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Final Focus Layouts and Stability Considerations

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Beam dynamics and technologies for future colliders

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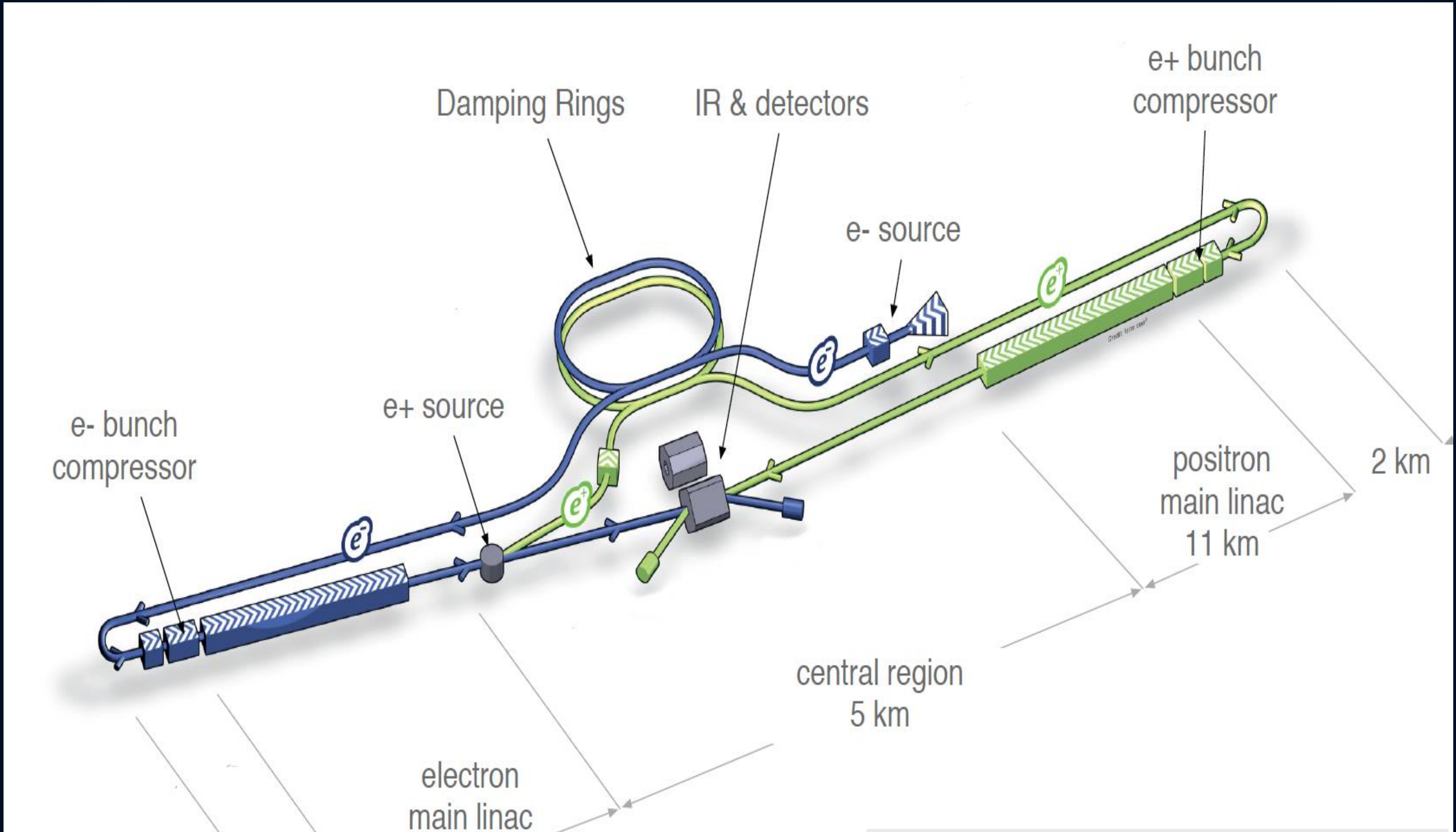
We will focus here on final focus design

As FF most challenging for linear colliders, we will first consider FF of LCs

We will then touch on stability issues of FFs of LCs

And then discuss design of FF in modern hadron or e+e- circular colliders

International Linear Collider ILC



ILC e^+e^- Linear Collider

Energy **250 GeV x 250 GeV**

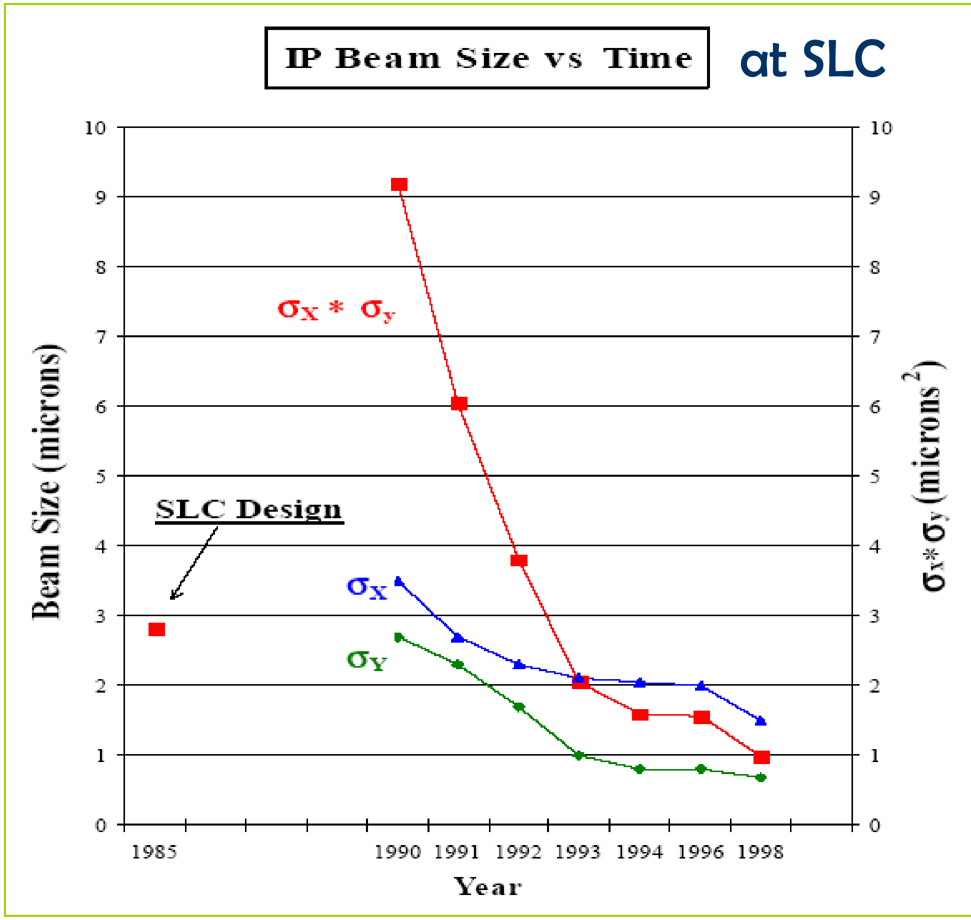
Linear Collider – two main challenges

- **Energy** – need to reach at least 250 GeV CM

- **Luminosity** – need to reach 10^34 level

The Luminosity Challenge

- Must jump by a Factor of 10000 in Luminosity !!! (from what is achieved in the only so far linear collider SLC)
- Many improvements, to ensure this : generation of smaller emittances, their better preservation, …



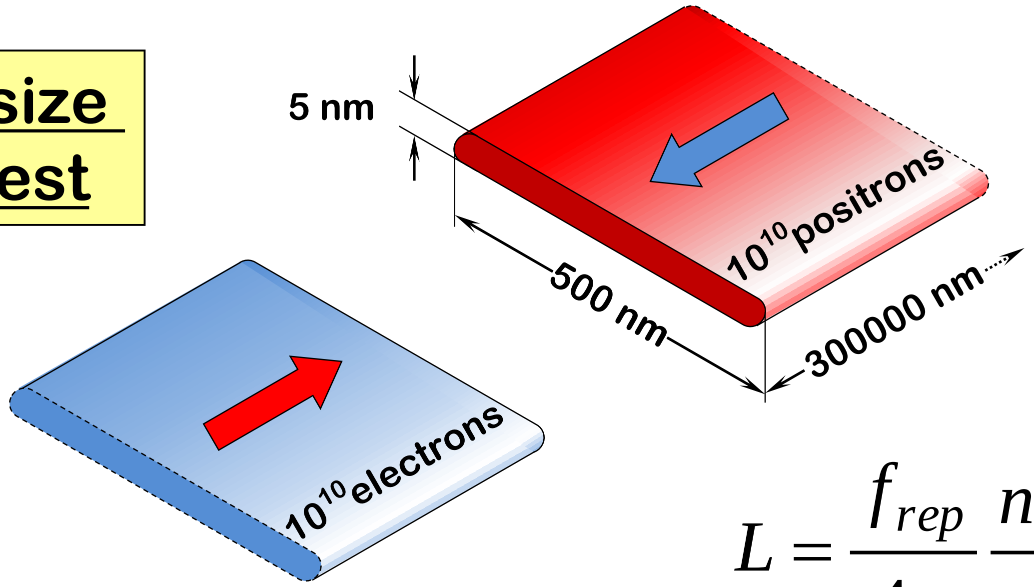
- Including better focusing, dealing with beam-beam, safely removing beams after collision and better stability

How to get higher Luminosity

- To increase probability of direct e^+e^- collisions (luminosity) and birth of new particles, beam sizes at IP must be very small
- E.g., ILC beam sizes just before collision (500GeV CM): 500 * 5 * 300000 nanometers

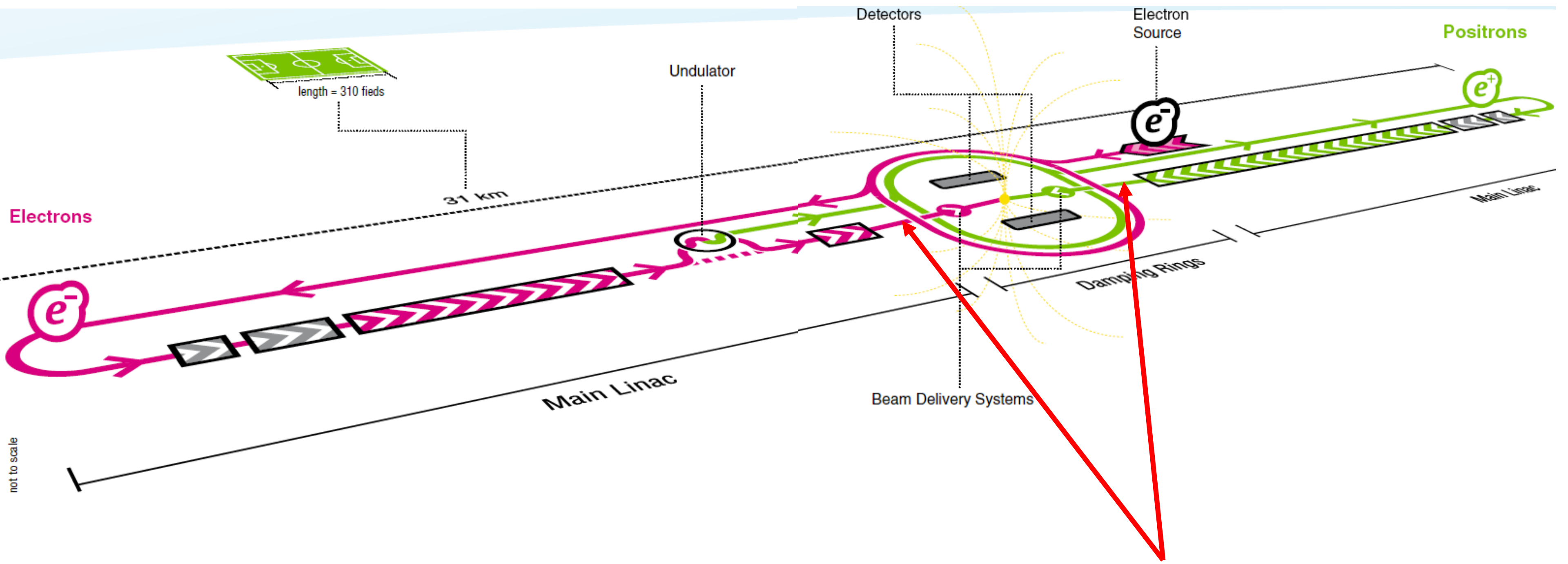
  (x y z)

Vertical size is smallest



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

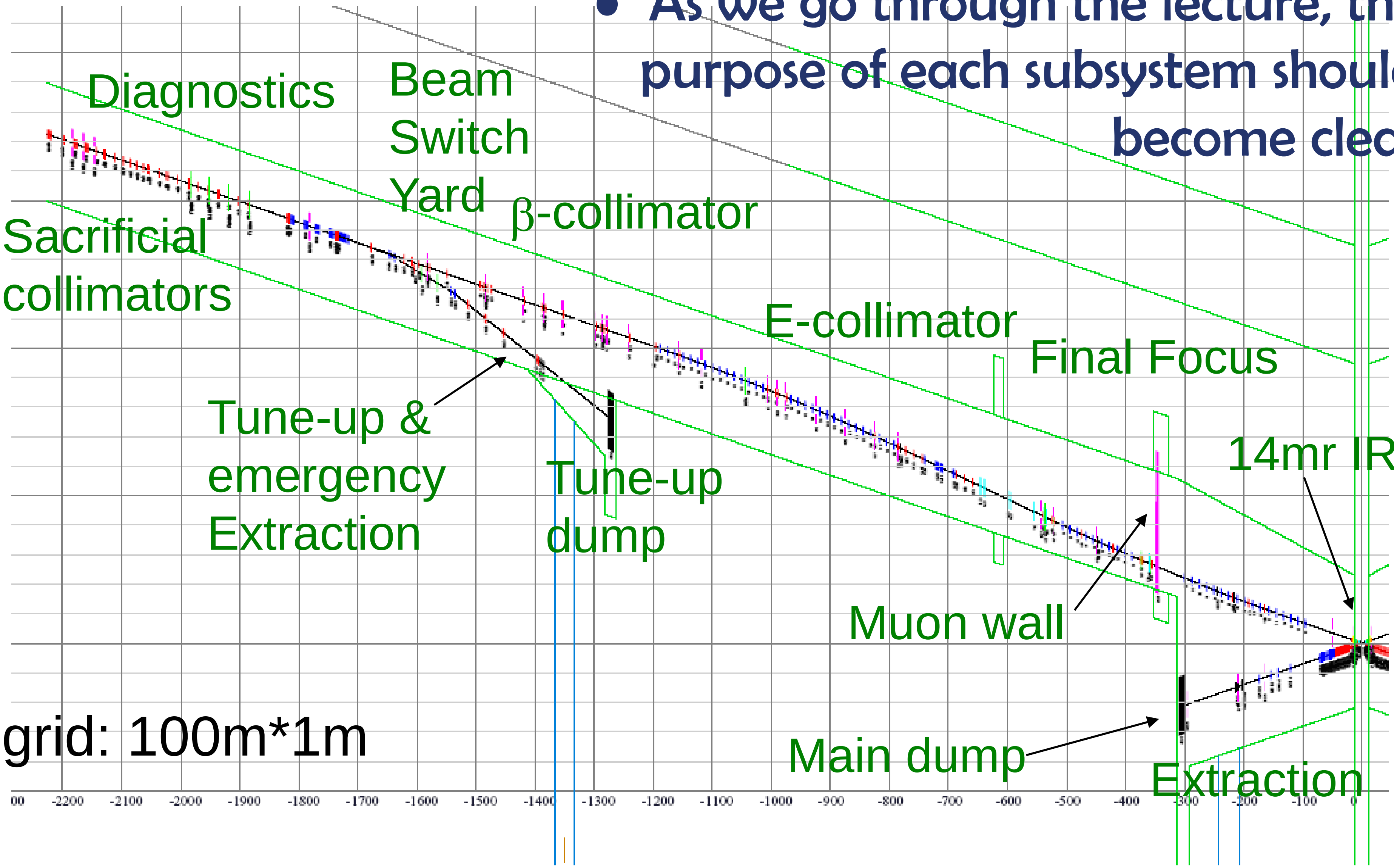
BDS: from end of linac to IP, to dumps



Beam Delivery System (BDS)
It includes FF, and many other systems

Beam Delivery subsystems

- As we go through the lecture, the purpose of each subsystem should become clear



Beam Delivery System tasks

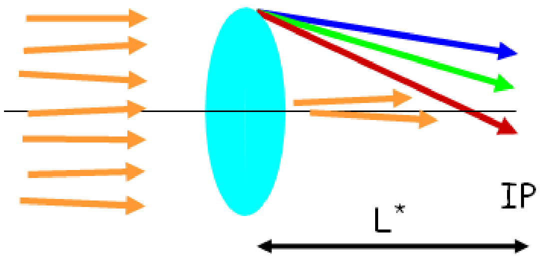
- measure the linac beam and match it into the final focus
- remove any large amplitude particles (beam-halo) from the linac to minimize background in the detectors
- measure and monitor the key physics parameters such as energy and polarization before and after the collisions
- ensure that the extremely small beams collide optimally at the IP
- protect the beamline and detector against mis-steered beams from the main linacs and safely extract them to beam dump
- provide possibility for two detectors to utilize single IP with efficient and rapid switch-over

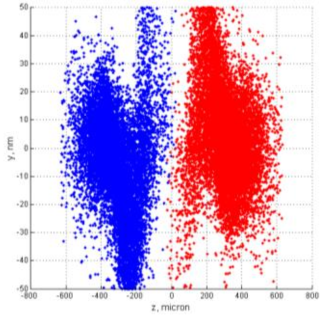
Parameters of ILC BDS

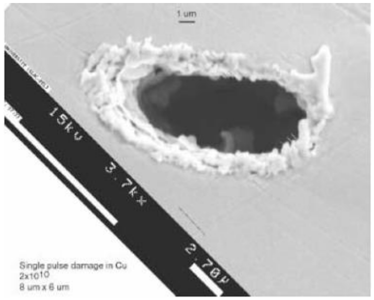
Length (linac exit to IP distance)/side	m	2226
Length of main (tune-up) extraction line	m	300 (467)
Max Energy/beam (with more magnets)	GeV	250 (500)
Distance from IP to first quad, L*	m	3.5-(4.5)
Crossing angle at the IP	mrad	14
Nominal beam size at IP, σ^*, x/y	nm	655/5.7
Nominal beam divergence at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

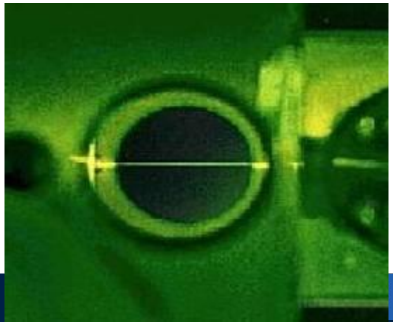
Factors driving design of BDS

- **Final Doublet chromaticity**
  - local compensation of chromaticity
- **Beam-beam effects**
  - background, IR and extraction design
- **SR emittance growth in BDS bends**
  - weak and long
- **Halo collimation**
  - survivability of spoilers
- **Beam diagnostics**
  - measurable size at laser wires
- **…**







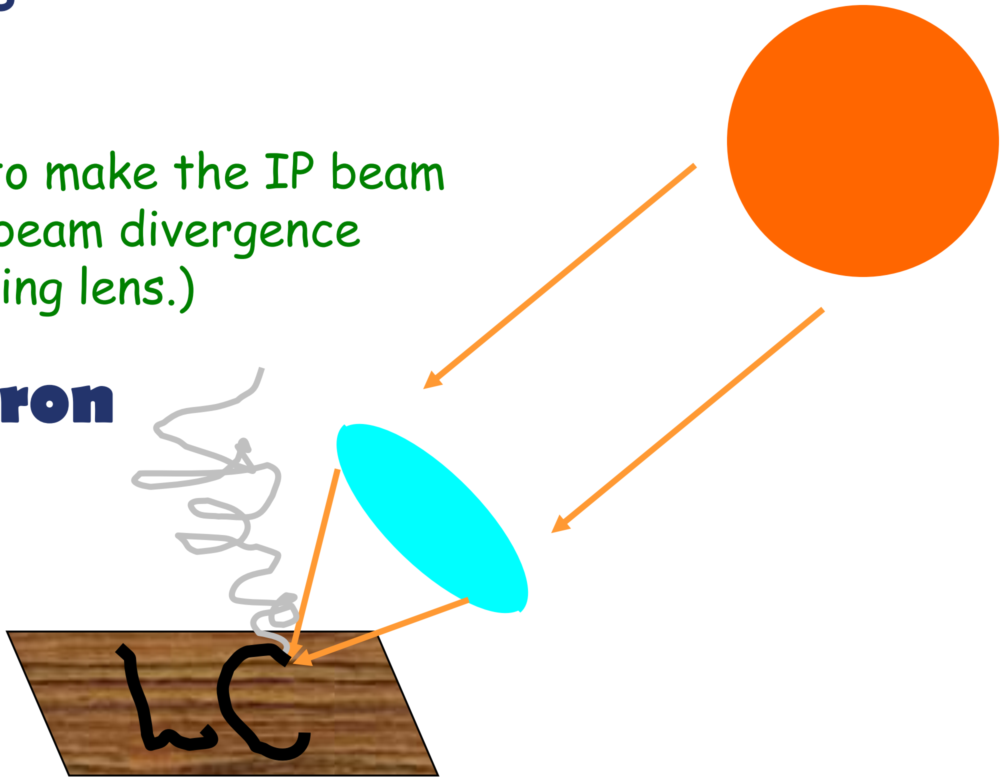


How to focus the beam to a smallest spot?

- If you ever played with a lens trying to burn a picture on a wood under bright sun, then you know that one needs a strong and big lens

(The emittance ε is constant, so, to make the IP beam size $(\varepsilon\ \beta)^{1/2}$ small, you need large beam divergence at the IP $(\varepsilon\ /\ \beta)^{1/2}$ i.e. short-focusing lens.)

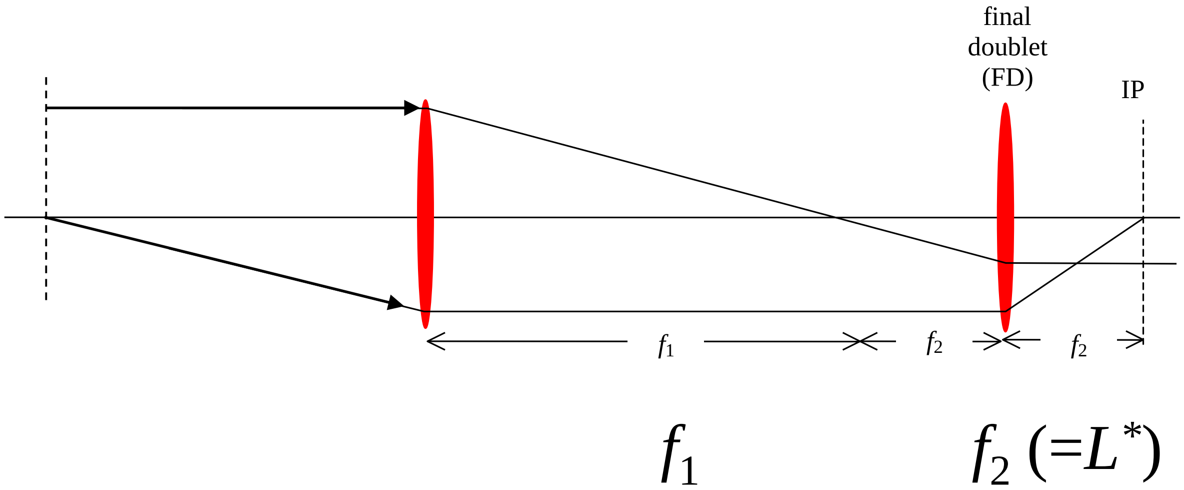
- It is very similar for **electron** or **positron** beams
- But one have to use **magnets**



Optics building block: telescope

Essential part of final focus is final telescope. It "demagnify" the incoming beam ellipse to a smaller size. Matrix transformation of such telescope is diagonal:

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



A minimal number of quadrupoles, to construct a telescope with arbitrary demagnification factors, is four.

Use telescope optics to demagnify beam by factor $m = f1/f2 = f1/L^*$

If there would be no energy spread in the beam, a telescope could serve as your final focus (or two telescopes chained together).

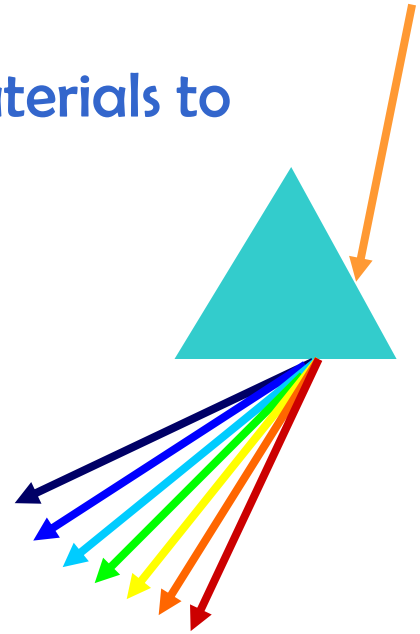
Matrix formalism for beam transport:

$$x_i^{out} = R_{ij}\ x_j^{in}$$

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

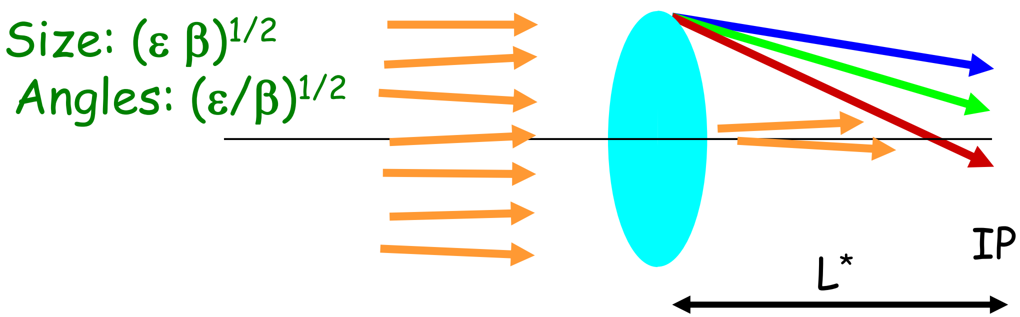
Why nonlinear elements

- As sun **light** contains different colors, **electron beam** has energy spread and get dispersed and distorted => **chromatic aberrations**
- For **light**, one uses lenses made from different materials to compensate chromatic aberrations



- Chromatic compensation for particle beams is done with **nonlinear** magnets
  - Problem: Nonlinear elements create **geometric** aberrations
- The **task** of **Final Focus system** (FF) is to focus the beam to required size and compensate aberrations

How to focus to a smallest size and how big is chromaticity in FF?



Size at IP:
$L^*\ (\varepsilon/\beta)^{1/2}$
$+\ (\varepsilon\ \beta)^{1/2}\ \sigma_E$

Beta at IP:
$L^*\ (\varepsilon/\beta)^{1/2} = (\varepsilon\ \beta^*)^{1/2}$
$\Rightarrow\ \beta^* = L^{*2}/\beta$

Chromatic dilution:
$(\varepsilon\ \beta)^{1/2}\ \sigma_E\ /\ (\varepsilon\ \beta^*)^{1/2}$
$= \sigma_E\ L^*/\beta^*$

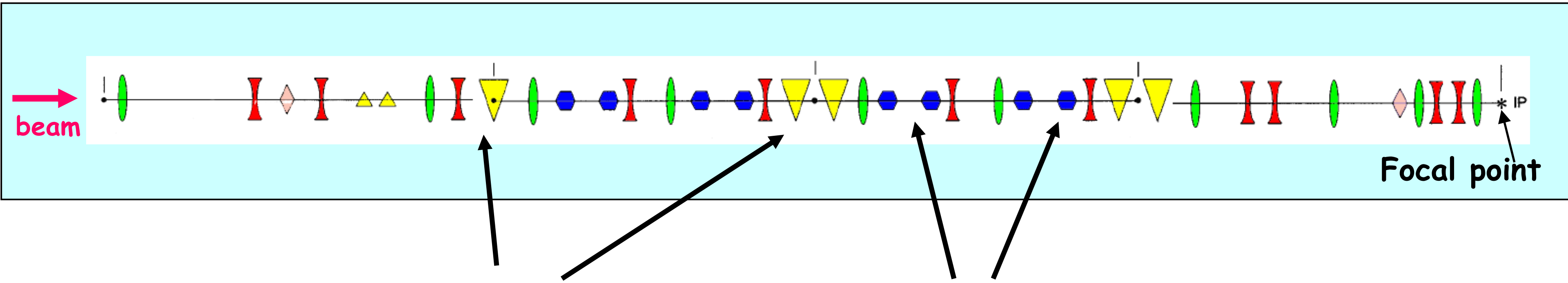
- The final lens need to be the strongest
  - (two lenses for both x and y => "Final Doublet" or FD)
- FD determines chromaticity of FF
- Chromatic dilution of the beam size is $\Delta\sigma/\sigma \sim \sigma_E\ L^*/\beta^*$

Typical:
σ_E -- energy spread in the beam ~ 0.002-0.01
L^* -- distance from FD to IP ~ 3 - 5 m
β^* -- beta function in IP ~ 0.4 - 0.1 mm

- For typical parameters, $\Delta\sigma/\sigma$ ~ 15-500 too big !
- => Chromaticity of FF need to be compensated

Example of traditional Final Focus

Sequence of elements in ~100m long Final Focus Test Beam



Dipoles. They bend trajectory, but also disperse the beam so that x depend on energy offset δ

Sextupoles. Their kick will contain energy dependent focusing

$x' \Rightarrow S\,(x+\delta)^2 \Rightarrow 2S\,x\,\delta + ..$

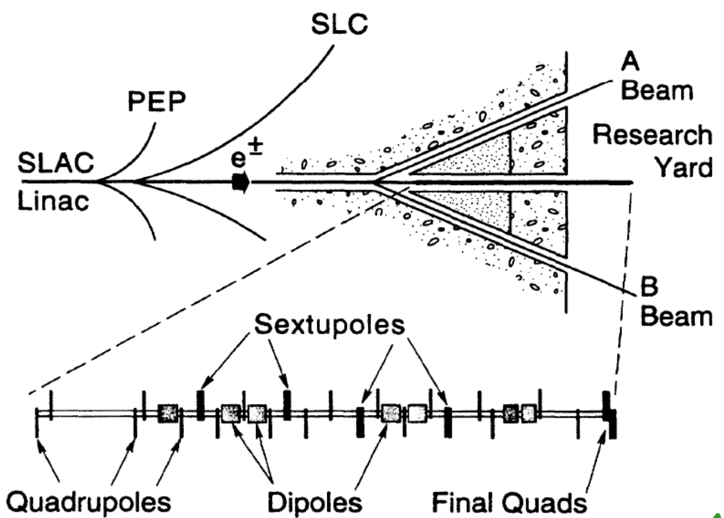
$y' \Rightarrow -S\,2(x+\delta)y \Rightarrow -2S\,y\,\delta + ..$

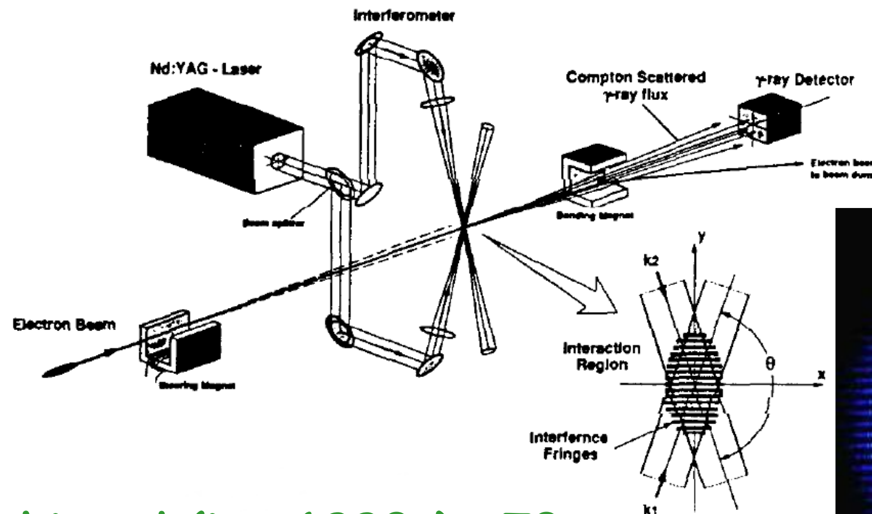
that can be used to arrange chromatic correction

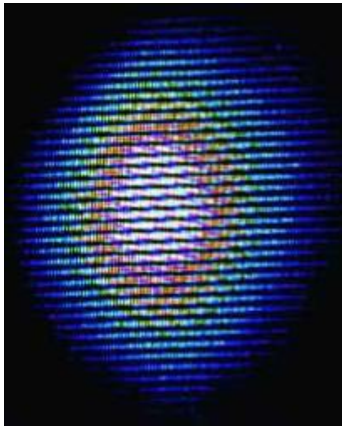
Terms x^2 are geometric aberrations and need to be compensated also

Necessity to compensate chromaticity is a major driving factor of FF design

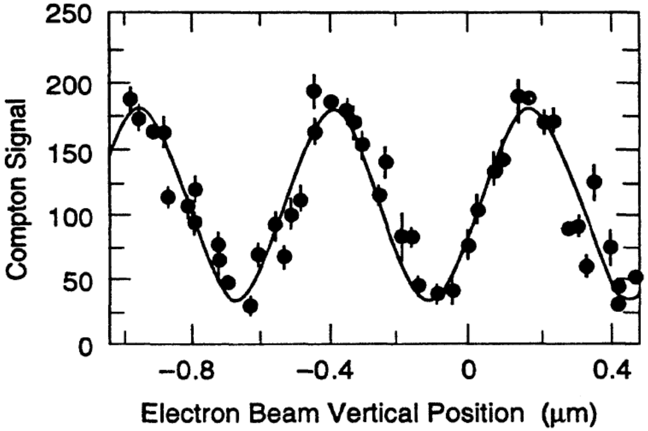
Final Focus Test Beam –
optics with traditional non-local chromaticity compensation



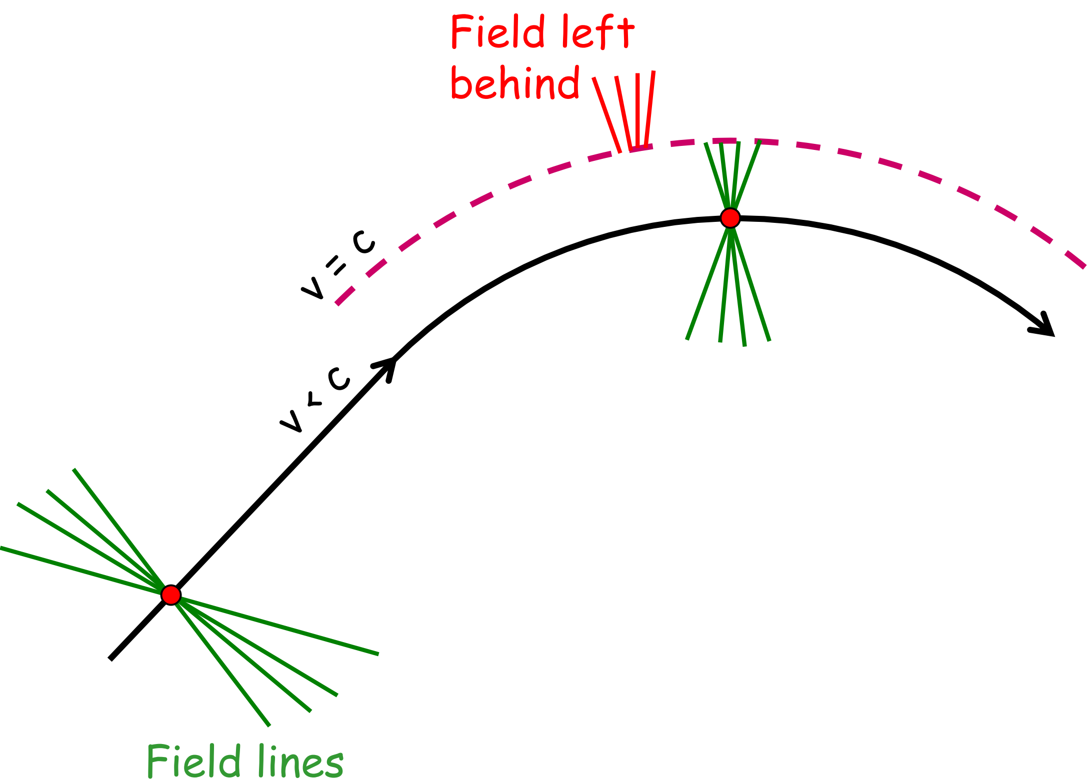




Achieved (in ~1990s) ~70nm vertical beam size



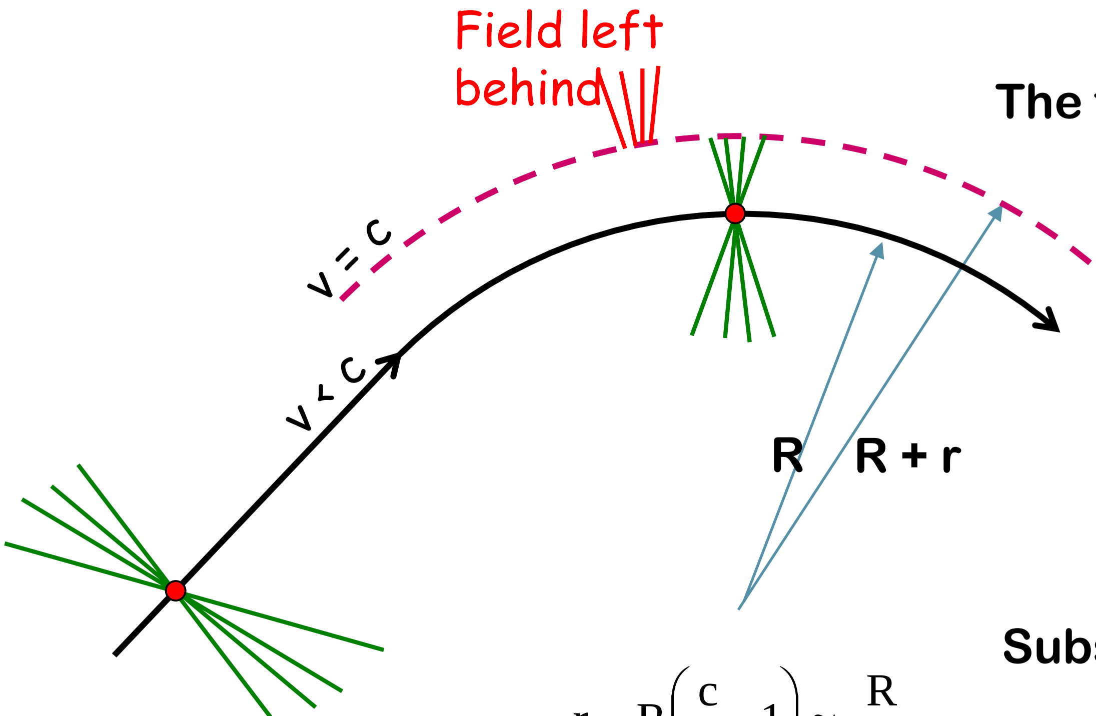
Synchrotron Radiation in FF magnets



- Bends are needed for compensation of chromaticity
- SR causes increase of energy spread which may perturb compensation of chromaticity
- Bends need to be long and weak, especially at high energy
- SR in FD quads is also harmful (Oide effect) and may limit the achievable beam size

Energy spread caused by SR in bends and quads is also a major driving factor of FF design

Synchrotron radiation
on-the-back-of-the envelope – power loss

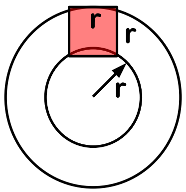


$$r = R\left(\frac{c}{v} - 1\right) \approx \frac{R}{2\gamma^2}$$

Energy in the field left behind (radiated !):

$$W \approx \int E^2 \, dV$$

The field $E \approx \dfrac{e}{r^2}$ **the volume** $V \approx r^2 \, dS$



Energy loss per unit length:

$$\frac{dW}{dS} \approx E^2 r^2 \approx \left(\frac{e}{r^2}\right)^2 r^2$$

Substitute $r \approx \dfrac{R}{2\gamma^2}$ **and get an estimate:**

$$\frac{dW}{dS} \approx \frac{e^2\gamma^4}{R^2}$$

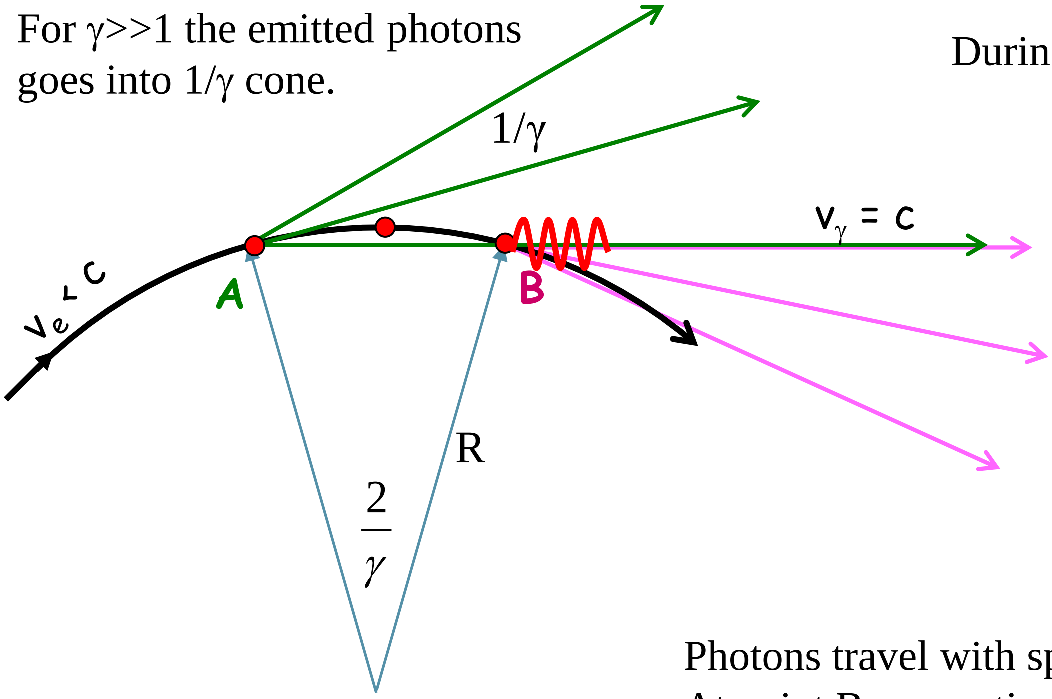
Gaussian units on this page!

