Design of beam optics for FCC-ee

KEK Accelerator Seminar

4 Aug. 2015

K. Oide (KEK)

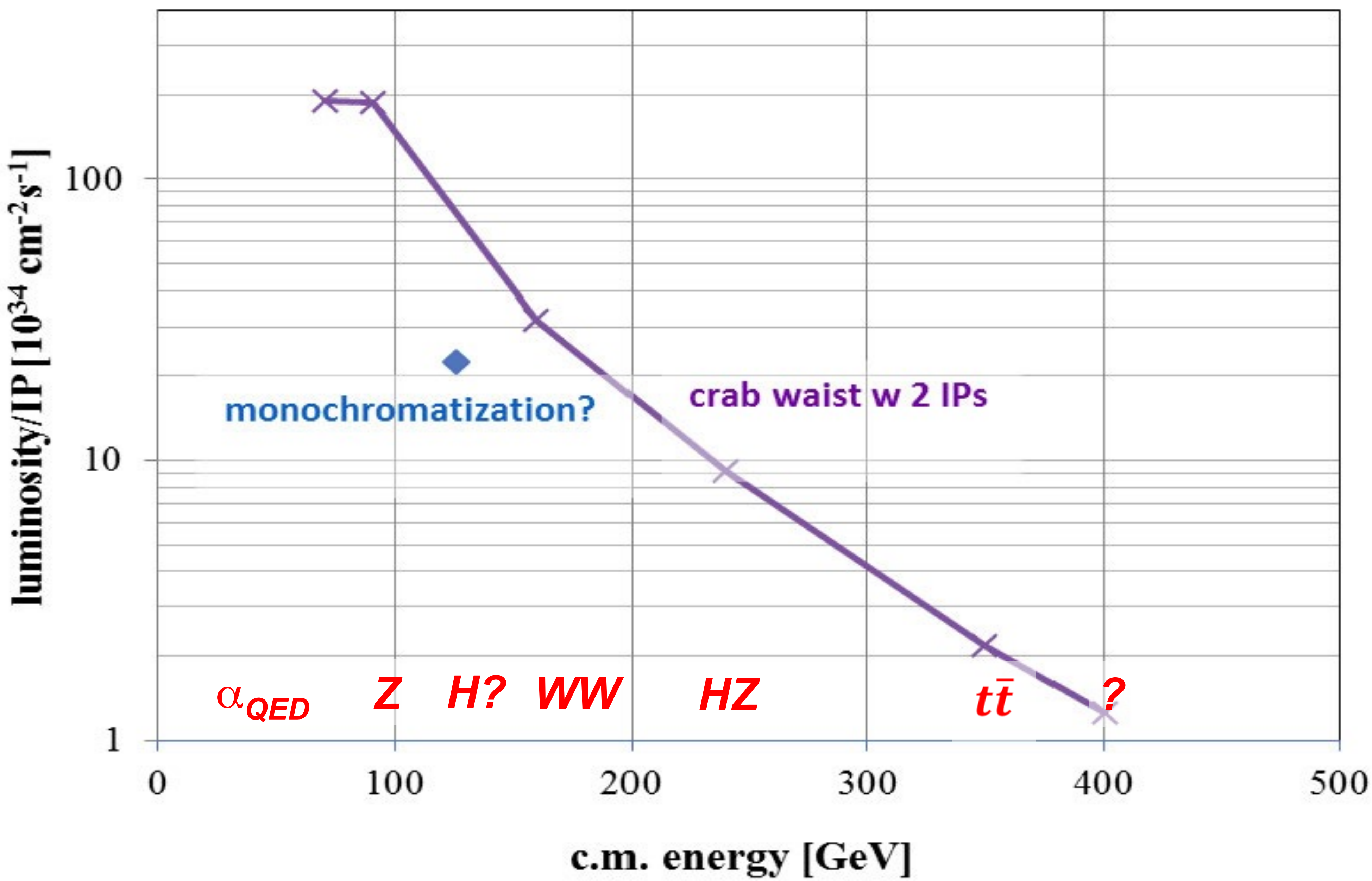
Many thanks to M. Benedikt, A. Bogomyagkov. H. Burkhardt, B. Holzer, J. Jowett, I. Koop, E. Levitchev, P. Piminov, D. Shatilov, S. Sinyatkin, D. Zhou, F. Zimmermann.

physics requirements for *FCC-ee*

- highest possible luminosity
- *beam energy range from 35 GeV to ~200 GeV*
- physics programs / energies:
  - *α_{QED} (35 GeV): running coupling constant close to the Z pole ?*
  - *Z (45.5 GeV): Z pole, 'TeraZ' and high precision M_Z & Γ_Z,*
  - *H (63 GeV): H production in s channel (with mono-chromatization) ??*
  - *W (80 GeV): W pair production threshold, high precision M_W*
  - *H (120 GeV): ZH production (maximum rate of H's),*
  - *t (175 GeV): $t\bar{t}$ threshold*
  - *>175 GeV: physics?*
- some polarization up to ≥80 GeV for beam energy calibration
- optimized for operation at 120 GeV?! (2nd priority "*Tera-Z*")

F. Zimmermann

luminosity vs c.m. energy



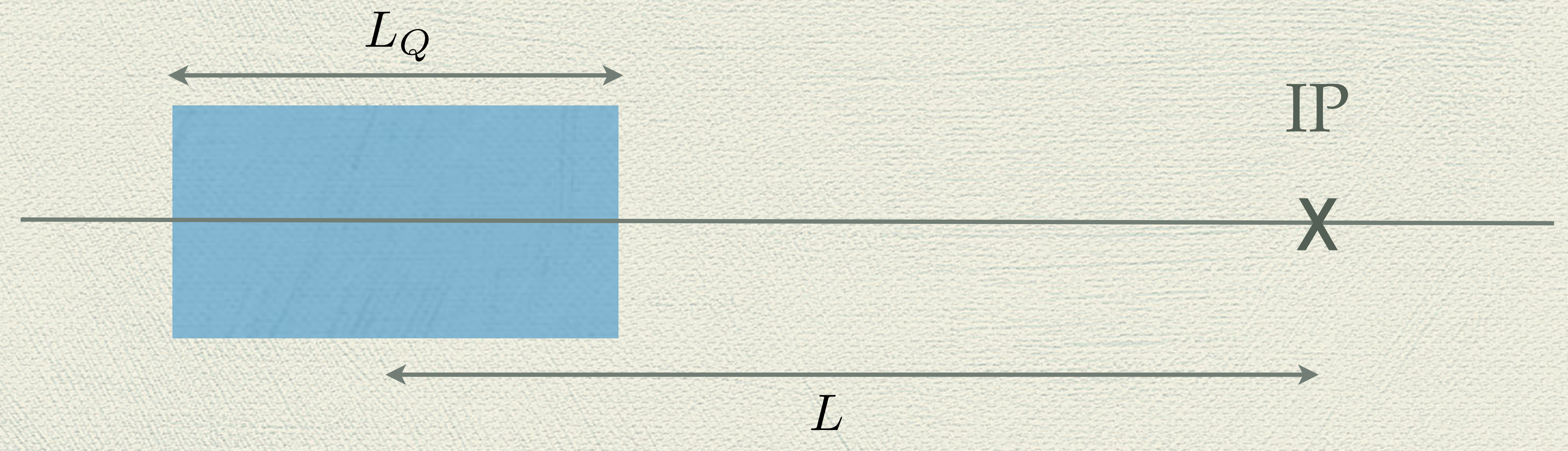
F. Zimmermann

The tentative parameters

parameter	FCC-ee crab waist (2 IPs)	
	Z	t
E_{beam} [GeV]	45.5	175
current [mA]	1450	6.6
$P_{SR,tot}$ [MW]	100	100
no. bunches	45154	51
N_b [10^{11}]	0.66	2.6
ε_x [nm]	0.13	2
ε_y [pm]	1.0	2
β^*_x [m]	0.5	0.5 (1)
β^*_y [mm]	1	1 (2)
RF frequency [MHz]	400	
RF voltage [GV]	0.4	11
circumference [km]	100	
mom. comp. [10^{-5}]	0.5	
synchrotron tune	-0.03	-0.07
$\sigma_{z,SR}$ [mm]	1	2.31
$\sigma_{z,tot}$ [mm] (w beamstr.)	2.8	2.83
$\sigma_{\delta,SR}$ [%]	0.037	0.202
$\sigma_{\delta,tot}$ [%] (w beamstr.)	0.127	0.248
θ_c [mrad]	30	
Piwinski angle	5.3	1.8
L* [m]	2	
beam-beam param. ξ_x/IP	0.07	0.06
beam-beam param. ξ_y/IP	0.18	0.12
luminosity/IP [10^{34} cm^{-2}s^{-1}]	247	2.6

- Highest energy ever reached by an electron by (not only) a ring.
- A double ring collider.
- Very strong focusing at the IP.
- Very flat beam ($\varepsilon_y/\varepsilon_x$ = 0.1%).
- Very strong synchrotron radiation (u_c > ~1 MeV in the arc dipoles at tt).
- Very large dynamic momentum acceptance, ±2% at tt, is required to hold the beam with strong beamstrahlung at the IP.
- A large horizontal crossing angle ≳ 30 mrad at the IP.
- 2IPs, "crab waist" scheme.
- Local chromaticity correction system around the IR.
- Based on IPAC'15 CW parameters, by F. Zimmermann.

Scaling of final quads



$$k_1 = \frac{B' L_Q}{B\rho} = c_f / L \qquad \text{(inverse focal length)}$$

$$L_Q = c_Q L$$

$$B' b = B_0 \qquad \text{(pole tip field)}$$

$$b > \max(\sqrt{2\beta_{x,y} J_{x,y}}) \qquad \text{(required acceptance)}$$

$$\beta_{x,y} = \beta^*_{x,y} + \frac{L^2}{\beta^*_{x,y}}$$

$$\xi_y = k_1 \beta_y \qquad \text{(vertical chromaticity)}$$

$$L_0 = \frac{c_f B\rho}{c_Q B_0} \sqrt{\frac{2J_{x,y}}{\beta^*_{x,y}}}$$

$$L > \frac{L_0}{2}\left(1 + \sqrt{1 + 4\frac{\beta^{*2}_{x,y}}{L_0^2}}\right)$$

$$\xi_y = \frac{c_f L}{\beta^*_y}$$

A measure of difficulty in chromaticity correction

Scaling of final quads (cont'd)

$$L_0 = \frac{c_f B\rho}{c_Q B_0}\sqrt{\frac{2J_{x,y}}{\beta^*_{x,y}}}$$

$$L > \frac{L_0}{2}\left(1+\sqrt{1+4\frac{\beta^{*2}_{x,y}}{L_0^2}}\right)$$

$$\xi_y = \frac{c_f L}{\beta^*_y}$$

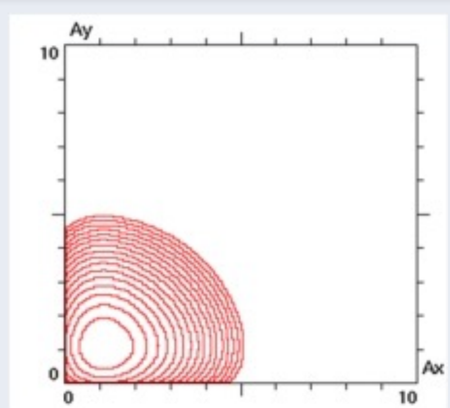
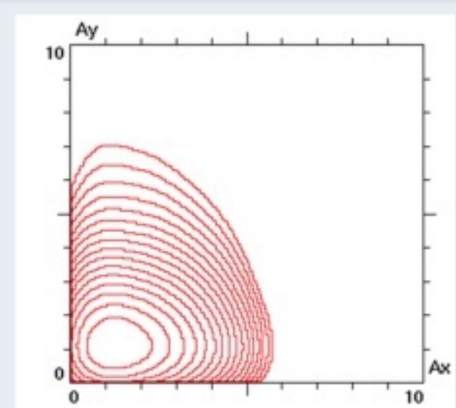
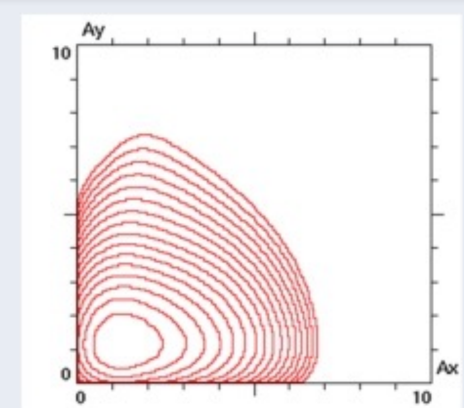
Rings	SuperKEKB LER	FCC-ee-tt	
Beam energy	4	175	GeV
$B\rho$	13.3	584	Tm
B_0	0.7	1	T
$c_f \equiv k_1 L$	1.56	1.69	
$c_Q \equiv L_Q/L$	0.35	0.84	
β^*_x	32	1000	mm
β^*_y	0.27	1	mm
$2J_x$	3.7	0.8	μm
$2J_y$	10	0.8	nm
L_0	0.935	1.05	m
L	0.935	3.8	m
L_Q	0.33	3.2	m
b	10	10	mm
ξ_y	5,400	6,400	

Similar level of difficulty!

If FCC-ee-tt uses a chromaticity correction similar to SuperKEKB, the resulting momentum acceptance will be similar, about ±1.4%.

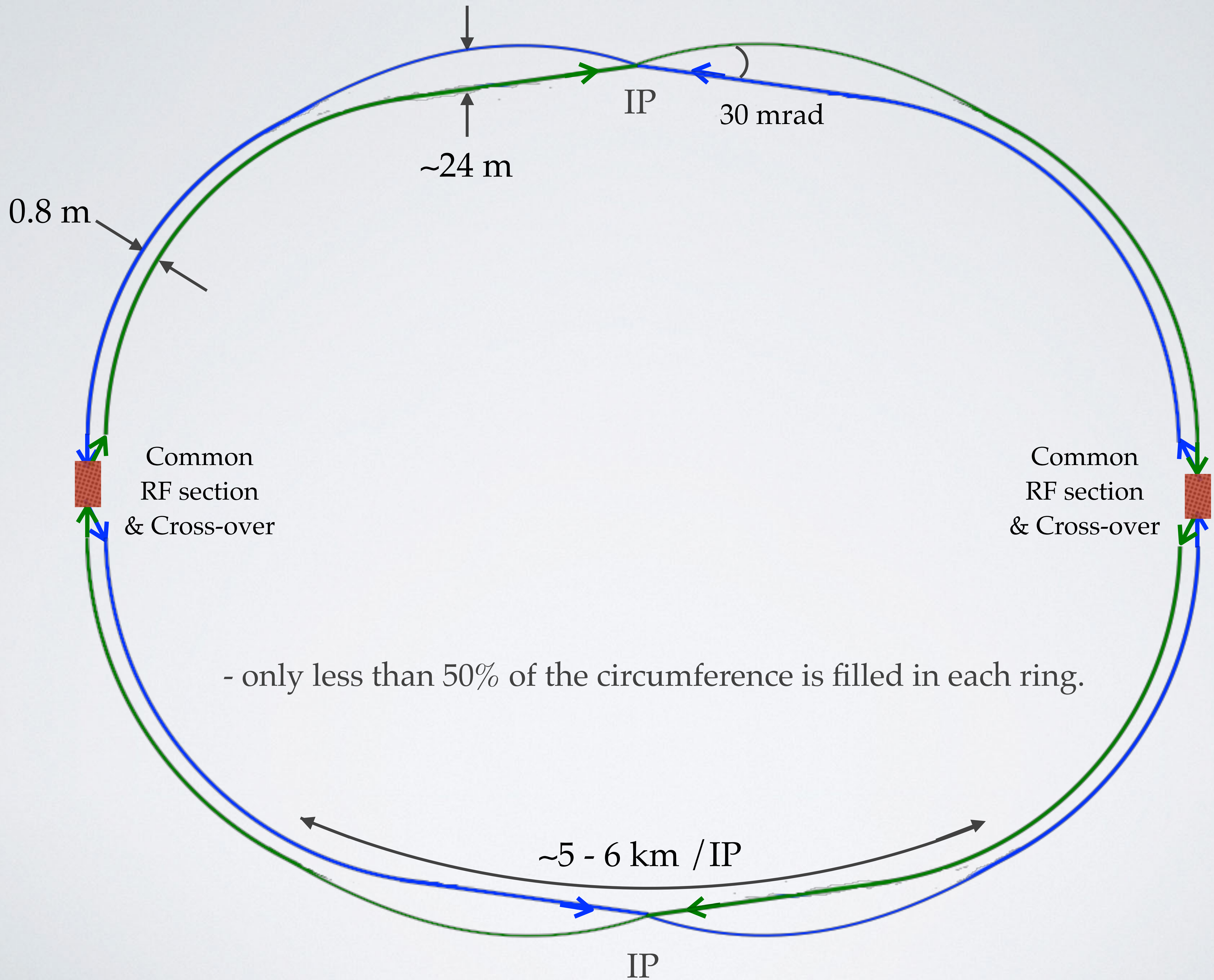
175 GeV, β_y= 2 mm

(Simulation Results of December 2014, to be updated)

