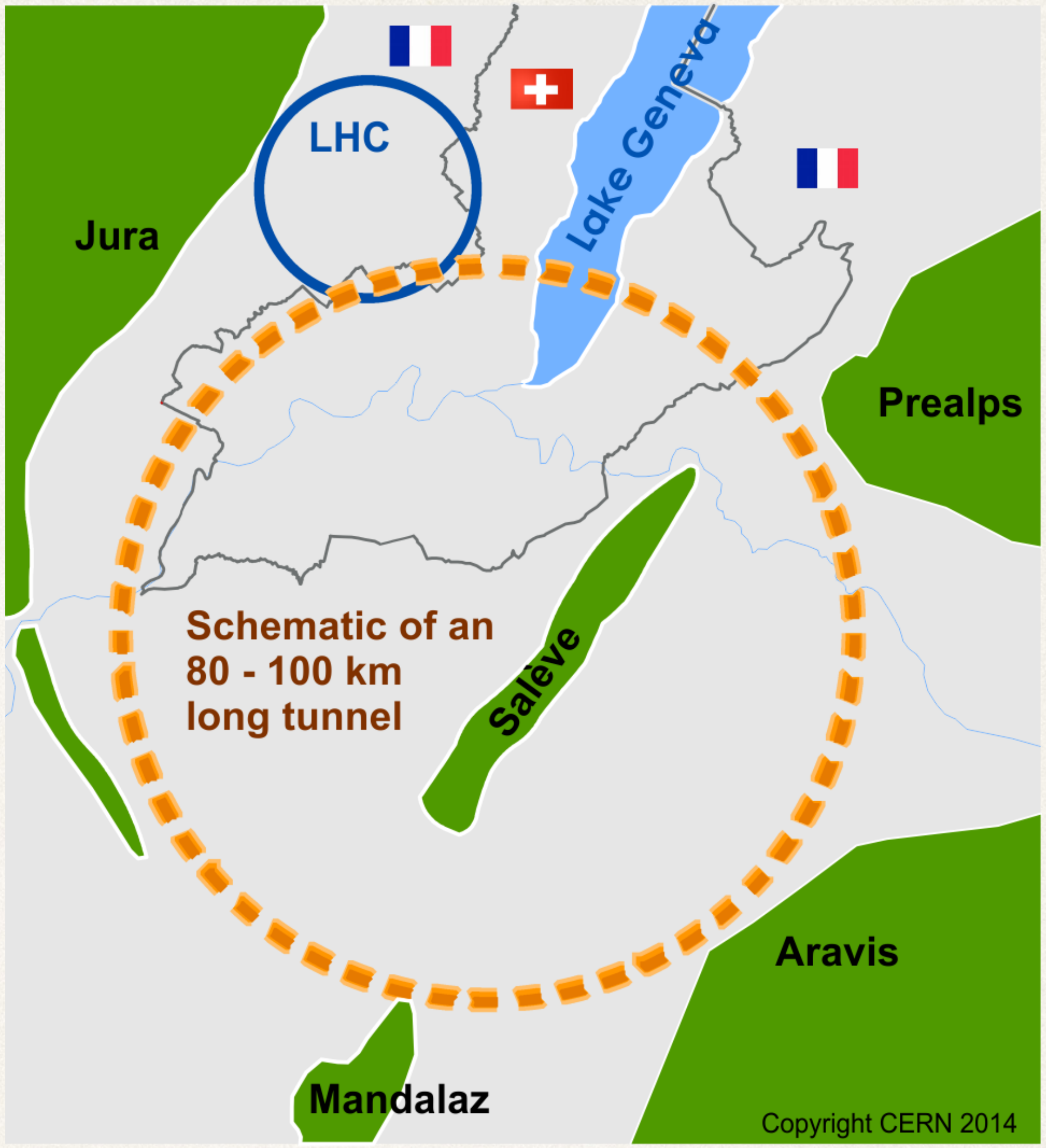
FCC-ee Optics



FCC-ee MDI Workshop

Jan. 16, 2017

K. Oide (KEK)

Contributions for FCC-ee: M. Aiba, S. Aumon, M. Benedikt, A. Blondel, A. Bogomyagkov, M. Boscolo, H. Burkhardt, Y. Cai, A. Doblehammer, B. Haerer, B. Holzer, J.M. Jowett, I. Koop, M. Koratzinos, E. Levitchev, L. Medrano, S. Ogur, K. Ohmi, Y. Papaphilippou, P. Piminov, D. Shatilov, S. Sinyatkin, M. Sullivan, J. Wenninger, U. Wienands, D. Zhou, F. Zimmermann.

2016 Parameters

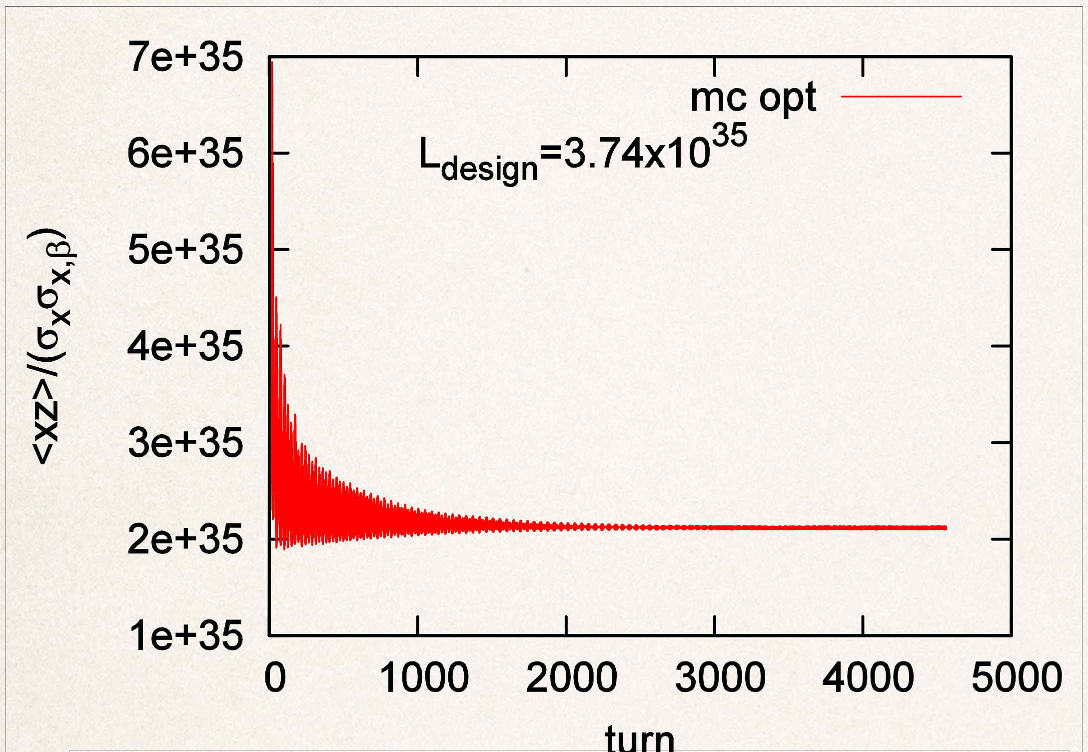
parameter	FCC-ee				CEPC		LEP2
energy/beam [GeV]	**45**		**120**	**175**	**45**	**120***	105
bunches/beam	91500	30180	770	78	1100	67	4
beam current [mA]	1450		30	6.6	45.4	16.9	3
energy loss/turn [GeV]	0.03		1.67	7.55	0.062	2.96	3.34
synchrotron power [MW]	100				2.8	100	22
RF voltage [GV]	0.2	0.4	3.0	10	0.12	3.6	3.5
rms bunch length (SR,+BS) [mm]	1.6, 3.8	1.2, 6.7	2.0, 2.4	2.1, 2.5	3.9, 4.0	3.1, 4.1	12, 12
rms emittance $\varepsilon_{x,y}$ [nm, pm]	0.1, 1	0.2, 1	0.6, 1	1.3, 2.5	0.62,2.8	2.45,7.4	22, 250
$\beta^*_{x,y}$ [m, mm]	1, 2	0.5, 1	1, 2	1, 2	0.1, 1	0.25, 1.4	1.5, 50
long. damping time [turns]	1320		72	23	726	41	31
crossing angle [mrad]	30				30		0
beam lifetime [min]	185	94	67	57	79	20	434
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**70**	**207**	**5.1**	**1.3**	**3.6**	**2.96**	0.0012

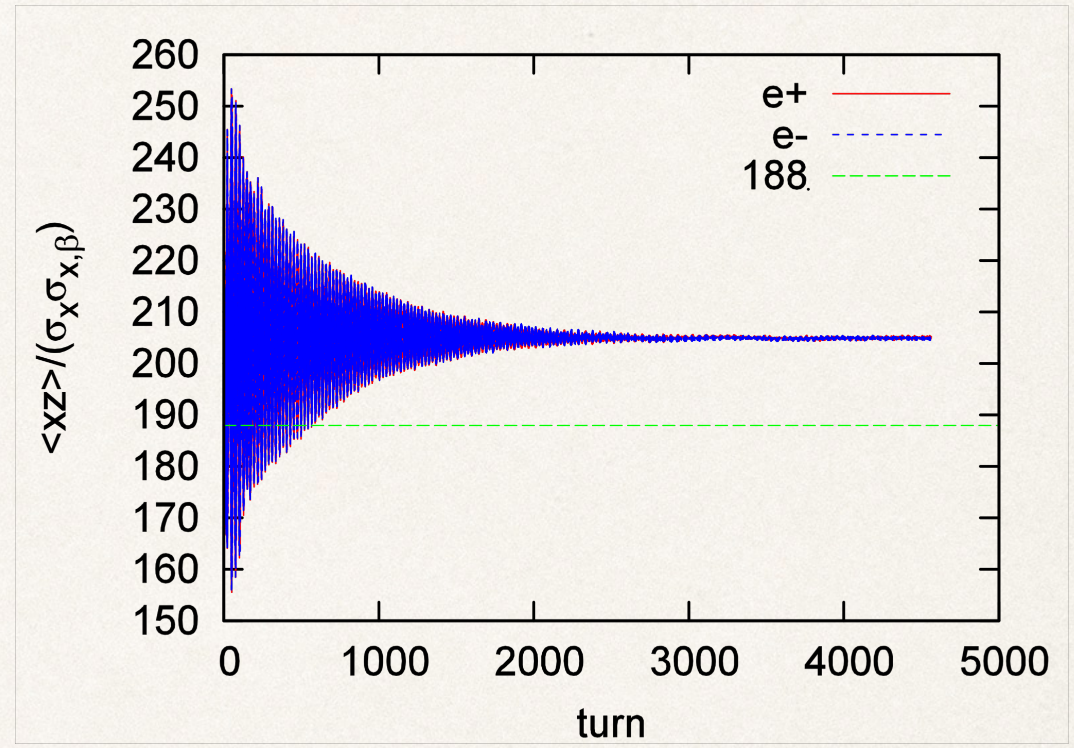
FCC-ee: 2 separate ring

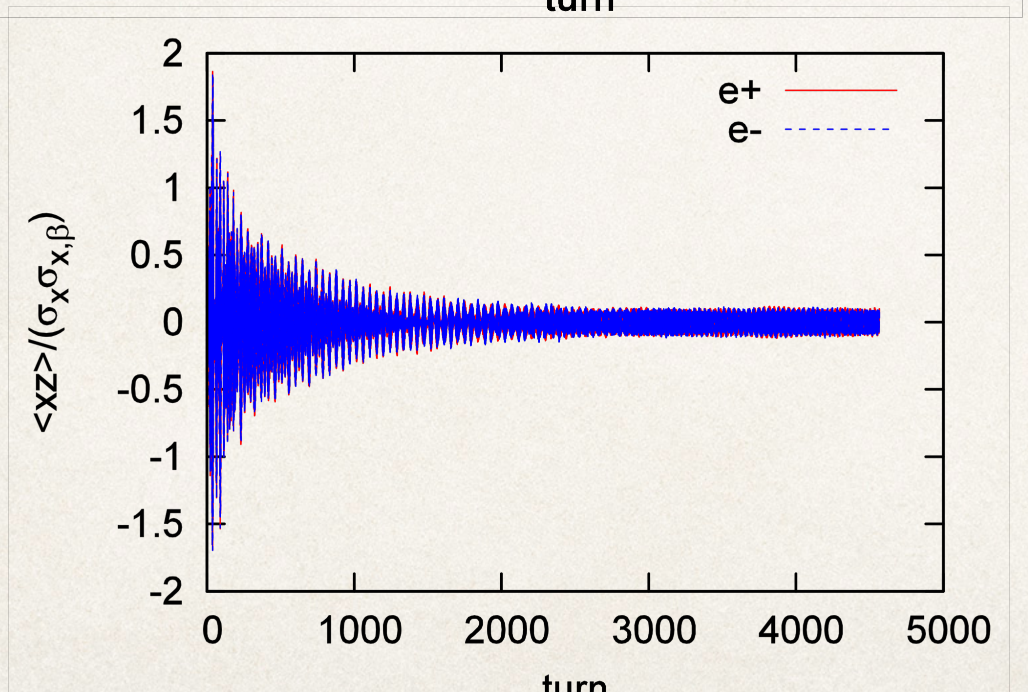
CEPC: Partial double ring (PDR), 120*: high-lumi version

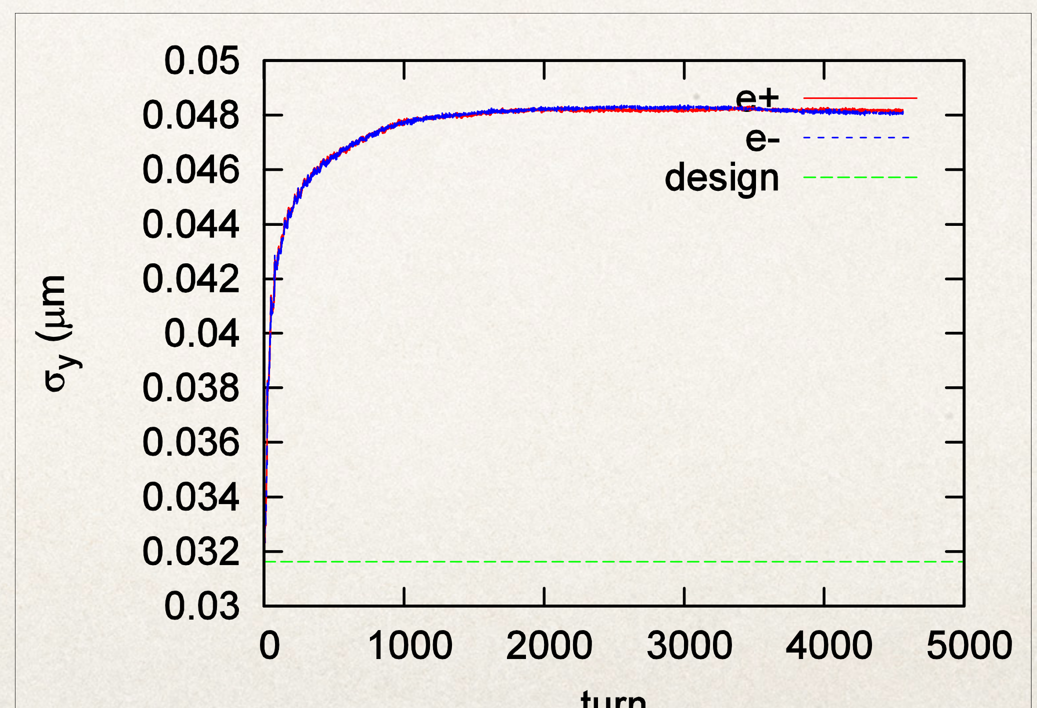
Strong-Strong beam-beam instability (FCC-ee @ Z)

- x-z coherent instability is seen in early stage and beam size blow up.
- Residual x-z motion remains.
- Luminosity is reduced to 60% of the design.









K. Ohmi

Design constraints & assumptions (FCC-ee)

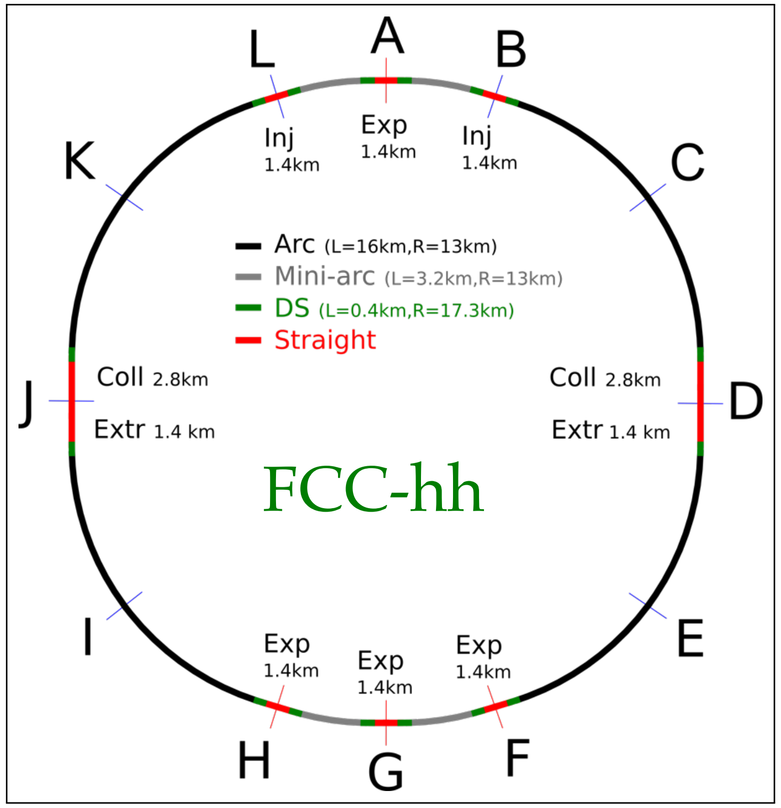
- C = 100 km, fits to the FCC-hh tunnel and footprint as much as possible.
- 2 IPs / ring.
- 30 mrad crossing angle at the IP with crab waist.
- Common lattice for all energies, except for the detector solenoid.
- $\varepsilon_x \leqq 1.3$ nm @ 175 GeV, basically scaling with energy.
- ±2% momentum acceptance at 175 GeV to hold the large energy spread caused by beamstrahlung.
- Vertical emittance less than 2.5 pm at 175 GeV before collision.
- $\beta_{x,y}^*$ = (1 m, 2 mm) at 175 GeV, (0.5 m, 1 mm) at 45.6 GeV as the baseline.
- Suppress the critical energy of the synchrotron radiation to the IP below 100 keV, up to 500 m upstream. No dipole magnets 100m upstream from the IP.
- "tapering" to cure the sawtooth at high energy.

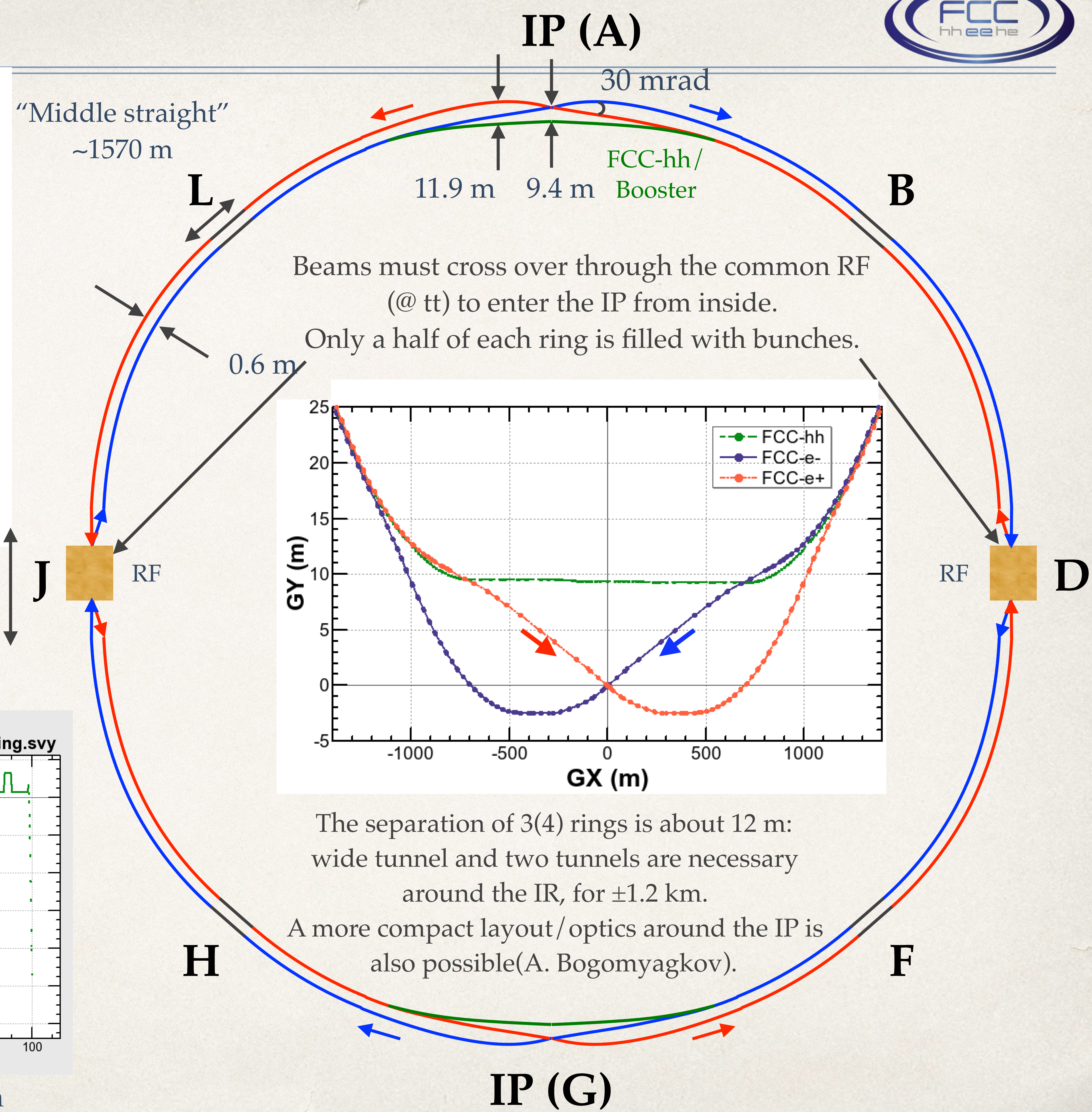
Phys. Rev. Accel. Beams 19, 111005 (2016)

