# Introduction of the BDS magnets for ILC

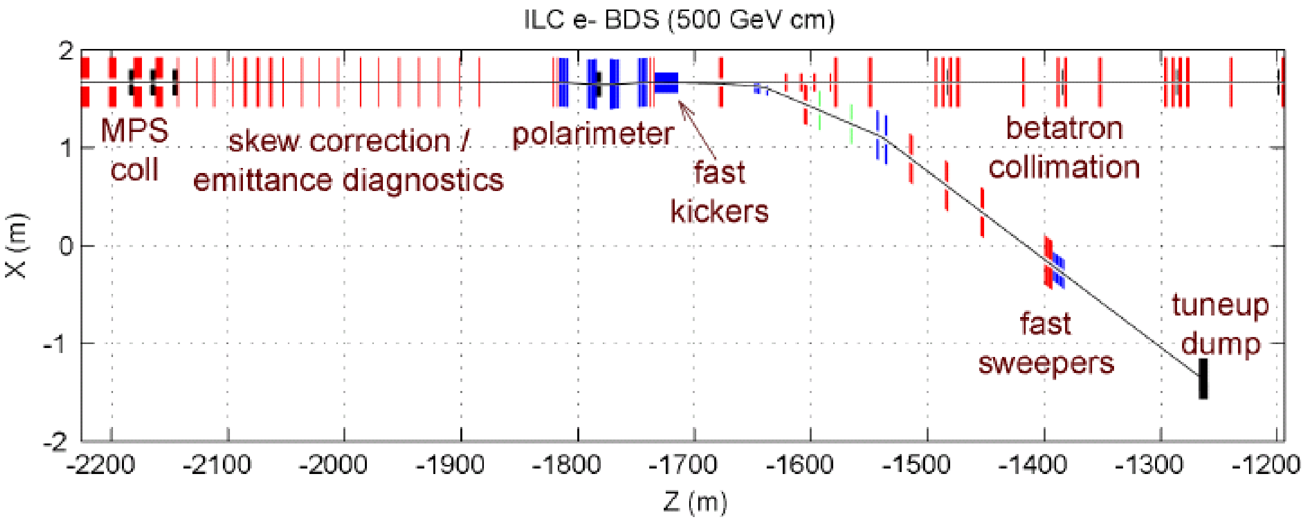
2021/09/17
Toshiyuki OKUGI, KEK
IDT WG3 MDI meeting

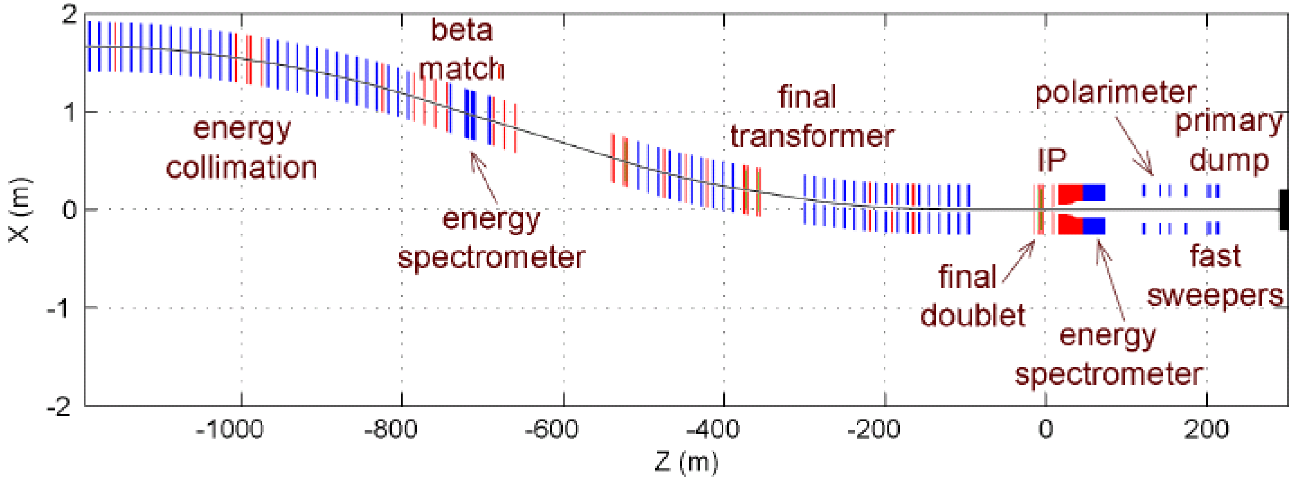
# Overview of BDS (Beam Delivery System)

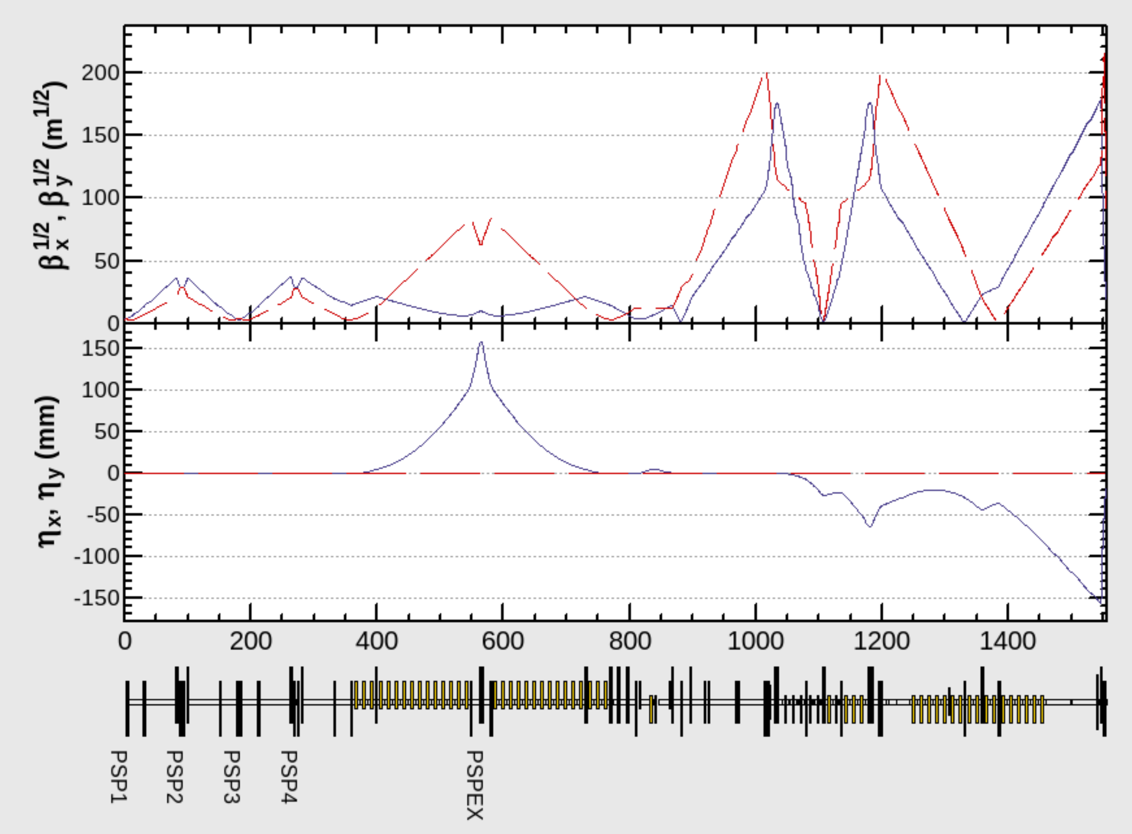
*BDS is the beamline after main linac.*

*BDS consists of*

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





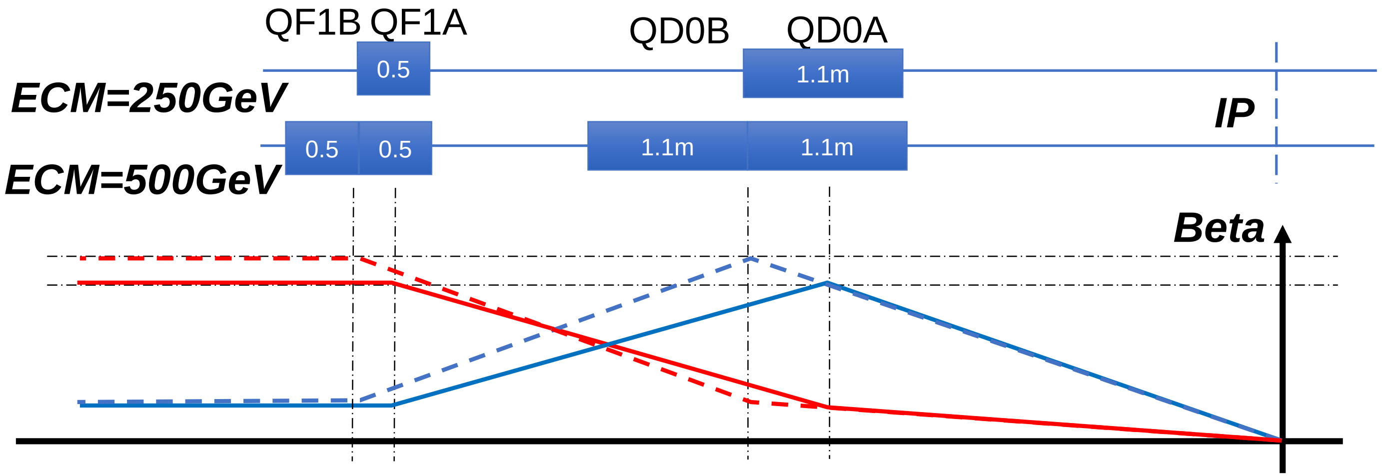


# Application to low energy ($E_{CM}$=250GeV)

The field strength for ECM=250GeV is a half to ECM=500GeV.

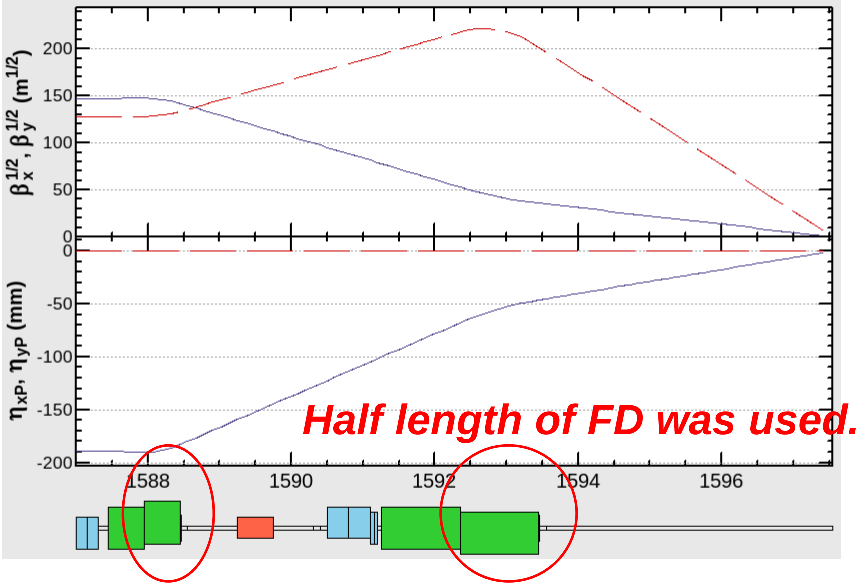
When we only use a half of FD magnets,
the beta functions at FD magnets are decreased.

Therefore, the collimation depth can be increased.



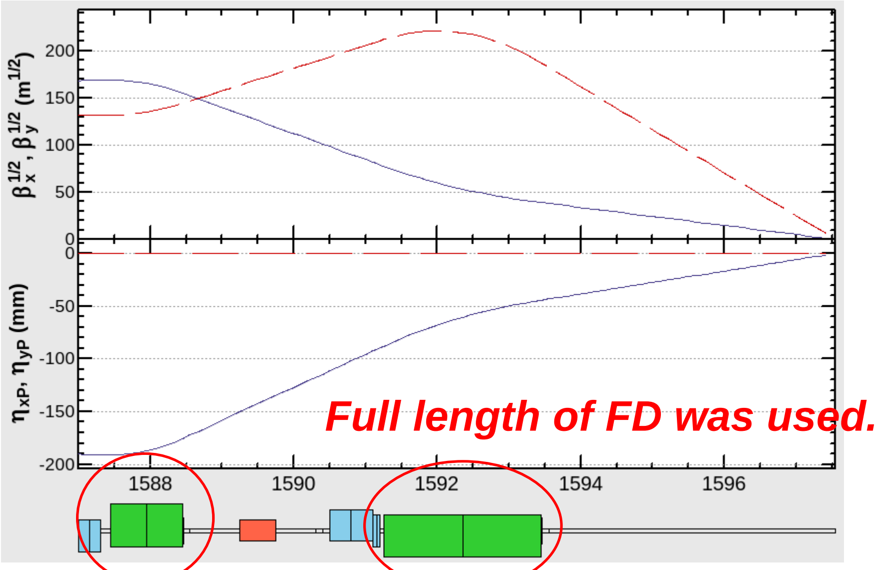
The geometry optimizes the more difficult low-energy optics
and allows the higher-energy optics to deviate slightly from the optimum value.

