A design of beam optics for FCC-ee

CEPC AP Meeting @ IHEP

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K. Oide (KEK)

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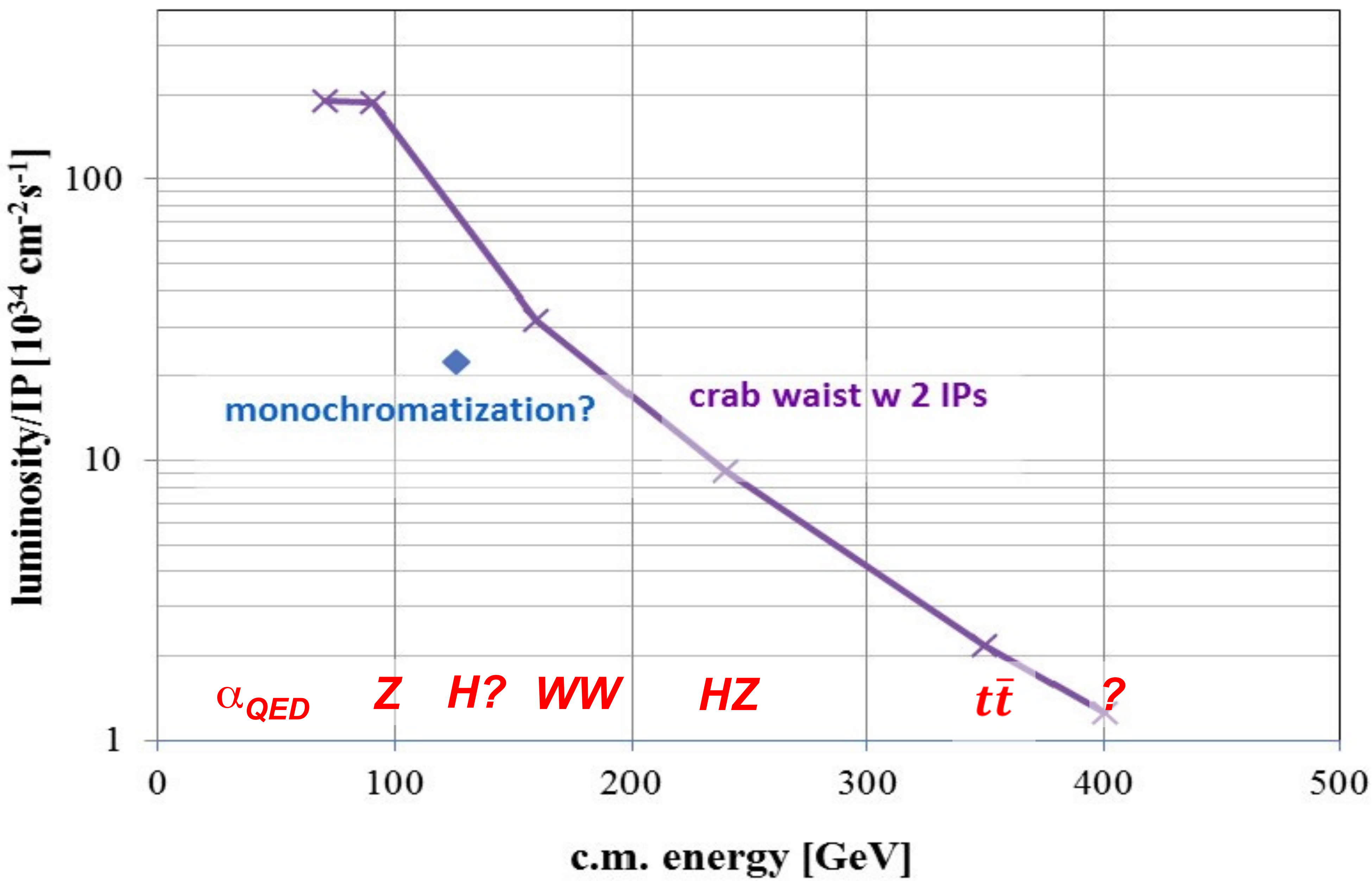
physics requirements for *FCC-ee*

- 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

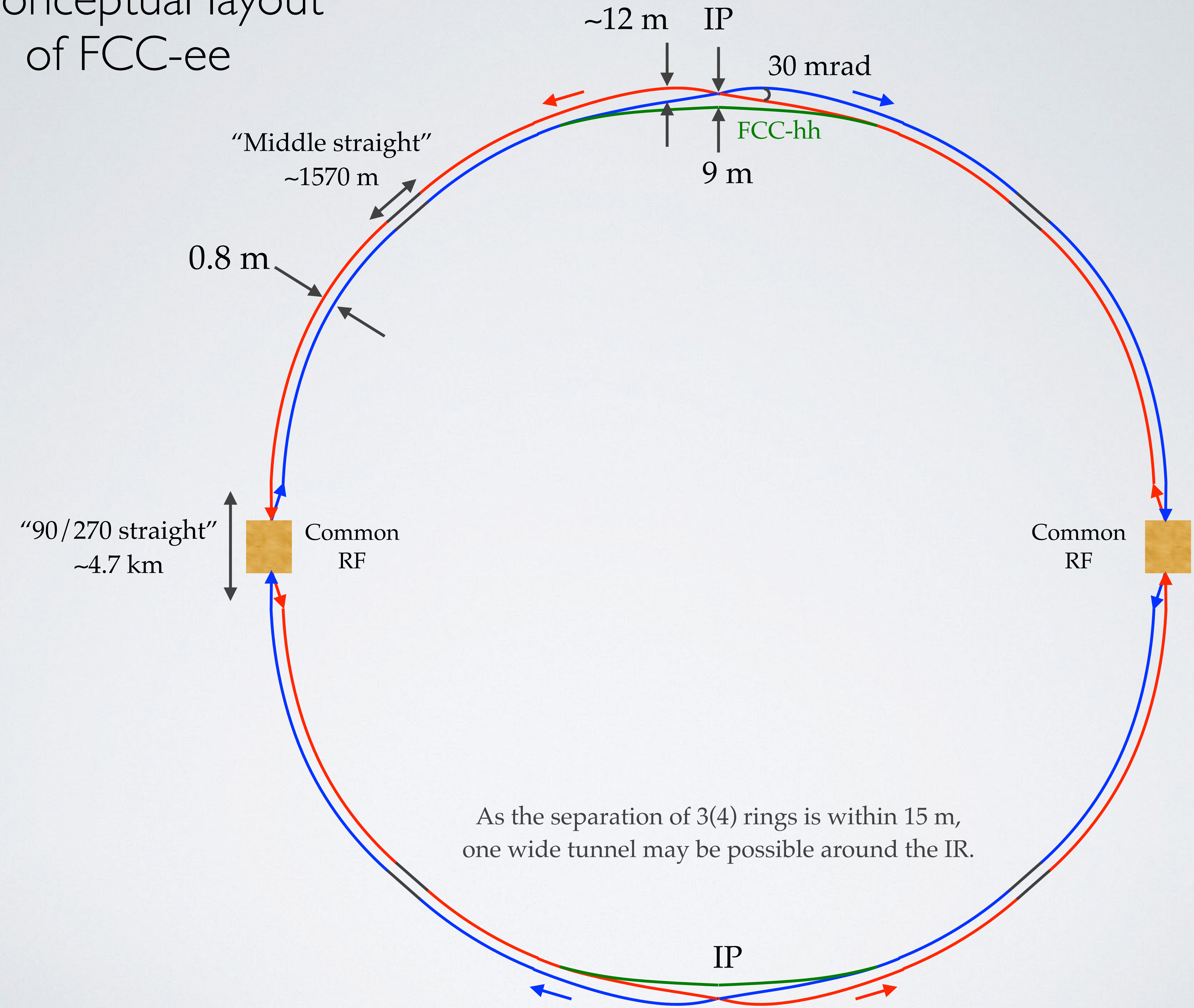


F. Zimmermann

The tentative parameters

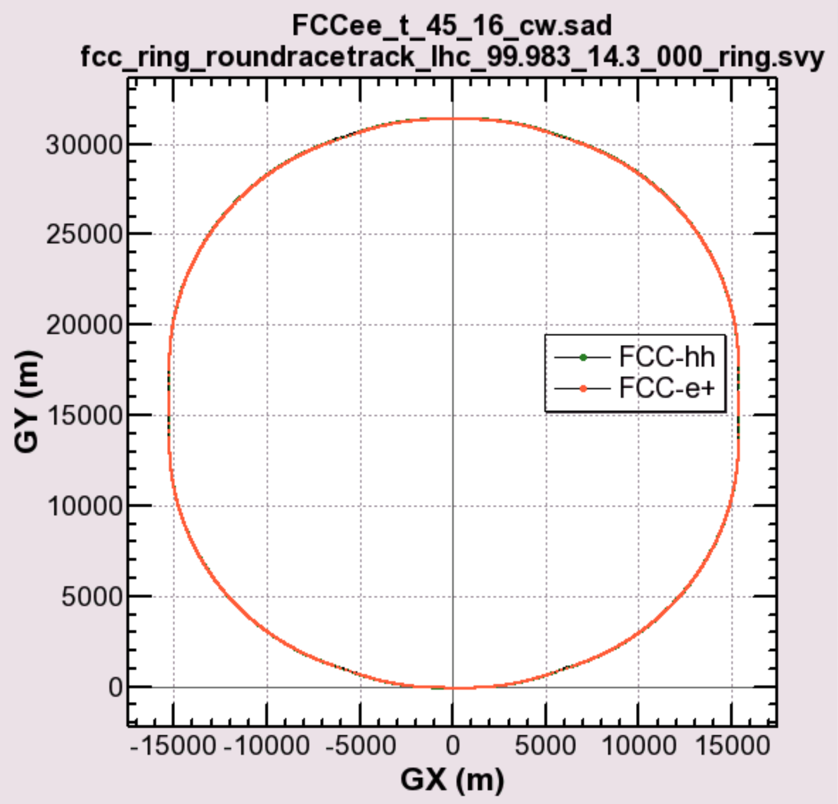
parameter	FCC-ee crab waist (2 IPs)			
	Z (IPAC'15)	Z (this design)	t (IPAC'15)	t (this design)
E_{beam} [GeV]	45.5	45.6	175	←
current [mA]	1450	←	6.6	←
$P_{SR,tot}$ [MW]	100	**95**	100	**94**
no. bunches	45154	←	51	←
N_b [10^{11}]	0.66	←	2.6	←
ε_x [nm]	0.13	0.15	2	1.83
ε_y [pm]	1.0	1.0	2	1.83
β^*_x [m]	0.5	**1**	0.5	**1**
β^*_y [mm]	1	**1**	1	**2**
RF frequency [MHz]	400			
RF voltage [GV]	0.4	**0.08**	11	**9.6**
circumference [km]	100	99.938	100	99.938
mom. comp. [10^{-5}]	0.5	**0.936**	0.5	**0.936**
synchrotron tune	-0.03	**-0.018**	-0.07	-0.0856
$\sigma_{z,SR}$ [mm]	1	**3.4**	2.31	2.4
$\sigma_{z,tot}$ [mm] (w	2.8		2.83	
$\sigma_{\delta,SR}$ [%]	0.037	0.041	0.202	**0.138**
$\sigma_{\delta,tot}$ [%] (w beamstr.)	0.127		0.248	
θ_c [mrad]	30			
Piwinski angle	5.3	←	1.8	←
L* [m]	2	**2.2**	2	**2.2**
beam-beam param.	0.07		0.06	
beam-beam param.	0.18		0.12	
luminosity/IP [10^{34}	247		2.6	

A conceptual layout of FCC-ee



As the separation of 3(4) rings is within 15 m,
one wide tunnel may be possible around the IR.

A conceptual layout of FCC-ee



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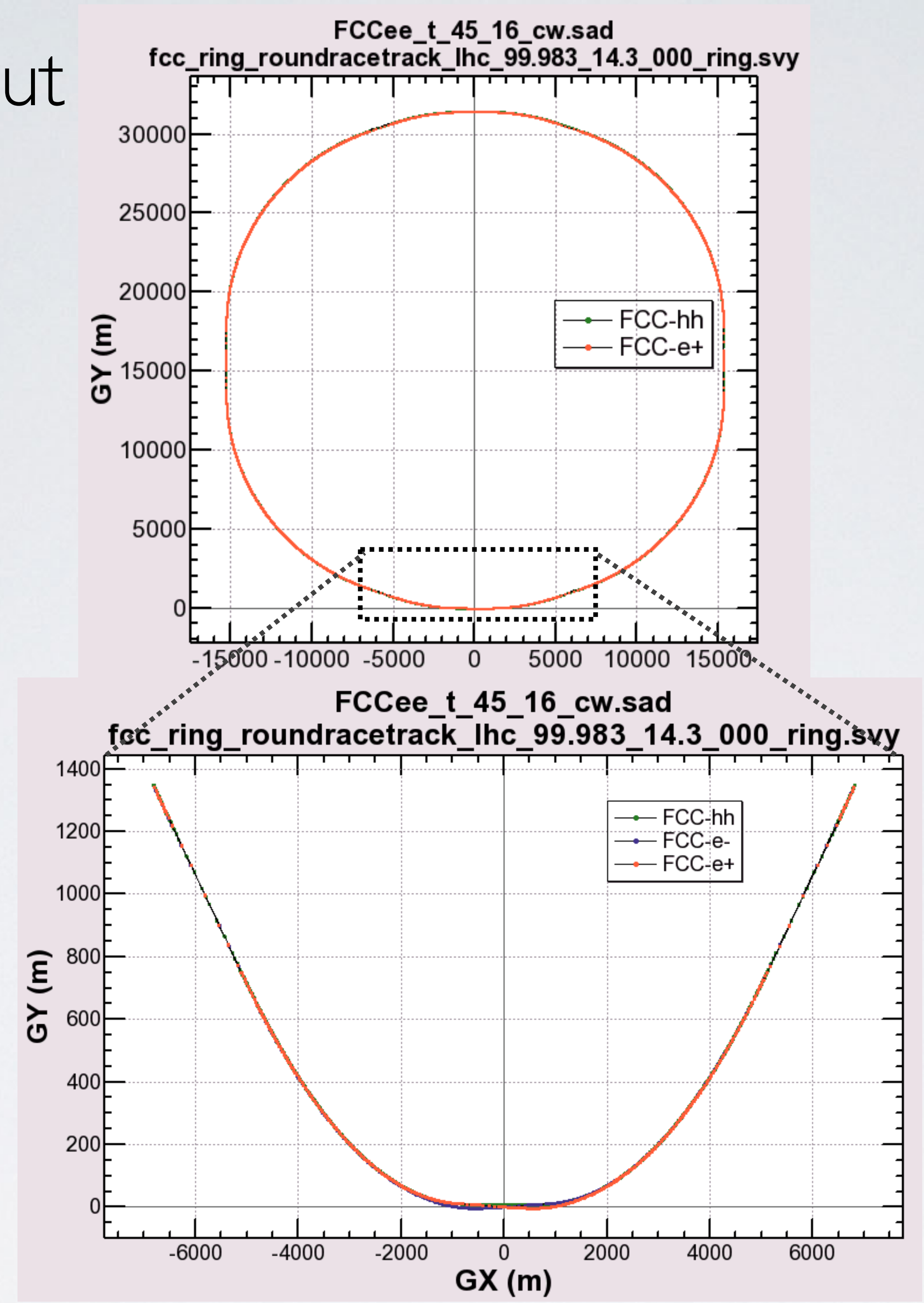

