Accelerator Lecture A4 – PART 1

Beam Delivery & beam-beam

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Linear Collider – two main challenges

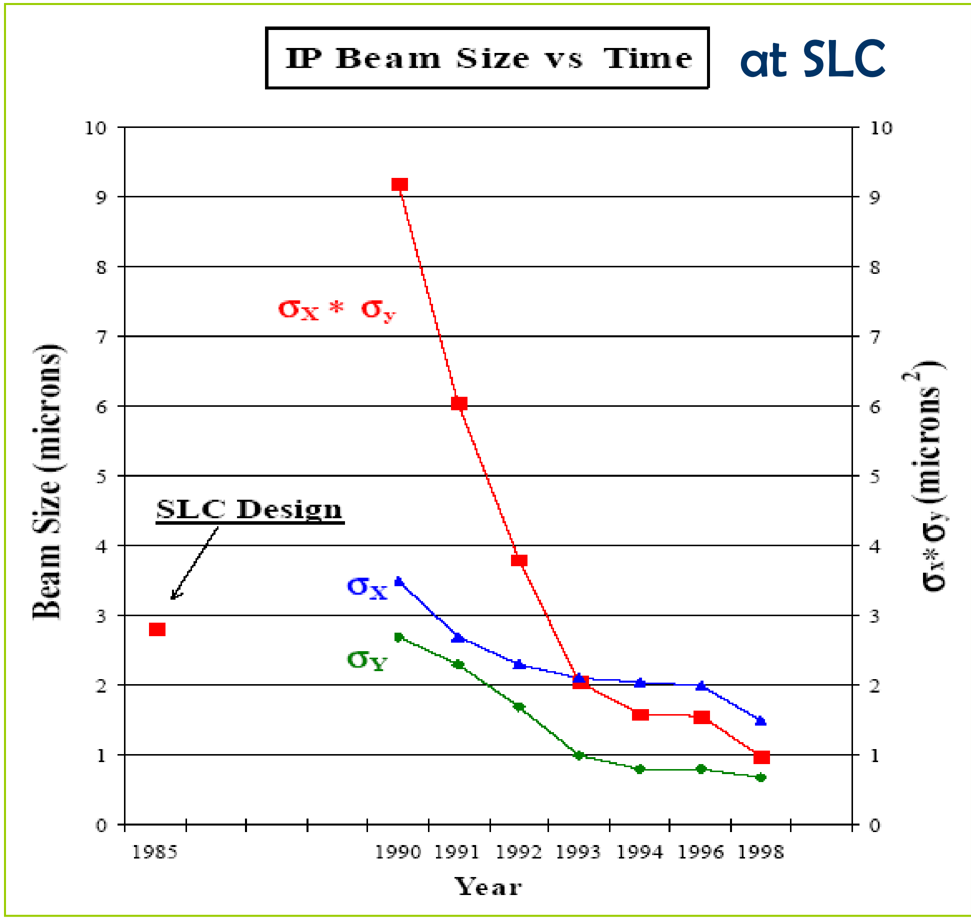
- **Energy** – need to reach at least 500 GeV CM

- **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, ...

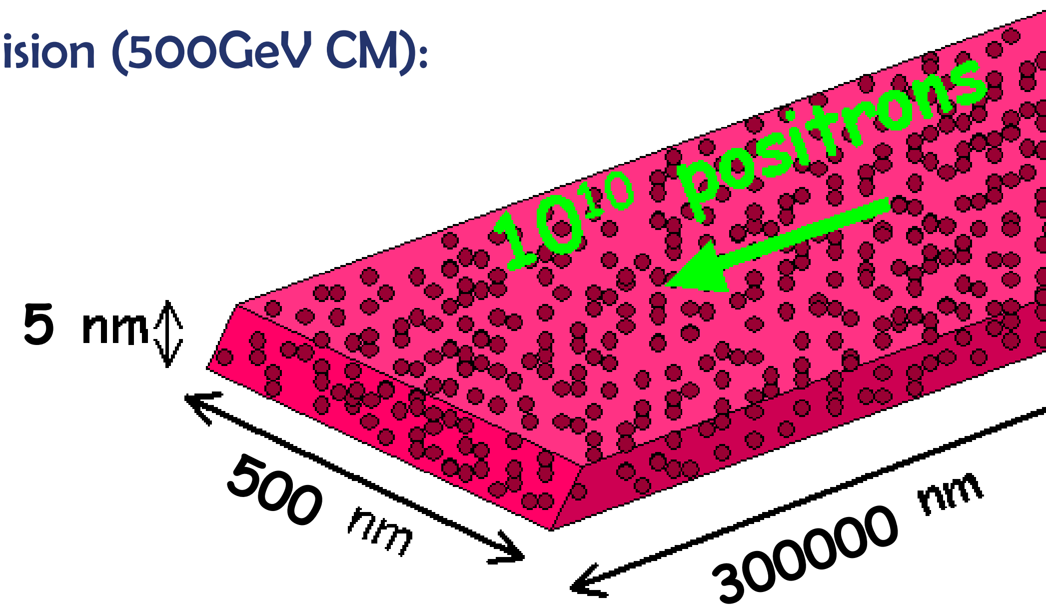


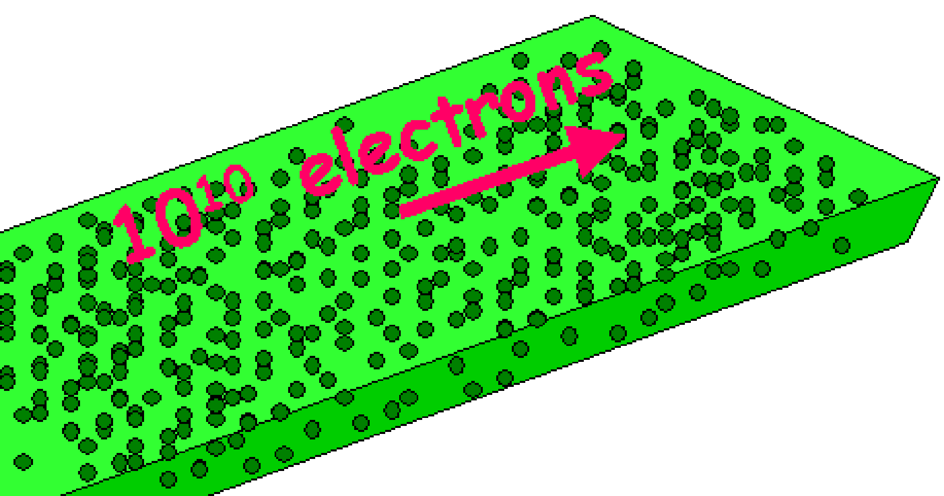
- Including better focusing, dealing with beam-beam, safely removing beams after collision and better stability

How to get 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)

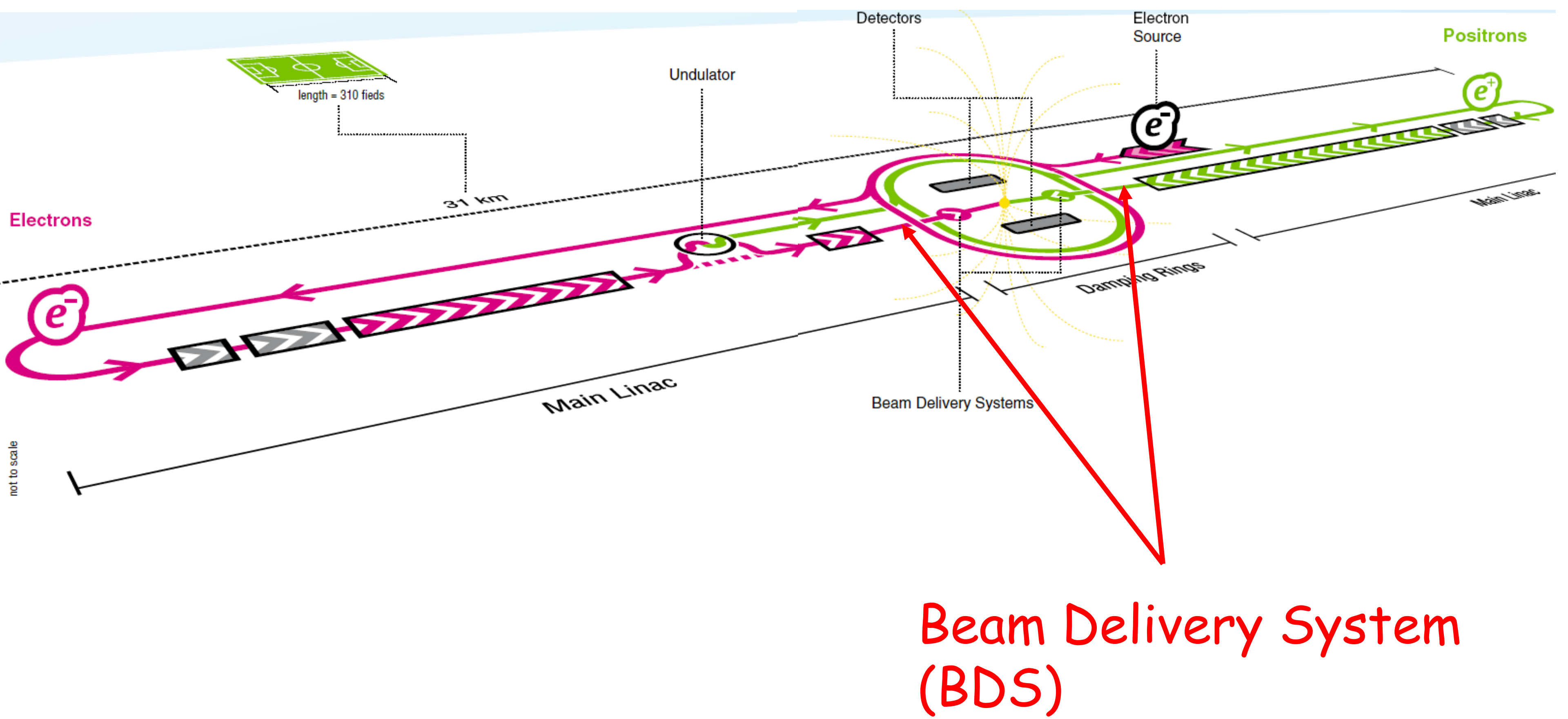
Vertical size is smallest





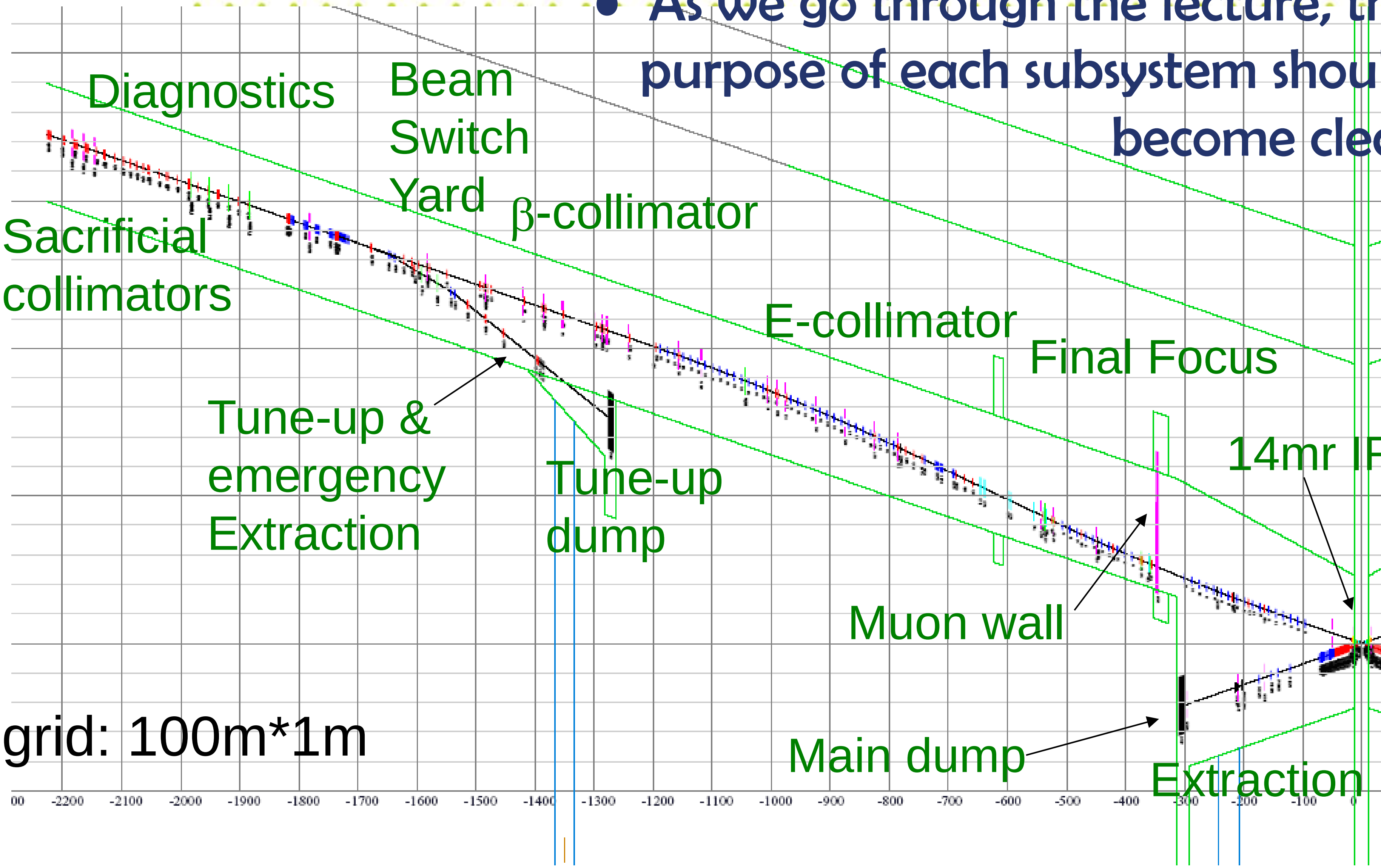
$$L = \frac{f_{rep}}{4\pi} \frac{n_b N^2}{\sigma_x \sigma_y} H_D$$

BDS: from end of linac to IP, to dumps



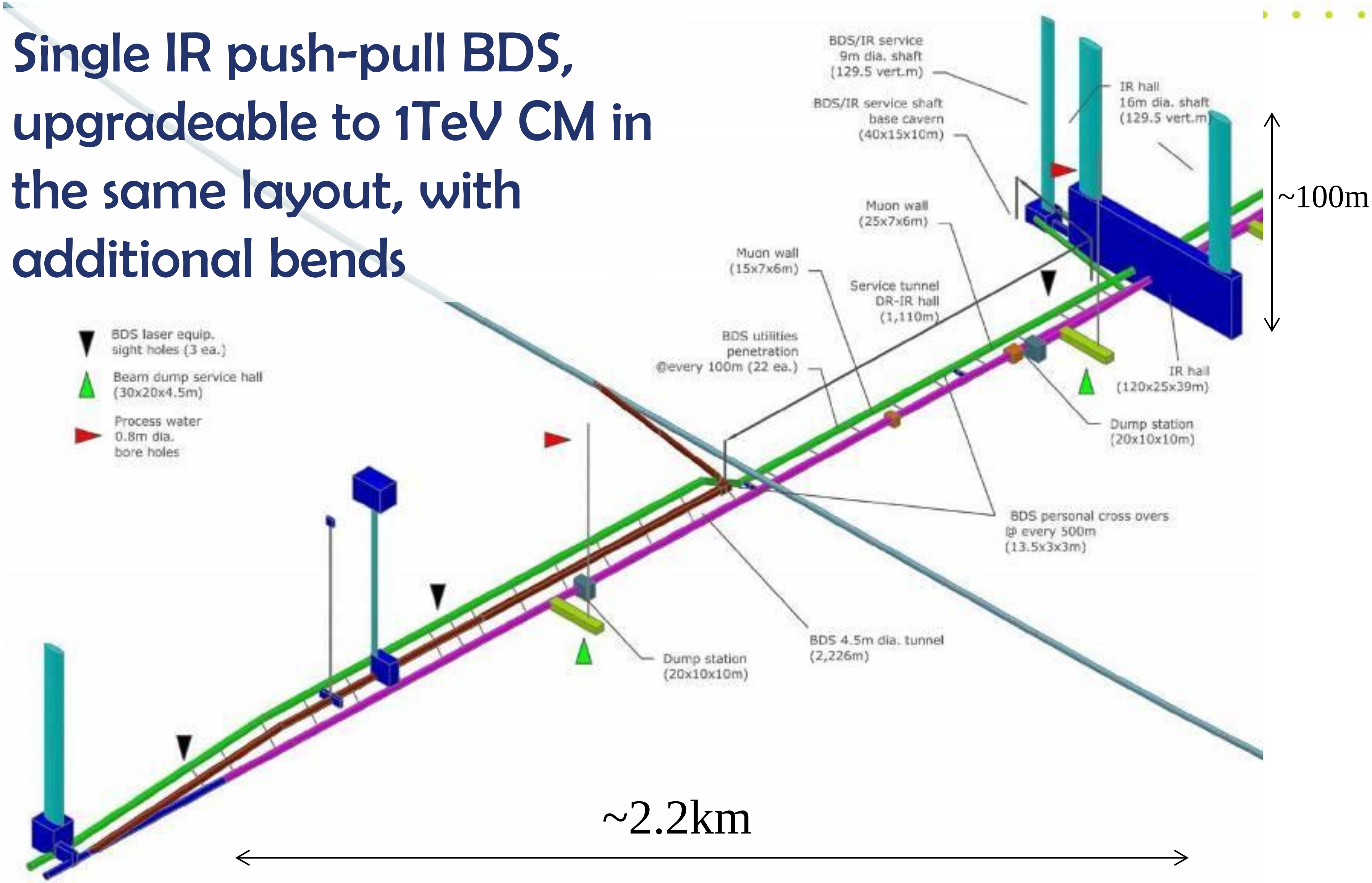
Beam Delivery subsystems

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



Layout of Beam Delivery tunnels

- Single IR push-pull BDS, upgradeable to 1TeV CM in the same layout, with additional bends



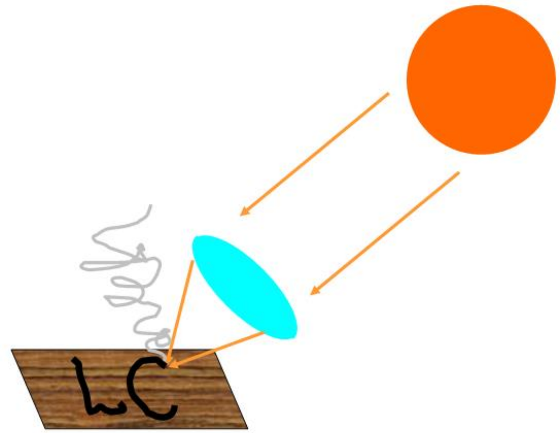
Beam Delivery System challenges

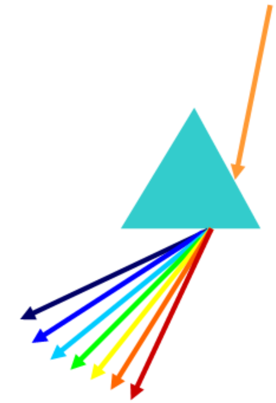
- measure the linac beam and match it into the final focus
- remove any large amplitude particles (beam-halo) from the linac to minimize background in the detectors
- measure and monitor the key physics parameters such as energy and polarization before and after the collisions
- ensure that the extremely 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

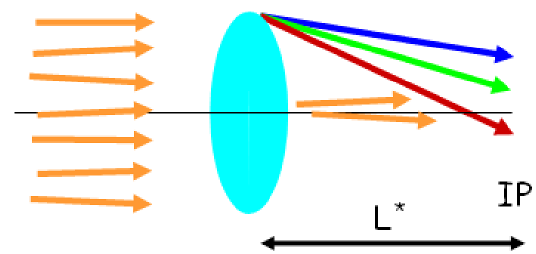
Factor driving BDS design



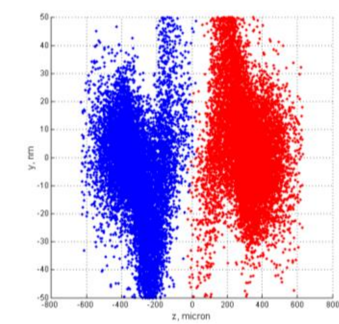


- Strong focusing

- Chromaticity



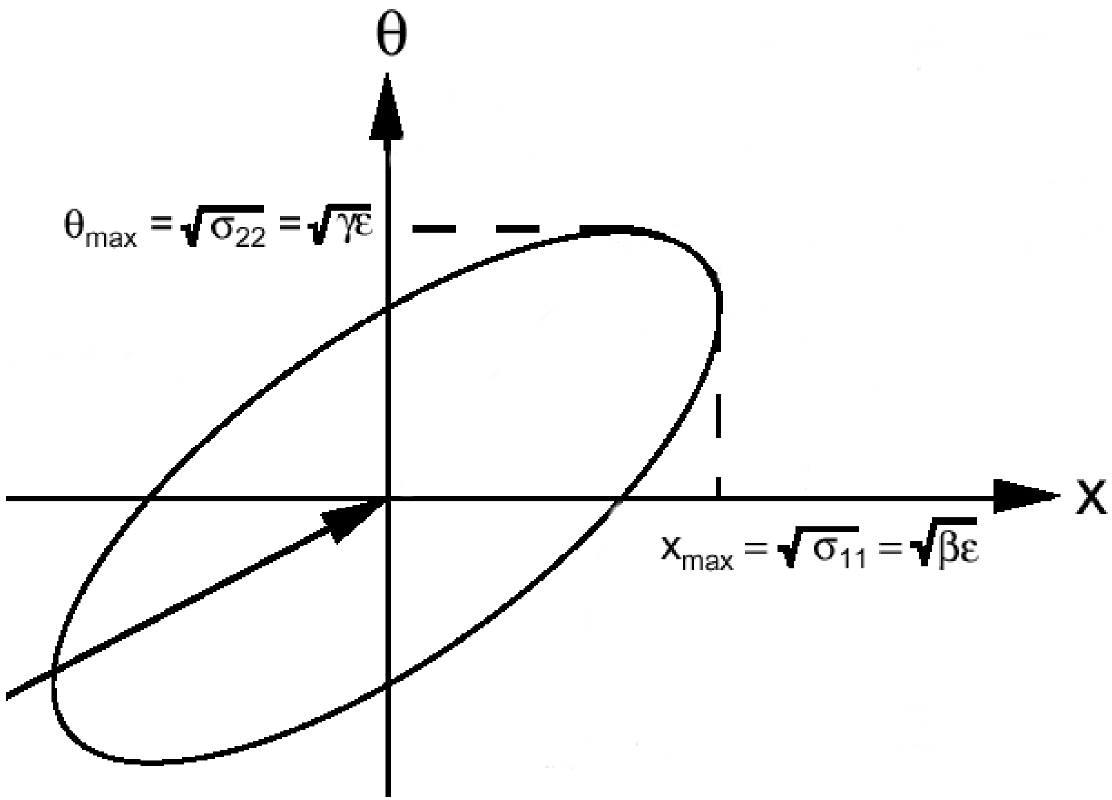
- Beam-beam effects



- Synchrotron radiation
  - let's consider some of this in more details

Recall couple of definitions

- Beta function β characterize optics
- Emittance ε is phase space volume of the beam
- Beam size: $(\varepsilon\ \beta)^{1/2}$
- Divergence: $(\varepsilon/\beta)^{1/2}$