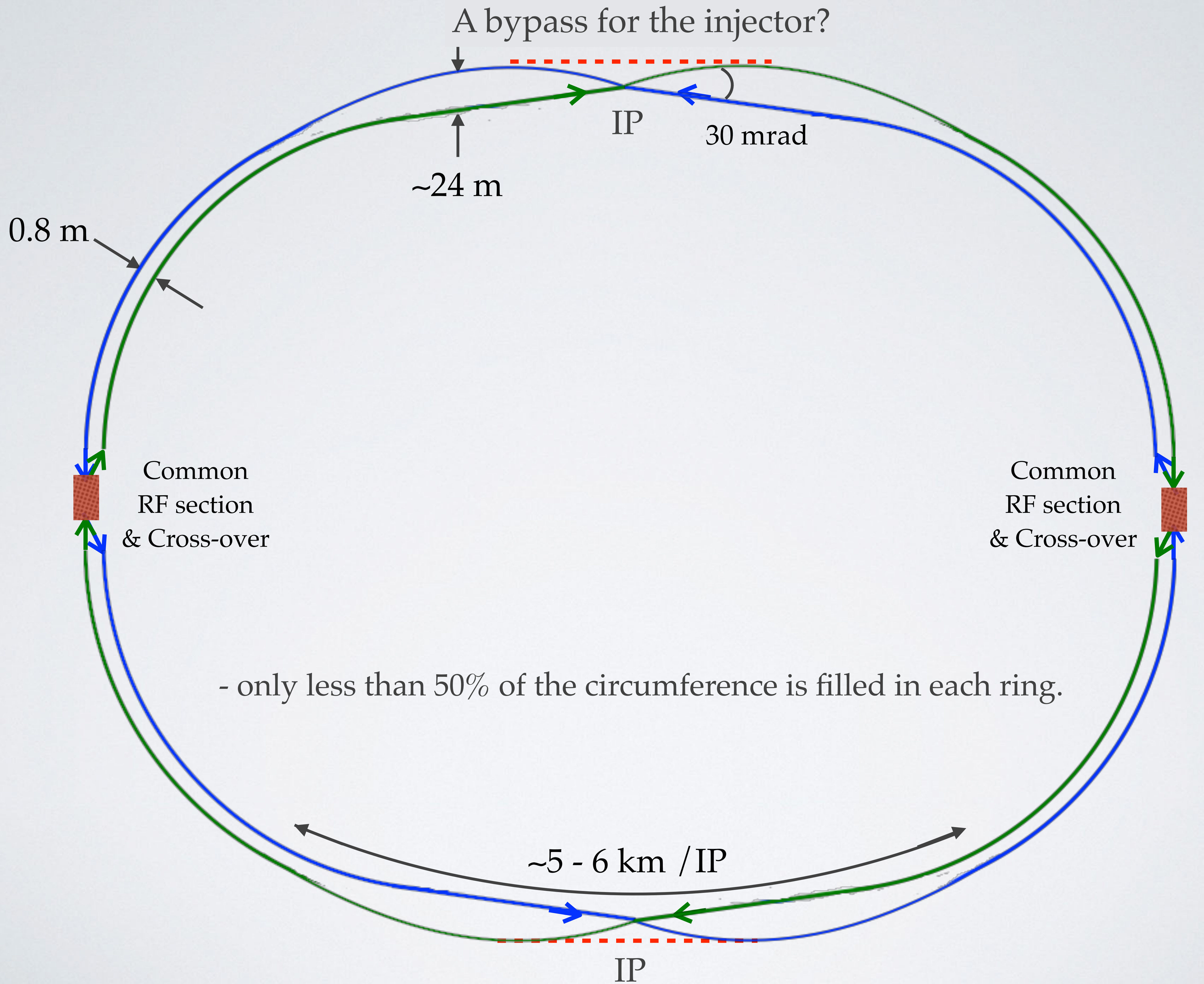
Collision scheme	Crab Waist	Head-on	Crossing (11
RF voltage [GV]	9.5	11	11
RF frequency [MHz]	400	400	400
Tunes $\nu_x / \nu_y / \nu$	0.54 / 0.57 / 0.0132	0.54 / 0.61 / 0.0172	0.52 / 0.57 / 0.0172
Bunch length [mm]	2.75 / 3.74	2.11 / 2.56	2.11 / 2.68
Bunch population	$2.0 \cdot 10^{11}$	$1.1 \cdot 10^{11}$	$1.2 \cdot 10^{11}$
Footprint size $\Delta\nu_x / \Delta_y$	0.023 / 0.079	0.071 / 0.137	0.047 / 0.106
Lifetime τ_{bs} [min]	18	35	25
Luminosity [$cm^{-2}s^{-1}$]	$1.15 \cdot 10^{34}$	$1.3 \cdot 10^{34}$	$1.2 \cdot 10^{34}$
Luminosity (β_y = 1 mm)	$1.25 \cdot 10^{34}$	$1.3 \cdot 10^{34}$ (800 MHz)	$1.25 \cdot 10^{34}$ (800 MHz)
Density contour plots $10\sigma_x \times 10\sigma_y$			

D. Shatilov

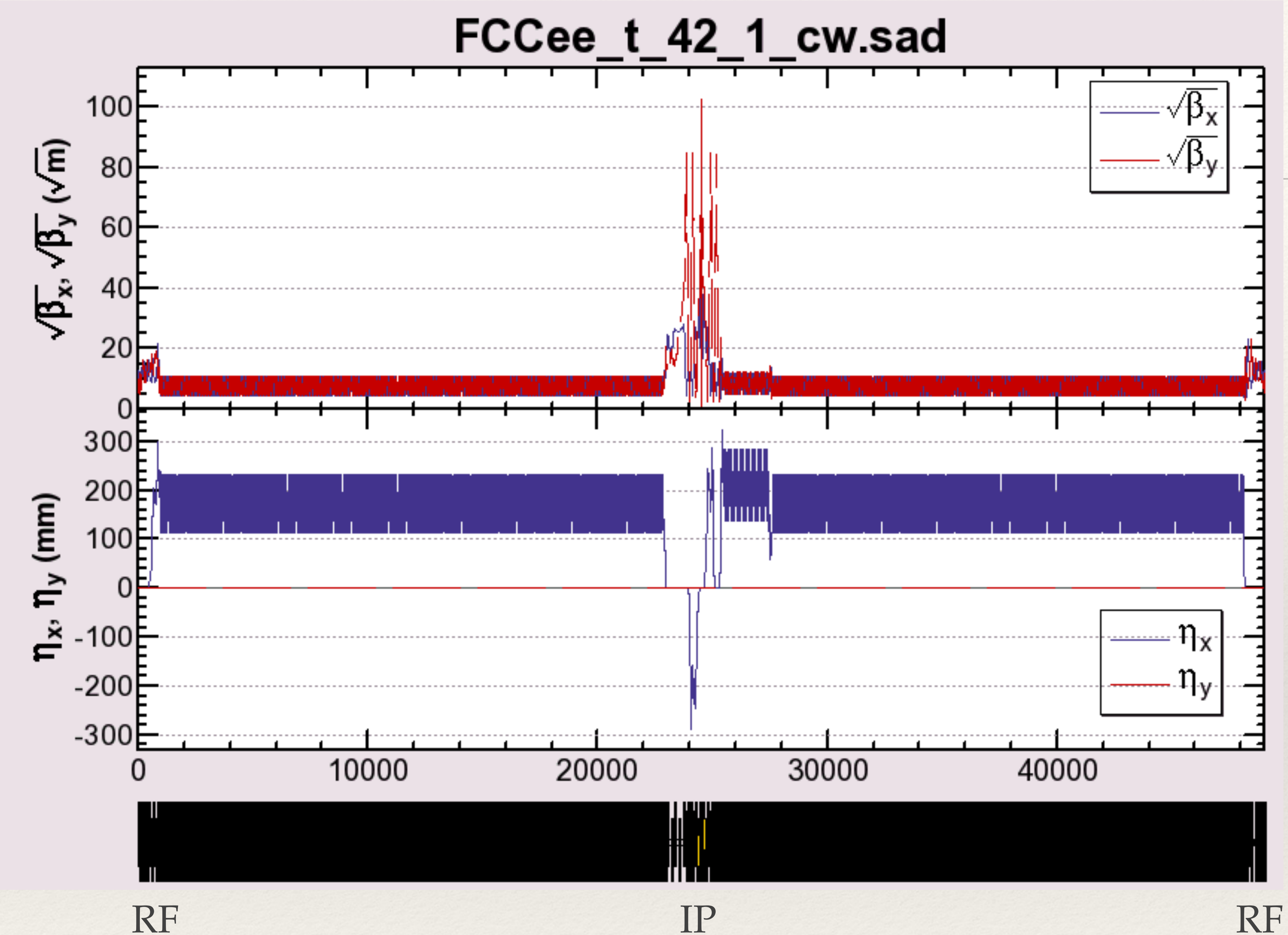
A conceptual layout of FCC-ee



A conceptual layout of FCC-ee

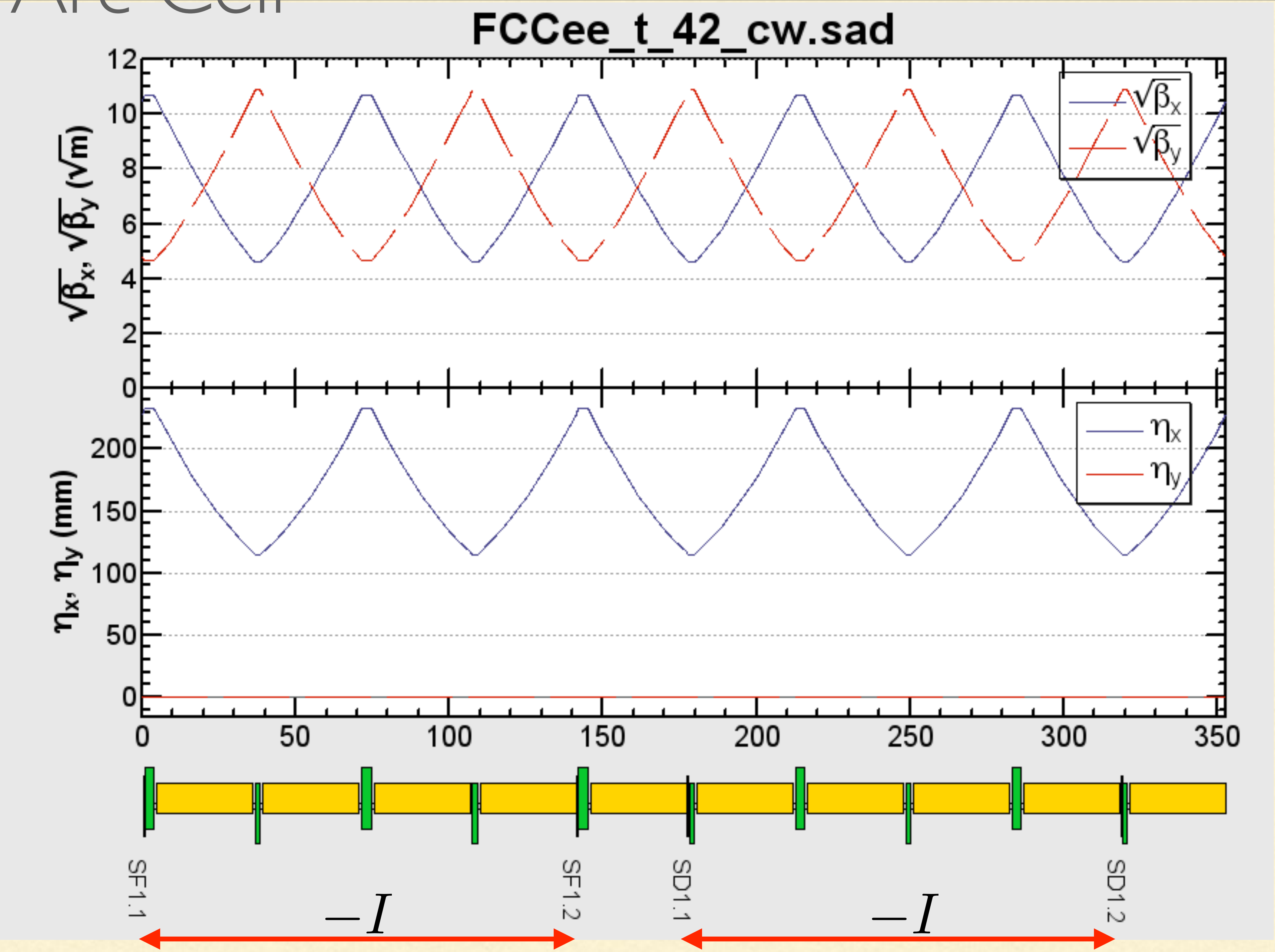


Half Ring Optics



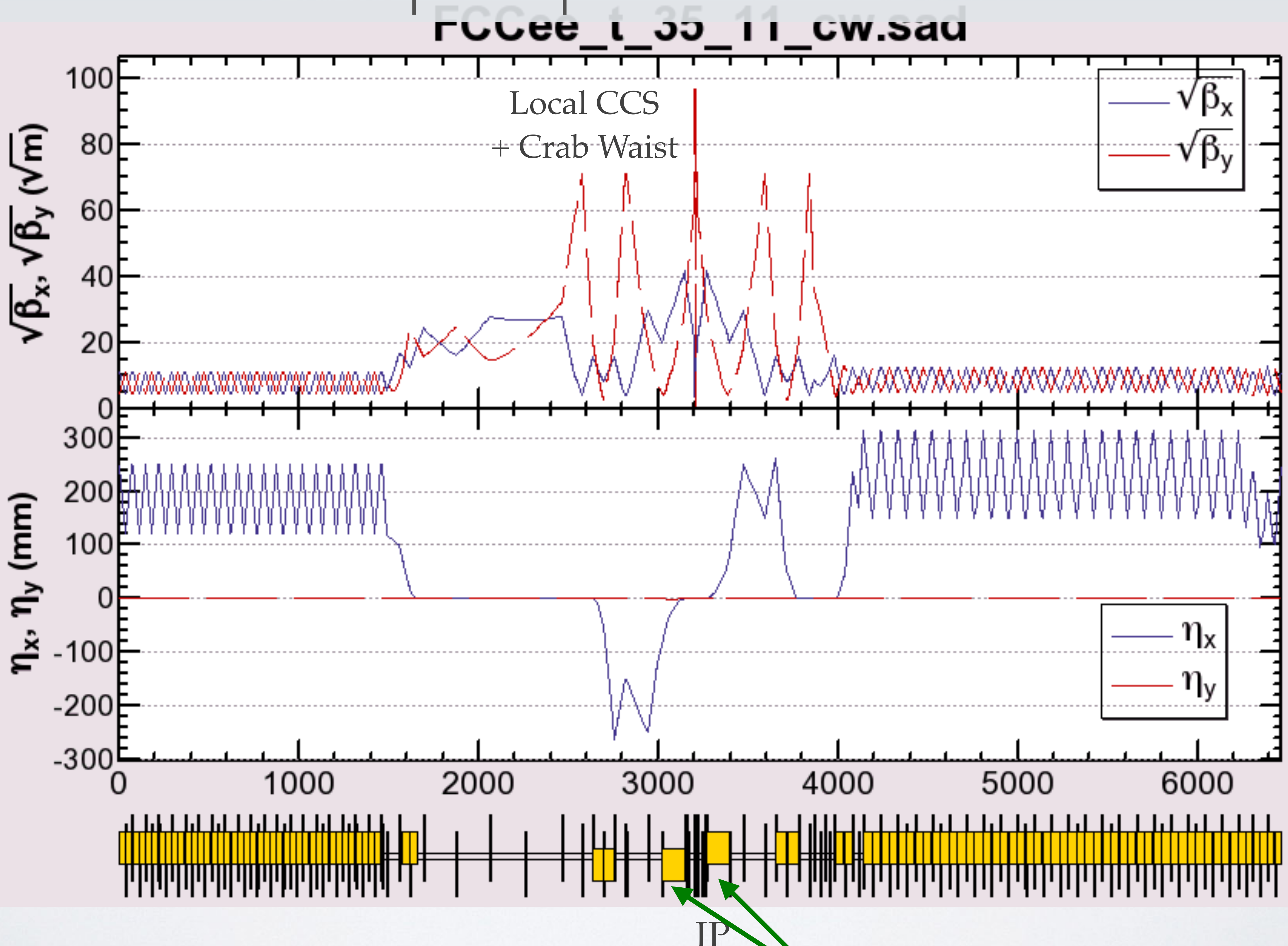
- $\beta_{x,y}{}^* = (1\text{ m}, 1\text{ mm})$.
- The optics is basically common for all energies.

The Arc Cell



- Basically a 90 degree FODO cell.
- QFs are longer (3 m) than QDs (1.5 m) to mitigate the radiation, as discussed later.
- All sextupoles are paired with -*I* transformation.
- 248 sextupole pairs per half ring.

An example optics around the IR

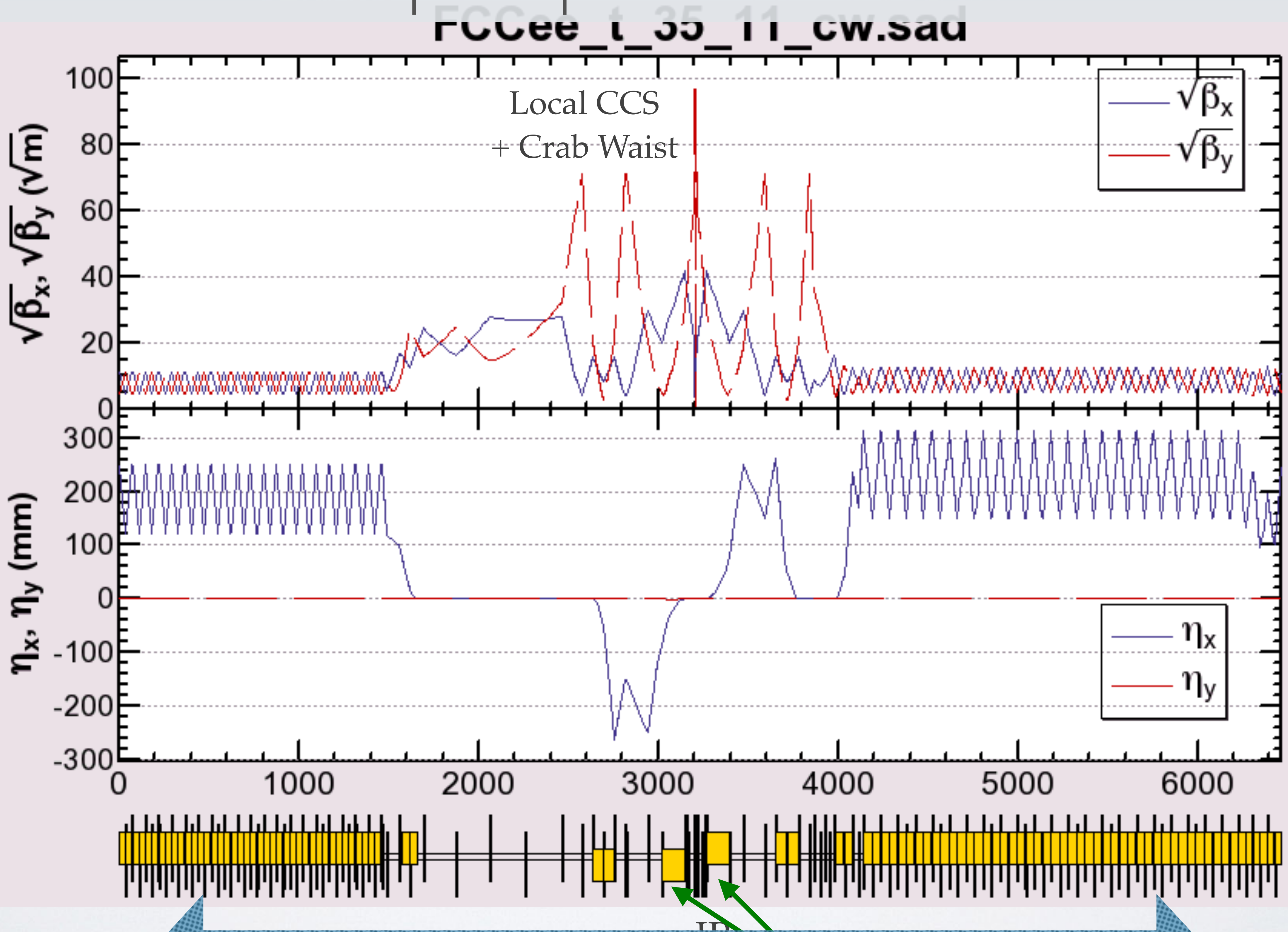


Local CCS + 30 mad crossing
+ crab waist + solenoids

Less than 100 keV for the critical energy of photons from the dipoles near the IP.

These plots of beam optics are not always the latest ones.