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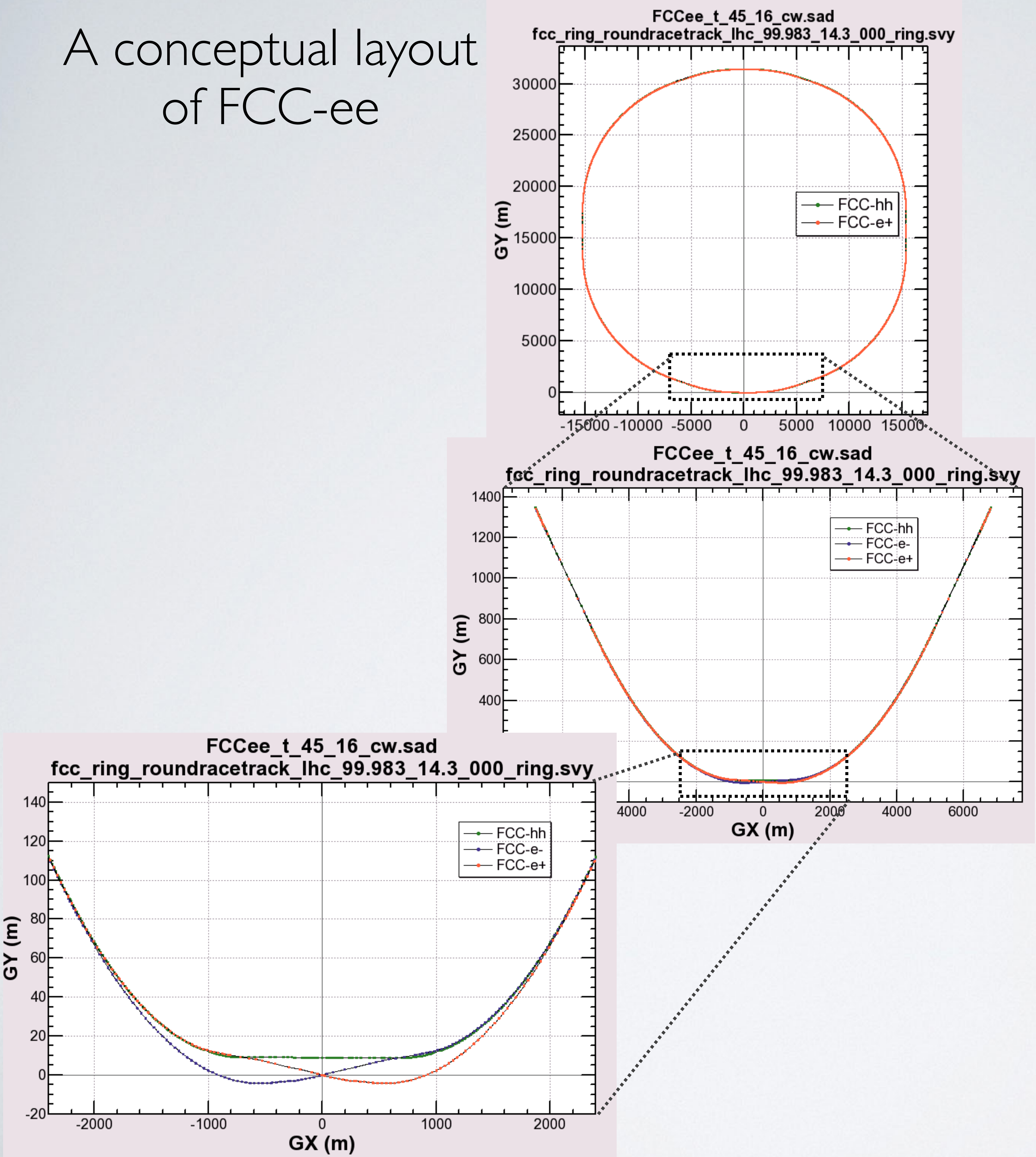

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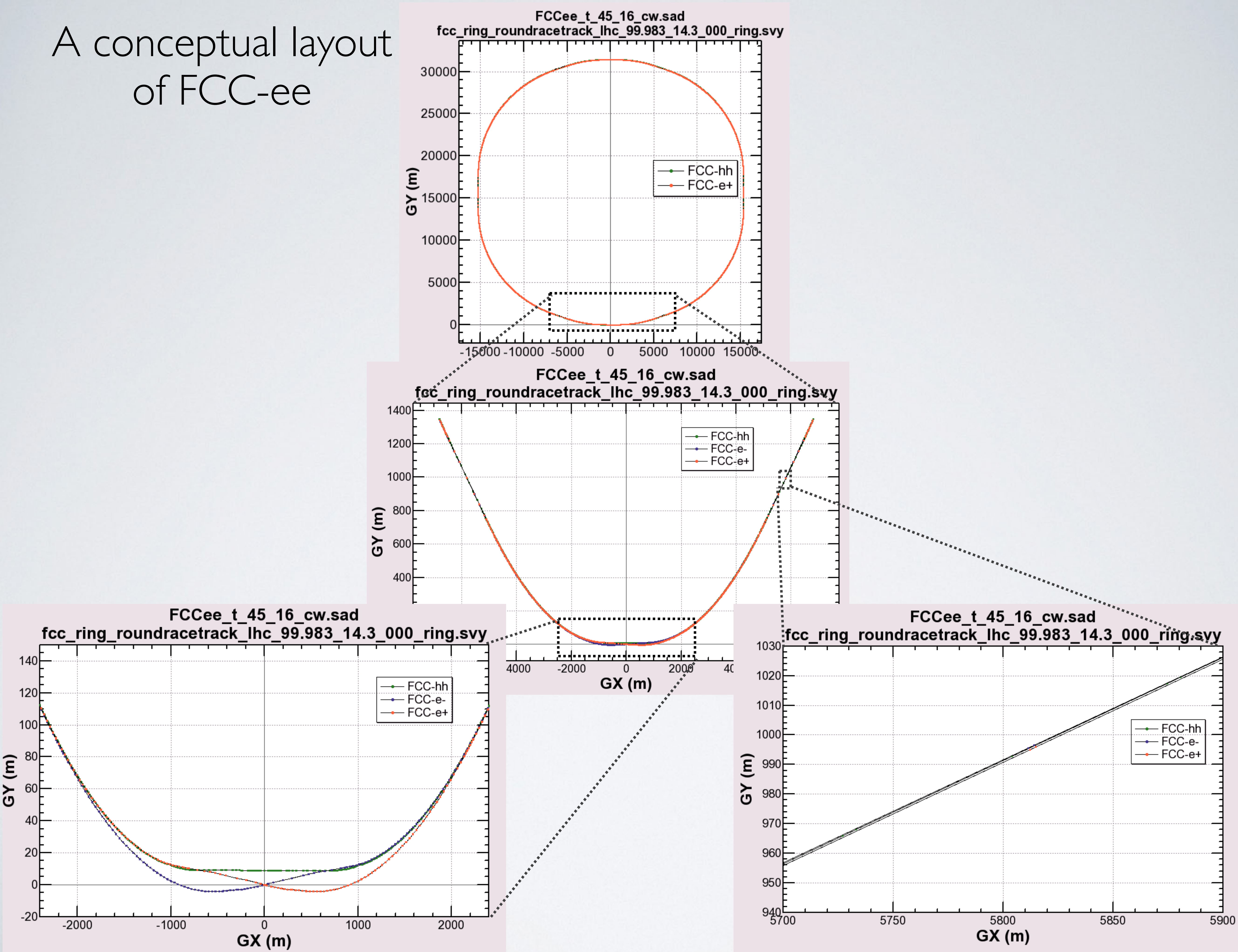
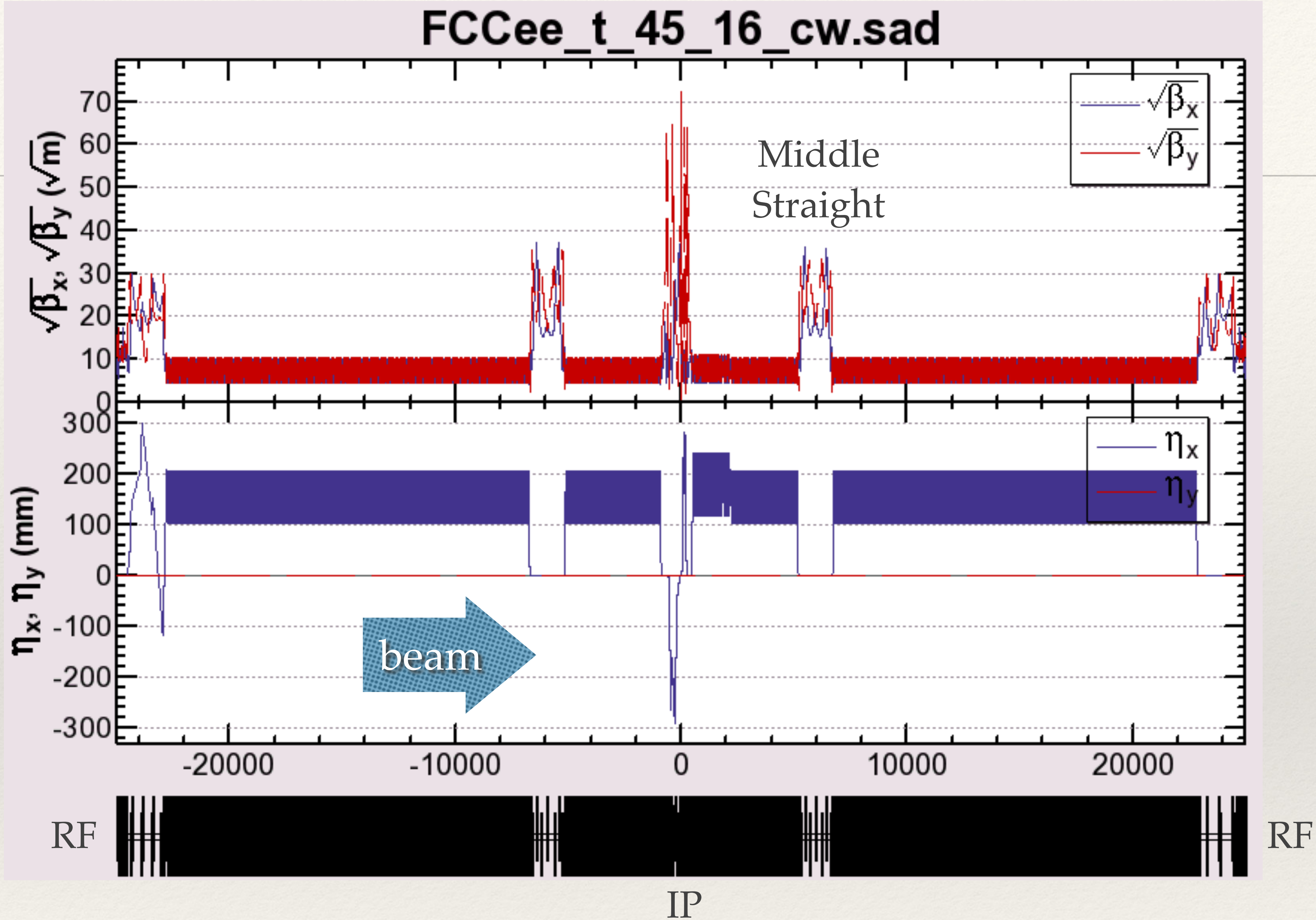
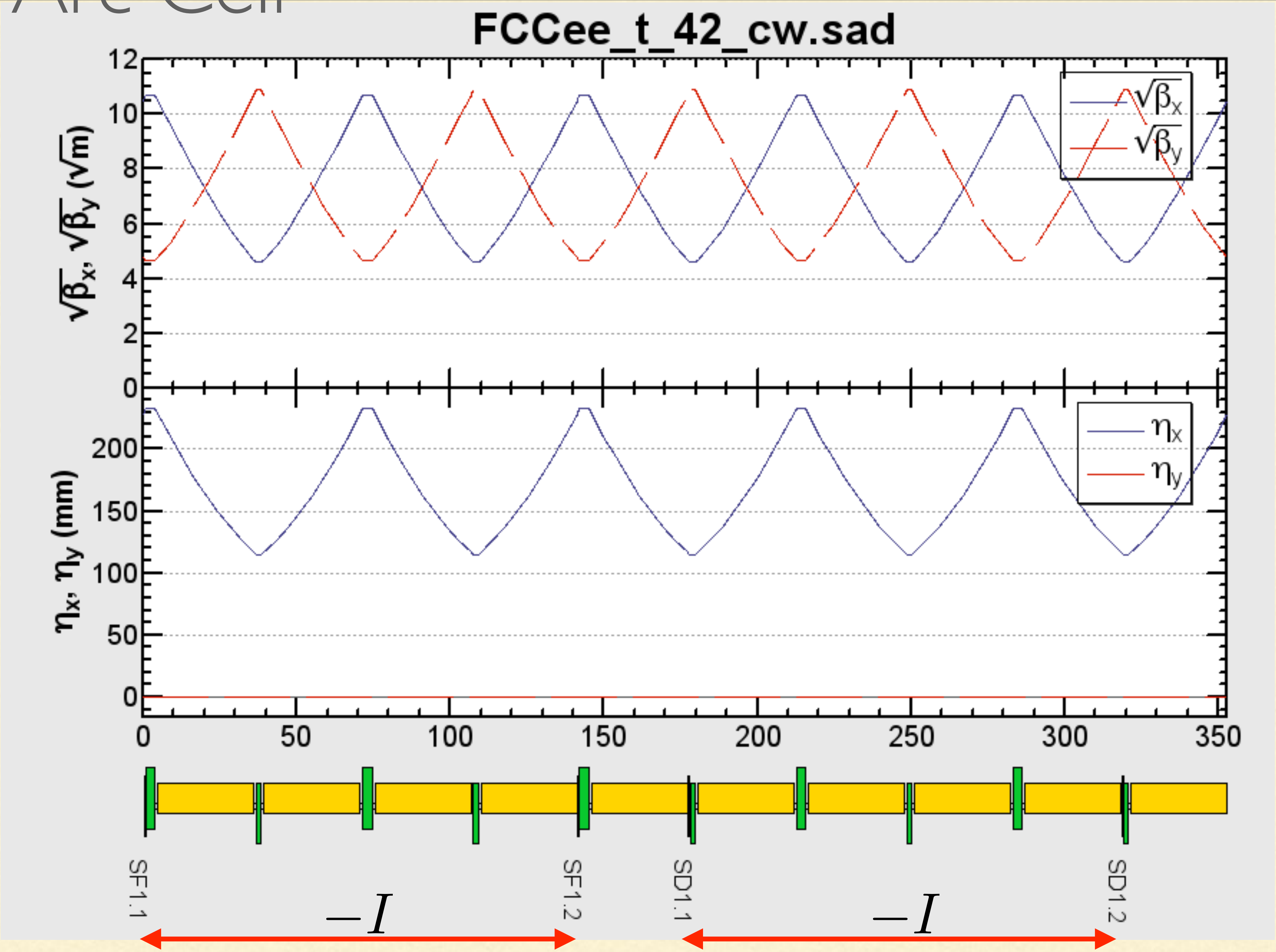


Half Ring Optics



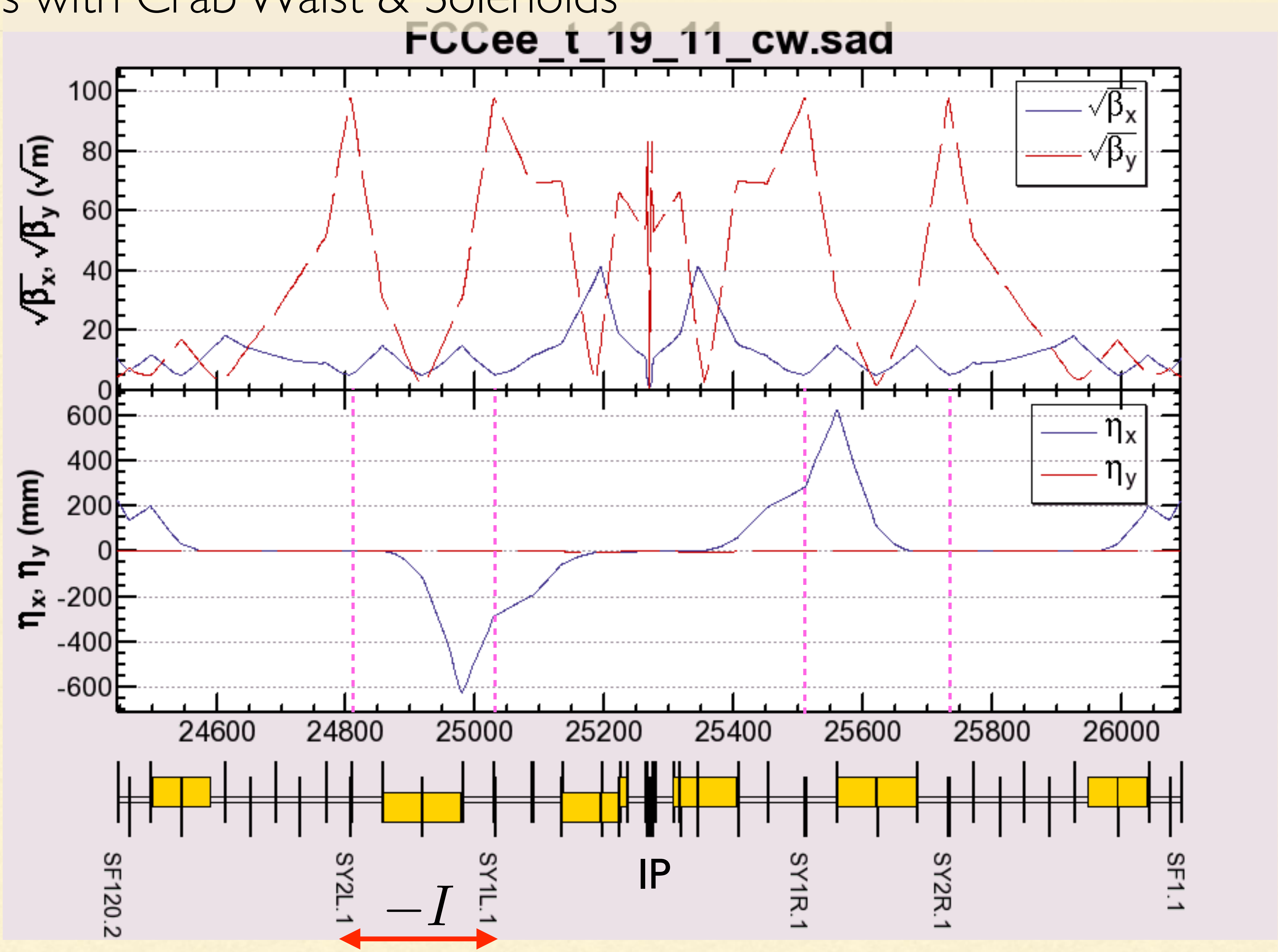
- $\beta_{x,y}^* = (1\text{ m}, 2\text{ mm})$.
- The optics for the Middle & RF straights are tentative.

