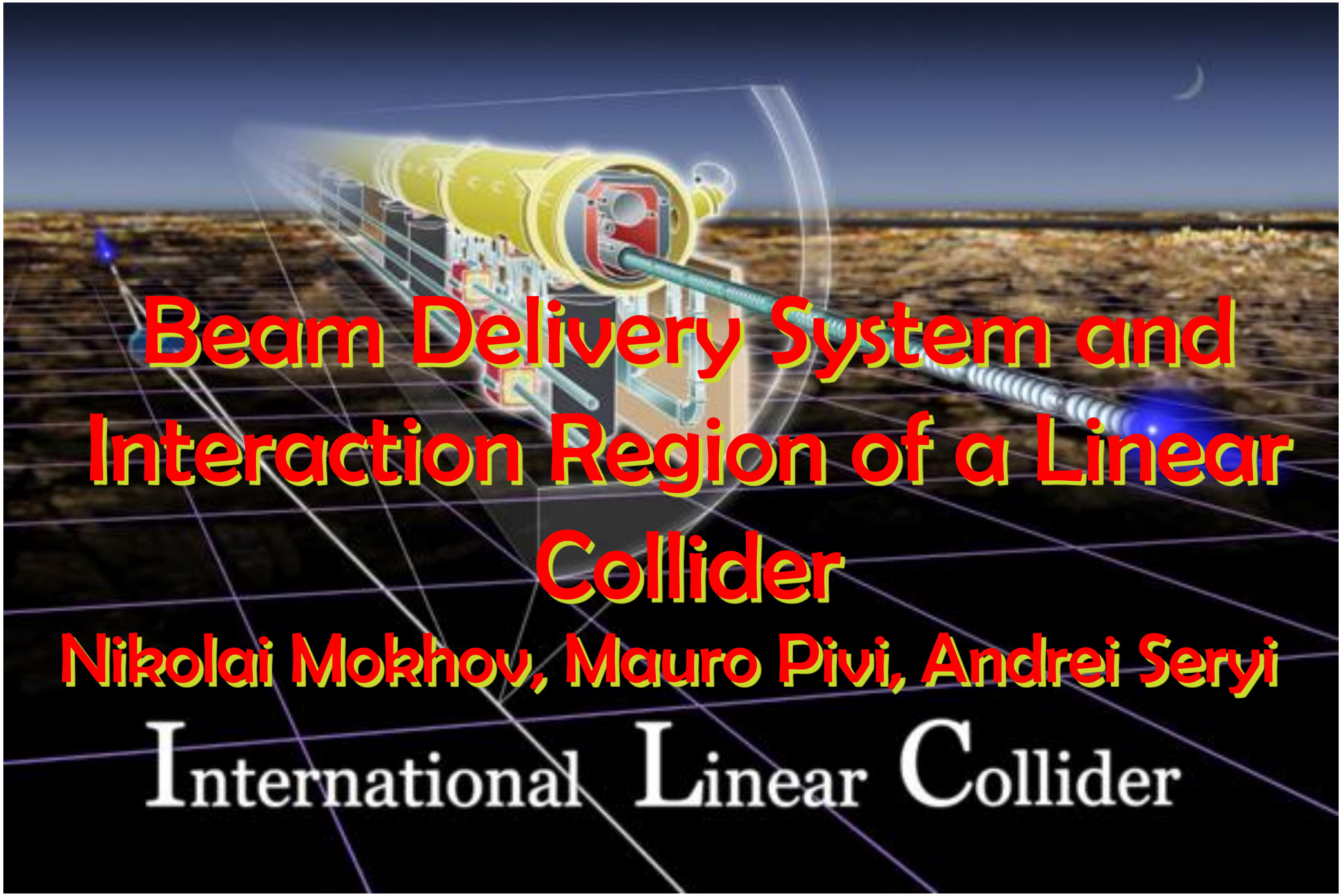
Beam Delivery System and Interaction Region of a Linear Collider

Nikolai Mokhov, Mauro Pivi, Andrei Seryi



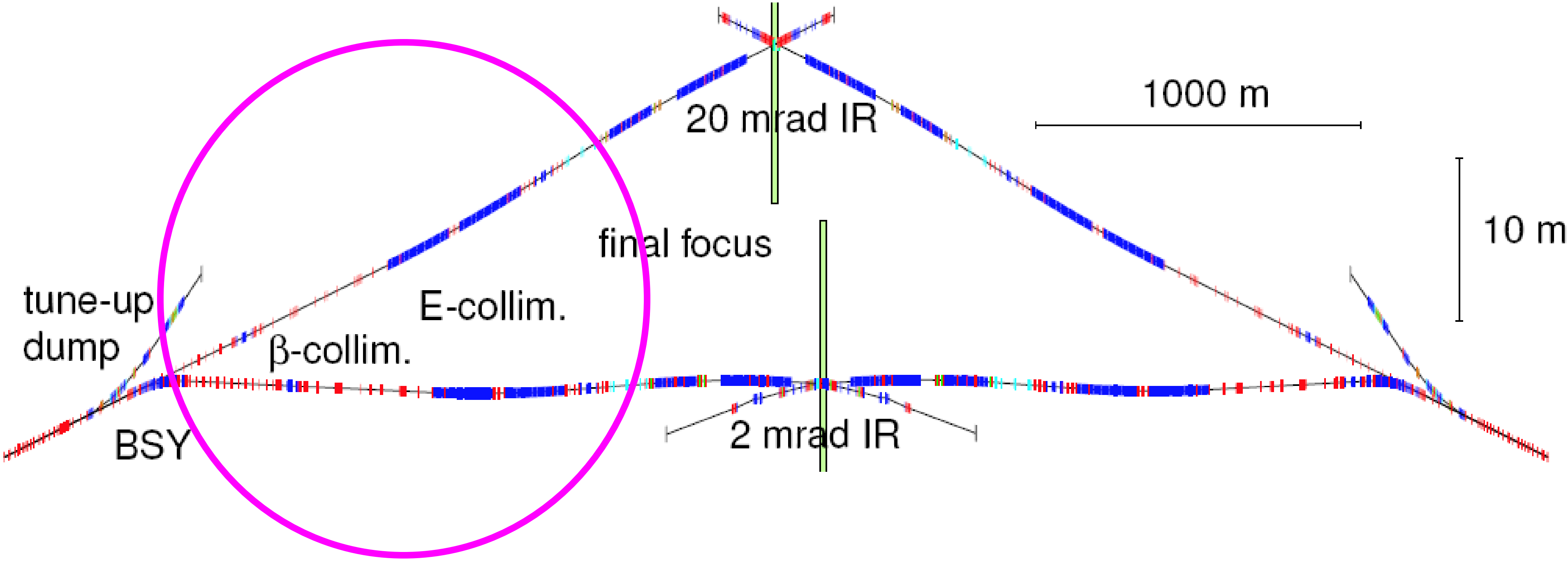
The US Particle Accelerator School
January, 2011 in Norfolk, Virginia

BEAM DELIVERY

PIVI, SERYI & MOKHOV

COLLIMATION (& FF) BEAM DYNAMICS Lecture

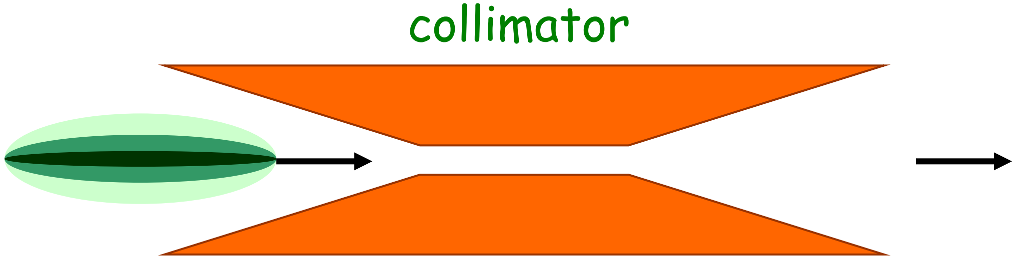
BDS subsystems

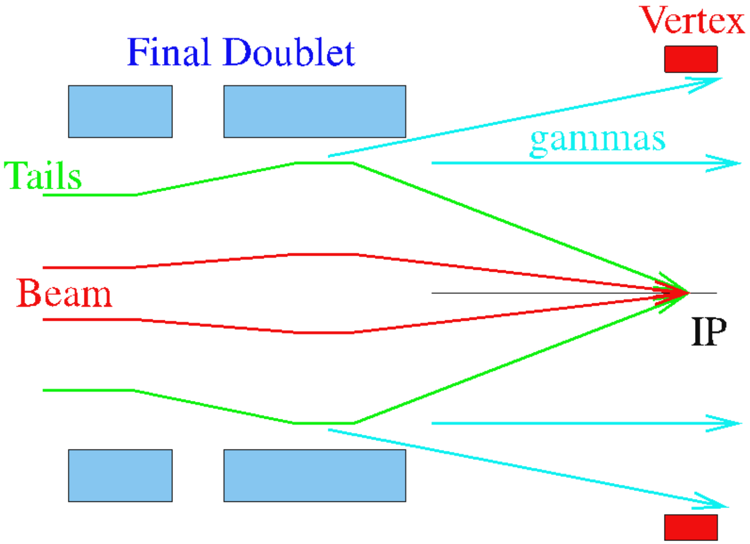


Collimation, tail folding octupoles

More details on collimation

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

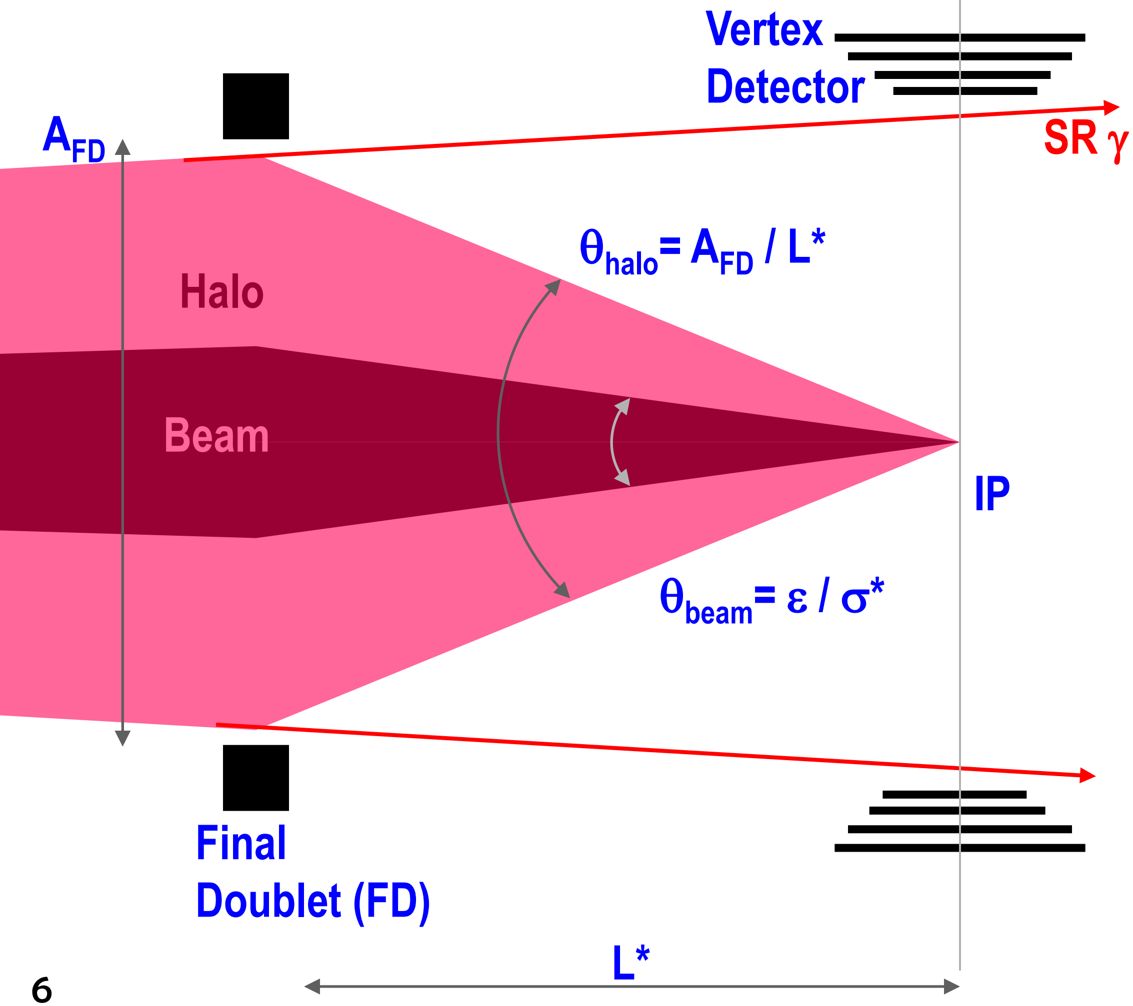




- Collimation depth (esp. in x) can be only ~10 or even less
- It is not unlikely that not only halo (1e-3 – 1e-6 of the beam) but full errant bunch(s) would hit the collimator