An example optics around the IR



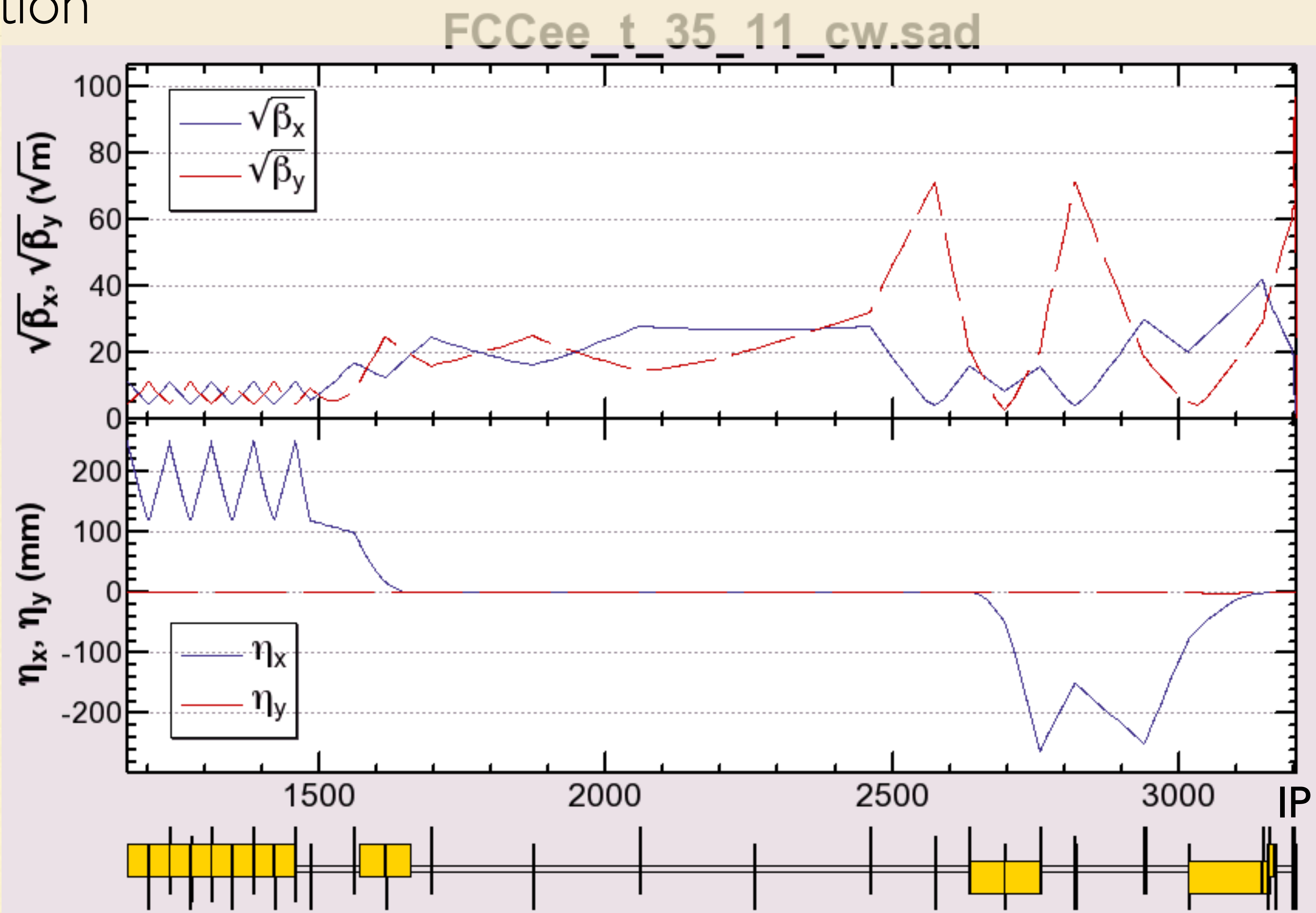
Separated tunnel, ~5 - 6 km / IP

Local CCS + 30 mrad crossing
+ crab waist + solenoids

Less than 100 keV for the critical energy of photons from the dipoles near the IP.

These plots of beam optics are not always the latest ones.

IR Radiation



u_c	891	202	314	100 100 46	keV
P_{SR}/dipole	16.7	1.1	3.7	0.79 0.05 0.01	kW

B1.34 B1.40

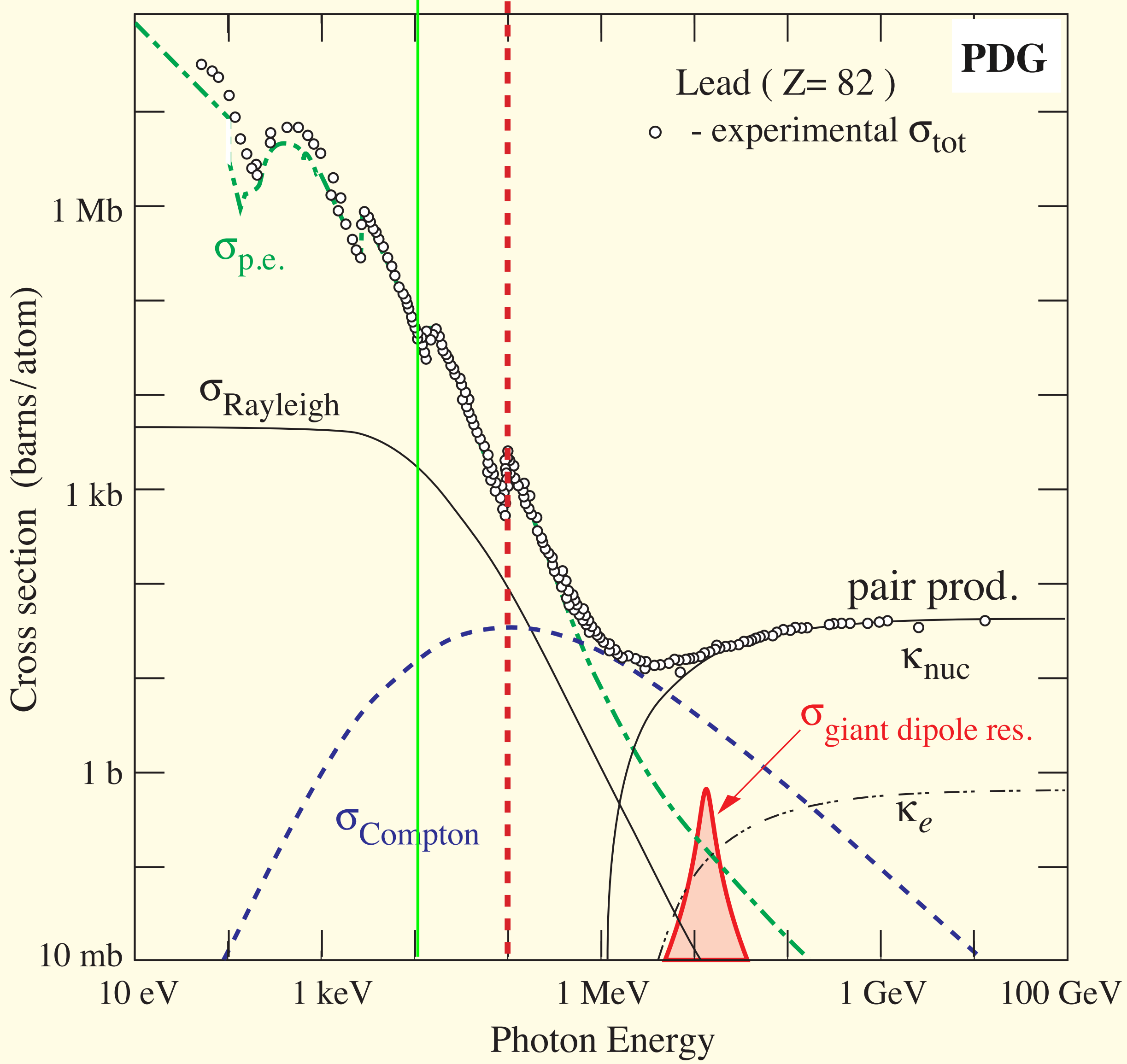
- The critical energy and radiation power of the dipoles are as above.

These plots of beam optics are not always the late ones.

✔ < 10 keV

> 100 keV very difficult

10 MeV significant neutron flux, giant dipole res.



Critical photon energies

SuperKEKB ~ 2 keV (LER)
FCC-hh ~ 5 keV

LEP1 : 69 keV

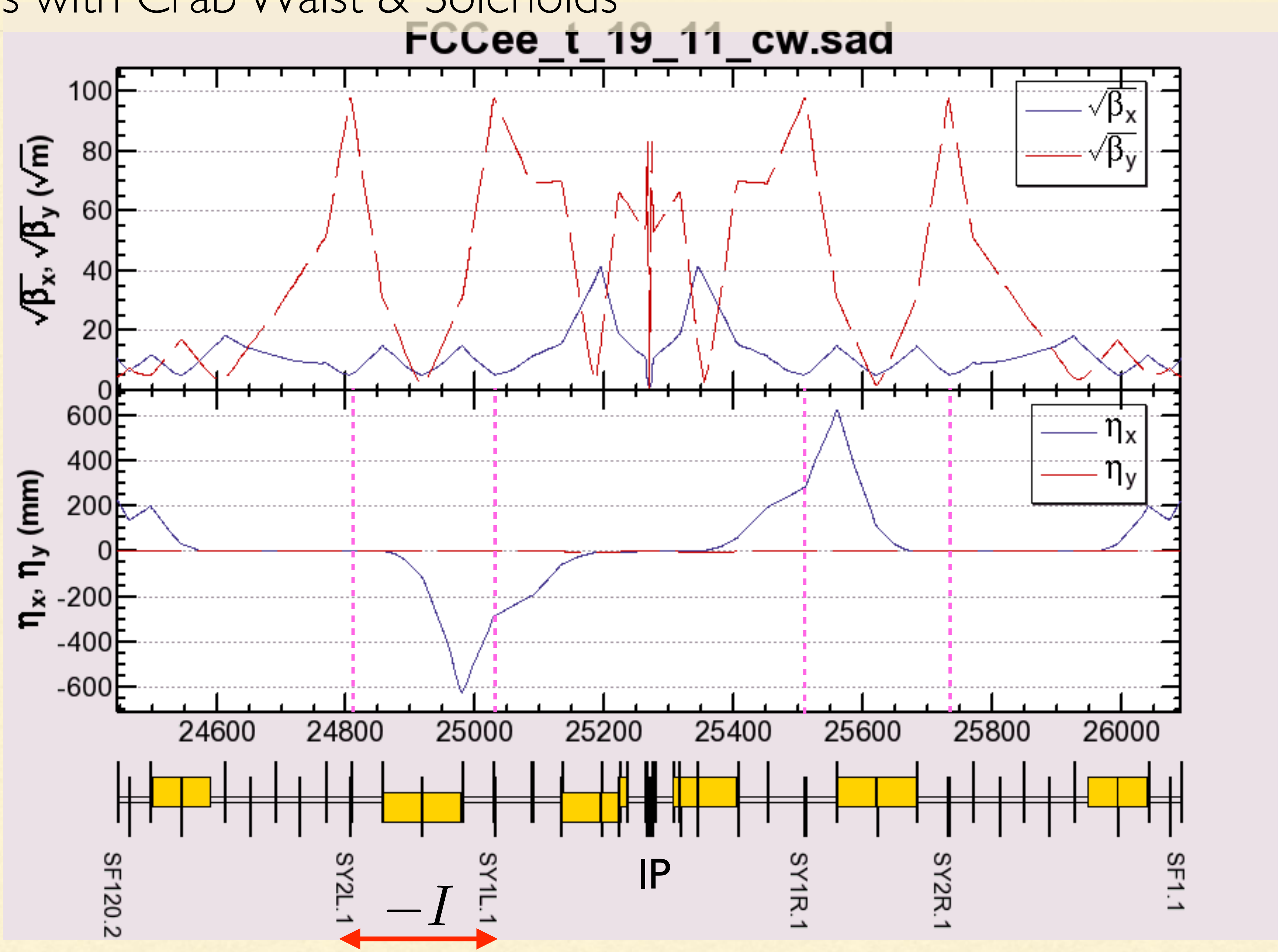
LEP2 : 724 keV (arc, last bend 10× lower)

TLEP : ~ 350 keV (arc, 175 GeV)
similar to LEP2
Enormous photon flux, MWs of power
can get kW locally, melt equipment, detectors
Very difficult but not impossible as
demonstrated in LEP2

as long as no hard synchrotron radiation
is generated towards experiments in the IR !!

H. Burkhardt

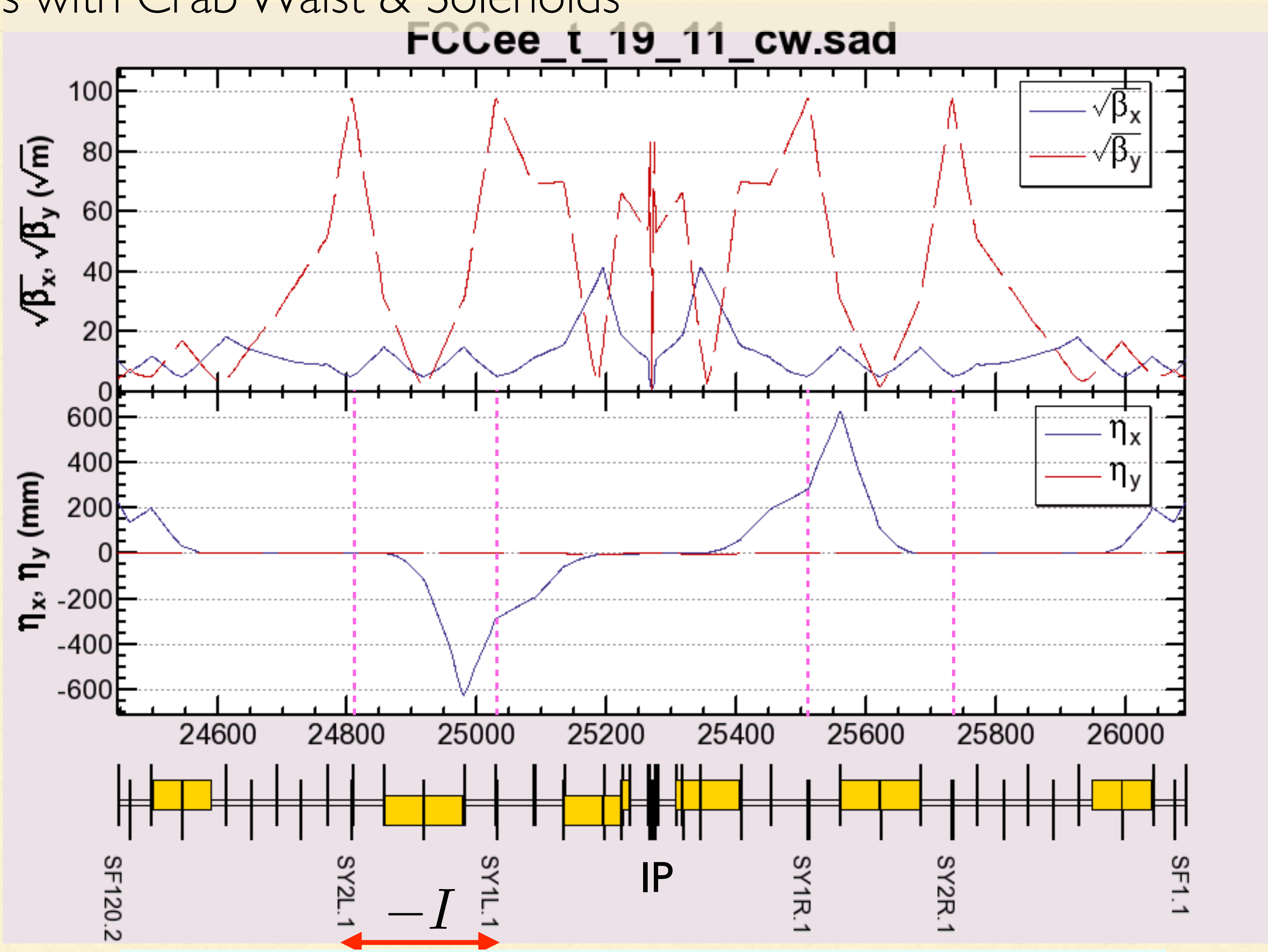
IR Optics with Crab Waist & Solenoids



- Local chromaticity correction only for Y.
- Dispersion are "concentrated" only at the nearest sexts to the IP.

$\beta_x^* = 1$ m, $\beta_y^* = 1$ mm, $L^* = 2$ m

IR Optics with Crab Waist & Solenoids



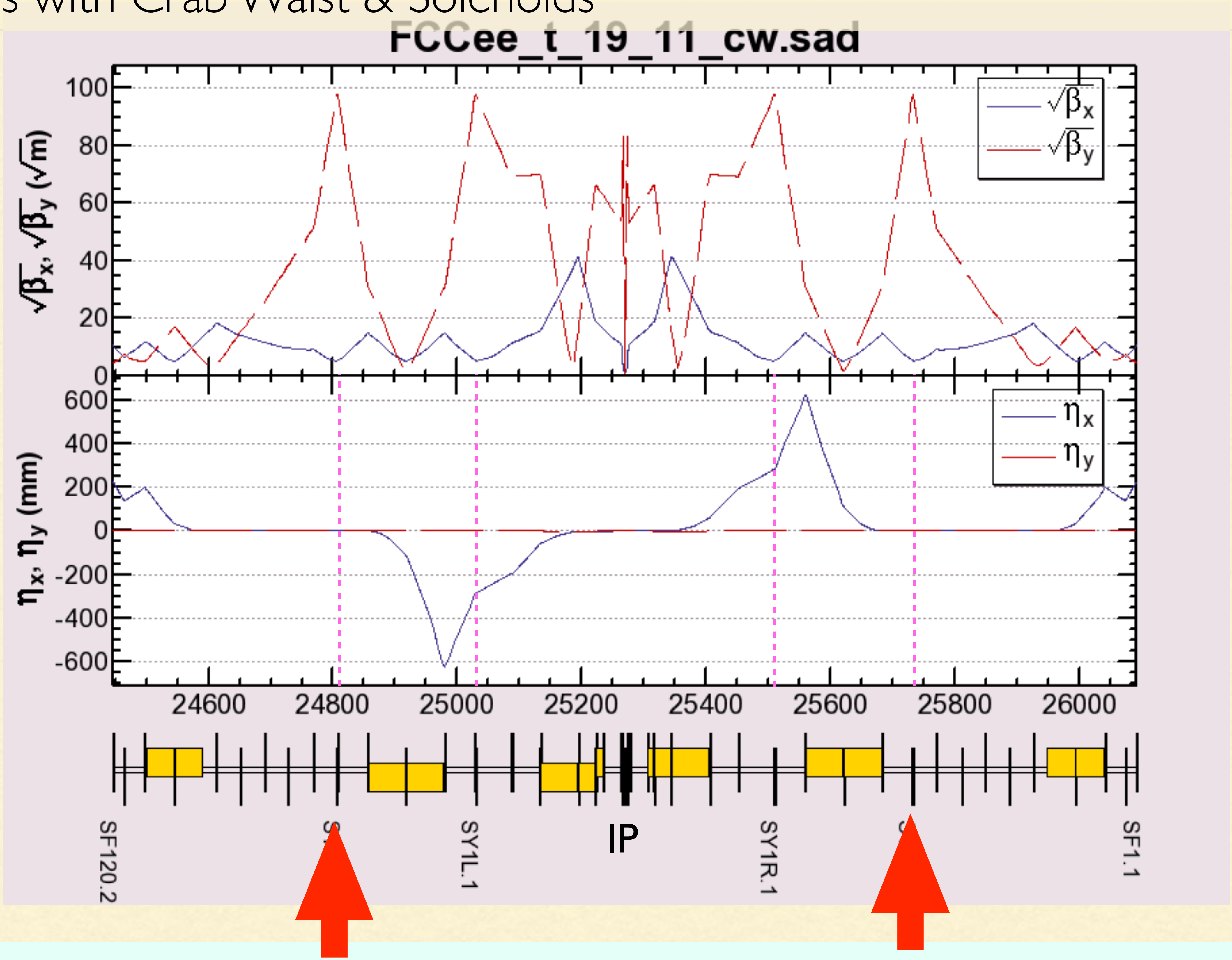
Where are the crab sextupoles?

