FCC-ee:
Optics update with element-by-element radiation

FCC-ee optics meeting

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Summary of the update

- Made thickness of all quadrupoles longer, **0.6 m to 3 m**, except for the final doublets.
  - to reduce the radiation-induced synchrotron motion, which affects the DA.
- Adopted the **local solenoid compensation**, similar to Sergei's.
  - no need for skew quads and sexts.
- Tried $\beta_{x,y}$ = 1 m, **2 mm**. Betatron tunes are changed from (0.53, 0.57) to (0.52, 0.57).
- Improved the RF section:
  - the optics of the common part are **compatible for both beams**.
  - straightend the beam line for the incoming beam.
- The number of cells in the arc was increased to adjust the emittance.
- Optimized the dynamic aperture with **element-by-element radiation**.
  - strengths of the magnets are **automatically tapered** with the local energy of the closed orbit.

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 $\pm\Delta p/p_0$:

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

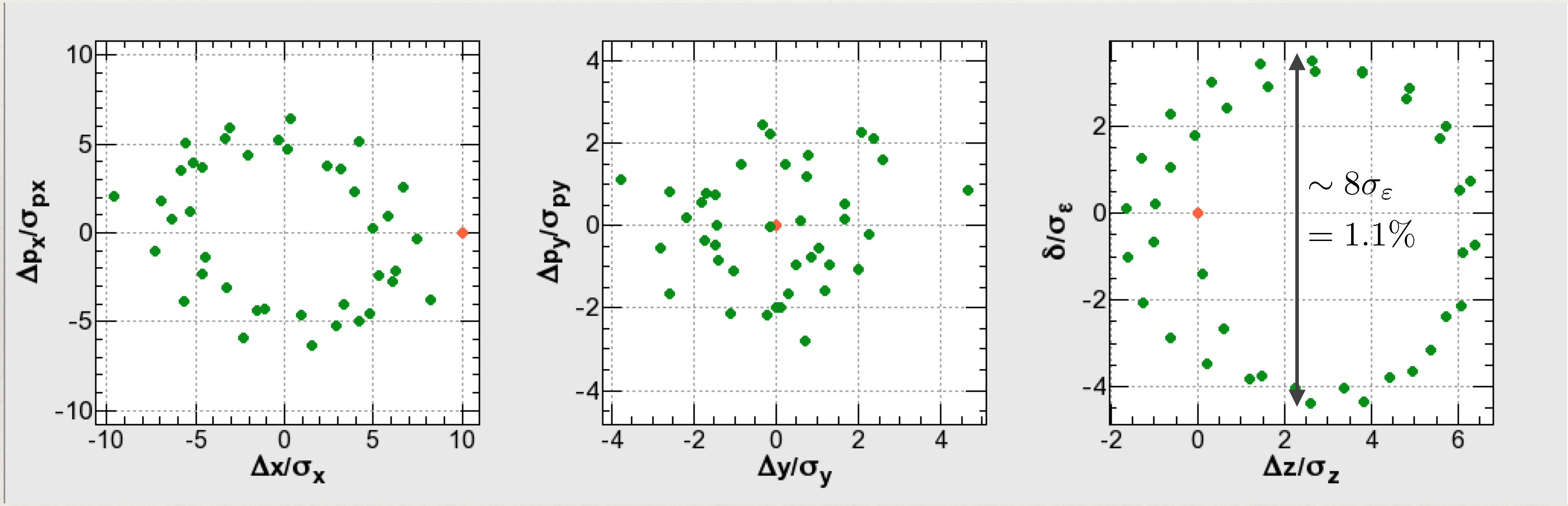
A rough estimation of radiation by arc quads (cont'd)