Beam halo & collimation

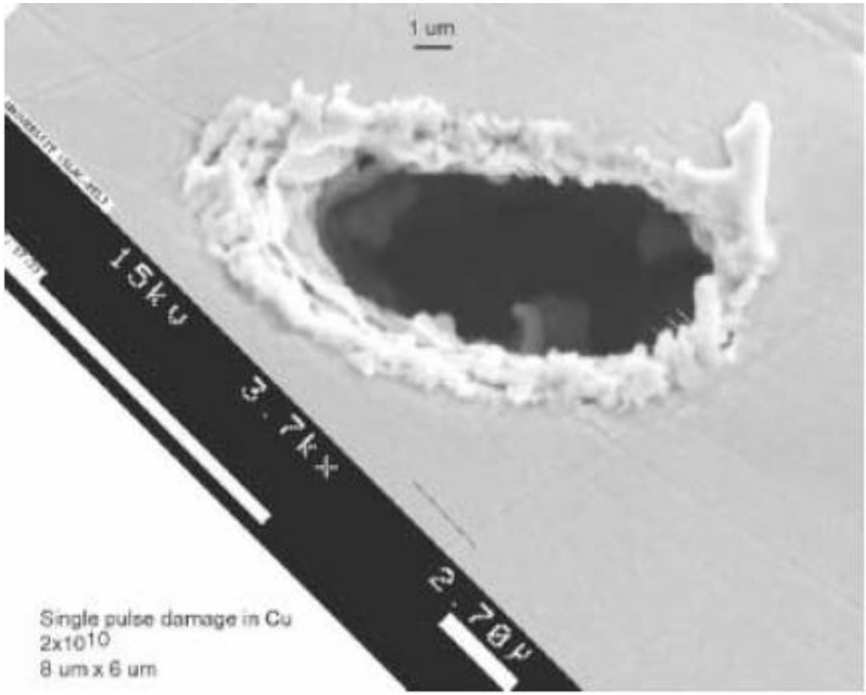
- Even if final focus does not generate beam halo itself, the halo may come from upstream and need to be collimated



- 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.

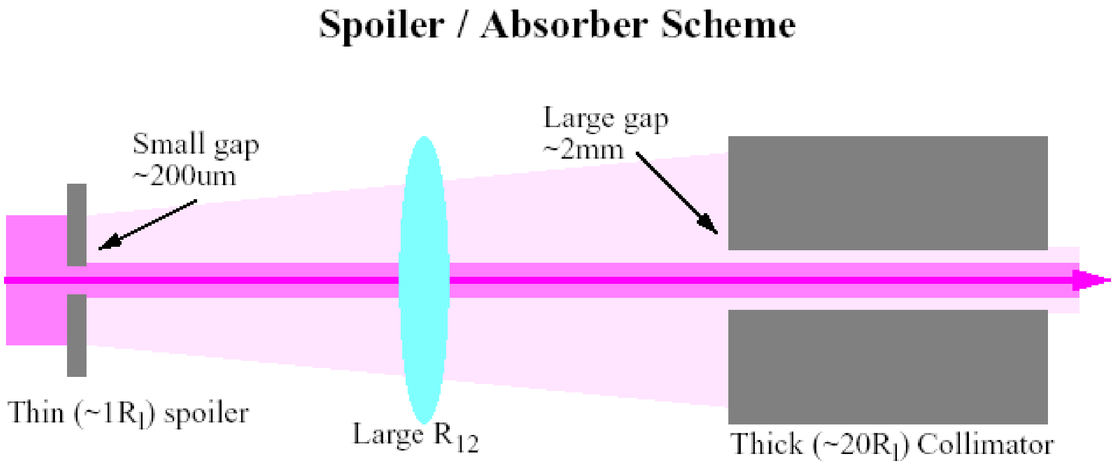
MPS and collimation design

- 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

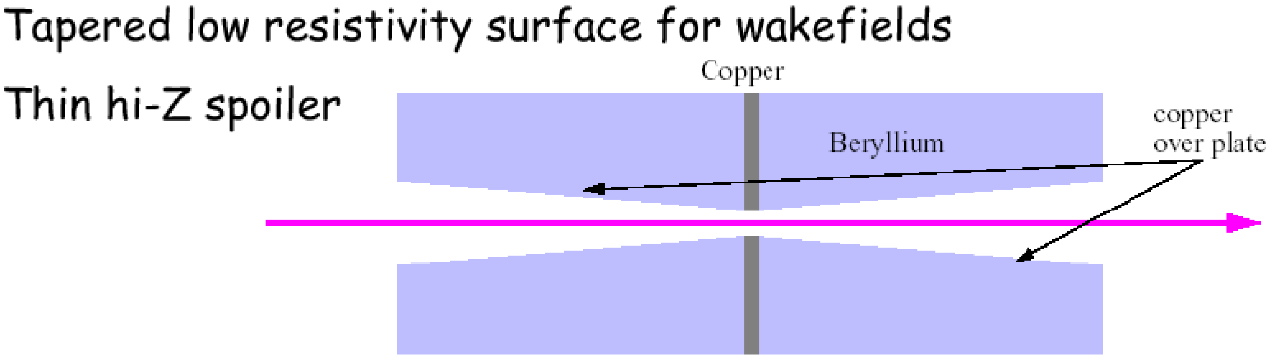


Picture from beam damage experiment at FFTB. The beam was 30GeV, 3-20x10^9 e-, 1mm bunch length, s~45-200um^2. Test sample is Cu, 1.4mm thick. Damage was observed for densities > 7x10^{14}e-/cm^2. Picture is for 6x10^{15}e-/cm^2

Spoiler-Absorber & spoiler design

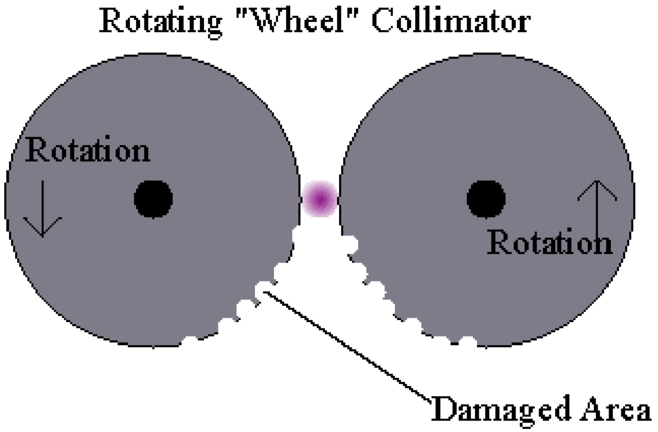


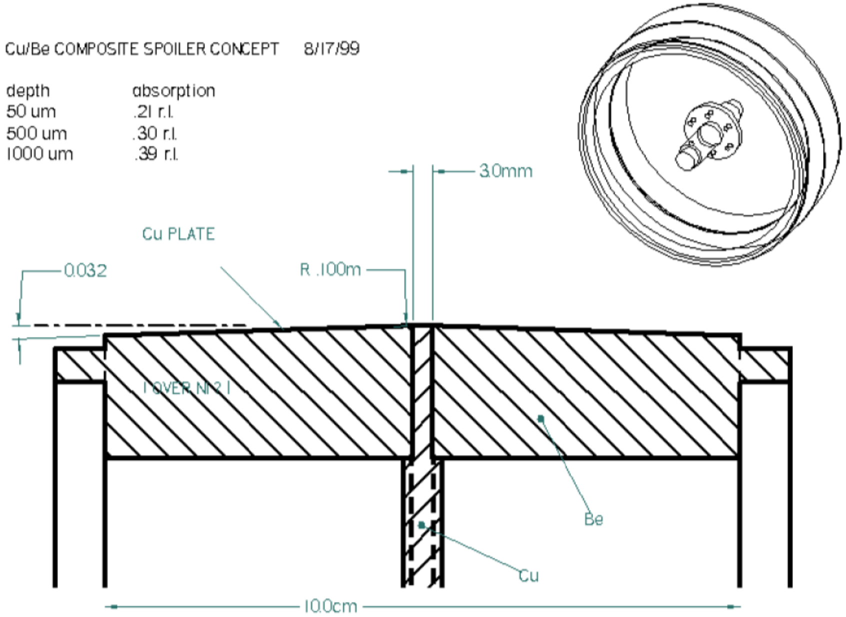
Thin spoiler increases beam divergence and size at the thick absorber already sufficiently large. Absorber is away from the beam and contributes much less to wakefields.



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.

Renewable spoilers

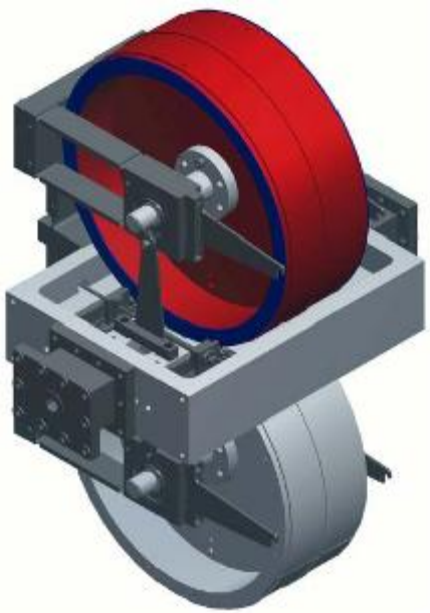



Cu/Be COMPOSITE SPOILER CONCEPT 8/17/99

depth	absorption
50 um	.21 r.l.
500 um	.30 r.l.
1000 um	.39 r.l.

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.