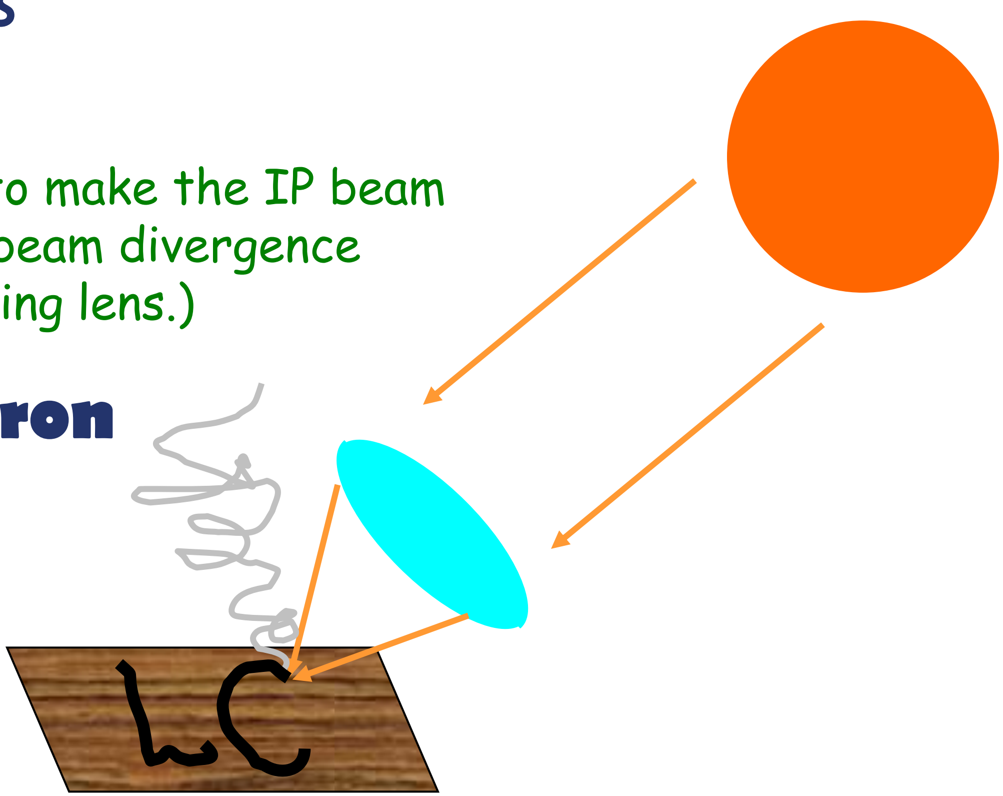
- Focusing makes the beam ellipse rotate with "betatron frequency"
- Phase of ellipse is called "betatron phase"

How to focus the beam to a smallest spot?

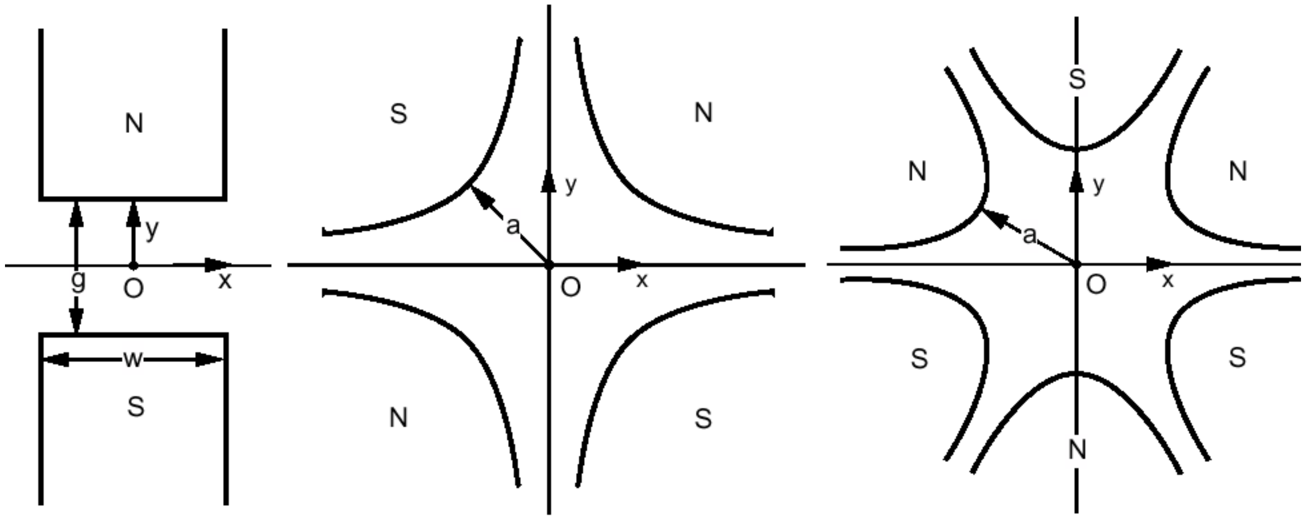
- If you ever played with a lens trying to burn a picture on a wood under bright sun, then you know that one needs a strong and big lens

  (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**



What we use to handle the beam



DIPOLE QUADRUPOLE SEXTUPOLE

Etc...

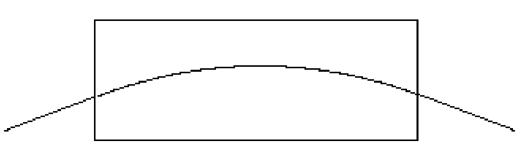
Just bend the trajectory

Focus in one plane, defocus in another:

$$x' = x' + G\,x$$
$$y' = y' - G\,y$$

Second order effect:

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



Here x is transverse coordinate, x' is angle

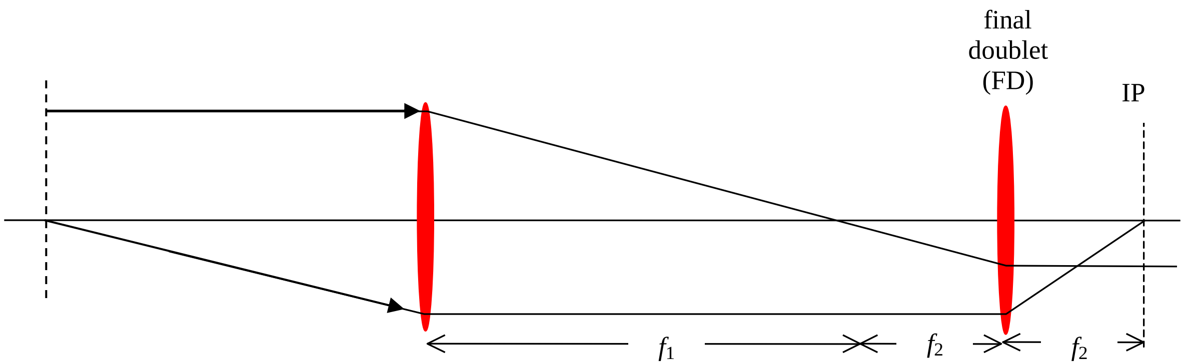
Optics building block: telescope

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.

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



f_1 $\qquad$ $f_2\ (=L^*)$

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

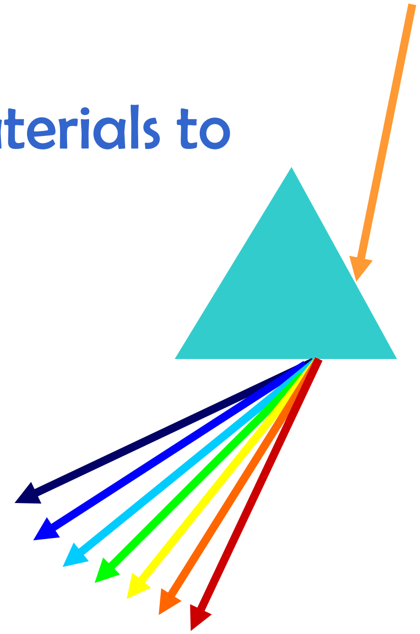
Matrix formalism for beam transport:

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

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

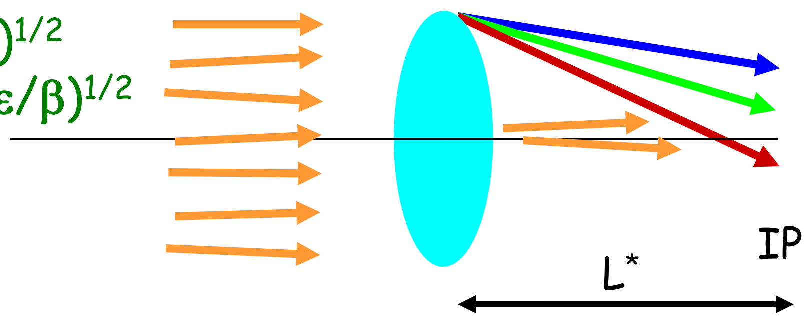
Why nonlinear elements

- 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 $\Delta\sigma/\sigma \sim \sigma_E\, L^*/\beta^*$

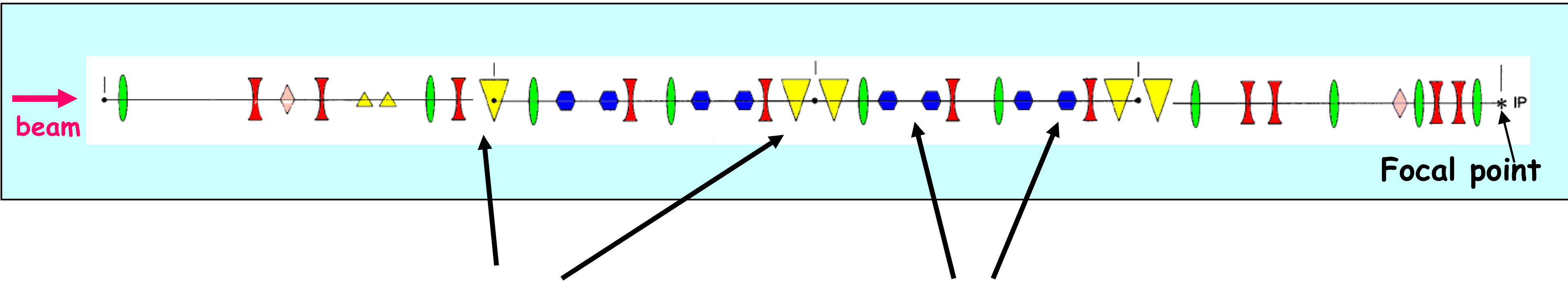
Typical:

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, $\Delta\sigma/\sigma \sim 15\text{-}500$ 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

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

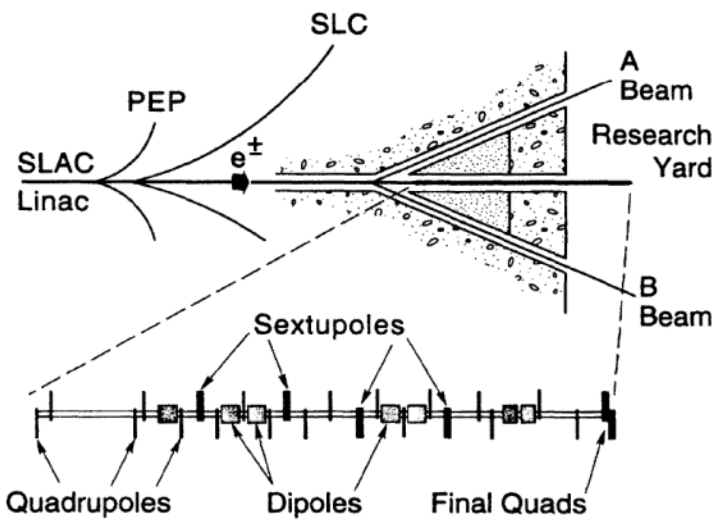
$$y' \Rightarrow -S\,2(x+\delta)y \Rightarrow -2S\,y\,\delta + ..$$

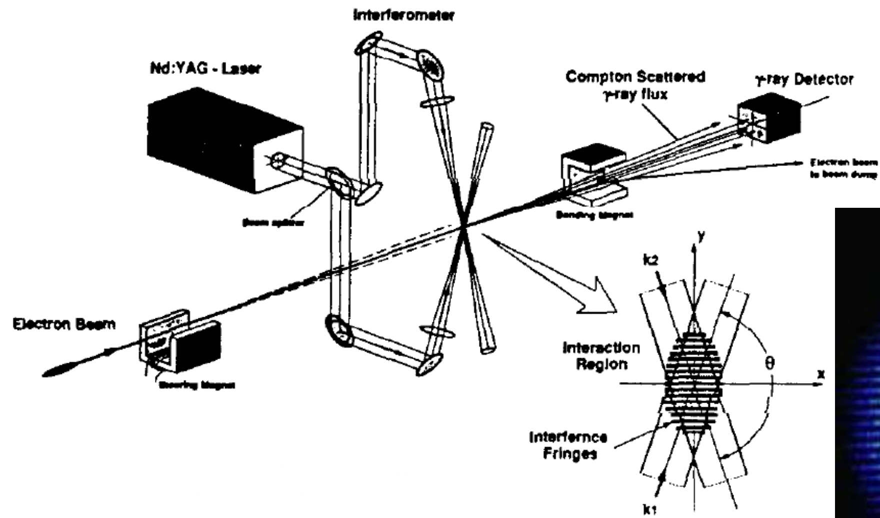
that can be used to arrange chromatic correction

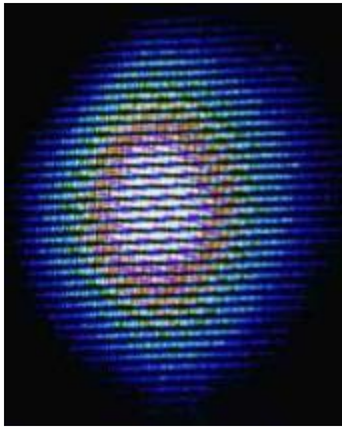
Necessity to compensate chromaticity is a major driving factor of FF design

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

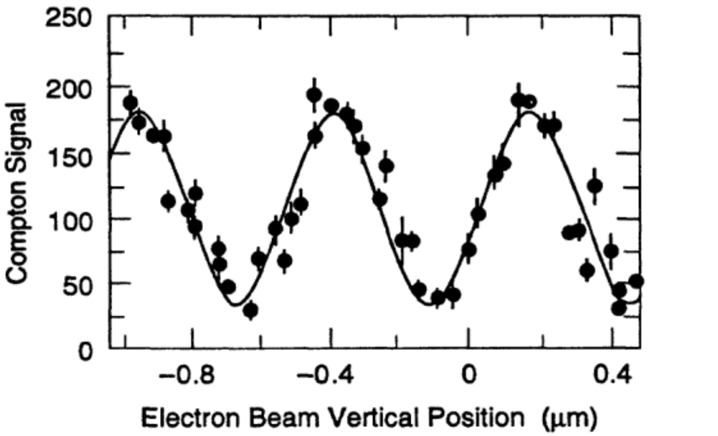
Final Focus Test Beam



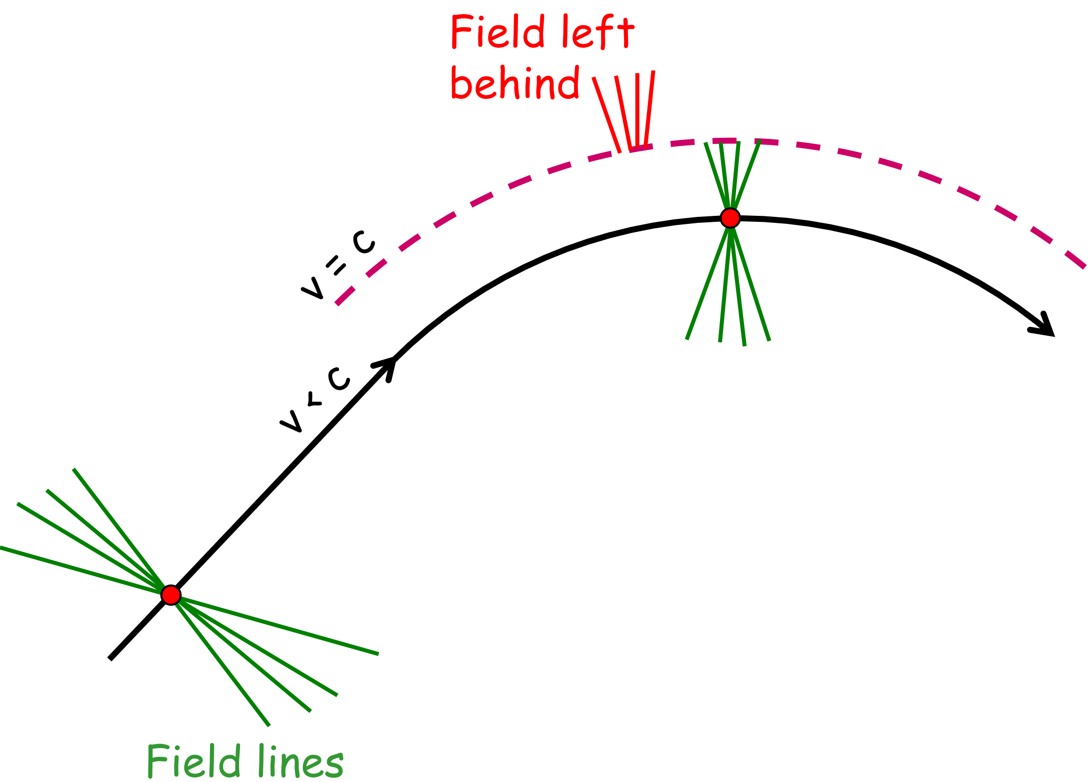




Achieved ~70nm vertical beam size



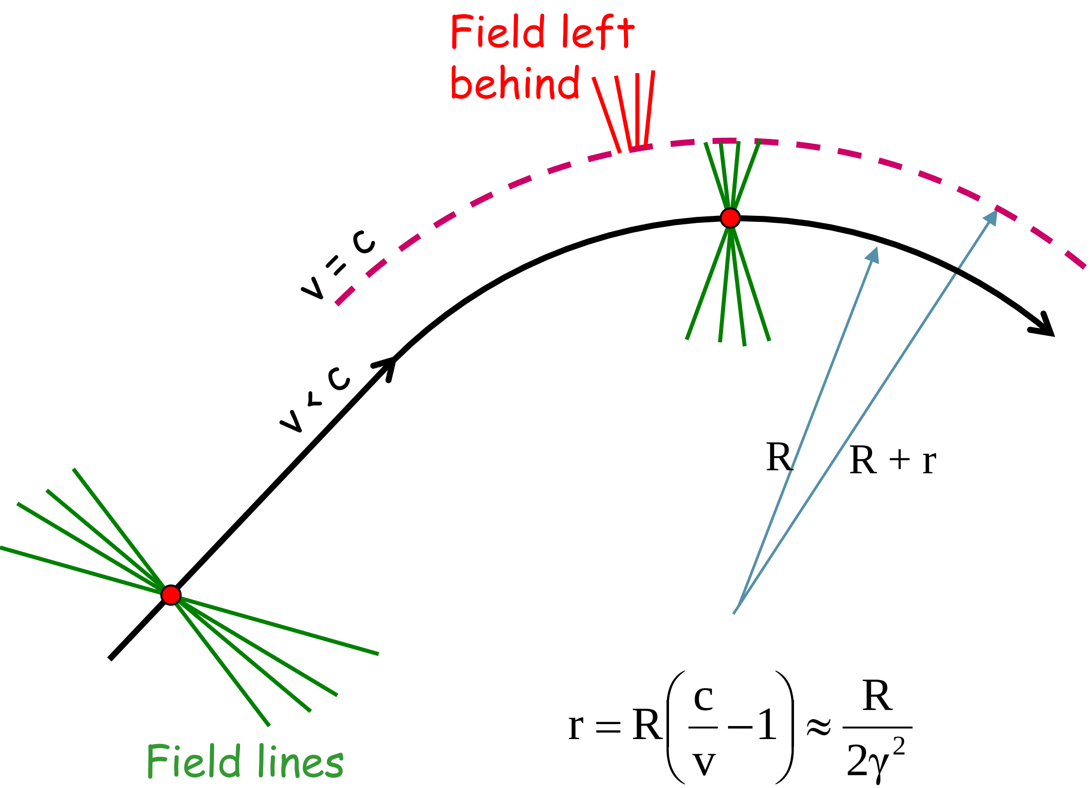
Synchrotron Radiation in FF magnets



- 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

Let's estimate SR power



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

Energy in the field left behind (radiated !):

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

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

Energy loss per unit length:

