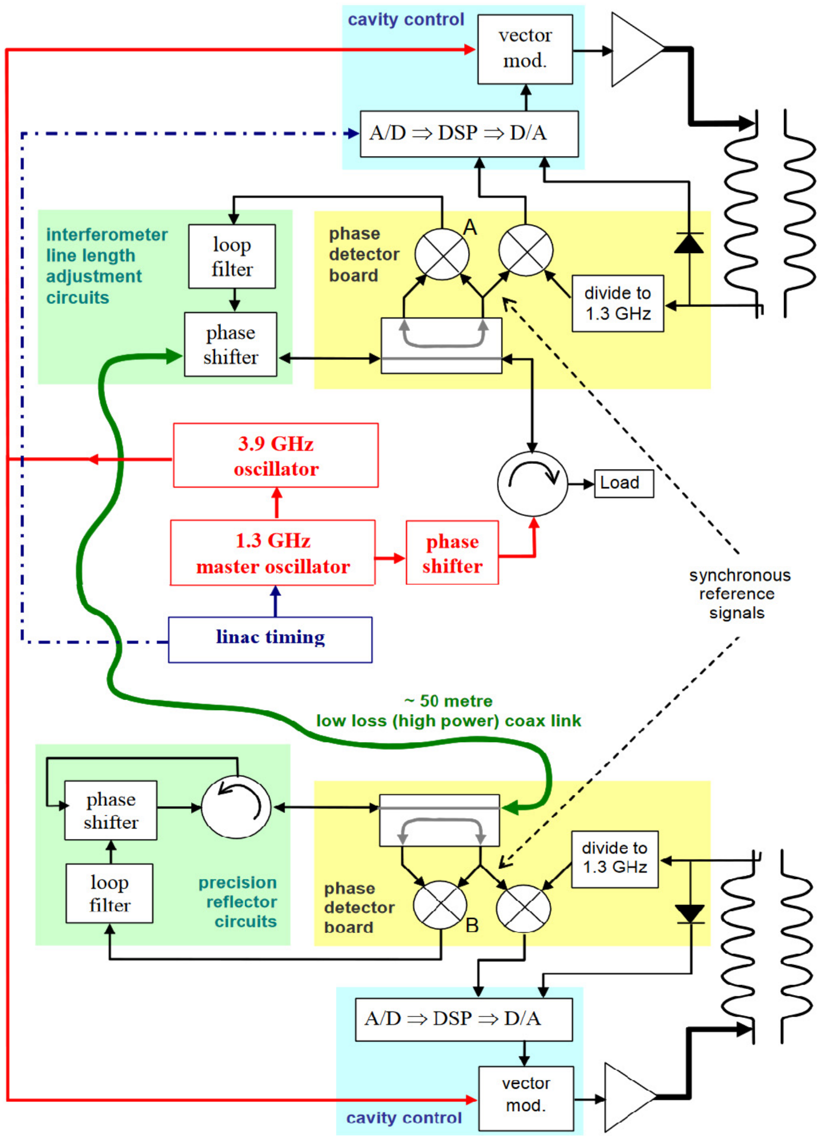


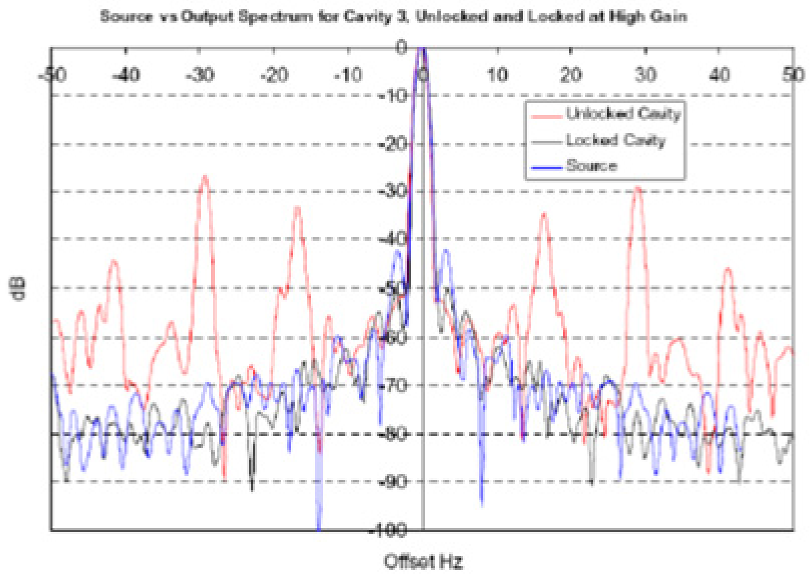


Prototype of 3-cell Crab Cavity

Phase lock for 2 crab cavities

It is very important to synchronize the RF for 2 crab cavities.





Phase lock achieved for both cavities

10° r.m.s. *for unlocked*

0.135° r.m.s. *for phase-locked*

Summary of geometrical Luminosity reduction

$$H_{\text{geo}} \approx \left\{ 1 + \frac{0.8\sigma_z^2}{\beta_y^{*2}} + \left(\frac{\sigma_z \sin\phi_c}{2\ \sigma_x^*} \right)^2 \right\}^{-\frac{1}{2}}$$

Hour-glass effect **Effect of crossing angle**

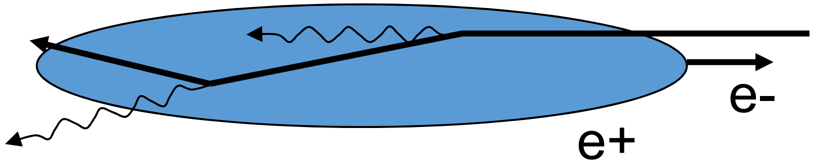
	No crab cavity	With crab cavity
E_{CM}= 500GeV	0.218	0.837
E_{CM}= 1 TeV	0.258	0.745

Hour-glass effect

By applying the crab crossing,
the geometrical Luminosity reduction can be recovered.

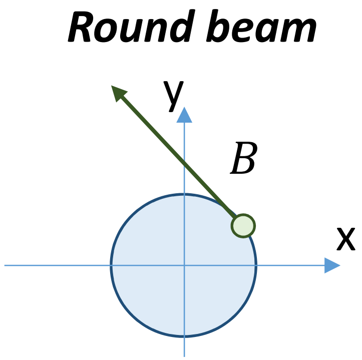
But the hour-glass effect cannot compensate.

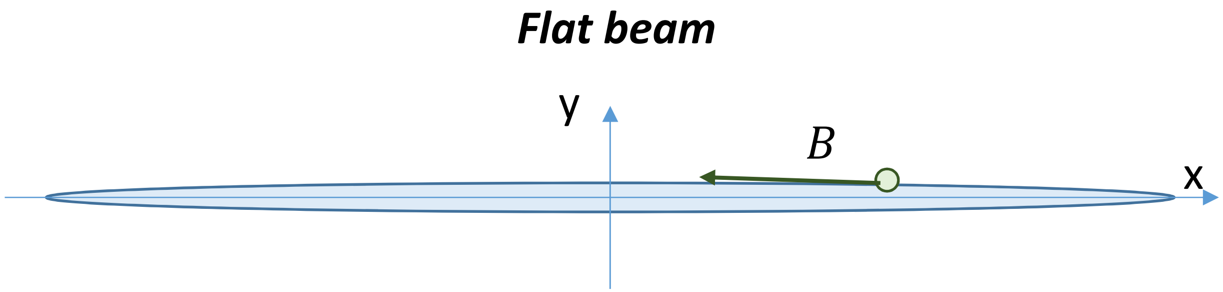
Beam-beam Effect (Beamstrahlung)



Aspect ratio of the IP beam

Since the magnetic field of flat beam is weaker than that of round beam, ILC IP parameter is assumed to the flat beam.





$\sigma_x \sigma_y = (constant)$

- *The basic luminosity is same.*
- *The magnetic field is weaker for flat beam.*

⇒ ILC adopted for flat beam

Disruption Parameter

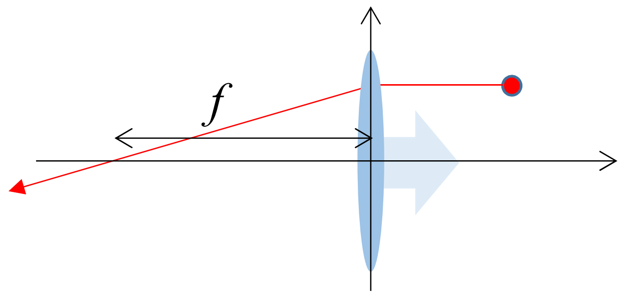
$$D_{x,y} \equiv \frac{2r_e\sigma_z N}{\gamma(\sigma_x^* + \sigma_y^*)\sigma_{x,y}^*}$$ (Vertical direction is important.)

Very roughly speaking,
the disruption parameter is the strength of the beam oscillation at beam-beam crossing.

$$\frac{d^2y}{ds^2} + K_y y = 0 \quad \left(K_y = \frac{D_y}{\sigma_z^2}\right)$$

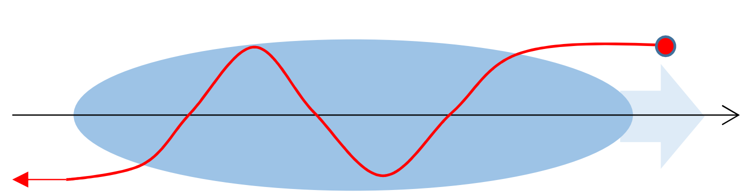
- $D_y \ll 1$

  The disruption shows the focal length as $f \approx \dfrac{\sigma_z}{D_y}$



- $D_y \gg 1$ (ILC case ; $D_y = 25$)

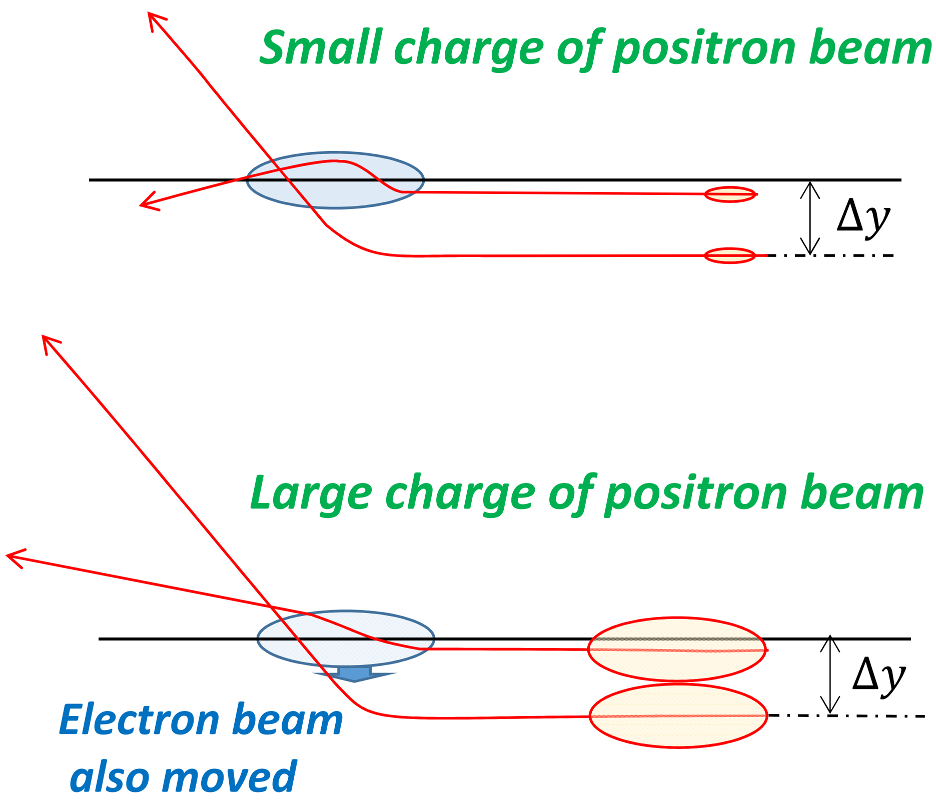
  The disruption shows the number of oscillation as $n \approx 1.3\dfrac{\sqrt{D_y}}{2\pi}$

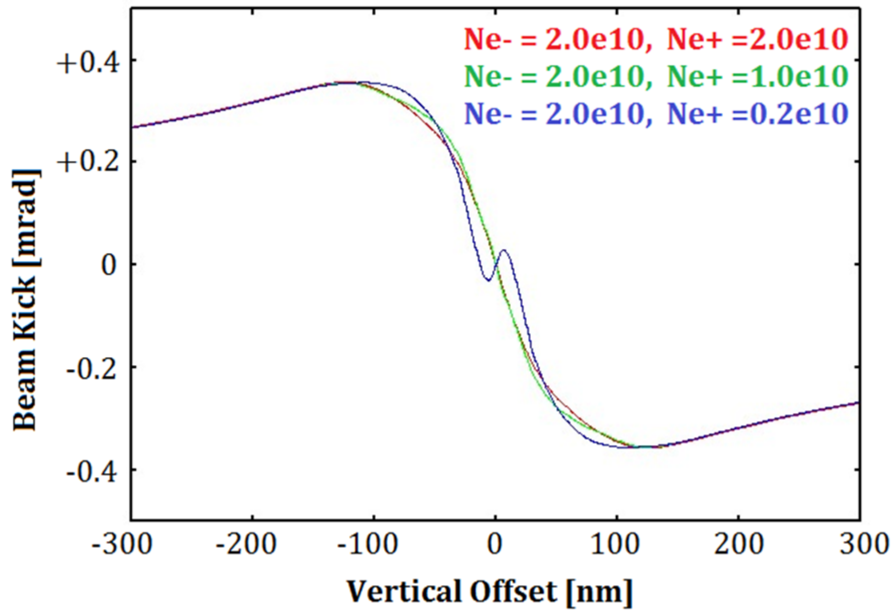


Beam-beam simulation with CAIN

Beam center position change by beam-beam effect at IP

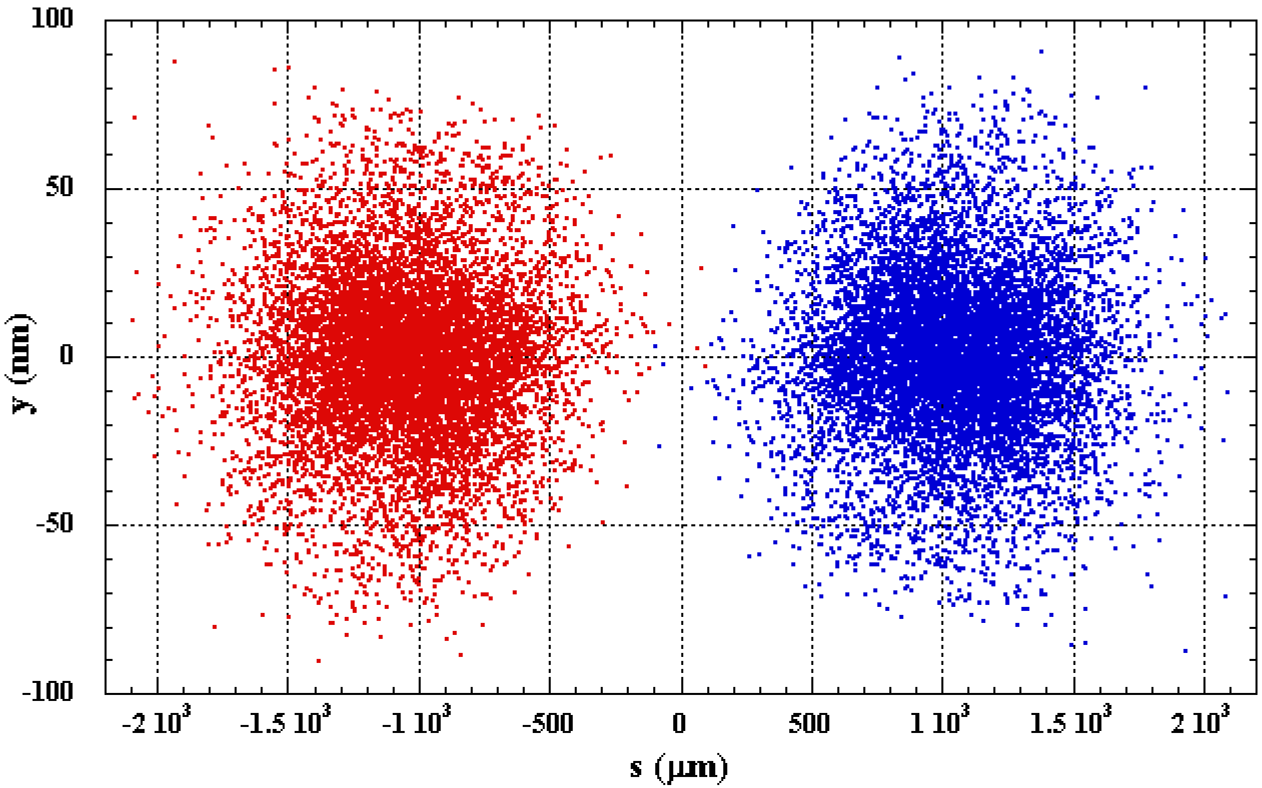
ILC 500 GeV IP parameter was used in simulation.

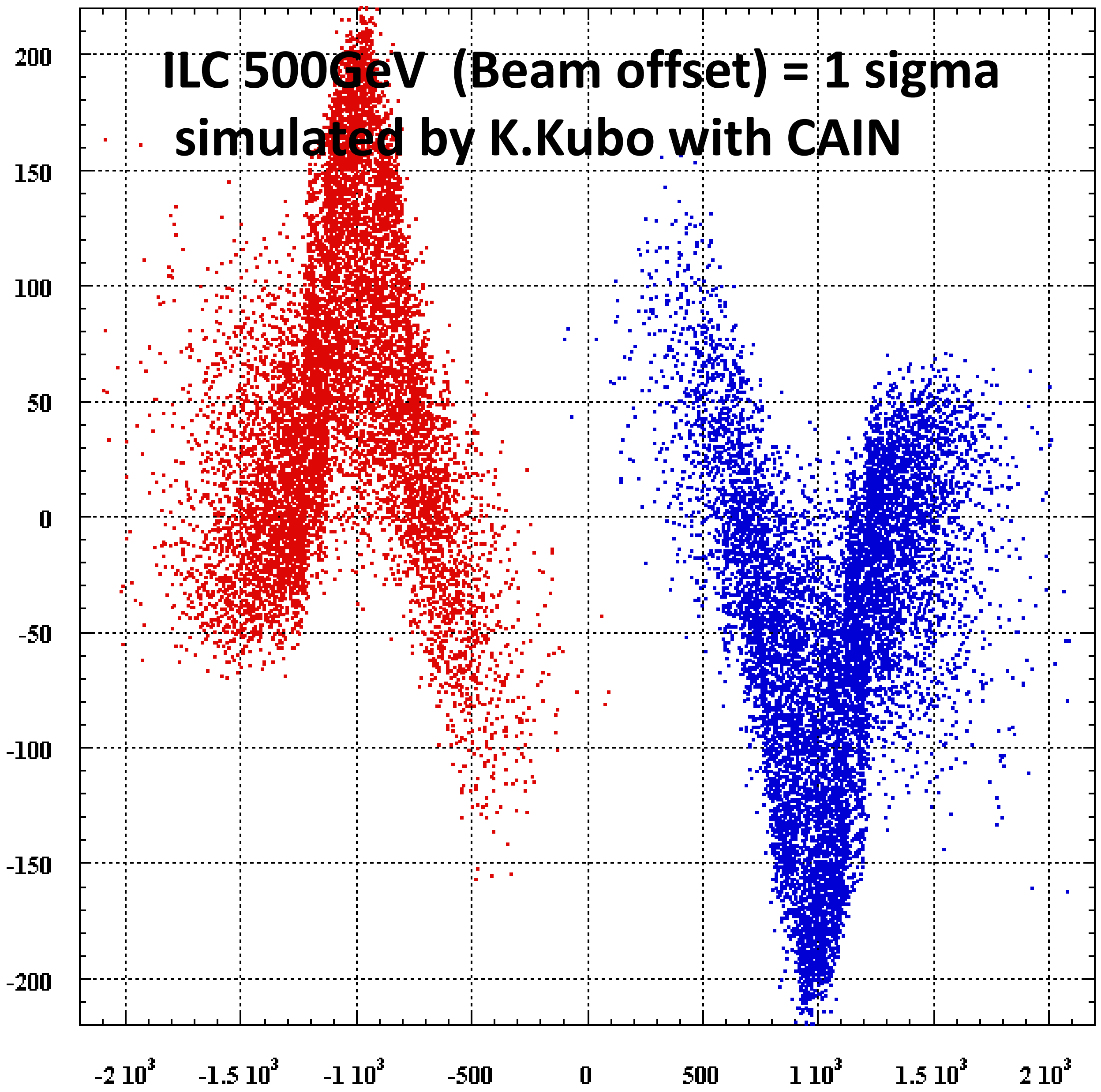




For the beam-beam simulation, we must take care not only the drive beam motion, but also target beam motion.

ILC 500GeV (Beam offset) = 0
simulated by K.Kubo with CAIN



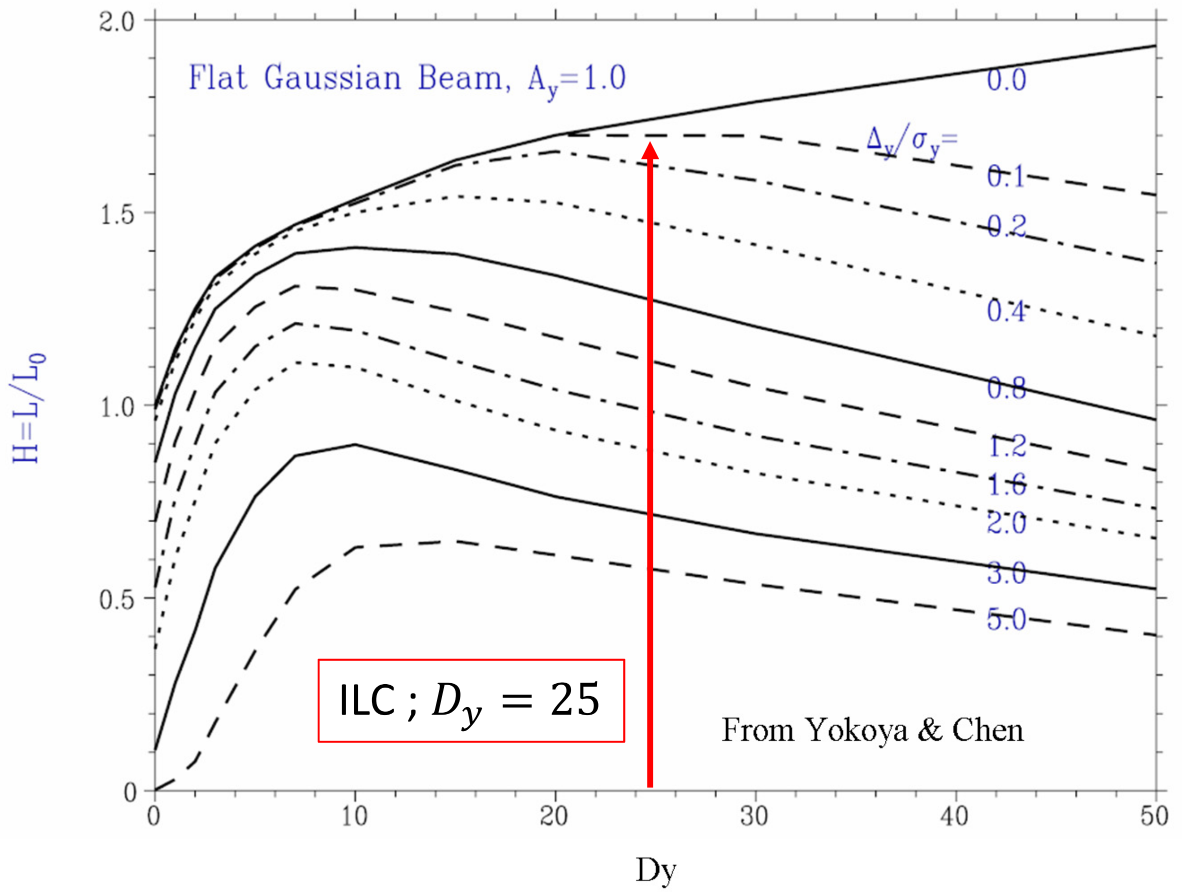


ILC 500GeV (Beam offset) = 1 sigma
simulated by K.Kubo with CAIN
200
150
100
50
0
-50
-100
-150
-200
-2 10³
-1.5 10³
-1 10³
-500
0
500
1 10³
1.5 10³
2 10³

Luminosity enhancement by beam-beam effect

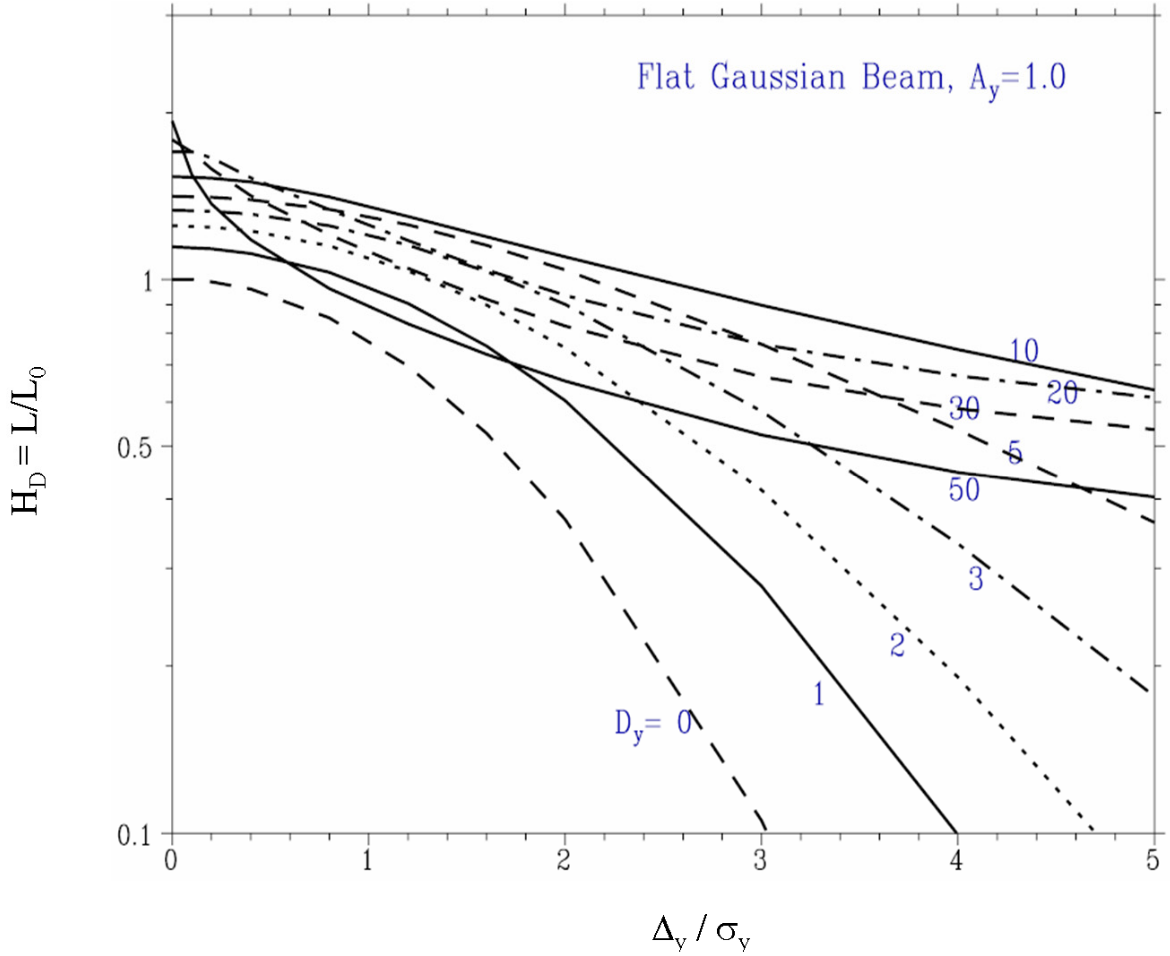
Since the beam is focused by beam-beam effect for larger disruption,
the beam-beam effect generate the luminosity enhancement.

Calculation of the luminosity enhancement by beam-beam effect



IP beam offset and the luminosity

Luminosity reduction by the beam offset



The luminosity reduction of the beam offset for large disruption beam is smaller than that of small disruption beam for the beam focusing.

