Desirable optics code features for the FCC-ee collider rings

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Essential features

- Orbit & optics calculation (in 6D, when necessary):
  - Optical/geometrical matching
  - Off-momentum optics
- Emittance/beam envelope calculation with machine errors:
  - Intrabeam scattering and space charge may be included.
  - Extendable to "synchro-beta emittance"

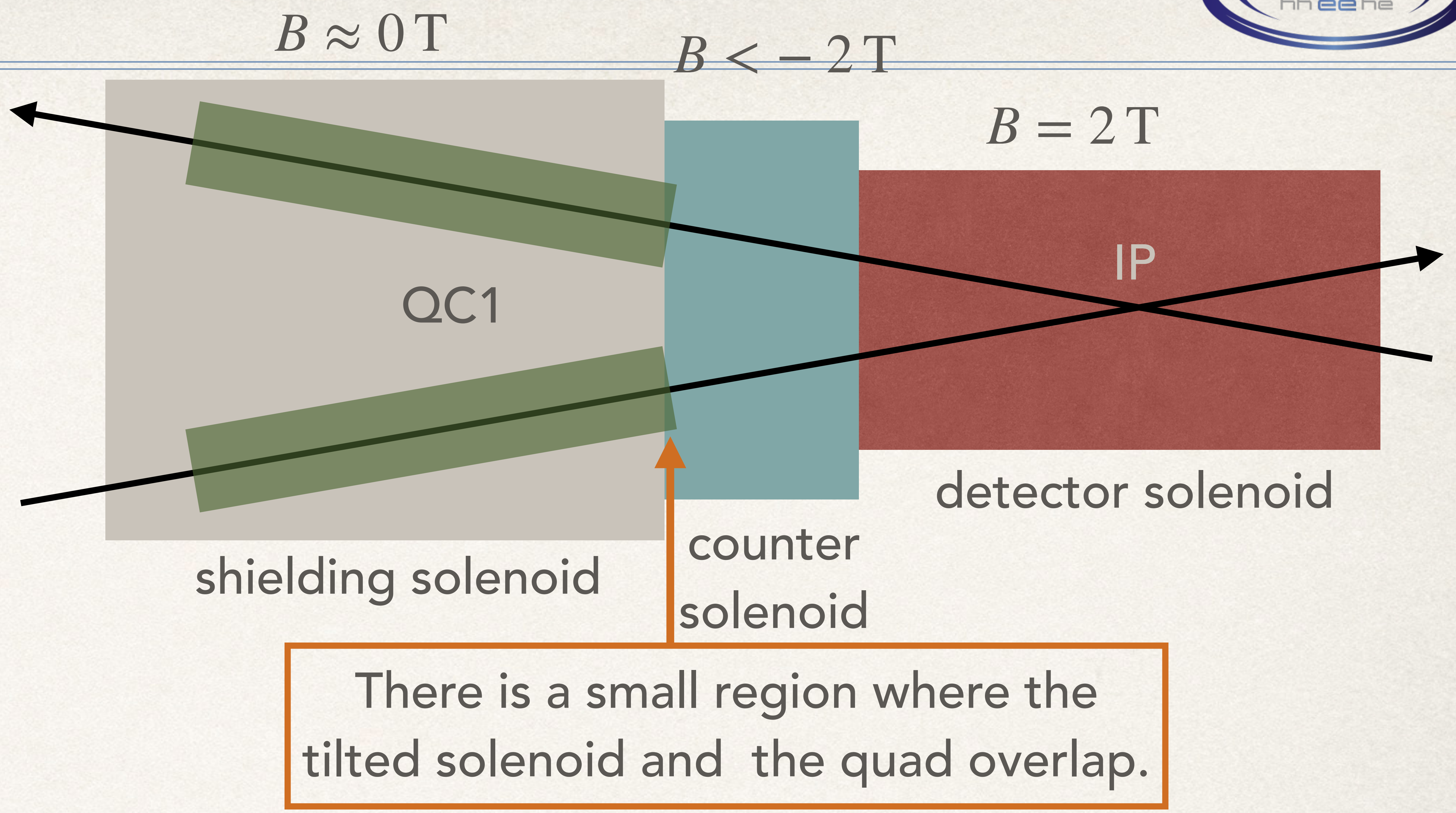
$$\langle X_i X_j \rangle = \mathrm{M} \langle X_i X_j \rangle \mathrm{M}^T + \Delta_{ij}$$

- Multi-particle tracking with synchrotron radiation:
  - Estimation & optimization of the dynamic aperture
  - Beam-beam, at least by strong-weak model, should be included
- Spin tracking and estimation of polarization

- In all above, *tilted solenoids with possible overlap* with quads and multipoles are necessary to express the IR optics.
- Everything should be unified into one code, or tightly & seamlessly combined under a scripting language.