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.
- 255 sextupole pairs per half ring.

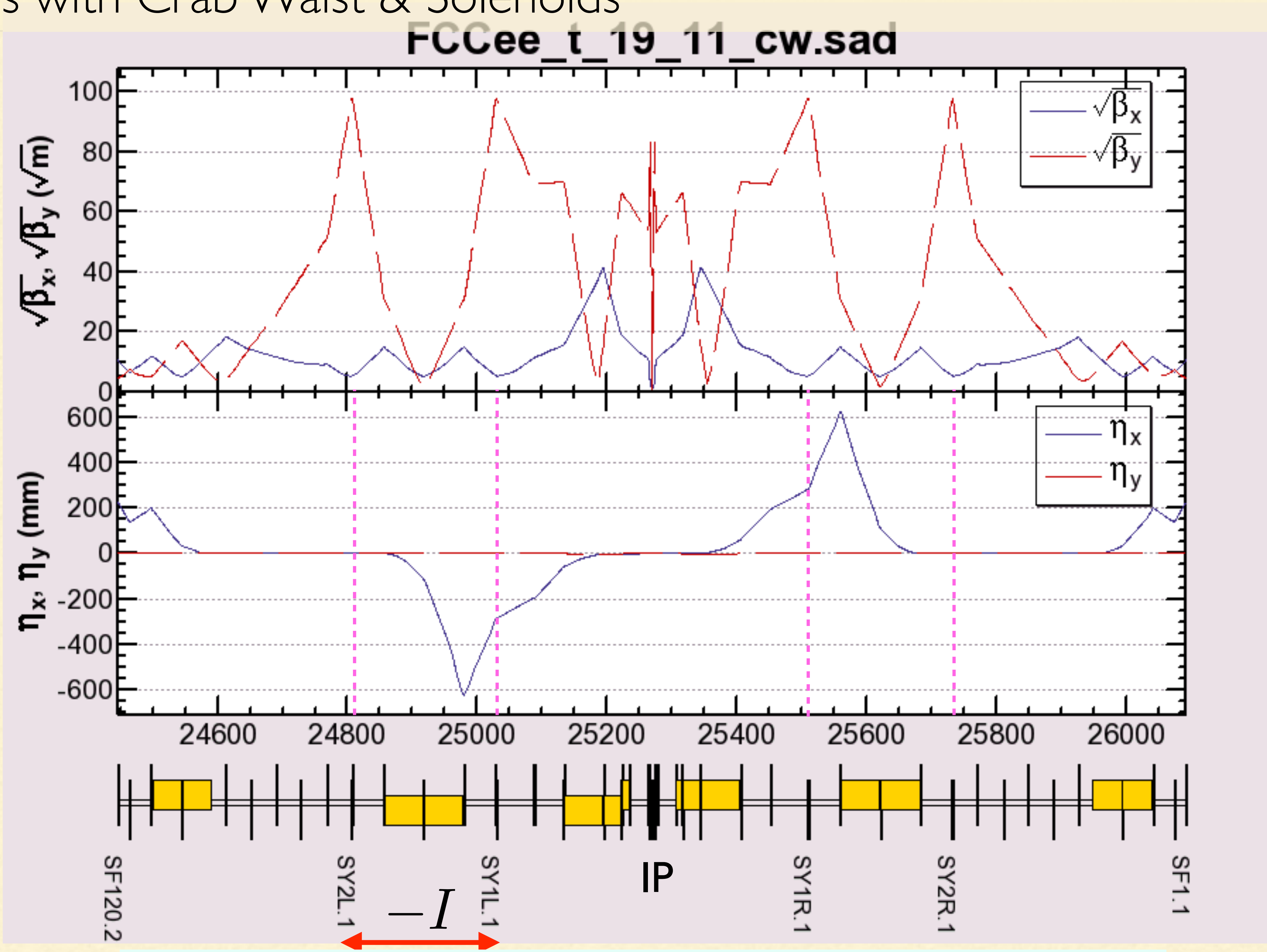
IR Optics with Crab Waist & Solenoids



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

These plots of beam optics are not the latest ones.

IR Optics with Crab Waist & Solenoids



Where are the crab sextupoles?

- Local chromatic

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

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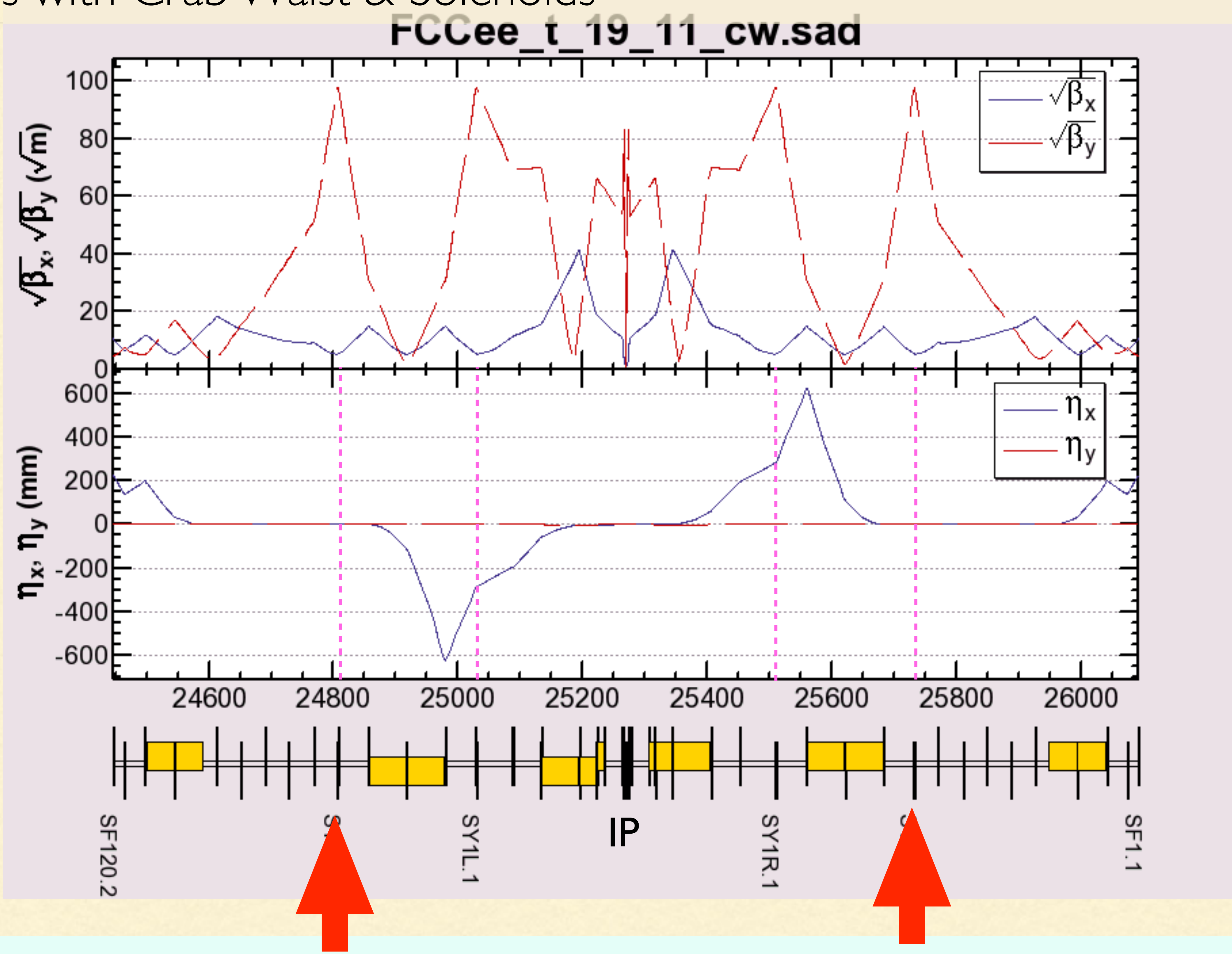
IR Optics with Crab Waist & Solenoids



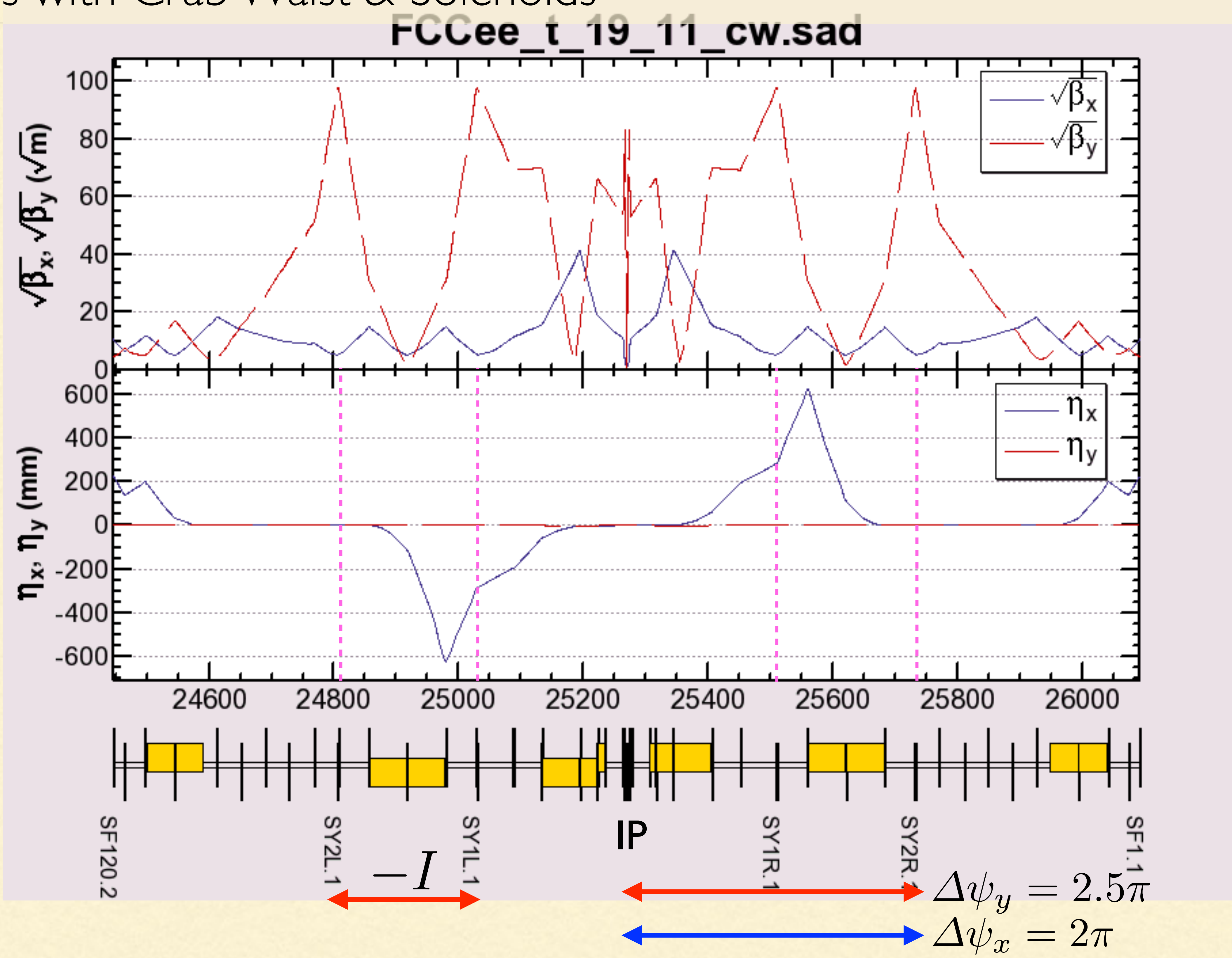
These sexts work as the crab sextupoles!

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

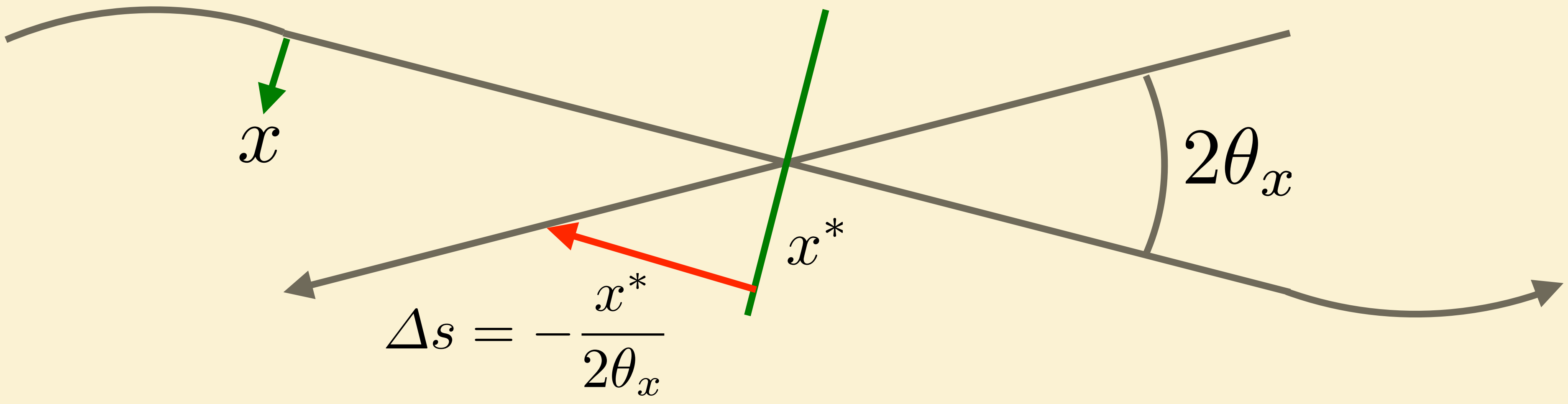
These plots of beam optics are not the latest ones.

IR Optics with Crab Waist & Solenoids

These plots of beam optics are not the latest ones.