Parameters

Circumference [km]	99.984	
Vending radius of arc dimple [km]	11.190	
Number of IPs / ring	2	
Crossing angle at IP [mrad]	30	
Solenoid field at the IP [T]	±2	
ℓ^* [m]	2.2	
Local chromaticity correction	y-plane with crab sextuple effect	
Arc cell	FODO, 90°/90°	
Arc sextuple families	292 (paired)	
mom. comp. [10^{-6}]	6.99	
Tunes (x/y)	387.08 / 387.14	
RF frequency [MHz]	400	
Ebeam [GeV]	**45.6**	**175**
SR energy loss per turn [GeV]	0.0346	7.47
Current / beam [mA]	1450	6.6
Bunches / ring	30180 (91500)	81
$P_{SR,tot}$ [MW]	100.3	98.6
ε_x [nm]	0.86	1.26
β^*_x [m]	0.5 (1)	1 (0.5)
β^*_y [mm]	1 (2)	2 (1)
$\sigma_{\delta,SR}$ [%]	0.038	0.141
$\sigma_{z,SR}$ [mm]	2.6 @ V_c = 88 MV	2.4 @ V_c = 9.04 GV
Synchrotron tune	-0.0163 @ V_c = 88 MV	-0.0657 @ V_c = 9.04 GV
RF bucket height [%]	2.3 @ V_c = 88 MV	11.6 @ V_c = 9.04 GV
Luminosity [10^{34}/cm^{2}s]	210 (90)	1.3 (1.5)

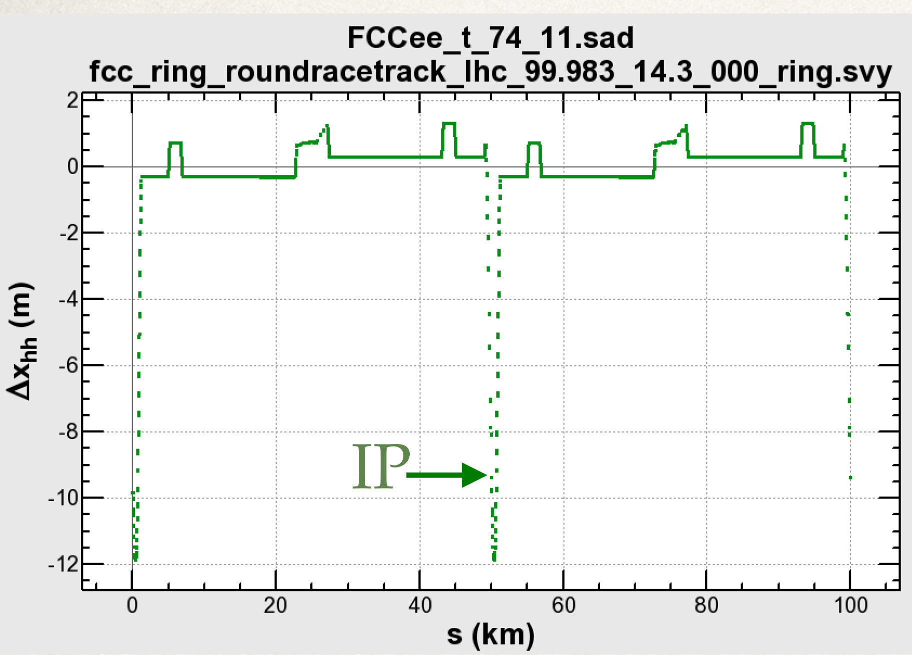
Layout of FCC-ee





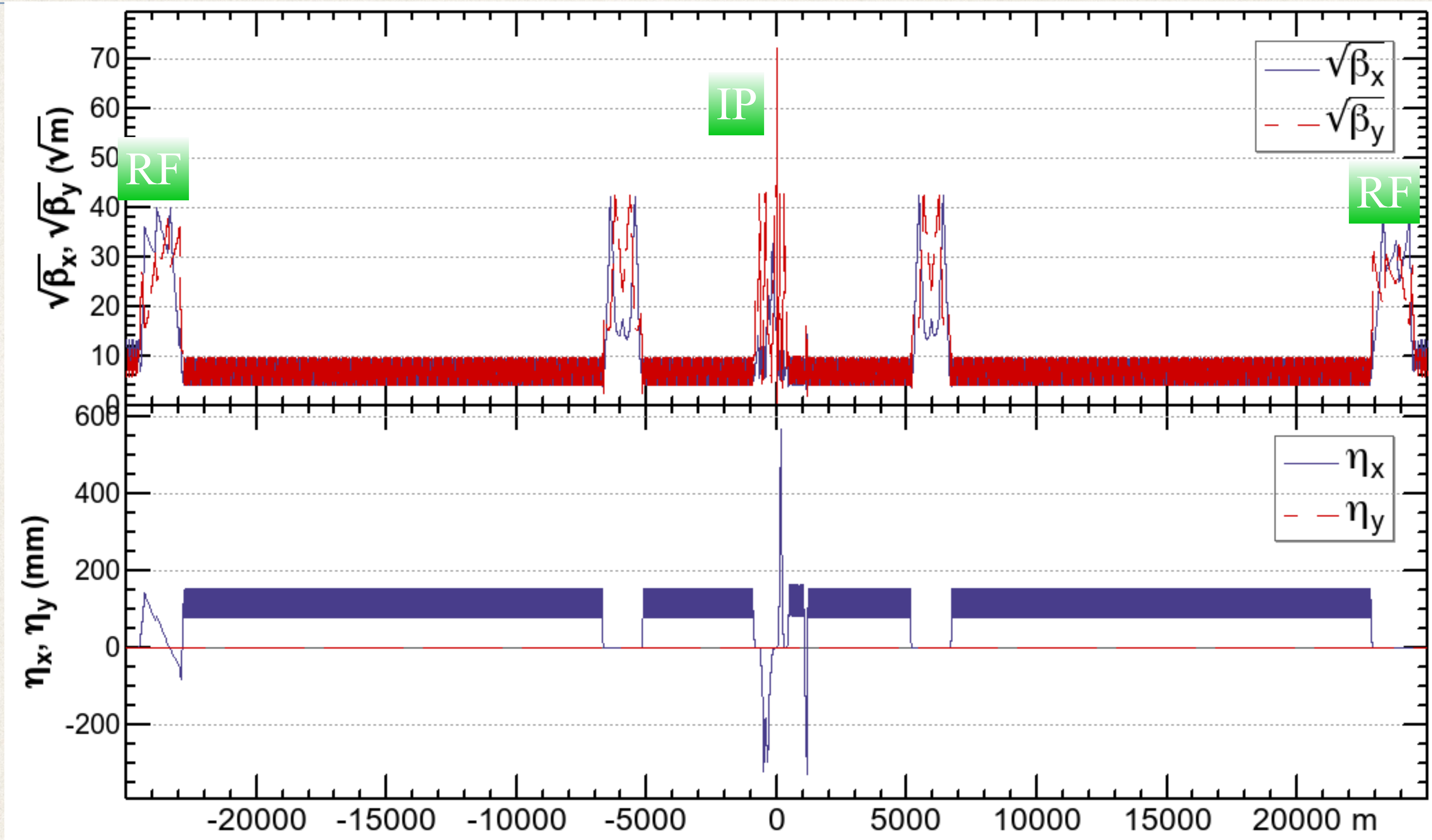
Beams must cross over through the common RF (@ tt) to enter the IP from inside.
Only a half of each ring is filled with bunches.

The separation of 3(4) rings is about 12 m: wide tunnel and two tunnels are necessary around the IR, for ±1.2 km.
A more compact layout/optics around the IP is also possible(A. Bogomyagkov).



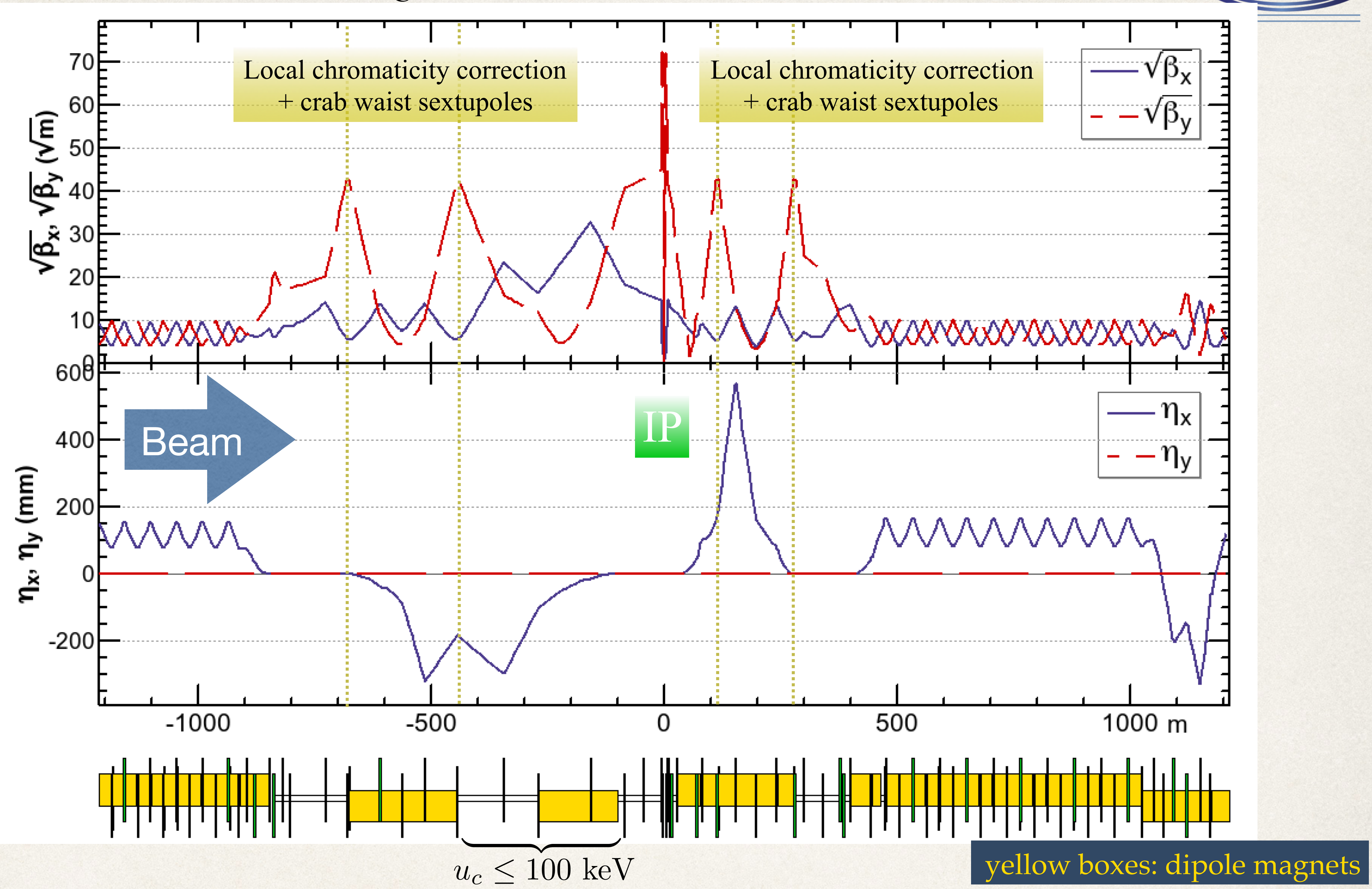
Relative distance to FCC-hh

Half Ring Optics



- Above are the half optics $\beta^*_{x/y}$ = 1 m / 2 mm.
- 2 IP/ring.
- The optics for straight sections except for the IR are tentative, to be customized for infection/extraction/collimation/beam instumentation, etc.

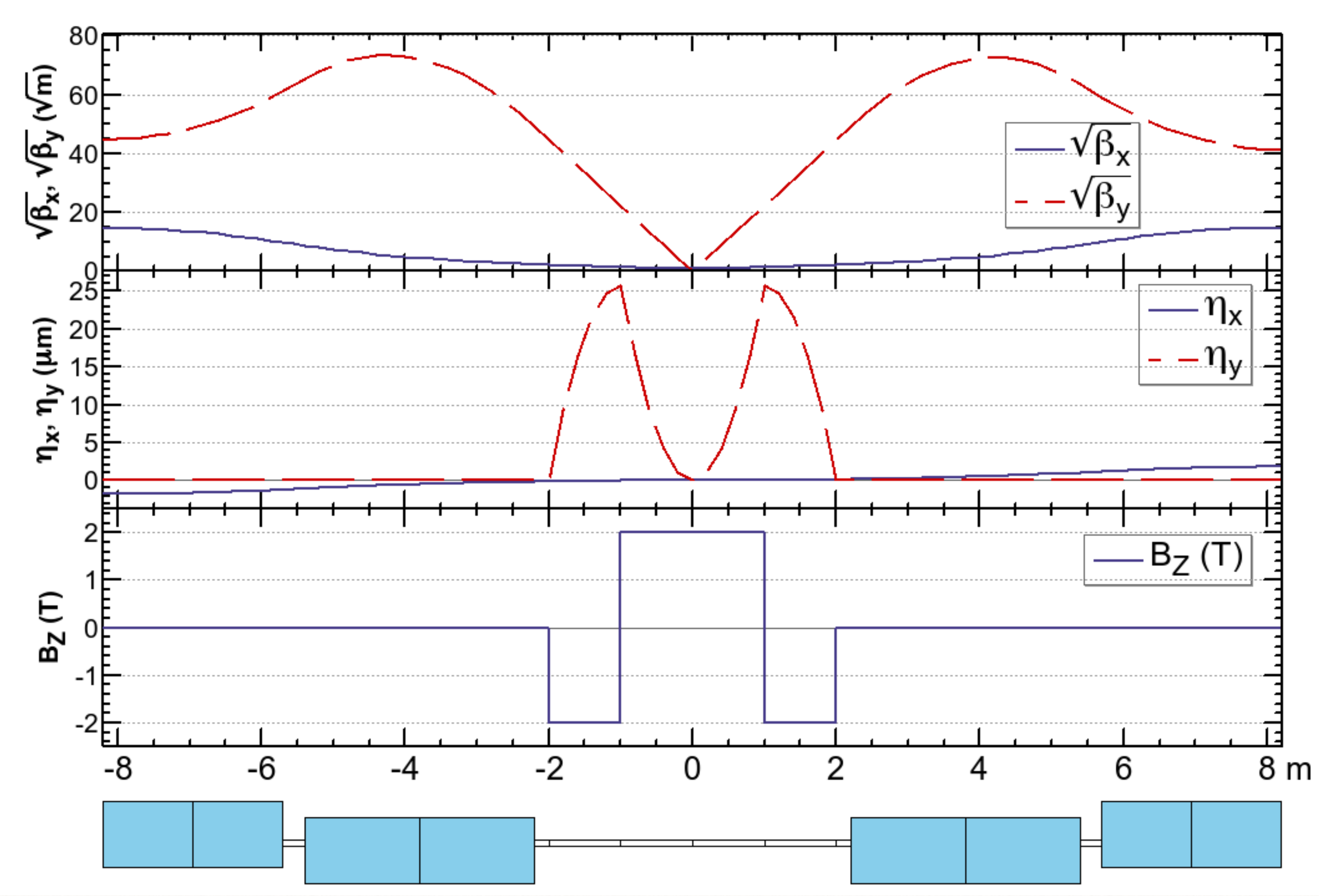
FCC-ee Interaction Region



- The optics in the interaction region are asymmetric.
- The synchrotron radiation from the upstream dipoles are below 100 keV up to 450 m from the IP.
- The crab sextuples are integrated in the local chromaticity correction system in the vertical plane.

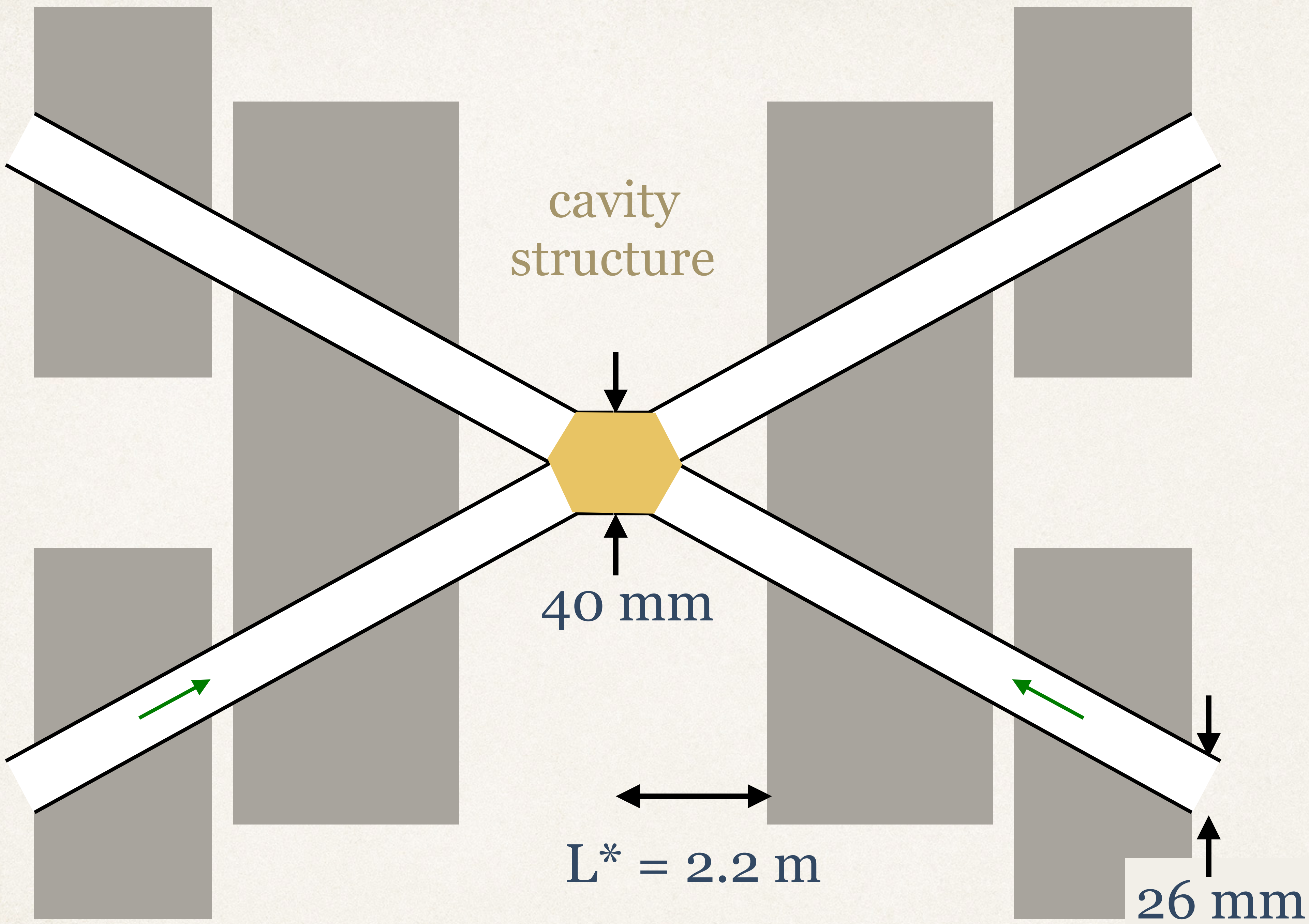
Optics at the FCC-ee IP

175 GeV, $\beta^*_{x,y}$ = (1 m, 2 mm)



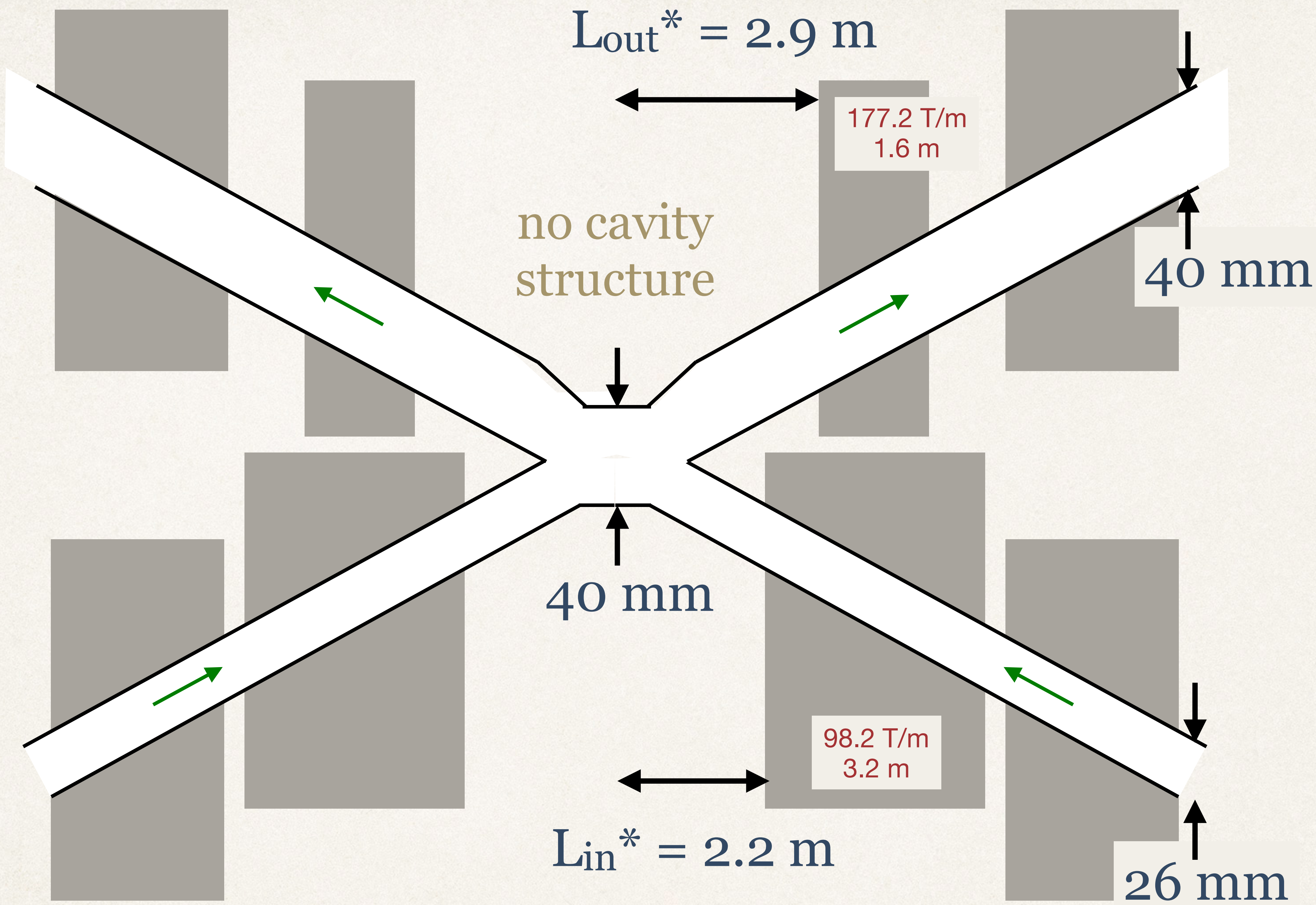
- The effect of detector solenoid field is locally compensated by counter solenoids.
- The solenoid field is shielded on the quadrupoles.
- If the compensation/shielding is perfect, their effects on the beam optics is minimal. No coupling, no vertical dispersion leak to the outside.