Compare with exact formula: $\dfrac{dW}{dS} = \dfrac{2}{3}\dfrac{e^2\gamma^4}{R^2}$

Estimation of characteristic frequency of SR photons

For γ>>1 the emitted photons goes into $1/\gamma$ cone.

During what time Δt the observer will see the photons?



Photons emitted during travel along the $2R/\gamma$ arc will be observed.

Photons travel with speed c, while particles with v.
At point B, separation between photons and particles is

$$dS \approx \frac{2R}{\gamma}\left(1 - \frac{v}{c}\right)$$

Therefore, observer will see photons during $\Delta t \approx \frac{dS}{c} \approx \frac{2R}{c\gamma}(1-\beta) \approx \frac{R}{c\gamma^3}$

Estimation of characteristic frequency $\boxed{\omega_c \approx \frac{1}{\Delta t} \approx \frac{c\gamma^3}{R}}$

Compare with exact formula: $\omega_c = \frac{3}{2}\frac{c\gamma^3}{R}$

Estimation of energy spread growth due to SR

We estimated the rate of energy loss : $\frac{dW}{dS} \approx \frac{e^2 \gamma^4}{R^2}$ And the characteristic frequency $\omega_c \approx \frac{c\gamma^3}{R}$

The photon energy $\varepsilon_c = \eta\omega_c \approx \frac{\gamma^3 \eta c}{R} = \frac{\gamma^3}{R}\lambda_e mc^2$ where $r_e = \frac{e^2}{mc^2}$ $\alpha = \frac{e^2}{\eta c}$ $\lambda_e = \frac{r_e}{\alpha}$

Number of photons emitted per unit length $\frac{dN}{dS} \approx \frac{1}{\varepsilon_c}\frac{dW}{dS} \approx \frac{\alpha\gamma}{R}$ (per angle θ : $N \approx \alpha\gamma\theta$)

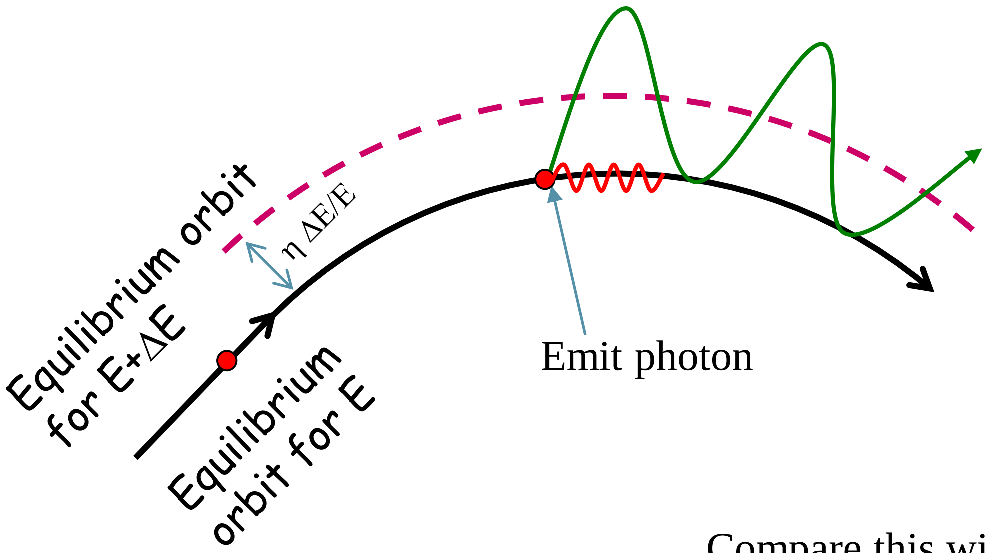
The energy spread $\Delta E/E$ will grow due to statistical fluctuations ($\sqrt{N}$) of the number of emitted photons :

$$\frac{d\left((\Delta E/E)^2\right)}{dS} \approx \varepsilon_c^2 \frac{dN}{dS}\frac{1}{(\gamma mc^2)^2}$$

Which gives: $$\frac{d\left((\Delta E/E)^2\right)}{dS} \approx \frac{r_e \lambda_e \gamma^5}{R^3}$$

Compare with exact formula: $$\frac{d\left((\Delta E/E)^2\right)}{dS} = \frac{55}{24\sqrt{3}}\frac{r_e \lambda_e \gamma^5}{R^3}$$

Estimation of emittance growth rate due to SR



Dispersion function η shows how equilibrium orbit shifts when energy changes

When a photon is emitted, the particle starts to oscillate around new equilibrium orbit

Amplitude of oscillation is $\Delta x \approx \eta \, \Delta E/E$

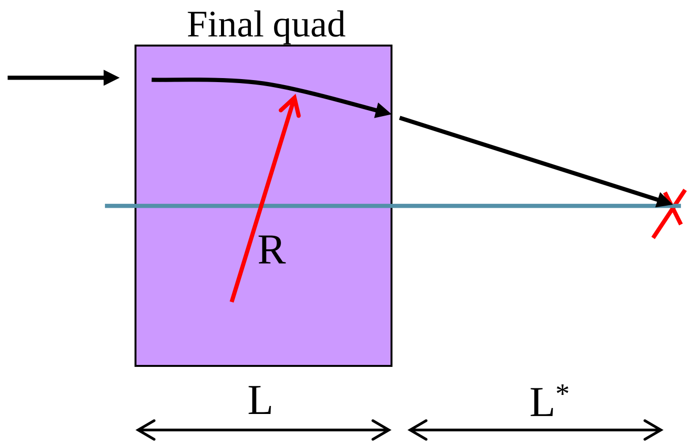
Compare this with betatron beam size: $\sigma_x = (\varepsilon_x \, \beta_x)^{1/2}$

And write emittance growth: $\Delta\varepsilon_x \approx \dfrac{\Delta x^2}{\beta}$

Resulting estimation for emittance growth: $$\frac{d\varepsilon_x}{dS} \approx \frac{\eta^2}{\beta_x} \frac{d\left((\Delta E/E)^2 \right)}{dS} \approx \boxed{\frac{\eta^2}{\beta_x} \frac{r_e \, \lambda_e \, \gamma^5}{R^3}}$$

Compare with exact formula (which also takes into account the derivatives): $$\frac{d\varepsilon_x}{dS} = \underbrace{\boxed{\frac{\left(\eta^2 + (\beta_x \eta' - \beta'_x \eta /2)^2 \right)}{\beta_x}}}_{= \mathcal{H}} \frac{55}{24\sqrt{3}} \frac{r_e \, \lambda_e \, \gamma^5}{R^3}$$

Let's apply SR formulae to estimate Oide effect (SR in FD)



IP divergence:

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

IP size:

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

Energy spread obtained in the quad:

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

Radius of curvature of the trajectory: $R = L / \theta^*$

Growth of the IP beam size: $\sigma^2 \approx \sigma_0^2 + \left(L^*\,\theta^*\right)^2 \left(\frac{\Delta E}{E}\right)^2$

Which gives $\sigma^2 \approx \varepsilon\,\beta^* + C_1 \left(\frac{L^*}{L}\right)^2 r_e\,\lambda_e\,\gamma^5 \left(\frac{\varepsilon}{\beta^*}\right)^{5/2}$ (where C_1 is ~ 7 (depend on FD params.))

This achieve minimum possible value:

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

When beta* is:

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

Note that beam distribution at IP will be non-Gaussian. Usually need to use tracking to estimate impact on luminosity. Note also that optimal β may be smaller than the σ_z (i.e cannot be used).

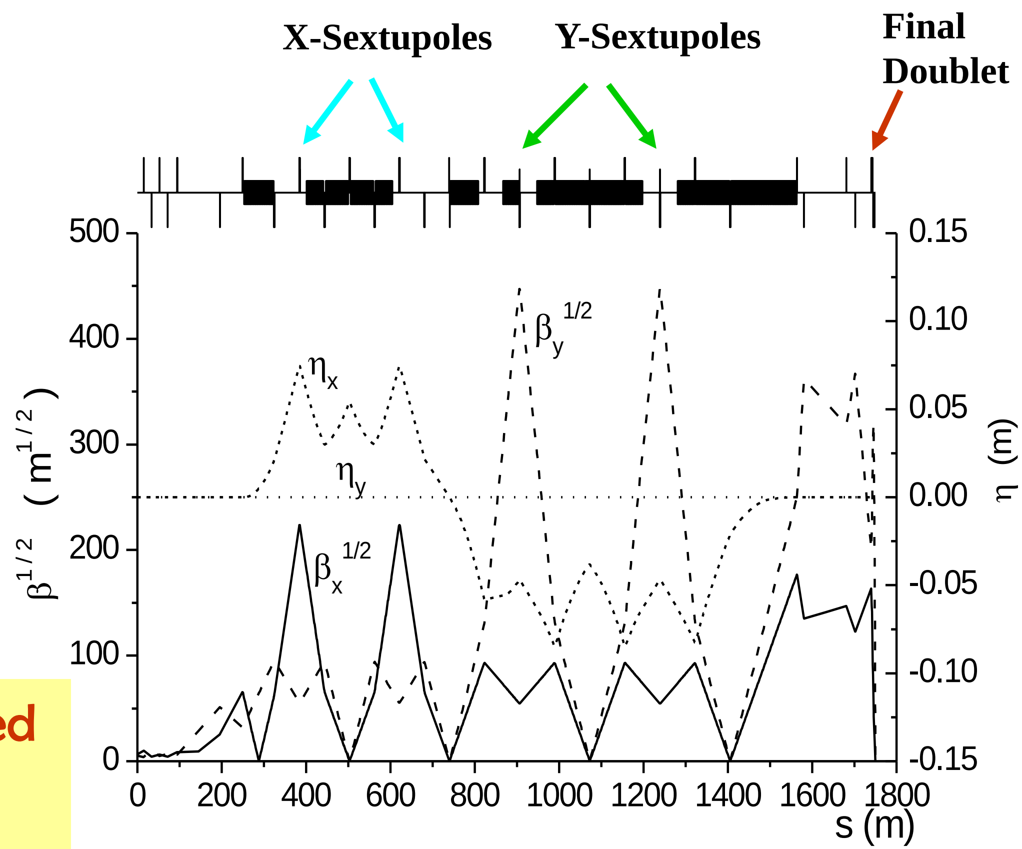
TeV FF with non-local chromaticity compensation

- Chromaticity is compensated by sextupoles in dedicated sections
- Geometrical aberrations are canceled by using sextupoles in pairs with M= -I

Chromaticity arise at FD but pre-compensated 1000m upstream

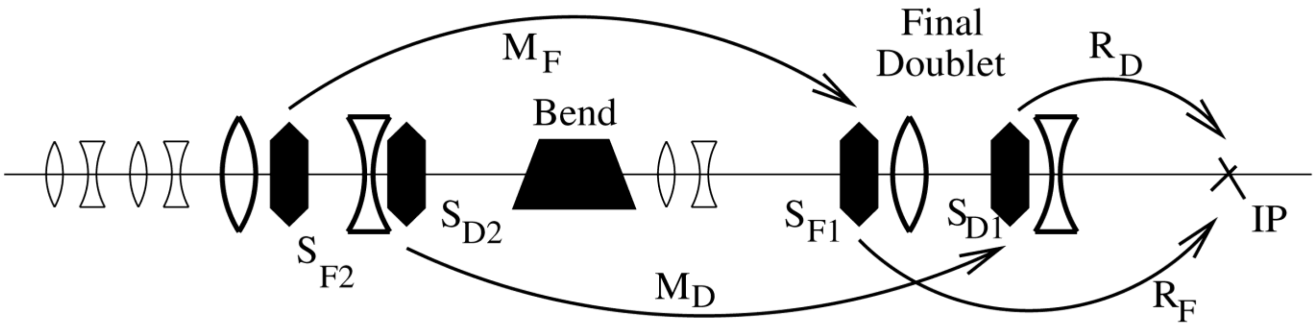
Problems:

- Chromaticity <u>not locally</u> compensated
  - Compensation of aberrations is not ideal since M ≠ -I for off energy particles
  - Large aberrations for beam tails



Traditional FF (NLC FF, circa 1999) L*=2m, TeV energy reach

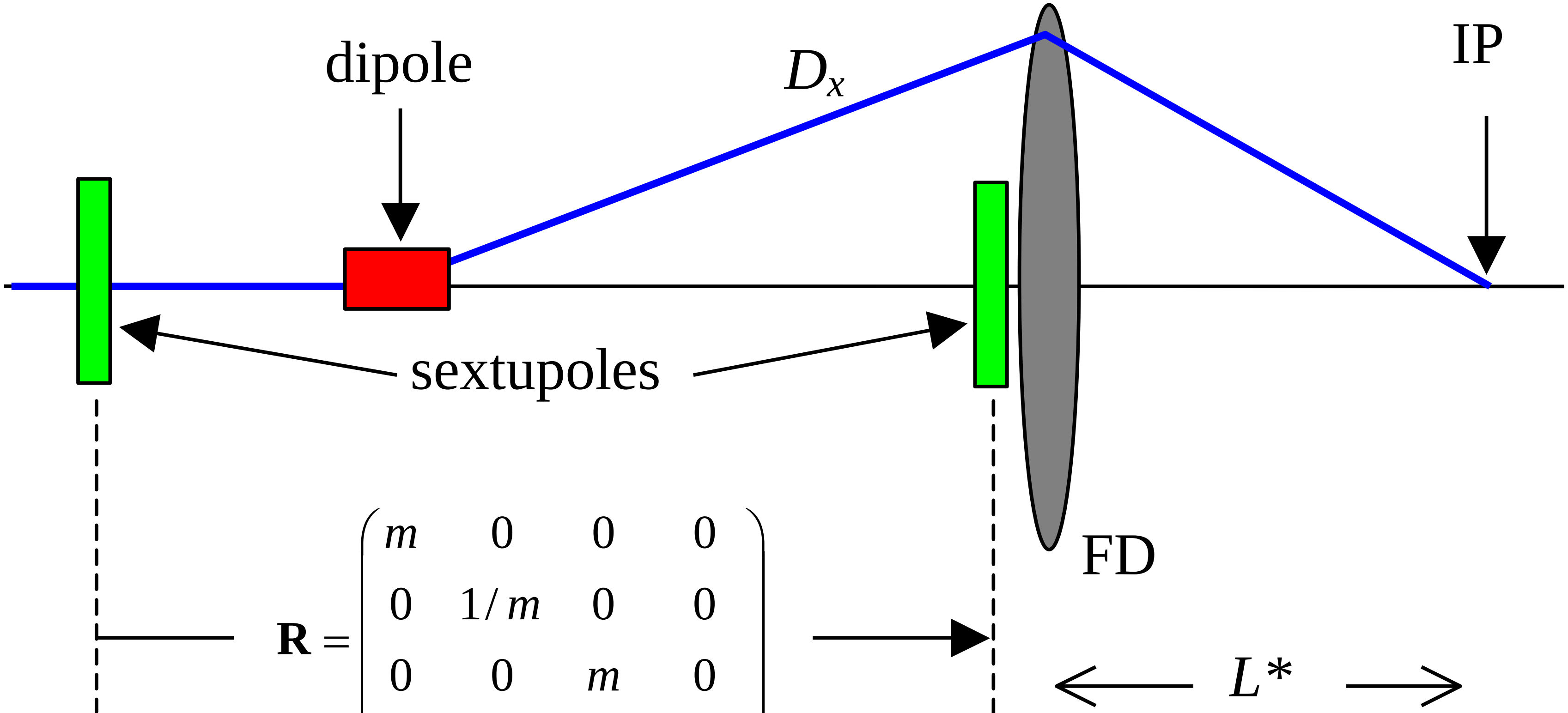
FF with local chromatic correction



- **Chromaticity is cancelled <u>locally</u> by two sextupoles interleaved with FD, a bend upstream generates dispersion across FD**
- **2nd order dispersion produced in FD is cancelled locally provided that half of horizontal chromaticity arrive from upstream**
- **Geometric aberrations of the FD sextupoles are cancelled by two more sextupoles placed in phase with them and upstream of the bend**
- **Higher order aberrations are cancelled by optimizing transport matrices between sextupoles**

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

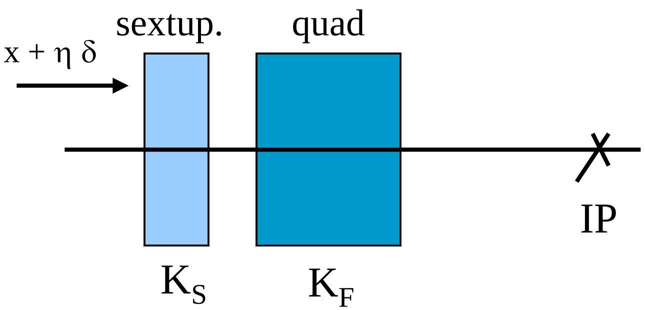
Local chromatic correction



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

- The value of dispersion in FD is usually chosen so that it does not increase the beam size in FD by more than 10-20% for typical beam energy spread

Chromatic correction in FD



- Straightforward in Y plane
- a bit tricky in X plane:

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

chromaticity

Second order dispersion

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

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

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

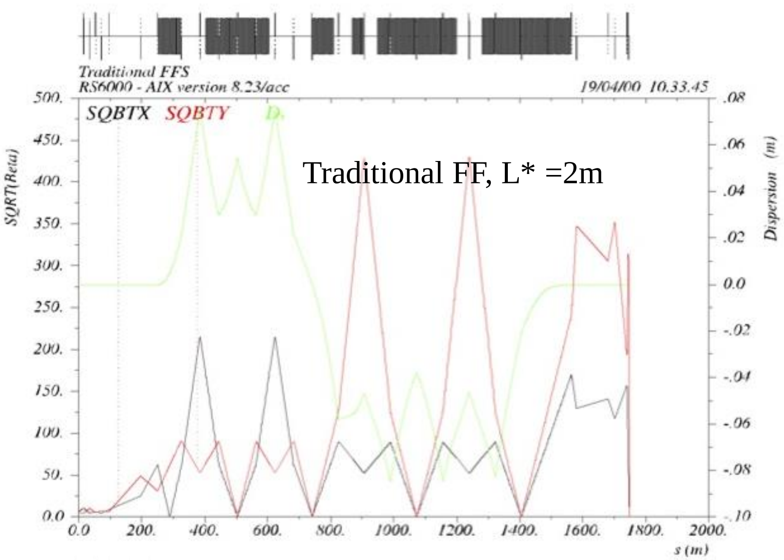
$$K_{\beta\text{-match}} = K_F \qquad K_S = \frac{2K_F}{\eta}$$

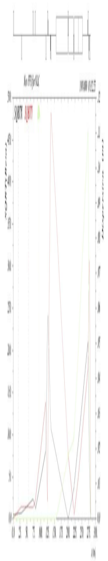
Solution:
The β-matching section produces as much X chromaticity as the FD, so the X sextupoles run twice stronger and cancel the **second order dispersion** as well.

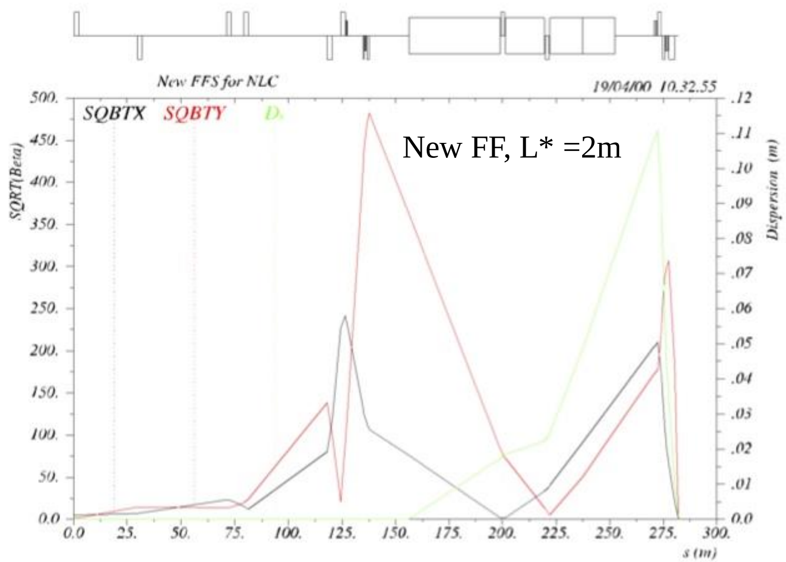
Compare FF designs

FF with local chromaticity compensation with the same performance can be ~300m long, i.e. 6 times shorter

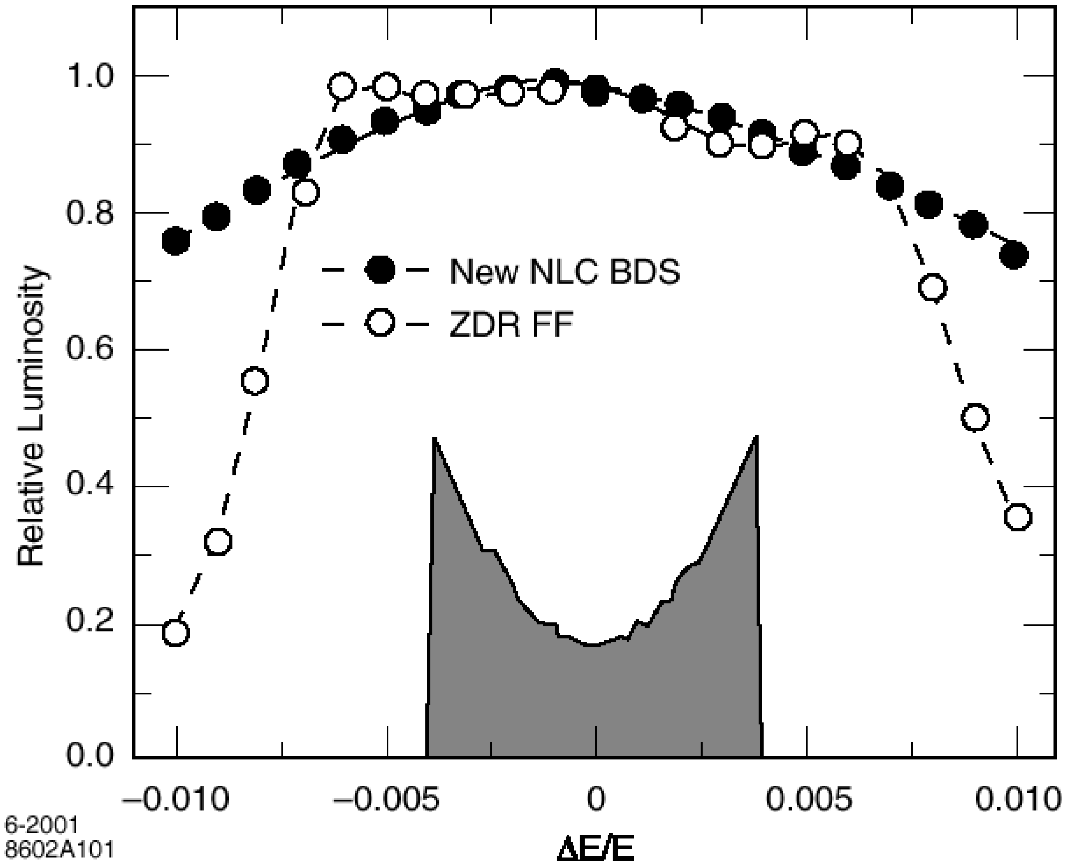
Moreover, its necessary length scales only as $E^{2/5}$ with energy! One can design multi-TeV FF in under a km!







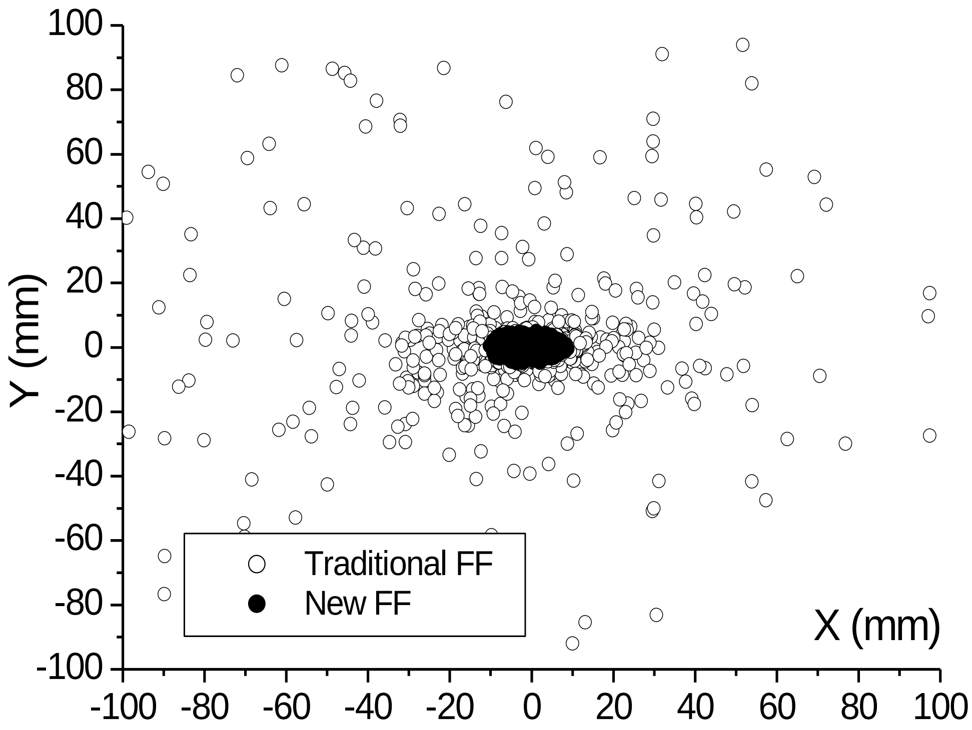
IP bandwidth

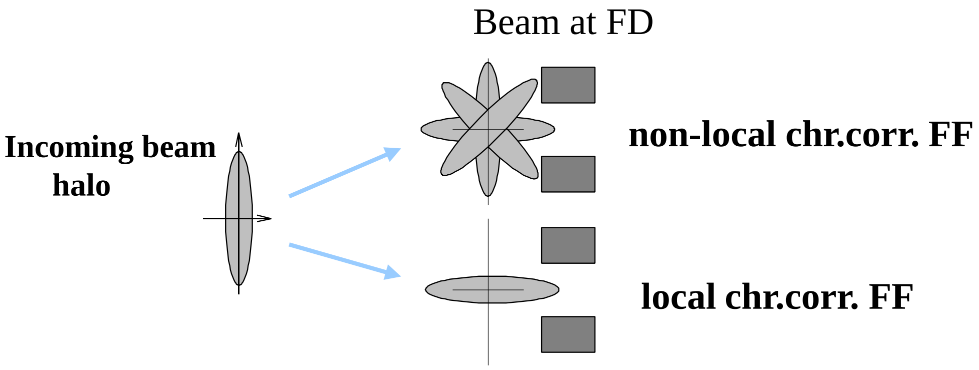


Bandwidth of FF with local chromaticity correction can be better than for system with non-local correction

Aberrations & halo generation in FF

- FF with non-local chr. corr. generate beam tails due to aberrations and it does not preserve betatron phase of halo particles
- FF with local chr. corr. has much less aberrations and it does not mix phases particles

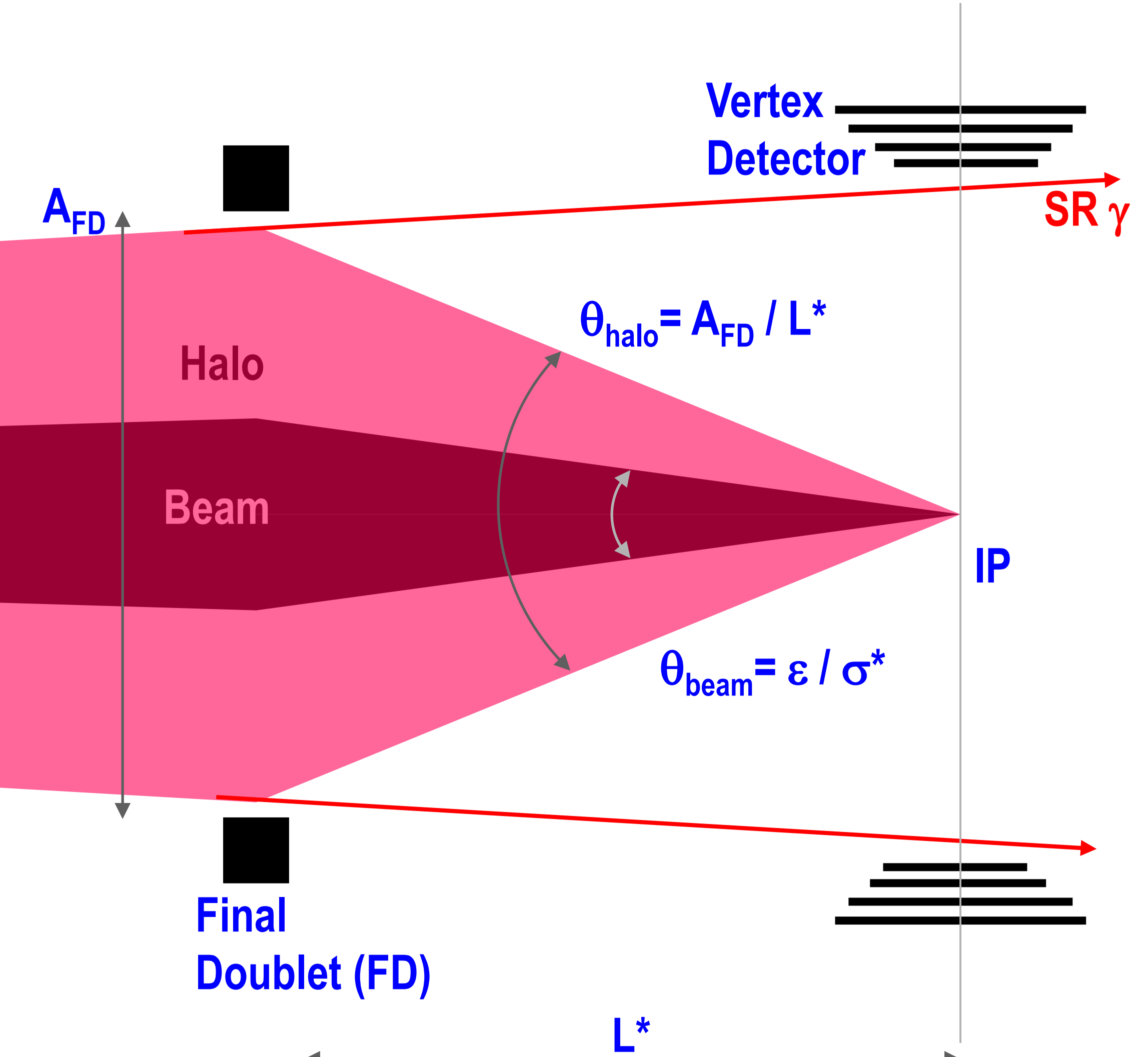




Halo beam at the FD entrance. Incoming beam is ~ 100 times larger than nominal beam

Beam halo & collimation

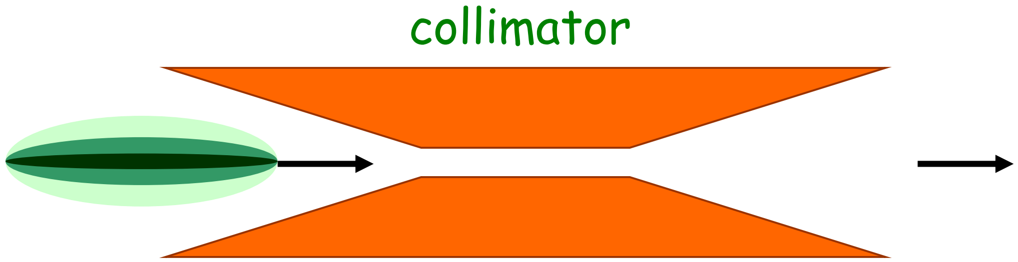
- Even if final focus does not generate beam halo itself, the halo may come from upstream and need to be collimated

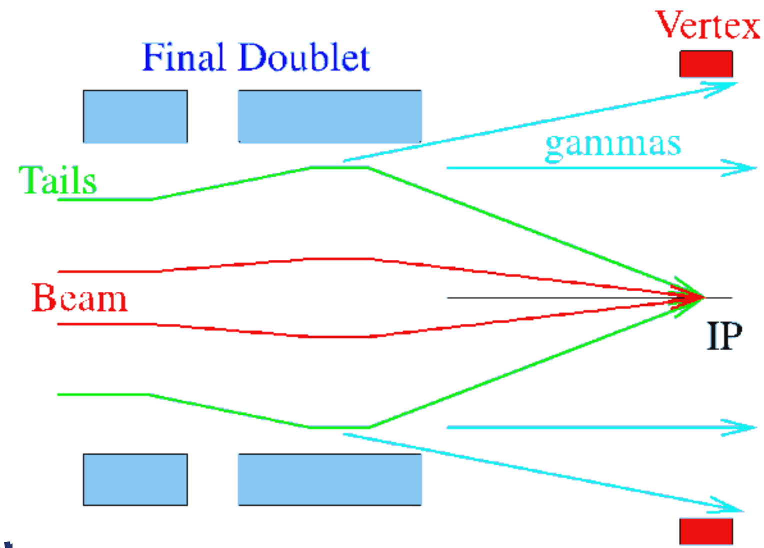


- Halo must be collimated upstream in such a way that SR γ & halo e^{+-} do not touch VX and FD
- => VX aperture needs to be somewhat larger than FD aperture
- Exit aperture is larger than FD or VX aperture
- Beam convergence depend on parameters, the halo convergence is fixed for given geometry
=> $\theta_{halo}/\theta_{beam}$ (collimation depth) becomes tighter with larger L* or smaller IP beam size
- Tighter collimation => MPS issues, collimation wake-fields, higher muon flux from collimators, etc.

More details on collimation

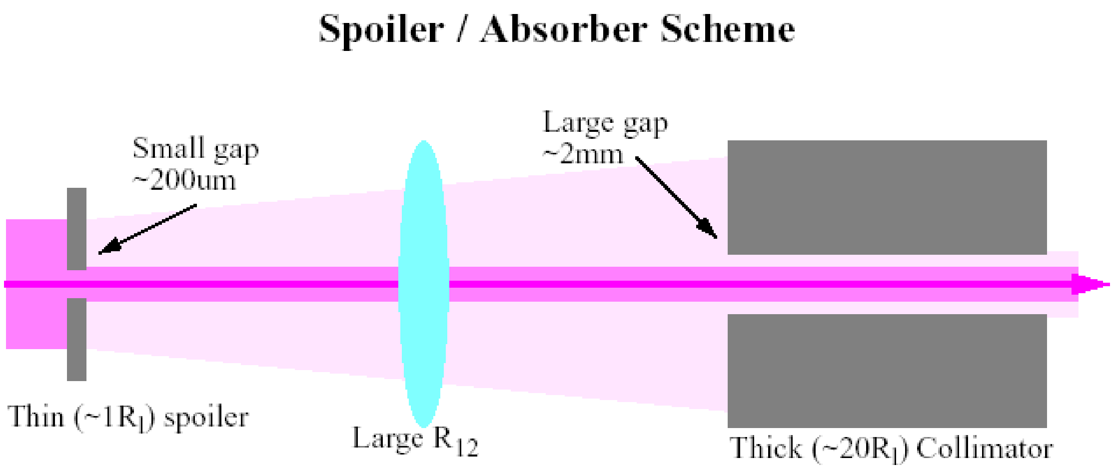
- Collimators has to be placed far from IP, to minimize background
- Ratio of beam/halo size at FD and collimator (placed in “FD phase”) remains





- Collimation depth (esp. in x) can be only ~10 or even less
- It is not unlikely that not only halo (1e-3 – 1e-6 of the beam) but full errant bunch(s) would hit the collimator

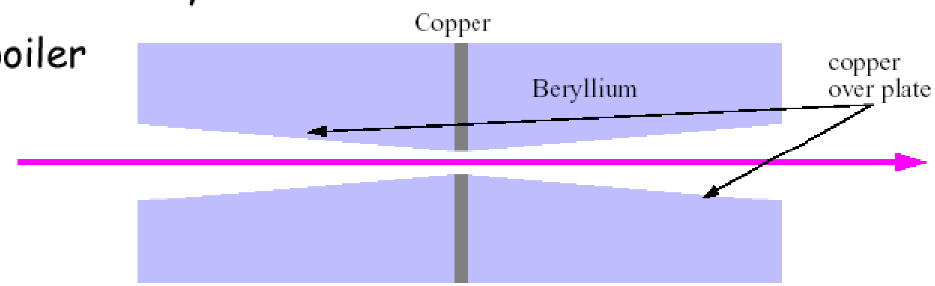
Spoiler-Absorber & spoiler design

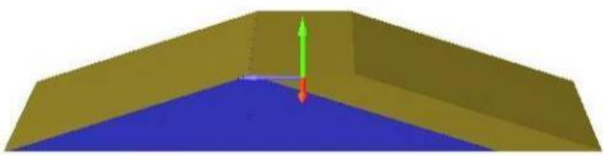


Thin spoiler increases beam divergence and size at the thick absorber already sufficiently large. Absorber is away from the beam and contributes much less to wakefields.

Tapered low resistivity surface for wakefields

Thin hi-Z spoiler



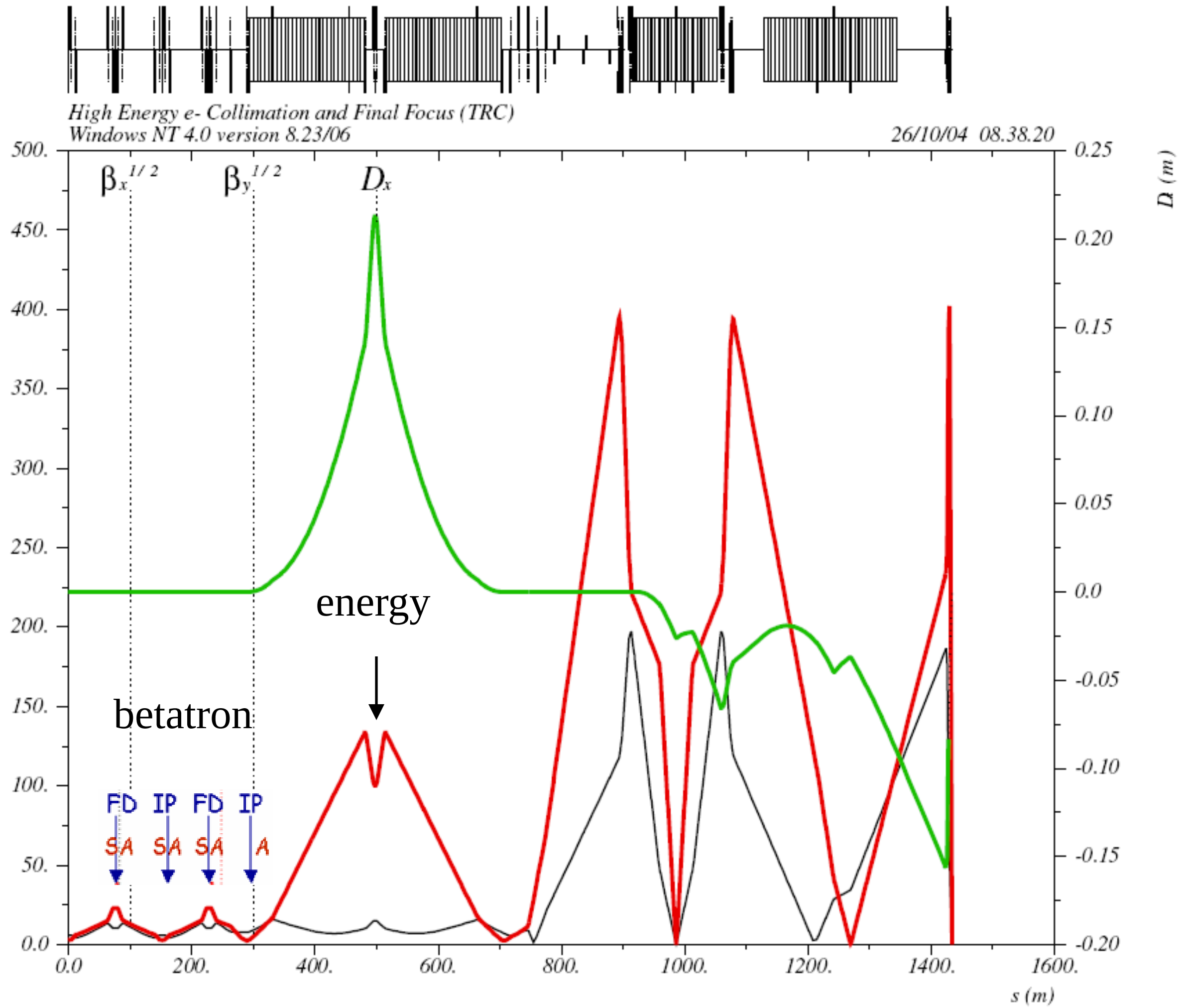


Possible design:
0.6 Xo of Ti alloy leading taper (gold), graphite (blue), 1 mm thick layer of Ti alloy

Need the spoiler thickness increase rapidly, but need that surface to increase gradually, to minimize wakefields. The radiation length for Cu is 1.4cm and for Be is 35cm. So, Be is invisible to beam in terms of losses. Thin one micron coating over Be provides smooth surface for wakes.