**ECM=250GeV**



*Half length of FD was used.*

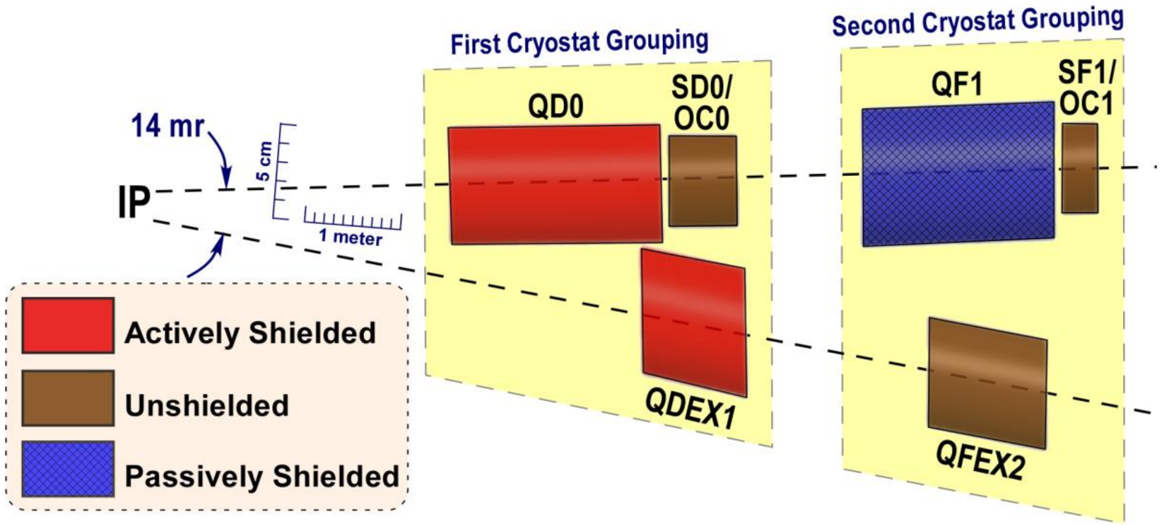
**ECM=500GeV**



*Full length of FD was used.*

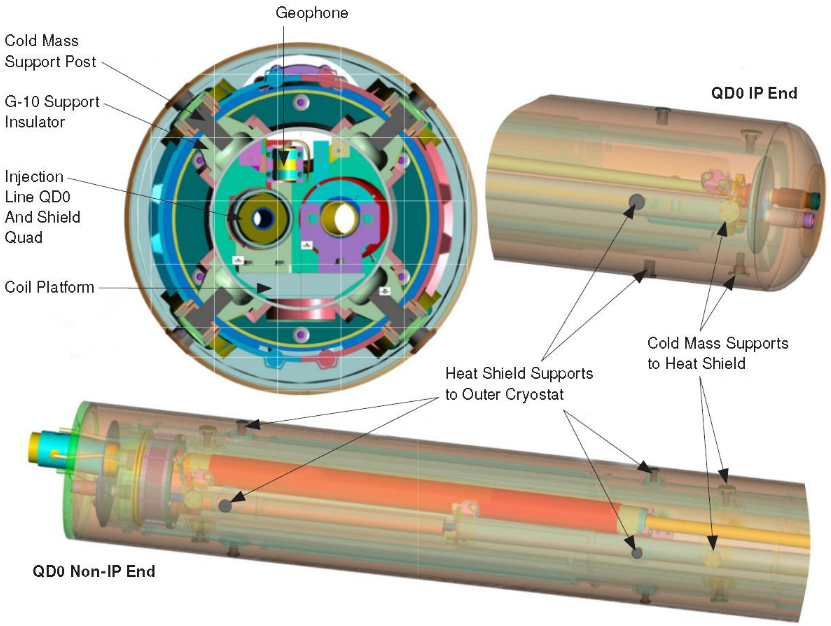
# Cryomodule of Final Doublet and Extraction Quads

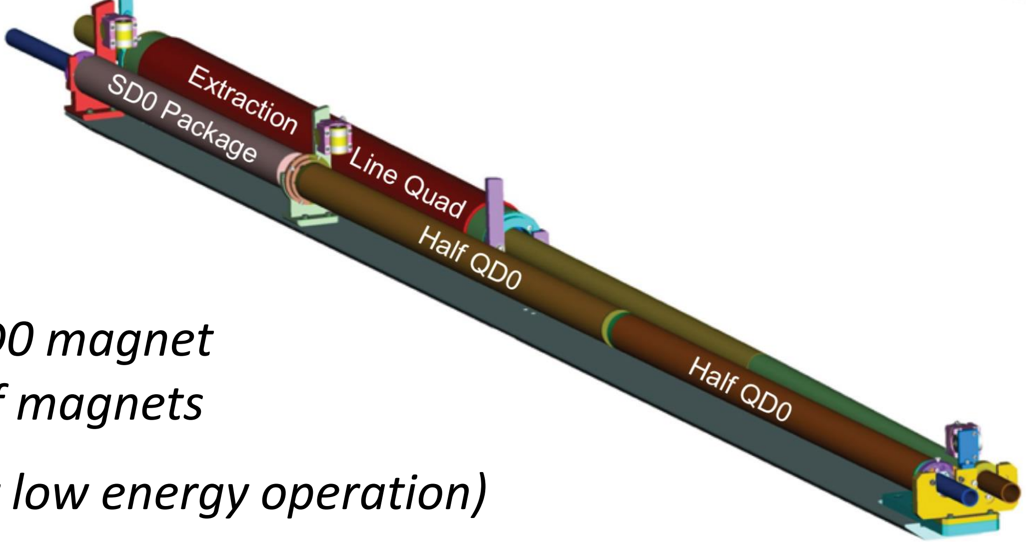
*We will use the 2 set of cryomodules for ILC IP region.*



*Supported with Detector*

*Supported to Accelerator Tunnel*





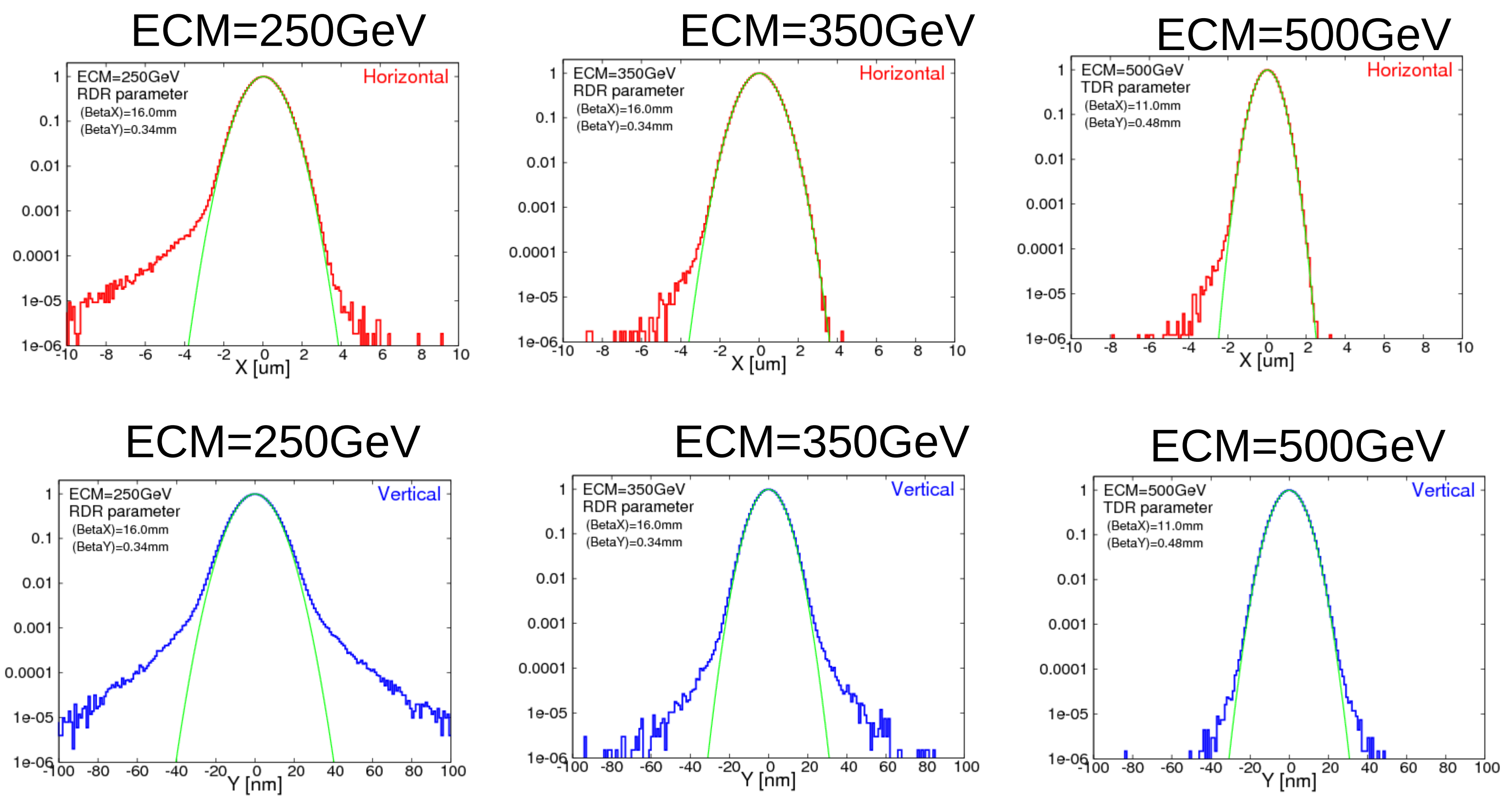
*We can split the QD0 magnet to be half length of magnets*

*(to be explained for low energy operation)*

# IP beam profile

***Horizontal Profile***

***Vertical Profile***



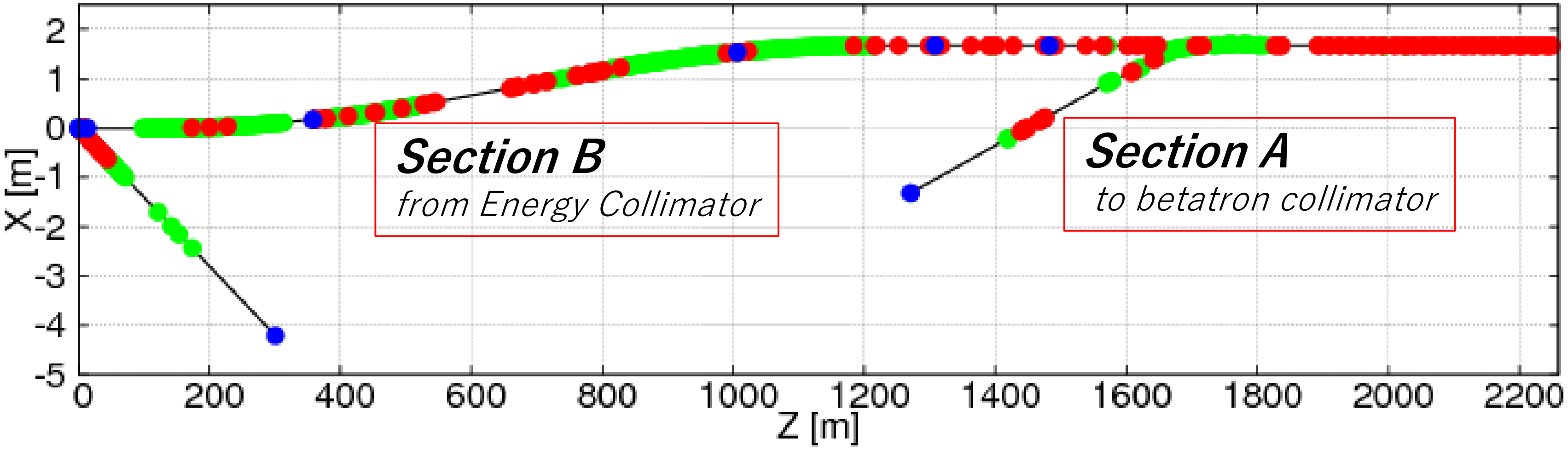
## Simulation Results for ECM<500GeV optics ( no SR )

| ECM | Horizontal | | Vertical | | Relative Luminosity |
|---|---|---|---|---|---|
| | design beam size | simulation (core) | design beam size | simulation (core) | |
| 250GeV | 0.729um | 0.755um | 7.66nm | 7.81nm | 94.7% |
| 350GeV | 0.683um | 0.690um | 5.89nm | 5.97nm | 97.8% |
| 500GeV | 0.474um | 0.482um | 5.86nm | 5.89nm | 97.8% |

# Application to high energy ($E_{CM}$=1TeV)

- The beam optics is designed to be expandable to ECM=1TeV in the same tunnel.
- Beam optics up to 500 GeV can be used with electromagnets to support beam optics up to 1 TeV.

- When ECM=1TeV, the Final Doublet strength must be twice as strong as when ECM=250-500GeV. What technology will be used for this purpose has not been decided at present.