Beamstrahlung effect to beam

Average critical energy by beamstrahlung

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

α ; fine structure constant

Number of photons by beamstrahlung

$$\frac{N_\gamma}{N} \cong \frac{2.16 \alpha N r_e}{\sigma_x^* + \sigma_y^*} \frac{1}{\sqrt{1 + \langle \Upsilon \rangle^{2/3}}}$$

Beam energy reduction by beamstrahlung

$$\delta_{BS} \equiv -\frac{\Delta E_\gamma}{E} \cong \frac{0.836\, \gamma N^2 r_e^3}{\sigma_z (\sigma_x^* + \sigma_y^*)^2} \frac{1}{(1 + 1.31 \langle \Upsilon \rangle^{2/3})^2} \approx \frac{\gamma N^2 r_e^3}{\sigma_z (\sigma_x^* + \sigma_y^*)^2}$$

For ILC 500GeV, the $\delta_{BS} = 4.5\ \%$

Beam energy spread by beamstrahlung

$$\frac{\sigma_{E_\gamma}}{E} \cong \frac{\delta_{BS}}{2} \sqrt{\frac{N}{N_\gamma}}$$

- *Beamstrahlung makes energy spread in collisions.*

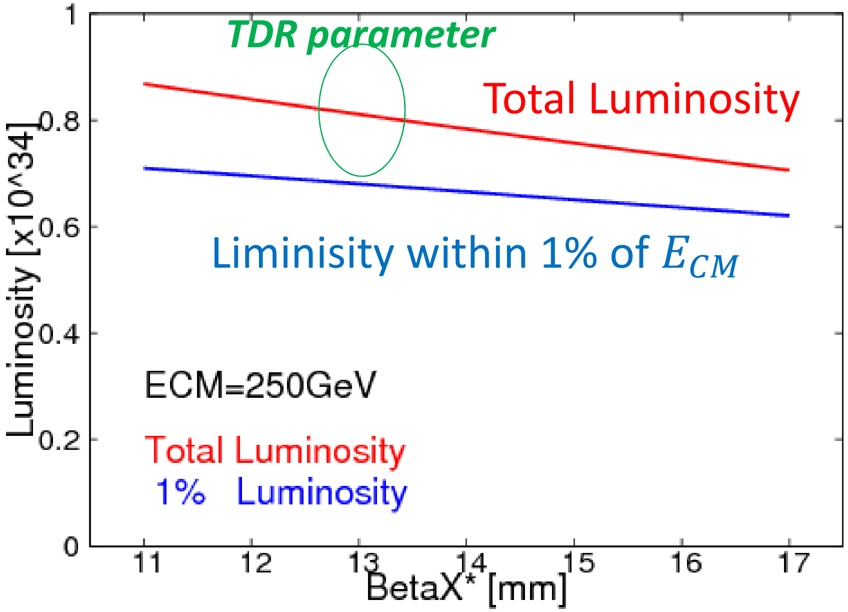
  ⇒ *It affect to the quality of experimental data.*

Simulation of beam-beam effect (1% Luminosity)

Luminosity dependence of IP horizontal beta function by keeping $\sigma_x^* \sigma_y^*$

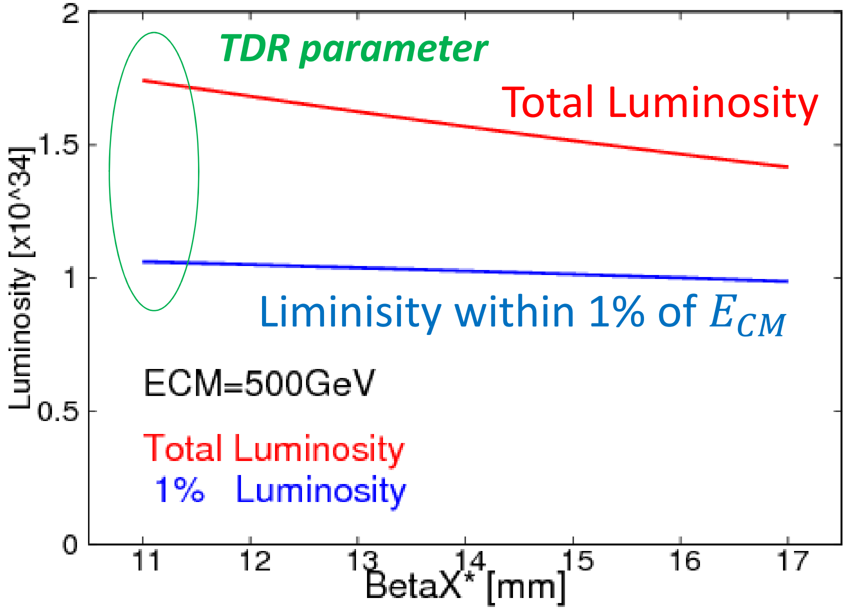
ECM=250GeV

Simulated with CAIN by K.Kubo



ECM=500GeV

Simulated with CAIN by K.Kubo



For smaller σ_x^* / σ_y^* ,

- *Total Luminosity is increased by weaker hour-glass effect.*
- *E_{CM} Spread is larger by beam-beam effect.*
  The effect is larger for higher E_{CM}.

ILC TDR IP parameters

Table 8.2. Energy-dependent parameters of the Beam Delivery System [84].

ILC TDR

		Center-of-mass energy, E_{cm} (GeV)							
		Baseline				Upgrades			
Parameter		200	250	350	500	500	1000 (A1)	1000 (B1b)	Unit
Nominal bunch population	N	2.0	2.0	2.0	2.0	2.0	1.74	1.74	$\times 10^{10}$
Pulse frequency	f_{rep}	5	5	5	5	5	4	4	Hz
Bunches per pulse	N_{bunch}	1312	1312	1312	1312	2625	2450	2450	
Nominal horizontal beam size at IP	σ^*_x	904	729	684	474	474	481	335	nm
Nominal vertical beam size at IP	σ^*_y	7.8	7.7	5.9	5.9	5.9	2.8	2.7	nm
Nominal bunch length at IP	σ^*_z	0.3	0.3	0.3	0.3	0.3	0.250	0.225	mm
Energy spread at IP, e^-	$\delta E/E$	0.206	0.190	0.158	0.124	0.124	0.083	0.085	%
Energy spread at IP, e^+	$\delta E/E$	0.190	0.152	0.100	0.070	0.070	0.043	0.047	%
Horizontal beam divergence at IP	θ^*_x	57	56	43	43	43	21	30	µrad
Vertical beam divergence at IP	θ^*_y	23	19	17	12	12	11	12	µrad
Horizontal beta-function at IP	β^*_x	16	13	16	11	11	22.6	11	mm
Vertical beta-function at IP	β^*_y	0.34	0.41	0.34	0.48	0.48	0.25	0.23	mm
Horizontal disruption parameter	D_x	0.2	0.3	0.2	0.3	0.3	0.1	0.2	
Vertical disruption parameter	D_y	24.3	24.5	24.3	24.6	24.6	18.7	25.1	
Energy of single pulse	E_{pulse}	420	526	736	1051	2103	3409	3409	kJ
Average beam power per beam	P_{ave}	2.1	2.6	3.7	5.3	10.5	13.6	13.6	MW
Geometric luminosity	L_{geom}	0.30	0.37	0.52	0.75	1.50	1.77	2.64	$\times 10^{34}$ cm^{-2} s^{-1}
– with enhancement factor		0.50	0.68	0.88	1.47	2.94	2.71	4.32	$\times 10^{34}$ cm^{-2} s^{-1}
Beamstrahlung parameter (av.)	Υ_{ave}	0.013	0.020	0.030	0.062	0.062	0.127	0.203	
Beamstrahlung parameter (max.)	Υ_{max}	0.031	0.048	0.072	0.146	0.146	0.305	0.483	
Simulated luminosity (incl. waist shift)	L	0.56	0.75	1.0	1.8	3.6	3.6	4.9	$\times 10^{34}$ cm^{-2} s^{-1}
Luminosity fraction within 1 %	$L_{1\%}/L$	91	87	77	58	58	59	45	%
Energy loss from BS	δE_{BS}	0.65	0.97	1.9	4.5	4.5	5.6	10.5	%
e^+e^- pairs per bunch crossing	n_{pairs}	45	62	94	139	139	201	383	$\times 10^3$
Pair energy per B.C.	E_{pairs}	25	47	115	344	344	1338	3441	TeV

CLIC CDR parameters

CLIC CDR

Description [units]	**500 GeV**	**3 TeV**
Total (peak 1%) luminosity	$2.3\ (1.4)\times10^{34}$	$5.9\ (2.0)\times10^{34}$
Total site length [km]	58% 61% 13.0	34% 48.4
Loaded accel. gradient [MV/m]	80	100
Main Linac RF frequency [GHz]	12	
Beam power/beam [MW]	4.9	14
Bunch charge [10^9 e^+/e^-]	6.8	3.72
Bunch separation [ns]	300 0.5	
Bunch length [μm]	72	44
Beam pulse duration [ns]	177	156
Repetition rate [Hz]	10/35 50	
Hor./vert. norm. emitt. [$10^{-6}/10^{-9}$m]	2.4/25	0.66/20
Hor./vert. IP beam size [nm]	202/2.3	40/1
Beamstrahlung photons/electron	1.3	2.2
Hadronic events/crossing at IP	0.3	3.2
Coherent pairs at IP	200	6.8×10^8

Blue ; ILC

Determination of the luminosity for Linear Colliders

Luminosity $L = f n_b \dfrac{N^2}{4\pi\sigma_x^* \sigma_y^*}$

The vertical beta function is roughly optimized to the bunch length to minimize the ***hour-glass effect*** *as*

$$\sigma_y^{*2} = \beta_y^* \varepsilon_y \qquad \beta_y^* \approx \sigma_z$$

Determined by main linac

The horizontal beam size was defined with ***beamstrahlung parameter***

$$\sigma_x^{*2} \approx \frac{r_e^3 N^2 \gamma}{\sigma_z \delta_{BS}}$$

Then, the luminosity can be expressed as

$$\boxed{L = \frac{f n_b N}{4\pi r_e^{3/2}} \sqrt{\frac{\delta_{BS}}{\gamma \varepsilon_y}}}$$

In order to increased the luminosity,

1) *Make small vertical emittance*
2) *Make beamstrahlung parameter large.*

   ⇒ *make the balance of the luminosity and energy spread.*

Determined by damping ring

Summary of IP parameter Optimization

In generally, it is better to design the IP beam size as small as possible in order to have a higher luminosity.

But, there are IP beam size limits.

The theoretical limit is the aberration by Synchrotron radiation from final focus quarupole, so called to "Oide limit".
But, the Oide limit is not the limit for most of linear collider IP design.

The actual luminosity is limited as the total system of machine.
- *the bunch length is limited by main linac.*
- *the vertical emittance is limited by damping ring.*
- *the beam-beam parameter is limited by the requirement of physics group.*

The crossing angle also reduce the luminosity.
But, the effect of the crossing angle will be compensated with crab cavity in ILC.

before the short break …

beam-beam effect
for "circular collider"

SuperKEKB IP parameters

KEKB IP configuration

Weak focusing $\beta_x^* = 1.2\ \mathrm{m}$

$\beta_y^* = 5.9\ \mathrm{mm}$

22mrad crossing angle

⇒ Compensated with Crab cavity

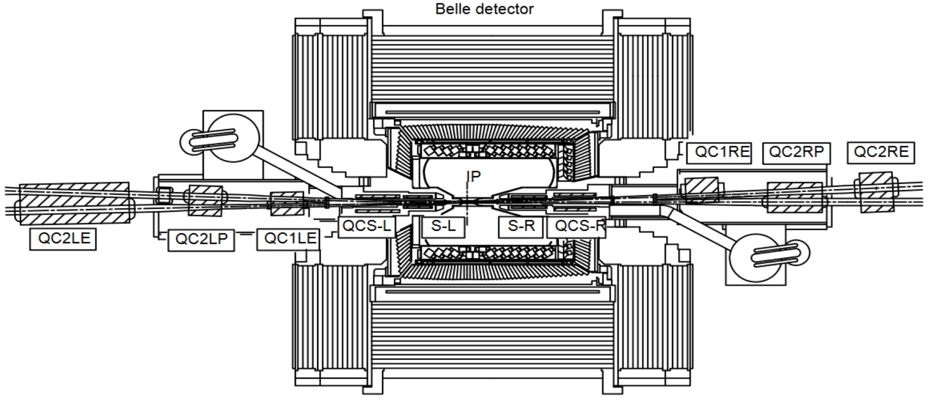
SuperKEKB IP configuration

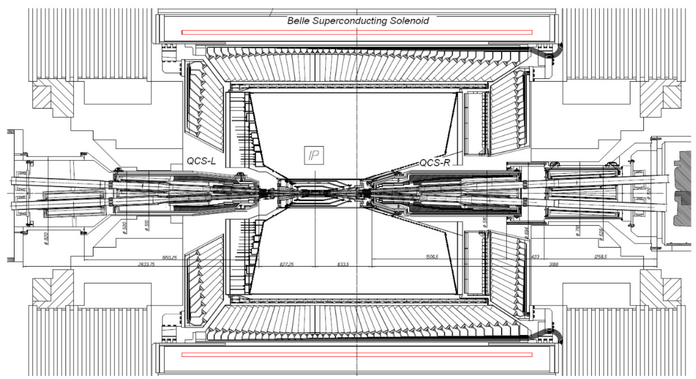
Strong focusing $\beta_x^* = 30\ \mathrm{mm}$

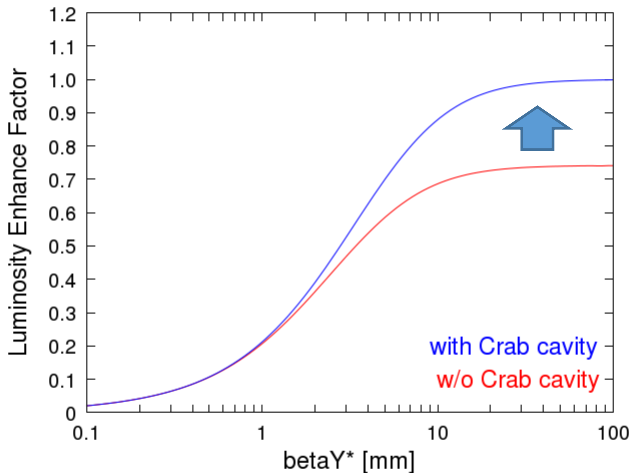
$\beta_y^* = 0.3\ \mathrm{mm}$

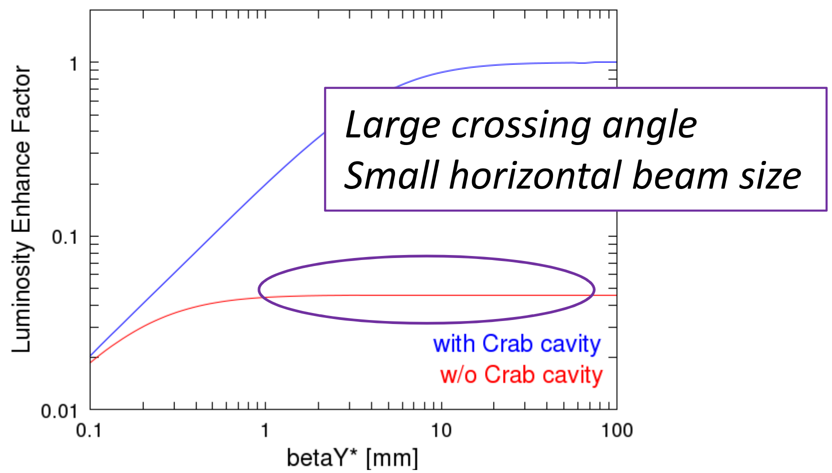
83mrad crossing angle

⇒ not be compensated



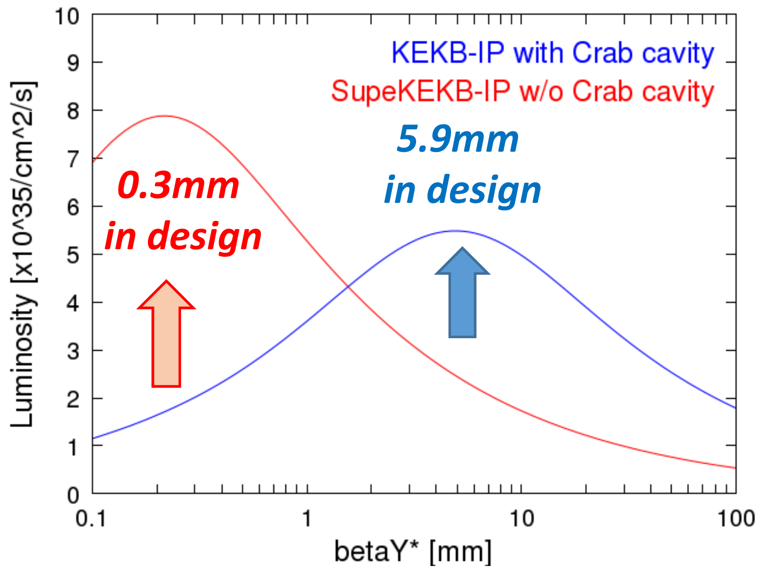




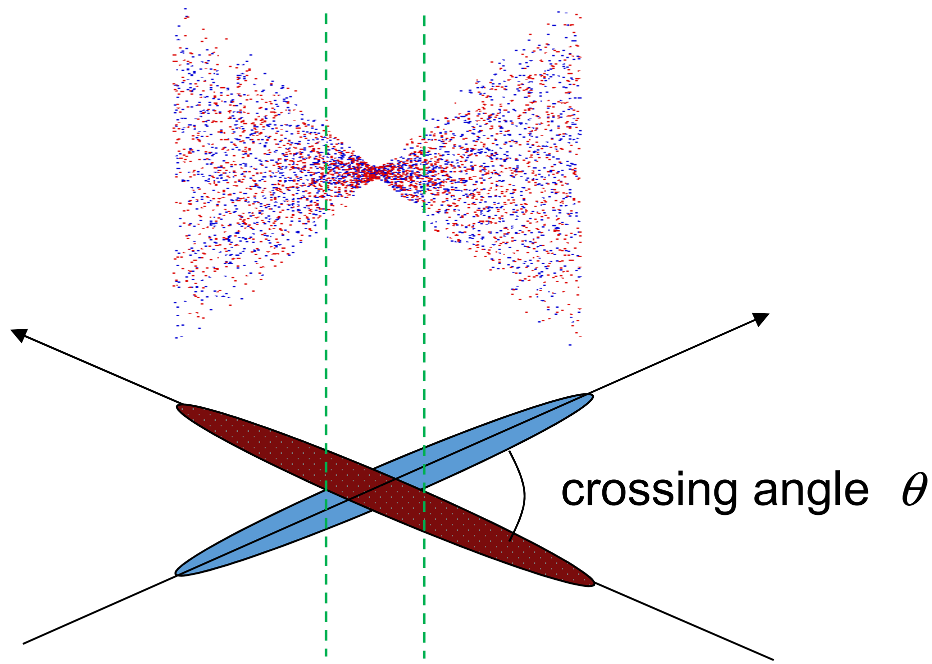


Nano-beam scheme of SuperKEKB IP parameters

Calculated the luminosity as a function of IP vertical beta-function with SuperKEKB beam currents and emittances.



There is an optimum vertical beam sizes for each IP configuration.



Luminosity is defined only be this area.

The luminosity of SuperKEKB IP configuration is higher than that for KEKB IP configuration, even if SuperKEKB will not use the crab crossing.

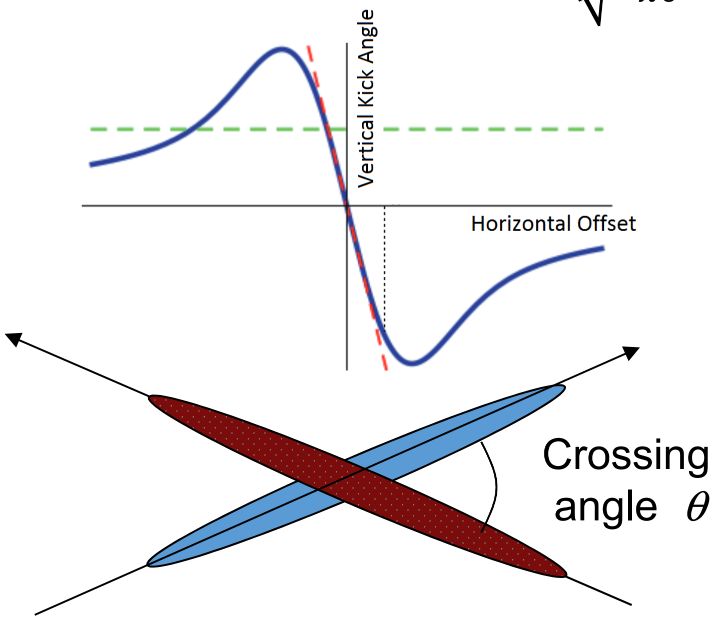
Beam-beam effect in circular collider

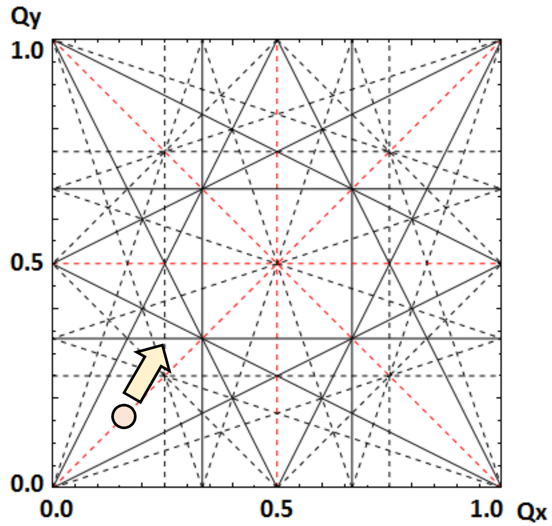
The beam-beam parameter is roughly tune shift in storage ring for small $\xi_{x,y}$, when the tunes are not too close to $Q_{x,y} = 0/0.5$. $\Delta Q_{x,y} \approx \xi_{x,y}$

Beam-beam parameter

$$\xi_{x,y} \equiv \frac{N r_e \beta^*_{x,y}}{2\pi\gamma\left(\sigma^*_x + \sigma^*_y\right)\sigma^*_{x,y}}$$

$$\sigma^*_x = \sqrt{\sigma^{*2}_{x0} + \sigma^2_z \tan^2\theta/2}$$





Beam can not circulate at resonance.
see the lecture of Y. Papaphilippou.

*For the circular collider,
when the beam is strongly focused at IP,
the beam cannot be stored
by the beam-beam tune shift.*

Beam-beam tune shift for SuperKEKB

Ring Parameter	IP Parameter	Beam-beam parameter	
		Positron Ring	Electron Ring
KEKB	KEKB	0.129	0.090
KEKB	SuperKEKB	1.3	1.1
SuperKEKB	SuperKEKB	0.088	0.081

When we will improve only the ring parameter (beam current and emittances), the luminosity is expected to improve to be comparable to SuperKEKB.

But, the beam cannot stored in the ring by beam-beam tune shift.

The IP beam size for high luminosity circular collider is limited to be able to circulate by beam-beam effect.

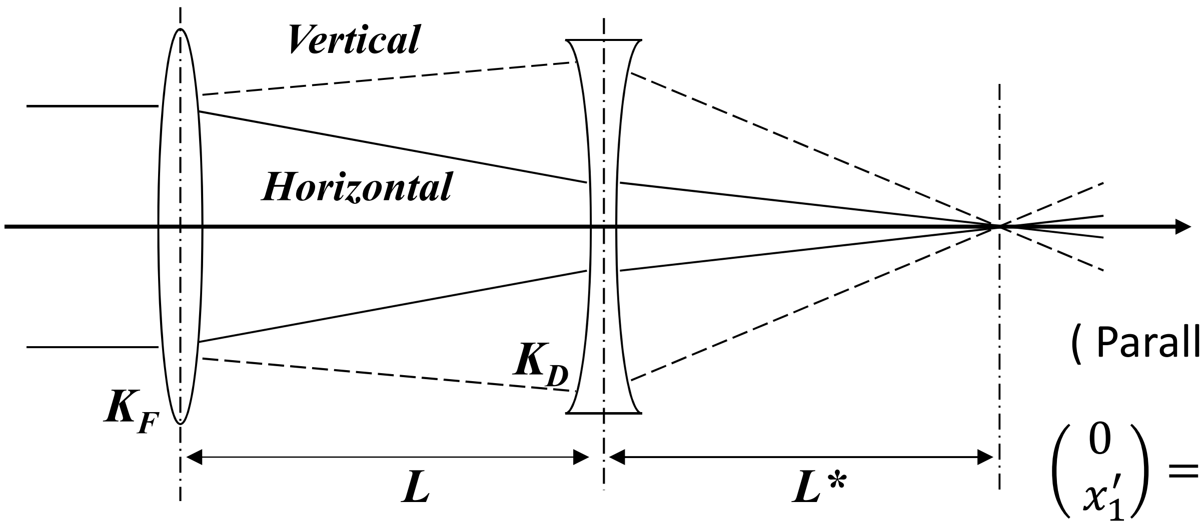
On the other hand, the IP parameter for linear collider is determined to the limit of energy spread growth by beam-beam effect.

Beam-beam effect is important to the IP beam size limit both for circular and linear colliders.

Optics Design Concept of Final Focus Beamline for Linear Colliders

Final Doublet System

In order to focus the beam both for horizontal and vertical direction, it is necessary to use the combination lens system for final focus lens.



(Parallel beam) ⇒ (Focus at IP)

$$\begin{pmatrix} 0 \\ x_1' \end{pmatrix} = M_x \begin{pmatrix} x_0 \\ 0 \end{pmatrix} \Rightarrow M_x(1,1) = 0$$

$$\begin{pmatrix} 0 \\ y_1' \end{pmatrix} = M_y \begin{pmatrix} y_0 \\ 0 \end{pmatrix} \Rightarrow M_y(1,1) = 0$$

Transfer Matrix of thin lens approximation

$$M_x = \begin{pmatrix} 1 & L^* \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ +K_D & 1 \end{pmatrix}\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -K_F & 1 \end{pmatrix}$$

$$M_y = \begin{pmatrix} 1 & L^* \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -K_D & 1 \end{pmatrix}\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ +K_F & 1 \end{pmatrix}$$

$$\boxed{K_F = \frac{1}{\sqrt{L(L+L^*)}}\ ,\ \ K_D = \frac{1}{L^*}\sqrt{\frac{L+L^*}{L}}}$$

Beta Function Propagation

$$K_F = \frac{1}{\sqrt{L(L+L^*)}}$$

$$K_D = \frac{1}{L^*}\sqrt{\frac{L+L^*}{L}}$$

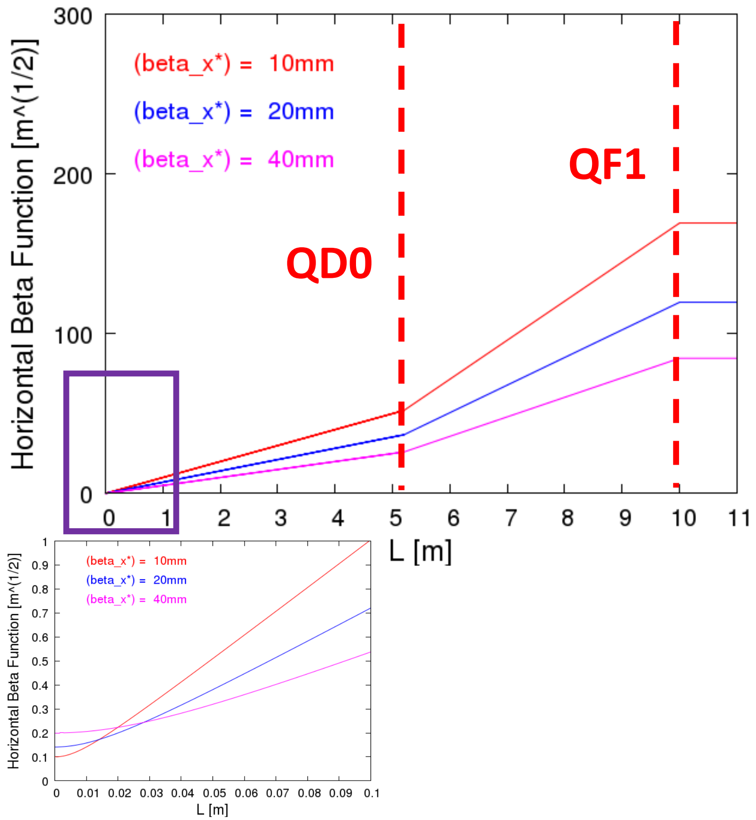
The transfer matrix M_x, M_y can be calculated.

The beta function can be also calculated.

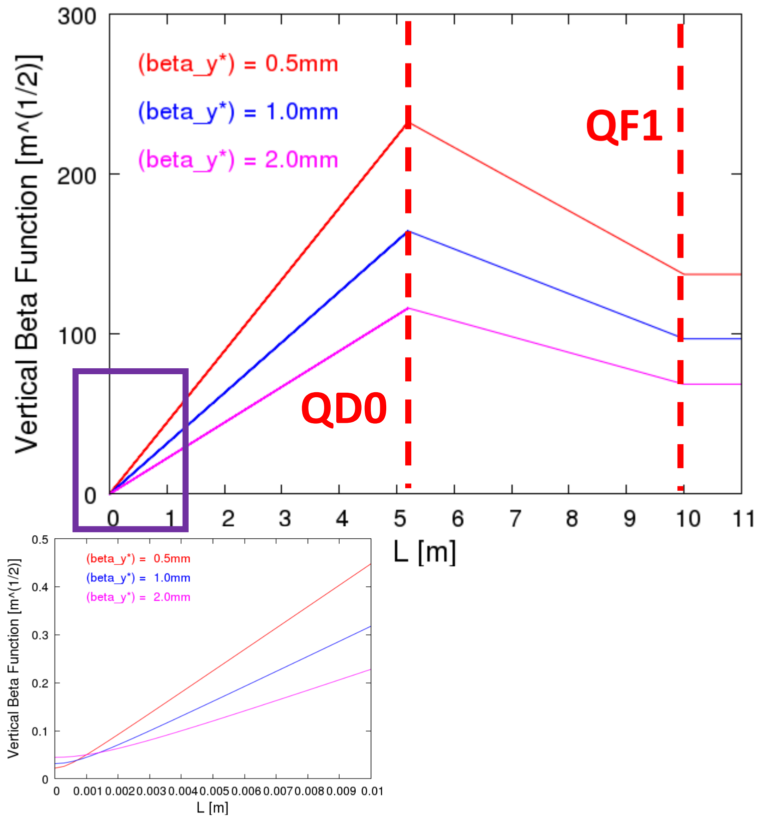
Homework

Calculate the transfer Matrix of entire final doublet.