- Local chromatic

- Dispersion are "concentrated" only at the nearest sexts to the IP.

$\beta_x^* = 1$ m, $\beta_y^* = 1$ mm, $L^* = 2$ m

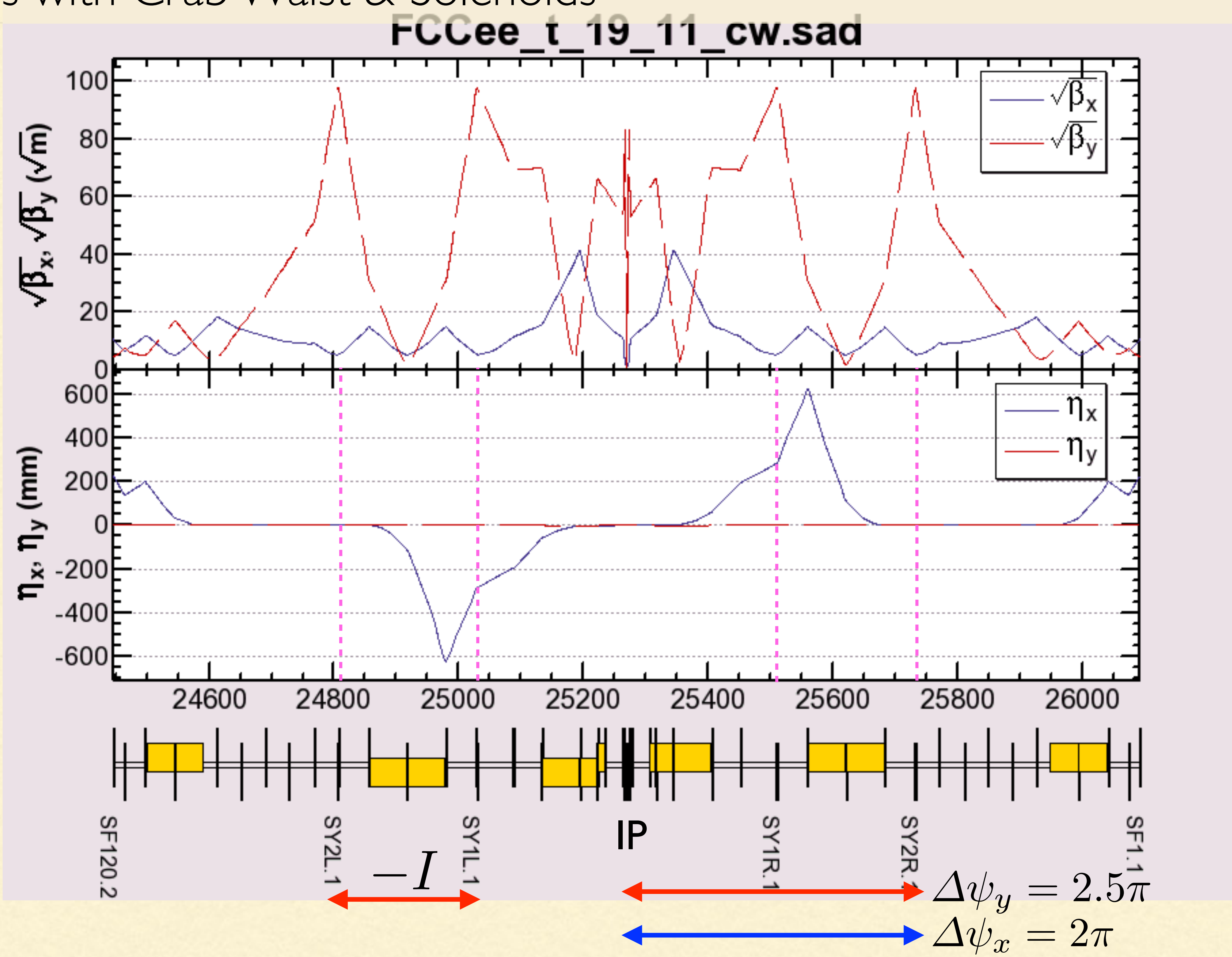
IR Optics with Crab Waist & Solenoids



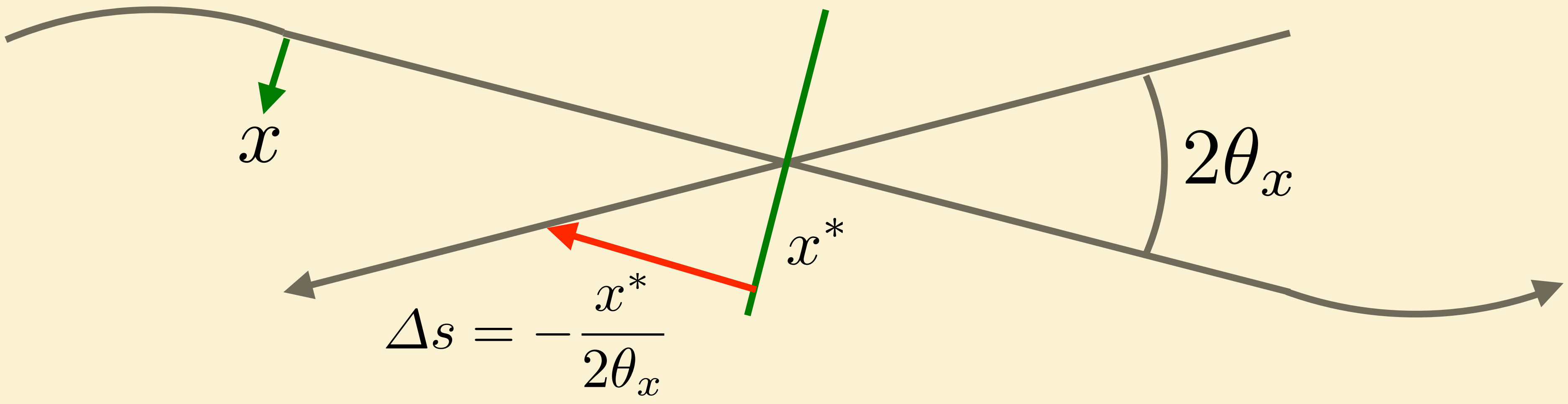
These sexts work as the crab sextupoles!

- The second sextupoles of the Y-CCS indeed work as the crab sextupoles, if the strengths and phases to the IP are properly chosen.

IR Optics with Crab Waist & Solenoids



- The second sextuple works as the crab sext, if the phases between the IP are 2.5π (y) and 2π (x), The original optics was already very close to satisfy these conditions!
- Sexts on the both sides of the IP cancel the geometrical effects to each other.



The crab waist scheme shifts the vertical waist of a beam by

$$\Delta s = -\frac{x^*}{2\theta_x} \ . \tag{1}$$

Thus the associated transformation is

$$y^* \to y^* - p_y^* \Delta s = y^* + \frac{p_y^* x^*}{2\theta_x} \ , \tag{2}$$

which is performed by a Hamiltonian at the IP:

$$H^* = \frac{x^* p_y^{*2}}{4\theta_x} \ . \tag{3}$$

If there are the phase relations between the IP and the sextupoles:

$$\Delta\psi_x = 2\pi \quad \text{and} \quad \Delta\psi_y = 2.5\pi, \tag{4}$$

then the variables at the IP (x^*, p_y^*) are expressed in those at the sext (x, y):

$$x^* = \sqrt{\frac{\beta_x^*}{\beta_x}} x, \quad p_y^* = \frac{y}{\sqrt{\beta_y^* \beta_y}} \ . \tag{5}$$

Thus the Hamitonian at the IP is equivalent to a Hamiltonian at the sext:

$$H = \frac{xy^2}{4\theta_x \beta_y^* \beta_y} \sqrt{\frac{\beta_x^*}{\beta_x}} \ , \tag{6}$$

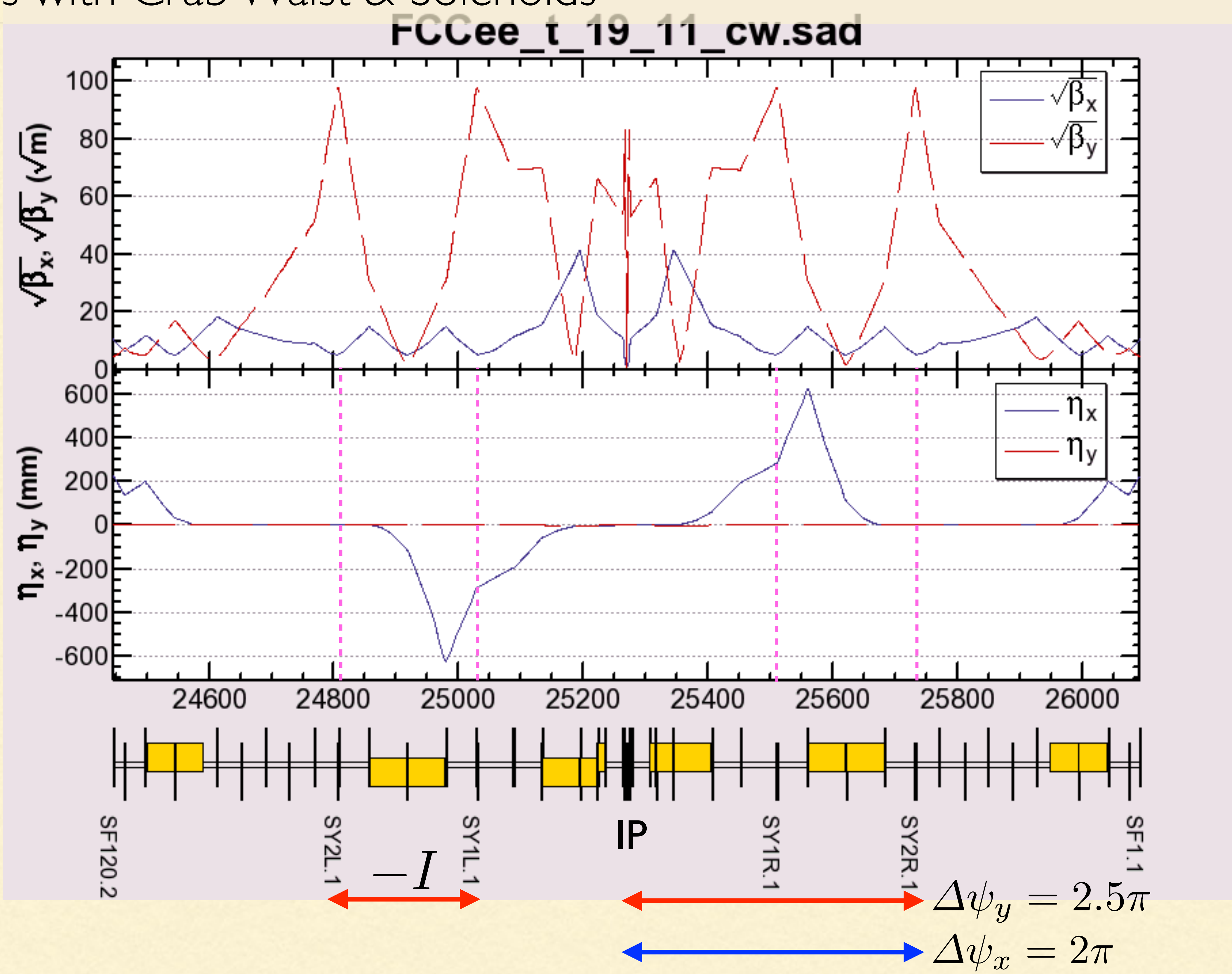
which can be approximated by a Hamiltonian of a sextupole:

$$H_s = \frac{k_2}{6} \left(x^3 - 3xy^2 \right) \ , \tag{7}$$

with

$$k_2 = -\frac{1}{2\theta_x \beta_y^* \beta_y} \sqrt{\frac{\beta_x^*}{\beta_x}} \ . \tag{8}$$

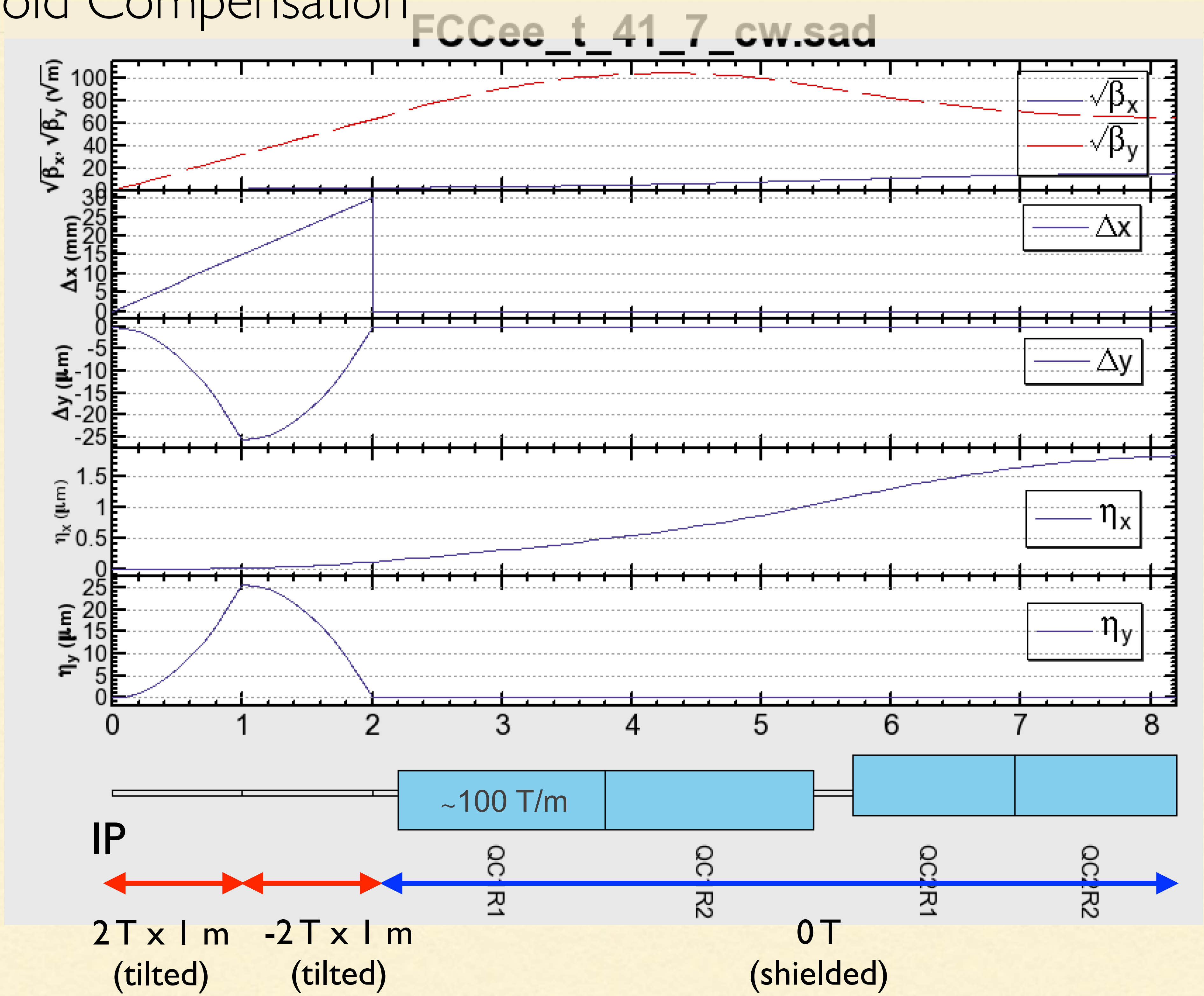
IR Optics with Crab Waist & Solenoids



- The crab waist is realized by tweaking the strength of the second sextupole **by about 30% weaker** in this case.

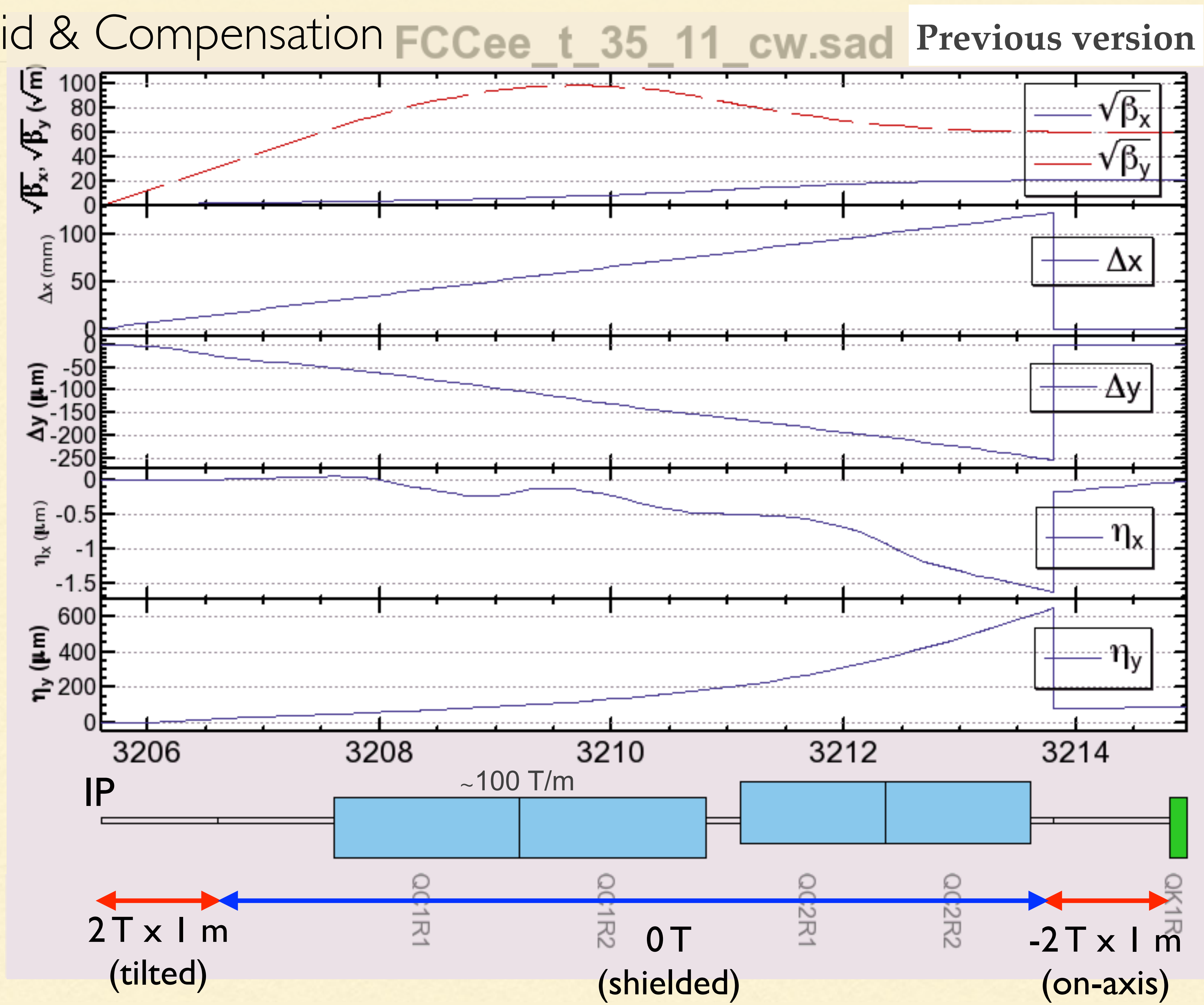
$$\beta_{x/y} = 30/9,400 \text{ m}$$
$$\beta^*_{x/y} = 1,000/1 \text{ mm}$$
$$\theta_x = 30 \text{ mrad}$$

Local Solenoid Compensation



- Local solenoid compensation like above is the ideal solution, if it is technically possible.
- No leak orbit, no vertical dispersion, no coupling outside for all beam energy.
- Thus use this scheme unless it is technically denied. The previous solution with skew quads is not dead.