FF and Collimation

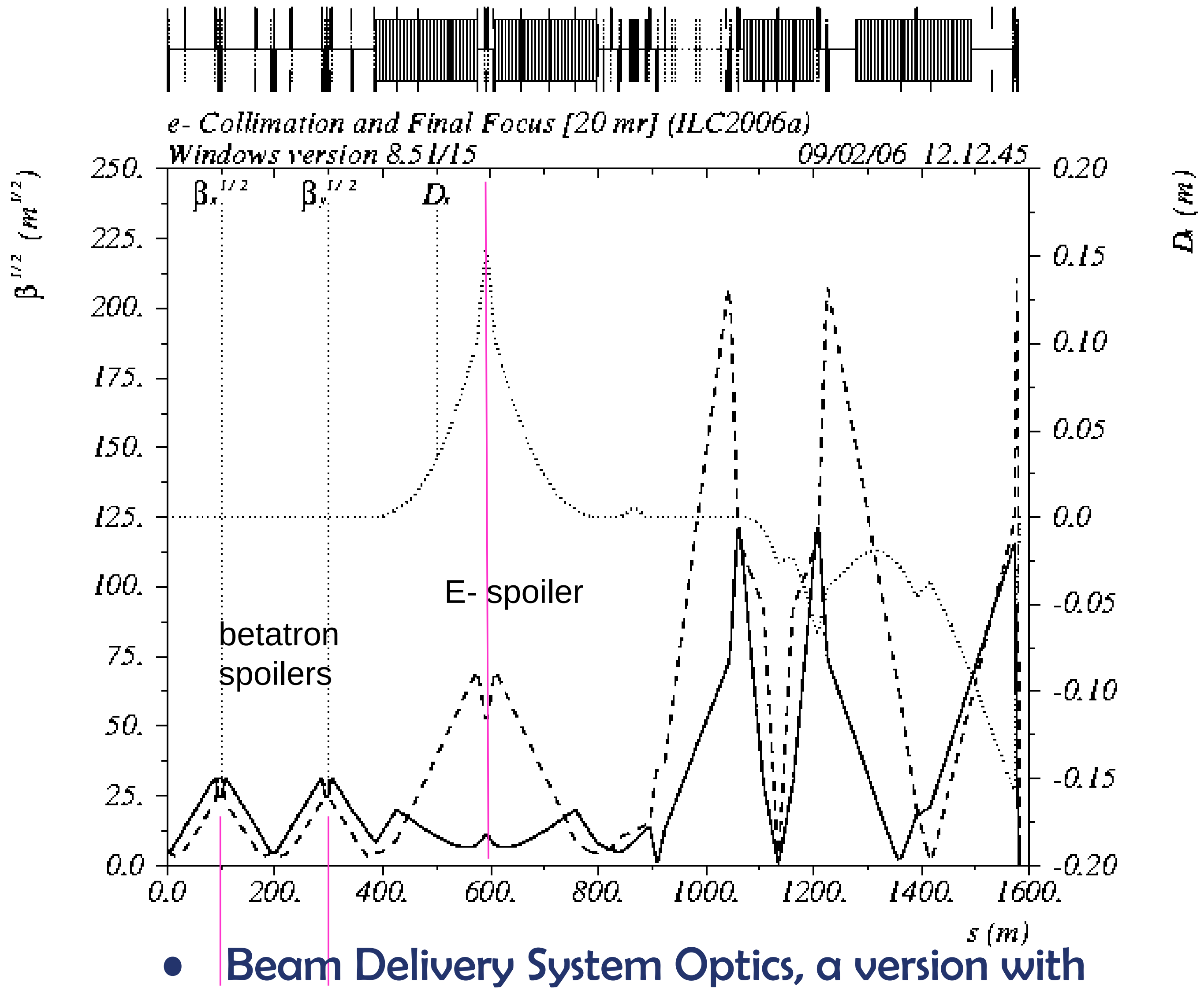
- Location of spoiler and absorbers is shown
- Collimators were placed both at FD betatron phase and at IP phase
- Two spoilers per FD and IP phase
- Energy collimator is placed in the region with large dispersion
- Secondary clean-up collimators located in FF part
- Tail folding octupoles (see below) are included



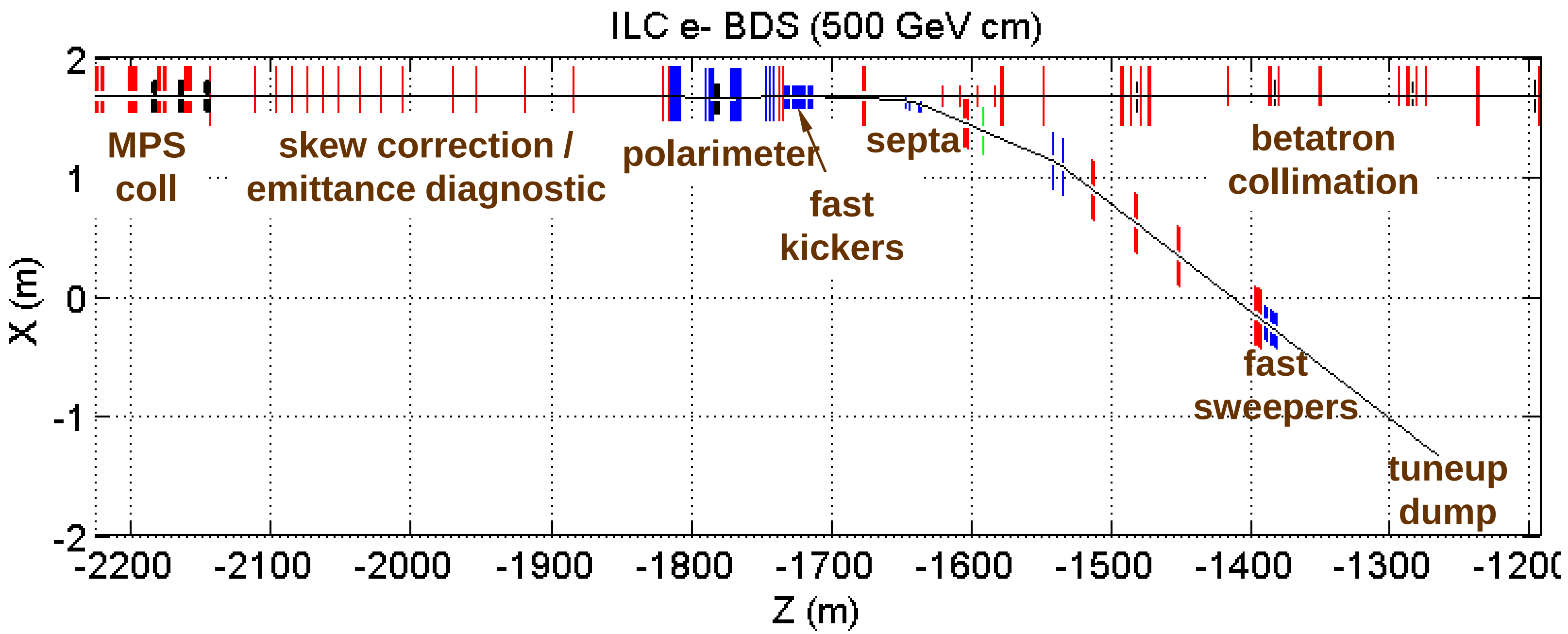
- Beam Delivery System Optics, a version with consumable spoilers

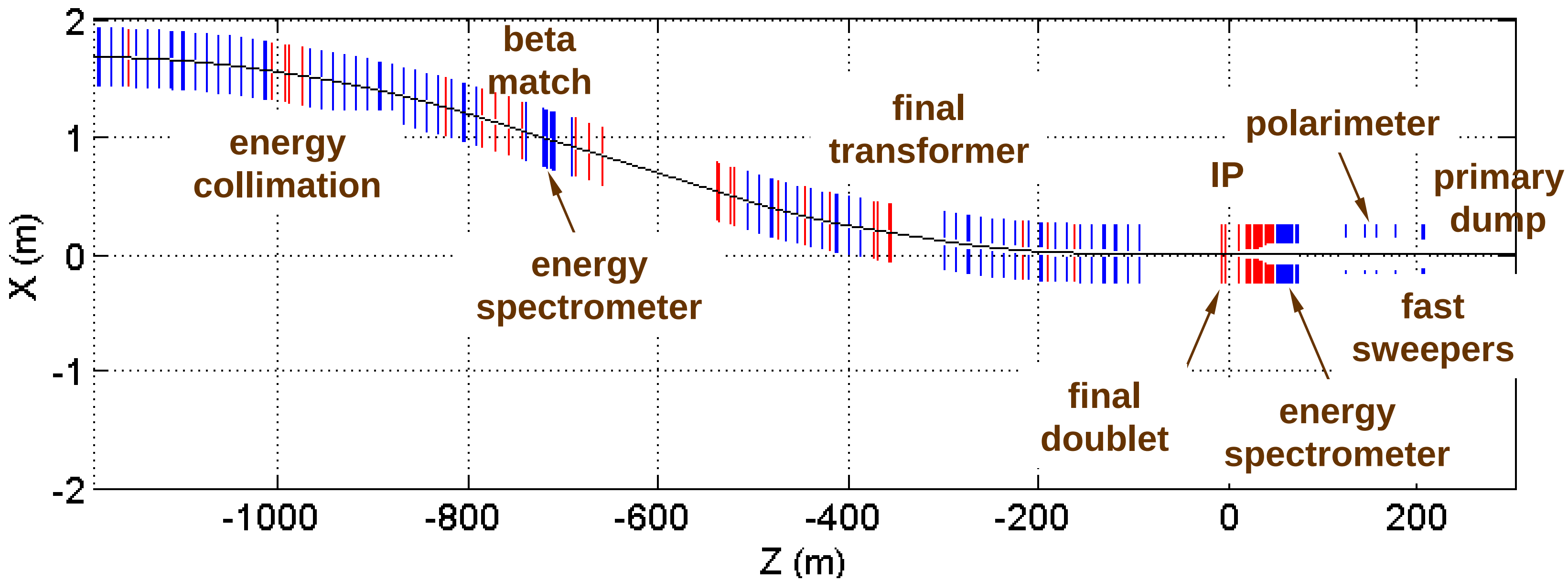
ILC FF & Collimation

- Betatron spoilers survive up to two bunches
- E-spoiler survive several bunches
- One spoiler per FD or IP phase



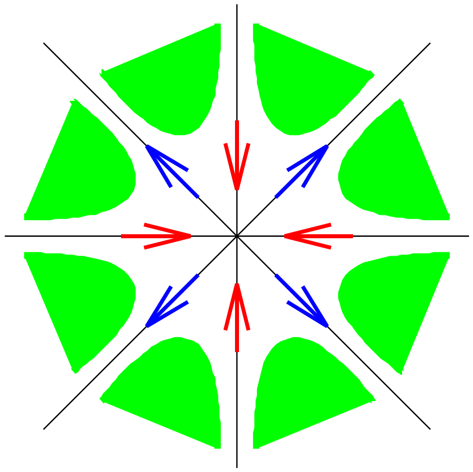
- Beam Delivery System Optics, a version with survivable spoilers


ILC e- BDS (500 GeV cm)
MPS coll
skew correction / emittance diagnostic
polarimeter
fast kickers
septa
betatron collimation
fast sweepers
tuneup dump
X (m)
Z (m)
-2200
-2100
-2000
-1900
-1800
-1700
-1600
-1500
-1400
-1300
-1200
2
1
0
-1
-2


beta match
energy collimation
final transformer
polarimeter
IP
primary dump
energy spectrometer
fast sweepers
final doublet
energy spectrometer
X (m)
Z (m)
-1000
-800
-600
-400
-200
0
200
2
1
0
-1
-2

Nonlinear handling of beam tails in ILC BDS

- **Can we ameliorate the incoming beam tails to relax the required collimation depth?**
- One wants to **focus beam tails** but not to change the core of the beam
  - use **nonlinear** elements
- **Several** nonlinear elements needs to be **combined** to provide **focusing in all directions**
  - (analogy with **strong focusing by FODO**)



Single octupole focus in planes and defocus on diagonals.

An octupole doublet can focus in all directions !

- **Octupole Doublets (OD)** can be used for **nonlinear tail folding** in ILC FF

Strong focusing by octupoles

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

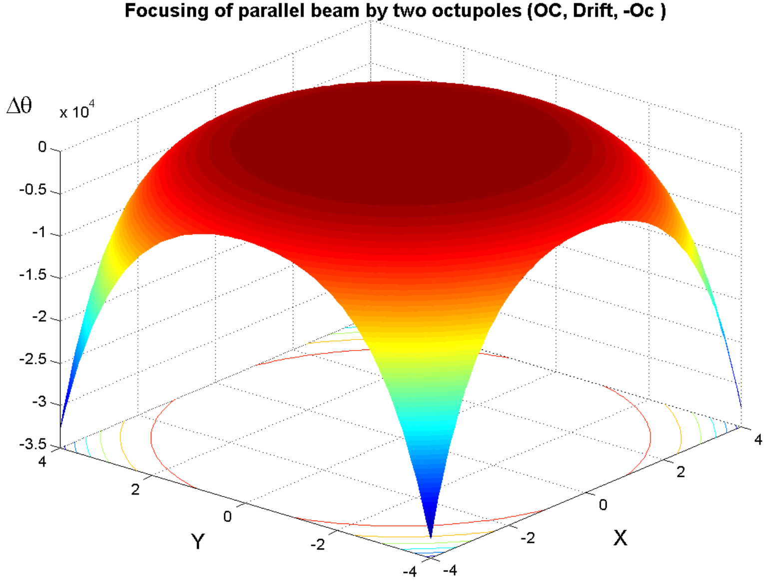
$$\Delta\theta = \alpha r^3 e^{-i3\varphi} - \left(\alpha r^3 e^{i3\varphi}\left(1+\alpha r^2 L e^{-i4\varphi}\right)^3\right)^*$$

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

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

Focusing in <u>all directions</u>

Next nonlinear term focusing – defocusing depends on φ

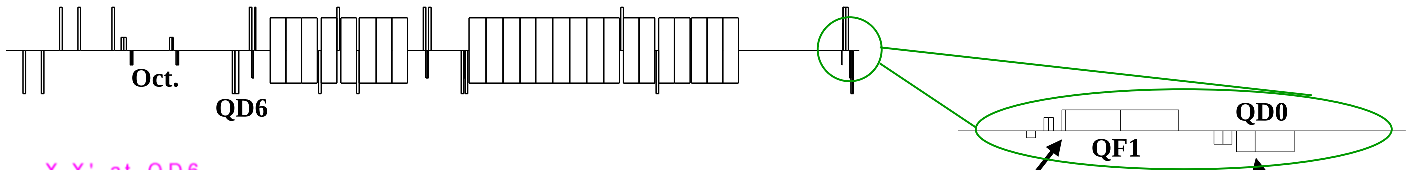


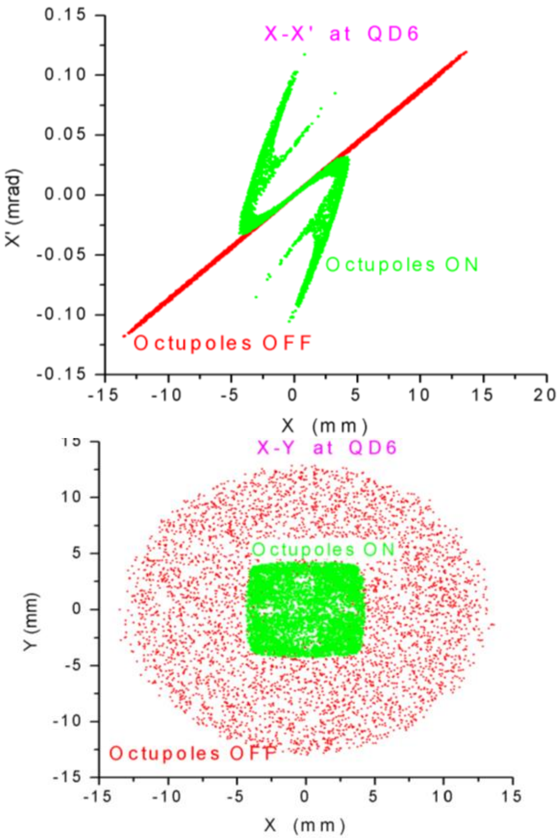
Effect of octupole doublet (Oc,Drift,-Oc) on parallel beam, ΔΘ(x,y).

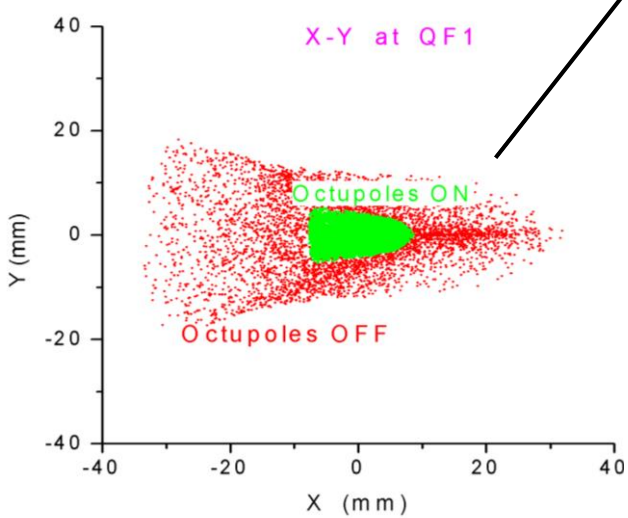
- For this to work, the beam should have **small angles**, i.e. it should be parallel or **diverging**

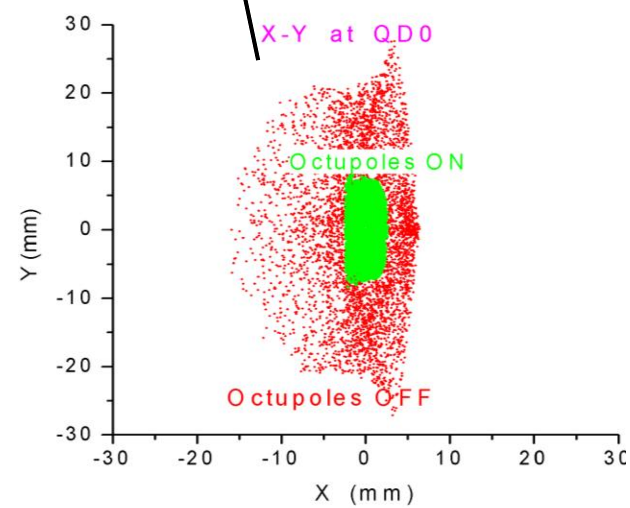
Tail folding in ILC FF

- **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**



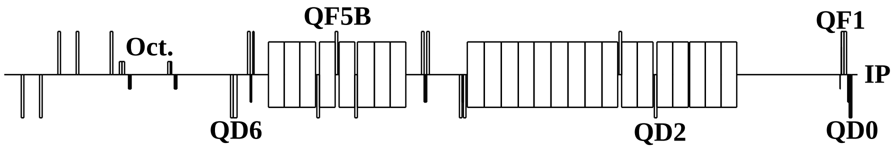


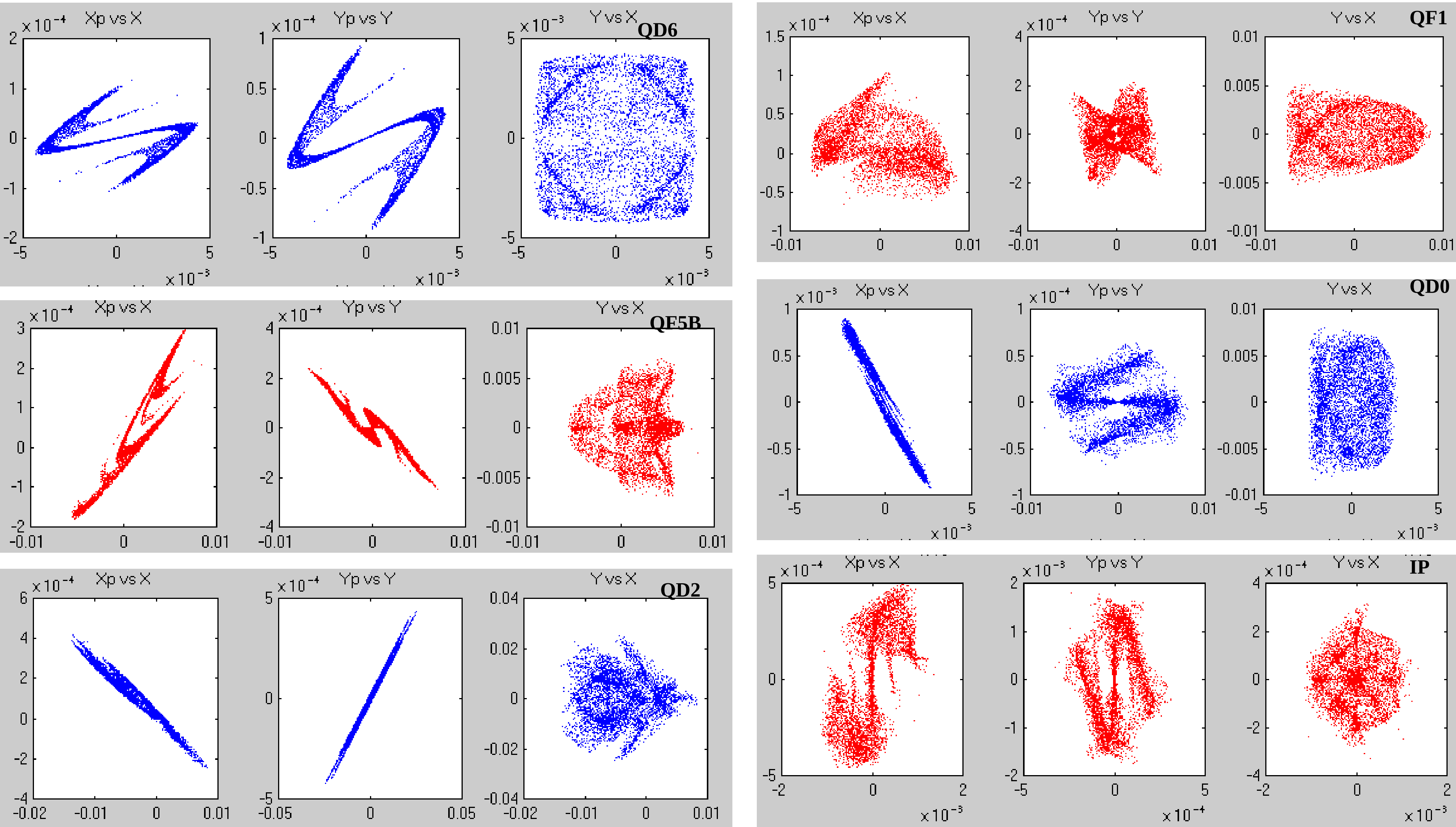




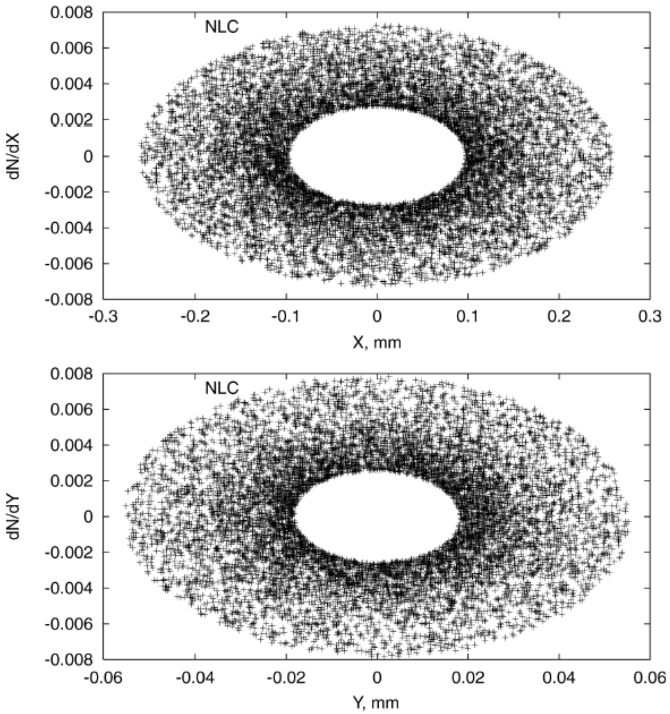
Tail folding by means of two octupole doublets in the ILC final focus
Input beam has (x,x',y,y') = (14μm,1.2mrad,0.63μm,5.2mrad) in IP units (flat distribution, half width) and ±2% energy spread, that corresponds approximately to N_σ=(65,65,230,230) sigmas with respect to the nominal beam

Tail folding
or Origami Zoo

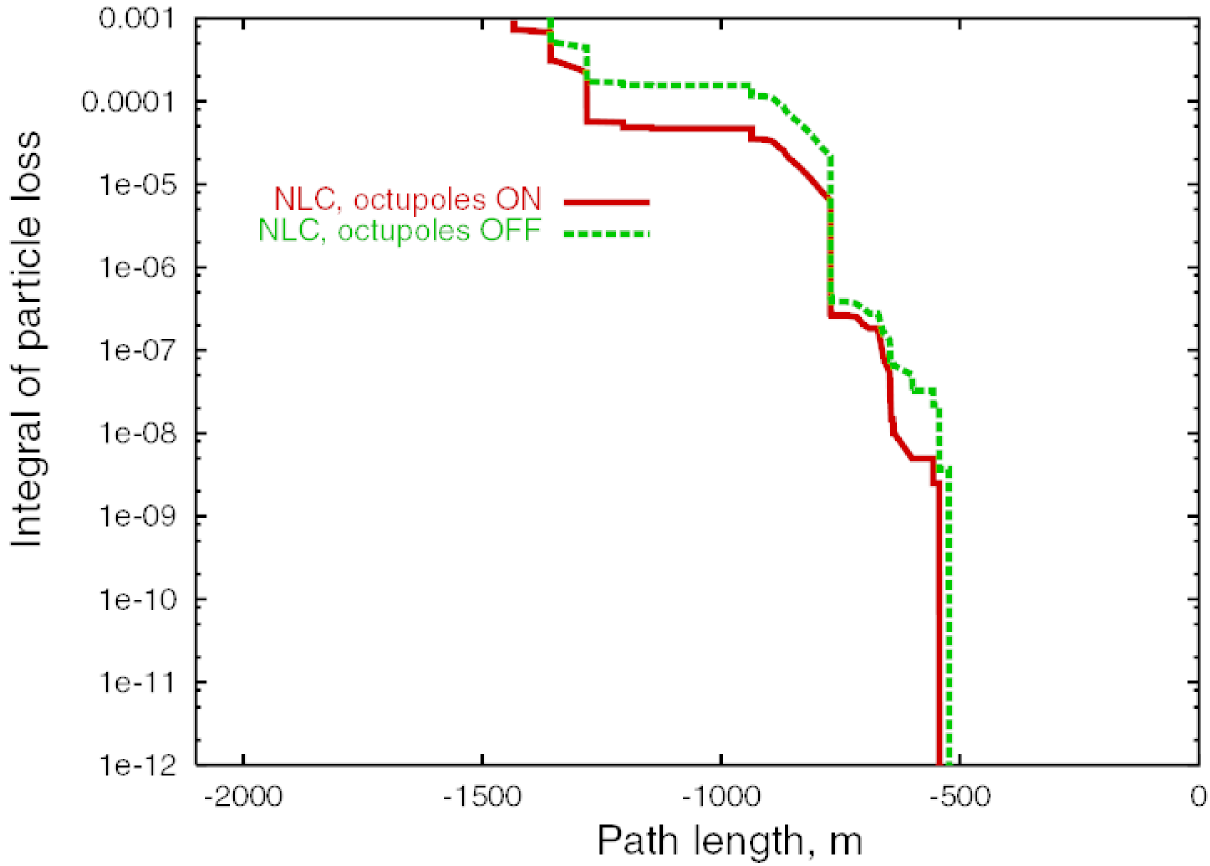




Halo collimation



Assumed halo sizes. Halo population is 0.001 of the main beam.

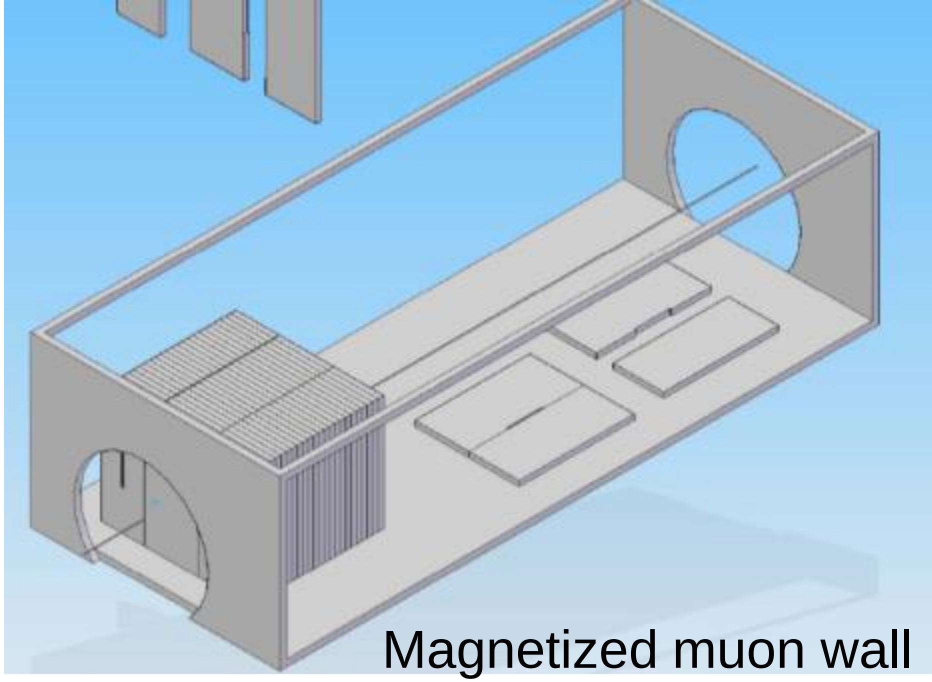


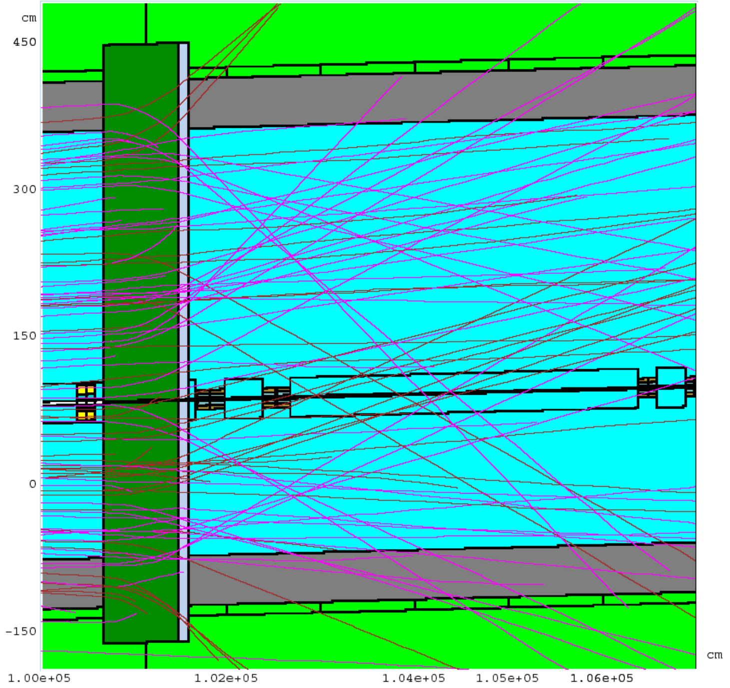
Assuming 0.001 halo, beam losses along the beamline behave nicely, and SR photon losses occur only on dedicated masks

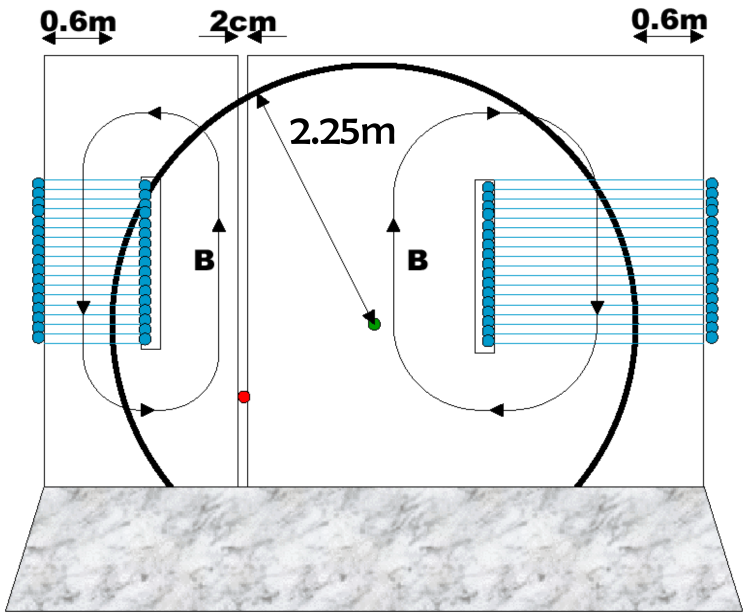
Smallest gaps are +-0.6mm with tail folding Octupoles and +-0.2mm without them.

Dealing with muons in BDS

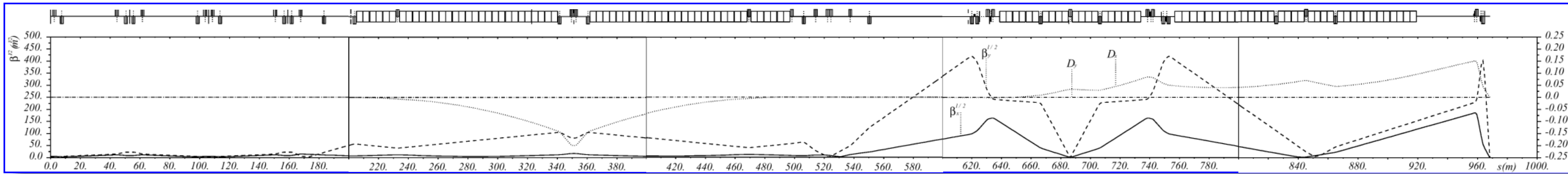
- Muons are produced during collimation
- Muon walls, installed ~300m from IP, reduce muon background in the detectors

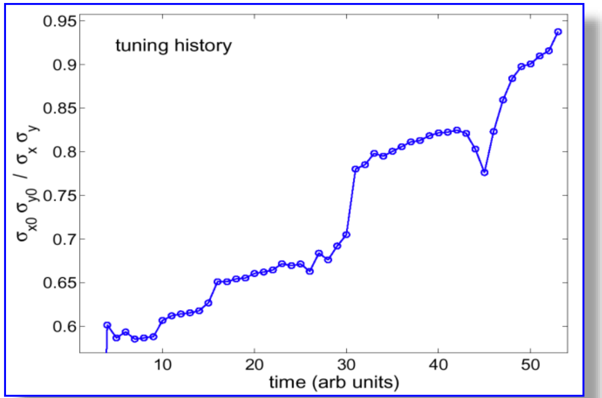




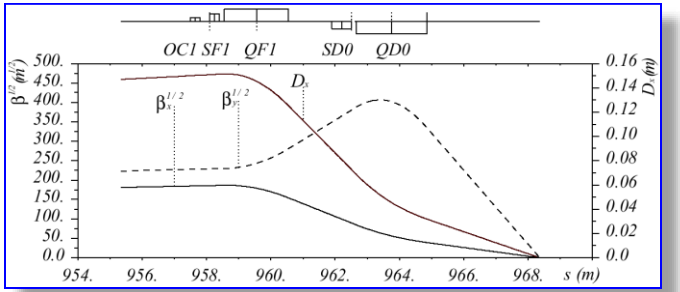


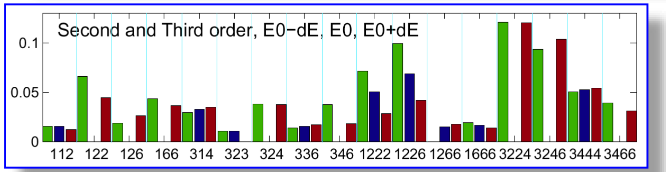
BDS design methods & examples

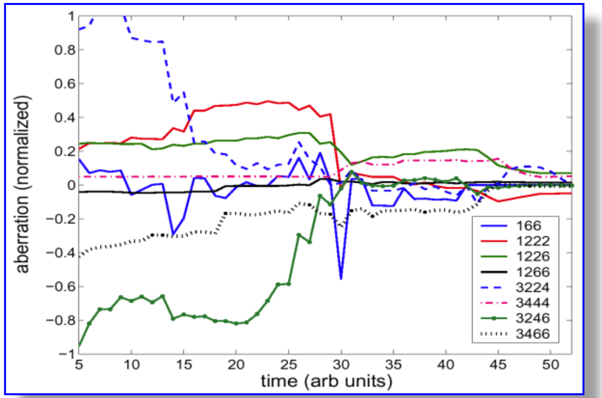


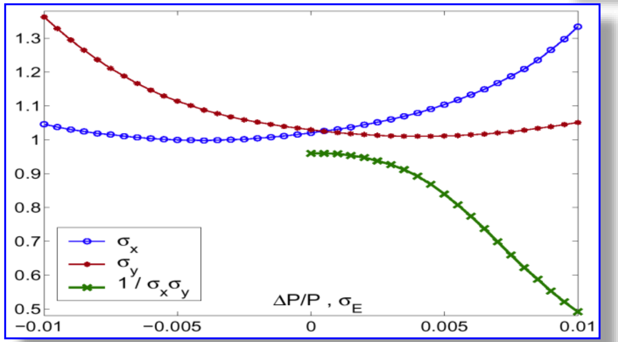


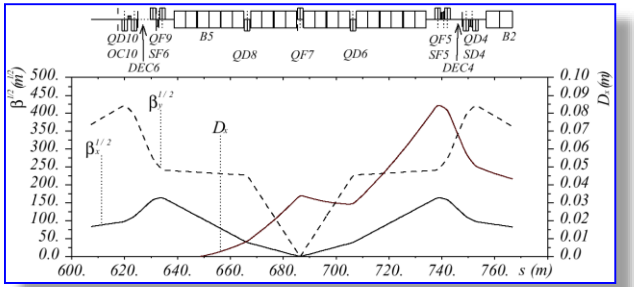
Example BDS optics; design history; location of design knobs



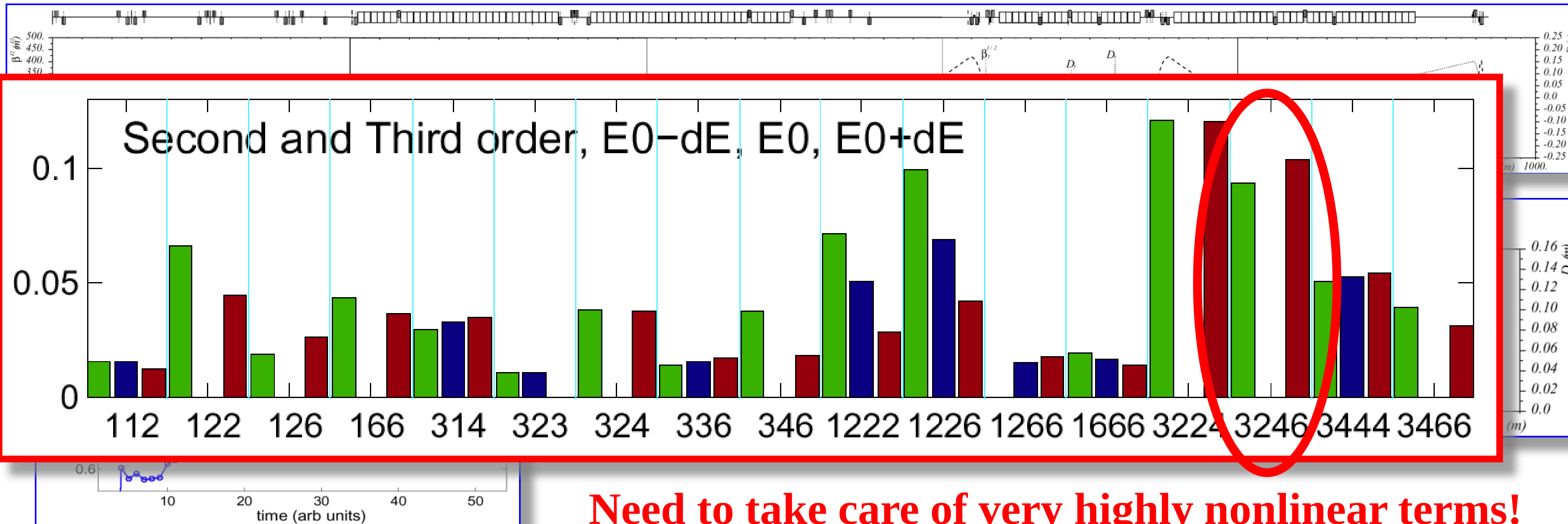






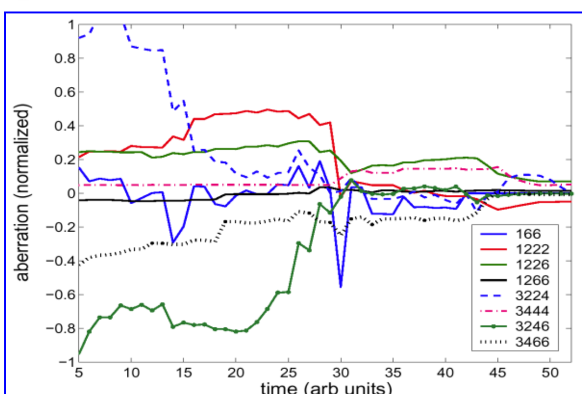


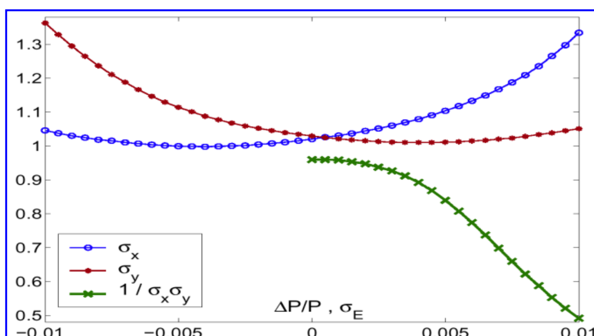
BDS design methods & examples

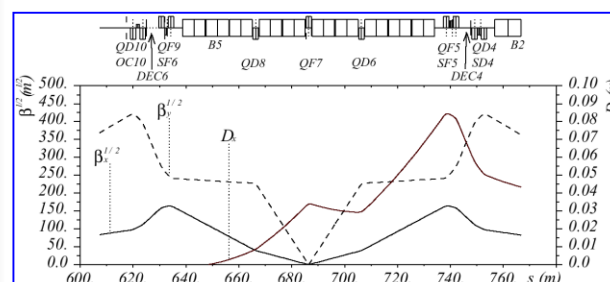


Need to take care of very highly nonlinear terms!