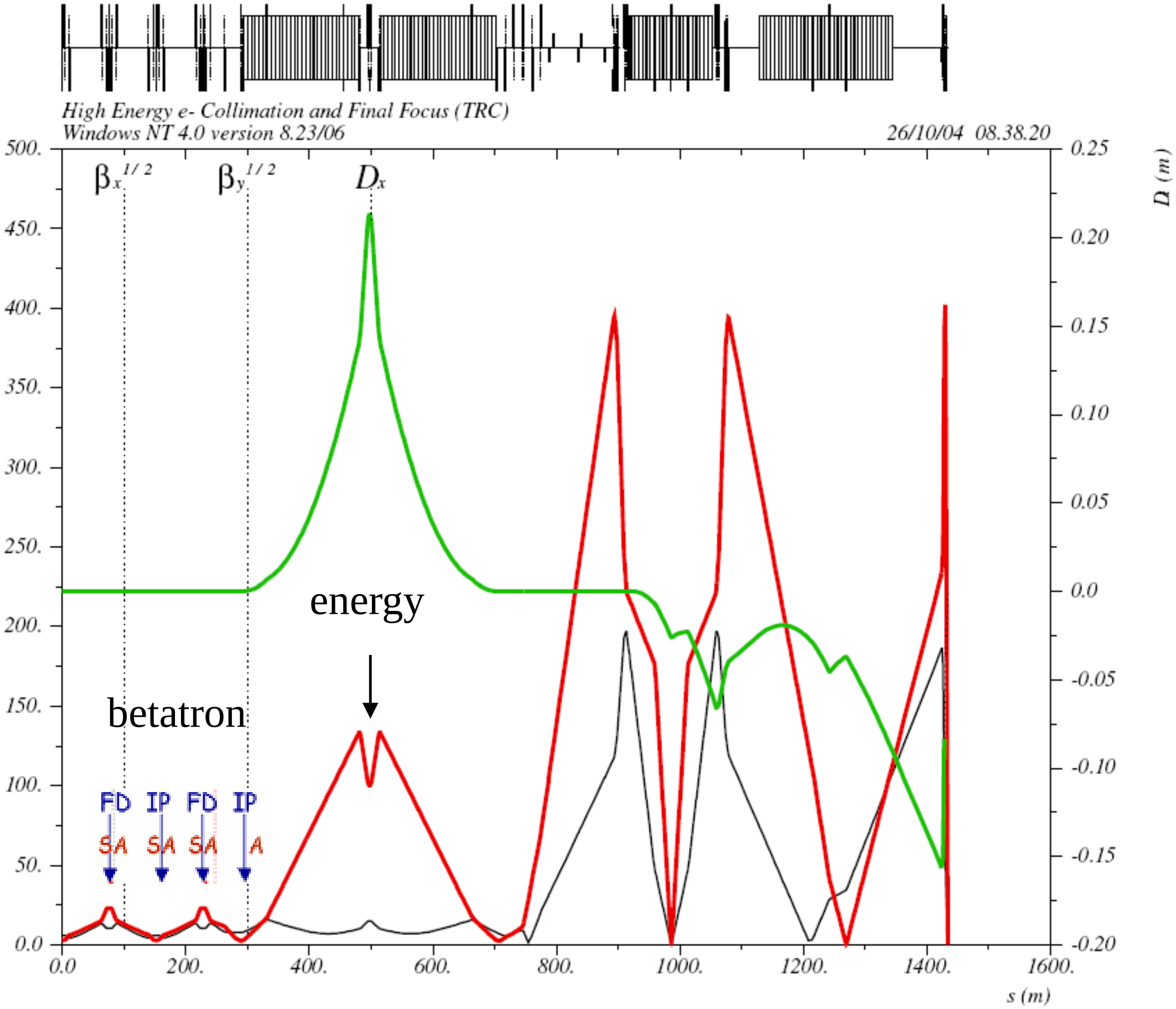


Survivable and consumable spoilers

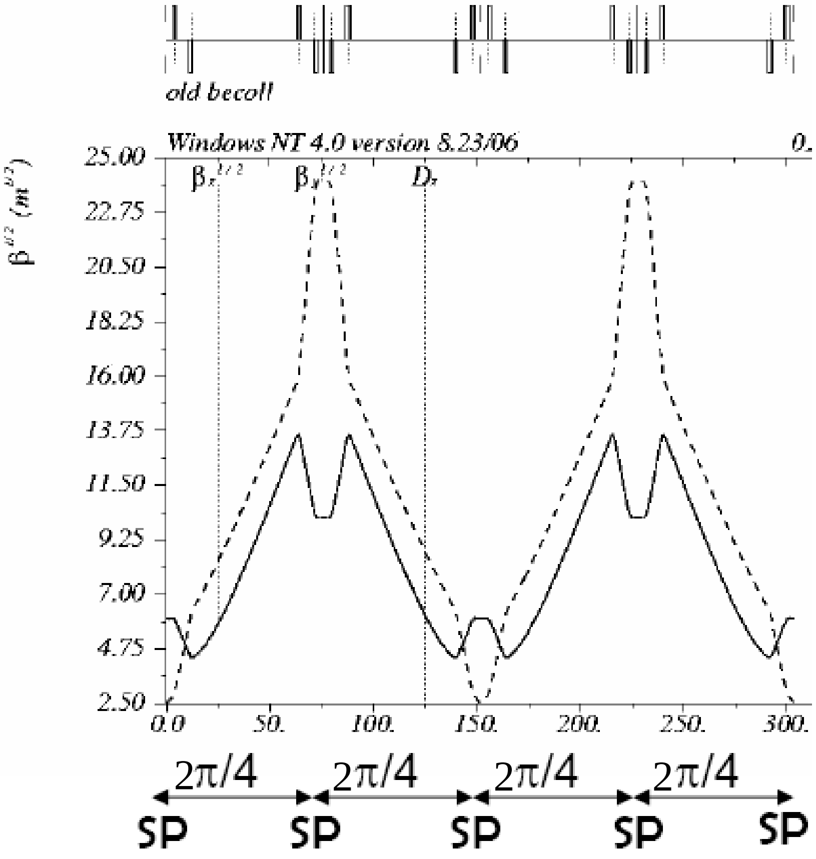
- A critical parameter is number of bunches #N that MPS will let through to the spoiler before sending the rest of the train to emergency extraction
- If it is practical to increase the beam size at spoilers so that spoilers survive #N bunches, then they are survivable
- Otherwise, spoilers must be consumable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

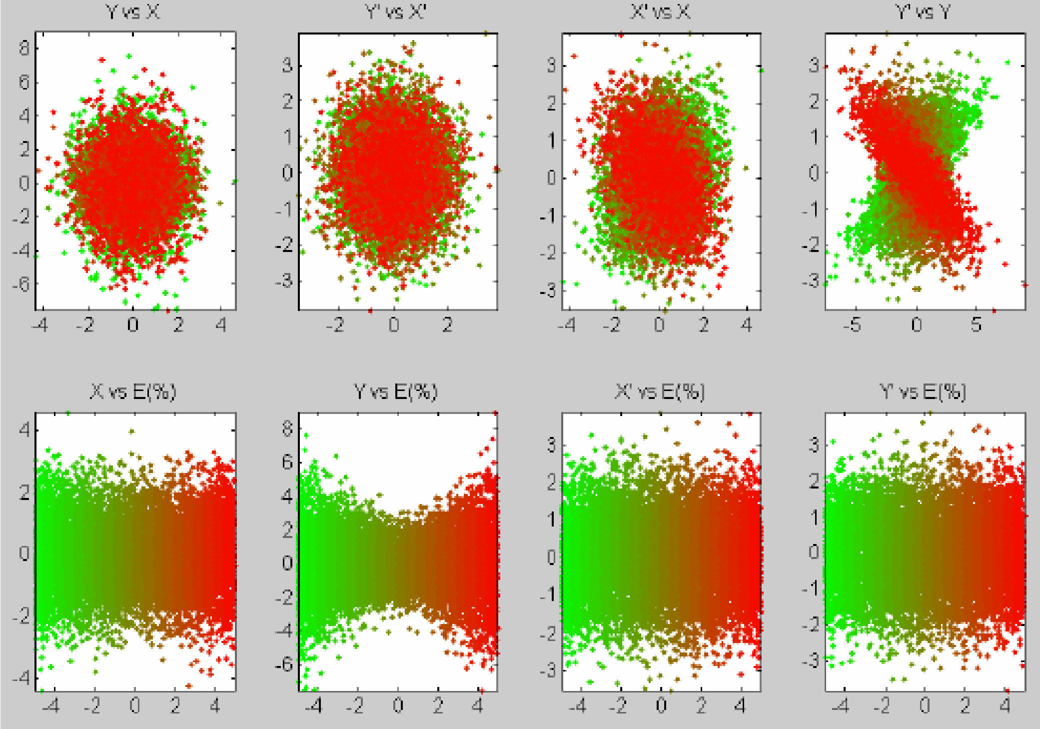
BDS with renewable spoilers

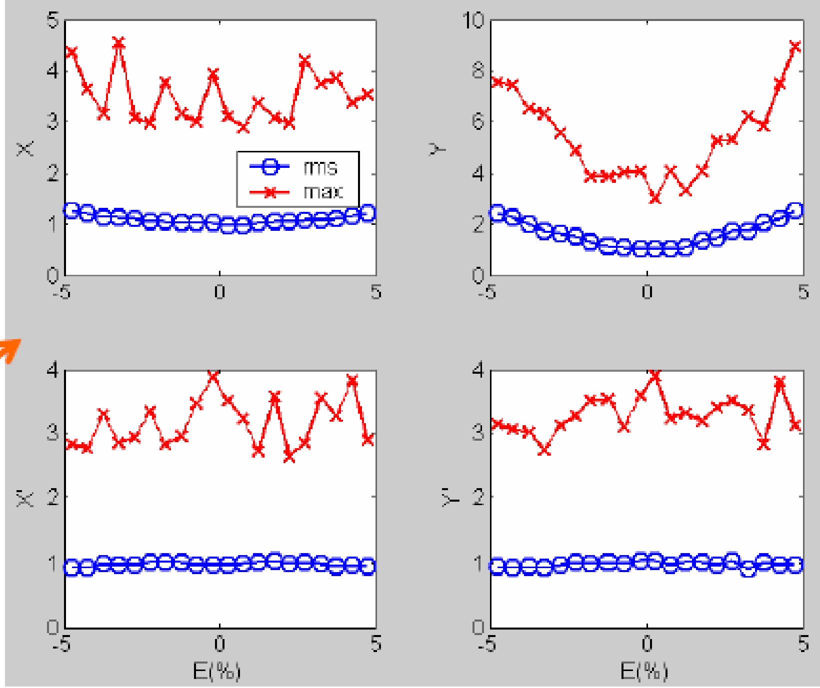
- Location of spoiler and absorbers is shown
- Collimators were placed both at FD betatron phase and at IP phase
- Two spoilers per FD and IP phase
- Energy collimator is placed in the region with large dispersion
- Secondary clean-up collimators located in FF part
- Tail folding octupoles (see below)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



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

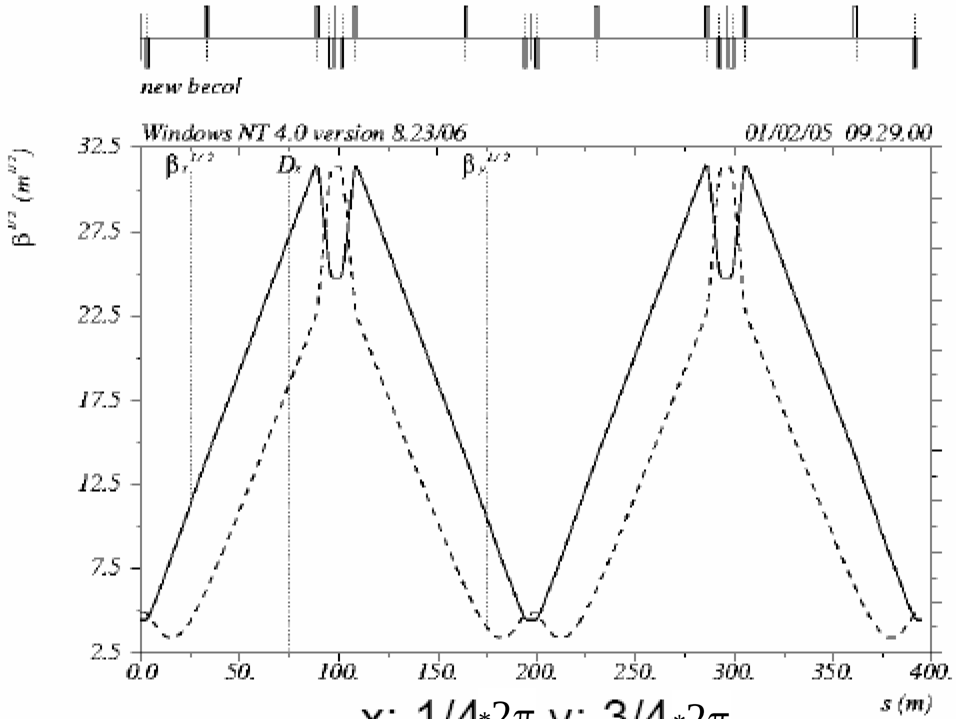






- **NLC beta-collimator optimized for consumable spoilers**
- **At max: $\beta_x * \beta_y$ = 60,000 m^2**

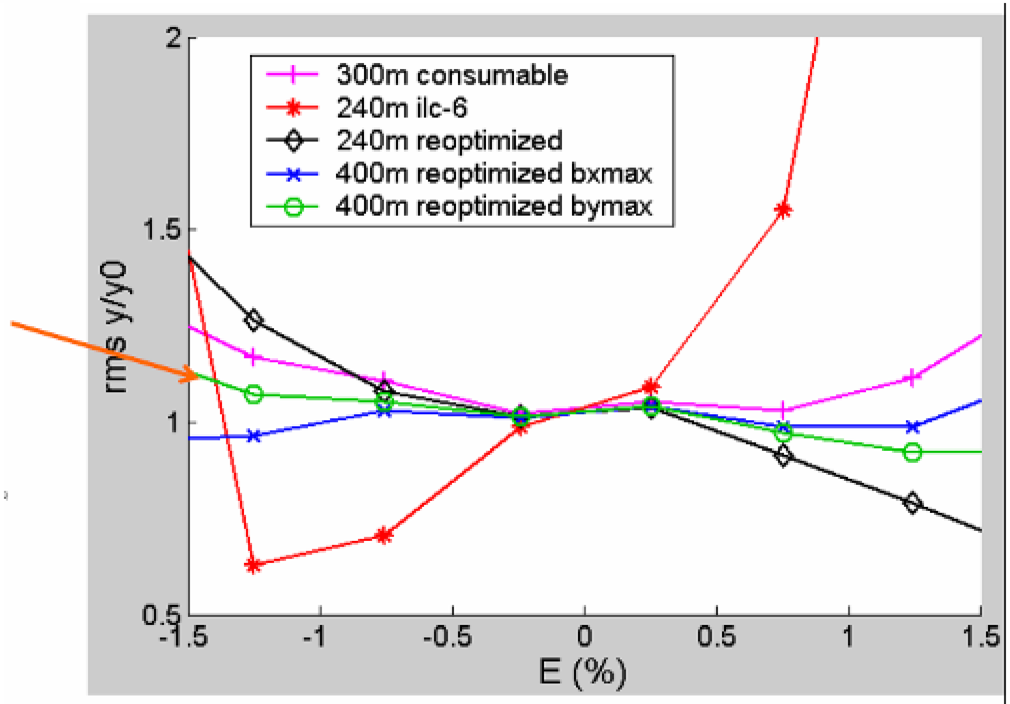
Beam (normalized to Xo) at the exit of the collimator