Horizontal



Vertical



Chromaticity of Quadrupole Magnet

The focal length is changed for off-momentum particle as $K \rightarrow \dfrac{K}{1+\delta} \approx K(1-\delta)$

Then, the position at the exit of quadrupole is also changed for off-momentum particle

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -K(1-\delta) & 1 \end{pmatrix} T_x^{-1} \begin{pmatrix} u_x \\ v_x \end{pmatrix} = \begin{pmatrix} x_0 \\ x_0' \end{pmatrix} + \begin{pmatrix} 0 \\ +K\sqrt{\beta_x}\, u_x \delta \end{pmatrix}$$

$$\begin{pmatrix} y \\ y' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ +K(1-\delta) & 1 \end{pmatrix} T_y^{-1} \begin{pmatrix} u_y \\ v_y \end{pmatrix} = \begin{pmatrix} y_0 \\ y_0' \end{pmatrix} + \begin{pmatrix} 0 \\ -K\sqrt{\beta_y}\, u_y \delta \end{pmatrix}$$

Since the transfer Matrix is expressed with Twiss parameters as

$$M(s_1, s_2) = \begin{pmatrix} \sqrt{\dfrac{\beta_2}{\beta_1}}(\cos\theta + \alpha_1 \sin\theta) & \sqrt{\beta_1\beta_2}\sin\theta \\ \dfrac{1}{\sqrt{\beta_1\beta_2}}\{(\alpha_1 - \alpha_2)\cos\theta - (1+\alpha_1\alpha_2)\sin\theta\} & \sqrt{\dfrac{\beta_1}{\beta_2}}(\cos\theta - \alpha_2\sin\theta) \end{pmatrix}$$

The IP position with momentum offset δ *is changed from the on-momentum particle as*

Phase advance $\theta_{x,y} = 90°$

$$\Delta x_{IP} = +(K\beta_x \sin\theta_x)\sqrt{\beta_x^*}\, u_x\delta \approx \boxed{+(K\beta_x)}\sqrt{\beta_x^*}\, u_x\delta$$

$$\Delta y_{IP} = -(K\beta_y \sin\theta_y)\sqrt{\beta_y^*}\, u_y\delta \approx \boxed{-(K\beta_y)}\sqrt{\beta_y^*}\, u_y\delta$$

Chromaticity

Chromaticity of Final Doublet

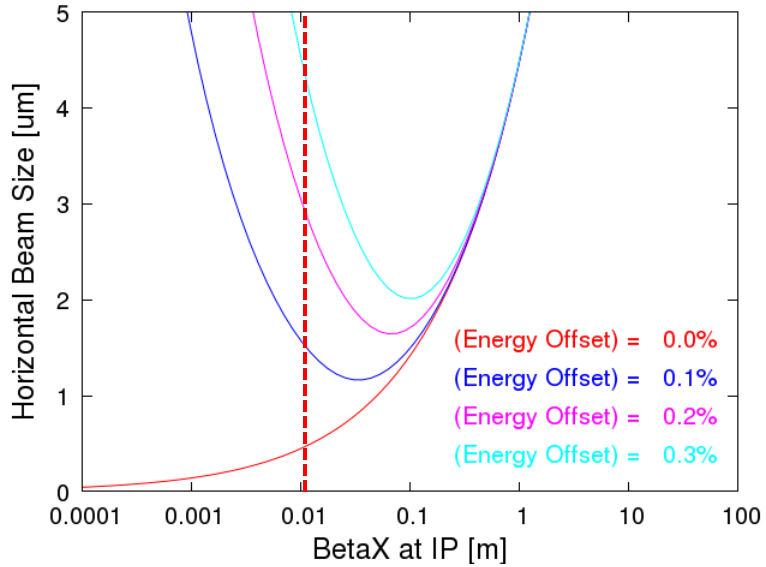
The aberration of off-momentum particle is called to "chromaticity".

$$K_F = \frac{1}{\sqrt{L(L+L^*)}} \quad \Rightarrow \quad K_F = \frac{1}{\boxed{(1+\delta)}\sqrt{L(L+L^*)}}$$

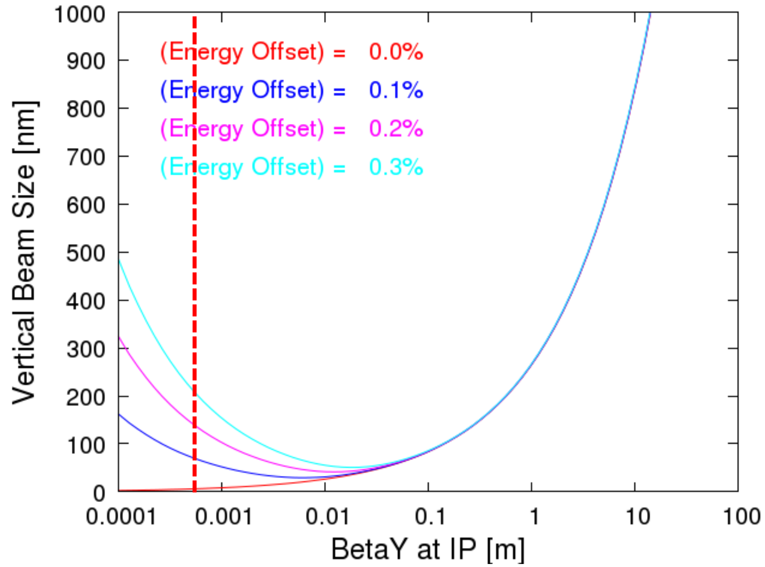
$$K_D = \frac{1}{L^*}\sqrt{\frac{L+L^*}{L}} \quad \Rightarrow \quad K_D = \frac{1}{\boxed{(1+\delta)}L^*}\sqrt{\frac{L+L^*}{L}}$$

Focusing strength is different for off-momentum particle

Horizontal



Vertical



Limit of IP beta function w/o chromaticity correction.
(ILC 500 GeV design BetaX=0.011m, BetaY*=0.00048m)*

We need correction !

Particle motion in sextupole magnet

Vector potential of normal sextupole magnet

$$-\frac{q}{p_0}A_{s,2N}=\frac{k_{2N}r^3}{3!}\cos 3\theta=\frac{k_{2N}}{6}r^3(\cos^3\theta-3\cos\theta\sin^2\theta)=\frac{k_{2N}}{6}(x^3-3xy^2)$$

Beam has a horizontal offset Δx

$$x\rightarrow x_0+\Delta x,\qquad y\rightarrow y_0$$

$$-\frac{q}{p_0}A_{s,2N}=\frac{k_{2N}}{6}(x_0^3-3x_0y_o^2)+\frac{k_{2N}}{2}(x_0^2-y_0^2)\,\Delta x+\mathrm{o}(\Delta x^2)$$

Normal sextupole field

Normal quadrupole field

The strength is proportional to the offset.

Beam has a vertical offset Δy

$$x\rightarrow x_0,\qquad y\rightarrow y_0+\Delta y$$

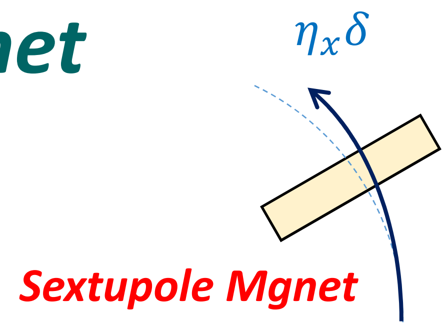
$$-\frac{q}{p_0}A_{s,2N}=\frac{k_{2N}}{6}(x_0^3-3x_0y_o^2)+k_{2N}x_0y_0\,\Delta y+\mathrm{o}(\Delta y^2)$$

Normal sextupole field

Skew quadrupole field

The strength is proportional to the offset.

Chromaticity of Sextupole Magnet



When we put the horizontal dispersion at the sextupole, the quadrupole field is generated at the sextupole magnet.

$$
\begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ -K_2\left(\sqrt{\beta_x}u_x + \eta_x\delta\right) & 1 & +K_2\sqrt{\beta_y}\,u_y & 0 \\ 0 & 0 & 1 & 0 \\ +K_2\sqrt{\beta_y}\,u_y & 0 & +K_2\left(\sqrt{\beta_x}u_x + \eta_x\delta\right) & 1 \end{pmatrix} \begin{pmatrix} \sqrt{\beta_x}u_x + \eta_x\delta \\ x_0' \\ \sqrt{\beta_y}\,u_y \\ y_0' \end{pmatrix}
$$

$$
= \begin{pmatrix} x_0 \\ x_0' \\ y_0 \\ y_0' \end{pmatrix} + \underbrace{\begin{pmatrix} 0 \\ -2\eta_x K_2\sqrt{\beta_x}\,u_x\delta \\ 0 \\ +2\eta_x K_2\sqrt{\beta_y}\,u_y\delta \end{pmatrix}}_{\text{Chromaticity}} + K_2 \underbrace{\begin{pmatrix} 0 \\ \beta_y u_y^2 - \beta_x u_x^2 - \eta_x^2\delta^2 \\ 0 \\ 2\sqrt{\beta_x\beta_y}\,u_x u_y \end{pmatrix}}_{\text{2nd order aberrations}}
$$

Chromaticity

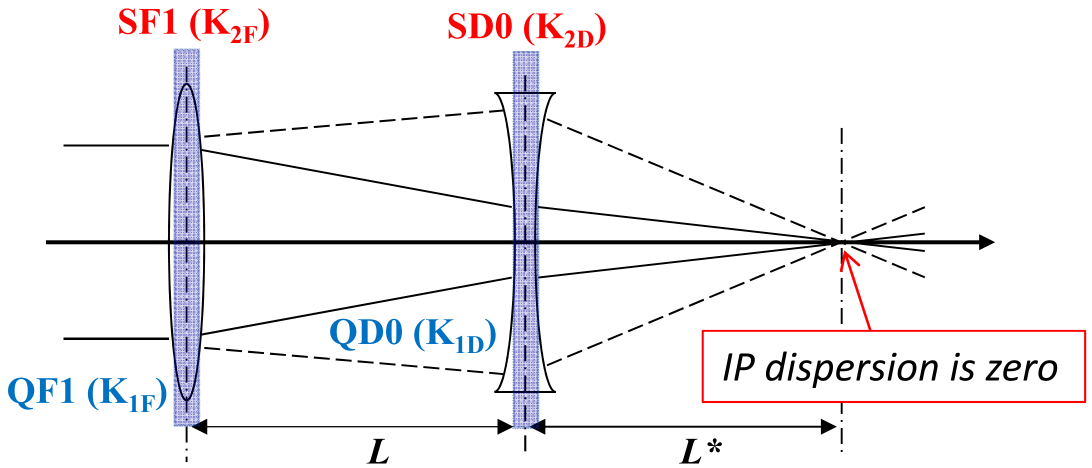
2nd order aberrations

$$\xi_x = -2\eta_x K_2 \beta_x$$

$$\xi_y = +2\eta_x K_2 \beta_y$$

We can produce the chromaticity.
The amplitude is proportional to η_x and K_2.

Chromaticity Correction of Final Doublet



$$K_{1F} = \frac{1}{\sqrt{L(L+L^*)}}$$

$$K_{1D} = \frac{1}{L^*}\sqrt{\frac{L+L^*}{L}}$$

$$\beta_{Dx} = \beta_x^* + \frac{L^{*2}}{\beta_x^*} \qquad \beta_{Fx} = (1+K_{1D}L)^2\beta_x^* + \frac{(L+L^*+K_{1D}LL^*)^{*2}}{\beta_x^*}$$

$$\beta_{Dy} = \beta_y^* + \frac{L^{*2}}{\beta_y^*} \qquad \beta_{Fy} = (1-K_{1D}L)^2\beta_y^* + \frac{(L+L^*-K_{1D}LL^*)^{*2}}{\beta_y^*}$$

$$\eta_{Dx} = -L^*\,\eta'_x \qquad \eta_{Fx} = -(L+L^*+K_{1D}LL^*)\eta'_x$$

Summary of chromaticity, generated by magnets

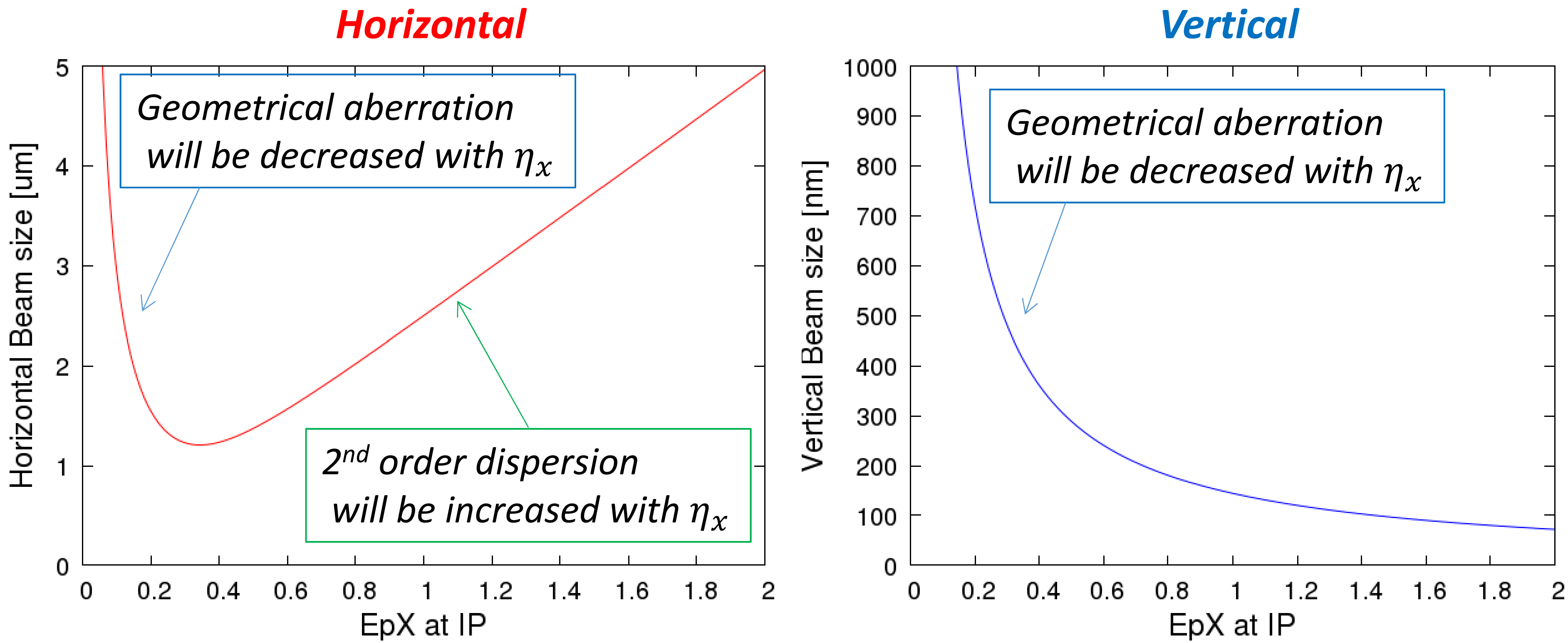
	Horizontal	*Vertical*
QF1	$+K_{1F}\beta_{Fx}$	$-K_{1F}\beta_{Fy}$
SF1	$-2\eta_{Fx}K_{2F}\beta_{Fx}$	$+2\eta_{Fx}K_{2F}\beta_{Fy}$
QD0	$-K_{1D}\beta_{Dx}$	$+K_{1D}\beta_{Dy}$
SD0	$-2\eta_{Dx}K_{2D}\beta_{Dx}$	$+2\eta_{Dx}K_{2D}\beta_{Dy}$

$$K_{2F}(\beta'_x,\ \beta^*_y,\ \eta'_x),$$
$$K_{2D}(\beta'_x,\ \beta^*_y,\ \eta'_x)$$

is calculated to make x&y chromaticities zero.

Geometrical Aberration and 2nd order Dispersion

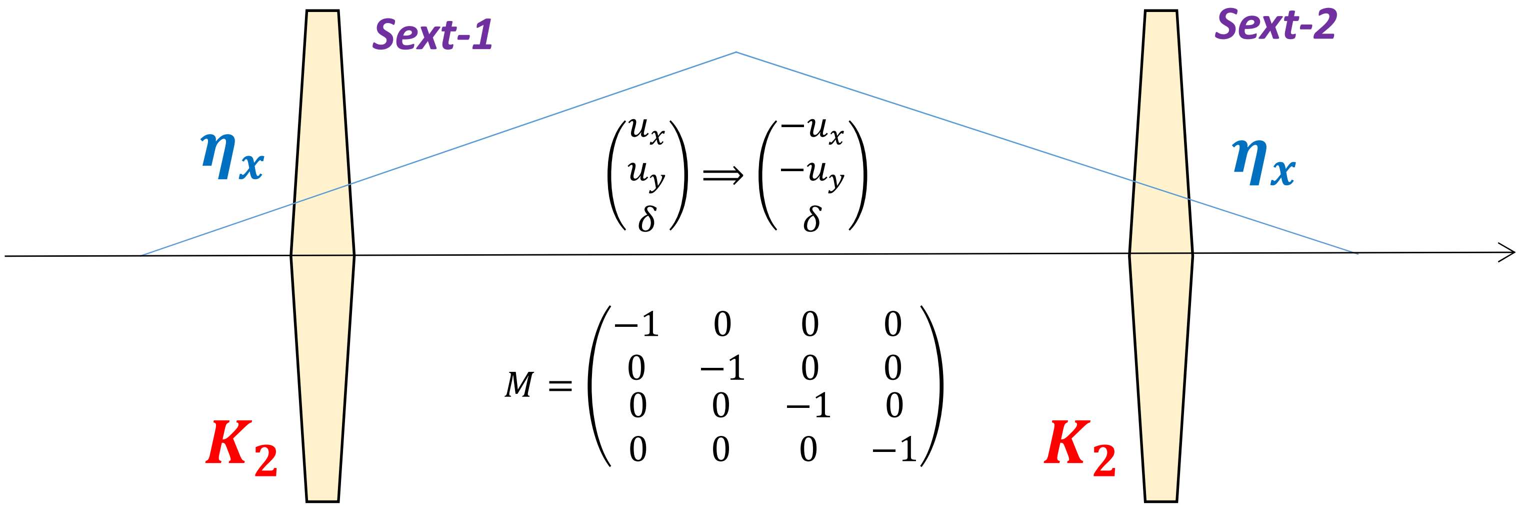
Calculated with ILC $E_{CM} = 500\ GeV$ parameters
after chromaticity correction with sextupoles (SF1, SD0)



We cannot focus the beam at IP only by putting the sextupoles at Final Doublet.

Idea to avoid 2nd order aberration 1

2 sextupoles are put to the following condition.



$$\begin{pmatrix} u_x \\ u_y \\ \delta \end{pmatrix} \Rightarrow \begin{pmatrix} -u_x \\ -u_y \\ \delta \end{pmatrix}$$

$$M = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Sext-1

$$\begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix} = \begin{pmatrix} -2\eta_x K_2 \sqrt{\beta_x}\, u_x \delta \\ +2\eta_x K_2 \sqrt{\beta_y}\, u_y \delta \end{pmatrix} + K_2 \begin{pmatrix} \beta_y u_y^2 - \beta_x u_x^2 - \eta_x^2 \delta^2 \\ 2\sqrt{\beta_x \beta_y}\, u_x u_y \end{pmatrix} \Rightarrow \begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix} = -\begin{pmatrix} -2\eta_x K_2 \sqrt{\beta_x}\, u_x \delta \\ +2\eta_x K_2 \sqrt{\beta_y}\, u_y \delta \end{pmatrix} - K_2 \begin{pmatrix} \beta_y u_y^2 - \beta_x u_x^2 - \eta_x^2 \delta^2 \\ 2\sqrt{\beta_x \beta_y}\, u_x u_y \end{pmatrix}$$

$$+$$

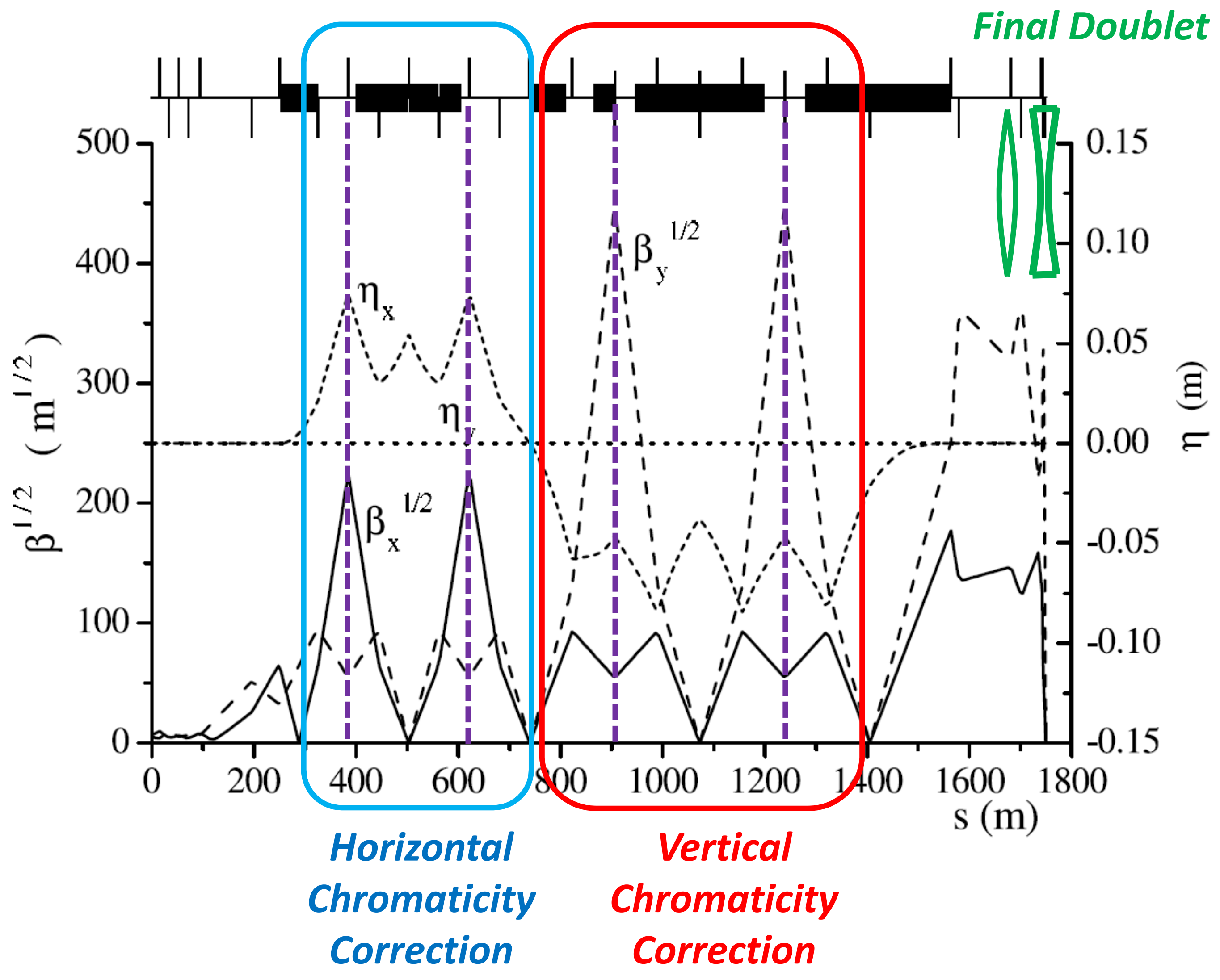
Sext-2 $$\begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix} = -\begin{pmatrix} -2\eta_x K_2 \sqrt{\beta_x}\, u_x \delta \\ +2\eta_x K_2 \sqrt{\beta_y}\, u_y \delta \end{pmatrix} + K_2 \begin{pmatrix} \beta_y u_y^2 - \beta_x u_x^2 - \eta_x^2 \delta^2 \\ 2\sqrt{\beta_x \beta_y}\, u_x u_y \end{pmatrix}$$

$$\Downarrow$$

Total $$\begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix} = \underbrace{\begin{pmatrix} +4\eta_x K_2 \sqrt{\beta_x}\, u_x \delta \\ -4\eta_x K_2 \sqrt{\beta}\;\; u_y \delta \end{pmatrix}}_{\text{Chromaticity}}$$

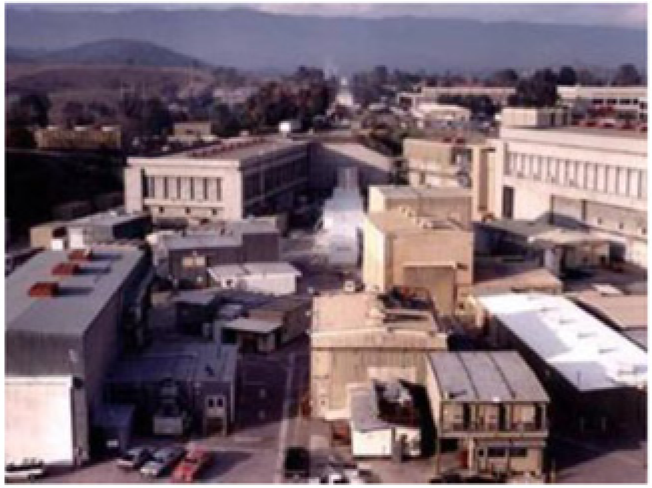
Only chromaticities are generated as total system.

Global Chromaticity Correction System

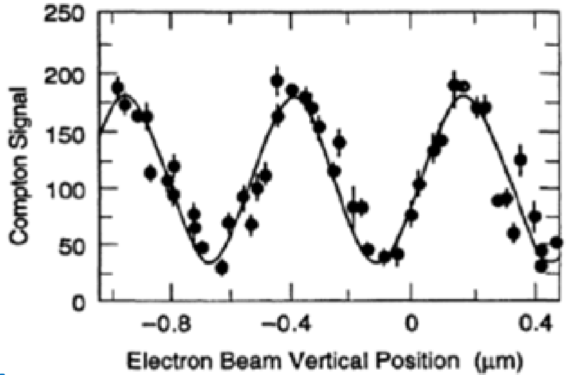


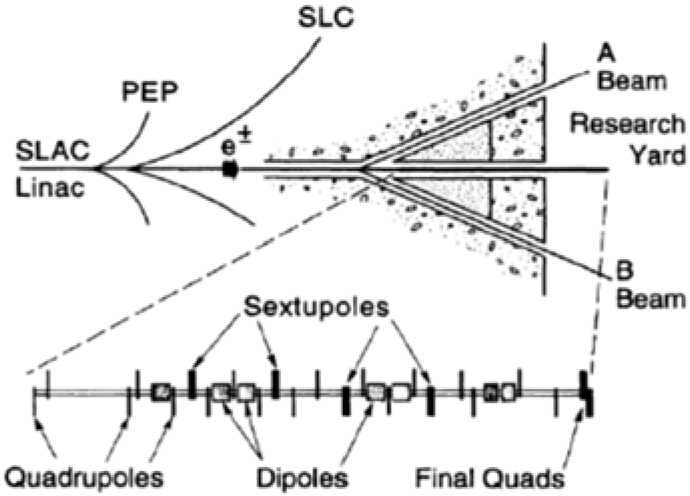
Final Focus Test Beam (FFTB)

*FFTB is built in SLC research yard (SLAC) for the LC final focus test with **global chromticity correction system**.*

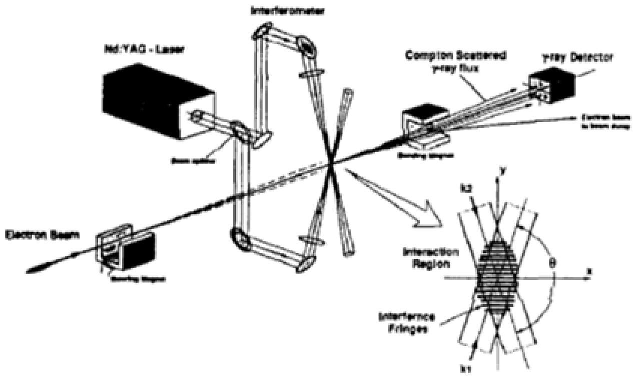


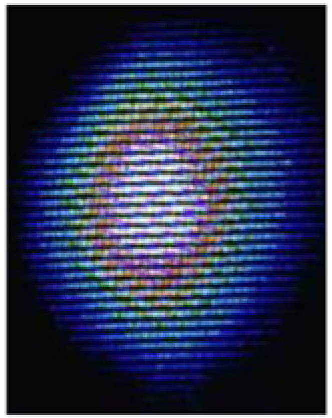
	IP beam size
Design	*45 nm*
Achieved	*70 nm*





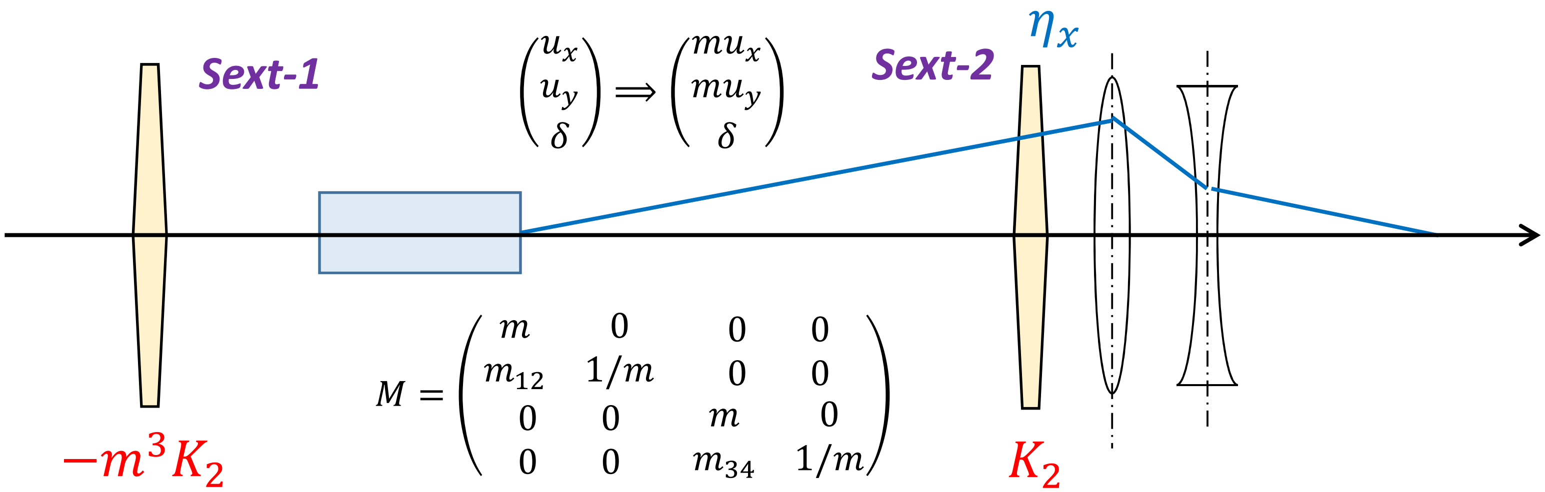
Shintake Monitor





detail will be shown in later.