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

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

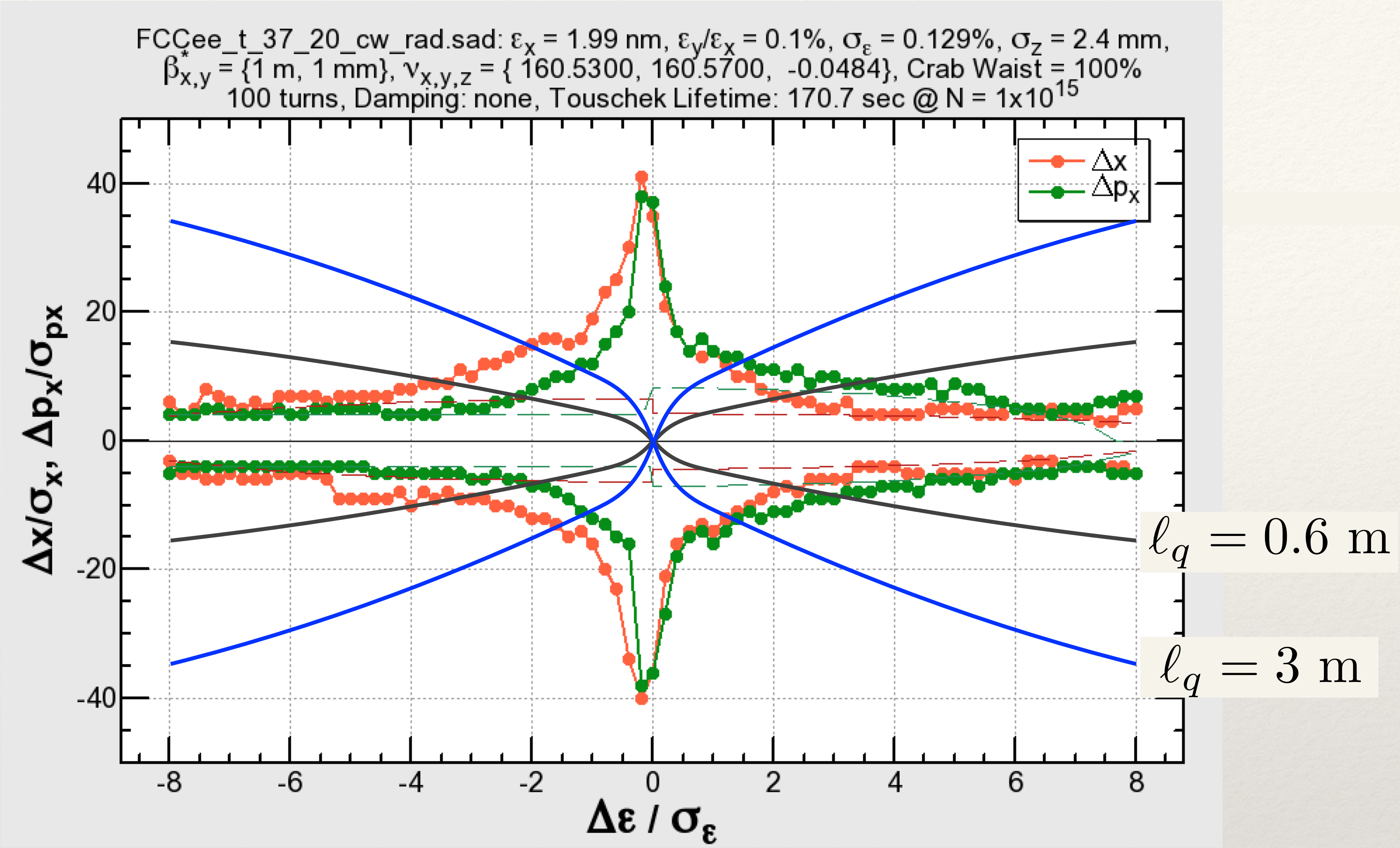
$$\frac{\Delta p}{p_0} = 0.58\% \left(\frac{n}{10}\right)^2 \left(\frac{0.6\ \mathrm{m}}{\ell_q}\right)$$

