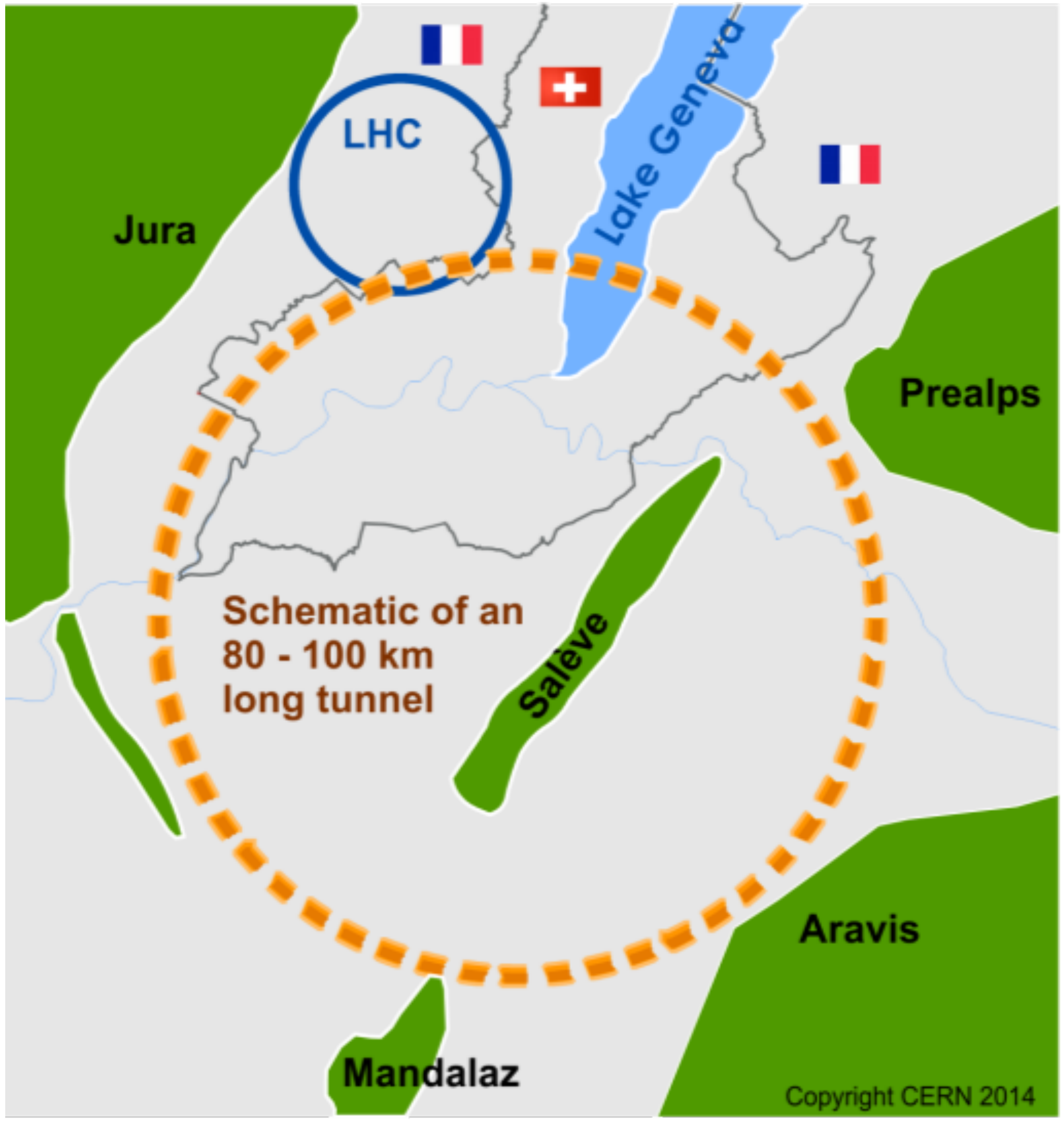
Beam Optics & Dynamic Aperture of FCC-ee

Nov. 1, 2017 @ DA Workshop

K. Oide (KEK) on behalf of the FCC-ee Collaboration

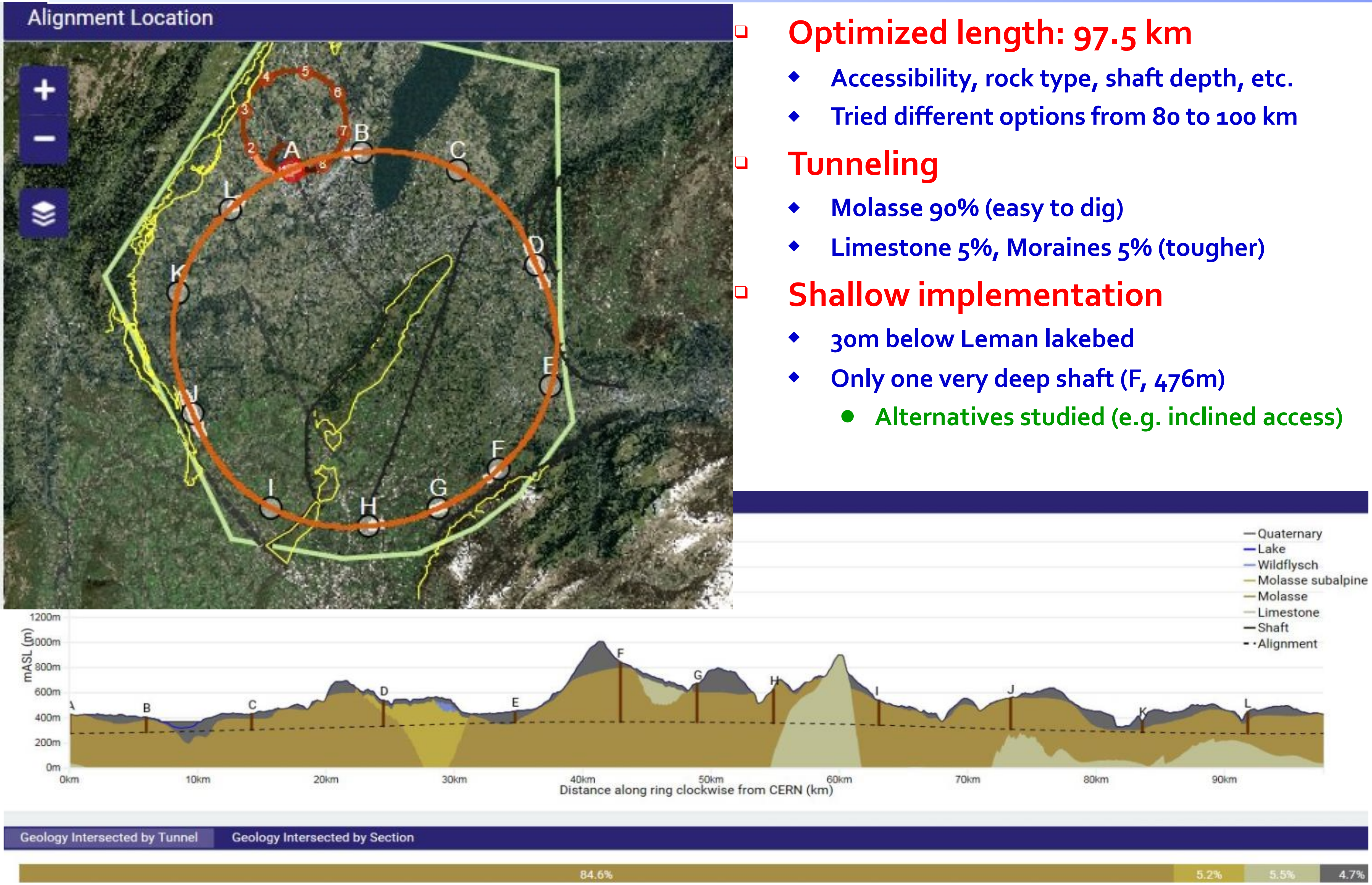
The FCC Design Study

- Requested from European Strategy (2013)
  - "Ambitious post-LHC accelerator project"
    - Study kicked off in Geneva in Feb. 2014
- International collaboration to study circular colliders (111 institutes)
  - Fitting in a new 100 km infrastructure, in the Geneva area
- Ultimate goal: 100TeV pp collider (FCC-hh)
  - Requires R&D for 16T magnets
  - Defines the infrastructure
- Possible first steps
  - e^+e^- collider (FCC-ee) at the intensity frontier
    - High luminosity, $\sqrt{s}$ = 90-400 GeV
  - pp collider (HE-LHC) in the LEP/LHC tunnel
    - With FCC-hh technology (16T → 28 TeV)
- Possible add-on
  - e-p option (FCC-eh)



- European Strategy update (2019)
  - Conceptual design report (CDR)
  - Cost review for tunnel and each collider
  - Schedules and operation models

The FCC Home



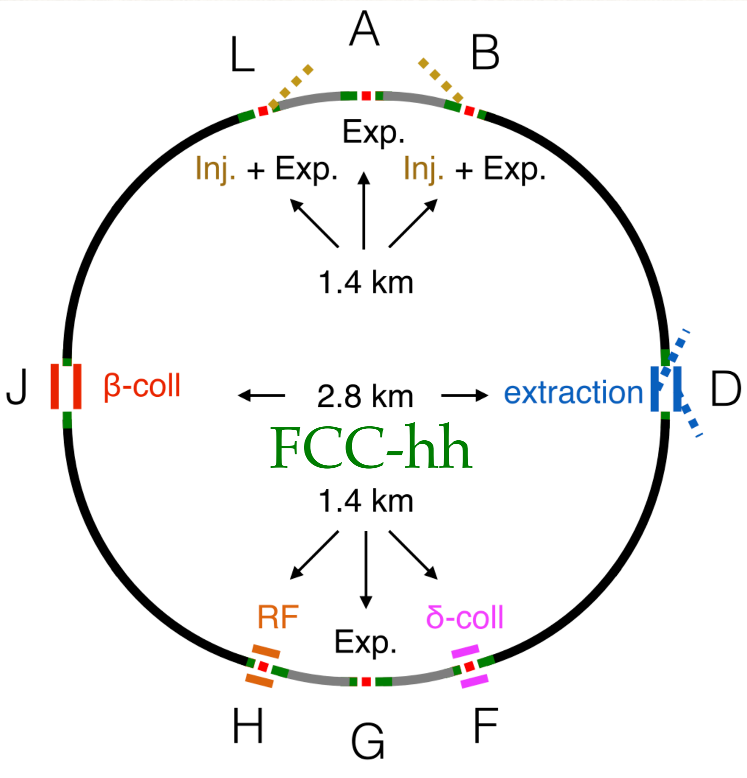
- **Optimized length: 97.5 km**
  - Accessibility, rock type, shaft depth, etc.
  - Tried different options from 80 to 100 km
- **Tunneling**
  - Molasse 90% (easy to dig)
  - Limestone 5%, Moraines 5% (tougher)
- **Shallow implementation**
  - 30m below Leman lakebed
  - Only one very deep shaft (F, 476m)
    - Alternatives studied (e.g. inclined access)

