Beam Delivery System

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SLAC

"Lunch-time accelerator lecture"

Snowmass, CO, August 2005

picture taken in 2001

thanks

- This lecture is heavily based on the one given at USPAS school in 2003
- Many slides are borrowed from, Tom Markiewicz, Nikolai Mokhov, Brett Parker, Nick Walker and many other colleagues. Thanks!

Linear Collider – two main challenges

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

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

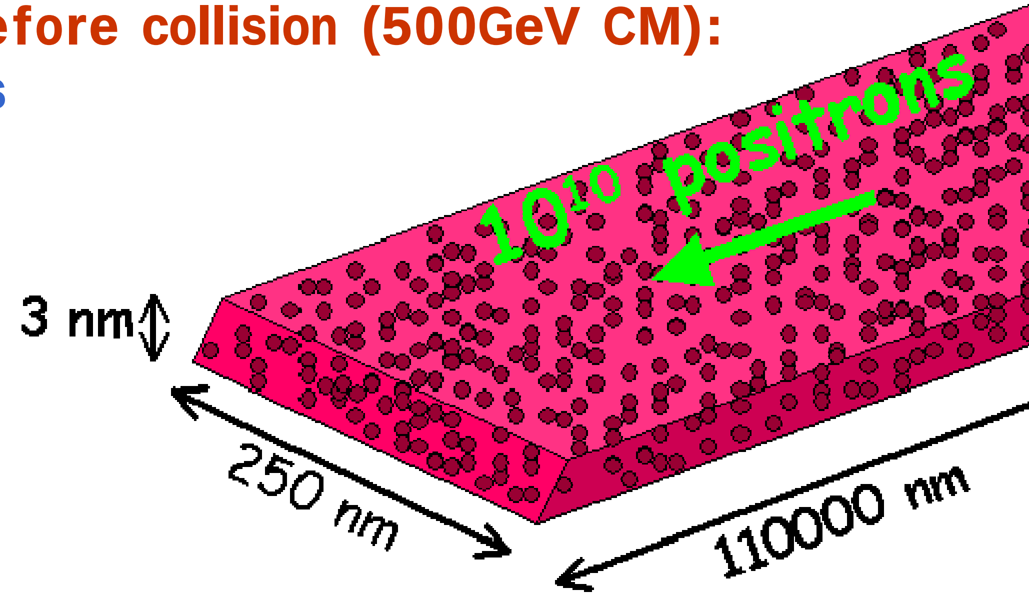
The Luminosity Challenge

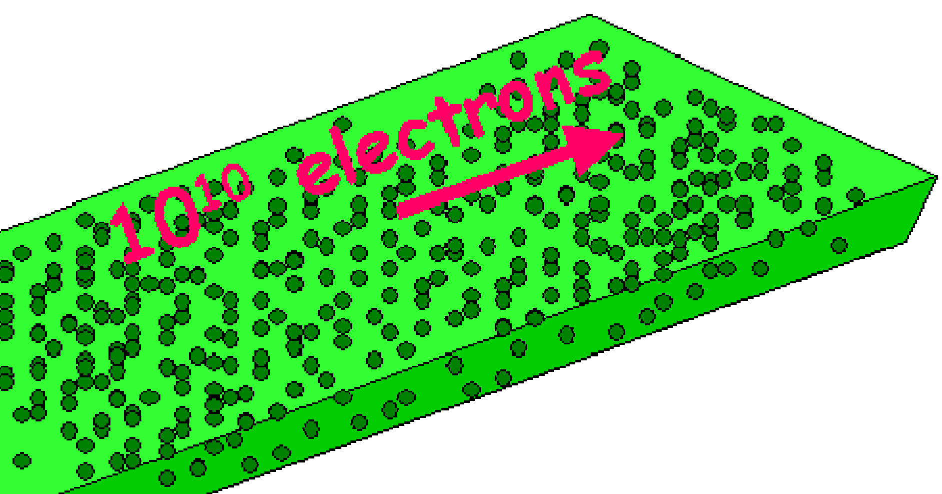
- Must jump by a Factor of 10000 in Luminosity !!! (from what is achieved in the only so far linear collider SLC)
- Many improvements, to ensure this : generation of smaller emittances, their better preservation, …
- Including better focusing, dealing with beam-beam, safely removing beams after collision 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., NLC beam sizes just before collision (500GeV CM):
  250 * 3 * 110000 nanometers
  (x y z)

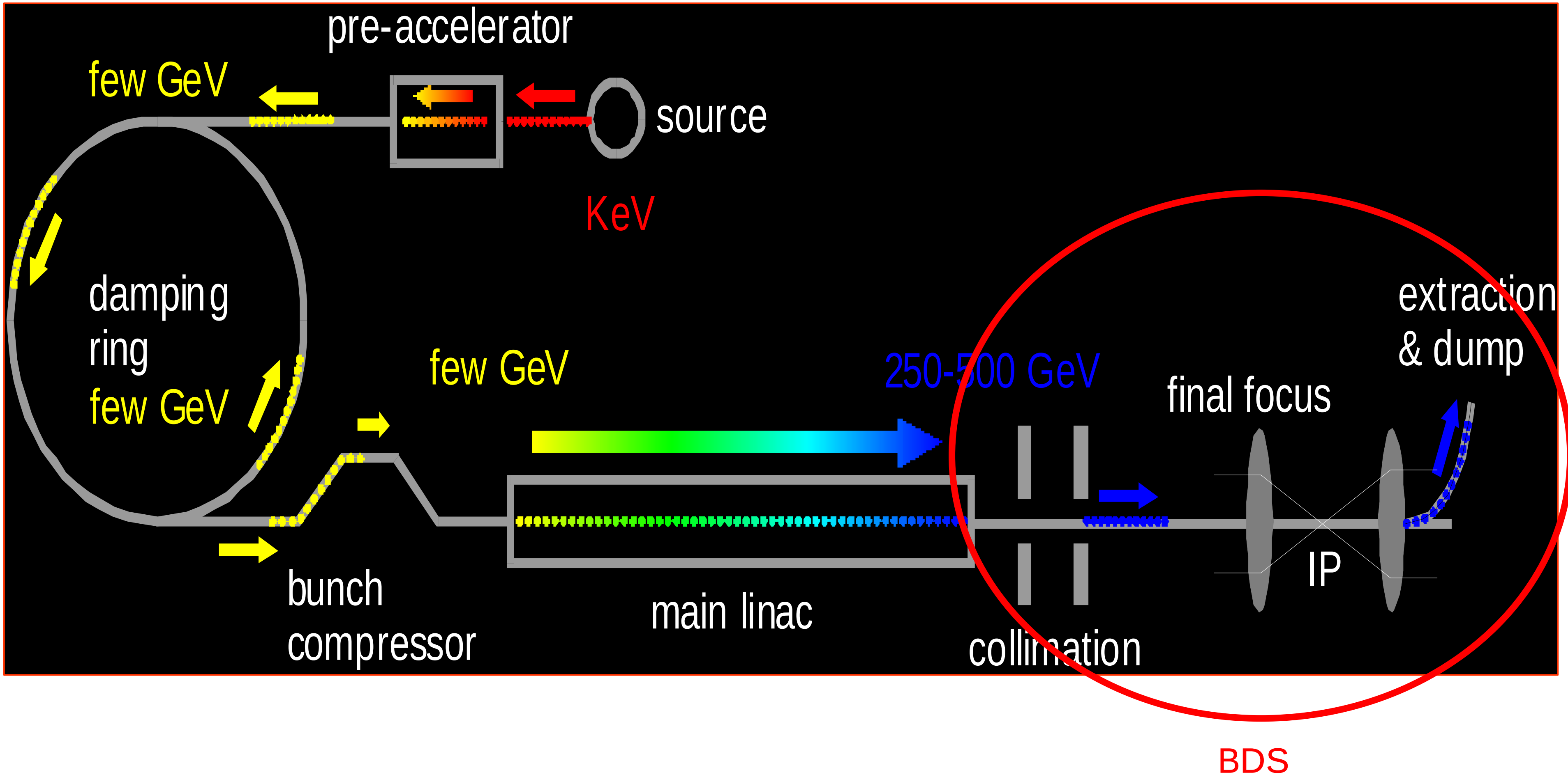
Vertical size is smallest





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

BDS: from end of linac to IP, to dumps



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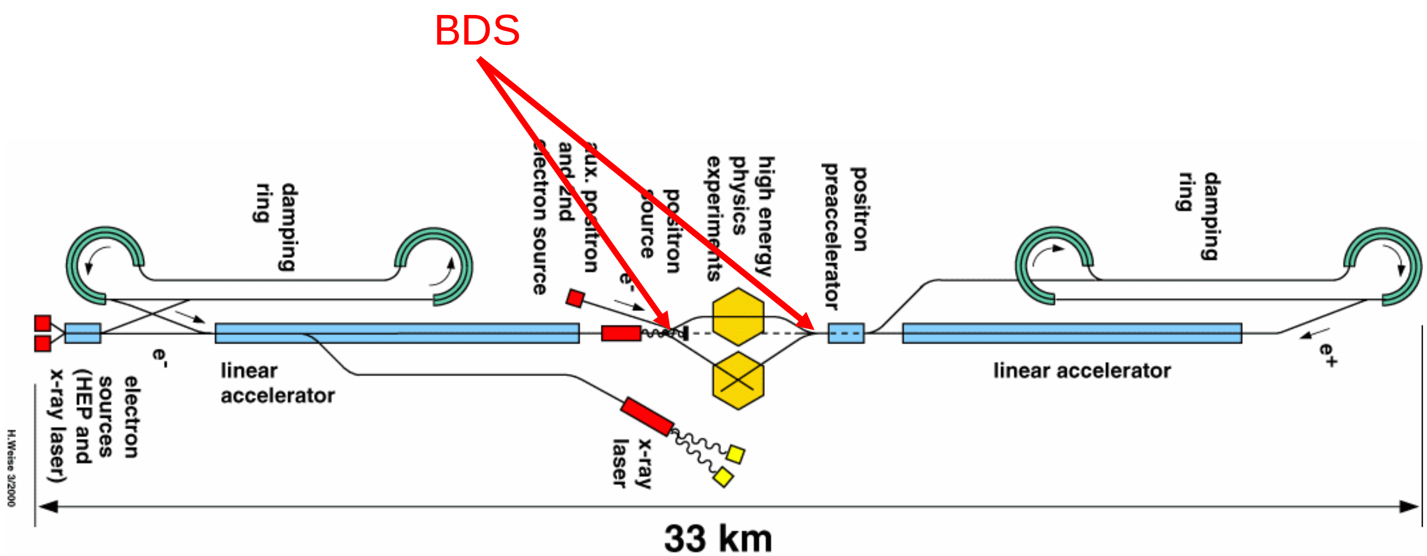
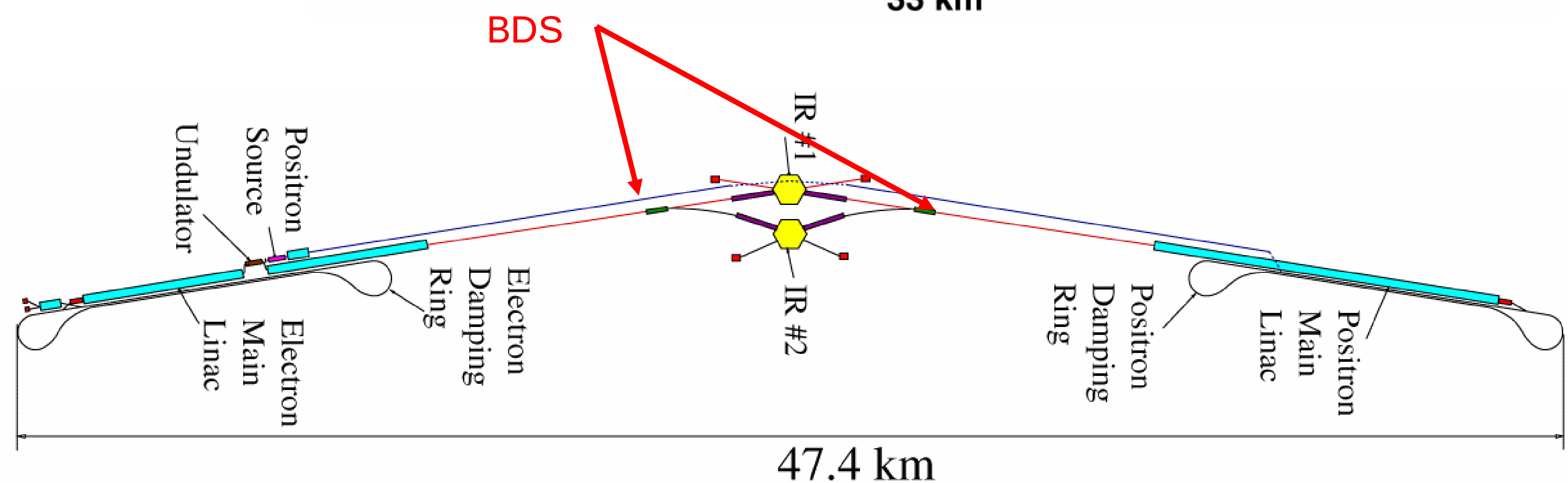




Beam Delivery System challenges

- Focus the beam to size of about 500 * 5 nm at IP
- Provide acceptable detector backgrounds
  - collimate beam halo
- Monitor the luminosity spectrum and polarization
  - diagnostics both upstream and downstream of IP is desired
- Measure incoming beam properties to allow tuning of the machine
- Keep the beams in collision & maintain small beam sizes
  - fast intra-train and slow inter-train feedback
- Protect detector and beamline components against errant beams
- Extract disrupted beams and safely transport to beam dumps
- Optimize IR for all considered detector concepts
- Minimize cost & ensure Conventional Facilities constructability

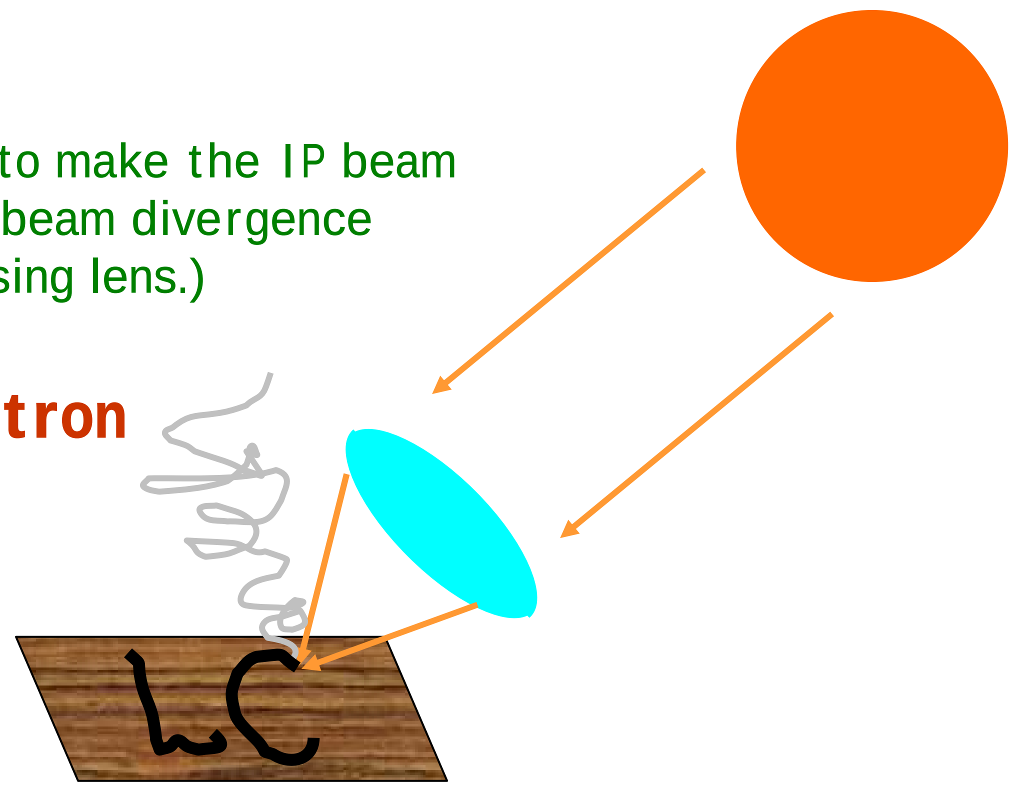
How to focus the beam to a smallest spot?

- Did 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.)

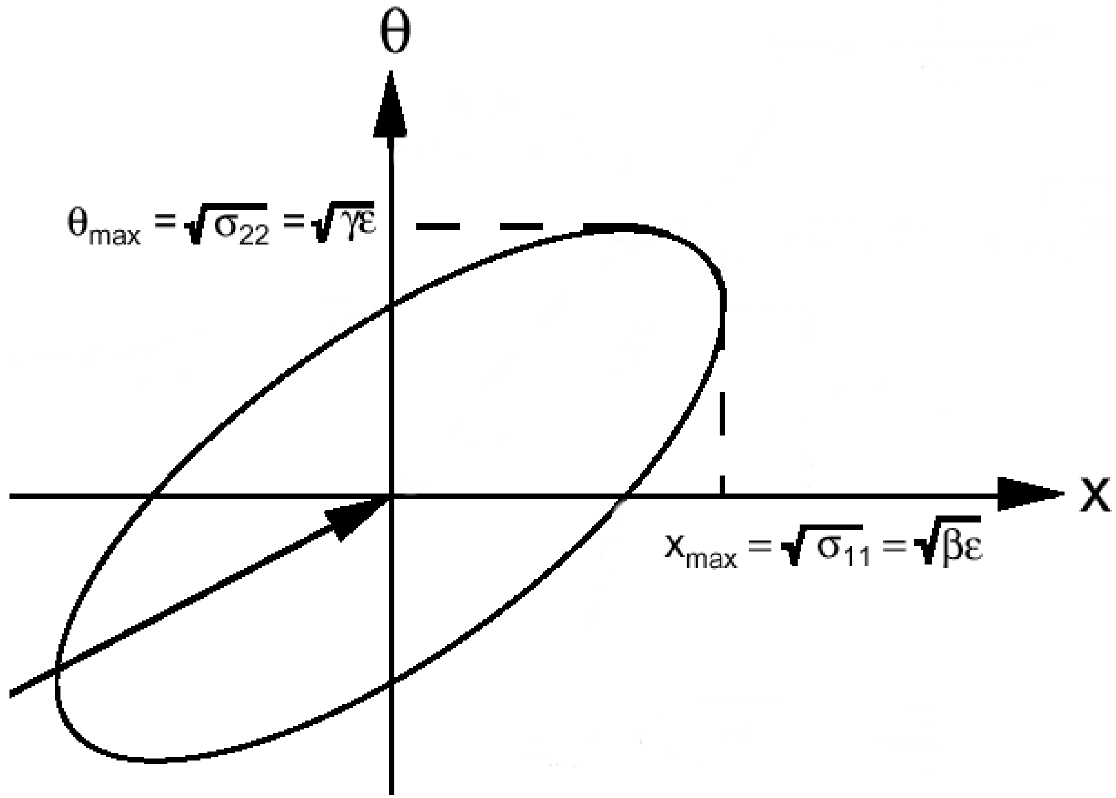
- It is very similar for **electron** or **positron** beams

- But one have to use **magnets**



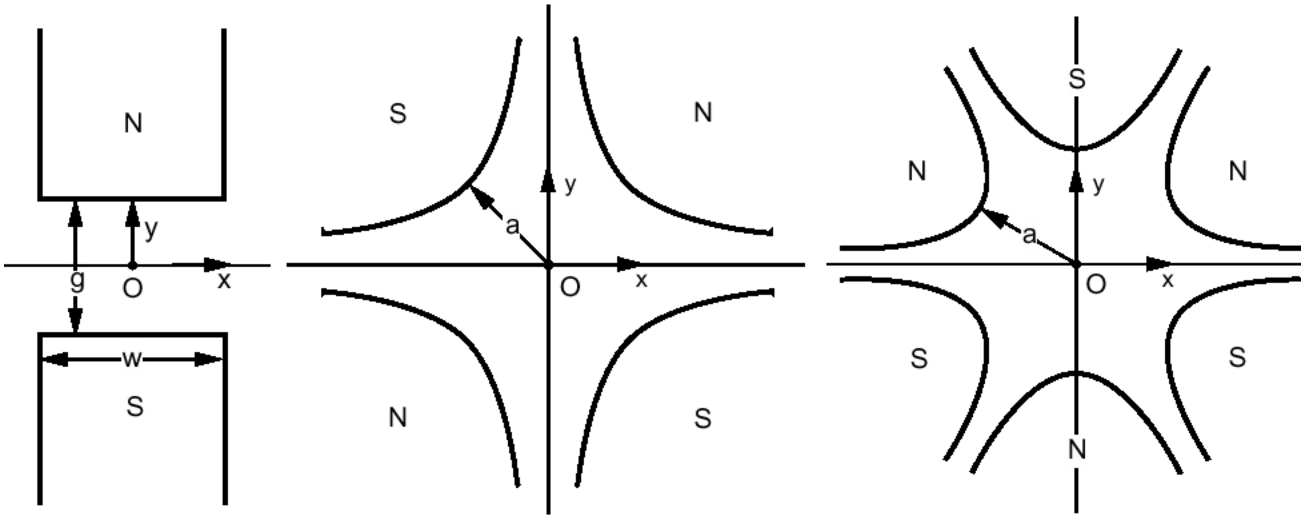
Recall couple of definitions

- 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”

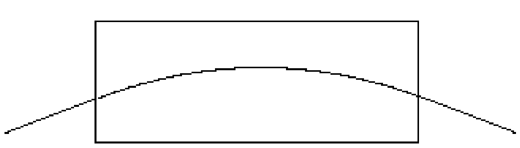
What we use to manipulate with the beam



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

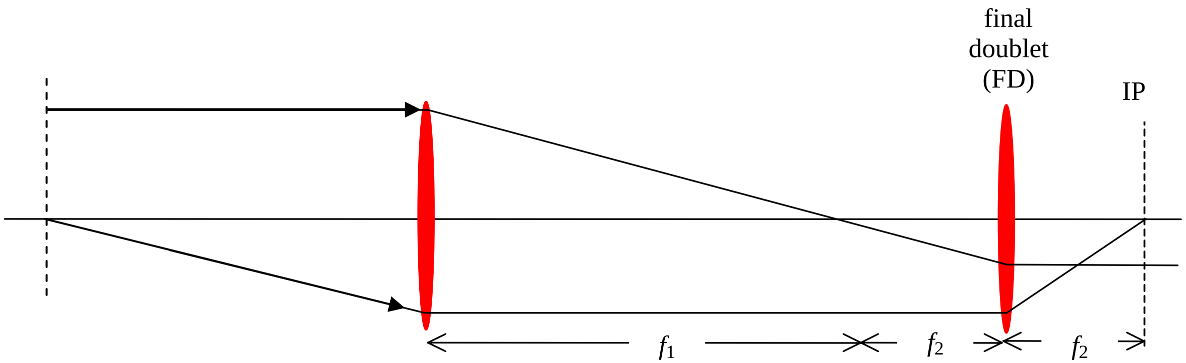
Optics building block: telescope

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 $\quad$ f_2 $(=L^*)$

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

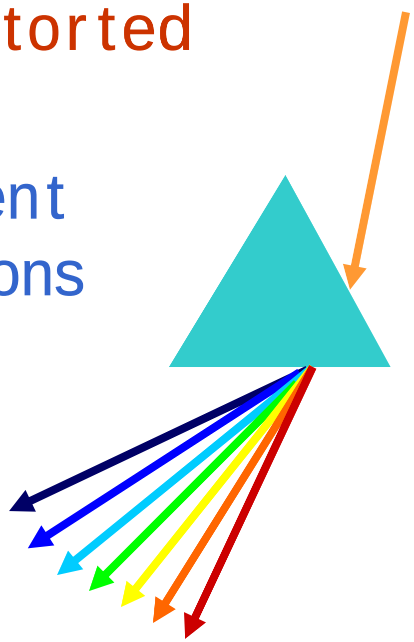
Matrix formalism for beam transport:

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

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

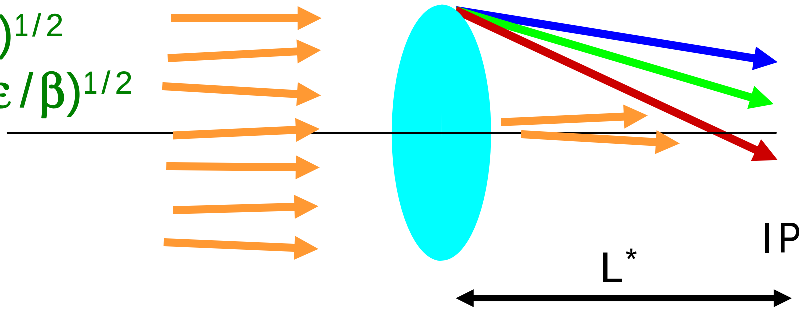
Why nonlinear elements

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

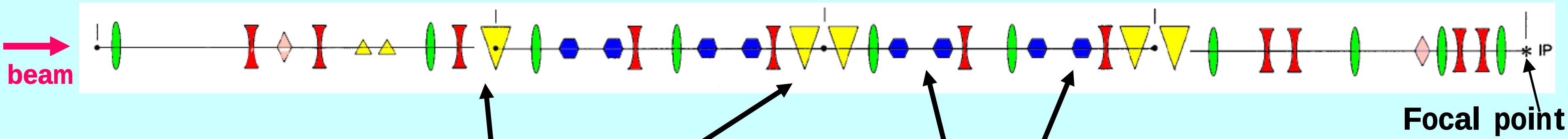
- **The last (final) lens need to be the strongest**
  - **(two lenses for both x and y => “Final Doublet” or FD)**
- **FD determines chromaticity of FF**
- **Chromatic dilution of the beam size is $\Delta\sigma/\sigma \sim \sigma_E\ L^*/\beta^*$**

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

- **For typical parameters, $\Delta\sigma/\sigma \sim 300$ 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

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

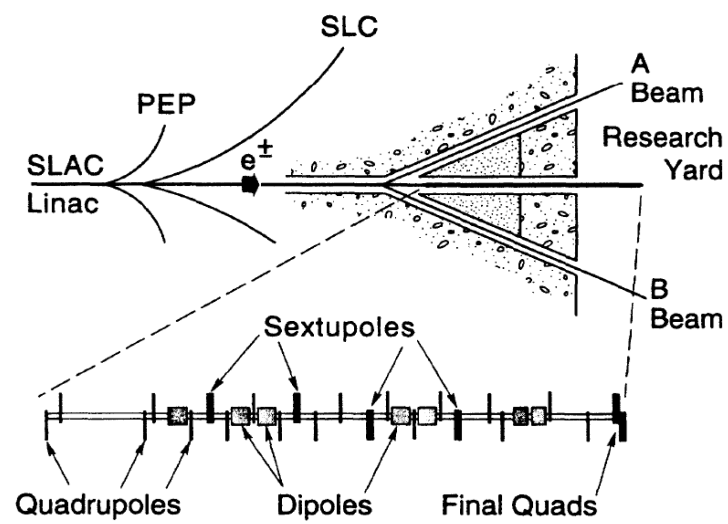
$y' \;\Rightarrow\; -S\,2(x+\delta)y \;\Rightarrow\; -2S\,y\,\delta + \ldots$

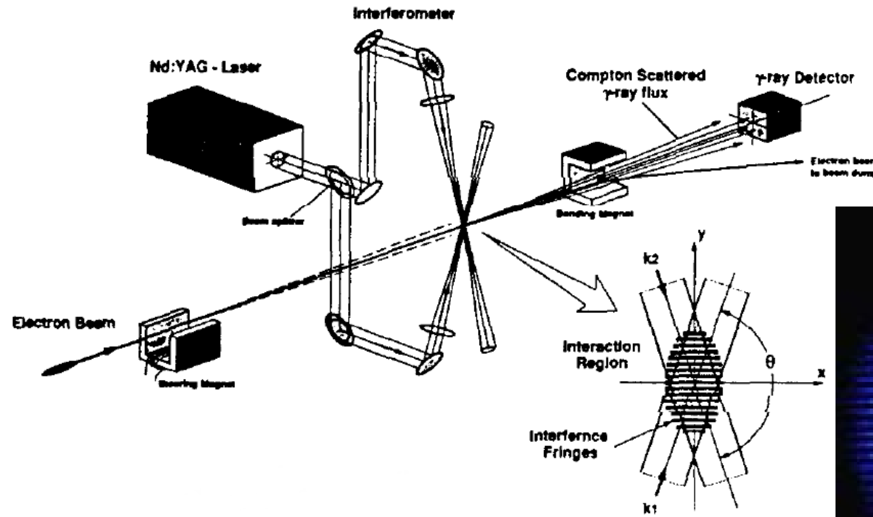
that can be used to arrange chromatic correction

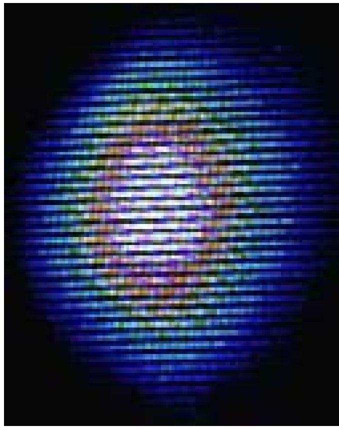
Terms x^2 are geometric aberrations and need to be compensated also