- 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:

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

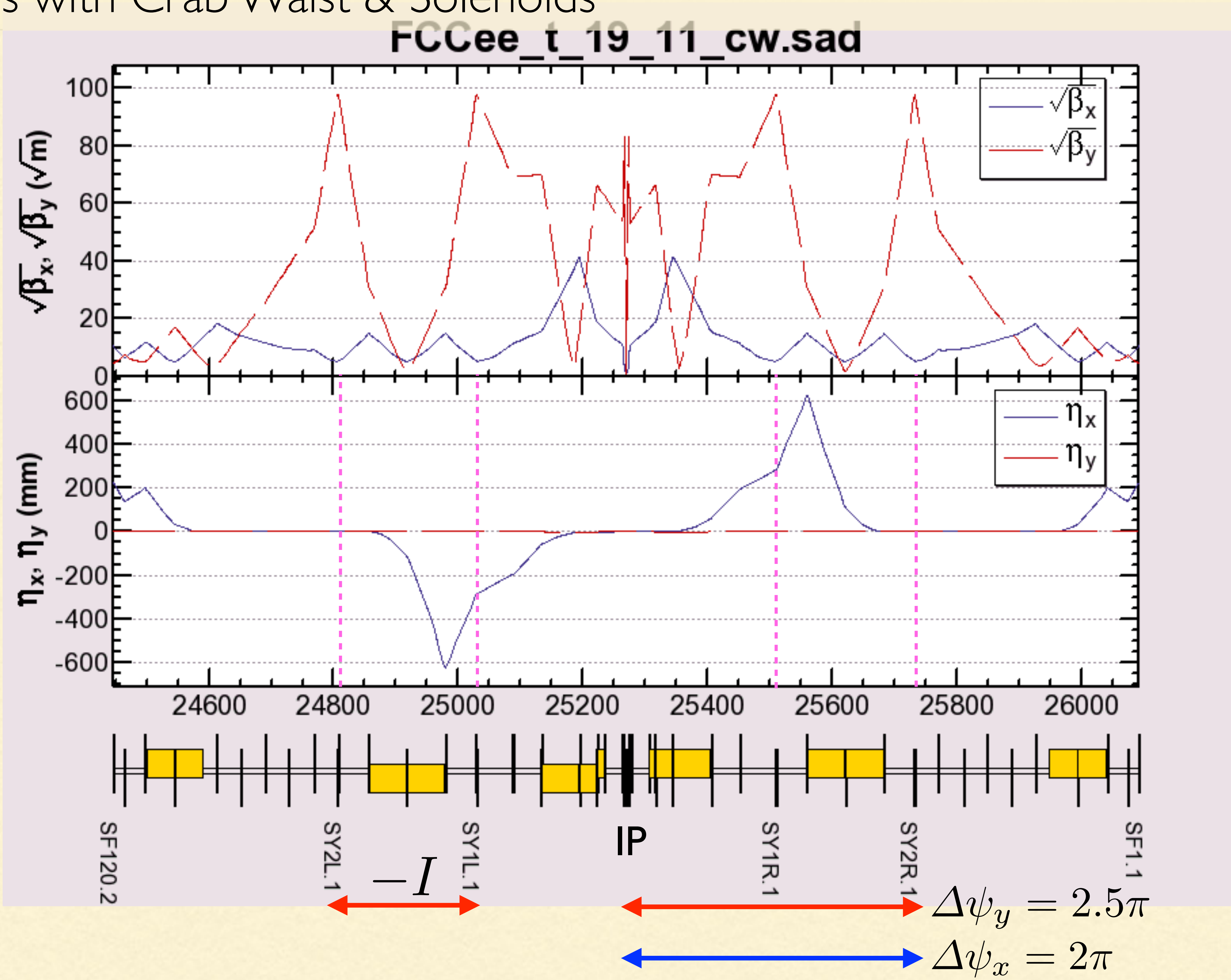
which can be approximated by a Hamiltonian of a sextupole:

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

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

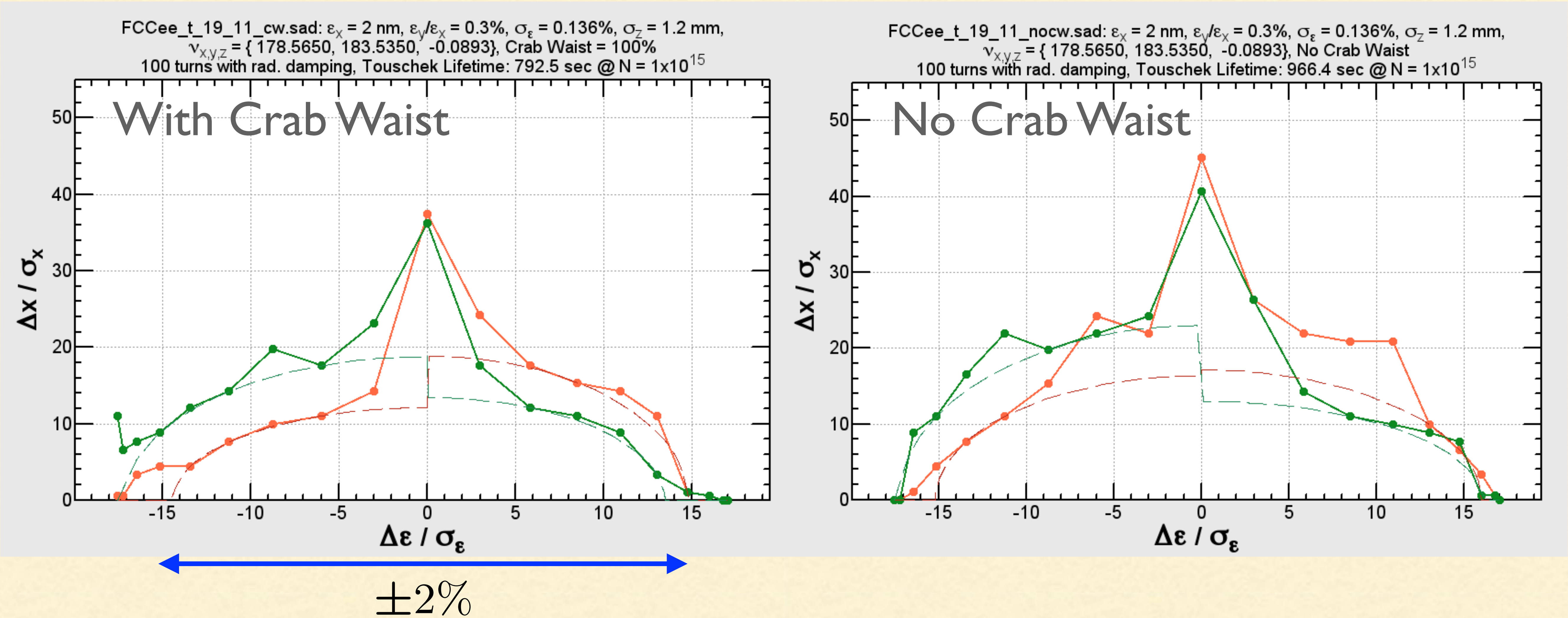


- The crab waist is realized by tweaking the strength of the second sextupole **by about 30% weaker** in this case.

These plots of beam optics are not the latest ones.

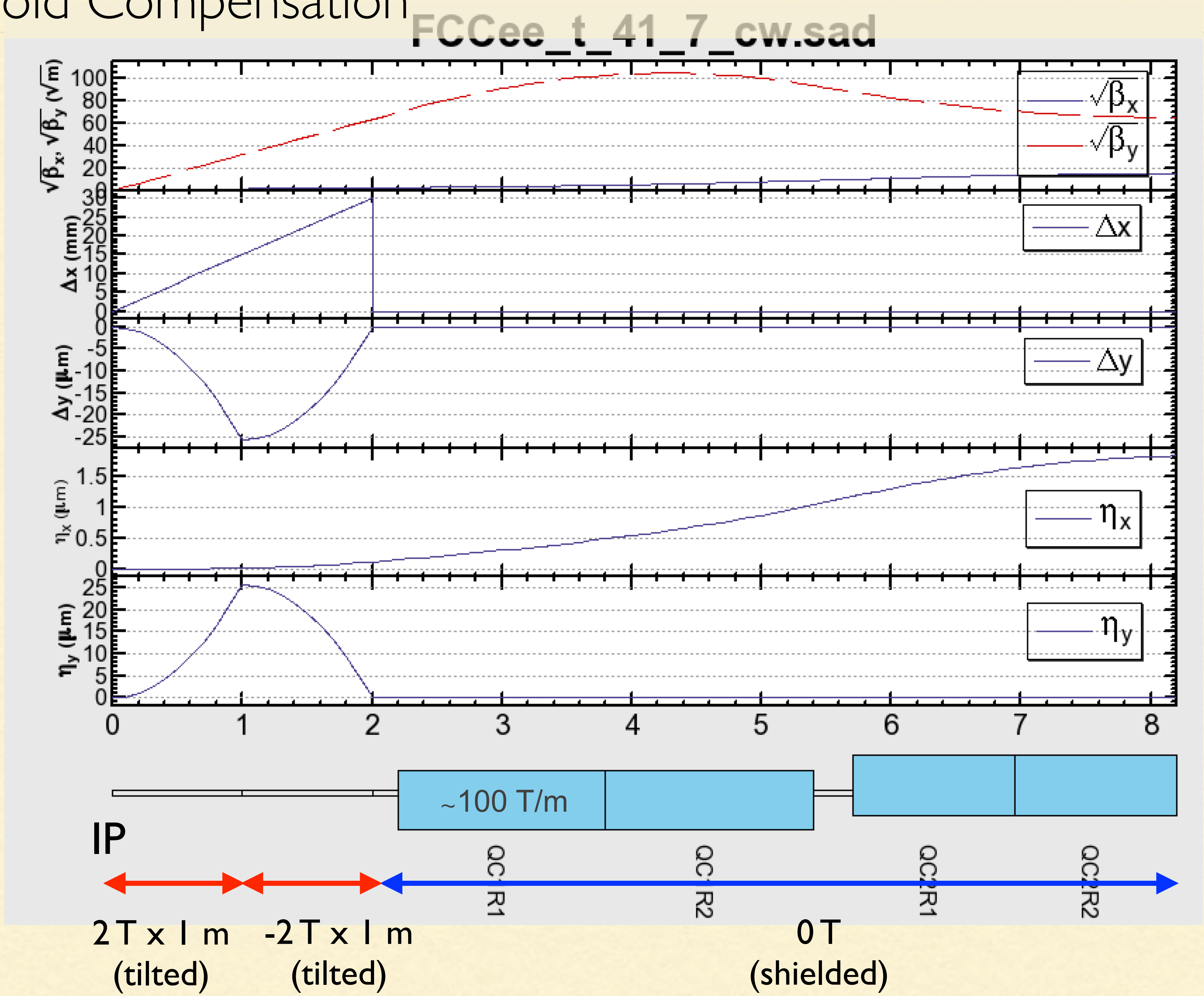
The effect of crab waist on the dynamic aperture

for the same linear lattice



- 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.

Local Solenoid Compensation

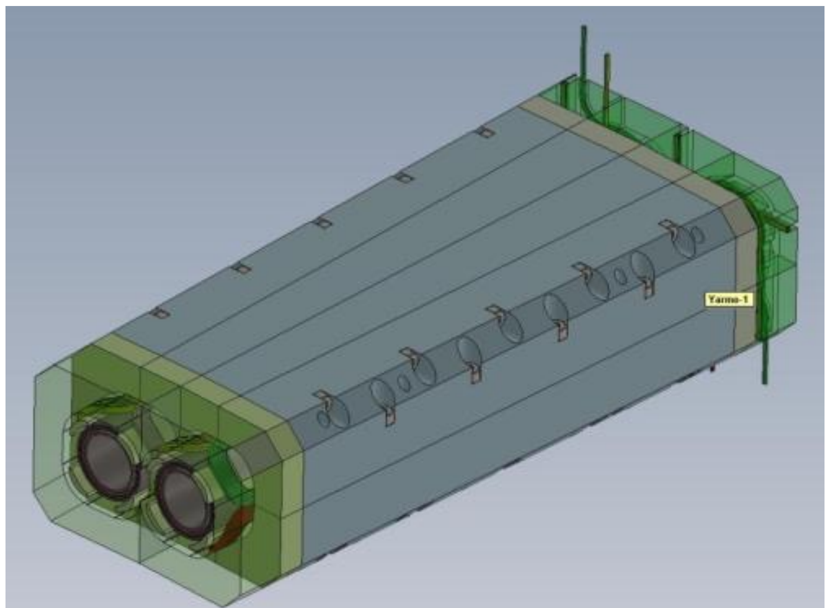


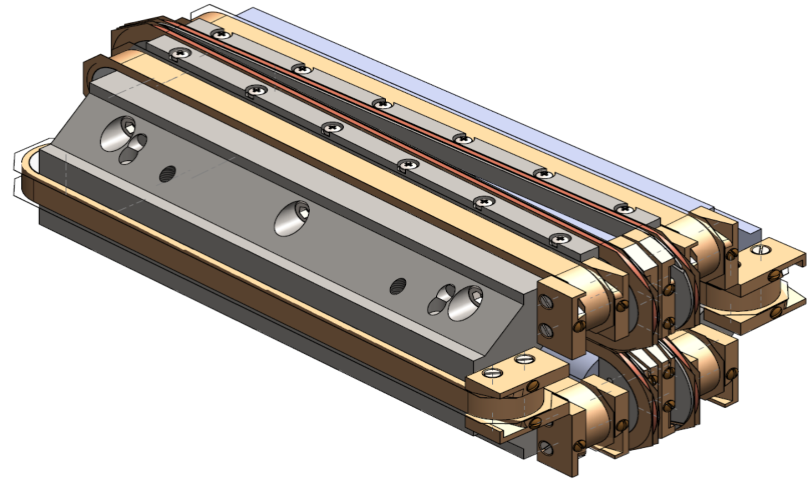
- Local solenoid compensation like above is the ideal solution, if it is technically possible.
- No leak orbit, no vertical dispersion, no coupling outside for all beam energy.
- Thus use this scheme unless it is technically denied. The previous solution with skew quads is not dead.

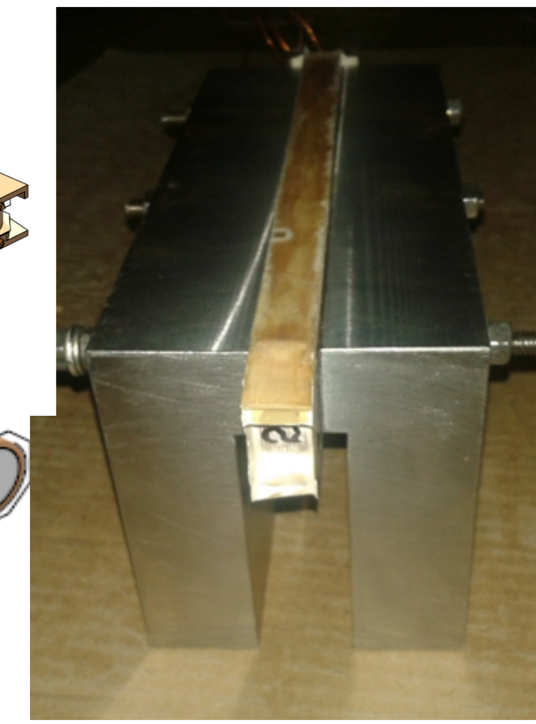
SC final focus quadrupole

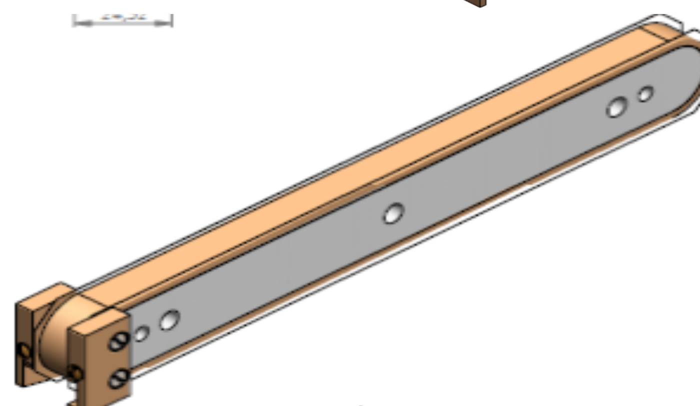
Main contributors are Ivan Okunev and Pavel Vobly

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)