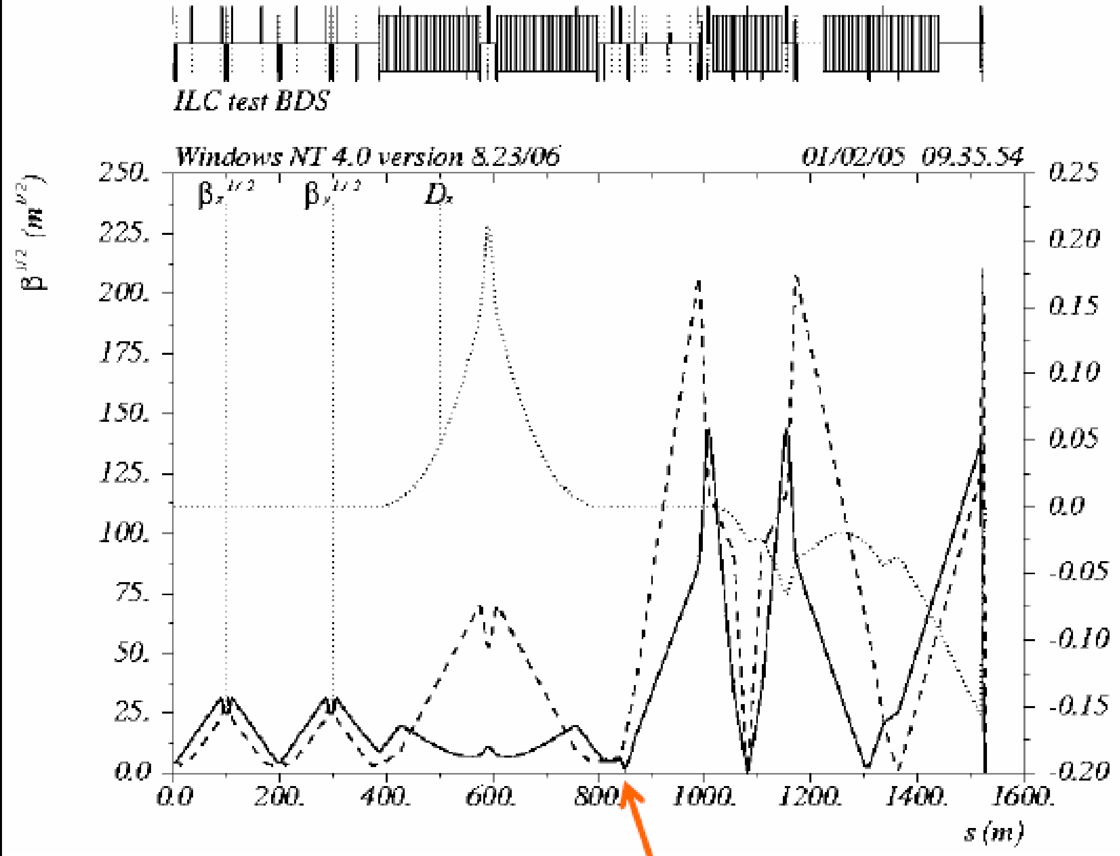


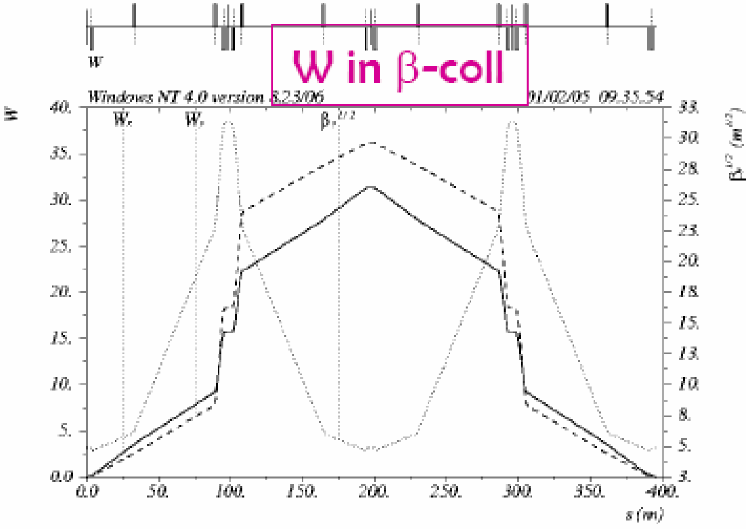
x: 1/4$*2\pi$ y: 3/4$*2\pi$

SP ⟷ SP

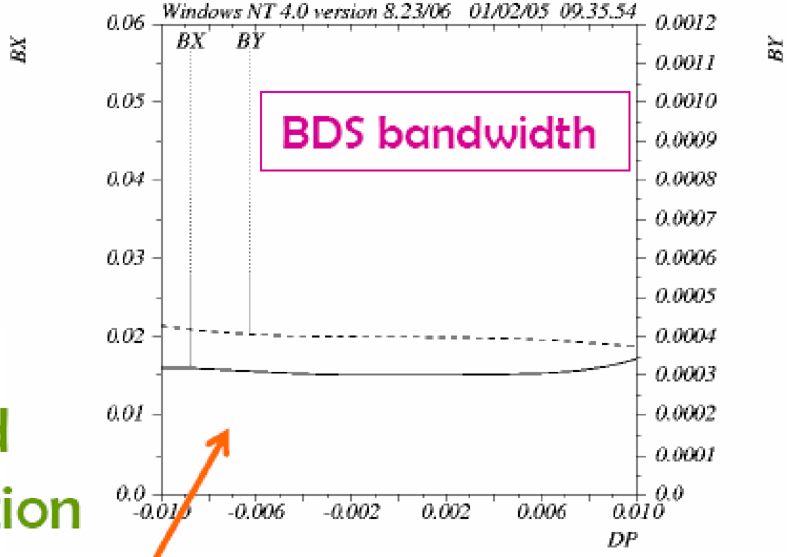
- **At max: $\beta_x * \beta_y$ = 600,000 m^2 suitable for passive survival spoilers**







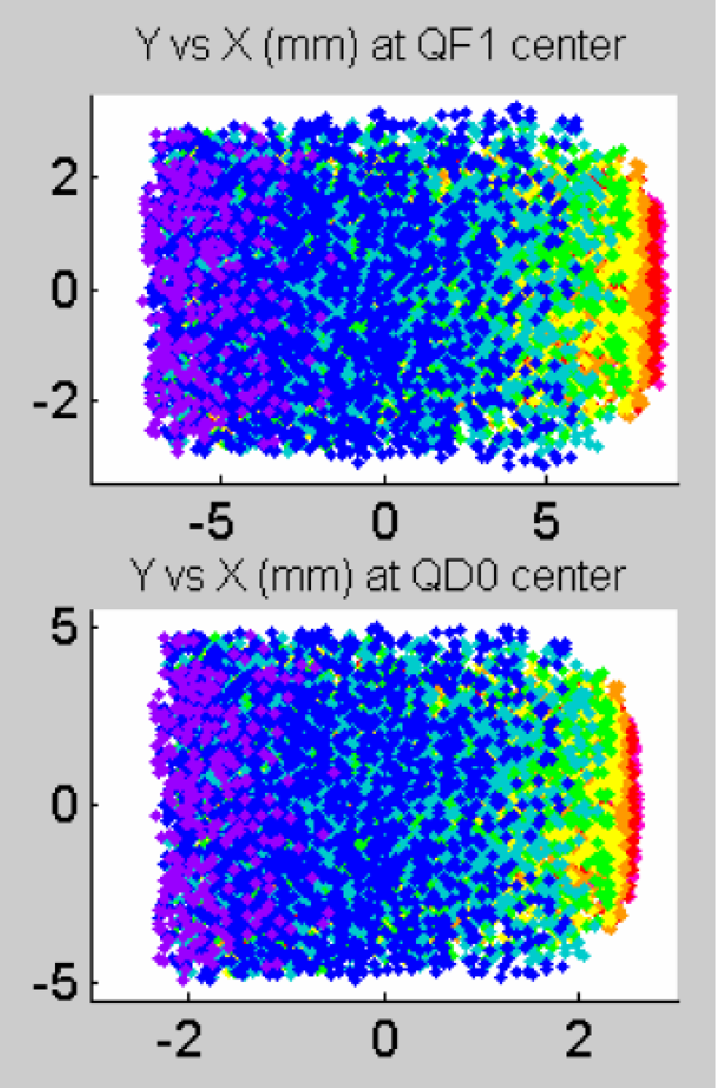
W in β-coll



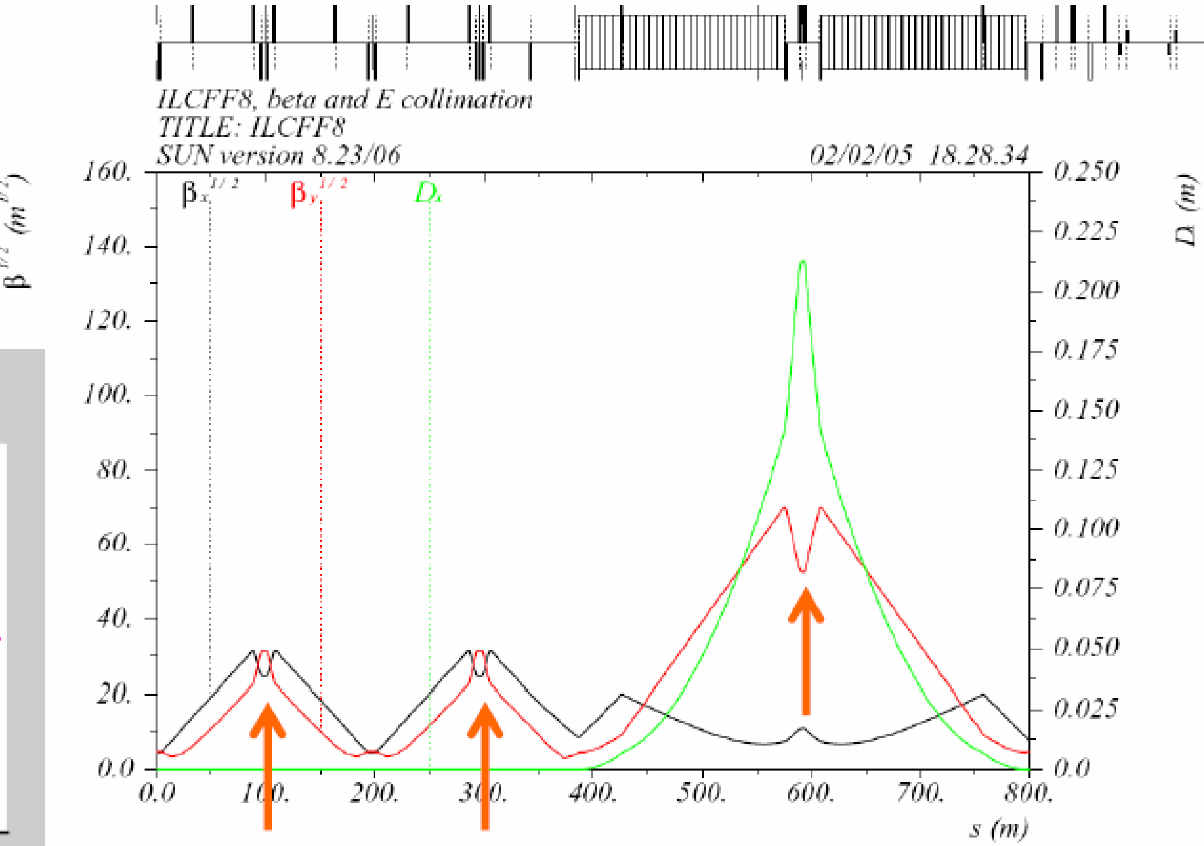
BDS bandwidth

- The E-spectrometer is being inserted here (plus ~50m), but this modification is not yet ready
- Improved b-collimator makes it easier to optimize IP bandwidth as well