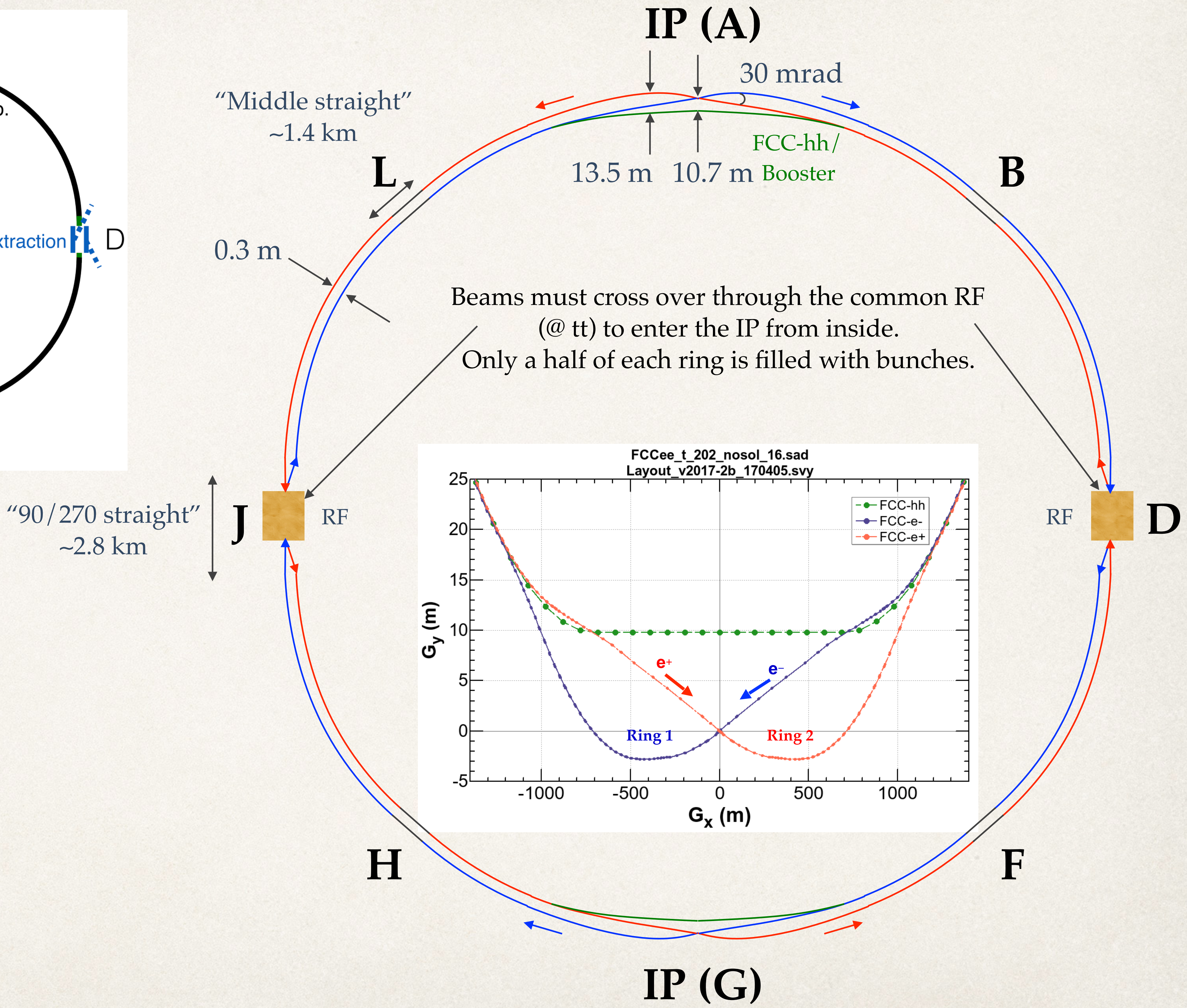
FCC-ee Beam Optics

- A baseline optics* for FCC-ee was once established in Oct. 2016 characterized by:
  - 100 km circumference, 2 IP/ring
  - Common lattice for all energies
  - 90°/90° FODO cell in the arc with non-interleaved sextupole pairs (294 families)
  - 30 mrad crossing angle at the IP, with the crab-waist scheme
  - Local chromaticity correction for y-plane, incorporated with crab sextupoles
  - 100 MW total SR power for all energies
  - Limit the SR toward the IP below 100 keV at 175 GeV, up to 450 m upstream
  - Tapering of magnets along the ring to compensate the effects of SR on orbit/optics
  - Sufficient dynamic aperture for beamstrahlung and top-up injection
- Motivations for changes in 2017:
  - Mitigation of the coherent beam-beam instability at Z
    - *Smaller β_x^* at Z, W, Zh.*
    - *60°/60° cell in the arc at Z*
    - *Longer bunch lengths by SR and beamstrahlung.*
  - The baseline beam energy for ttbar is set at 182.5 GeV.
  - Adopt the "Twin Aperture Quadrupole" scheme for arc quadrupoles
  - Fit the footprint to a new FCC-hh layout

*Phys.Rev.Accel.Beams 19 (2016) no.11, 111005

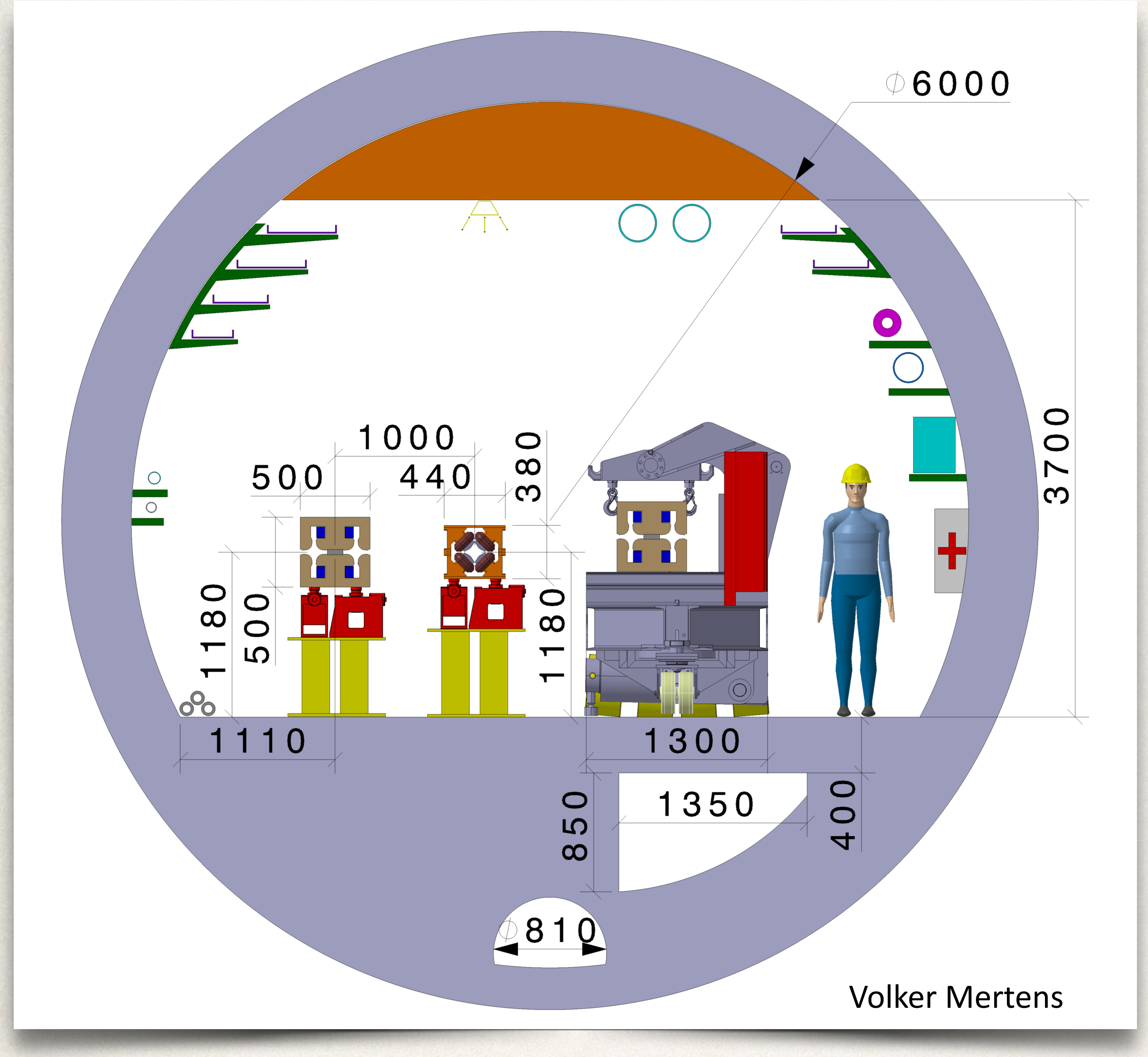
Layout of FCC-ee



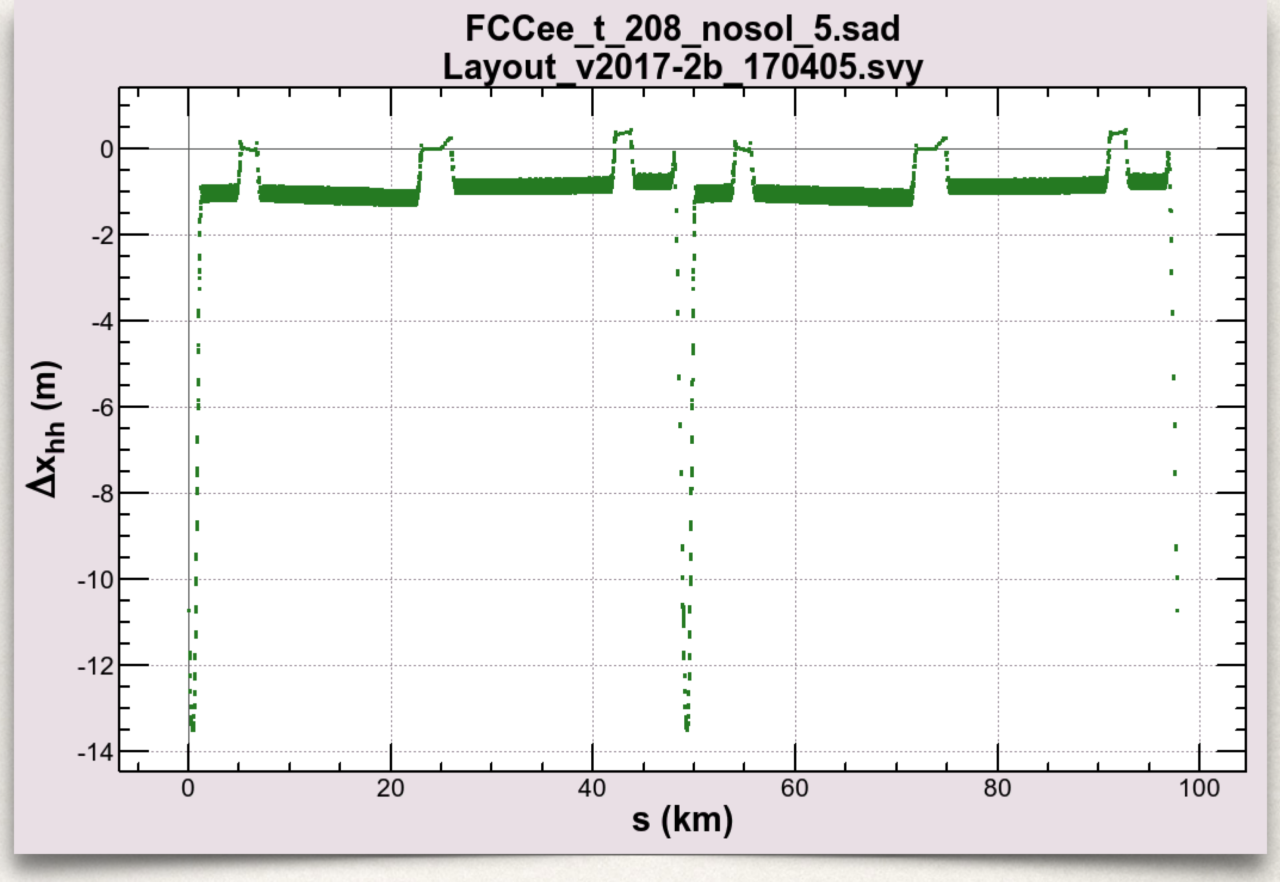


Beams must cross over through the common RF (@ tt) to enter the IP from inside.
Only a half of each ring is filled with bunches.