A tilted solenoid

- The current design assumes a "perfect" compensation of the integrated solenoid field around the IP.
- However, an small overlap of the fringe of the counter solenoid and the final quad (QC1) is unavoidable.
- So the code must handle this situation, for instance as treated in SAD:
- The synchrotron radiations arising from the body and the fringe of the solenoids are essential.
- The *design* orbit and dispersion must connect to the outer area smoothly.



$$\begin{pmatrix} u \\ p_u \\ v \\ p_v \end{pmatrix} = \sqrt{U} \begin{pmatrix} \frac{w_1+w_2}{2} & -\frac{i}{p} & -\frac{\sqrt{w_1^2-w_2^2}}{2} & \frac{1}{p}\sqrt{\frac{w_1-w_2}{w_1+w_2}} \\ -\frac{ip}{4}(w_1+w_2)^2 & \frac{w_1+w_2}{2} & -\frac{p(w_1-w_2)}{4}\sqrt{w_1^2-w_2^2} & -\frac{w_1-w_2}{2}\sqrt{\frac{w_1-w_2}{w_1+w_2}} \\ -\frac{\sqrt{w_1^2-w_2^2}}{2} & \frac{1}{p}\sqrt{\frac{w_1-w_2}{w1+w2}} & \frac{w_1+w_2}{2} & \frac{1}{p} \\ -\frac{p(w_1-w_2)}{4}\sqrt{w_1^2-w_2^2} & -i\frac{w_1-w_2}{2}\sqrt{\frac{w_1-w_2}{w_1+w_2}} & -\frac{ip}{4}(w_1+w_2)^2 & \frac{w_1+w_2}{2} \end{pmatrix} \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix} . \tag{44}$$

+ higher orders.

Note that H_{2u} is real. Thus the transformation of the longitudinal coordinate is obtained as