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

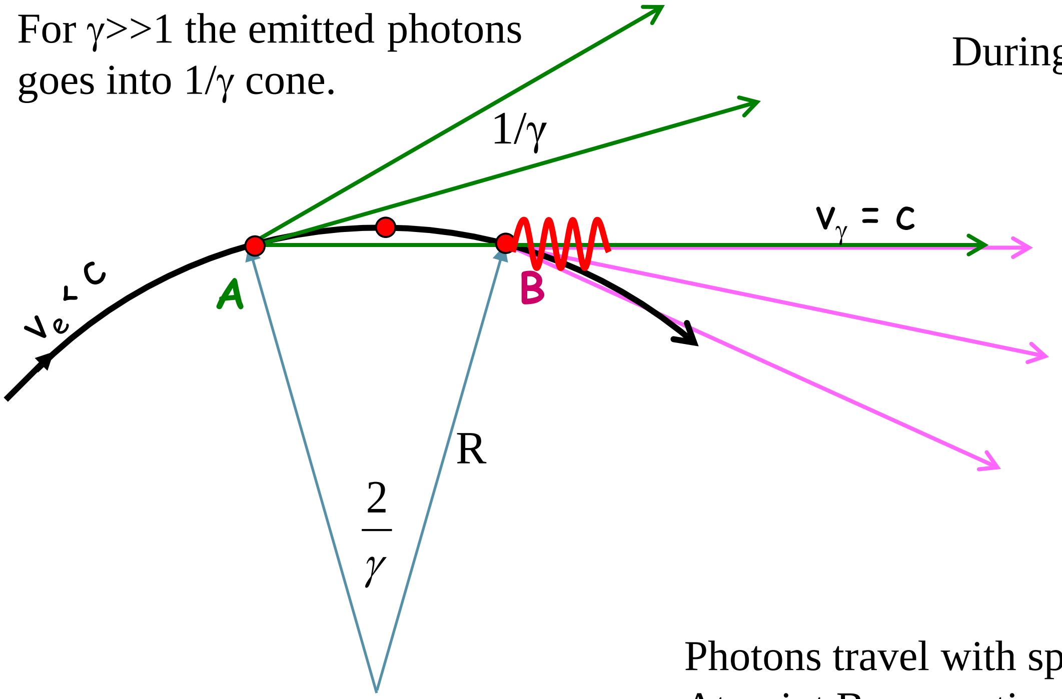
Substitute $r \approx \frac{R}{2\gamma^2}$ and get an estimate:

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

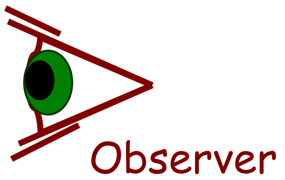
Compare with exact formula: $\frac{dW}{dS} = \frac{2}{3} \frac{e^2 \gamma^4}{R^2}$

Let's estimate typical frequency of SR photons

For $\gamma>>1$ 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 $\omega_c \approx \frac{1}{\Delta t} \approx \frac{c\gamma^3}{R}$

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

Let's estimate 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 $\varepsilon_c = \hbar\omega_c \approx \frac{\gamma^3 \hbar c}{R} = \frac{\gamma^3}{R} \lambda_e mc^2$

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

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 :

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

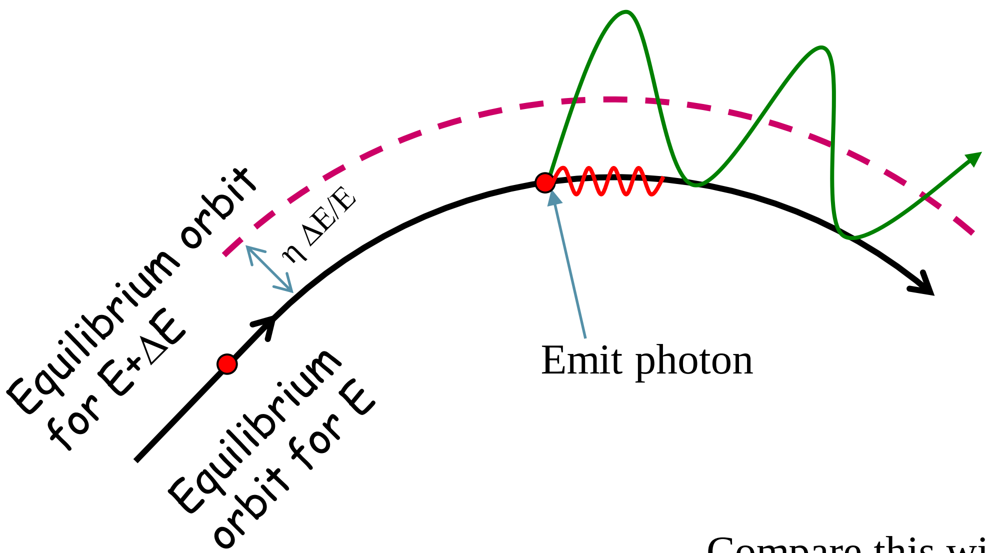
Which gives:

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

Compare with exact formula:

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

Let's estimate 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 $\Delta x \approx \eta\, \Delta E/E$

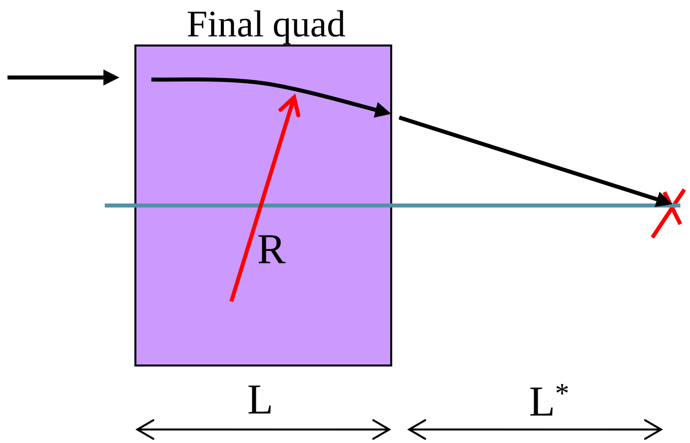
Compare this with betatron beam size: $\sigma_x = (\varepsilon_x\, \beta_x)^{1/2}$

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).

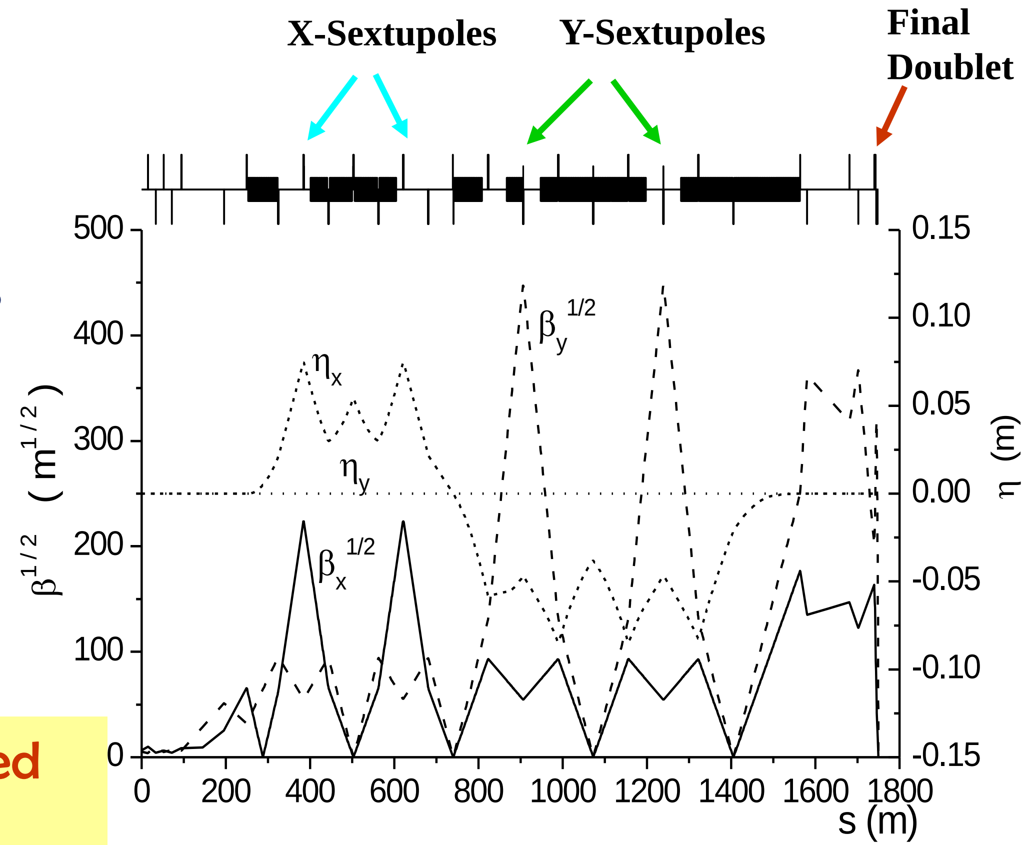
FF with non-local chromaticity compensation

- 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

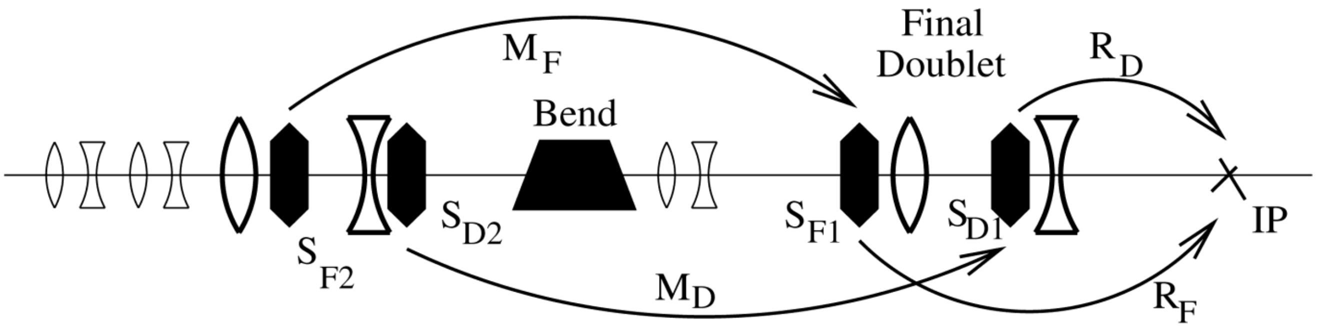
Problems:

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



Traditional FF

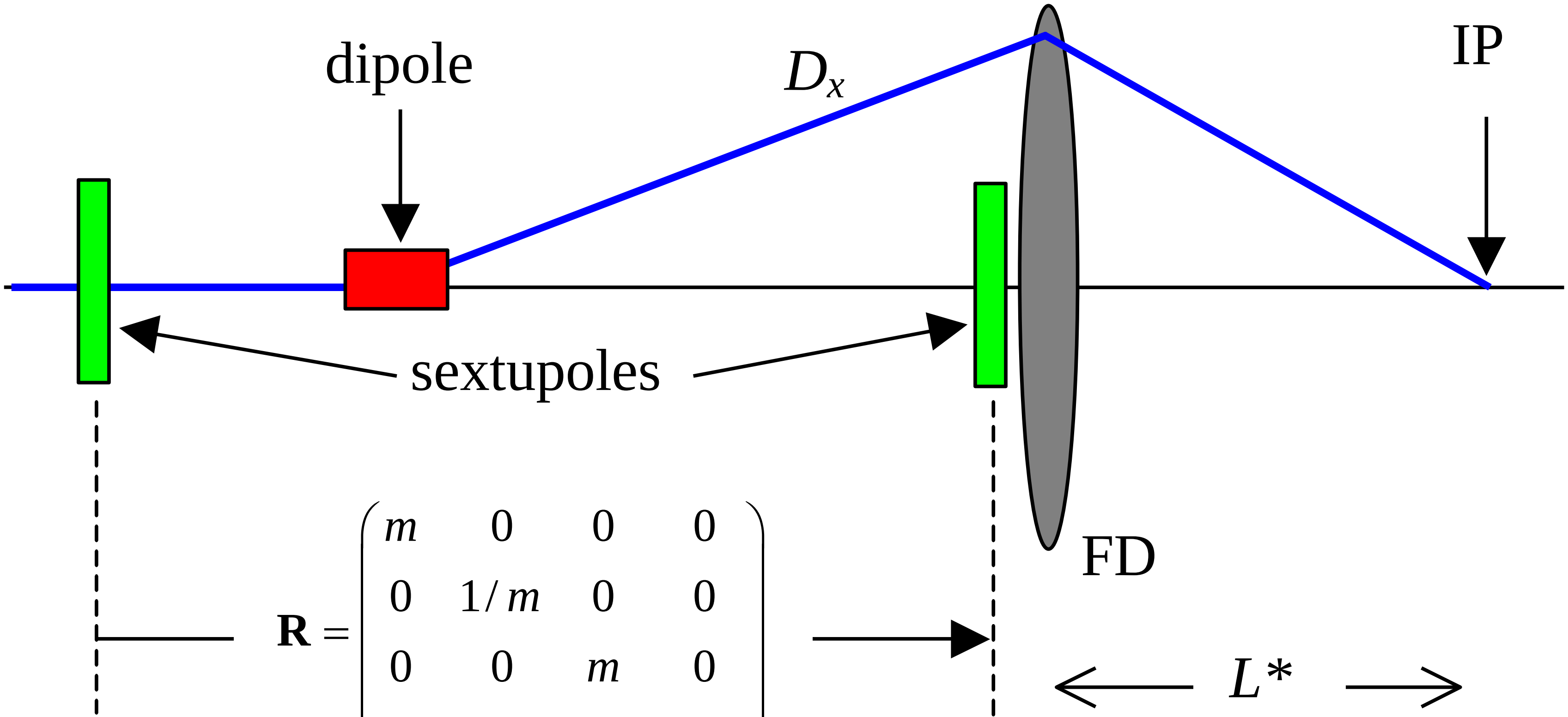
FF with local chromatic correction



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

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

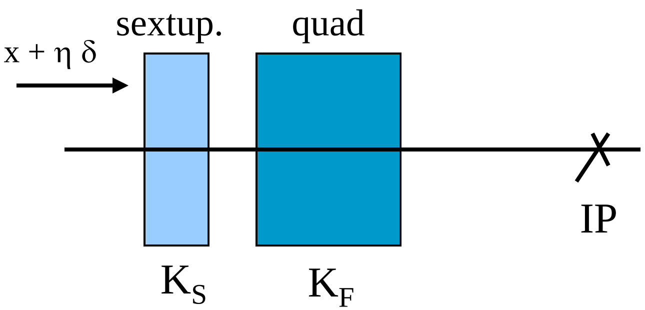
Local chromatic correction



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

- 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.

Definitions of chromaticity
1st : TRANSPORT

Storage Rings: chromaticity defined as a change of the betatron tunes versus energy.

In single path beamlines, it is more convenient to use other definitions.

$$x_i = \begin{pmatrix} x \\ x' \\ y \\ y' \\ \Delta l \\ \delta \end{pmatrix} \qquad x_i^{out} = R_{ij}\ x_j^{in}$$

The second, third, and so on terms are included in a similar manner:

$$x_i^{out} = R_{ij}\ x_j^{in} + T_{ijk}\ x_j^{in}\ x_k^{in} + U_{ijkn}\ x_j^{in}\ x_k^{in}\ x_n^{in} + \ldots$$

In FF design, we usually call ‘chromaticity’ the second order elements T_{126} and T_{346}. All other high order terms are just ‘aberrations’, purely chromatic (as T_{166}, which is second order dispersion), or chromo-geometric (as U_{32446}).

Definitions of chromaticity

2nd : W functions

Lets assume that betatron motion without energy offset is described by twiss functions $\boldsymbol{\alpha_1}$ and $\boldsymbol{\beta_1}$ and with energy offset $\boldsymbol{\delta}$ by functions $\boldsymbol{\alpha_2}$ and $\boldsymbol{\beta_2}$

Let's define chromatic function **W** (for each plane) as $W = (i\,A + B)/2$ where $i = \sqrt{-1}$

And where: $$B = \frac{\beta_2 - \beta_1}{\delta\,(\beta_2 \cdot \beta_1)^{1/2}} \approx \frac{\Delta\beta}{\delta\;\beta} \quad \text{and} \quad A = \frac{\alpha_2\beta_1 - \alpha_1\beta_2}{\delta\,(\beta_2 \cdot \beta_1)^{1/2}} \approx \frac{\Delta\alpha}{\delta} - \frac{\alpha}{\beta}\frac{\Delta\beta}{\delta}$$

Using familiar formulae $$\frac{d\beta}{ds} = -2\alpha \quad \text{and} \quad \frac{d\alpha}{ds} = K \cdot \beta - \frac{(1+\alpha^2)}{\beta} \quad \text{where} \quad K = \frac{e}{pc}\frac{dB_y}{dx}$$

And introducing $\Delta K = \frac{K(\delta(- K(0)}{\delta} \approx -K$ we obtain the equation for **W** evolution:

Can you show this?

$$\frac{dW}{ds} = \frac{2i}{\beta} W + \frac{i}{2}\beta\,\Delta K$$

knowing that the betatron phase is $\frac{d\Phi}{ds} = \frac{1}{\beta}$

can see that if $\boldsymbol{\Delta K}$=0, then **W** rotates with double betatron frequency and stays constant in amplitude. In quadrupoles or sextupoles, only imaginary part changes.

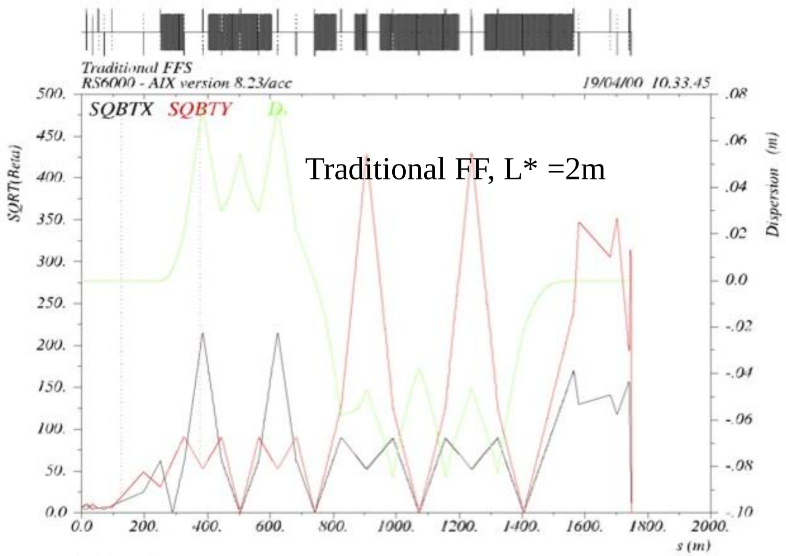
Show that if in a final defocusing lens α=0, then it gives $\Delta W = L^*/(2\beta^*)$

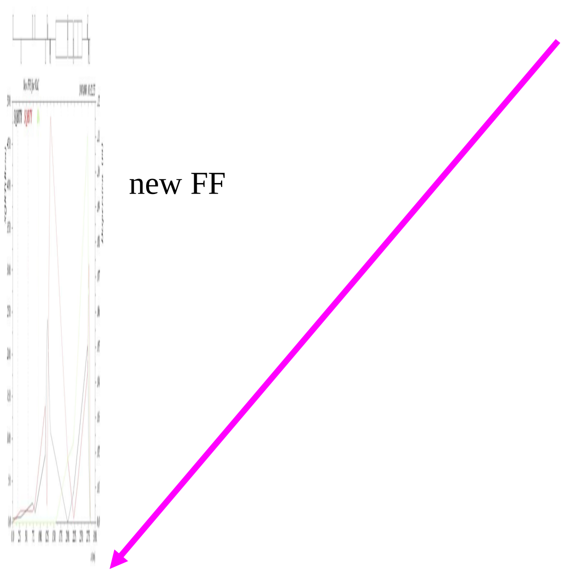
Show that if T_{346} is zeroed at the IP, the W_y is also zero. Use approximation $\Delta R_{34} = T_{346} {}^* \delta$, use $R_{34} = (\beta\beta_0)^{1/2} \sin(\Delta\Phi)$, and the twiss equation for $d\alpha/d\Phi$.