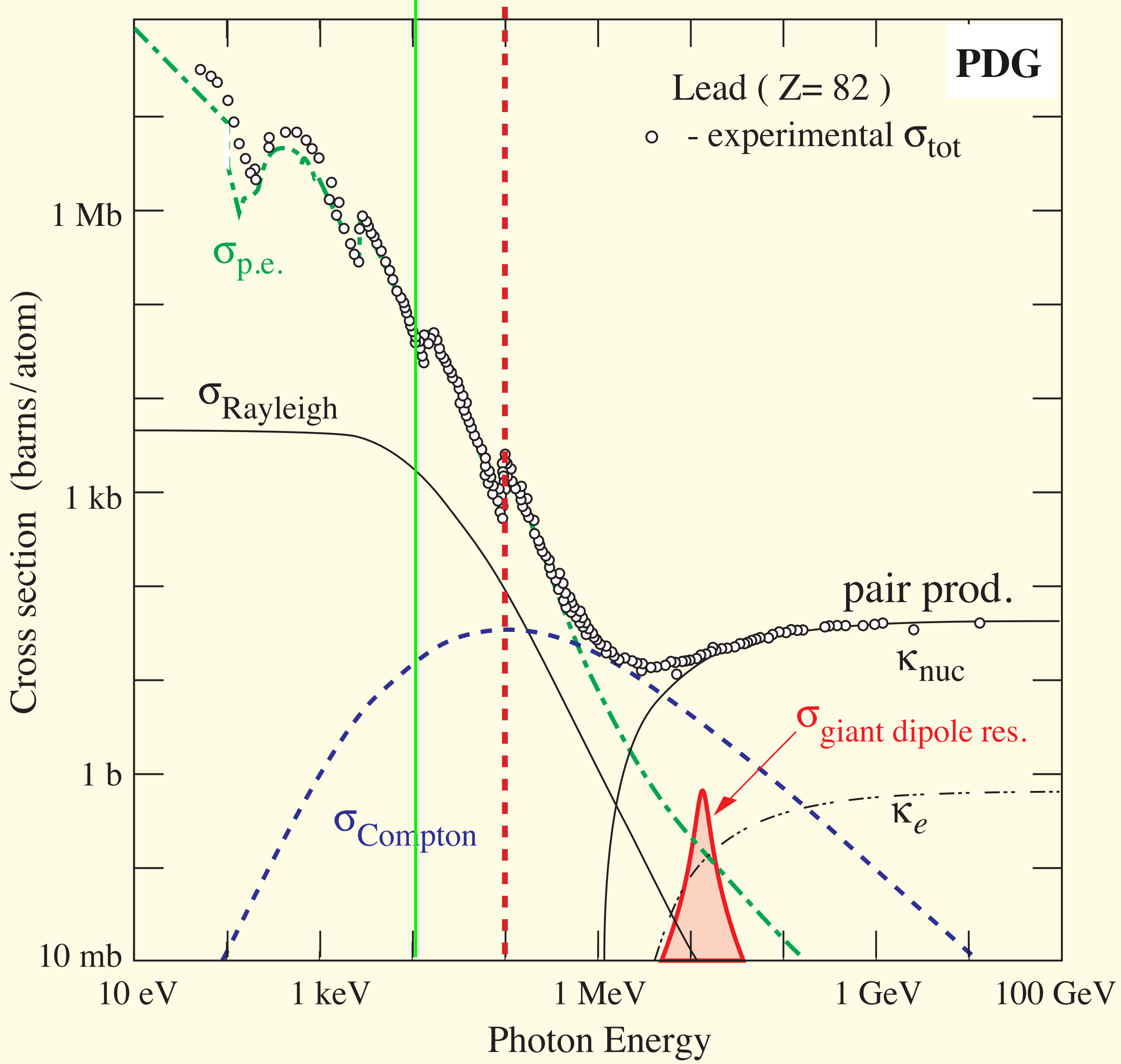
The work has low priority and small contract with CERN would help

E. Levitchev

Spectrum and absorption

✔ < 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

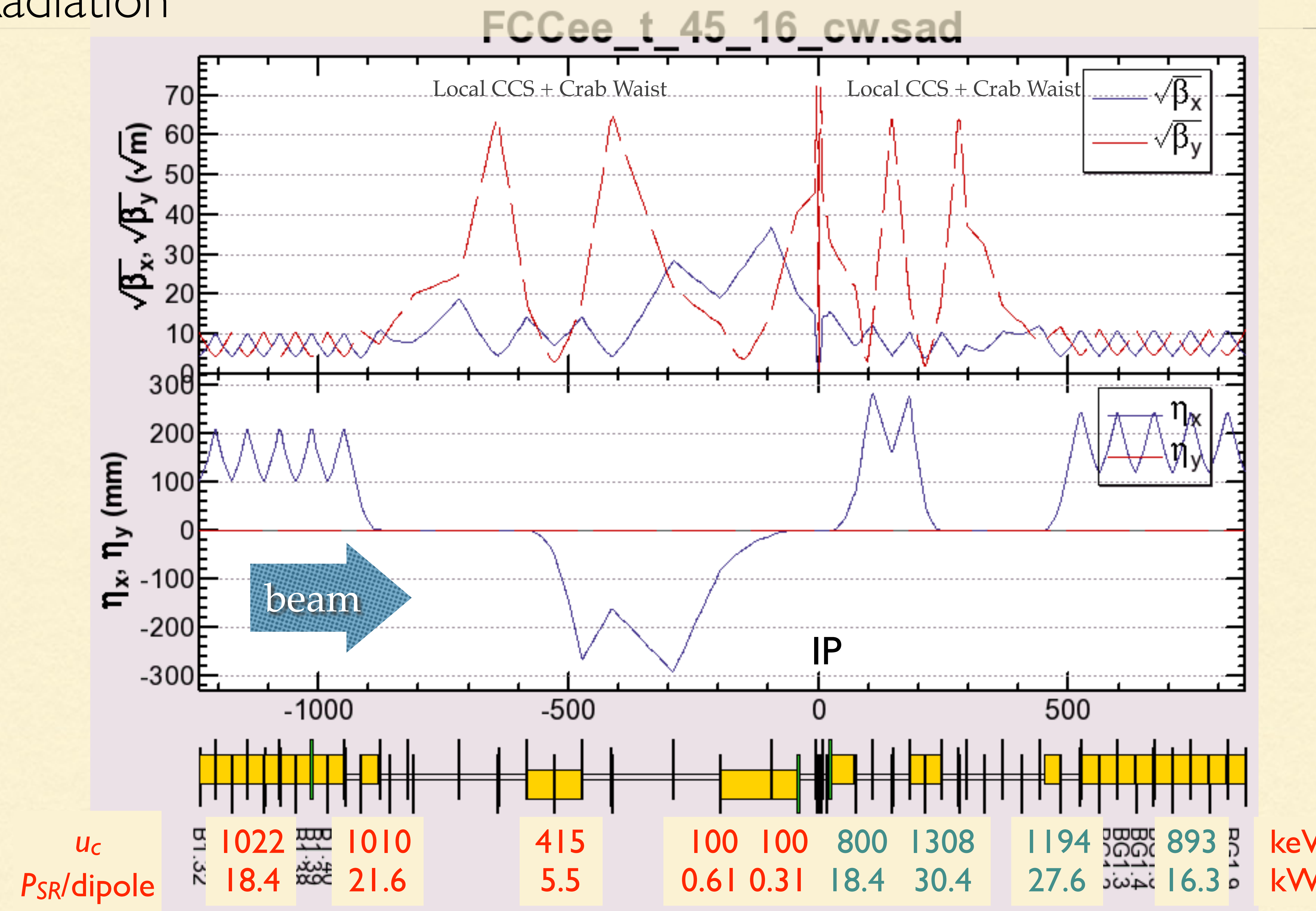
LEP2 : 724 keV (arc, last bend 10× lower)

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 !!

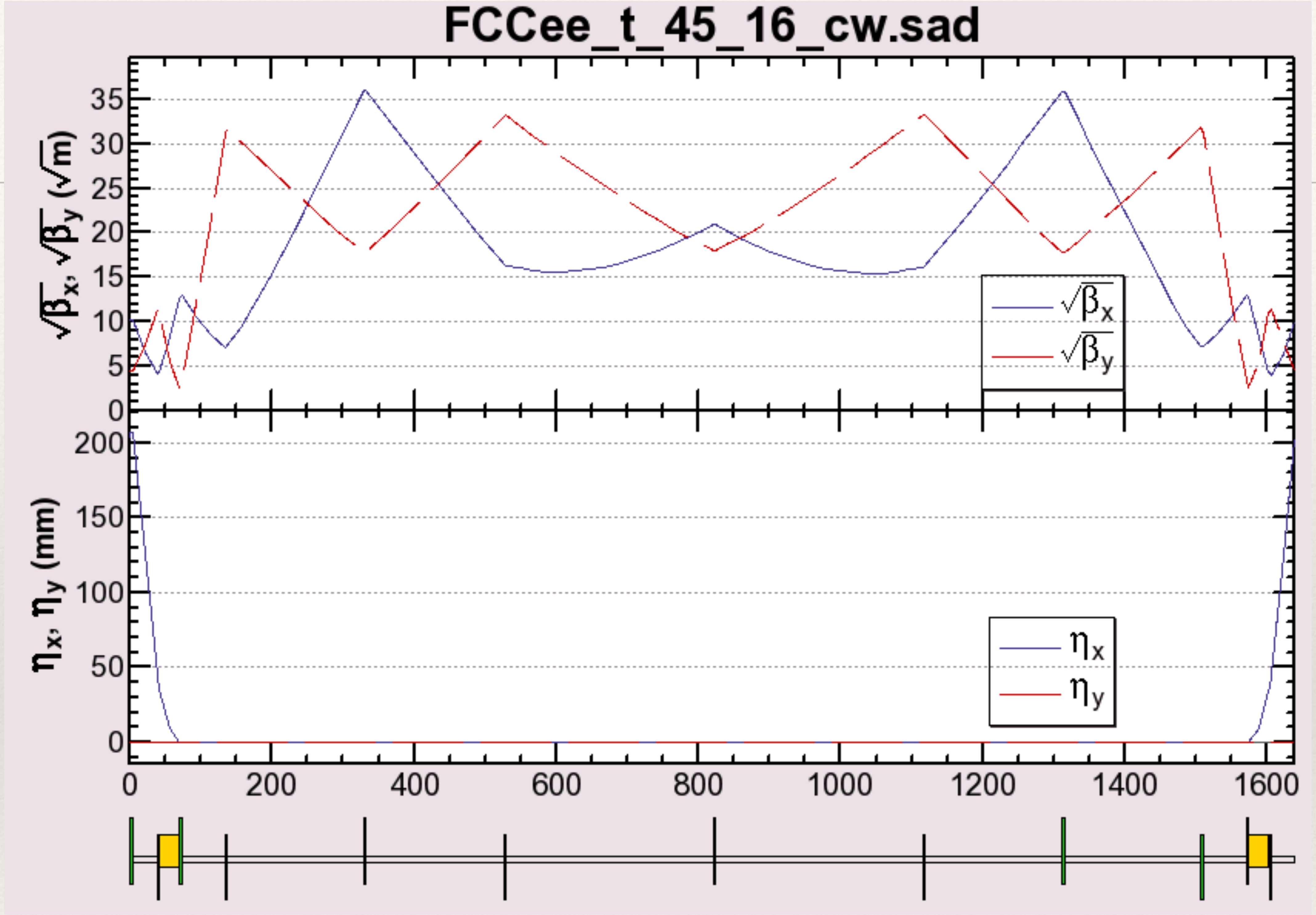
H. Burkhardt

IR Radiation



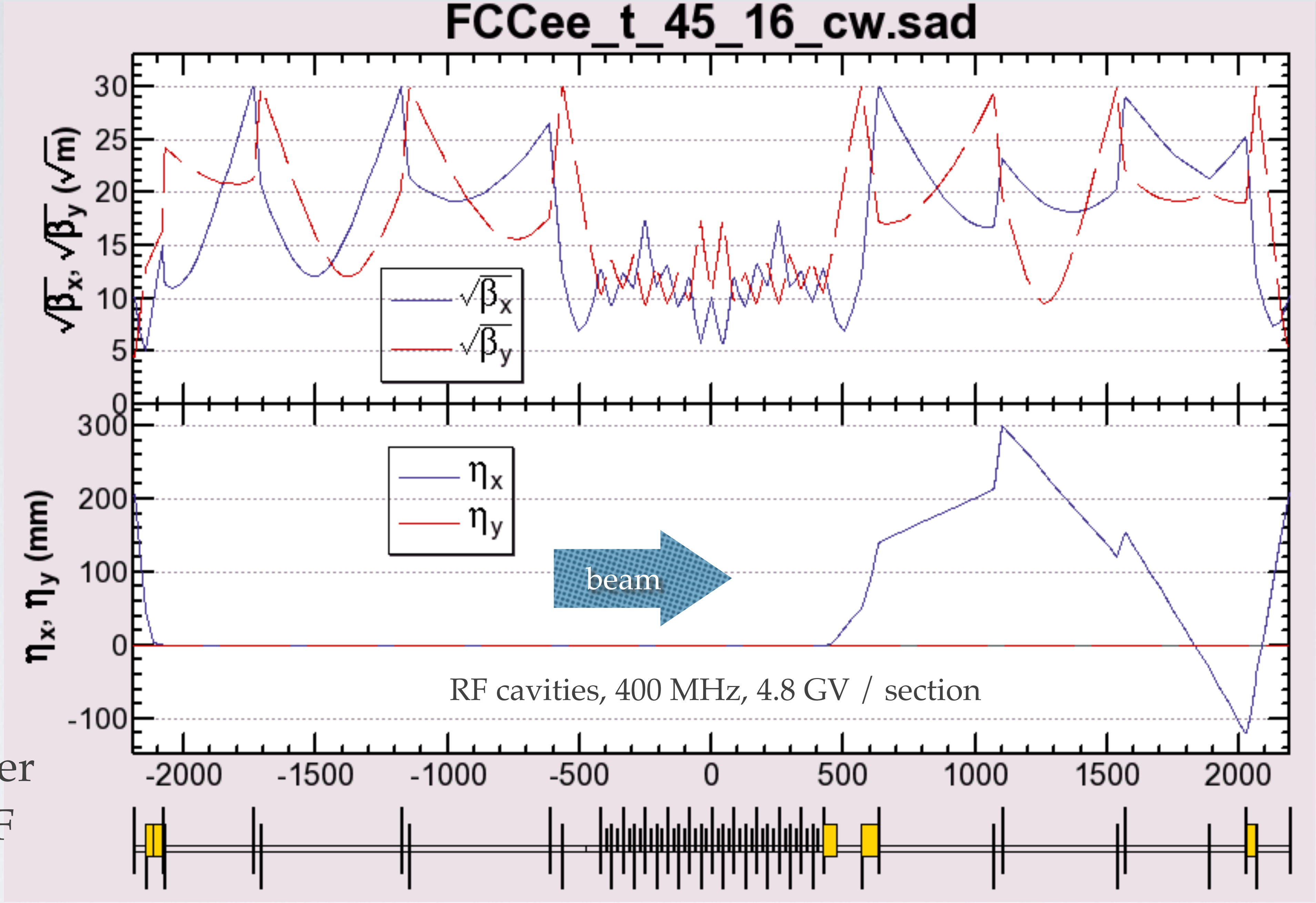
- The critical energy and radiation power of the dipoles are as above.

Middle Straight



- Above are just tentative optics.
- Usage of these sections is to be determined.

The RF section



Beams cross over through the RF section.

- The usage of the straights on the both sides of the RF is to be determined.
- 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.