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

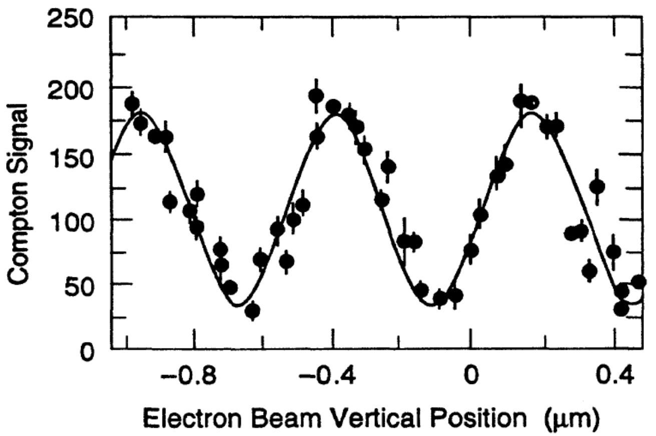
Final Focus Test Beam



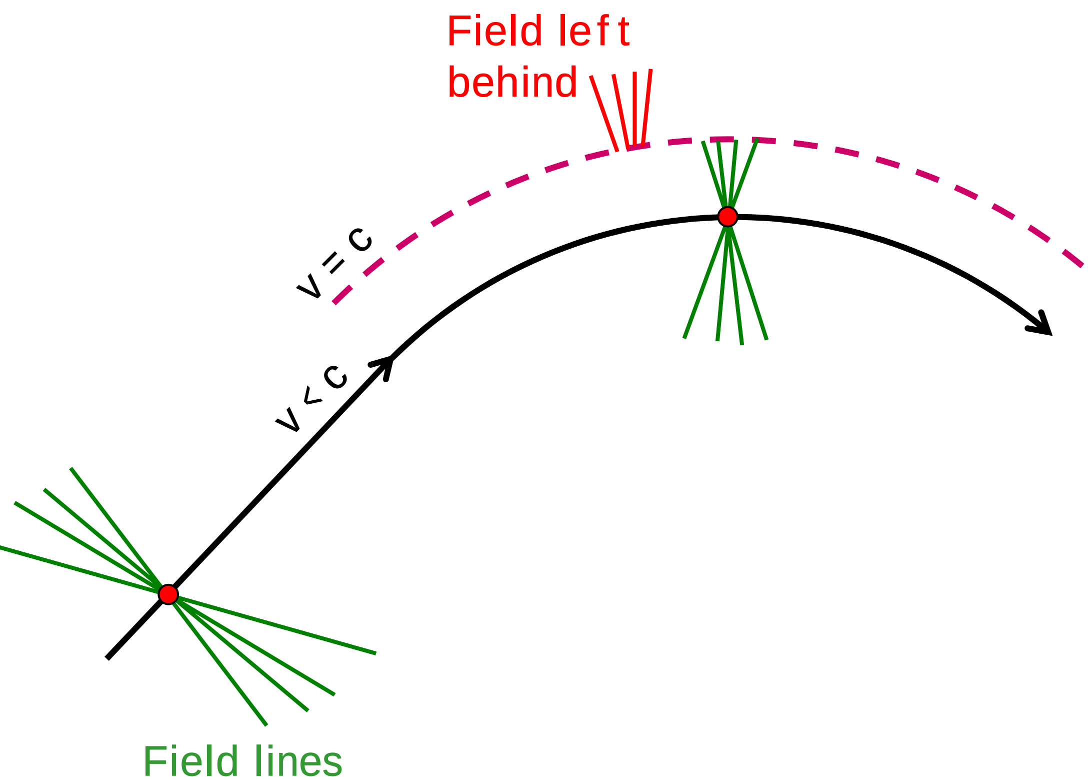




Achieved ~70nm vertical beam size



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

Beam-beam (D_y, δ_E , Υ) affect choice of IP parameters and are important for FF design also

$$\mathrm{Lumi} \sim \frac{N^2}{\sigma_x \sigma_y}$$

- Luminosity per bunch crossing

$$D_y \sim \frac{N\,\sigma_z}{\gamma\,\sigma_x \sigma_y}$$

- “Disruption” – characterize focusing strength of the field of the bunch ($D_y \sim \sigma_z / f_{beam}$)

$$\delta_E \sim \frac{N^2 \gamma}{\sigma_x^2\,\sigma_z}$$

- Energy loss during beam-beam collision due to synchrotron radiation

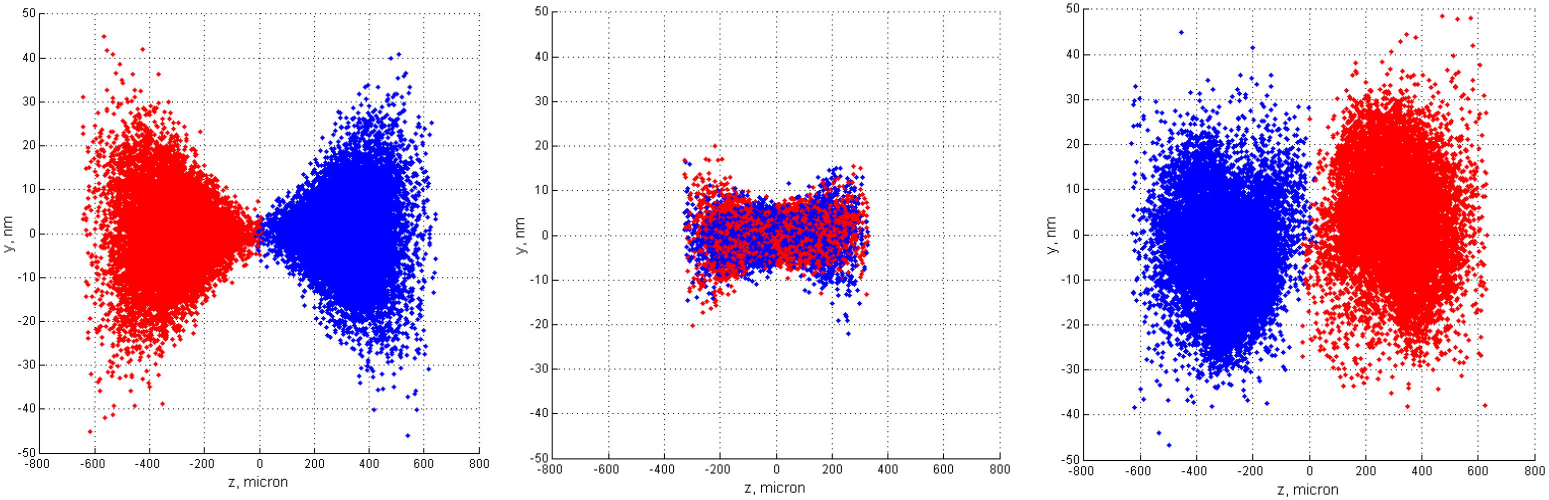
$$\Upsilon \sim \frac{N\,\gamma}{\sigma_x \sigma_z}$$

- Ratio of critical photon energy to beam energy (classic or quantum regime)

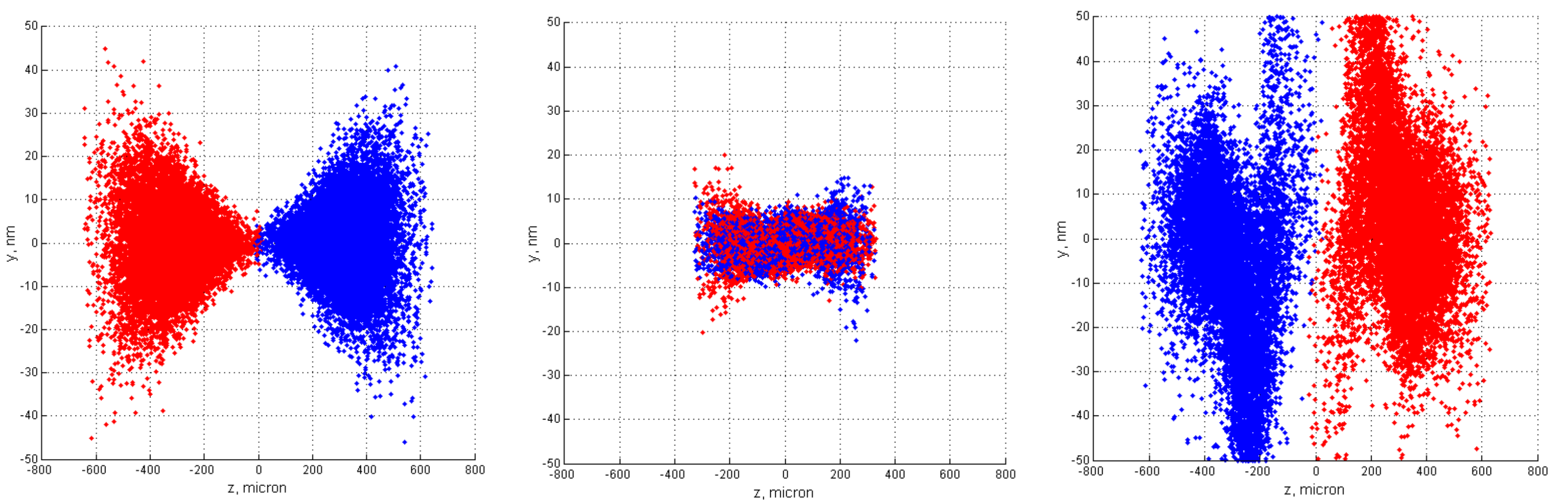
Beam-beam effects

H_D and instability

$$D_y = \frac{2r_e}{\gamma}\frac{Nc_z}{\sigma_x\sigma_y}$$



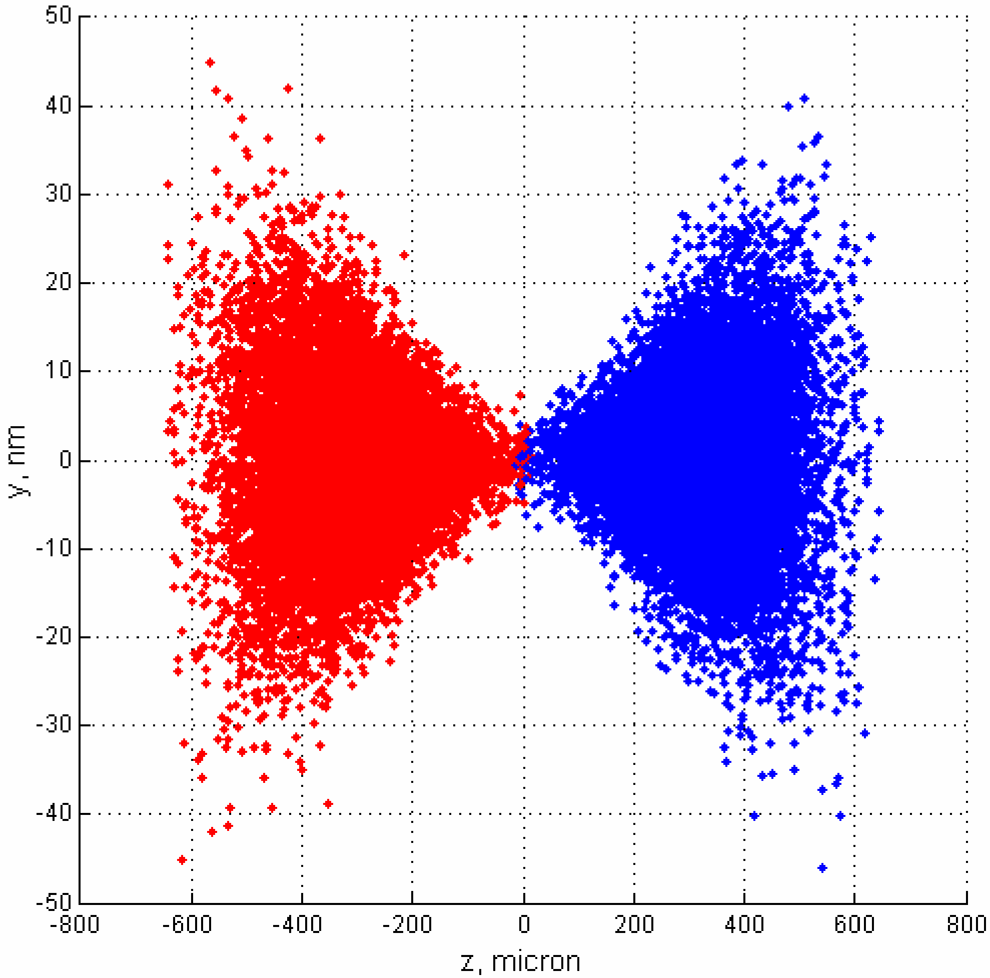
D_y~12



Nx2

D_y~24

Beam-beam effects
H_D and instability



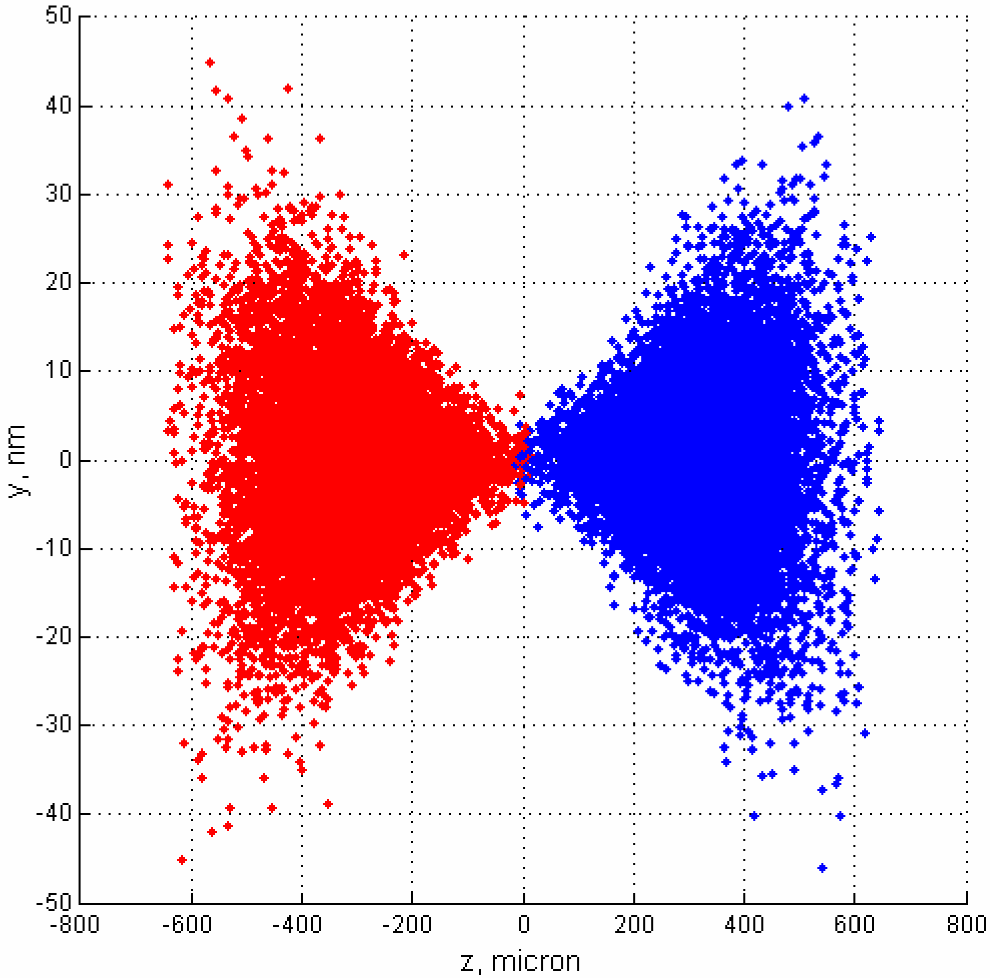
D_y~12

Luminosity enhancement H_D ~ 1.4

Not much of an instability

Beam-beam effects

H_D and instability



Nx2

D_y~24

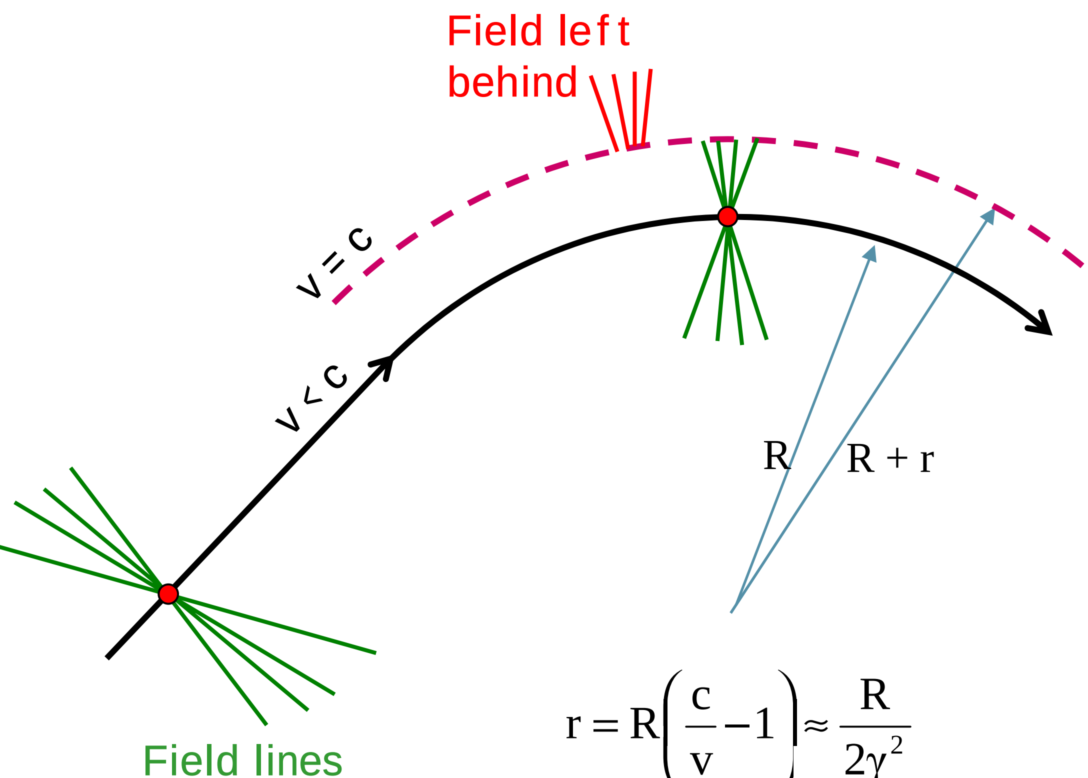
Beam-beam instability is clearly pronounced

Luminosity enhancement is compromised by higher sensitivity to initial offsets

Factor driving BDS design

- Chromaticity
- Beam-beam effects
- Synchrotron radiation
  - let's consider it in more details

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

Energy loss per unit length:

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

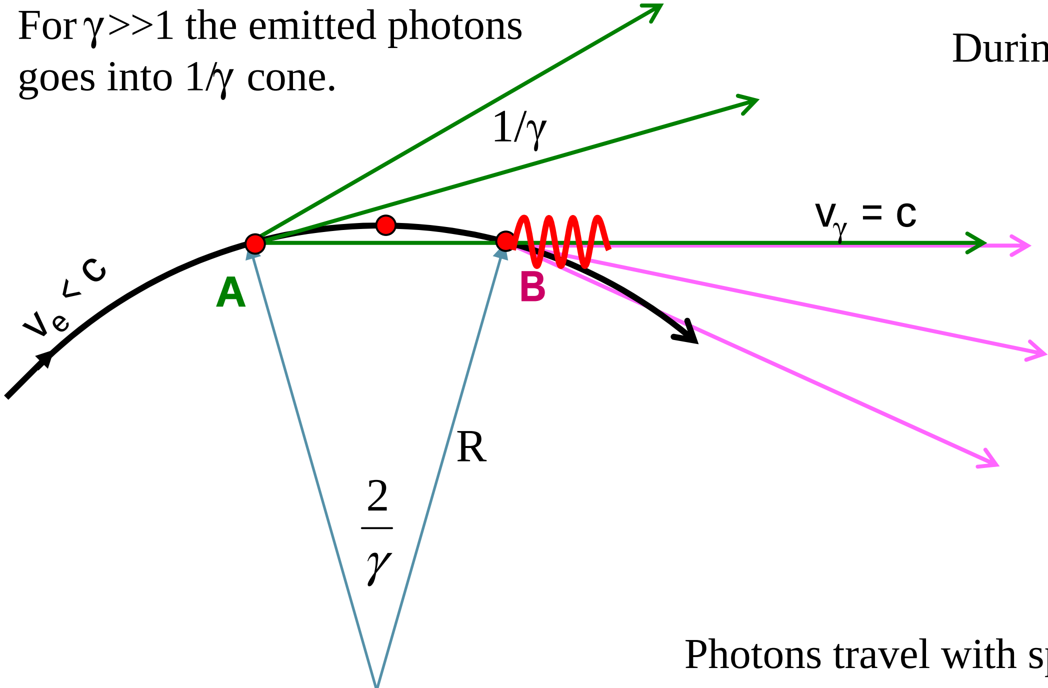
Substitute $r \approx \dfrac{R}{2\gamma^2}$ and get an estimate:

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

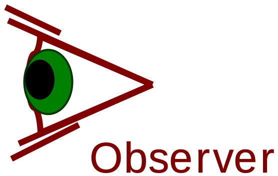
Compare with exact formula: $\dfrac{dW}{dS} = \dfrac{2}{3}\dfrac{e^2\gamma^4}{R^2}$

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

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

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 : $N \approx \alpha\gamma\theta$)

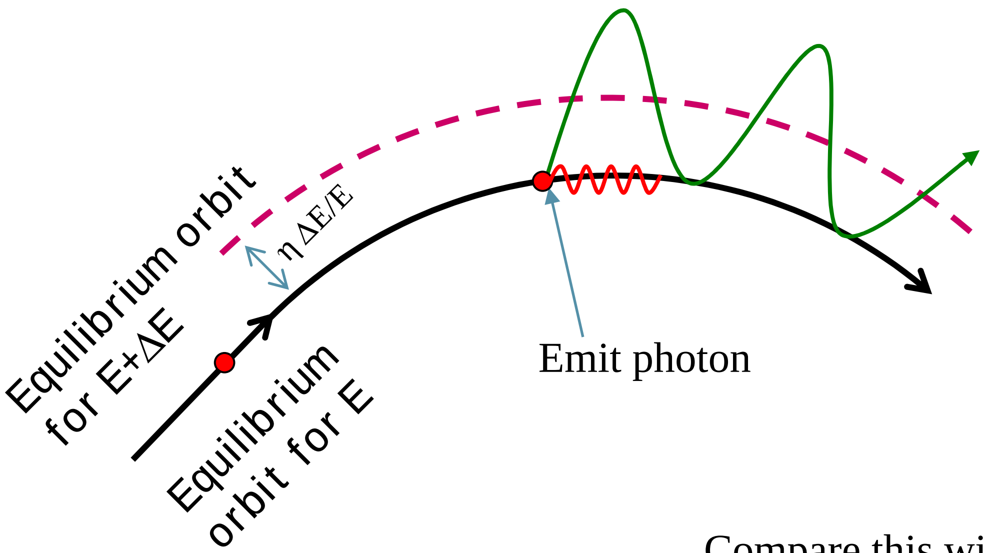
The energy spread $\Delta E/E$ will grow due to statistical fluctuations ($\sqrt{N}$) of the number of emitted photons :

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

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

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 $\quad \Delta x \approx \eta\, \Delta E/E$

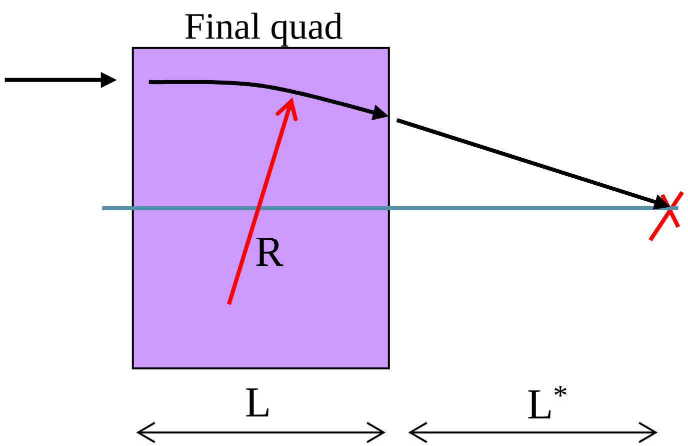
Compare this with betatron beam size: $\quad \sigma_x = (\varepsilon_x\, \beta_x)^{1/2}$

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

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):
$$\frac{d\varepsilon_x}{dS} = \underbrace{\boxed{\frac{\left(\eta^2 + \left(\beta_x \eta' - \beta_x' \eta/2\right)^2\right)}{\beta_x}}}_{=\mathcal{H}}\;\frac{55}{24\sqrt{3}}\;\frac{r_e\,\lambda_e\,\gamma^5}{R^3}$$

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:

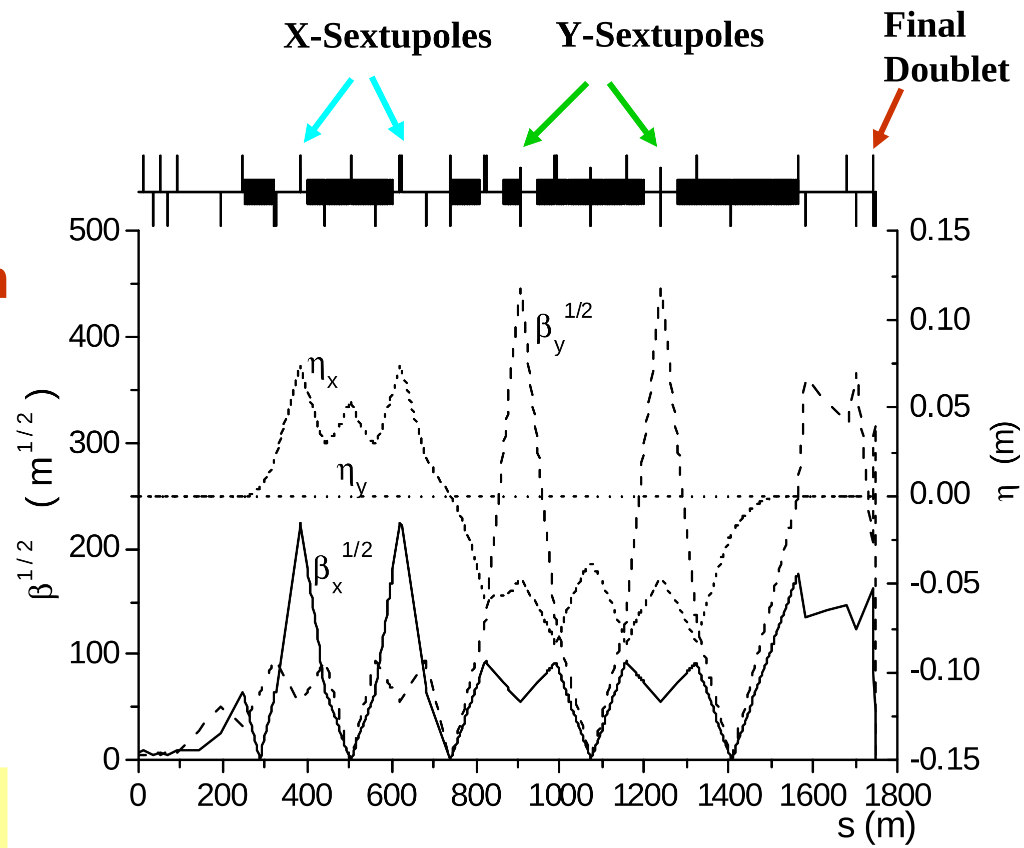
$$\beta_{optimal} \approx 1.29\,C_1^{2/7} \left(\frac{L^*}{L}\right)^{4/7} \left(r_e\,\lambda_e\right)^{2/7}\,\gamma\left(\gamma\varepsilon\right)^{3/7}$$

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).