HOM trapping by the cavity structure at IP, FCC-ee



- HOM is trapped in the IP beam pipe, if all beam pipes are narrower than the IP, which needs to be larger that 40 mm (M. Sullivan).
- Heating, esp. at Z.
- Leak of HOM to the detector, through the thin Be beam pipe at the IP.

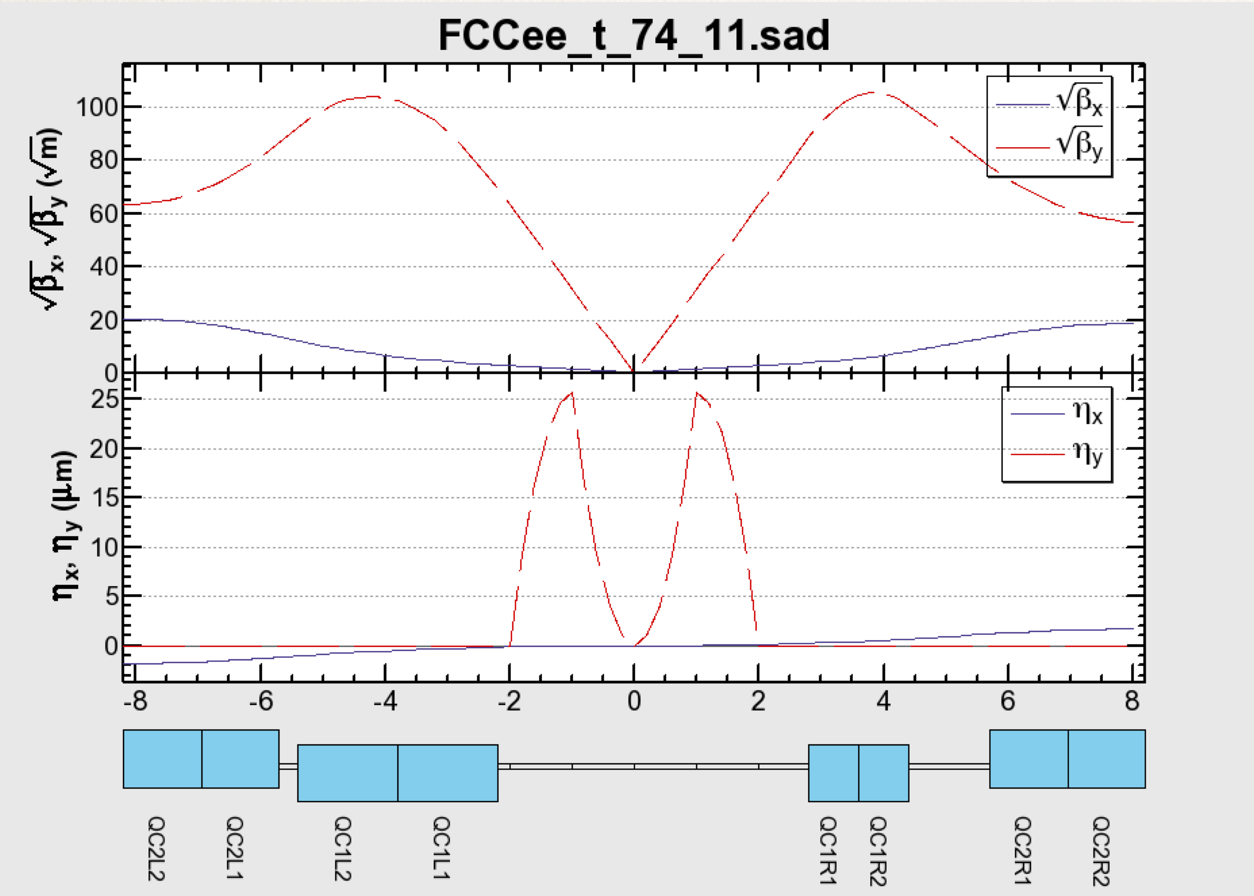
A solution: larger outgoing beam pipe & thinner final quads



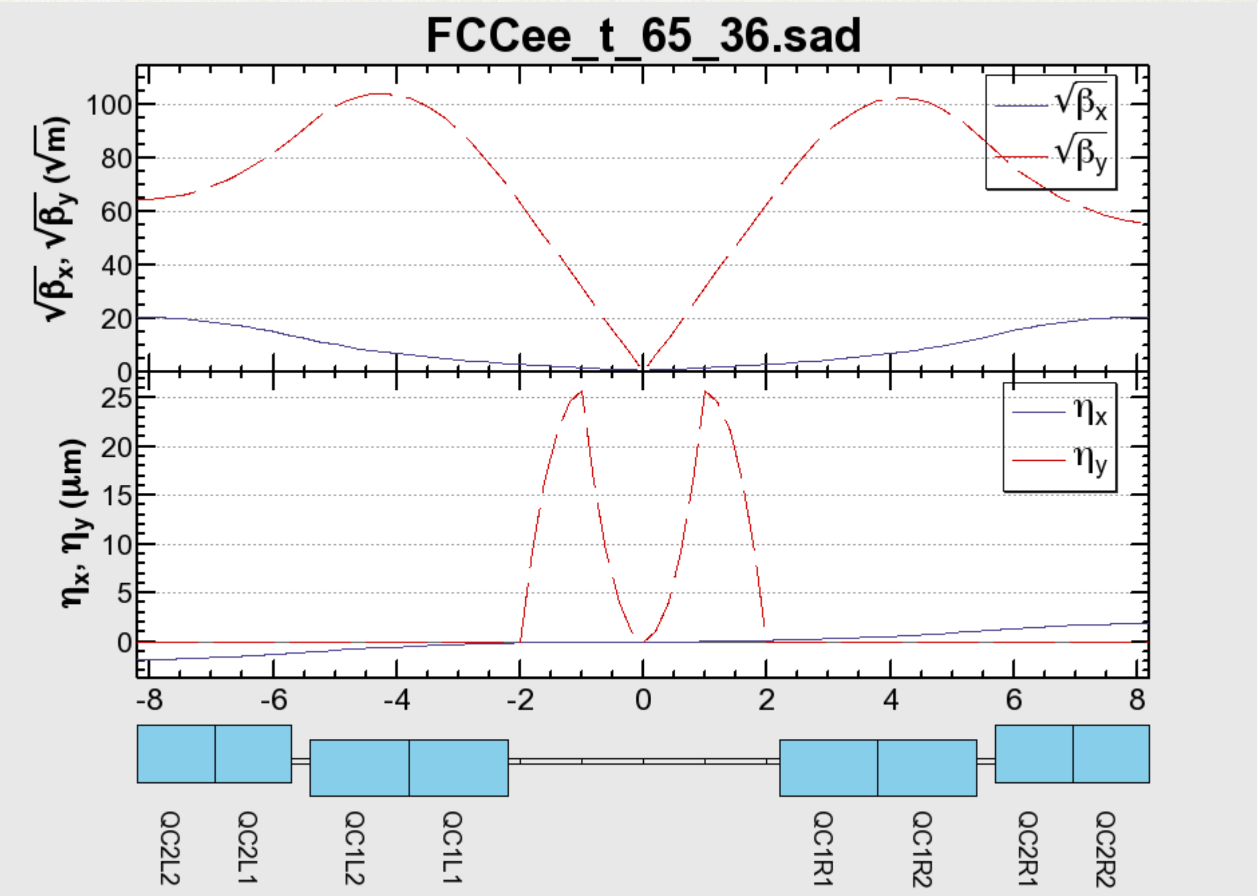
- The most of HOM can escape to the outside through the outgoing beam pipe, which has a diameter not smaller than IP.
- L* depends on the design of the final quadrupole.

Asymmetric L* at the FCC-ee IP

Asymmetric L*

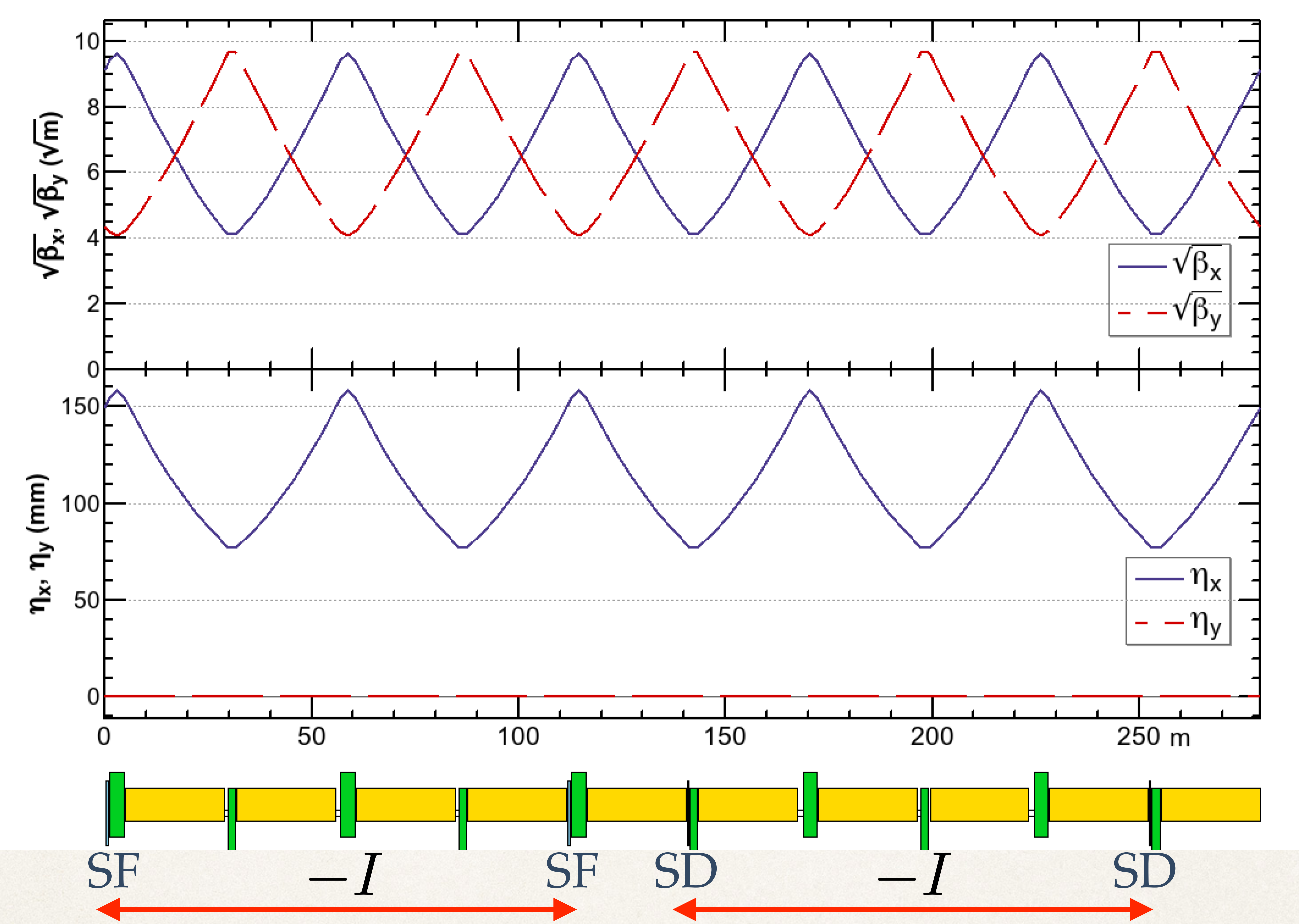


Symmetric L*



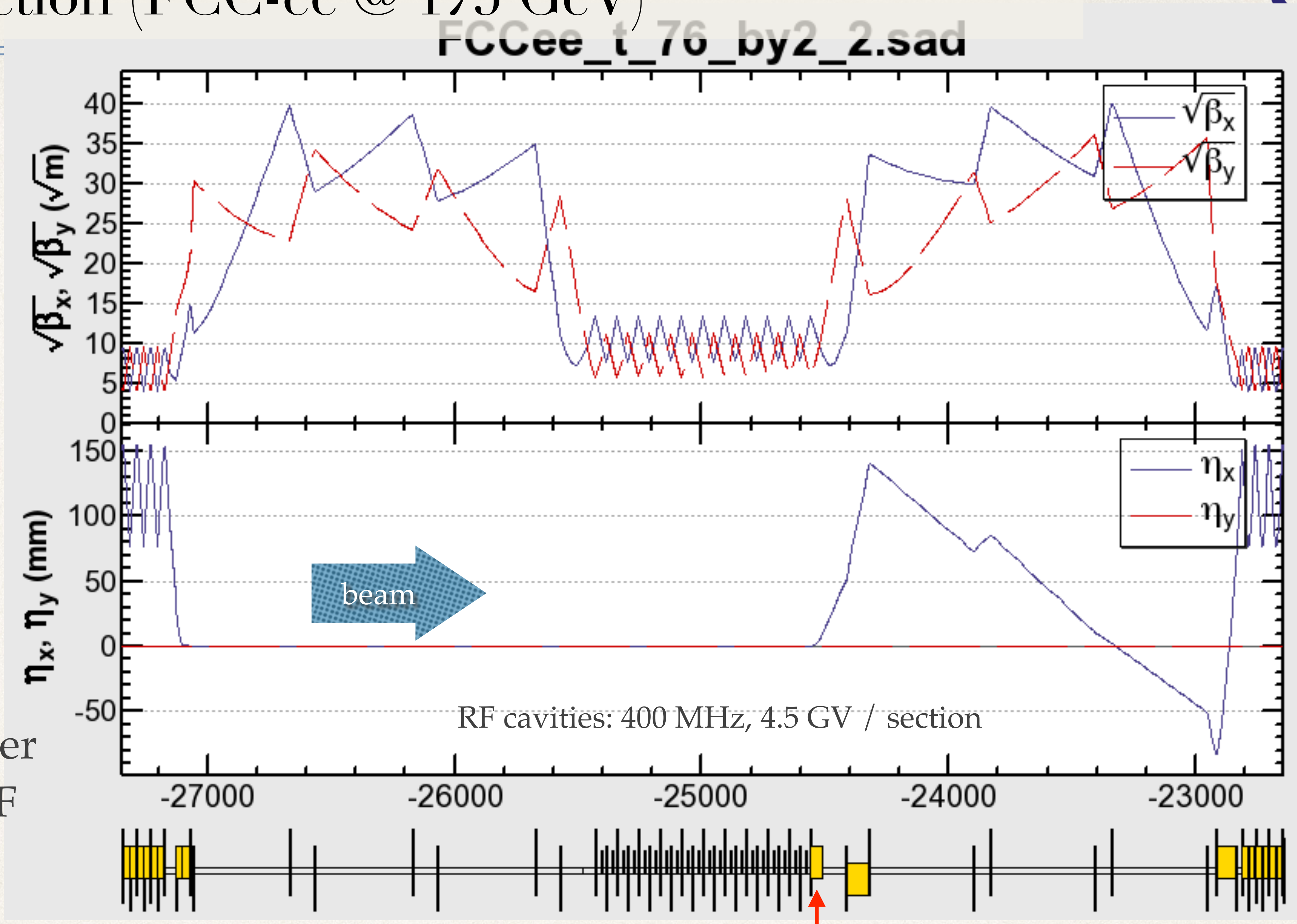
- Even with the asymmetric L*, the optics, so as the chromaticity, look similar.
- The solenoid compensation is unchanged: locally compensated up to 2.2 m from the IP.
- Longer L* downstream has no merit on the luminometer.

The Arc Cell (FCC-ee)



- Basically a 90/90 degree FODO cell.
- The quadrupoles QF/QD are 3.5 m/1.8 m long, respectively, to reduce the synchrotron radiation. They also depends on the design of quads and the beam pipe (A. Milanese, F. Zimmermann).
- All sextupoles are paired with -*I* transformation.
- 292 sextupole pairs per half ring.

The RF section (FCC-ee @ 175 GeV)



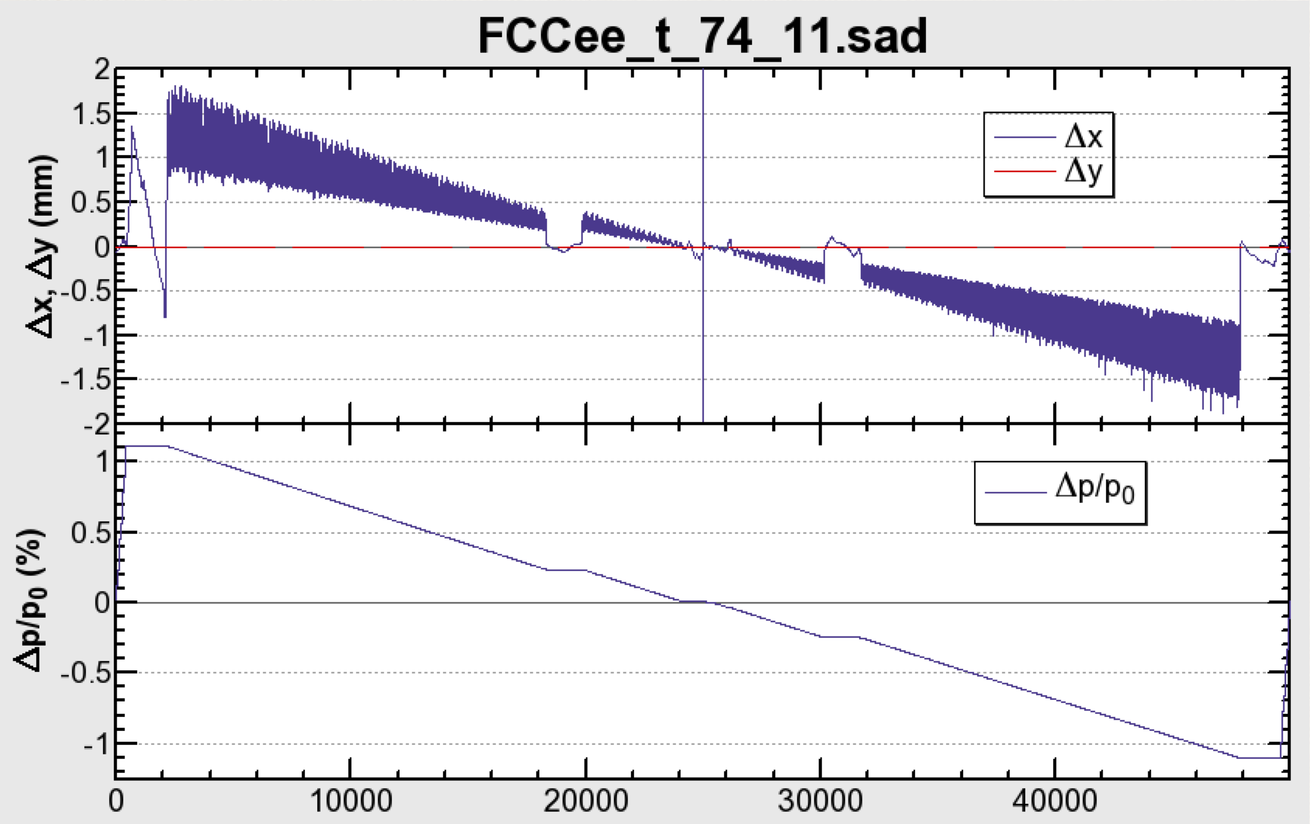
Beams cross over through the RF section.