IP Solenoid & Compensation

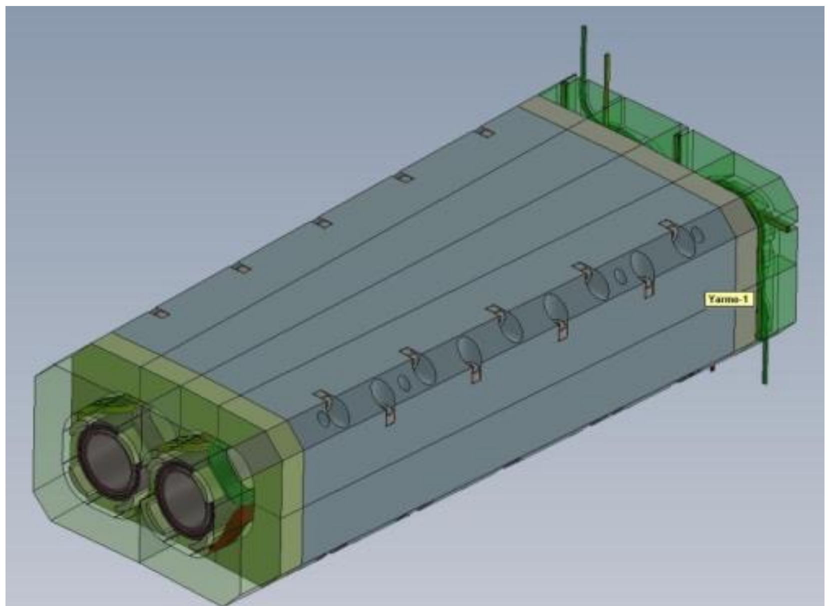


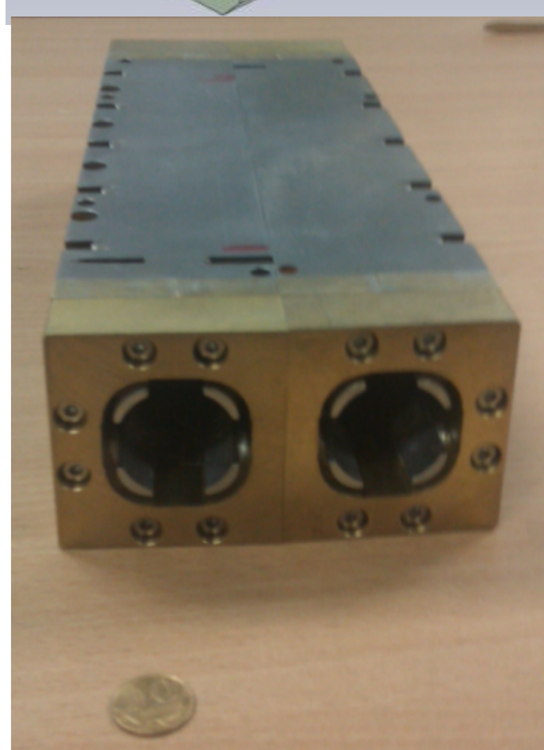
- Compensation solenoids (1) shield the final quads (2) cancel the integrated rotation.
- Residual couplings are corrected by a roll of QC2 and skew quads outside, 7 skews/side (I assume QC1 cannot roll).

SC final focus quadrupole

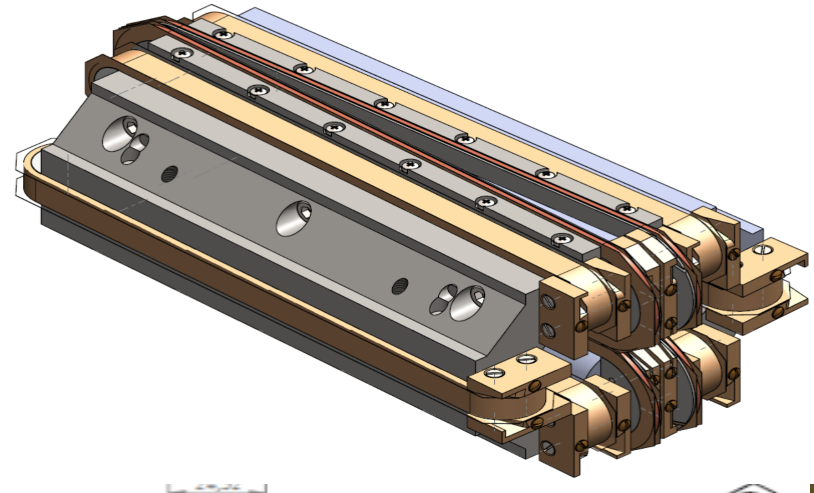
Main contributors are Ivan Okunev and Pavel Vobly

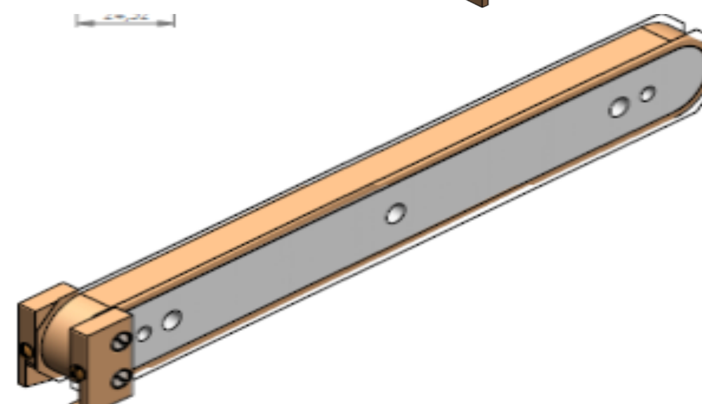
Two versions of the FF twin-aperture iron yoke quad prototype with 2 cm aperture and 100 T/m gradient are in production.

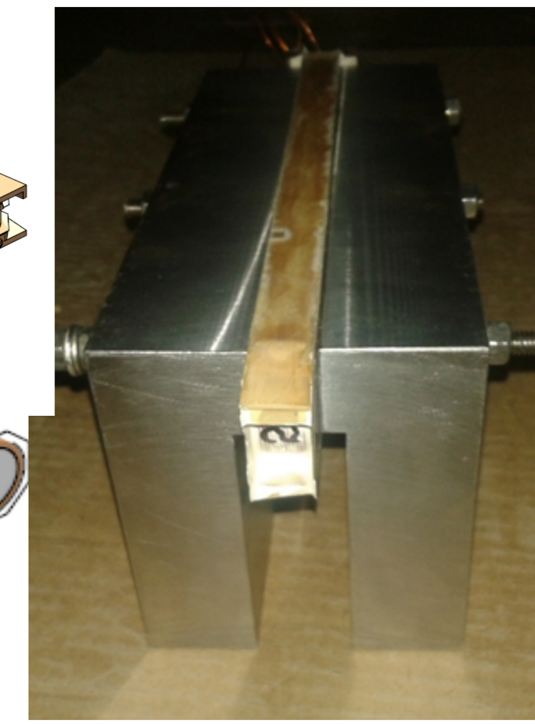




Saddle-shaped coils, complicated in production, the first coil failed. New winding device is in development.







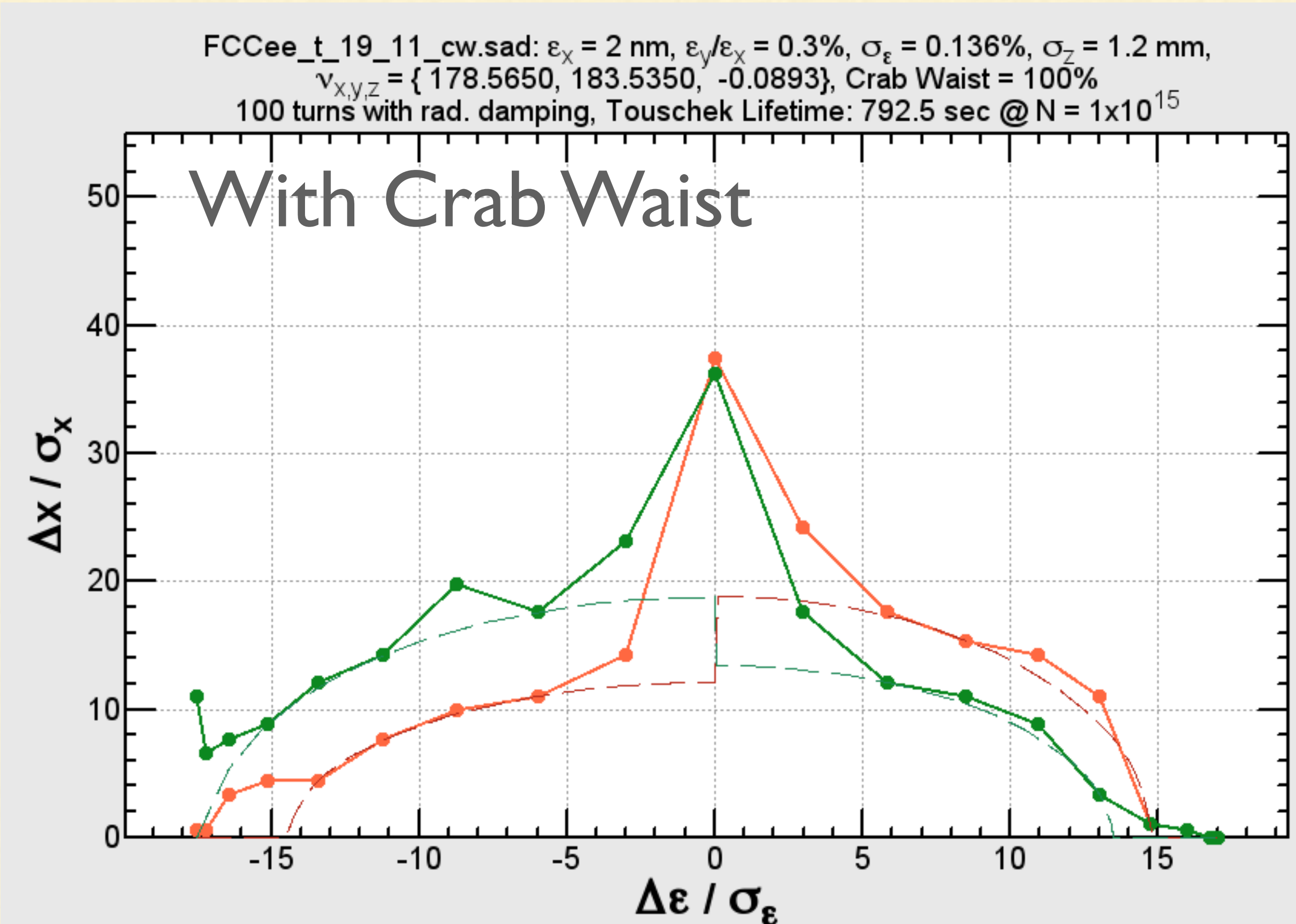
Straight coil, successfully wound and tested (650 A instead of the nominal 400 A)

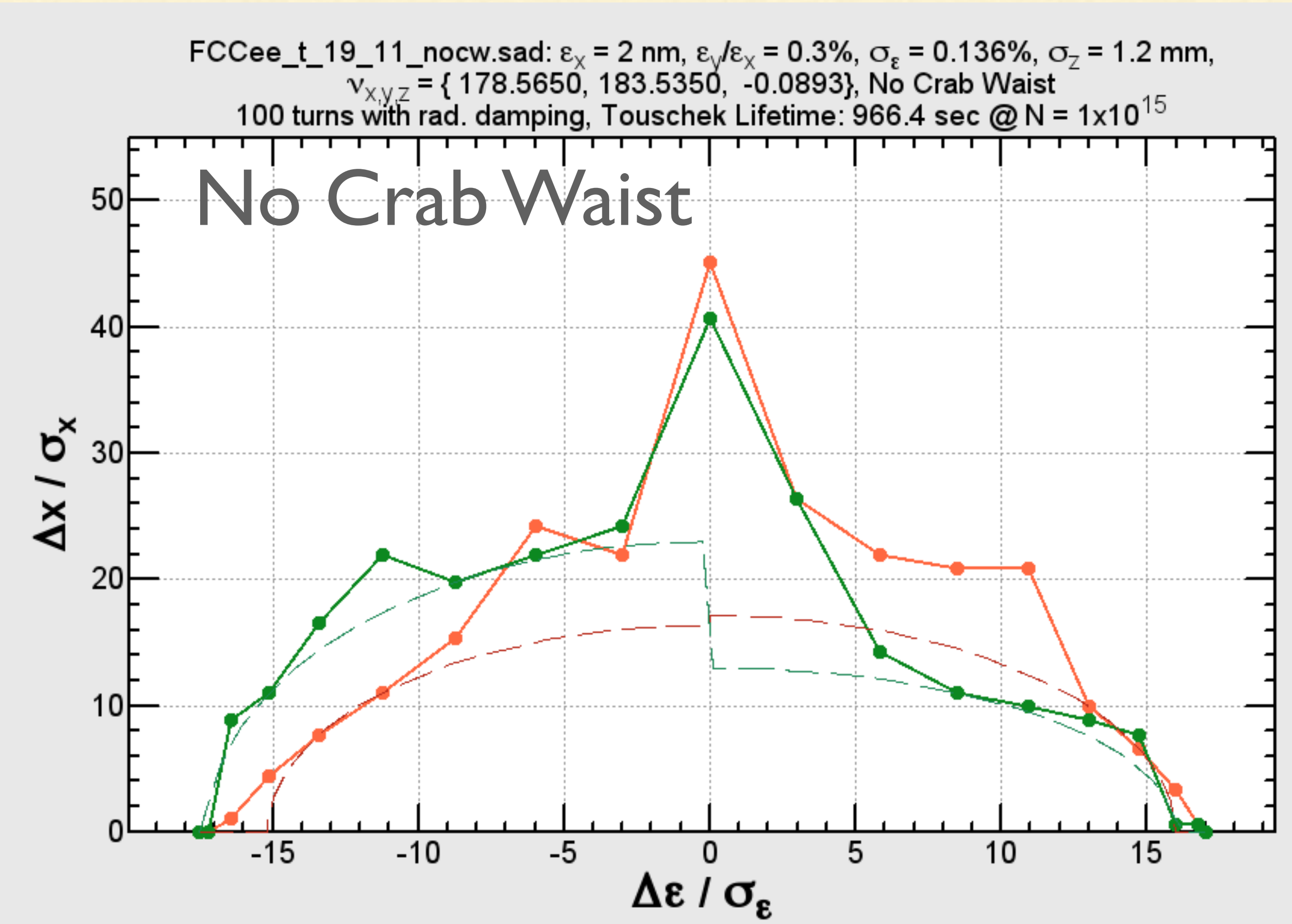
The work has low priority and small contract with CERN would help