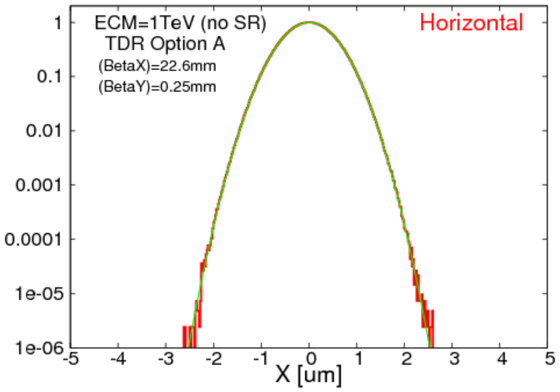
## The number of components both for ECM=500GeV and ECM=1TeV

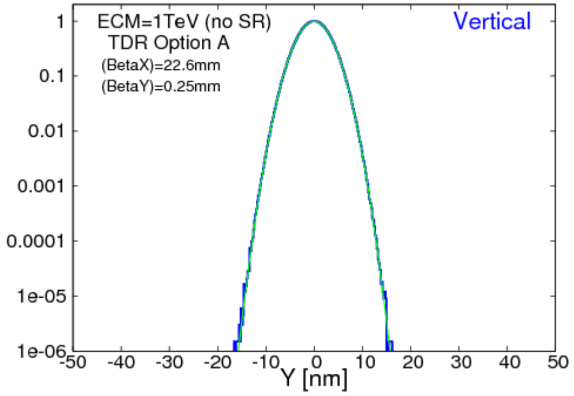
( not include the dumpline )

| | Energy [GeV] | # of BEND | # of QUAD | # of SEXT | # of Steer | # of PS | # of Mover | # of BPM |
|---|---|---|---|---|---|---|---|---|
| Section A | 500 | 16 | 64 | 0 | 19 | 73 | 70 | 78 |
| | 1000 | 43 | 108 | 0 | 19 | 115 | 108 | 116 |
| Section B | 500 | 63 | 33 | 7 | 55 | 46 | 40 | 101 |
| | 1000 | 176 | 41 | 7 | 55 | 56 | 48 | 112 |

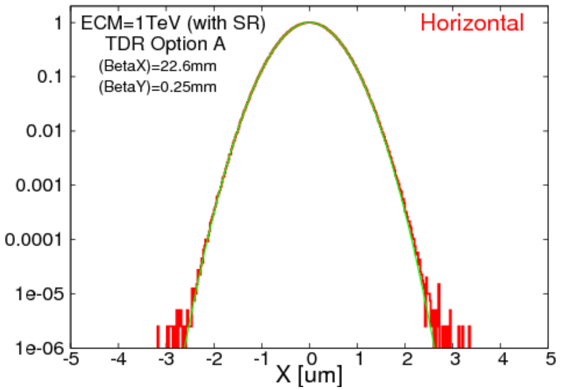
# Simulation Results for ECM=1TeV optics

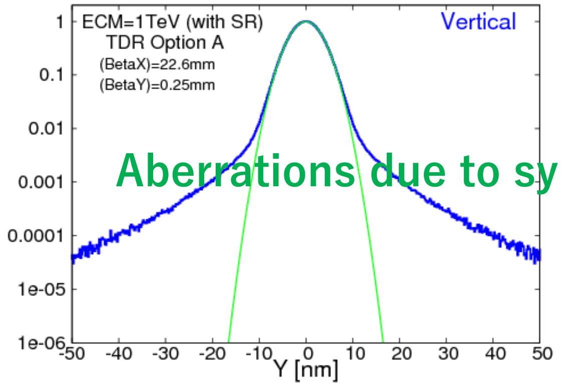
**<< no SR >>**





**<< with SR >>**





Aberrations due to synchrotron radiation

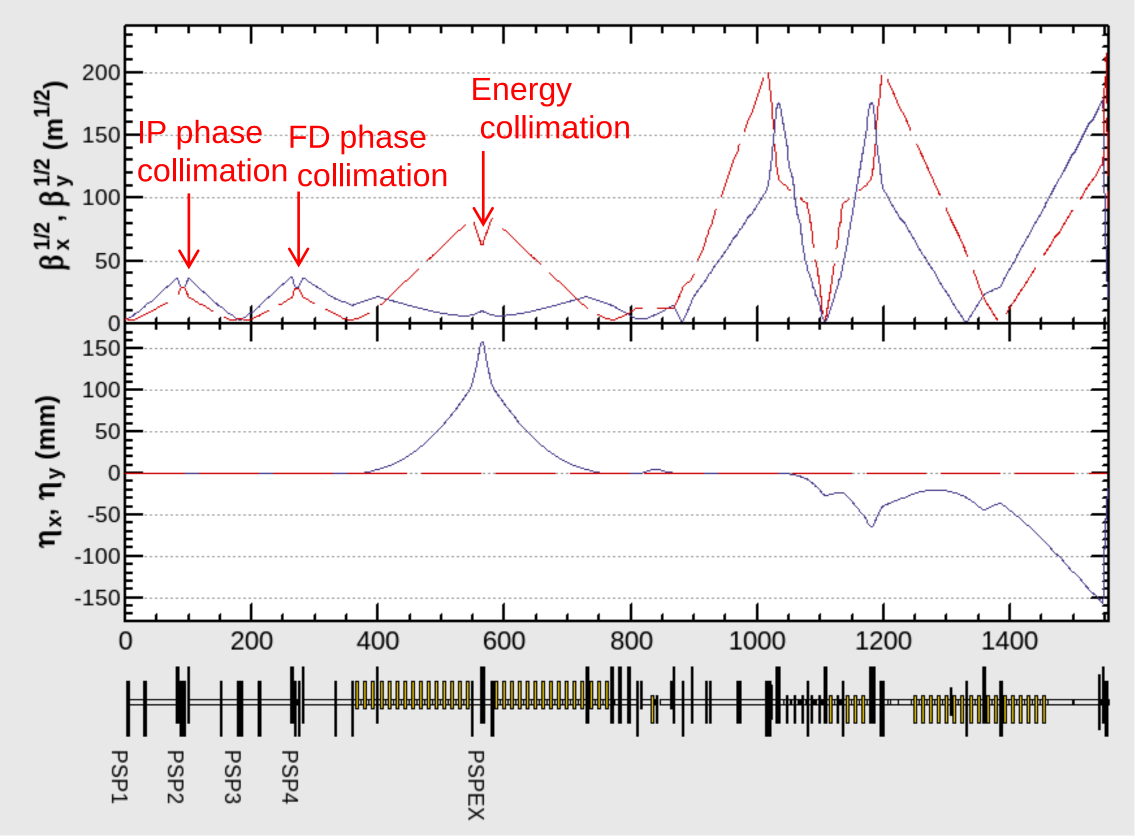
| | Horizontal | | | Vertical | | | Relative Luminosity |
|---|---|---|---|---|---|---|---|
| | design | rms | core | design | rms | core | |
| no SR | 0.481um | 0.481um | 0.481um | 2.99nm | 2.99nm | 2.99nm | 99.8% |
| with SR | | 0.499um | 0.498um | | 3.71nm | 3.15nm | 91.7% |

Luminosity of more than 90% can be achieved for ECM=1TeV, even with the effect of synchrotron radiation on the beamline.

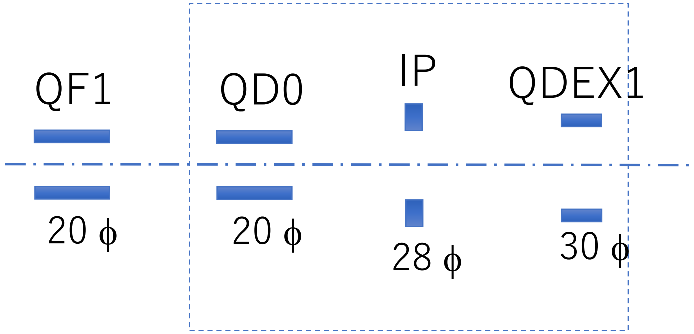
# Consideration of collimation depth

## Arrangement of the Collimators

Beta Function at SP2/SP4 = (X; 1000m / Y; 1000m)
Phase Advance (SP2/SP4) = (X; 0.5 pi / Y; 1.5 pi )
Phase Advance (SP4/ IP ) = (X; 5.5 pi / Y; 4.5 pi )
EtaX at SPEX = 0.158m



## *Detector apertures*

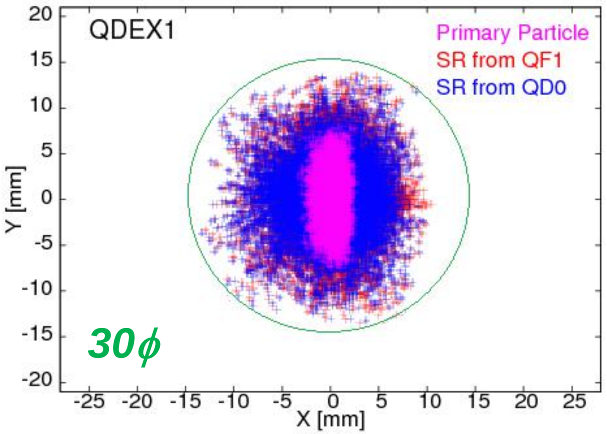


**Source for background**

1) Halo particles
2) **SR form halo particles**

When the L* of QD0 is increased, the L* of QDEX1 in the extraction line must also be increased.

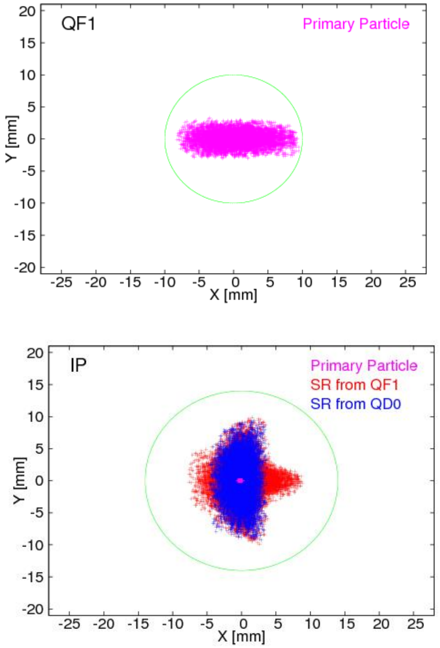
Since the collimation depth is limited mainly by the fact that SR from the Final Doublet hits QDEX1, the collimation depth becomes more severe when L* is increased.



SP2/SP4 X ; 0.86mm
SP2/SP4 Y ; 0.98mm
SPEX X ; 1.60mm
( Dp/p = 1% )

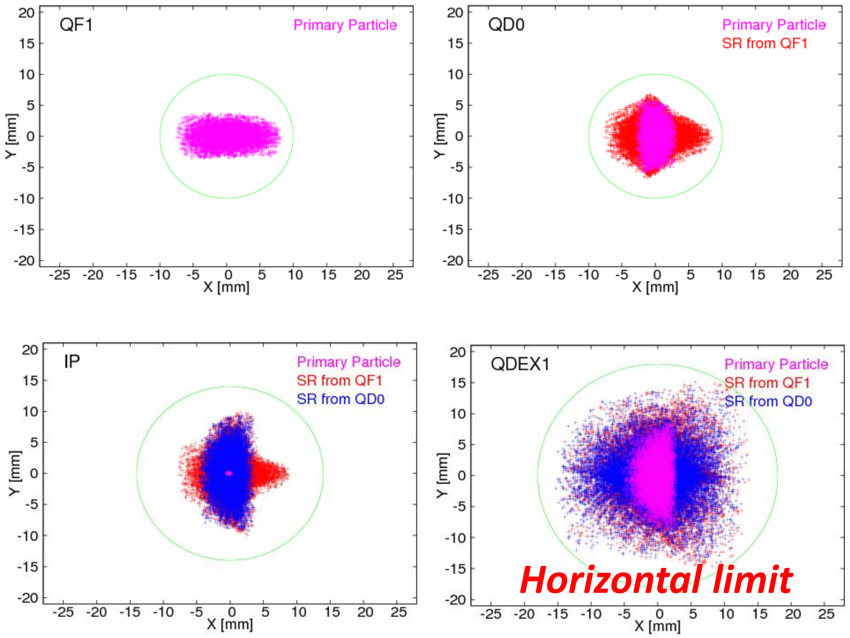
# Synchrotron radiation around IP area

## Shorter QD0 L*

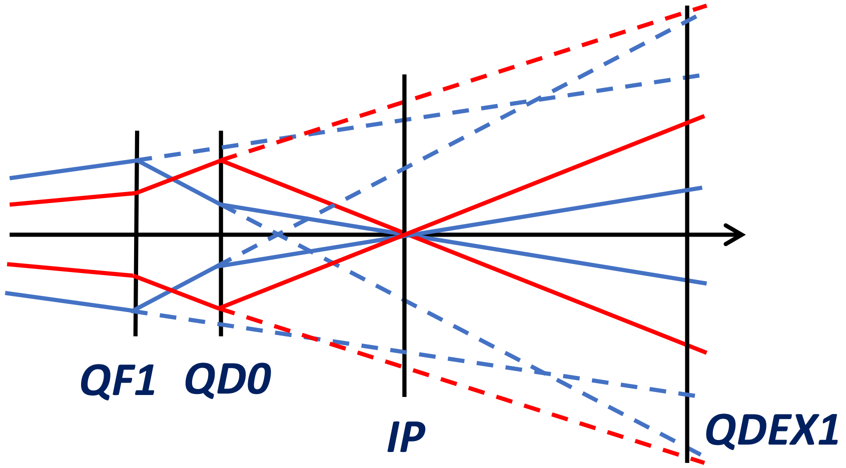


Horizontal limit

## Longer QD0 L*



Horizontal limit

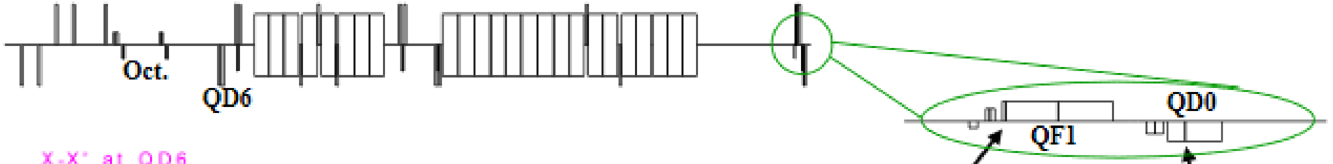


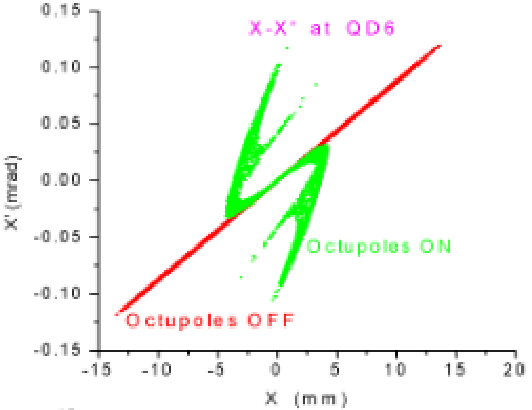
*The situation of QDEX1 limit will be changed by the parameters*