Example: $y \sim U(x', y', E^2)$ - FOURTH ORDER

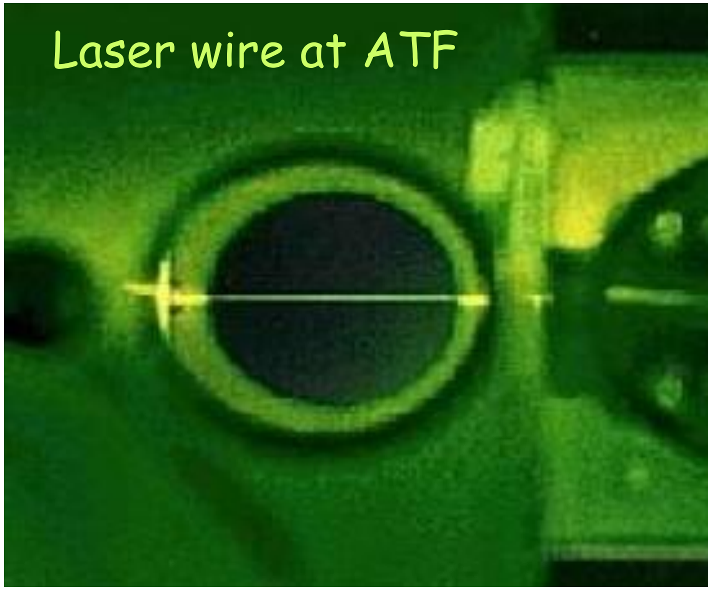






In a practical situation …

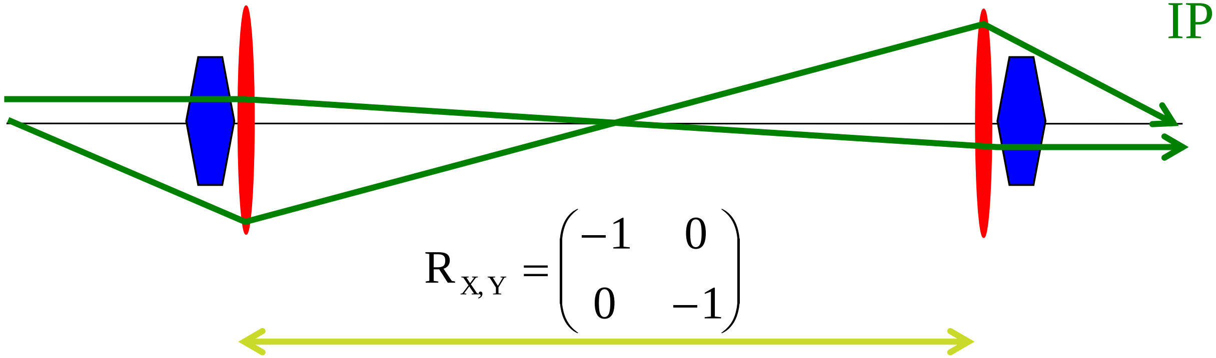
- While **designing** the FF, one has a **total control**
- When the system is built => limited number of observable parameters (measured orbit position, beam size measured in several locations)
- The system, however, may initially have **errors** (errors of strength of the elements, transverse misalignments) and initial aberrations may be large



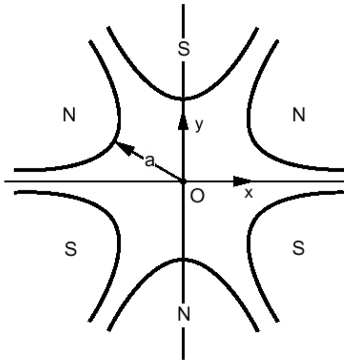
Laser wire will be a tool for tuning and diagnostic of FF

- **Tuning** of FF is done by optimization of "**knobs**" (strength, position of group of elements) chosen to affect some particular aberrations
- Experience in SLC FF and FFTB, and simulations with new FF give confidence that this is possible

Sextupole knobs for BDS tuning



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



SEXTUPOLE

Second order effect:

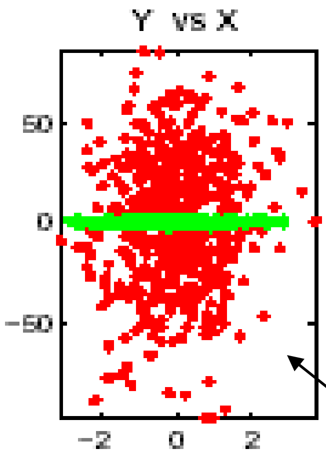
$x' = x' + S\,(x^2 - y^2)$

$y' = y' - S\,2xy$

- Combining offsets of sextupoles (symmetrical or anti-symmetrical in X or Y), one can produce the following corrections at the IP
  - waist shift
  - coupling
  - dispersion

To create these knobs, sextupole placed on movers

IR coupling compensation

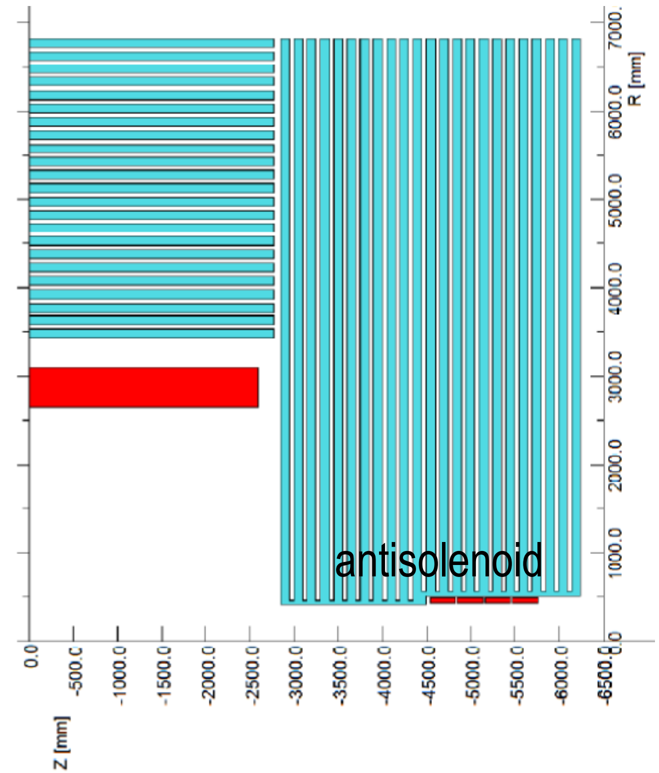


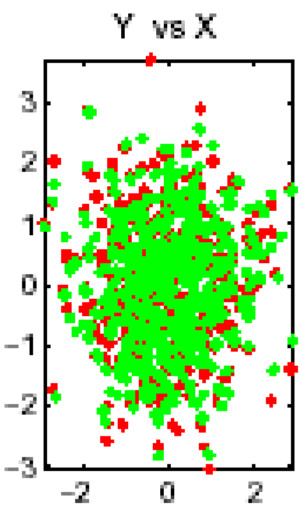
without compensation

$\sigma_y / \sigma_y(0) = 32$

When detector solenoid overlaps QD0, coupling between y & x' and y & E causes large (30 – 190 times) increase of IP size (green=detector solenoid OFF, red=ON)

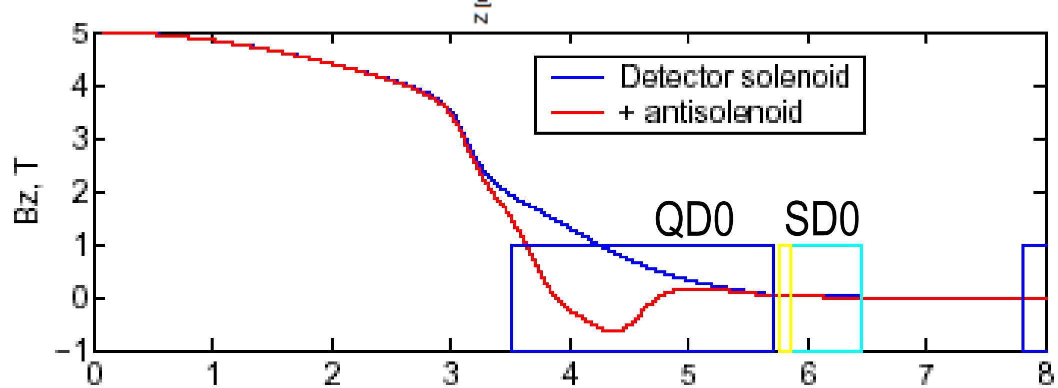
Even though traditional use of skew quads could reduce the effect, the local compensation of the fringe field (with a little skew tuning) is the most efficient way to ensure correction over wide range of beam energies





with compensation by antisolenoid

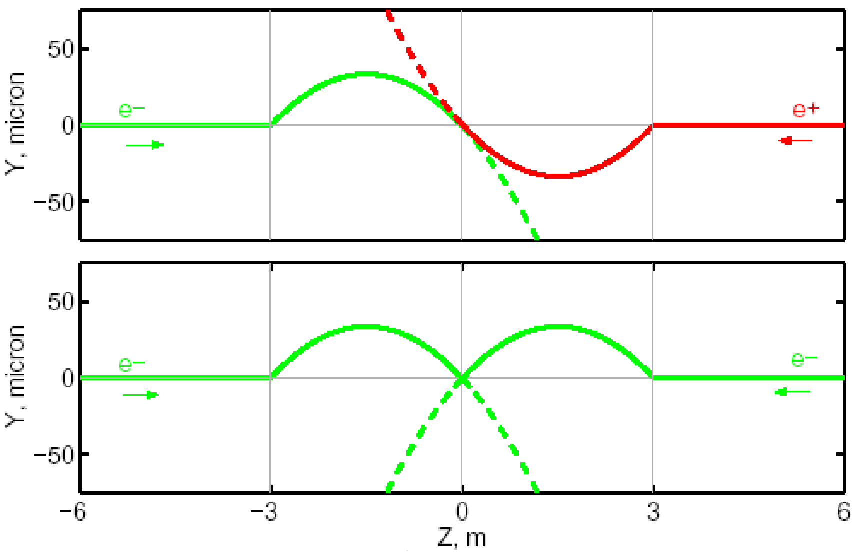
$\sigma_y / \sigma_y(0) < 1.01$

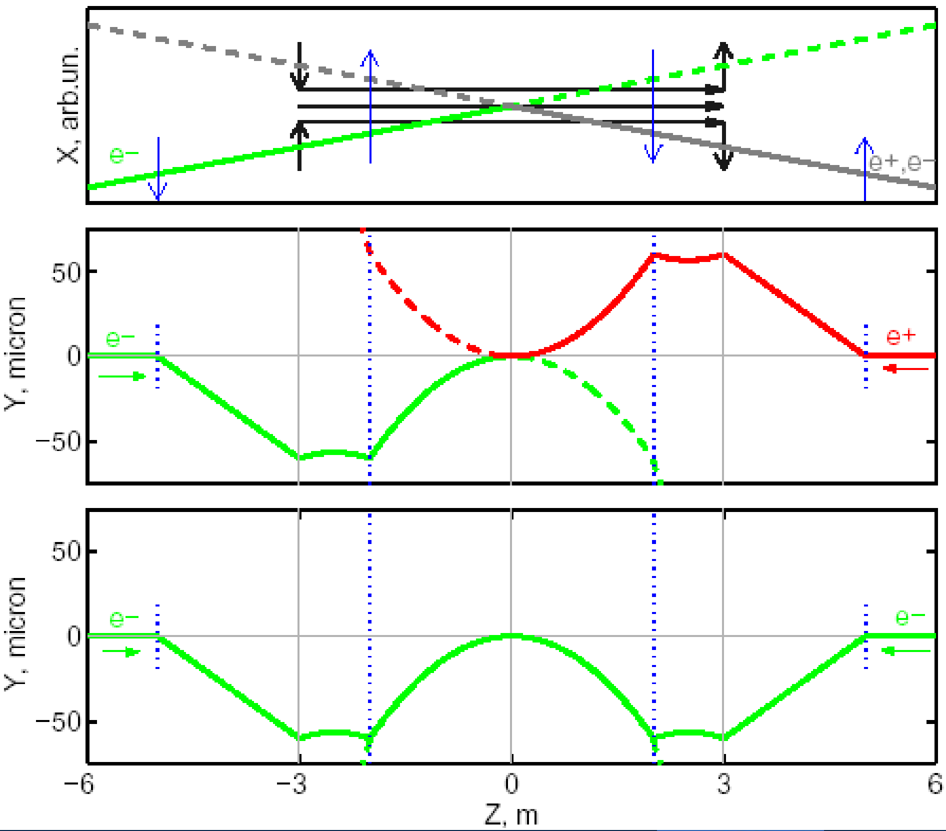


Y. Nosochkov, A. Seryi, Phys.Rev.ST Accel.Beams 8:021001, 2005

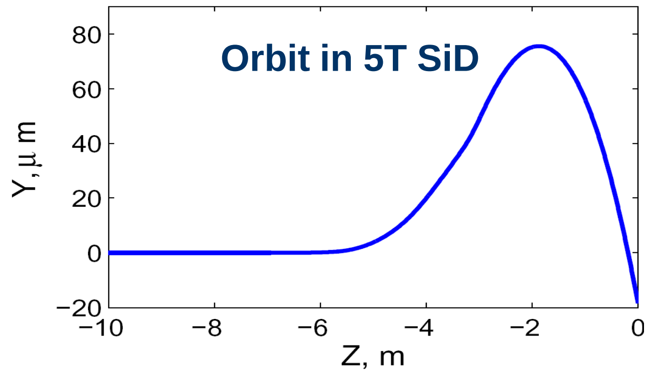
Detector Integrated Dipole

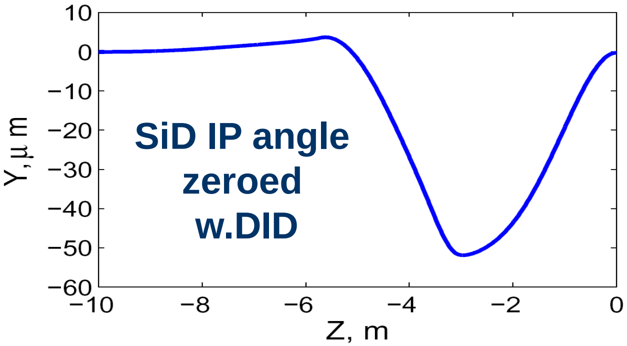
- With a crossing angle, when beams cross solenoid field, vertical orbit arise
- For e+e- the orbit is anti-symmetrical and beams still collide head-on
- If the vertical angle is undesirable (to preserve spin orientation or the e-e- luminosity), it can be compensated locally with DID
- Alternatively, negative polarity of DID may be useful to reduce angular spread of beam-beam pairs (anti-DID)





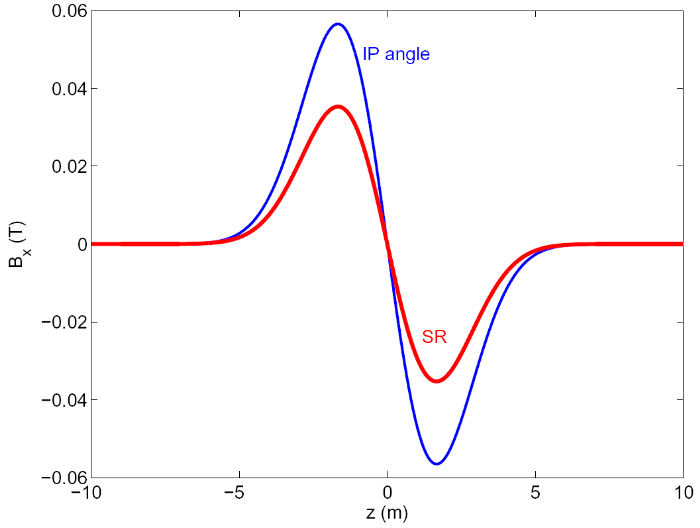
Use of DID or anti-DID

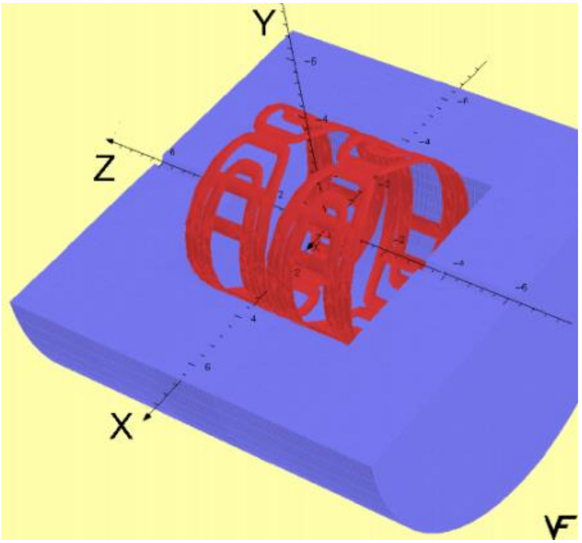




DID case

DID field shape and scheme



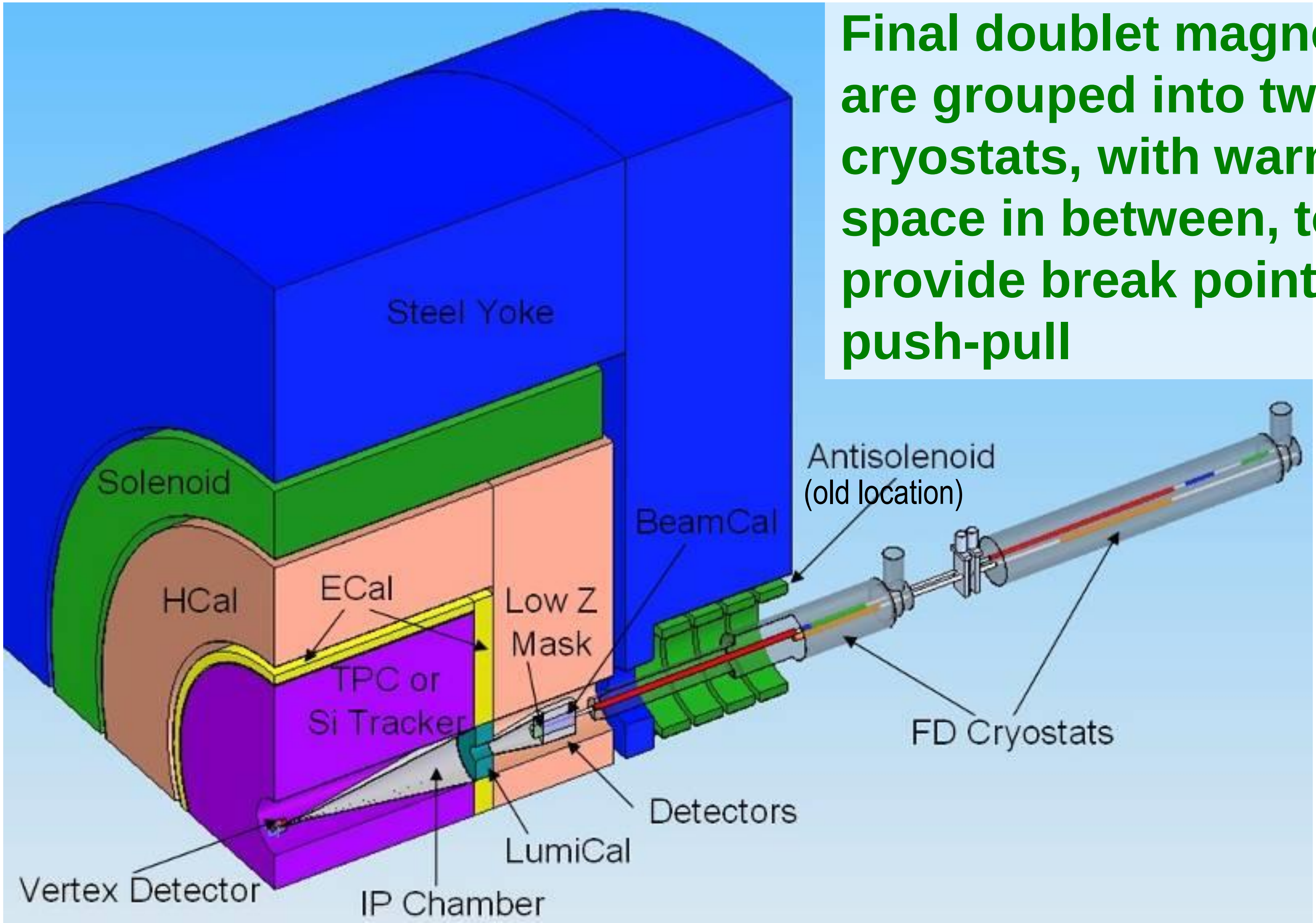


- The negative polarity of DID is also possible (called anti-DID)

- In this case the vertical angle at the IP is somewhat increased, but the background conditions due to low energy pairs (see below) and are improved

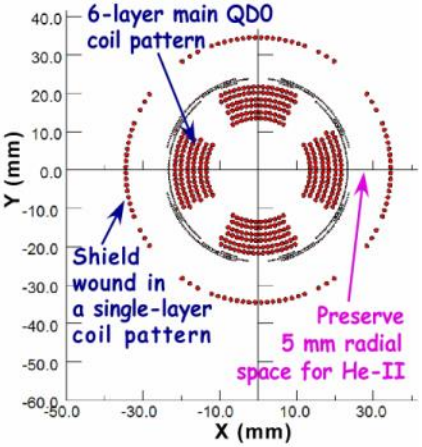
B. Parker, A. Seryi Phys. Rev. ST Accel. Beams 8, 041001, 2005

IR integration

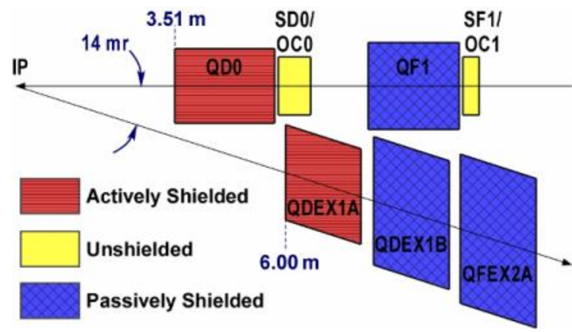


Final doublet magnets are grouped into two cryostats, with warm space in between, to provide break point for push-pull

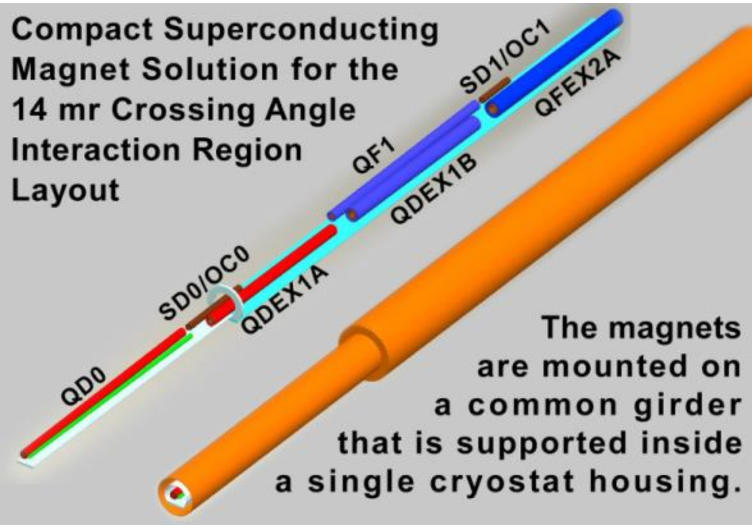
14 mrad IR



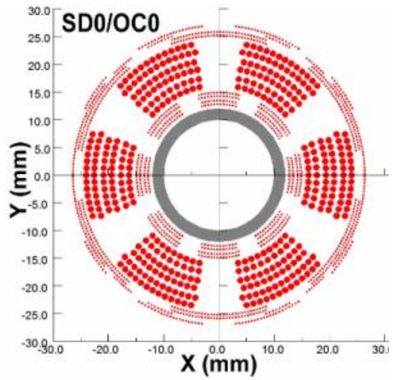
6-layer main QD0 coil pattern
Shield wound in a single-layer coil pattern
Preserve 5 mm radial space for He-II
Y (mm)
X (mm)



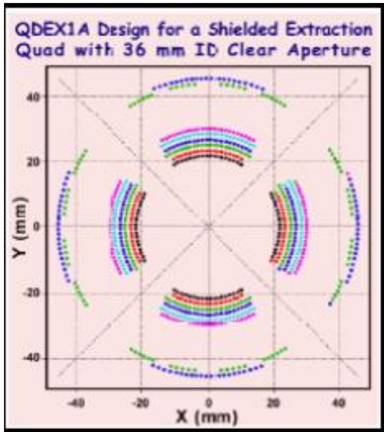
IP
14 mr
3.51 m
SD0/ OC0
SF1/ OC1
QD0
QF1
QDEX1A
QDEX1B
QFEX2A
6.00 m
Actively Shielded
Unshielded
Passively Shielded



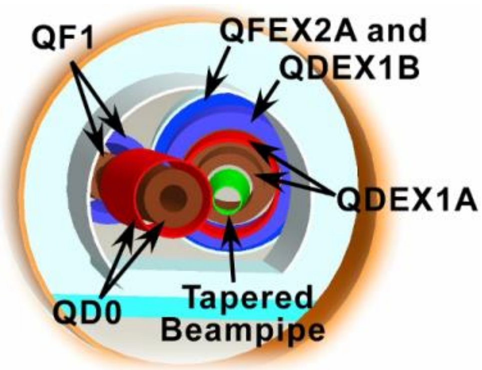
Compact Superconducting Magnet Solution for the 14 mr Crossing Angle Interaction Region Layout
SD1/OC1
QFEX2A
QF1
QDEX1B
SD0/OC0
QDEX1A
QD0
The magnets are mounted on a common girder that is supported inside a single cryostat housing.



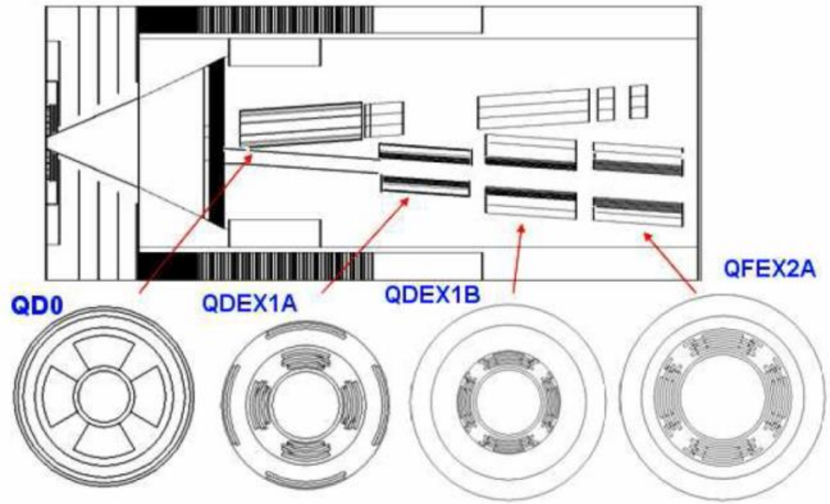
SD0/OC0
Y (mm)
X (mm)



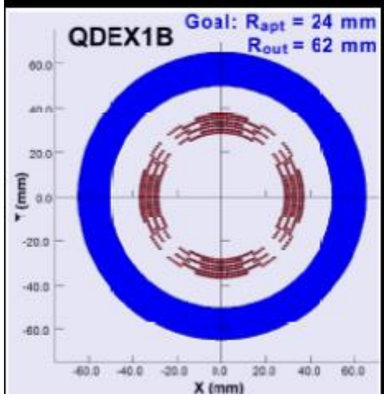
QDEX1A Design for a Shielded Extraction Quad with 36 mm ID Clear Aperture
Y (mm)
X (mm)



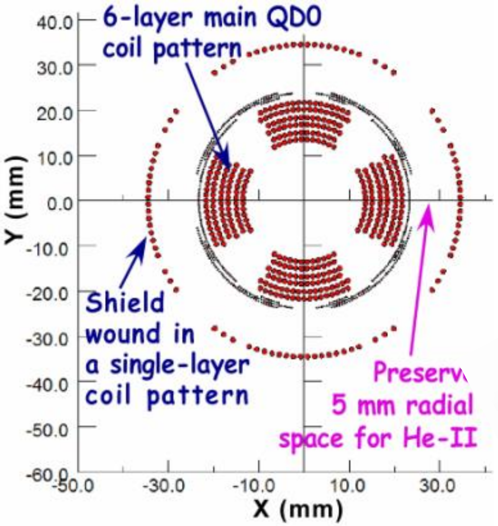
QF1
QFEX2A and QDEX1B
QDEX1A
QD0
Tapered Beampipe



QD0
QDEX1A
QDEX1B
QFEX2A

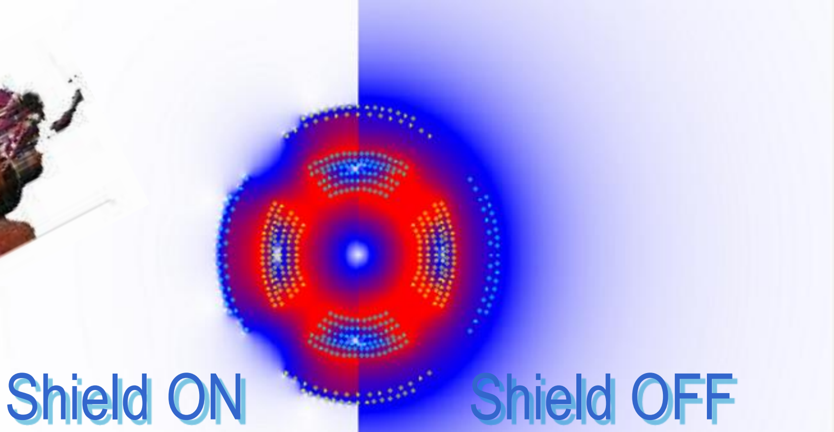


QDEX1B
Goal: R_{apt} = 24 mm
R_{out} = 62 mm
X (mm)

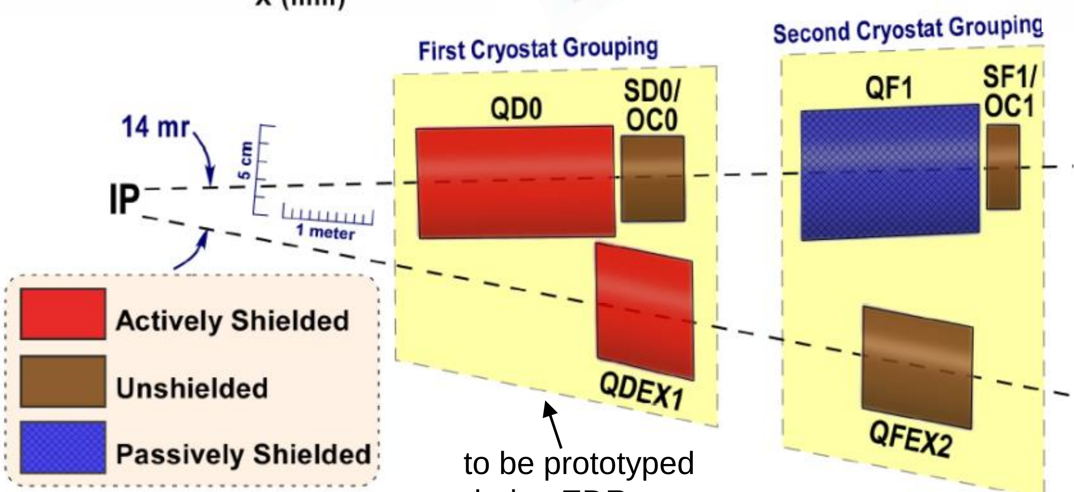


Actively shielded QD0

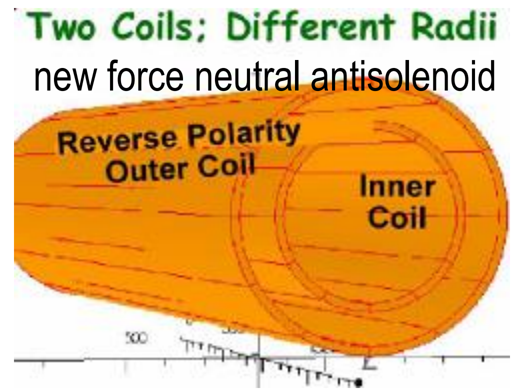
BNL



Intensity of color represents value of magnetic field.

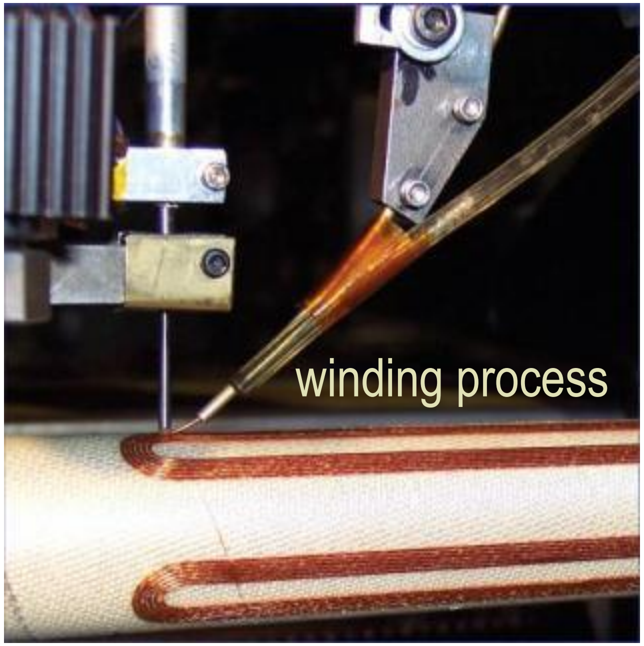


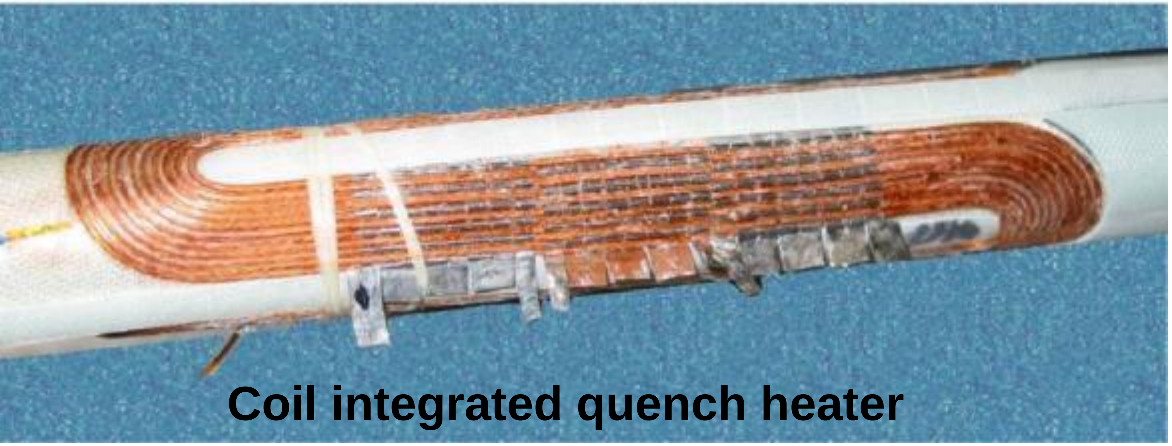
to be prototyped during EDR

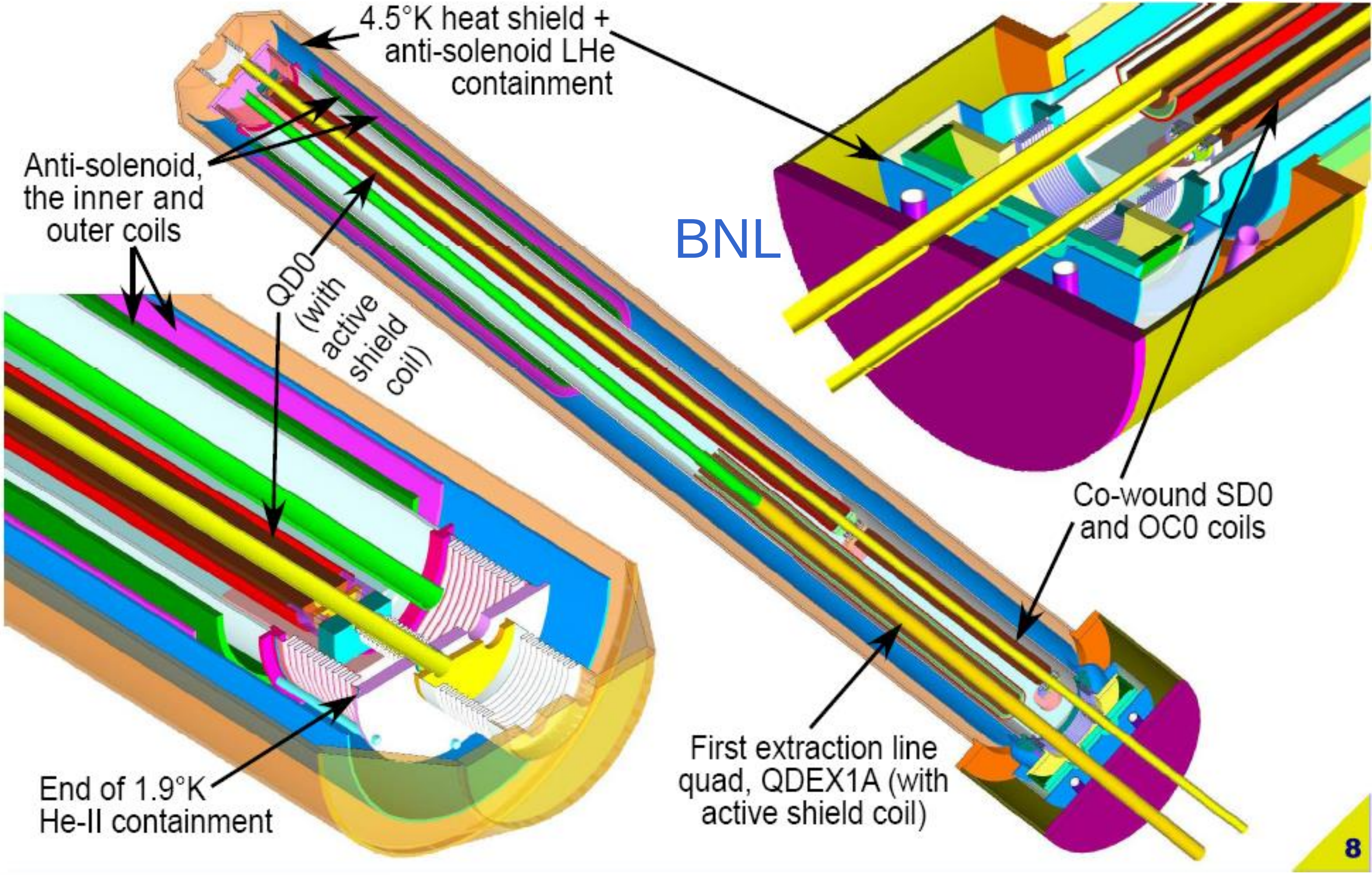


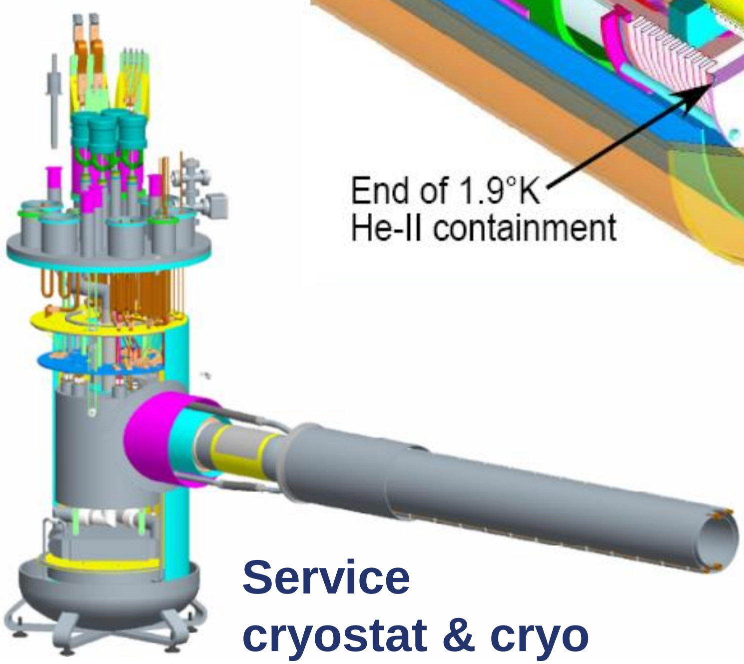
- Interaction region uses compact self-shielding SC magnets
- Independent adjustment of in- & out-going beamlines
- Force-neutral anti-solenoid for local coupling correction