E. Levitchev

The effect of crab waist on the dynamic aperture

for the same linear lattice



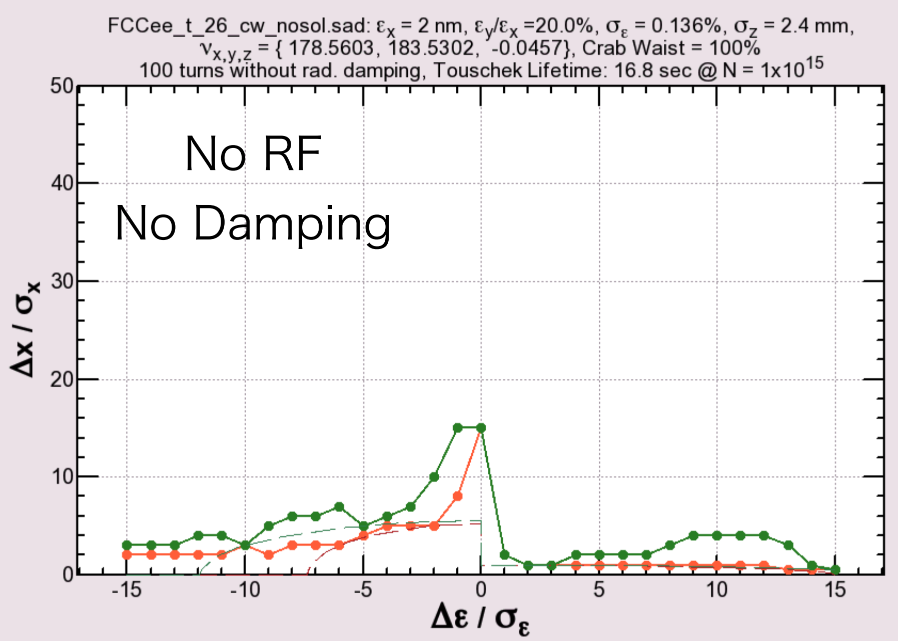


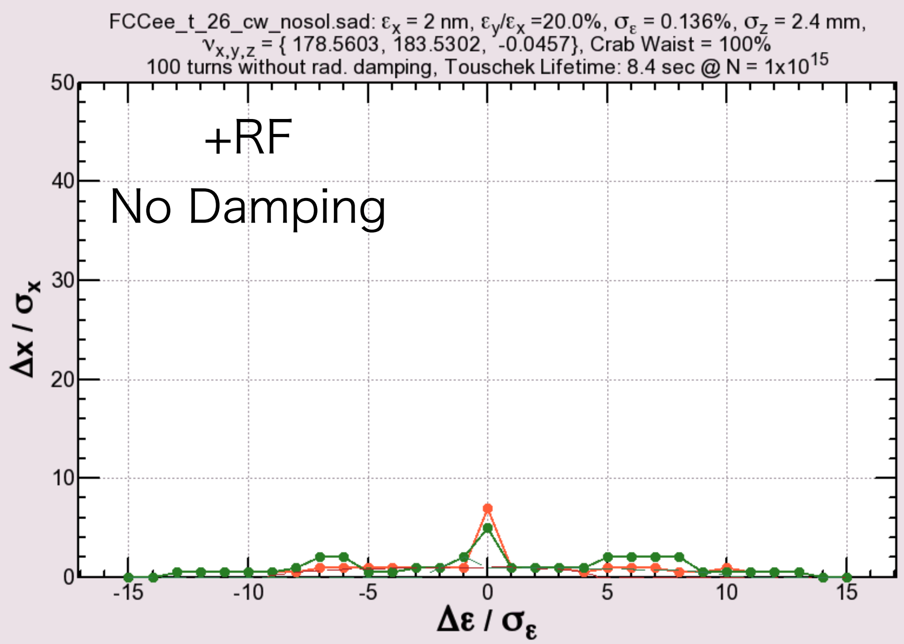
$\pm 2\%$

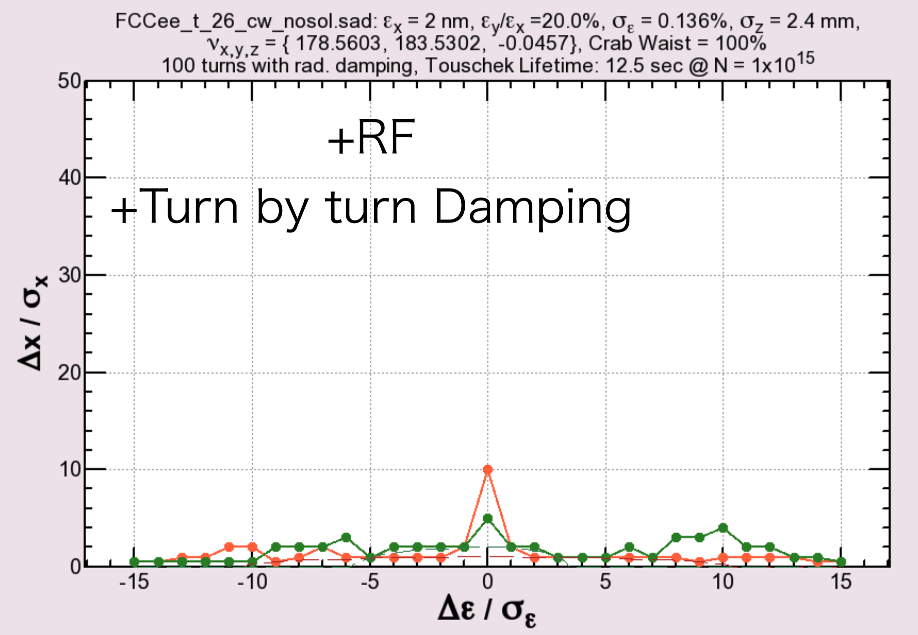
- Crab waist reduces the dynamic aperture, but recovered by re-optimizing the sextupoles.
- Momentum acceptance of ±2% is achieved assuming turn-by-turn (fake) rad. damping.
- Skew sextupoles are added on some sexupoles near the IR to compensate the chromatic coupling.
- Octupoles are added to CCS sextupoles for the optimization.