Idea to avoid 2nd order aberration 2



$$\begin{pmatrix} u_x \\ u_y \\ \delta \end{pmatrix} \Longrightarrow \begin{pmatrix} m u_x \\ m u_y \\ \delta \end{pmatrix}$$

$$M = \begin{pmatrix} m & 0 & 0 & 0 \\ m_{12} & 1/m & 0 & 0 \\ 0 & 0 & m & 0 \\ 0 & 0 & m_{34} & 1/m \end{pmatrix}$$

Sext-1 $\begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix} = -m^3 K_2 \begin{pmatrix} \beta_y u_y^2 - \beta_x u_x^2 \\ 2\sqrt{\beta_x \beta_y}\, u_x u_y \end{pmatrix} \Rightarrow \begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix} = -m^2 K_2 \begin{pmatrix} \beta_y u_y^2 - \beta_x u_x^2 \\ 2\sqrt{\beta_x \beta_y}\, u_x u_y \end{pmatrix}$

$+$

Sext-2 $\begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix} = \begin{pmatrix} -2m\, \eta_x K_2 \sqrt{\beta_x}\, u_x \delta \\ +2m\, \eta_x K_2 \sqrt{\beta}\ \ u_y \delta \end{pmatrix} + m^2 K_2 \begin{pmatrix} \beta_y u_y^2 - \beta_x u_x^2 - \eta_x^2 \delta^2 / m^2 \\ 2\sqrt{\beta_x \beta_y}\, u_x u_y \end{pmatrix}$

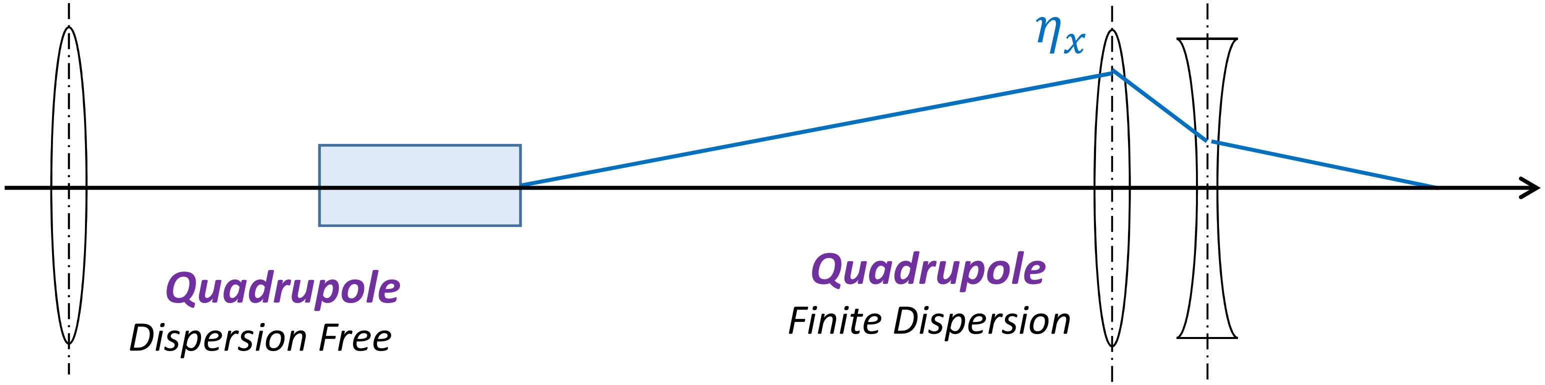
$\Downarrow$

Total $\begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix} = \underbrace{\begin{pmatrix} -2m\, \eta_x K_2 \sqrt{\beta_x}\, u_x \delta \\ +2m\, \eta_x K_2 \sqrt{\beta_y}\ \ u_y \delta \end{pmatrix}}_{\text{Chromaticity}} + \underbrace{\begin{pmatrix} -K_2 \eta_x^2 \delta^2 \\ 0 \end{pmatrix}}_{\text{2nd order dispersion}}$

Geonetrical aberration was cancelled.

Local Dispersion Correction System

Quadrupole at dispersive area generate not only chromaticity but also 2nd order dispersion.



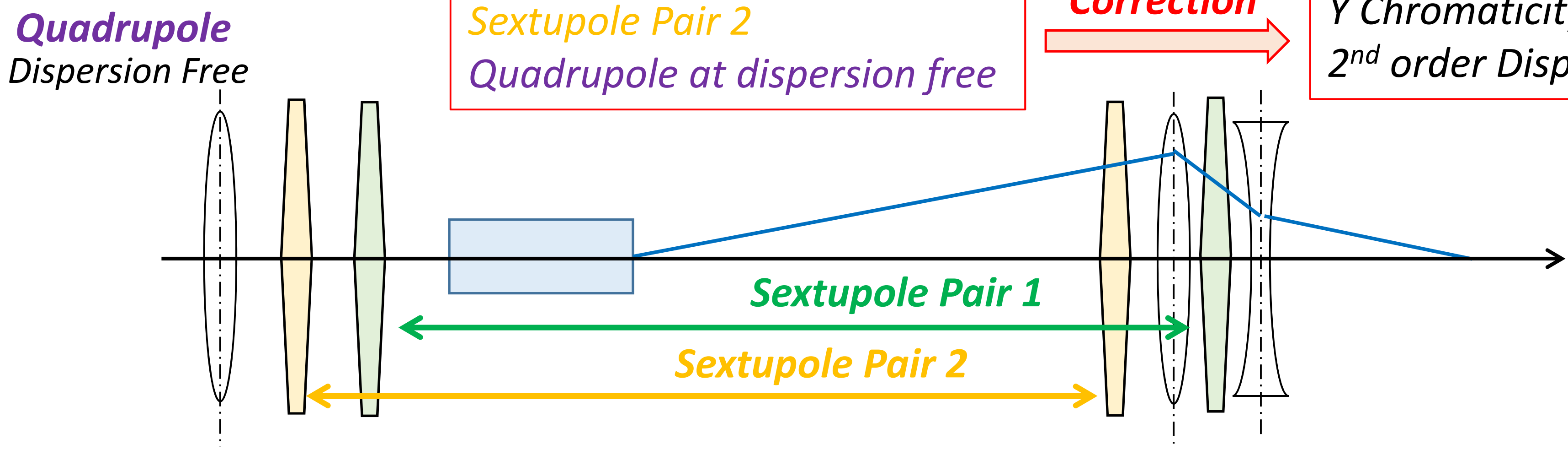
$$\begin{pmatrix}\Delta x_{IP}\\ \Delta y_{IP}\end{pmatrix} = \underbrace{\begin{pmatrix}+K\beta_x\sqrt{\beta_x^*}\,u_x\delta\\ -K\beta_y\sqrt{\beta_y^*}\,u_y\delta\end{pmatrix}}_{\text{Chromaticity}}$$

$$\begin{pmatrix}\Delta x_{IP}\\ \Delta y_{IP}\end{pmatrix} = \underbrace{\begin{pmatrix}+K\beta_x\sqrt{\beta_x^*}\,u_x\delta\\ -K\beta_y\sqrt{\beta_y^*}\,u_y\delta\end{pmatrix}}_{\text{Chromaticity}} + \underbrace{\begin{pmatrix}+K\eta_x\sqrt{\beta_x\beta_x^*}\,\delta^2\\ 0\end{pmatrix}}_{\text{2nd order dispersion}}$$

Sextupole Pair 1
Sextupole Pair 2
Quadrupole at dispersion free

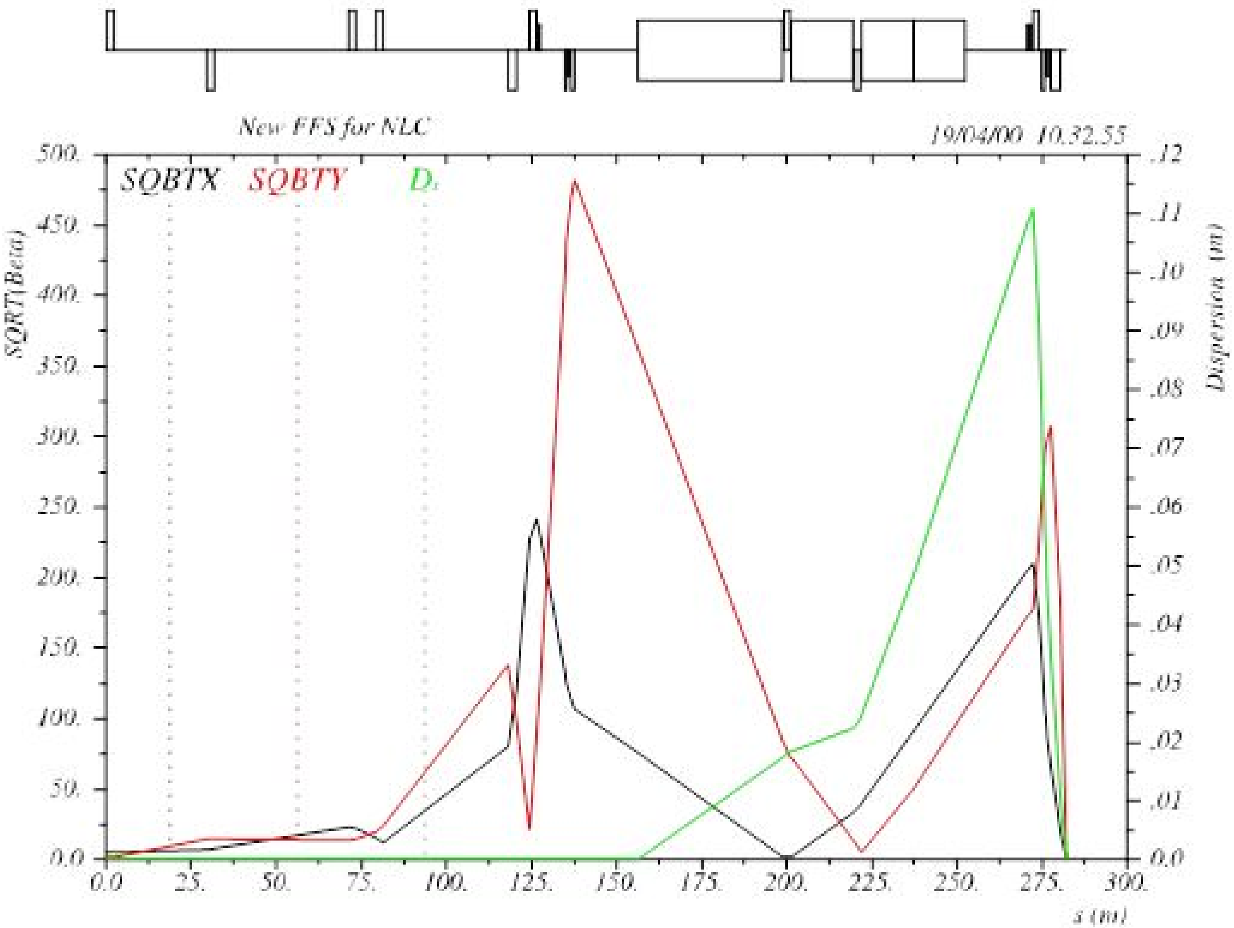
Correction →

X Chromaticity
Y Chromaticity
2nd order Dispersion



Beam Optics of LC Final Focus System with Local Chromaticity Correction Method

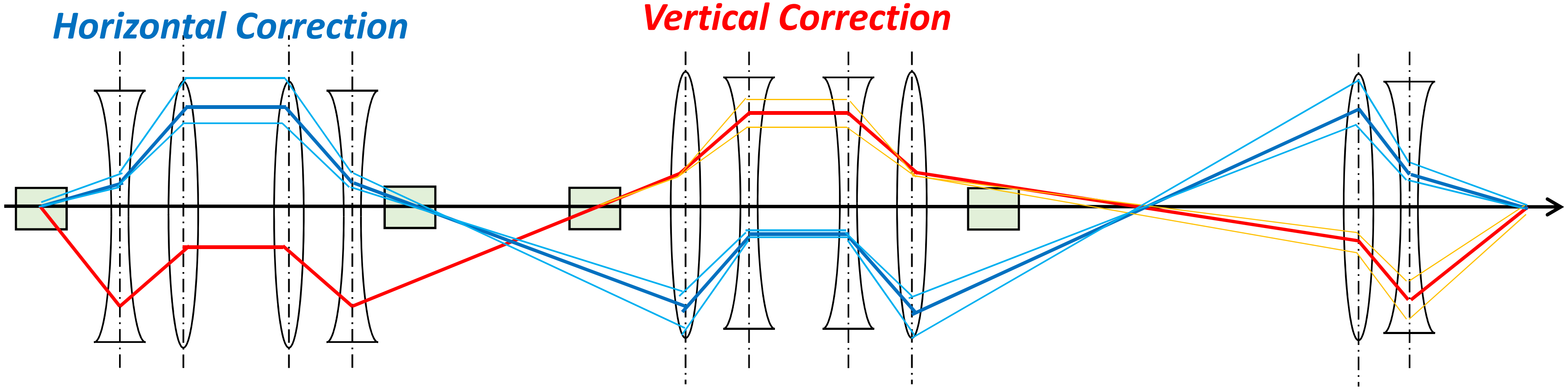
6times shorter than LC FF beamline with Global Chromaticity Correction.



P. Raimondi and A. Seryi, PRL Vol. 86 3779 (2001)

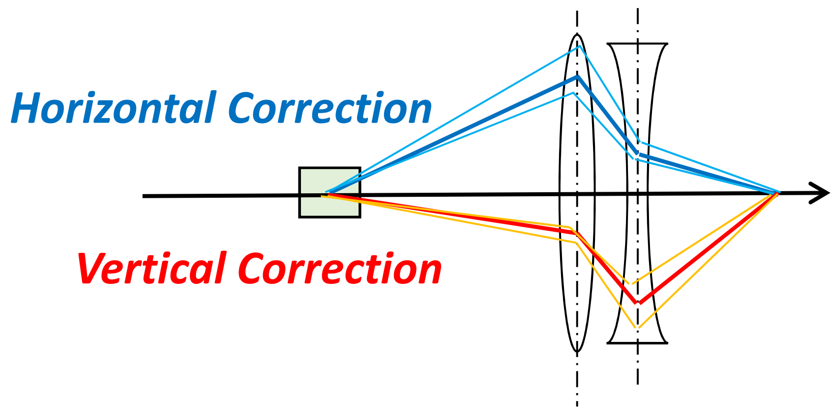
Orbit Distortion of off-momentum particle

Global Chromaticity Correction



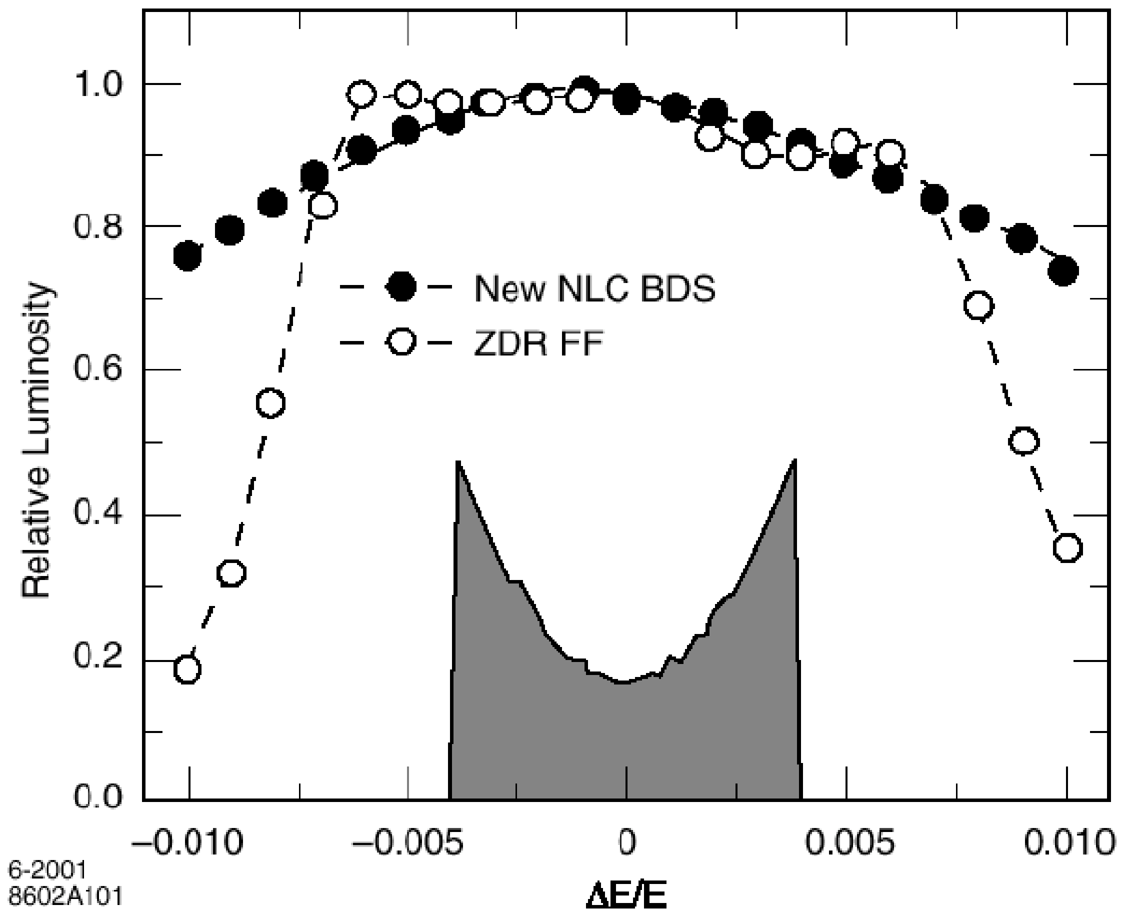
Orbit distortion through long beamline of off-momentum particle exists for global chromaticity correction beamline.

Local Chromaticity Correction



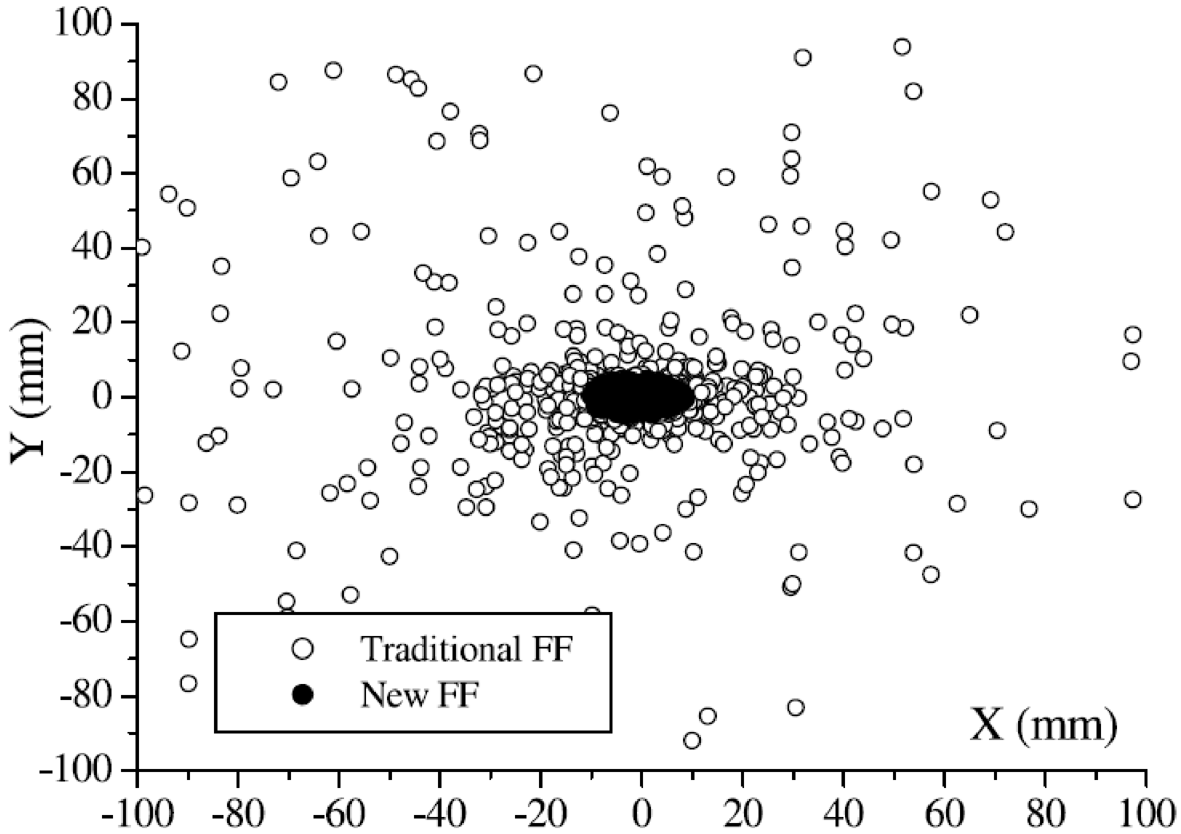
IP Energy Bandwidth

Luminosity bandwidth of off-momentum beam



Energy Bandwidth of local chromaticity correction optics is larger than that of global chromaticity correction optics.

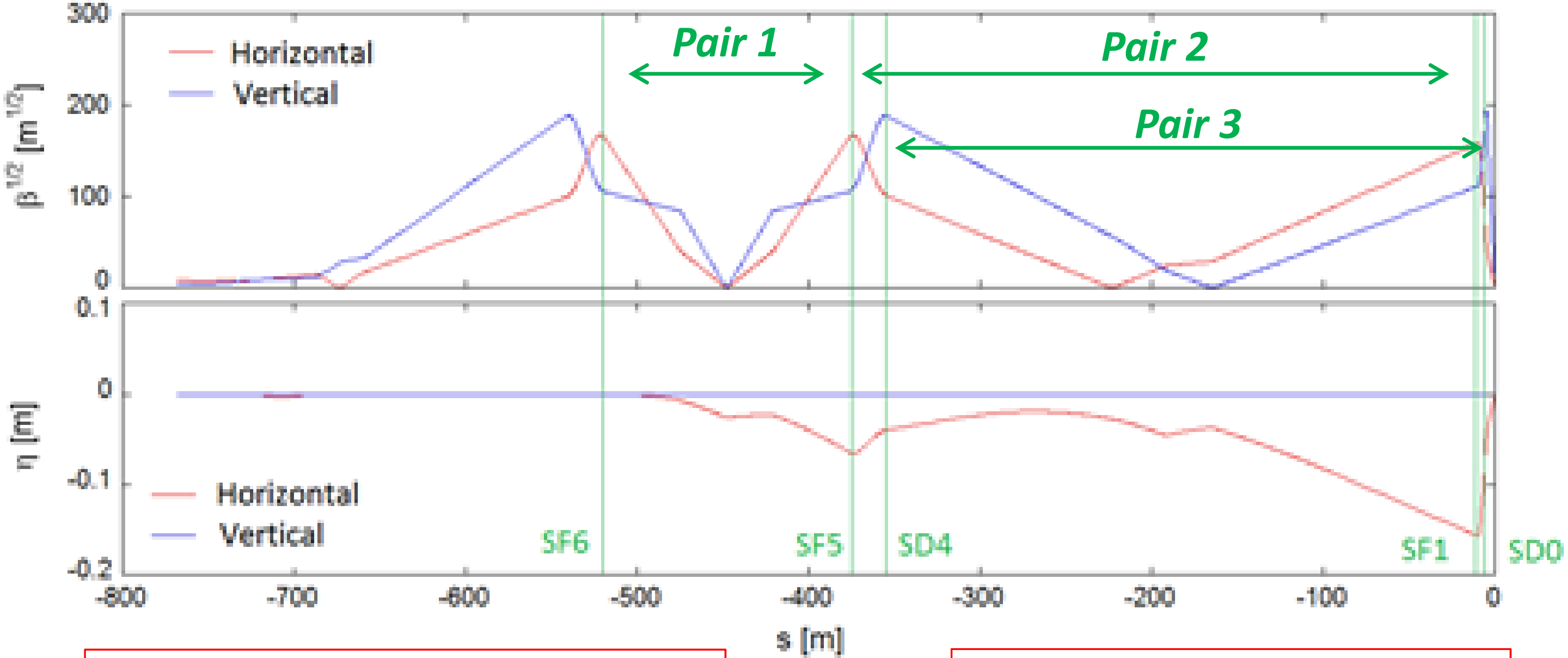
Beam Halo at IP



Beam halo of local chromaticity correction optics is smaller than that of global chromaticity correction optics.

Present ILC Final Focus Optics

We adopted the modified Local Chromaticity Correction Optics.



3 parameters to be corrected

- X Chromaticity
- Y Chromaticity
- 2^{nd} order Dispersion

3 sext. pair for correction

- SF6 and SF5
- SF5 and SF1
- SD4 and SD0

We can correct 2^{nd} order aberration

- *only with sextupole magnet.*
- *without linear optics change.*

Since SF5 is common for 2 pairs, total 5 sextupole is used for correction.

Chromaticities of quad/sext in ILC FF beamline

Name-	X	Y
QD10B	-131.9	757.6
QD10A	-168.7	673.4
QF9B	437.4	-377.5
SF6	0.0	0.0
QF9A	460.6	-295.4
QD8	-45.0	379.0
QF7B	0.2	-1.2
QF7A	0.2	-1.2
QD6	-45.0	379.0
QF5B	460.9	-295.6
SF5	155.6	-112.9
QF5A	437.6	-377.8
QD4B	-162.6	650.6
SD4	1238.1	-6089.7
QD4A	-126.0	736.6
QD2B	0.0	-3.9
QF3	5.8	-7.5
QD2A	-13.7	0.1
SF1	-9095.3	4954.9
QF1	4830.8	-2934.4
SD0	2497.5	-12835.6
QD0	-1002.9	14564.7
Total	-266.5	-236.9

The chromaticities are generated not only Final Doublet, but also other quadrupoles.

The chromaticities are corrected by sextupole magnets within the Final Focus Beamline.

The large chromaticities are generated by sextupole near by Final Doublet. (Not perfect local correction)

Summary of Final Focus Optics Design for LC

We must correct the chromaticity in order to focus the beam at IP strongly.

The sextupole magnet at the dispersive area make a chromaticity.
The chromaticity can correct that generated by final doublet.

The sextupoles generate not only chromaticity, but also other 2^{nd} order aberrations.
Therefore, we must correct the FD chromaticity as a total final focus system.

One idea is global chromaticity correction system.
The global chromaticity correction system is tested at FFTB (SLAC).

Other idea is local chromaticity correction system.
- *Local correction system makes the beamline shorter.*
- *Local correction system makes the energy bandwidth wider.*
- *Local correction system makes the beam halo smaller.*
- *But, the beam line tuning is complex to that of global correction system.*

The present ILC final focus optics is adopted the modified local chromaticity correction.
The optics can be control the 2^{nd} order aberration only by using sextupole magnets.

Test facility of final focus beam line have been tested at ATF2 beamline (KEK).
The detail will be lectured in later.

Beam Size Tuning of ILC Final Focus System

Linear Optics Tuning Knobs

Sextupole magnet is moved by Δx horizontally

$$x \to x_0 - \Delta x, \qquad y \to y_0$$

Normal quadrupole field

$$-\frac{q}{p_0} A_{s,2N} = \frac{k_{2N}}{6}(x_0^3 - 3x_0 y_o^2) - \underline{\underline{\frac{k_{2N}}{2}(x_0^2 - y_0^2)\,\Delta x}} + \mathrm{o}(\Delta x^2)$$

5 sextupoles in FF beamline.
Since SF5 is too weak to correct, we use 4 other sextupoles.

⇒ $\alpha_x^*, \alpha_y^*, \eta_x^*, \eta_x'^*$ *are changed.*

Orthogonal to make $\alpha_x^*, \alpha_y^*, \eta_x^*, \eta_x'^*$ correction knobs .