Concepts and problems of traditional FF

- **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

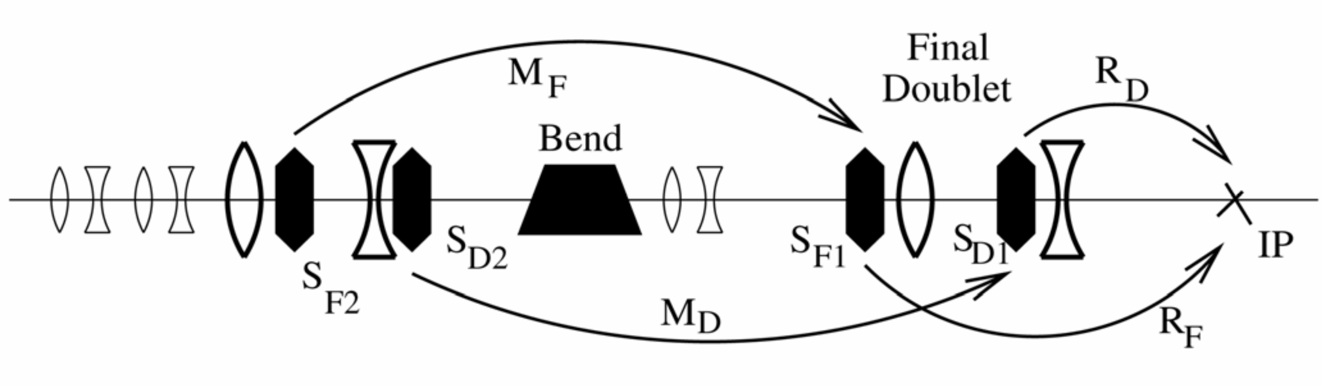


Traditional NLC FF

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**
  - **…**

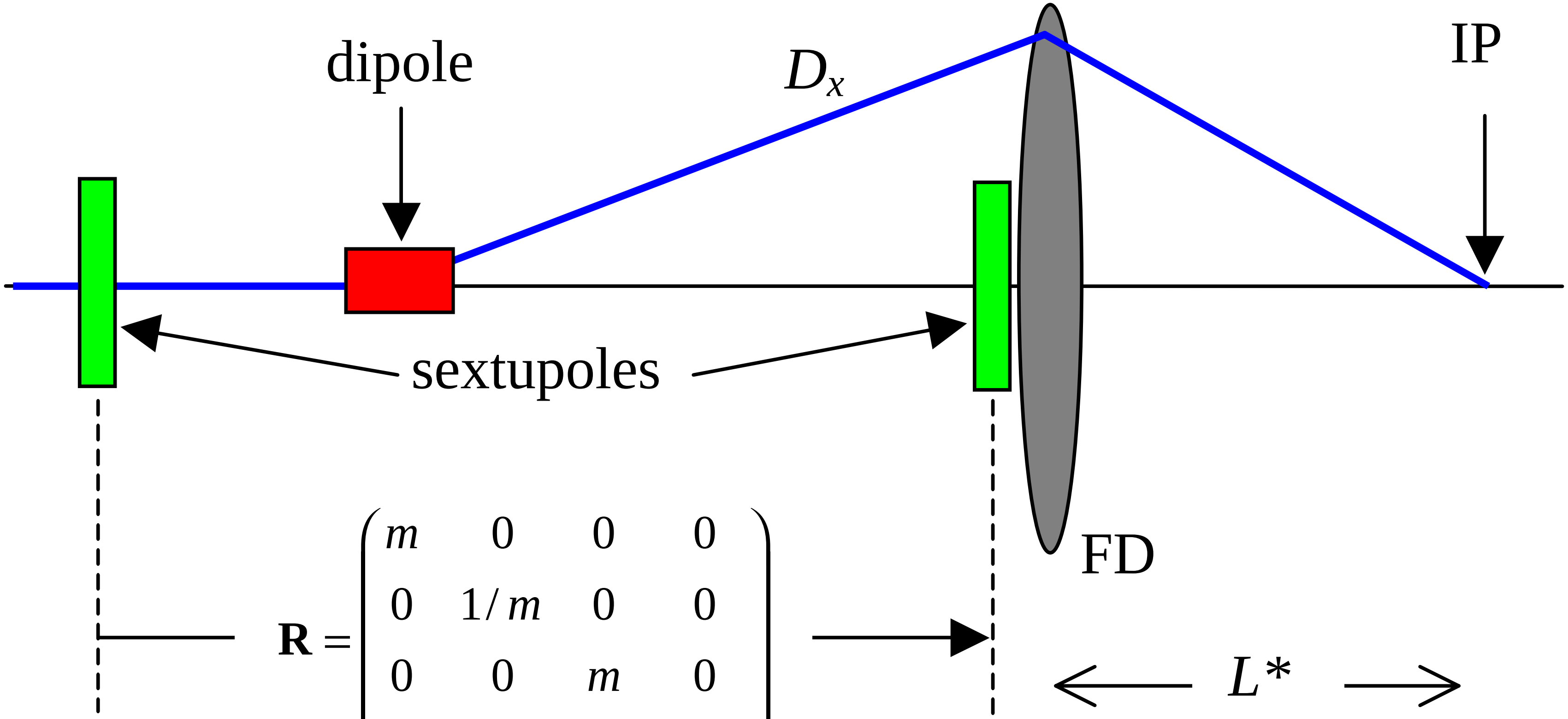
Principles of new FF



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

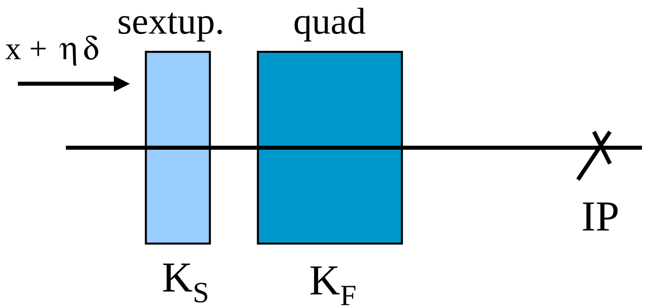
- Geometric aberrations of the FD sextupoles are cancelled by two more sextupoles placed in phase with them and upstream of the bend

Local chromatic correction



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

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

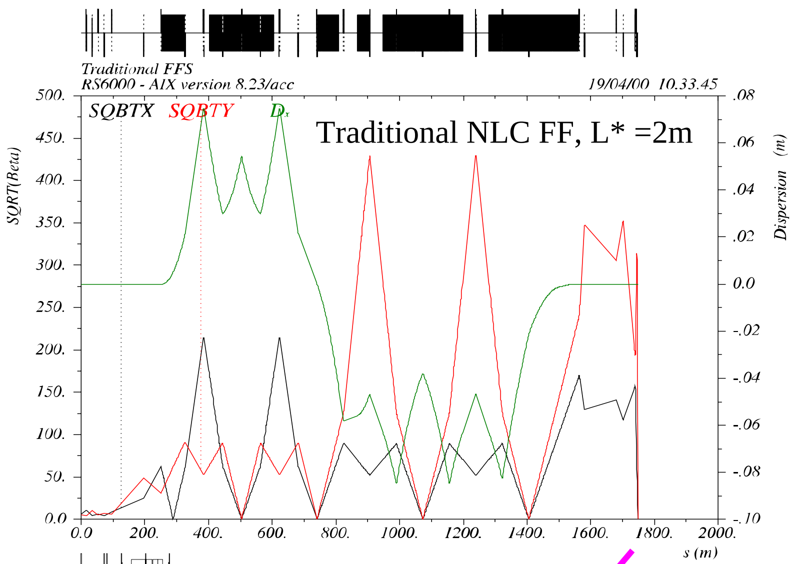
$$\Delta x' = \frac{K_F}{(1+\delta)}(x+\eta\delta) + \frac{K_{\beta\text{-match}}}{(1+\delta)}x \Rightarrow 2K_F(-\delta x - \frac{\eta\delta^2}{2})$$

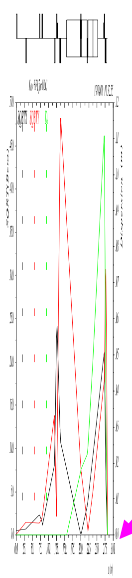
$$K_{\beta\text{-match}} = K_F \qquad K_S = \frac{2K_F}{\eta}$$

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

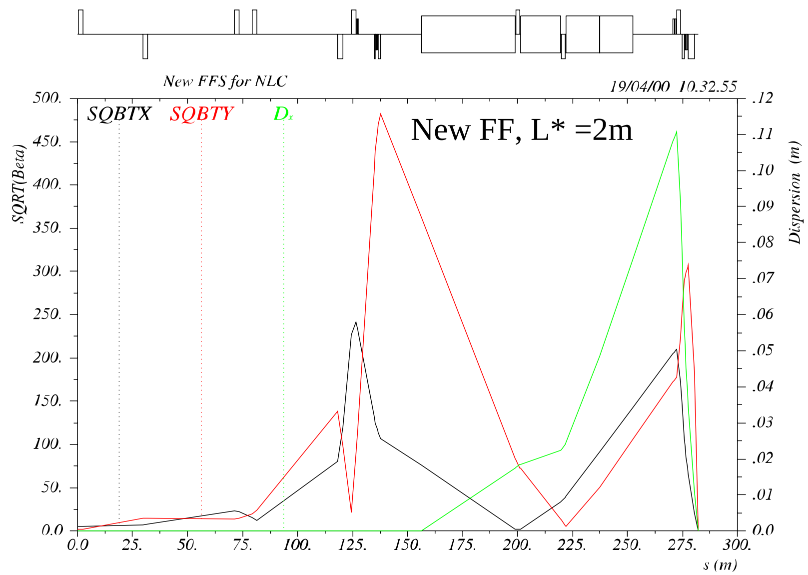
Solution:
The β-matching section produces as much X chromaticity as the FD, so the X sextupoles run twice stronger and cancel the **second order dispersion** as well.

Traditional and new FF





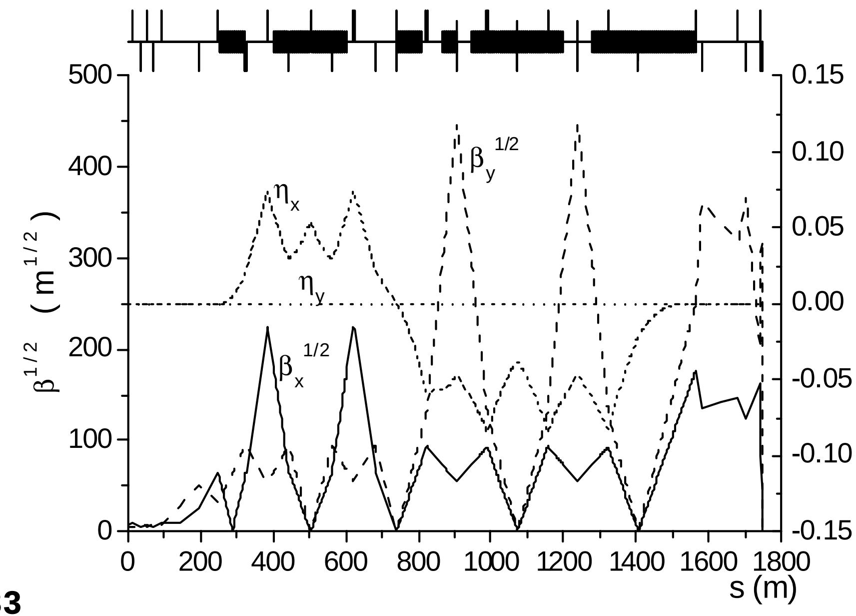
A new FF with the same performance as NLC FF can be ~300m long, i.e. 6 times shorter



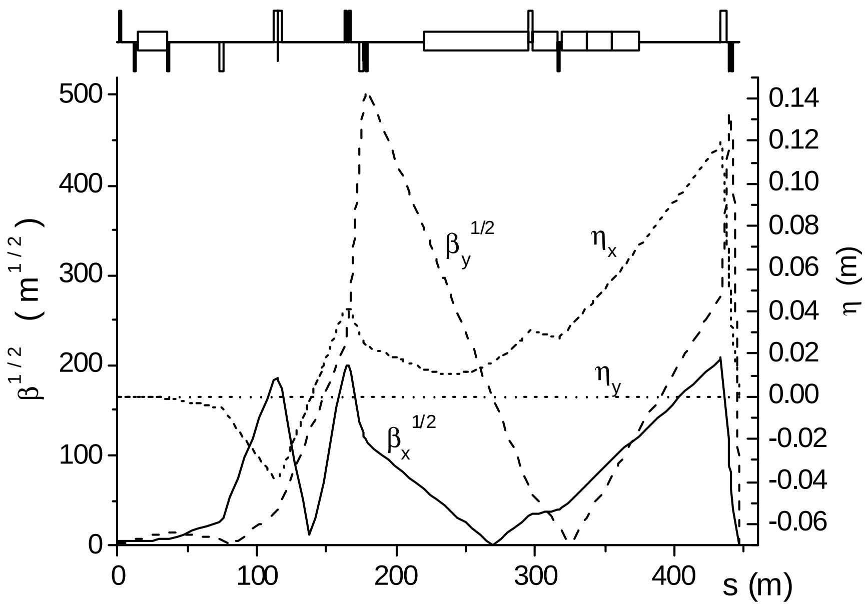
New Final Focus

- One third the length - many fewer components!
- Can operate with 2.5 TeV beams (for 3 ~ 5 TeV cms)
- 4.3 meter L* (twice 1999 design)

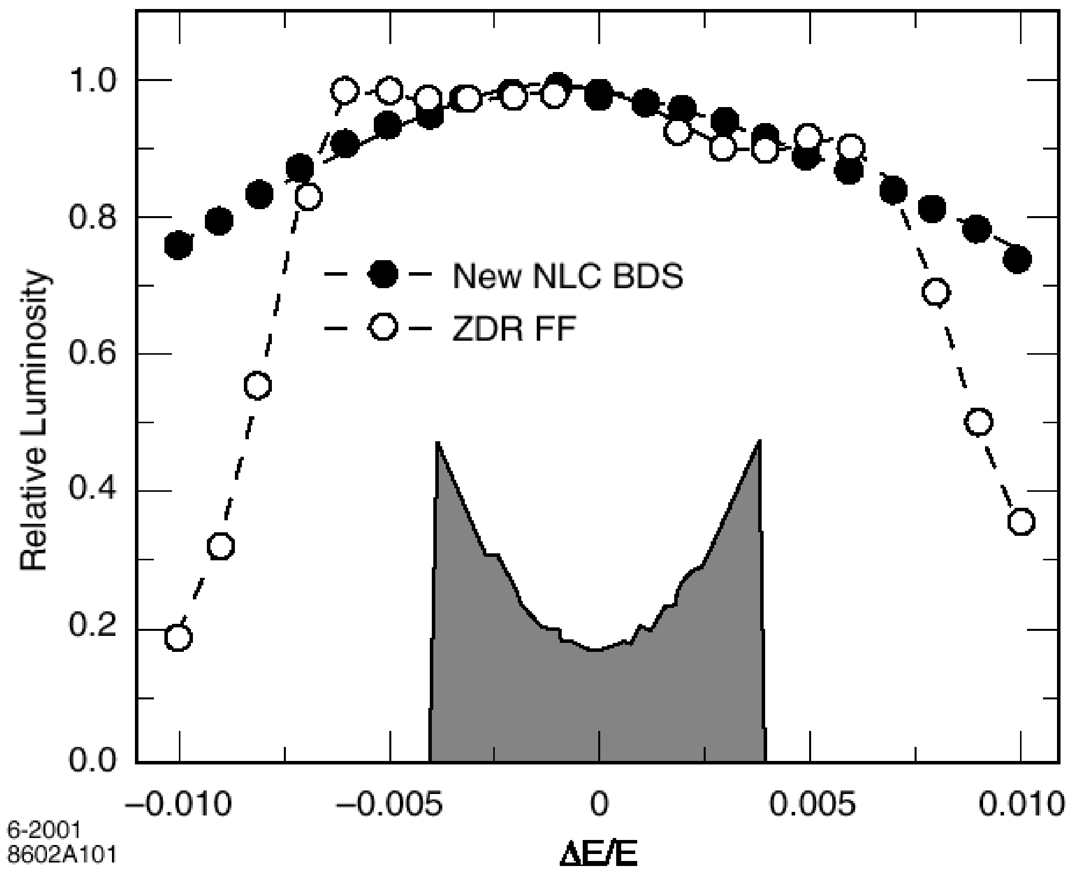
1999 Design



2000 Design



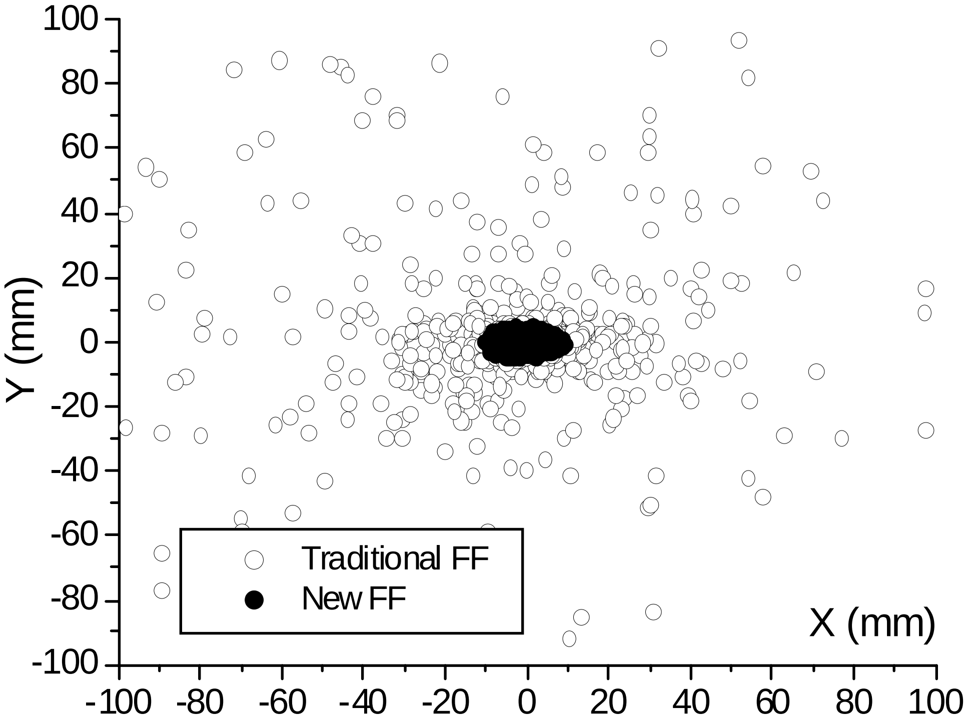
IP bandwidth

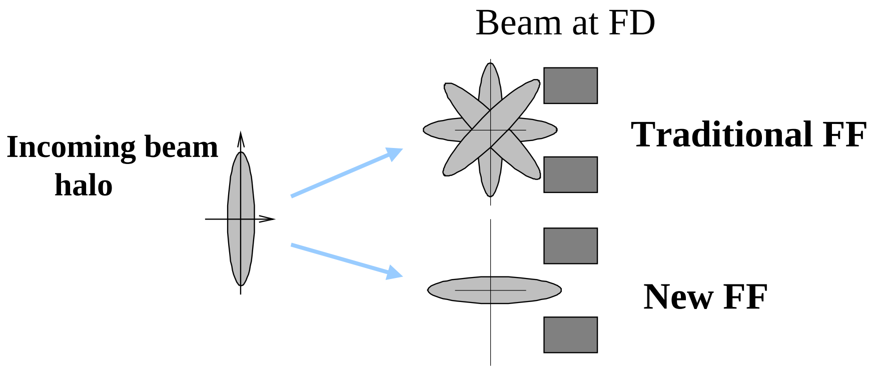


Bandwidth is much better for New FF

Aberrations for beam halo

- Traditional FF **generate beam tails** due to **aberrations** and it **does not preserve** betatron phase of halo particles
- New FF is virtually **aberration free** and it **does not mix** phases particles

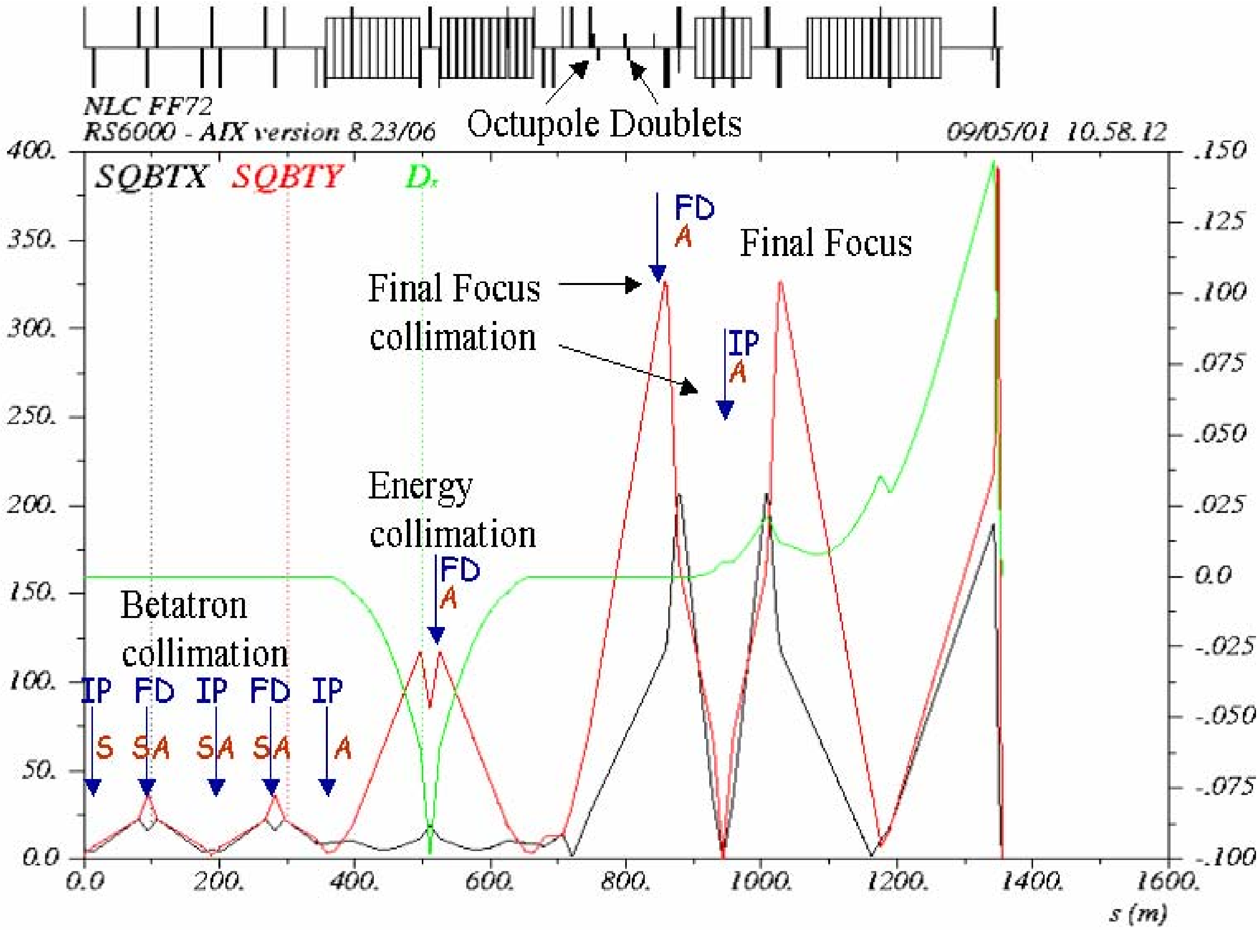




Halo beam at the FD entrance.
Incoming beam is ~ 100 times larger than nominal beam

Overview of a complete BDS

- **Compact system with local chromaticity corrections**
- **Collimation system has been built in the Final Focus system**
- **Two octupole doublets are placed in NLC FF for active folding of beam tails**

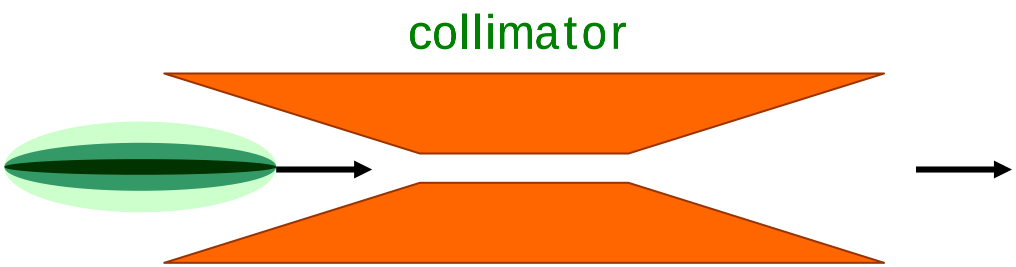


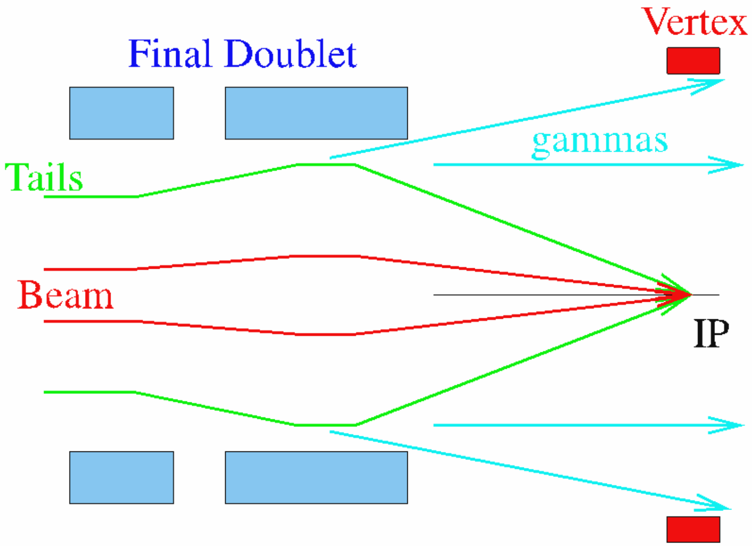
- Beam Delivery System Optics

on the example of NLC BDS

Why collimation?

- Would like to scrape out the beam halo well before the IP, to prevent halo particle hitting FD or detector and blinding the detector

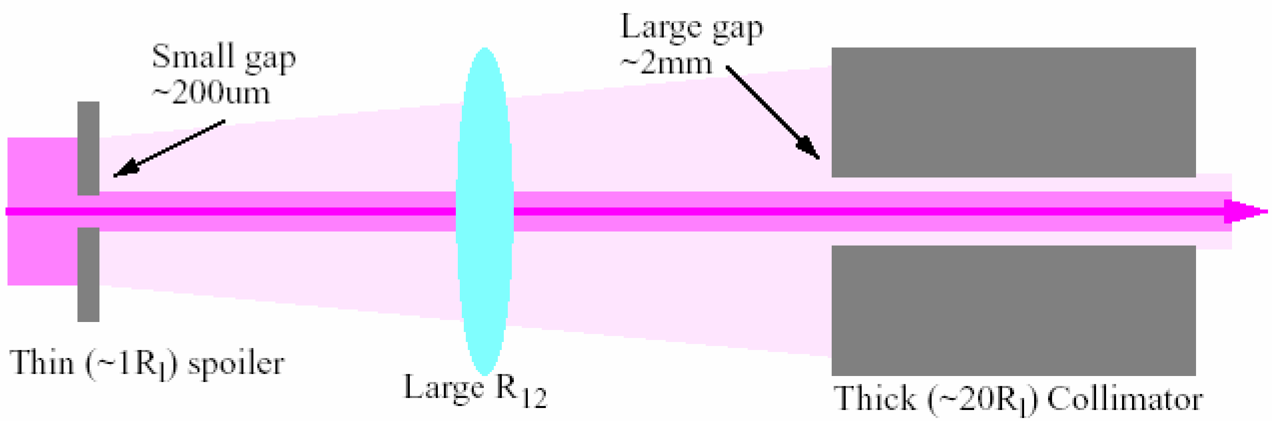




- Issues with collimators:
  - Survivability – may consider rotating renewable collimators
  - Wakes (effect on the beam core) – small gaps (sub mm) may be an issue

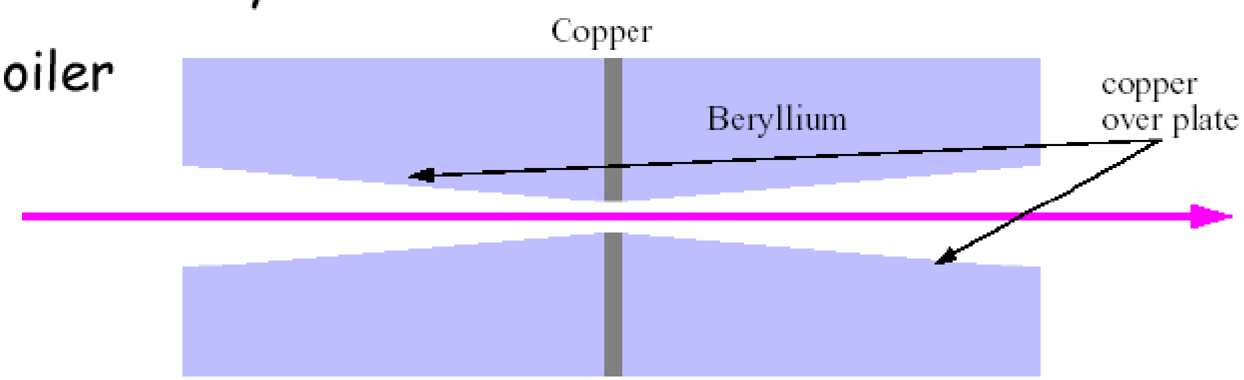
Consumable / renewable spoilers

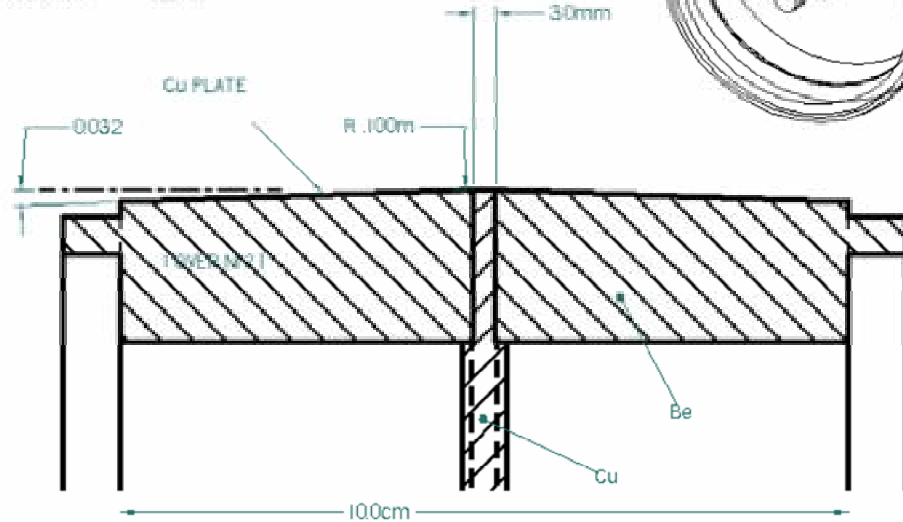
Spoiler / Absorber Scheme

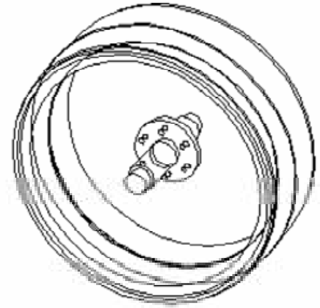


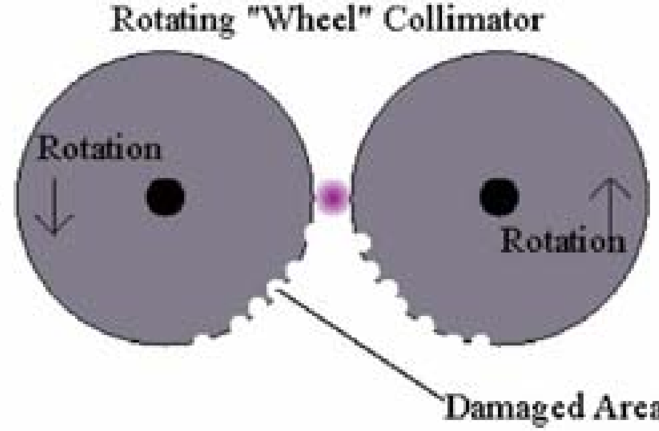
Tapered low resistivity surface for wakefields