Layout in the tunnel



Volker Mertens

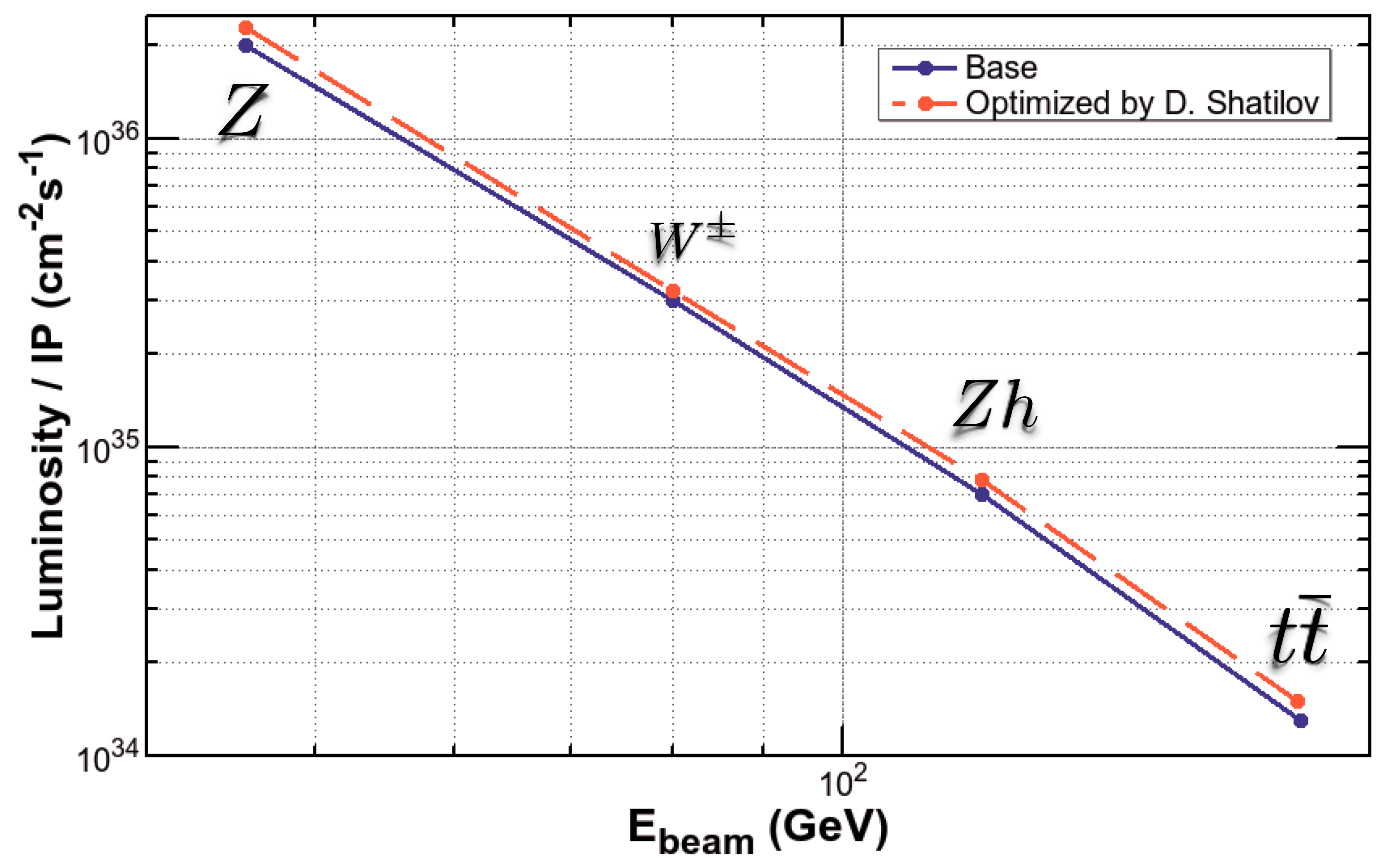


- A new layout of the FCC-ee collider and booster has been proposed by V. Mertens as above.
- The main booster sits right on the FCC-hh footprint.
- The collider comes outside of the booster/FCC-hh by 1 m.
- The collider optics has been modified to fit the new layout.
- The shift of the ee's IP from the hh's IP is 10.7 m.
- The layouts in the straight sections are subject to change.

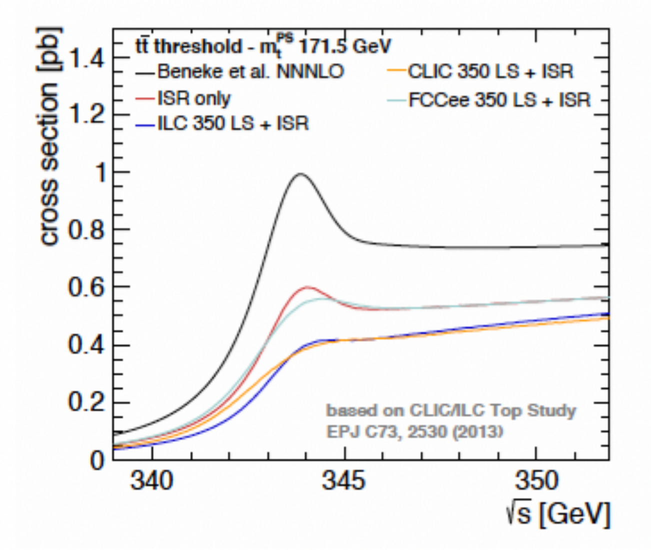
Parameters 2017

parameter	Z	W	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	**182.5**
Circumferene [km]	97.756			
arc cell optics	60/60	90/90		
momentum compaction [10^{-5}]	1.48	0.73		
horizontal emittance [nm]	0.27	0.28	0.63	1.43
vertical emittance [pm]	1.0	1.0	1.3	2.9
horizontal beta* [m]	**0.15**	**0.2**	**0.3**	1
vertical beta* [mm]	**0.8**	1	1	2
length of interaction area [mm]	0.42	0.5	0.9	2.0
tunes, half-ring (x, y)	(0.569, 0.60)	(0.577, 0.61)	(0.565, 0.60)	(0.552, 0.588)
synchrotron tune (half ring)	0.0124	0.0114	0.0180	0.0340
long. damping time [ms]	414	77	23	6.6
SR energy loss / turn [GeV]	0.0360	0.334	1.69	9.05
total RF voltage [GV]	0.096	0.43	1.96	10.6
RF acceptance [%]	1.9	1.9	2.3	4.7
energy acceptance [%]	**±1.3**	**±1.3**	**±1.5**	**-2.8/+2.4**
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.153	0.099 / 0.151	0.153 / 0.195
bunch length (SR / BS) [mm]	3.5 / 12.1	3.3 / 7.65	3.15 / 4.9	2.5 / 3.3
Piwinski angle (SR / BS)	8.2 / 28.5	6.6 / 15.3	3.4 / 5.3	1.0 / 1.3
bunch intensity [10^{11}]	1.7	1.5	1.5	2.8
number of bunches / beam	16640	2030	401	40
beam current [mA]	1390	150	29.6	5.5
luminosity [10^{34} $cm^{-2}s^{-1}$]	**> 200**	**> 30**	**> 7**	**> 1.3**
beam-beam parameter (x / y)	0.004 / 0.133	0.0065 / 0.118	0.016 / 0.108	0.090 / 0.148
luminosity lifetime [min]	70	50	42	39
time between injections [sec]	122	44	31	32
allowable asymmetry [%]	±5	±3	±3	±3
required lifetime by BS [min]	29	16	11	12
actual lifetime (w) by BS [min]	> 200	20	20	25