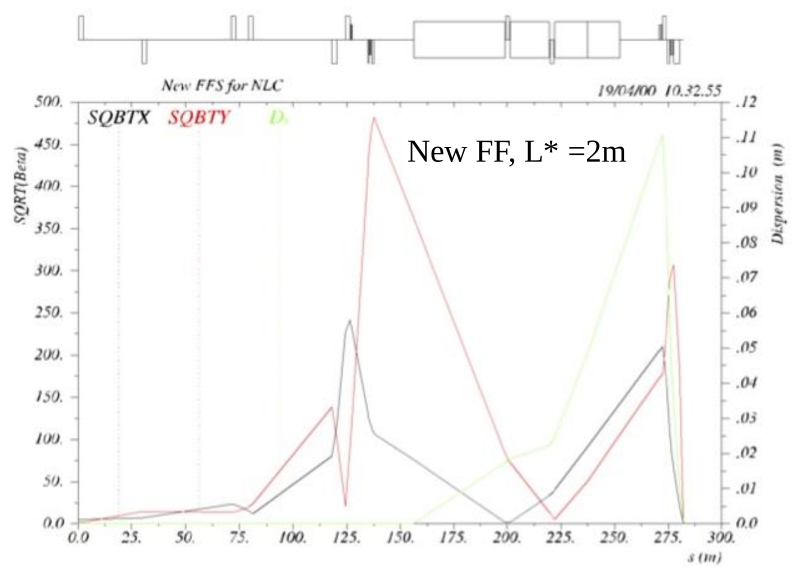
Compare FF designs

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

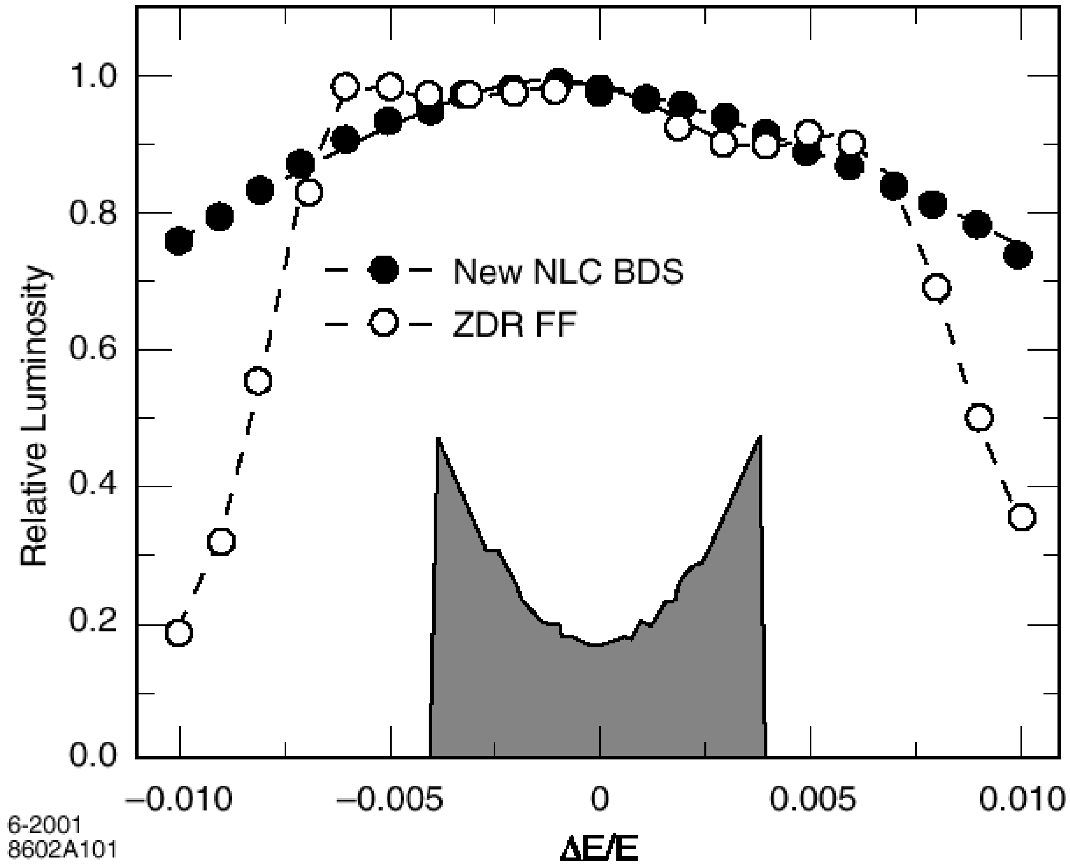
Moreover, its necessary length scales only as $E^{2/5}$ with energy! One can design multi-TeV FF in under a km!







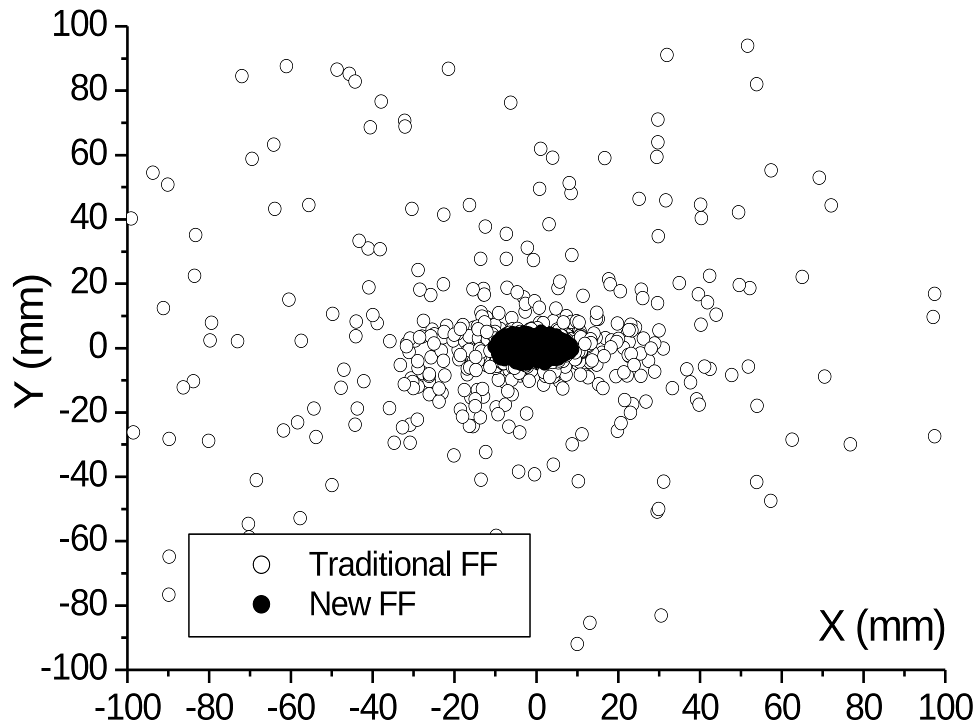
IP bandwidth



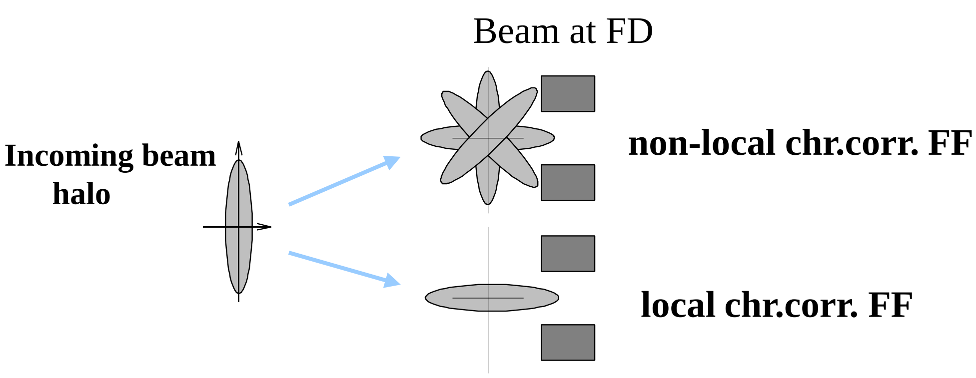
Bandwidth of FF with local chromaticity correction can be better than for system with non-local correction

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

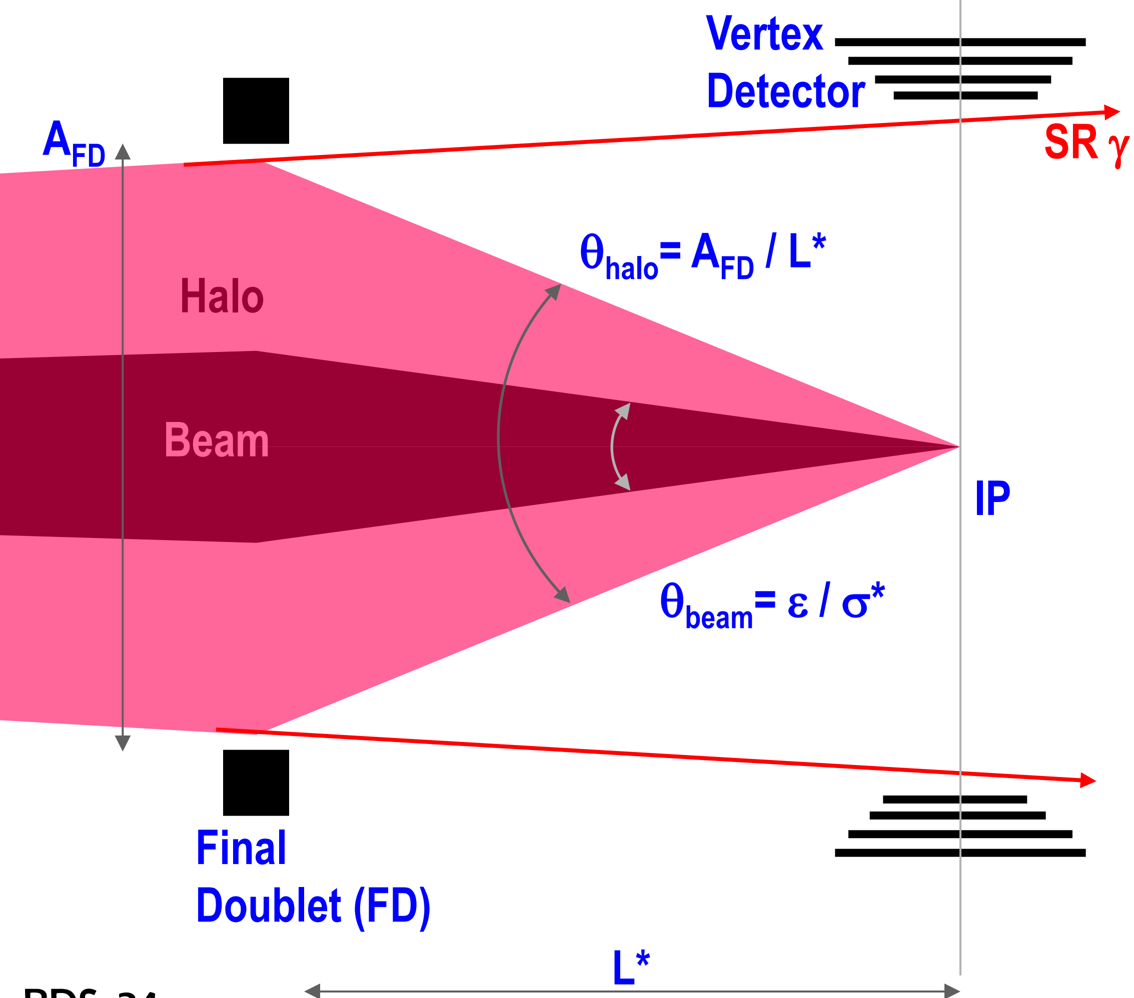


Halo beam at the FD entrance. Incoming beam is ~ 100 times larger than nominal beam



Beam halo & collimation

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



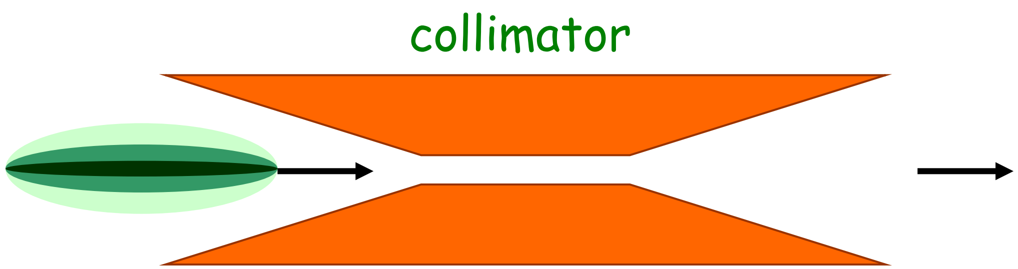
- Halo must be collimated upstream in such a way that SR γ & halo e^{+-} do not touch VX and FD
- => VX aperture needs to be somewhat larger than FD aperture
- Exit aperture is larger than FD or VX aperture
- Beam convergence depend on parameters, the halo convergence is fixed for given geometry

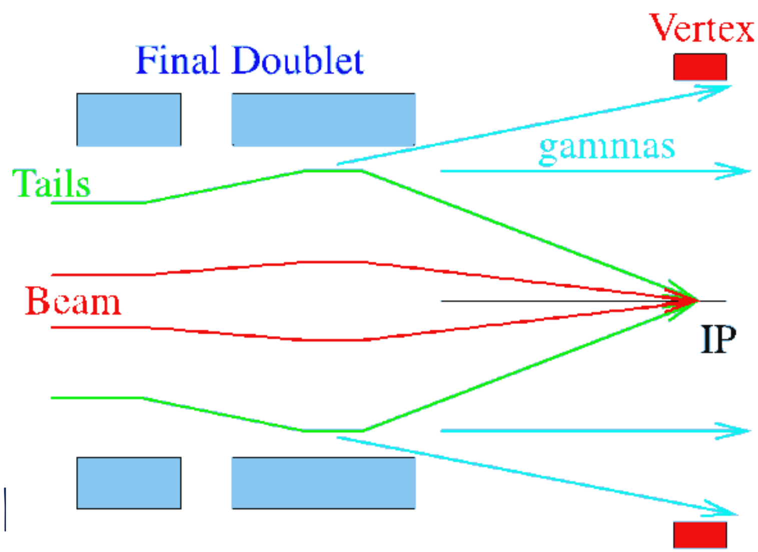
=> $\theta_{halo}/\theta_{beam}$ (collimation depth) becomes tighter with larger L^* or smaller IP beam size

- 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

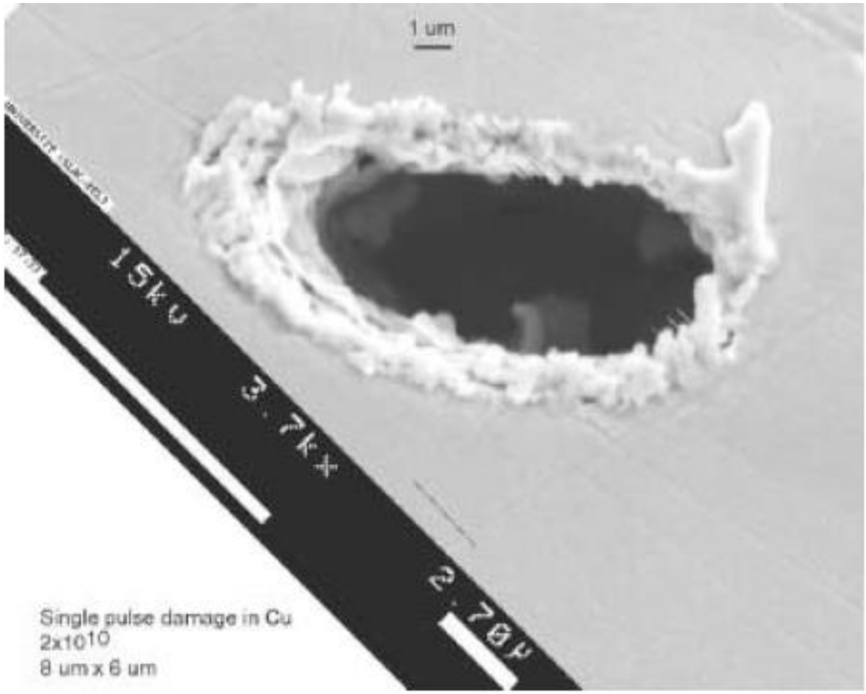




- Collimation depth (esp. in x) can be onl
- It is not unlikely that not only halo (1e-3 – 1e-6 of the beam) but full errant bunch(s) would hit the collimator

MPS and collimation design

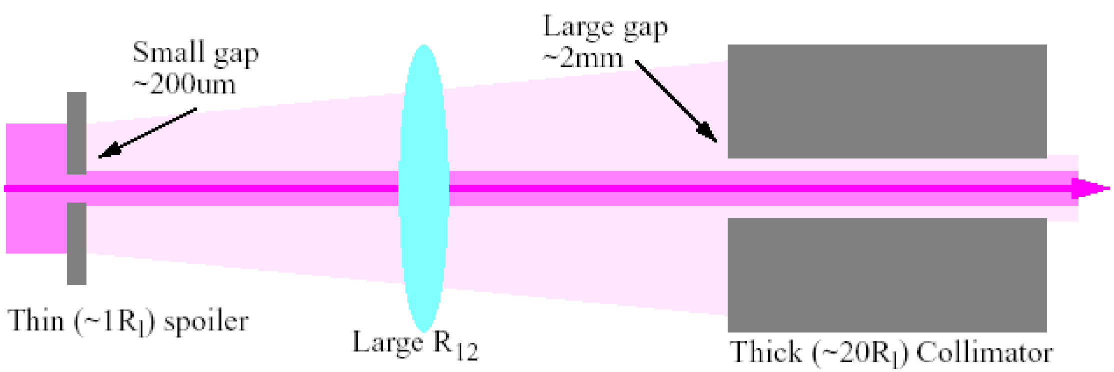
- The beam is very small => single bunch can punch a hole => the need for MPS (machine protection system)
- Damage may be due to
  - electromagnetic shower damage (need several radiation lengths to develop)
  - direct ionization loss (~1.5MeV/g/cm^2 for most materials)
- Mitigation of collimator damage
  - using spoiler-absorber pairs
    - thin (0.5-1 rl) spoiler followed by thick (~20rl) absorber
  - increase of beam size at spoilers
  - MPS divert the beam to emergency extraction as soon as possible



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

Spoiler-Absorber & spoiler design

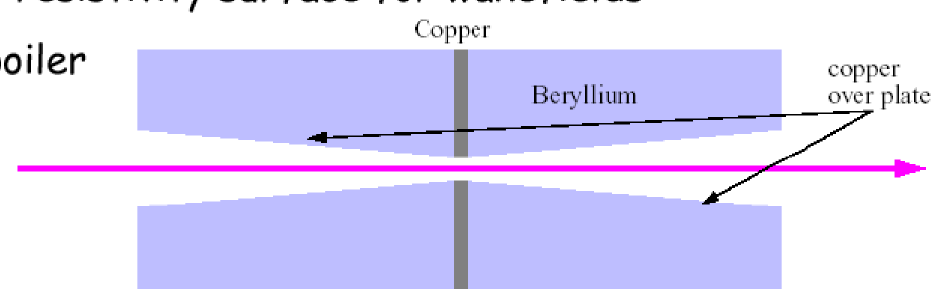
Spoiler / Absorber Scheme

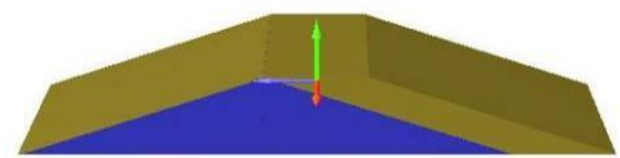


Thin spoiler increases beam divergence and size at the thick absorber already sufficiently large. Absorber is away from the beam and contributes much less to wakefields.

Tapered low resistivity surface for wakefields

Thin hi-Z spoiler





Recently considered 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.

Spoiler damage

Spoiler material properties and temperature rise due to a single bunch of 1.25 x 10^{10} electrons within a beam spot with $\sigma_x = \sigma_y = 3.16$ μm.

	Be	C	Al	Ti	Cu	Fe
Radiation Length (cm)	35.7	21.7	9.0	3.7	1.4	1.8
dE/dx_{min} (MeV cm^{-1})	3.1	3.6	4.4	7.2	12.8	11.6
Specific Heat, C_p (J cm^{-3} °C^{-1})	3.3	1.9	2.5	2.4	3.5	3.8
Meltng Point, T_{melt} (°C)	1280	3600	660	1800	1080	1530
Stress Limit, T_{stress} (°C)	150	2500	140	770	180	135
Temperature Rise, ΔT (°C)	2350	4740	4403	7506	9150	7637
$\Delta T / T_{melt}$	1.8	1.3	6.7	4.2	8.5	5.0
$\Delta T / 4T_{stress}$	3.9	0.36	7.9	2.4	12.7	14.1

Temperature rise for thin spoilers (ignoring shower buildup and increase of specific heat with temperature):

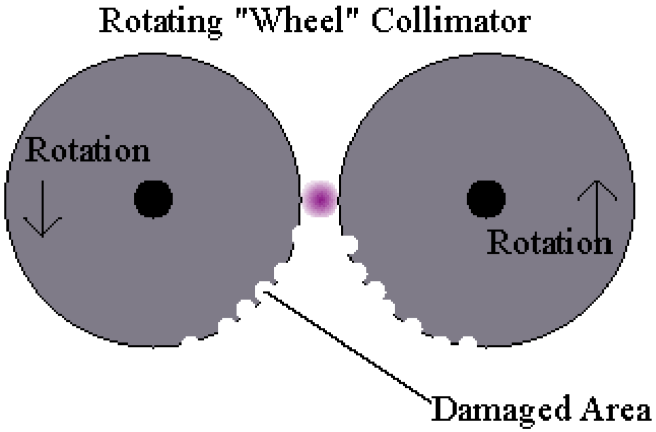
$$\Delta T = \frac{0.393 N}{\pi \sigma_x \sigma_y} \frac{dE/dx_{min}}{C_p}$$

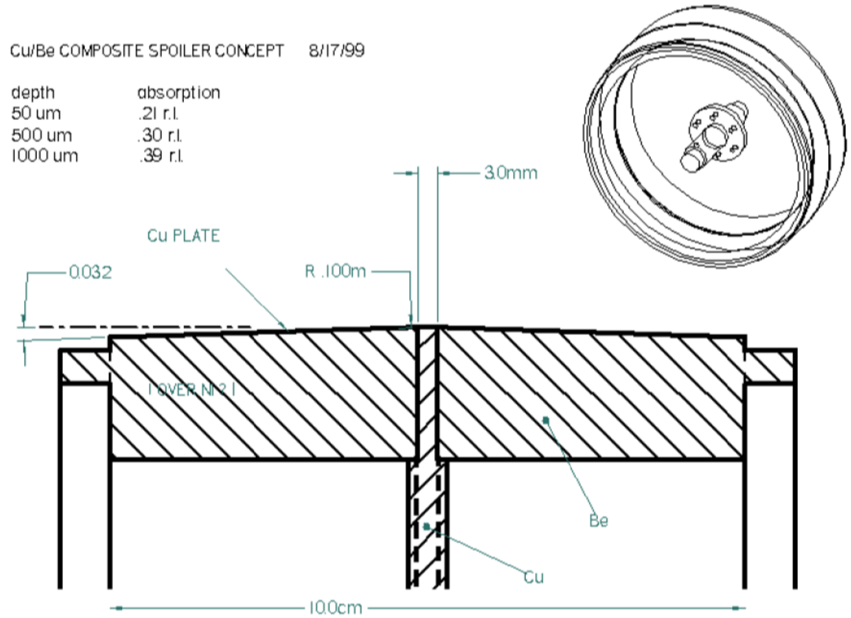
The stress limit based on tensile strength, modulus of elasticity and coefficient of thermal expansion. Sudden T rise create local stresses. When ΔT exceed stress limit, micro-fractures can develop. If ΔT exceeds $4T_{stress}$, the shock wave may cause material to delaminate. Thus, allowed ΔT is either the melting point or four time stress limit at which the material will fail catastrophically.