IR magnets prototypes at BNL





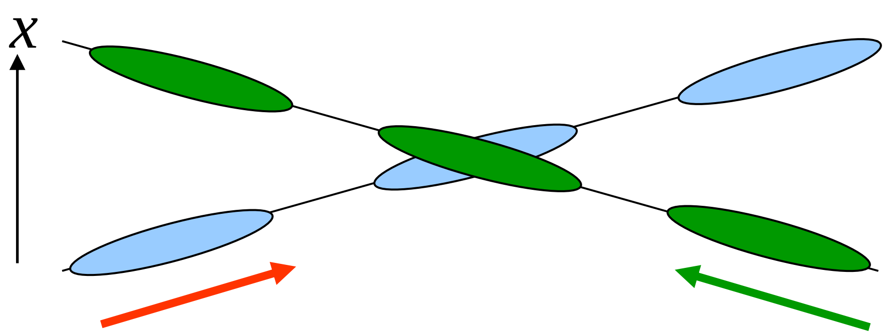




Service cryostat & cryo connections

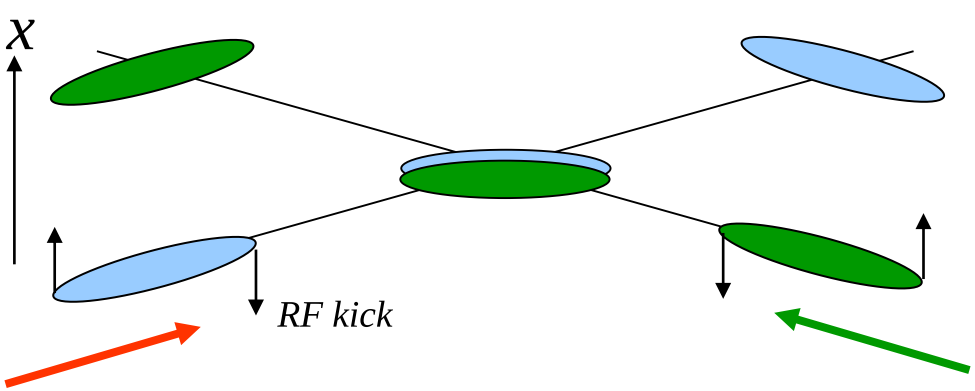
- **Detailed engineering design of IR magnets and their integration**

Crab crossing

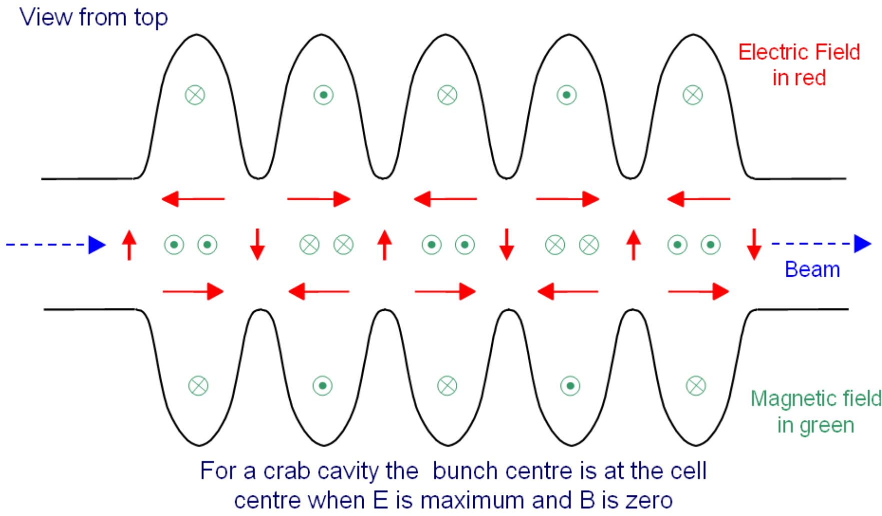


With crossing angle θ_c, the projected x-size is $(\sigma_x^2+\theta_c^2\sigma_z^2)^{0.5} \sim\theta_c\sigma_z \sim 4\mu m$

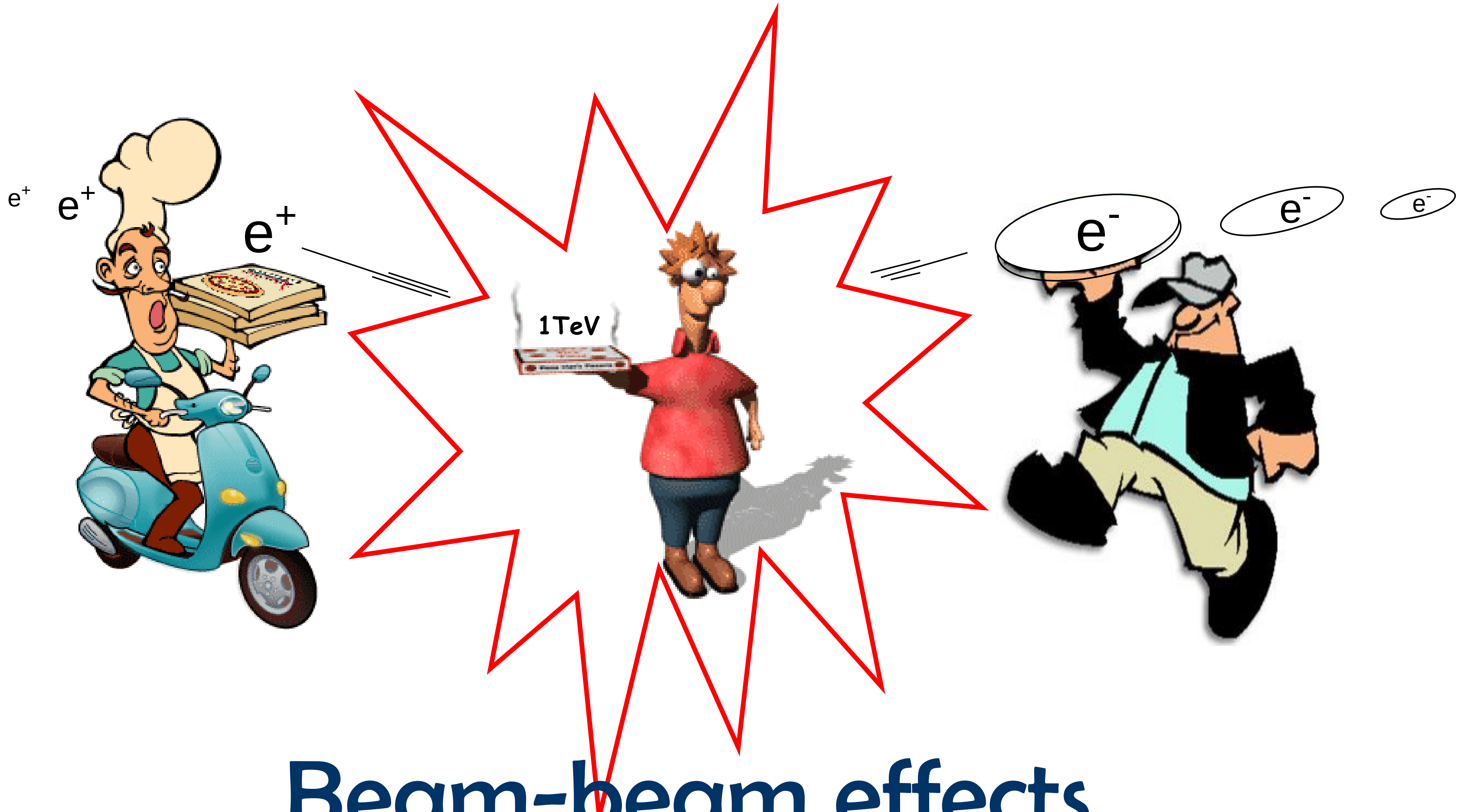
→ several time reduction in *L* without corrections



Use transverse (crab) RF cavity to 'tilt' the bunch at IP



Beam Delivered...

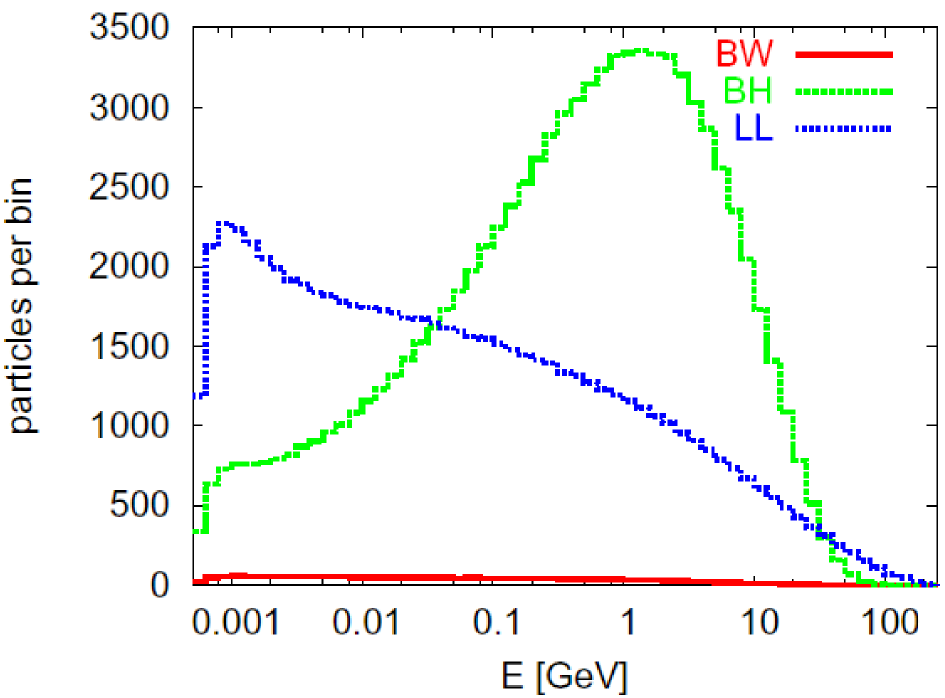


Beam-beam effects

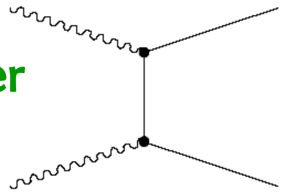
Beam-beam effects are not discussed in this lecture in detail as I assume you had a dedicated lecture on that

Incoherent* production of pairs

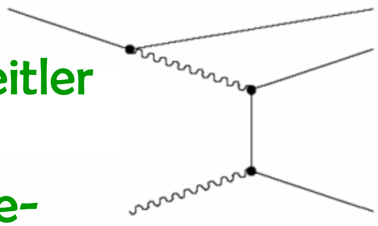
- Beamstrahling photons, particles of beams or virtual photons interact, and create e+e- pairs



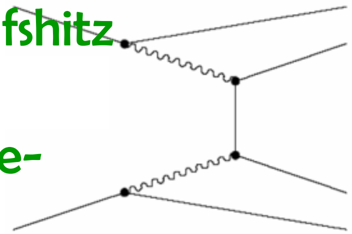
Breit-Wheeler process
$\gamma\gamma \rightarrow$ e+e-



Bethe-Heitler process
$e\gamma \rightarrow$ ee+e-

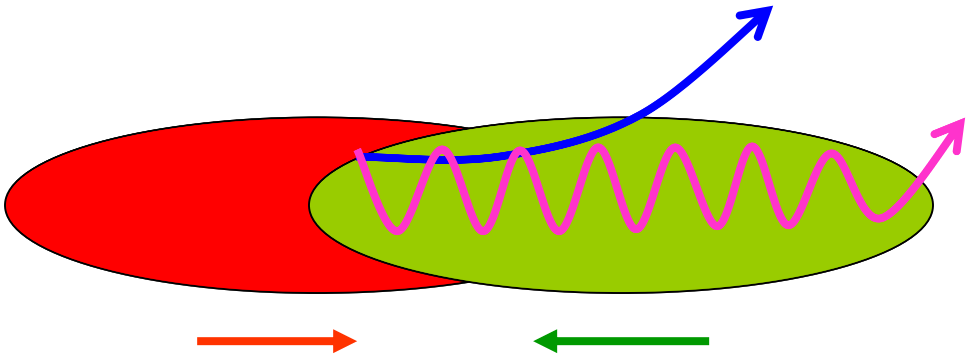


Landau-Lifshitz process
ee $\rightarrow$ eee+e-



*) Coherent pairs are generated by photon in the field of opposite bunch. It is negligible for ILC parameters.

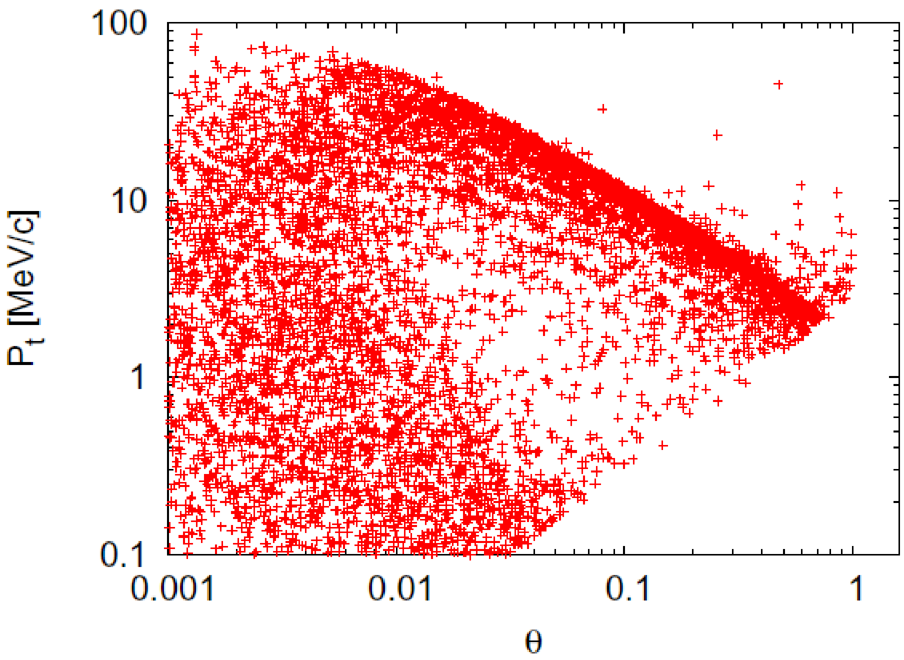
Deflection of pairs by beam



- Pairs are affected by the beam (focused or defocused)
- Deflection angle and P_t correlate
- Max angle estimated as (where ϵ is fractional energy):

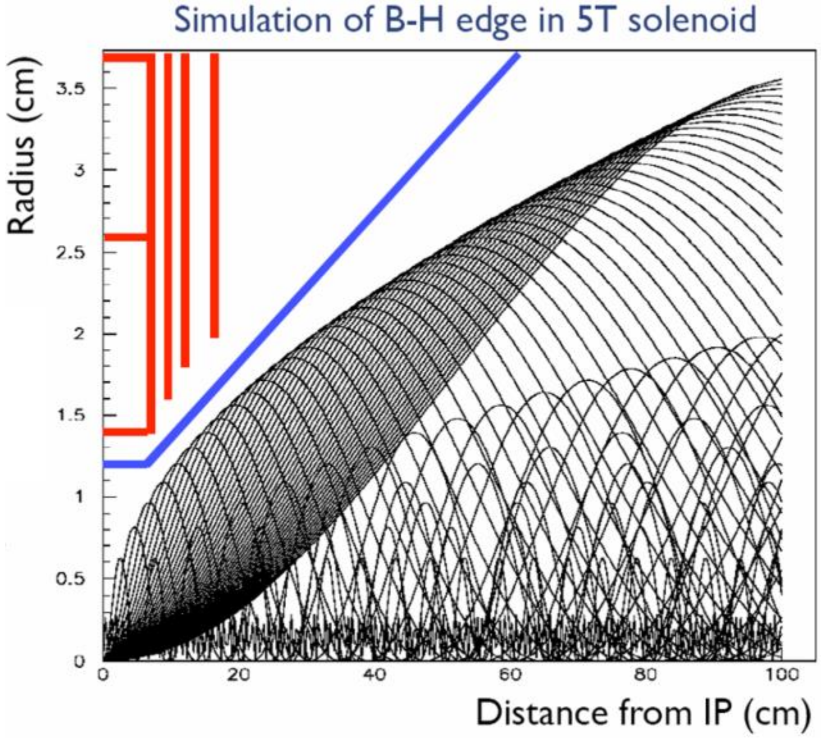
$$\theta_m = \sqrt{4 \frac{\ln\left(\frac{D}{\epsilon}+1\right) D\sigma_x^2}{\sqrt{3}\epsilon\sigma_z^2}}$$

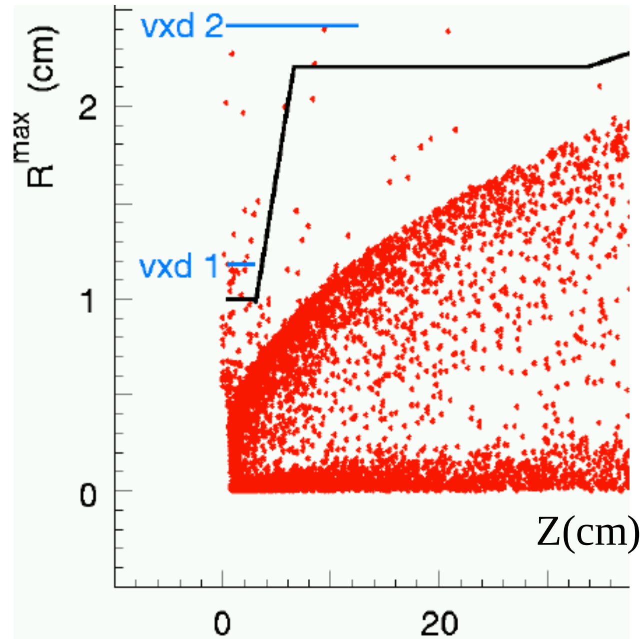
- Bethe-Heitler pairs have hard edge, Landau-Lifshitz pairs are outside



Deflection of pairs by detector solenoid

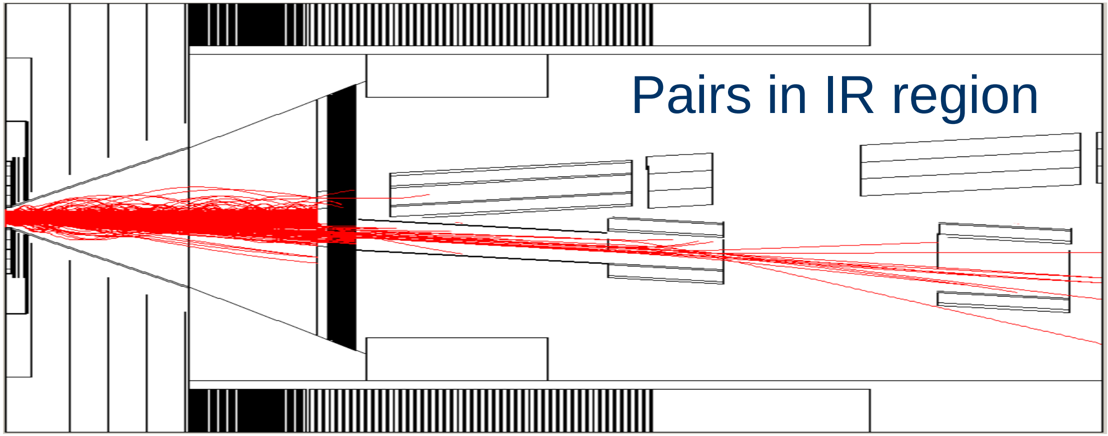
- Pairs are curled by the solenoid field of detector
- Geometry of vertex detector and vacuum chamber chosen in such a way that most of pairs (B-H) do not hit the apertures
- Only small number (L-L) of pairs would hit the VX apertures

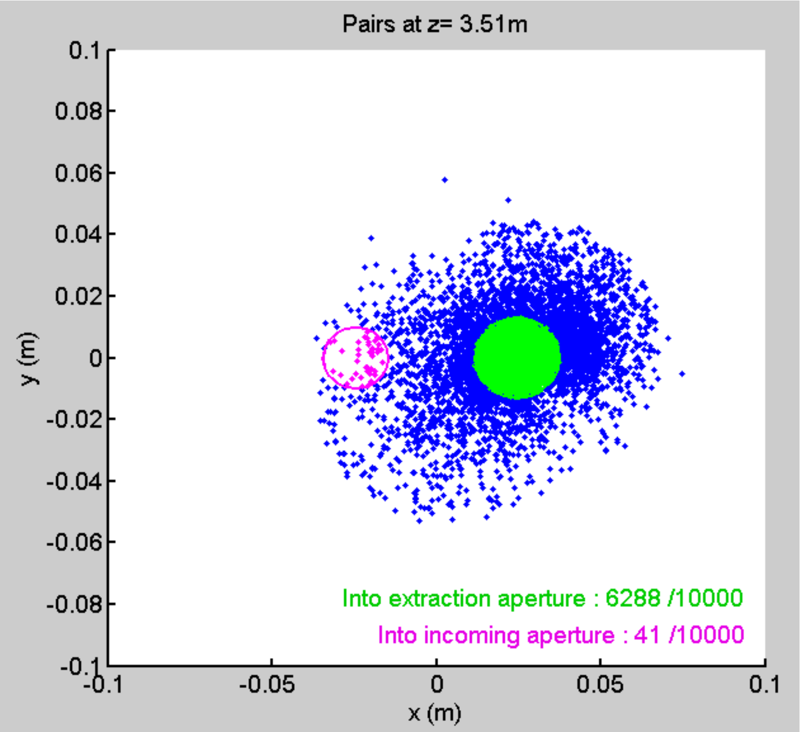


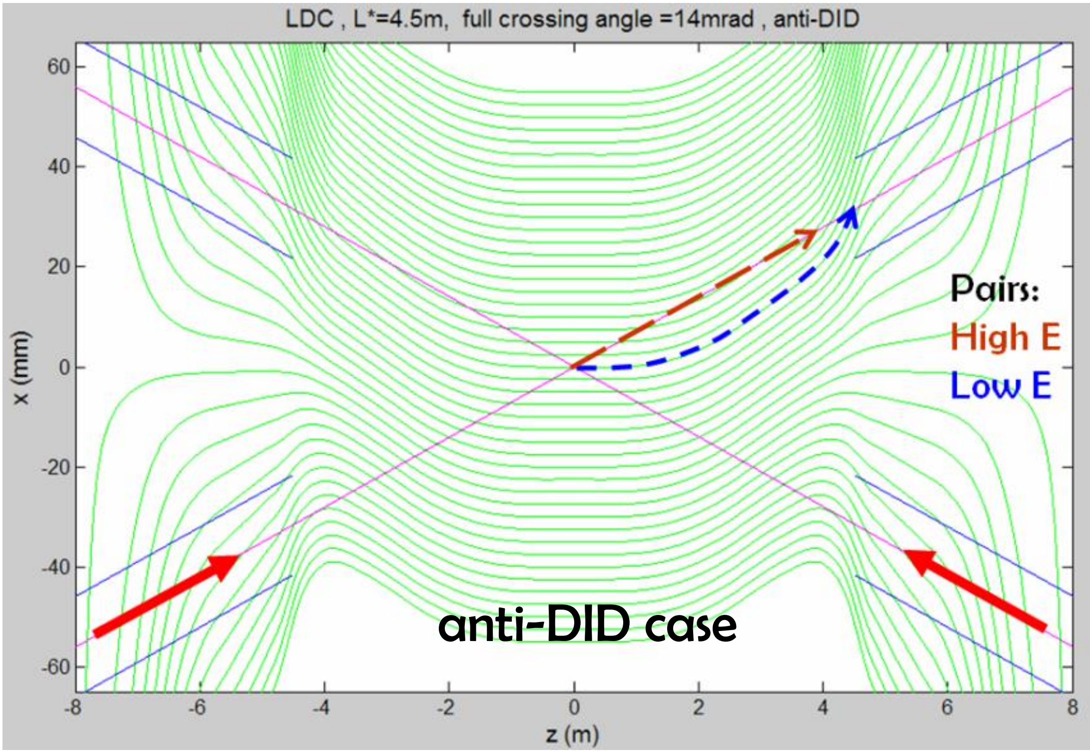


Use of anti-DID to direct pairs

Anti-DID field can be used to direct most of pairs into extraction hole and thus improve somewhat the background conditions

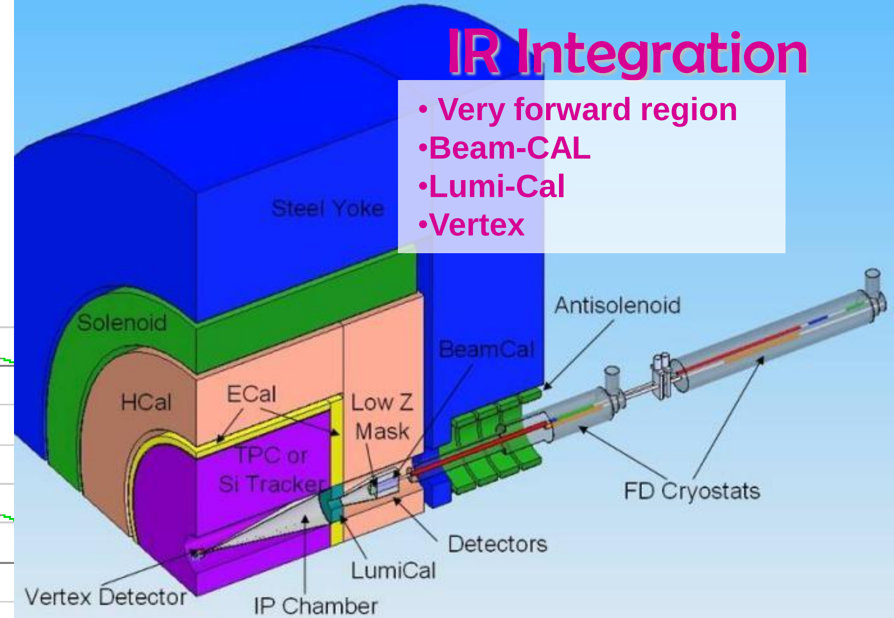


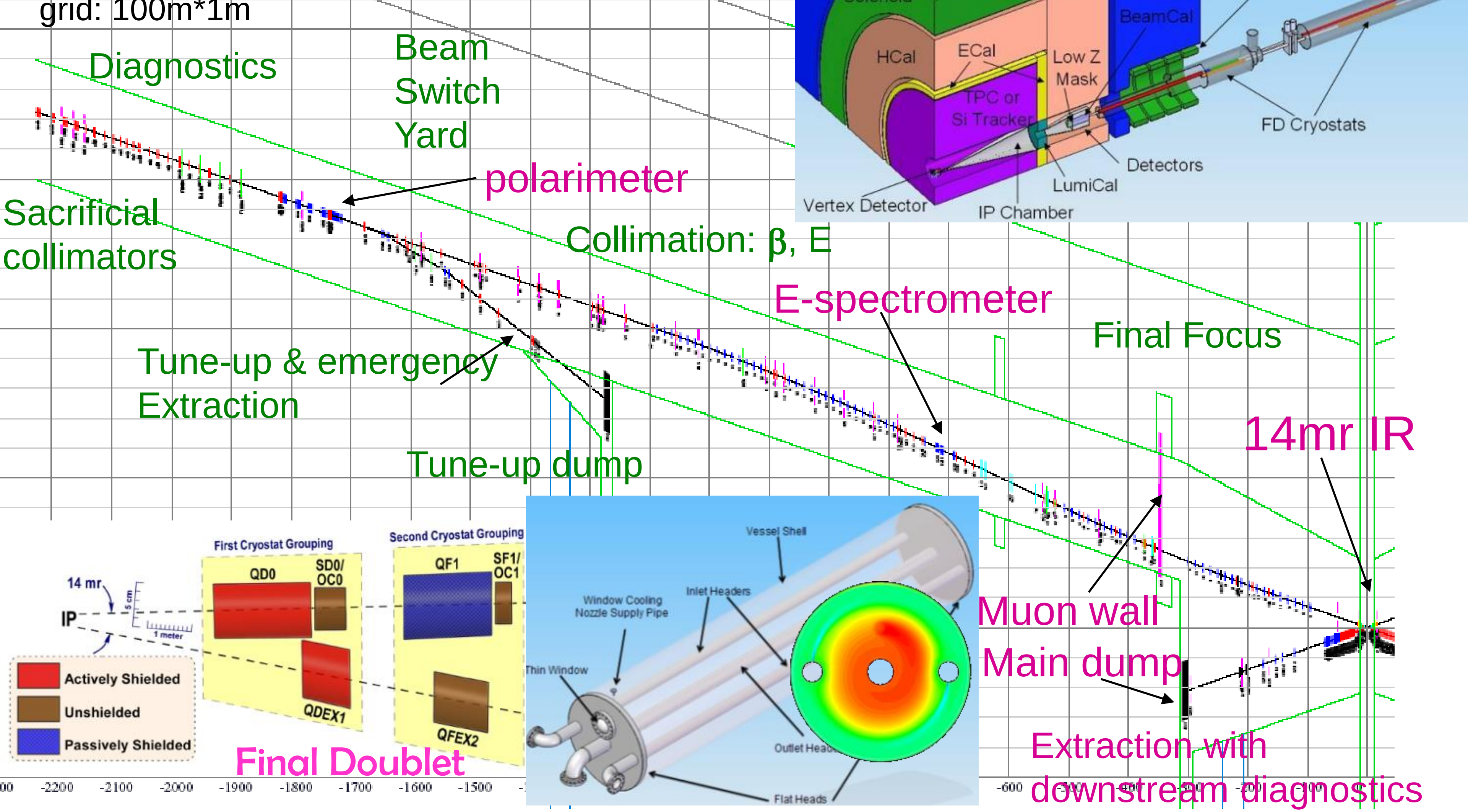




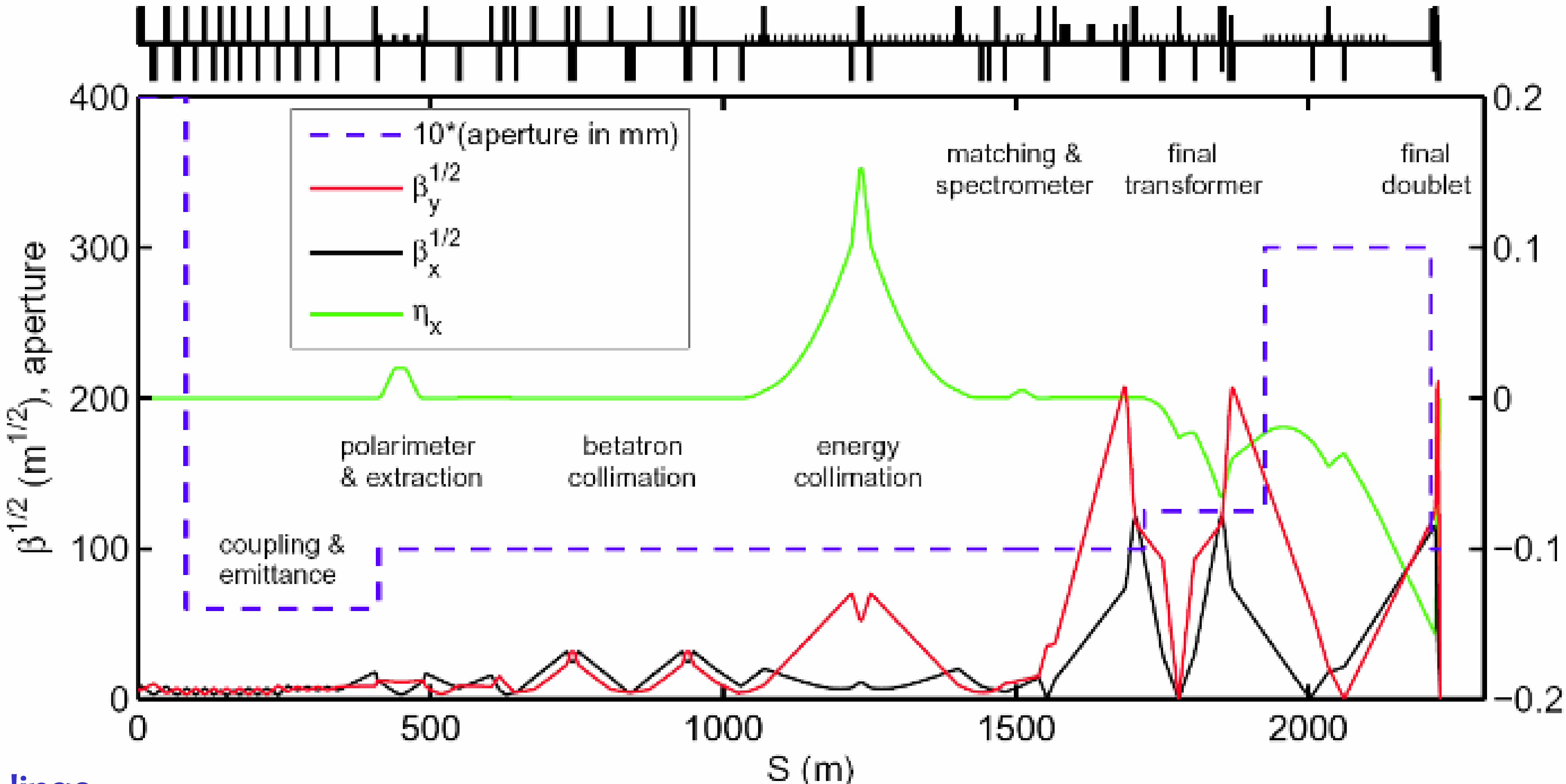
Beam Delivery & MDI elements

1TeV CM, single IR, two detectors, push-pull





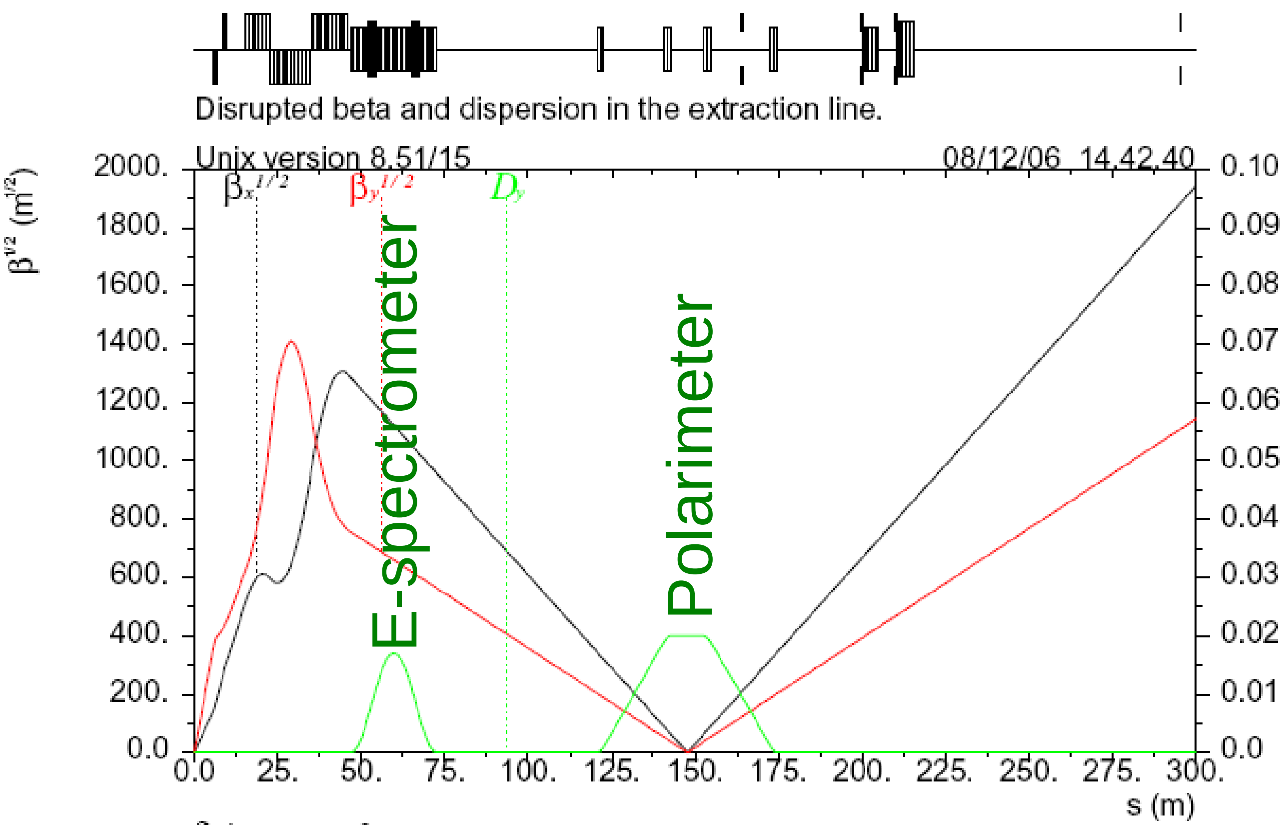
BDS functions and optics

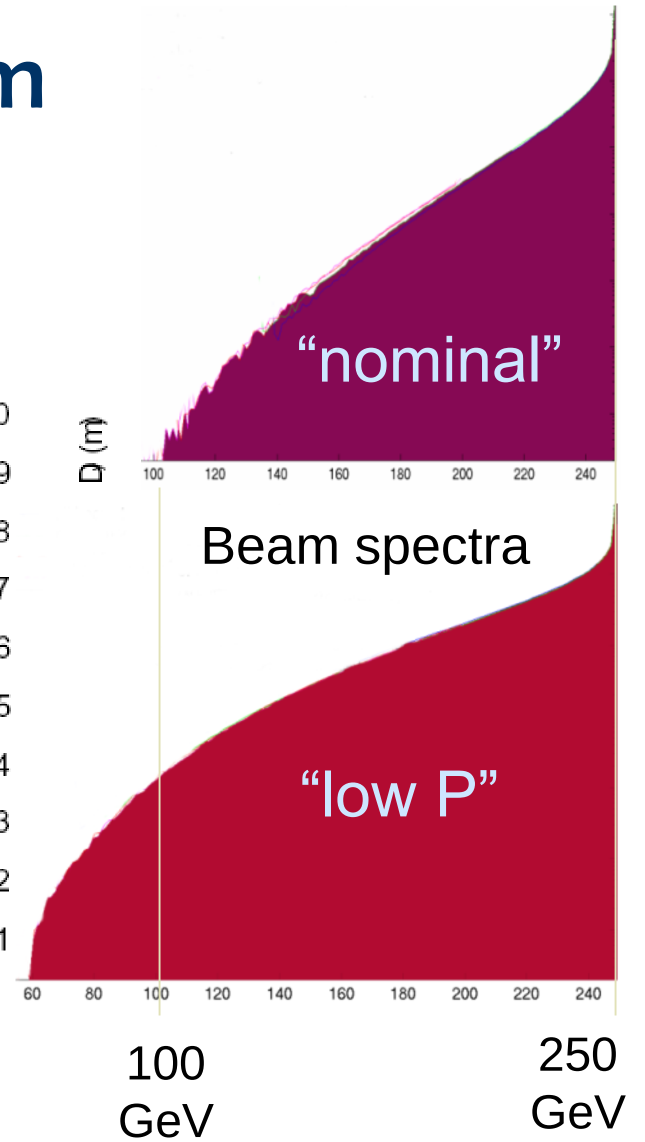


linac

IP

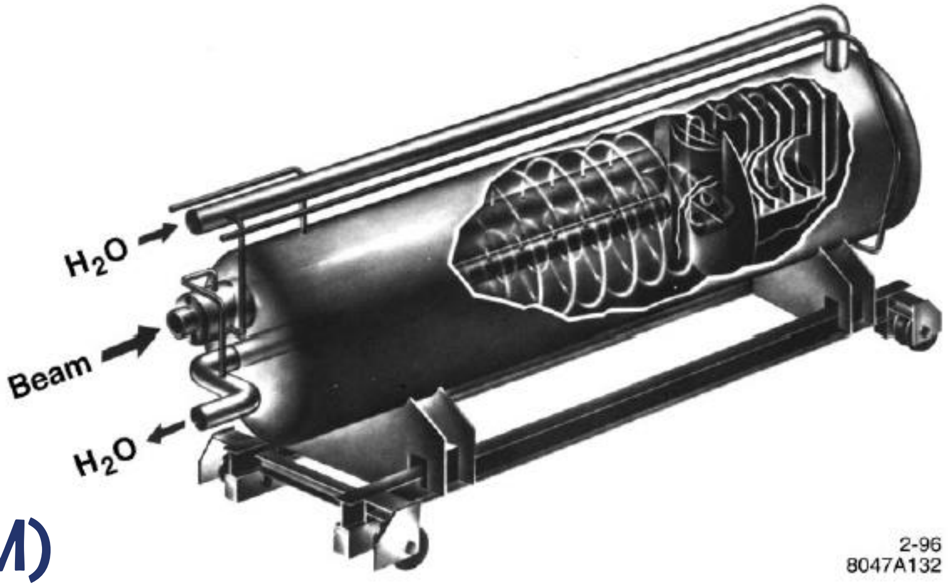
Optics for outgoing beam





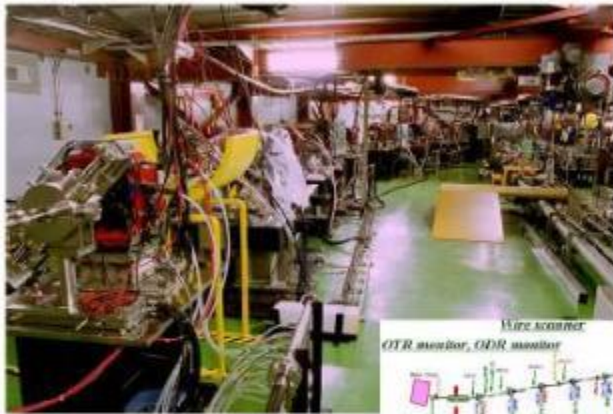
Extraction optics need to handle the beam with ~60% energy spread, and provides energy and polarization diagnostics