Luminosity vs. Energy

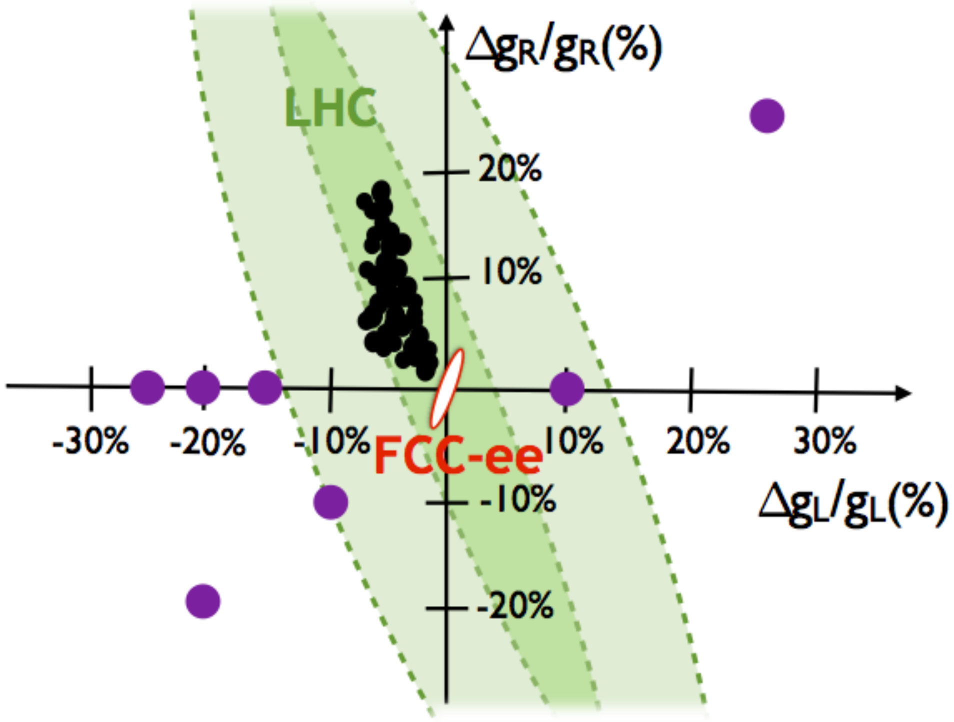


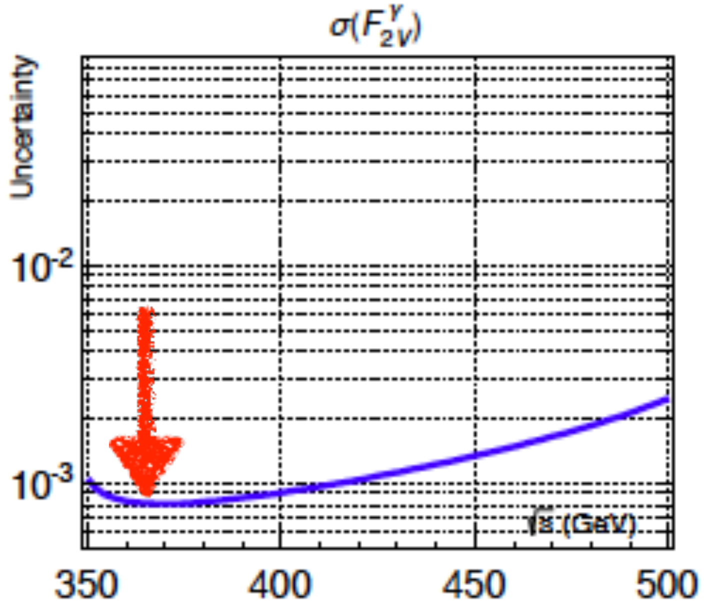
Why 365 GeV CM for ttbar?



ELECTROWEAK COUPLINGS OF THE TOP QUARK(2)

- Large statistics and final state polarization allow a full separation of the ttZ/γ couplings with **NO need for polarization in the initial state.**
- **Optimal √s= 365-370 GeV**





- Fit includes conservative assumptions detector performance
- Theory uncertainty on production mechanism dominates

FCC-ee expected precision of order 10^{-2} to 10^{-3}

conservative revised operation model

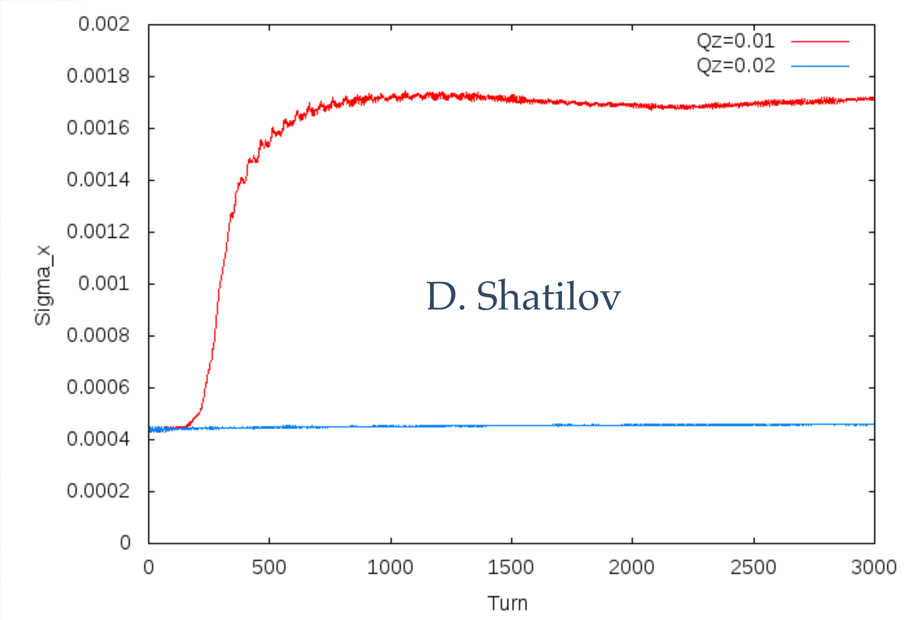
working point	**luminosity/IP [10^{34} cm^{-2}s^{-1}]**	**total luminosity (2 IPs)/ year**	**physics goal**	**run time [years]**
Z first 2 years	100	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	52 ab^{-1}/year		
W	30	7.8 ab^{-1}/year	10 ab^{-1}	~1
H	7.0	1.8 ab^{-1}/year	5 ab^{-1}	3
top	1.3	0.34 ab^{-1}/year	1.5 ab^{-1}	5

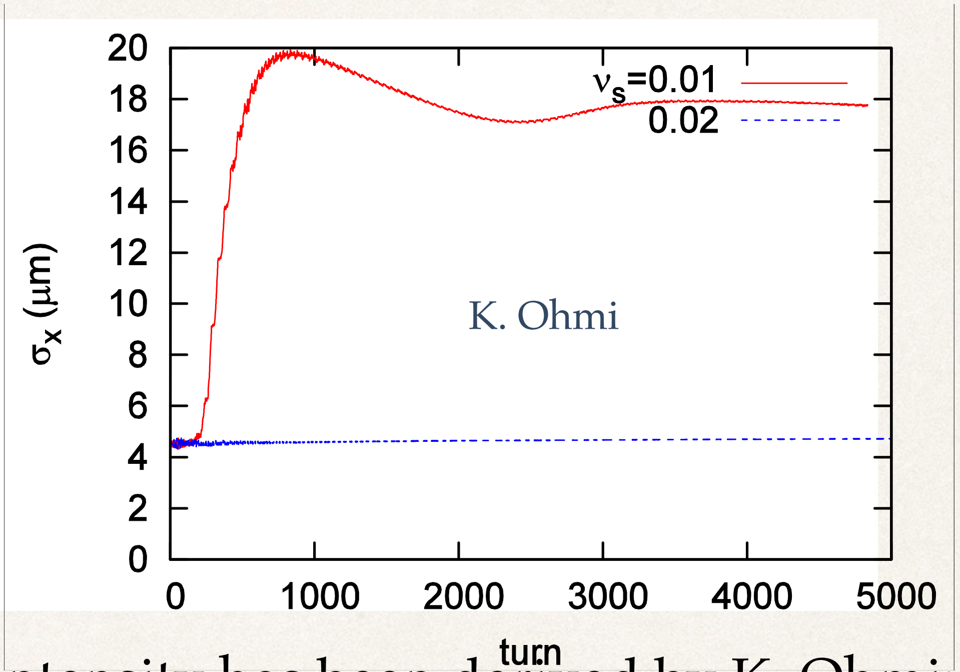
total run time: 12-13 years

F. Zimmermann

Mitigation of Coherent Beam-Beam Instability

- A new coherent instability in x-z plane was first found by K. Ohmi by FCC Week 2016 with a strong-strong beam-beam simulation.
- D. Shatilov confirmed their phenomenon by a completely independent simulation, with a turn-by-turn alternating quasi-strong-strong method. The results of these two agree to each other very well.





- A semi-analytic scaling the threshold bunch intensity has been derived by K. Ohmi:

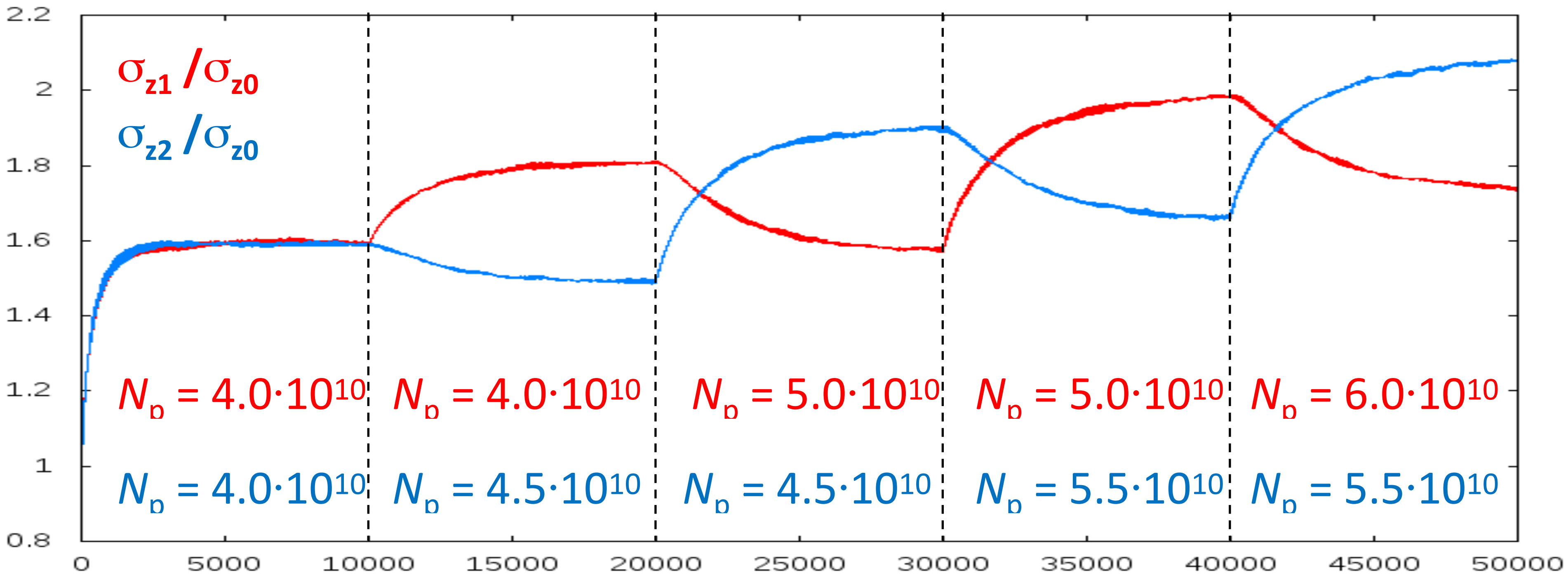
$$N_{\rm th} \propto \frac{\alpha_p \sigma_\delta \sigma_z}{\beta_x^*}$$