An electrostatic separator, combined with a dipole magnet

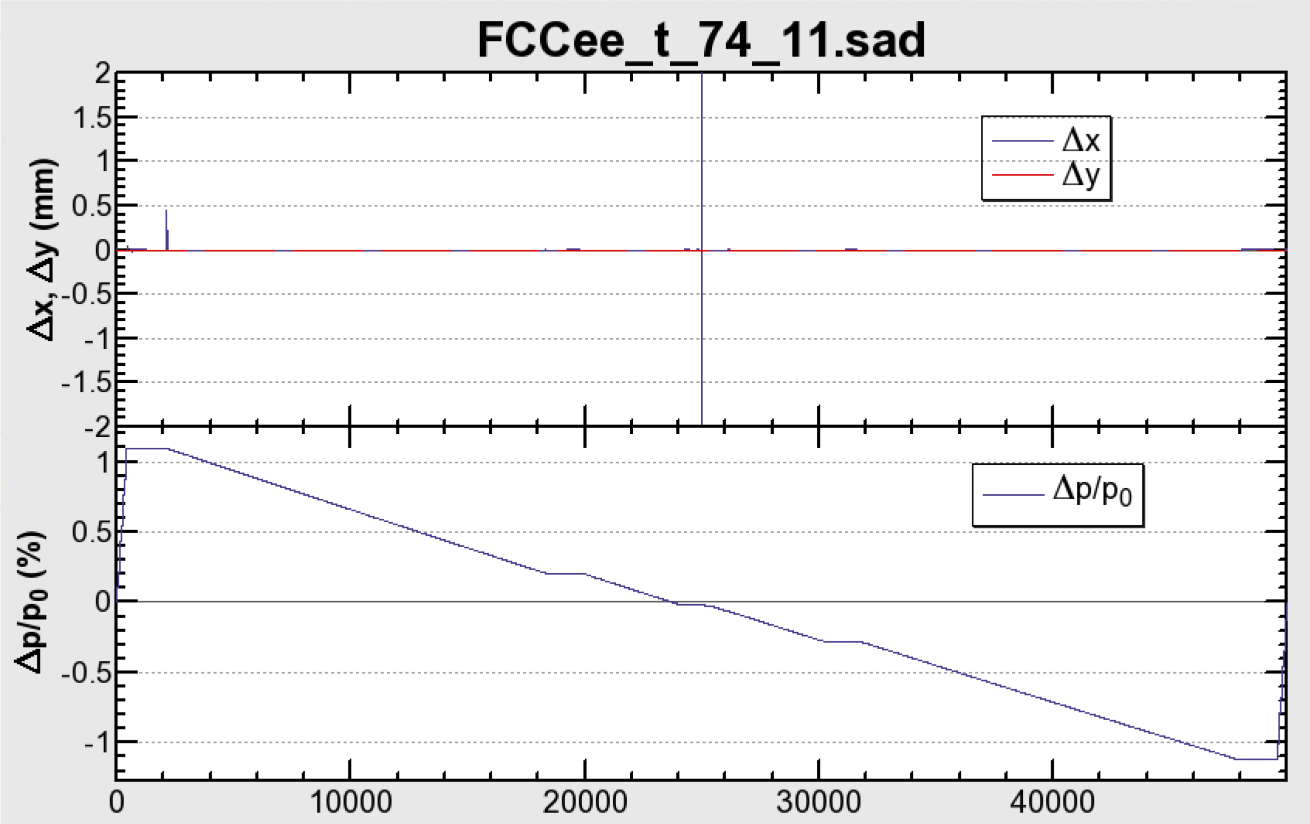
- The usage of the straights on the both sides of the RF is to be determined.
- If the nominal strengths of quads are symmetrical in the common section, it matches to the optics of both beam.
- This section is compatible with the RF staging scenario. For lower energy, the common RF and cross over will not be necessary.

The Sawtooth & Tapering (FCC-ee @ 175 GeV)

No Taper



Tapered

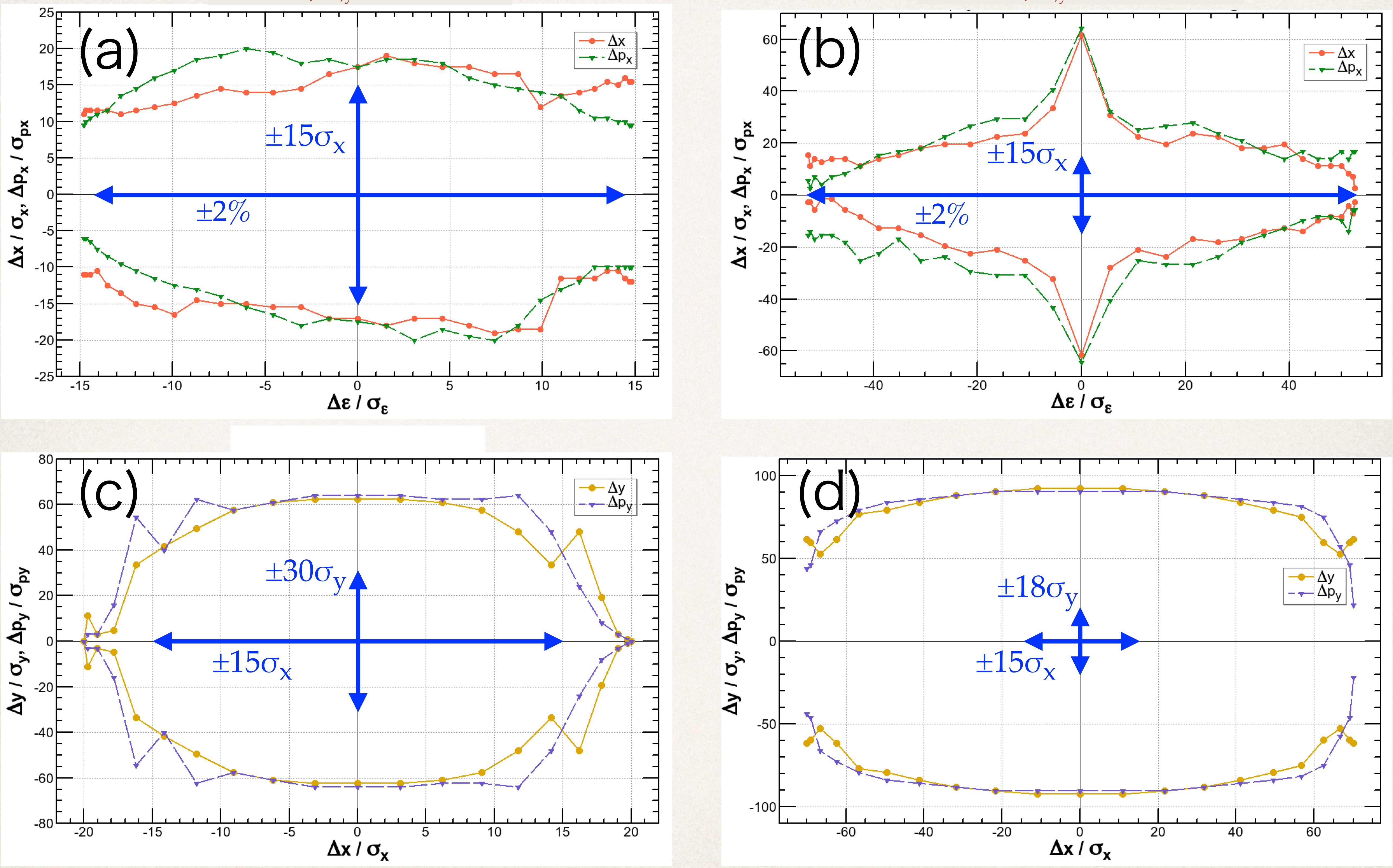


- The change of the orbit due to energy loss along the arc causes serious deformation on the optics, causing the loss of the dynamic aperture.
- Everything can be cured almost completely by "tapering", i.e. scaling the strengths of all magnets along the local energy of the beam: this is one of the best merits of a double-ring collider (F. Zimmermann).

Dynamic Aperture satisfies the requirements (FCC-ee).

175 GeV, $\beta^*_{x,y}$ = (1 m, 2 mm)

45.6 GeV, $\beta^*_{x,y}$ = (0.5 m, 1 mm)

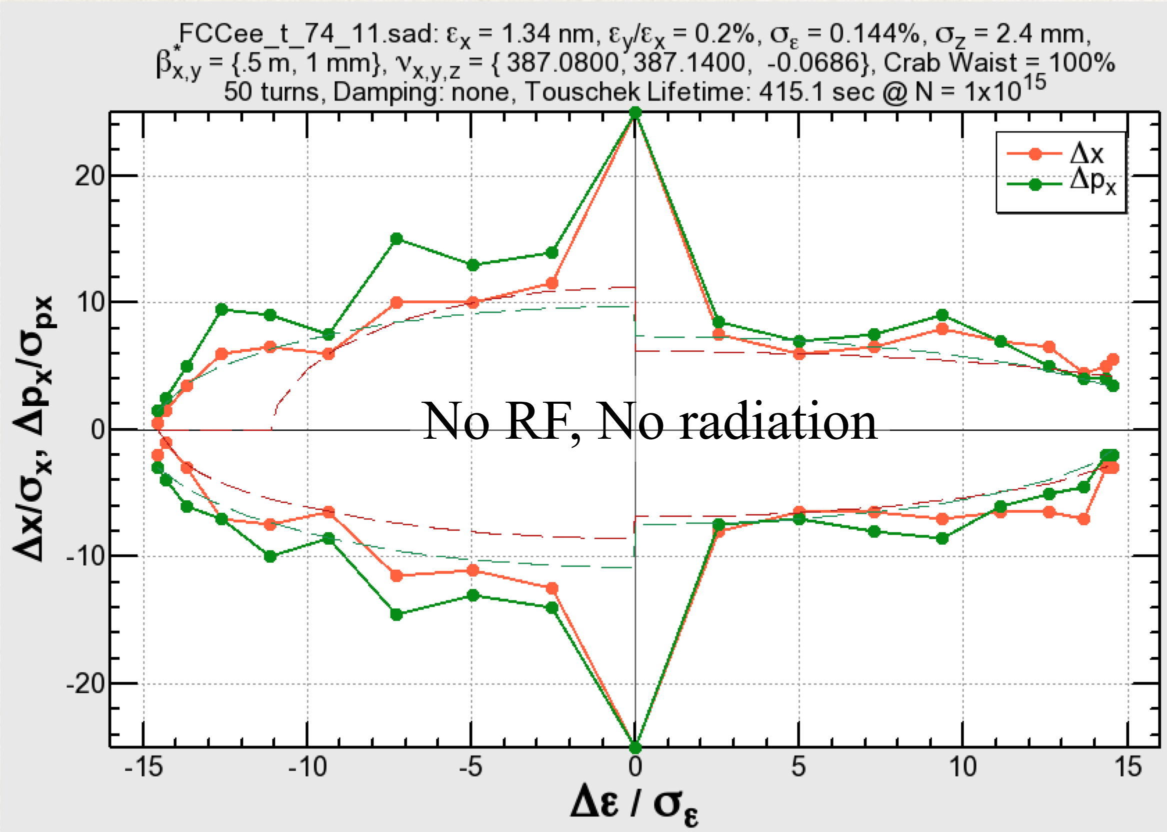


All effects in the next slide are included except for radiation fluctuation and beam-beam.
Effects by the radiation fluctuation will be shown in the later slides.

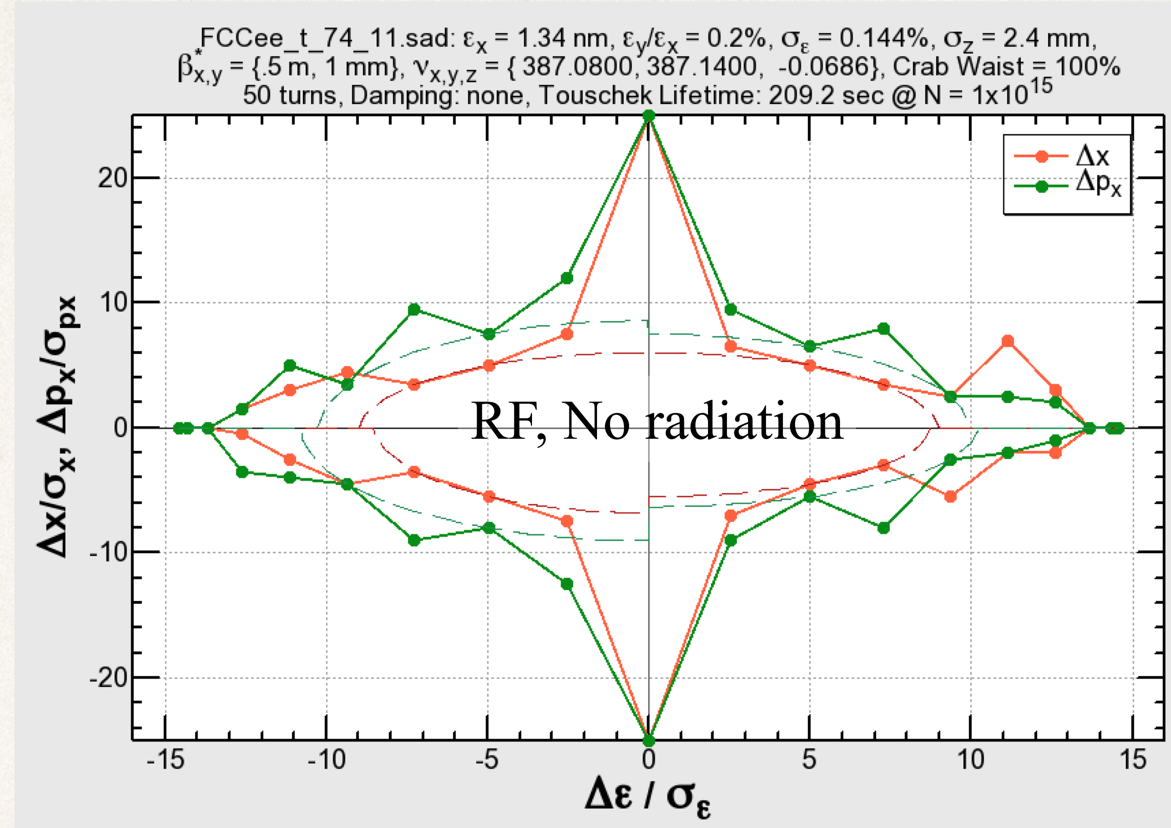
Effects included in the dynamic aperture survey

Effects	Included?	Significance at $t\bar{t}$
Synchrotron motion	Yes	**Essential**
Radiation loss in dipoles	Yes	**Essential** – improves the aperture
Radiation loss in quadrupoles	Yes	**Essential** – reduces the aperture
Radiation fluctuation	Yes	**Essential**
Tapering	Yes	**Essential**
Crab waist	Yes	transverse aperture is reduced by $\sim 20\%$
Solenoids	Yes	minimal, if locally compensated
Maxwellian fringes	Yes	small
Kinematical terms	Yes	small
Beam-beam effects (strong-weak model)	Yes (D. Zhou)	affects the lifetime for $\beta_y^* = 1$ mm
Higher order fields/errors/misalignments	No	**Essential**, development of correction/tuning scheme is necessary