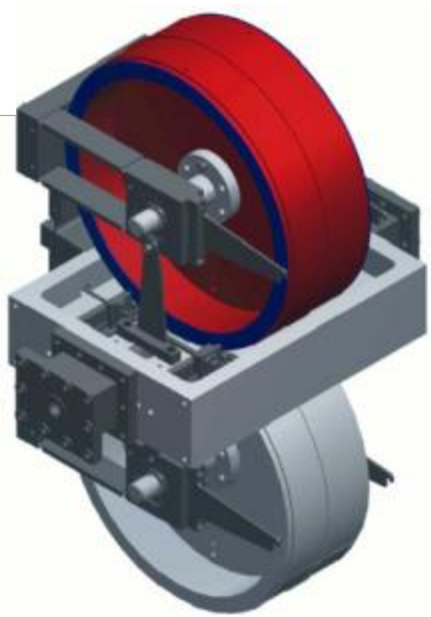
Survivable and consumable spoilers

- A critical parameter is number of bunches #N that MPS will let through to the spoiler before sending the rest of the train to emergency extraction
- If it is practical to increase the beam size at spoilers so that spoilers survive #N bunches, then they are survivable
- Otherwise, spoilers must be consumable or renewable

Renewable spoilers





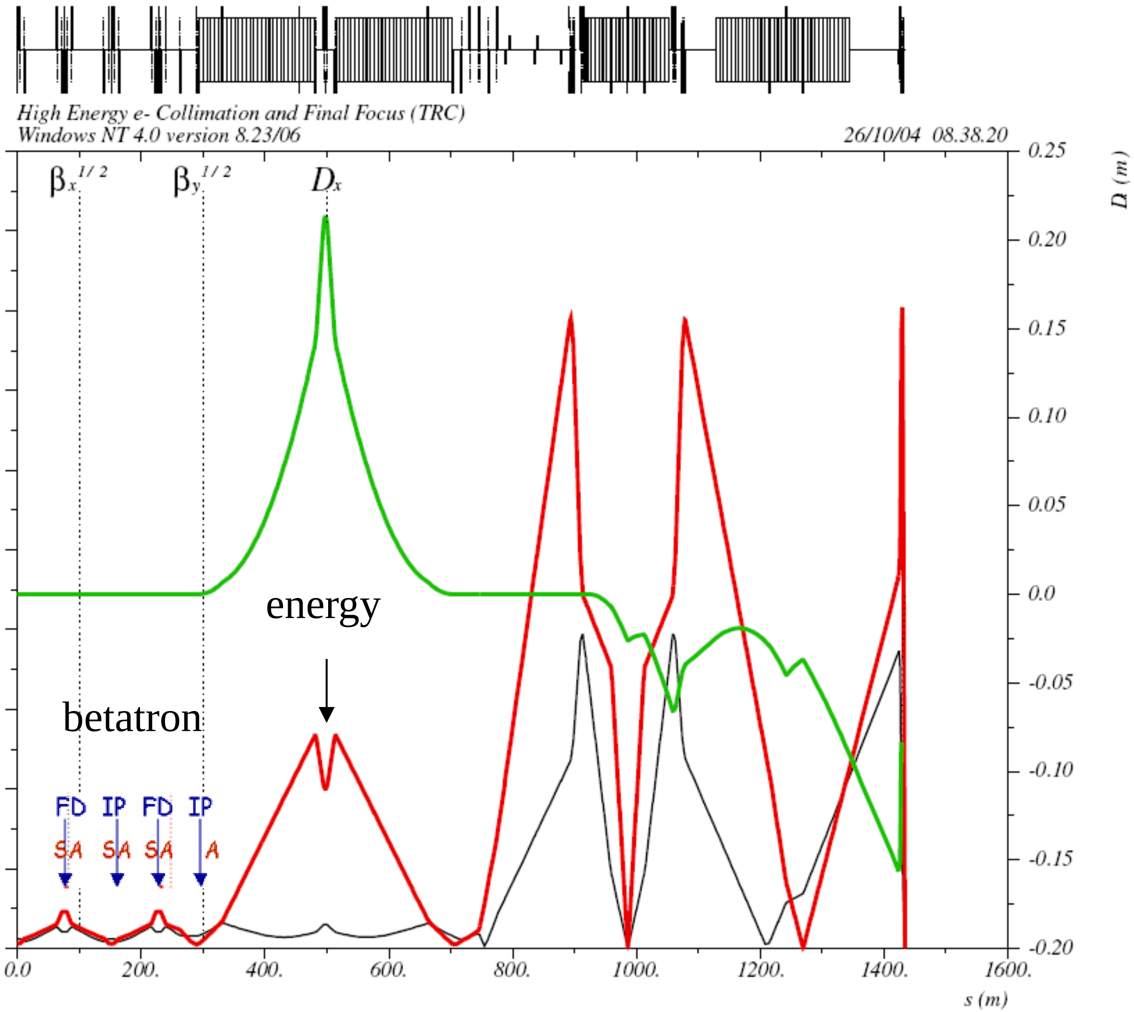


This design was essential for NLC, where short inter-bunch spacing made it impractical to use survivable spoilers.

This concept is now being applied to LHC collimator system.

BDS with renewable spoilers

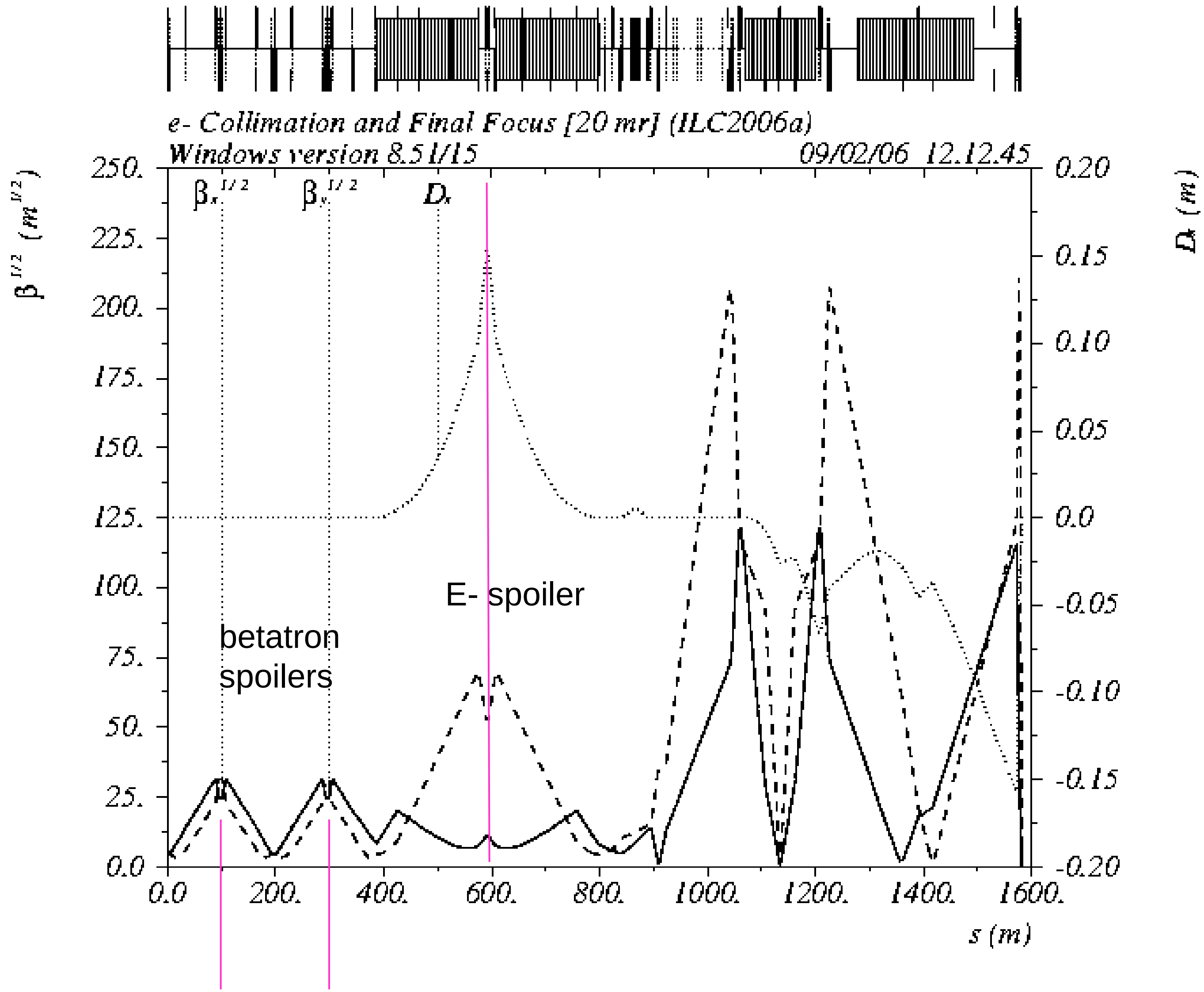
- Location of spoiler and absorbers is shown
- Collimators were placed both at FD betatron phase and at IP phase
- Two spoilers per FD and IP phase
- Energy collimator is placed in the region with large dispersion
- Secondary clean-up collimators located in FF part
- Tail folding octupoles (see below)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

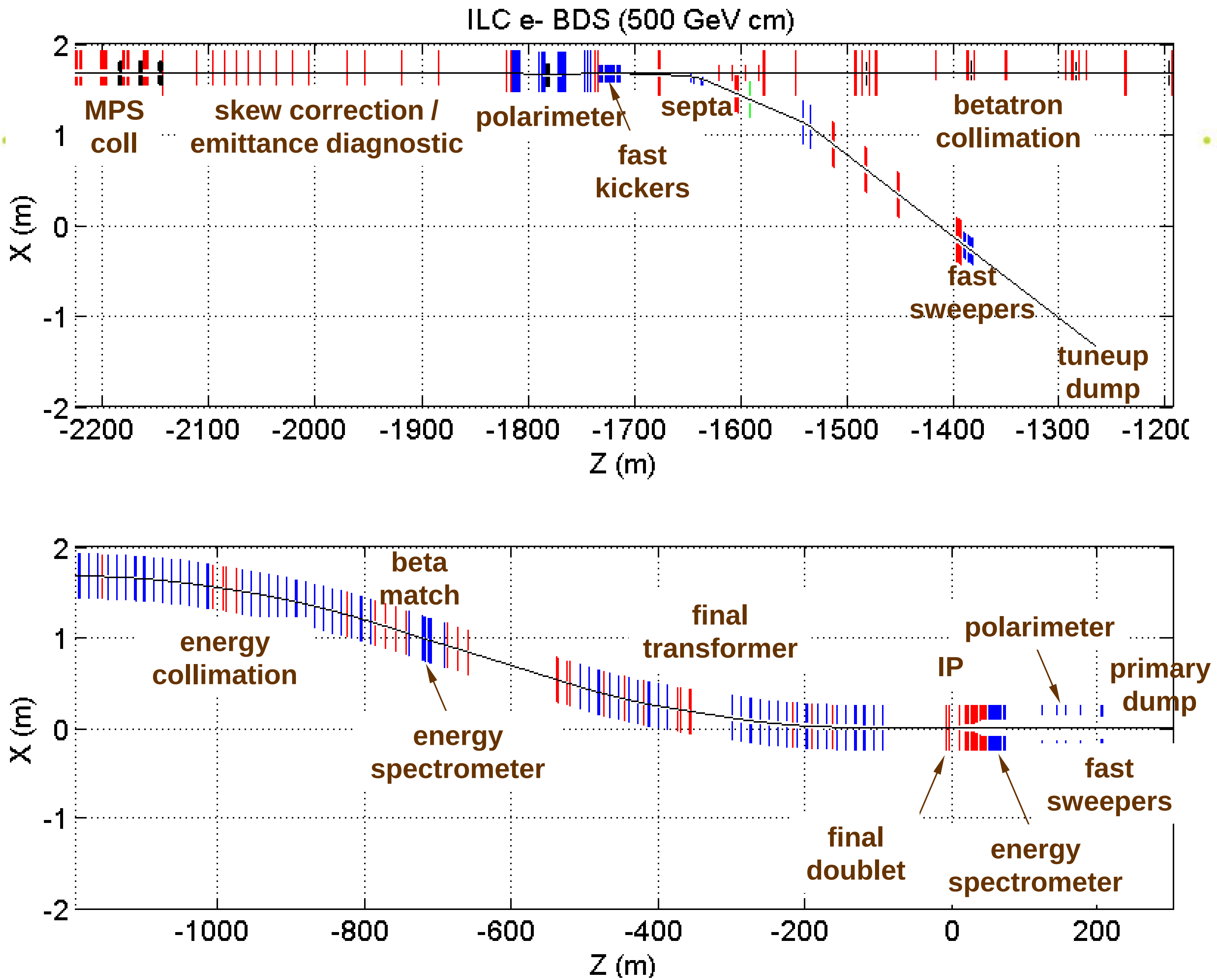


- Beam Delivery System Optics, an earlier version with consumable spoilers

ILC FF & Collimation

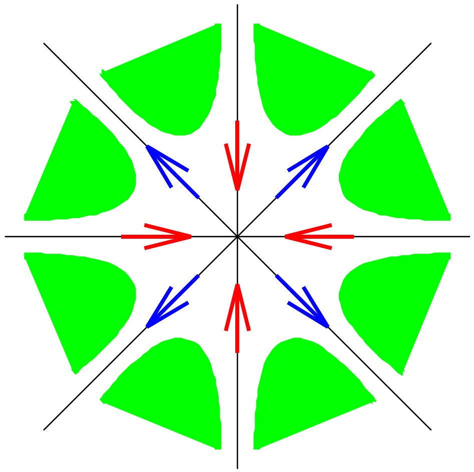
- Betatron spoilers survive up to two bunches
- E-spoiler survive several bunches
- One spoiler per FD or IP phase




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)
energy collimation
beta match
energy spectrometer
final transformer
IP
polarimeter
primary dump
fast sweepers
final doublet
energy spectrometer
X (m)
Z (m)

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



Single octupole focus in planes and defocus on diagonals.

An octupole doublet can focus in all directions !

Strong focusing by octupoles

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

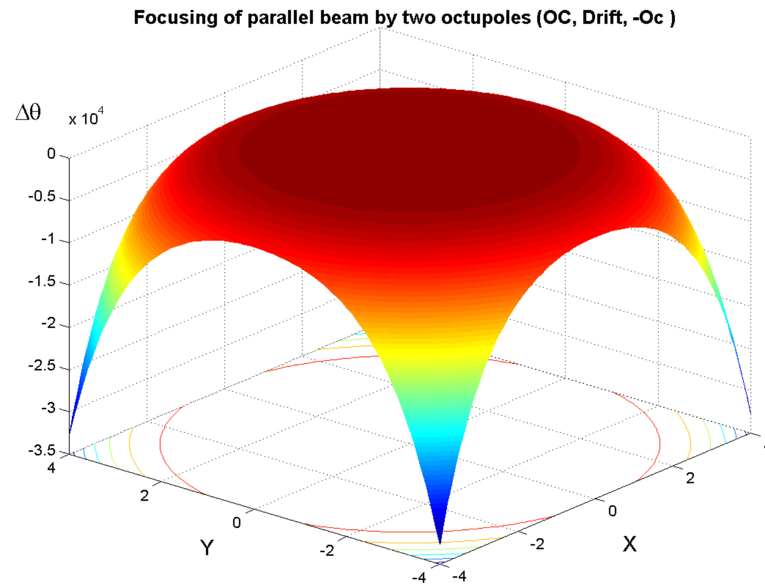
$$\Delta\theta = \alpha r^3 e^{-i3\varphi} - \left(\alpha r^3 e^{i3\varphi}\left(1+\alpha r^2 L e^{-i4\varphi}\right)^3\right)^*$$

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

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

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

Next nonlinear term focusing – defocusing depends on φ

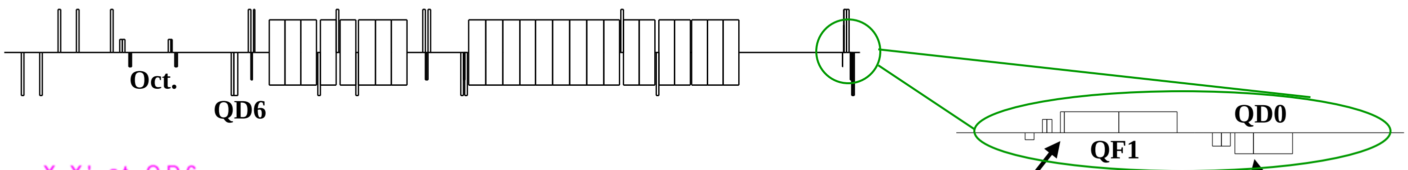


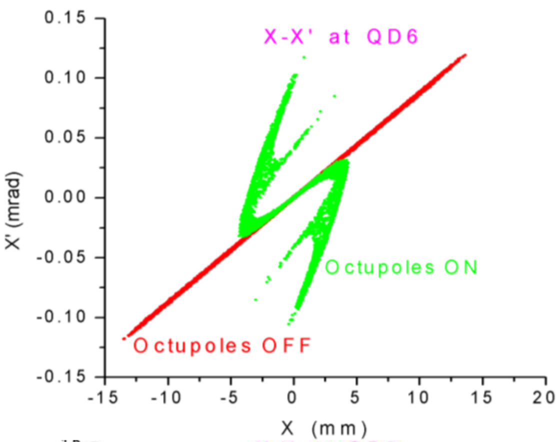
Effect of octupole doublet (Oc,Drift,-Oc) on parallel beam, ΔΘ(x,y).

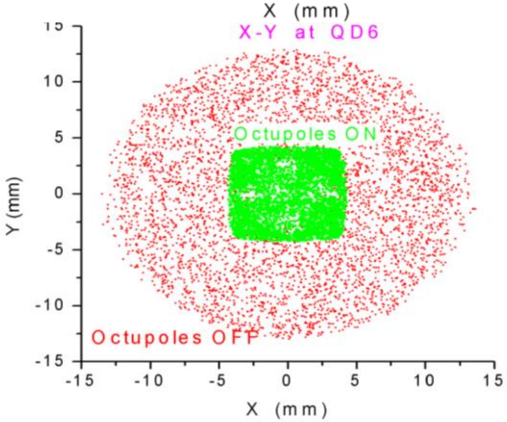
- For this to work, the beam should have **small angles**, i.e. it should be parallel or **diverging**

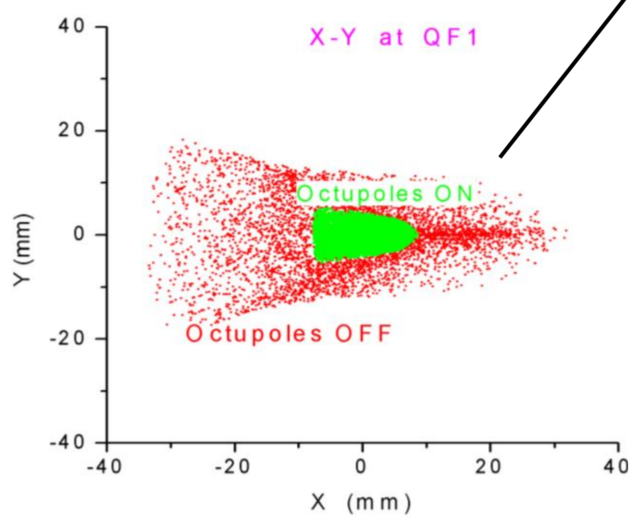
Tail folding in ILC FF

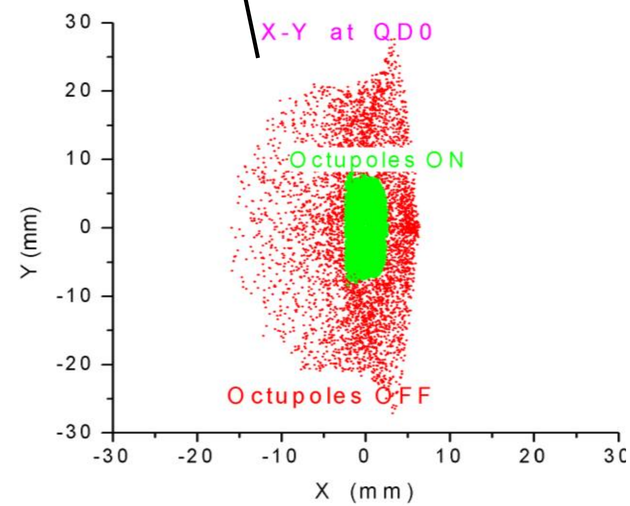
- **Two octupole doublets give tail folding by ~ 4 times in terms of beam size in FD**
- **This can lead to relaxing collimation requirements by ~ a factor of 4**