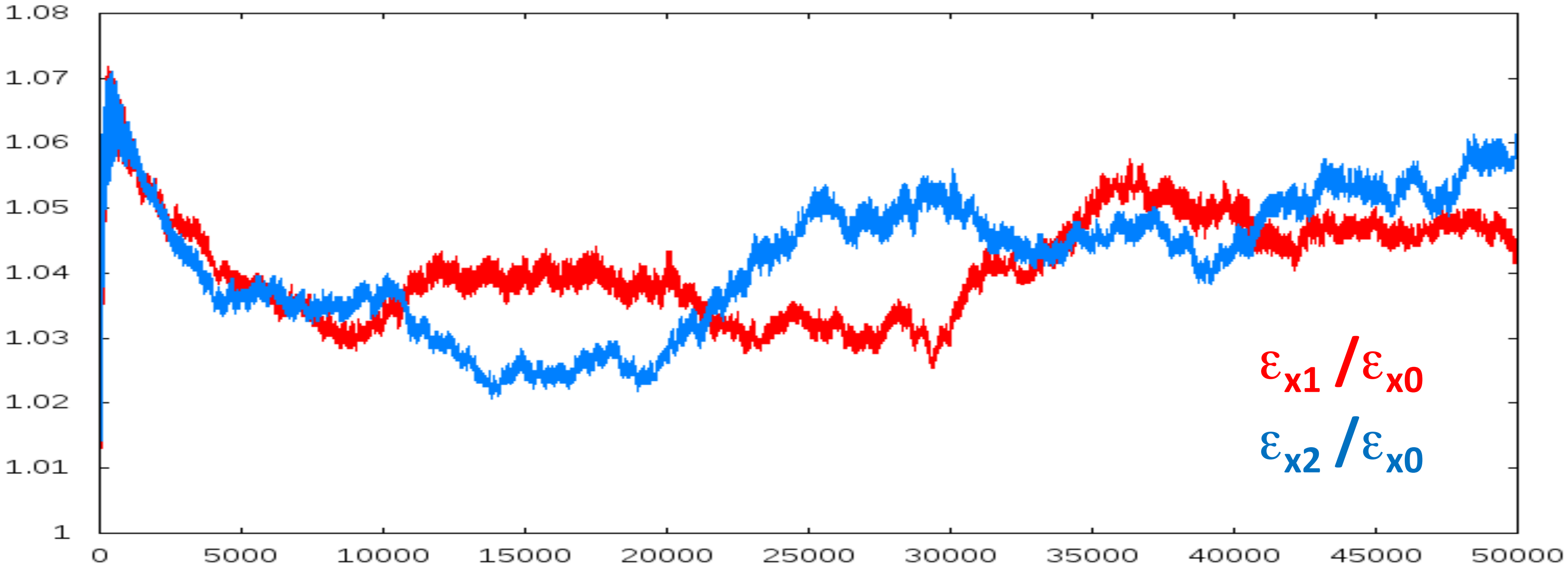
- Thus a smaller $\beta_x{}^*$ and a larger momentum compaction α_p are favorable. The latter can be achieved by changing the phase advances to 60°/60° of the arc at Z.
- Longer bunch lengths by SR as well as beamstrahlung stabilizes the instability.
- This instability appears up to Zh (120 GeV). A longer bunch length by a strong beamstrahlung can mitigate it, then an imbalance in the charges of the two colliding bunches may cause flip-flop: a “bootstrap” injection is necessary (D. Shatilov).

K. Ohmi, et al., Phys.Rev.Lett. 119 (2017) no.13, 134801

Bootstrapping

D. Shatilov

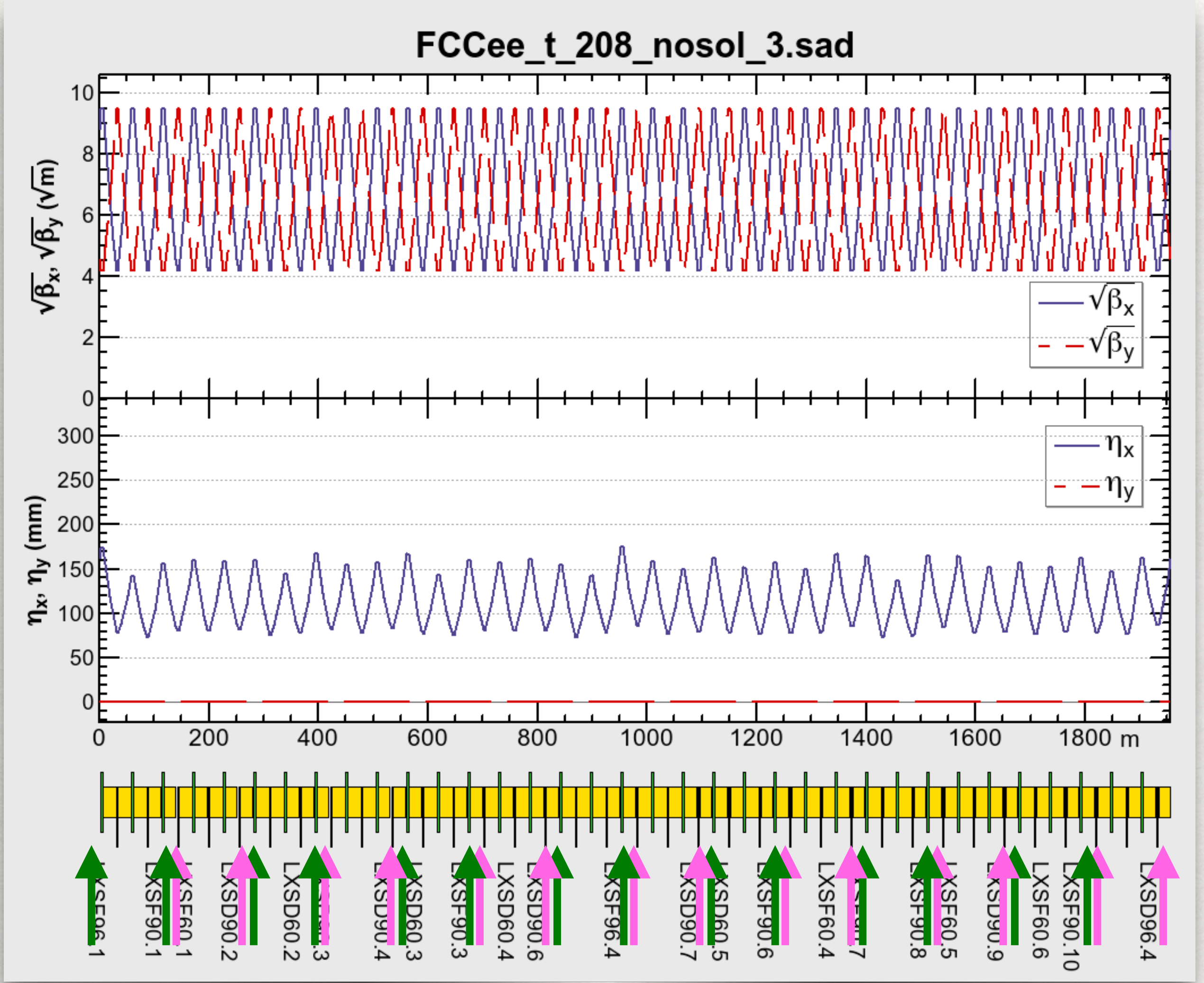




- The maximum bunch charge is determined considering the balance of beamstrahlung, momentum acceptance, and the capability of injector.

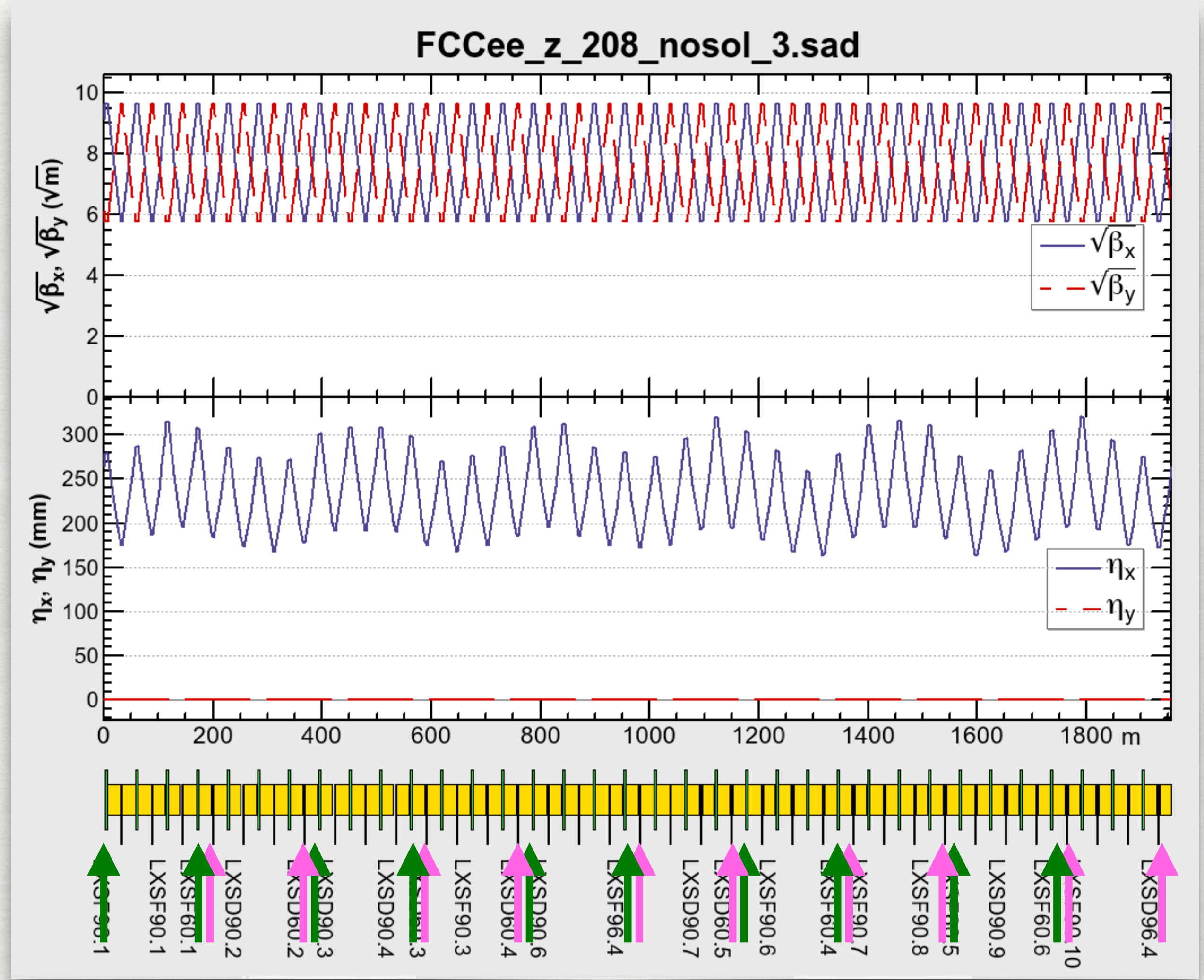
The arc cells

90°/90° (tt, Zh, WW)



14 sext pairs / 28 FODOs

60°/60° (Z)