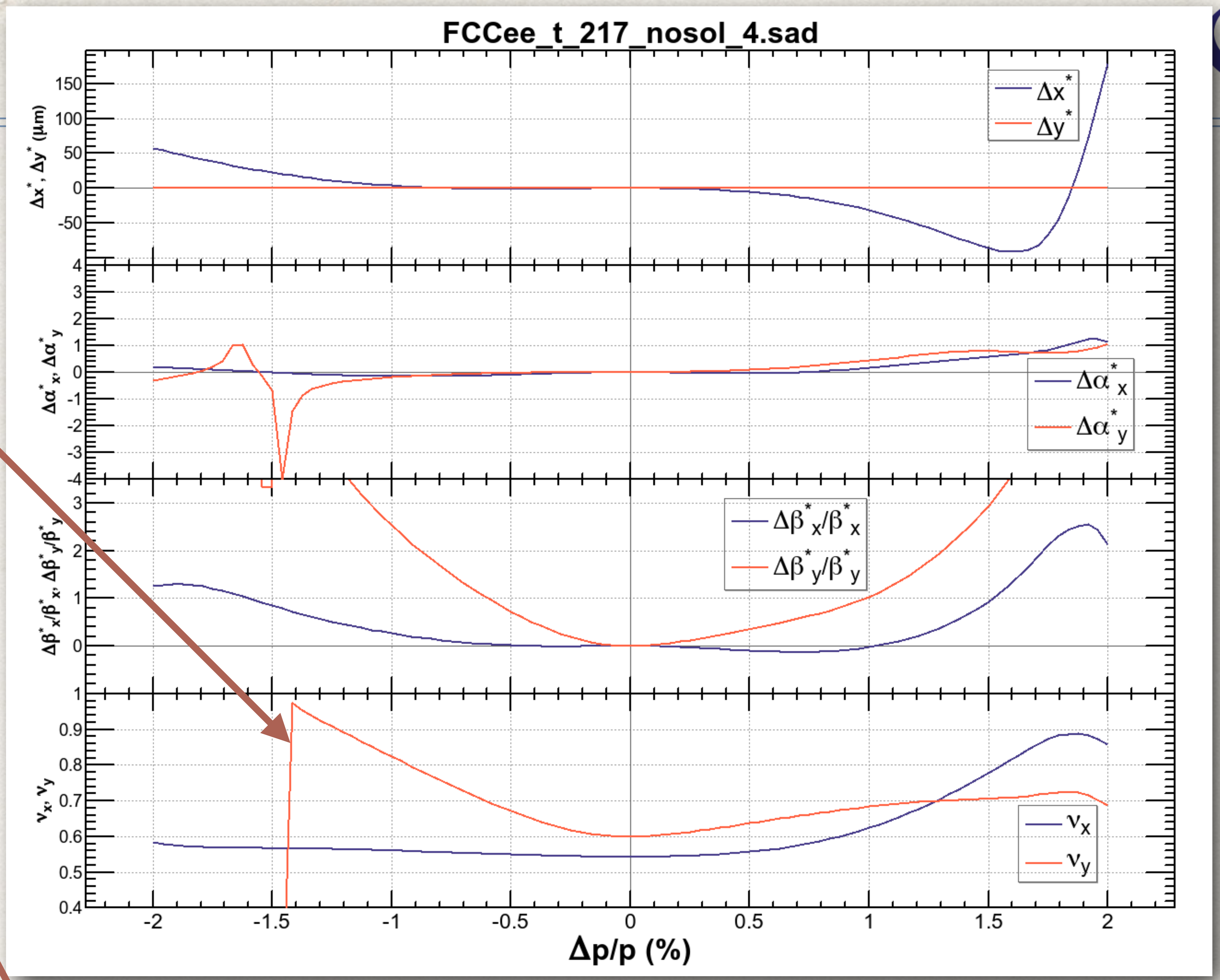
$$z = z_0 + \left(-iup_u\frac{\partial w_1}{\partial p} - vp_v\frac{\partial w_2}{\partial p} + \Delta v\right)\ell \tag{45}$$