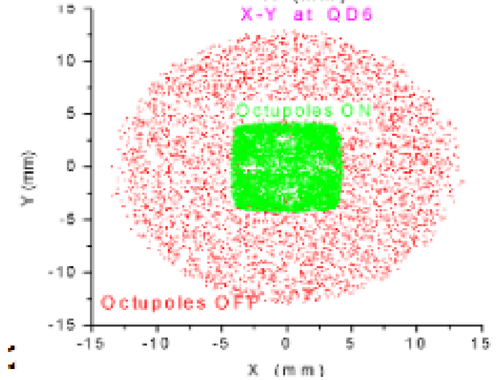
- *the location of QDEX1.*
- *the aperture of QDEX1.*
- *the vertical aperture of collimator.*

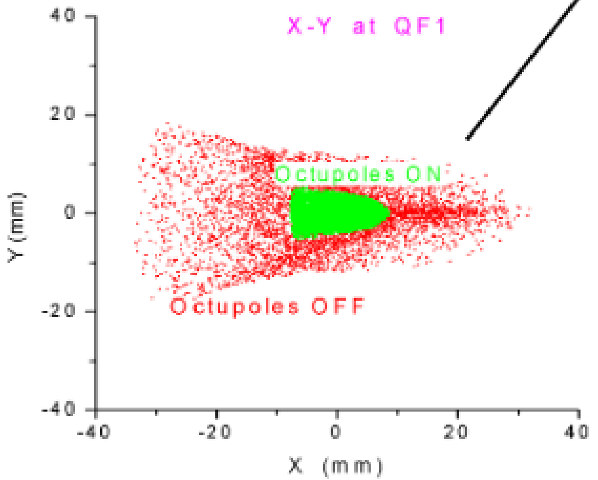
# Tail folding in ILC FF

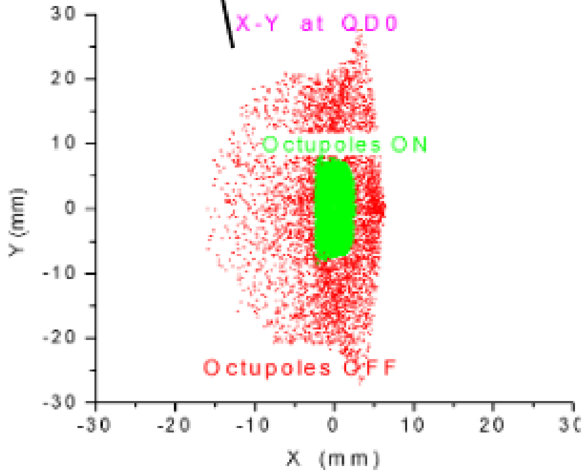
- Two octupole doublets give tail folding by ~ 4 times in terms of beam size in FD
- This can lead to relaxing collimation requirements by ~ a factor of 4











**Tail folding by means of two octupole doublets in the ILC final focus**
Input beam has (x,x',y,y') = (14μm,1.2mrad,0.63μm,5.2mrad) in IP units (flat distribution, half width) and ±2% energy spread, that corresponds approximately to $N_\sigma$=(65,65,230,230) sigmas with respect to the nominal beam

- Two octupoles of different sign separated by drift provide focusing in all directions for parallel beam:

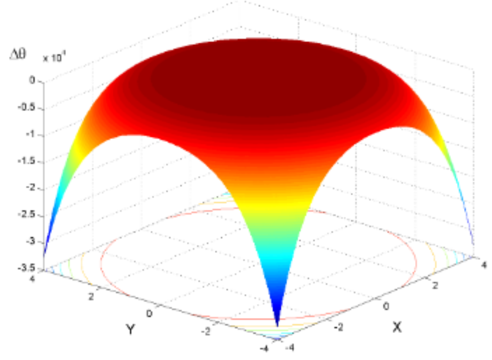
$$\Delta\theta = \alpha r^3 e^{-i3\varphi} - \left(\alpha r^3 e^{i3\varphi}\left(1+\alpha r^2 L e^{-i4\varphi}\right)^3\right)^*$$

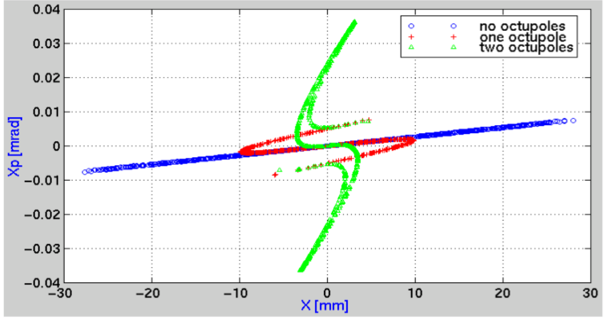
$$x + iy = re^{i\varphi}$$

$$\Delta\theta \approx -3\alpha^2 r^5 e^{i\varphi} - 3\alpha^3 r^7 L^2 e^{i5\varphi}$$

**Focusing in** **<u>all directions</u>**

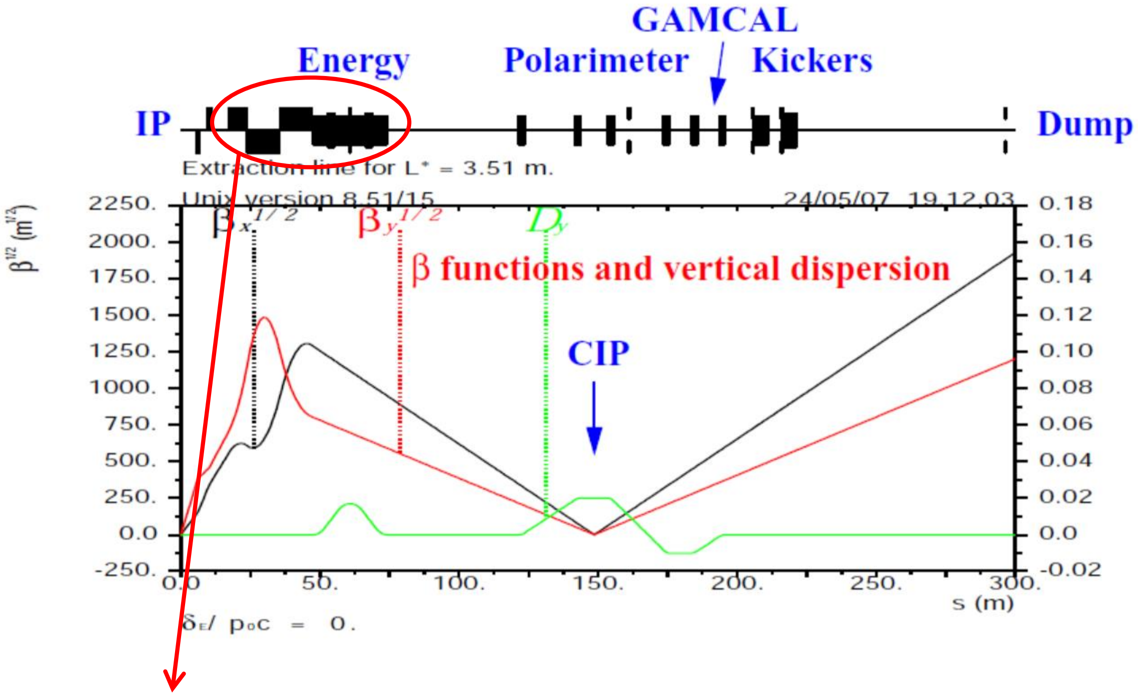
**Next nonlinear term focusing – defocusing depends on φ**





Folding of the horizontal phase space distribution at the entrance of the Final Doublet with one or two octupoles in a "Chebyshev Arrangement".

# ILC beam extraction line



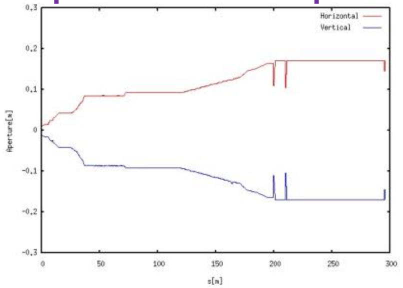
## Quadrupole magnets in extraction line

Y. Nosochkov et al., LCWS/ILC 2007

First two quadrupoles : SC magnets in FD package
Other quadrupoles : Large aperture NC magnets

| Name | Qty | B′ | L | R |
|---|---|---|---|---|
| QDEX1 (SC) | 1 | 89.41 | 1.150 | 17 |
| QFEX2A (SC) | 1 | 33.67 | 1.100 | 30 |
| QFEX2 (B,C,D) | 3 | 11.27 | 1.904 | 44 |
| QDEX3 (A,B,C) | 3 | 11.37 | 2.083 | 44 |
| QDEX3D | 1 | 9.81 | 2.083 | 51 |
| QDEX3E | 1 | 8.20 | 2.083 | 61 |
| QFEX4A | 1 | 7.04 | 1.955 | 71 |
| QFEX4 (B,C,D,E) | 4 | 5.88 | 1.955 | 85 |

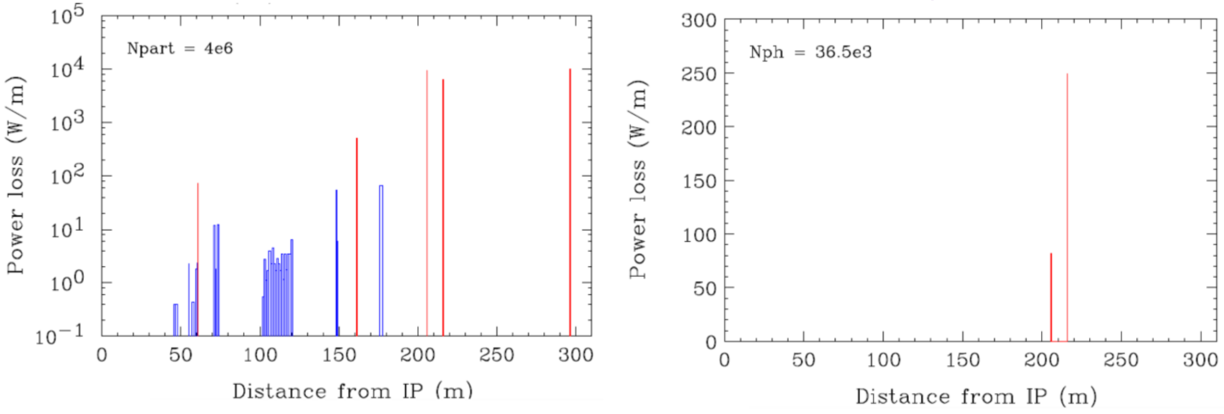
**Apertures for Dumpline**



## Power loss at extraction line (beam-beam effect)

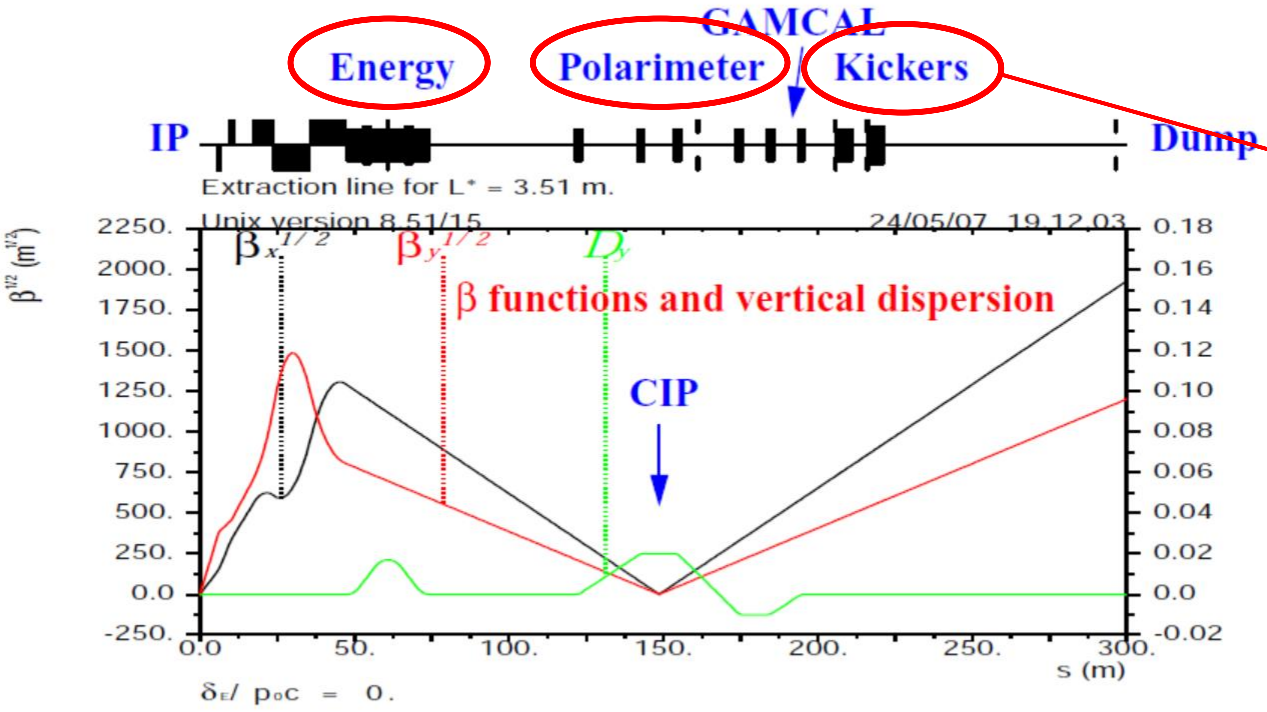
E. Marin and Y. Nosochkov et al., LCWS 2013