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

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

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

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

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

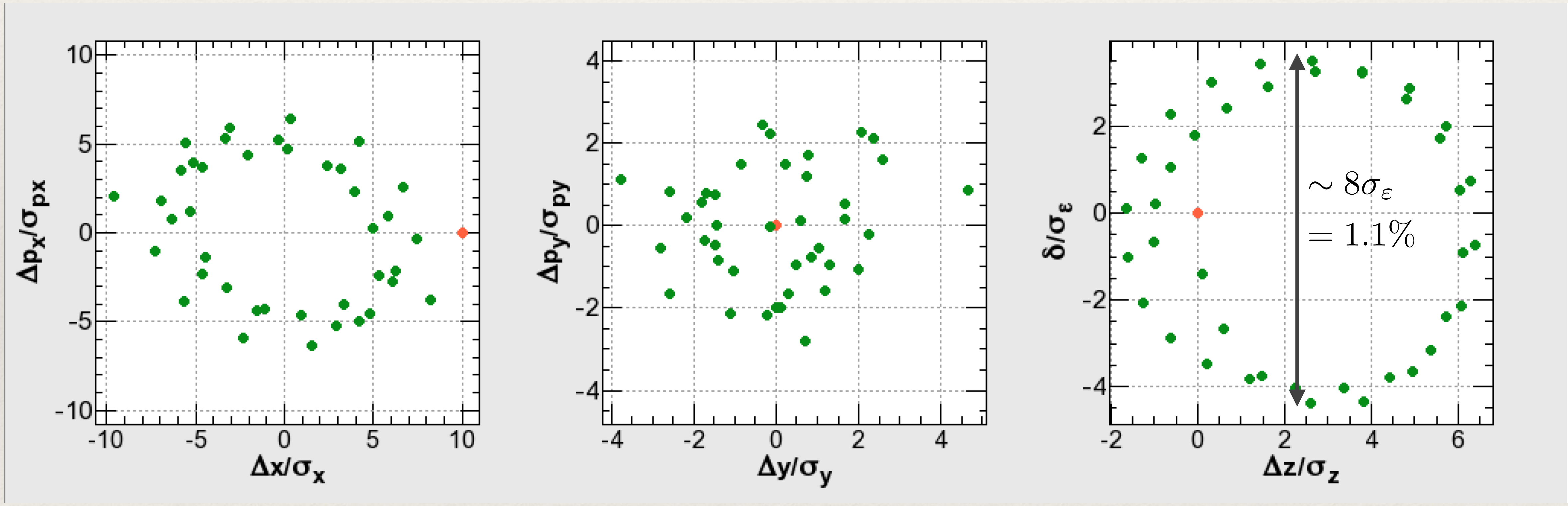
A rough estimation of radiation by arc quads (cont'd)

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

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

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

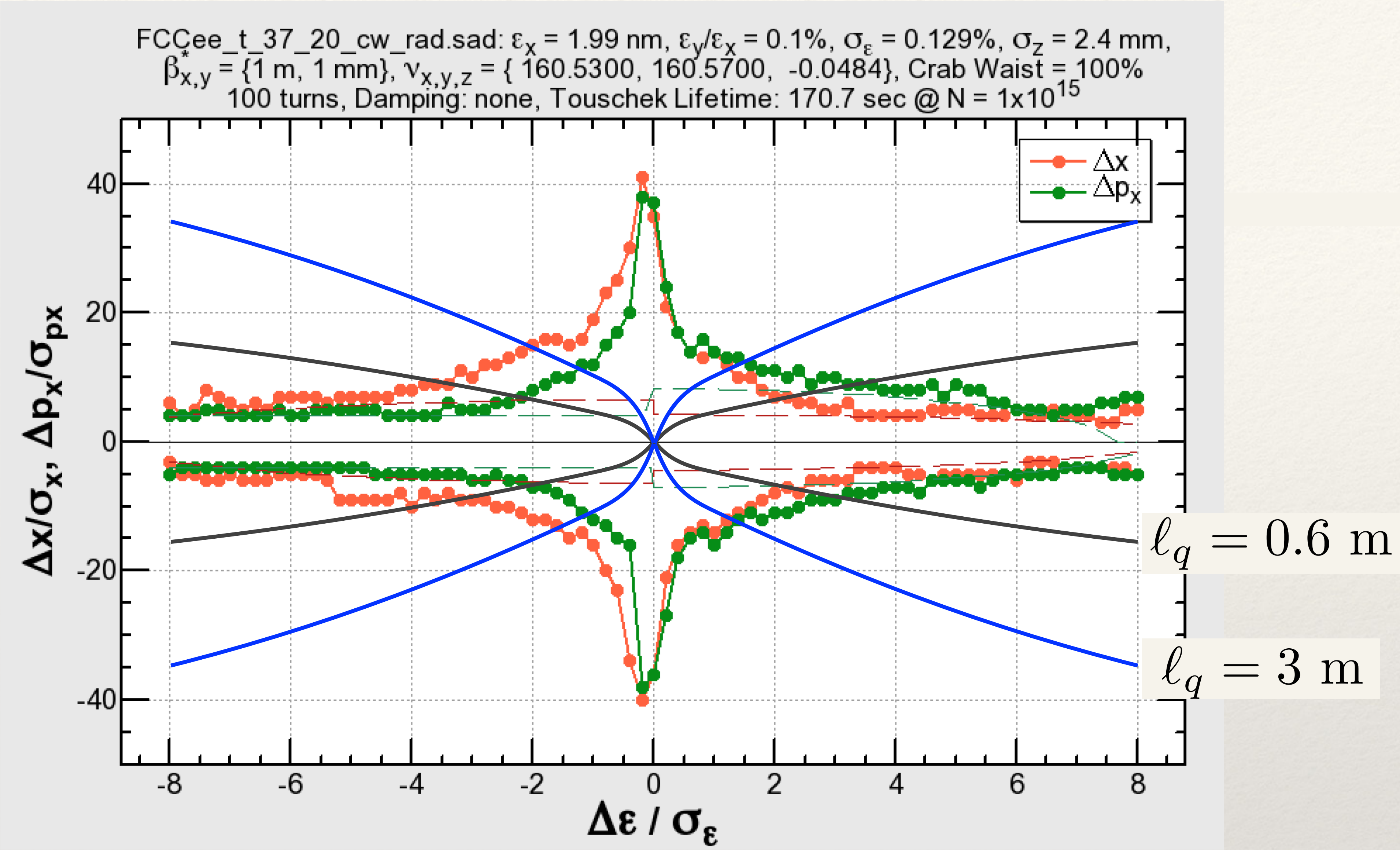
- Indeed, this estimation agrees with the tracking with element-by-element radiation*:



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

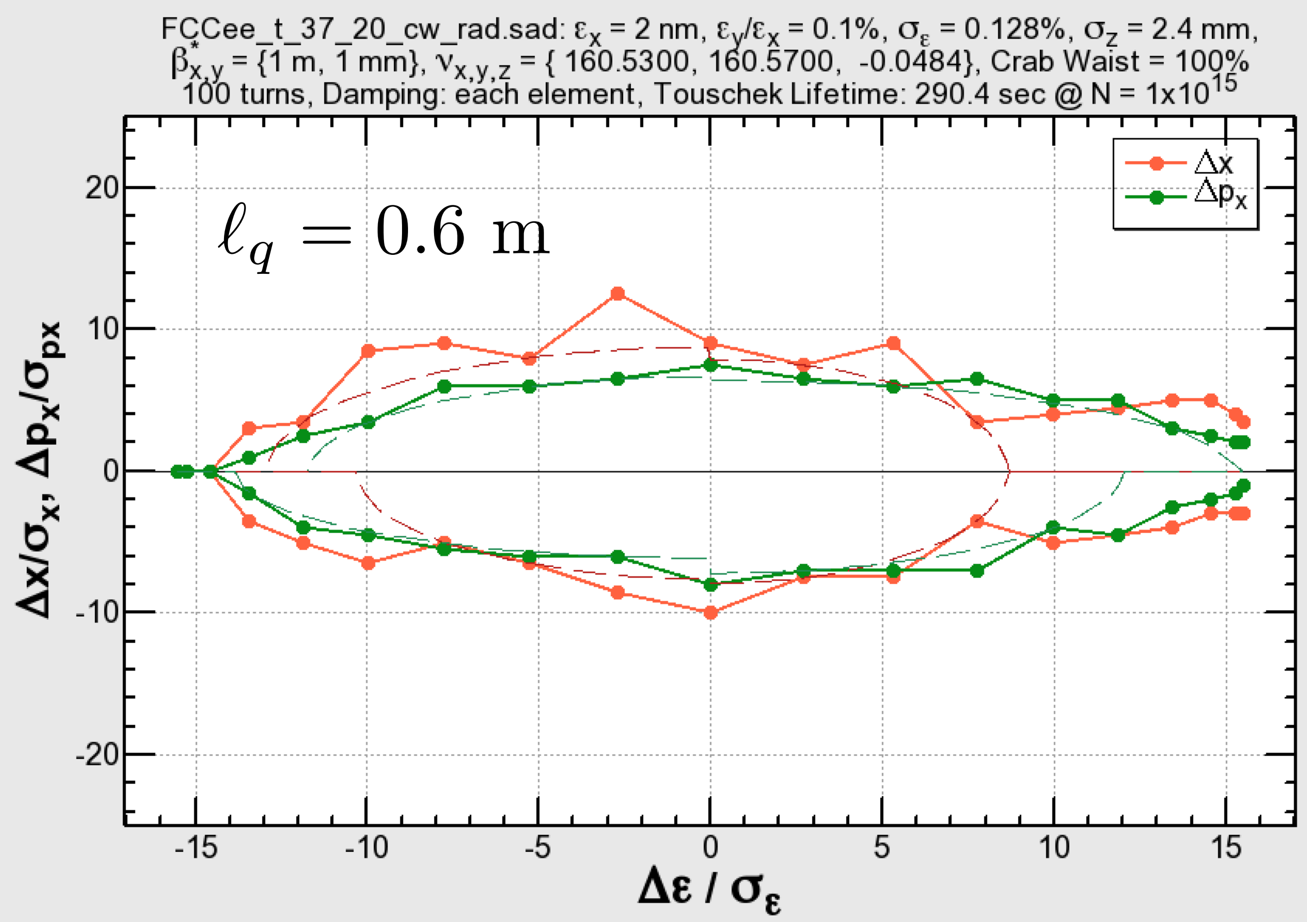
Cf. Barbarin, F ; Iselin, F Christoph ; Jowett, John M, 4th European Particle Accelerator Conference, London, UK, 27 Jun - 1 Jul 1994, pp.193-195

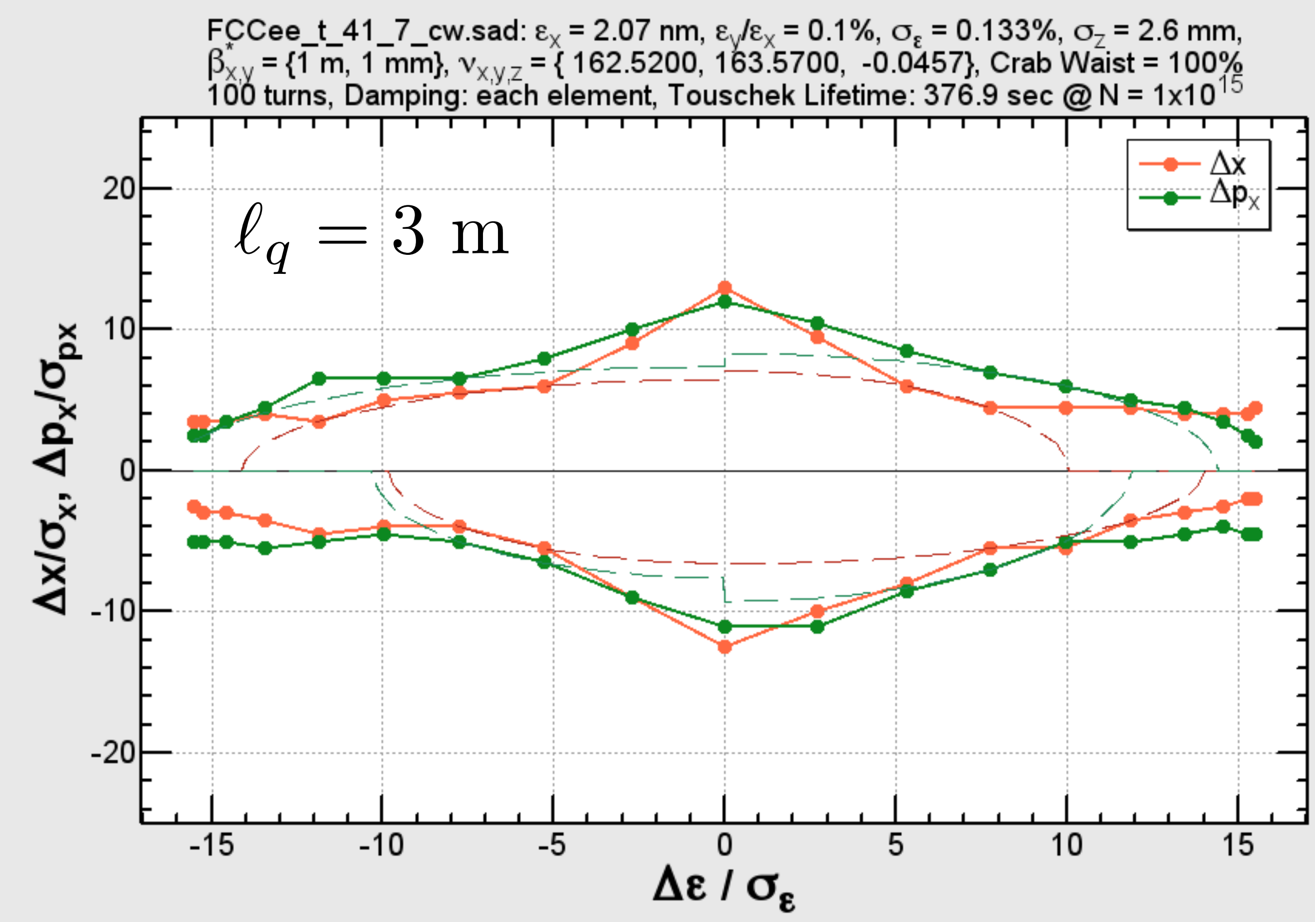
The effect on the dynamic aperture



- 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.

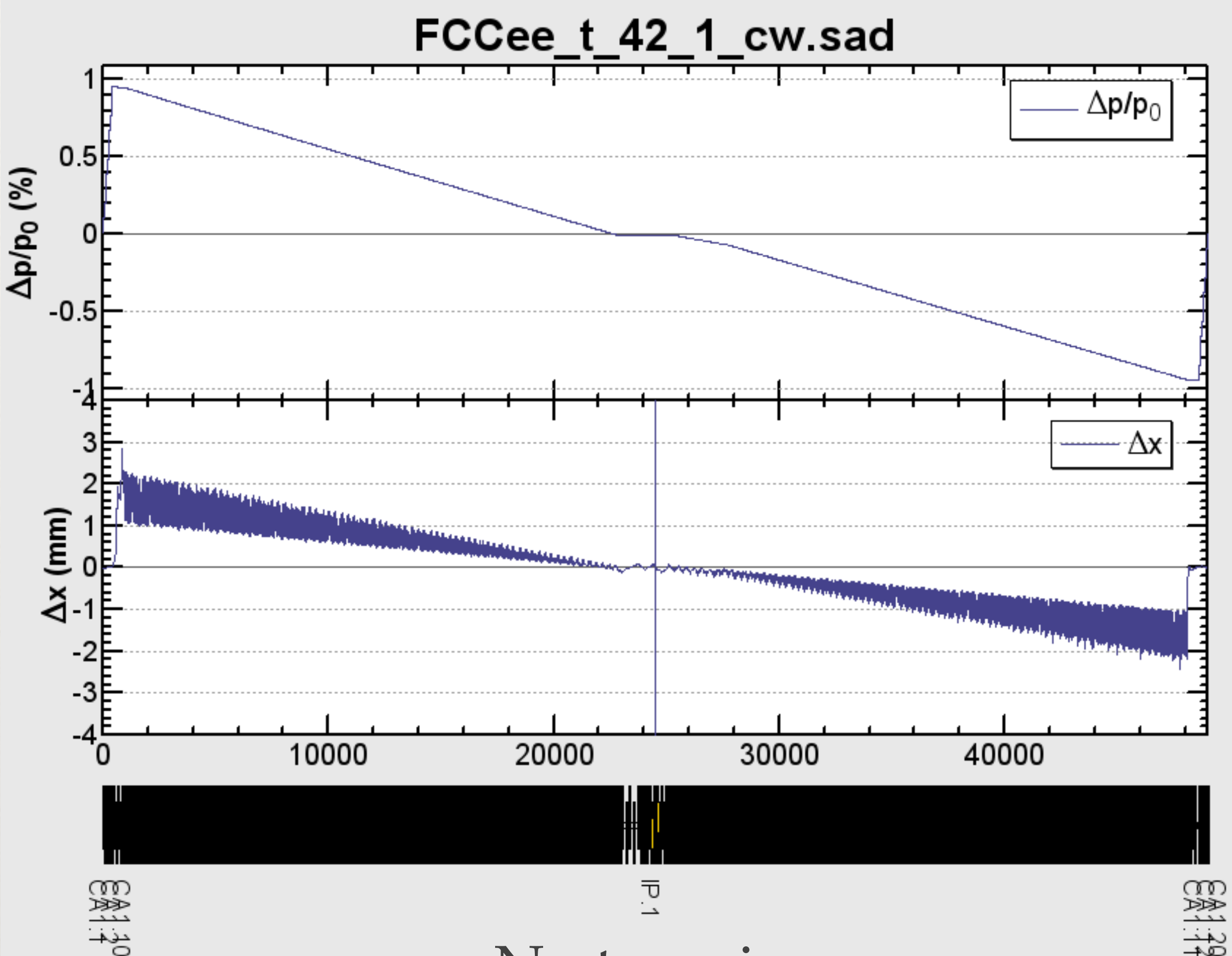
The effect on the dynamic aperture (cont'd)