Beam dump



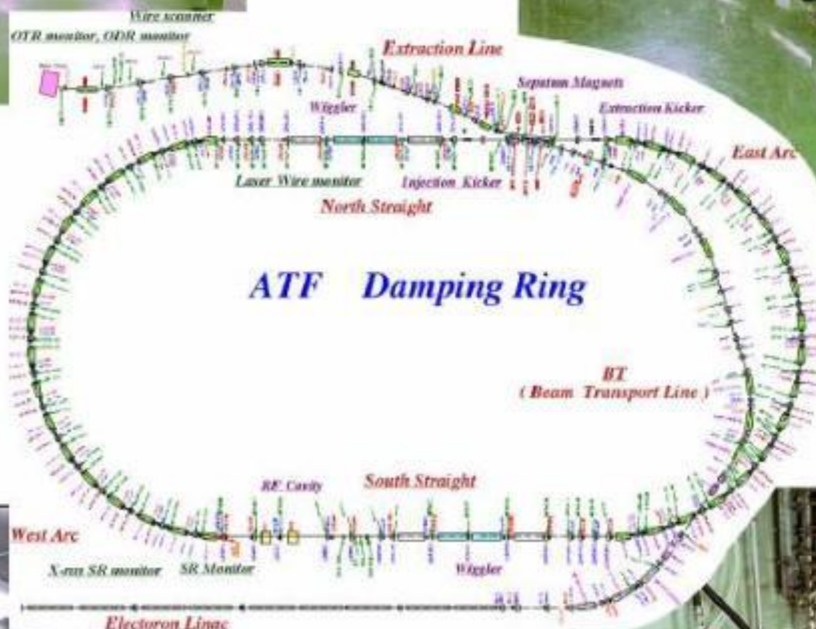
- 17MW power (for 1TeV CM)
- Rastering of the beam on 30cm double window
- 6.5m water vessel; ~1m/s flow
- 10atm pressure to prevent boiling
- Three loop water system
- Catalytic H_2-O_2 recombiner
- Filters for 7Be
- Shielding 0.5m Fe & 1.5m concrete

ATF and ATF2



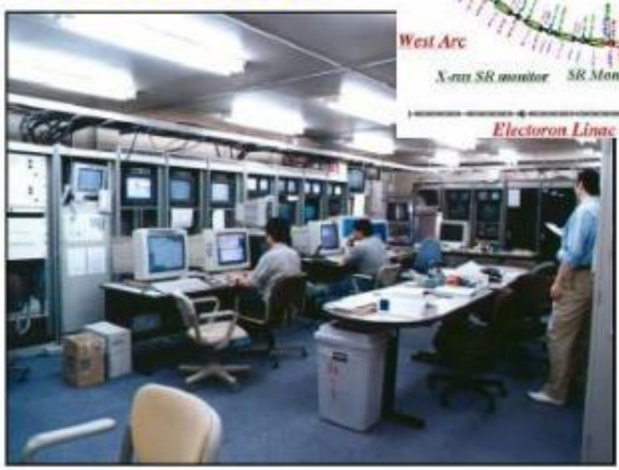
Extraction Line

Damping Ring



Linac

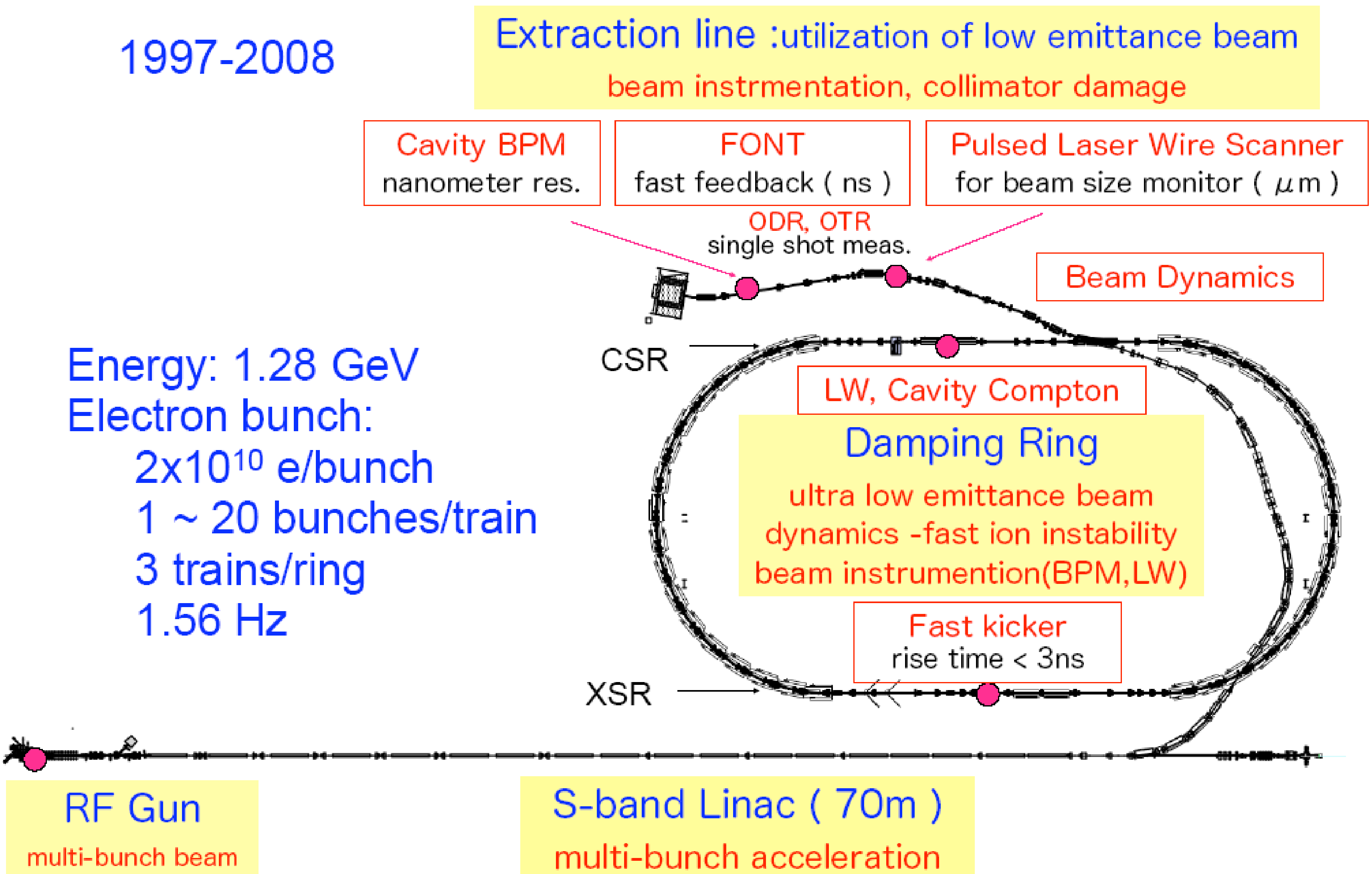
Control Room

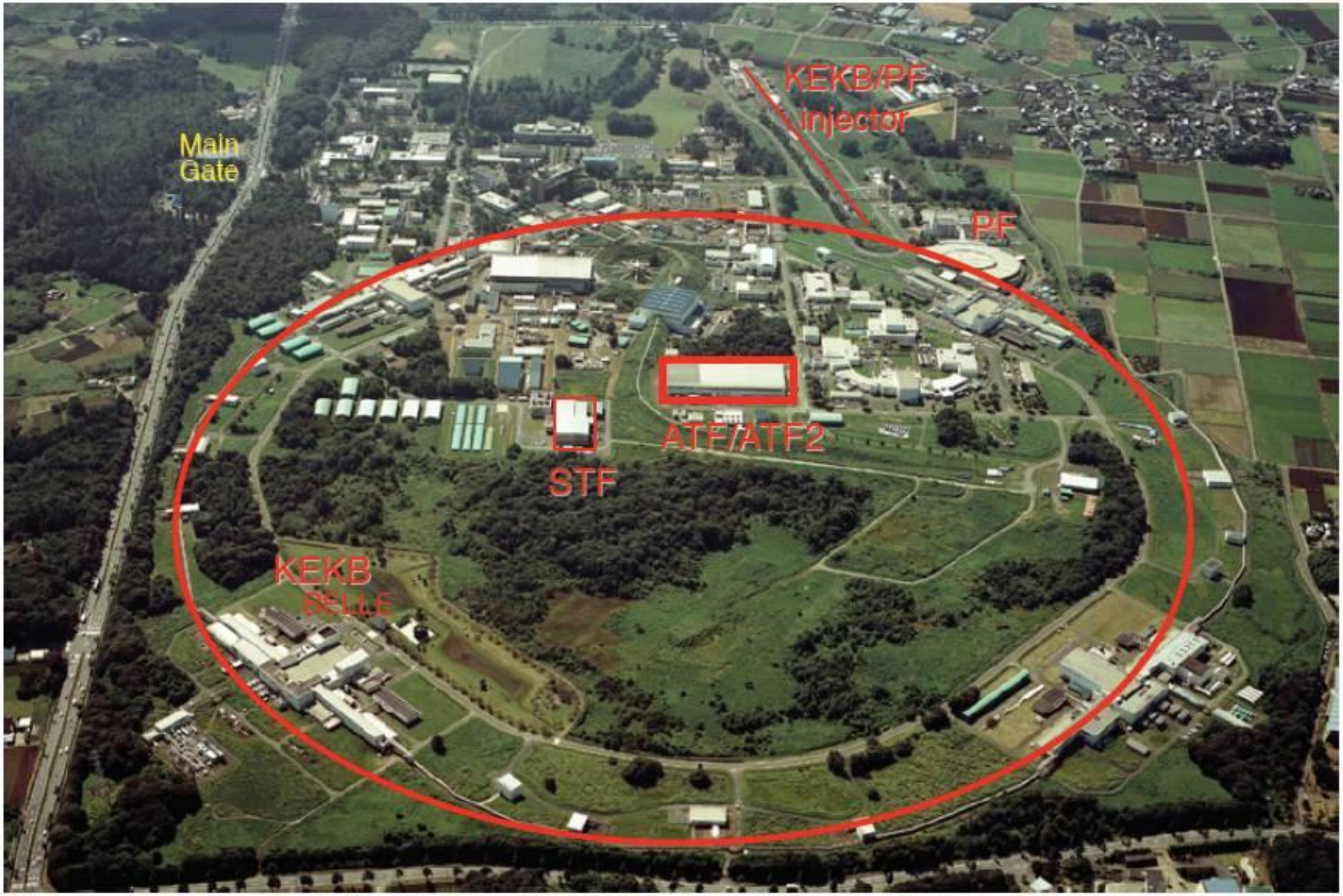


Accelerator Test Facility, KEK

1997-2008

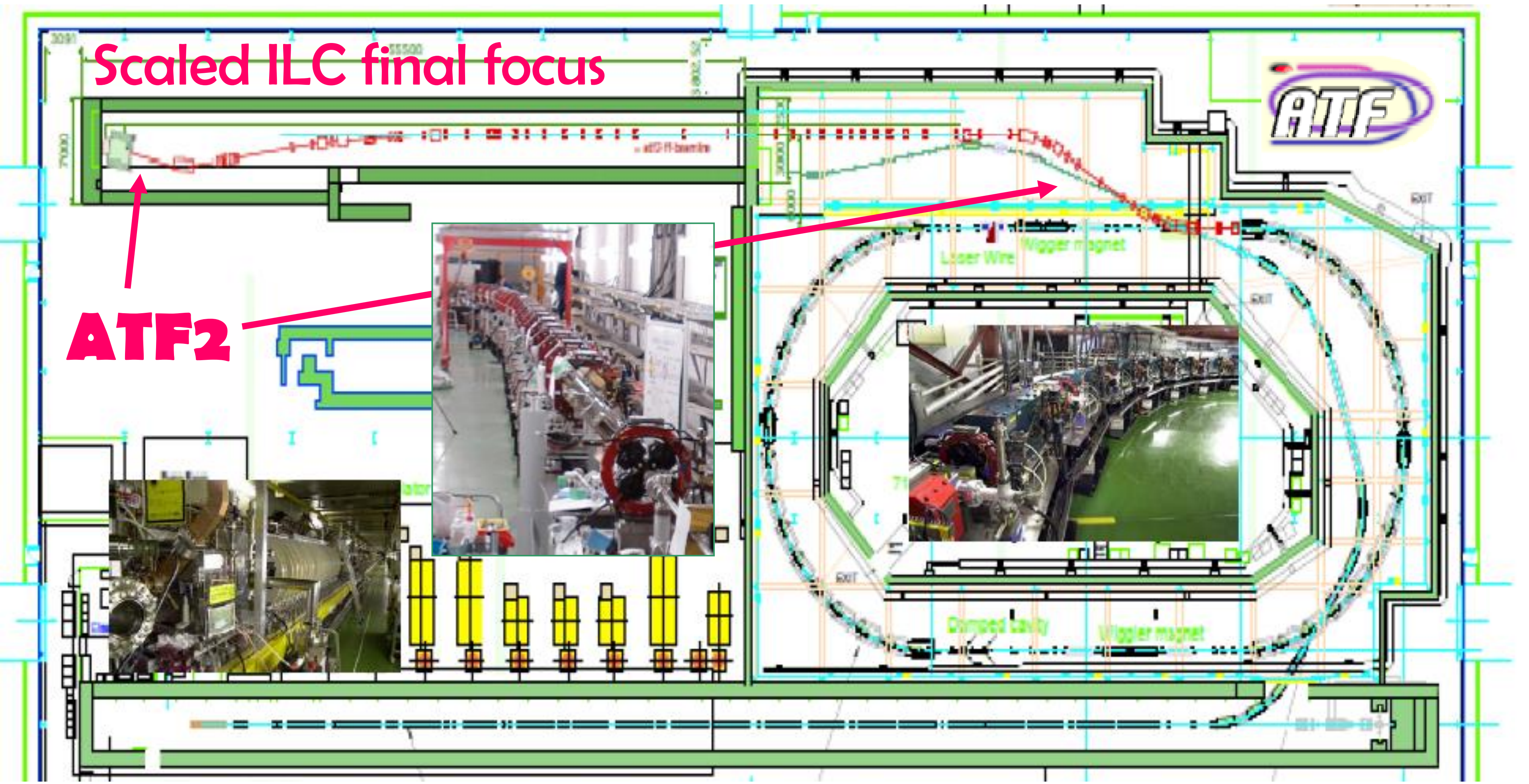
Energy: 1.28 GeV
Electron bunch:
- 2×10^{10} e/bunch
- 1 ~ 20 bunches/train
- 3 trains/ring
- 1.56 Hz



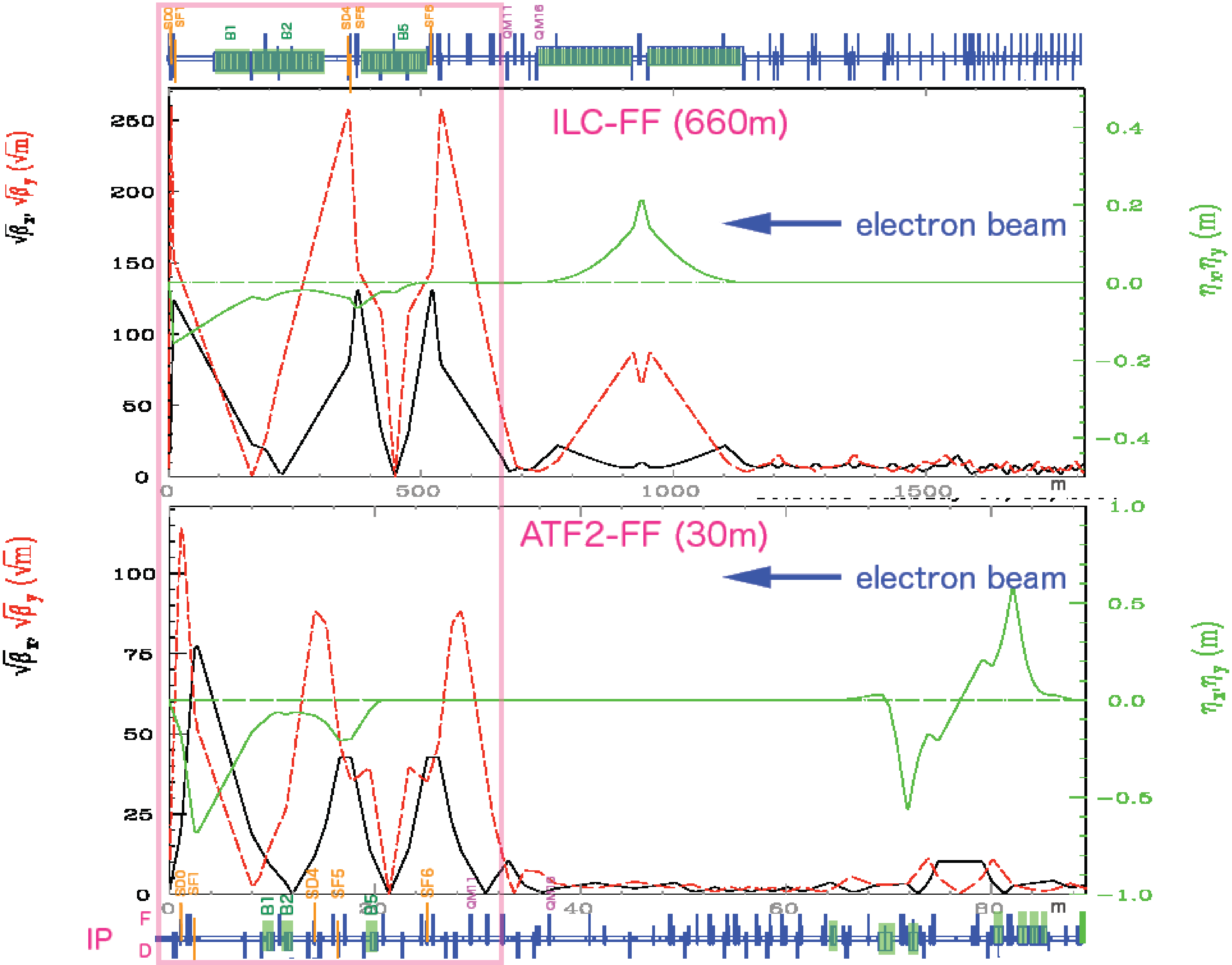

Main
Gate
KEKB/PF
injector
PF
ATF/ATF2
STF
KEKB
BELLE

ATF2: model of ILC beam delivery

goals: ~37nm beam size; nm level beam stability



- Dec 2008: first pilot run; Jan 2009: hardware commissioning
- Feb-Apr 2009: large β; BSM laser wire mode; tuning tools commissioning
- Oct-Dec 2009: commission interferometer mode of BSM & other hardware

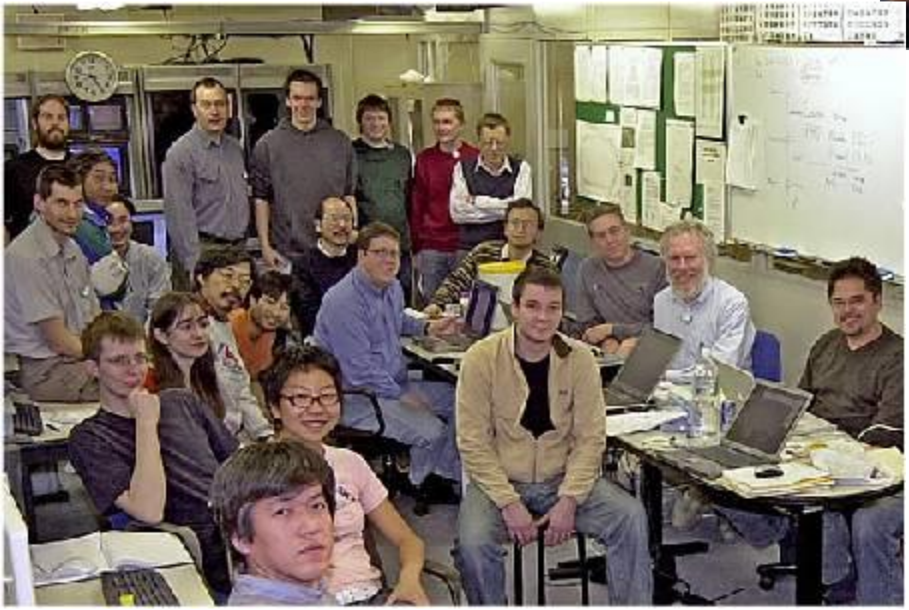

ILC-FF (660m)
electron beam
ATF2-FF (30m)
electron beam
IP
F
D

ATF2 & ILC parameters

Parameters	ATF2	ILC
Beam Energy, GeV	1.3	250
L*, m	1	3.5-4.2
$\gamma\varepsilon_{x/y}$, m*rad	3E-6 / 3E-8	1E-5 / 4E-8
IP $\beta_{x/y}$, mm	4 / 0.1	21 / 0.4
IP η', rad	0.14	0.094
σ_E, %	~0.1	~0.1
Chromaticity	~1E4	~1E4
$n_{bunches}$	1-3 (goal A)	~3000
$n_{bunches}$	3-30 (goal B)	~3000
N_{bunch}	1-2E10	2E10
IP σ_y, nm	37	5

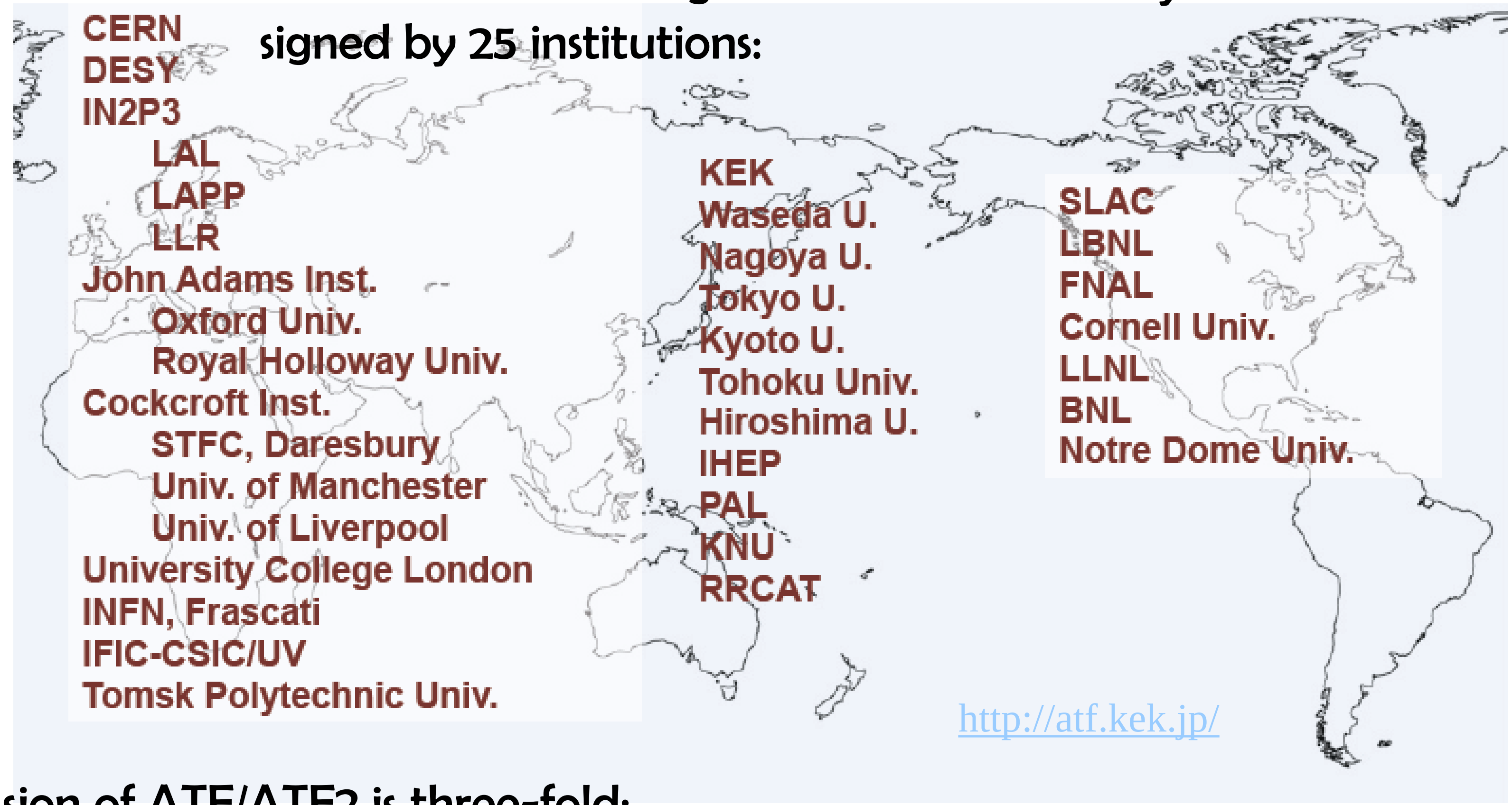
ATF collaboration & ATF2 facility

- ATF2 will prototype FF,
- help development tuning methods, instrumentation (laser wires, fast feedback, submicron resolution BPMs),
- help to learn achieving small size & stability reliably,



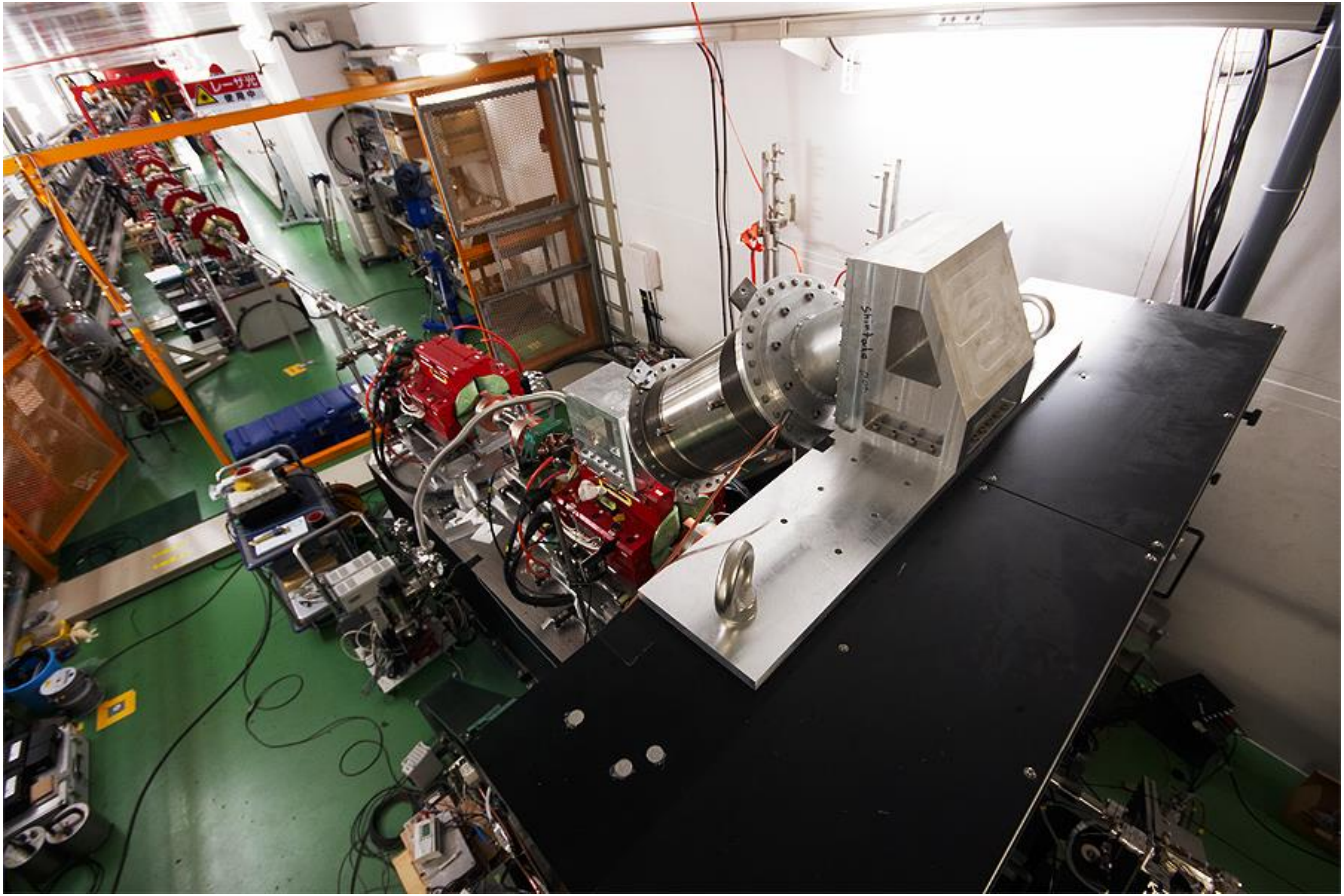
- ATF2 was constructed as ILC model, with in-kind contribution from partners and host country providing civil construction

ATF International organization is defined by MOU signed by 25 institutions:



MOU: Mission of ATF/ATF2 is three-fold:

- ATF, to establish the technologies associated with producing the electron beams with the quality required for ILC and provide such beams to ATF2 in a stable and reliable manner.
- ATF2, to use the beams extracted from ATF at a test final focus beamline which is similar to what is envisaged at ILC. The goal is to demonstrate the beam focusing technologies that are consistent with ILC requirements. For this purpose, ATF2 aims to focus the beam down to a few tens of nm (rms) with a beam centroid stability within a few nm for a prolonged period of time.
- Both the ATF and ATF2, to serve the mission of providing the young scientists and engineers with training opportunities of participating in R&D programs for advanced accelerator technologies.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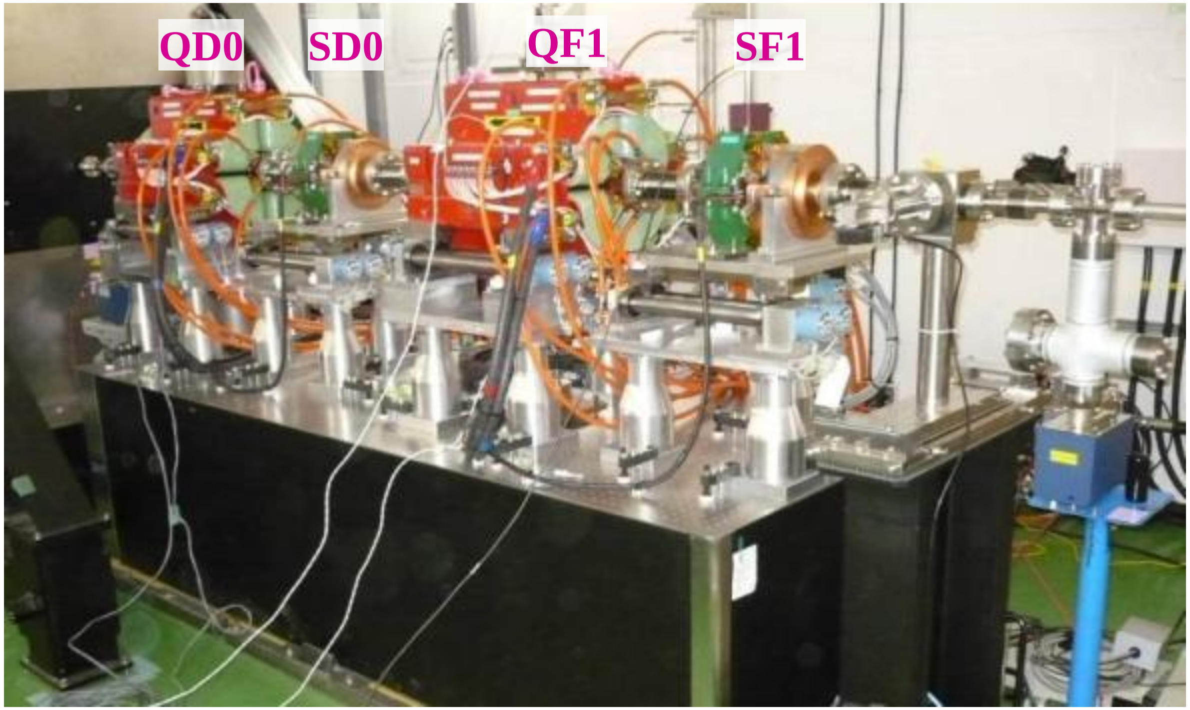
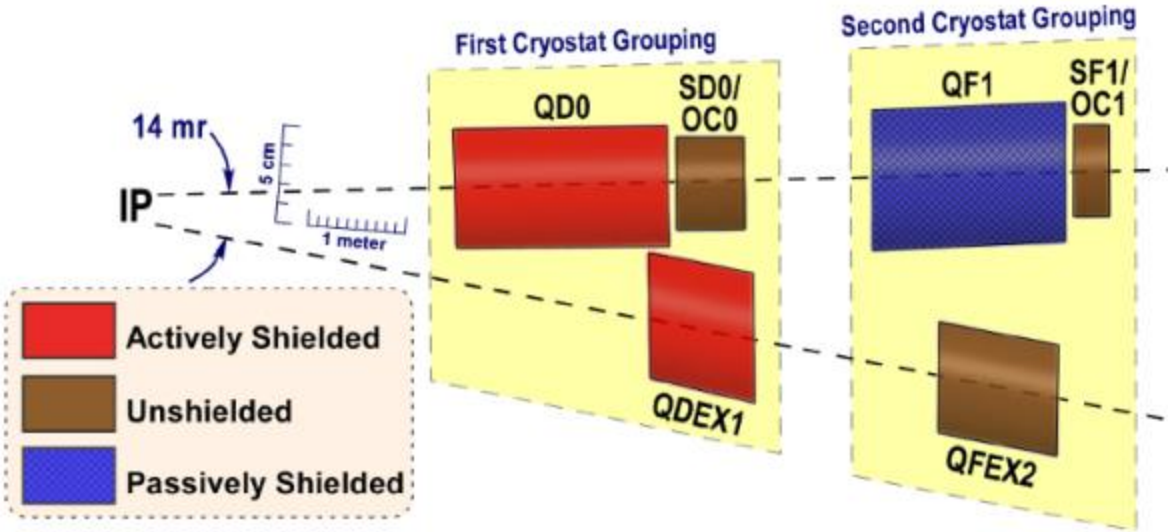
使用中



ATF2 final doublet



ILC Final Doublet layout

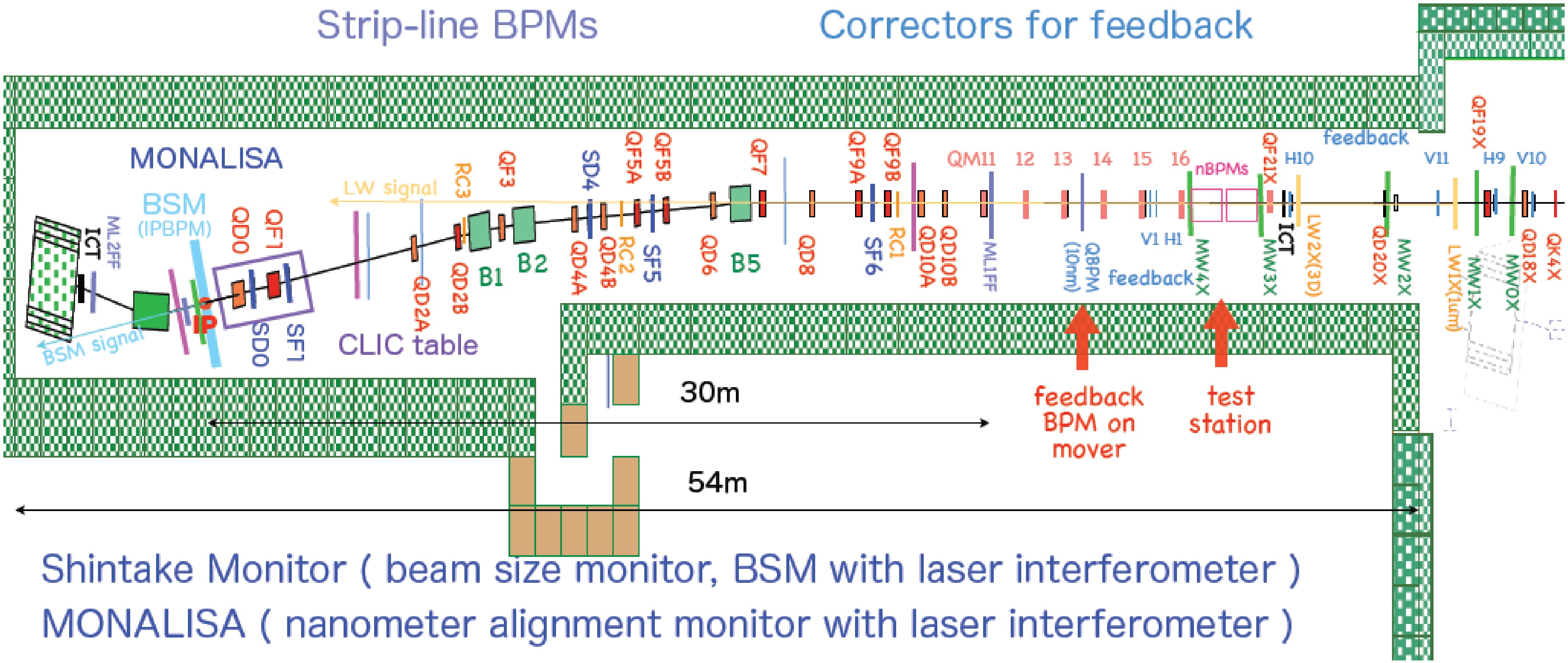
Magnets and Instrumentation at ATF2

22 Quadrupoles(Q), 5 Sextupoles(S), 3 Bends(B) in downstream of QM16

All Q- and S-magnets have cavity-type beam position monitors(QBPM, 100nm).