Crab waist, no solenoid

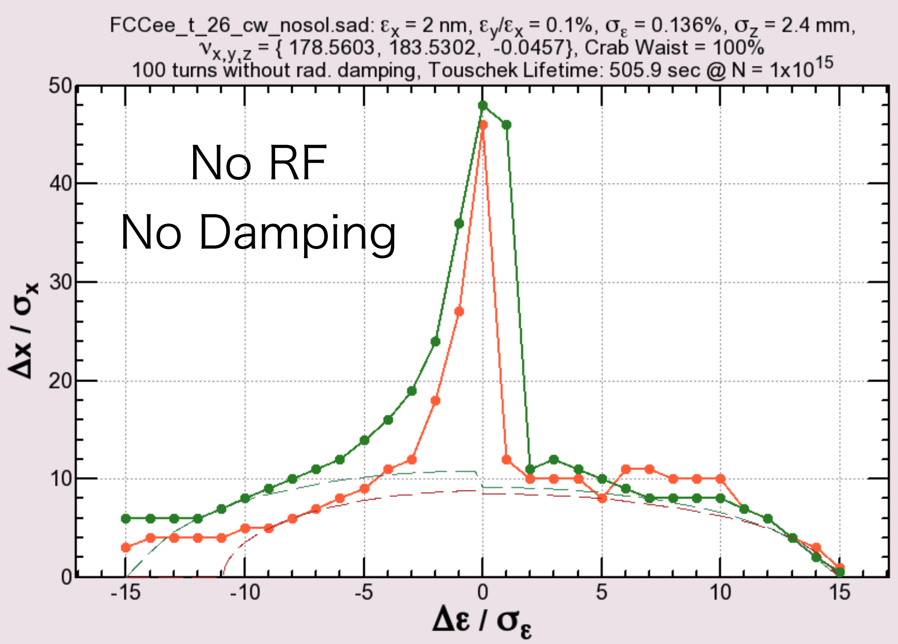
Jy/Jx = 20%

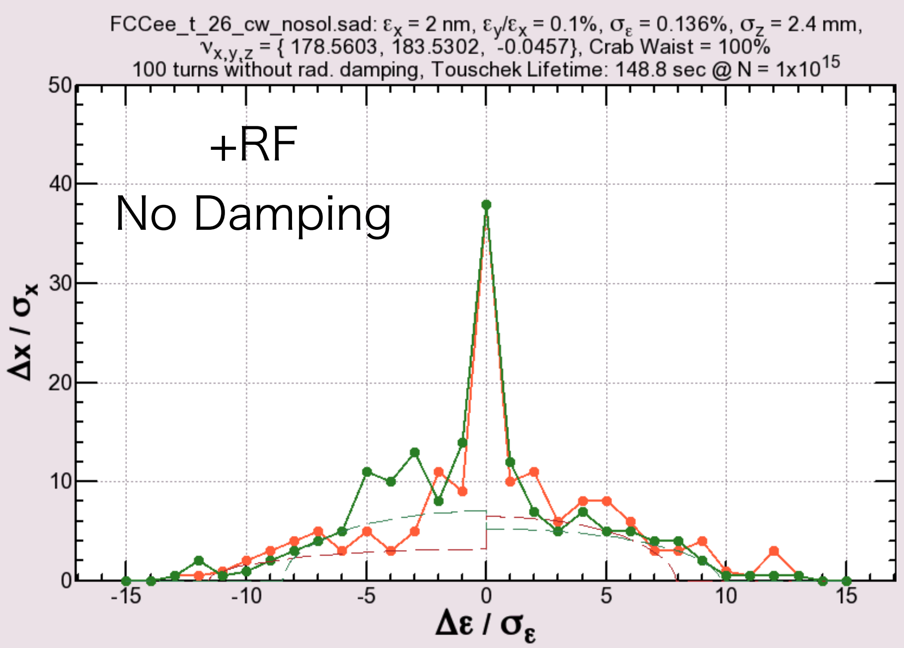


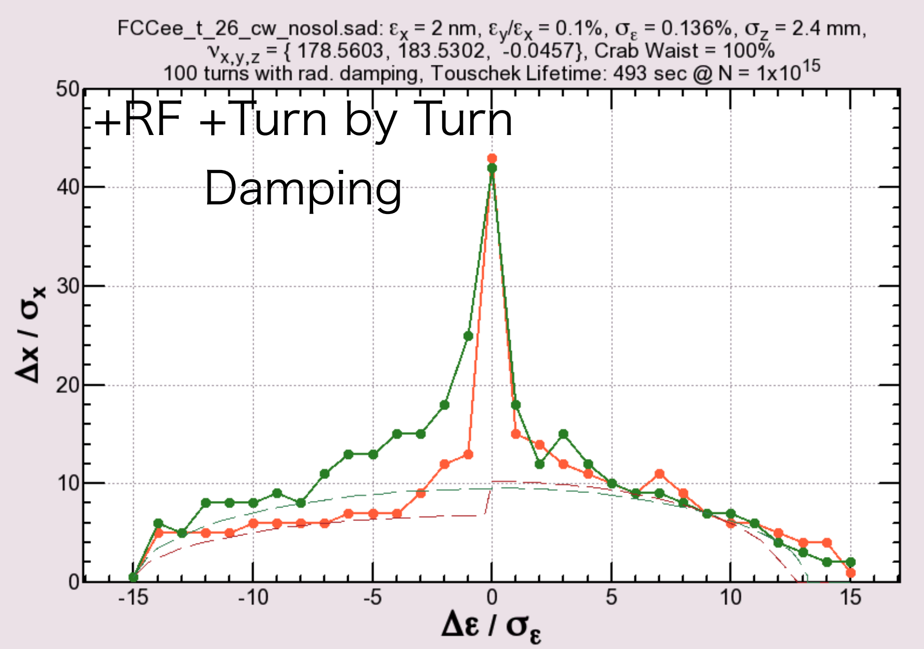




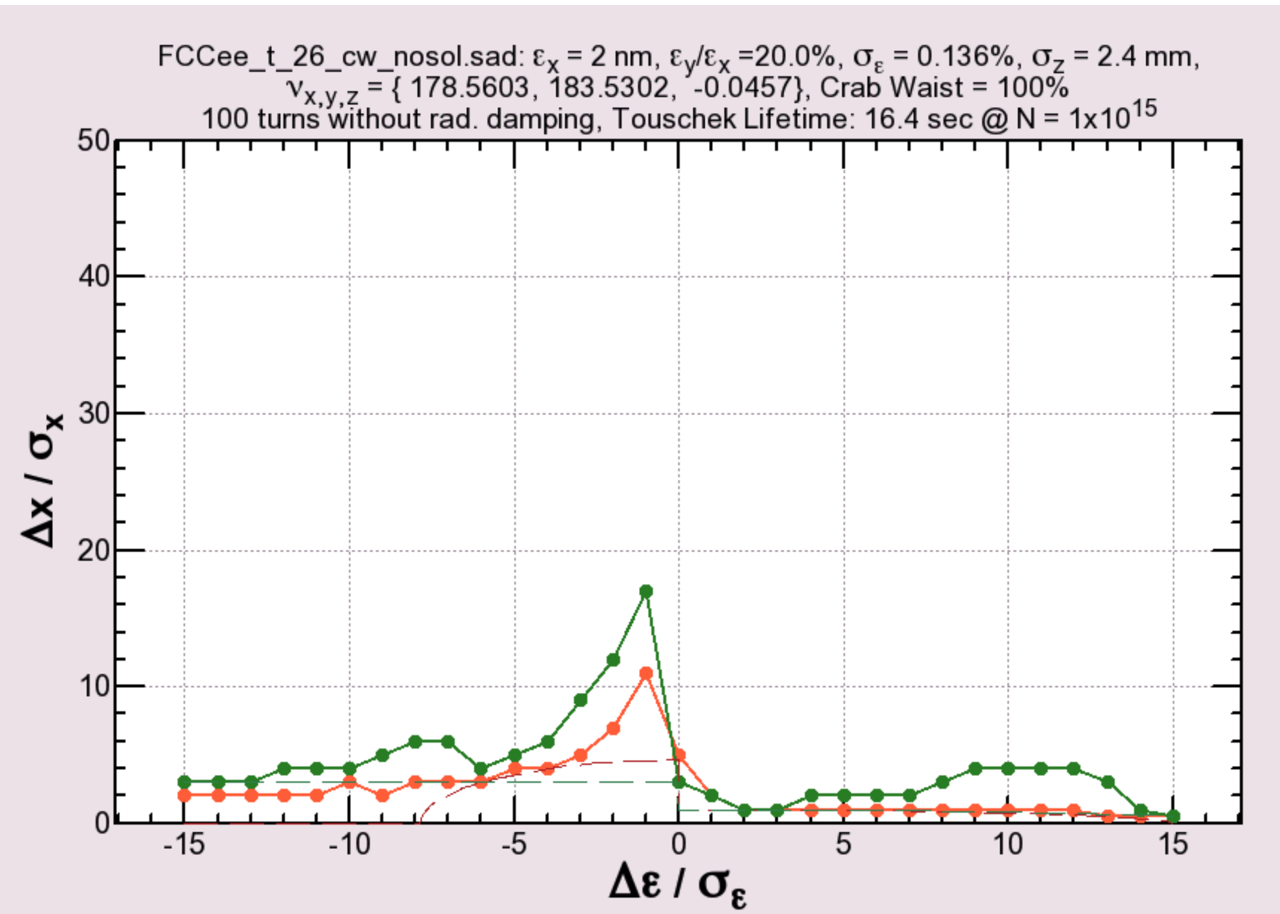
Jy/Jx = 0.1%



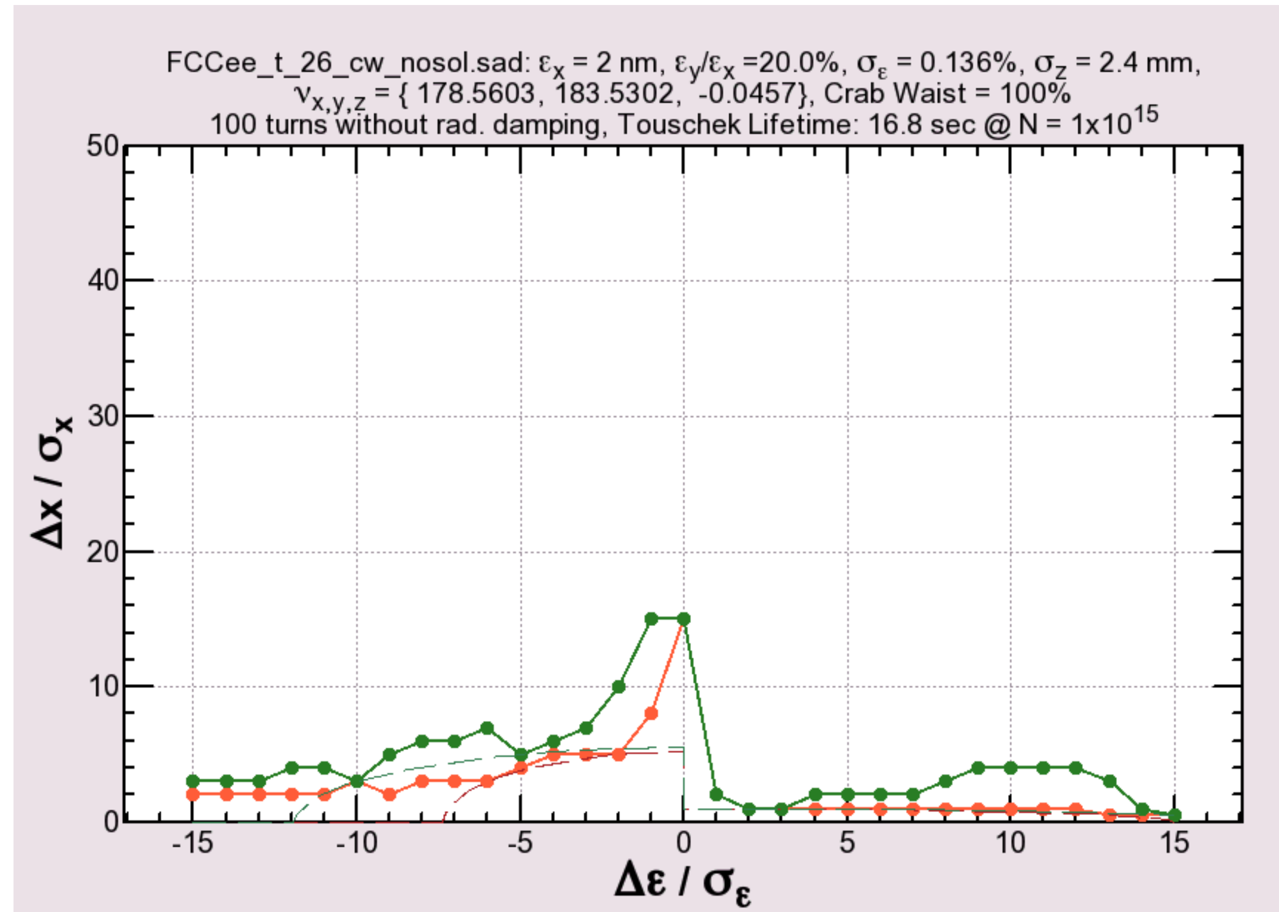




Crab waist, no solenoid



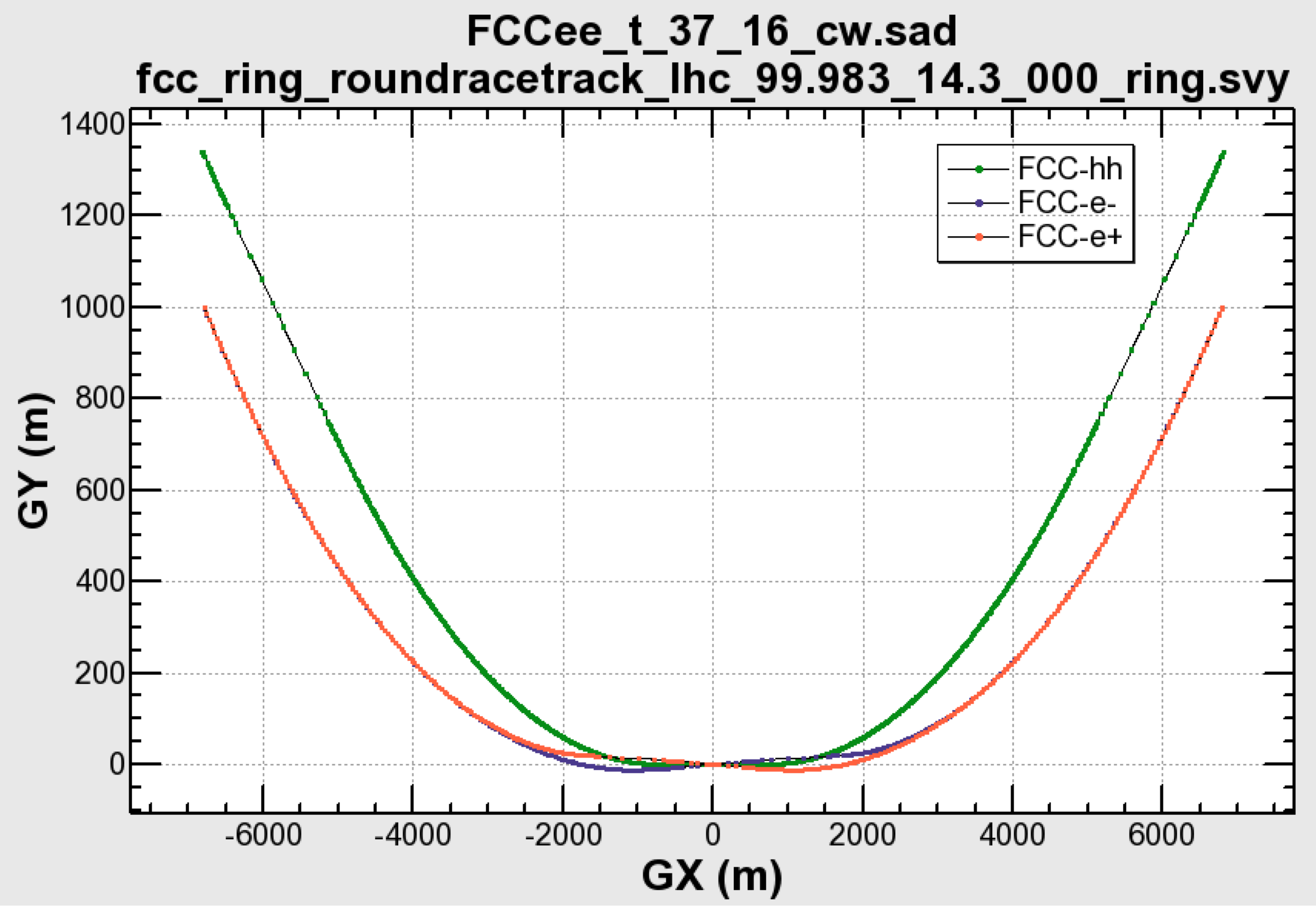
Fringe OFF

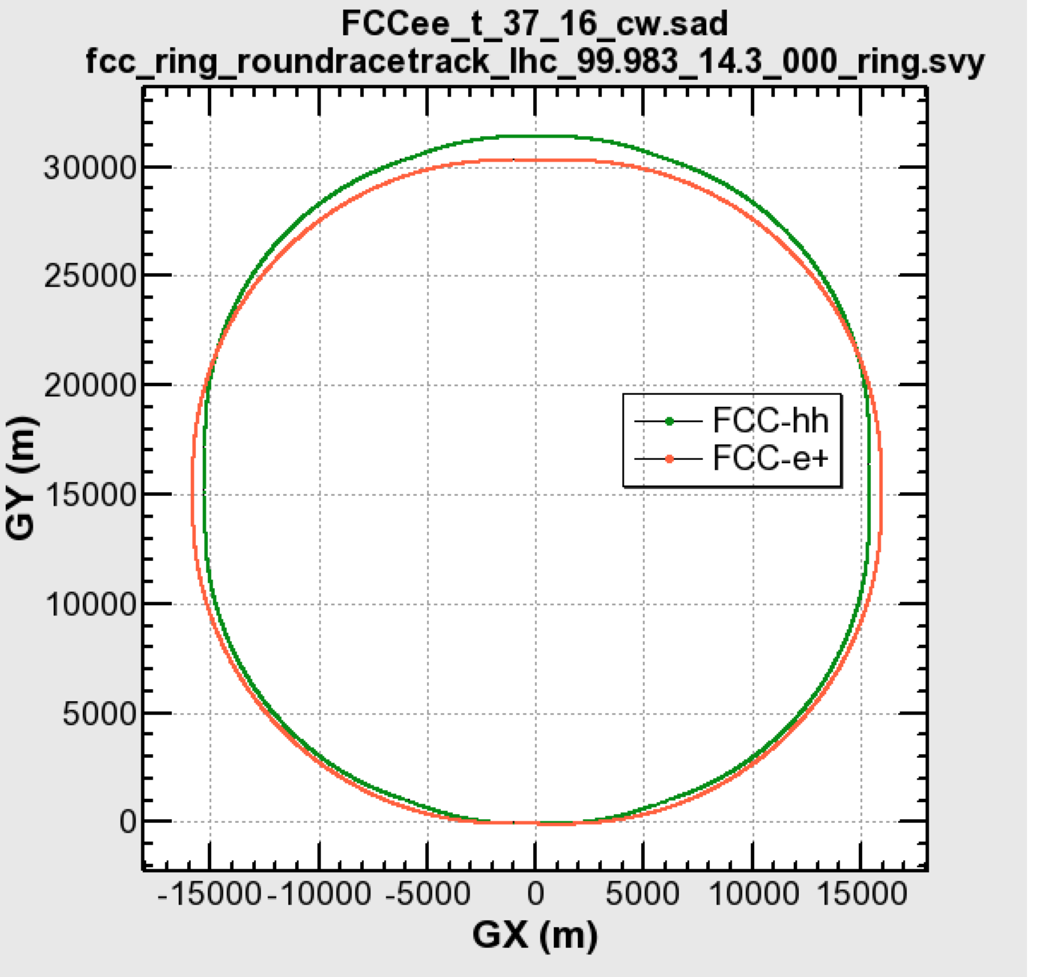


Fringe ON

Jy/Jx = 20%, no synchrotron motion, no damping.

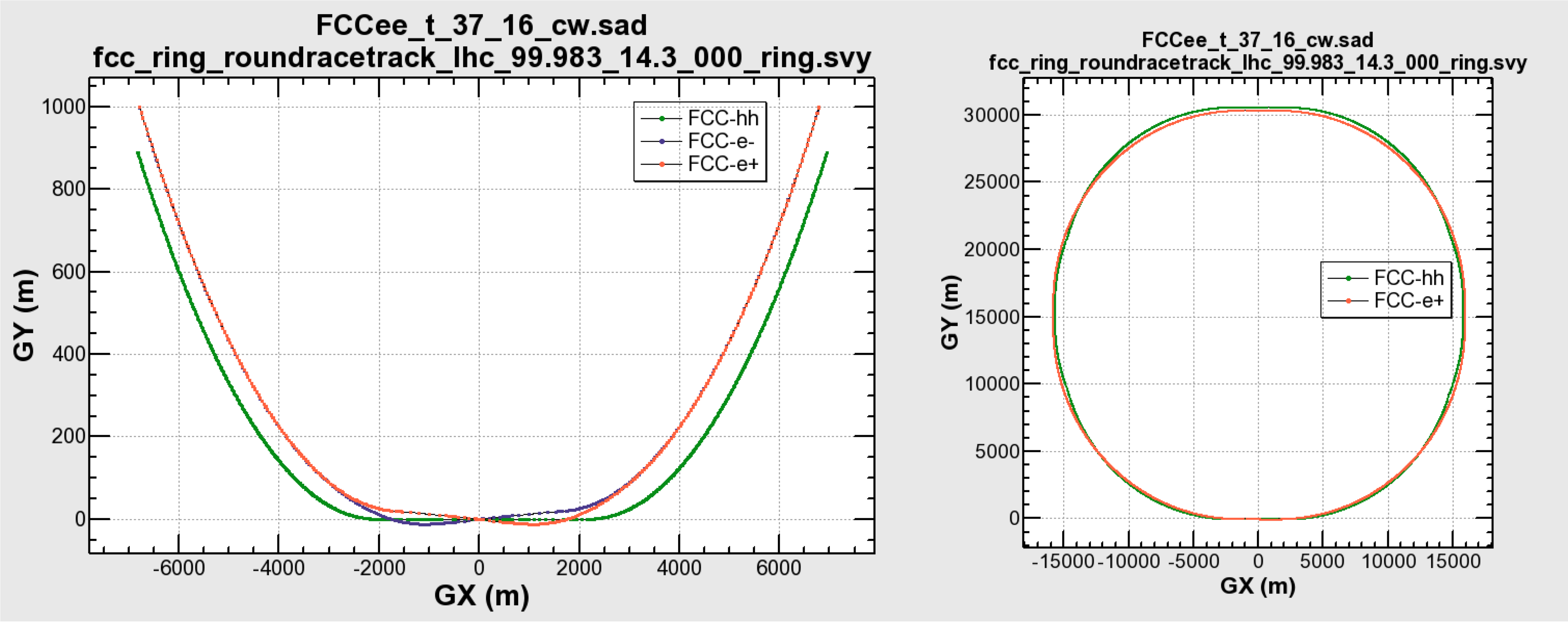
Comparison of the geometry around the main IR of FCC-hh





Comparison of the geometry: e+e- IPs at 90°/270°

suggested by D. Schulte



- By placing the FCC-ee IPs at 90°/270°, the matching with FCC-hh looks better.
- The residual differences can be reduced by tweaking the ee rings.
- Additional halls for FCC-ee detectors are required.

A rough estimation of radiation by arc quads

- The radiation power:

$$P \propto \gamma^2 B^2 \ell$$

- Ratio of powers by dipoles and quadrupoles per unit cell:

  - dipole: $$P_d \propto \gamma^2 \left(\frac{B\ell_{\text{cell}}}{B\rho}\right)^2 \left(\frac{B\rho}{\ell_{\text{cell}}}\right)^2 \ell_{\text{cell}} \propto \gamma^4 \frac{\theta^2}{\ell_{\text{cell}}}$$
  - quadrupole: $$P_q \propto \frac{\gamma^2}{2} \left(\frac{B' \Delta x \ell_q}{B\rho}\right)^2 \left(\frac{B\rho}{\ell_q}\right)^2 \ell_q \propto \frac{\gamma^4}{2} \frac{k_1^2 \Delta x^2}{\ell_q}$$
  - ratio: $$\frac{P_q}{P_d} = \frac{(k_1 \ell_{\text{cell}})^2}{2} \frac{\beta_{xq}}{\ell_{\text{cell}}} \frac{n^2 \varepsilon_x}{\theta^2 \ell_q}, \qquad \Delta x^2 = n^2 \beta_{xq} \varepsilon_x$$

- In the case of a 90° cell, $k_1 \ell_{\text{cell}} = 2\sqrt{2}, \beta_{xq}/\ell_{\text{cell}} = 1 + \frac{1}{\sqrt{2}},$ then:

$$\frac{P_q}{P_d} = (4 + 2\sqrt{2}) \frac{n^2 \varepsilon_x}{\theta^2 \ell_q}$$

- or a particle with an amplitude of $n\sigma_x$ will receive an energy loss per every turn:

$$\frac{\Delta p_1}{p_0} = \frac{P_q}{P_d} \times \frac{U_0}{E} = (4 + 2\sqrt{2}) \frac{n^2 \varepsilon_x}{\theta^2 \ell_q} \alpha_\varepsilon \qquad (\alpha_\varepsilon\text{: long. damping per turn})$$

- which causes a synchrotron motion with a momentum amplitude $\pm \Delta p/p_0$:

$$\frac{\Delta p}{p_0} = \frac{1}{2\pi \nu_s} \frac{\Delta p_1}{p_0} = \left(2 + \sqrt{2}\right) \frac{n^2 \varepsilon_x}{\pi \theta^2 \ell_q} \frac{\alpha_\varepsilon}{\nu_s}$$

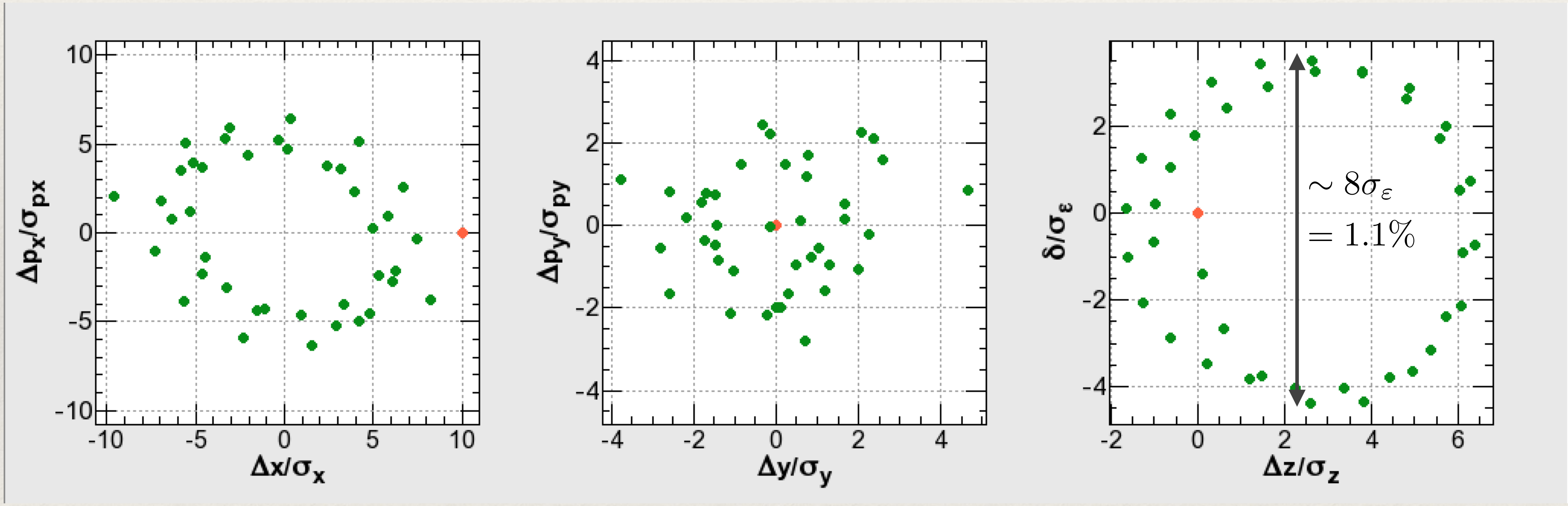
A rough estimation of radiation by arc quads (cont'd)

- If we plug-in the number for FCC-ee-tt:

$$\varepsilon_x = 2\ \mathrm{nm}, \theta = 2\pi/1240, \alpha_\varepsilon/\nu_s = 0.41 \quad \text{gives}$$

$$\frac{\Delta p}{p_0} = 0.58\% \left(\frac{n}{10}\right)^2 \left(\frac{0.6\ \mathrm{m}}{\ell_q}\right)$$

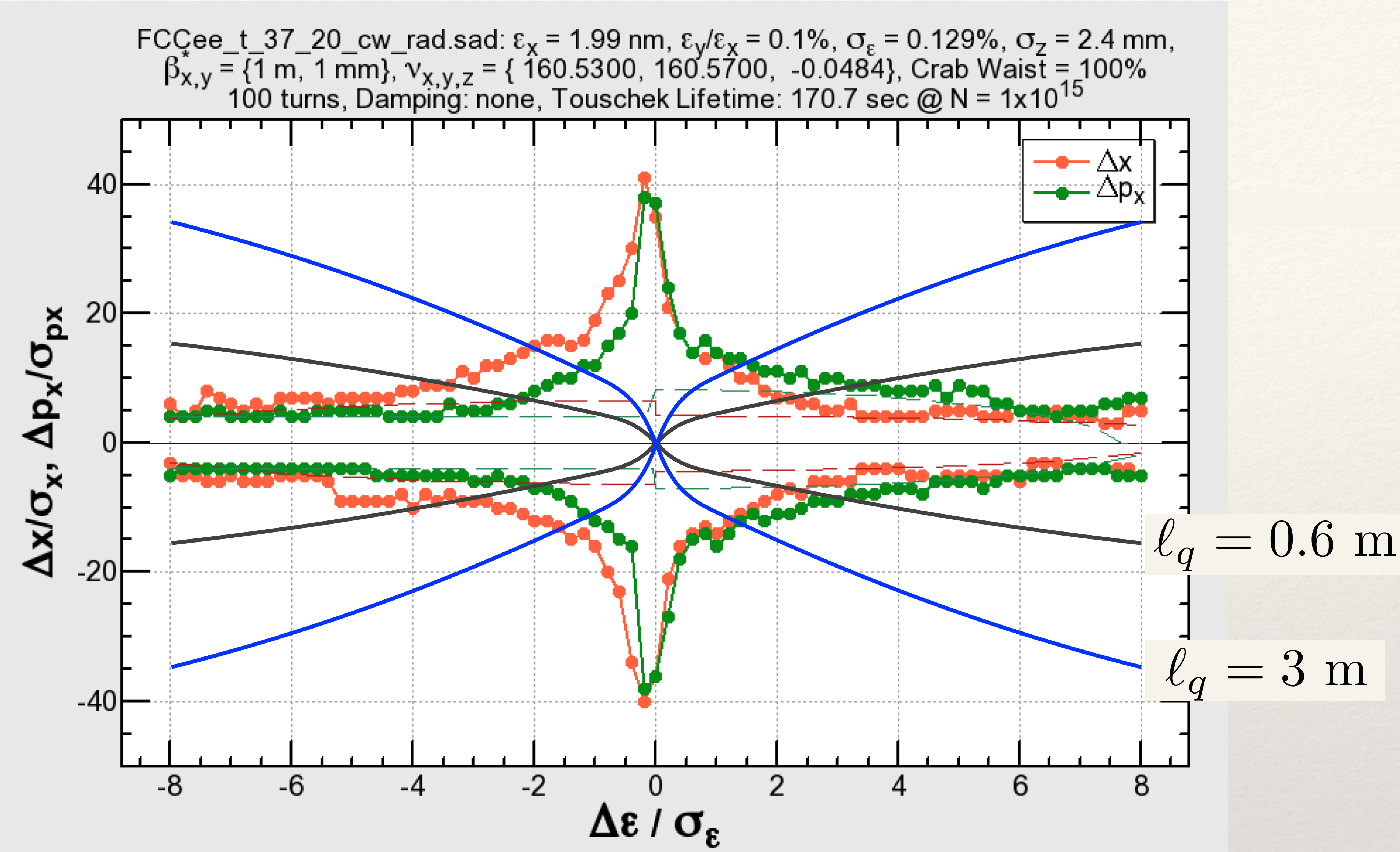
- Indeed, this estimation agrees with the tracking with element-by-element radiation*:



* only damping, no fluctuation, is taken into account in simulations in these slides.