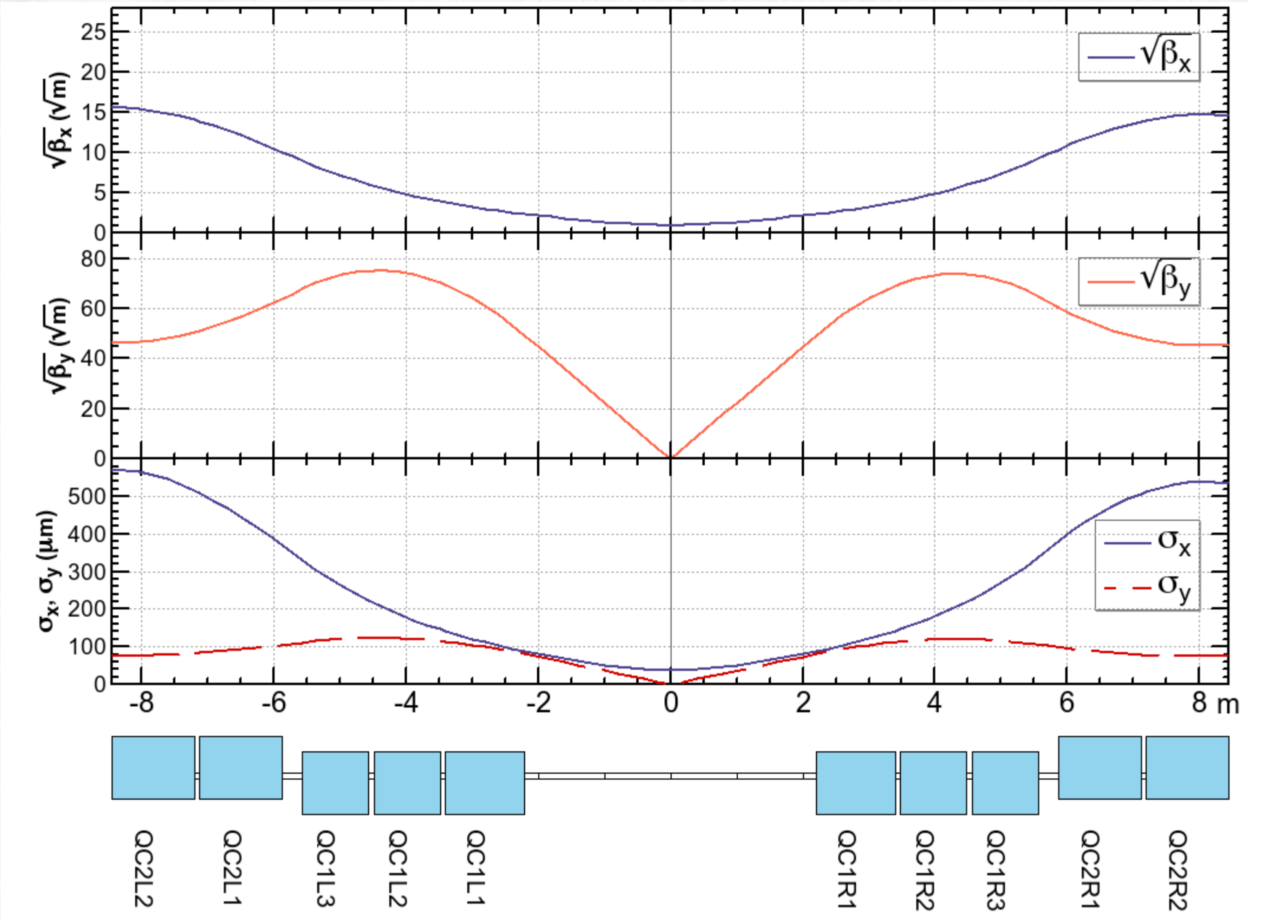


10 sext pairs / 28 FODOs

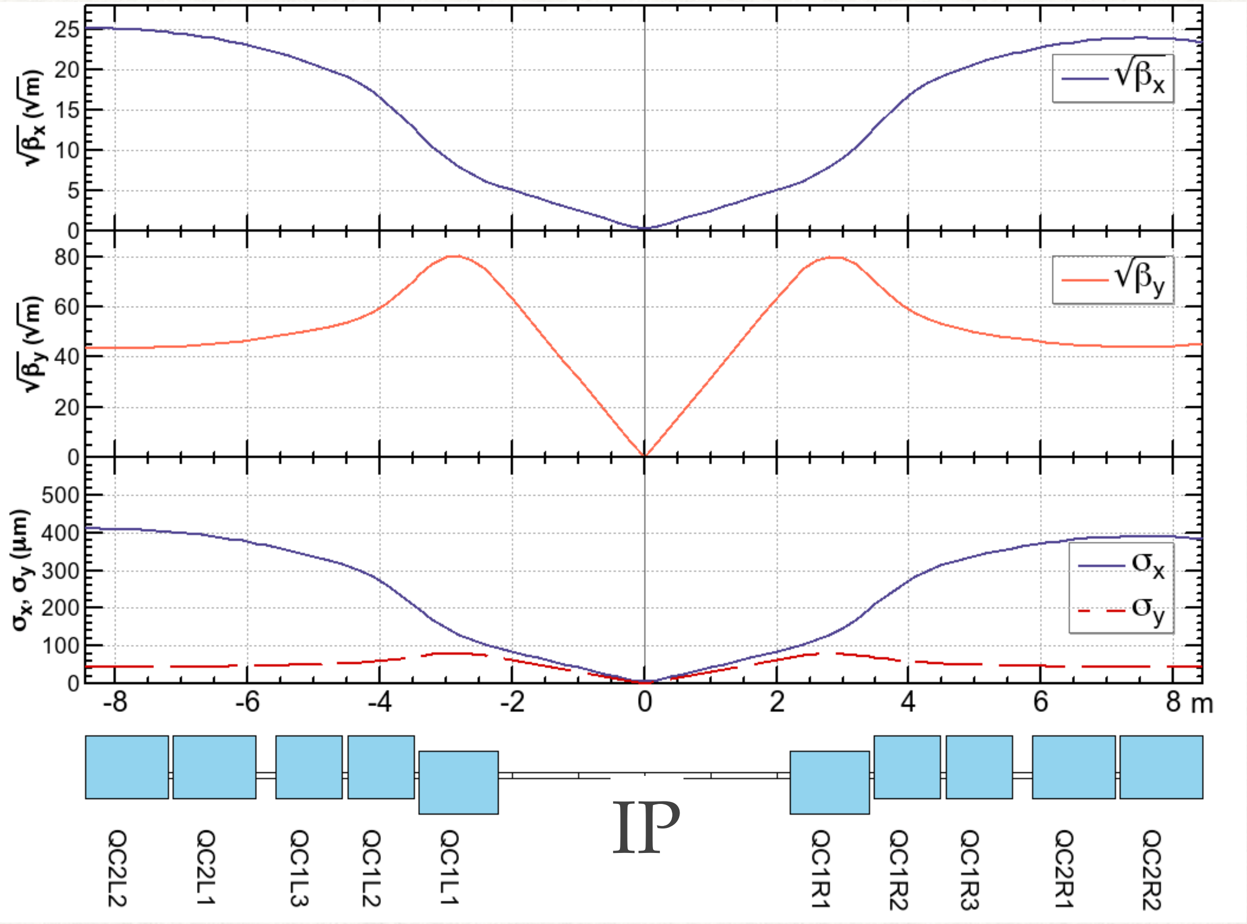
- The length of dipoles are adjusted to fill spaces, with three lengths of dipoles (21.84 m, 23.54 m, 24.44 m) with equal bending radius.
- While the **β**-functions are more or less uniform, there appear some wiggling in the horizontal dispersion.
- Sextupoles are made longer, from 0.7 m to 0.8 m (Z), and from 2.1 m to 2.4 m (tt).
- The resulting packing factor of the dipoles in the arc has been improved from 81.7% to 83.2%.

Reduction of βx* at Z, W, Zh

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



$\beta_{x,y}^* = (15\ \mathrm{cm}, 1\ \mathrm{mm})$ @ Z

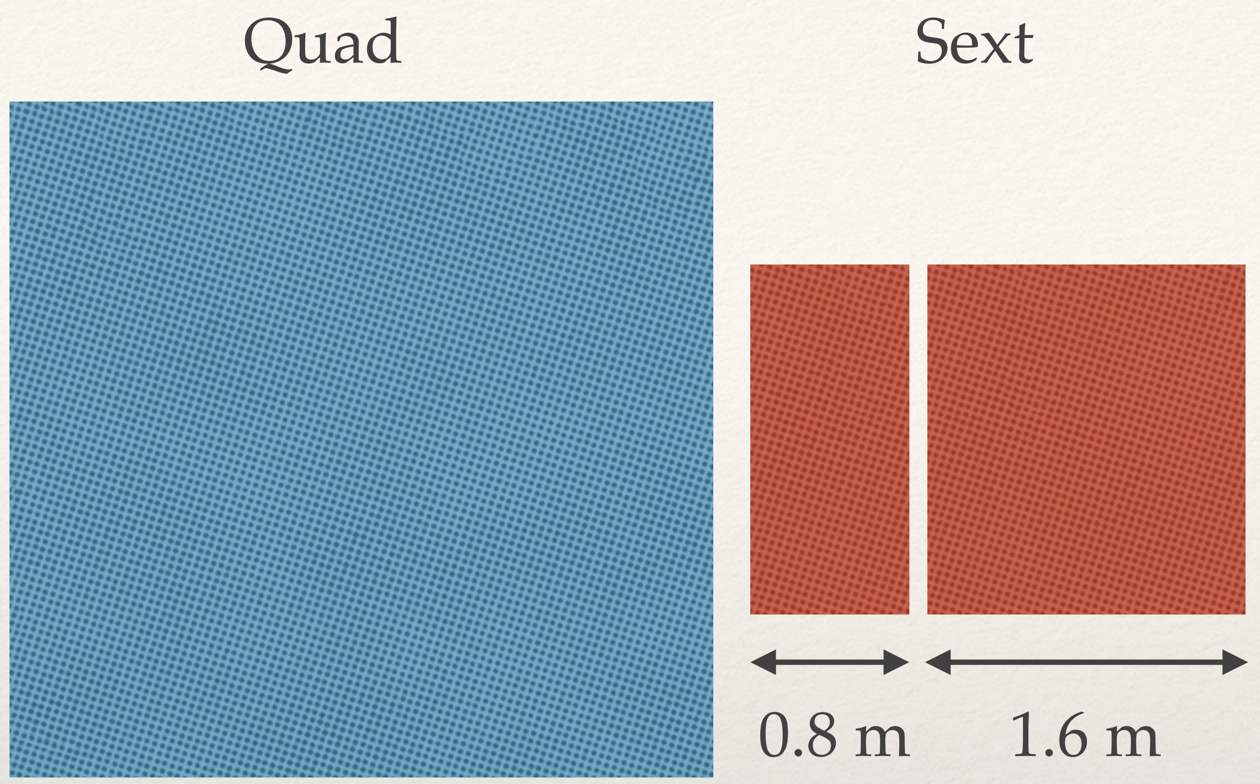


- Divide QC1 into three independent pieces, reverse the polarity at Z.