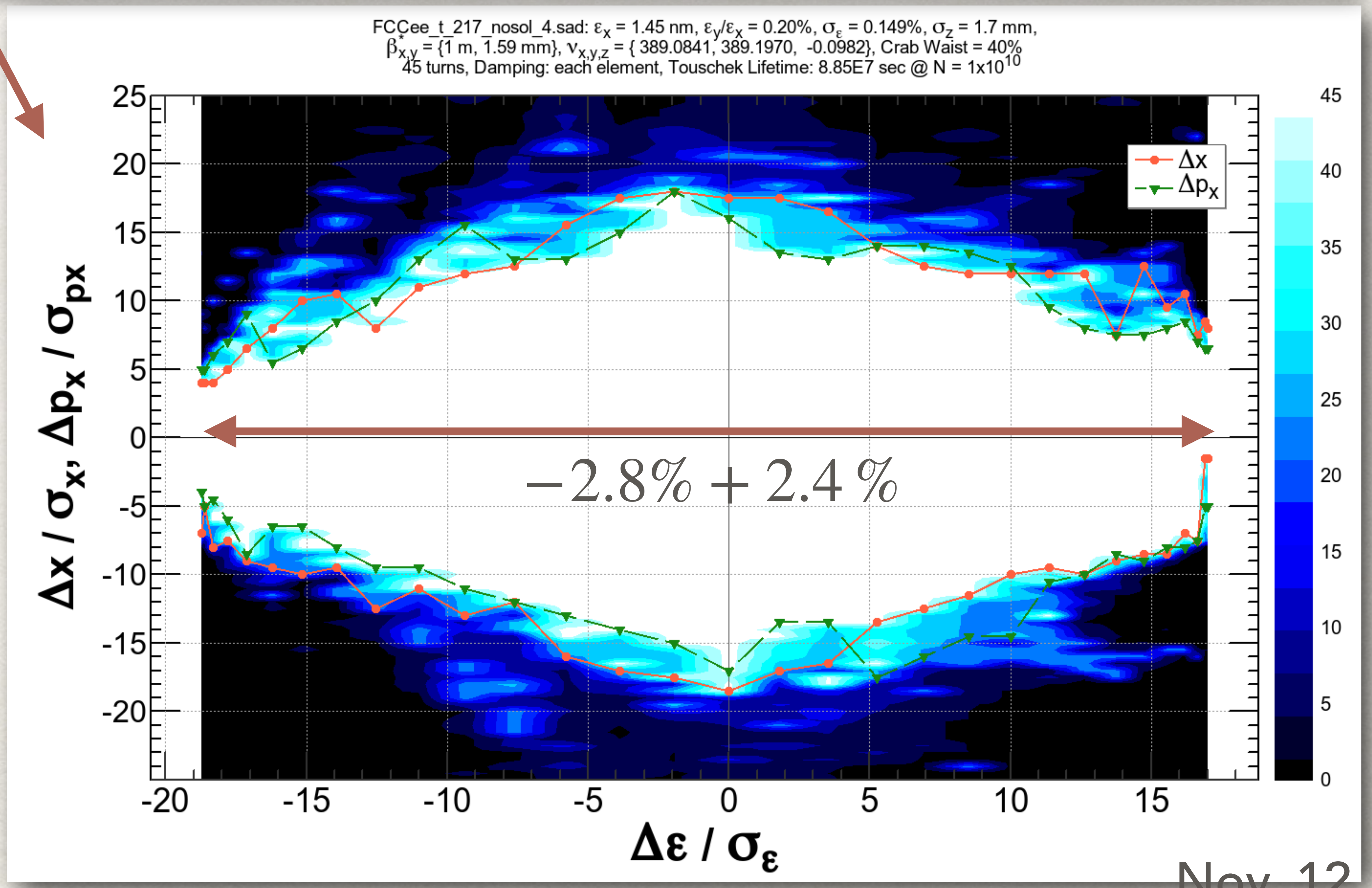
$$= z_0 + \frac{U}{p}\left(iw_1^3 u_0 p_{u0} + w_2^3 v_0 p_{v0} + \Delta v\right)\ell\ , \tag{46}$$