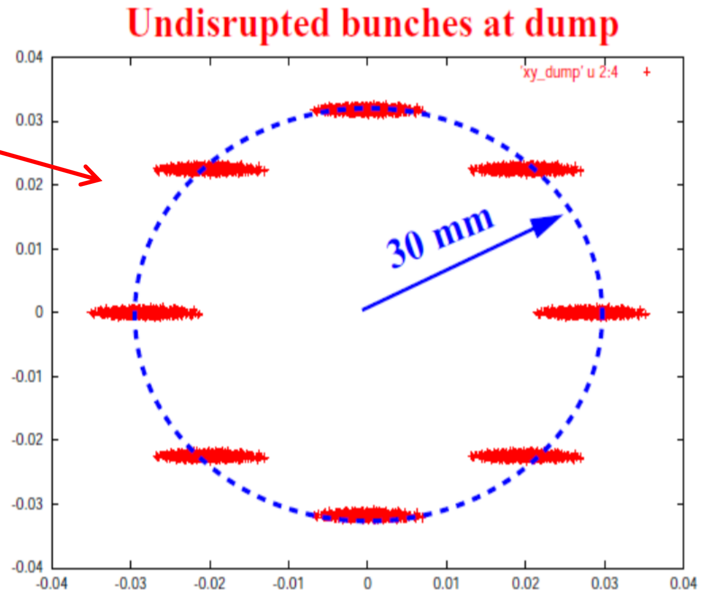
**Disrupted charged particles** **Beamstrahlung photons**



- The ILC extraction line uses large-diameter quadrupole magnets (maximum bore diameter 170 mm) to transport the beam with large beam spread by the beam-beam effect to the dump with minimal loss.
- When the L* of QD0 is lengthened, the L* of the extraction quadrupole magnet QDEX1 is also lengthened, and the diameter of the quadrupole magnet in the entire extraction line should be increased more.
- Therefore, the design of the entire extraction line needs to be redesigned.

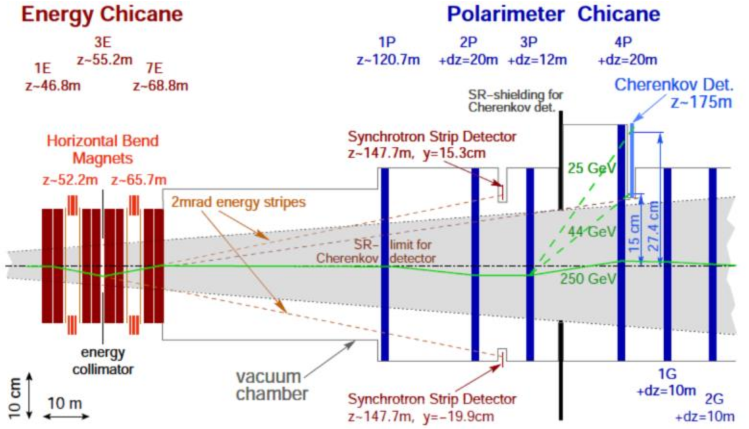
# Beam diagnostics for ILC beam extraction line

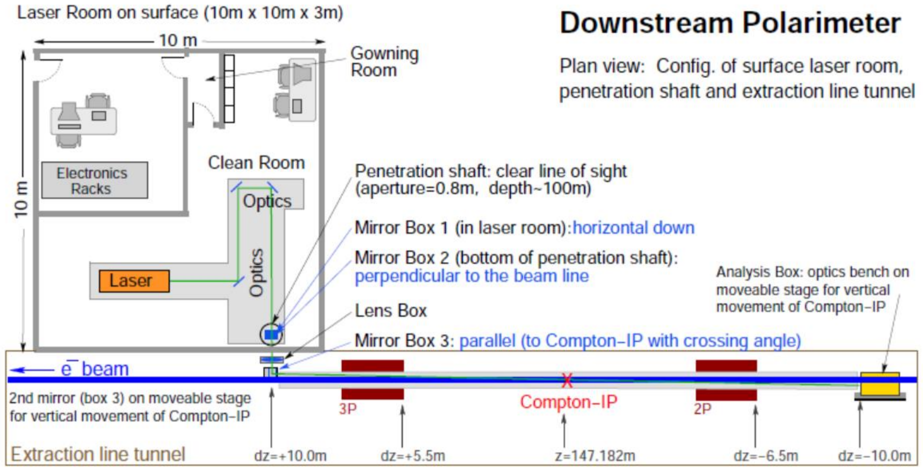




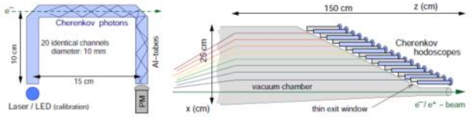
## ILC extraction line beam diagnostics

S Boogert *et al* 2009 *JINST* **4** P10015

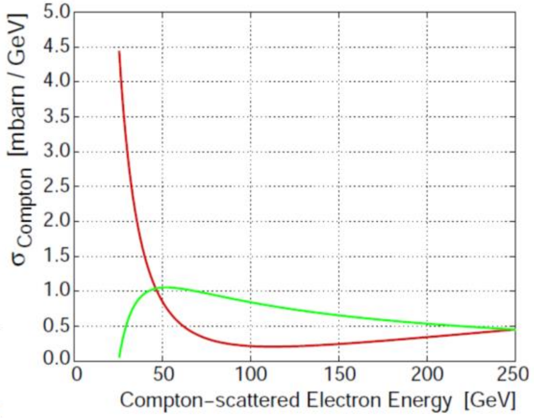



**Downstream Polarimeter**

Plan view: Config. of surface laser room, penetration shaft and extraction line tunnel



## Cross section of Compton scattering with different beam polarization

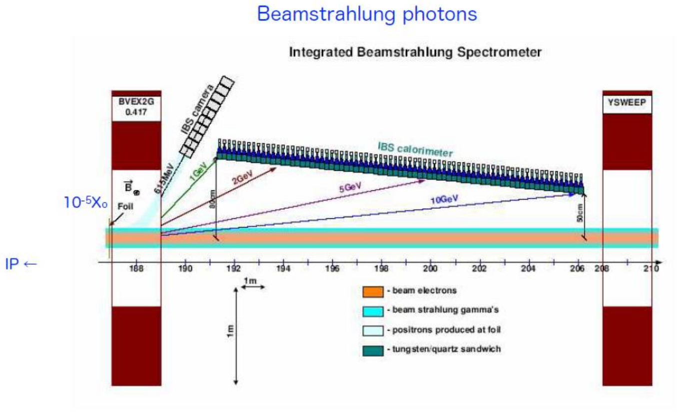


# IP beam size tuning

*The beam size will be optimized by monitoring the Luminosity monitor in actual ILC beam operation.*

*For large beam size*
*( larger than 1 um)*

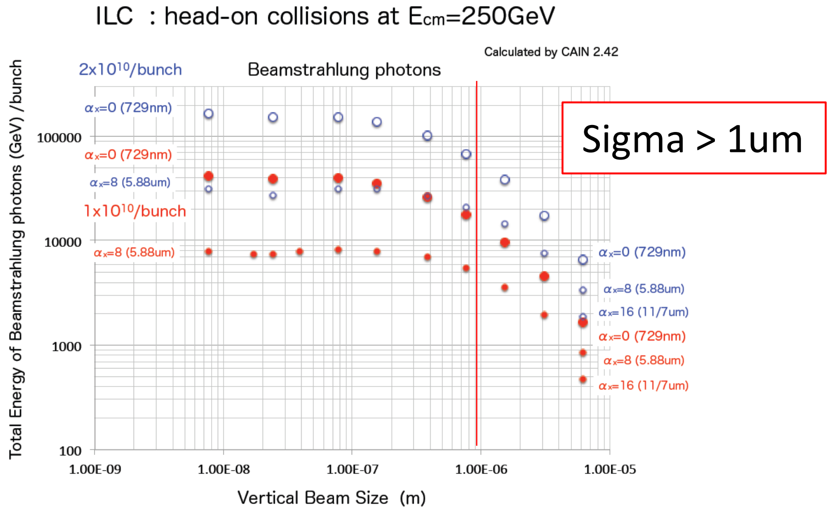
*For small beam size*
*( smaller than 1 um)*



Beamstrahlung photons

Figure 1: Concept for the GamCal.

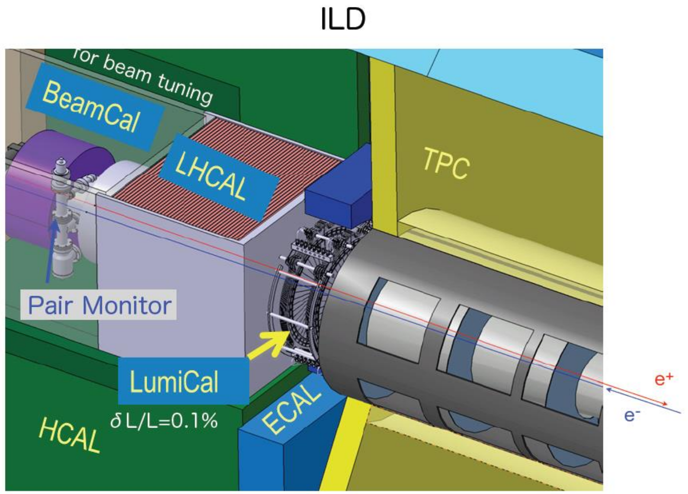
W.M. Morse, GamCal - A Beamstrahlung Gamma Detector for Beam Diagnostics, LCWS07

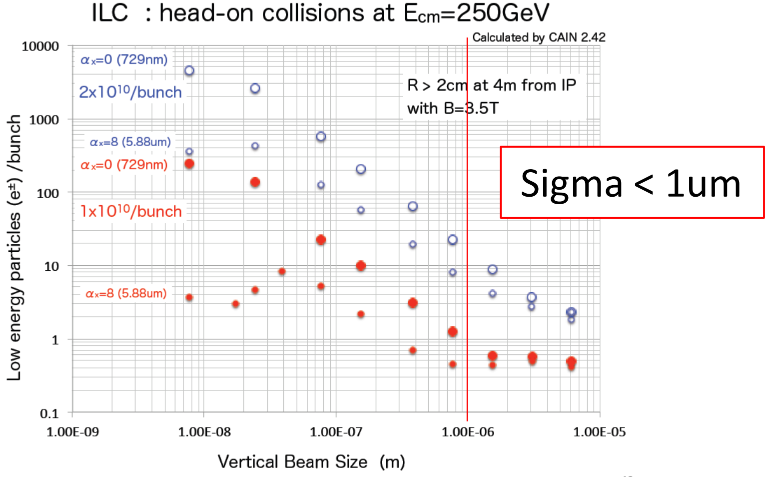


ILC : head-on collisions at $E_{cm}$=250GeV

Sigma > 1um

## Forward Calorimeter System for MDI





ILC : head-on collisions at $E_{cm}$=250GeV

Sigma < 1um

*presented by T.Tauchi (KEK) at AWLC2014*

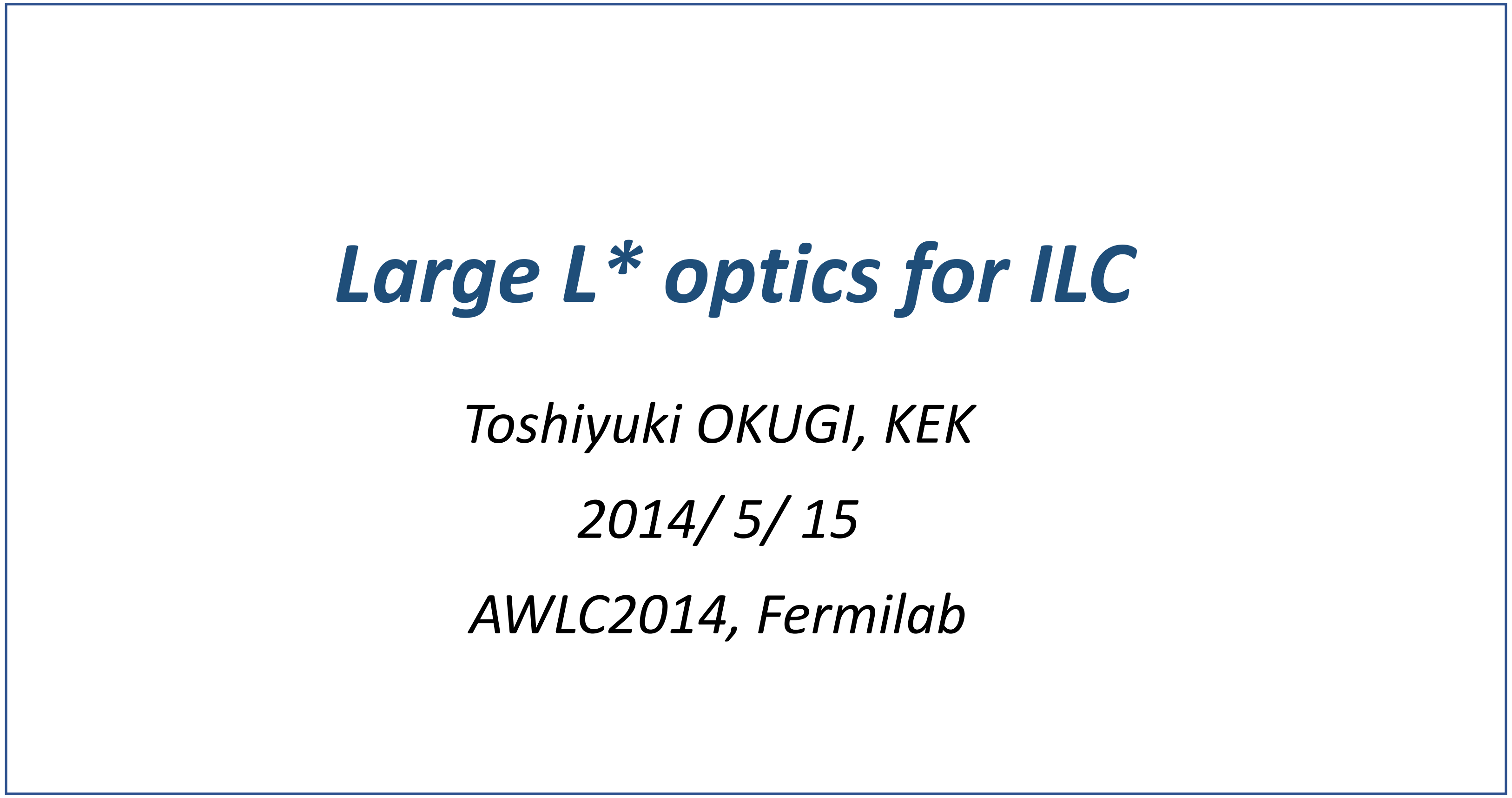
# Backup

Is it better to take the bending angle of the dipole magnet infinitely large?