Sextupole magnet is moved by Δy vertically

$$x \to x_0, \qquad y \to y_0 - \Delta y$$

Skew quadrupole field

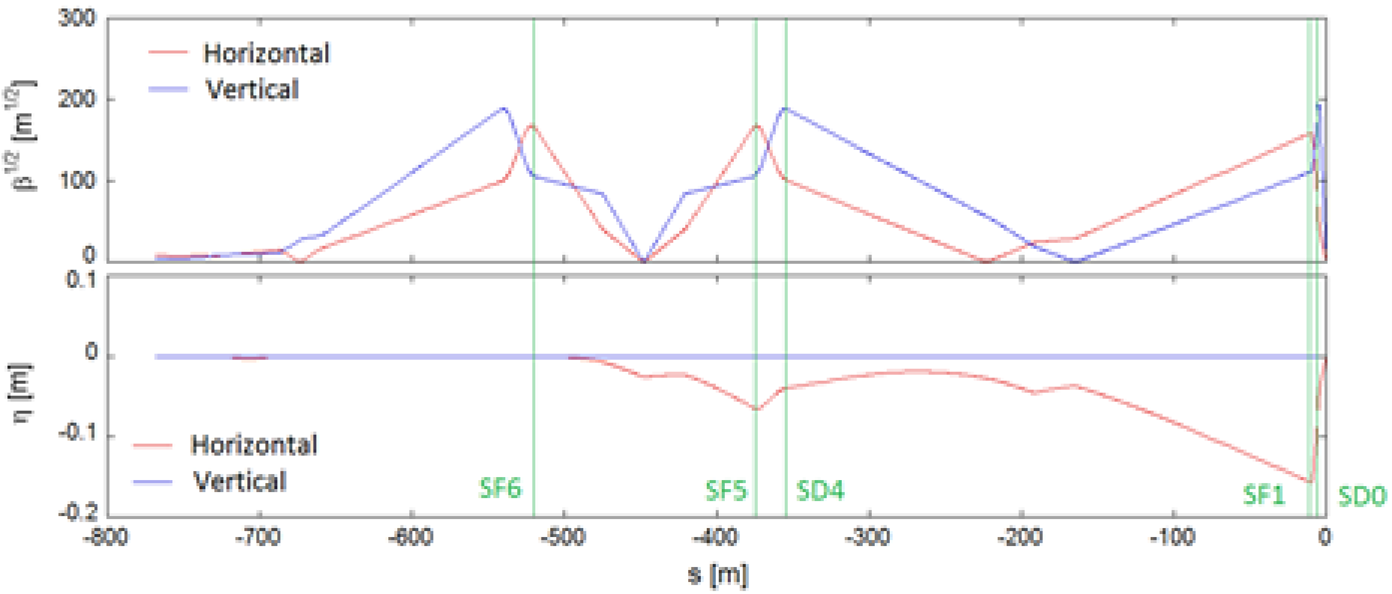
$$-\frac{q}{p_0} A_{s,2N} = \frac{k_{2N}}{6}(x_0^3 - 3x_0 y_o^2) + \underline{\underline{k_{2N} x_0 y_0\,\Delta y}} + \mathrm{o}(\Delta y^2)$$

5 sextupoles in FF beamline.
Since SF5 is too weak to correct, we use 4 other sextupoles.

⇒ $\langle xy \rangle_{IP}, \ \langle xy' \rangle_{IP}, \eta_y^*, \eta_y'^*$ *are changed.*

Orthogonal to make $\langle xy' \rangle_{IP}, \eta_y^*, \eta_y'^*$ correction knobs .

Sextupole Strength Change



Strength of normal sextupole magnet is changed by ΔK_2

$$\frac{\Delta x_{IP}}{\sqrt{\beta_x^*}} = \underbrace{\left(-\beta_x^{3/2}\Delta K_2\right) u_x^2}_{T_{122}} + \underbrace{(-2\eta_x\beta_x\Delta K_2)\, u_x\delta}_{T_{126}} + \underbrace{\left(-\eta_x^2\beta_x^{1/2}\Delta K_2\right)\delta^2}_{T_{166}} + \underbrace{\left(\beta_x^{1/2}\beta_y\Delta K_2\right) u_y^2}_{T_{144}}$$

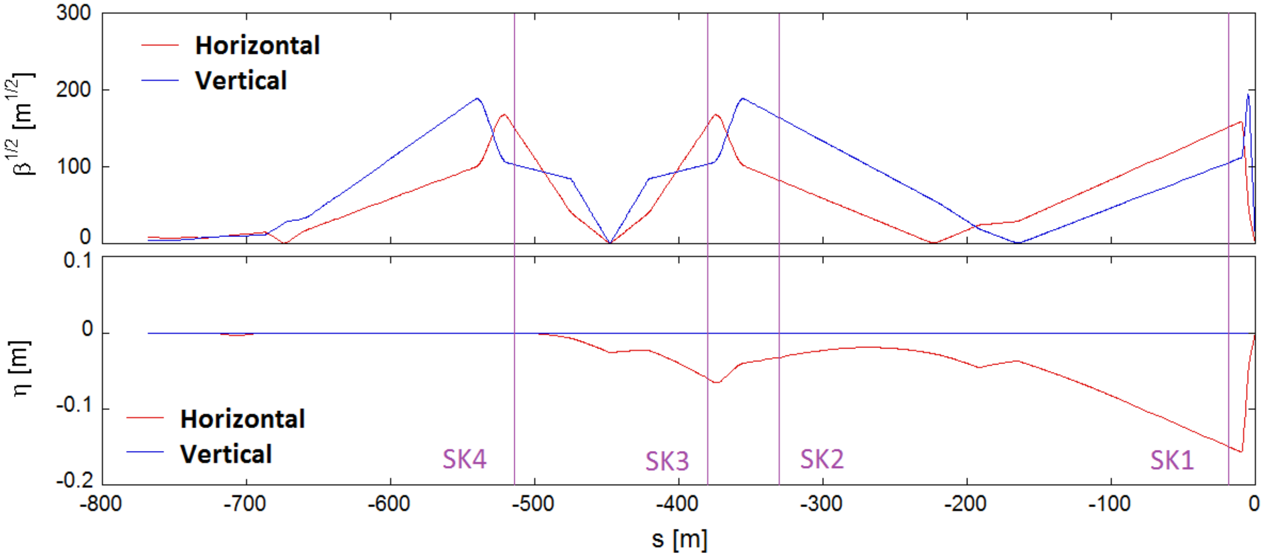
$$\frac{\Delta y_{IP}}{\sqrt{\beta_y^*}} = \underbrace{\left(2\beta_x^{1/2}\beta_y\Delta K_2\right) u_x u_y}_{T_{324}} + \underbrace{(+2\eta_x\beta_y\Delta K_2)\, u_y\delta}_{T_{346}}$$

Four 2^{nd} order optics components are changed for IP horizontal position.

Two 2^{nd} order optics components are changed for IP vertical position.

Skew Sextupoles for Optics Correction

In ILC Final Focus beamline, 4 skew sextupoles are arranged for optics correction.



Strength of skew sextupole magnet is changed by ΔK_2

$$\frac{\Delta x_{IP}}{\sqrt{\beta_x^*}} = \overbrace{\left(2\beta_x\beta_y^{1/2}\Delta K_2\right)}^{T_{124}} u_x u_y + \overbrace{\left(+2\eta_x\beta_x^{1/2}\beta_y^{1/2}\Delta K_2\right)}^{T_{146}} u_y\delta$$

$$\frac{\Delta y_{IP}}{\sqrt{\beta_y^*}} = \overbrace{\left(-\beta_x\beta_y^{1/2}\Delta K_2\right)}^{T_{322}} u_x^2 + \overbrace{\left(-2\eta_x\beta_x^{1/2}\beta_y^{1/2}\Delta K_2\right)}^{T_{326}} u_x\delta + \overbrace{\left(-\eta_x^2\beta_y^{1/2}\Delta K_2\right)}^{T_{366}} \delta^2 + \overbrace{\left(\beta_y^{3/2}\Delta K_2\right)}^{T_{344}} u_y^2$$

Two 2nd order optics components are changed for IP horizontal position.

Four 2nd order optics components are changed for IP vertical position.

2^{nd} order optics tuning knobs

	Horizontal beam size			Vertical beam size		
	Chromaticity	Geometrical Aberration	2^{nd} order Dispersion	Chromaticity	Geometrical Aberration	2^{nd} order Dispersion
Normal Sextupole	T_{126}	T_{122} T_{144}	T_{166}	T_{346}	T_{324}	
Skew Sextupole	T_{146}	T_{124}		T_{326}	T_{322} T_{344}	T_{366}

Ignored for small effect

Sextupole magnets are used for chromaticity correction.
But, the sextupoles generate other 2^{nd} order aberrations.

We use 5 sextupoles to correct 5 aberrations.

The aberrations are generated by the multipole errors of quad.

We use 4 skew sextupoles to correct 4 vertical aberrations.

T. Okugi et al., Physical Review Special Topics - Accelerators and Beams **17**(2014) 023501.

IP Beam size tuning Simulation

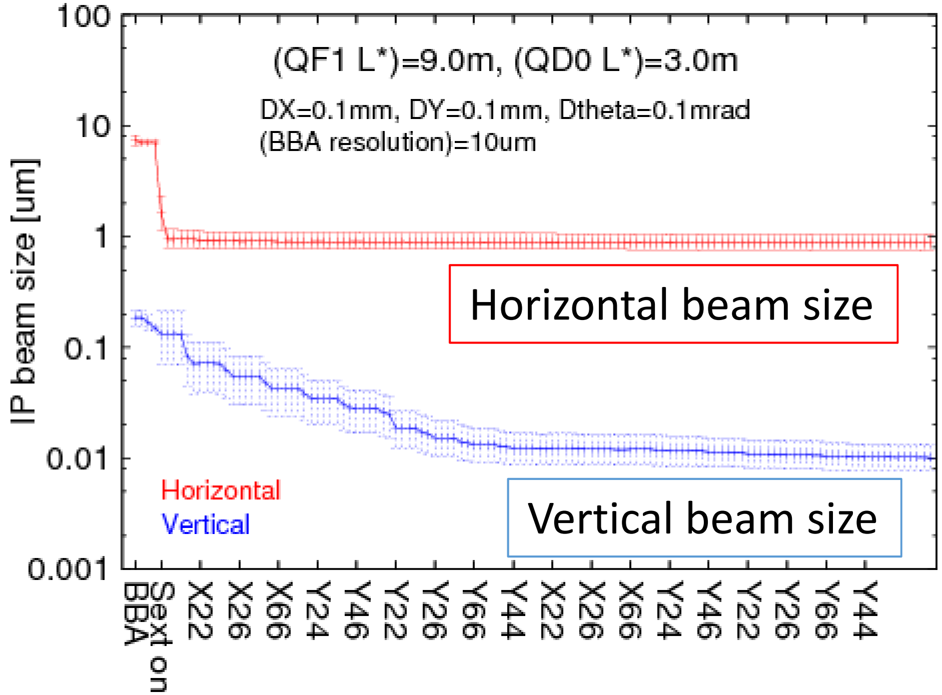
Procedures

1. *Put the errors in magnets in Final Focus beamline*
2. *Apply the orbit tuning*
3. *Tuned on the sextupole after sextupole BBA*
4. *Apply the linear and 2nd order optics tuning*

Example of the beam size minimization by the beam tuning simulation

Alignment errors

	Bend	Quad	Sext
ΔK	0.1%	0.1%	0.1%
ΔX	N. A.	0.1mm	0.1mm
ΔY	N. A.	0.1mm	0.1mm
Δθ	0.1mrad	0.1mrad	0.1mrad



Summary of Beam Size Tuning of ILC FF

In present ILC optics, the beam tuning will be done only by using sextupole magnets.

The linear optics correction will be done
by changing horizontal and vertical positions of sextupole magnets.

Horizontal position change;
- *horizontal and vertical beam waist adjustment.*
- *horizontal dispersion correction.*

Vertical position change;
- *vertical dispersion correction.*
- *coupling correction.*

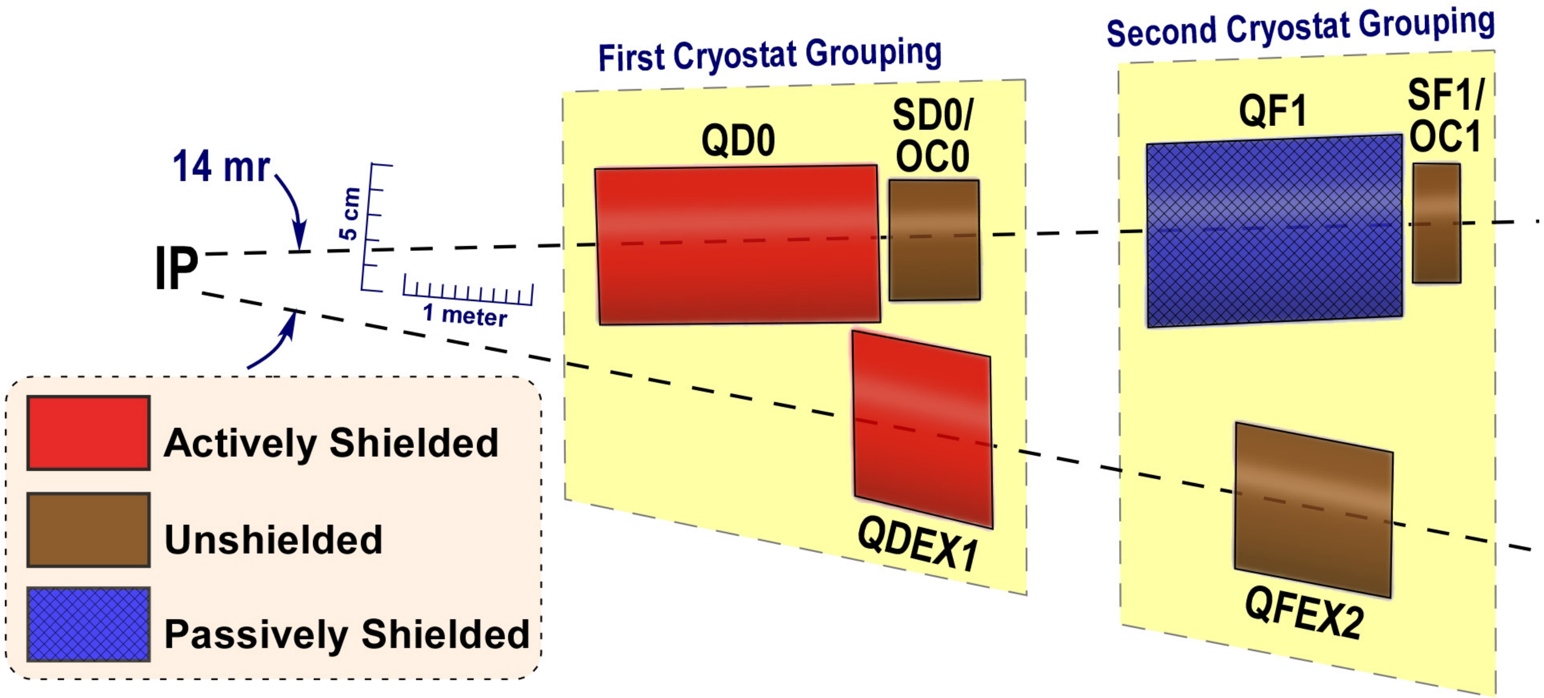
The 2nd order optics correction will be done
by changing the strengths of normal and skew sextupoles.

In order to tune the 2nd order aberration,
4 skew sextupole magnets will be installed in ILC final focus beamline.

Beam Collimation System for ILC

Cryomodule of Final Doublet and Extraction Quads

We will use the 2 set of cryomodules for ILC IP region.



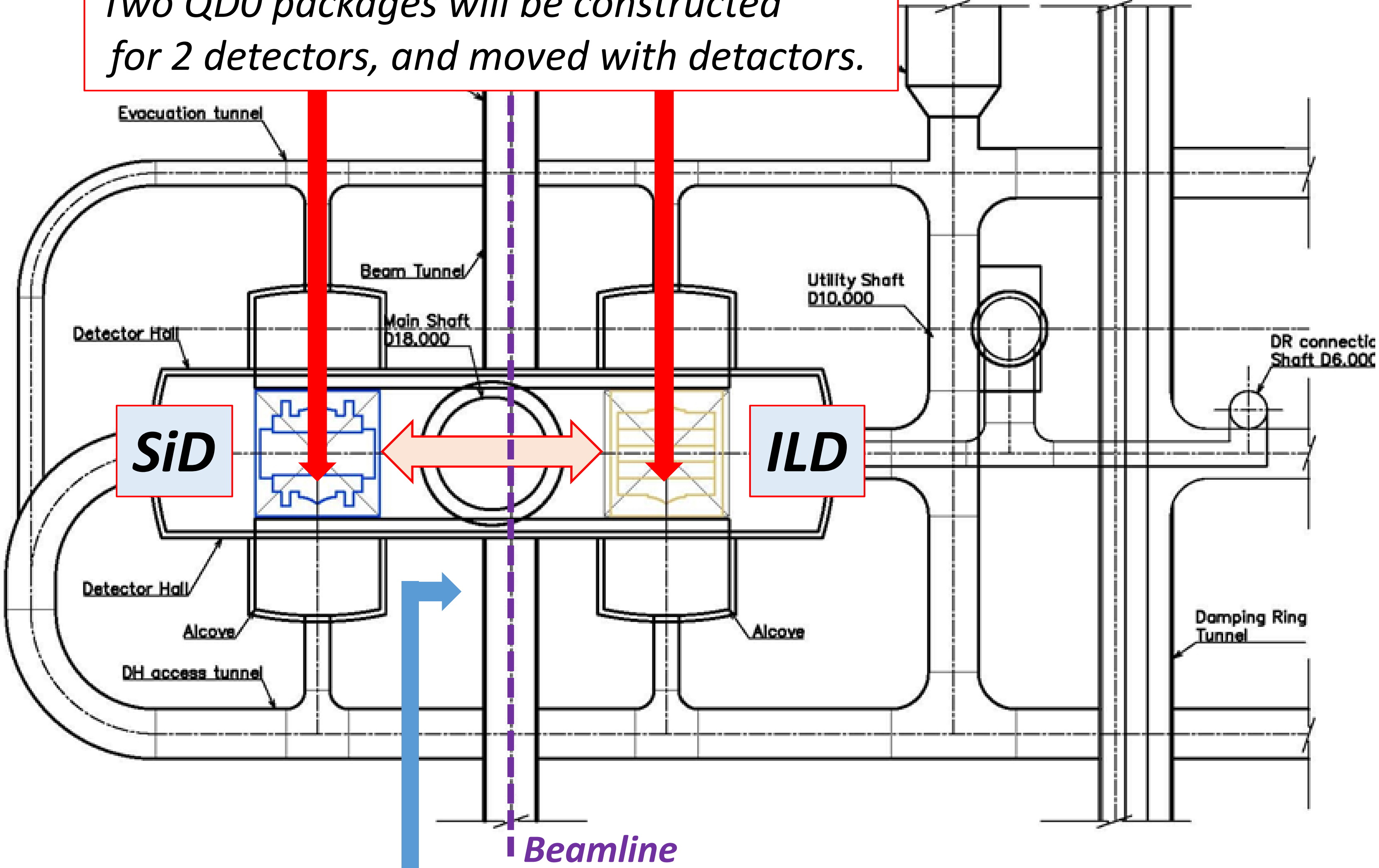
Supported with Detector

Supported to Accelerator Tunnel

Push-pull Detector System

For ILC design, 2 detectors can be exchanged within the detector hall.

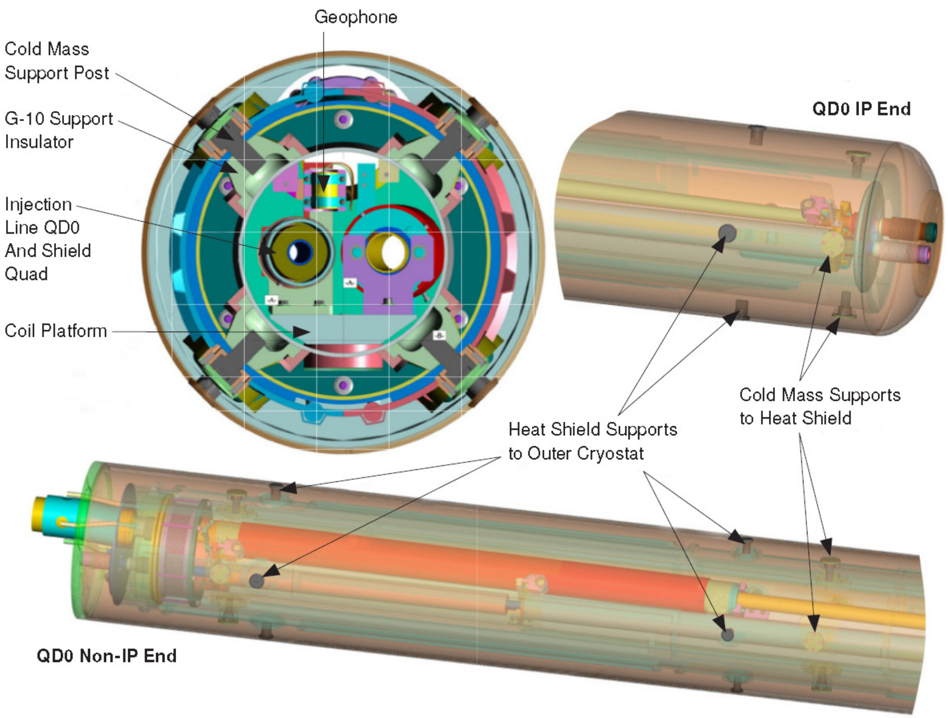
Two QD0 packages will be constructed for 2 detectors, and moved with detactors.

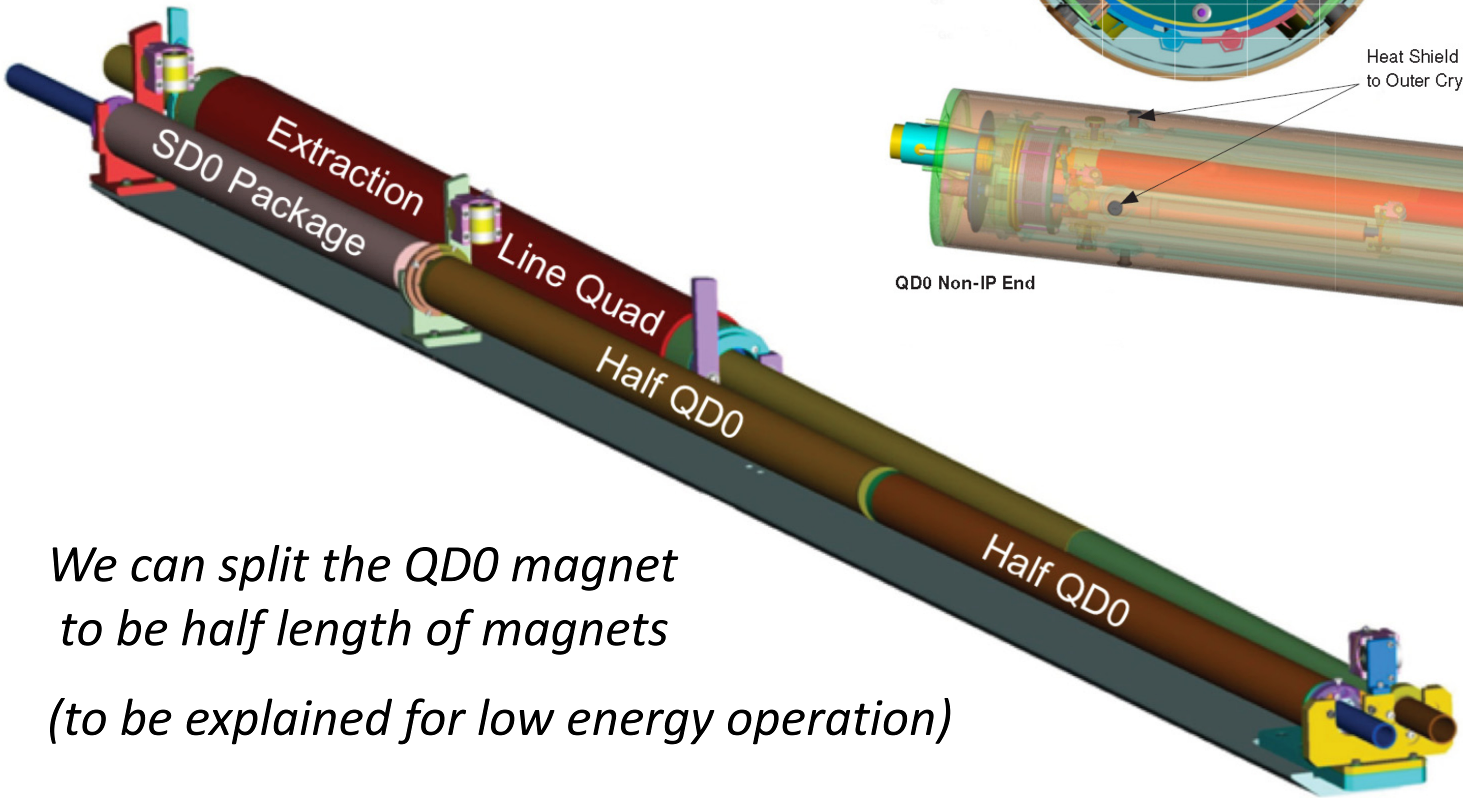


Common QF1 package will be supported to accelerator tunnel.

ILC QD0 Packages

Apertures of the final doublet are defined by the maximum field strength of supercondcting magnets.



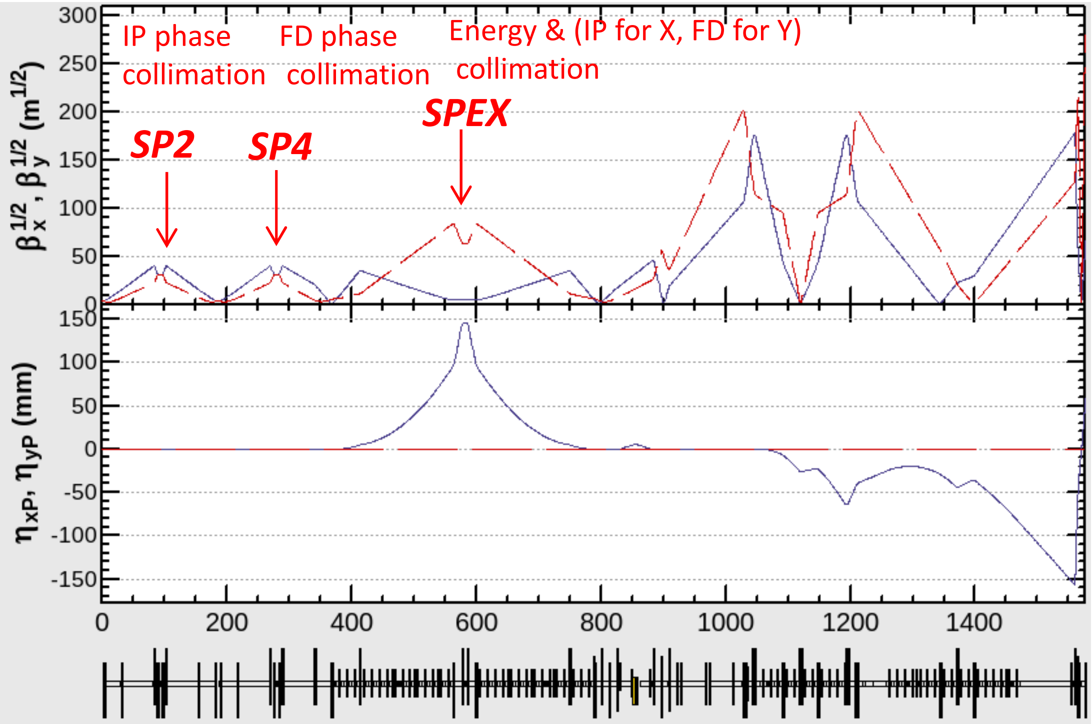


We can split the QD0 magnet to be half length of magnets

(to be explained for low energy operation)

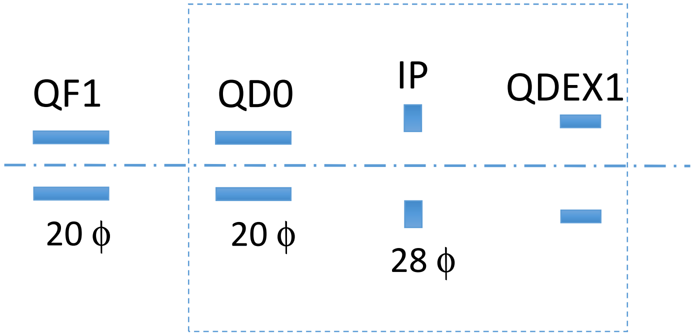
Configuration of the collimators and apertures

Beta Function at SP2/SP4 = (X; 1000m / Y; 1000m)
Beta Function at SPEX = (X; 36m / Y; 4000m)
Phase Advance (SP2 / IP) = (X; 7.0 pi / Y; 6.0 pi)
Phase Advance (SP4 / IP) = (X; 6.5 pi / Y; 4.5 pi)
Phase Advance (SPEX / IP) = (X; 5.0 pi / Y; 3.5 pi)
EtaX at SPEX = 0.145m



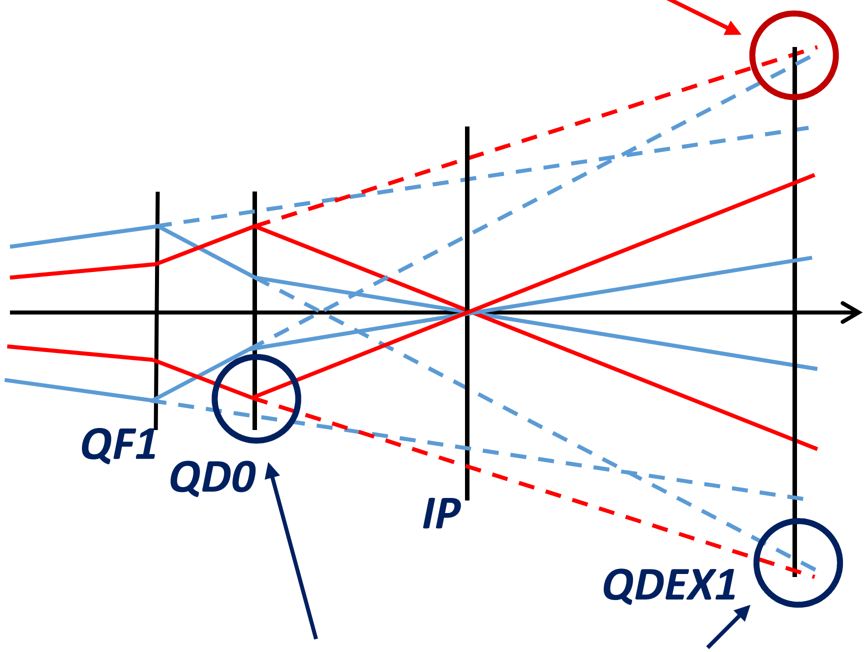
The aperture is limited by the synchrotron radiation around detector.