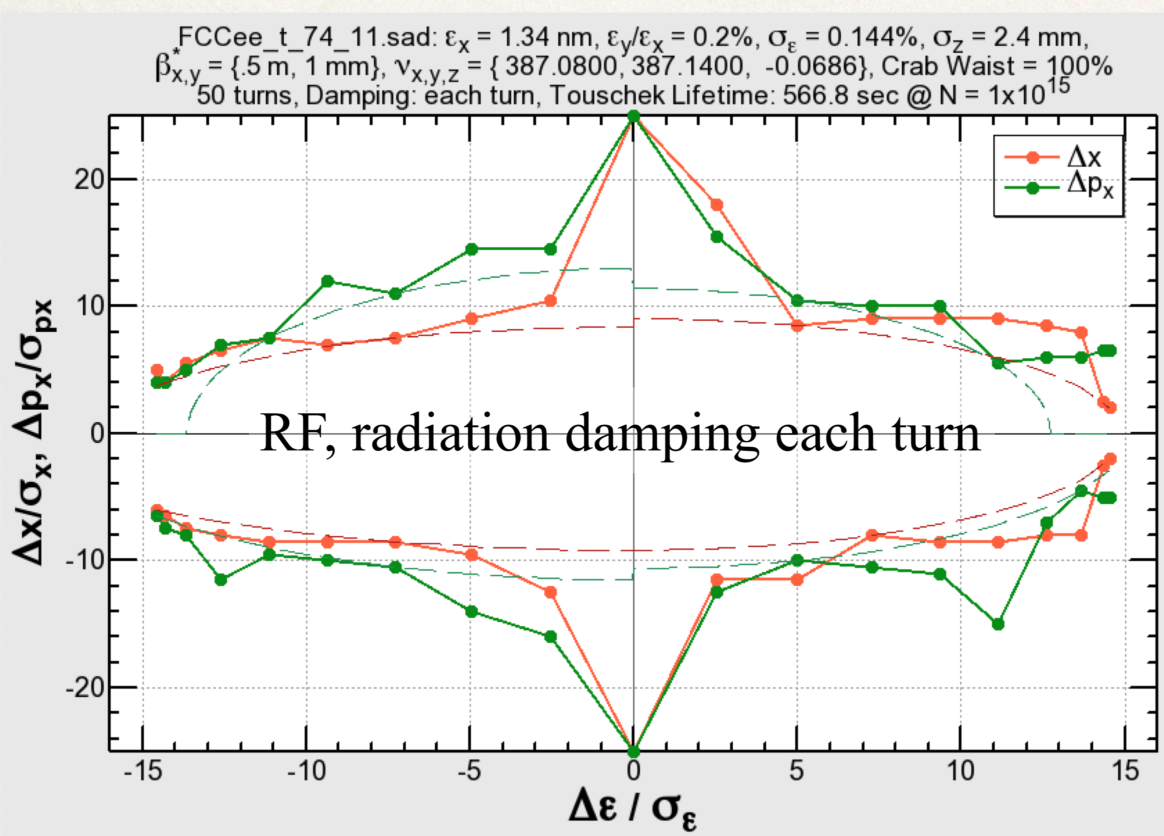
Several effects on the dynamic aperture

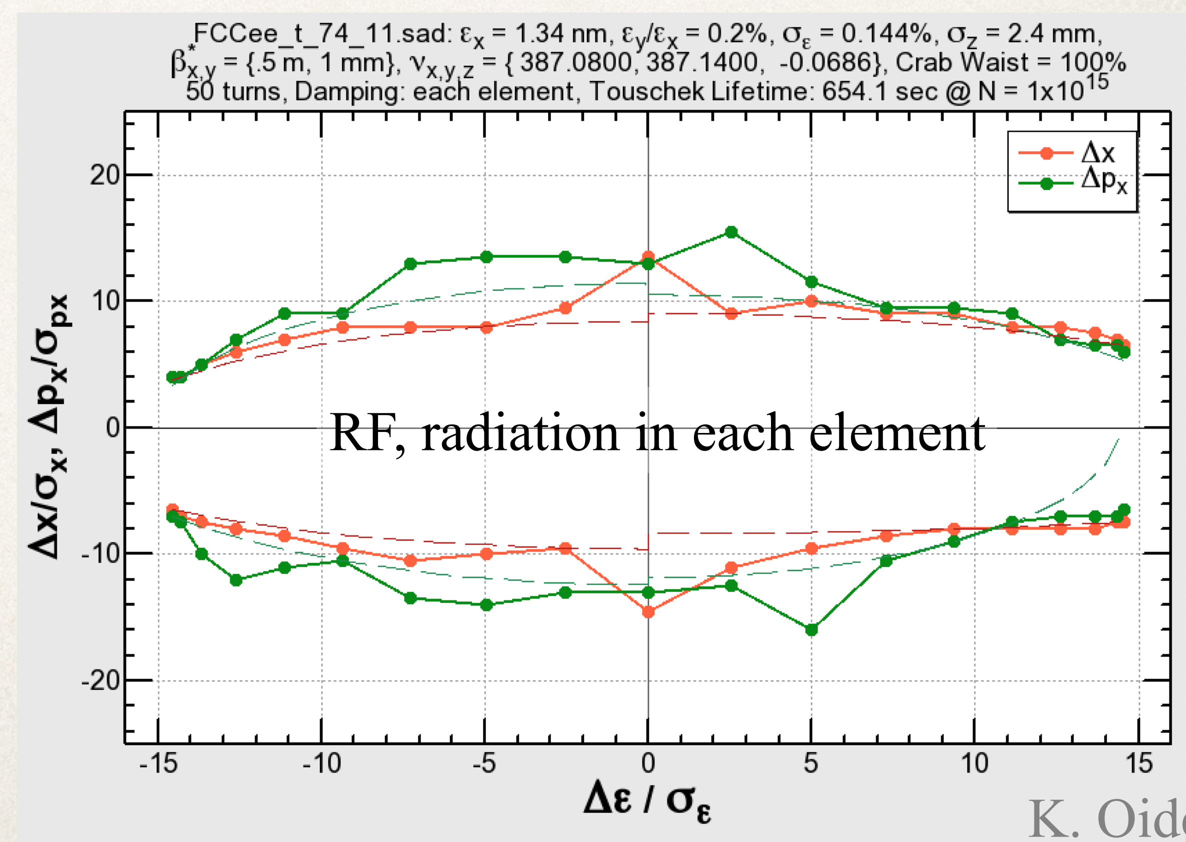


±2%



±2%





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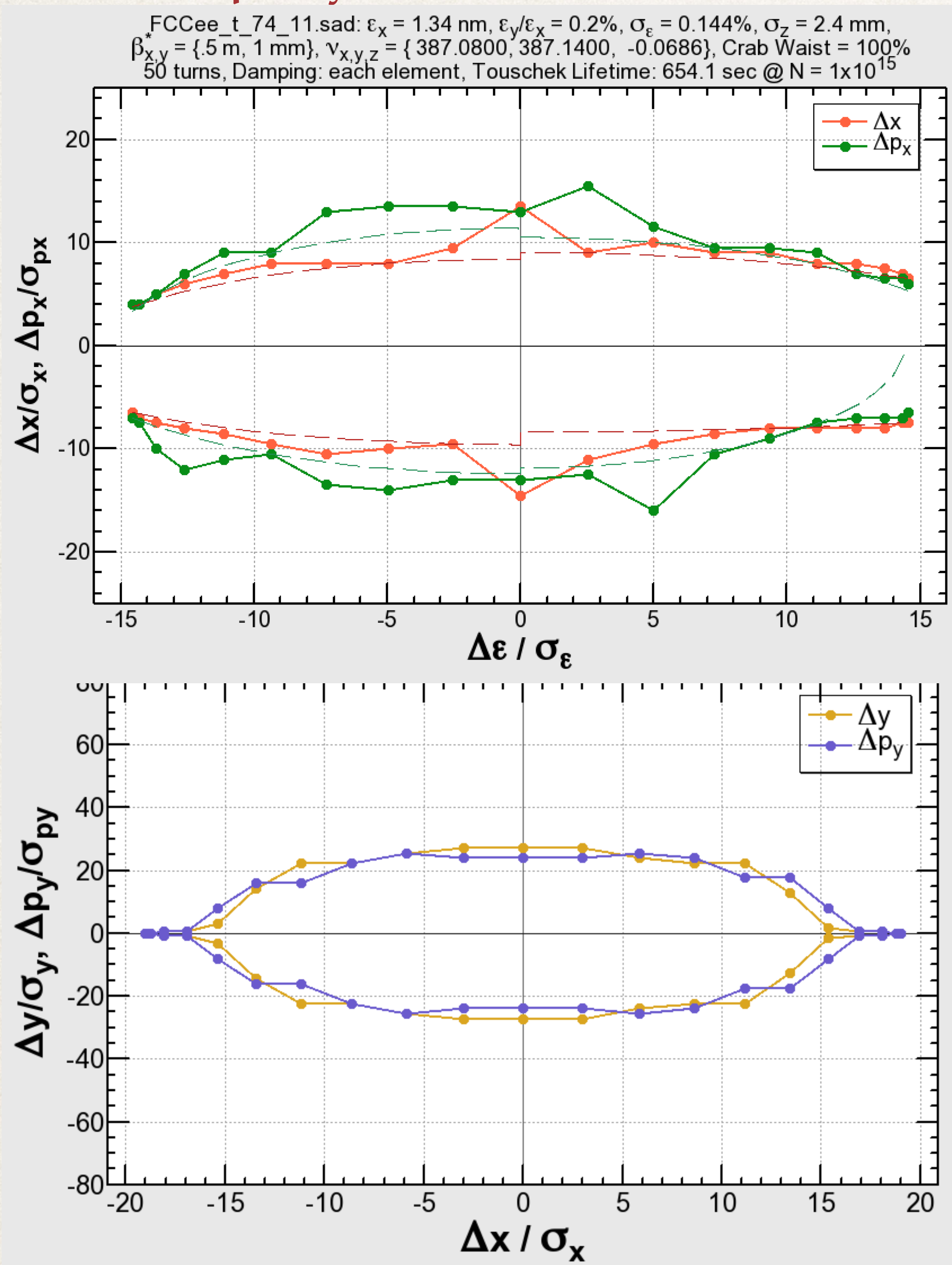
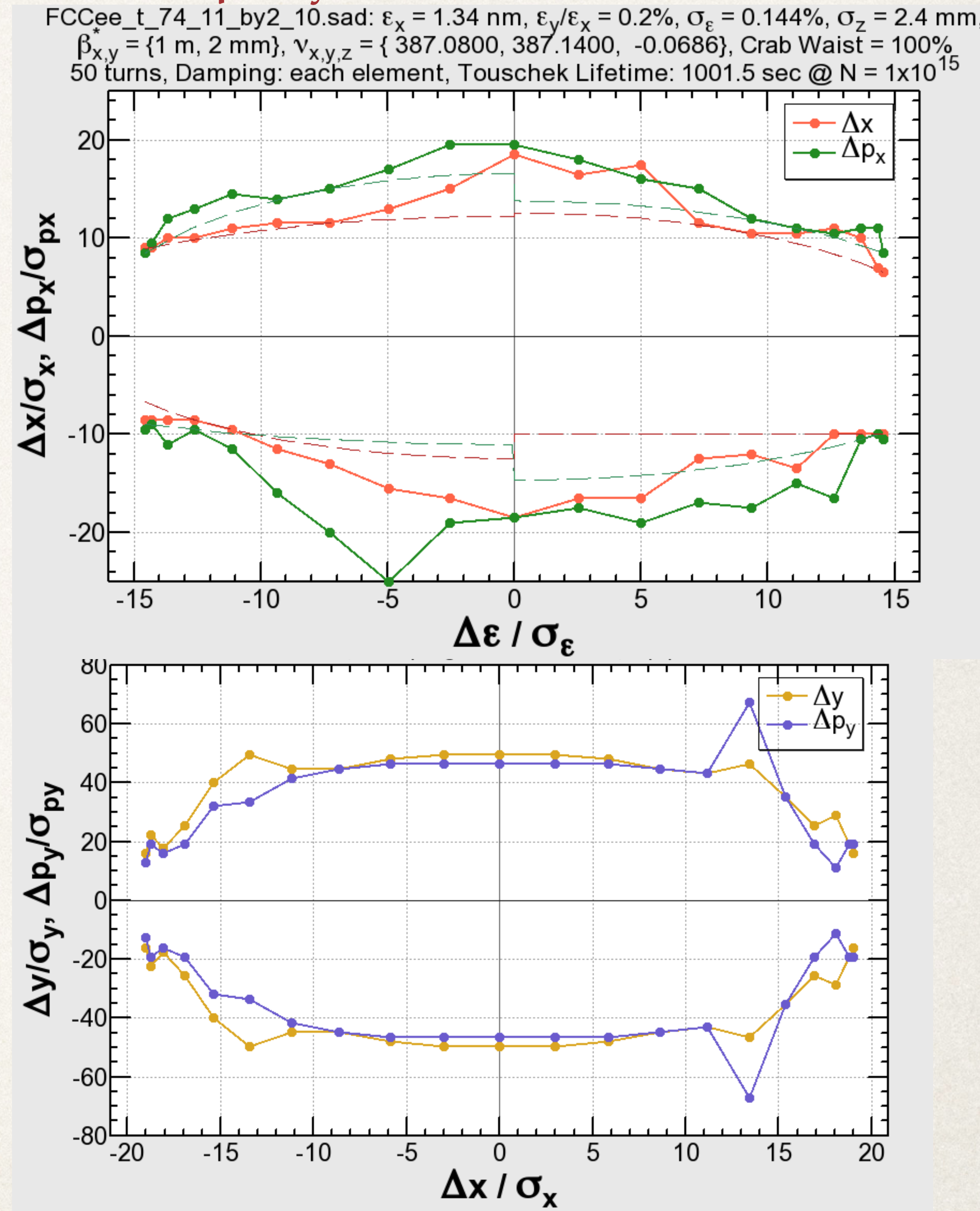
Several effects on the dynamic aperture (2)

$\beta^*_{x,y}$ = (0.5 m, 1 mm)



$\beta^*_{x,y}$ = (1 m, 2 mm)



The reduction of the vertical aperture for β^*_y = 1 mm is due to the synchrotron radiation in the final quads.

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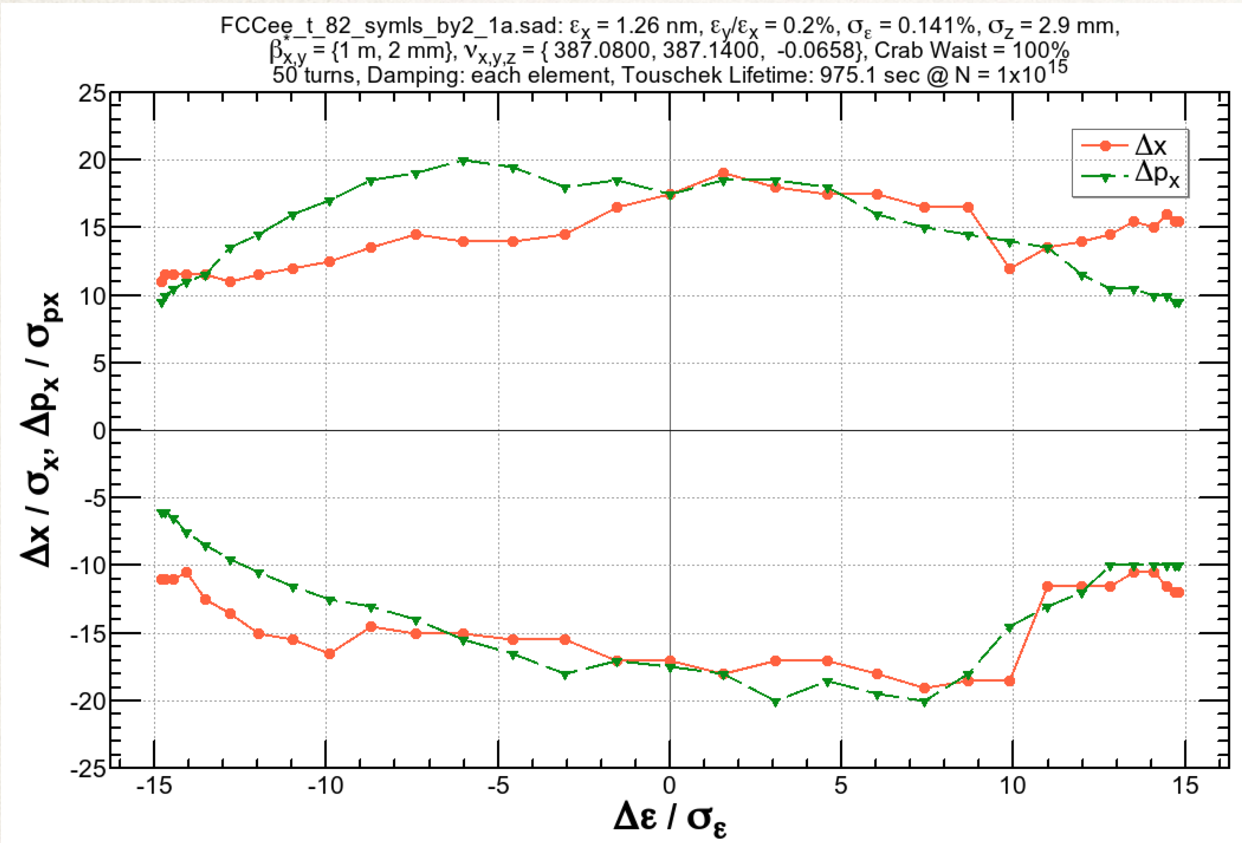
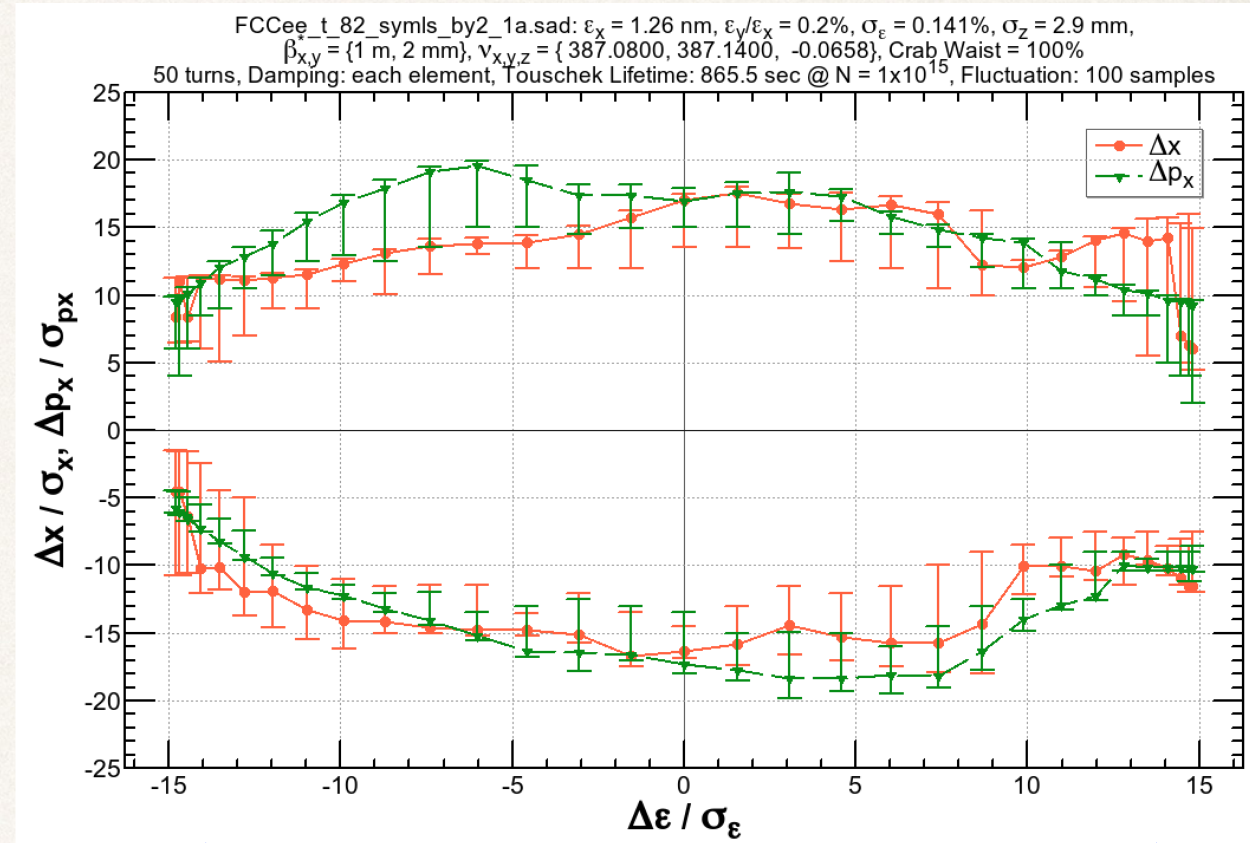
Effect of Radiation Fluctuation

E = 175 GeV, $\beta_{x,y}$ = (1 m, 2 mm)

Radiation damping only | **Radiation damping + fluctuation**





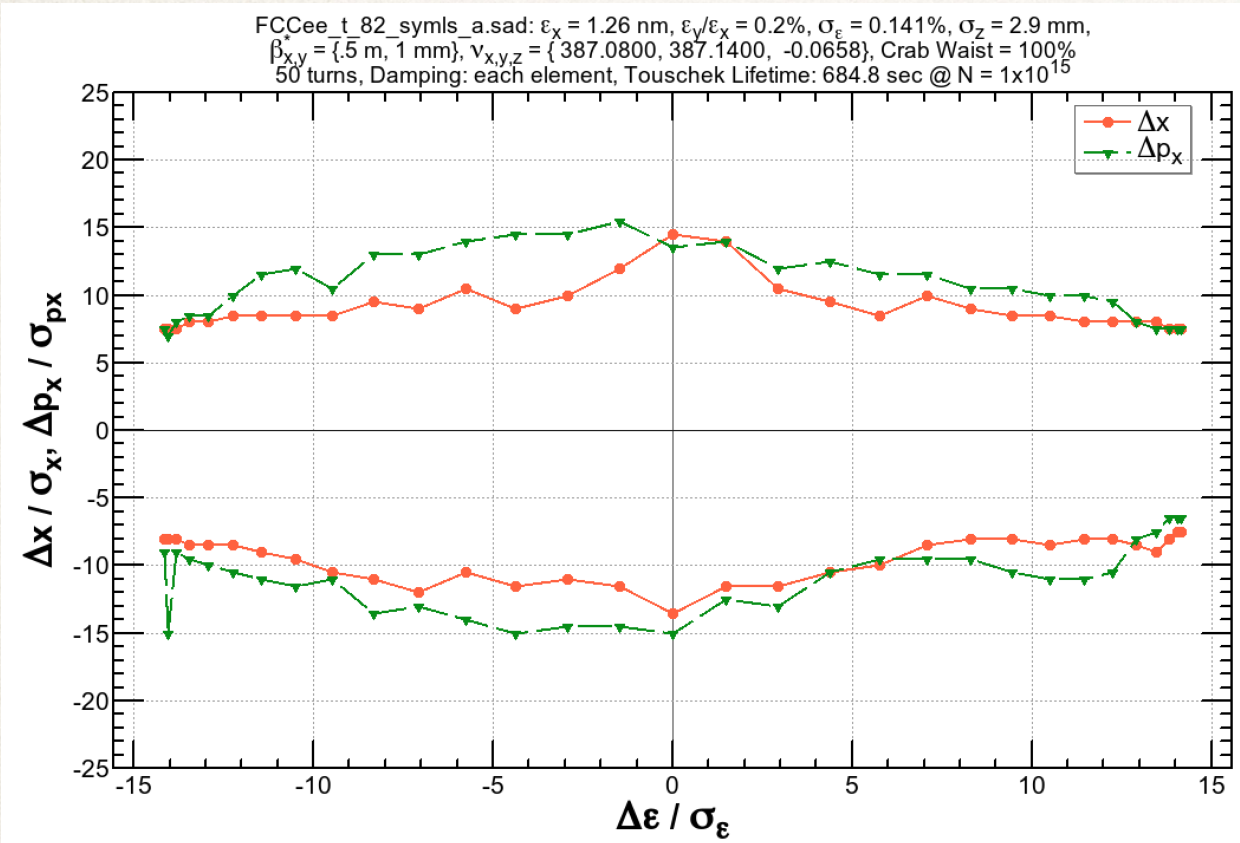
±2% | ±2%

- (Right figure) 100 samples are taken to evaluate the dynamic aperture with radiation fluctuation.
  - Within the lines: particles survive for 75% of the samples.
  - Error bars correspond to the range of survival between 50% and 100% of the samples.
- It may reasonable that the 50% loss corresponds to the original aperture.
- The thickness between 50% and 100% survival can be attributed to the fractal structure of unstable orbits or resonances in the phase space.

Effect of Radiation Fluctuation (2)

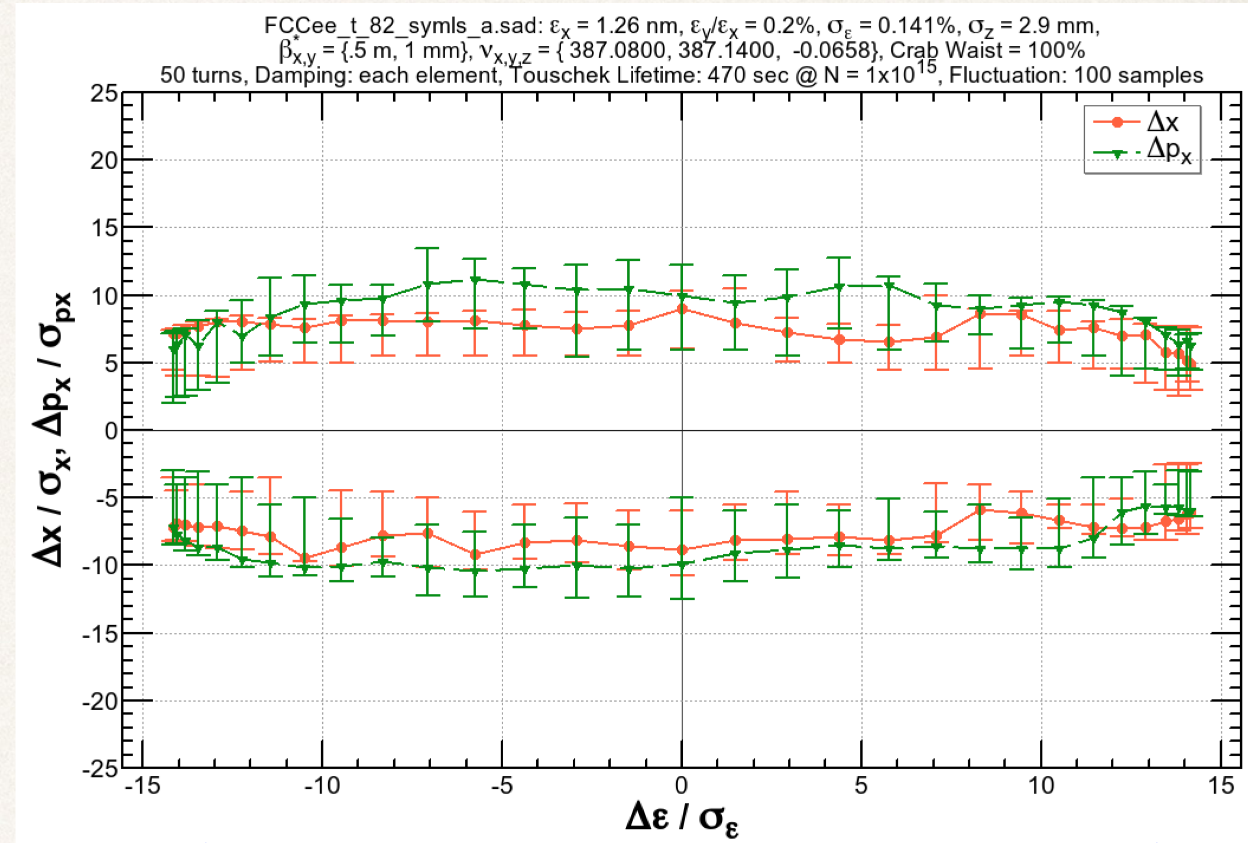
E = 175 GeV, βx,y = (0.5 m, 1 mm)

Radiation damping only



±2%

Radiation damping + fluctuation



±2%

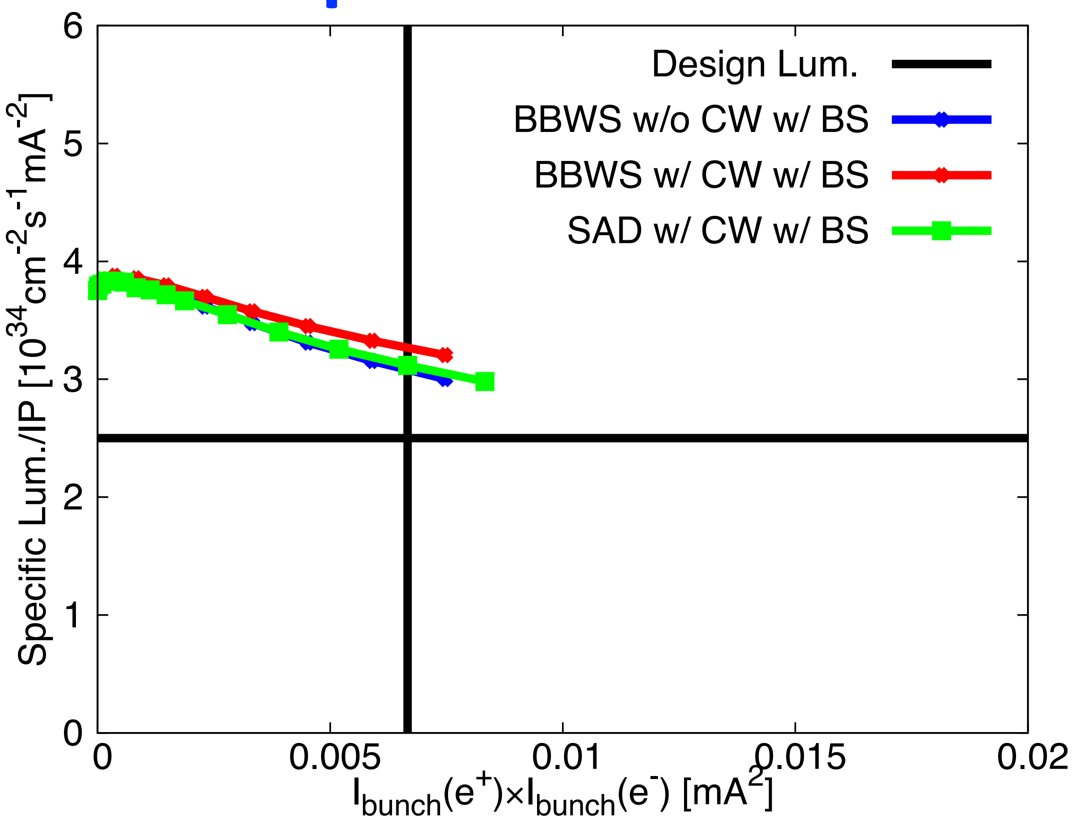
- (Right figure) 100 samples are taken to evaluate the dynamic aperture with radiation fluctuation.
    - Within the lines: particles survive for 75% of the samples.
    - Error bars correspond to the range of survival between 50% and 100% of the samples.
- The reduction of the 100% survival aperture is more significant than βx,y = (2 m, 2 mm). However, it still maintains ±2% momentum acceptance.