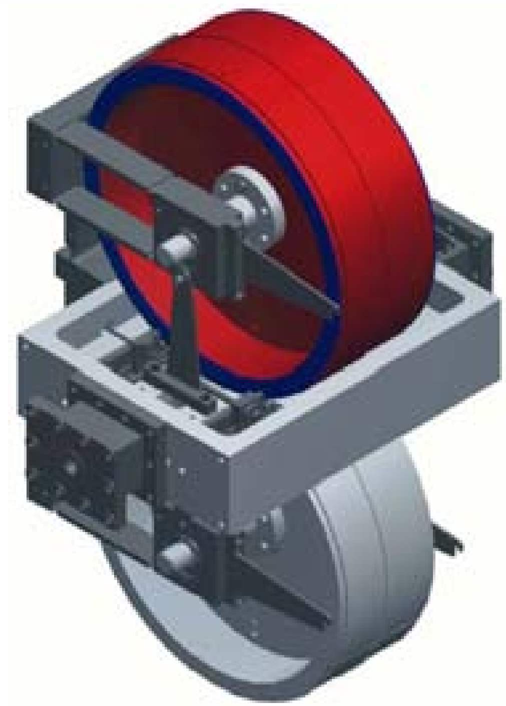
Thin hi-Z spoiler





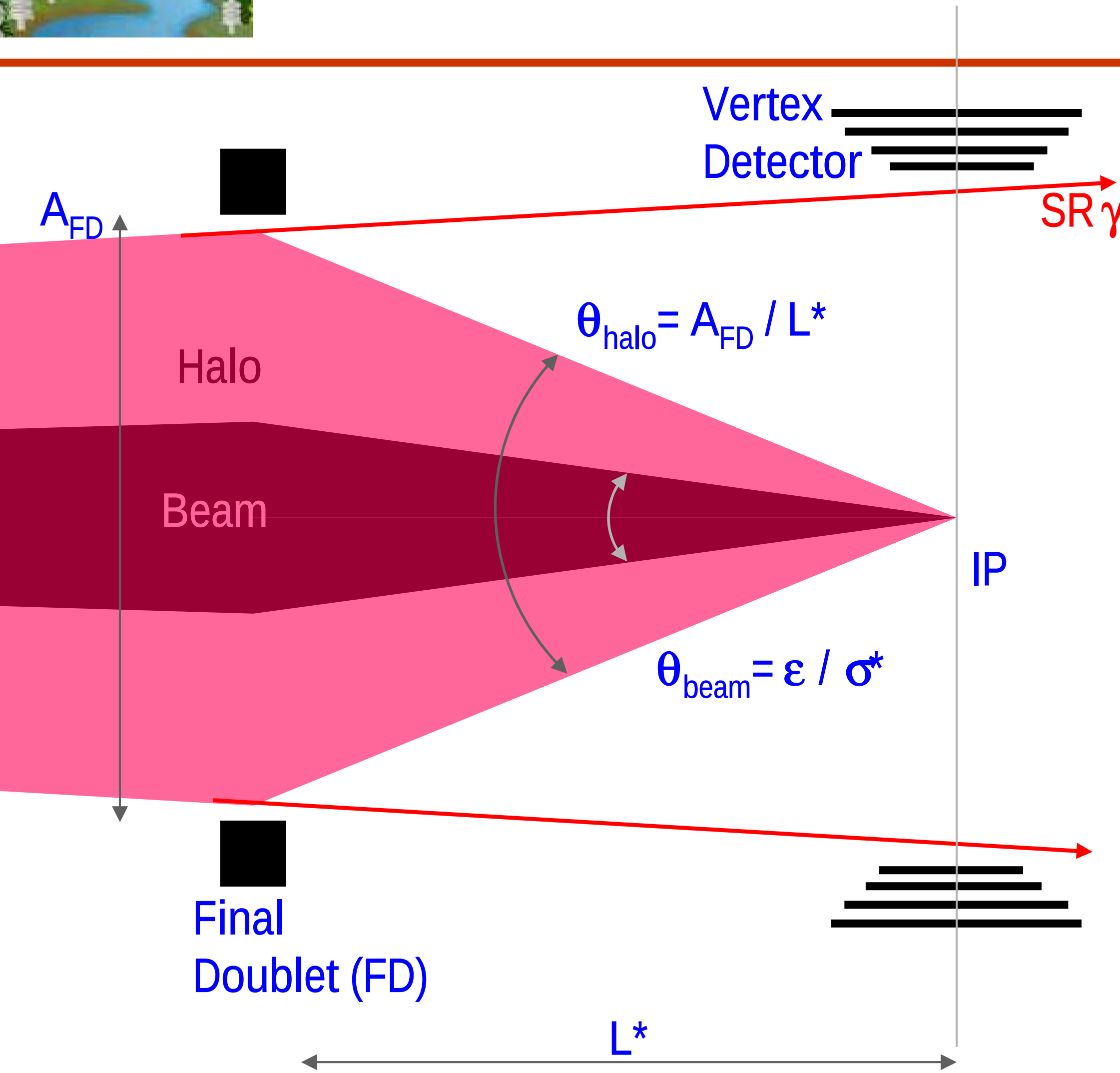






Passive survival or consumable collimators

Beam halo & background



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 is fixed,
halo convergence ~$1/L^*$
=> $\theta_{halo}/\theta_{beam}$ (collimation depth) becomes tighter with larger L^*

Tighter collimation => MPS issues, collimation wake-fields, higher muon flux from collimators, etc.

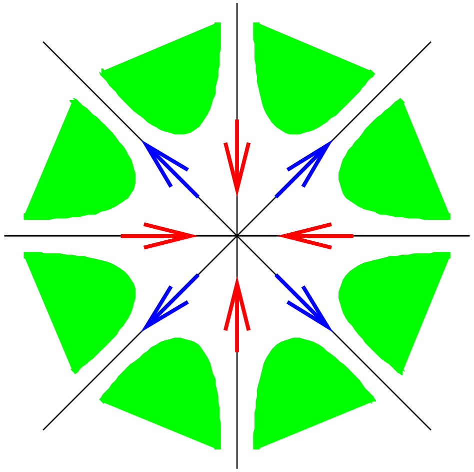
Nonlinear handling of beam tails in NLC BDS

- **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 NLC 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:**

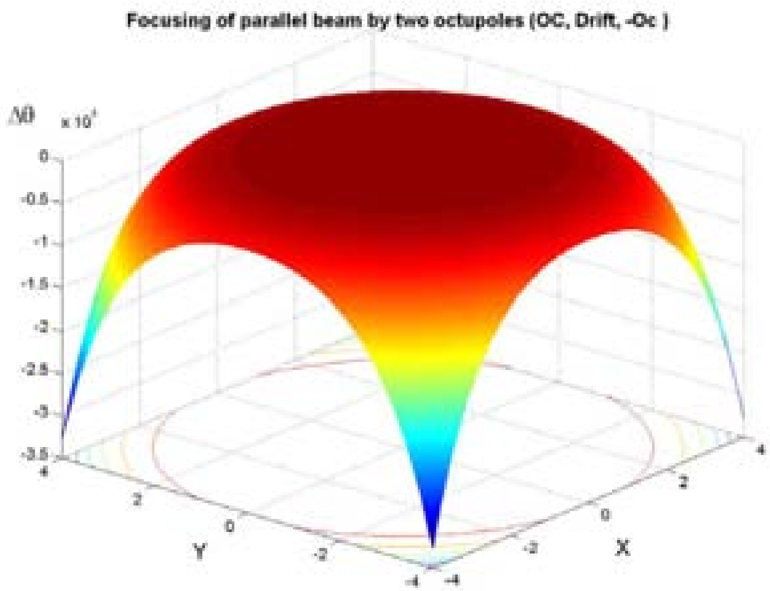
$$\Delta\theta = \alpha r^3 e^{-i3\varphi} - \left(\alpha r^3 e^{i3\varphi}\left(1+\alpha r^2 L e^{-i4\varphi}\right)^3\right)^*$$

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

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

Focusing in
<u>all directions</u>

Next nonlinear term focusing – defocusing depends on φ

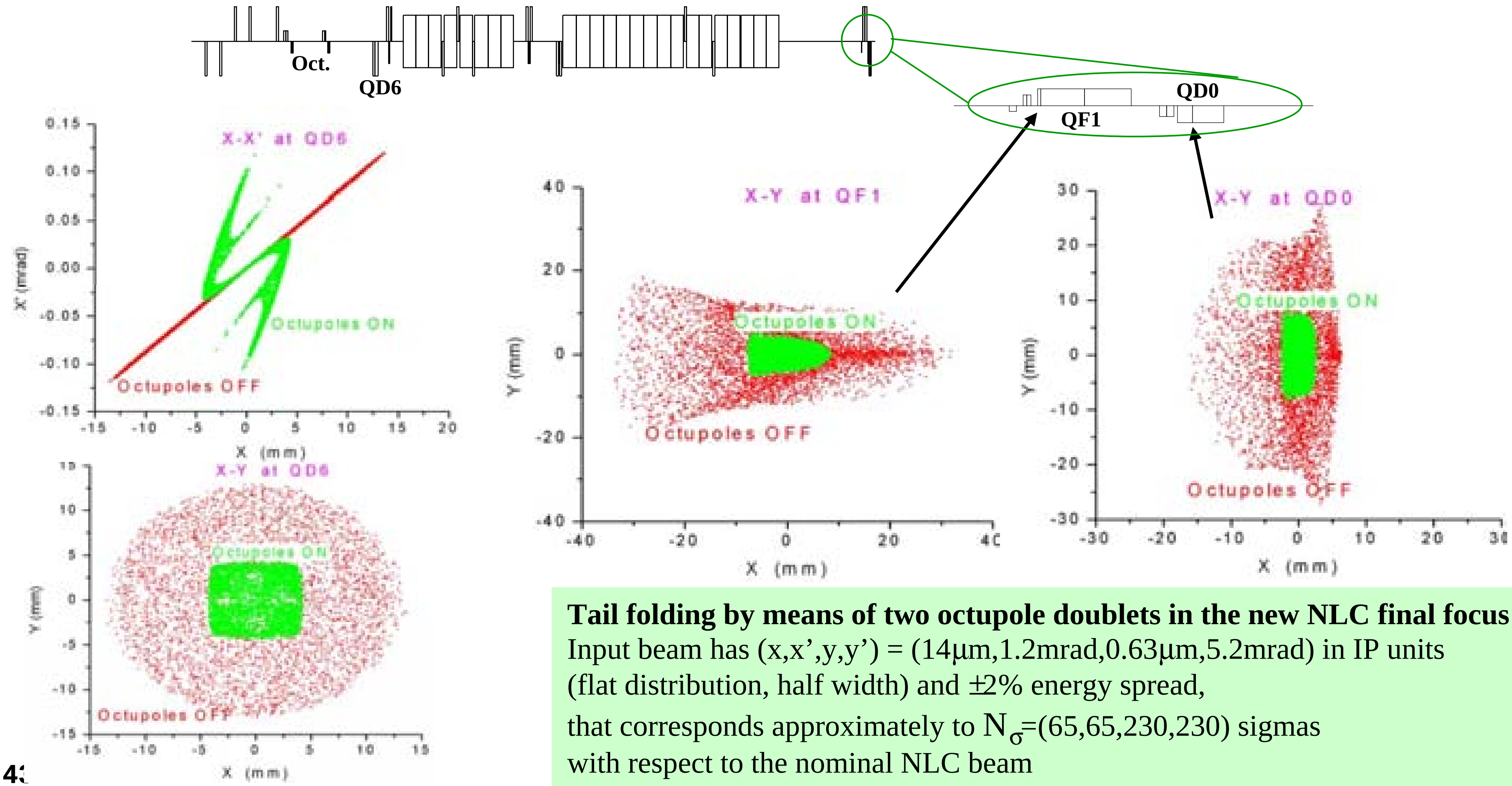


Effect of octupole doublet (Oc,Drift,-Oc) on parallel beam, ΔΘ(x,y).

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

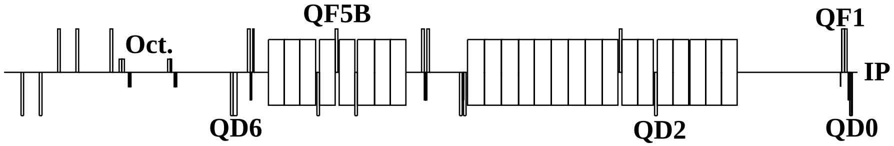
Tail folding in new NLC FF

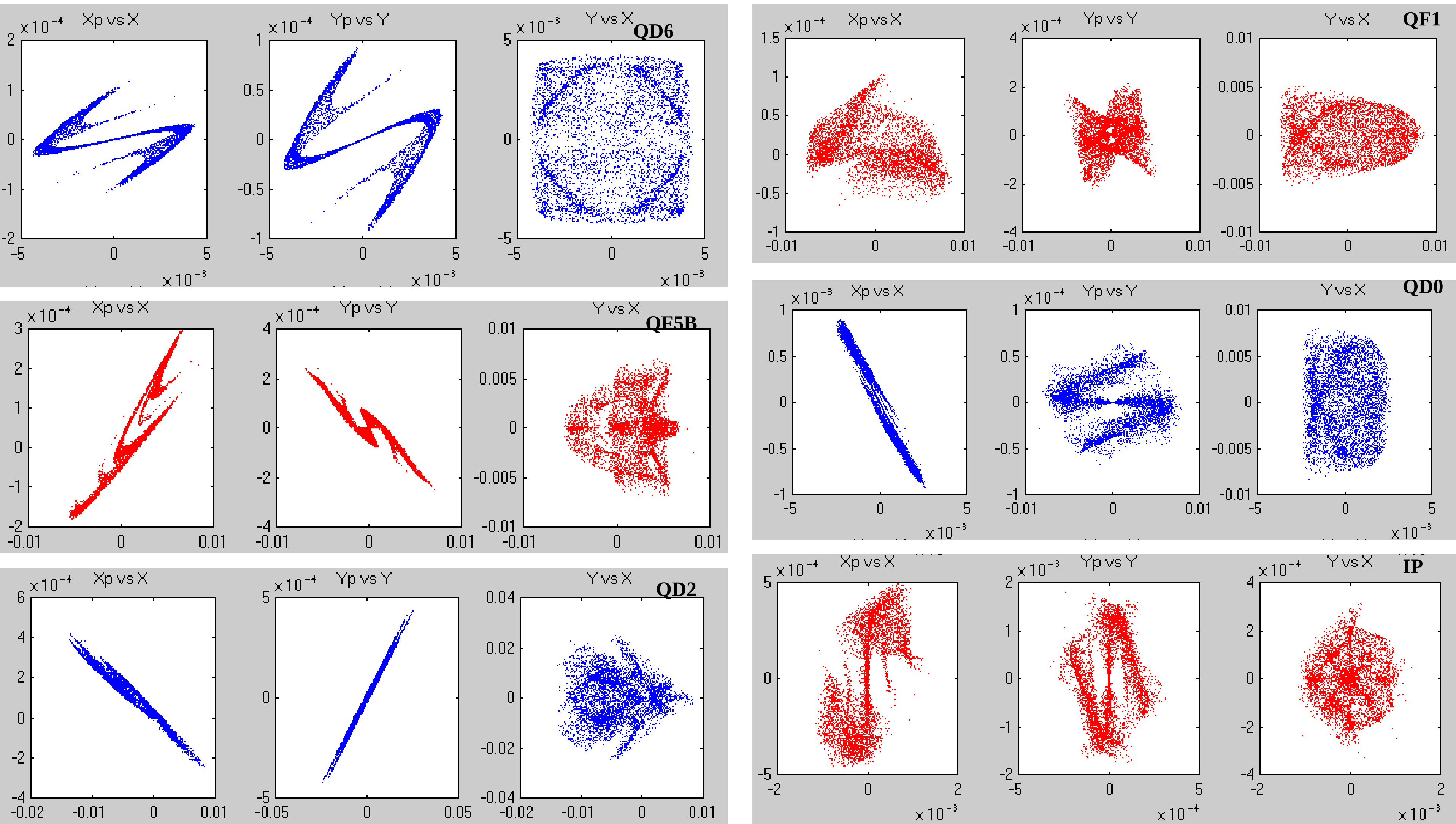
- **Two octupole doublets give tail folding by ~ 4 times in terms of beam size in FD**
- **This can lead to relaxing collimation requirements by ~ a factor of 4**



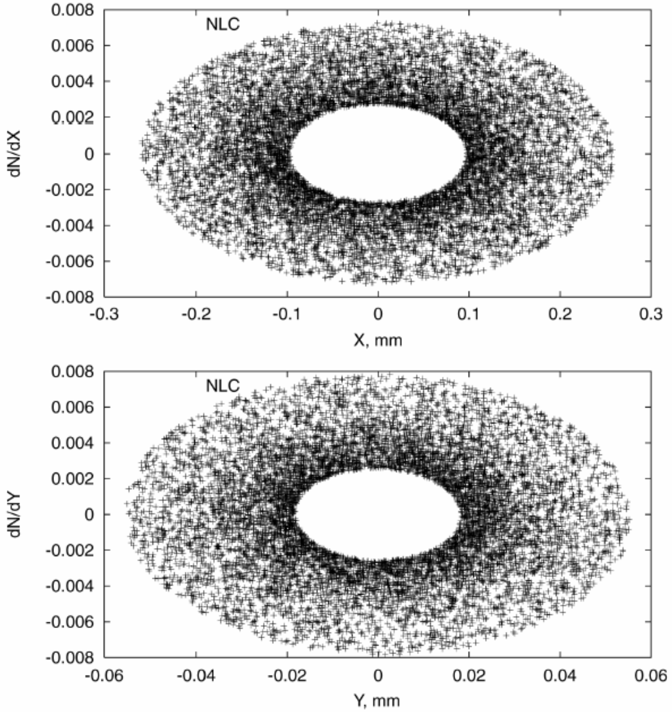
Tail folding by means of two octupole doublets in the new NLC final focus
Input beam has (x,x',y,y') = (14µm,1.2mrad,0.63µm,5.2mrad) in IP units
(flat distribution, half width) and ±2% energy spread,
that corresponds approximately to N_{σ}=(65,65,230,230) sigmas
with respect to the nominal NLC beam

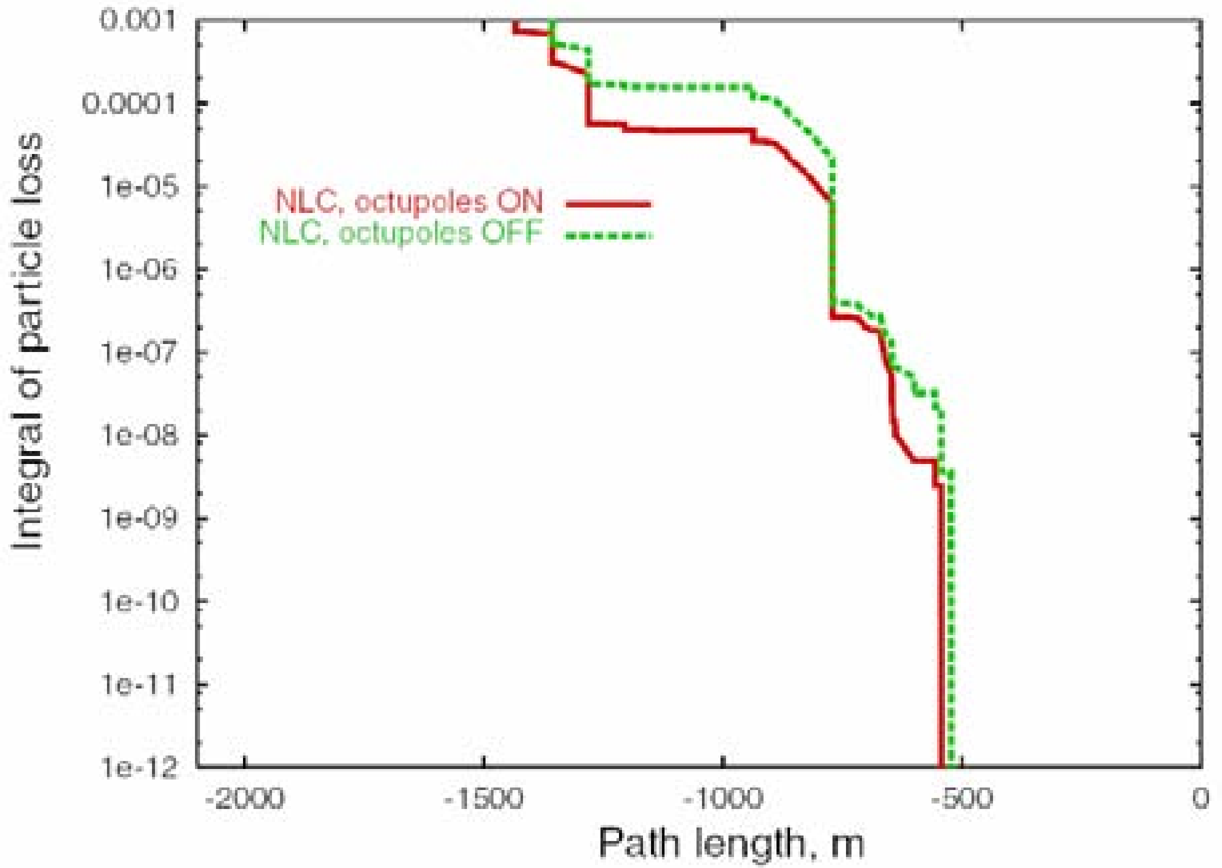
Tail folding
or Origami Zoo





Halo collimation in NLC BDS





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

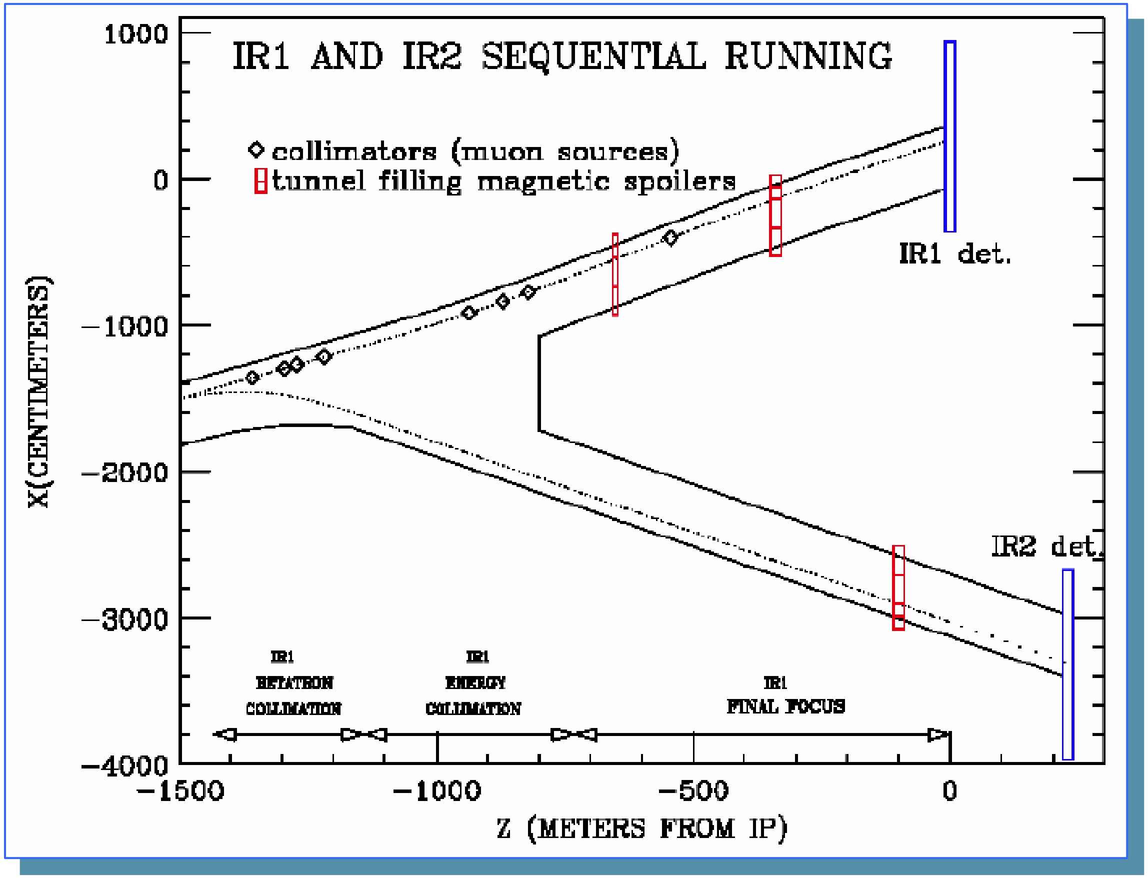
Assuming 0.001 halo, beam losses along the beamline behave nicely, and SR photon losses occur only on dedicated masks

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

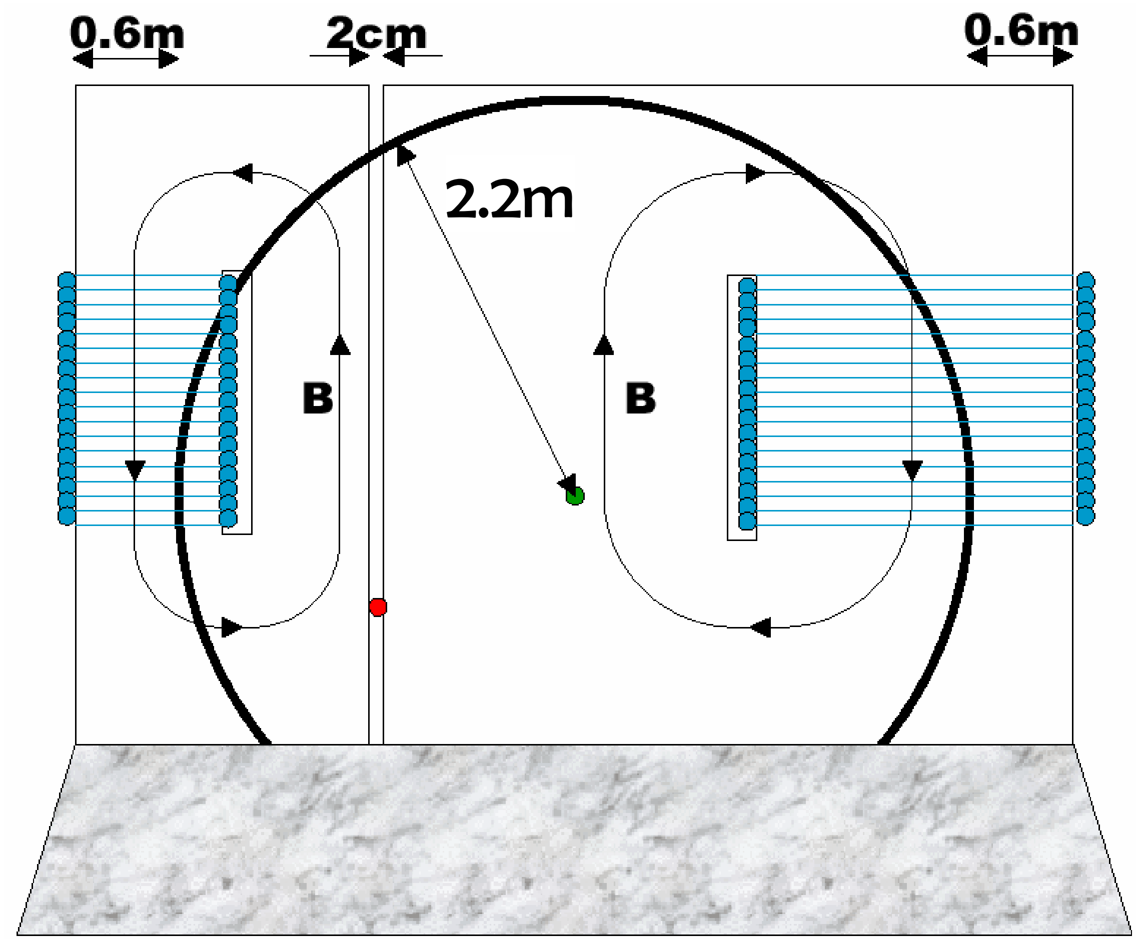
Dealing with muons in NLC BDS

Assuming 0.001 of the beam is collimated, two tunnel-filling spoilers are needed to keep the number of muon/pulse train hitting detector below 10

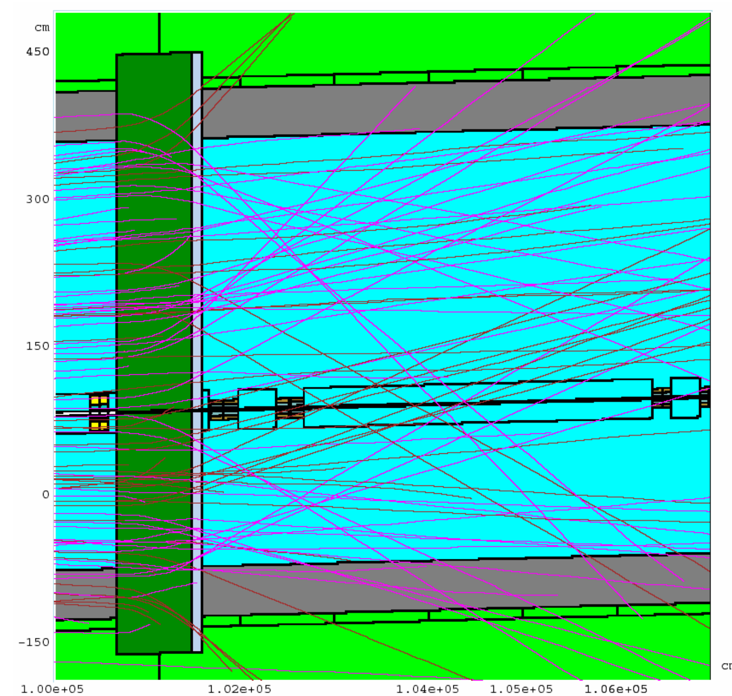
Good performance achieved for both Octupoles OFF and ON