Detector apertures



SR photon distribution at downstream beamline

Vertical aperture was limited by SR at QDEX1

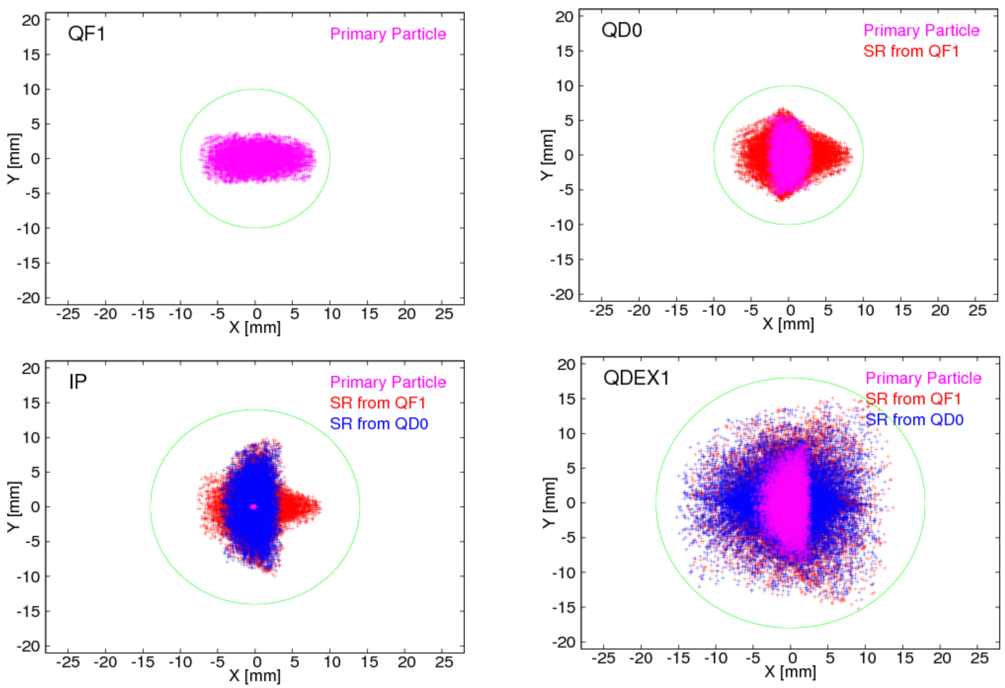


Horizontal aperture was limited by SR at QD0 / QDEX1.

Tolerable primary beam halo distribution

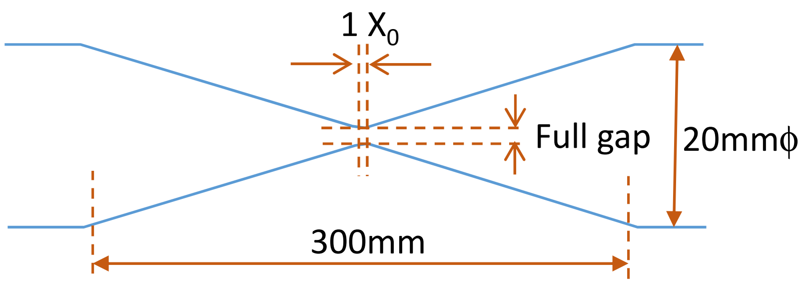
SR photon distribution from QF1

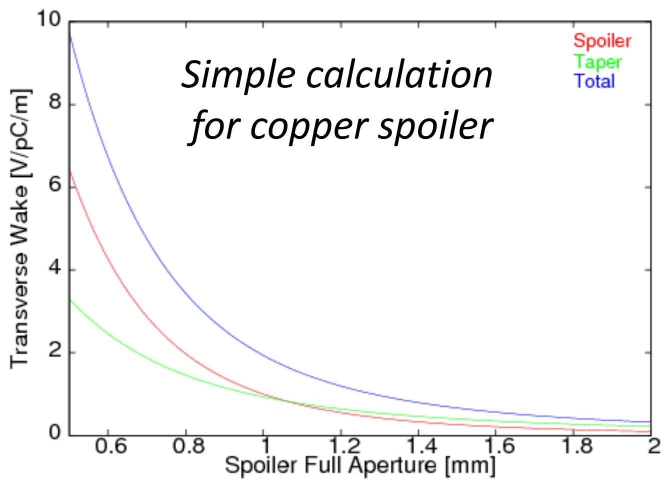
SR photon distribution from QD0



Consideration of the spoiler wake

Example of resistive wall

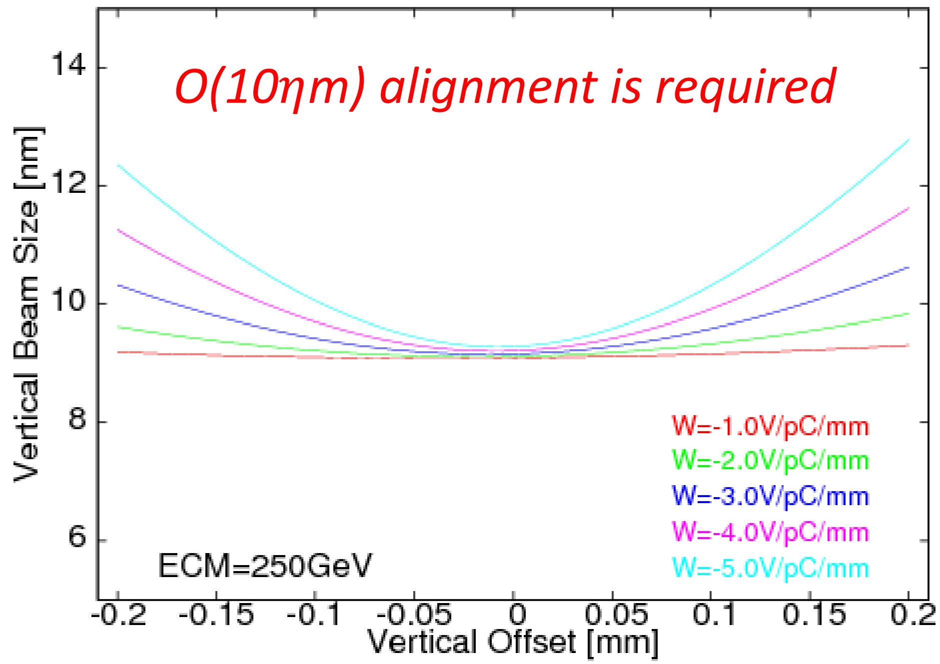




Material and geometry are different from ILC design.
see B. D. Fell et al., Proc. EPAC 08, 2883 (WEPP168).

Example for the effect of resistive wall

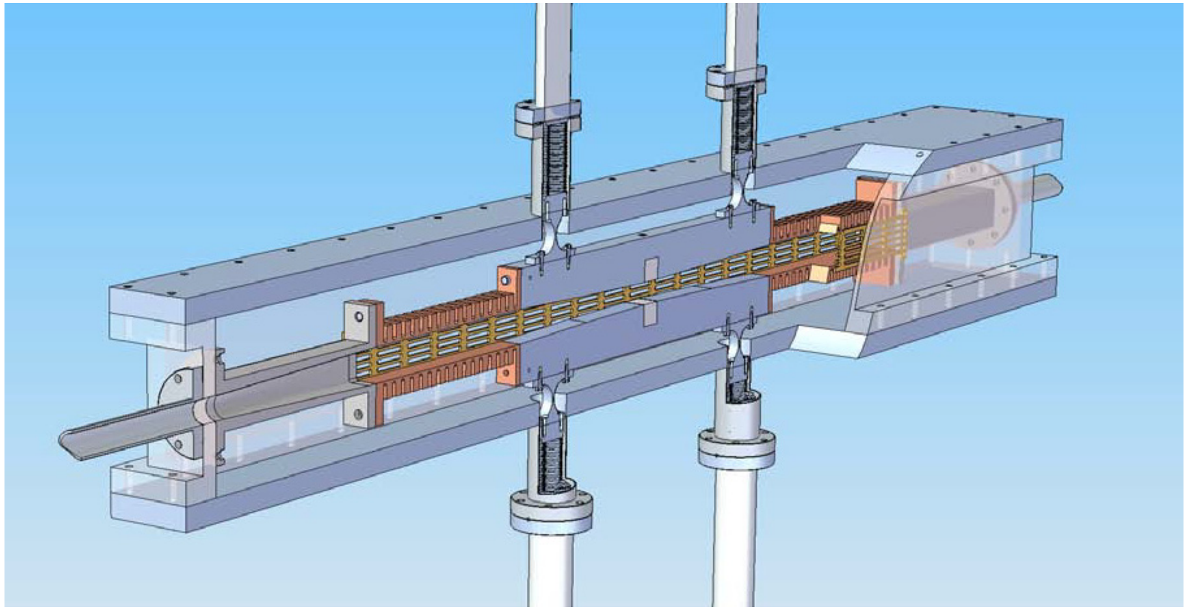
IP beam size simulation with wake for E_{CM}=250GeV
Wake source was put to SPEX

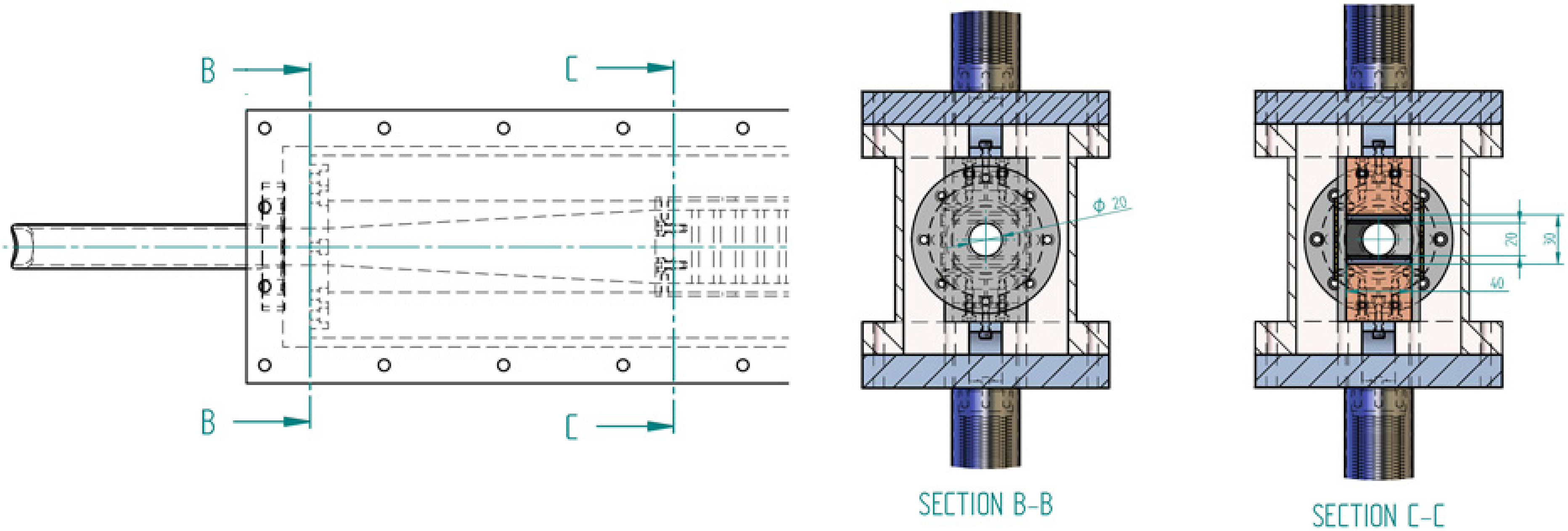


Smaller gap makes
the alignment tolerance tighter.

Collimation depth is important to reduce the wakefield.

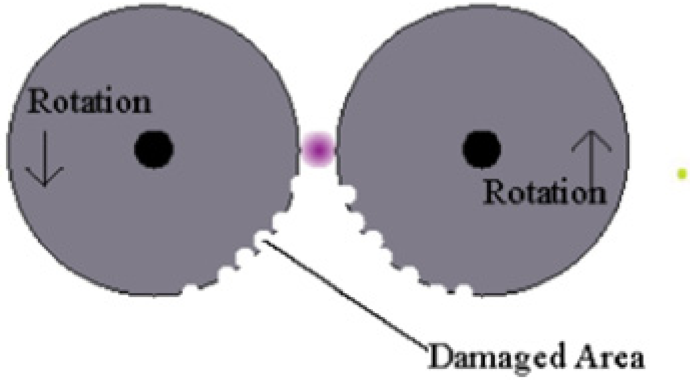
Gap adjustable Spoiler for ILC



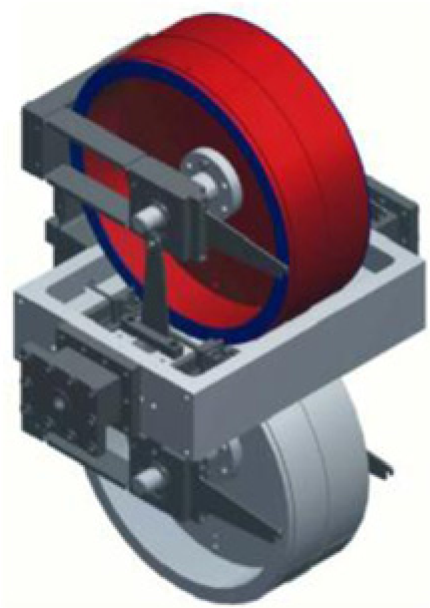


Rotation Wheel Spoiler

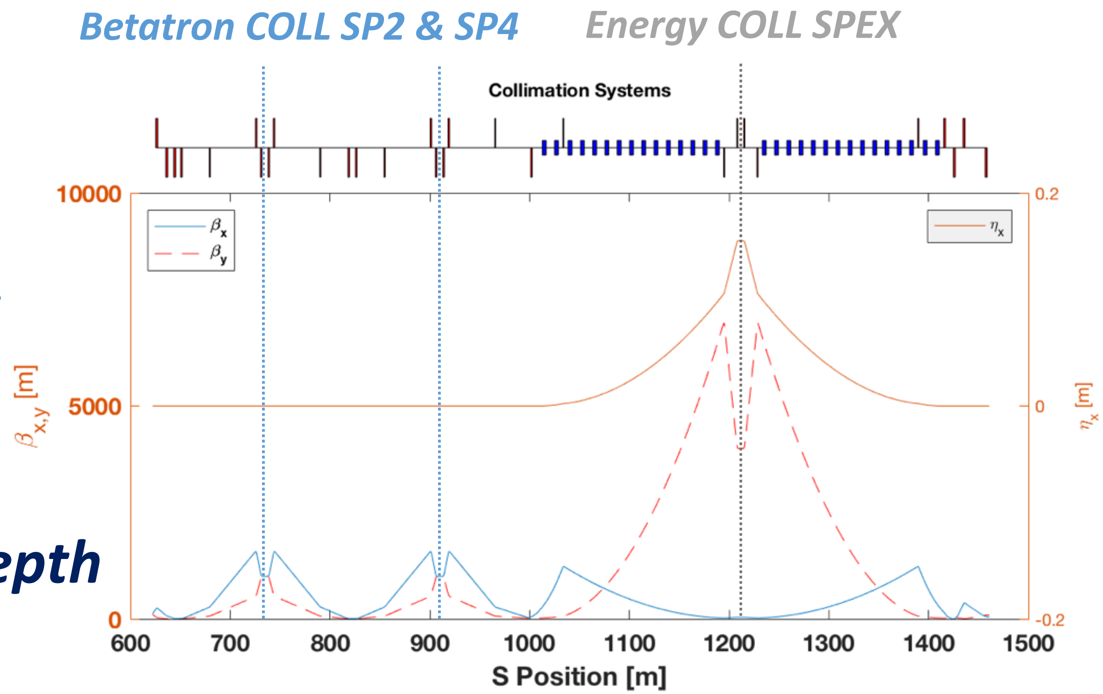
We can renew the collimator when the collimator will be damaged.



Since the beam energy is quite high for ILC, the collimator is broken only by a single beam hit.



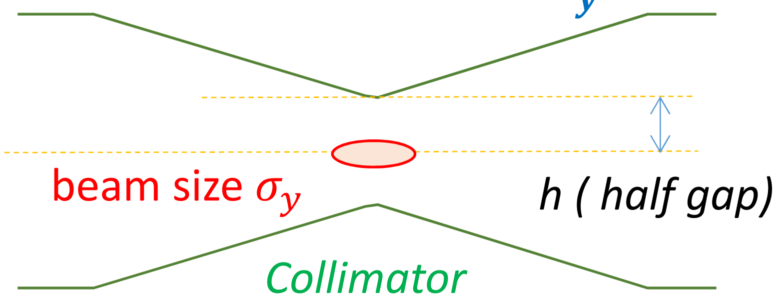
Collimation Depth



The collimation depth is very important parameter to design the final focus beam line.

Definition of Collimation Depth

Collimation Depth $\frac{h}{\sigma_y}$

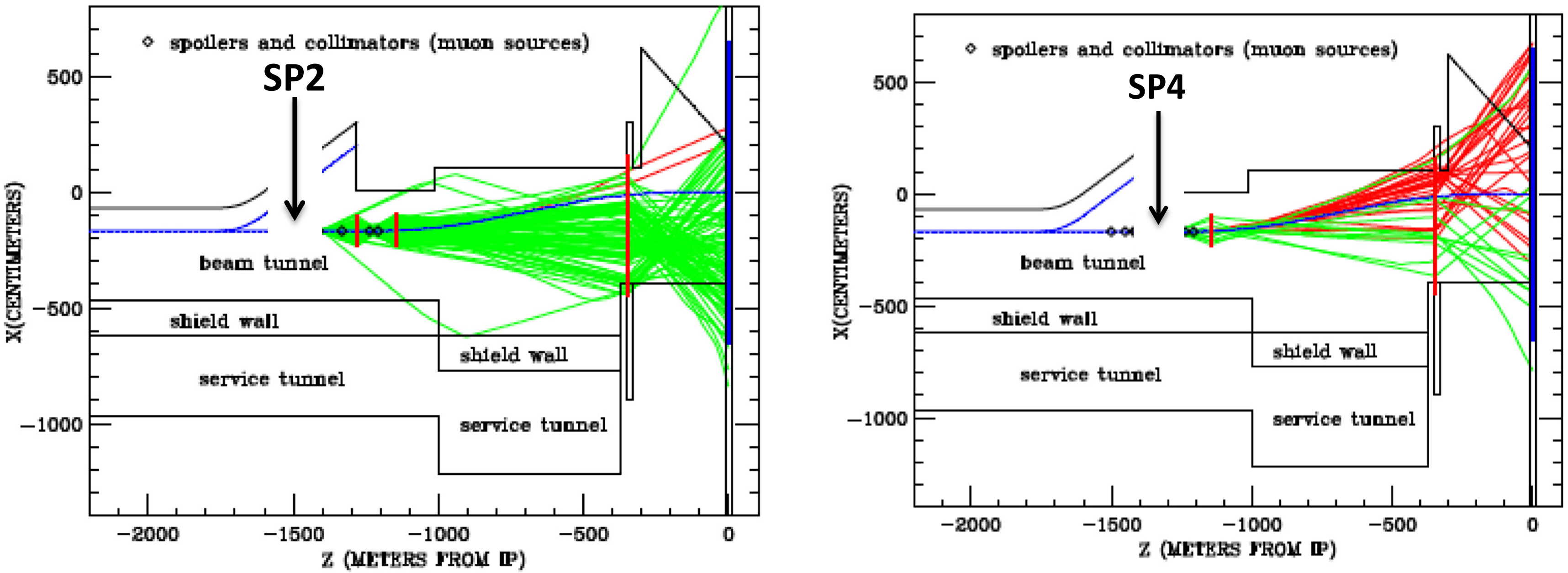


The collimation depth were defined to 70% of aperture limit for safety margin.

MUCARLO Tracking of Muon from Collimator

Since it is very hard to stop the muon,
we need to put large amount of materials to stop the muon.

Green = μ^+ Red = μ^-



When the collimation depth is small,
the collimator makes the beam loss large.

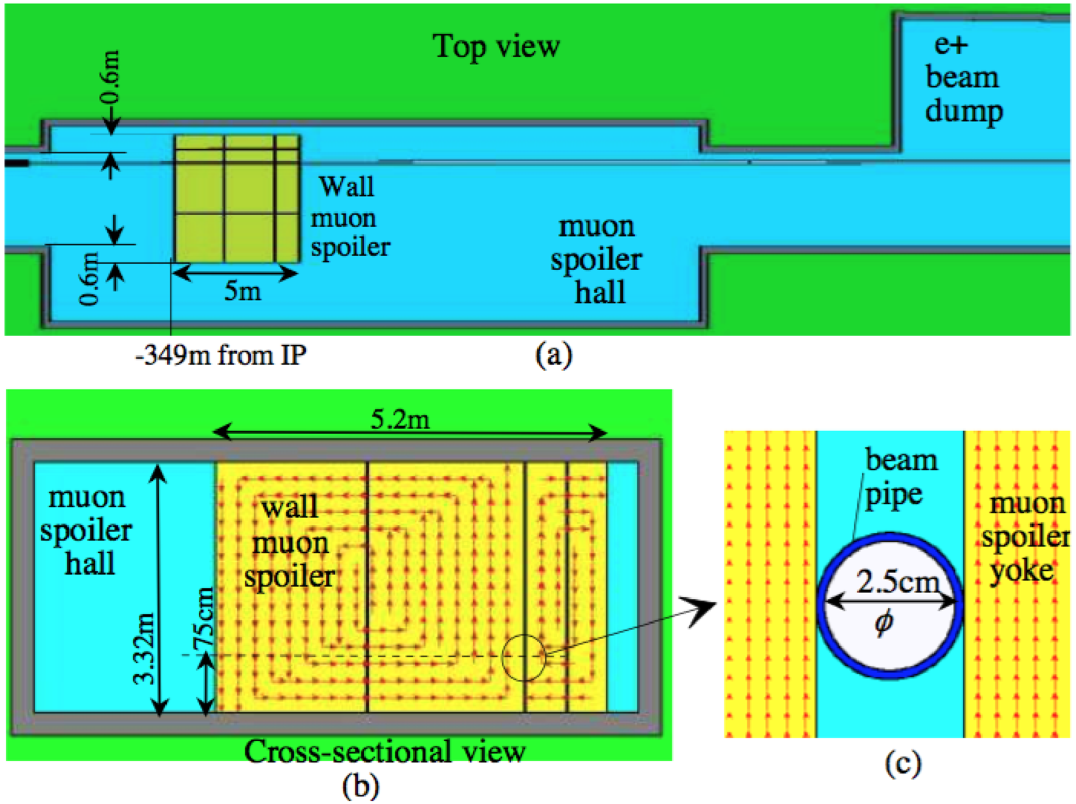
$\Rightarrow$ *generate large muon background*

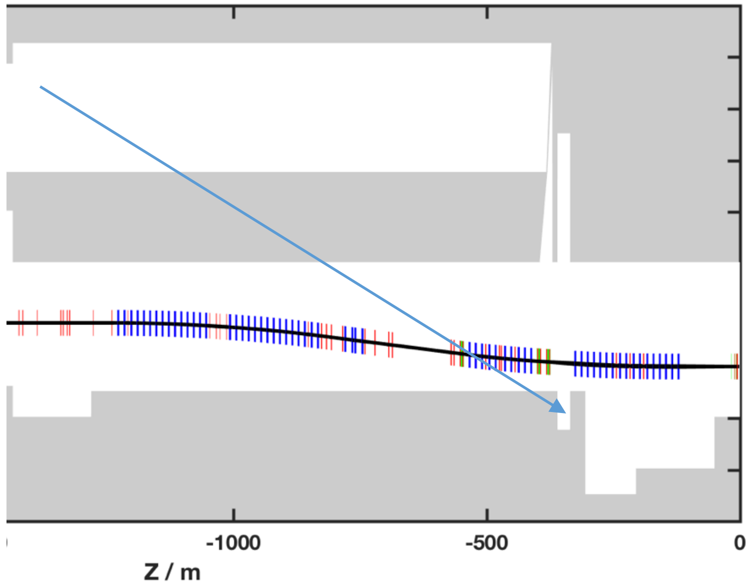
Collimation depth is important to reduce the muon background.

Muon Shielding - Wall

In order to reduce muon background to acceptable level to detector, we must put 5-18 m long muon shielding wall.

The thickness is depends on the amount of initial muon background.





SUPPRESSION OF MUON BACKGROUNDS GENERATED IN THE ILC BEAM DELIVERY SYSTEM *

A.I. Drozhdin, N.V. Mokhov, N. Nakao+, S.I. Striganov, Fermilab, Bavia, IL 60510, USA L. Keller, SLAC, Stanford, CA 94025, USA

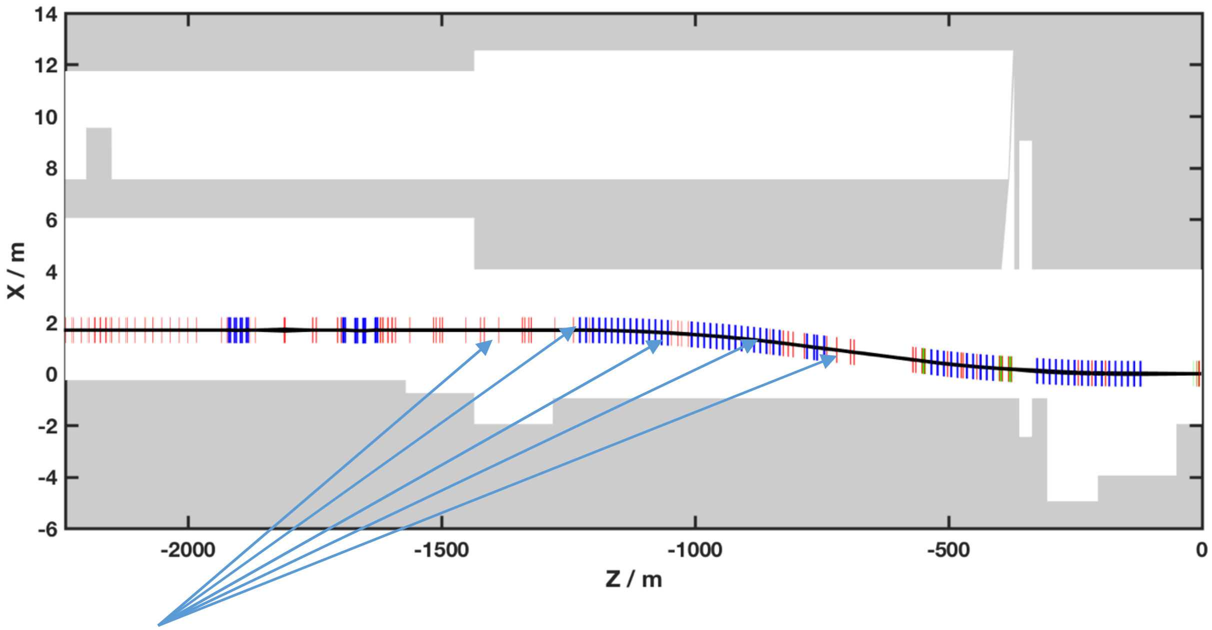
FERMILAB-CONF-07-276-AD

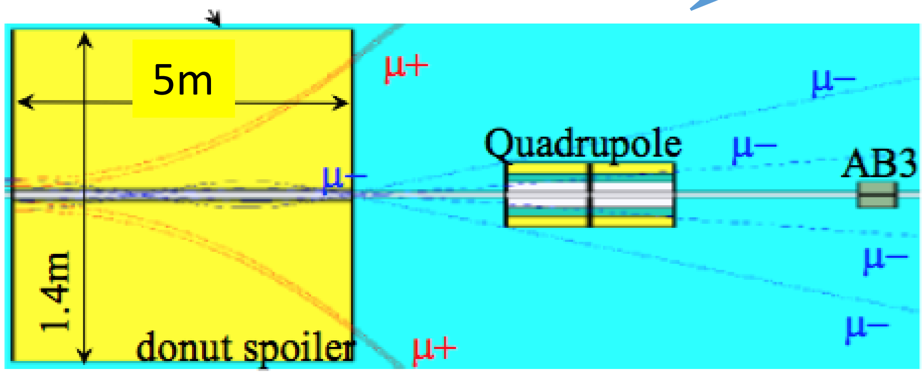
Muon Shielding – Toroid Spoilers

presented by G.White at ILC Central Region working group meeting at 2016/10/25

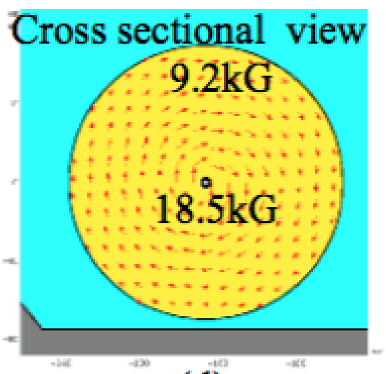
5 muon spoilers at z locations from IP:

- *804m*
- *977m*
- *1147m*
- *1235m*
- *1370m*





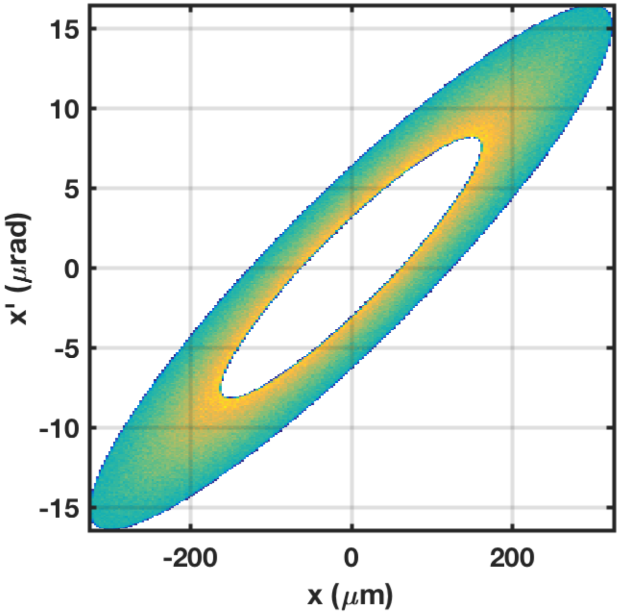
(c)



(d)

Muon background Tracking for Toroid Spoilers Case

Halo Distribution @ SP1



- *"1/r" distribution*
- *Normalized to **0.1%** of nominal beam power incident on collimation system*
- *Energy normally distributed with nominal 0.1% rms width.*

Number of muon at Detector

5m long doughnut spoilers at 1370, 1235, 1147, 977, 804

Muon Source	Fraction Hit	Number/bunch in 6.5 m radius at IP	
SP-2 1508	0.654	0.6	
PC-1 1452	0.24	0.3	
AB-3 1420	0.194	0.1	
PC2 1416	0.052	0.1	
PC3 1341	0.101	0.5	
SP4 1332	0.336	0.2	
PC5 1276	0.117	0.1	
AB5 1237	0.112	0.6	
PC6 1208	0.04	0.1	
PC7 1047	0.021	0.4	
ABE 852	0.01	0.5	
		3.5	Total

The number of muon will be larger for smaller collimation depth.