Collimation


Y vs X (mm) at QF1 center

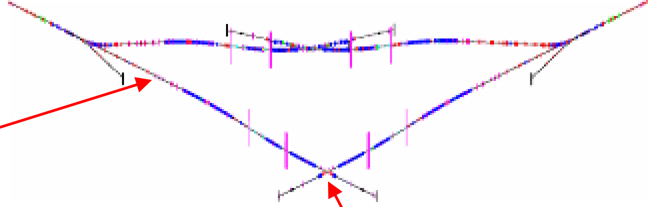
Y vs X (mm) at QD0 center

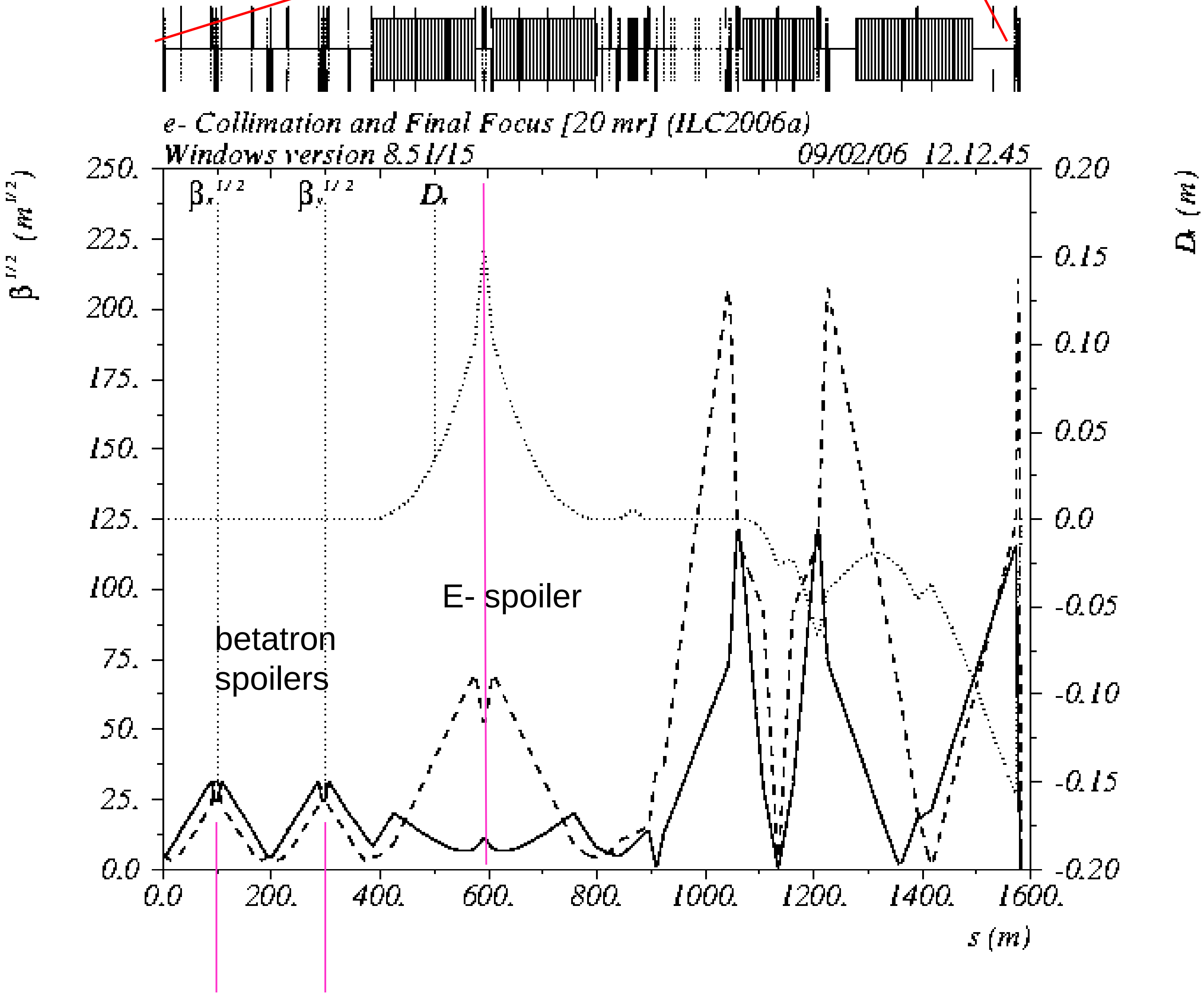


- SP2 & SP3 are at 12*75 σ, SPE at +-1.5%
- With black spoilers, the halo at FD has sharp edge
- Performance with scattering and full set of collimators is being evaluated by Fermilab colleagues

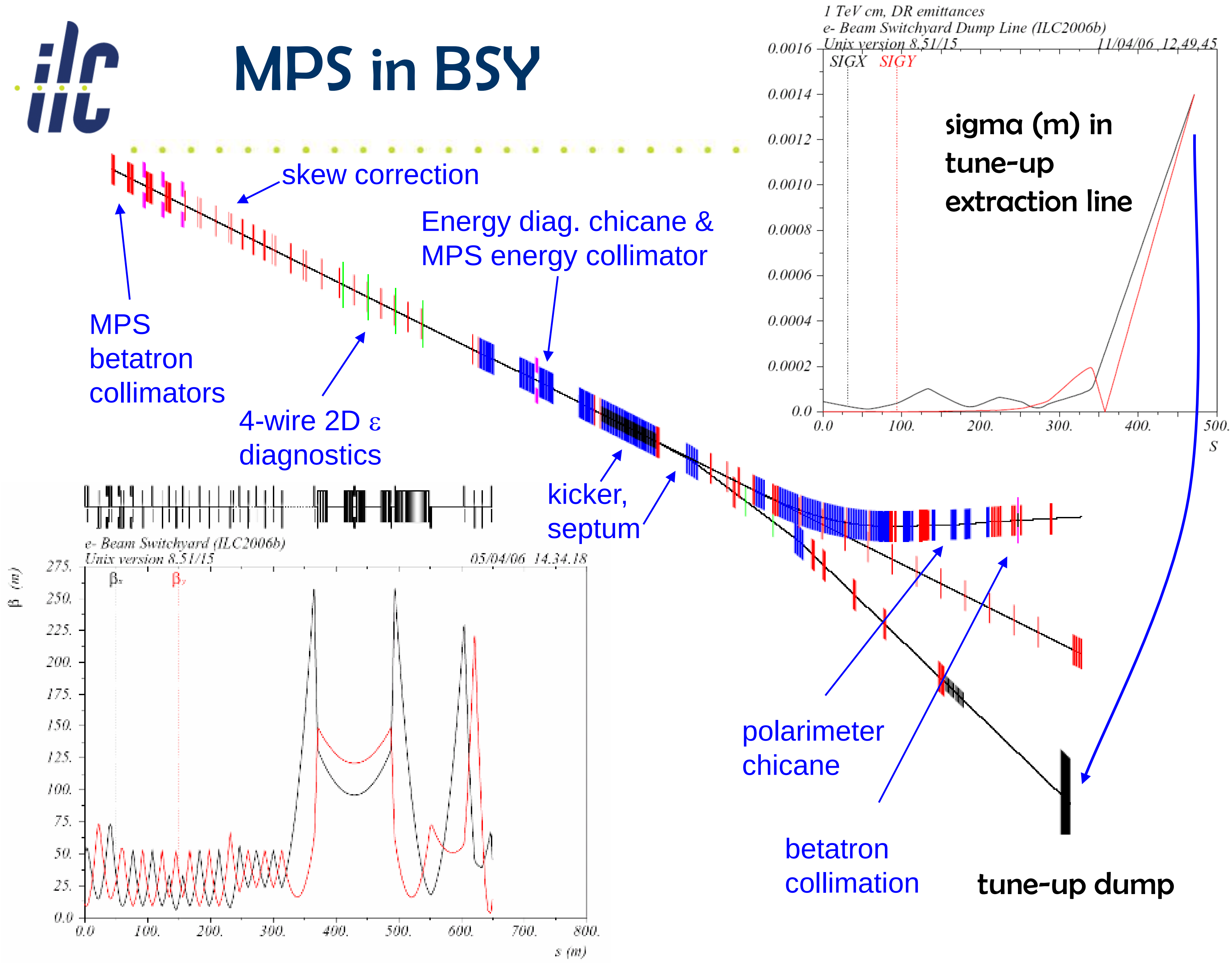
ILC FF & Collimation

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





MPS in BSY



sigma (m) in tune-up extraction line

skew correction

Energy diag. chicane & MPS energy collimator

MPS betatron collimators

4-wire 2D ε diagnostics

kicker, septum

polarimeter chicane

betatron collimation

tune-up dump

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 => $A_\beta = K\, \beta$

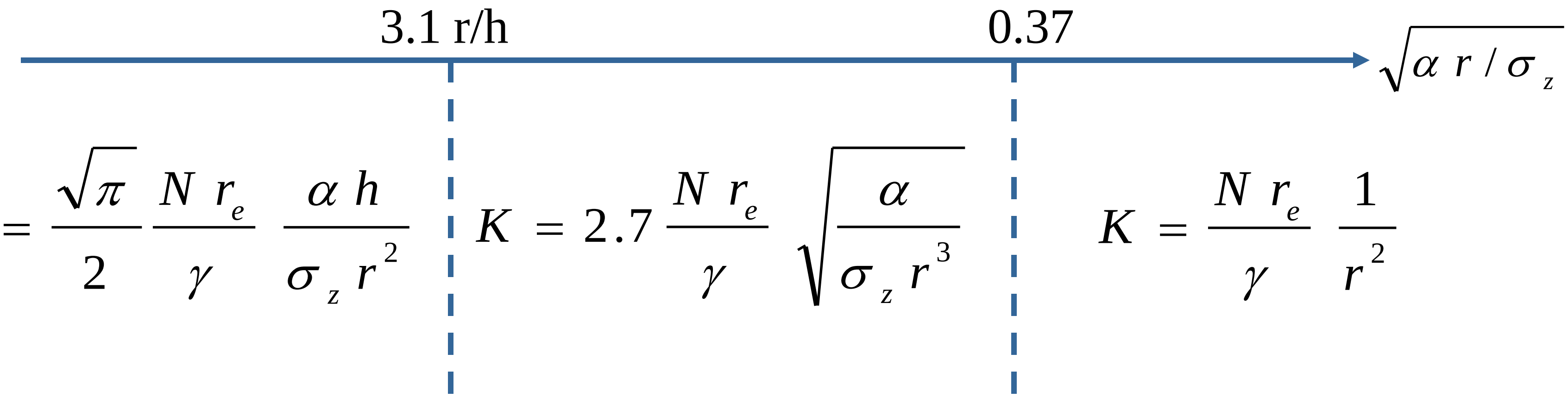
- If jitter is fraction of size in all planes, and y & y' not correlated , the fractional incoming jitter increases by

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

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

Wakes for tapered collimators

- Rectangular collimators



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

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

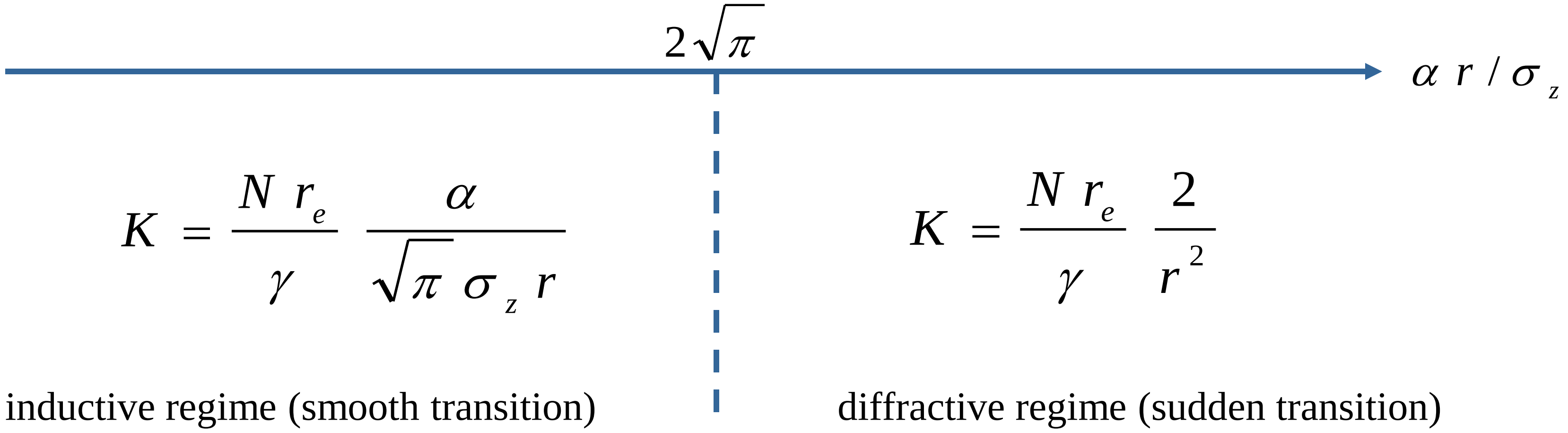
$$K = \frac{N r_e}{\gamma}\frac{1}{r^2}$$

- 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



$2\sqrt{\pi}$

$\alpha r / \sigma_z$

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

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

Exercises on collimators

- For your beam parameters, you will
  - knowing size of the beam at FD and vertex aperture, find the needed collimation depth
  - find the needed beam size so that spoiler survive certain number of bunches
  - knowing beam size at the spoiler and emittance you will find beta-function at the spoiler
  - knowing beam size at the spoiler and the collimation depth, find the aperture at the spoiler gaps
  - knowing beta-functions at the spoiler and gaps calculate wake-field effect for the spoiler

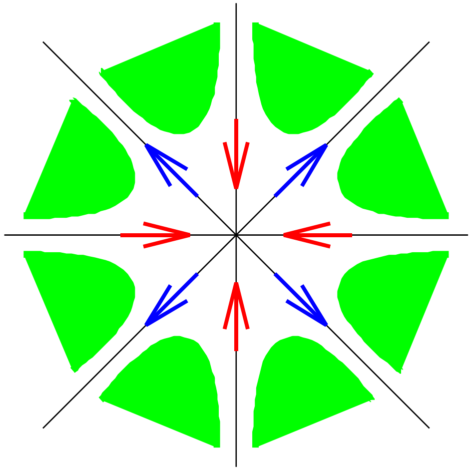
Nonlinear handling of beam tails in ILC BDS

- 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 !