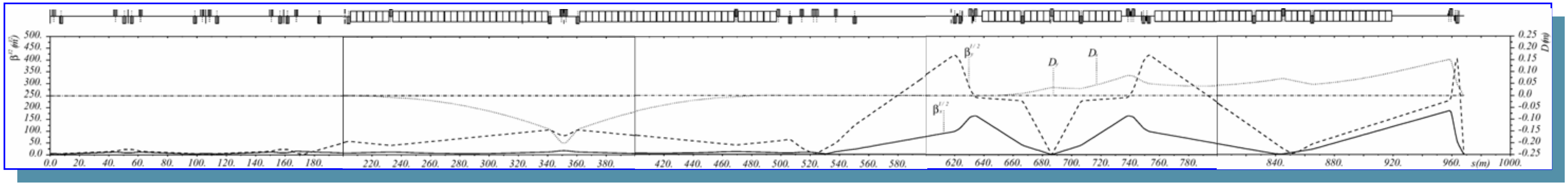
9 & 18 m Toroid Spoiler Walls

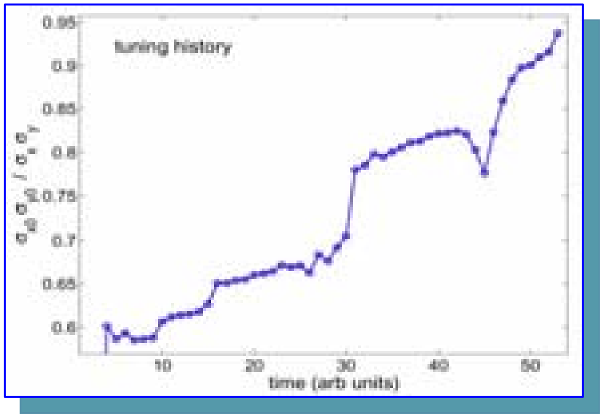


Long magnetized steel walls are needed to spray the muons out of the tunnel

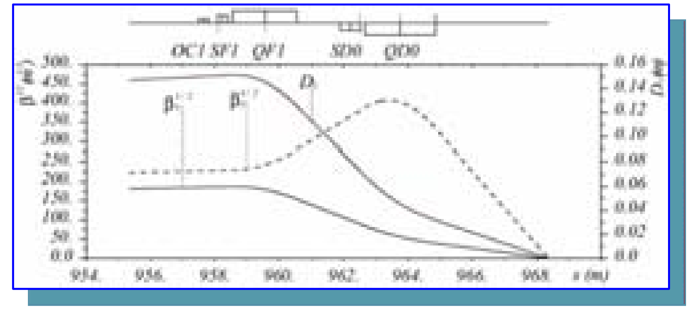


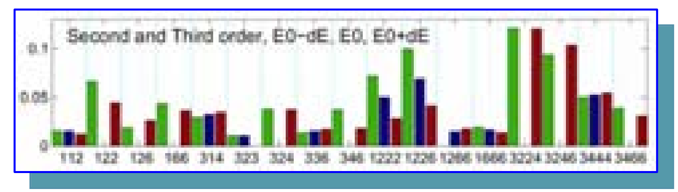
BDS design methods & examples

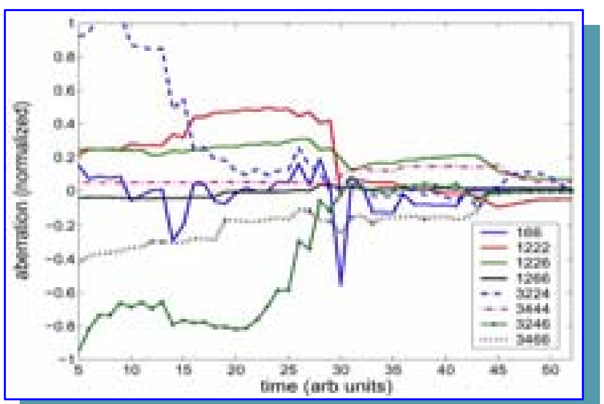


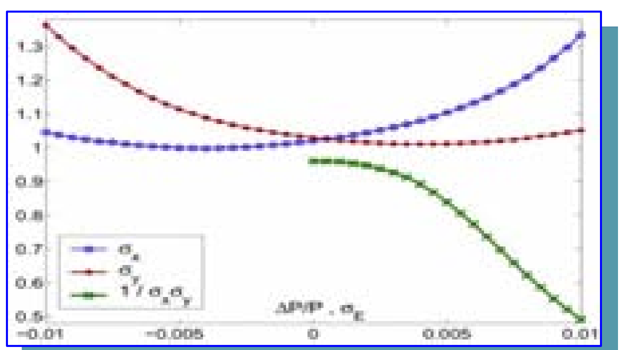


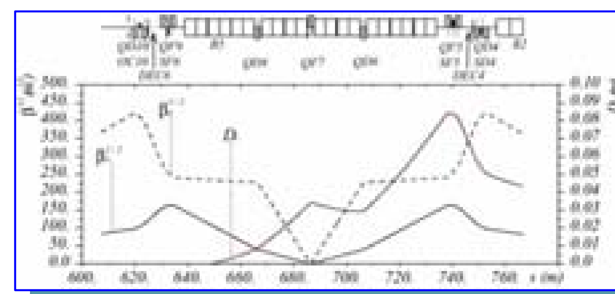
Example of a 2nd IR BDS optics for NLC; design history; location of design knobs





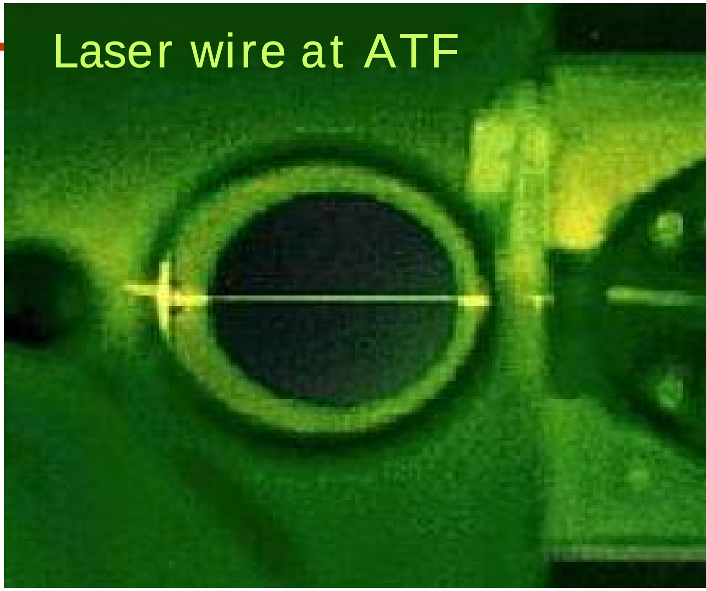






In a practical situation ...

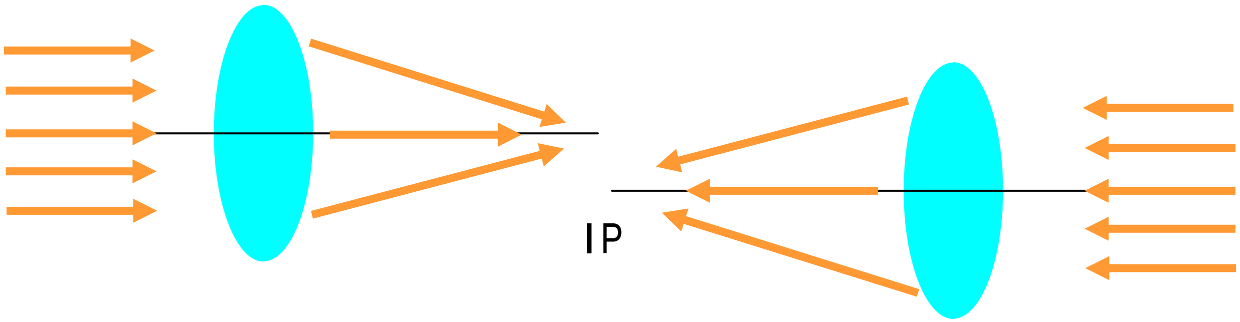
- While **designing** the FF, one has a **total control**
- When the system is built, one has just limited number of observable parameters (measured orbit position, beam size measured in several locations)
- The system, however, may initially have **errors** (errors of strength of the elements, transverse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



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

- **Tuning** of FF has been done so far by tedious 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

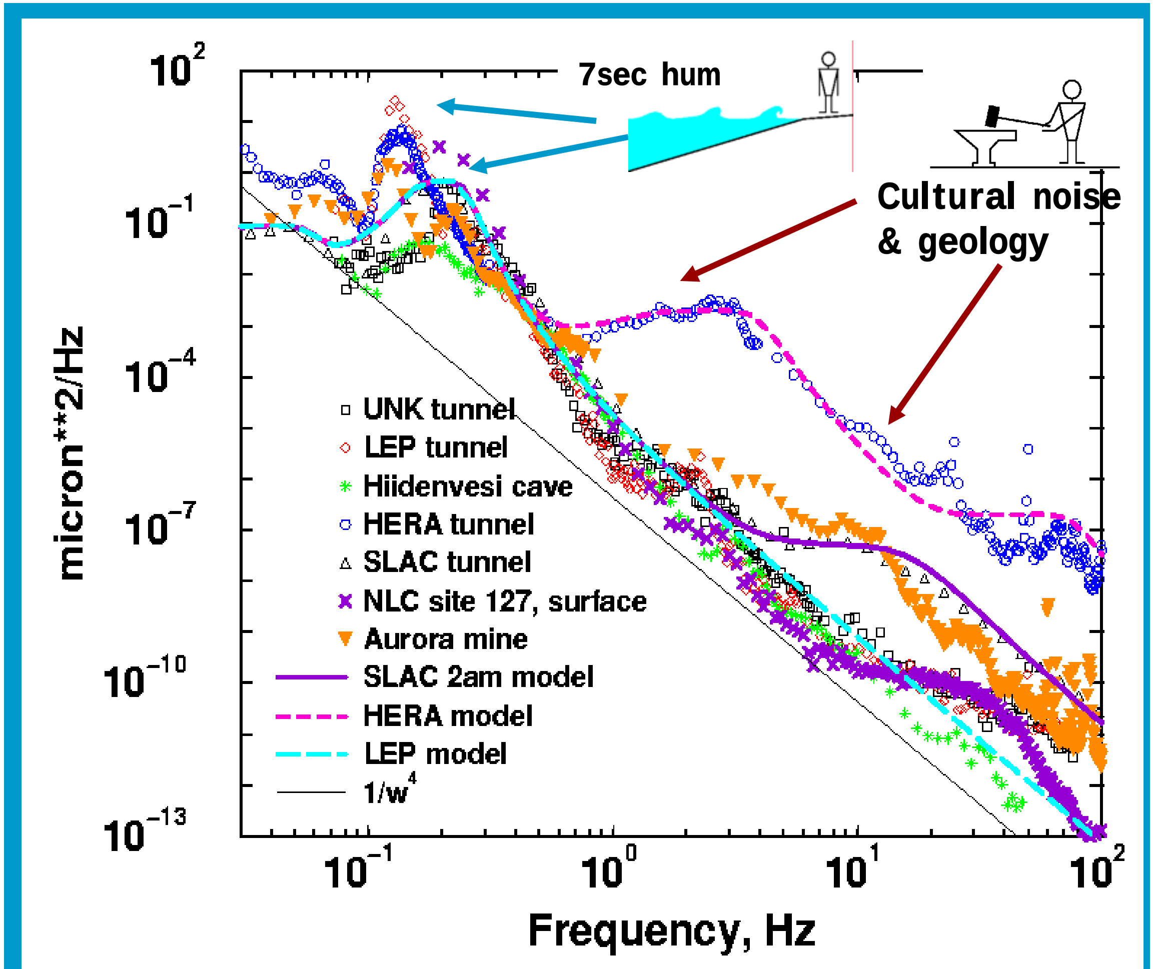
Stability – tolerance to FD motion



- Displacement of FD by dY cause displacement of the beam at IP by the same amount
- Therefore, stability of FD need to be maintained with a fraction of nanometer accuracy
- How would we detect such small offsets of FD or beams?
  - Using Beam-beam deflection !

- How misalignments and ground motion influence beam offset?

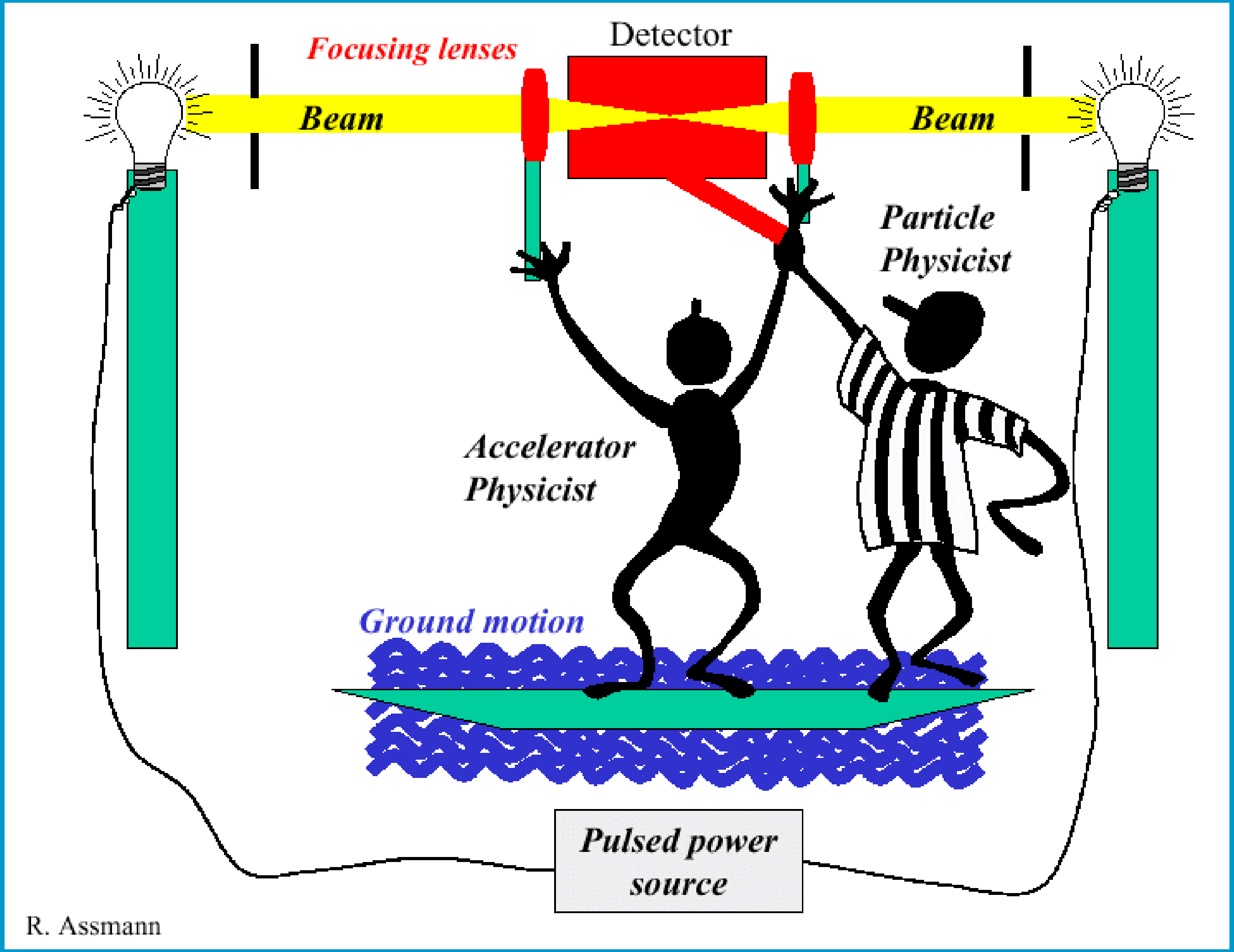
Ground motion & cultural noises



Power spectral density of absolute position

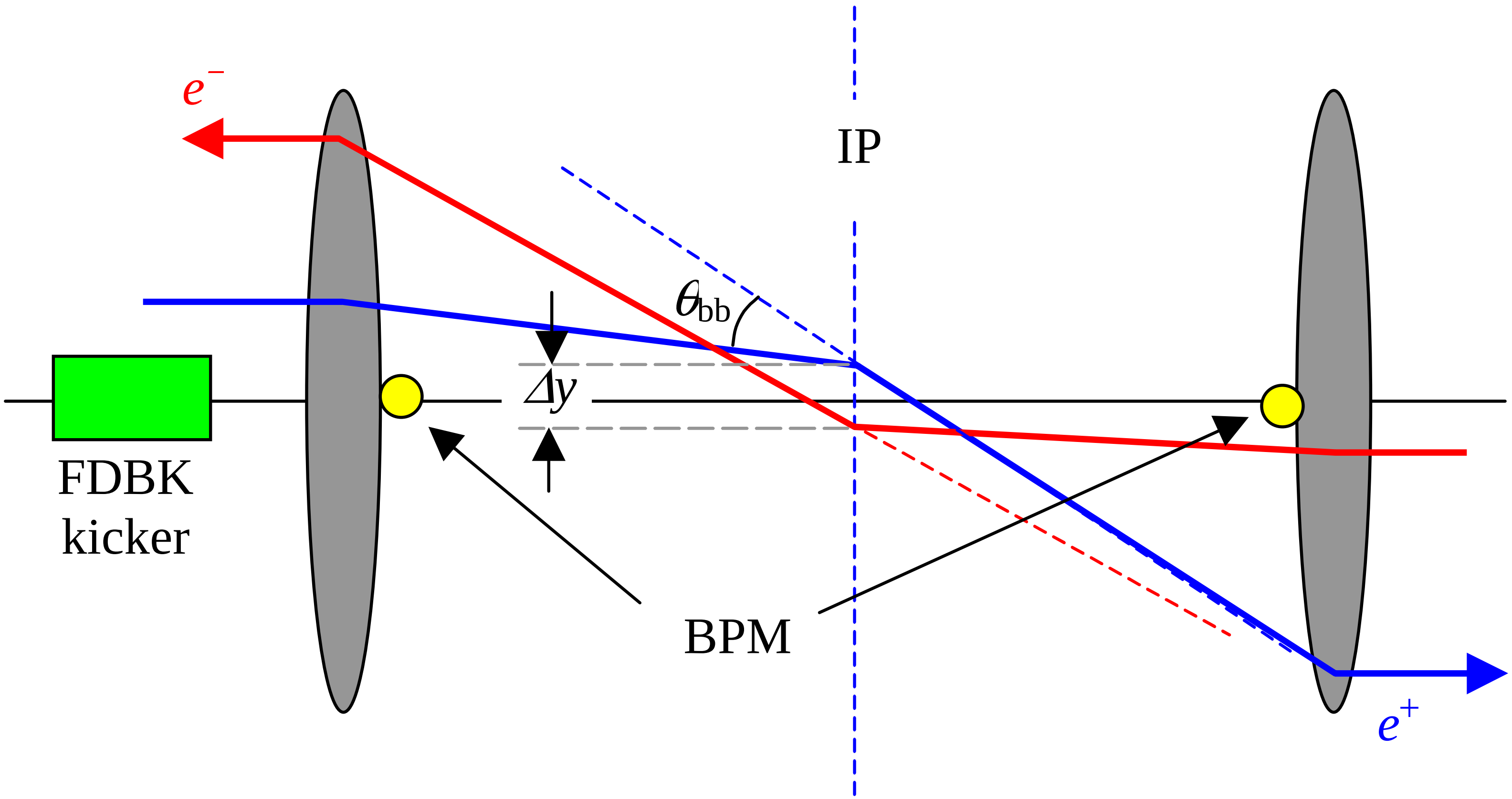
data from different labs 1989 - 2001

Detector complicates reaching FD stability



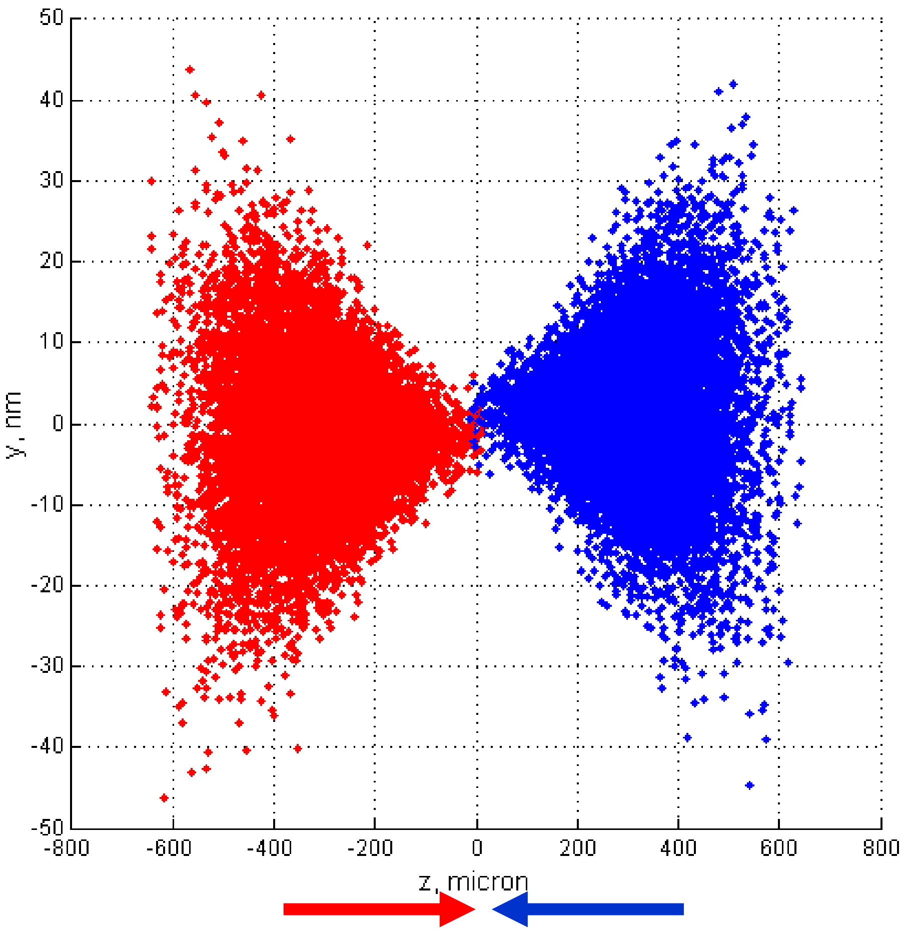
Cartoon from Ralph Assmann (CERN)

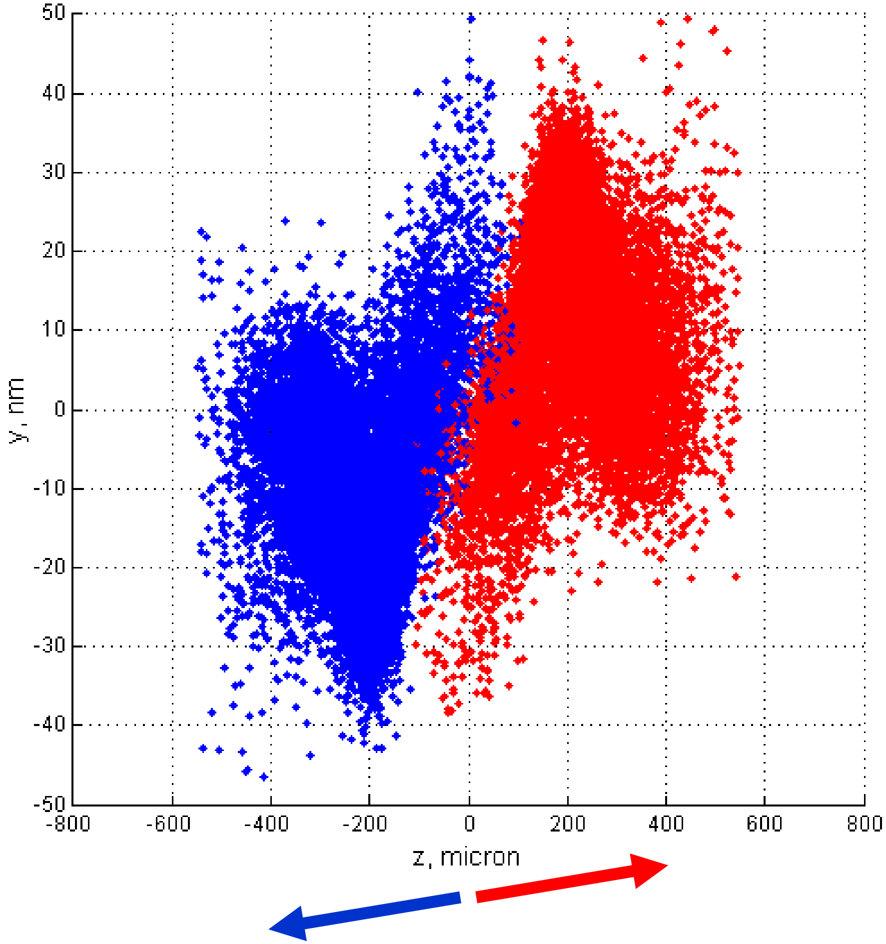
Beam-Beam orbit feedback



use strong beam-beam kick to keep beams colliding

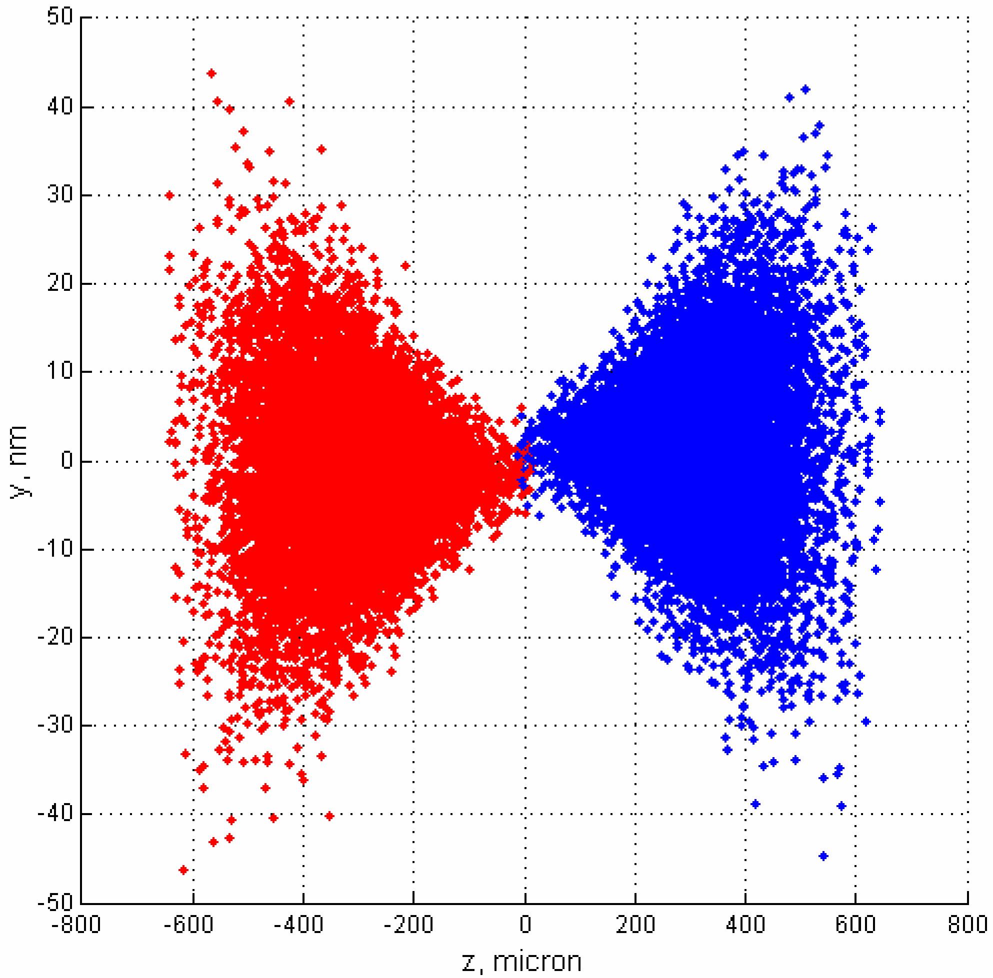
Beam-beam deflection





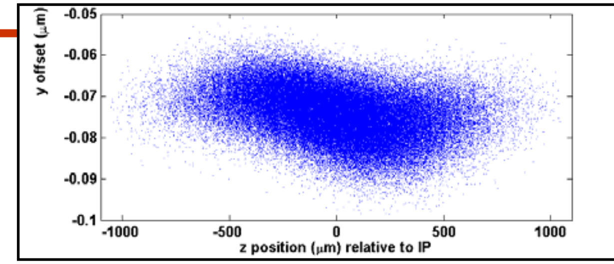
Sub nm offsets at IP cause large well detectable offsets (micron scale) of the beam a few meters downstream

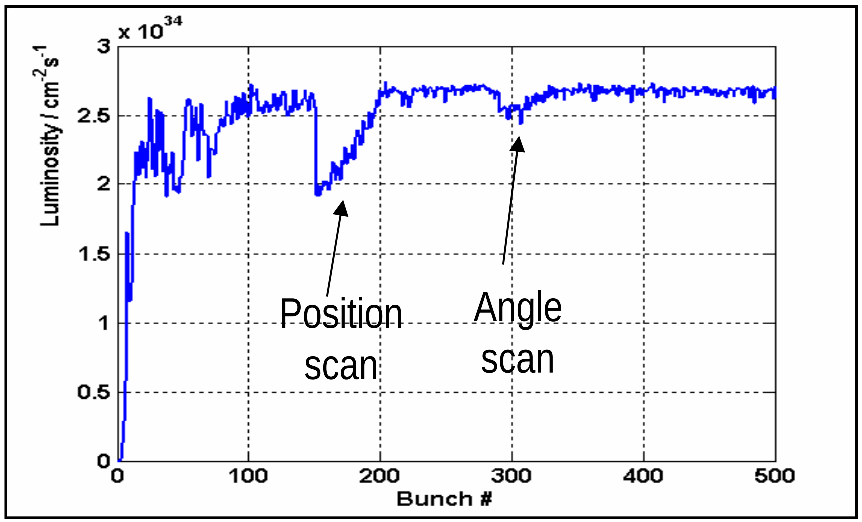
Beam-beam deflection allow to control collisions



TESLA intratrain simulation

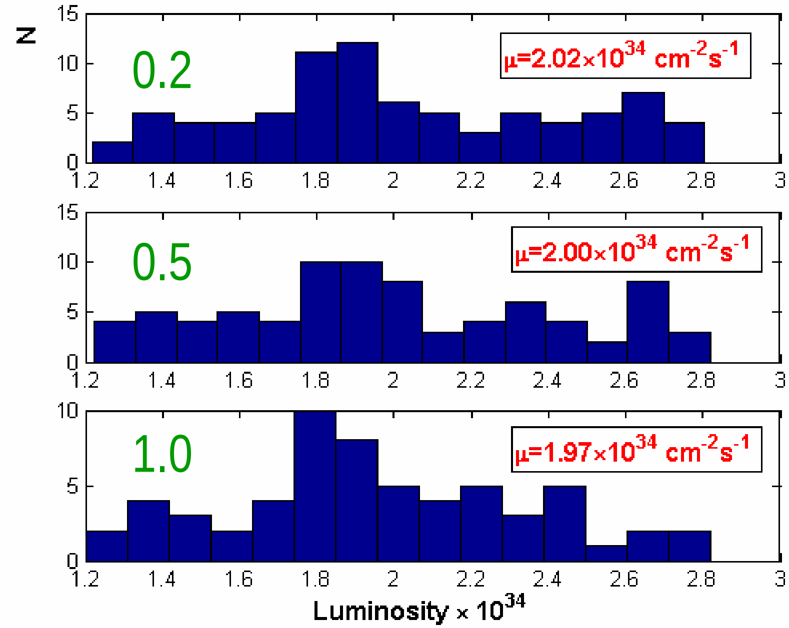
TESLA intratrain feedback (IP position and angle optimization), simulated with realistic errors in the linac and “banana” bunches, show Lumi ~2e34 (2/3 of design). Studies continue.