- The higher-order aberration derived energy spread becomes stronger.
- The larger the emittance dilution due to synchrotron radiation become larger for the high energy beam.

**There is an optimum value of bending angle for each beam energy.**

**I have considered the ILC final focus optics with long L* in the past.**



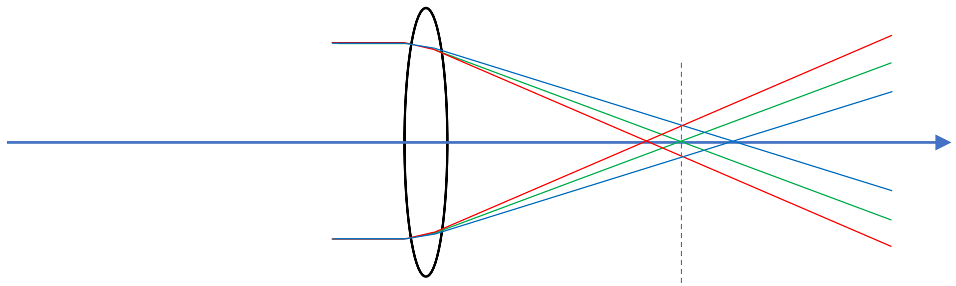
***Large L* optics for ILC***

*Toshiyuki OKUGI, KEK*

*2014/ 5/ 15*

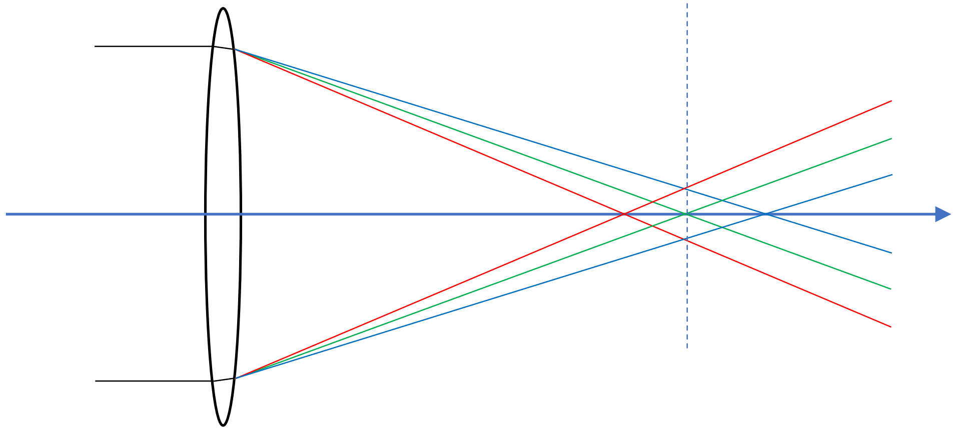
*AWLC2014, Fermilab*

# Long L* and Chromaticity



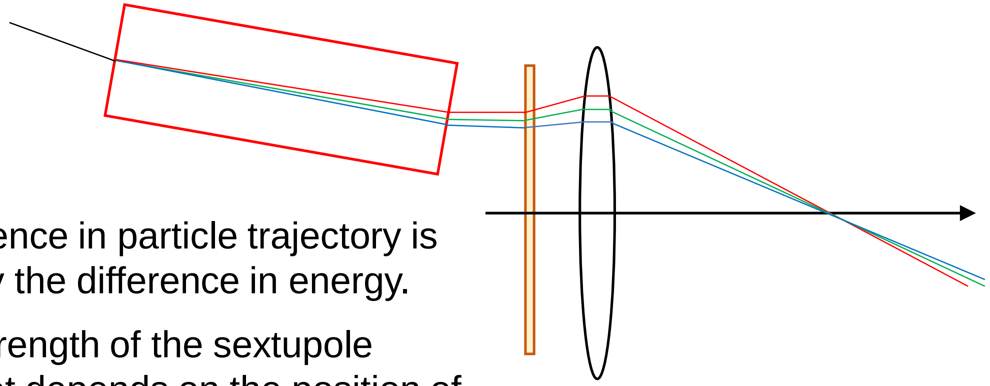
In order to squeeze the beam to the same size at the focus, it is necessary to squeeze the beam at the same divergence angle.

- The beam size at the final focus magnet becomes larger.
- The chromatic aberration at the focal point becomes larger.



When the L* is long, the chromatic aberration becomes larger, and a strong chromatic aberration compensation is needed.

# Chromaticity correction

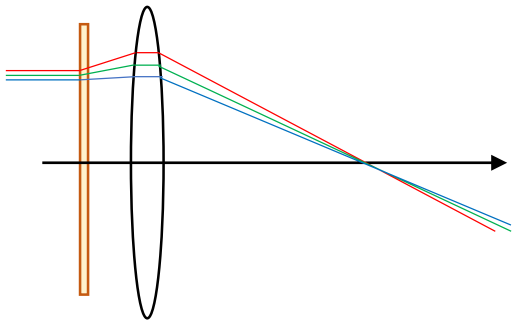


The difference in particle trajectory is created by the difference in energy.

- The strength of the sextupole magnet depends on the position of the particle passing through it.
- The angle at which a particle injects a quadrupole magnet depends on its energy.

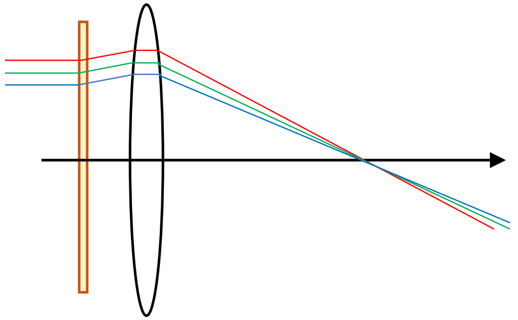
This is especially effective in “the low energy region”, because the beam size passing through the magnet is large.

**Small difference in position due to energy in sextupole**



- Requires strong sextupoles
- Spatial aberration becomes large

**Large difference in position due to energy in sextupole**

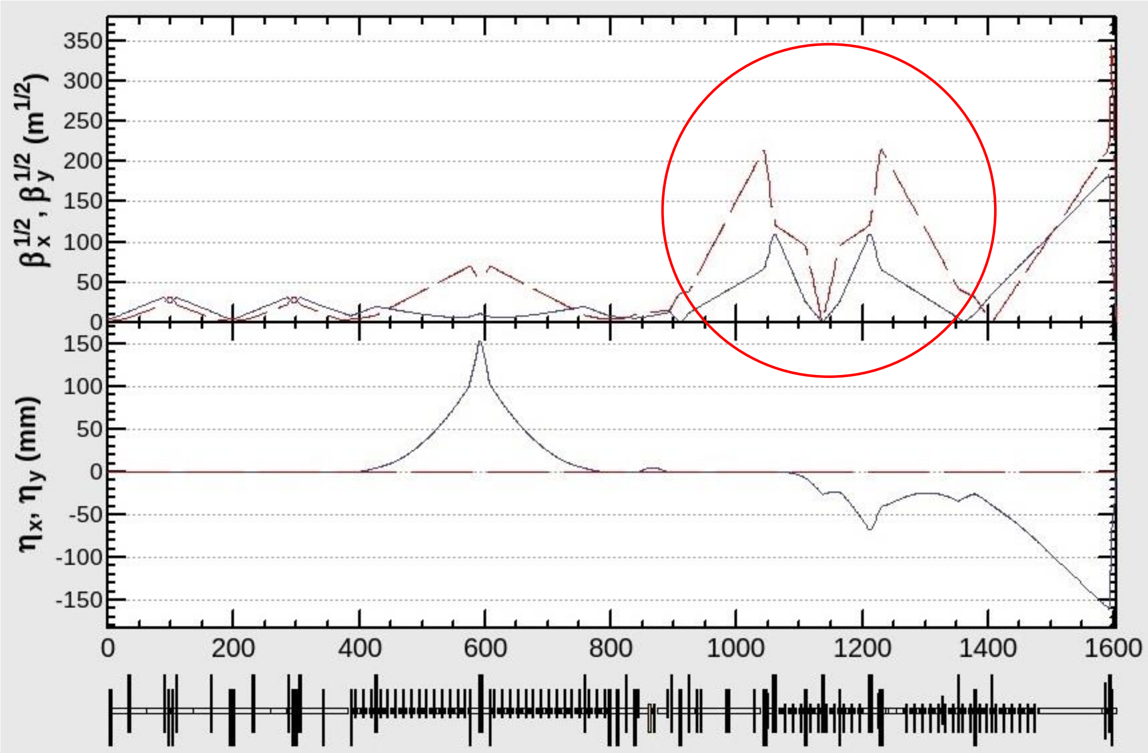


- Enough to use weak sextupoles
- Spatial aberrations are small.

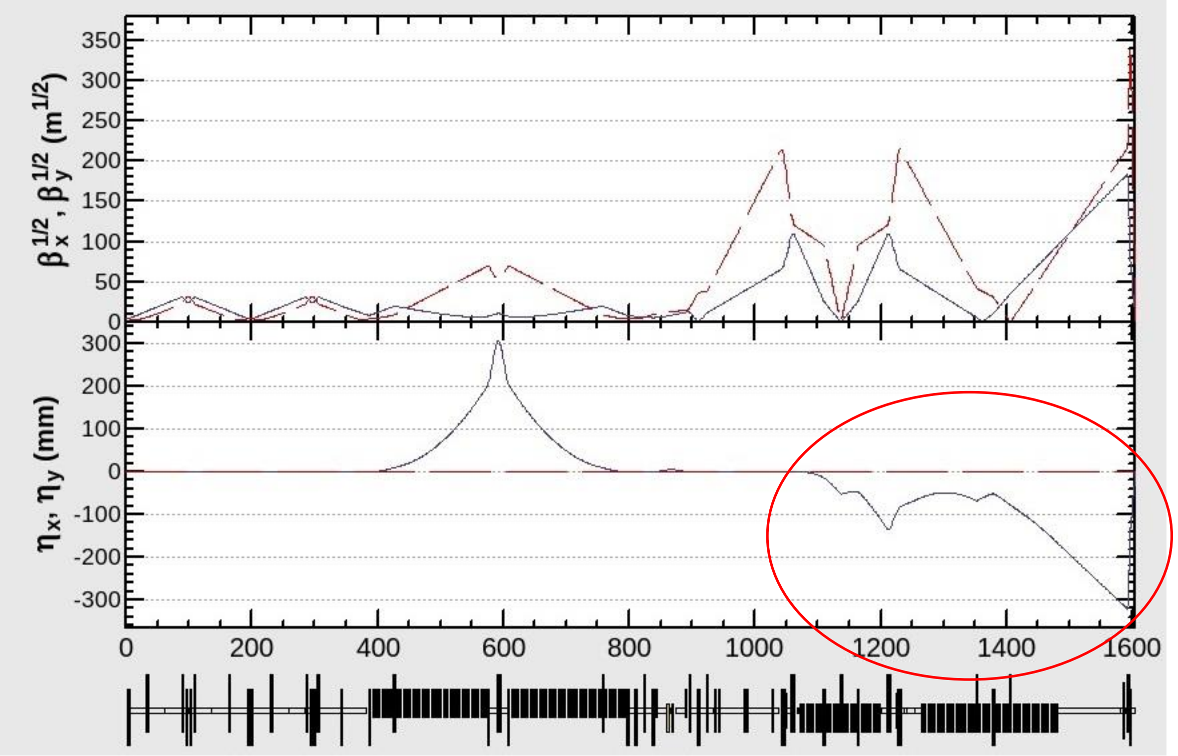
# L*=7.0m optics based on ILC RDR optics (ECM=500GeV)

Since the (2nd order and higher) geometrical aberration for large L* optics was large
the large L* optics is more difficult than the small L* optics, even if we set same chromaticity.

## 1st step optimization



## 2nd step optimization



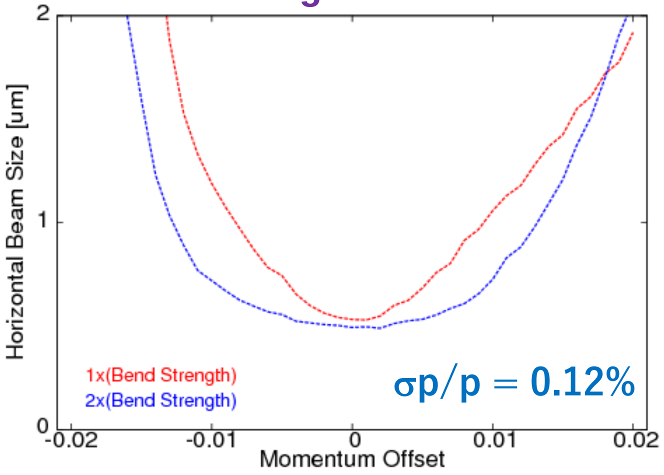
In order to reduce the beam size at SF6, SF5 and SD4, the beta function at the section was reduced (ATF2-like optimization).