R.Brinkmann, P.Raimondi, A.Seryi, PAC2001

Strong focusing by octupoles

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

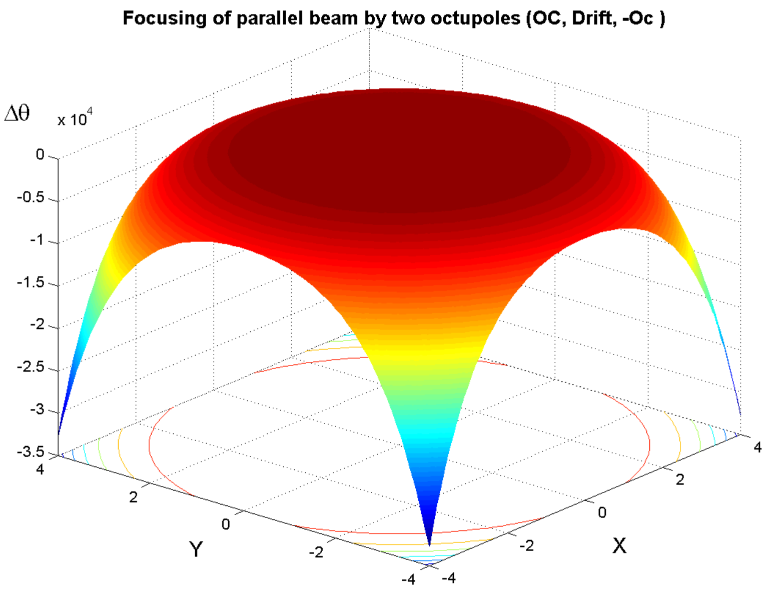
$$\Delta\theta = \alpha r^3 e^{-i3\varphi} - \left(\alpha r^3 e^{i3\varphi}\left(1+\alpha r^2 L e^{-i4\varphi}\right)^3\right)^*$$

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

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

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**

Schematic of folding with Octupole or OD

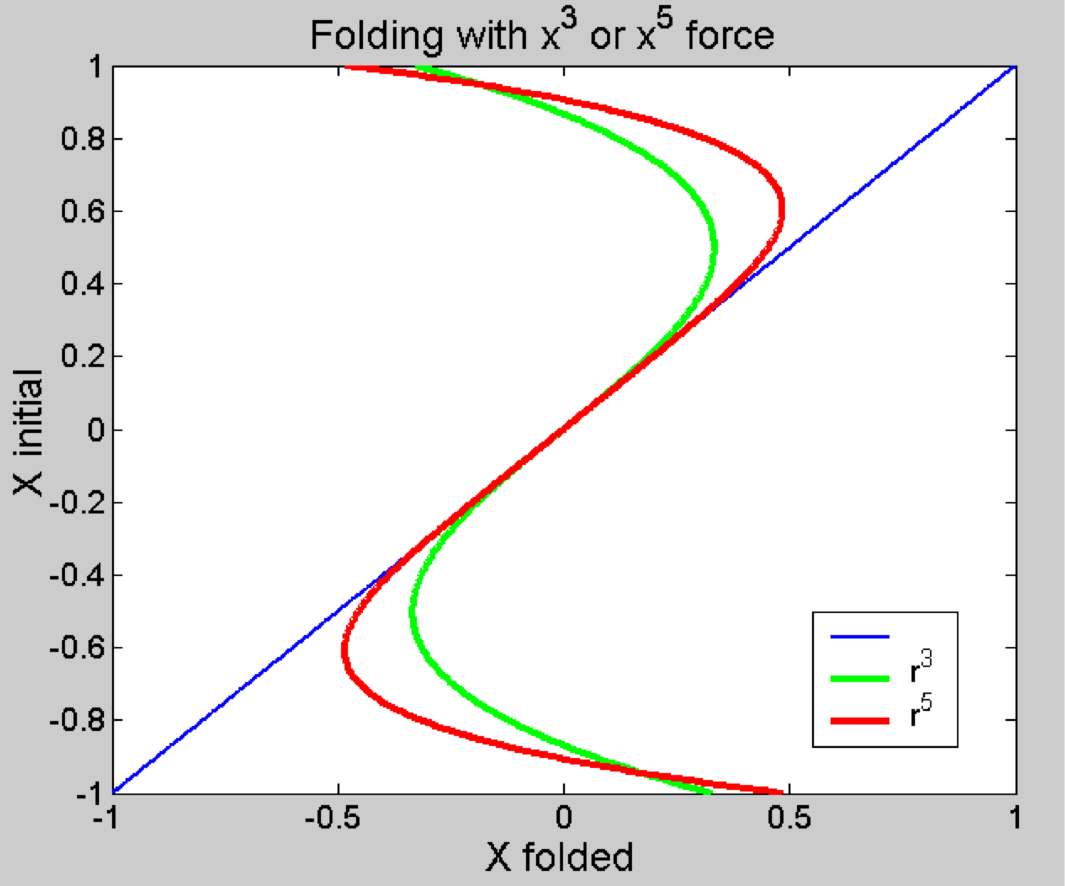


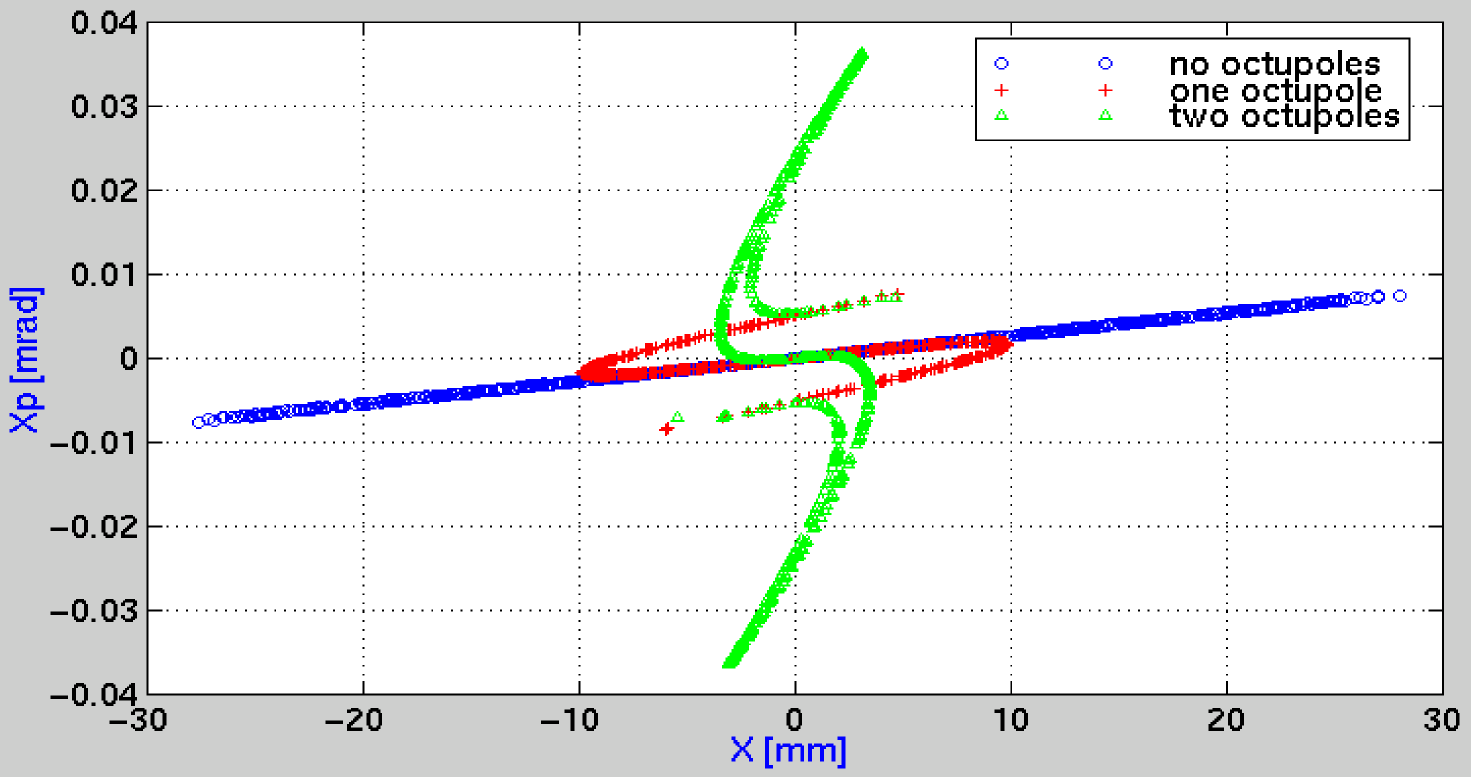
Illustration of folding of the horizontal phase space.

Octupole like force give factor of 3 (but distort diagonal planes)

OD-like force give factor of 2 (OK for all planes)

"Chebyshev Arrangement" of strength.

Schematic of double folding (with two doublets)



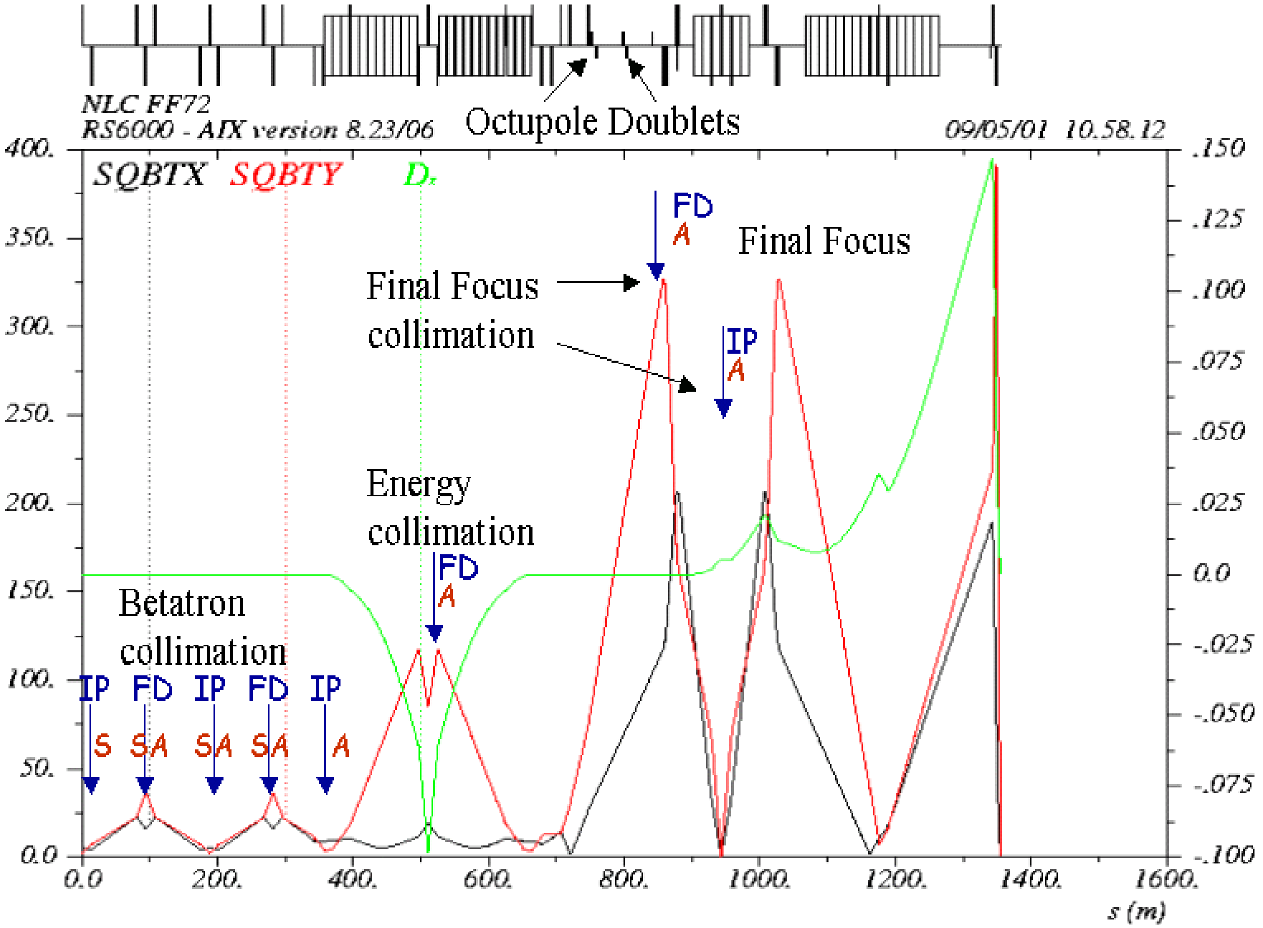
Folding of the horizontal phase space distribution at the entrance of the Final Doublet with one or two octupoles in a “Chebyshev Arrangement”.