Luminosity through bunch train showing effects of position/angle scans (small). Noisy for first ~100 bunches (HOM’s).

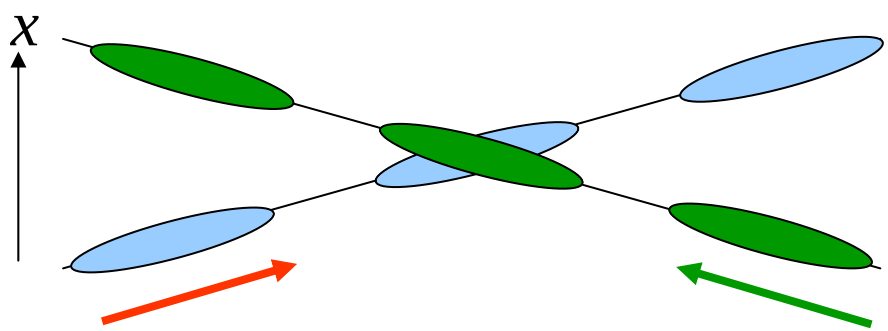
Luminosity for ~100 seeds / run



Injection Error (RMS/σ_y): 0.2, 0.5, 1.0

[Glen White, Queen Mary Univ. of London, talk at SLAC Nov.2003]

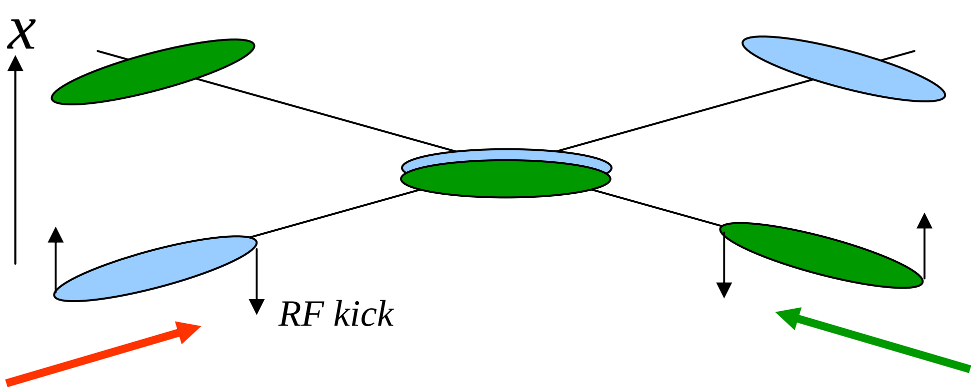
Crab crossing



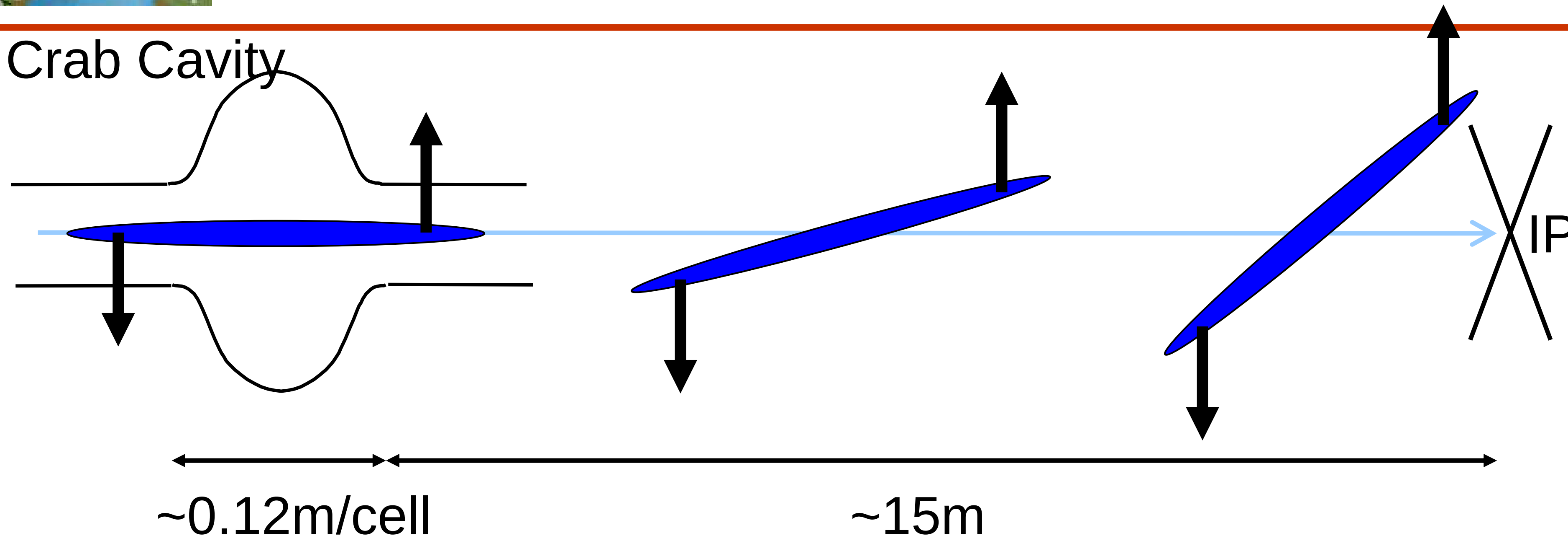
$$\sigma_{x,projected} \approx \sqrt{\sigma_x^2 + \phi_c^2 \sigma_z^2}$$
$$\approx \phi_c \sigma_z$$
$$= 20\text{mr} \times 100\mu\text{m} \approx 2\mu\text{m}$$

factor 10 reduction in *L*!

use transverse (crab) RF cavity to ‘tilt’ the bunch at IP

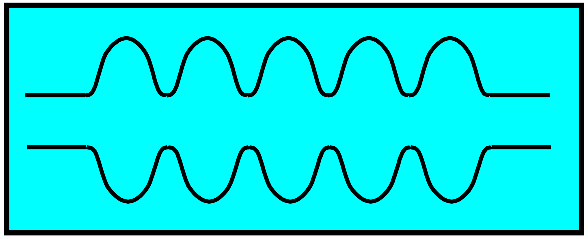


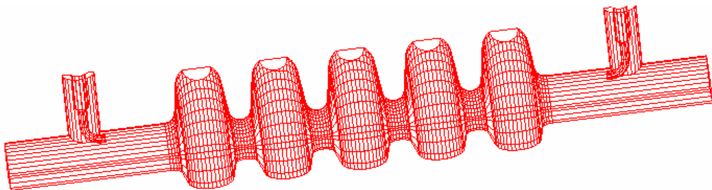
Crab cavity requirements



Use a particular horizontal dipole mode which gives a phase-dependant transverse momentum kick to the beam

Actually, need one or two multi-cell cavity



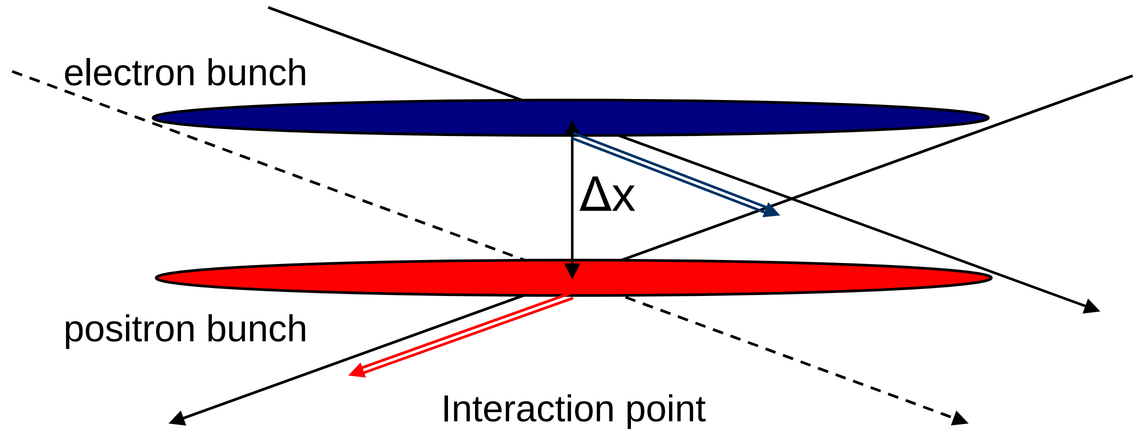


Slide from G. Burt & P. Goudket

Crab cavity requirements

Phase jitter need to be sufficiently small

Static (during the train) phase error can be corrected by intra-train feedback

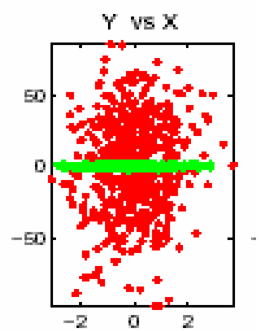


	Phase error (degrees)	
Crossing angle	*1.3GHz*	*3.9GHz*
2mrad	0.222	0.665
10mrad	0.044	0.133
20mrad	0.022	0.066

Slide from G. Burt & P. Goudket

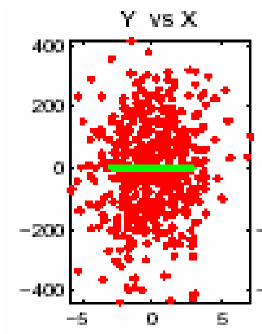
Anti-Solenoids in FD

When solenoid overlaps QD0 coupling between y & x' and y & E causes σ_y(Solenoid) / $\sigma_y(0)$ ~ 30 – 190 independent of crossing angle (green=no solenoid, red=solenoid, note scale)



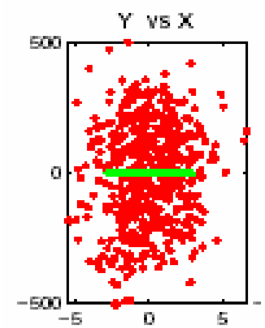
Si D

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



LD

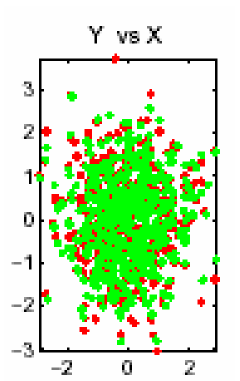
$\sigma_y / \sigma_y(0)=150$



LD, 0° x-ang

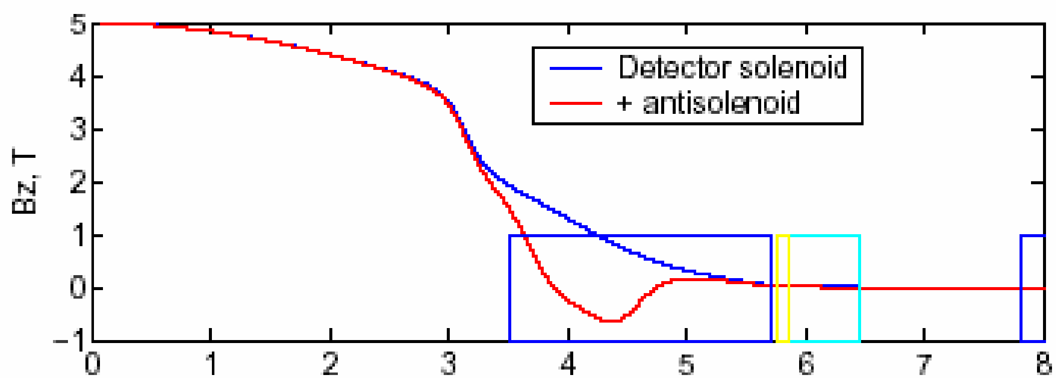
$\sigma_y / \sigma_y(0)=190$

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 best way to ensure excellent correction over wide range of beam energies



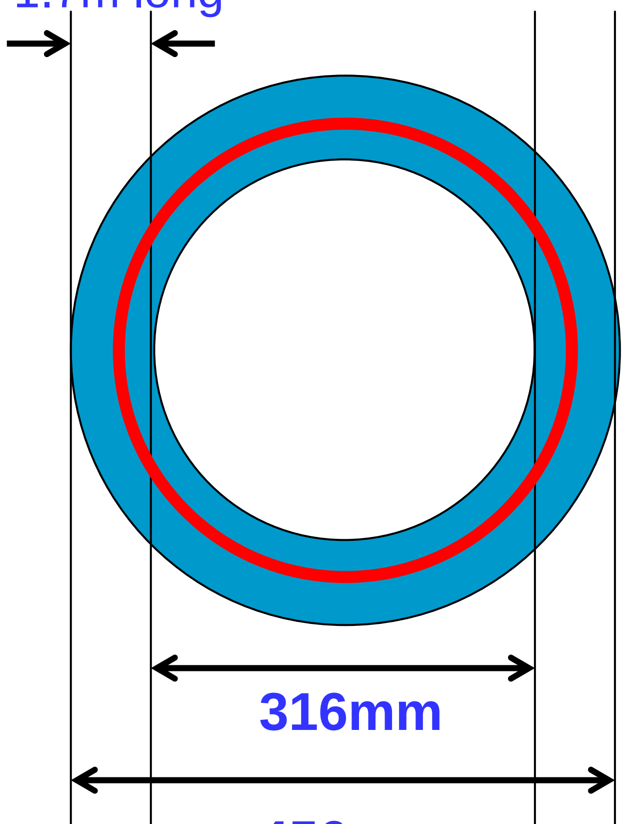
SiD or LD

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

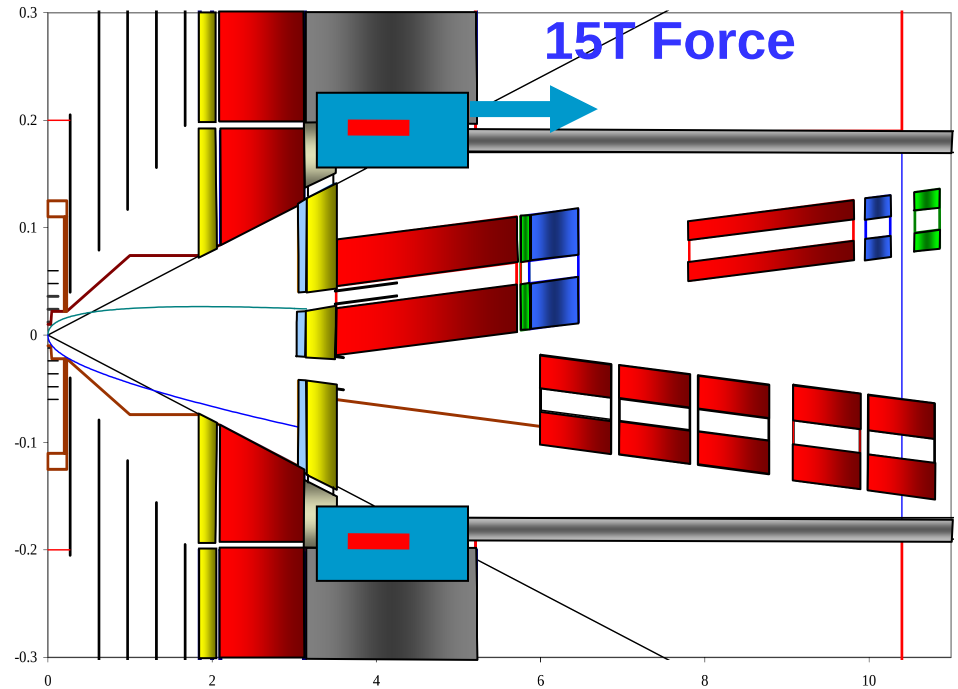


Preliminary Design of Anti-solenoid for Si D (B. Parker)

70mm cryostat
1.7m long

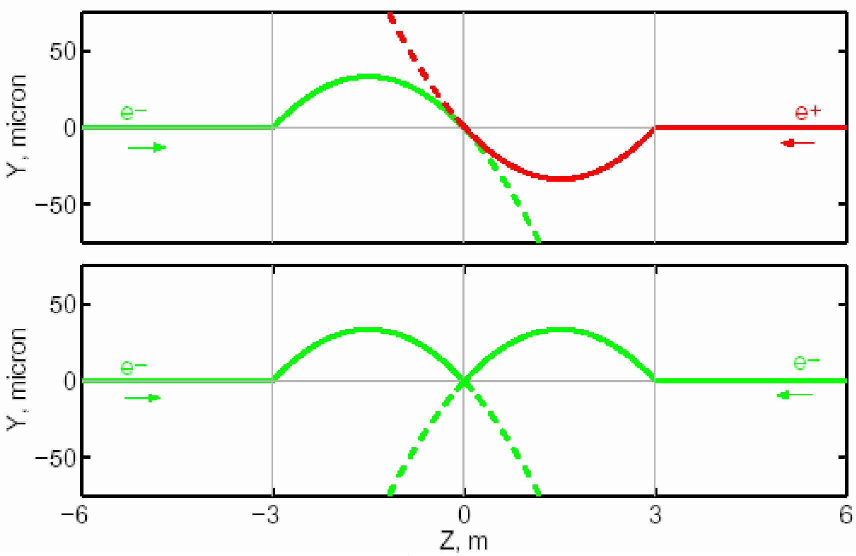


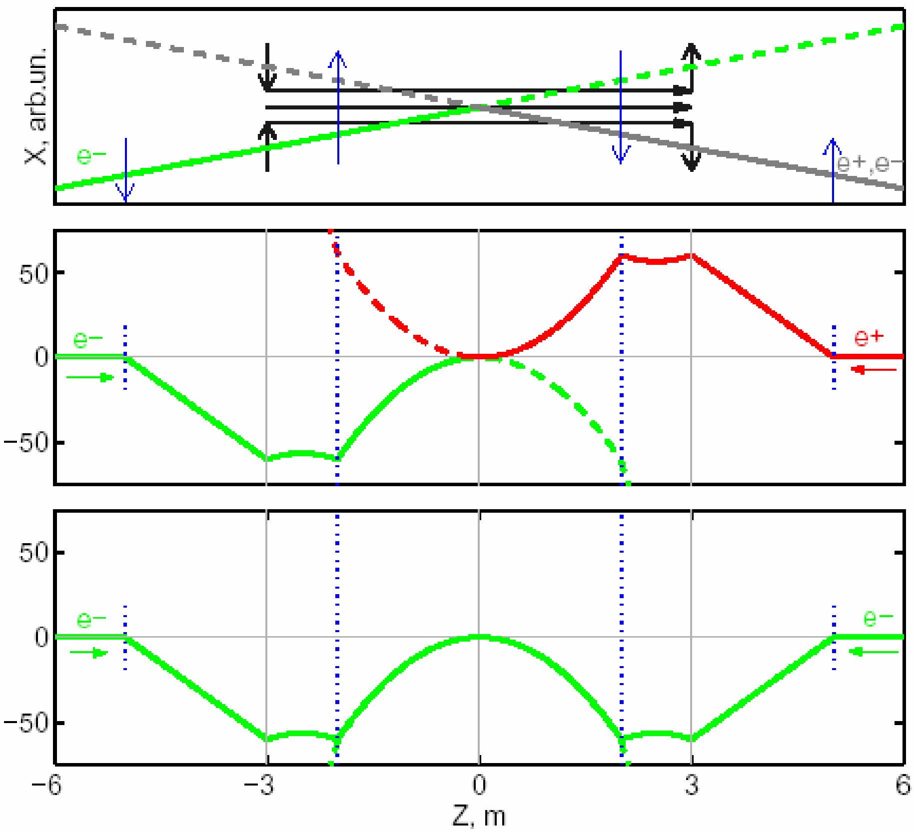
Four 24cm individual powered 6mm coils, 1.22m total length, r_{min}=19cm



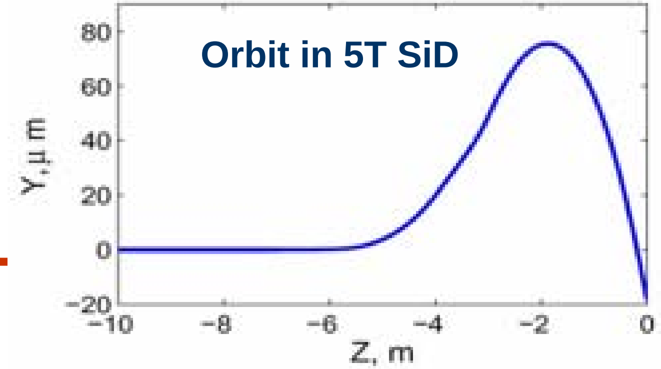
Detector Integrated Dipole

- In crossing angle case, if do nothing beams collide at IP but at non-zero angle.
- If we want to collide at zero angle to preserve angle of polarization vector (as well as e-e- luminosity) can move QD0 and QF1 in x but expense is large orbit variation in y and SR induced beam spot size growth.
- The best way is to compensate angles locally with DID.

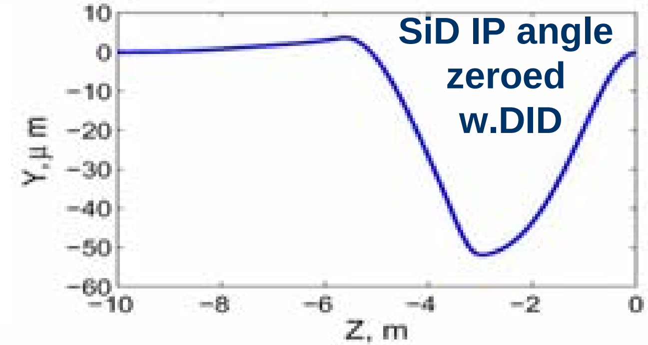


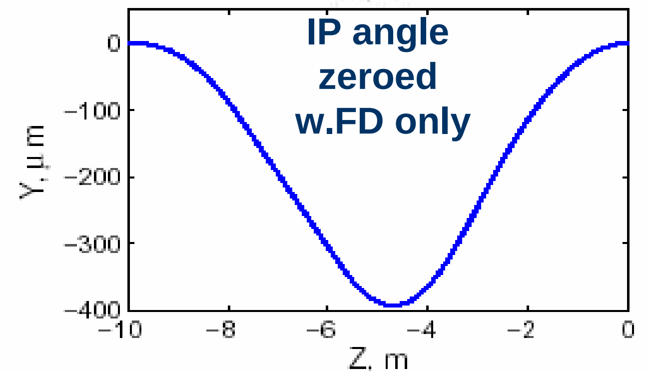


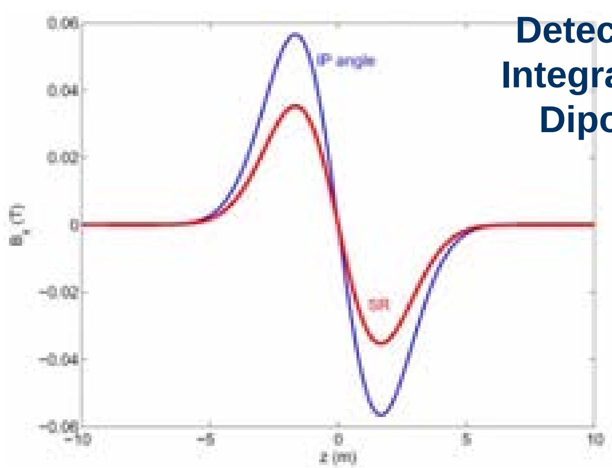
Solenoid Compensation with DID



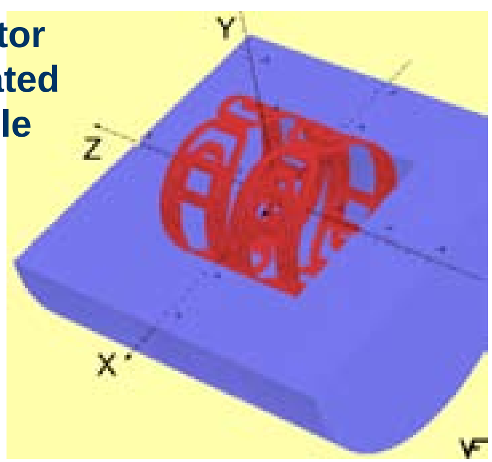
- **X-ing solenoid => vertical orbit**
  - **polarization rotation**
  - **SR beam size growth $\Delta\sigma_{sr} \sim (\theta_c L_D)^{5/2}$**
- Use of DID minimize SR growth and Y orbit
- Feasibility of detector physics analysis with additional DID field (TPC)
- Background increase due to DID field

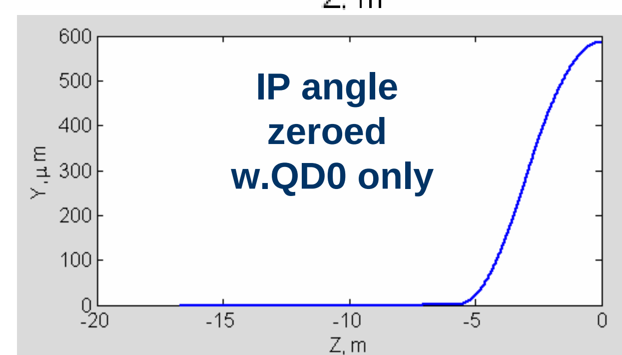




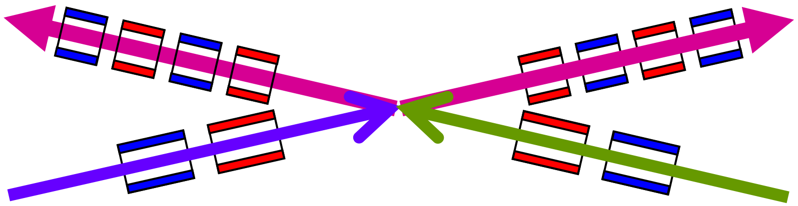


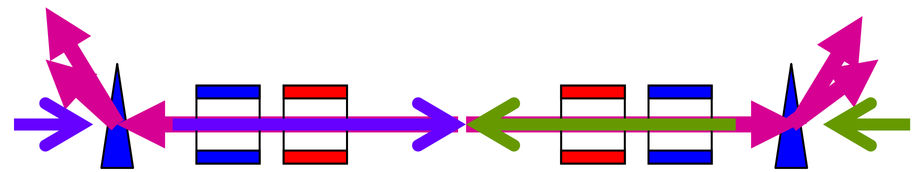
Detector Integrated Dipole





Choice of crossing angle has crucial influence on the machine performance, reliability, and affect physics reach