Summary of Beam Collimation System for ILC

The beam collimation system is important to reduce the detector background.

In order to protect the detector from the Synchrotron photons from FD, the betatron and energy collimators are arranged in ILC BDS beamline.
The apertures for the collimators are only a couple mm.

The collimation depth is important parameter to design the beamline.
The small collimation depth makes large beam loss at collimators, and it makes large muon background.

Since the muon is difficult to stop, we need a large apparatus for muon stopper.
The present candidate of muon stopper is donuts spoilers.

Optimization of
ILC Final Double Arrangement

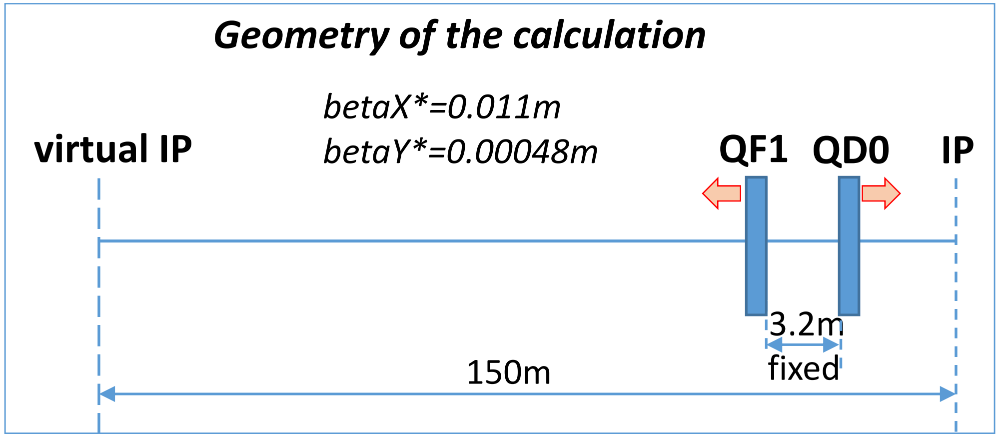
Actual design works of ILC final focus beamline

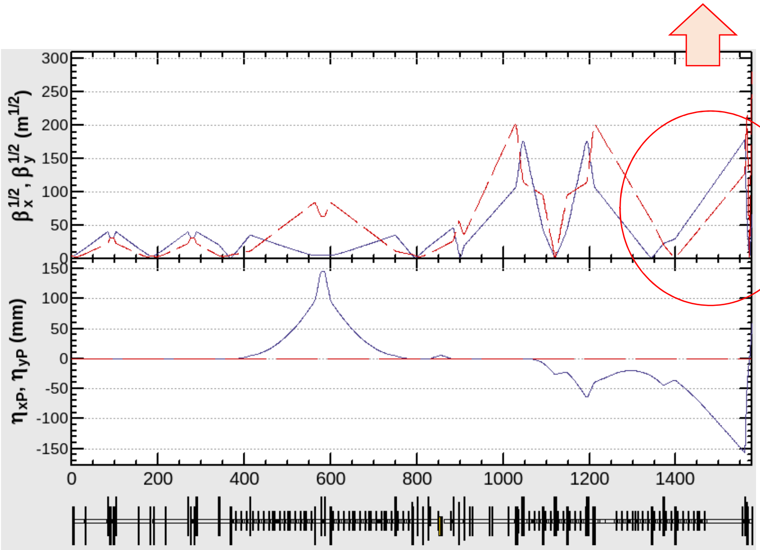
In actual ILC final focus beamline design,

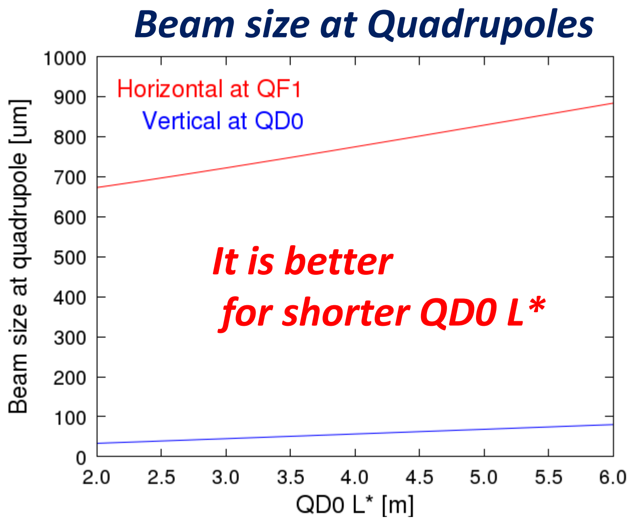
- the effect of the higher order aberration
- the collimation depth

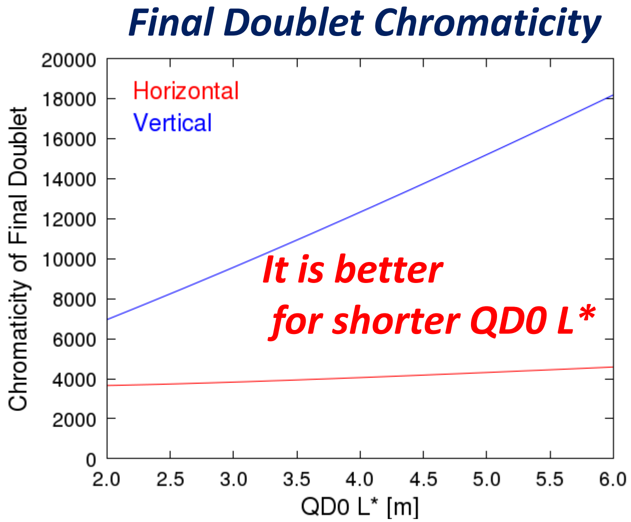
were optimized.

QD0 L* position dependence





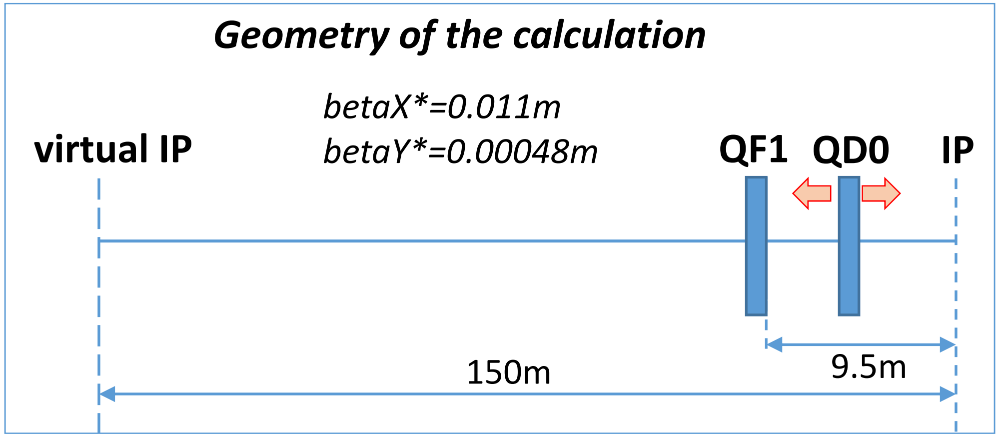


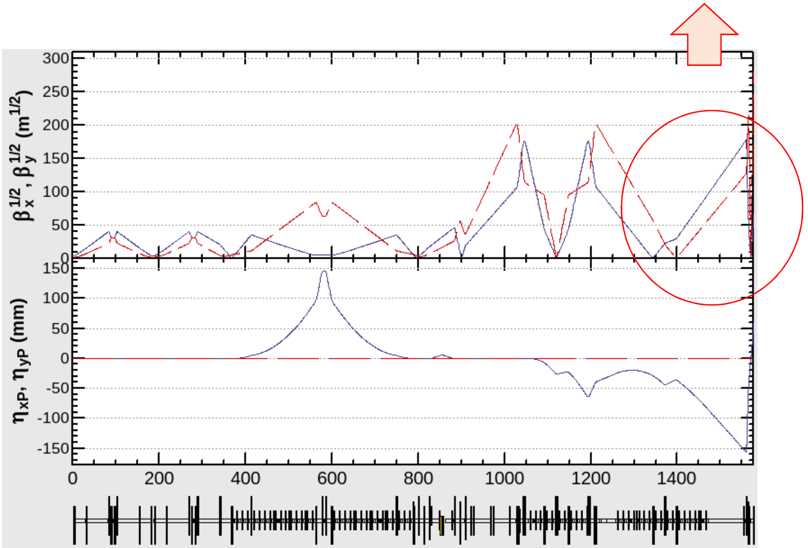


When QD0 is move to be closer to IP by keeping the distance between QD0 and QF1, the beta function at quadrupoles and the FD chromaticity is decreased.

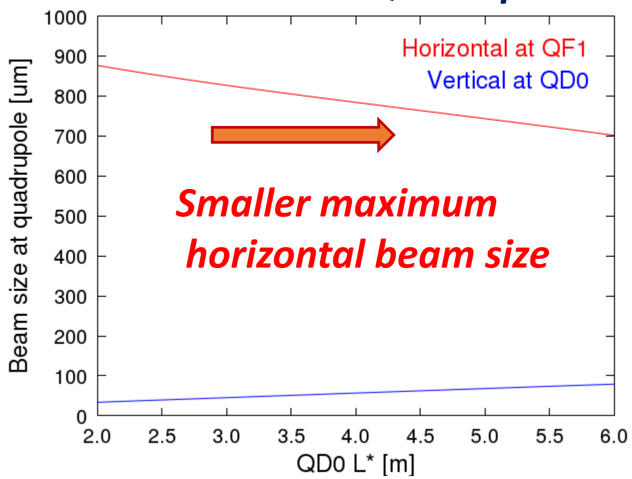
⇒ ***It is better for shorter QD0 L* in general*.**

QD0 L* dependence, when QF1 position is fixed

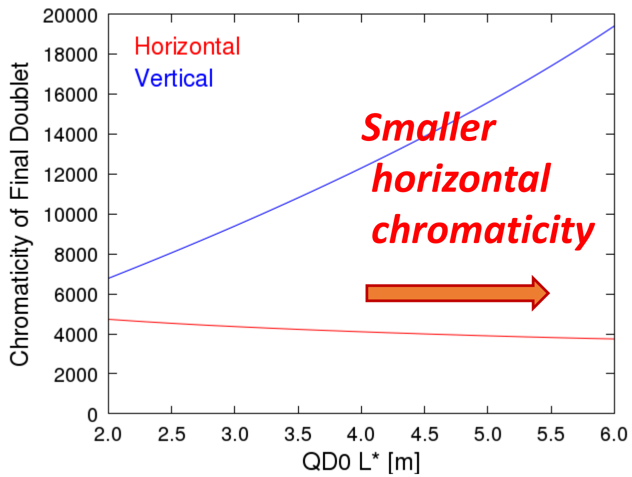




Beam size at Quadrupoles



Final Doublet Chromaticity



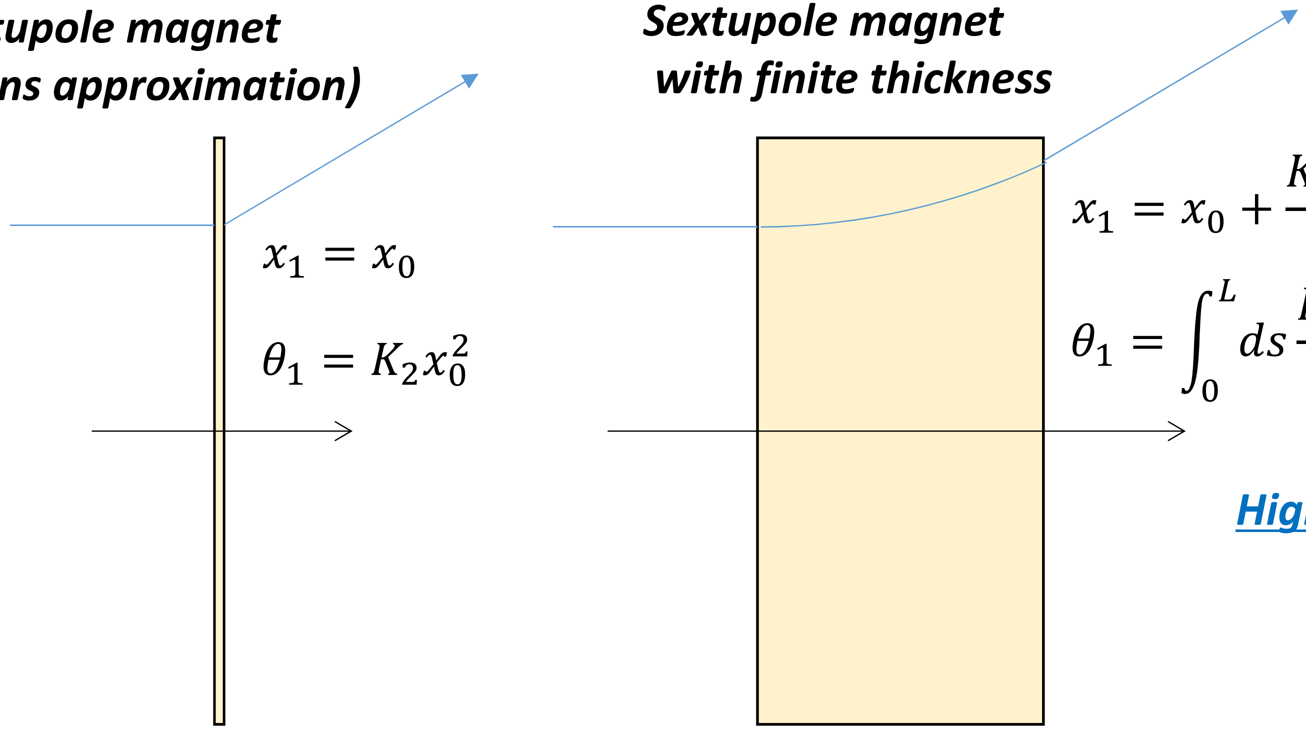
When QD0 is move to be closer to IP by keeping the QF1 L,*
the vertical direction is better for shorter QD0 L,*
the horizontal beta function at QF1 and horizontal chromaticity is increased.

Higher order multipole field

We calculated with tine lens approximation for sextupole magnets.
⇒ There are higher order aberrations in actual sextuple magnets.

Sextupole magnet (Thin lens approximation)

Sextupole magnet with finite thickness



$$x_1 = x_0$$

$$\theta_1 = K_2 x_0^2$$

$$x_1 = x_0 + \frac{K_2 L}{2} x_0^2$$

$$\theta_1 = \int_0^L ds \frac{K_2}{L}\left(x_0 + \frac{K_2 s^2}{2L^2} x_0^2\right)^2$$

<u>**Higher order aberration**</u>

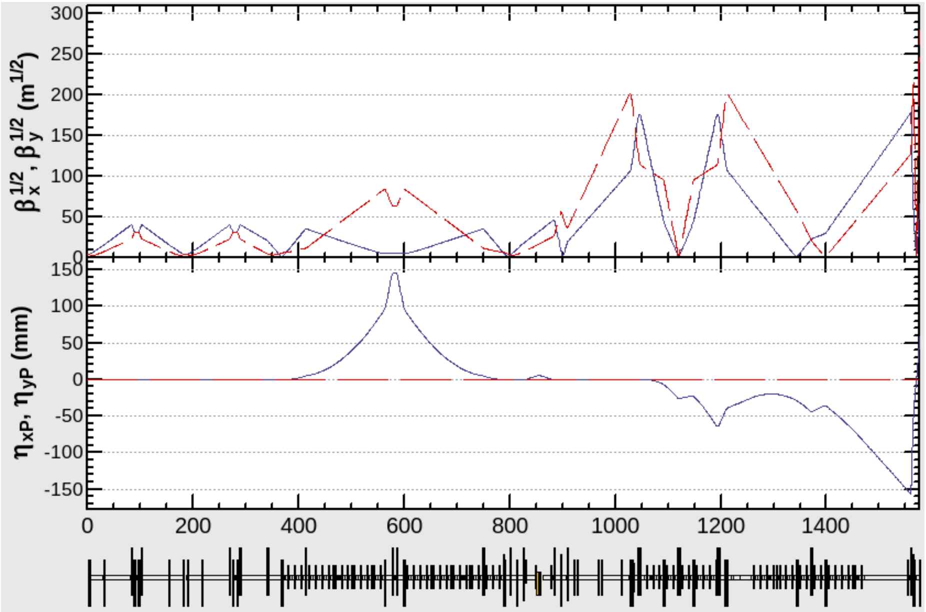
In order to avoid the higher order aberration,
it is better to reduce the beam size at sextupoles as small as possible.

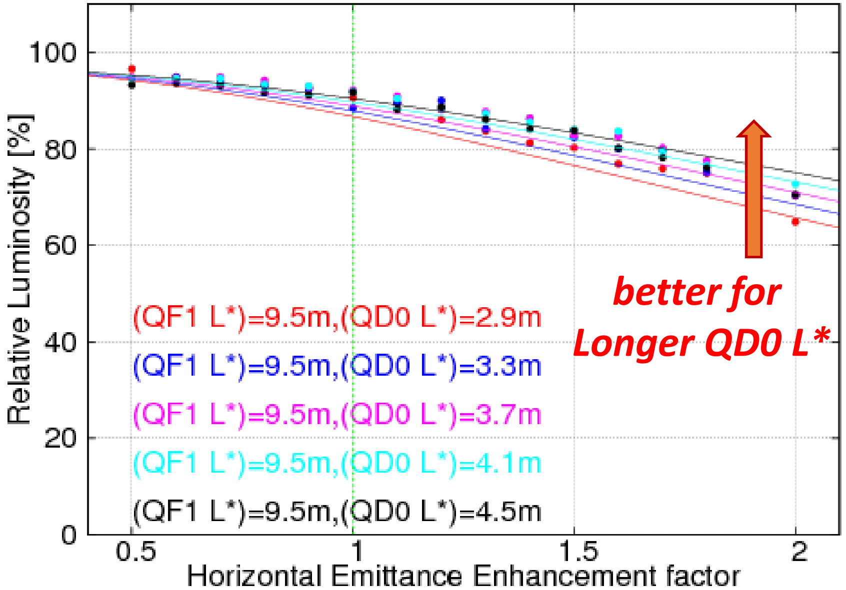
It is also better to reduce the beam size in FF beam line
to avoid the effects of multupole field error of magnets, especially for final doublet.

Horizontal emittance dependence of relative luminosity

ECM = 250GeV
beta (x/y) = 13mm / 0.41mm*
(QD0 L) = variable , (QD0 Length) = 2.2m*
(QF1 L) = 9.5m, (QF1 Length) = 1.0m (half length of TDR design)*

Tracking simulation with finite sextupole thickness



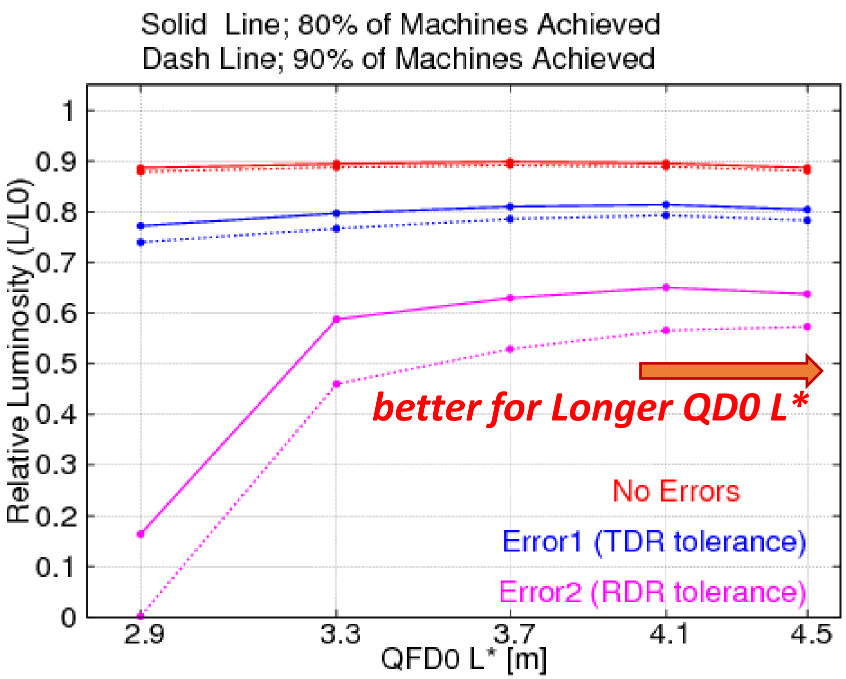


When the horizontal beam size at FF beamline is increased, the luminosity reduction is small for ***longer QD0 L*.***

Relative Luminosity by Beam Tuning Simulation

ECM = 250GeV
beta (x/y) = 13mm / 0.41mm*
(QD0 L) = variable , (QD0 Length) = 2.2m*
(QF1 L) = 9.5m, (QF1 Length) = 1.0m (half length of TDR design)*

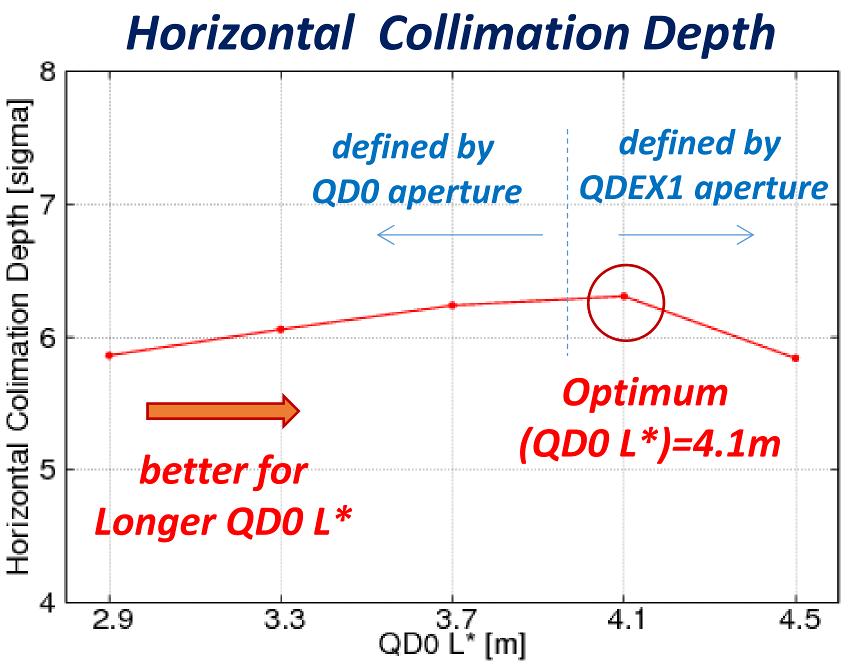
Parameters			Error 1	Error 2
Quadrupole	Initial Alignment	Position	> 200um	> 200um
		Roll	0.16mrad	0.20mrad
	Strength	K1	0.055%	0.087%
		K2 at R=1cm	0.078%	0.160%
	BBA		25um	48um
Sextupole	Initial Alignment	Position	> 200um	> 200um
		Roll	> 1mrad	> 1mrad
	Strength		0.60%	> 1%
	BBA		7.3um	12.5um
Bending Magnet	Initial Alignment	Position	> 200um	> 200um
		Roll	> 1mrad	> 1mrad
	Strength		> 1%	> 1%
	BPM Alignment		73um	103um

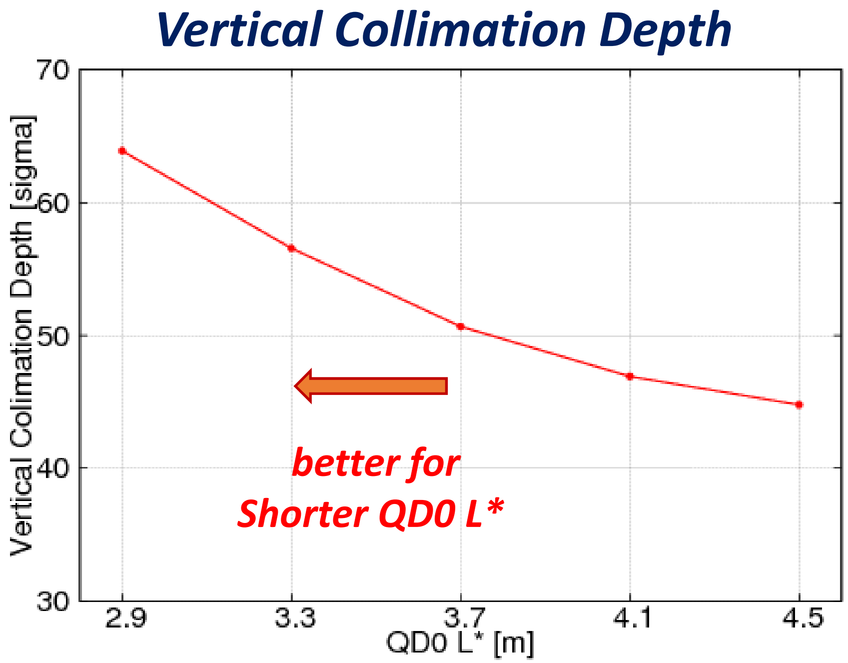


The IP beam tuning simulation also said the longer QD0 L is better.*

Effect of (QD0 L*) to collimation depth

ECM = 250GeV
beta (x/y) = 13mm / 0.41mm*
(QD0 L) = variable , (QD0 Length) = 2.2m*
(QF1 L) = 9.5m, (QF1 Length) = 1.0m (half length of TDR design)*





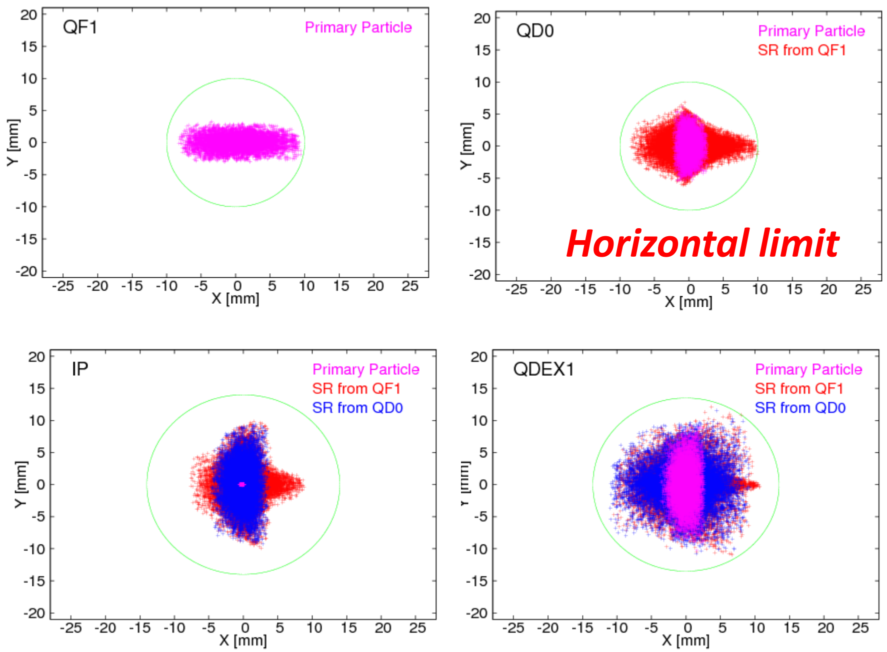
The maximum horizontal collimation depth is achieved at (QD0 L)= 4.1m.*
(The horizontal collimation depth defined by QD0 aperture is larger for longer QD0 L.)*

The vertical collimation depth is larger for shorter QD0 L.*

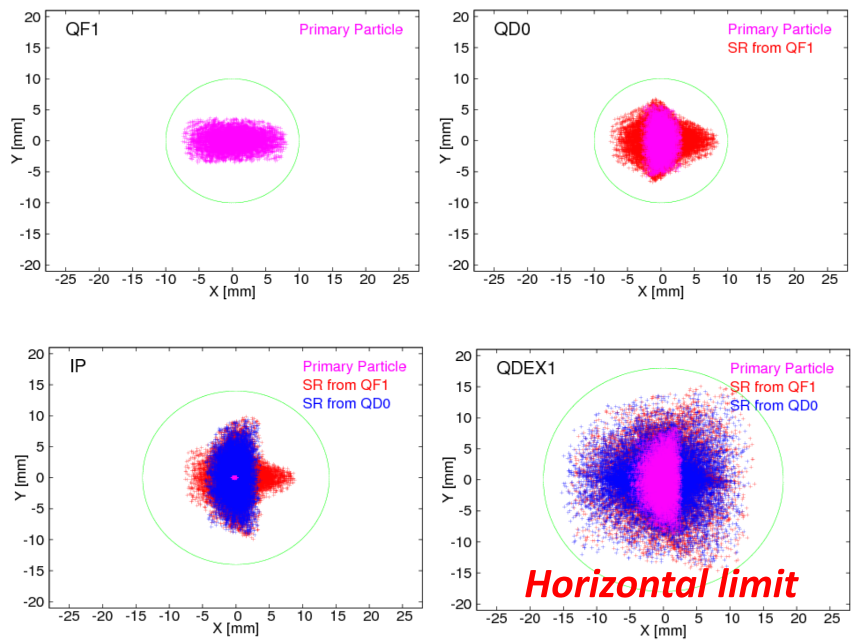
Consistent with expectation of beta function at FD.