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



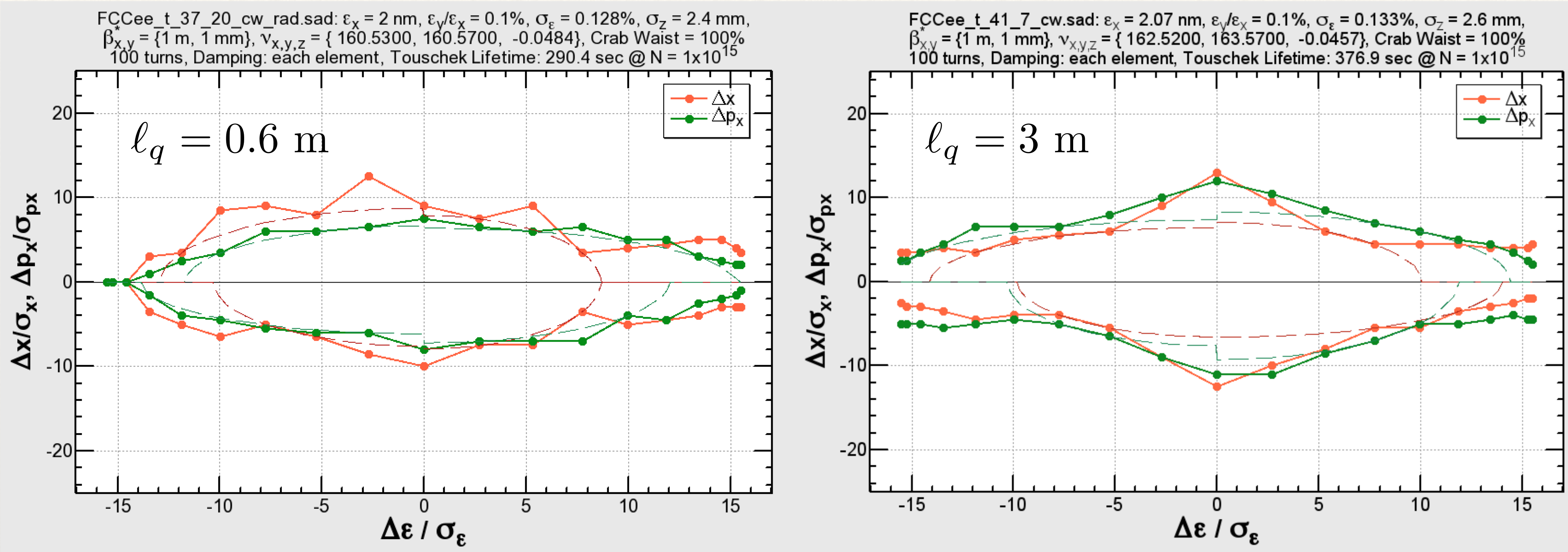
* only damping, no fluctuation, is taken into account in simulations in these slides.

The effect on the dynamic aperture



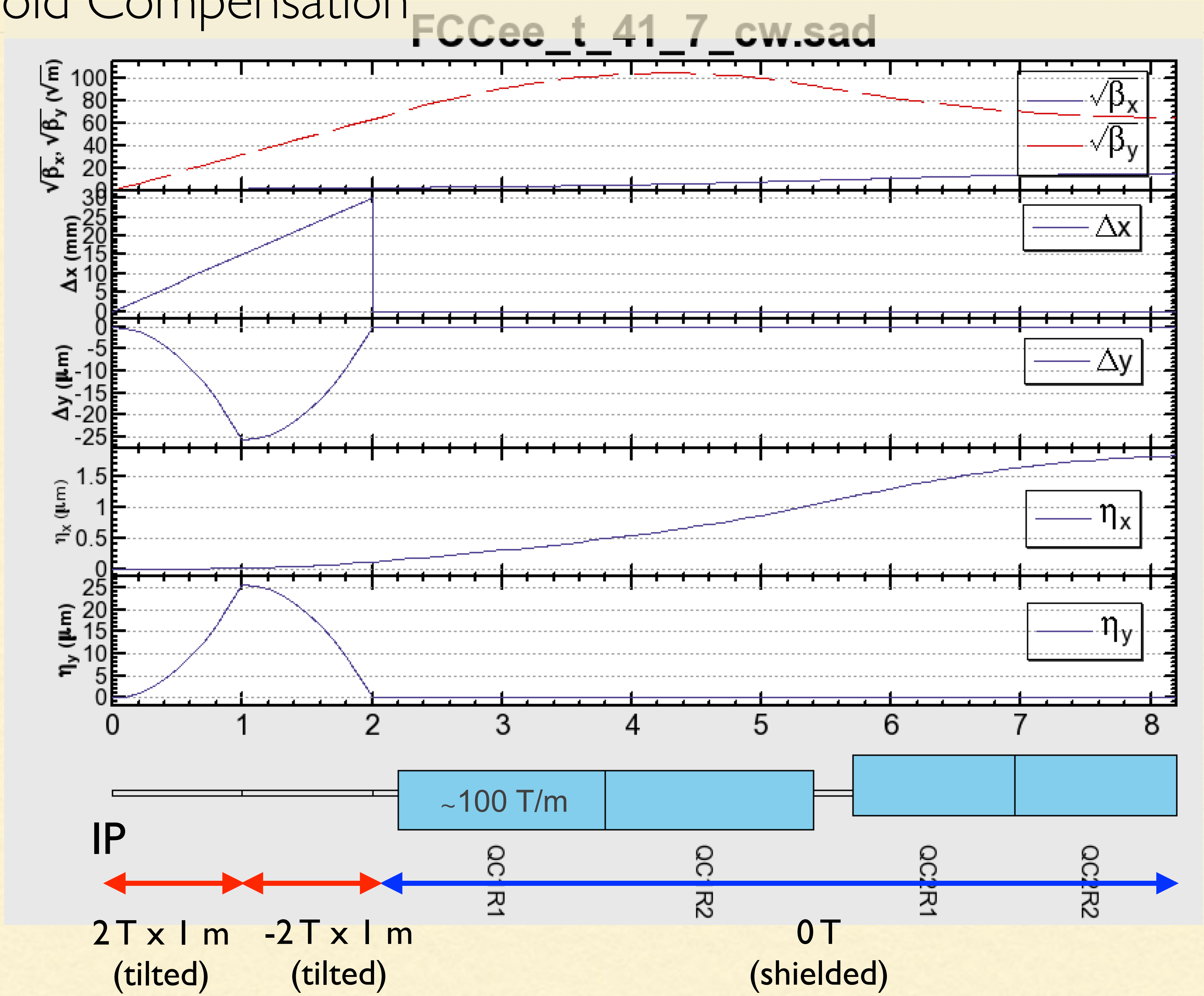
- The required momentum acceptance for $\Delta x/\sigma_x$ are shown by the curves above.
- To accept the radiation-induced synchrotron motion, the dynamic aperture must be wider than these curves.