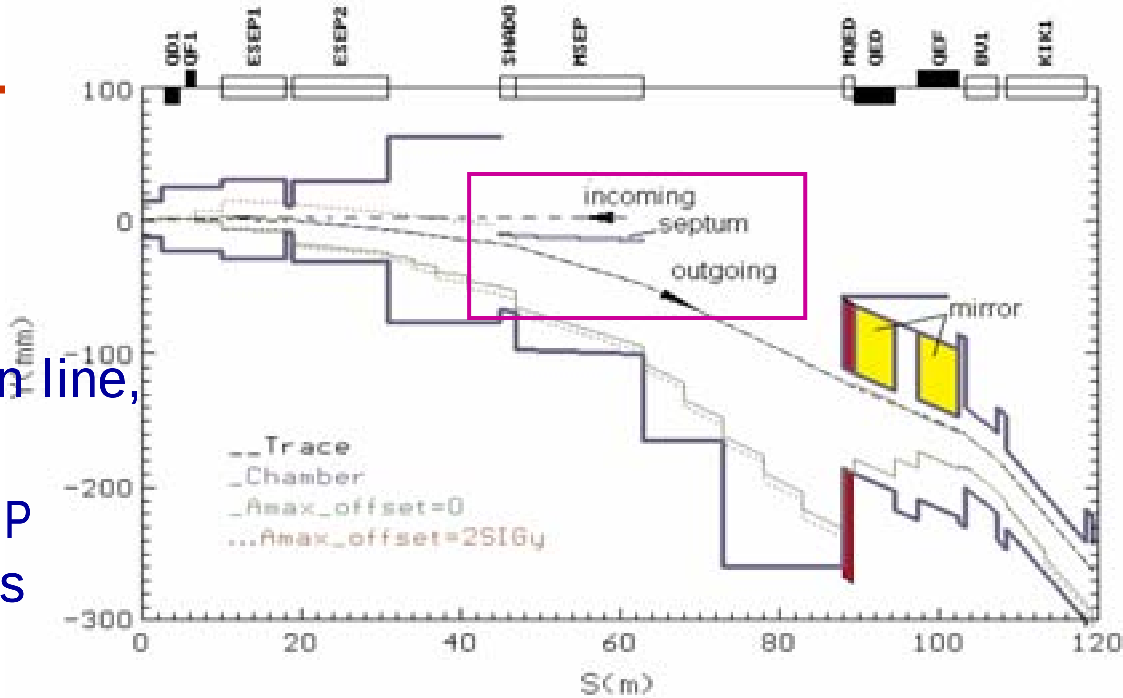




- Incoming and outgoing beam are independent (+)
- Disrupted beam with large energy spread captured by alternating focusing, no need to bend the beam after collision => easier to minimize beam losses (+)
- Require compact SC quads and crab cavity
- The exit hole un-instrumented => loss of detector hermeticity (-)
- Low energy pairs spread by solenoid field => somewhat larger background (-)

- No extra exit hole => somewhat better detector hermeticity (+)
- Low energy pairs spread less => somewhat better background (+)
- Require electrostatic separator with B-field or RF-kicker
- Incoming and outgoing magnets shared => difficult optics, collimation apertures set by outgoing beam (-)
- Need to bend disrupted beam with large energy spread => beam loss, especially at high energy, MPS (-)

Evaluation of head-on design by TRC

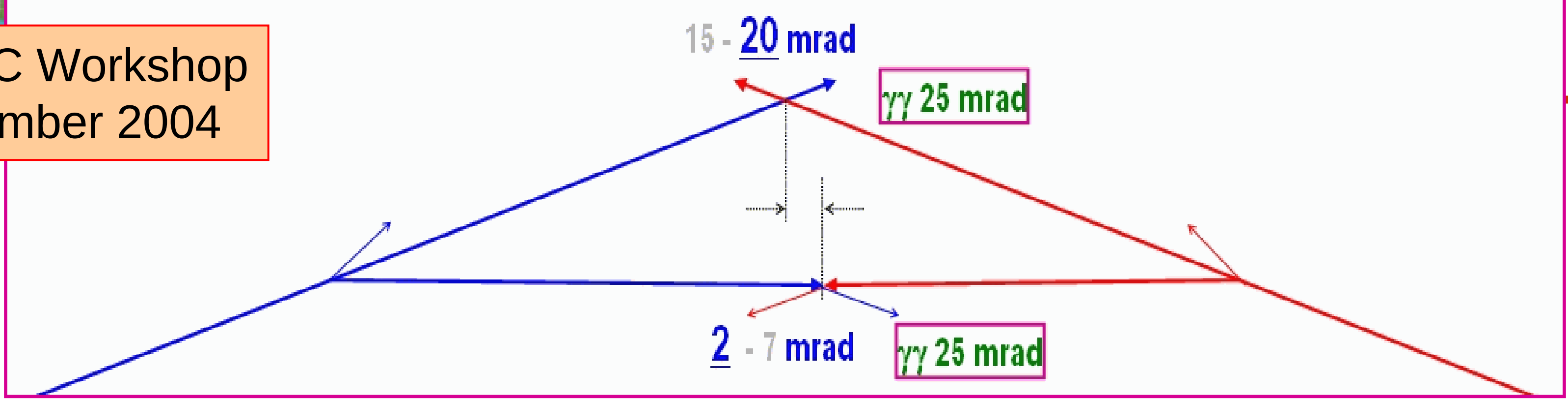


- ILC-TRC evaluation of BDS design and head-on scheme
  - Large losses in extraction line, especially at 1 TeV
  - Incompatible with post-IP E/Polarization diagnostics
  - Electrostatic separator 100kV/cm at 1TeV – feasibility in high SR environment
  - MPS issues
  - γ losses at (or near) septum: ~5-15kW
  - Parasitic collision 26.5 m from IP @ 1TeV
  - SR masking over-constrained

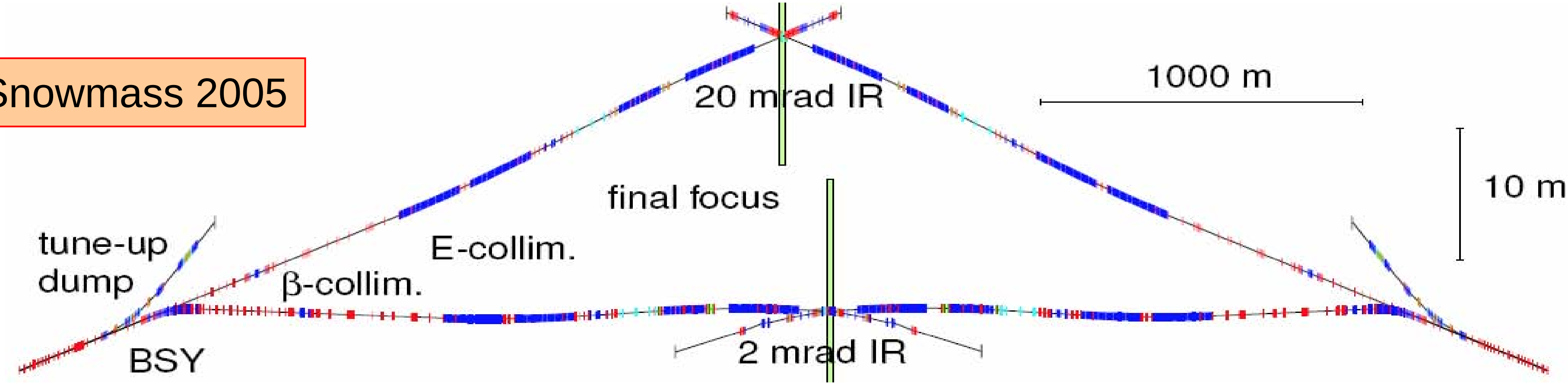
Recommendations from the WG4

Tentative, not frozen configuration, working hypotheses, "strawman"

1st ILC Workshop
November 2004



Snowmass 2005

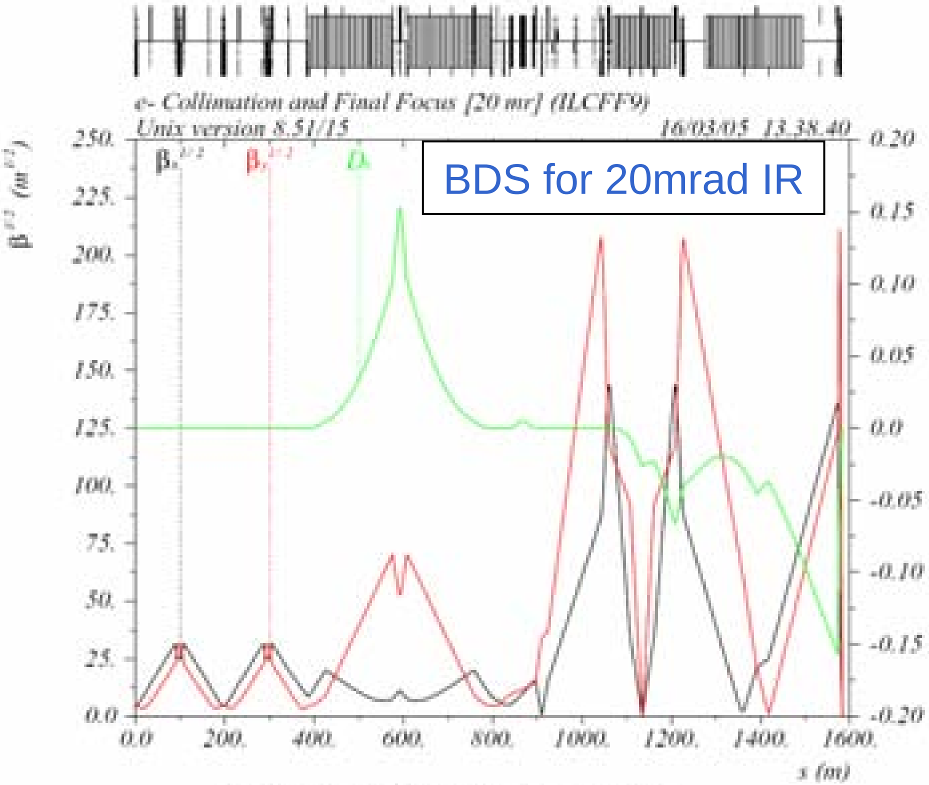


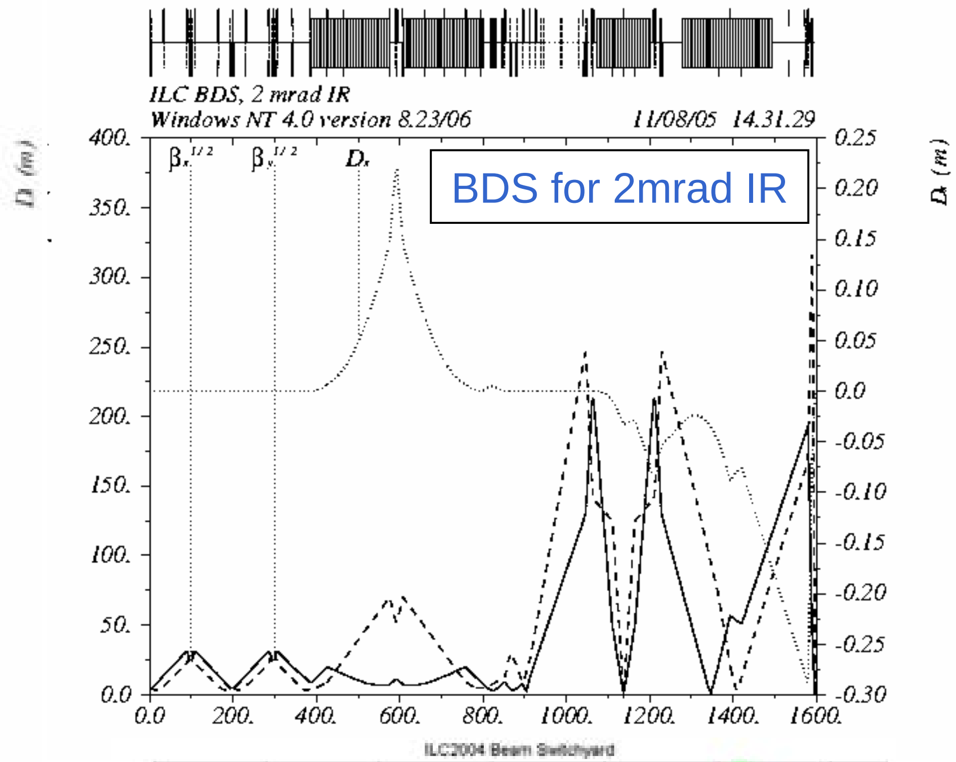
Strawman tentative configuration turns into real design:

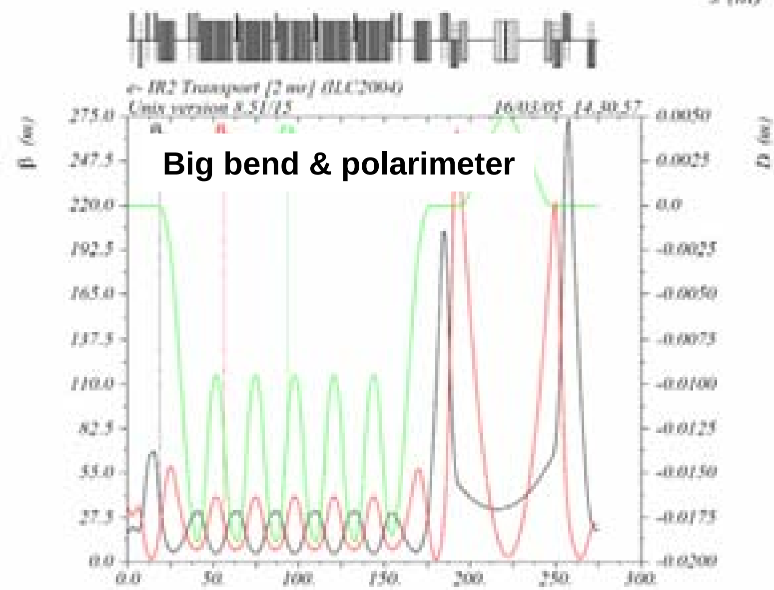
Full optics for all beamlines; Mature 20mrad optics and magnets design; Several iteration of optics for 2mrad IR; Upstream and downstream diagnostics for both IRs

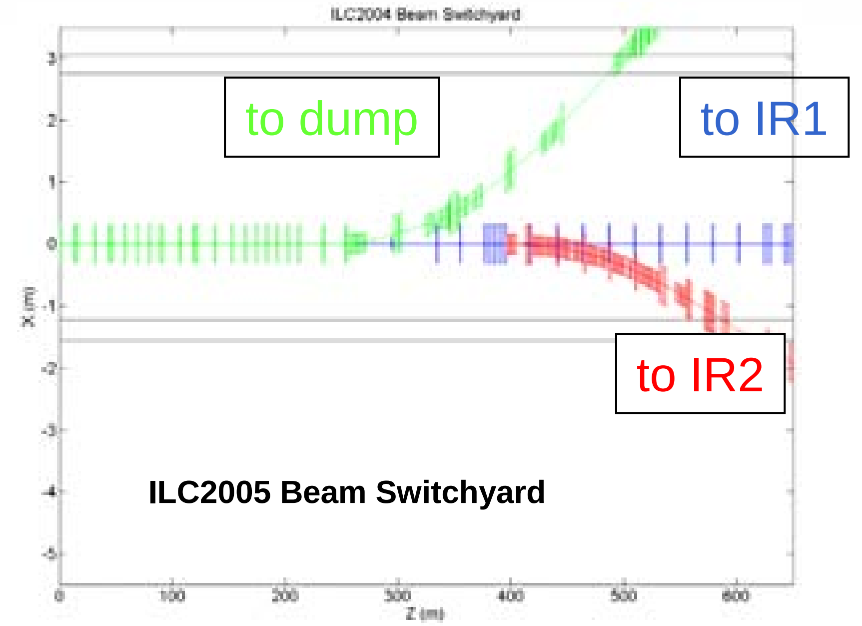
Baseline for two IRs: proceed with detailed design of

- 20mrad IR
  - stable and mature design
  - separate incoming & extraction beamlines
  - achieve high luminosity
  - clean upstream & downstream diagnostics
  - expect good operational margins, flexibility
  - may not preclude mTeV or gamma-gamma
  - somewhat larger backgrounds
- 2 mrad IR
  - better background & detector hermeticity
  - much more advanced design than head-on
  - achieve nominal luminosity and possibly somewhat higher
  - downstream diagnostics designed but higher background
  - more constrained design, less flexible
  - may be more difficult in operation


e- Collimation and Final Focus [20 mr] (ILCFF9)
Unix version 8.51/15
16/03/05 13.38.40
BDS for 20mrad IR
s (m)

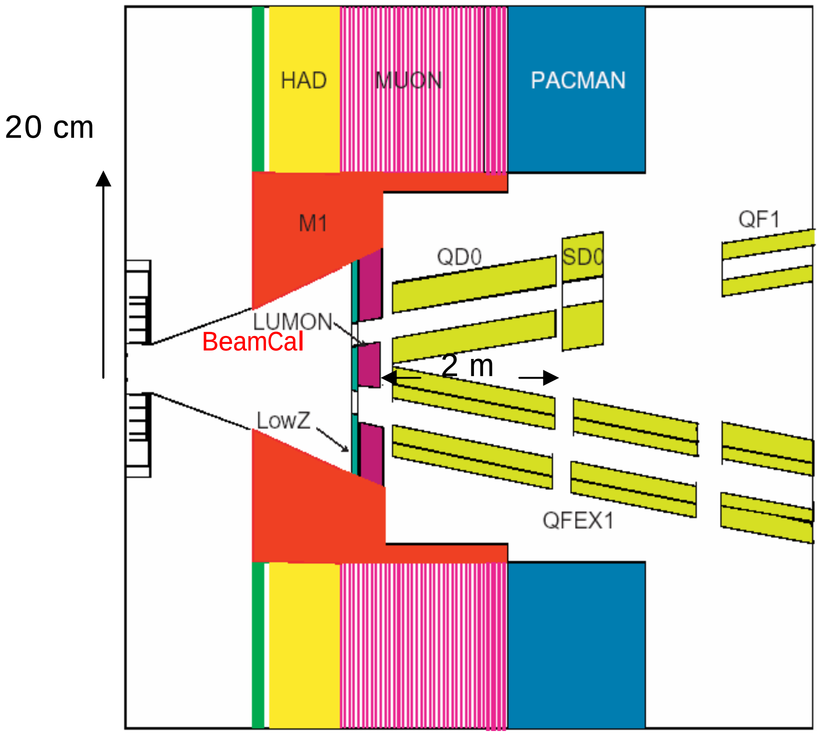

ILC BDS, 2 mrad IR
Windows NT 4.0 version 8.23/06
11/08/05 14.31.29
BDS for 2mrad IR


Big bend & polarimeter

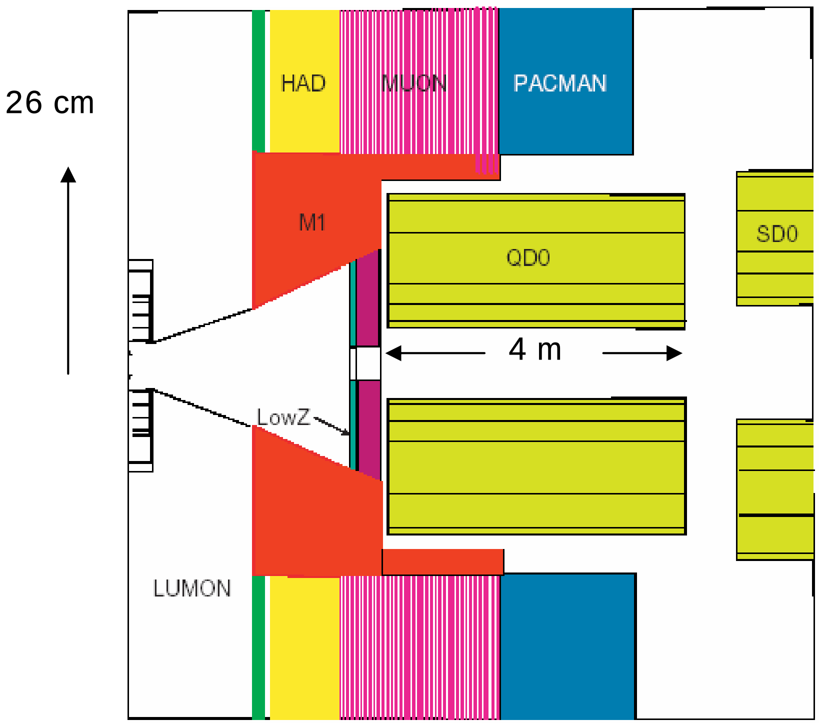

ILC2004 Beam Switchyard
to dump
to IR1
to IR2
ILC2005 Beam Switchyard
Z (m)

IR layout for 2o and 2 mrad with SiD and L*=3.5

20 mrad



2 mrad (earlier version)

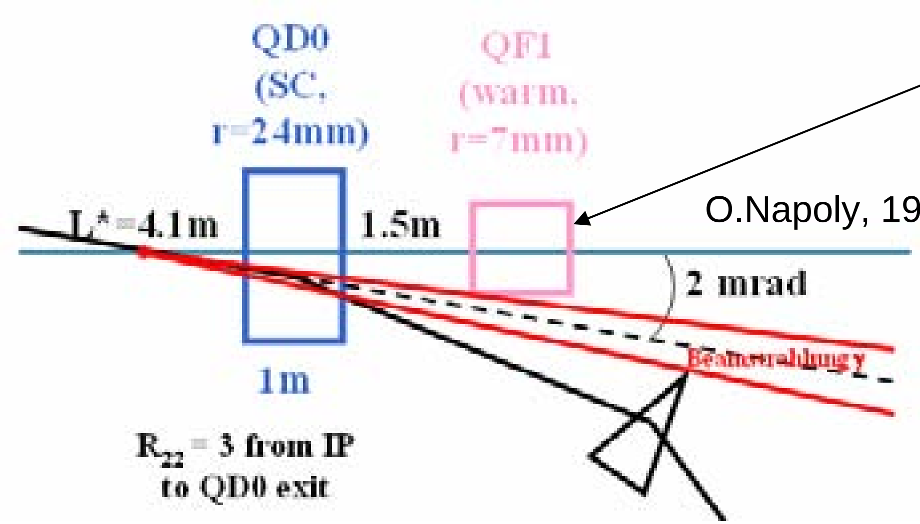


shows the version when FD not rotated w.r.to detector. In reality it is rotated. Geant model of the rotated version was evaluated as well.

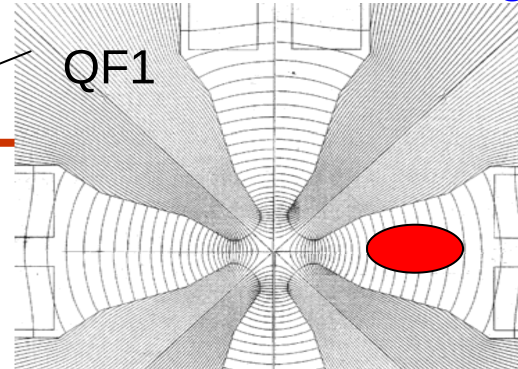
- IR layout includes correct sizes of magnets (internal and external), start to include solenoid compensation, feedback BPMs, kickers, and engineering details ...

2mrad IR: from concept to optics

SLAC-BNL-UK-France
Task Group



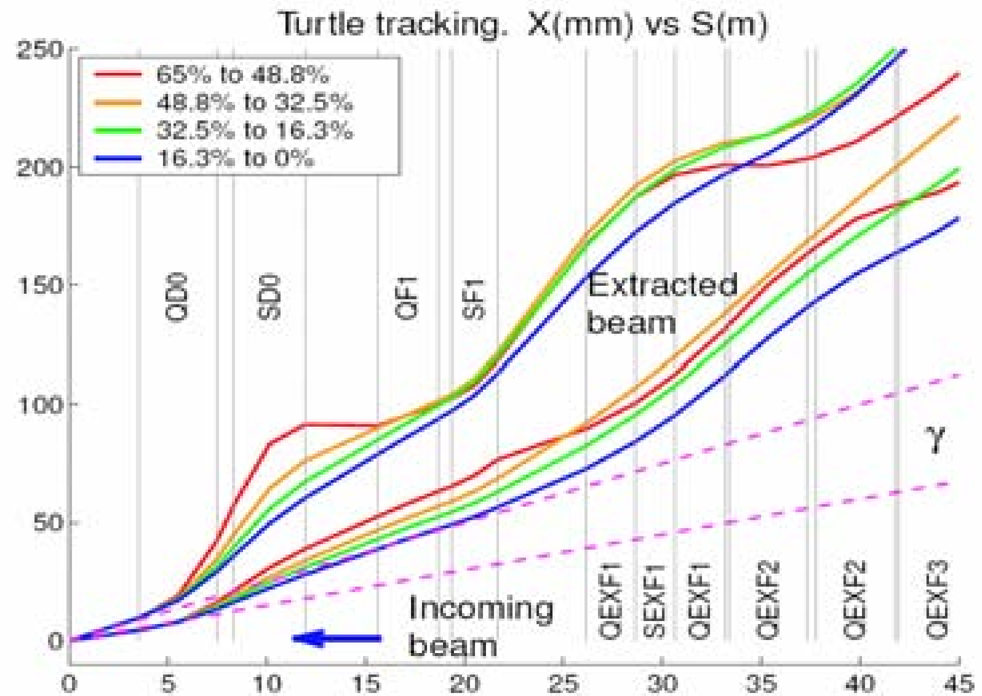
O.Napoly, 1997



pocket coil QF1 quad

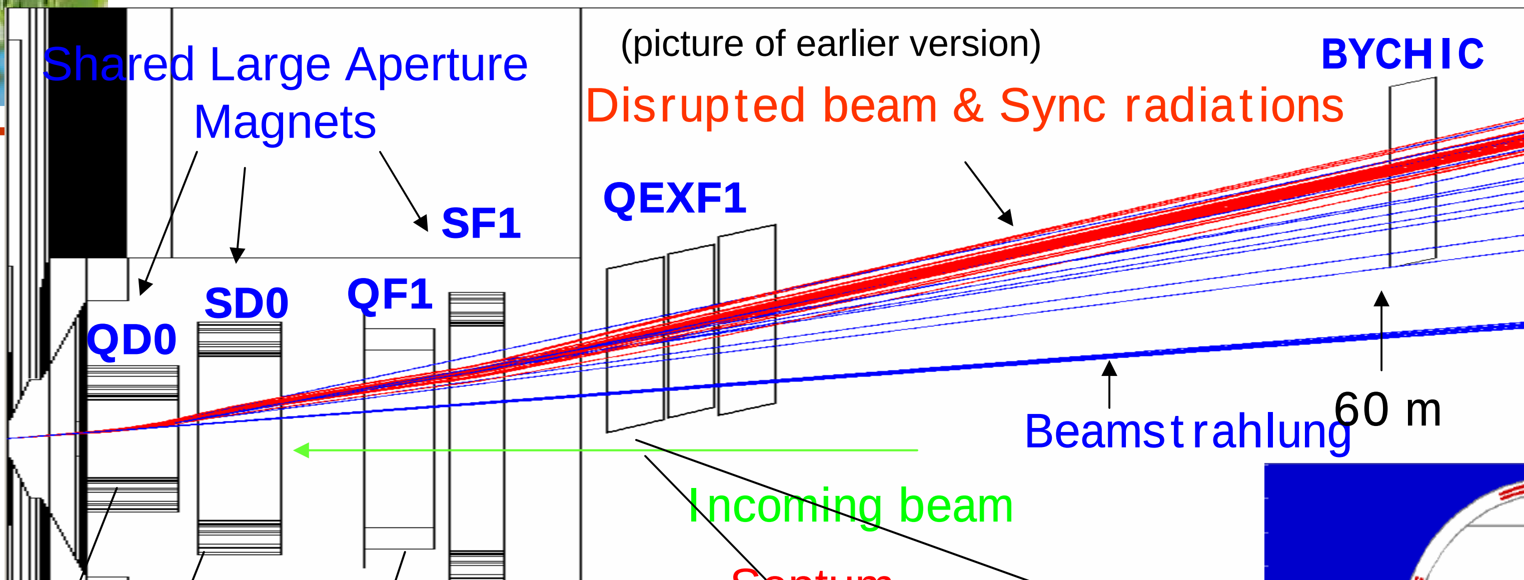
aperture 10mm=> 15mm to improve collimation depth. C.Spencer, Aug.18

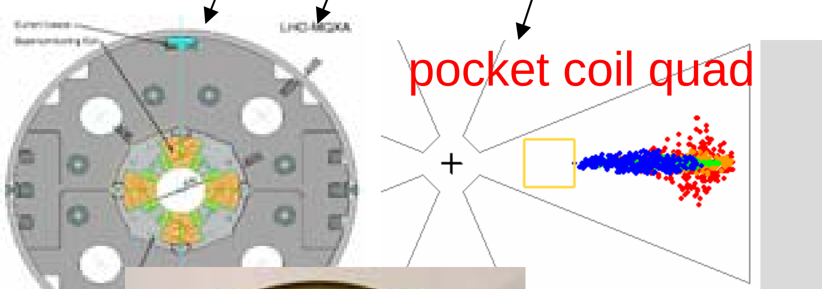
- FF and extraction line optimized simultaneously
- Quads and sextupoles in the FD optimized to
  - cancel FF chromaticity
  - focus the extracted beam
- Latest version works up to 1TeV with more conventional NbTi FD magnets (not Nb3Sn)



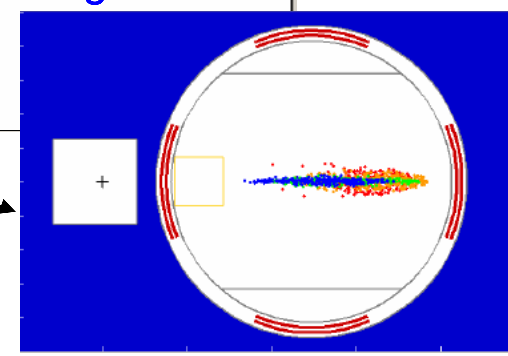
2mrad IP Extraction Line in Geant

SLAC-BNL-UK-France



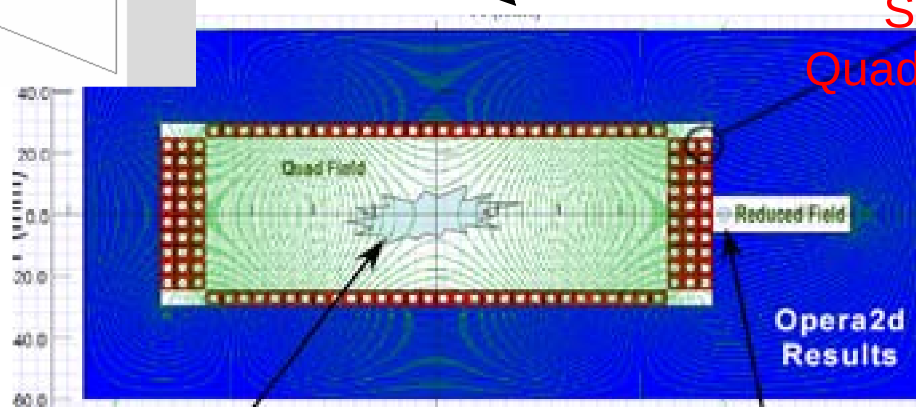


No beam & γ losses for nominal parameters



Rutherford cable SC quad and sextupole

Require R&D



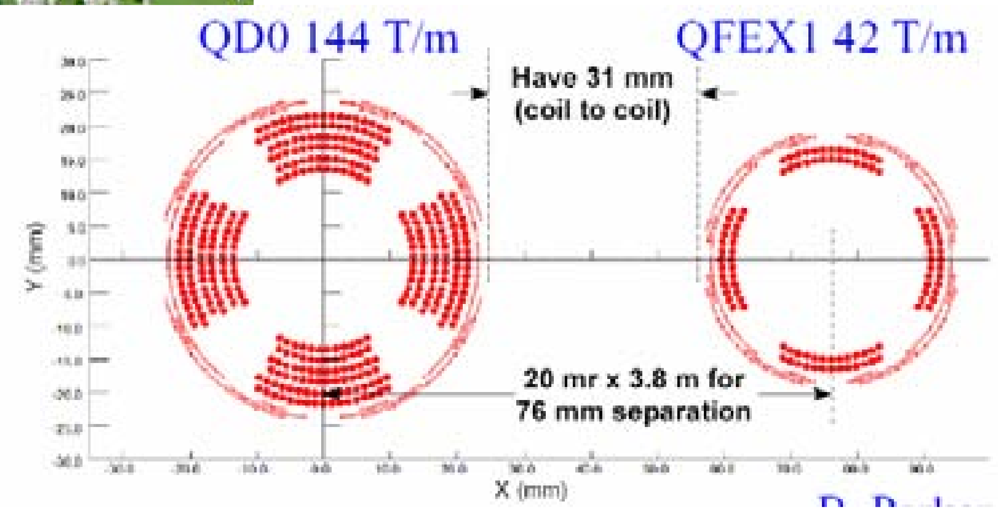
Super Septum Quad, B.Parker et al.)