https://hep-project-sad.web.cern.ch/SADHelp/SADHelp.html#Lsolution-H2

Optics & dynamic aperture

- Esp. at $t\bar{t}$, the off-momentum beam optics become unstable at large $|\Delta p/p|$.
- The dynamic aperture is much wider than the stable range of the optics, due to the strong radiation damping.
  - The higher order Taylor maps do not converge: chaotic.
  - The dynamic aperture even shrinks if the chromaticity is better corrected.
- The situation becomes more normal at lower energies.
- Synchrotron radiation, esp. in quadrupoles, is essential in all energies.





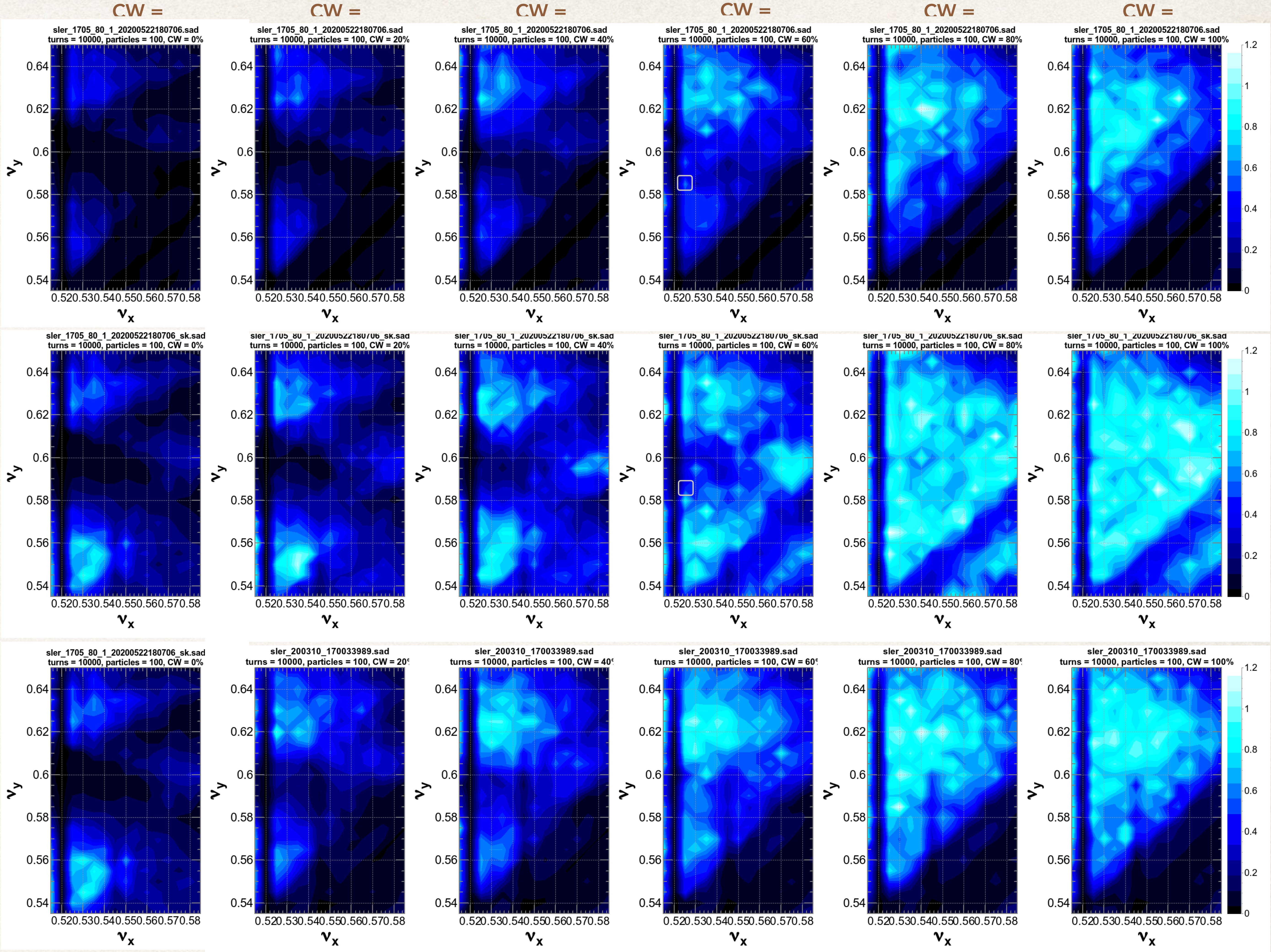
Beam-beam + lattice

- The lattice & beam-beam are tightly coupled to each other.
- A beam-beam simulation with lattice is essential to estimate the luminosity, strength of resonances, working pointe, etc.
- A strong-strong simulation, which require millions of particles may have an issue in the computation for the lattice.
  - The example on the right needs about 6 hours / plot on the CERN hpc cluster.

May 21-
4 nm

May 21-
Chromatic
Coupling
Correction

Mar. 10
2 nm
(no ChCC)



Emittance growth due to beam-beam + lattice for various crab waist ratios at SuperKEKB

Polarization

- It is nice to simulate the polarization seamlessly with the optics/correction code.
  - Such a simulation is also important in the machine operation.