2. Simulations: SAD: tt_{bar}

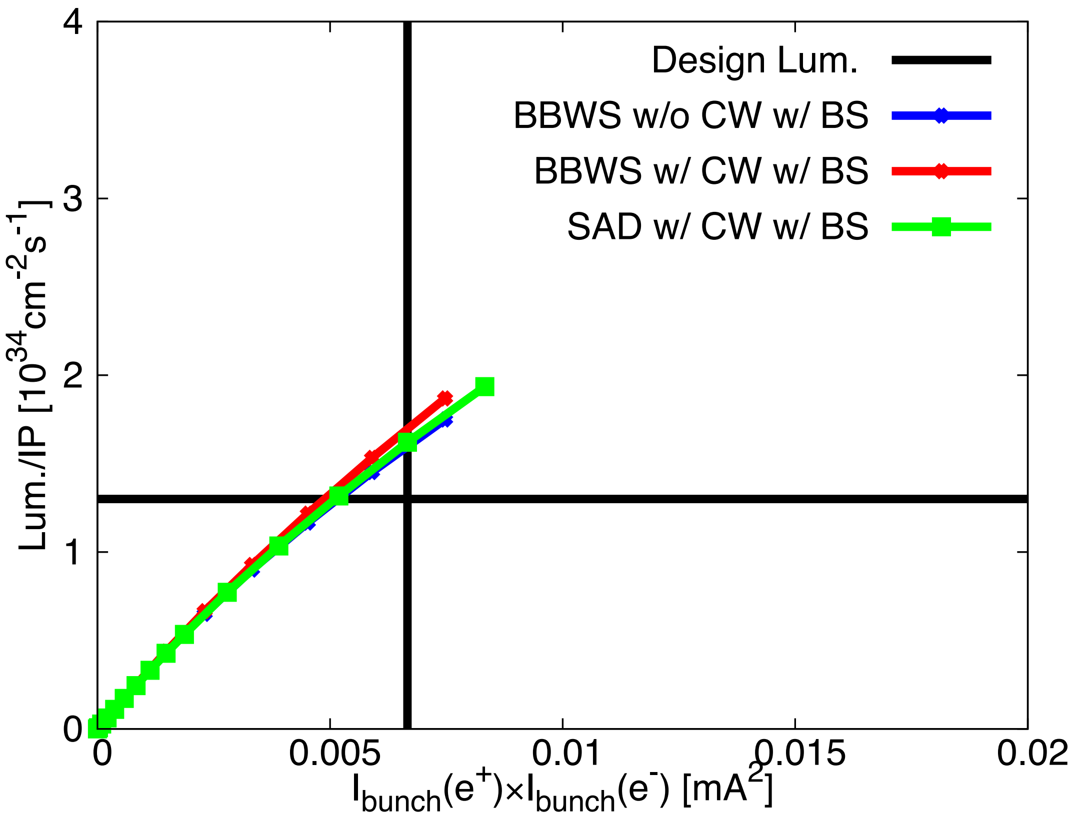
➤ **Luminosity for β_x^*=0.5m, β_y^*=1mm**

- Lattice ver. FCCee_t_65_26
- Small gain from CW
- Small loss(order of a few percents) due to BB+LN
- Allow lower beam current to achieve the same lum.

Specific lum.

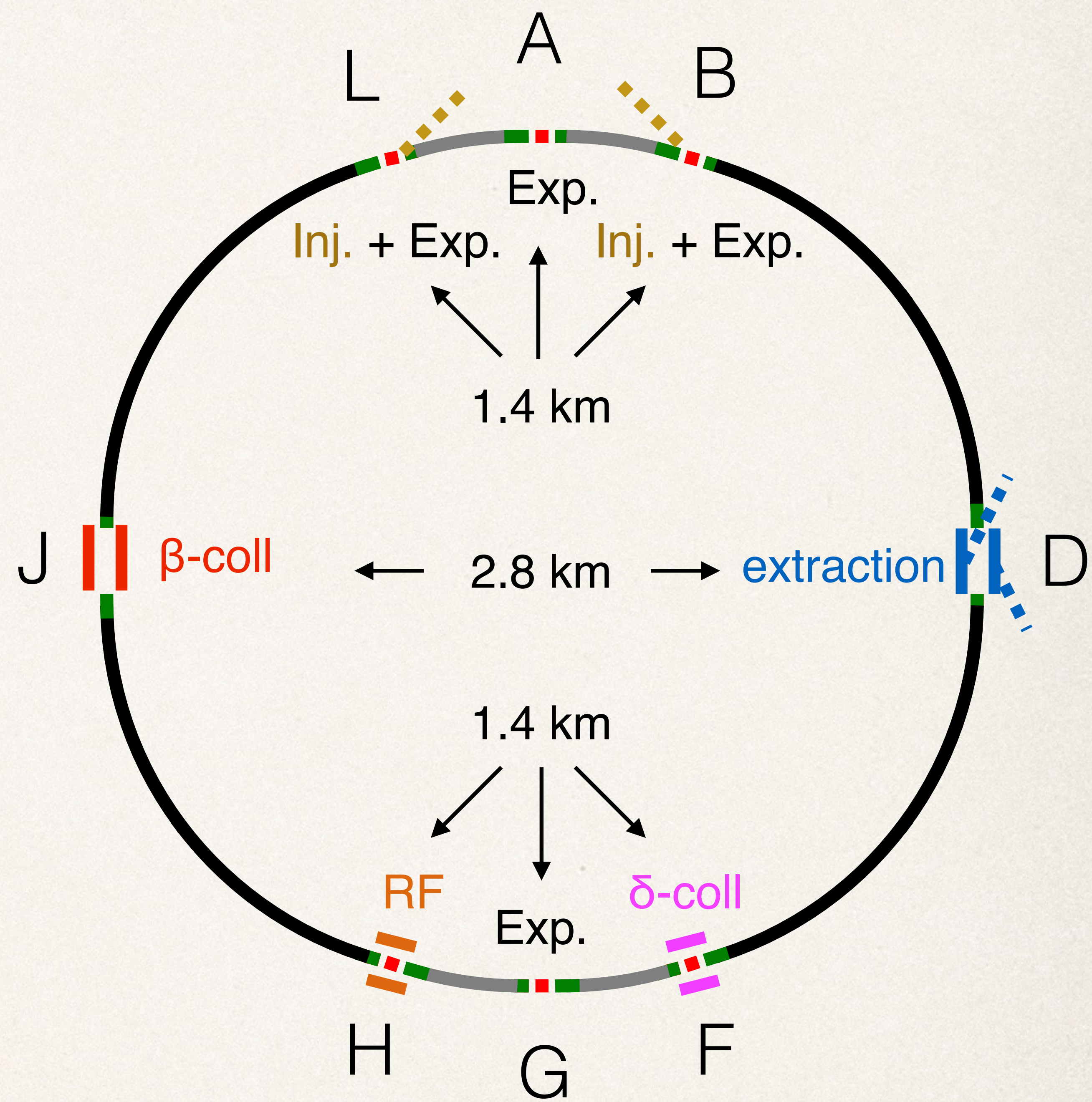


Total lum.



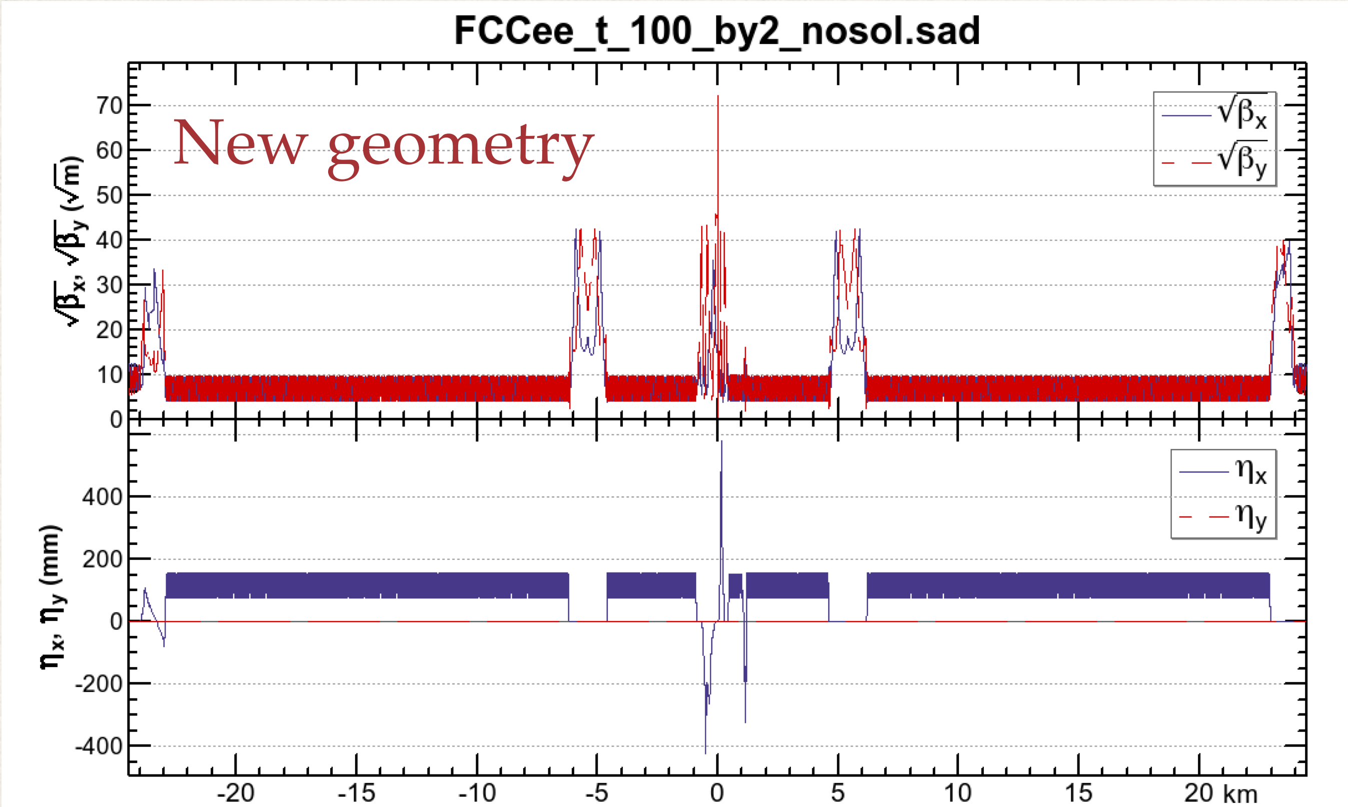
The new layout for FCC-hh

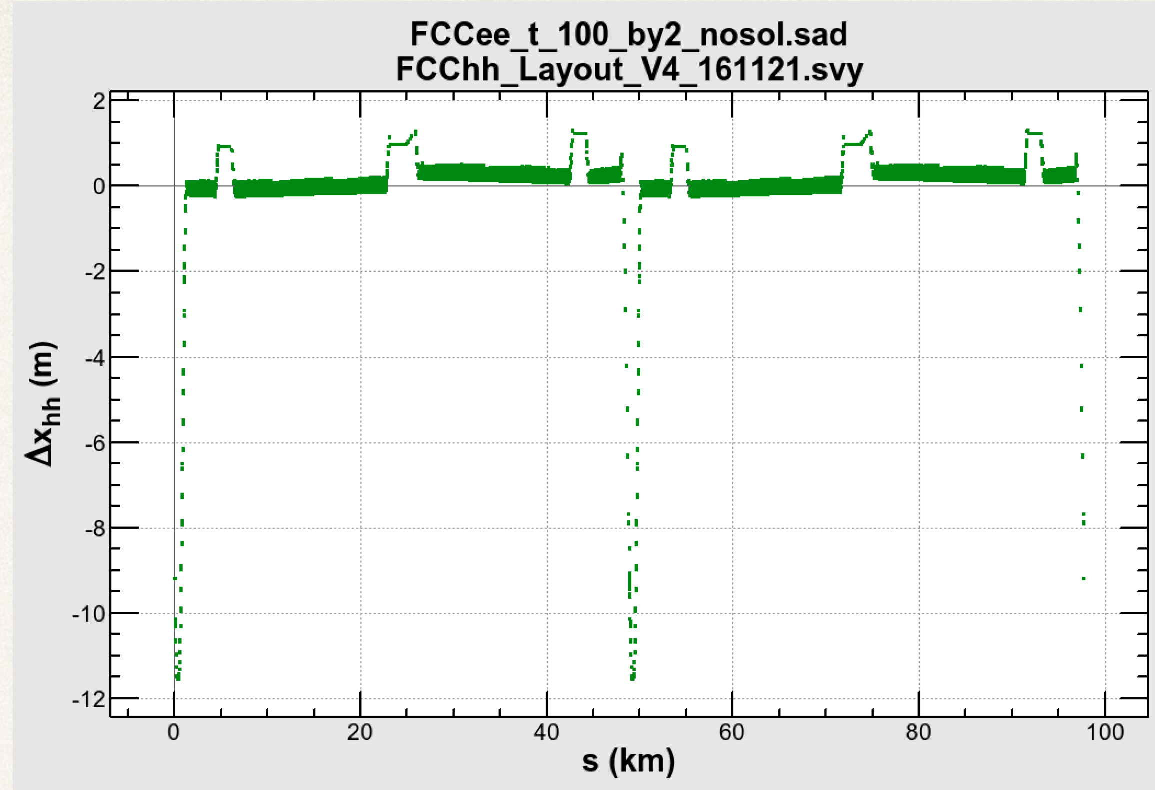
- The short straights B,L/F,H came closer to the IP A/G by about 550 m.
- The length of straights D and J becomes shorter by about 1.4 km each.
- The circumference: FCC-hh: 97.75 km = 11/3 of LHC. FCC-ee (this design): 97.747 km
- The average radius of curvature was nearly unchanged.
- The usage for each straight sections are changed as in the figure.