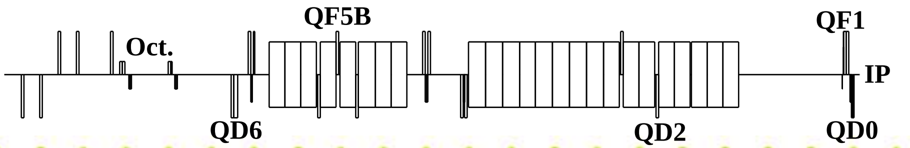


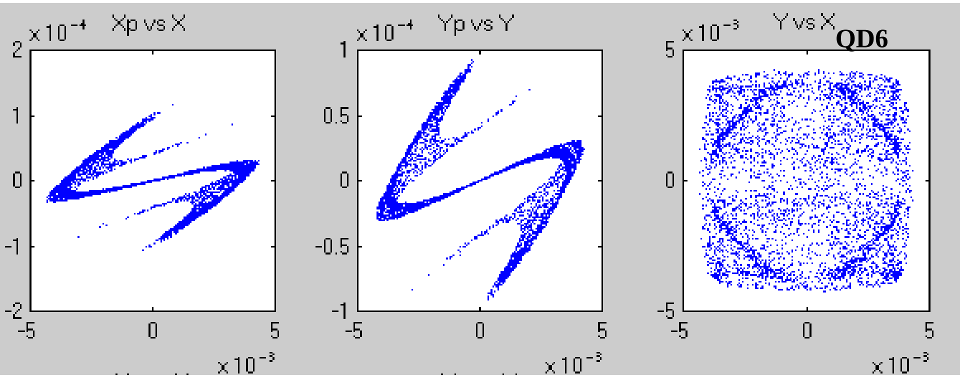


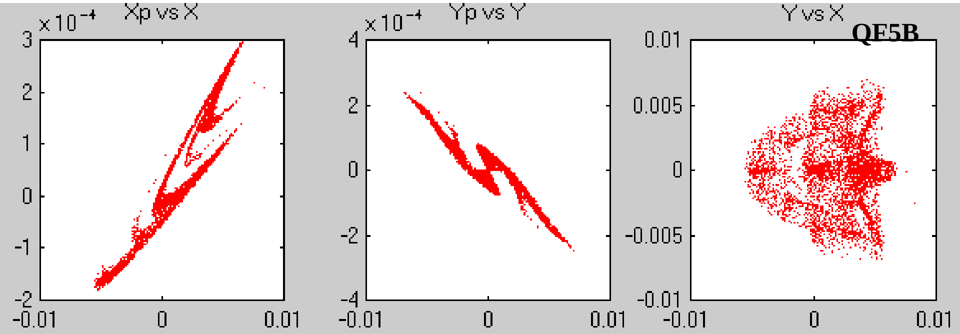


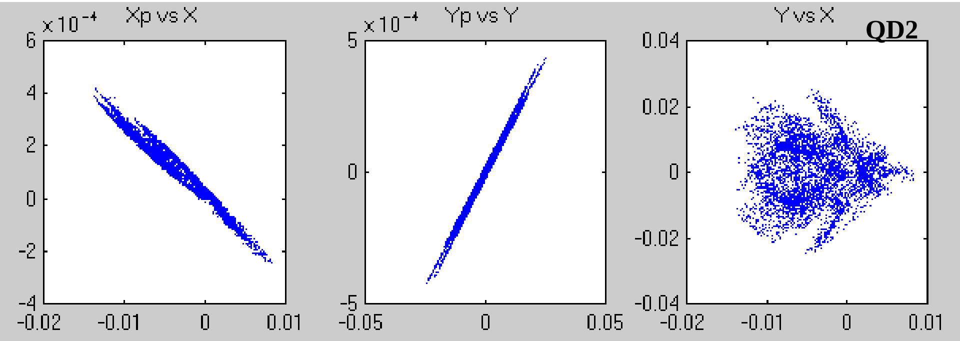
Tail folding by means of two octupole doublets in the ILC final focus
Input beam has (x,x',y,y') = (14μm,1.2mrad,0.63μm,5.2mrad) in IP units (flat distribution, half width) and ±2% energy spread, that corresponds approximately to N_σ=(65,65,230,230) sigmas with respect to the nominal beam

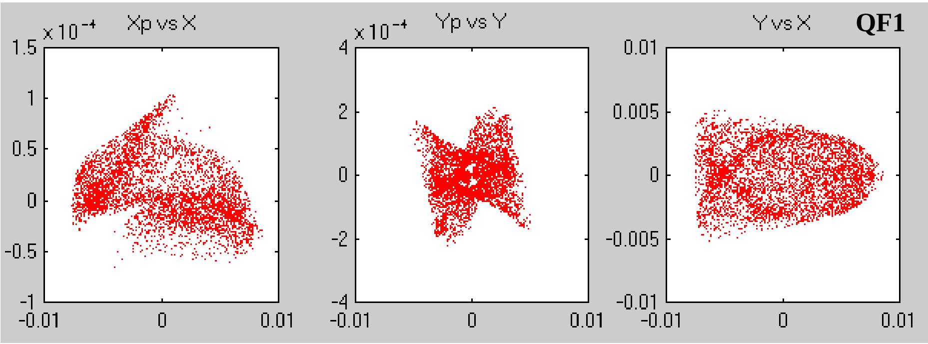
Tail folding
or Origami Zoo

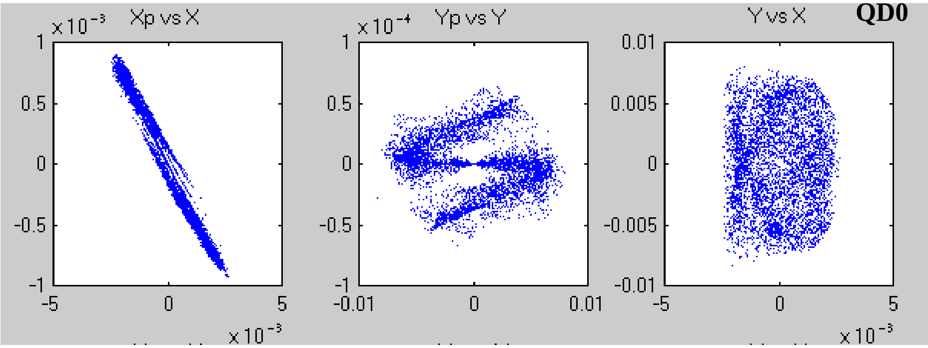


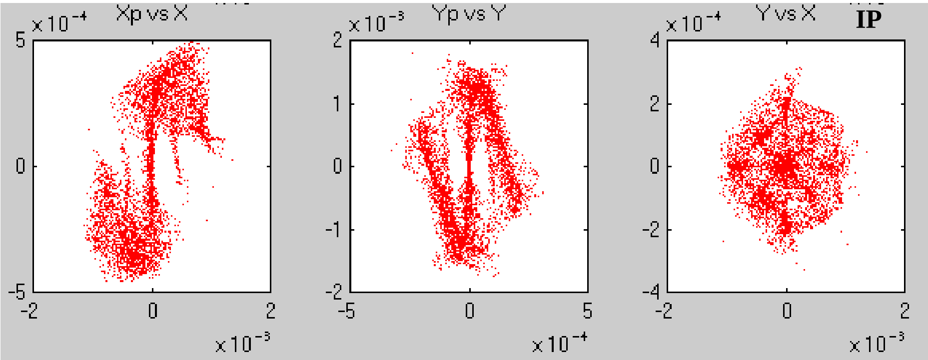




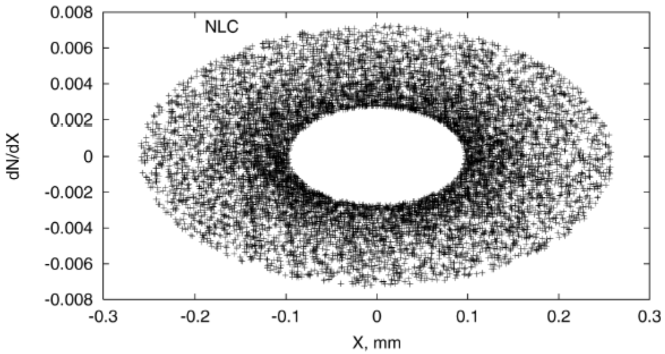


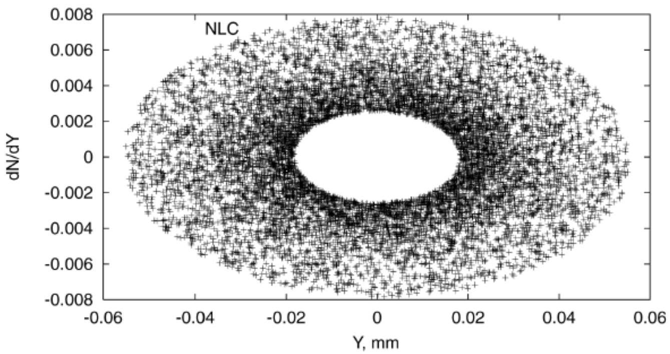


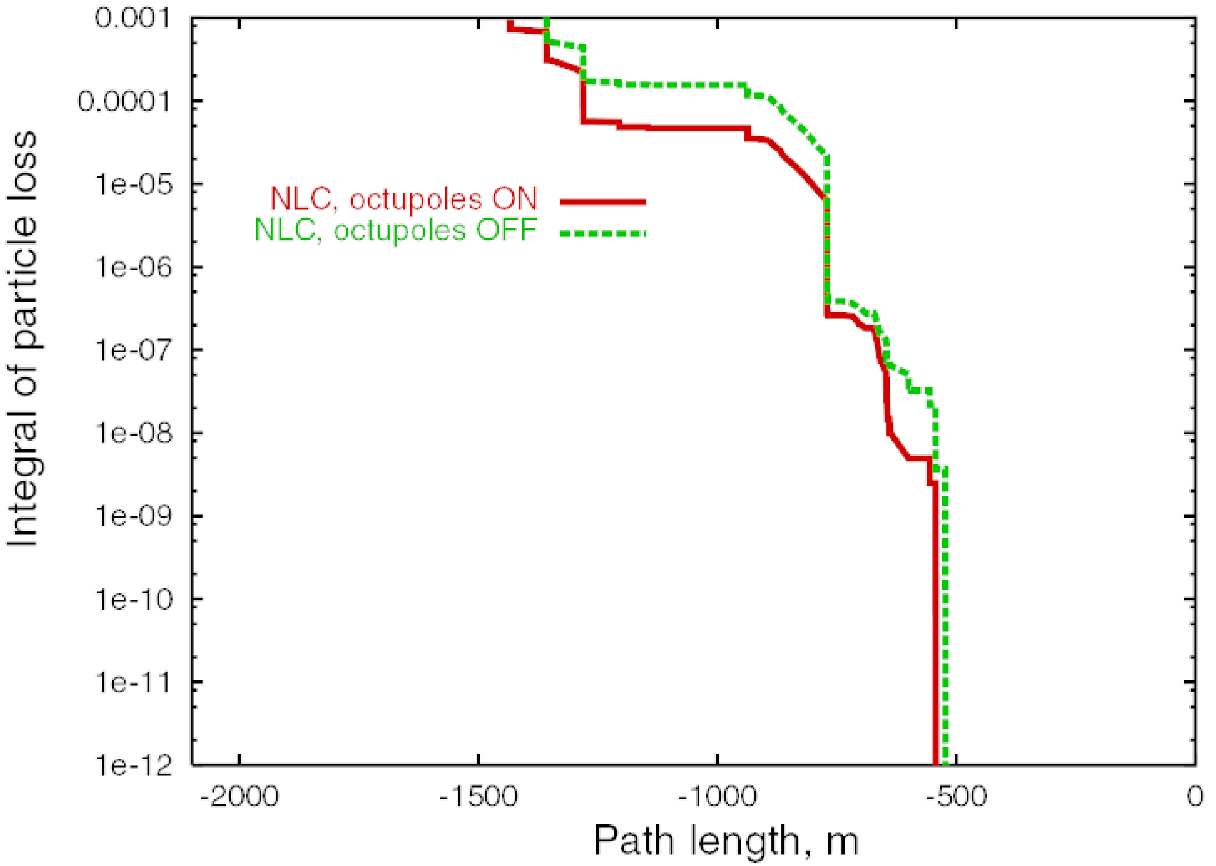




Halo collimation







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.

Collimator wakes

- Effect from offset of the beam at the collimator:

$$\Delta y' = K\, y$$

- Assume that beam jitter is a fixed fraction of the beam size

$$\frac{\Delta y'}{\sigma_{y'}} = K \frac{\sigma_y}{\sigma_{y'}} \frac{y}{\sigma_y}$$

- Jitter amplification factor

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

For locations with α=0 => $A_\beta = K\, \beta$

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

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

Following P.Tenenbaum, LCC-101 and G.Stupakov, PAC2001

Wakes for tapered collimators

- Rectangular collimators

3.1 r/h — 0.37 — $\sqrt{\alpha r / \sigma_z}$

$$K = \frac{\sqrt{\pi}}{2} \frac{N r_e}{\gamma} \frac{\alpha h}{\sigma_z r^2}$$

$$K = 2.7 \frac{N r_e}{\gamma} \sqrt{\frac{\alpha}{\sigma_z r^3}}$$

$$K = \frac{N r_e}{\gamma} \frac{1}{r^2}$$

- where α is tapering angle, r is half gap, h is half width

Following P.Tenenbaum, LCC-101 and G.Stupakov, PAC2001

Wakes for tapered collimators

- Circular collimators

$2\sqrt{\pi}$ $\qquad \alpha\, r / \sigma_z$

$$K = \frac{N\, r_e}{\gamma} \frac{\alpha}{\sqrt{\pi}\, \sigma_z\, r}$$

inductive regime (smooth transition)

$$K = \frac{N\, r_e}{\gamma} \frac{2}{r^2}$$

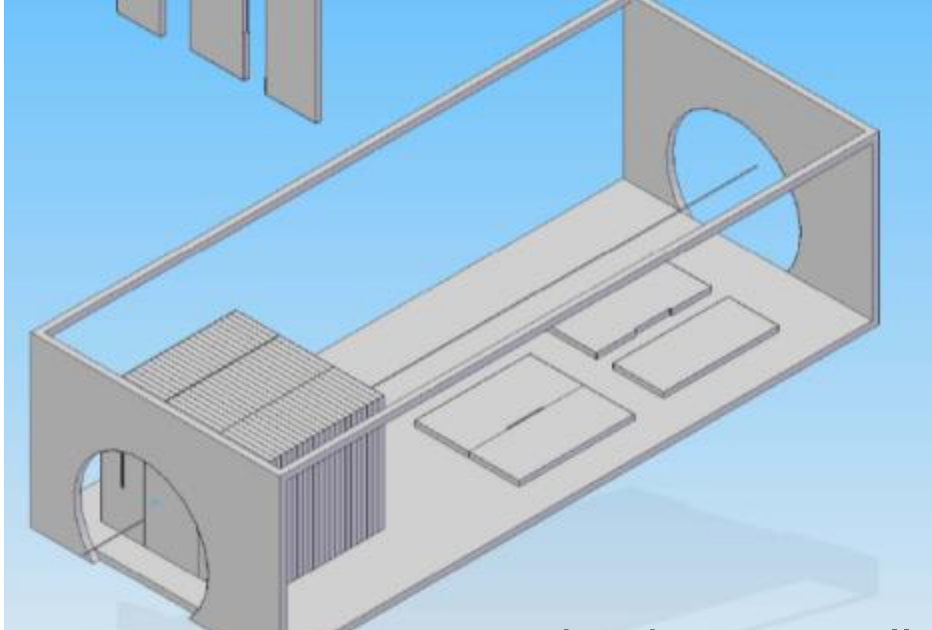
diffractive regime (sudden transition)

- where α is tapering angle, r is half gap

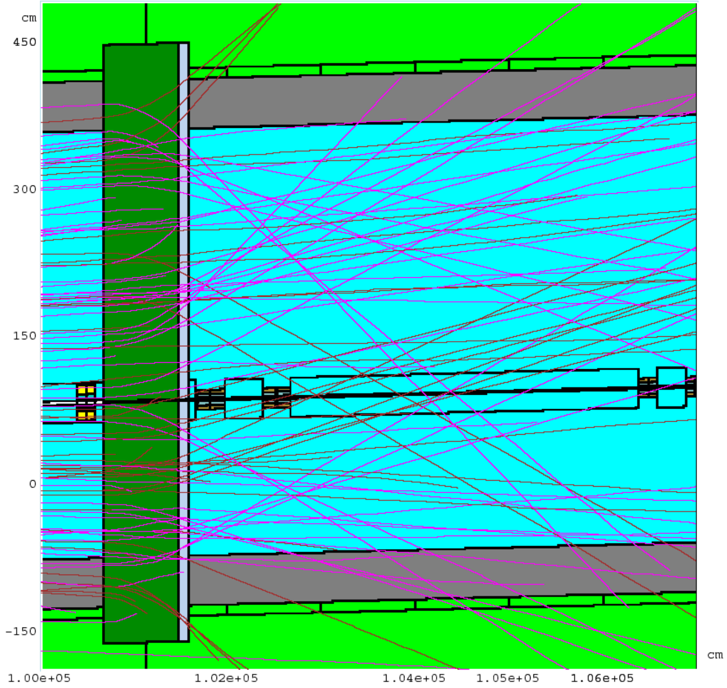
Following P.Tenenbaum, LCC-101 and G.Stupakov, PAC2001

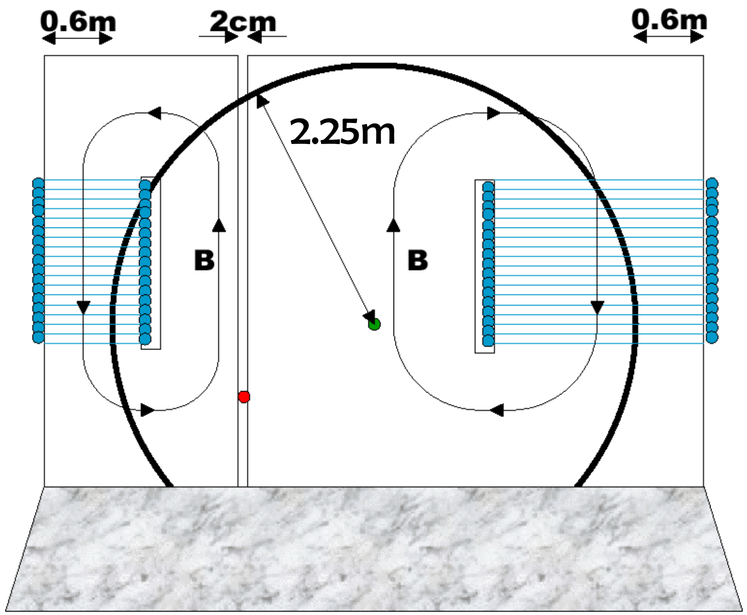
Dealing with muons in BDS

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

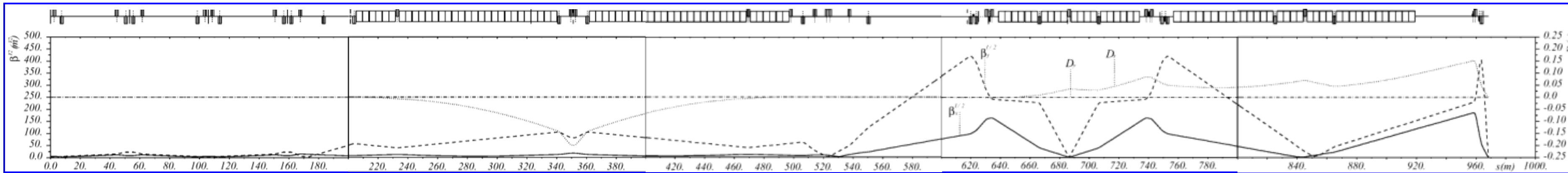


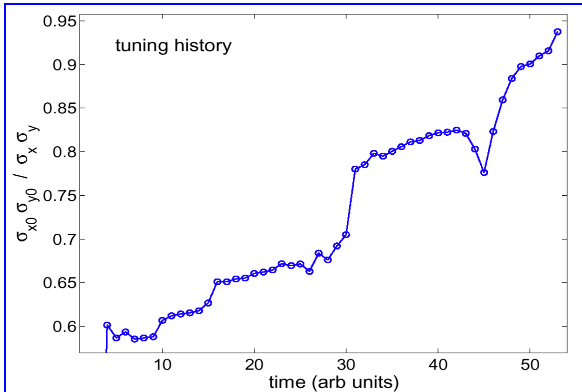
Magnetized muon wall



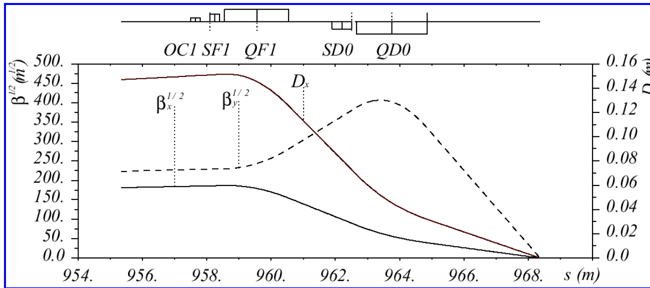


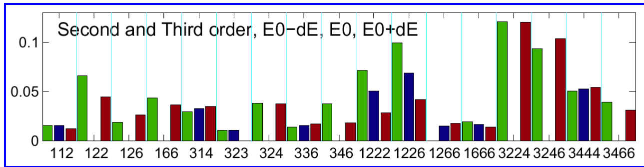
BDS design methods & examples

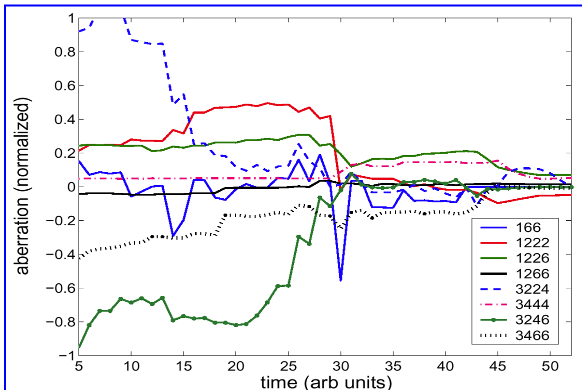


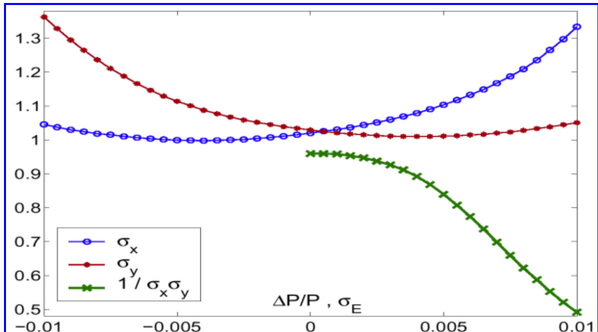


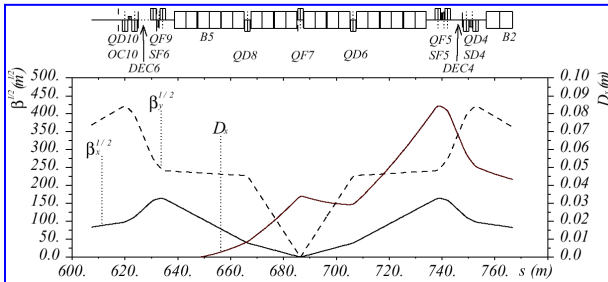
Example of a 2nd IR BDS optics for ILC; design history; location of design knobs