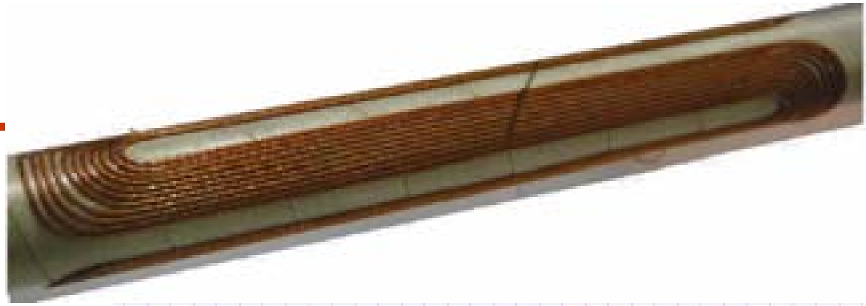
or

Warm Panofsky septum quad (C.Spencer)

Require R&D

Compact SC Final Doublet for 20mrad IR

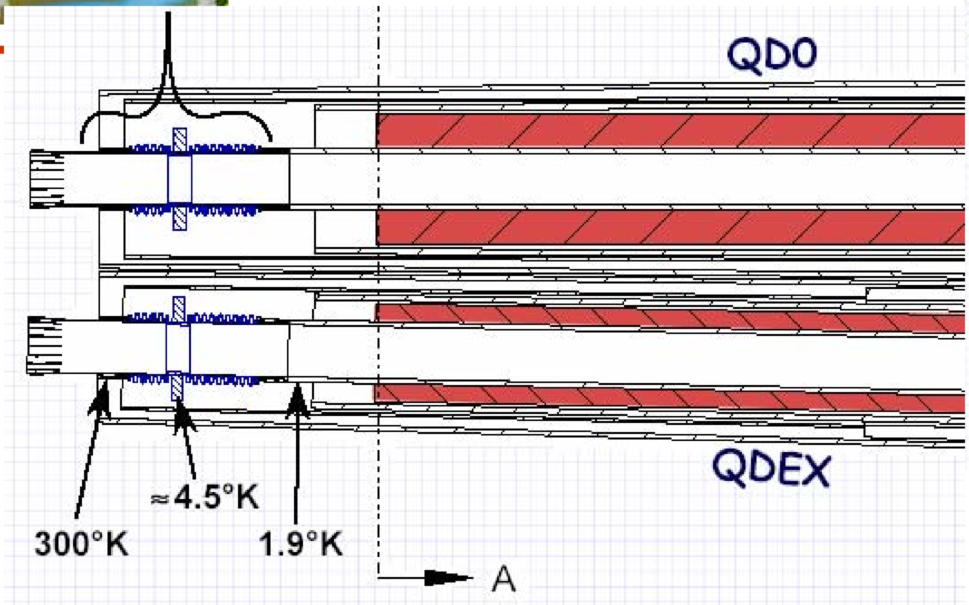


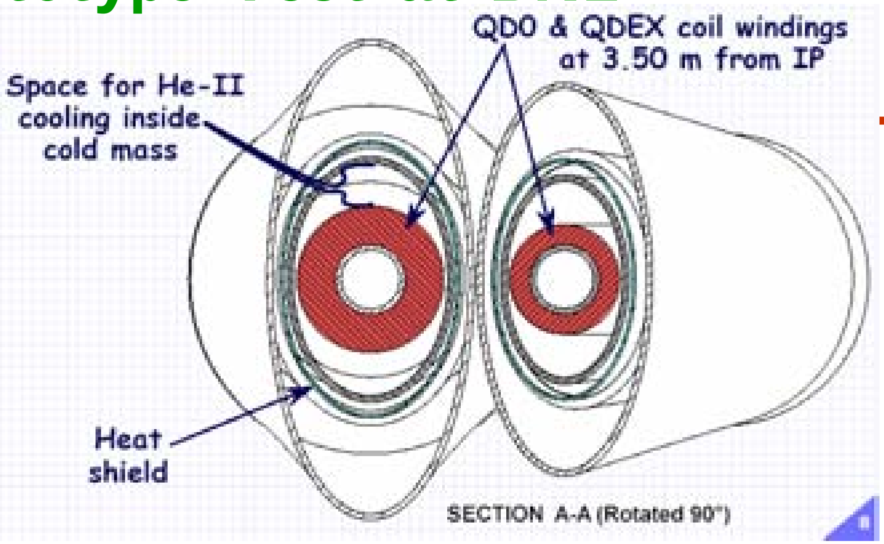


- Achievement in BNL direct wind technology allow to make even tighter bend radius => quad is more compact => allow to start the extraction quad at the same distance from IP as QD0

Ultrasonic heating bonds epoxy coated conductor to substrate on a support tube (tack in place).

Compact QD0 Mechanical & Cryo-engineering and Prototype Test at BNL





QT Quench Test Results

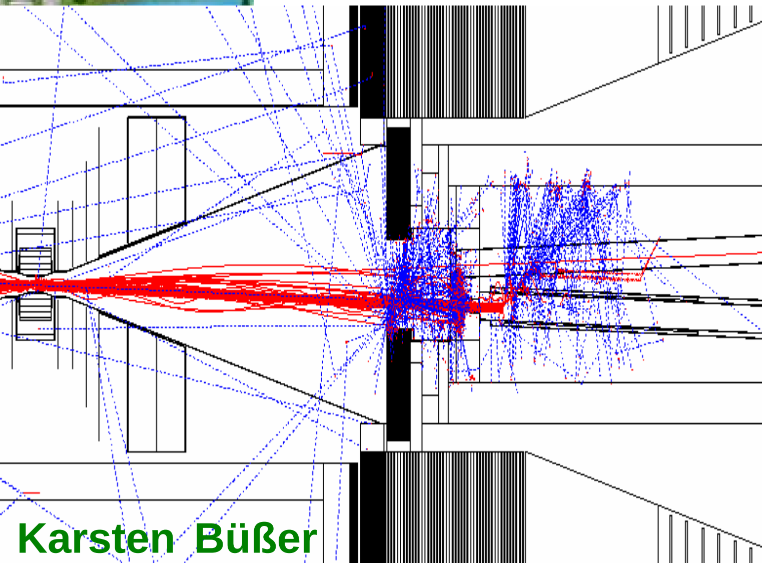
Background Solenoid (T)	Temp (°K)	Gradient (T/m)
3	4.30	158
4	4.22	139
5	4.22	134
6	3.00	137

380mm QD0 Test Prototype

Exceeded design goal !

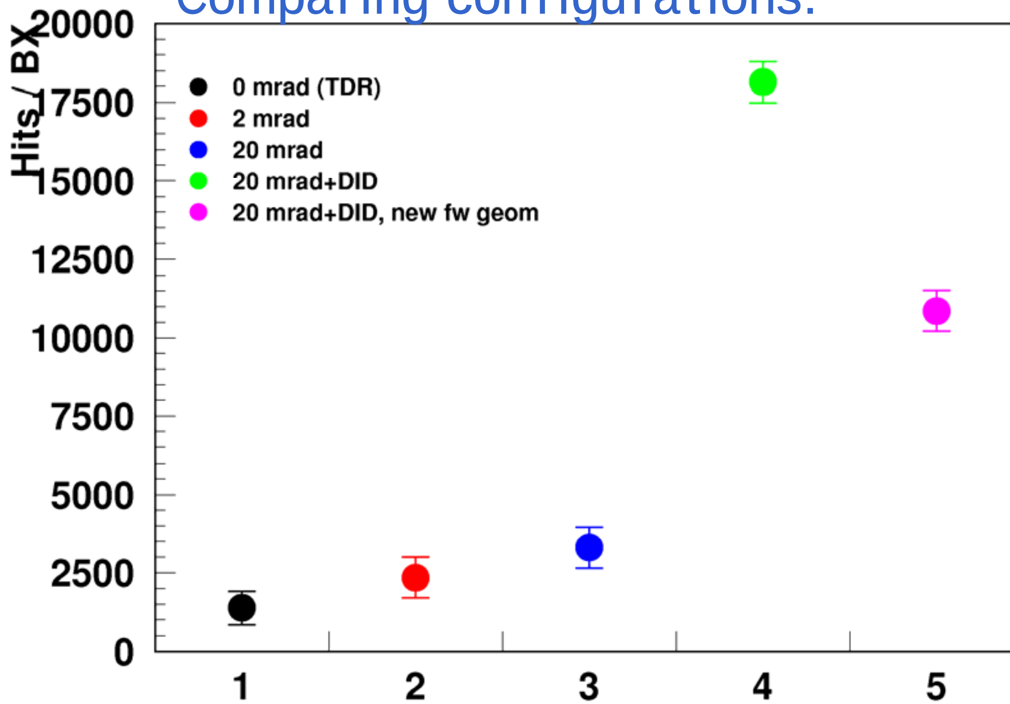
goal: 140T/m with 3T background field while cooled with pressurized He-II at 1.9K

20mrad & 2mrad IR comparison: Background: Hits in the TPC with Solenoid+DID



Origin of TPC photons:
pairs hit edge of LumiCal

Comparing configurations:

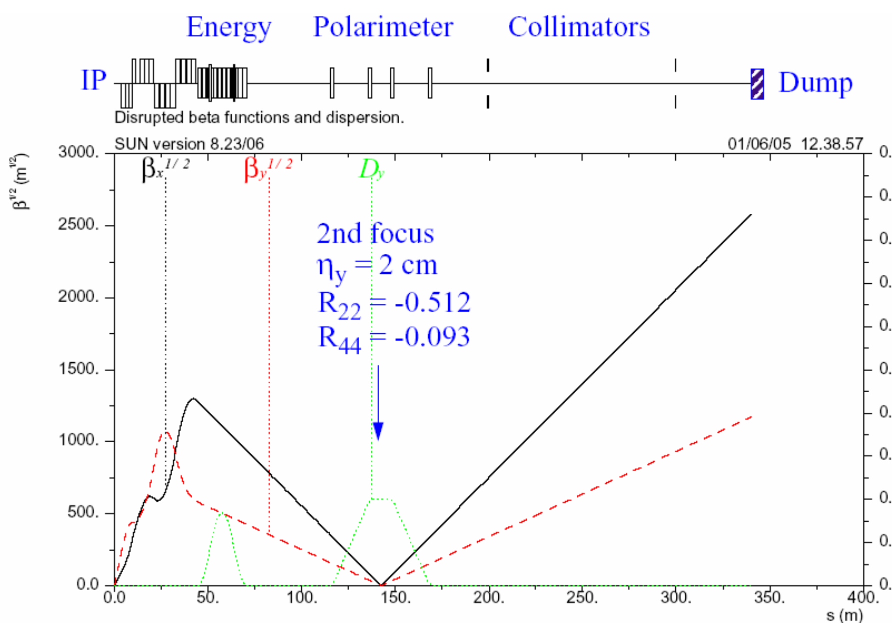


- Formed task force to come up with updated tolerances of detector systems (vetrex, TPC, etc) to background, based on experience of existing detectors => to be done during Snowmass
- Understand how details (e.g. fringe field of QD0) affect flow of pairs
- If still an issue -> DID switch off, less local compensation of IP y-angle

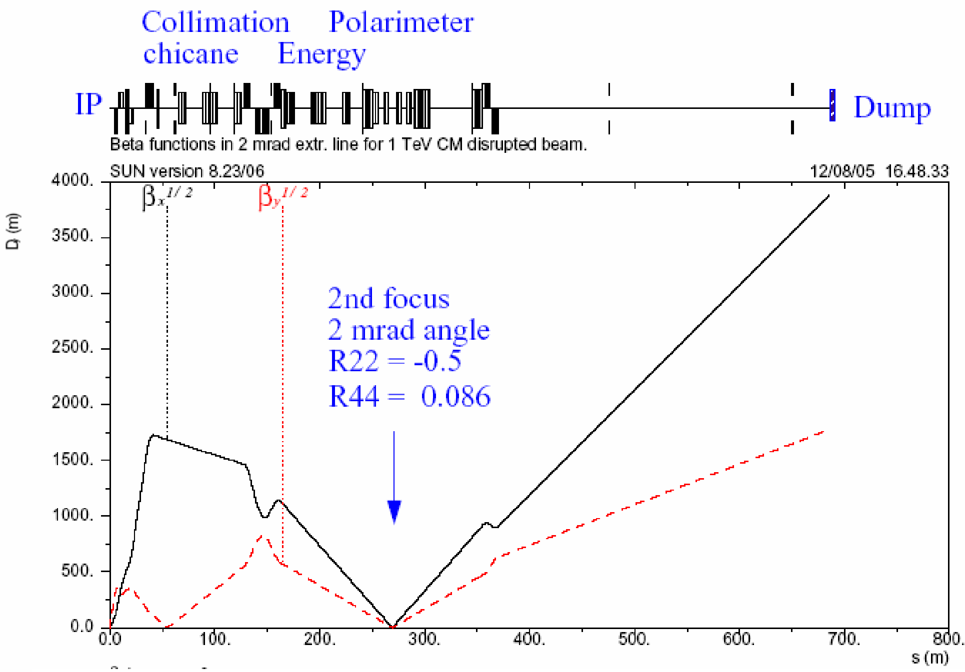
20mrad & 2mrad IR comparison: Lumi & diagnostics

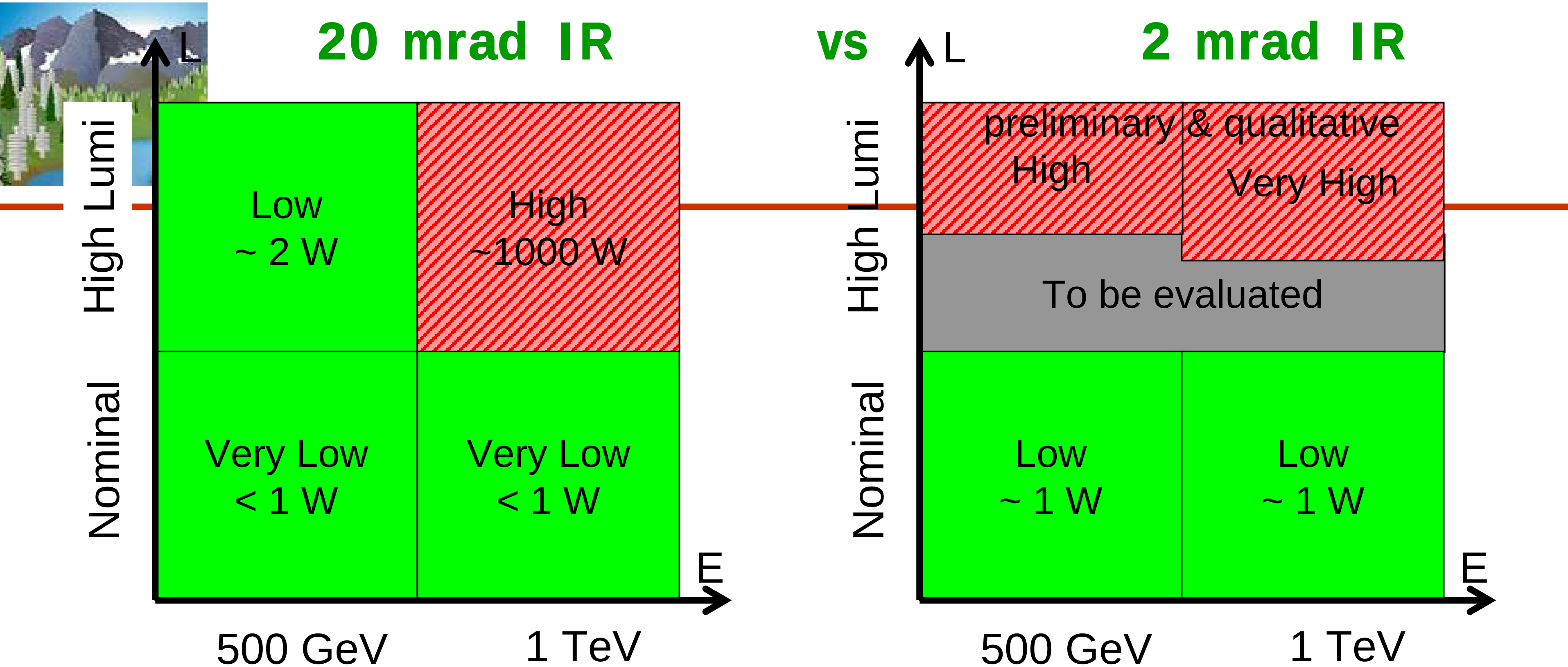
- Luminosity reach of IRs may be different
- Performance of downstream diagnostics may be different
- 20mrad likely the winner for both this criteria
- For Lumi, one of the limiting factors is losses of disrupted beam on SC elements of extraction line

20mrad extraction optics



2mrad extraction optics

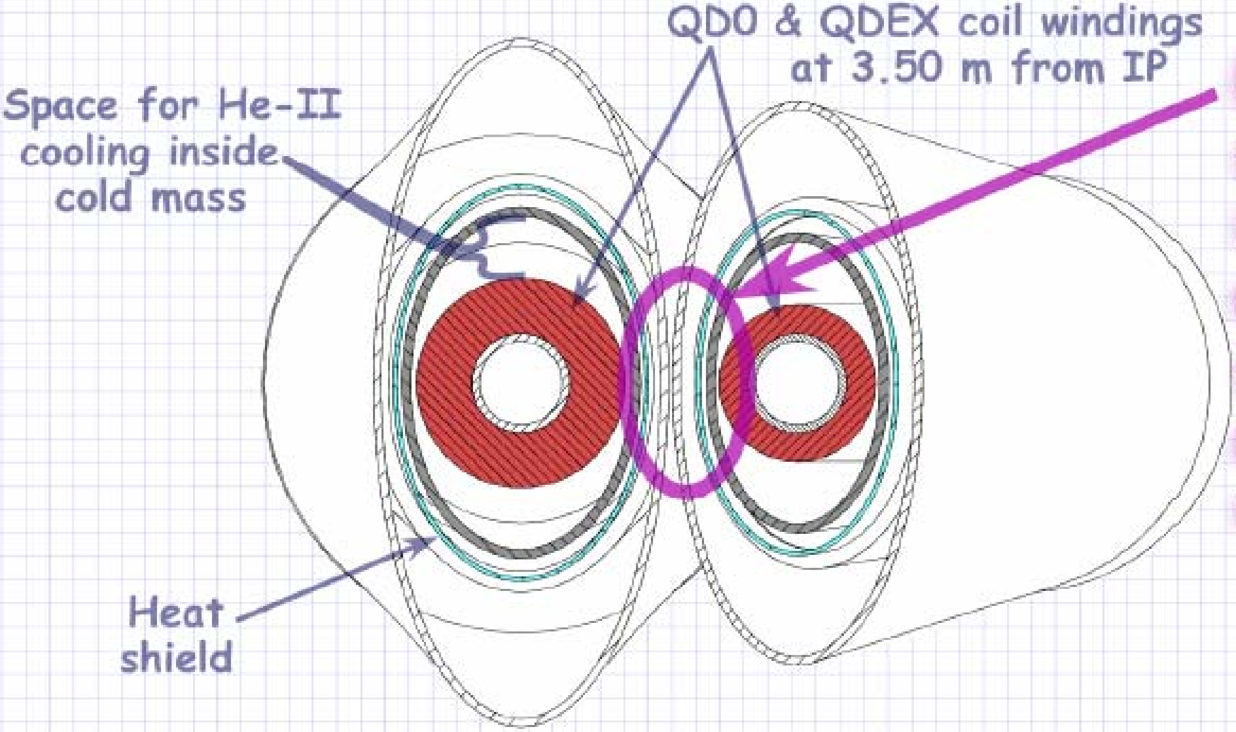




(Numbers in Watts show losses on SC FD magnets)

- Optimization of design and evaluation will continue, but clear that disrupted beam losses on SC elements limit performance
- Better detector hermeticity & background of 2mrad IR comes together with lower luminosity reach
- (20mrad IR works well with New High L parameters)
  (2mrad to be evaluated)

Crossing Angle Lower Limits Using Compact Superconducting Magnets



Eliminating some of the structure between the incoming and extraction apertures would allow smaller crossing angles but does have consequences which must be studied.

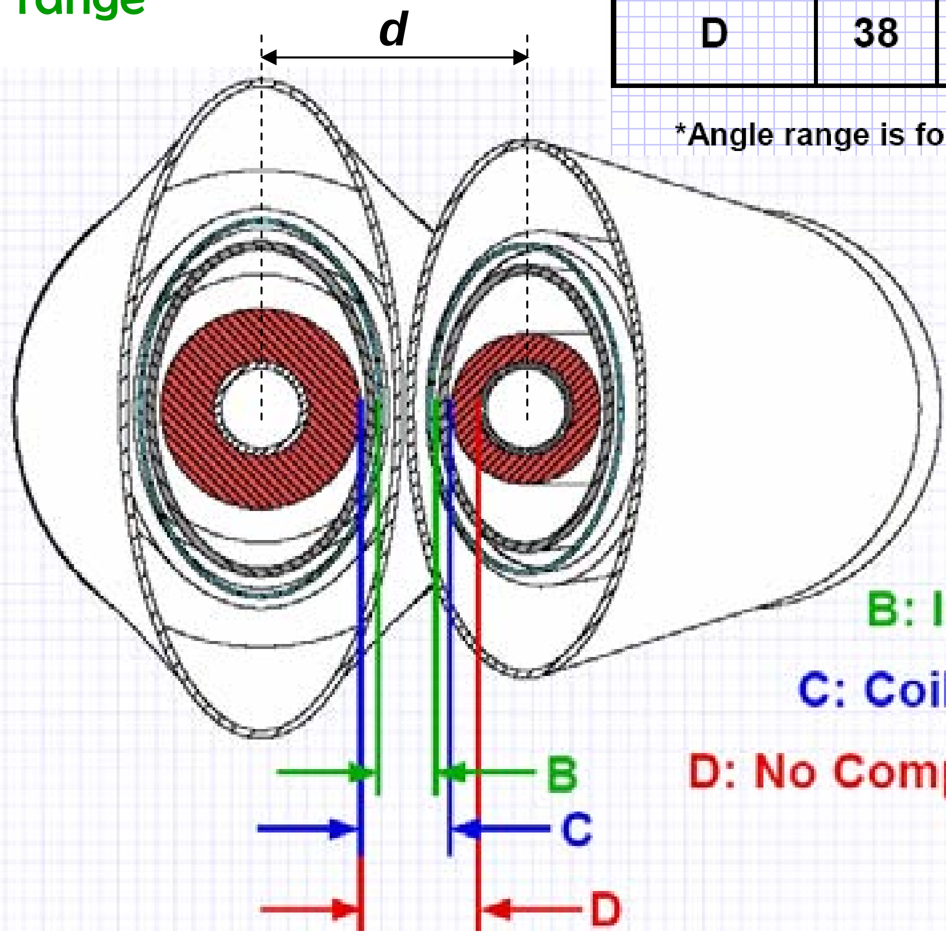
Brett Parker, BNL

Reference 20 mr X-ing Angle Design

Will proceed with studies of 10-12mrad range

Scenario	*d* (mm)	Angle Range* (mr)	Issues	Confidence Level
A	70	20 - 15.5	Standard	Recommended
B	53	15 - 11.8	+ Cold Support	Probably OK
C	44	12.5 - 9.8	+ Stronger Comp'	Needs Study
D	38	10.8 - 8.4	+ Give Up Comp'	Highest Risk

Angle range is for 3.5 m < L < 4.5 m



Brett Parker, BNL

$$\theta_{min} = d / L^*$$

A: Reference Design

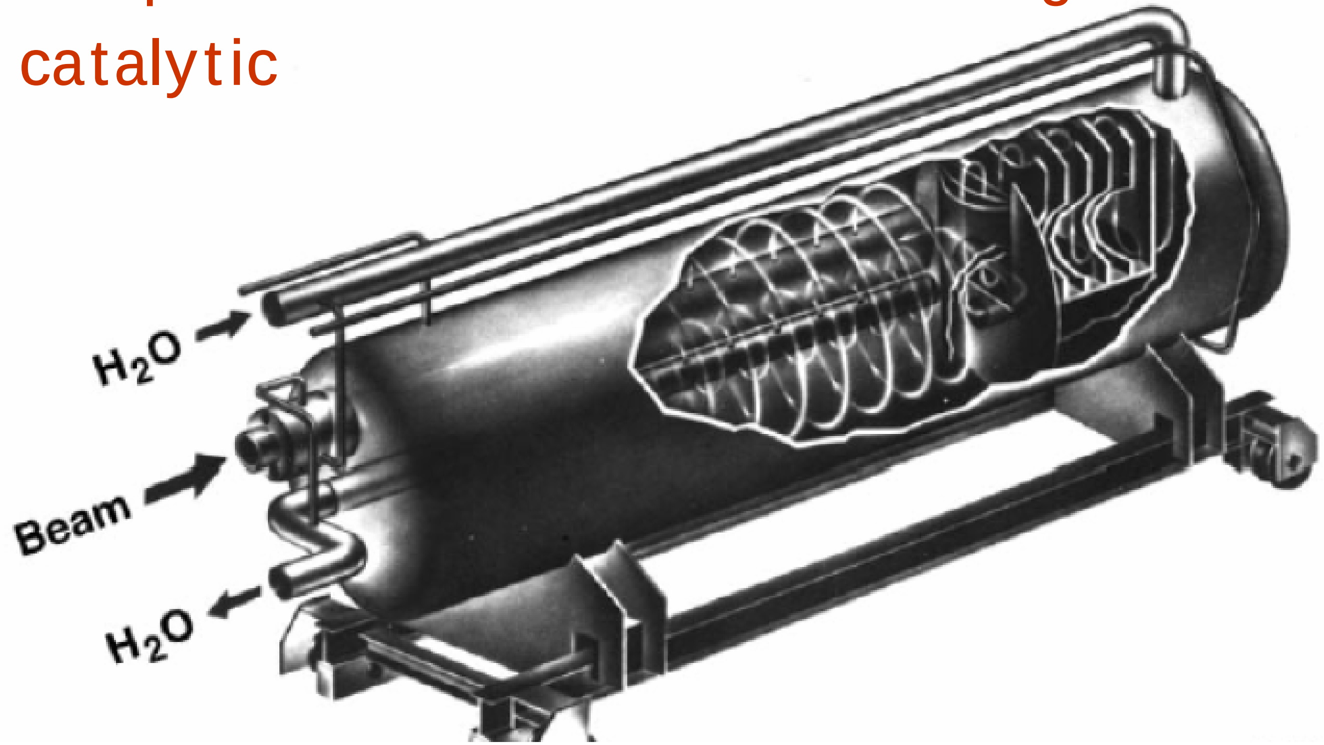
B: Independent Cold Mass

C: Coils Touching

D: No Compensation

Beam dump for 18MW beam

- Water vortex
- Window, 1mm thin, ~30cm diameter hemisphere
- Raster beam with dipole coils to avoid water boiling
- Deal with H, O, catalytic recombination
- etc.




Thank you for attention !
picture taken in 2005