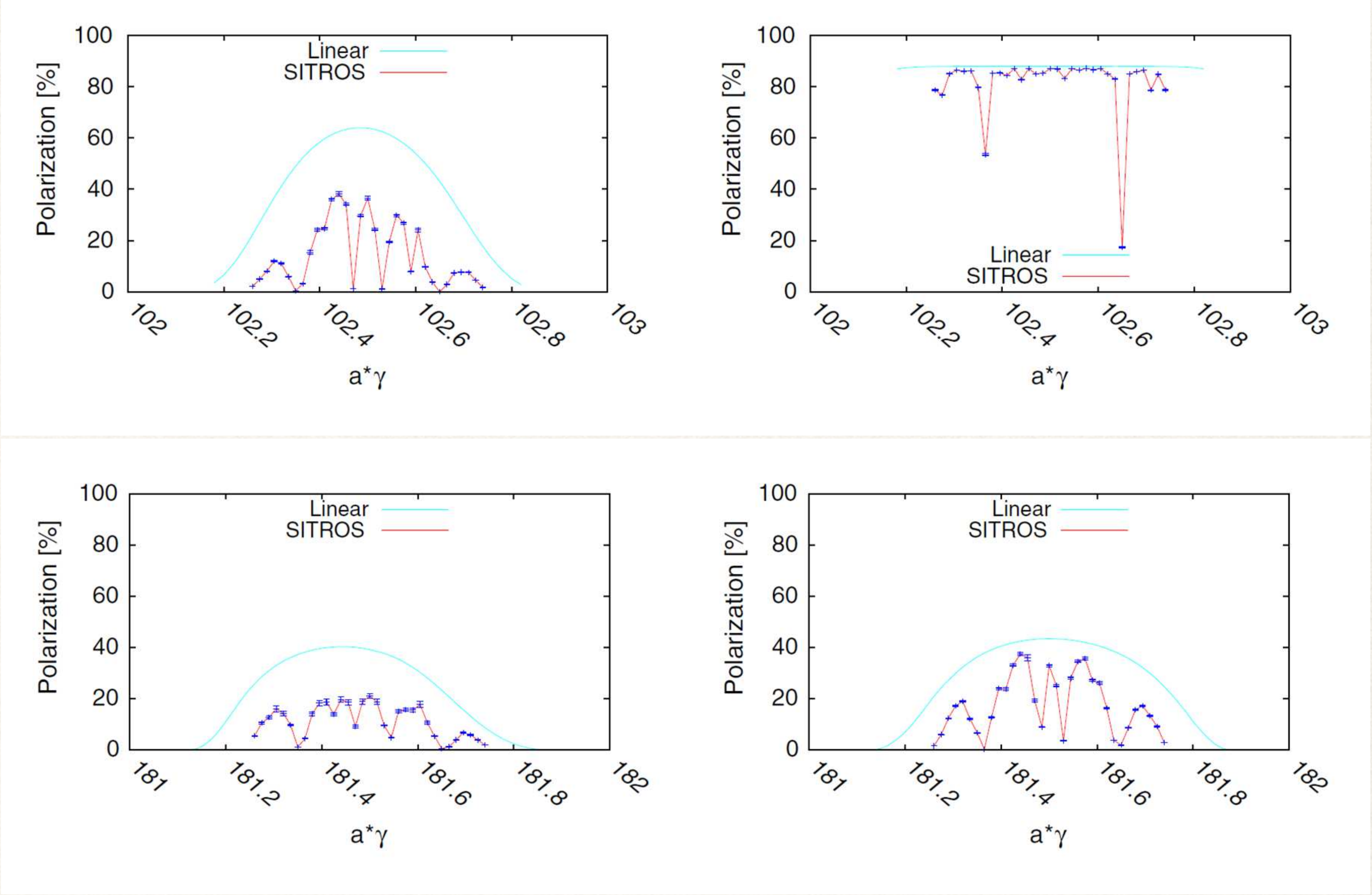


Figure 2.36: Example of simulations of beam polarisation in FCC-ee with linear spin theory or with the tracking code SITROS [235]. Top: near the Z pole with the 60/60 FODO optics. Left: polarisation versus spin tune after orbit is corrected with 1096 correctors with 200 μm quadrupole and BPM misalignments, plus 10% BPM calibration errors, including polarisation wigglers as described in the text. Right: adding the correction of the average spin vector through harmonic bumps. Bottom: same machine at the WW threshold, without wigglers. Left: after the orbit has been corrected with single value decomposition (SVD) in presence of BPMs errors and the spin vector further corrected by eight 3-corrector harmonic bumps, or (right) by eight dispersion-free 5-corrector harmonic bumps.

CDR, E. Gianfelice

More thing to be happy if available…

- Multi-core & multi-nodes computation for tracking, optics matching, etc.
  - Using GPUs, too.
- Scripting for data handling, graphics, etc. should be incorporated or tightly integrated with the optics code.
- The code should handle not only a storage ring, but also boosters, linacs, transport lines, etc. It will be convenient for a start-to-end simulation.
- The optics code should be used in the operation of the real machine.
  - Direct (controlling the machine from the optics code) or indirect: both have pros and cons.
- An AI-based optics design to eliminate aged experts (like myself)…
  - Even a design of linear optics (= solving a set of multi-dimension nonlinear equations under certain constraints) is not fully automatically done today, requiring a lot of human interventions, which may not be very attractive to young generations, I guess.
- .. and more!

Thank you!

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