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.

Local Solenoid Compensation

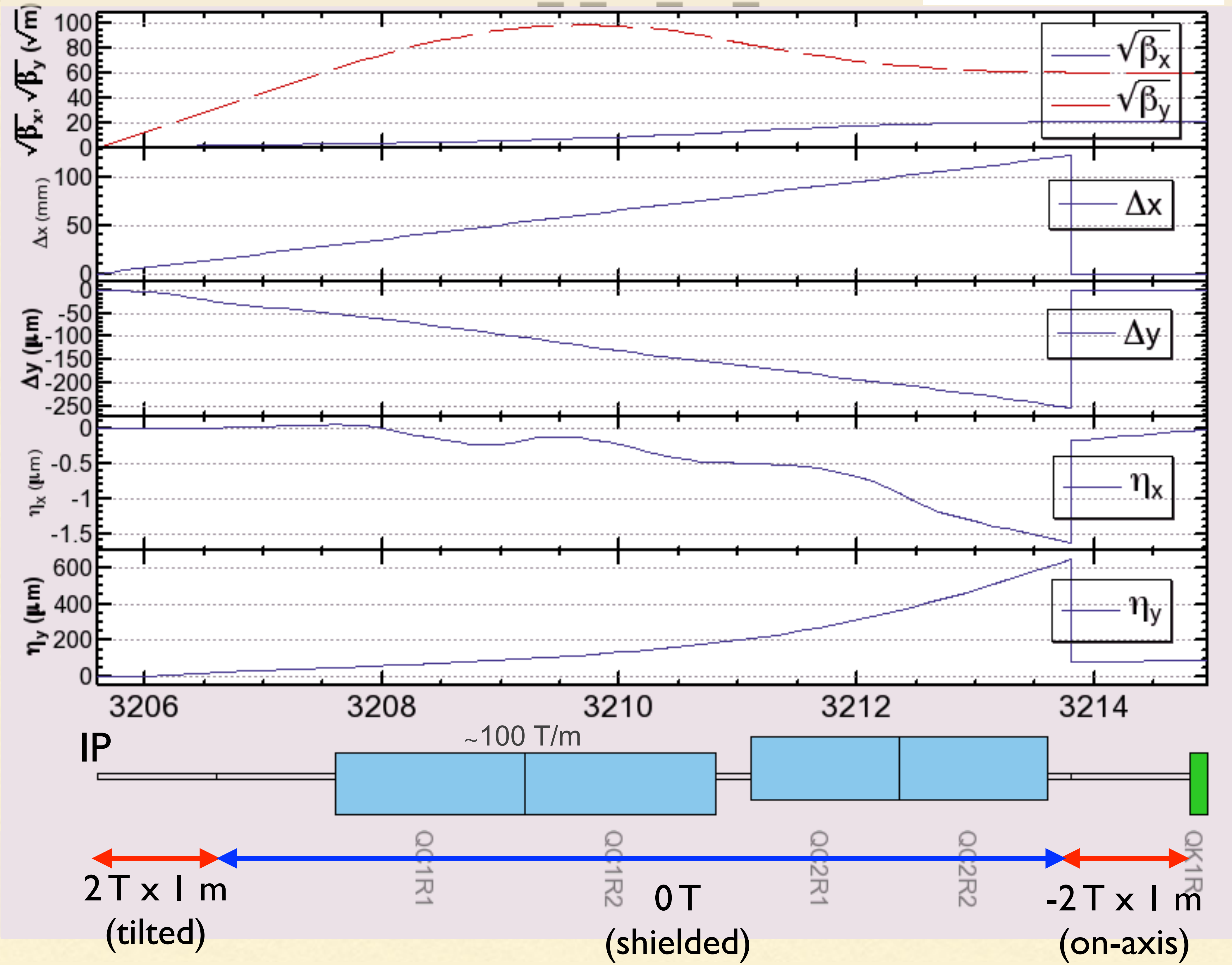


- Local solenoid compensation like above is the ideal solution, if it is technically possible.
- No leak orbit, no vertical dispersion, no coupling outside for all beam energy.
- Thus use this scheme unless it is technically denied. The previous solution with skew quads is not dead.