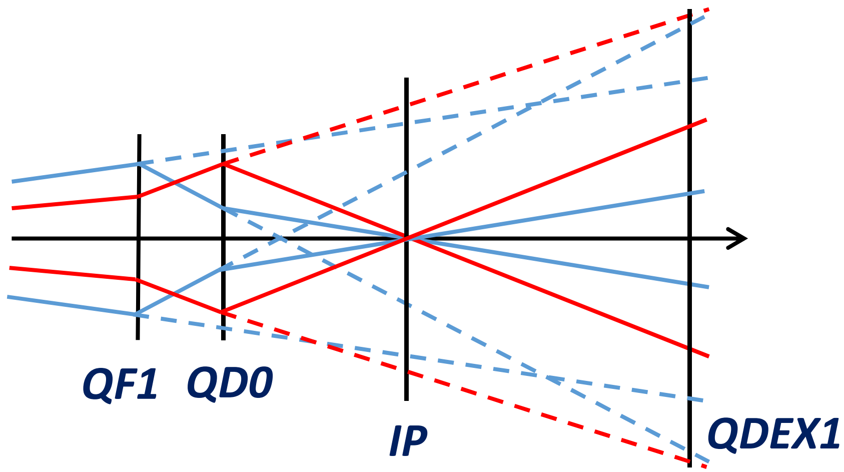
Synchrotron radiation around IP area

Shorter QD0 L*



Longer QD0 L*





The situation of QDEX1 limit will be changed by the parameters

- *the location of QDEX1.*
- *the aperture of QDEX1.*
- *the vertical aperture of collimator.*

It is better for shorter QD0 L in general.*

But, when QD0 is move to be closer to IP by keeping the QF1 L,*
the vertical direction is better for shorter QD0 L,*
the horizontal beta function at QF1
and horizontal chromaticity is increased.

Then, it is better for longer QD0 L for*
- the tolerances of magnets.
- the collimation depth.

It is very important to optimize not only QD0 L,*
but also the total arrangement of the final doublet.

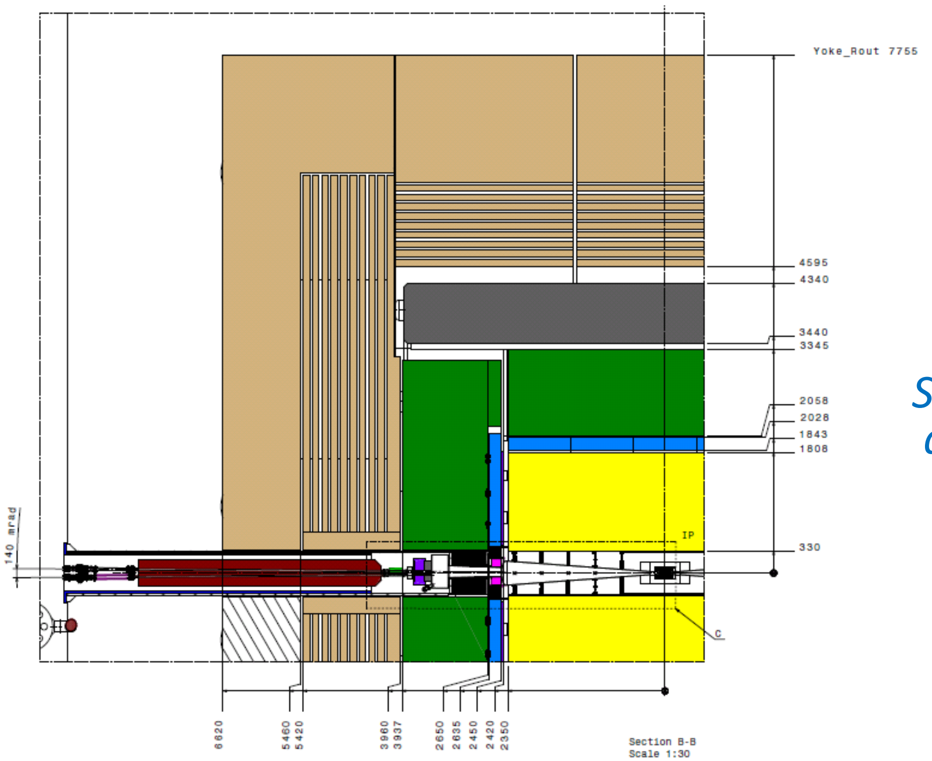
IP Geometry Requirement from Detector Group 1

The requirement of QD0 location was determined by the larger detector ILD.

ILD L* Issue

presented by Karsten Buesser at MDI/CFS meeting at 2014/09/05

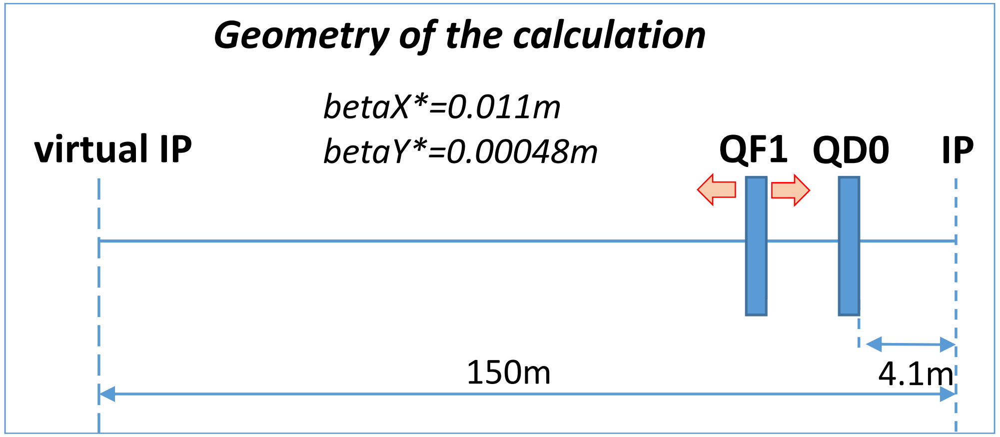
ILD Dimensions

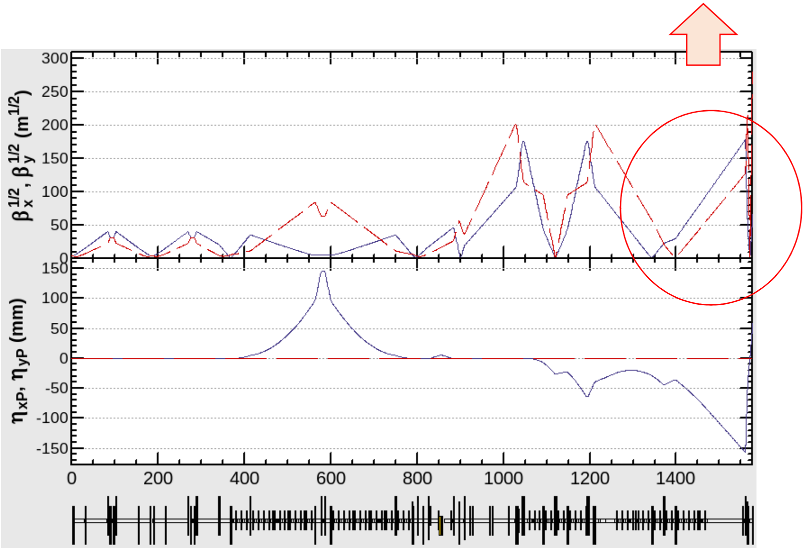


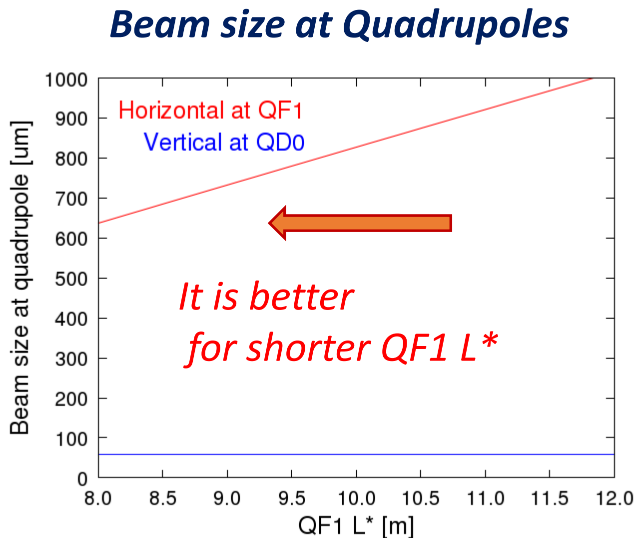
SiD can accommodate a QD0 L between 2.6-4.5m.*

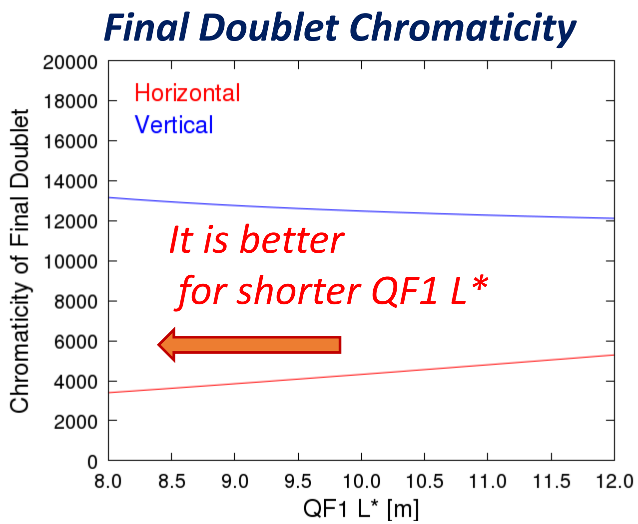
If the ion pump and valve will be removed, the QD0 L can be shorten to 4.4m -> 4.1m for ILD.*

QF1 L* dependence, when QD0 position is fixed









When QF1 is move to be closer to IP by keeping the QD0 L,*
the horizontal beta function at QF1 is decreased.

⇒Small aberration and large collimation depth are expected for shorter QF1 L.*

Effect of (QF1 L) to Luminosity*

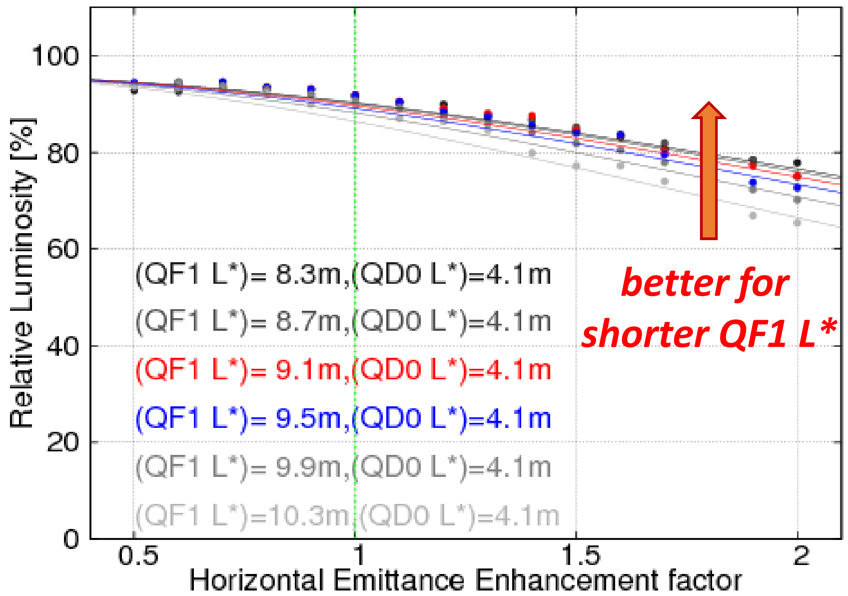
ECM = 250GeV

beta (x/y) = 13mm / 0.41mm*

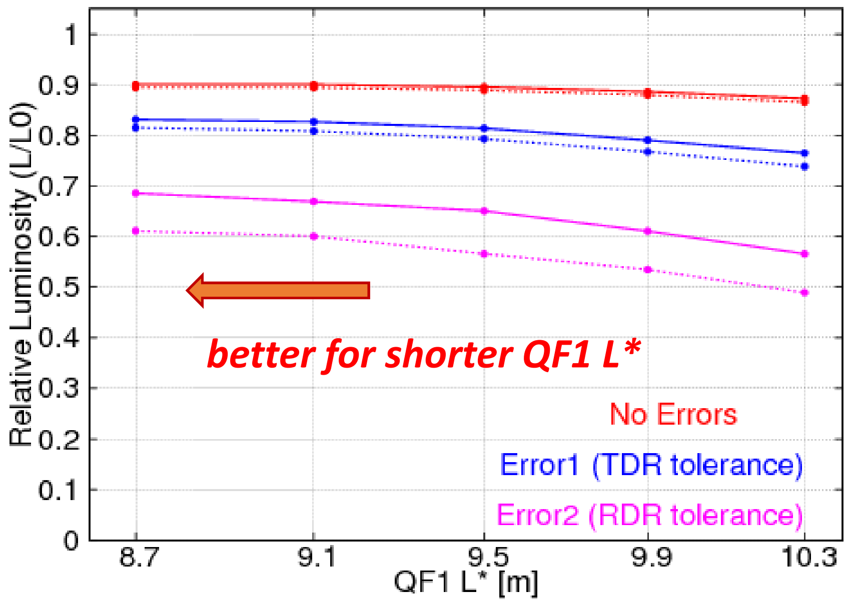
(QD0 L) = 4.1m , (QD0 Length) = 2.2m*

(QF1 L) = variable, (QF1 Length) = 1.0m (half length of TDR design)*

Horizontal emittance dependence of relative luminosity



Relative Luminosity by Beam Tuning Simulation



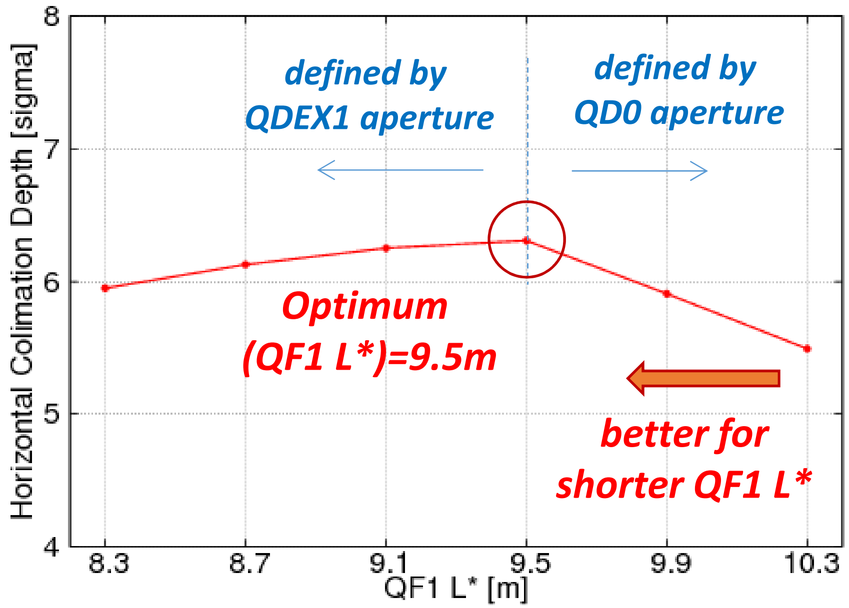
- When the horizontal beam size at FF beamline is increased, the luminosity reduction is small for shorter QF1 L.*

-The IP beam tuning simulation also said the shorter QF1 L is better.*

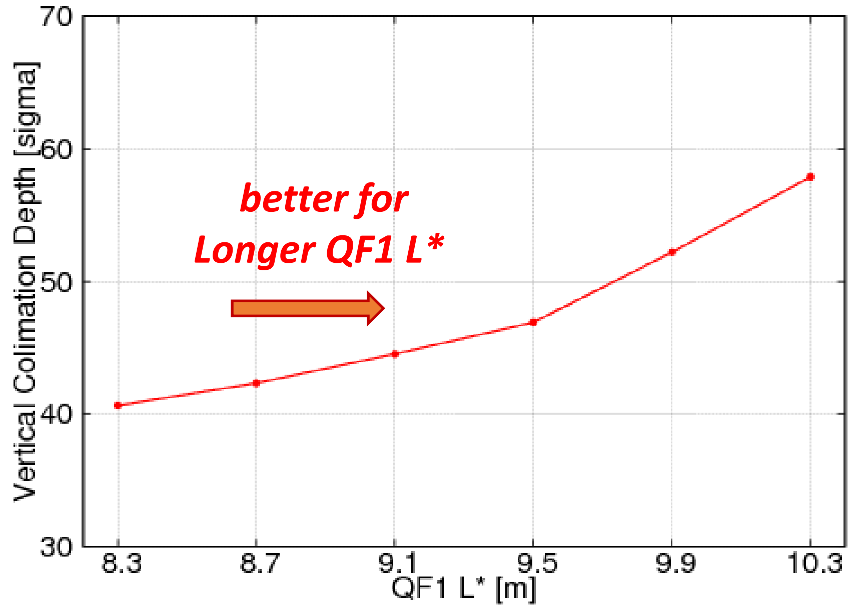
Effect of (QF1 L*) to collimation depth

ECM = 250GeV
beta* (x/y) = 13mm / 0.41mm
(QD0 L*) = 4.1m , (QD0 Length) = 2.2m
(QF1 L*) = variable, (QF1 Length) = 1.0m (half length of TDR design)

Horizontal Collimation Depth



Vertical Collimation Depth



The maximum horizontal collimation depth is achieved at (QF1 L*)= 9.5m.
(The horizontal collimation depth defined by QD0 aperture is larger for shorter QF1 L*.)

The vertical collimation depth is larger for longer QF1 L*.

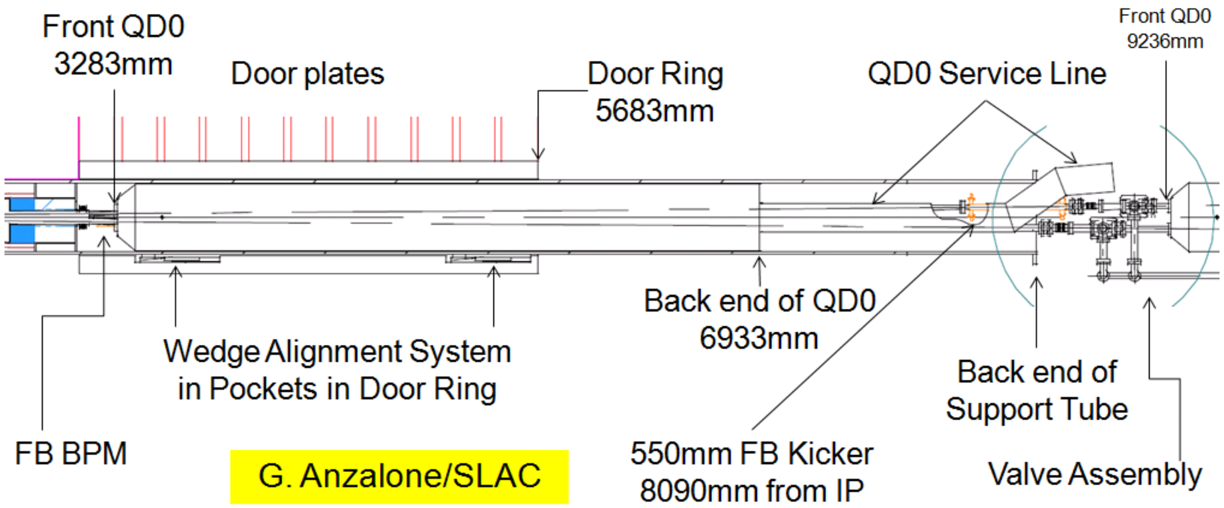
Consistent with expectation of beta function at FD.

IP Geometry Requirement from Detector Group 2

It is better to be shorter distance between QF1 and QD0.

presented by Tom Markiewicz
at MDI/CFS meeting at 2014/09/05

SiD L*



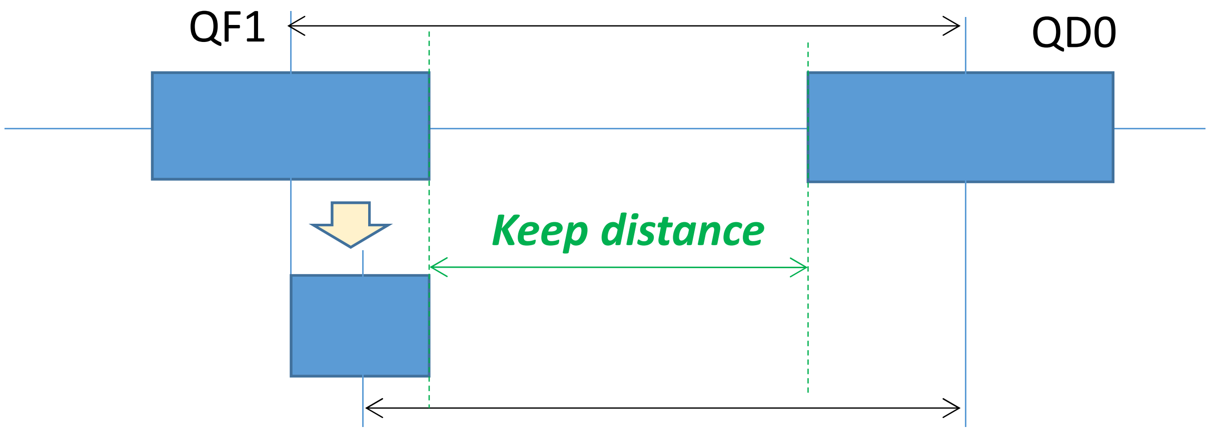
We must put the following components in between SD0 and QF1 .

- *Ion pump*
- *Vacuum port*
- *FB kicker etc.*

The distance between QF1 and QD0 can not shorten so much in the push-pull detector scheme.

Field strength of FD magnets

QF1 magnet length was shorten (2m -> 1m)
to make the distance of QF1 and QD0 shorter effectively.



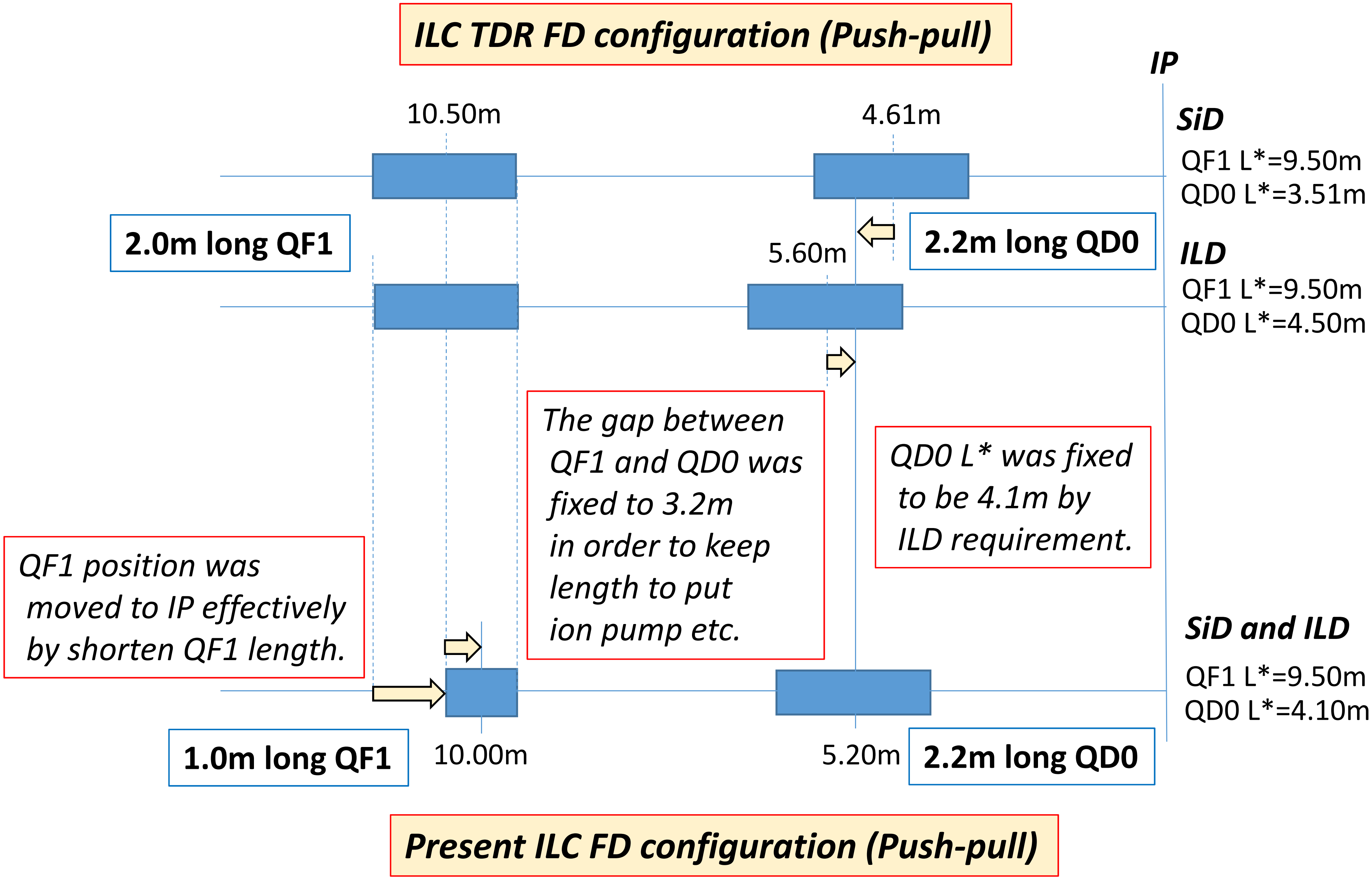
Magnet Strength of ILC Final Doublet

MAGNET	L* [m]	Length [m]	B (1) or 2B(2)	B at coil [T] (*)
QD0	4.10	2.20	124.66	1.745
SD0	6.45	0.60	4310.5	0.4224
QF1	9.10	1.00	144.40	2.022
SF1	10.25	0.30	4395.5	0.4308

(*) Evaluated with simple scaling with R=0.014m,
actual field will be larger than this simple scaling

Acceptable

Present ILC Final Doublet Configuration



Summary of optimization of ILC FF Beamline

In order to increase the collimation depth and magnet tolerances, we should optimize the arrangement of Final Doublet (QF1 and QD0).

In order to get larger collimation depth and larger magnet tolerances, it is better to be (QF1 L) shorter.*
⇒ We have constraints of QD0-QF1 distance for push-pull scheme.

The QF1 magnet length was shorten to make QD0-QF1 distance shorter.

When we keep the distance between QD0 and QF1, it is better to be (QD0 L) shorter.*
⇒ We have constraints of (QD0 L) to put large detector (ILD).*

Present ILC final doublet arrangement was determined by taking account of above issues.