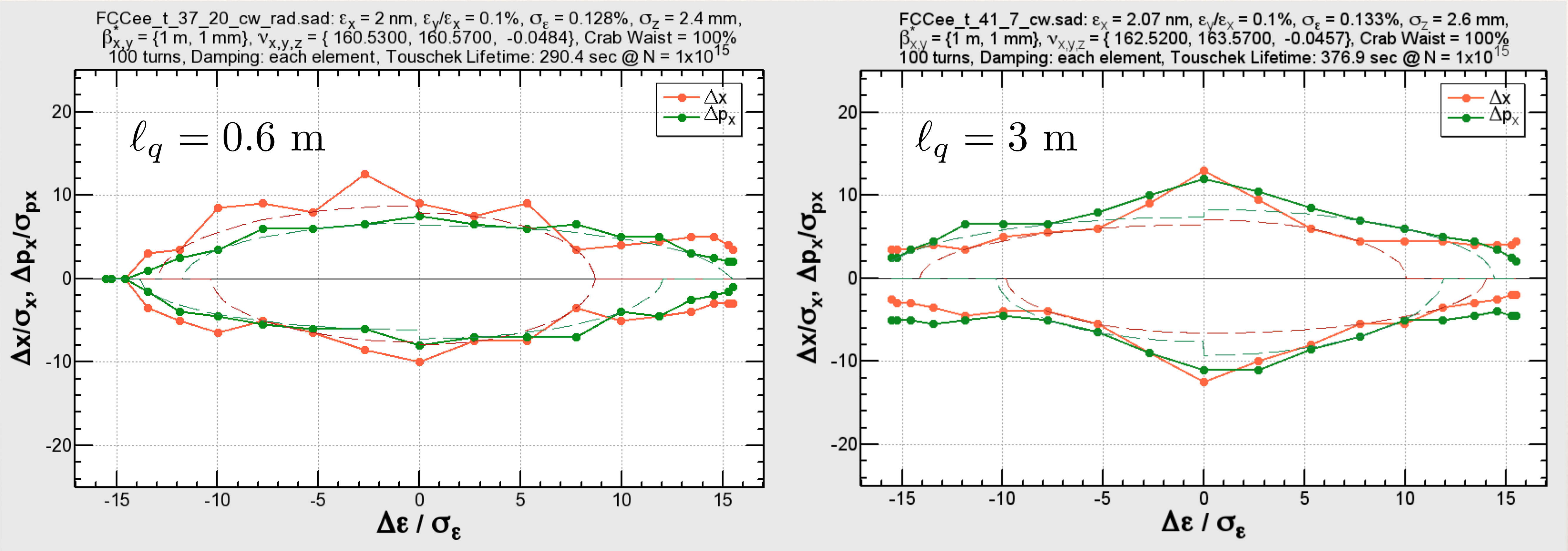
Cf. Barbarin, F ; Iselin, F Christoph ; Jowett, John M, 4th European Particle Accelerator Conference, London, UK, 27 Jun - 1 Jul 1994, pp.193-195

The effect on the dynamic aperture



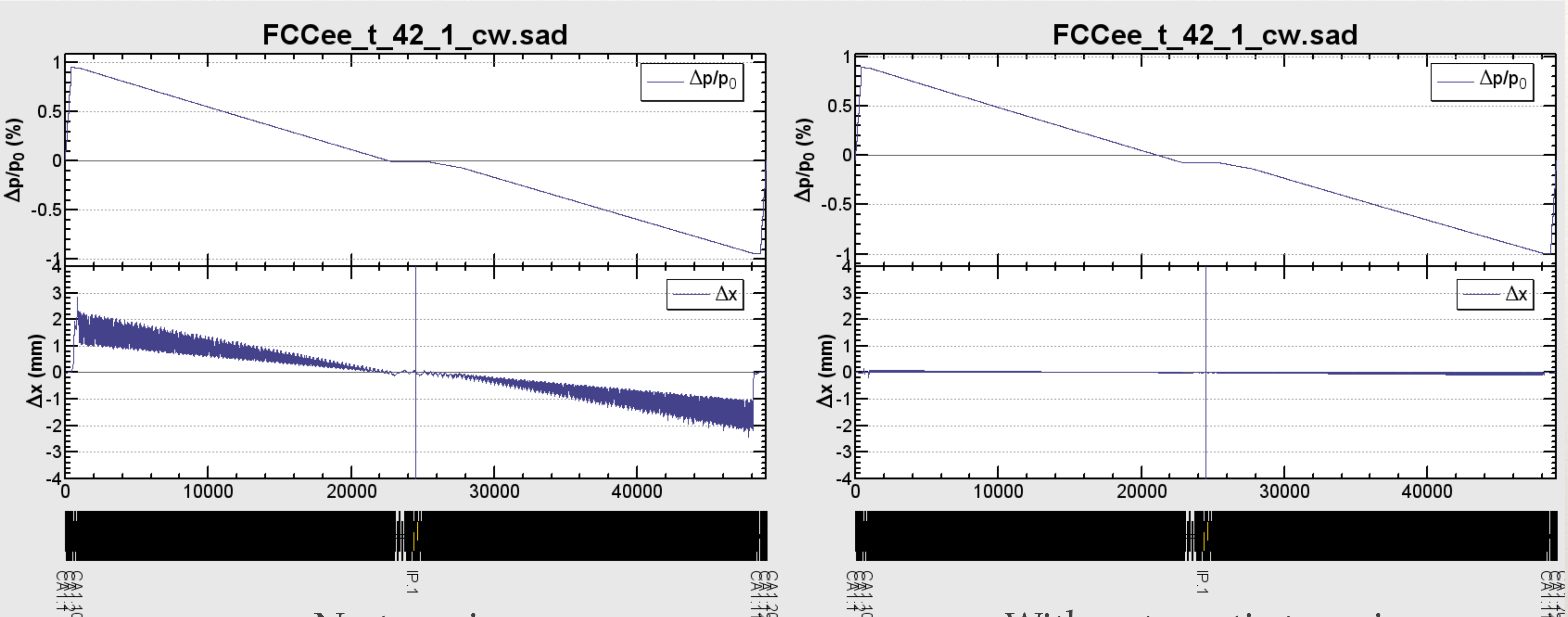
- The required momentum acceptance for $\Delta x/\sigma_x$ are shown by the curves above.
- To accept the radiation-induced synchrotron motion, the dynamic aperture must be wider than these curves.

The effect on the dynamic aperture (cont'd)



- The dynamic aperture with element-by-element radiation agrees with the estimation above.
- The on-momentum transverse aperture is somewhat improved by $\ell_q = 3\ \mathrm{m}$.
- Then one of the merits of non-interleaved sextuple, a very wide transverse aperture at on-momentum, is destroyed by the radiation in quadrupoles, at lease at 175 GeV.
- The non-interleaved scheme may still have merits at lower energies.

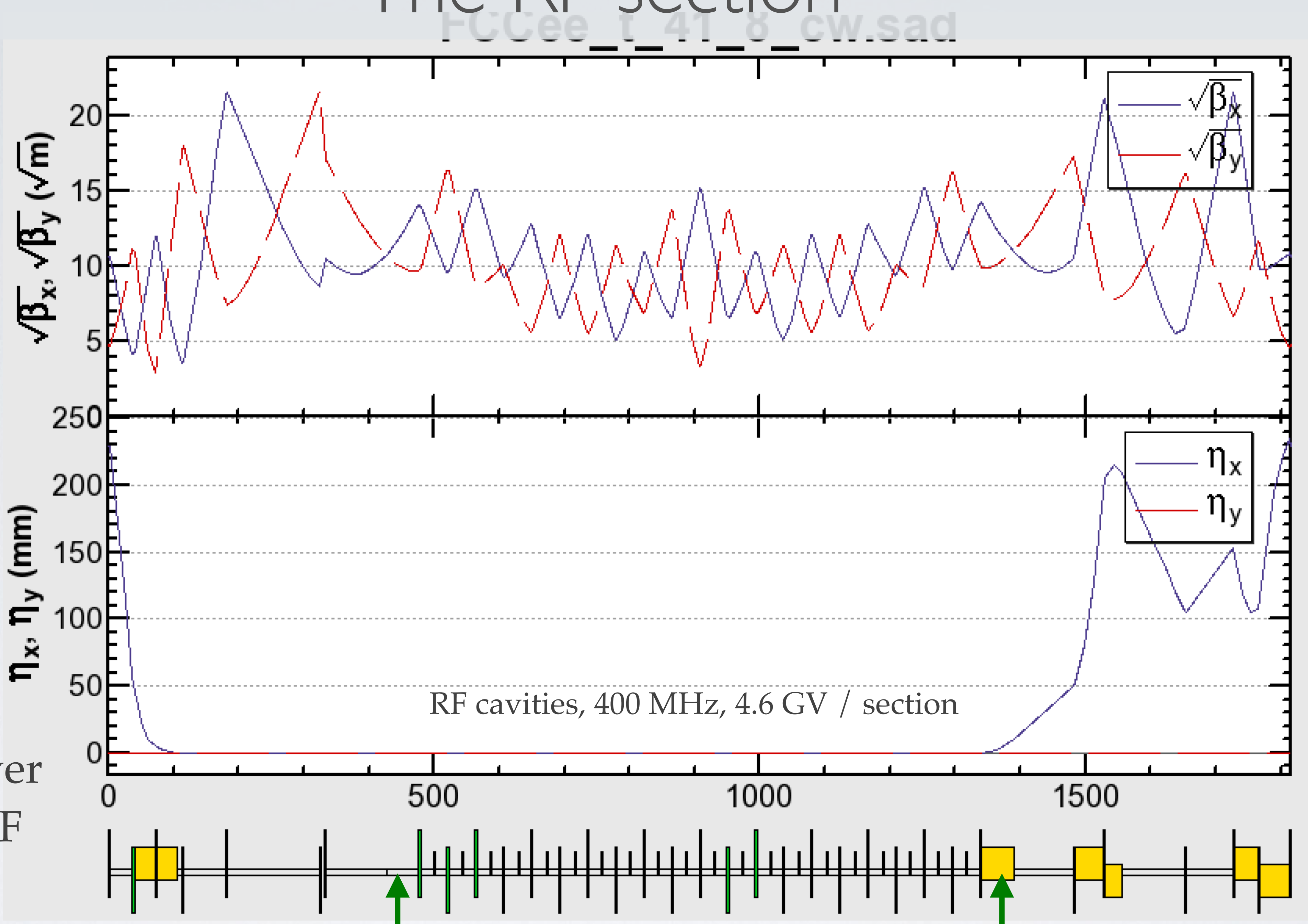
Tapering



No tapering   With automatic tapering

- The “automatic tapering” scales the strength of dipoles, quads, and sexts with the local momentum deviation of the closed orbit.
- Thus no sawtooth orbit nor optics deformation arise.
- This is one of the biggest merit of the double-ring scheme.

The RF section

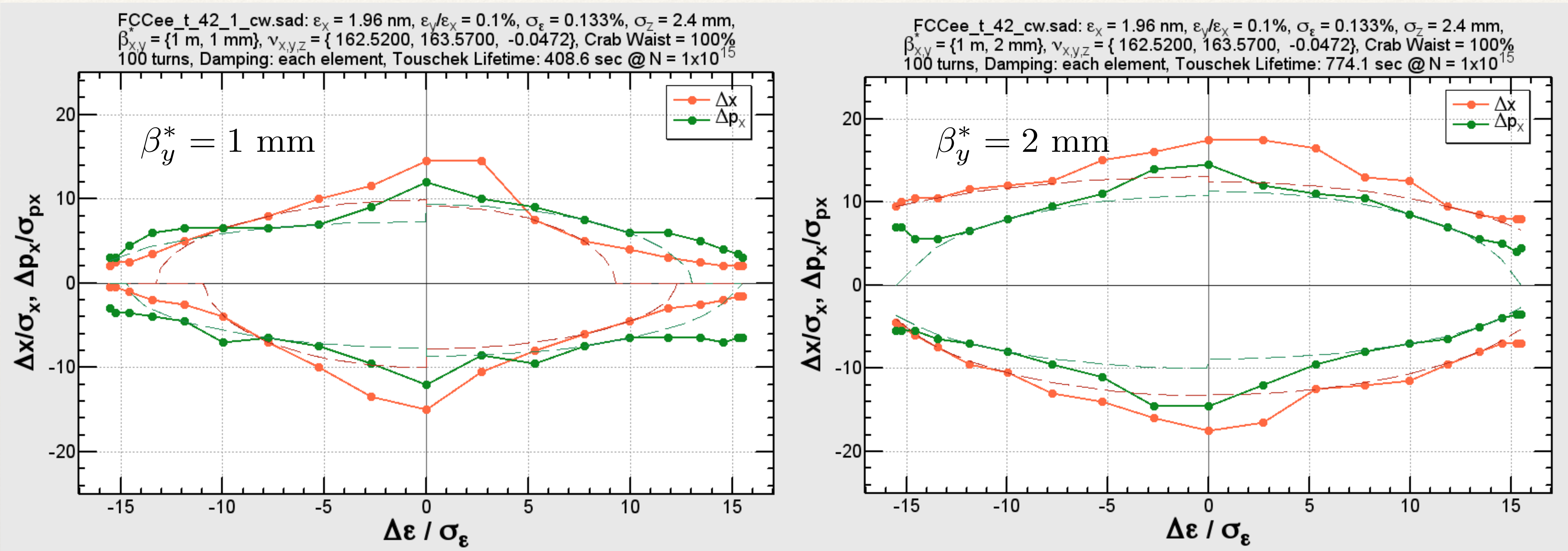


Beams cross over through the RF section.

Electrostatic beam separators are combined with magnets not to bend the incoming beam 150 kV, 10 cm gap, 50 m long.

- If the nominal strengths of quads are symmetrical in the common section, it matches to the optics of both beam.
- The strengths appear on the deck are not symmetric, due to "automatic tapering."
- This section is compatible with the RF staging scenario.

Dynamic Aperture

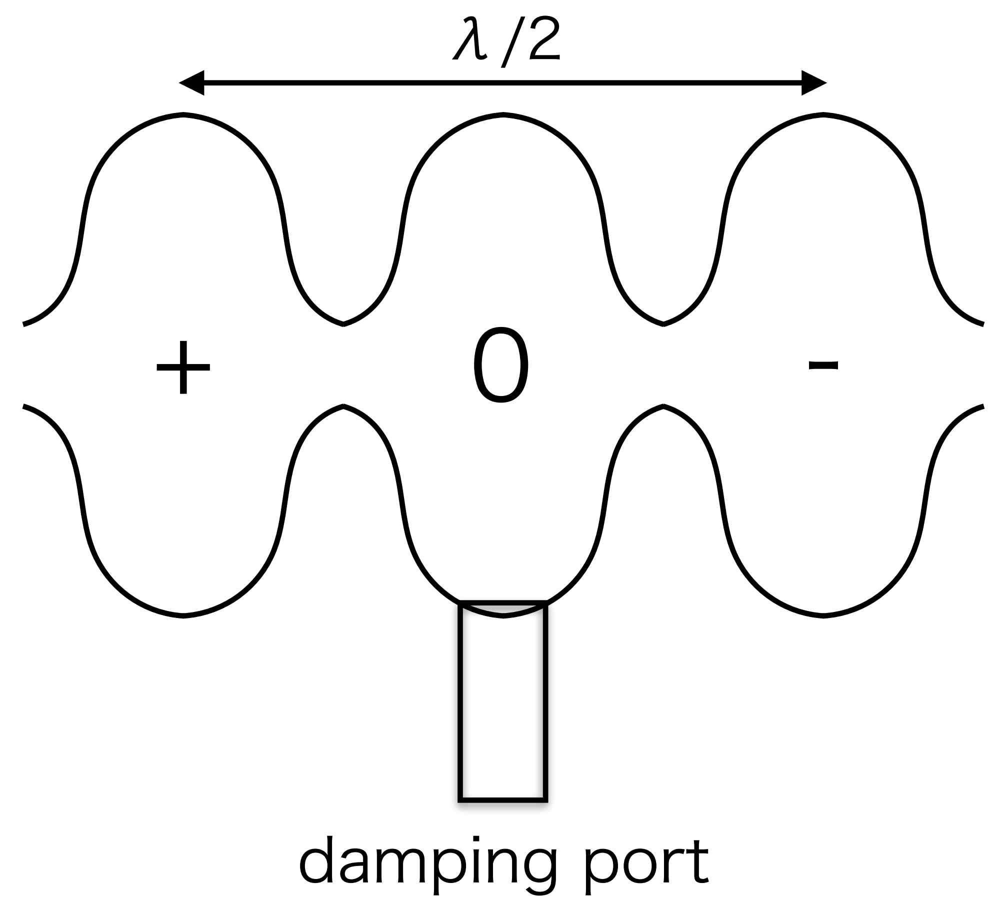


- The optimization of sextupoles is on going with element-by-element radiation.

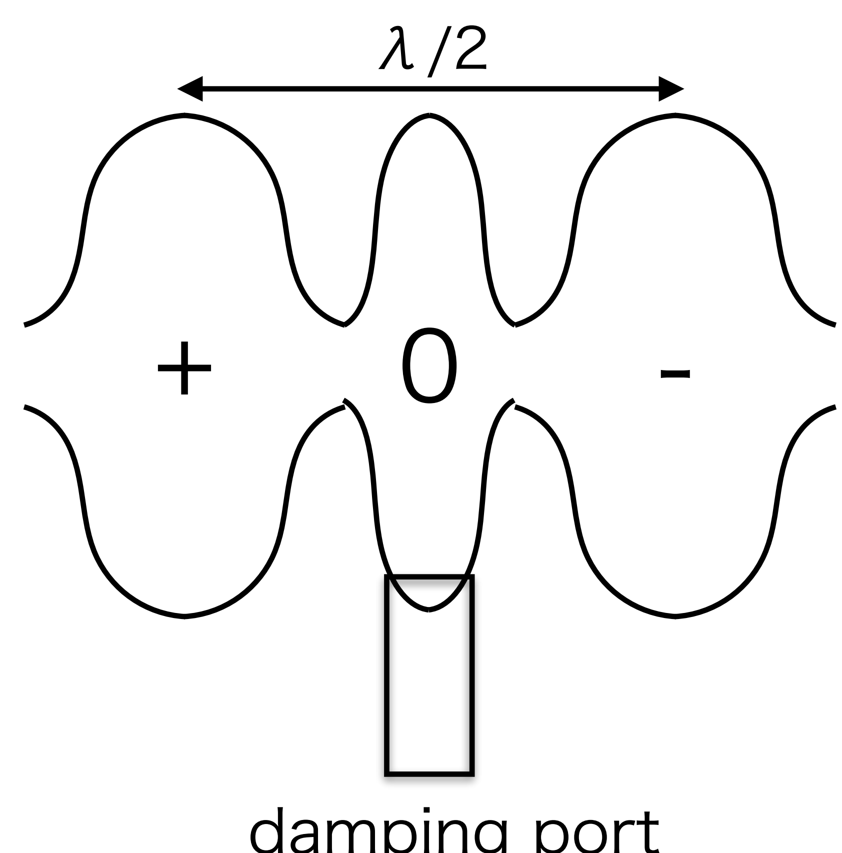
A possibility of multi-cell cavity?

- Put damping ports on half of cells alternatively.

- Then only $\pi/2$-mode remains undamped and usable for acceleration.



- By squeezing the damped cell, the effective gradient can be increased.



K. Oide, 25 Mar 05

Summary

- An example of beam optics for FCC-ee at 175 GeV has been presented, consisting of
  - 2 IPs/ring.
  - 30 mad crossing angle + crab waist.
  - Separated tunnel for 5 - 6 km /IP with local chromaticity correction system (LCCS).
  - Outer sextupoles in LCCS work as the crab sextupoles.
  - IP synchrotron radiation is suppressed to $u_c < 100$ keV.
  - Dynamic momentum acceptance > ±2%.
  - Transverse dynamic aperture ~$12\sigma_x$ ($\beta y^* = 1$ mm), ~$16\sigma_x$ ($\beta y^* = 2$ mm).
  - Two common RF sections per ring.
  - Tapering to suppress the sawtooth effect.
- The synchrotron radiation in quadrupoles plays a critical roll to limit the dynamic aperture, through the radiation-induced synchrotron motion.
  - The effect of radiation fluctuation must be evaluated.
- More studies are necessary:
  - Engineering of IP quads/solenoids / Injection scheme / RF system / machine errors & optics correction / MDI /etc.