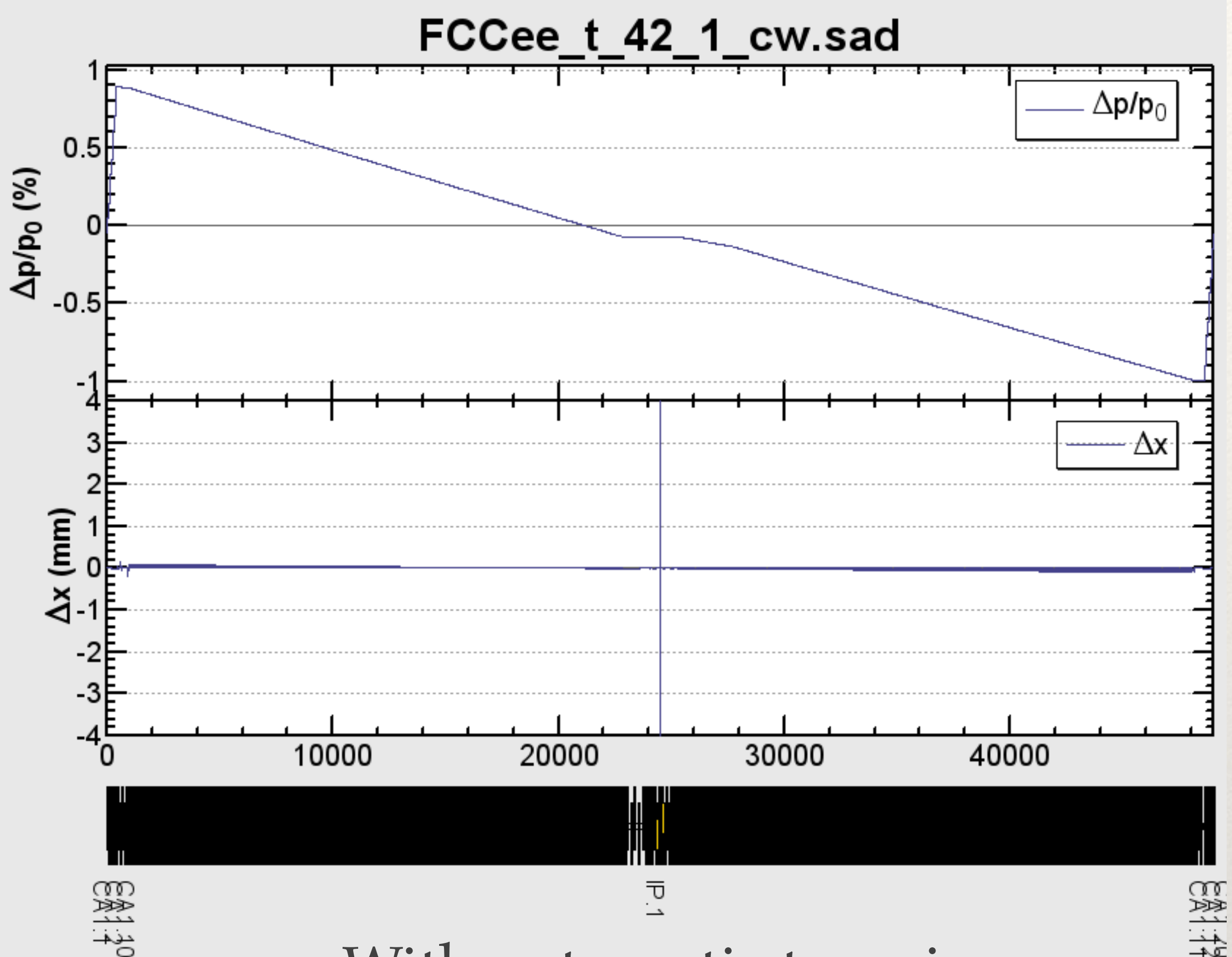


- The dynamic aperture with element-by-element radiation agrees with the estimation above.
- The on-momentum transverse aperture is somewhat improved by $\ell_q = 3$ m.
- Then one of the merits of non-interleaved sextuple, a very wide transverse aperture at on-momentum, is destroyed by the radiation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

Tapering



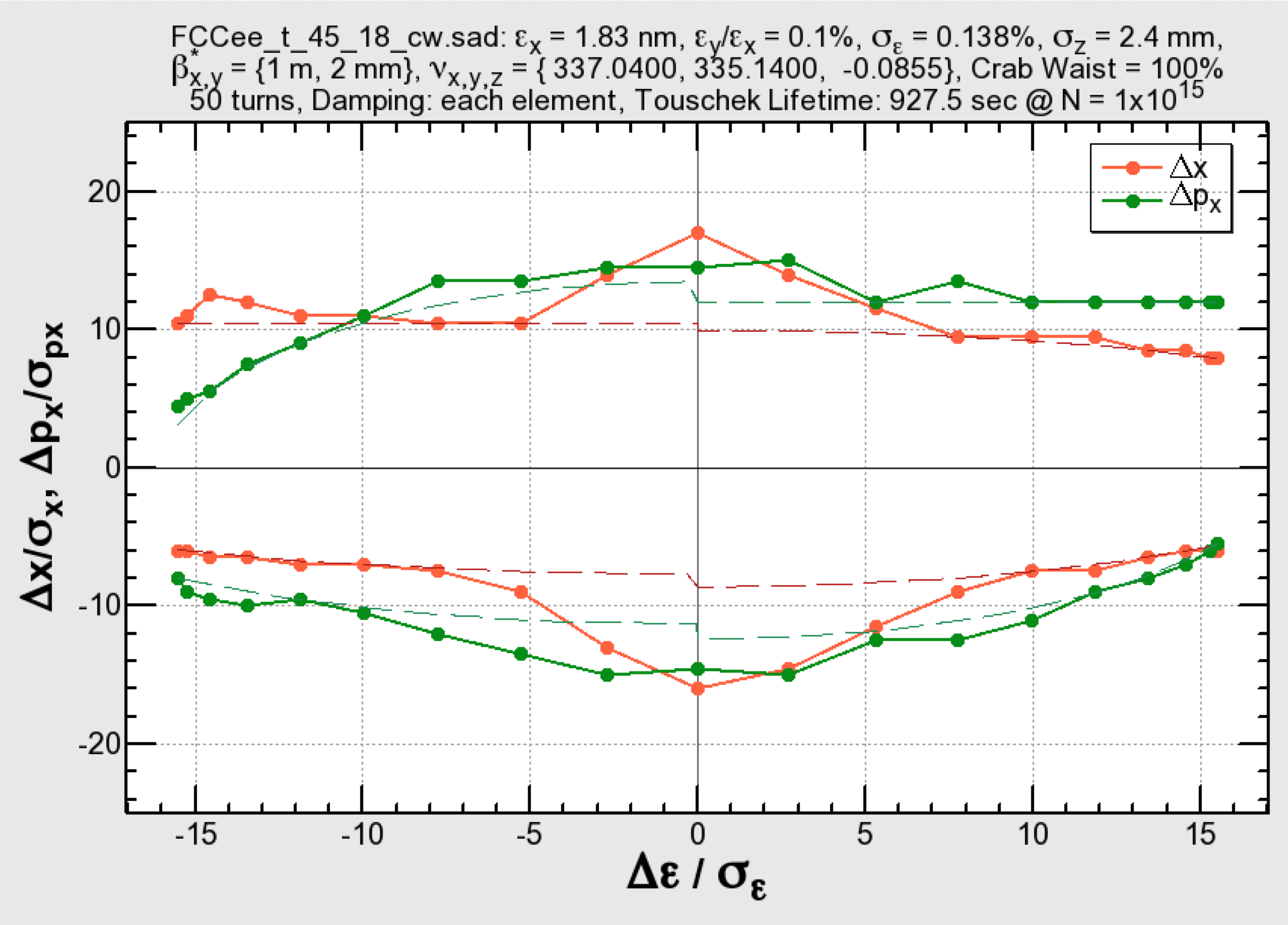
No tapering

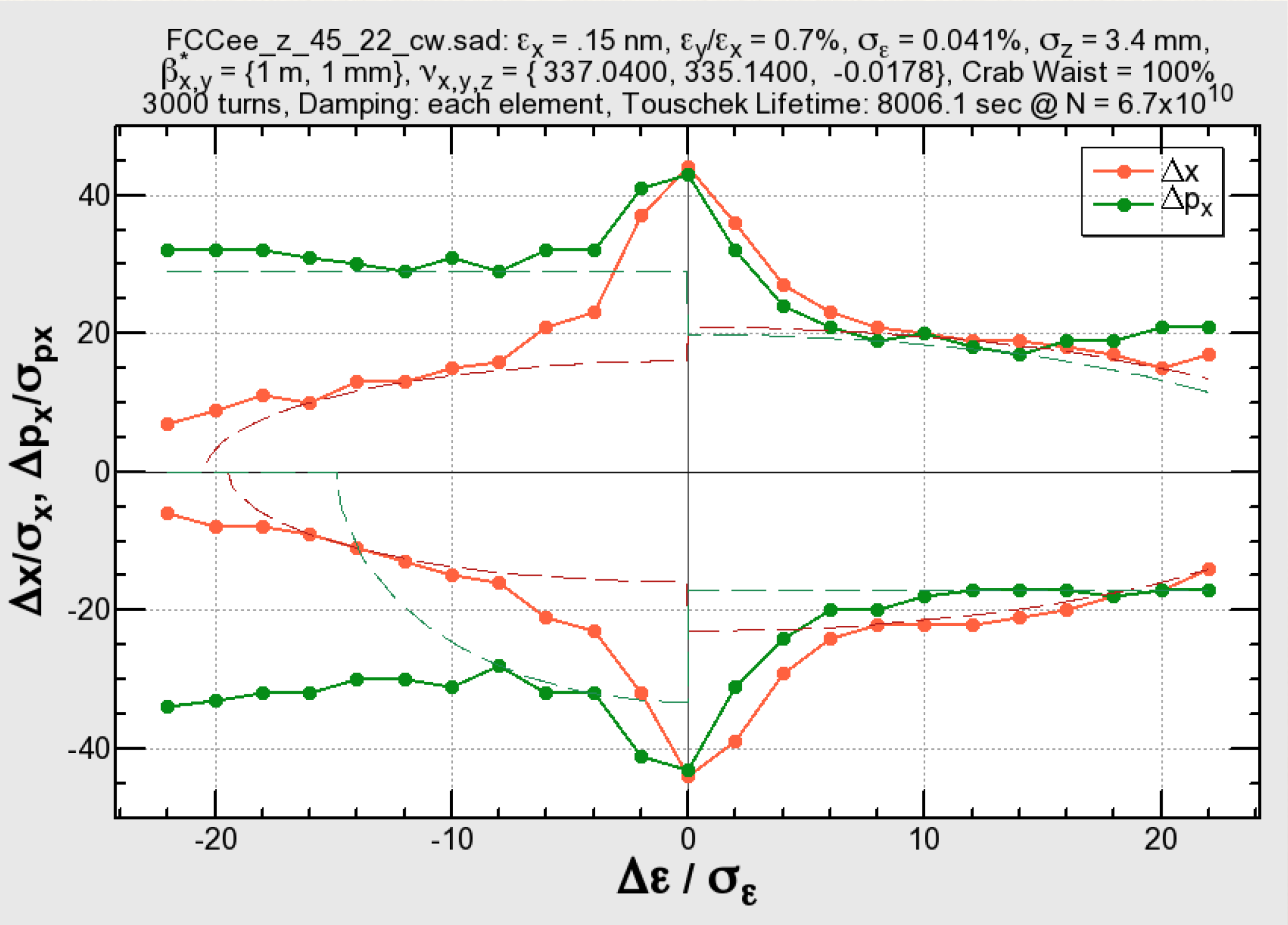


With automatic tapering

- 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.