IP Solenoid & Compensation

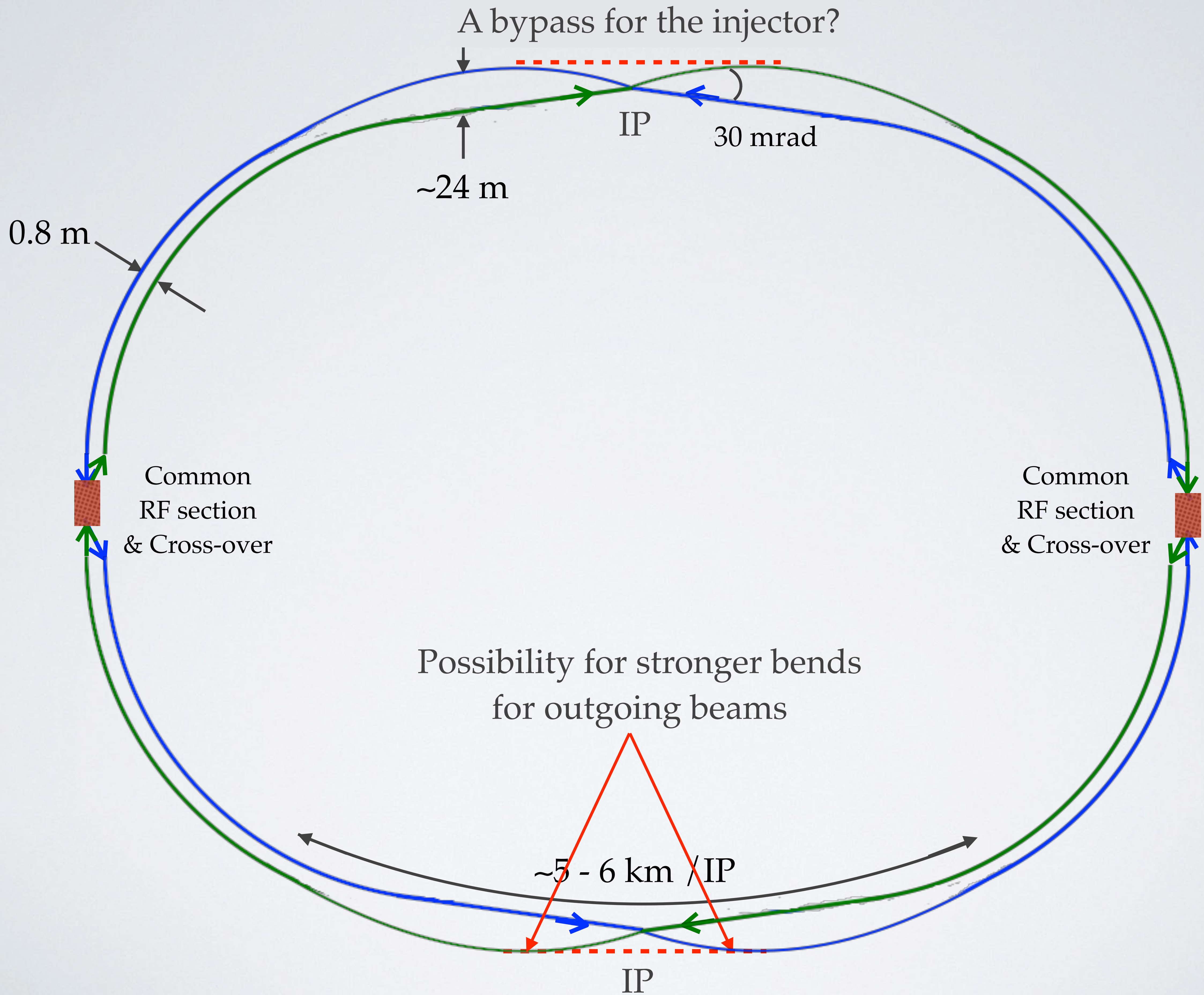
FCCee_t_35_11_cw.sad

Previous version

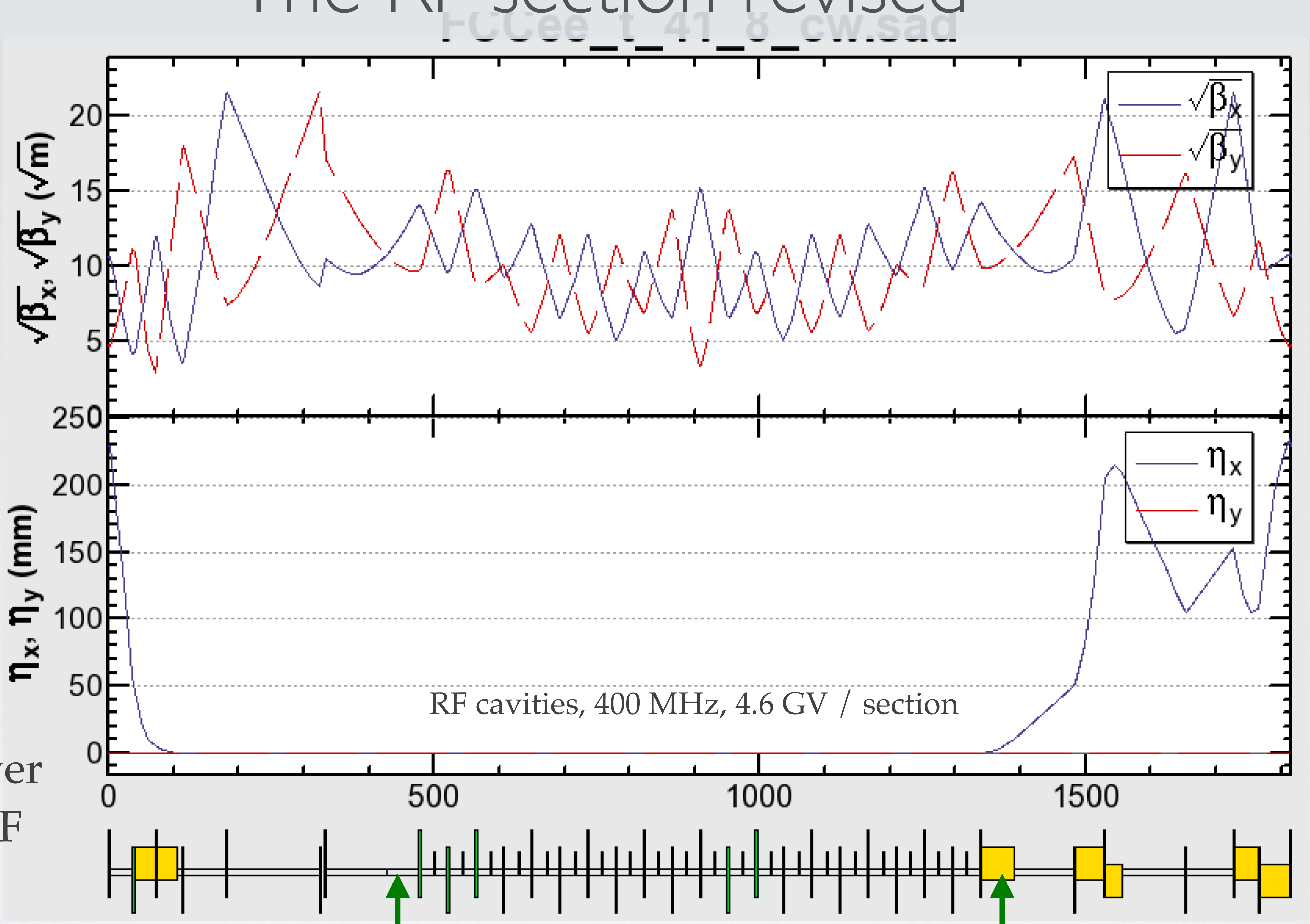


- Compensation solenoids (1) shield the final quads (2) cancel the integrated rotation.
- Residual couplings are corrected by a roll of QC2 and skew quads outside, 7 skews/side (I assume QC1 cannot roll).

The Layout


A bypass for the injector?
IP
30 mrad
~24 m
0.8 m
Common
RF section
& Cross-over
Common
RF section
& Cross-over
Possibility for stronger bends
for outgoing beams
~5 - 6 km / IP
IP