The strength of dipole magnet was increased to twice to increase the dispersion and reduce the strength of sextupoles.

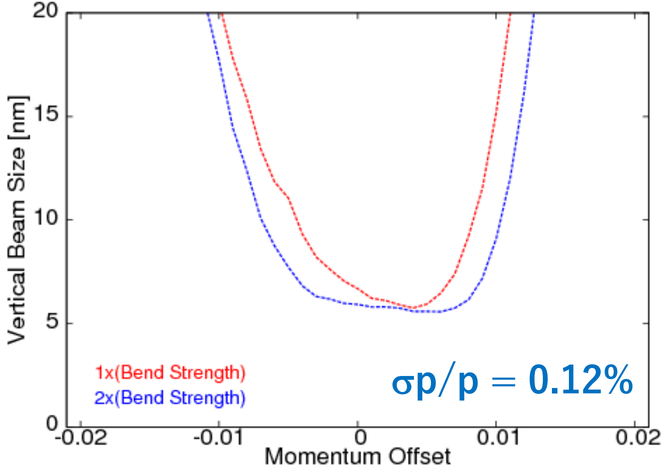
# Performances for the optics with strong bending magnet

## Optics was matched to ILC TDR parameters.

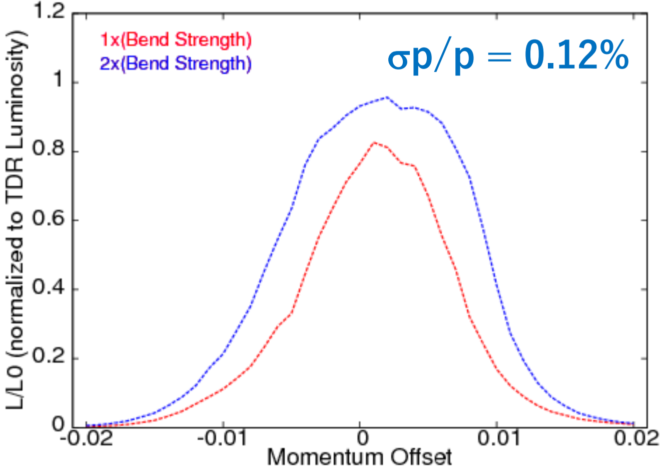
### Bandwidth of sigmaX for E=250GeV



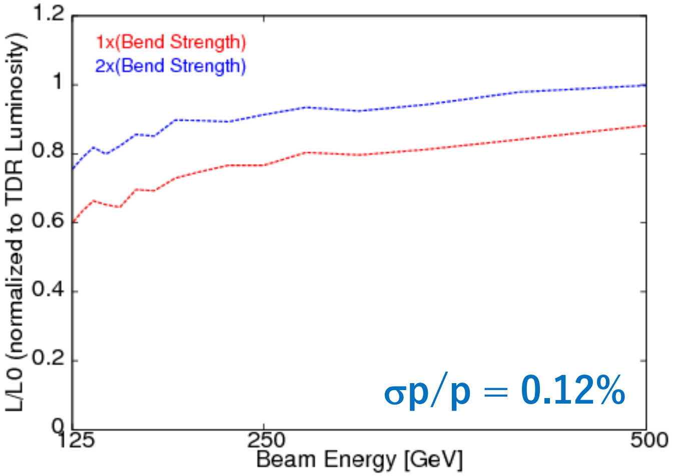
### Bandwidth of sigmaY for E=250GeV



### Luminosity Bandwidth for E=250GeV



### Energy Dependence of Luminosity



## Effect of SR

Even at ECM=500 GeV,
some effects of synchrotron radiation are appeared.

| IP Beam Size at E=250GeV | sigmaX* | sigmaY* |
|---|---|---|
| w/o Synchrotron Radiation | 0.50um | 5.81nm |
| with Synchrotron Radiation | 0.50um | 5.95nm |

At AWLC2014, this proposal was rejected.

The reasons are

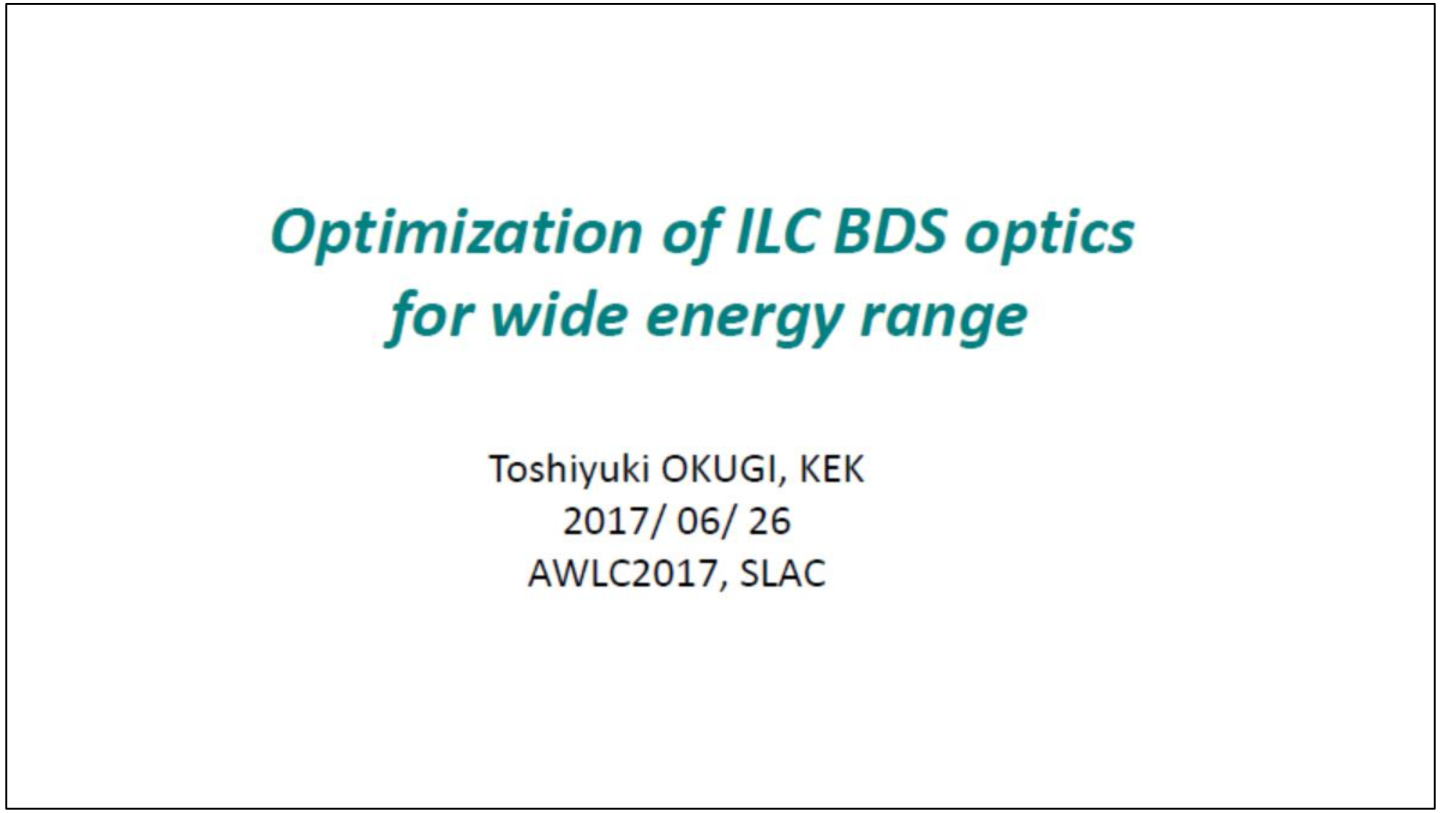
1) Energy extendability
2) Collimation depth
3) Aperture of the dumpline .

The luminosity was increased to almost 97%, and the bandwidth increased.
But, the luminosity reduction for low energy was still large.

The current ILC FF optics are designed to support energies of ECM=250GeV-1TeV with the same geometry.

However, the FF optics is not optimized for each energy, because the bending angle of the dipole magnet does not have an optimum angle for each energy.

- In order to optimize for each energy, we need to choose optimal bending angle of dipole for each beam energy.
- A layout to optimize for two energies, ECM=250GeV and 1TeV, was proposed in 2017.

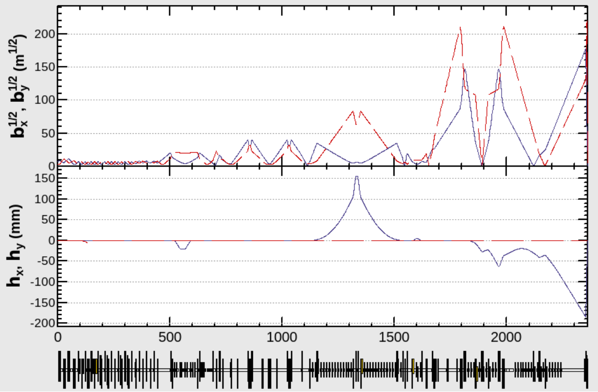


**Optimization of ILC BDS optics for wide energy range**

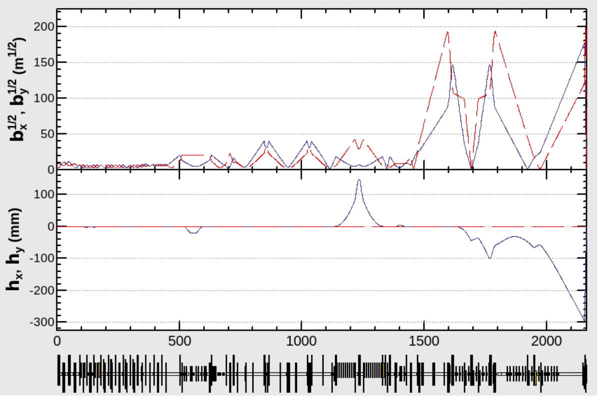
Toshiyuki OKUGI, KEK
2017/ 06/ 26
AWLC2017, SLAC

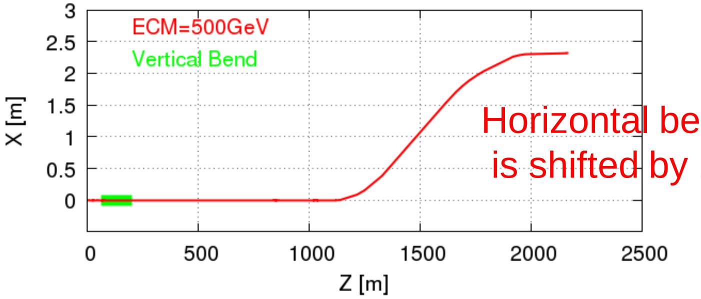
# Strong dipole for low energy

## Original beam optics



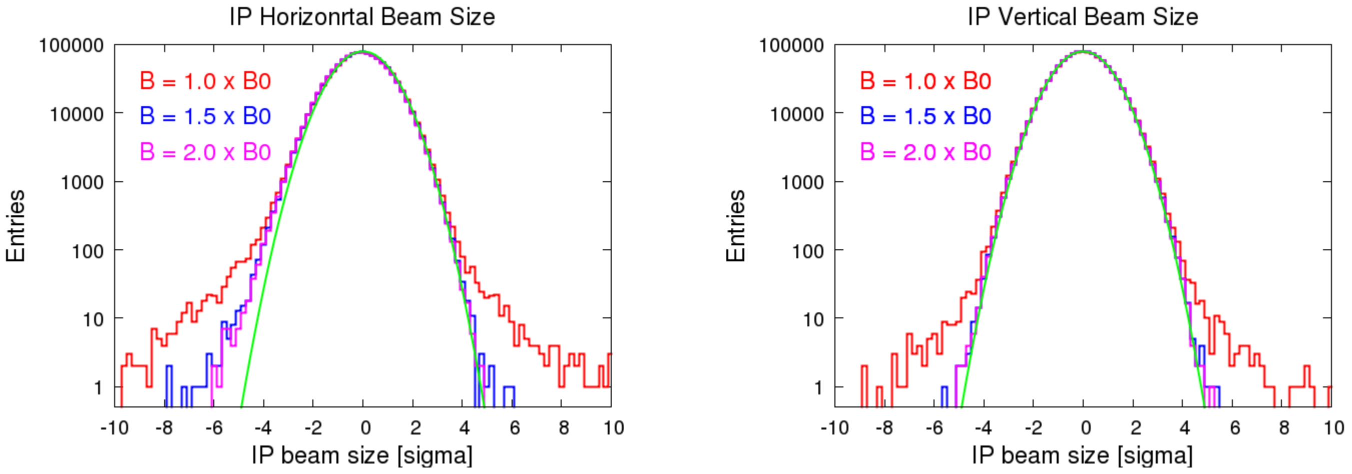
## Beam optics with strong bending magnet





Horizontal beamline offset is shifted by 1m at 2xB0.