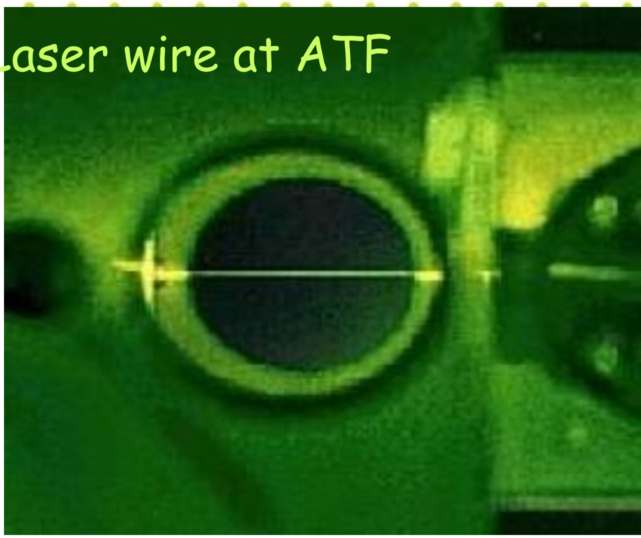








In a practical situation …

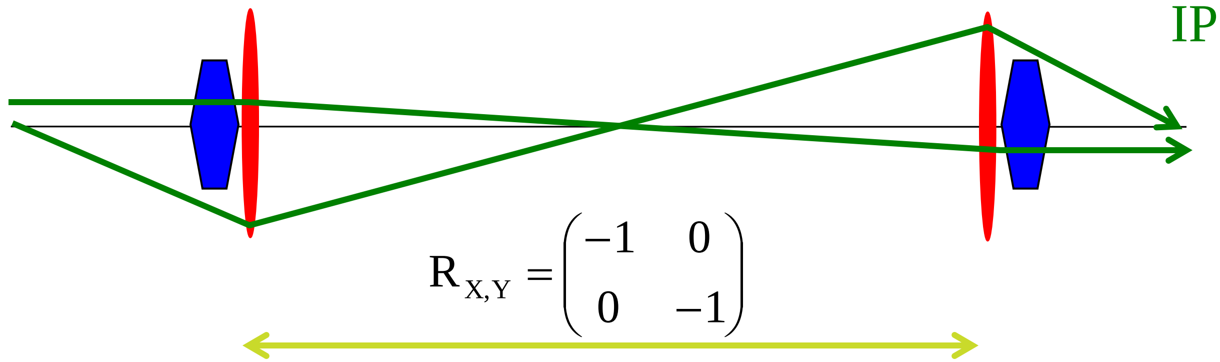


- While **designing** the FF, one has a **total control**
- When the system is built, one has just limited number of observable parameters (measured orbit position, beam size measured in several locations)
- The system, however, may initially have **errors** (errors of strength of the elements, transverse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

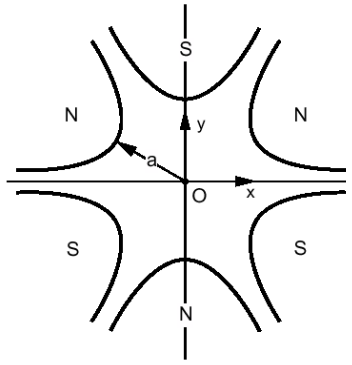
Laser wire will be a tool for tuning and diagnostic of FF

- **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:

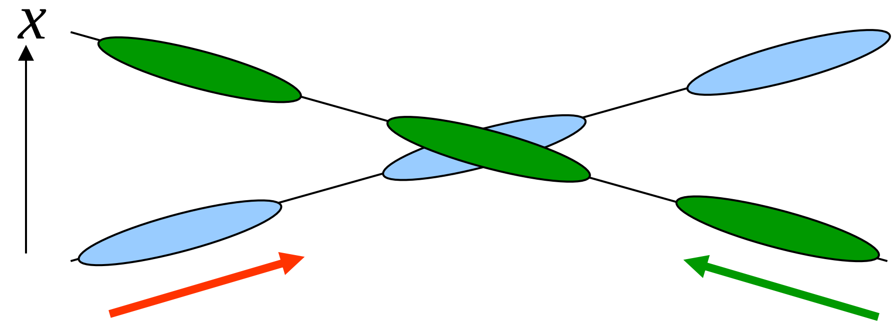
$x' = x' + S\,(x^2 - y^2)$

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

- 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

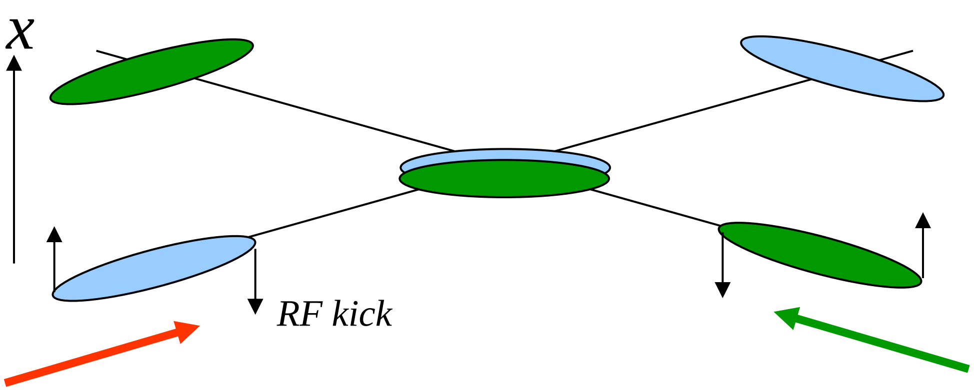
To create these knobs, sextupole placed on movers

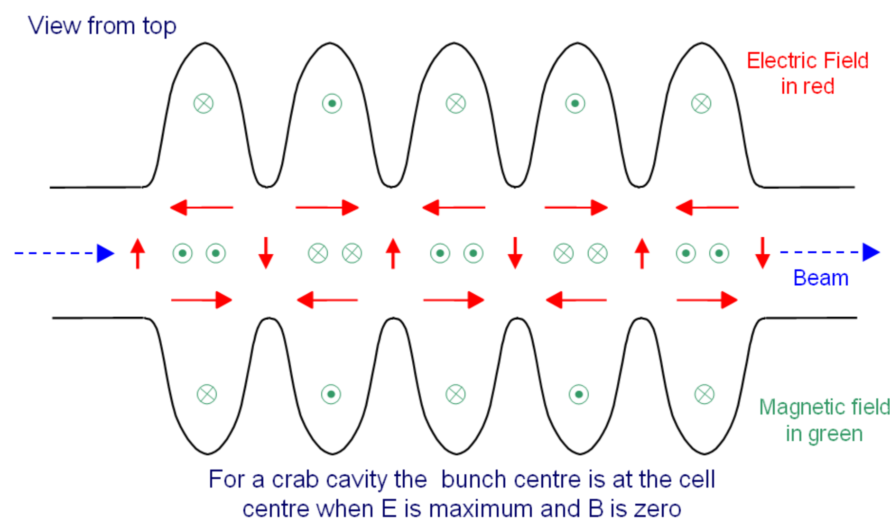
Crab crossing



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

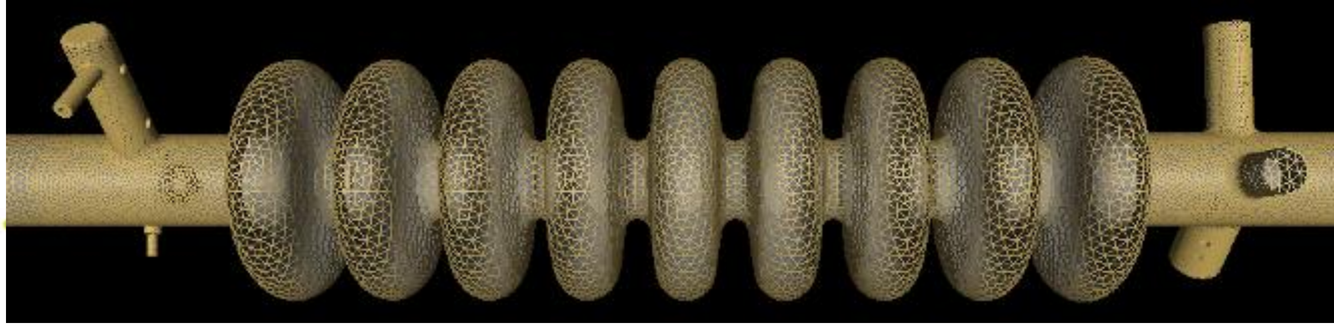
→ several time reduction in *L* without corrections





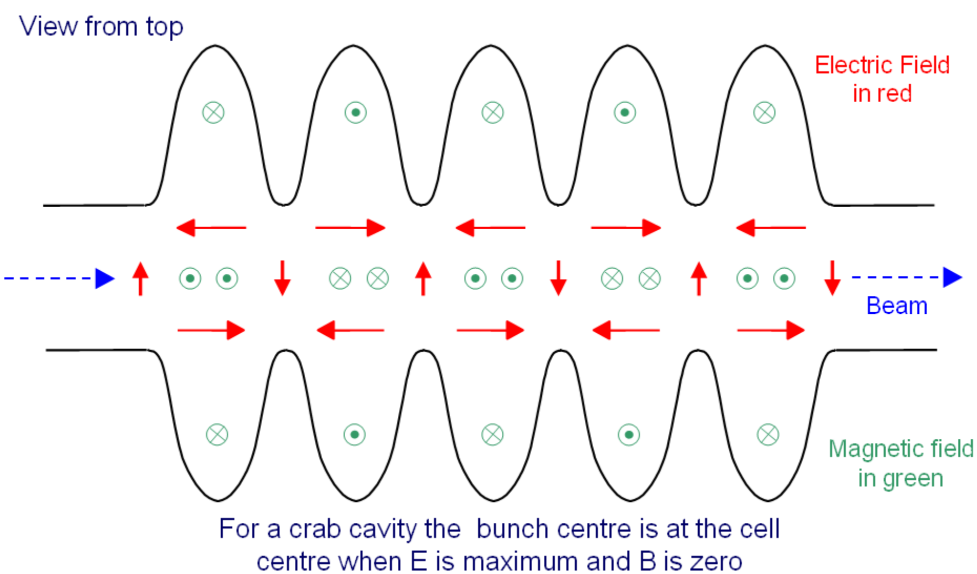
Use transverse (crab) RF cavity to 'tilt' the bunch at IP

Crab cavity design



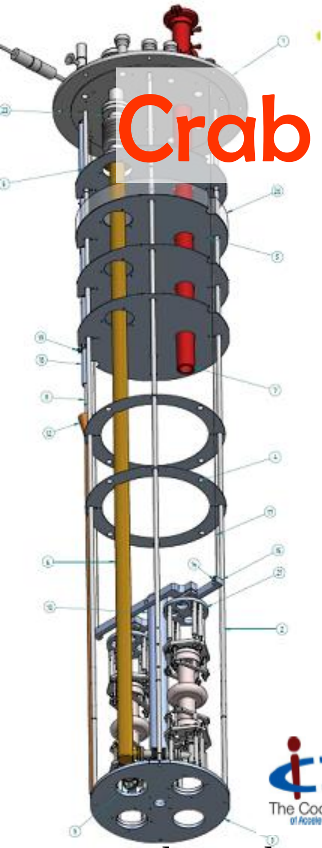
FNAL 3.9GHz 9-cell cavity in Opega3p. *K.Ko, et al*

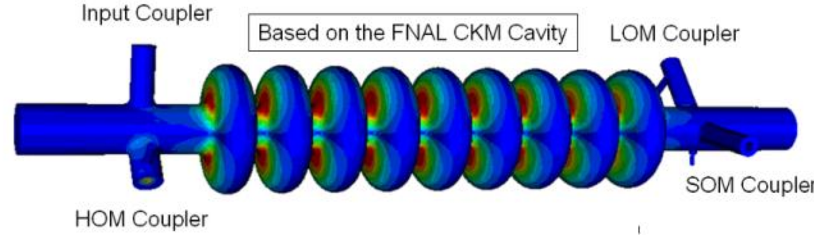
- Prototypes of crab cavity built at FNAL and 3d RF models
- Design & prototypes been done by UK-FNAL-SLAC collaboration

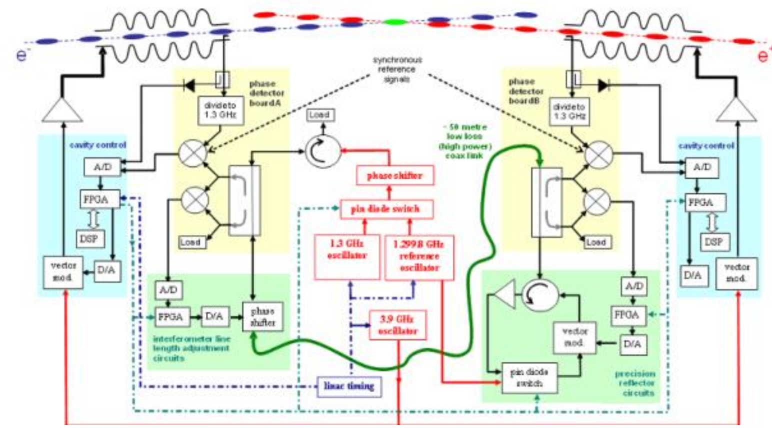


TM110 Dipole mode cavity

Crab cavity







Cavities limited in gradient to 1 MV/m (~40kV/cell) – shielding implications.

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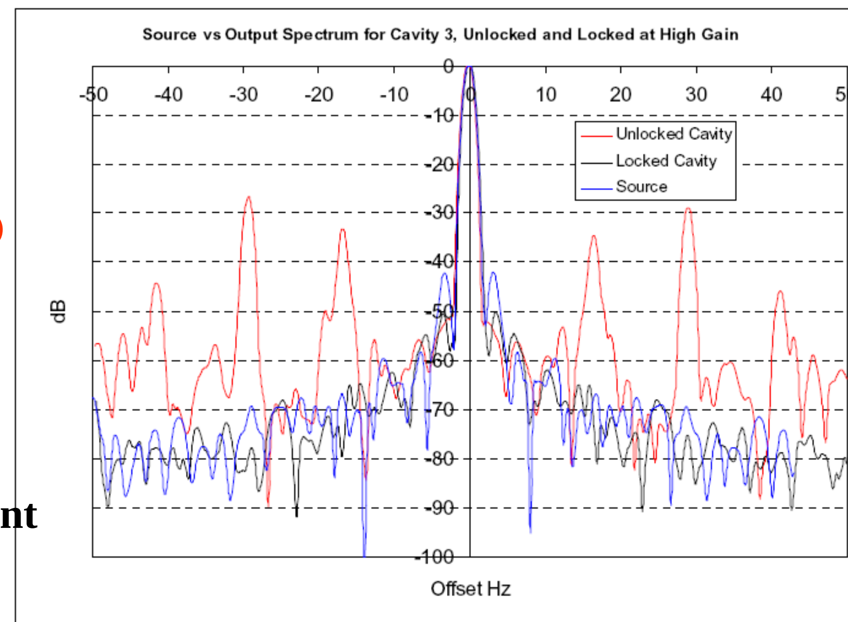


Independent phase lock achieved for both cavities:

– **Unlocked => 10º r.m.s.**

– **Locked => 0.135º r.m.s.**

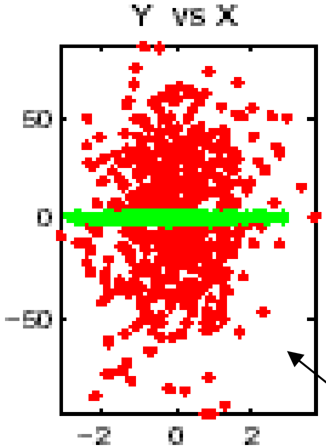
• Performance limited by:

– **Source noise (dominant); ADC noise; Measurement noise; – Cavity frequency drift; Microphonics**

• Improvements being made; new tests being prepared

P.McIntosh at al

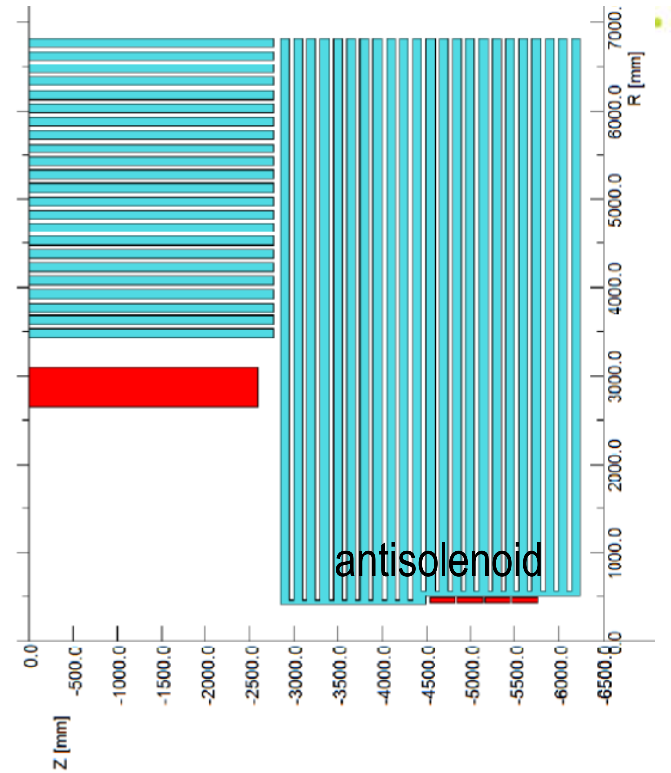
IR coupling compensation



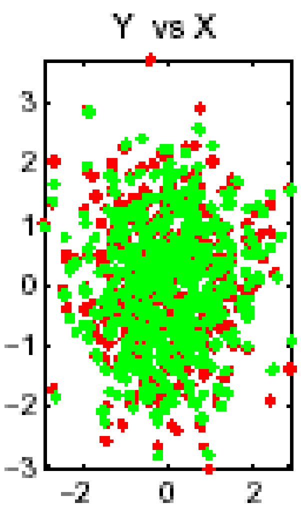
without compensation

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

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)

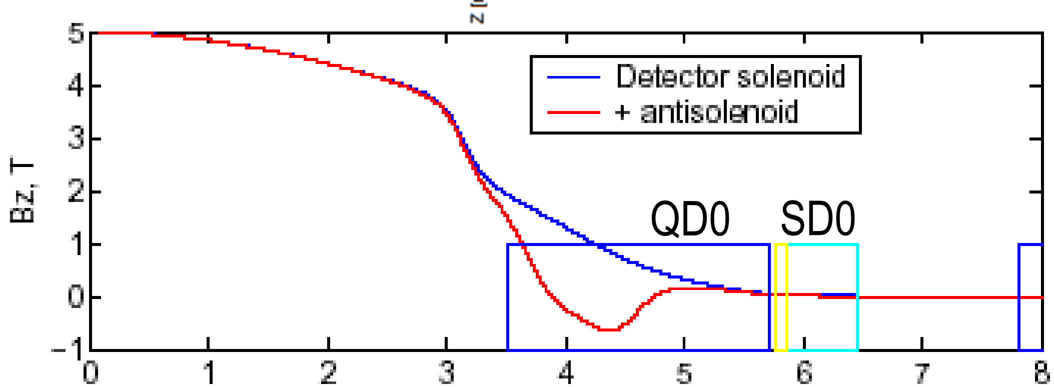


Even though traditional use of skew quads could reduce the effect, the local compensation of the fringe field (with a little skew tuning) is the most efficient way to ensure correction over wide range of beam energies

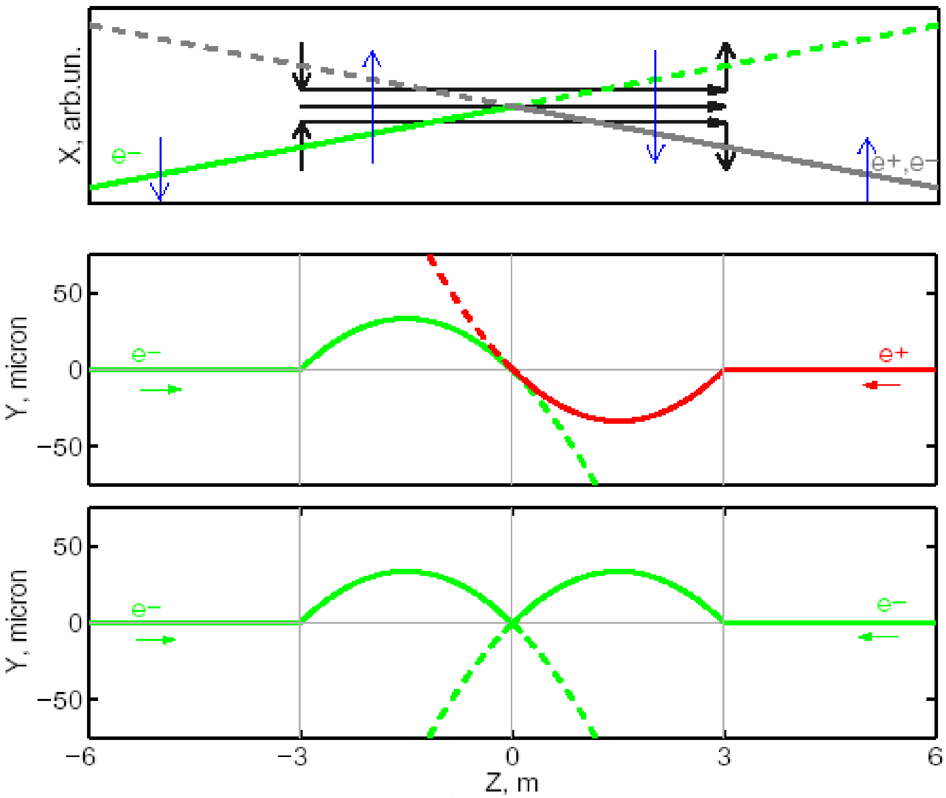


with compensation by antisolenoid

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



Beam orbits near IR



- 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...