	L (m)	B′ @ tt (T/	B′ @ Z (T/
QC1L1	1.2	-94.4	-96.3
QC1L2	1	-92.6	+50.3
QC1L3	1	-96.7	+9.8
QC2L1	1.25	+45.8	+6.7
QC2L2	1.25	+74.0	+3.2

	L (m)	B′ @ tt (T/	B′ @ Z (T/
QC1R1	1.2	-99.9	-97.2
QC1R2	1	-99.9	+51.2
QC1R3	1	-99.9	+12.0
QC2R1	1.25	+78.6	+7.3
QC2R2	1.25	+76.2	+7.2

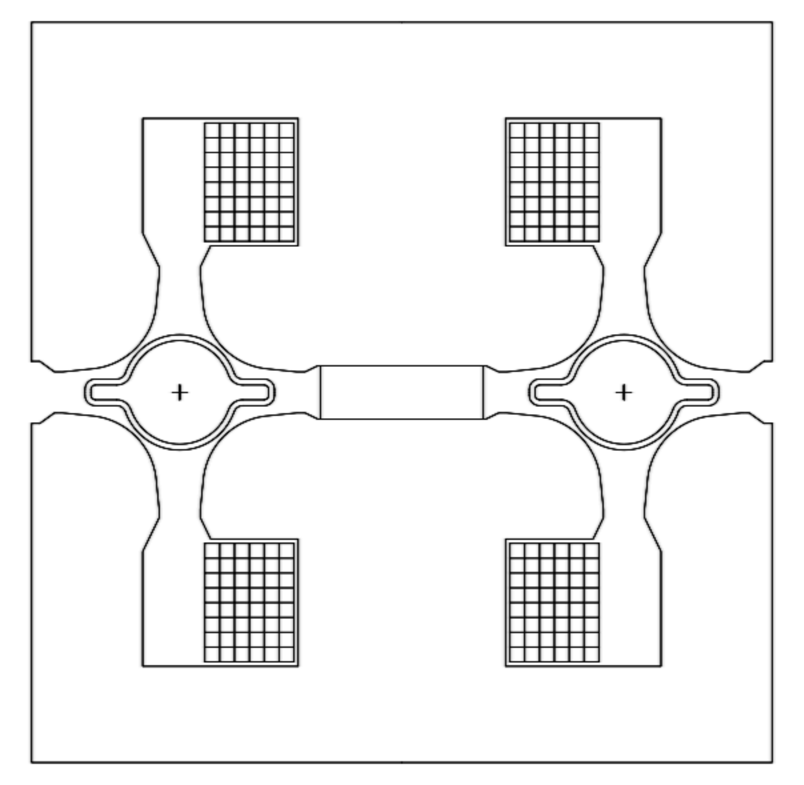
- By this split the chromaticity and the peaks of $\beta_{x,y}$ around the IP are suppressed for the reduction of $\beta_{x,y}^*$ at Z to (1/7, 1/2) at tt.



- A sext consists of two pieces, 0.8 m and 1.6 m long with same field strength.
- Only the thinner piece of the sext is used at Z.

Twin Aperture Quadrupole

- An idea of "twin aperture quadrupole" has been developed by A. Milanese to save the power consumption of quadrupole magnets.
- The currents in the magnet are always surrounded by iron to maximize the usage.

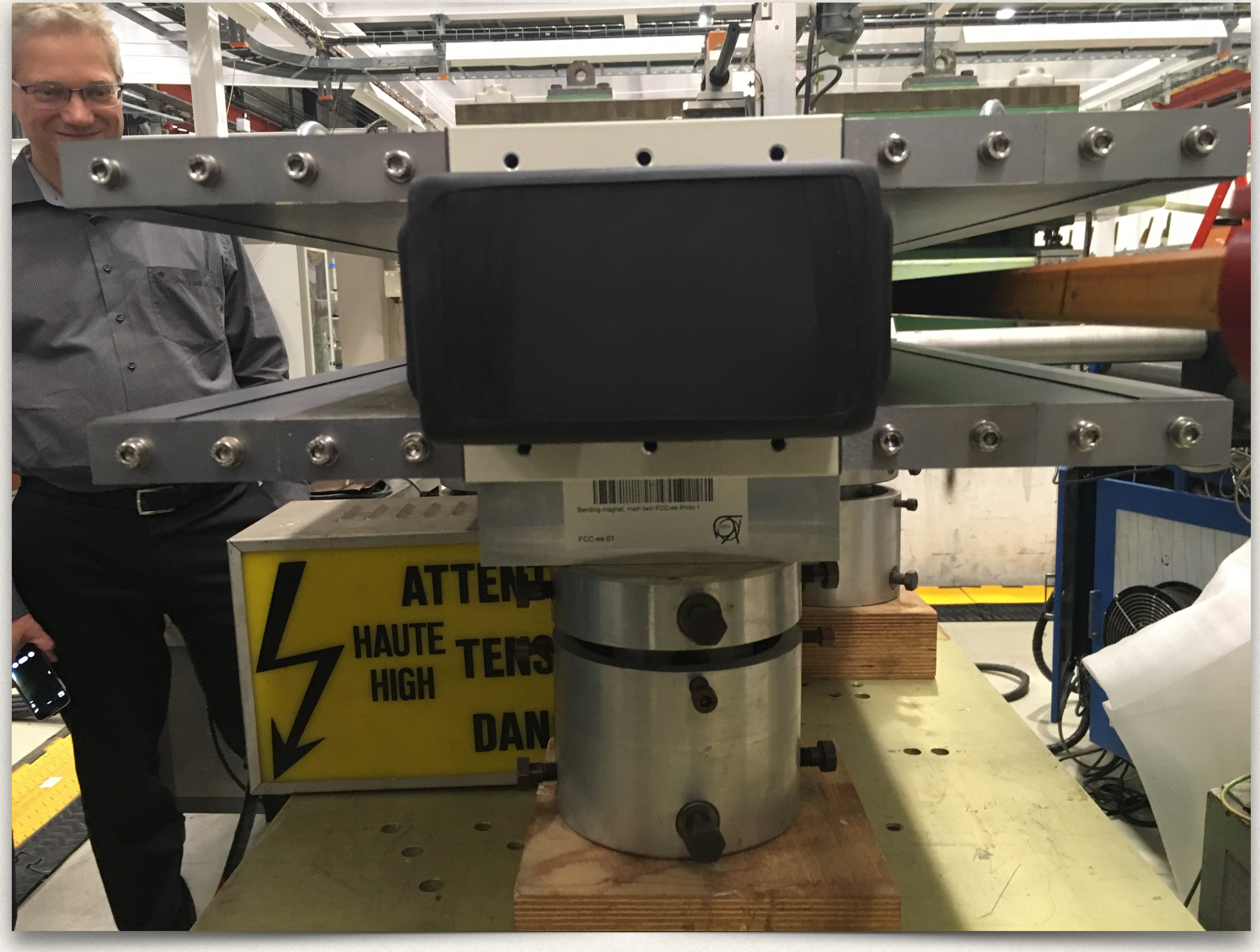


An example of the cross section of a twin aperture quadrupole for FCC-ee (A. Milanese).

The separation between two beams is 30 cm.

- The power consumption of the twin aperture quad: 22 MW at 175 GeV with Cu coil = half of single-aperture quads.
- Dipoles are also "twin": power consumption = 17 MW at 175 GeV with Al bus bar.

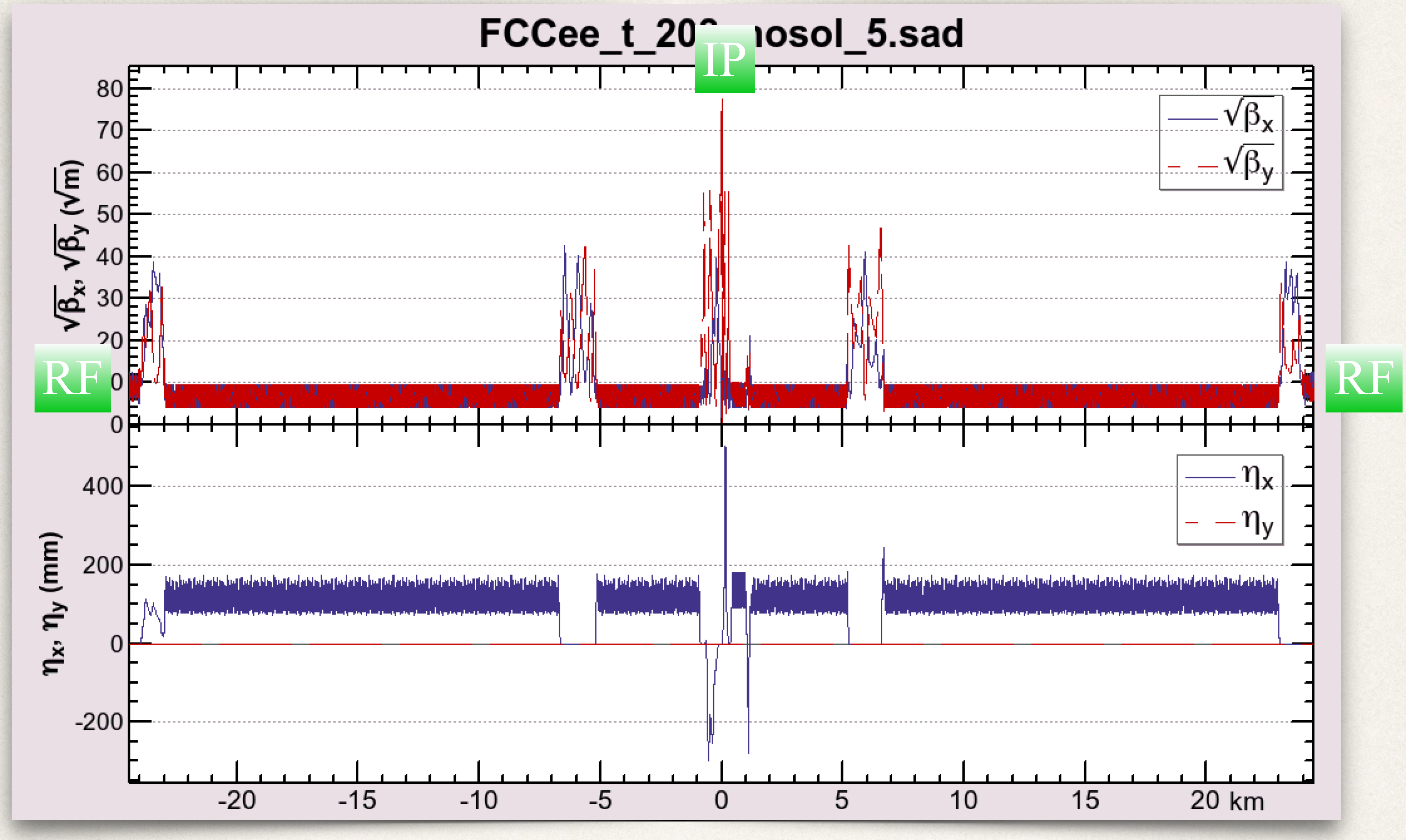
Dipole Prototype @ CERN



- Measurement of field quality is going on.
- A prototype of quadrupole comes soon.