3 Screen Monitors — 5 Wire Scanners, Laserwires

Strip-line BPMs — Correctors for feedback



Shintake Monitor (beam size monitor, BSM with laser interferometer)

MONALISA (nanometer alignment monitor with laser interferometer)

Laserwire (beam size monitor with laser beam for 1 μm beam size, 3 axies)

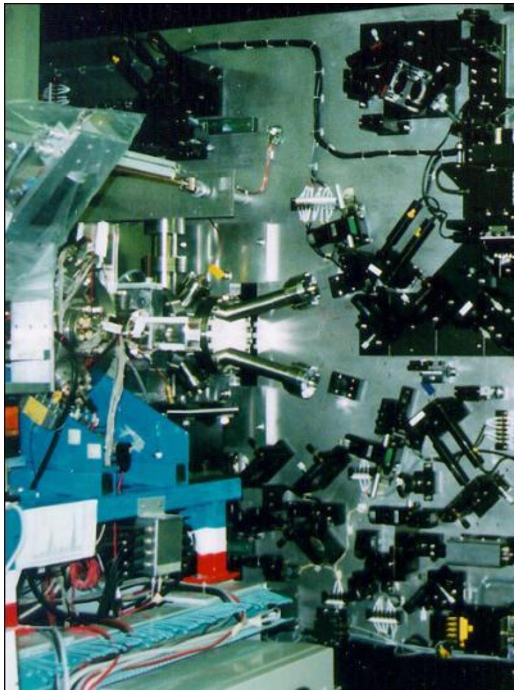
IP intra-train feedback system with latency of less than 150ns (FONT)

Magnet movers for Beam Based Alignment (BBA)

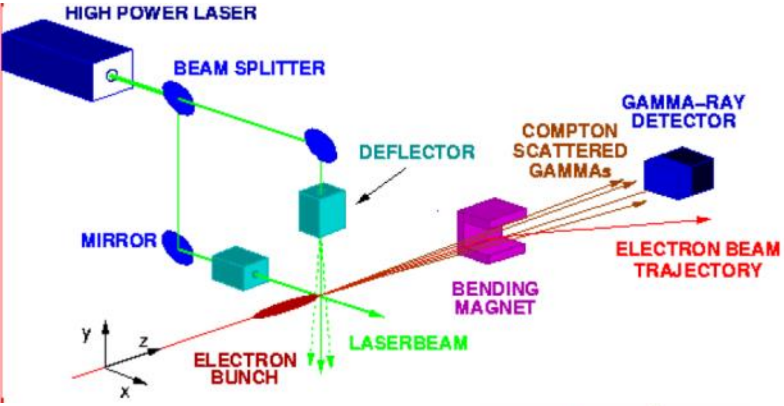
High Available Power Supply (HA-PS) system for magnets

Advanced beam instrumentation at ATF2

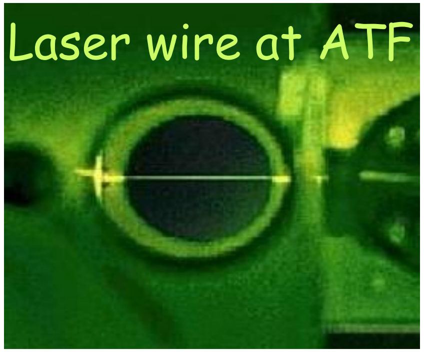
- BSM to confirm 35nm beam size
- nano-BPM at IP to see the nm stability
- Laser-wire to tune the beam
- Cavity BPMs to measure the orbit
- Movers, active stabilization, alignment system
- Intratrain feedback, Kickers to produce ILC-like train

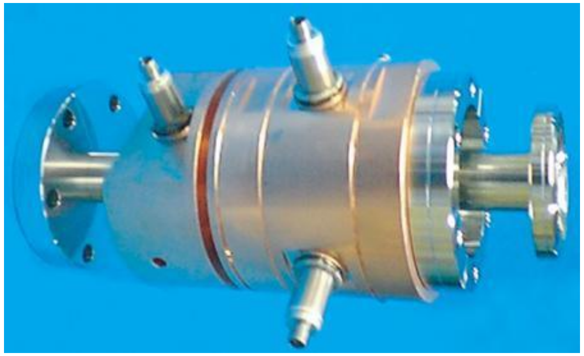


IP Beam-size monitor (BSM) (Tokyo U./KEK, SLAC, UK)



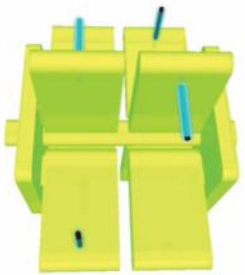
Laser-wire beam-size Monitor (UK group)





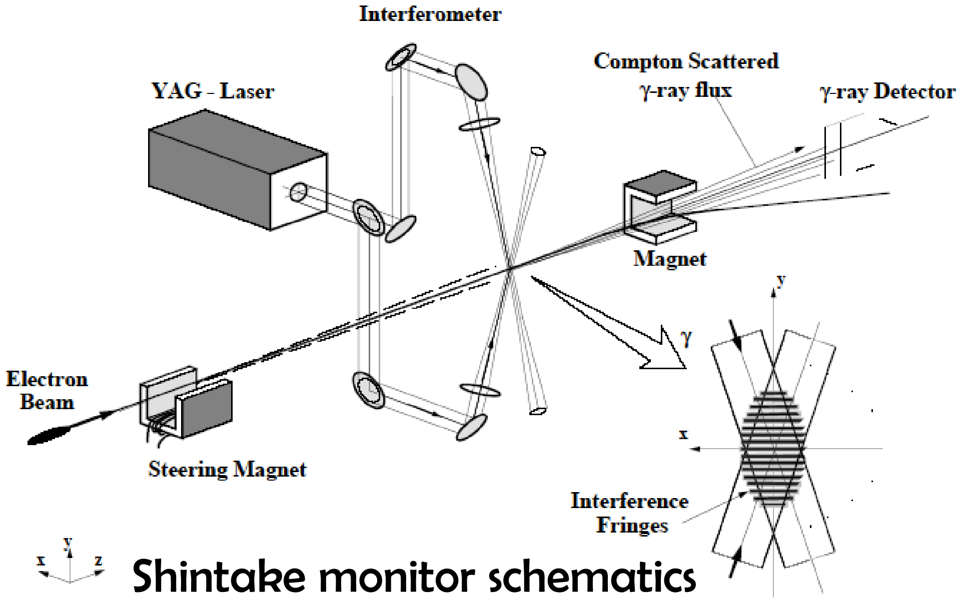
Cavity BPMs, for use with Q magnets with 100nm resolution (PAL, SLAC, KEK)

Cavity BPMs with 2nm resolution, for use at the IP (KEK)

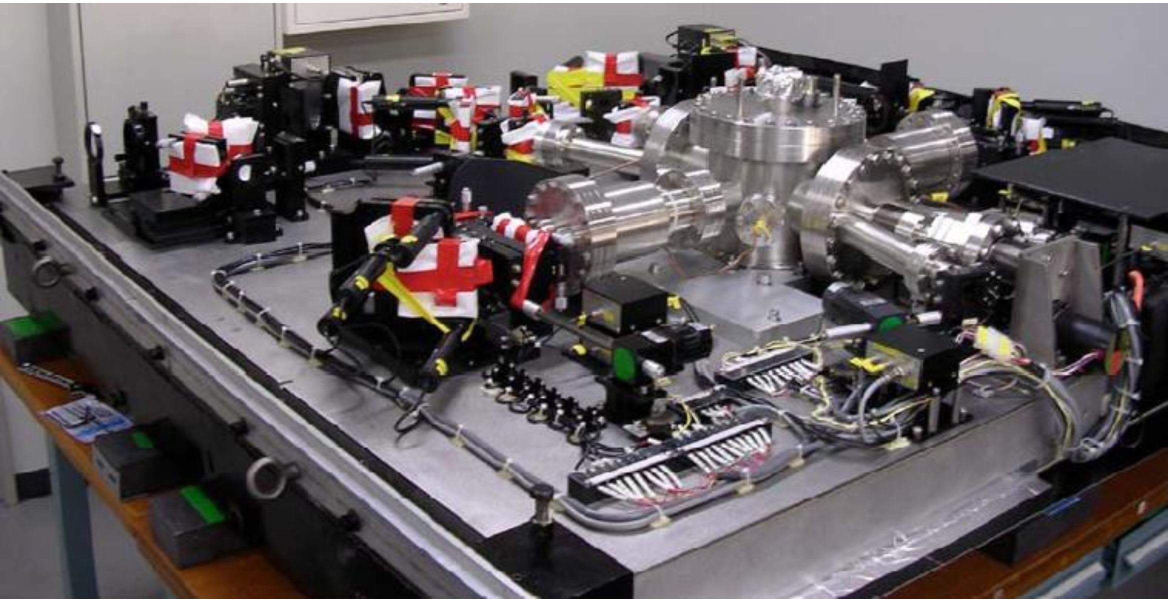


IP Beam Size monitor

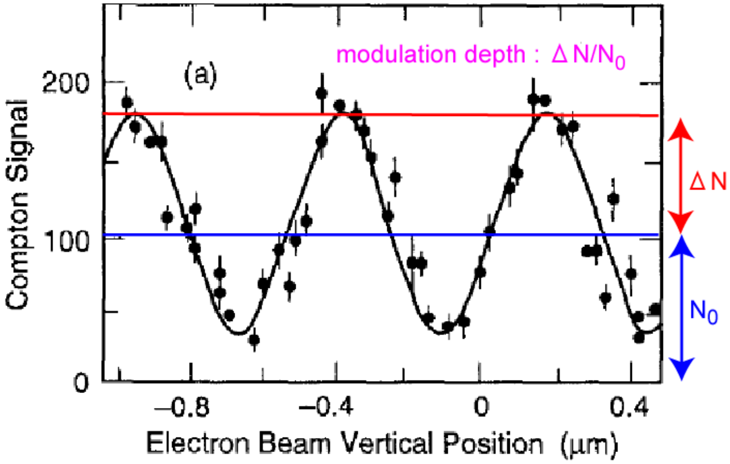
- BSM:
  - refurbished & much improved FFTB Shintake BSM
  - 1064nm=>532nm



Shintake monitor schematics

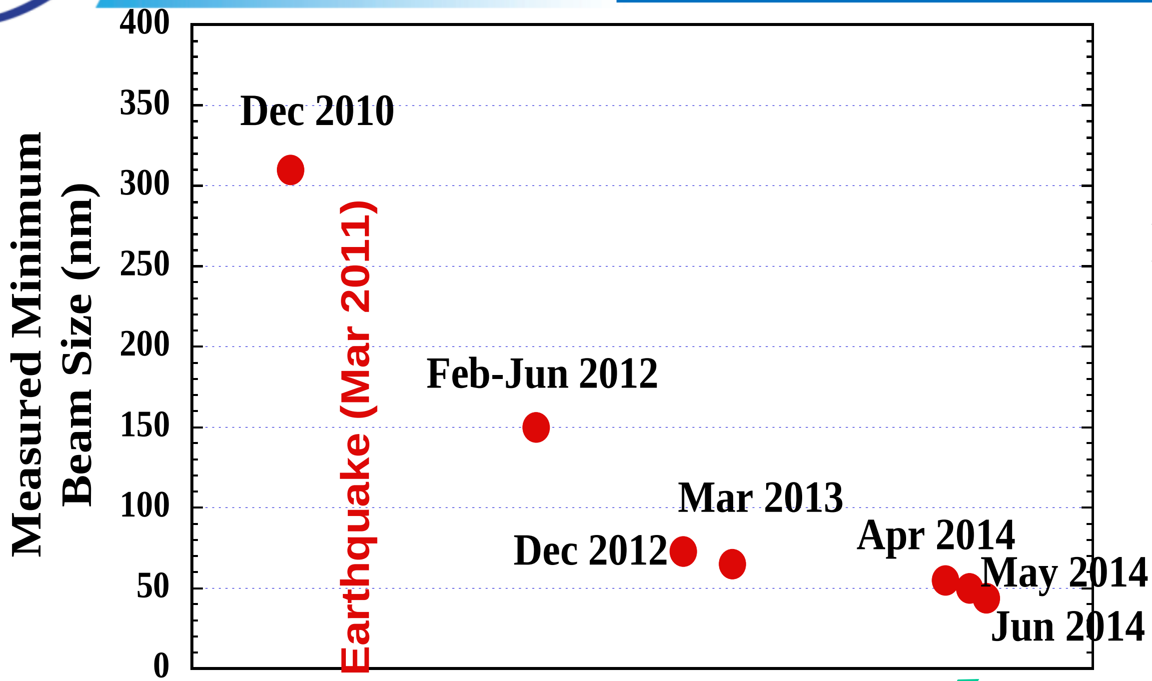


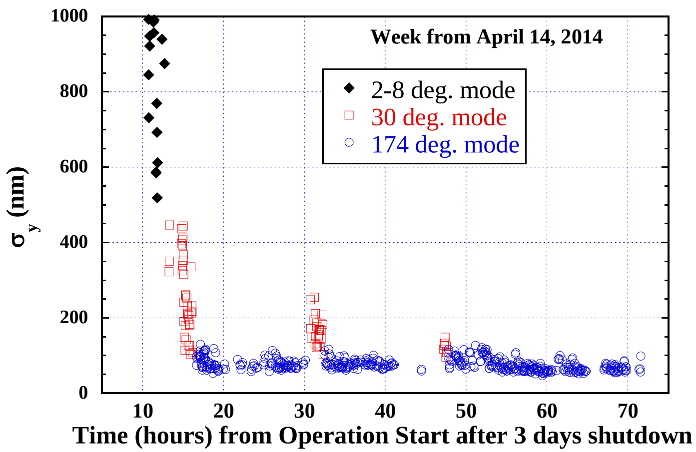
Jul 2005: BSM after it arrived to Univ. of Tokyo



FFTB sample : σ_y = 70 nm

Nanobeams at ATF2 Final Focus





Beam Size 44 nm observed*,
(Goal (ideal size): **37** nm
corresponding to **6** nm at ILC)

**) Effects (wakefields and magnet nonlinearities) contributing to ATF2 beam size (at 1.2 GeV) would not matter at ILC energy*

Operation of Final Focus with local chromatic correction verified successfully

It took long time as we needed to develop instrumentation and tuning procedures

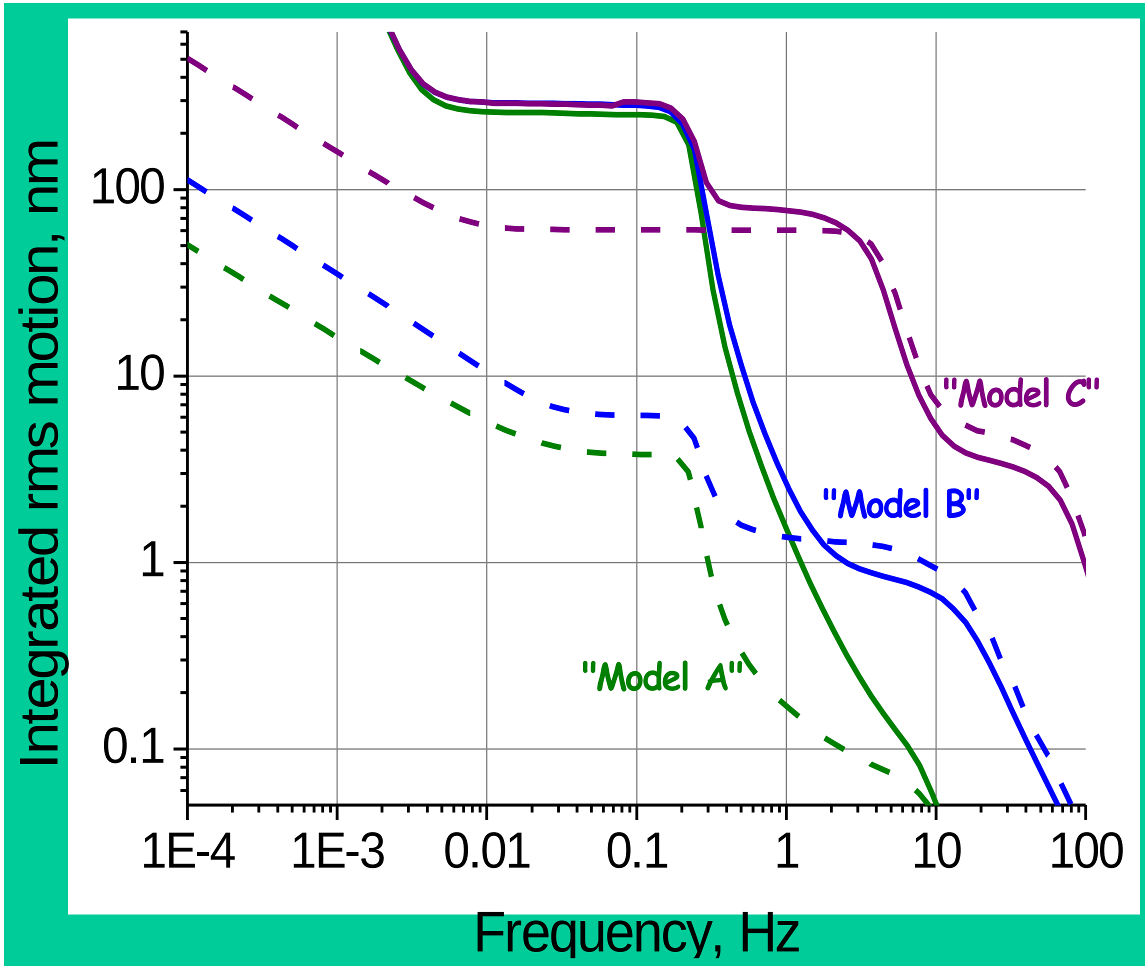
Some of ATF Collaboration photos

FF and stability

- In the previous lectures we have discussed how to estimate effects of dynamic misalignments on beams
- This can be done analytically, and even taking onto account feedbacks
  - E.g. one-to-one steering in linac
  - Or IP feedforward
- In practice, detailed estimations are performed by end-to-end simulations
  - Or “DR=>IP<=DR” simulations

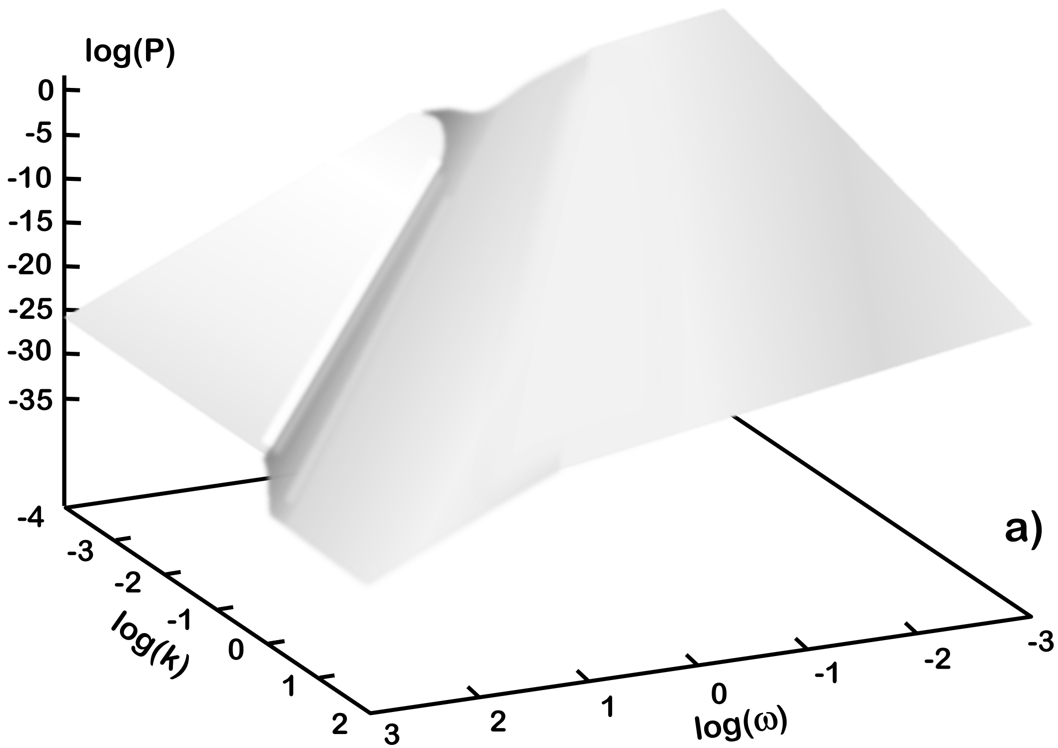
Ground motion models

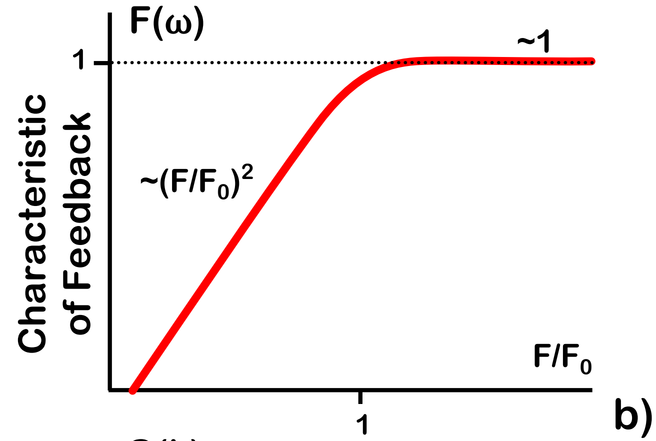
- **Based on data, build modeling P(ω,k) spectrum of ground motion which includes:**
  - **Elastic waves**
  - **Slow ATL motion**
  - **Systematic motion**
  - **Cultural noises**

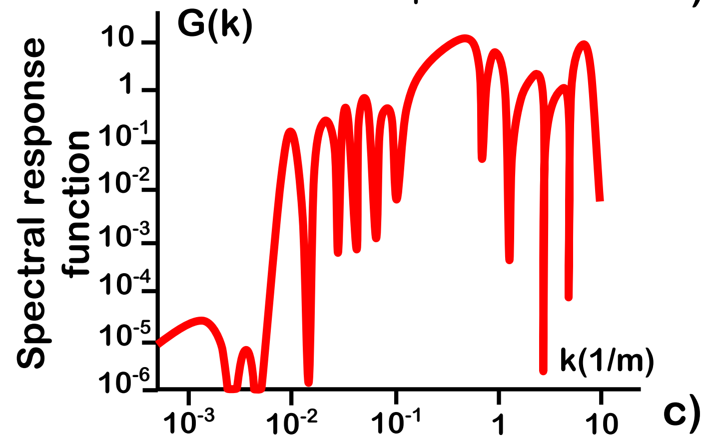


Example of integrated spectra of absolute (solid lines) and relative motion for 50m separation obtained from the models

Ground motion induced beam offset at IP

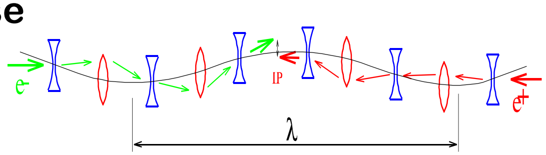






$P(\omega,k)$ - **2D spectrum of ground motion**

Spectral response function $G(k)$

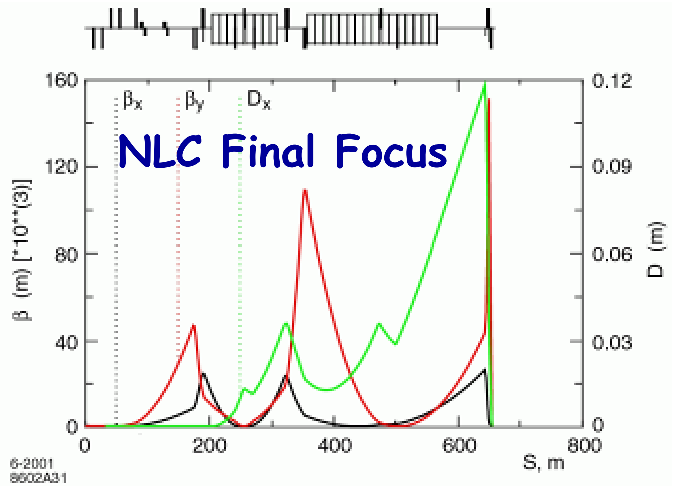


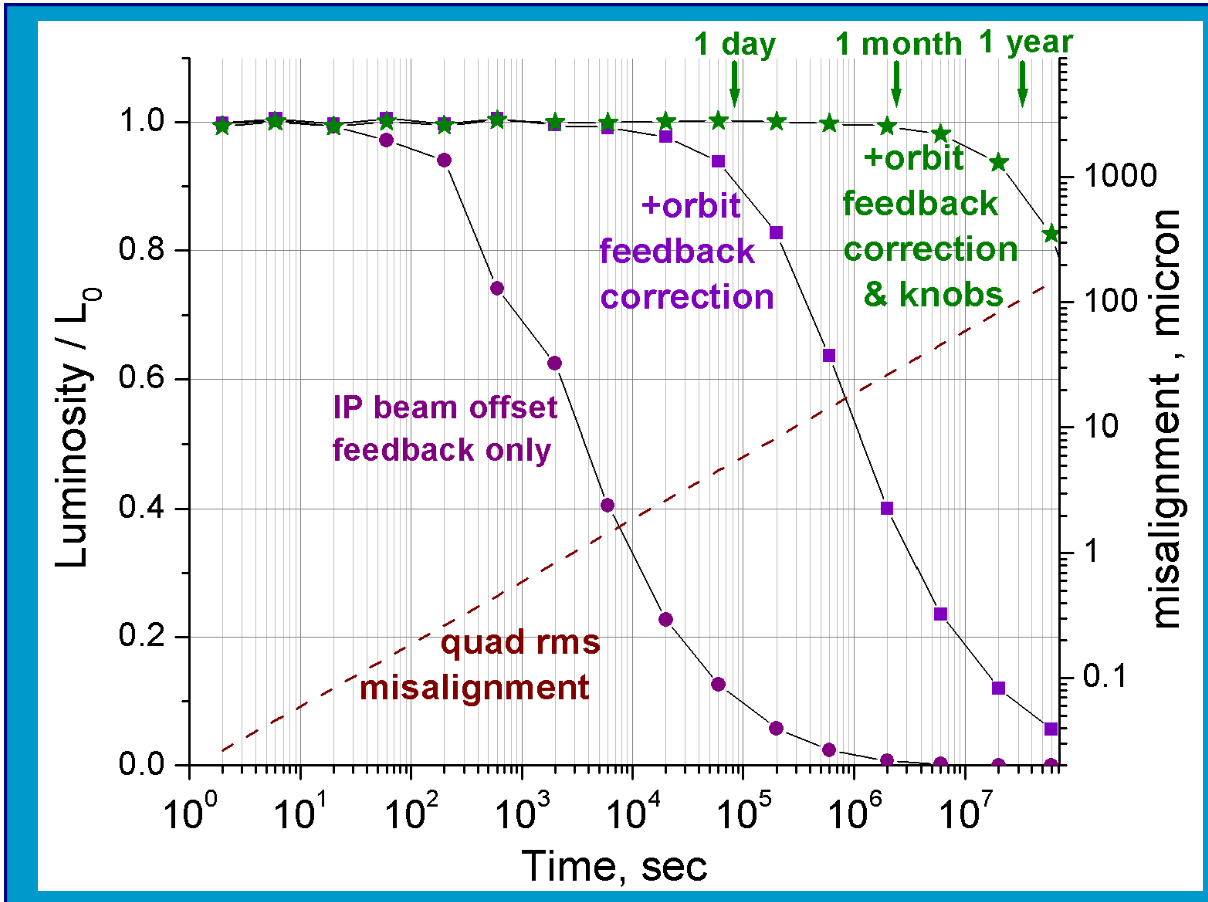
rms beam offset at IP: $\propto \iint P(\omega,k) \cdot G(k) \cdot F(\omega) \cdot dk \cdot d\omega$

Performance of inter-bunch feedback $F(\omega)$

Simulations of feedbacks and Final Focus knobs

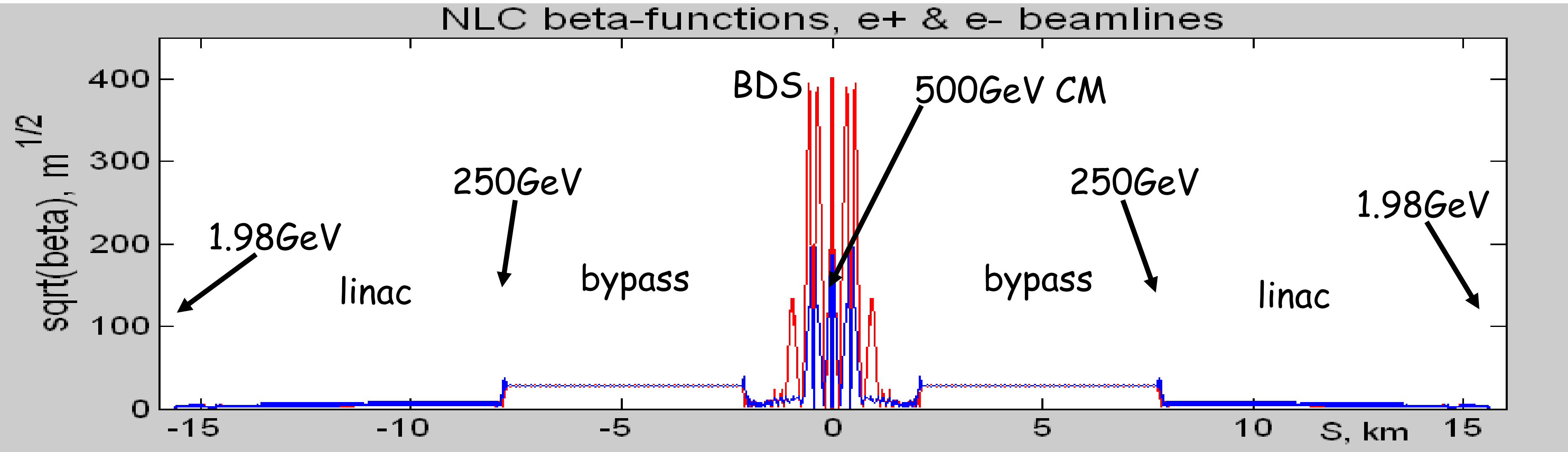
IP feedback, orbit feedback and dithering knobs suppress luminosity loss caused by ground motion



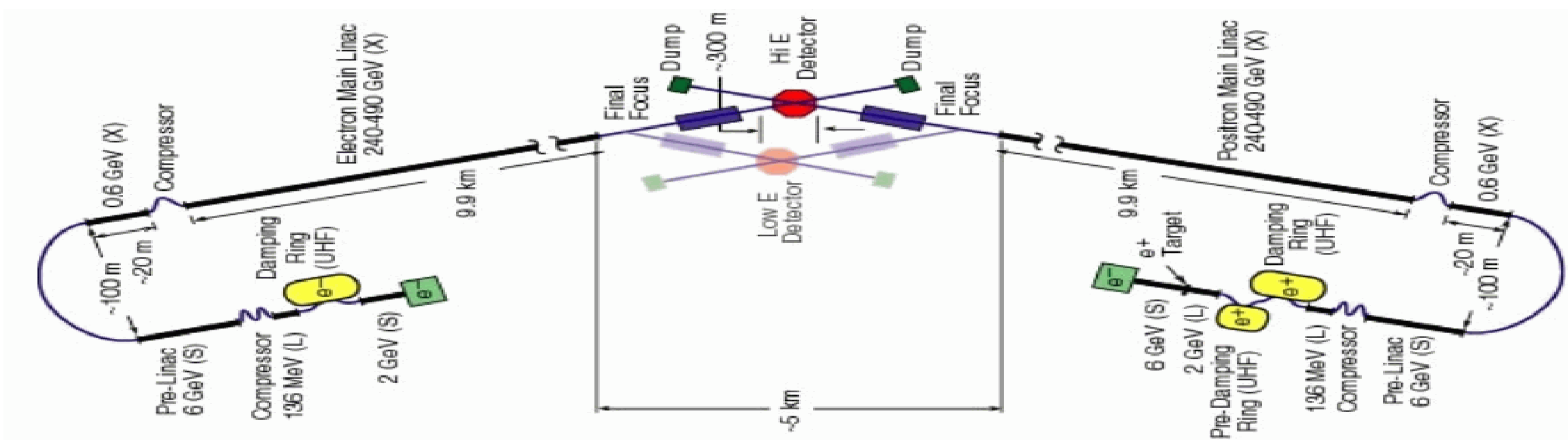


- Ground motion with $A=5*10^{-7}$ $\mu m^2/m/s$
- Simulated with MONCHOU

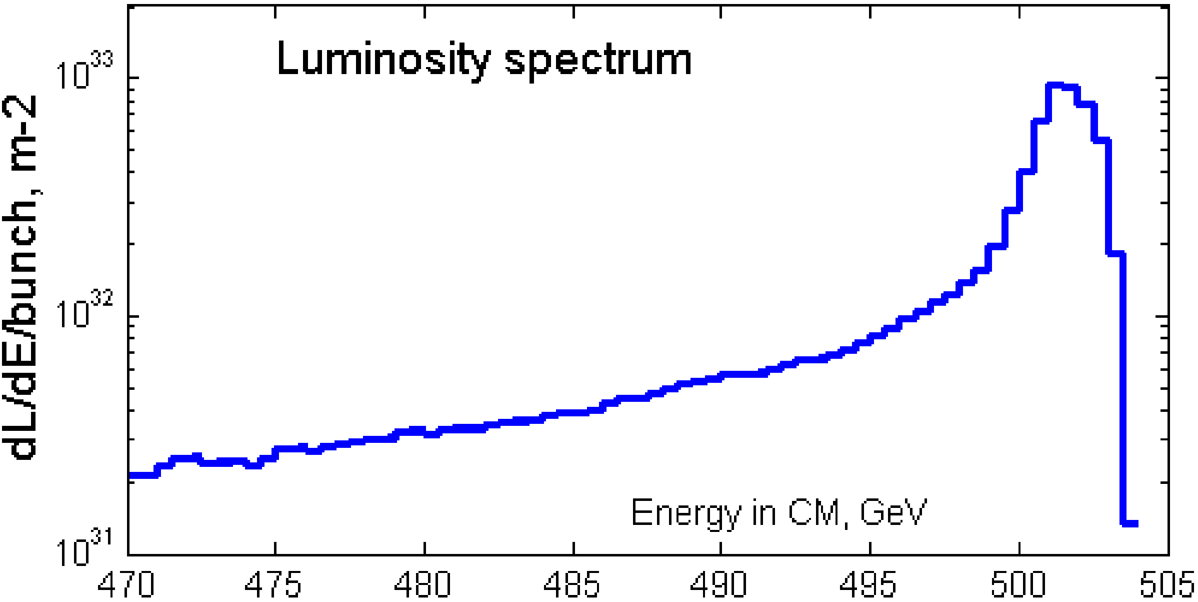
e- source => Interaction Point <= e+ source integrated simulations

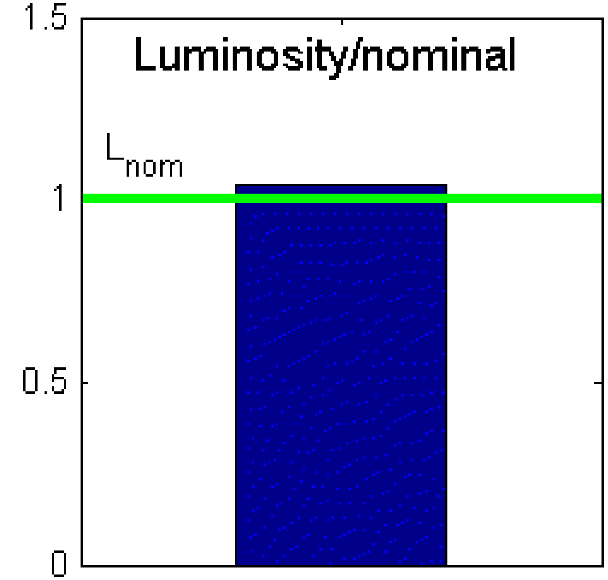


IP

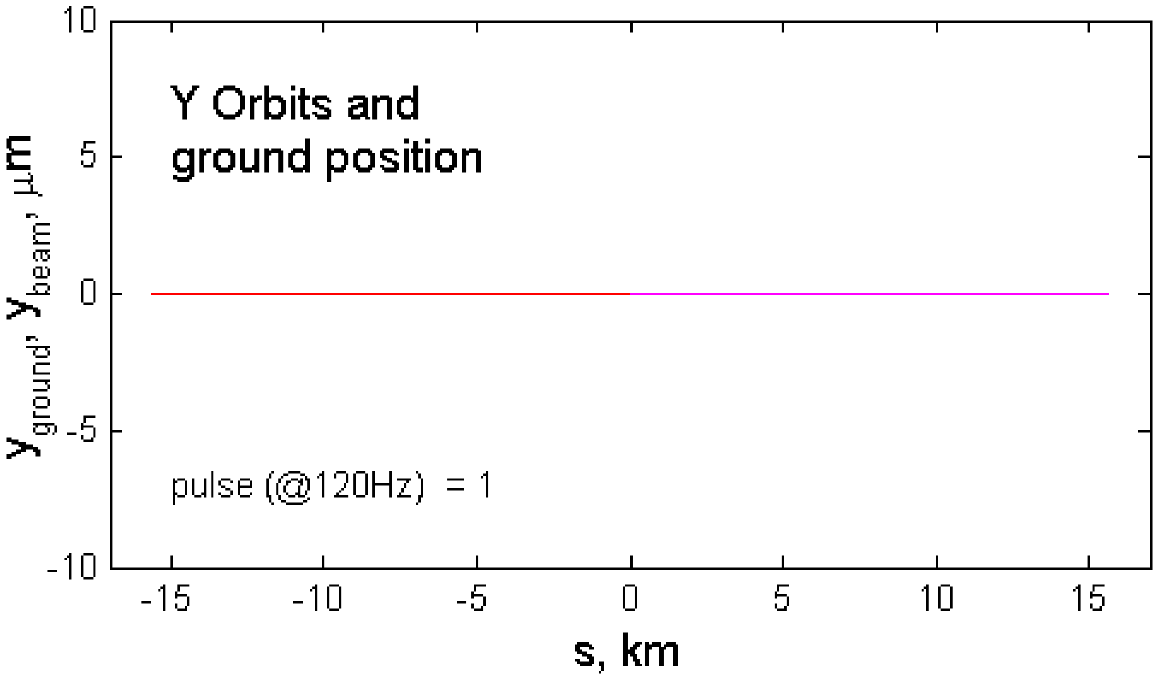


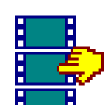
NLC, DR>IP<DR; GM B; RF misal(x,y)=75,15 microns, IP feedback



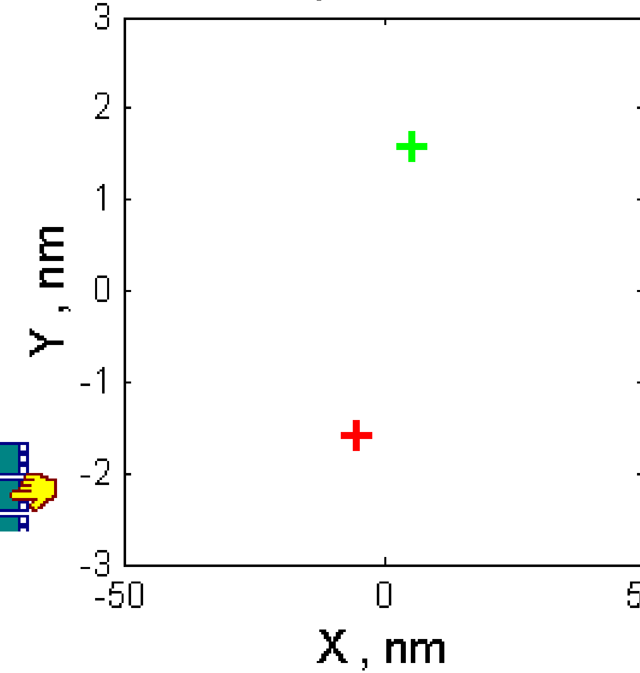


Intermediate ground motion

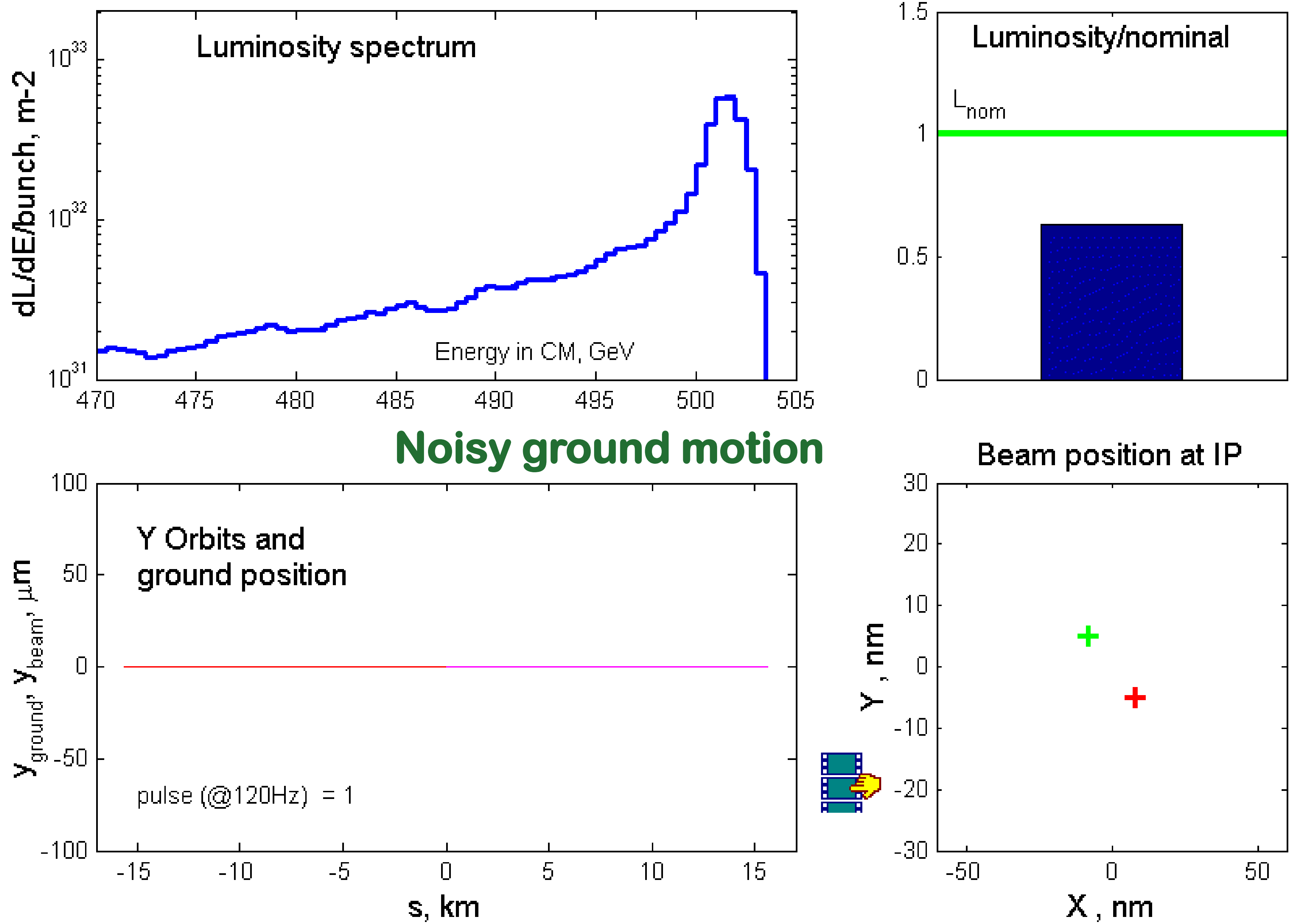




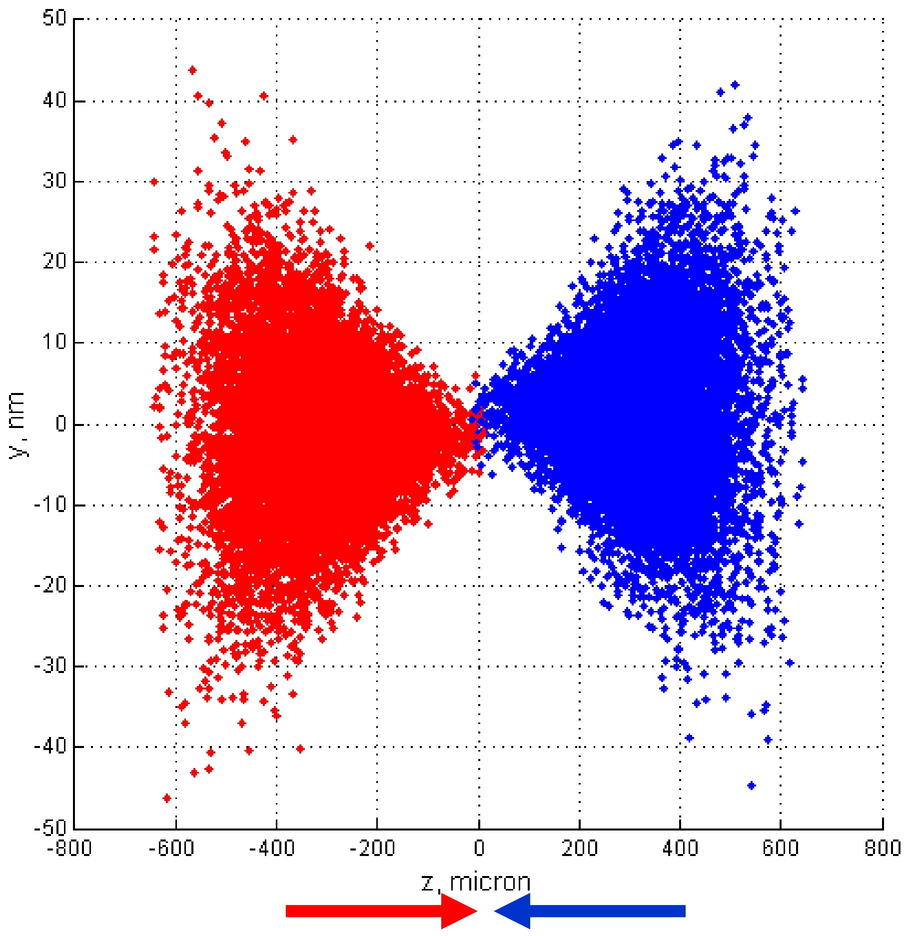
Beam position at IP

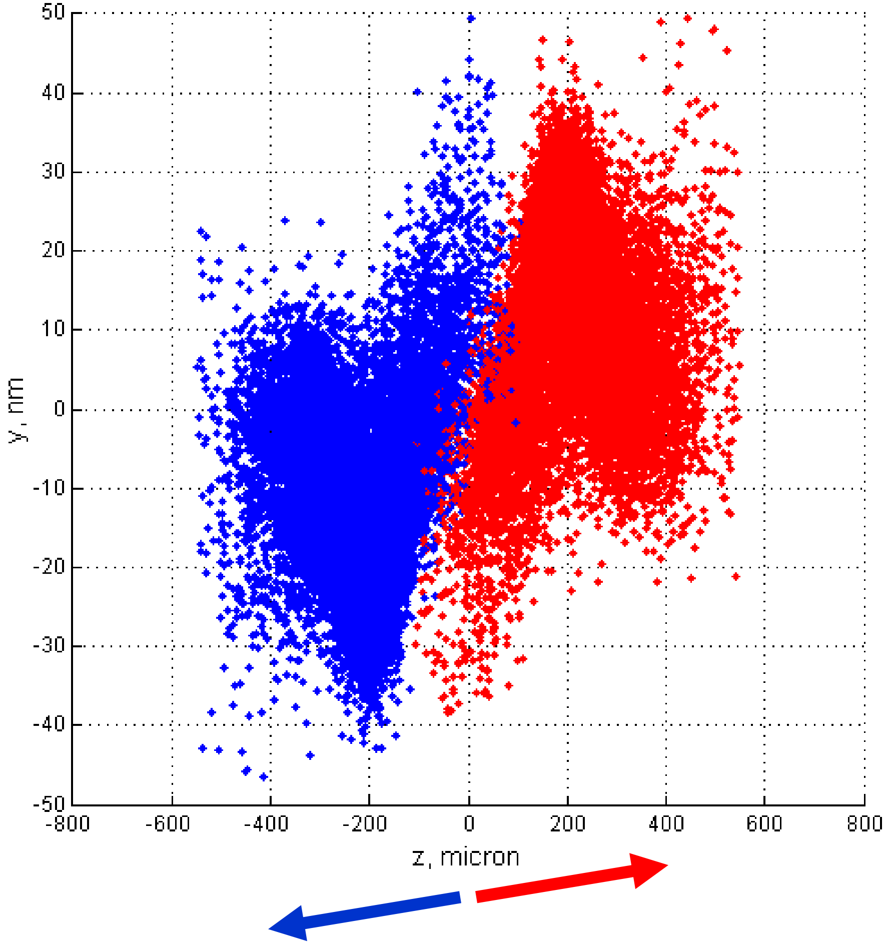


NLC, DR>IP<DR; GM C; RF misal(x,y)=75,15 microns, IP feedback



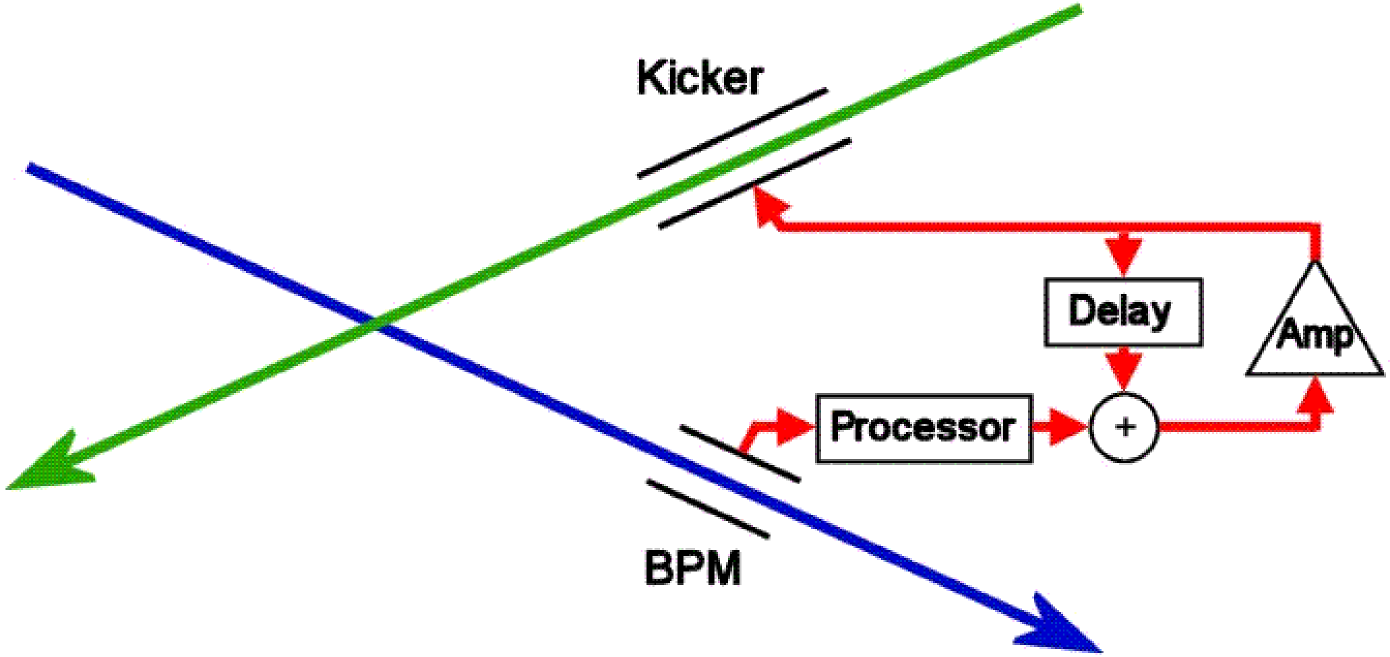
Beam-beam deflection





Sub nm offsets at IP cause large well detectable offsets (micron scale) of the beam a few meters downstream