Dynamic Aperture



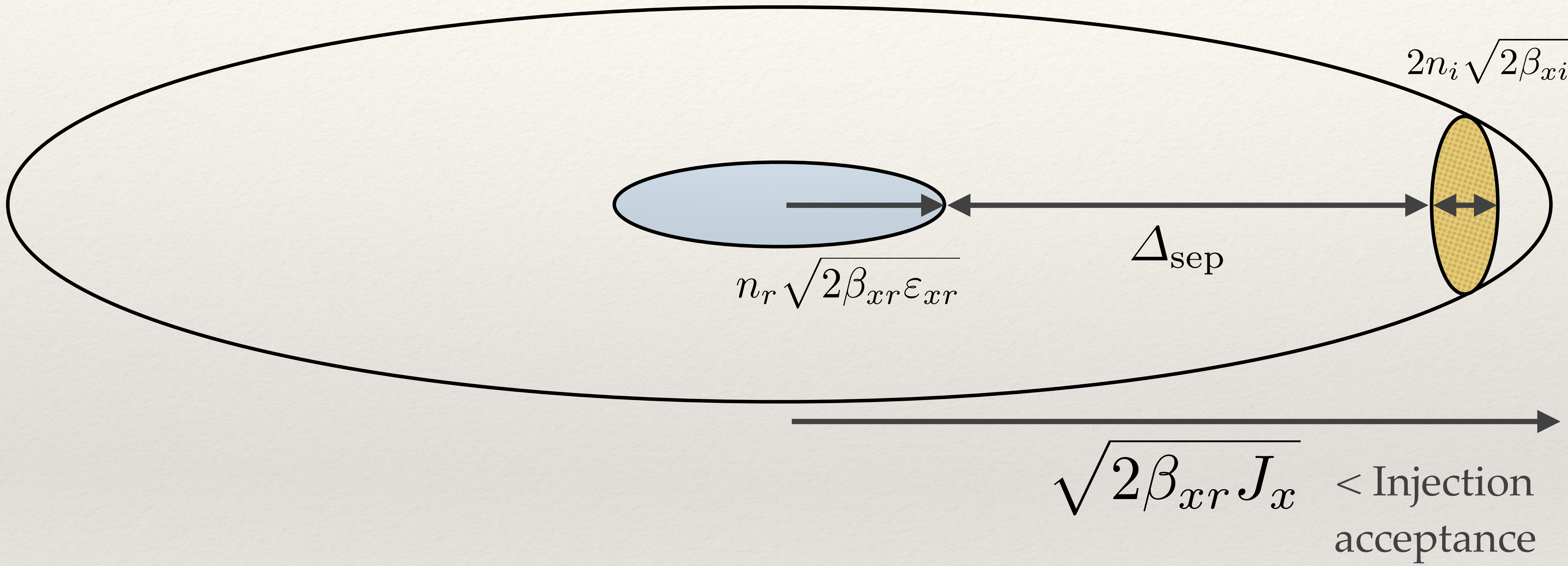


E = 175 GeV, $\beta_y^* = 2$ mm

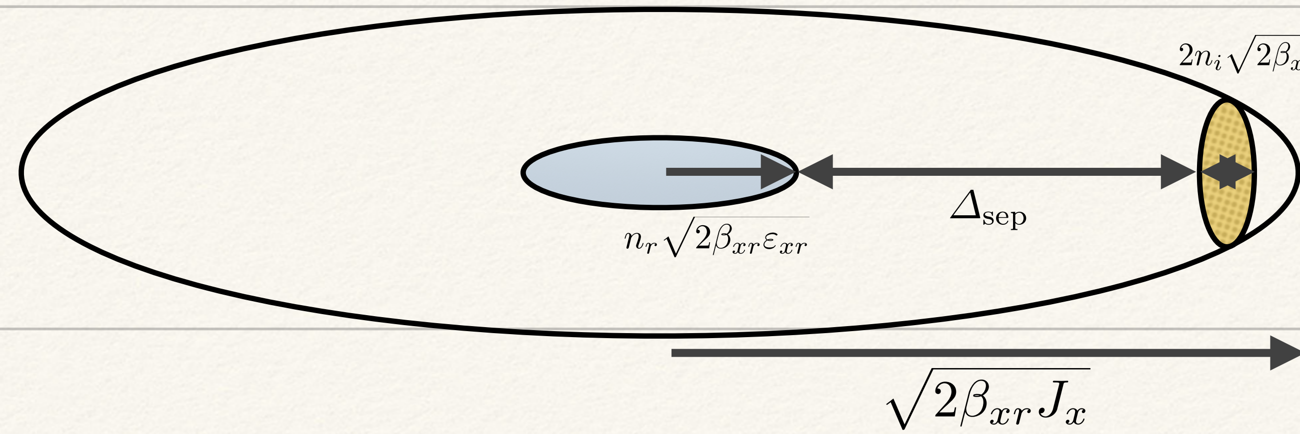
E = 45.6 GeV, $\beta_y^* = 1$ mm

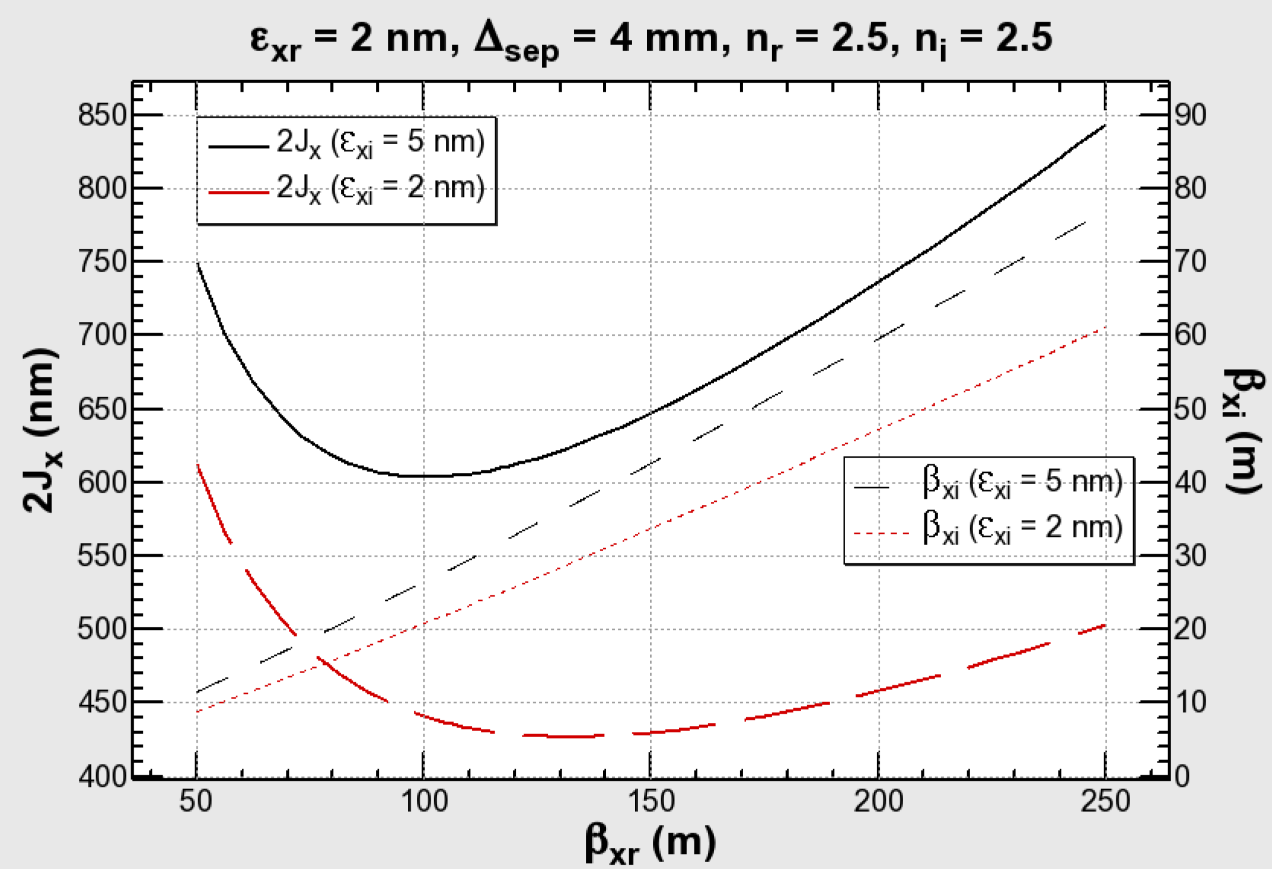
- The dynamic aperture was optimized with element-by-element radiation damping, automatic tapering, and crab waist.

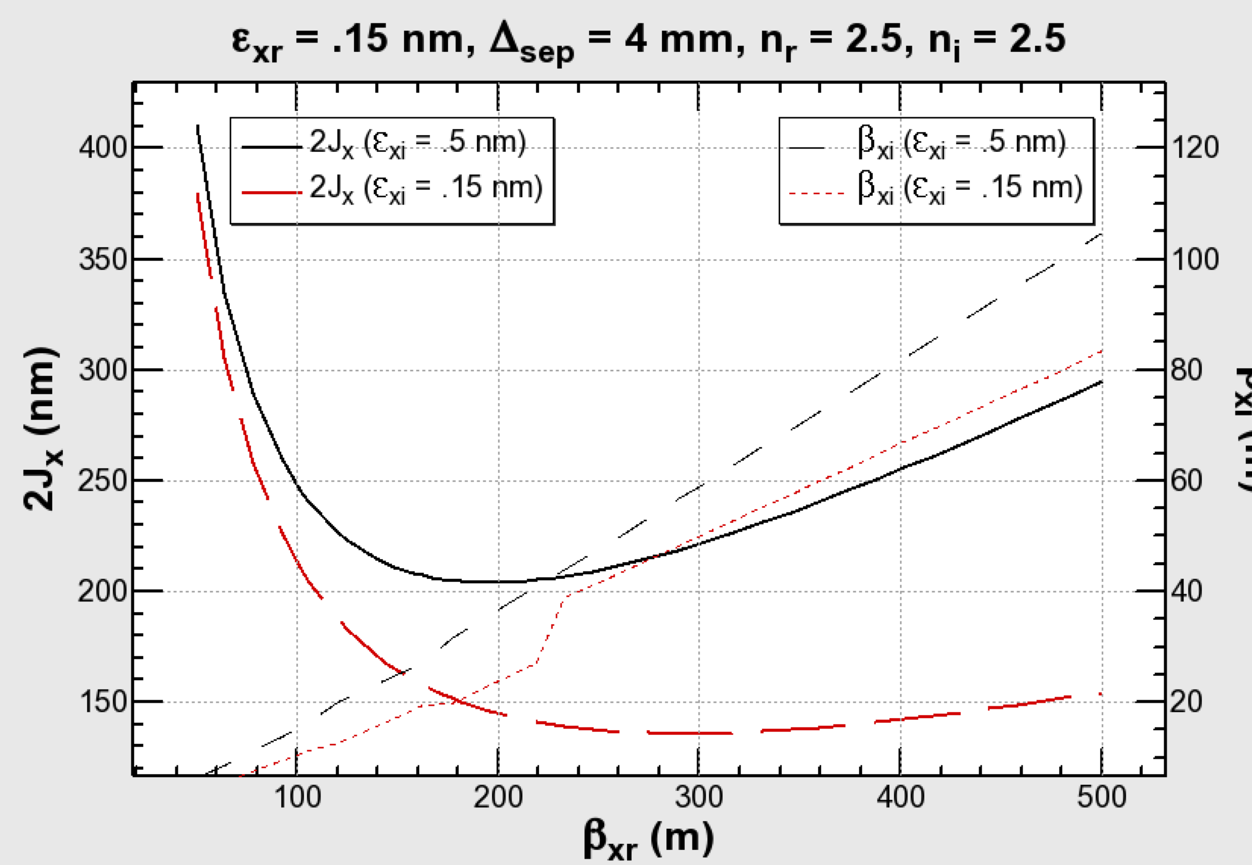
A rough estimation of requirement on injection acceptance



- β_i is optimized to minimize J_x .to touch the ellipse of the injection beam to the ring ellipse.
- α does not matter by setting $\alpha_i/\beta_i = \alpha_r/\beta_r$.







E = 175 GeV

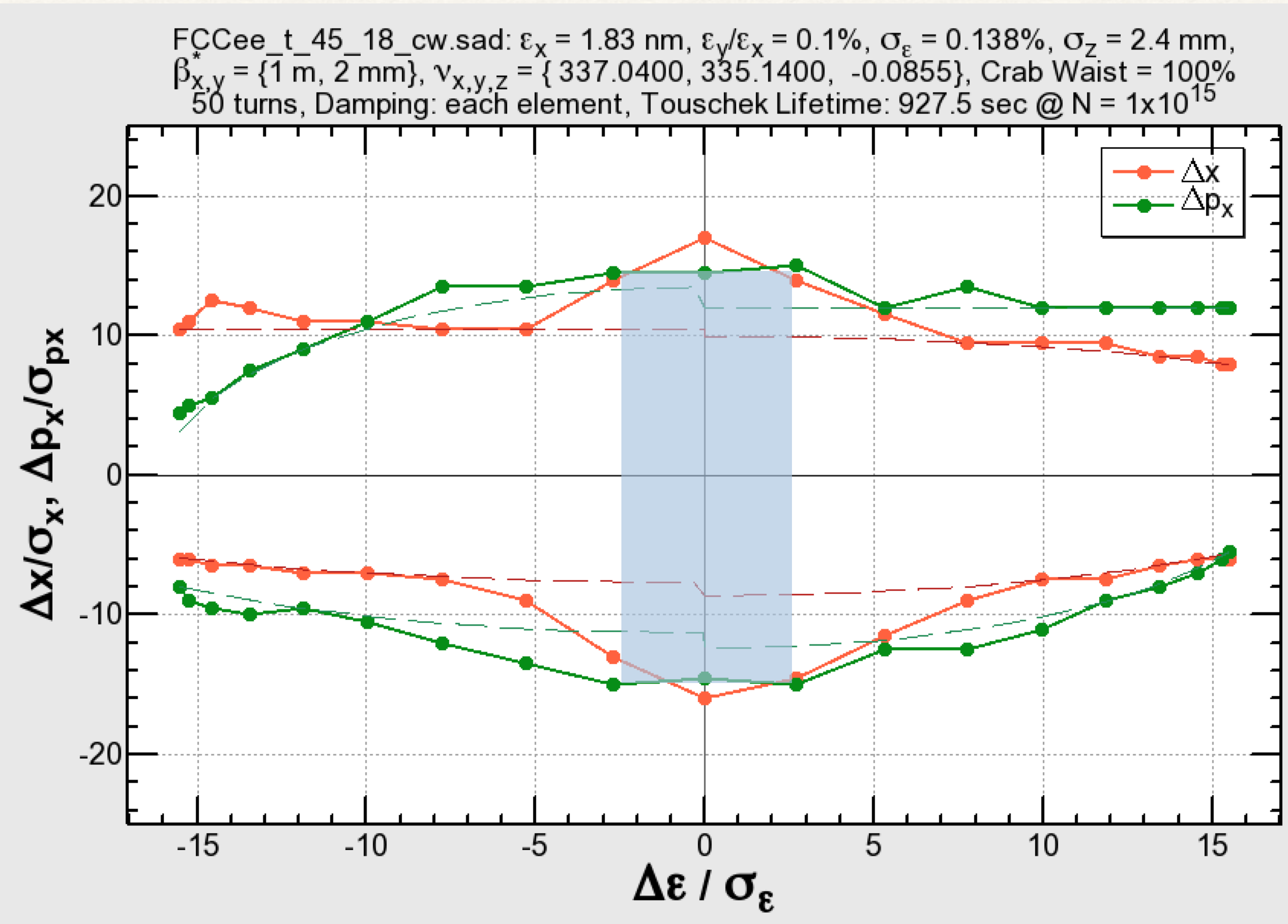
$2\,J_x = 425$ nm ($14.6\sigma_x$)

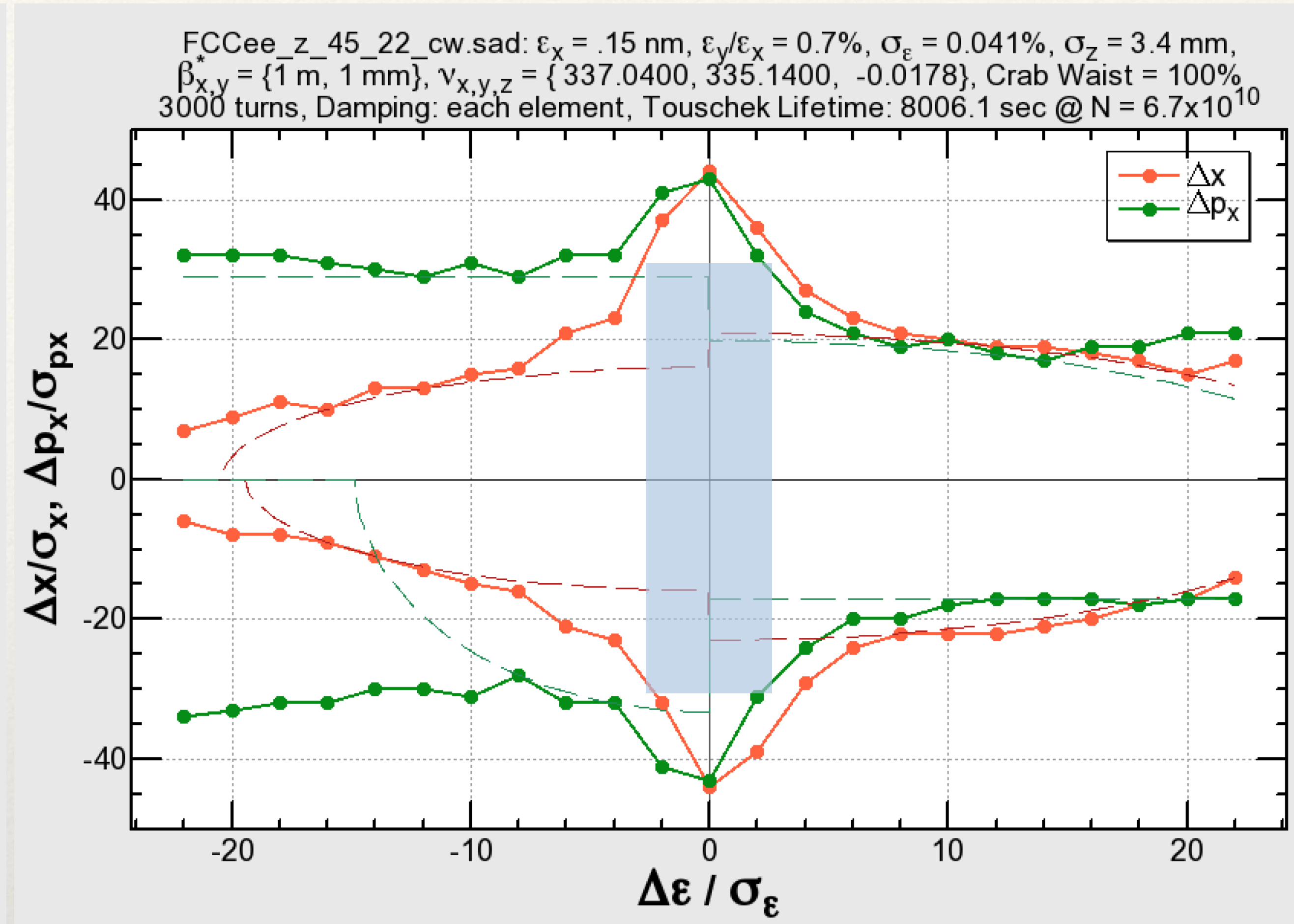
E = 45.6 GeV

$2\,J_x = 135$ nm ($30\sigma_x$)

$J_y/J_x = (2.5^2 \text{x} 0.015\text{ nm})/2J_x = 0.07\%$

Comparison with dynamic aperture





±2% ±0.9%

E = 175 GeV, $\pm 14.6\sigma_x$ & $\pm 2.5\sigma_\varepsilon$ E = 45.6 GeV, $\pm 30\sigma_x$ & $\pm 2.5\sigma_\varepsilon$

- The amplitude of the injected beam almost fits within the dynamic aperture, both for 175 GeV and 45.6 GeV.
- The required vertical emittance of the injected beam:
  - $\varepsilon_{yi} / \varepsilon_{xi} < 1.7\%$ (@175 GeV), $< 100\%$ (@45.6 GeV).

Summary

- An example of optics for FCC-ee has been presented, considering:
  - 2IPs/ring, with ±15 mrad crossing angle
  - Local chromaticity correction with crab waist
  - Suppression of synchrotron radiation in the IR below 100 keV
  - Solenoid at IP & its compensation
  - Element-by-element synchrotron radiation
  - No sawtooth by tapering of all magnets along with the local beam energy
  - Common RF sections with cross-over of two beams
  - Optimization of dynamic aperture with hundreds of sextuple families
  - Acceptance for top-up injection
  - Geometrical fitting to the FCC-hh tunnel
- Resulting dynamic aperture almost satisfies the requirements.