Practical solution of BDS with ODs

Two octupole doublets give ~4 times folding in terms of beam size in FD (i.e. open the spoiler gaps by same amount)

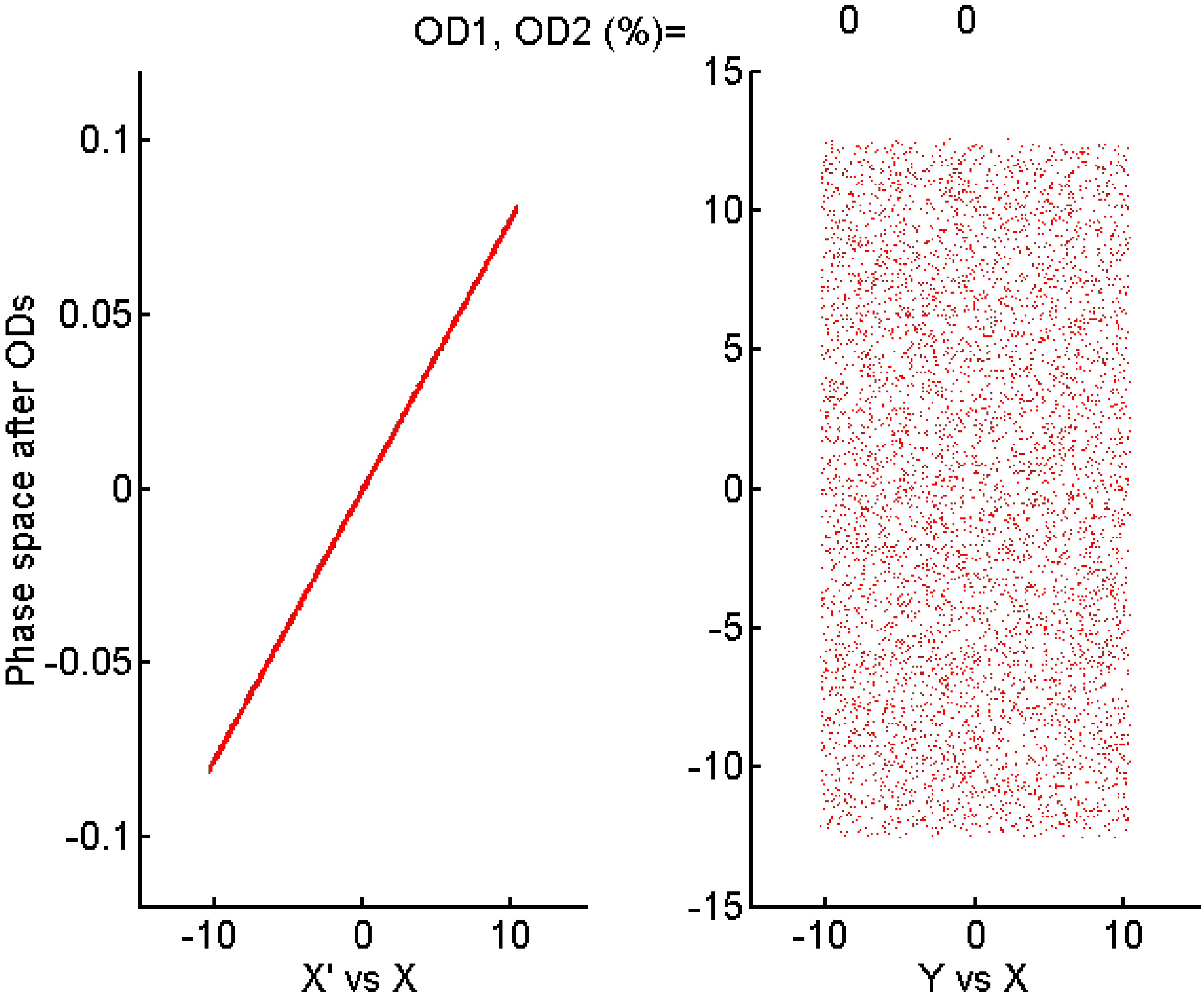
Works because:

- -use Oct. Doublets
- - in dispersion free region
- - only FD phase essential
- - in place where the beam is parallel (=divergent) and aberration free
- - the FF optics is nearly aberration free



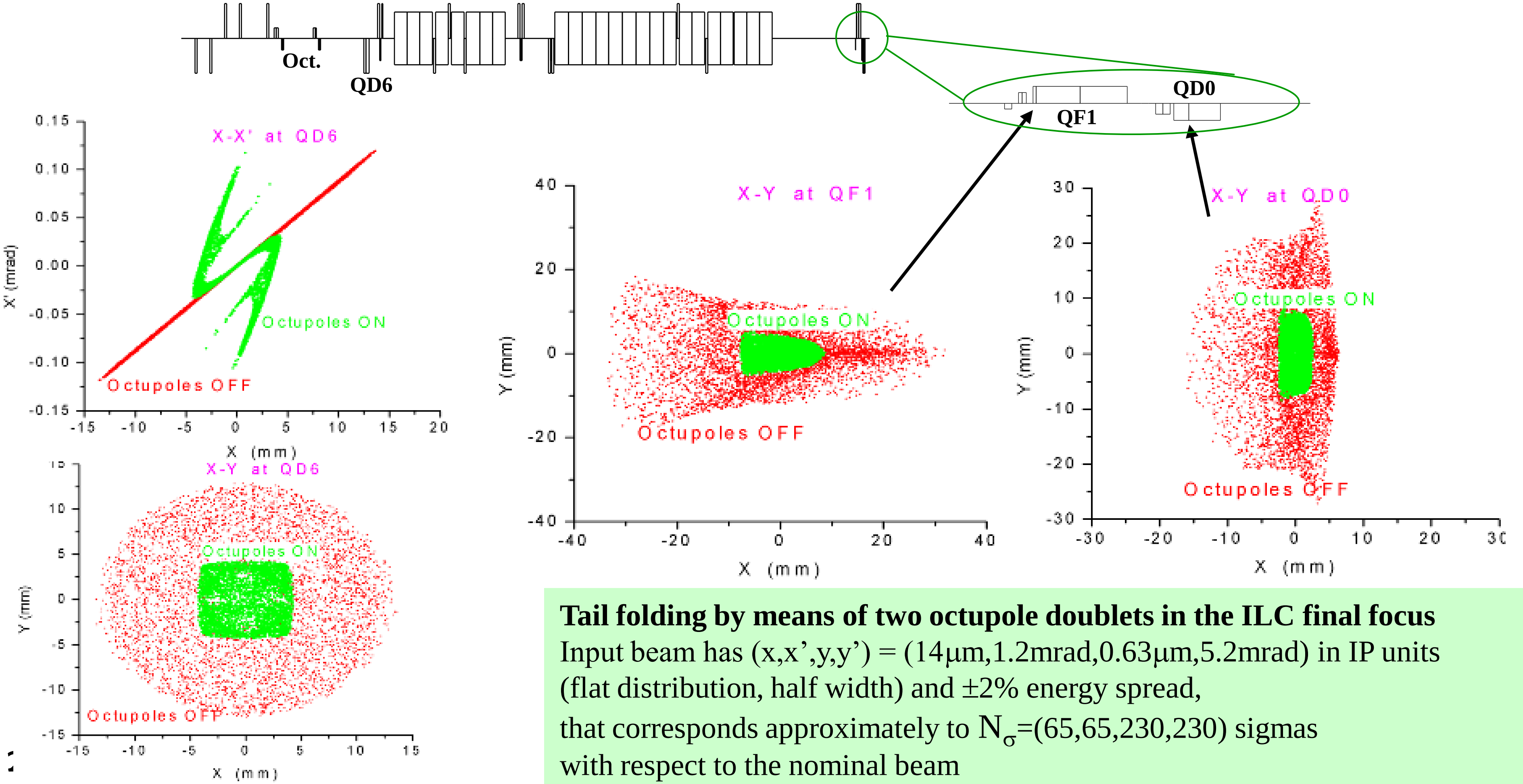
- Beam Delivery System Optics

Vary the ODs


OD1, OD2 (%)= 0 0
Phase space after ODs
0.1
0.05
0
-0.05
-0.1
-10
0
10
X' vs X
15
10
5
0
-5
-10
-15
-10
0
10
Y vs X

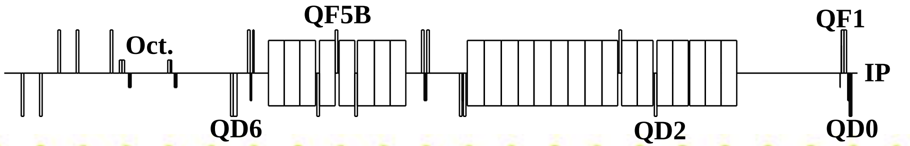
Tail folding in ILC FF

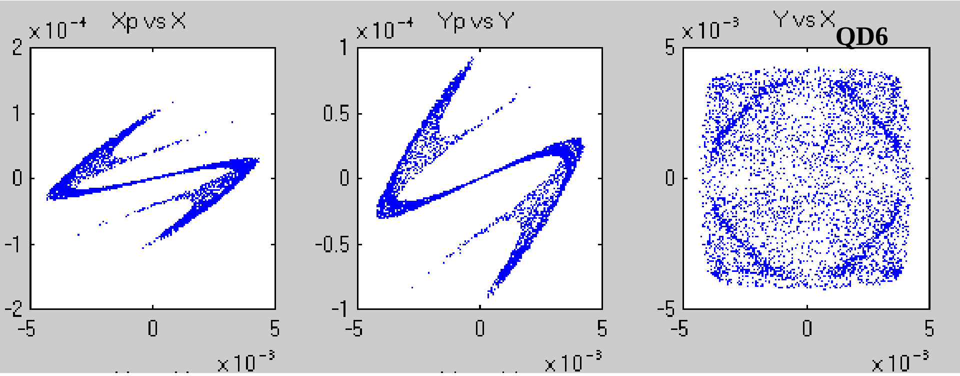
- Two octupole doublets give tail folding by ~ 4 times in terms of beam size in FD
- This can lead to relaxing collimation requirements by ~ a factor of 4

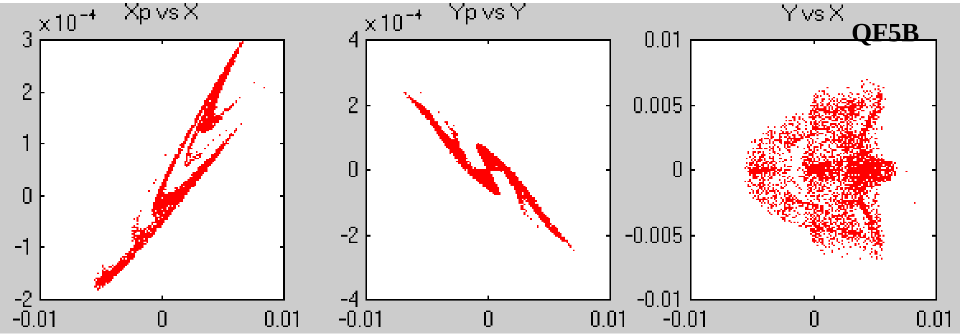


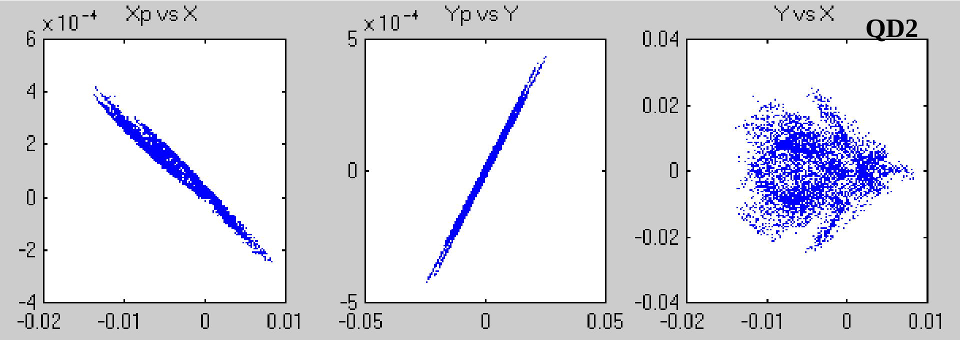
Tail folding by means of two octupole doublets in the ILC final focus
Input beam has (x,x',y,y') = (14µm,1.2mrad,0.63µm,5.2mrad) in IP units (flat distribution, half width) and ±2% energy spread,
that corresponds approximately to N_σ=(65,65,230,230) sigmas
with respect to the nominal beam