## *IP beam profile at ECM=250GeV*



## *Synchrotron radiation for BDS at ECM=500GeV*

**Momentum Spread Growth by Synchrotron Radiation**

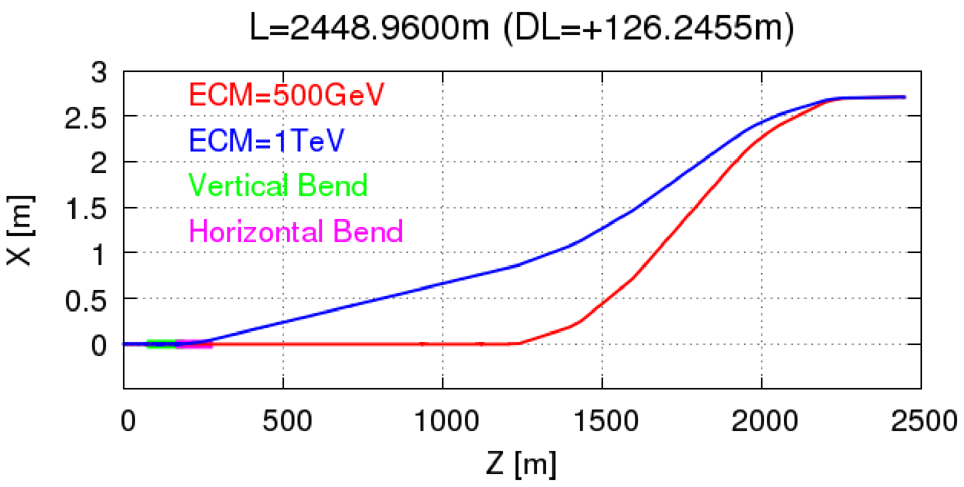
| | Collimator | FF beamline | Total |
|---|---|---|---|
| B = 1.0 x B0 | 0.0058% | 0.0017% | 0.0061% |
| B = 1.5 x B0 | 0.0059% | 0.0020% | 0.0062% |
| B = 2.0 x B0 | 0.0060% | 0.0024% | 0.0064% |

**Horizontal Emittance Growth by Synchrotron Radiation**

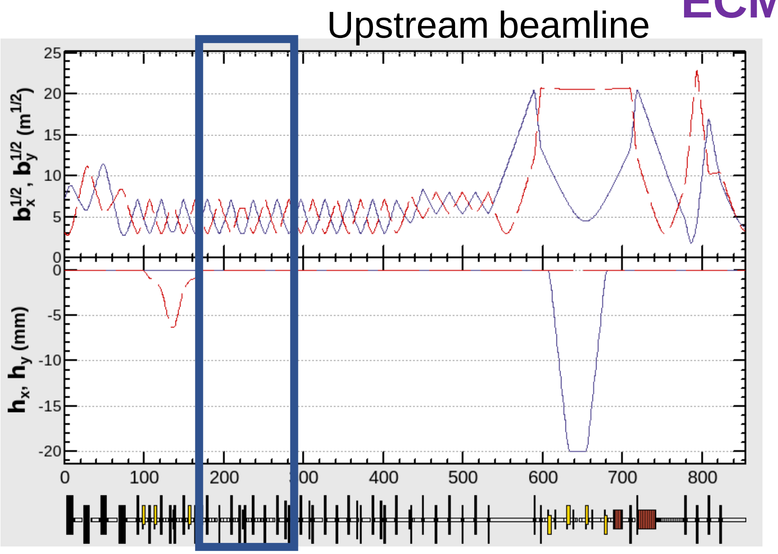
| | Collimator | FF beamline | Total |
|---|---|---|---|
| B = 1.0 x B0 | 0.45% | 0.07% | 0.52% |
| B = 1.5 x B0 | 0.67% | 0.49% | 1.16% |
| B = 2.0 x B0 | 1.49% | 2.06% | 3.55% |

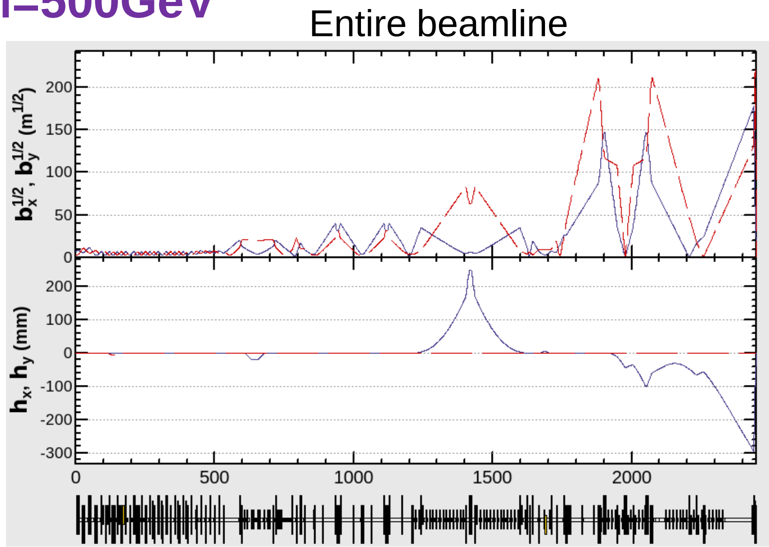
Even at ECM=500 GeV, the effect of SR is not so small (1 TeV is impossible).

# New beamline layout to allow ECM=250GeV to 1TeV

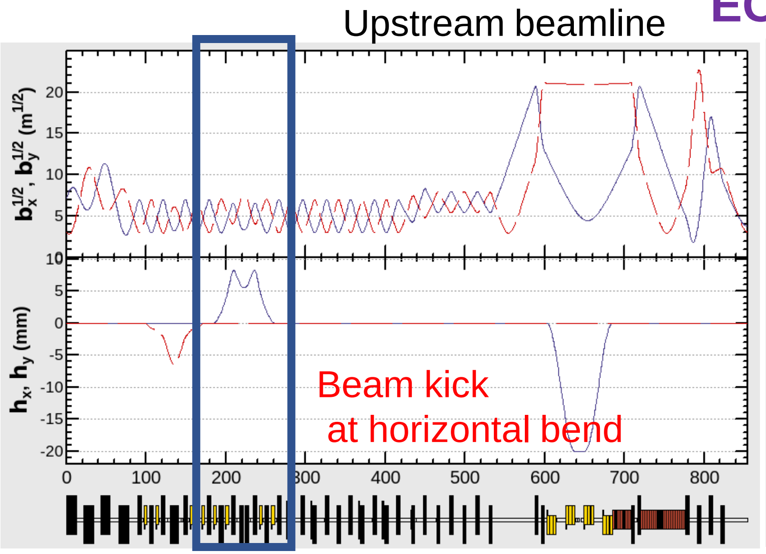


**ECM=500GeV**

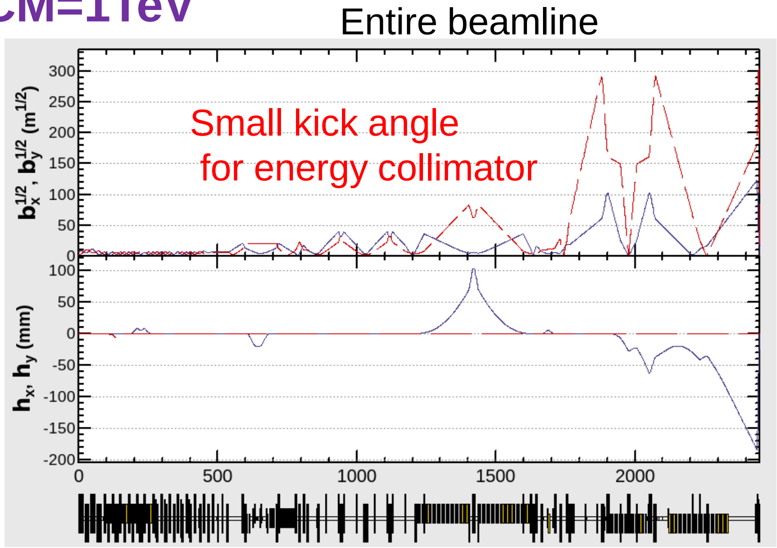




**ECM=1TeV**



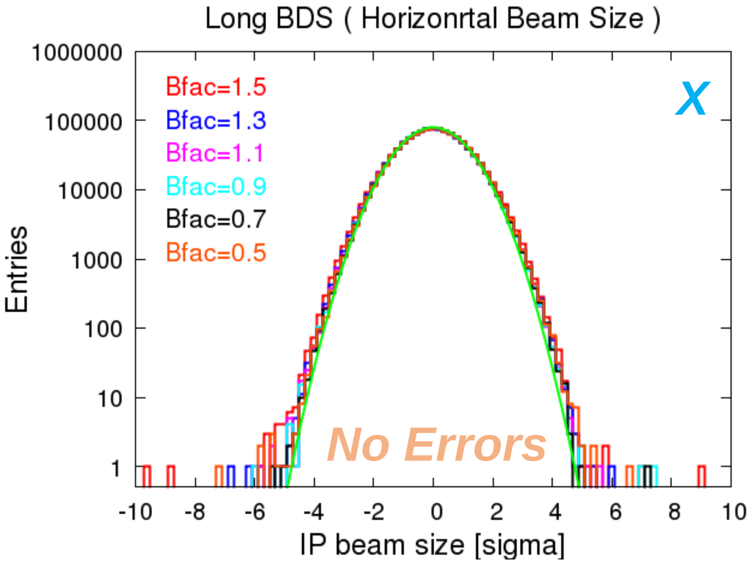
Beam kick at horizontal bend

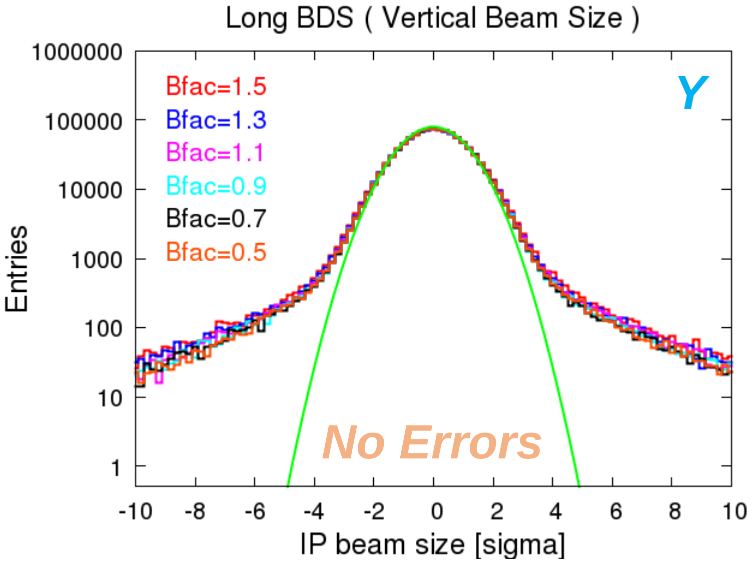


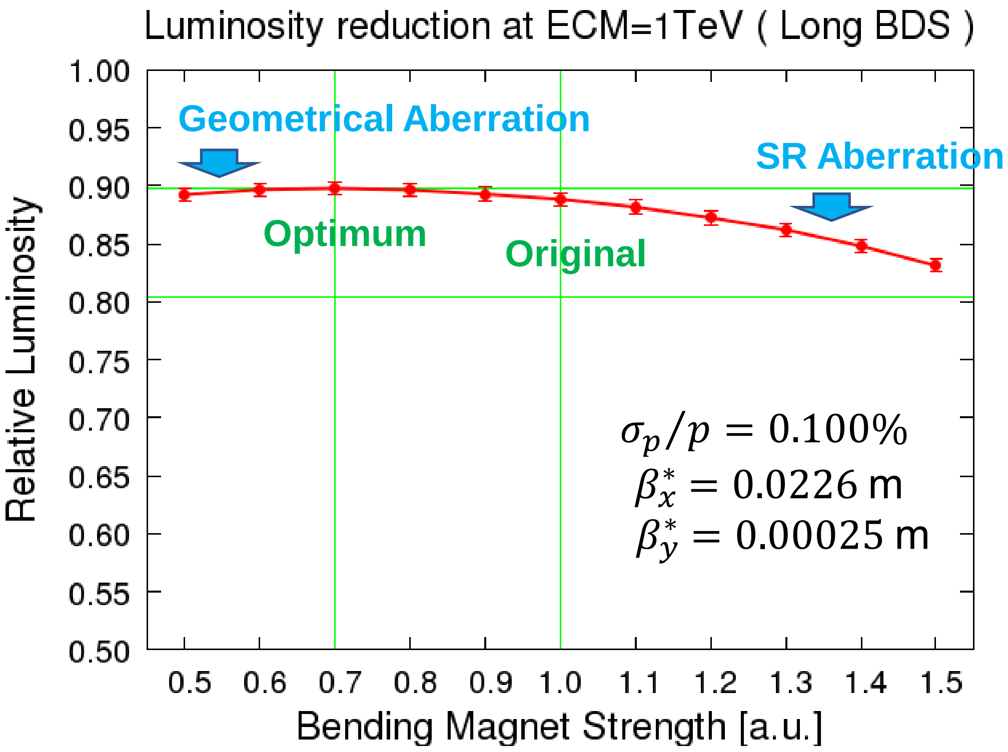
Small kick angle for energy collimator

- Add horizontal bend at BDS entrance.
- When we upgrade the energy to ECM=1TeV, we will align the IP position and angle of the two beamlines by adjusting the angle of this horizontal bend and the energy collimator.
- This beam optics improves the performance of ECM=250 GeV, and has the expendability up to ECM=1 TeV.
- This was proposed in 2017, but was rejected because of the slightly longer beamline (cost).

# Optimization of bending angle for ECM=1TeV







$\sigma_p/p = 0.100\%$
$\beta_x^* = 0.0226\ \mathrm{m}$
$\beta_y^* = 0.00025\ \mathrm{m}$

Optimum bending angle is 70% of original.

( balanced geometrical aberration and SR aberration )