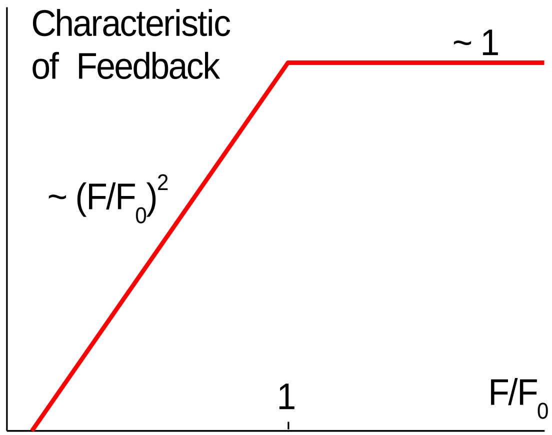
Beam-Beam orbit feedback

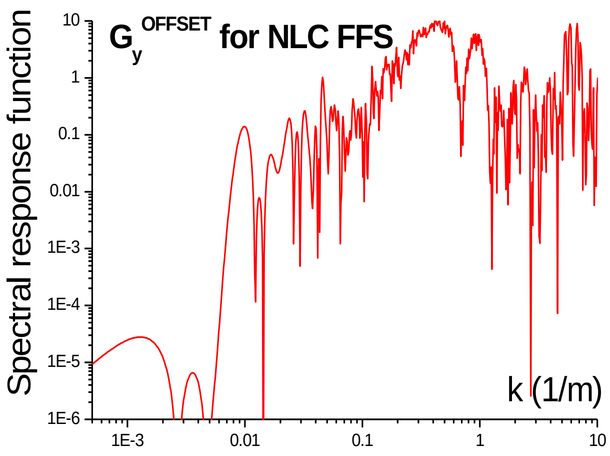


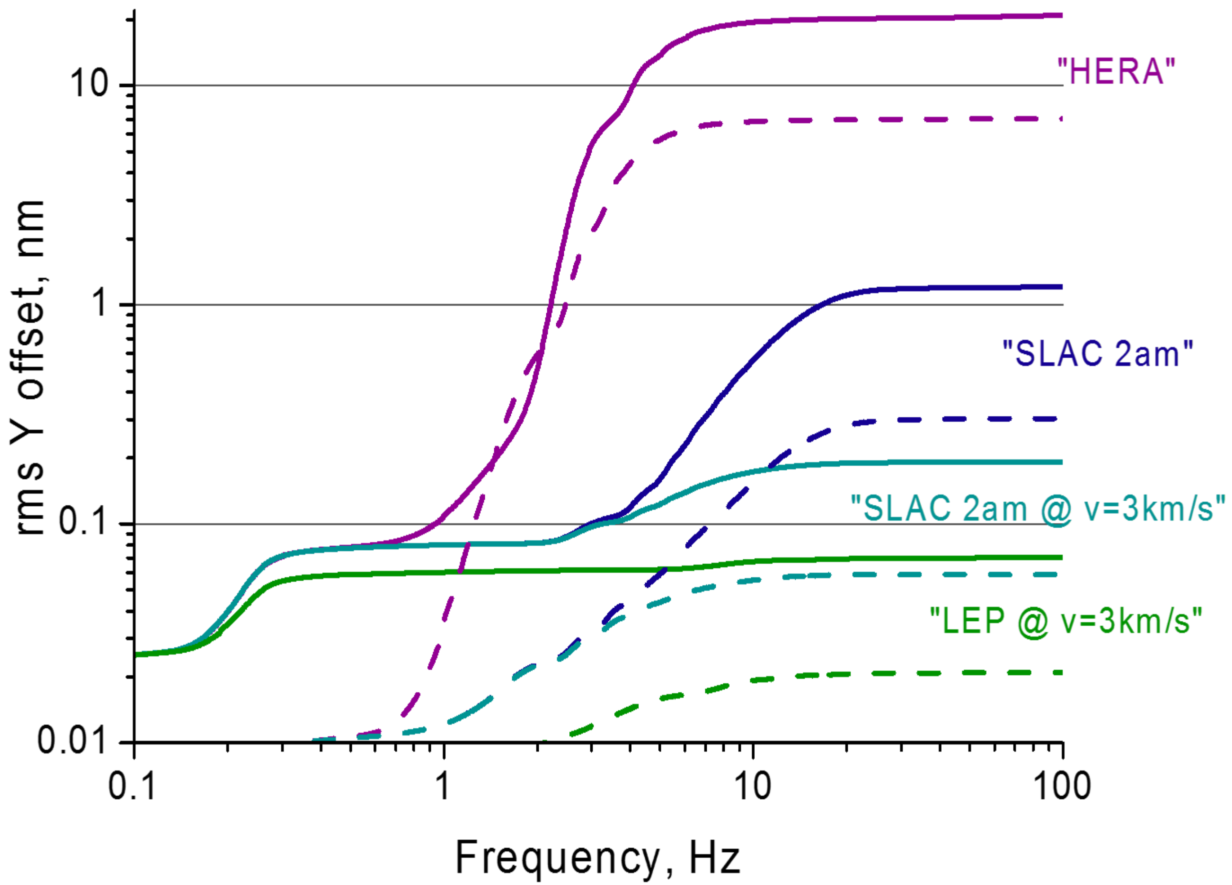
Use strong beam-beam kick to keep beams colliding

Shorten BPM-Kicker path for NLC or CLIC design

Beam offset at the IP of NLC FF for different GM models

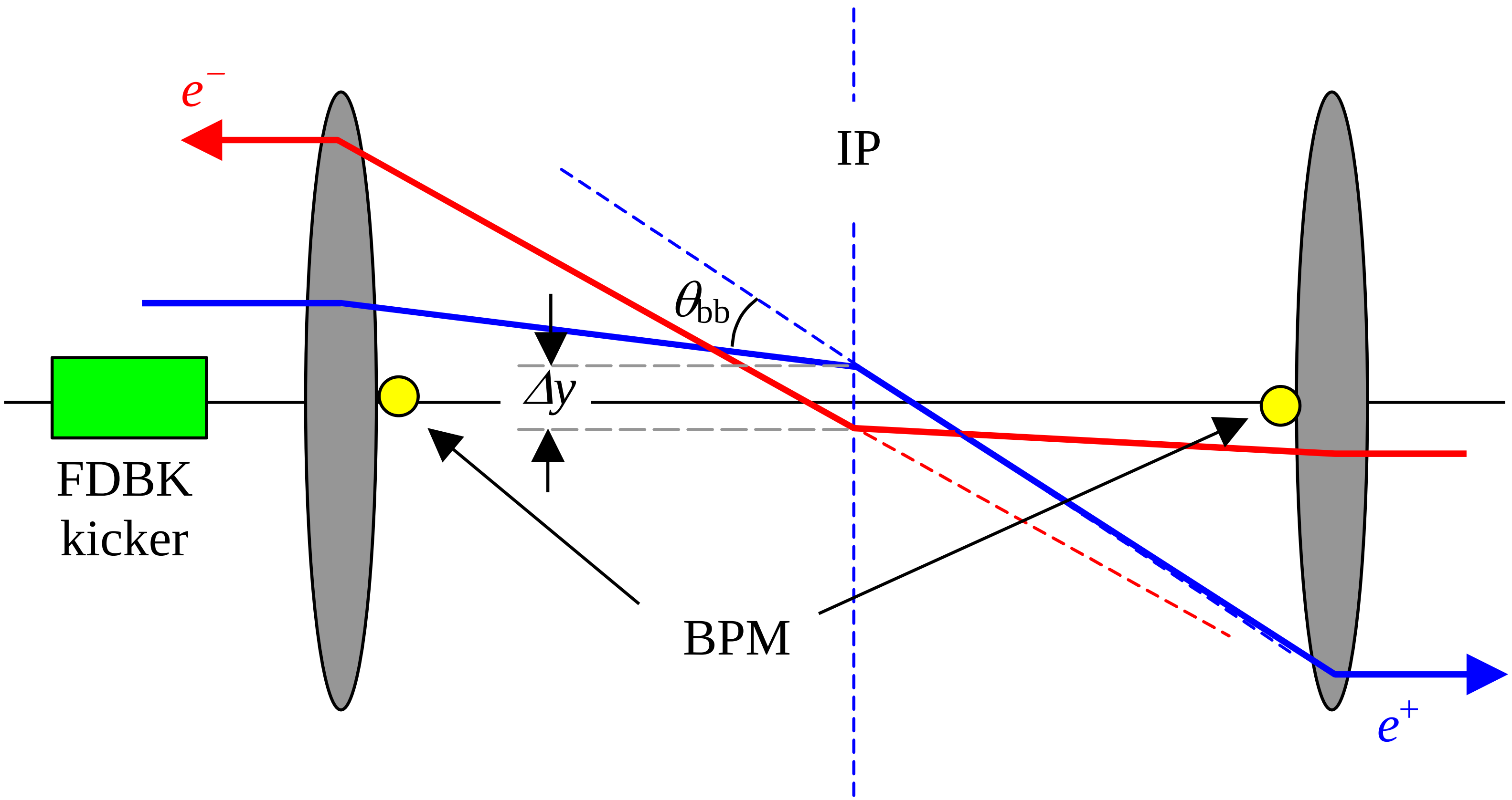






rms beam offset at IP: $\propto \iint P(\omega,k) \cdot G(k) \cdot F(\omega) \cdot dk \cdot d\omega$

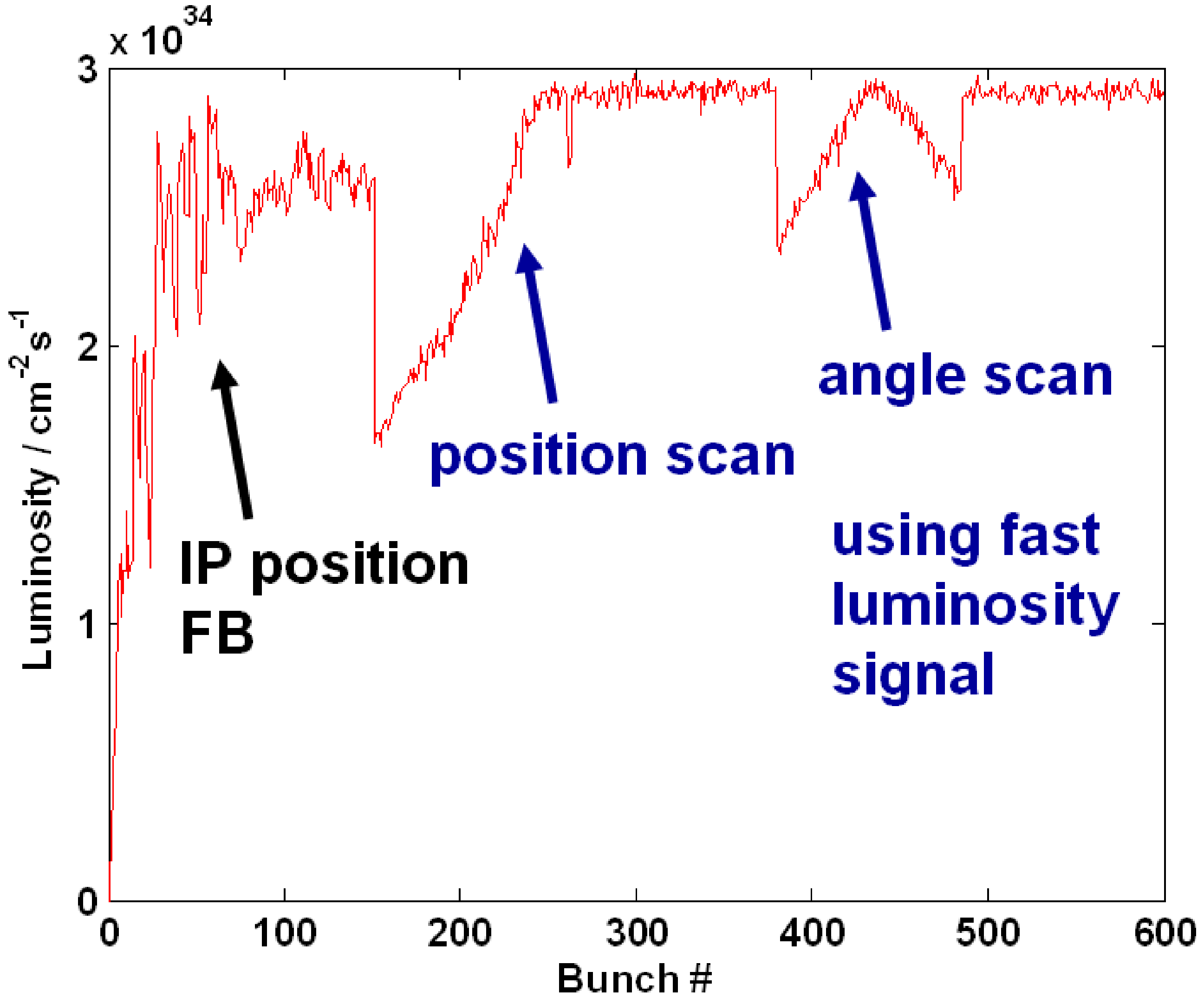
Beam-Beam orbit feedback



use strong beam-beam kick to keep beams colliding

ILC intratrain simulation

ILC intratrain feedback (IP position and angle optimization), simulated with realistic errors in the linac and "banana" bunches.

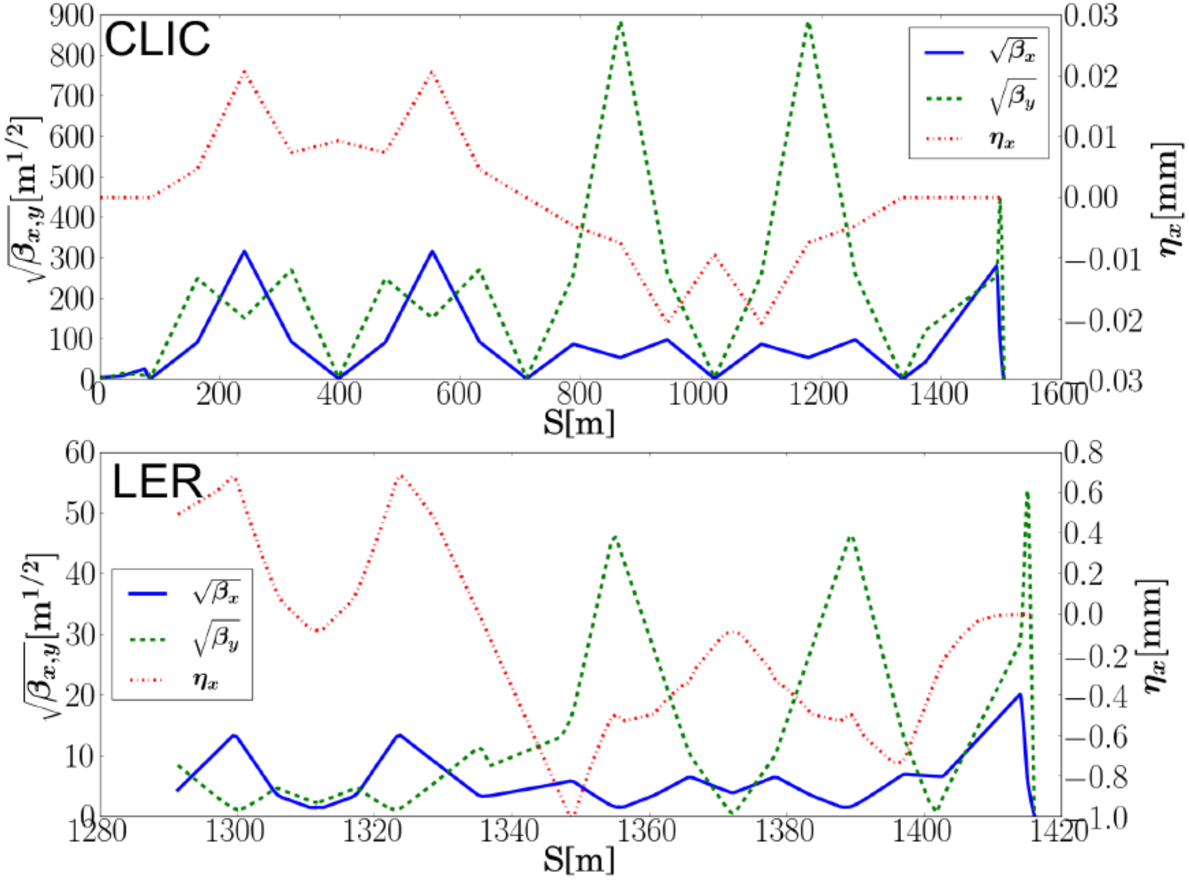


[Glen White]

FF for circular colliders

- To finish up, lets discuss what FF design approaches that we discussed apply to circular colliders
- Circular e+e- colliders – a lot in common:
  - Design challenges (chromaticity) similar to linear collider – similar design of FF
  - Non-local chromaticity compensation
  - Local chromaticity compensation
    - Note possible confusion of terminology:
      (in circular colliders sometime non-local means chromatic compensation by sextupoles in arcs, while local means by sextupoles in cc sections of FF, but not in final doublet)
- Circular hh – not a lot in common

B-Factory SuperKEKB



SuperKEKB FF is designed as classic FF with non-local chromaticity compensation
This version is more suitable for circular colliders, due to dynamic aperture performance

It has been discussed to test CLIC non-local chr comp FF version at SuperKEKB, P. Thrane et al, LCSW 2017

Comparisons of FF

	L^*[m]	$\beta_y^*[\mu m]$	$\xi_y \sim (L^*/\beta_y^*)$
CLIC	3.5	70	50 000
ILC	3.5 /4.5	480	7300 /9400
ATF2	1	100	10 000
FFTB	0.4	100	4 000
SuperKEKB LER	0.935	270	3 460
SuperKEKB HER	1.41	410	3 440

SuperB

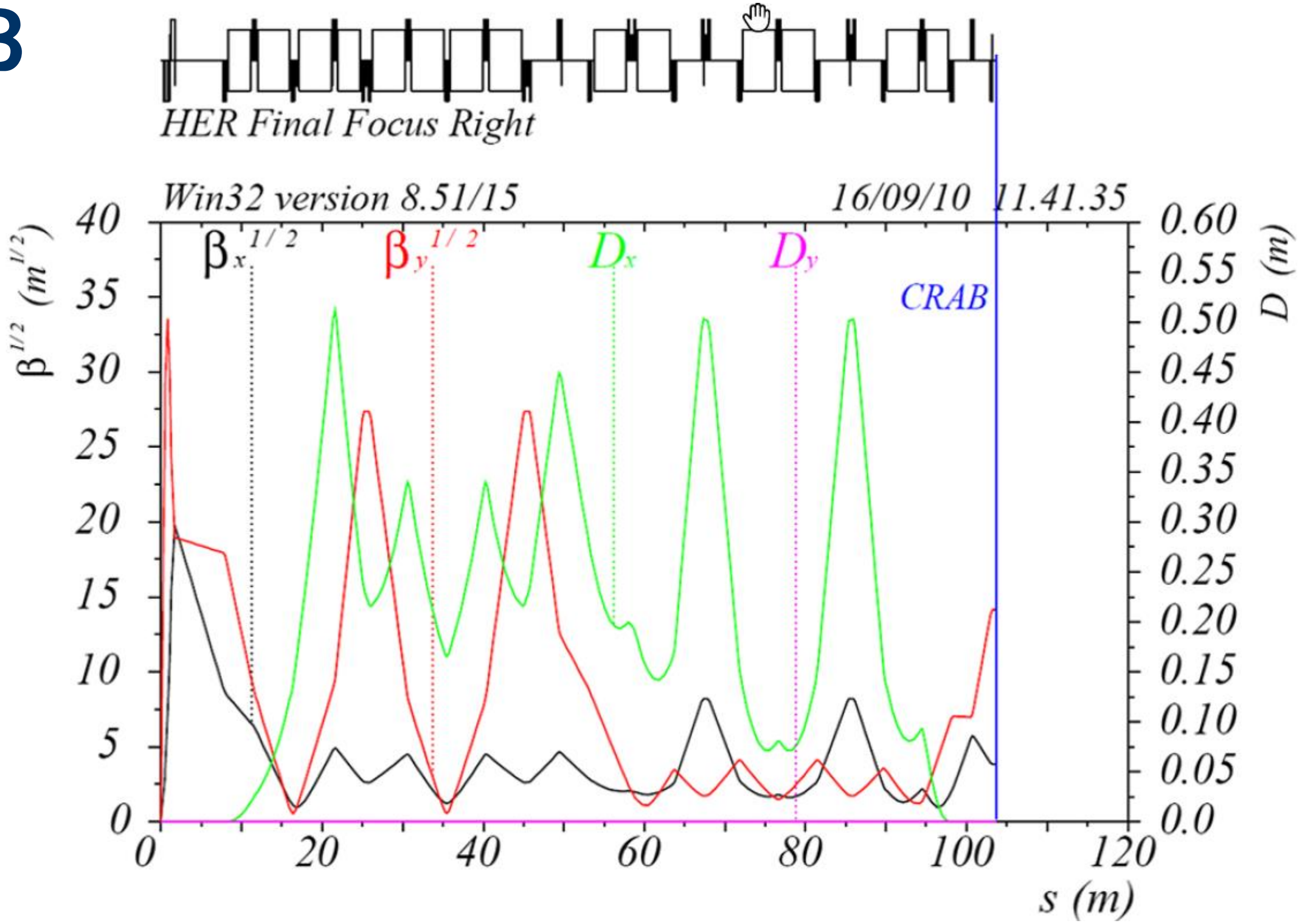


FIG. 7. Optical functions of SuperB HER interaction region with crab waist sextupoles.

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FCC-e+e-

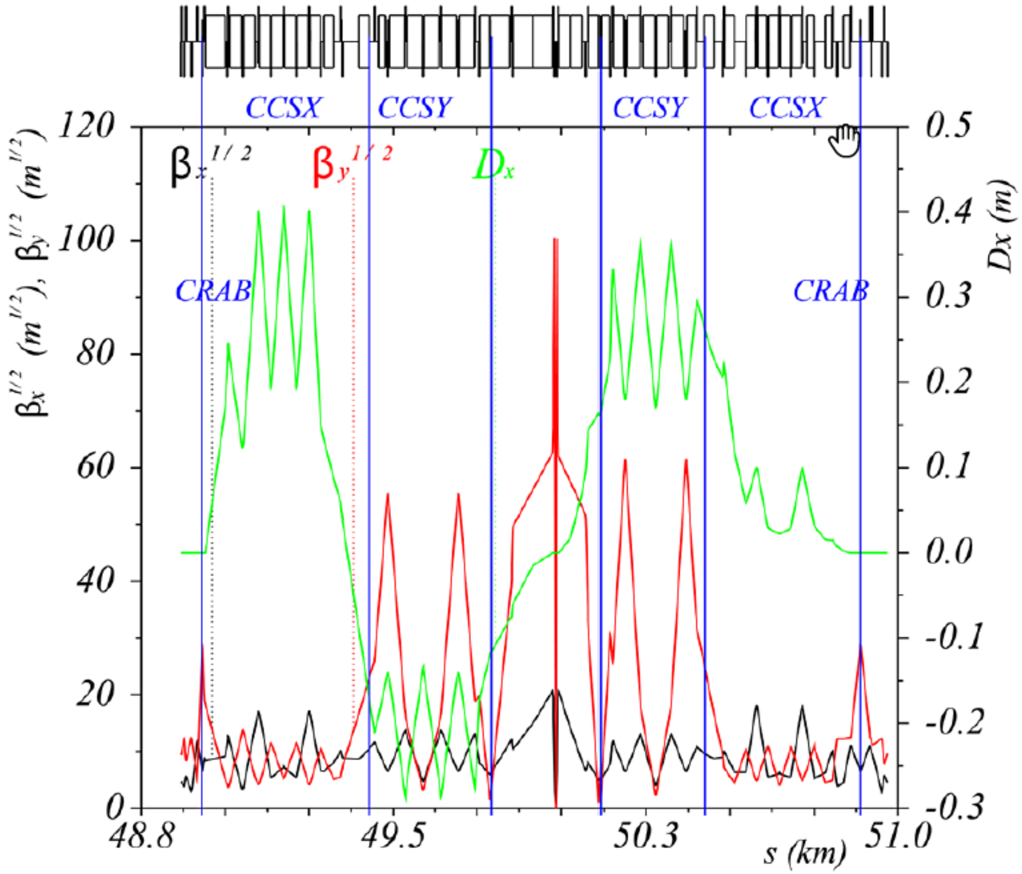

FIG. 12. Optical functions of FCC-ee interaction region variant 2.

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FCC-hh Parameters

We have two parameter sets

- Beam current is the same
- But luminosity differs

$$\mathcal{L} \propto \frac{N}{\epsilon} \frac{1}{\beta_y} N n_b f_r$$

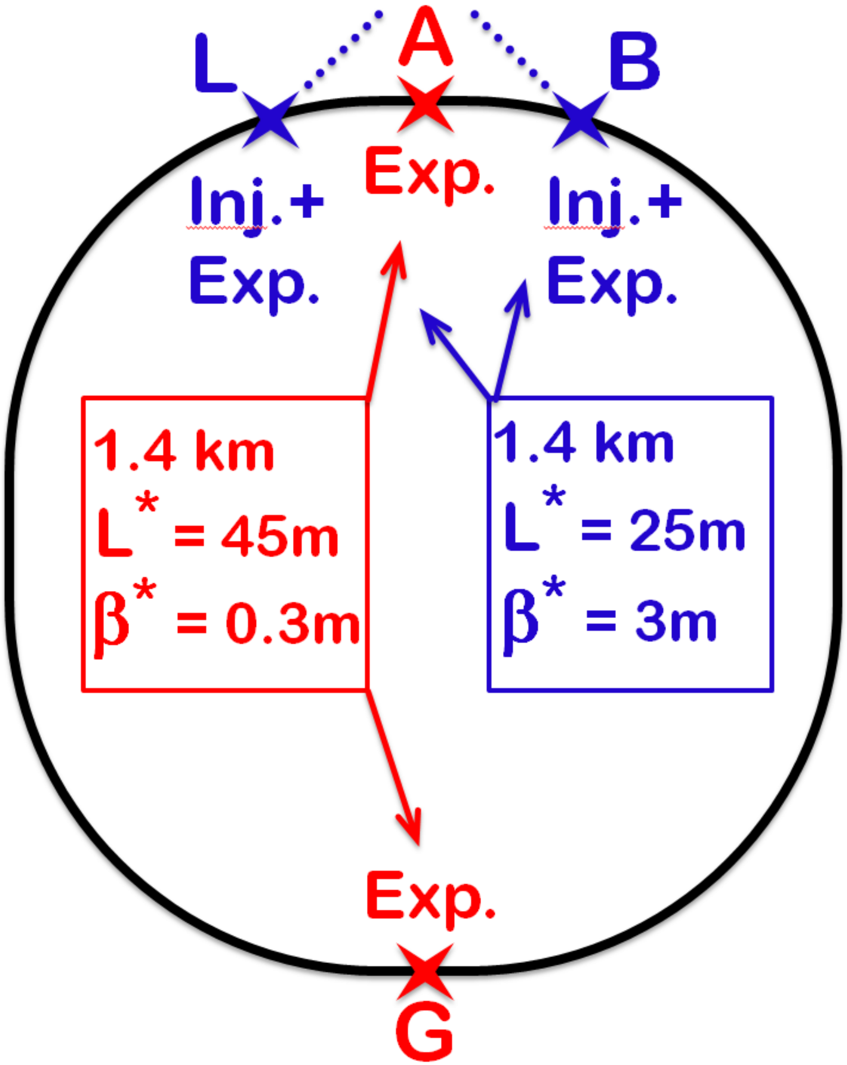
They have the same current but the ultimate set has more challenging collision parameters

The "baseline" in EuroCirCol should be capable to run with the **ultimate** parameters

	FCC-hh Baseline	FCC-hh Ultimate
Luminosity L [$10^{34}cm^{-2}s^{-1}$]	5	20
Background events/bx	170 (34)	680 (136)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μ**m**]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μ**m**]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ□]	14	Crab. Cav.
Turn-around time [h]	5	4

Slide from Daniel Schulte

FCC-hh

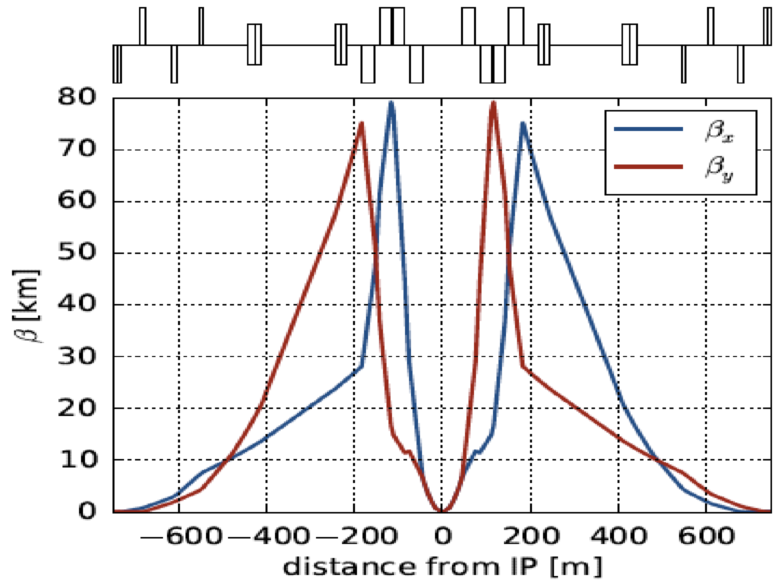


The FCC-hh, housed in a 97.75 km perimeter racetrack tunnel filled with 16 T SC magnets, includes four EIRs -- two for nominal/high luminosity and two for low-luminosity experiments

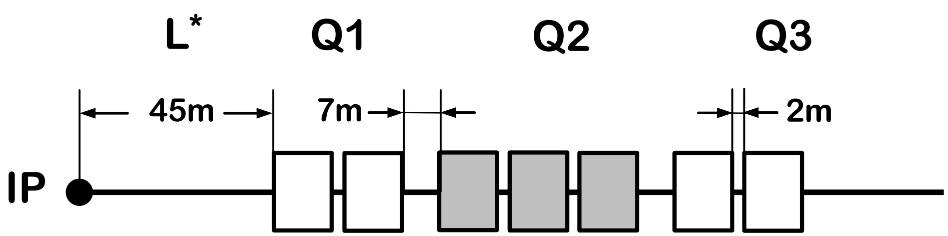
Each of the EIR straight sections is 1400 m long, while in low-luminosity EIR sections the experiments are combined with injection sections

FCC-hh

- FF needs to reach β* around 0.1 m
- From chromatic properties this is not a large challenge
- There is no need for dedicated chromatic correction sections
- Challenges come from other places:
- Dynamic aperture
- The need to provide shielding of triplets from collision debris – 15-50mm of shielding may be needed
- The need to provide good stay-clear for beam tails



Optics for $\beta^* = 0.3$ m



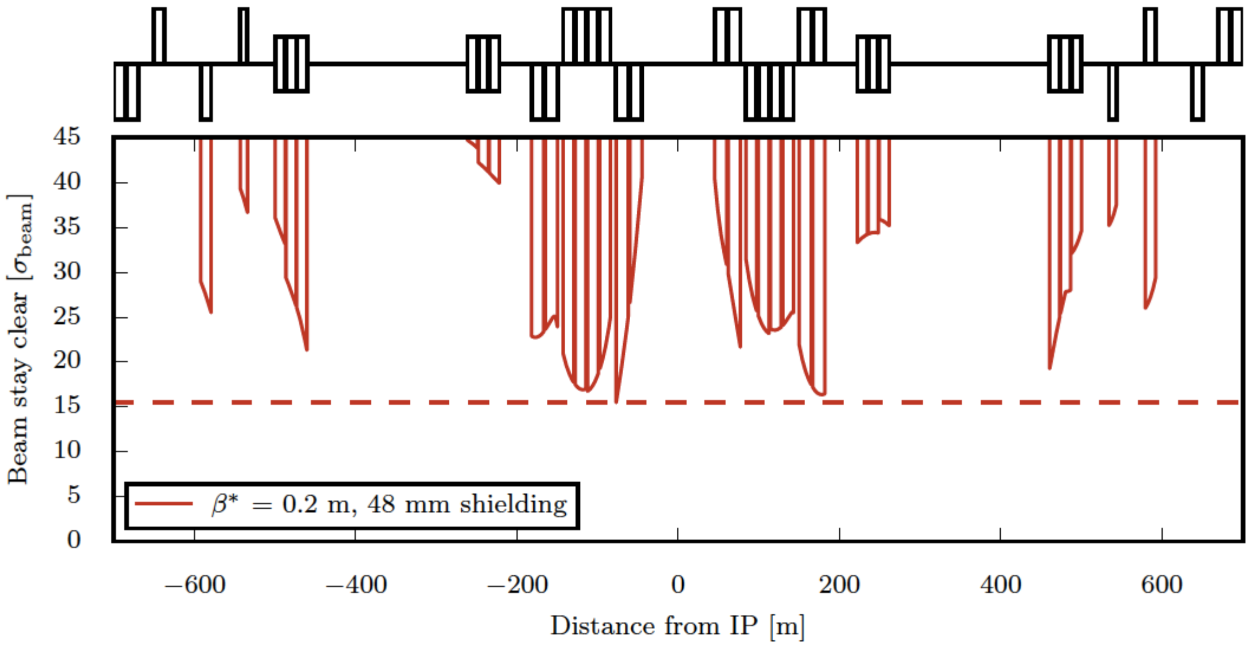
	Q1	Q2	Q3
Length (m)	15	15	15
Shielding (mm)	44.2	33.2	24.2
Gradient (T/m)	106	111	97
Aperture Ø (mm)	86	108	126
Coil Radius (mm)	98.3	98.3	98.3

Example of FCC-hh FF triplet layout

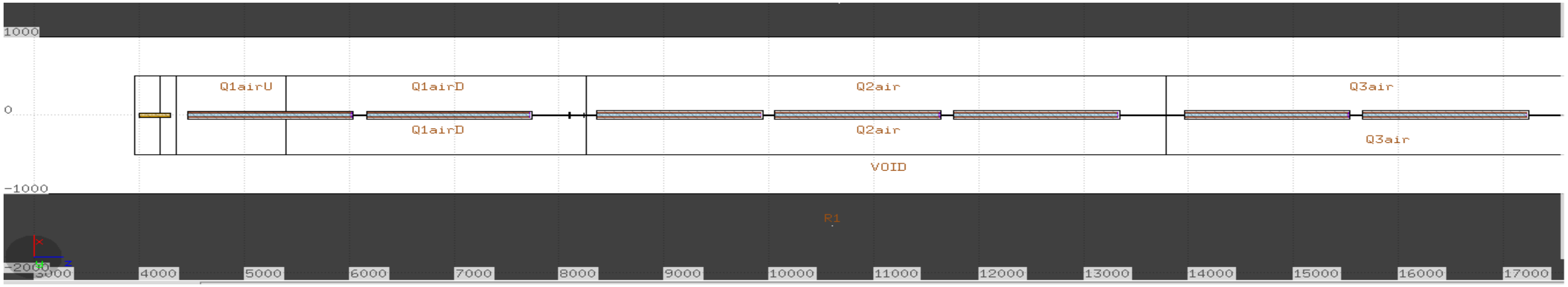
Main EIR inner triplet – inner coil radius, clear aperture, gradient, thickness of shielding and length of individual quadrupole

FCC-hh triplet FF and Beam Stay Clear

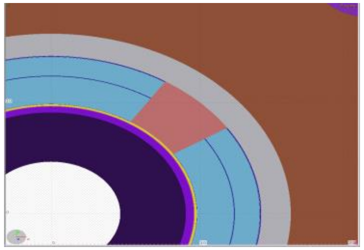
- Triplet aperture still allows for β* below 0.1m at beam stay clear of 15.5σ and with 15mm thick shielding inside quadrupole apertures
- Alternative option with thick shielding of 48mm still allows to reach β* = 0.2m



FCC-hh FF triplet and shielding

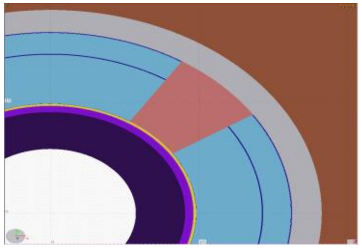


Q1
106 T/m



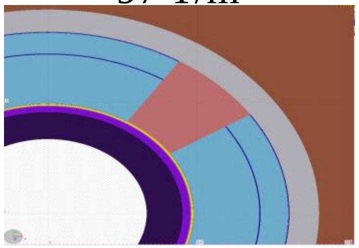
Abs:4.4 cm

Q2
111 T/m



Abs:3.3 cm

Q3
97 T/m



Abs: 2.4cm

- Thank you for your attention!