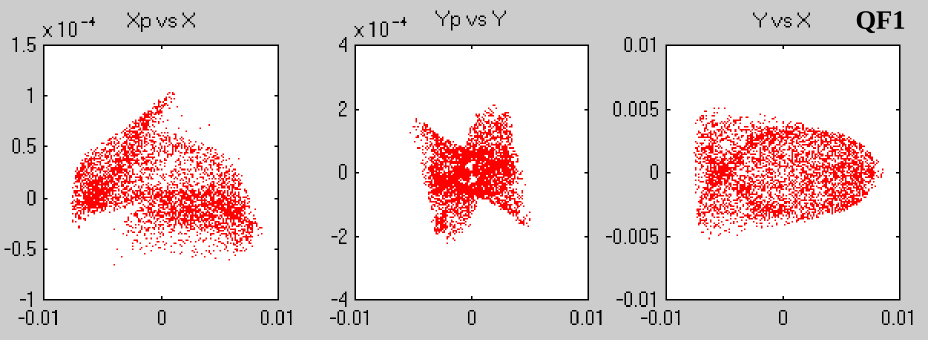
Tail folding
or Origami Zoo

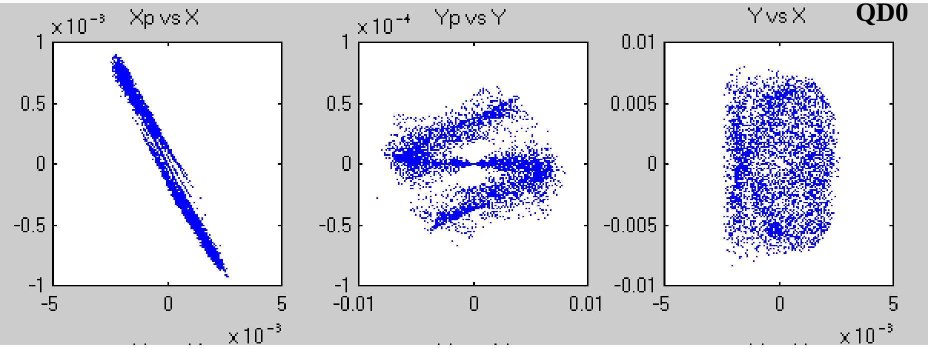


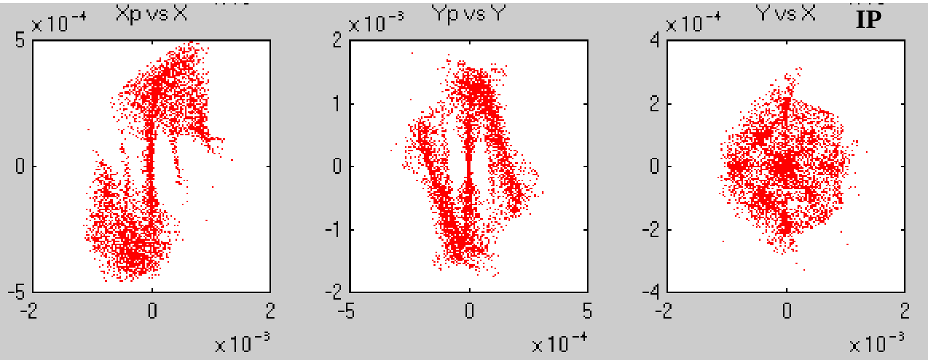






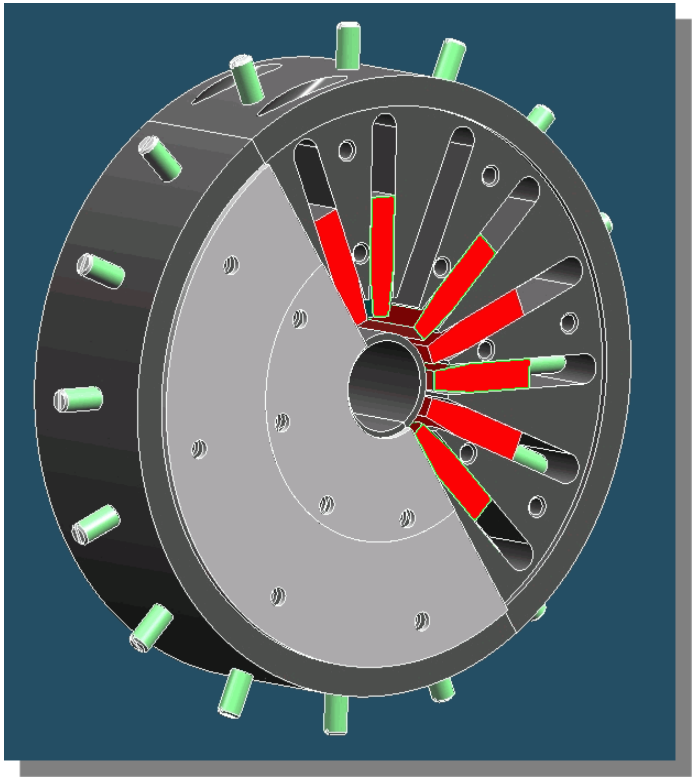






Tail folding octupoles design for ILC BDS

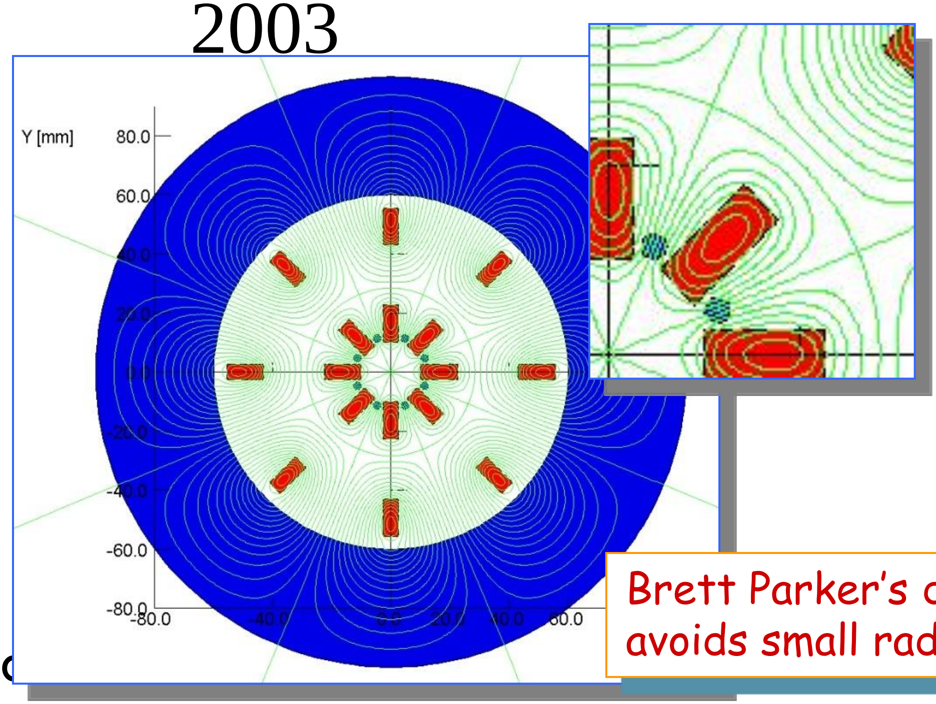
- One of the options is to use permanent magnet octupoles (achieved ~11kGs at 1cm radius in 1995)
- SC option seem to be possible. It will provide 2-2.5 times higher field, and will give flexibility for tuning and energy change.



One octupole slice (PM)

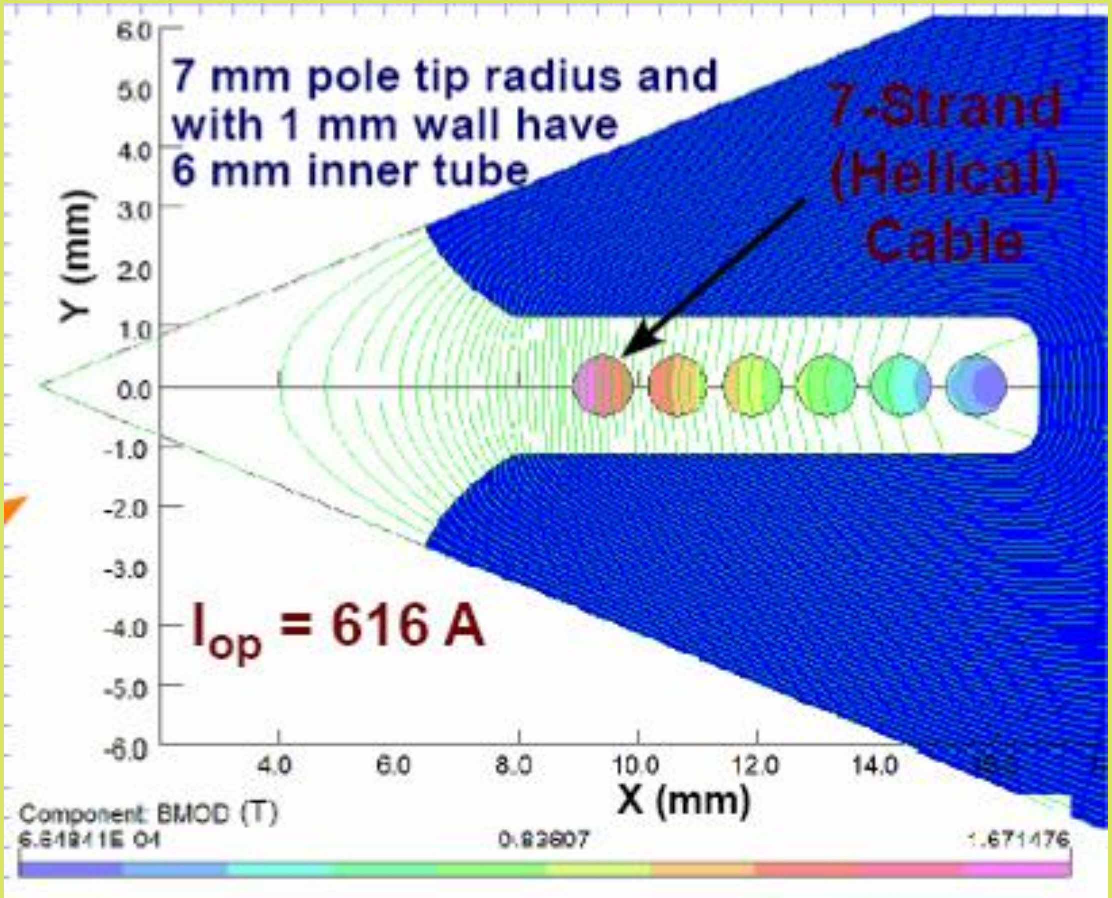
Built by Leif Eriksson in ~1995 for SLC FF

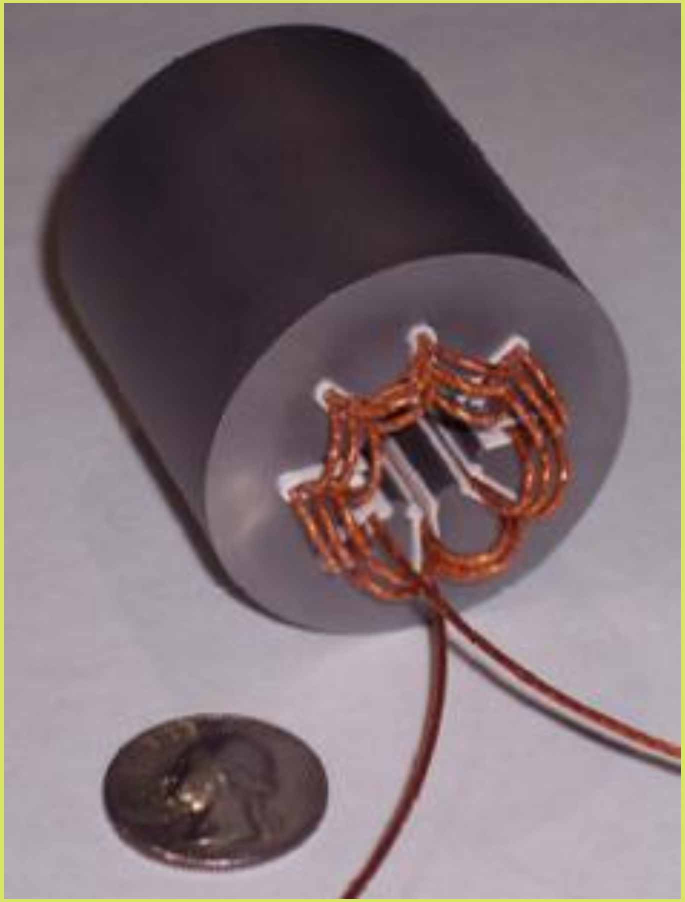
2003



Brett Parker's design of SC Octupoles which avoids small radius bending of SC cables

Tail folding octupoles





Superferric TFOs (for beam halo handling) with modified serpentine pattern can achieve 3T equivalent at r=10mm (BNL, B.Parker et al)