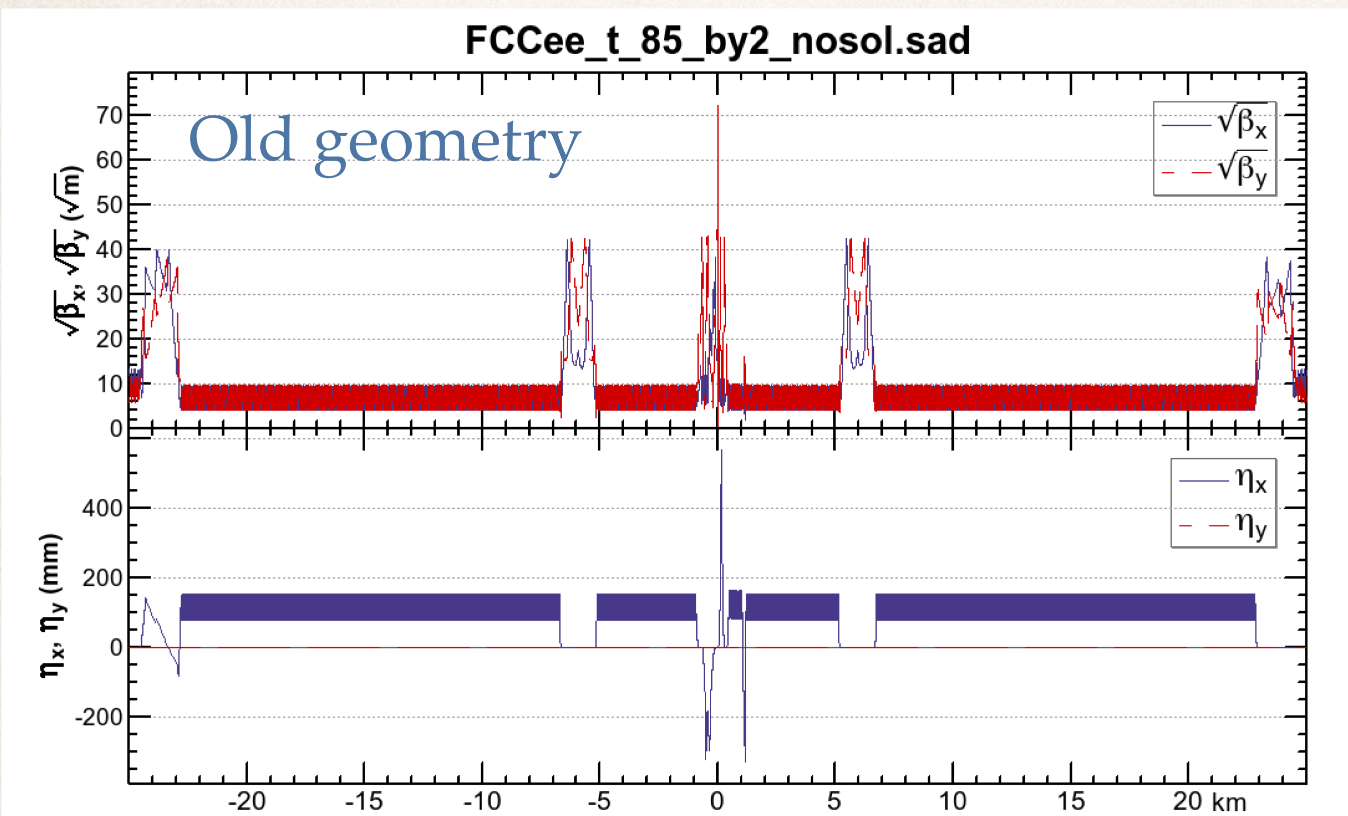


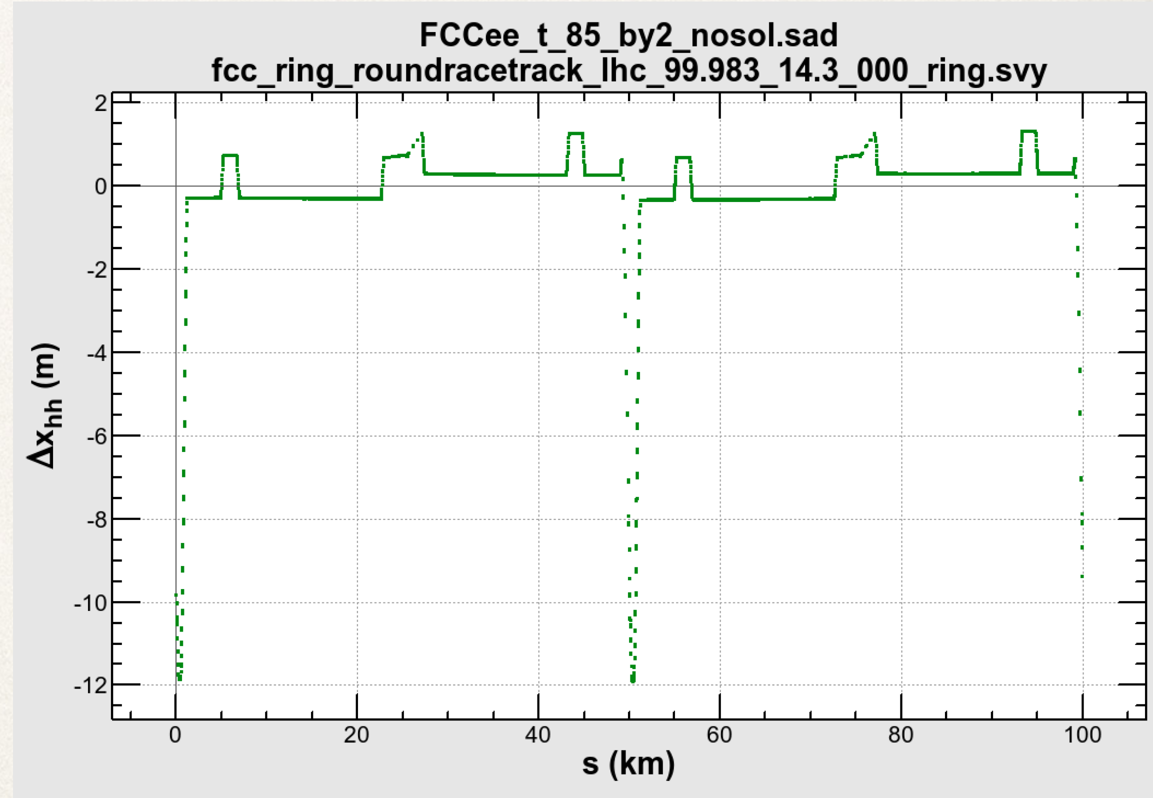
A. Langner

The new FCC-ee with the new layout





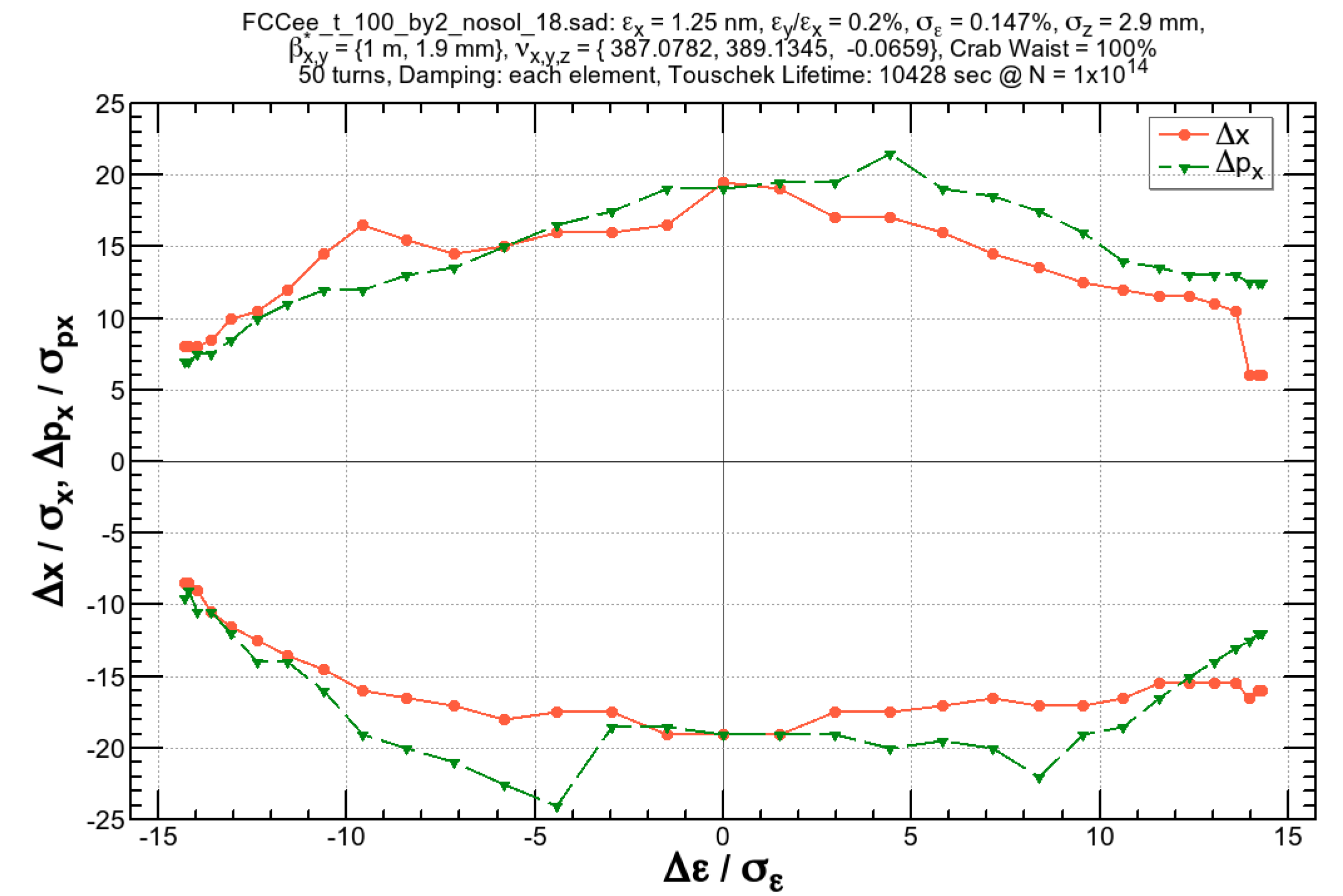




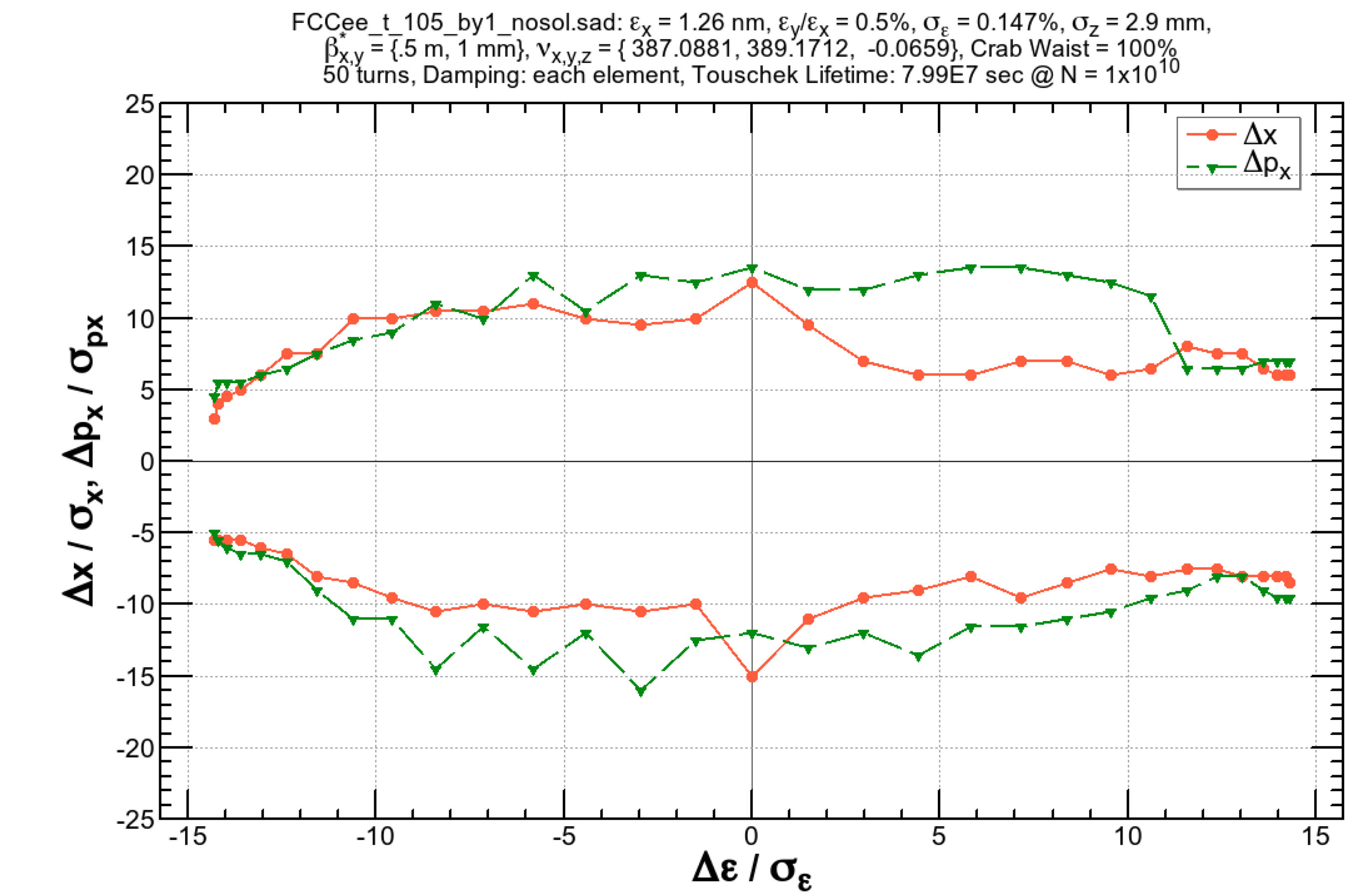
- The wiggling in Δx_{hh} in the arc of new geometry may be due to coarse data points in the new layout file.
- The separation between e+e- rings was set to 32 cm for the new layout. It was 60 cm before.

Dynamic Aperture @ 175 GeV

β*x,y = (1 m, 2 mm)



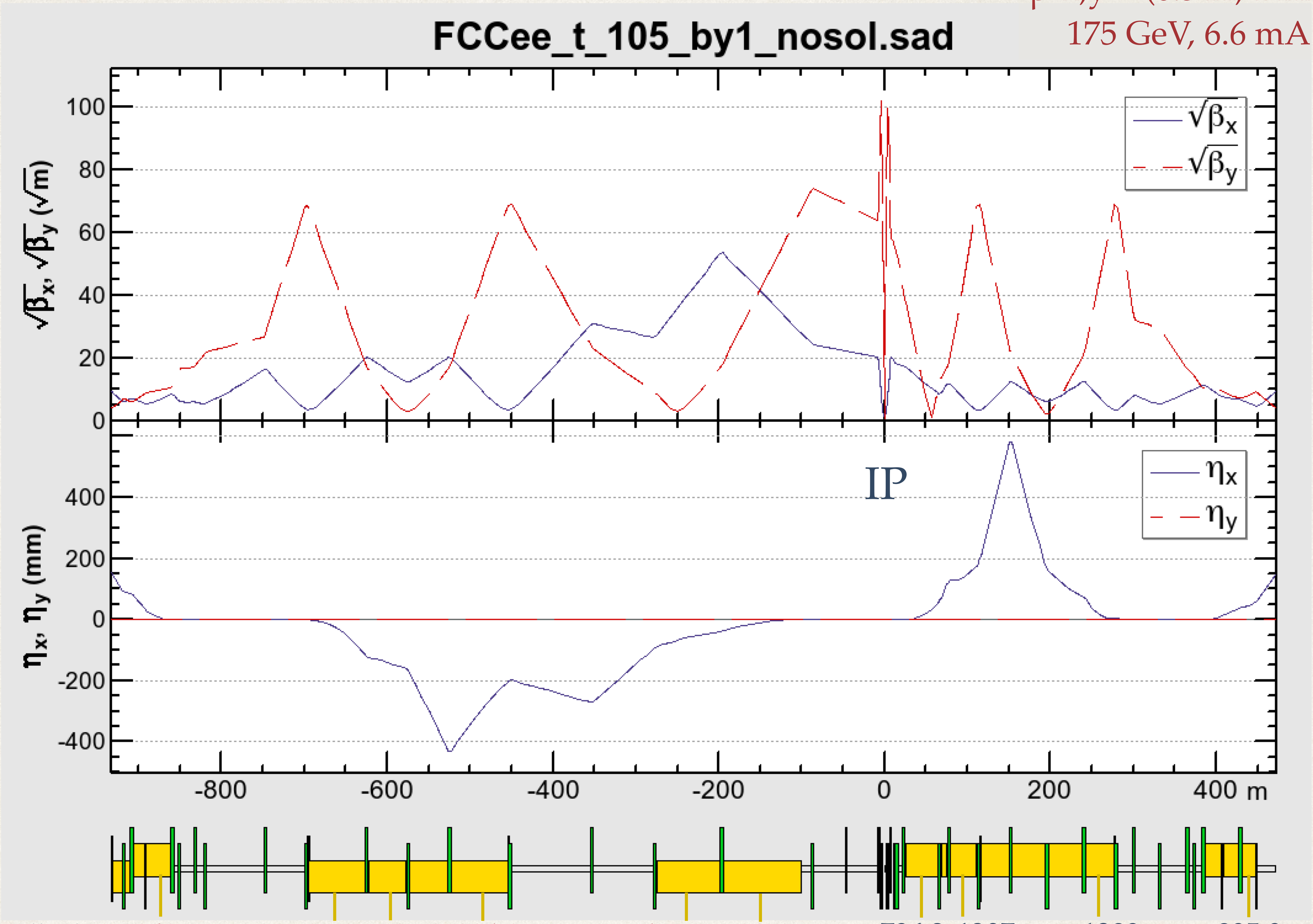
β*x,y = (0.5 m, 1 mm): in progress



- The dynamic aperture at 175 GeV looks OK.
- Solenoids have been temporarily removed.
- Optimization for 45.6 GeV is to be done with smaller β*x option (see next).

Synchrotron Radiation around IP

$\beta^*_{x,y}$ = (0.5 m, 1 mm)
175 GeV, 6.6 mA

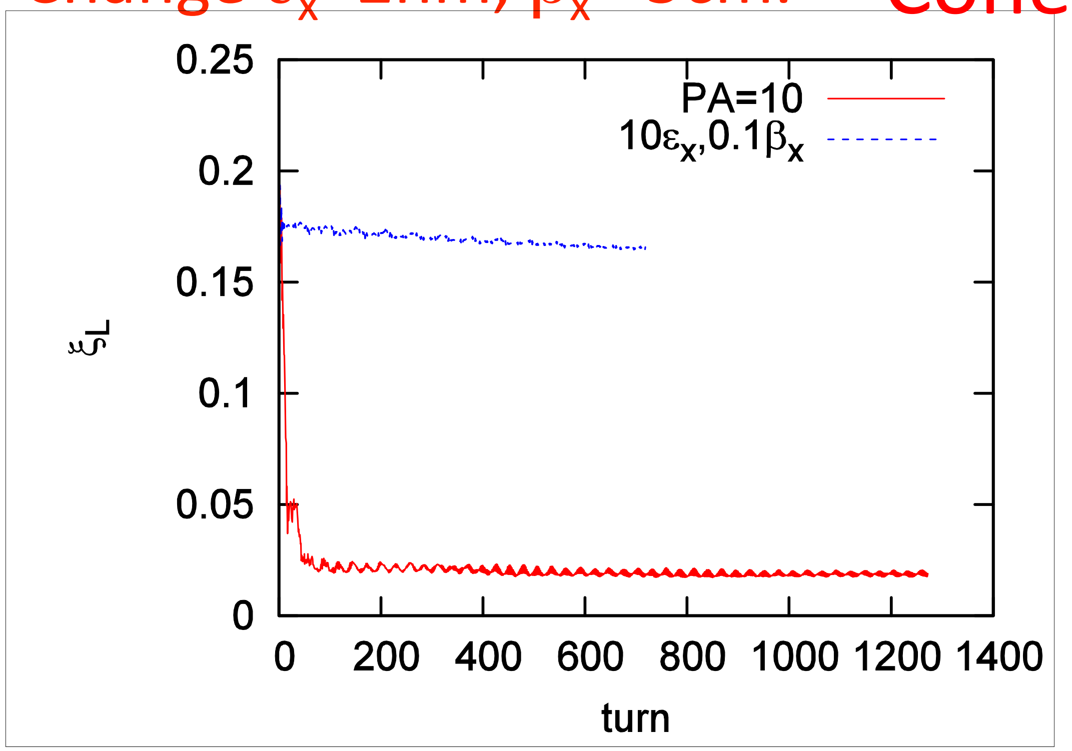


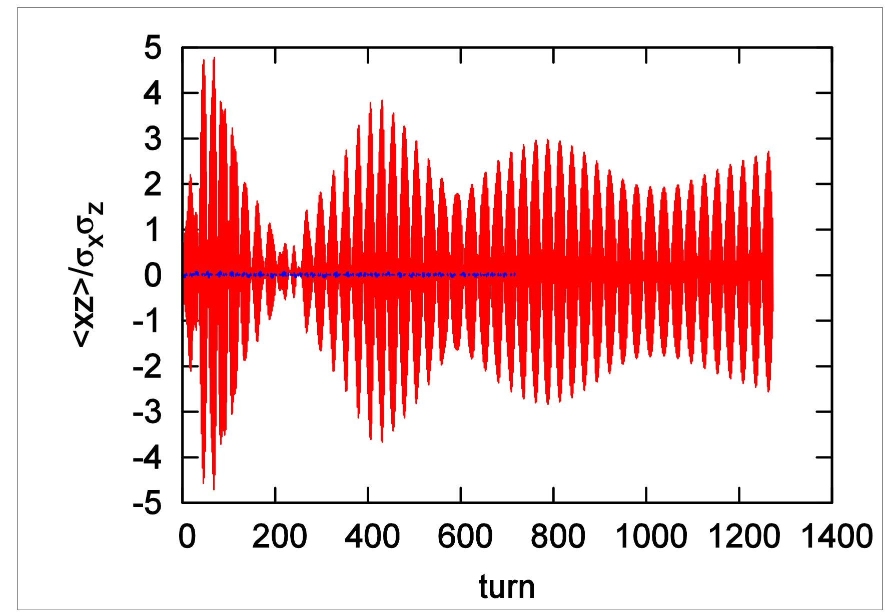
u_c (kV)	843	585.9	585.9	231.3	100.0	99.6	796.2	1207	1389	895.9
P (kW)	12.9	14.5	14.5	2.3	0.47	0.57	15.3	28.3	40.5	8.1

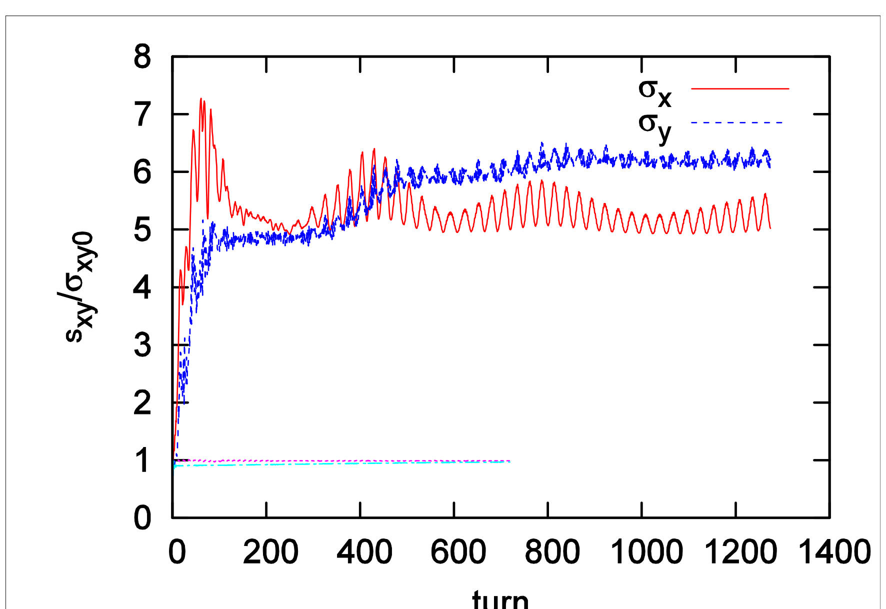
K. Ohmi

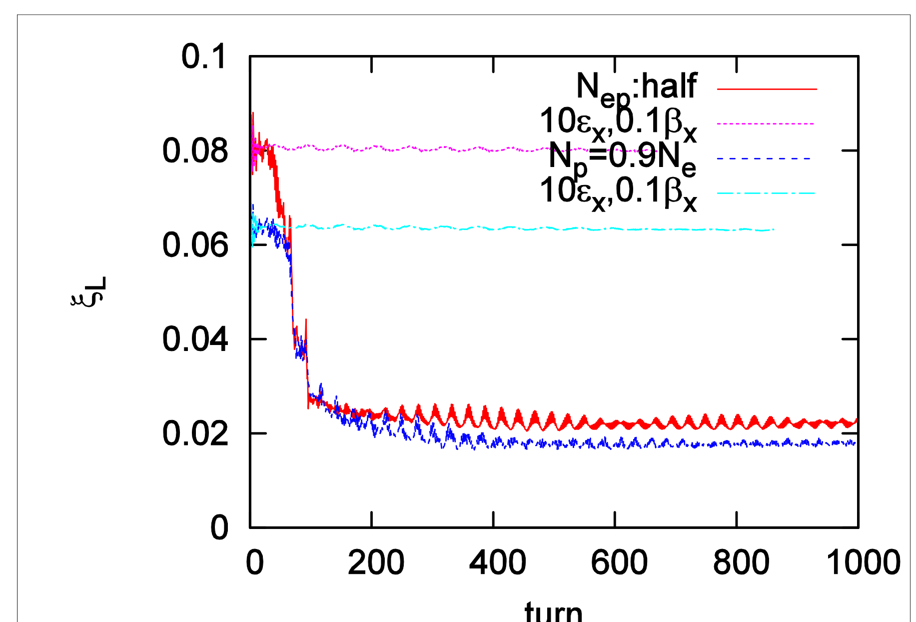
Strong-strong beam-beam instability

- The same σ_x=10μm, larger crossing angle for SuperKEKB.
- SuperKEKB ε_x=3.2nm, β_x=3.2cm FCCee-Z ε_x=0.2nm, β_x =50cm
- Change ε_x=2nm, β_x =5cm. Coherent instability disappears!