The RF section revised

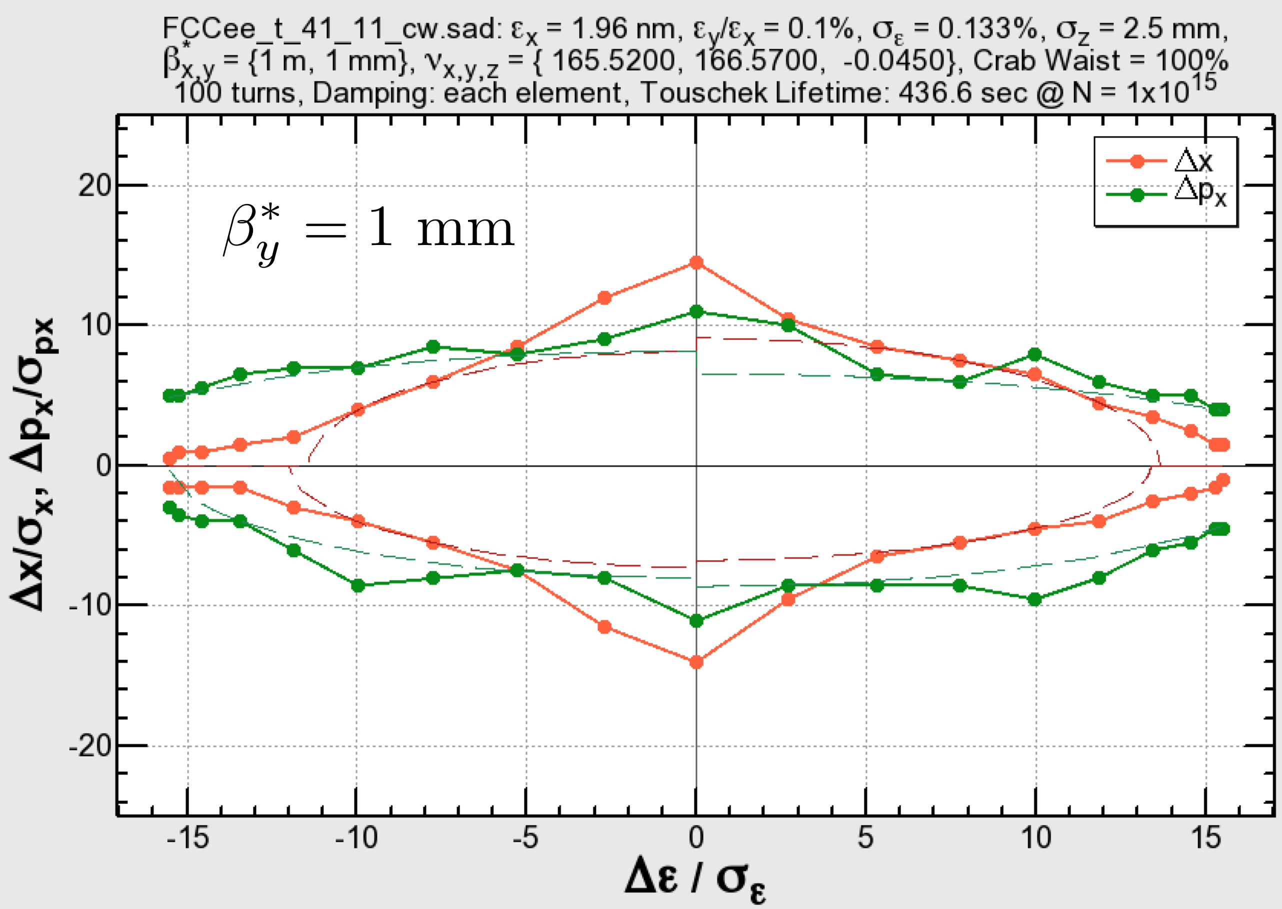


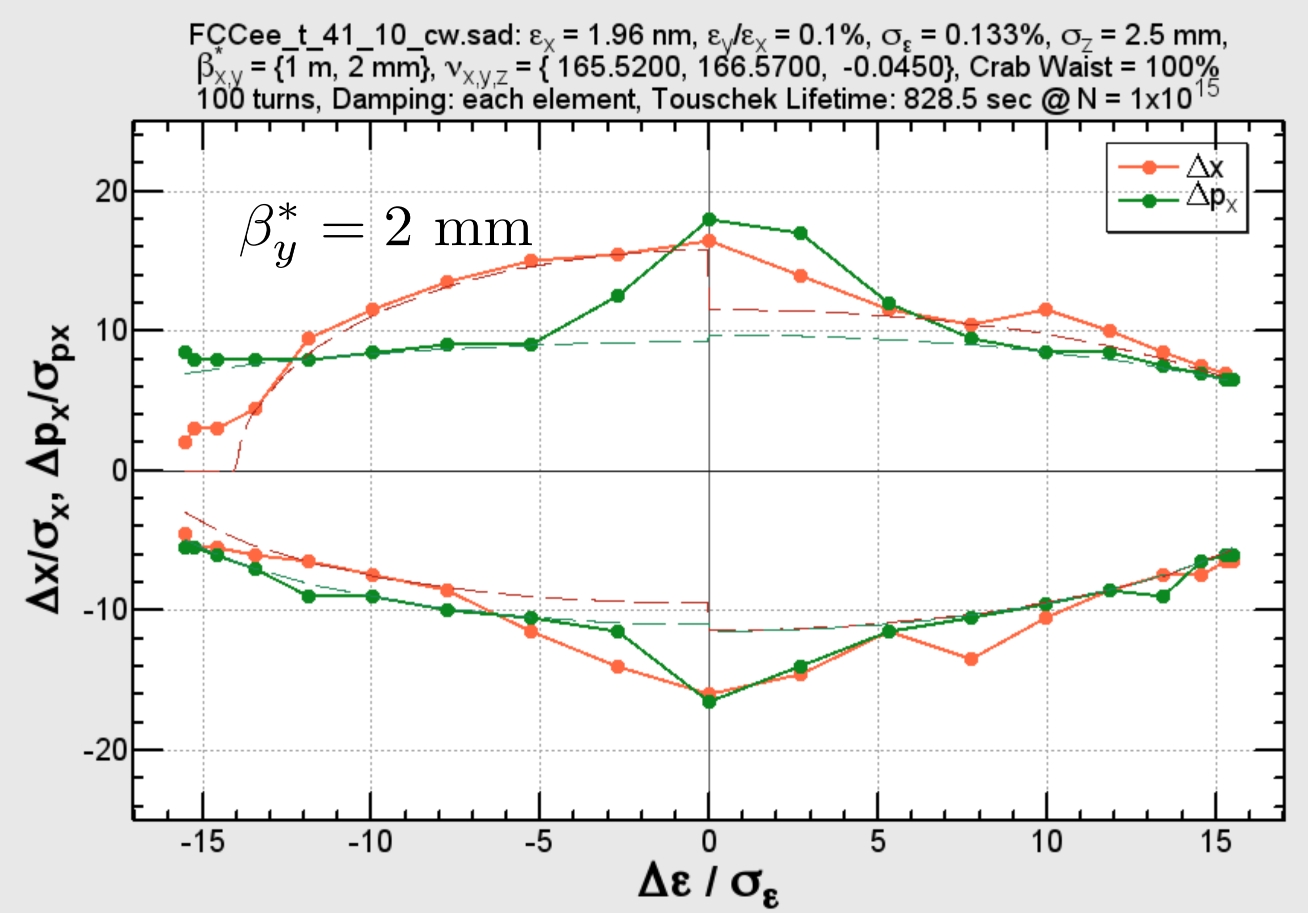
Beams cross over through the RF section.

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.