(ignore the effect of additional kicks shown by blue lines for the moment)

Orbits in the detector solenoid

Let us consider detector solenoid with sharp edges, as on the previous slide. In the case without compensation, the vertical deflection is caused by the edge kick

$$\Theta = \theta_c B_0 L / (2 B\rho)$$

which occurs when the beam enters the solenoid off axis at $\theta_c L$, and also by the kick linearly distributed in the body of the solenoid. Here θ_c is half of the crossing angle, L is the half-length of the detector solenoid, B_0 is the solenoid field, and $B\rho$ = pc/e is the magnetic rigidity of the beam.

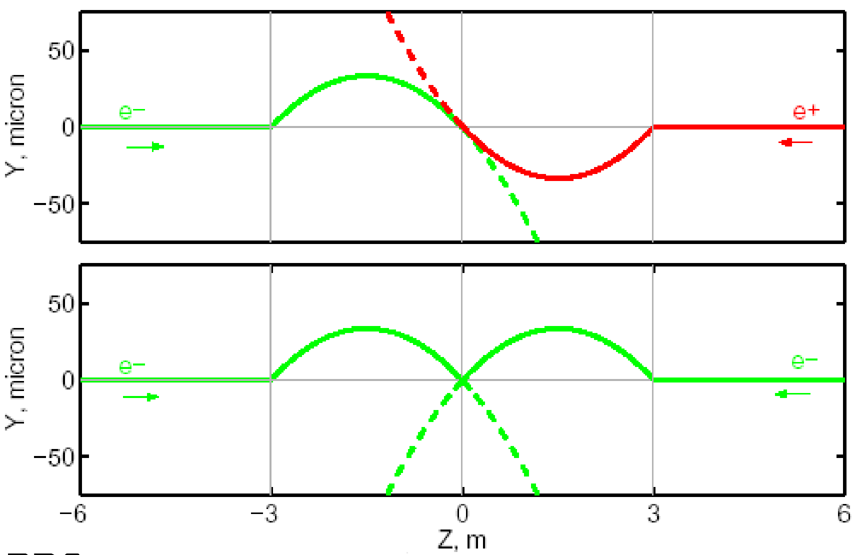
The body kick integrated from the solenoid entrance to the IP is equal to -2Θ, which is twice the edge kick, and since the body kick has half the lever arm, the resulting vertical offset at the IP cancels exactly.

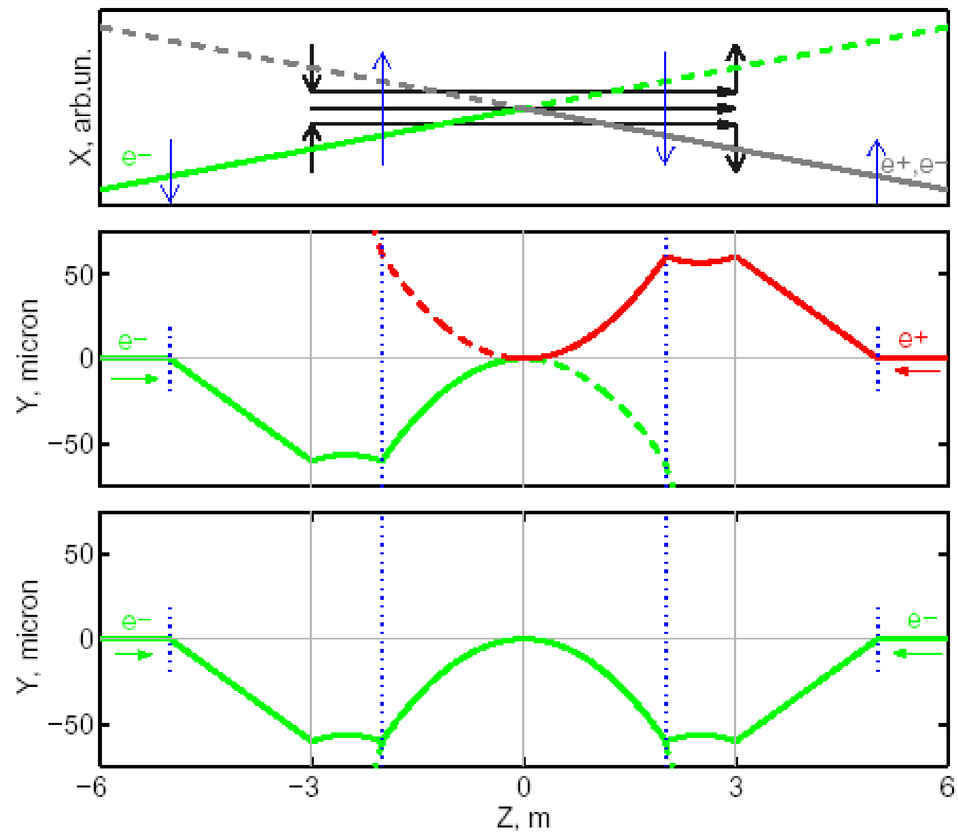
The remaining vertical angle at the IP is nonzero and equals $-\Theta$. The maximal deviation of the vertical orbit before the collision is $\Theta L/4$.

The vertical angle of the extracted beam, which passes through the entire solenoid, is -2Θ and the vertical offset at the exit is $-3\Theta L$.

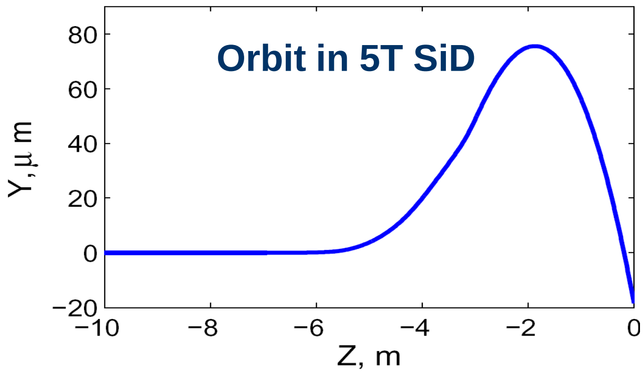
Detector Integrated Dipole

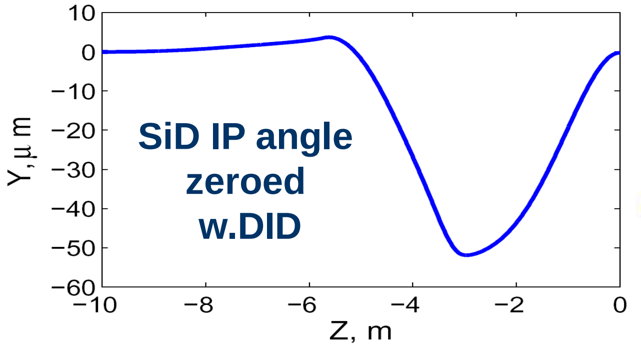
- With a crossing angle, when beams cross solenoid field, vertical orbit arise
- For e+e- the orbit is anti-symmetrical and beams still collide head-on
- If the vertical angle is undesirable (to preserve spin orientation or the e-e- luminosity), it can be compensated locally with DID
- Alternatively,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





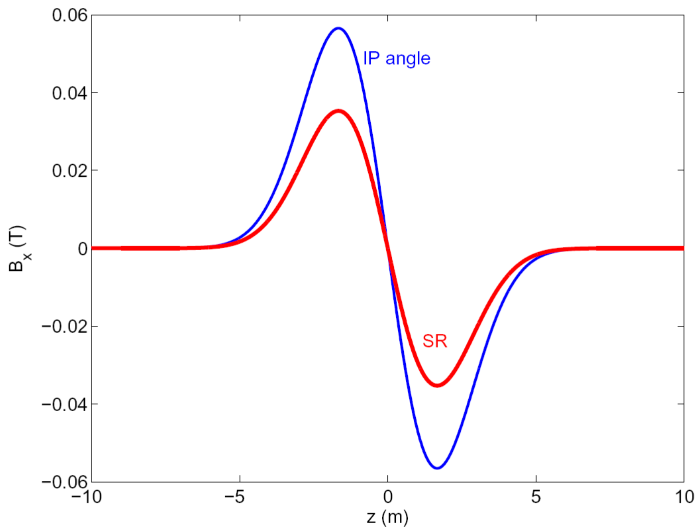
Use of DID or anti-DID

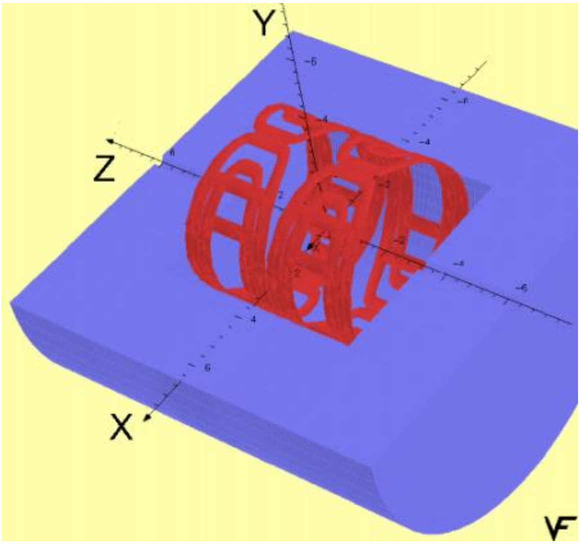




DID case

DID field shape and scheme

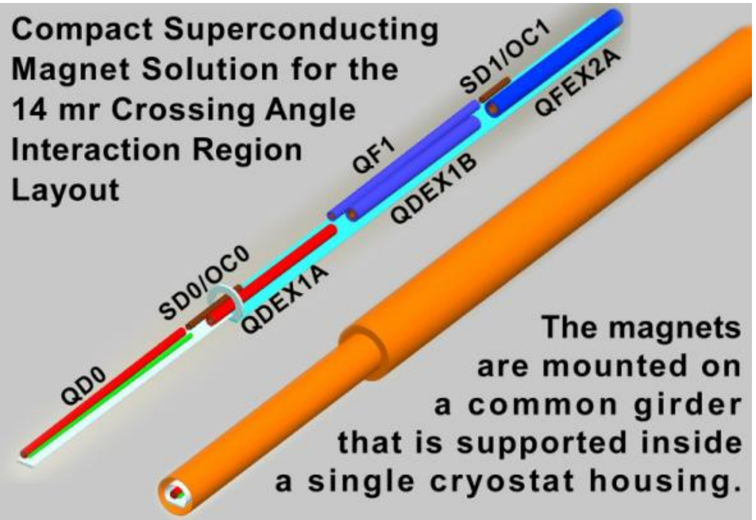


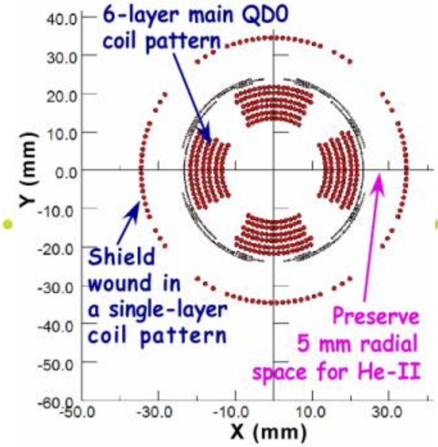


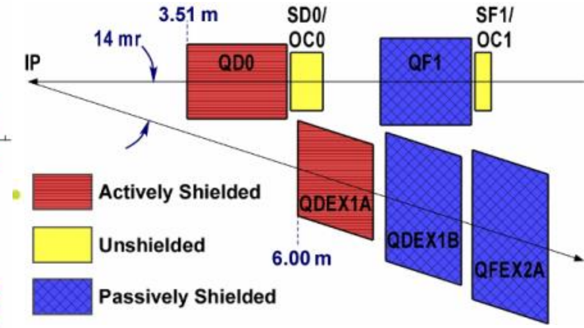
- The negative polarity of DID is also possible (called anti-DID)

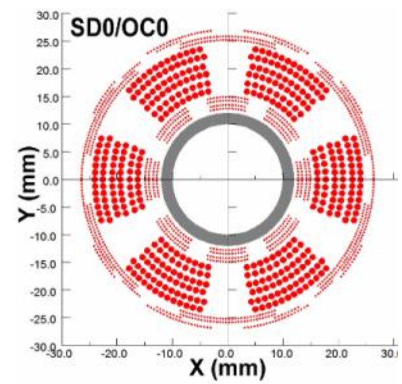
- In this case the vertical angle at the IP is somewhat increased, but the background conditions due to low energy pairs (see below) and are improved

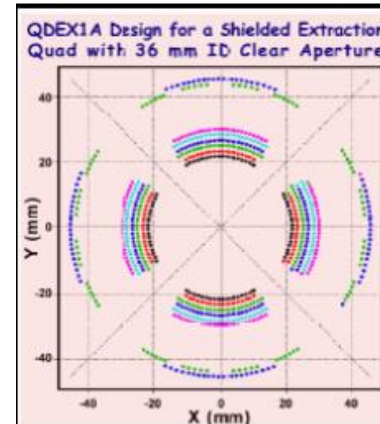
14 mrad IR

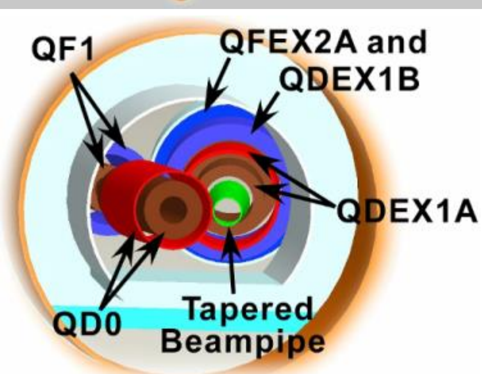

Compact Superconducting
Magnet Solution for the
14 mr Crossing Angle
Interaction Region
Layout
SD1/OC1
QFEX2A
QF1
QDEX1B
SD0/OC0
QDEX1A
QD0
The magnets
are mounted on
a common girder
that is supported inside
a single cryostat housing.

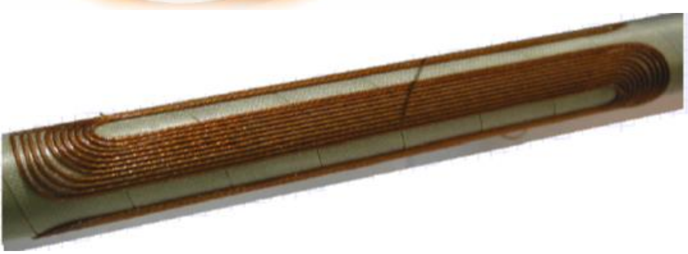

6-layer main QD0
coil pattern
Shield
wound in
a single-layer
coil pattern
Preserve
5 mm radial
space for He-II
Y (mm)
X (mm)

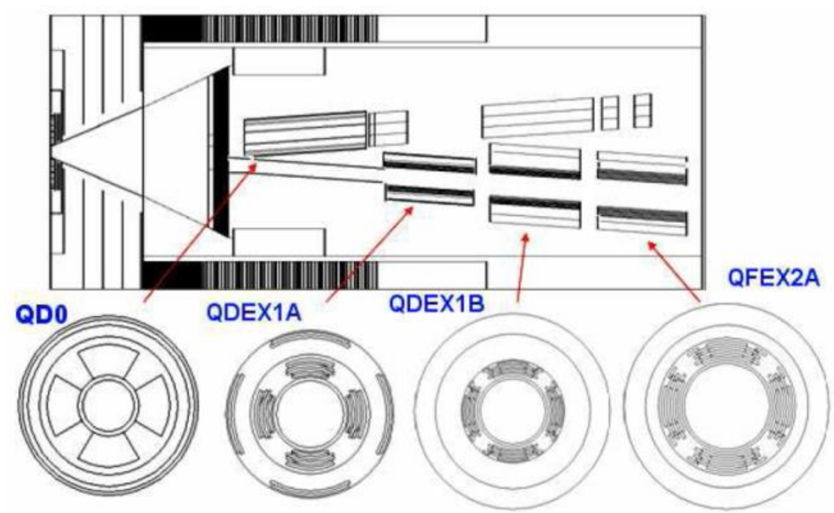

IP
14 mr
3.51 m
SD0/
OC0
SF1/
OC1
QD0
QF1
QDEX1A
QDEX1B
QFEX2A
6.00 m
Actively Shielded
Unshielded
Passively Shielded

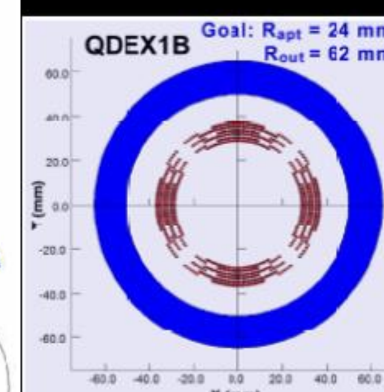

SD0/OC0
Y (mm)
X (mm)


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

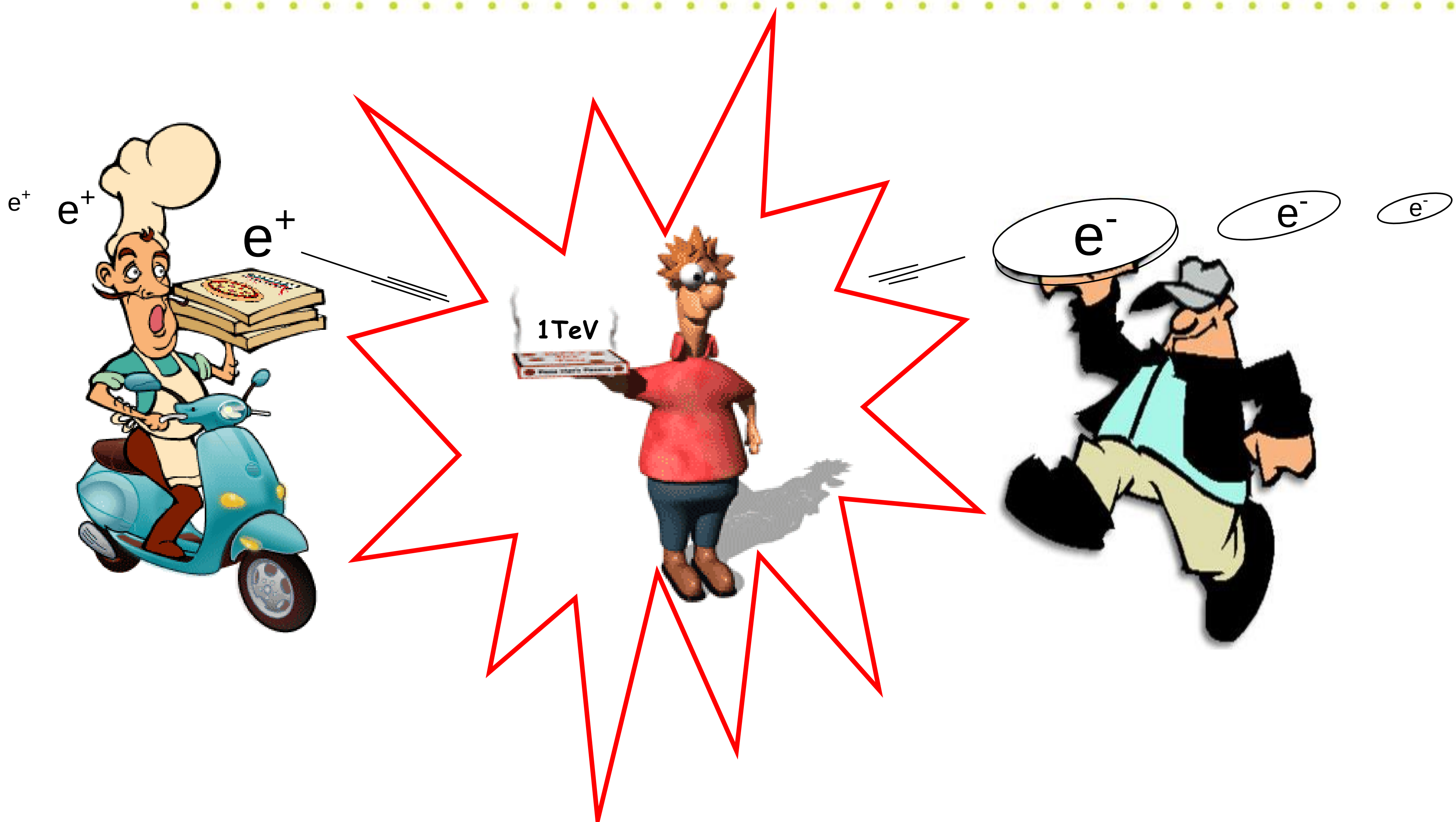

QF1
QFEX2A and
QDEX1B
QDEX1A
QD0
Tapered
Beampipe




QD0
QDEX1A
QDEX1B
QFEX2A


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

Beam Delivered...



Beam-beam effects

End of the PART 1

In the next lecture :

- We will carry on, starting from discussion of beam-beam effects...

- Many thanks to colleagues whose slides, results or photos were used in this lecture, namely Tom Markiewicz, Nikolai Mokhov, Daniel Schulte, Mauro Pivi, Nobu Toge, Brett Parker, Nick Walker, Timergali Khabibouline, Kwok Ko, Cherrill Spencer, Lew Keller, Sayed Rokni, Alberto Fasso, Joe Frisch, Yuri Nosochkov, Mark Woodley, Takashi Maruyama, Eric Torrence, Karsten Busser, Graeme Burt, Glen White, Phil Burrows, Tochiaki Tauchi, Junji Urakawa, Nobuhiro Terunuma and many other

Thanks to you for attention!