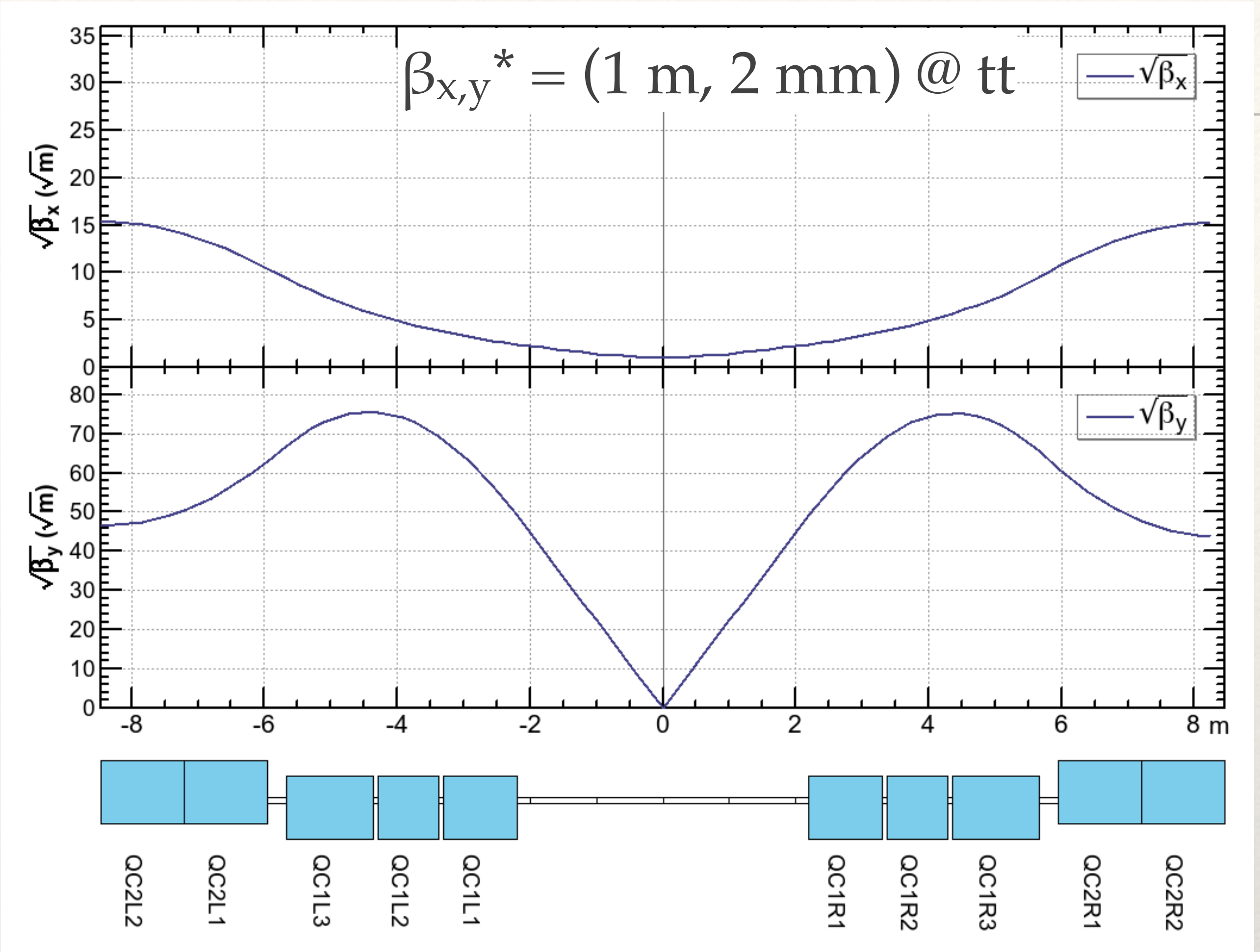


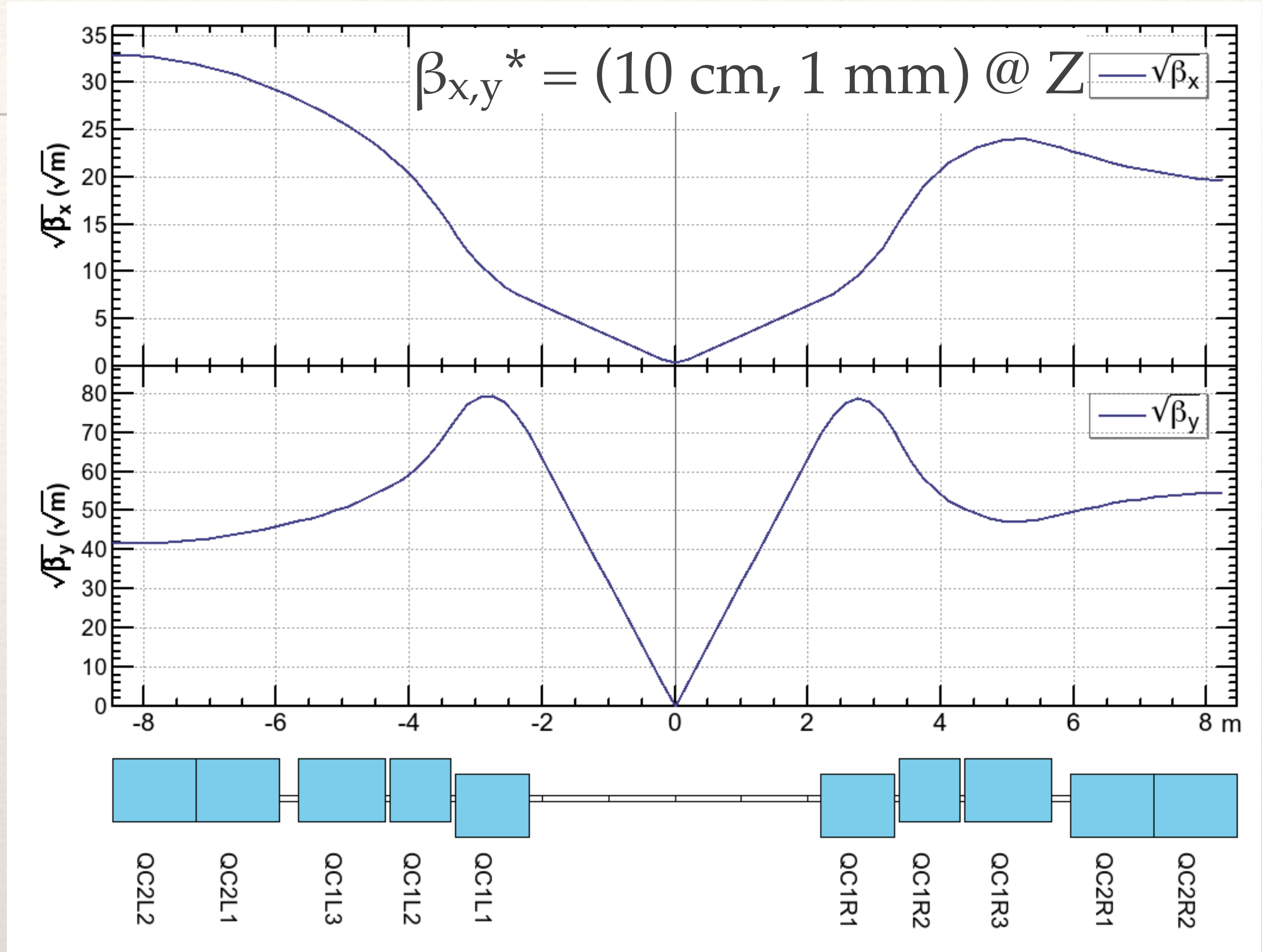






Let's try $\beta_{x,y}^* = (10\text{ cm}, 1\text{ mm})$!





- Divide QC1 into three independent pieces. (suggested by D. Shatilov)

	L (m)	B′ @ tt	B′ @ Z
QC1L1	1.1	-92.9	-102.4
QC1L2	0.9	-94.9	+44.1
QC1L3	1.3	-92.6	+11.4
QC2L1,2	1.25	+62.6	+6.0

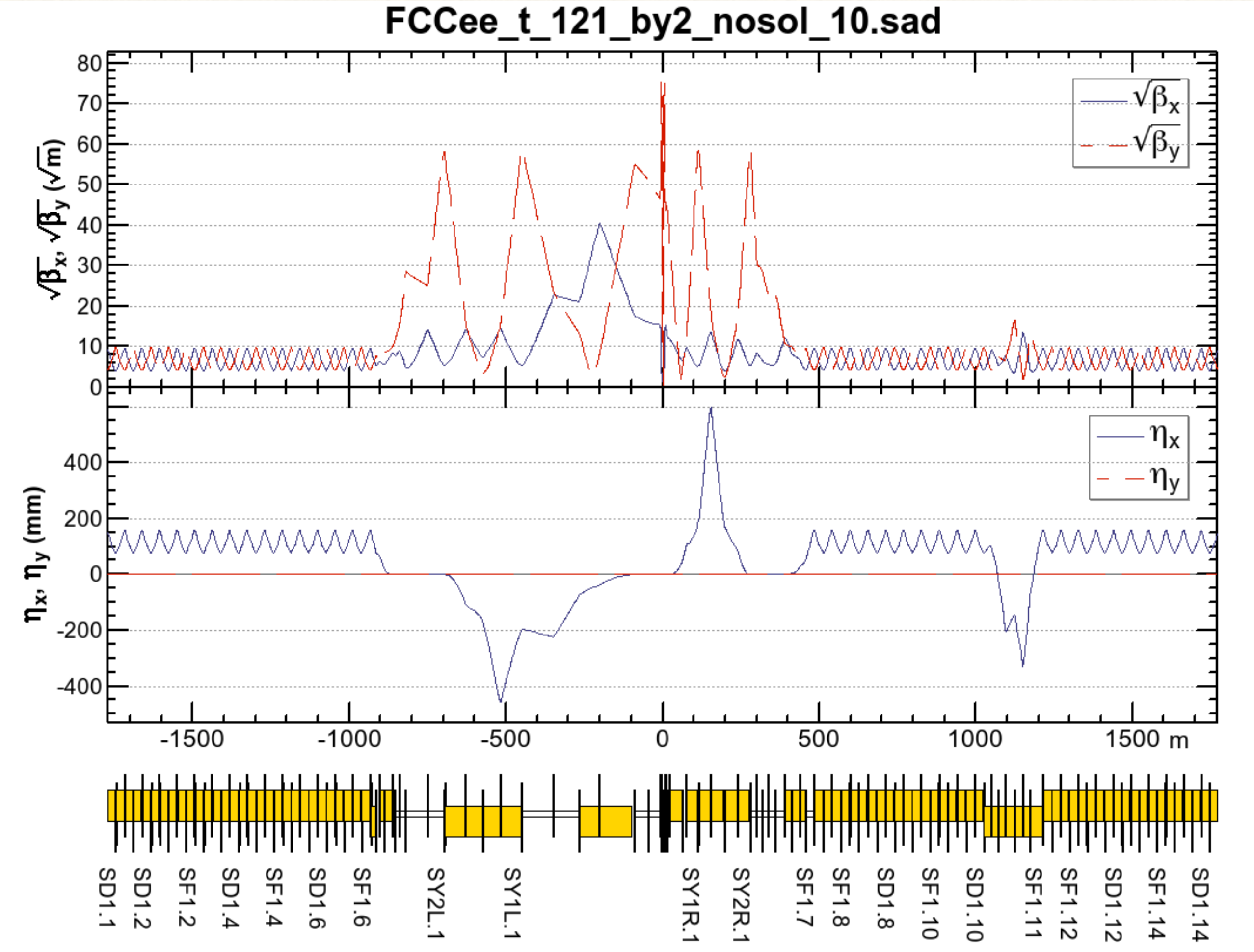
	L (m)	B′ @ tt	B′ @ Z
QC1R1	1.1	-92.9	-113.8
QC1R2	0.9	-99.9	+67.6
QC1R3	1.3	-97.6	+29.0
QC2R1,2	1.25	+71.6	-5.4

Chromaticity

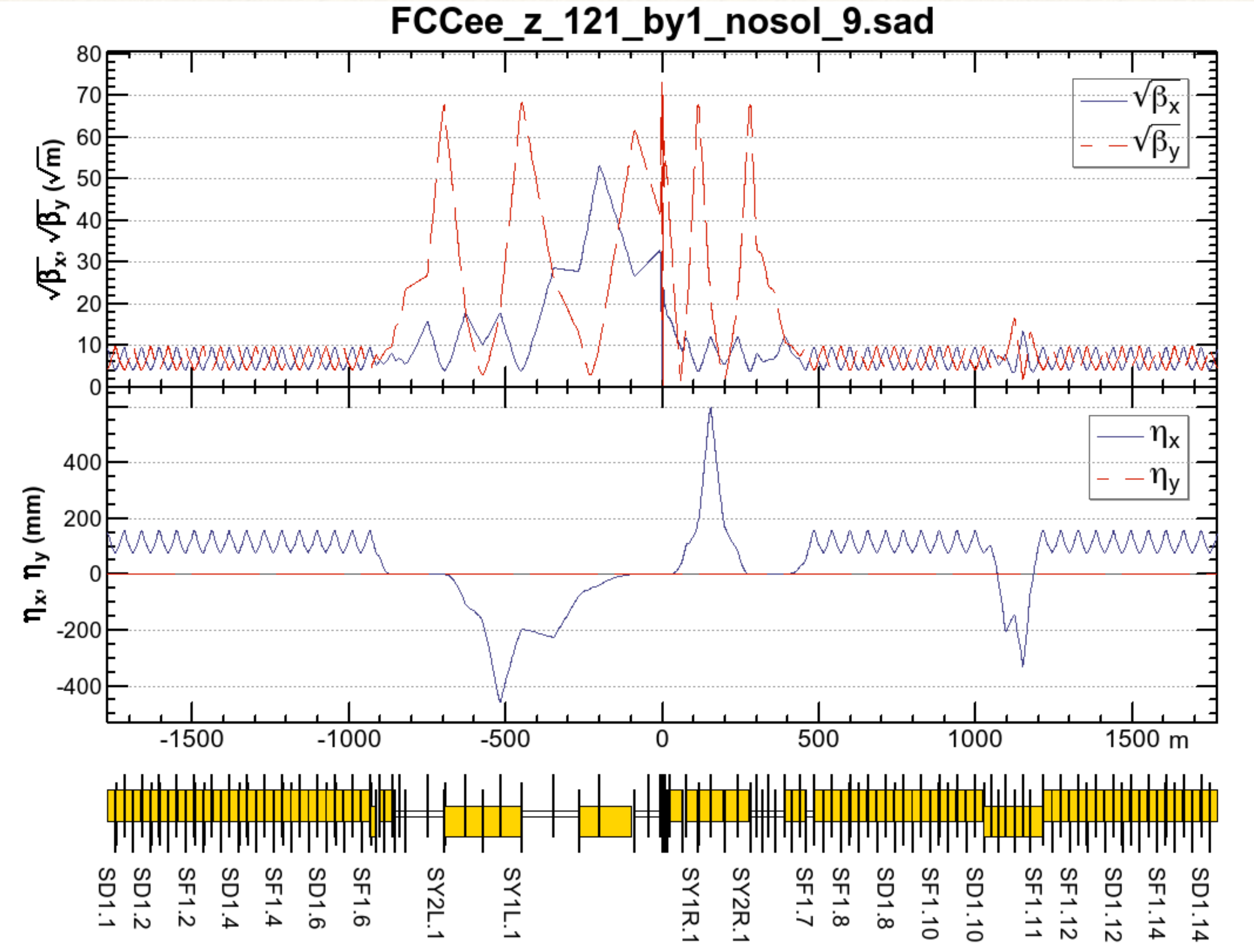
$\beta_{x,y}^* = (1\ m, 2\ mm)$ @ tt			$\beta_{x,y}^* = (10\ cm, 1\ mm)$ @ Z		
QC2L2	-29.886	307.593	QC2L2	-51.790	85.567
QC2L1	-20.901	420.427	QC2L1	-45.996	95.085
QC1L3	11.316	-1094.099	QC1L3	-64.450	253.302
QC1L2	3.125	-782.073	QC1L2	-93.626	1025.826
QC1L1	1.616	-630.295	QC1L1	74.290	-4368.569
QC1R1	1.616	-630.295	QC1R1	85.080	-4718.832
QC1R2	3.296	-821.146	QC1R2	-151.447	1337.262
QC1R3	12.126	-1128.264	QC1R3	-138.103	570.983
QC2R1	-24.640	441.618	QC2R1	20.762	-119.437
QC2R2	-34.239	309.613	QC2R2	17.759	-130.909

IR Optics

$\beta_{x,y}^* = (1\ \mathrm{m}, 2\ \mathrm{mm})$ @ tt



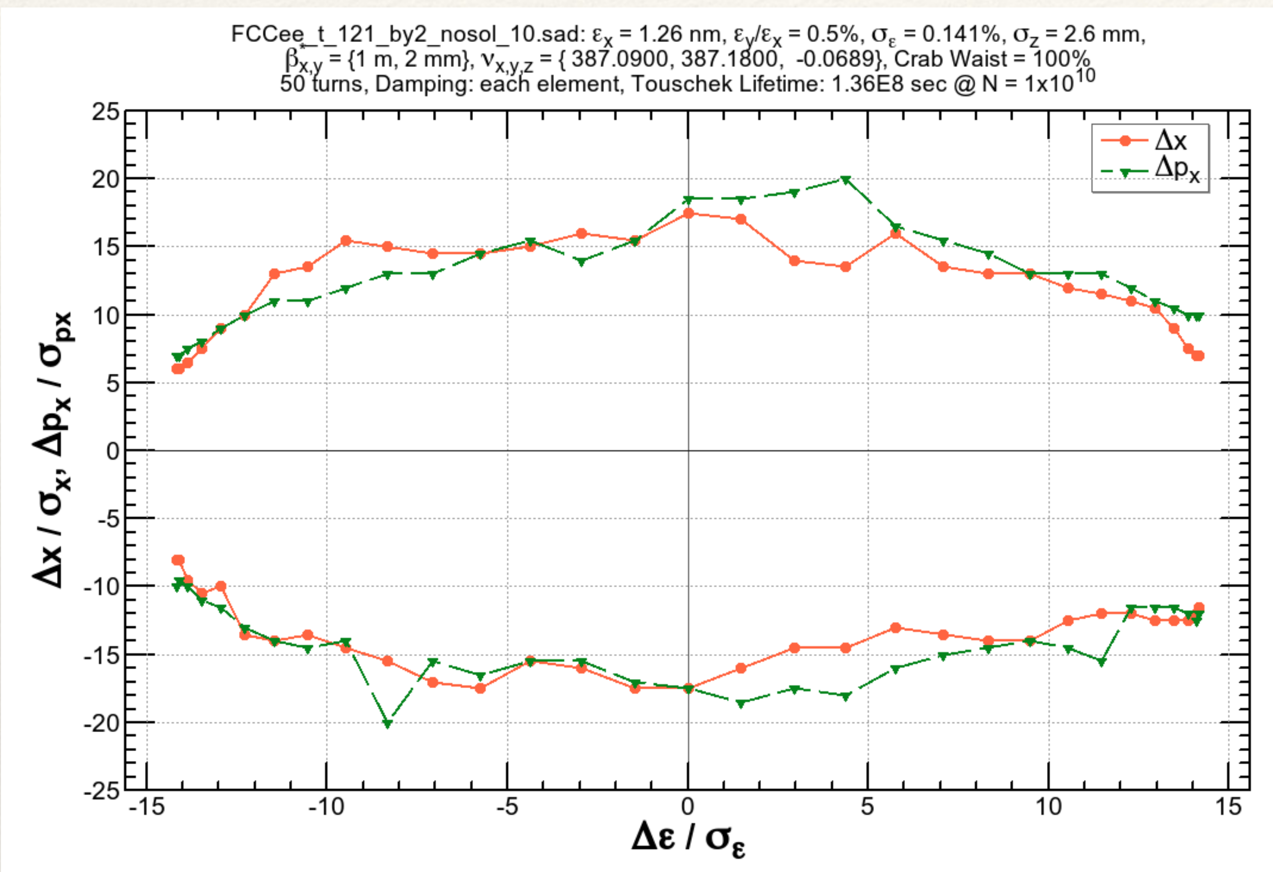
$\beta_{x,y}^* = (10\ \mathrm{cm}, 1\ \mathrm{mm})$ @ Z



- Only quadrupoles between dispersion suppressors are used to rematch β^*.
- Solenoids are temporarily removed.

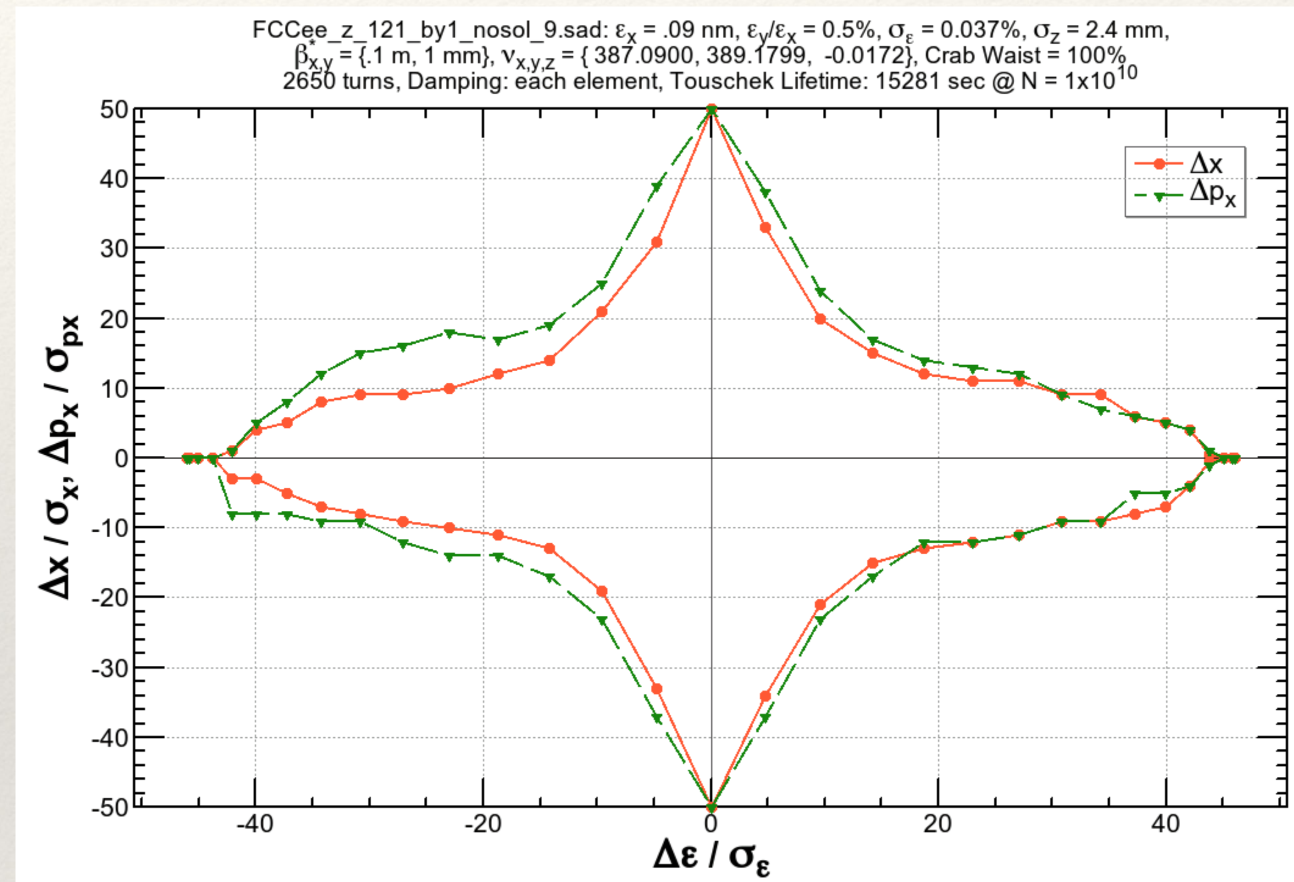
Dynamic Aperture

$\beta_{x,y}{}^* = (1\text{ m}, 2\text{ mm})$ @ tt



±2%

$\beta_{x,y}{}^* = (10\text{ cm}, 1\text{ mm})$ @ Z



±1.7%

- The momentum acceptance with $\beta_{x,y}{}^* = (10\text{ cm}, 1\text{ mm})$ @ Z has shrunk to ±1.6%, which is still allowable for beamstrahlung and injection @ Z.
- Further optimization should be done for the division of QC1.

Summary

- The baseline optics for FCC-ee has been presented, satisfying requirements on layout/luminosity/dynamic aperture/synchrotron radiation.
- Detailed matching to the new FCC-hh arc will be done when the FCC-hh optics is ready.
- The optics near the IP should be finalized considering synchrotron radiation background, HOM trapping, design of quadrupole, compensation solenoid, luminometer.
- The mitigation for the strong-strong instability at Z needs further investigation on the choice of parameters (β^*x, emittances, etc.). This will have a big impact on the optics near the IP.