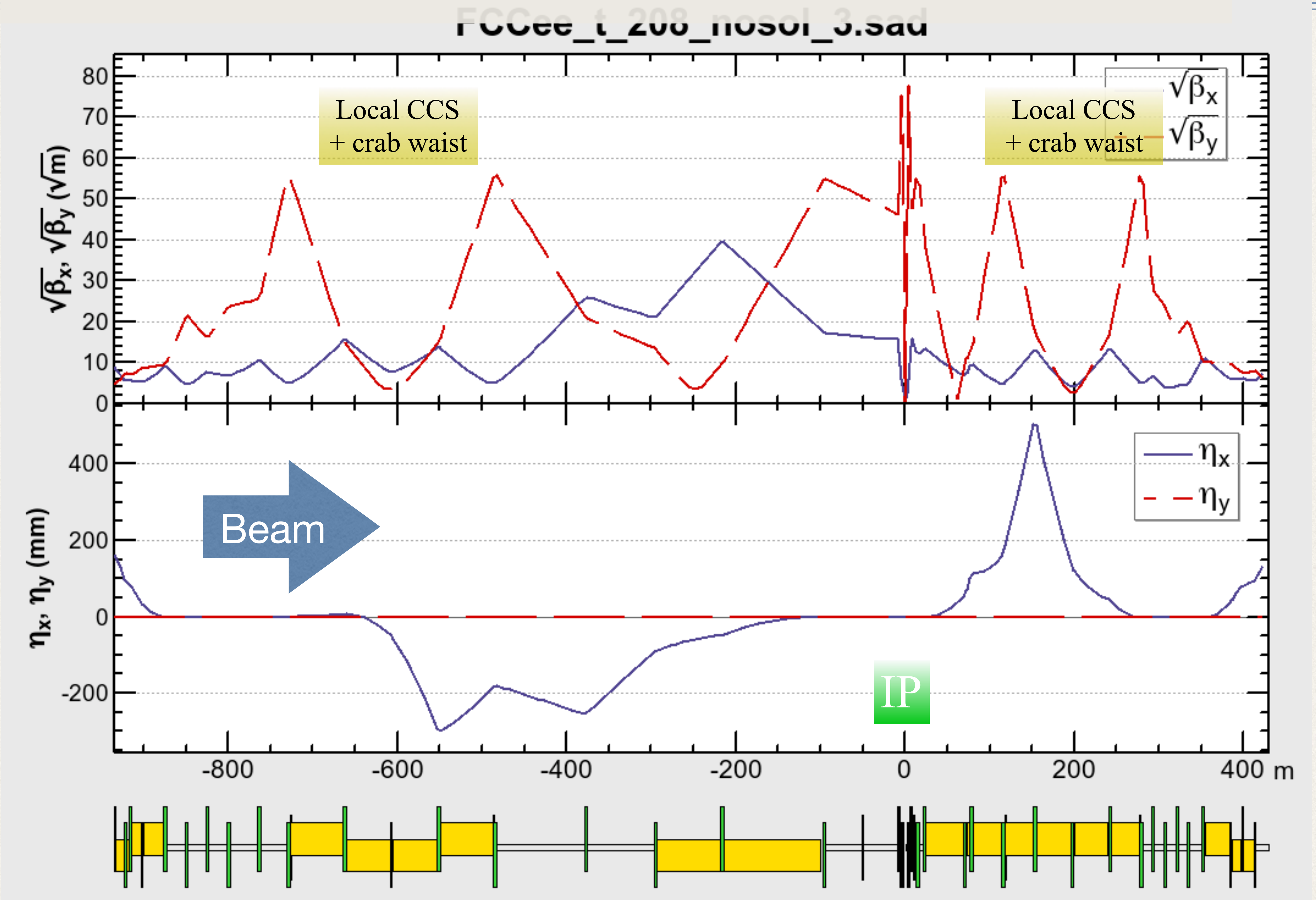
A. Milanese

Half Ring Optics



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

Synchrotron radiation toward the IP @ 182.5 GeV

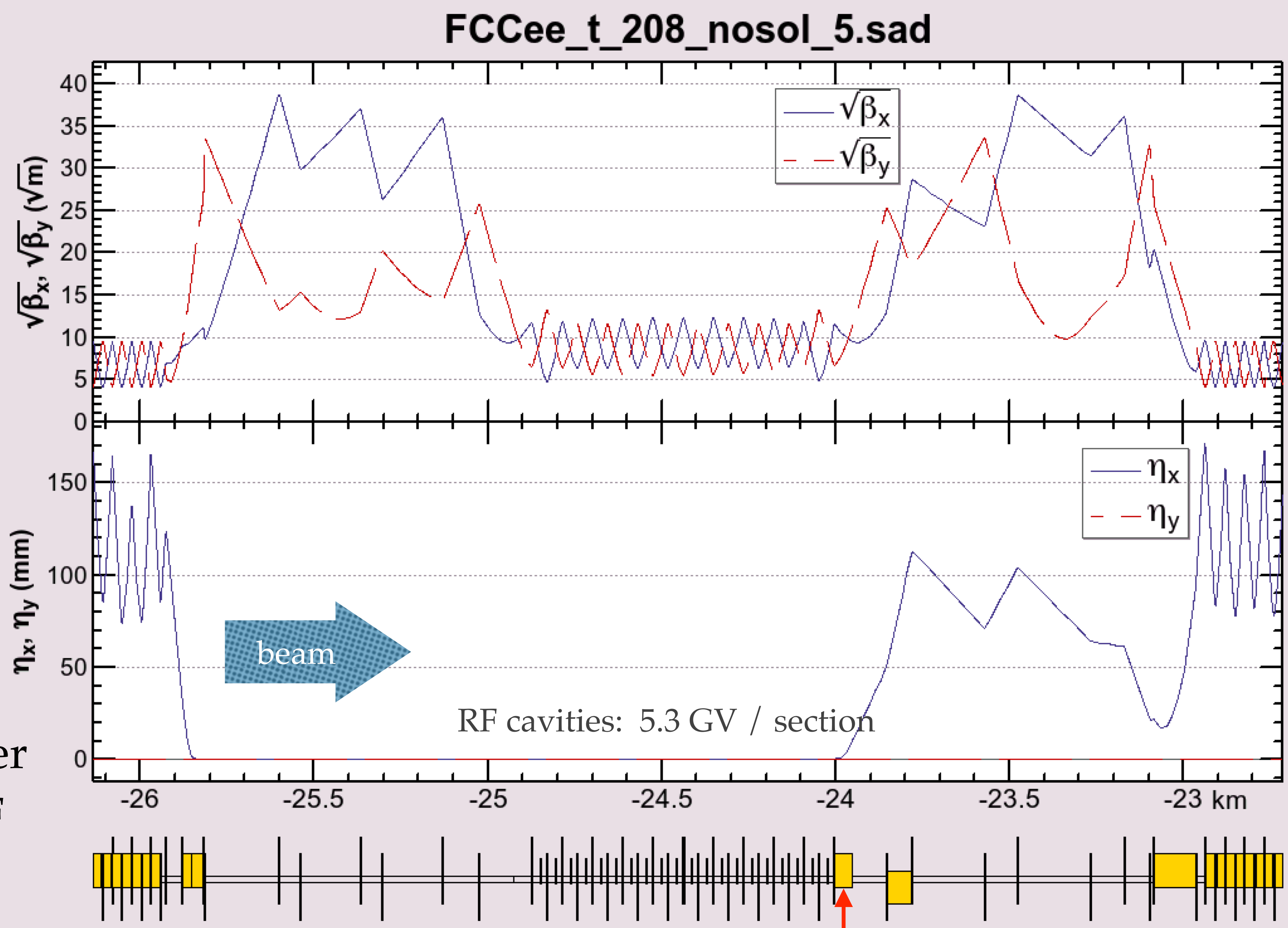


u_c (keV)	1460	571 472 572 226	88.9 93.2	741 648 1004 175 917 …
P_{SR} (kW)	24.2	7.9 7.9 7.9 1.5	0.28 0.47	11.5 0.75 15.9 0.47 0.16 …

$u_c < 100$ keV up to 480 m from the IP.

The RF section (FCC-ee @ 182.5 GeV)

Beams cross over through the RF section.



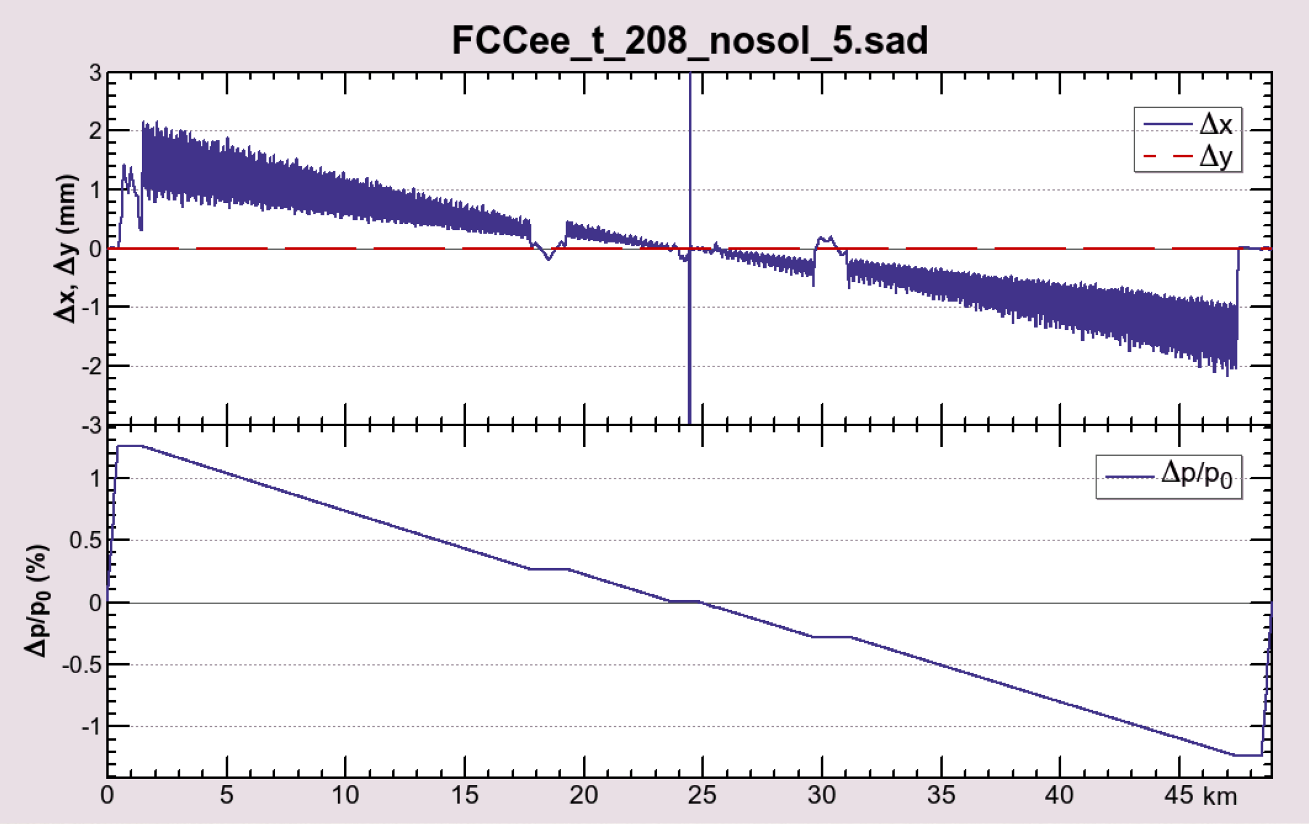
RF cavities: 5.3 GV / section

An electrostatic separator, combined with a dipole magnet

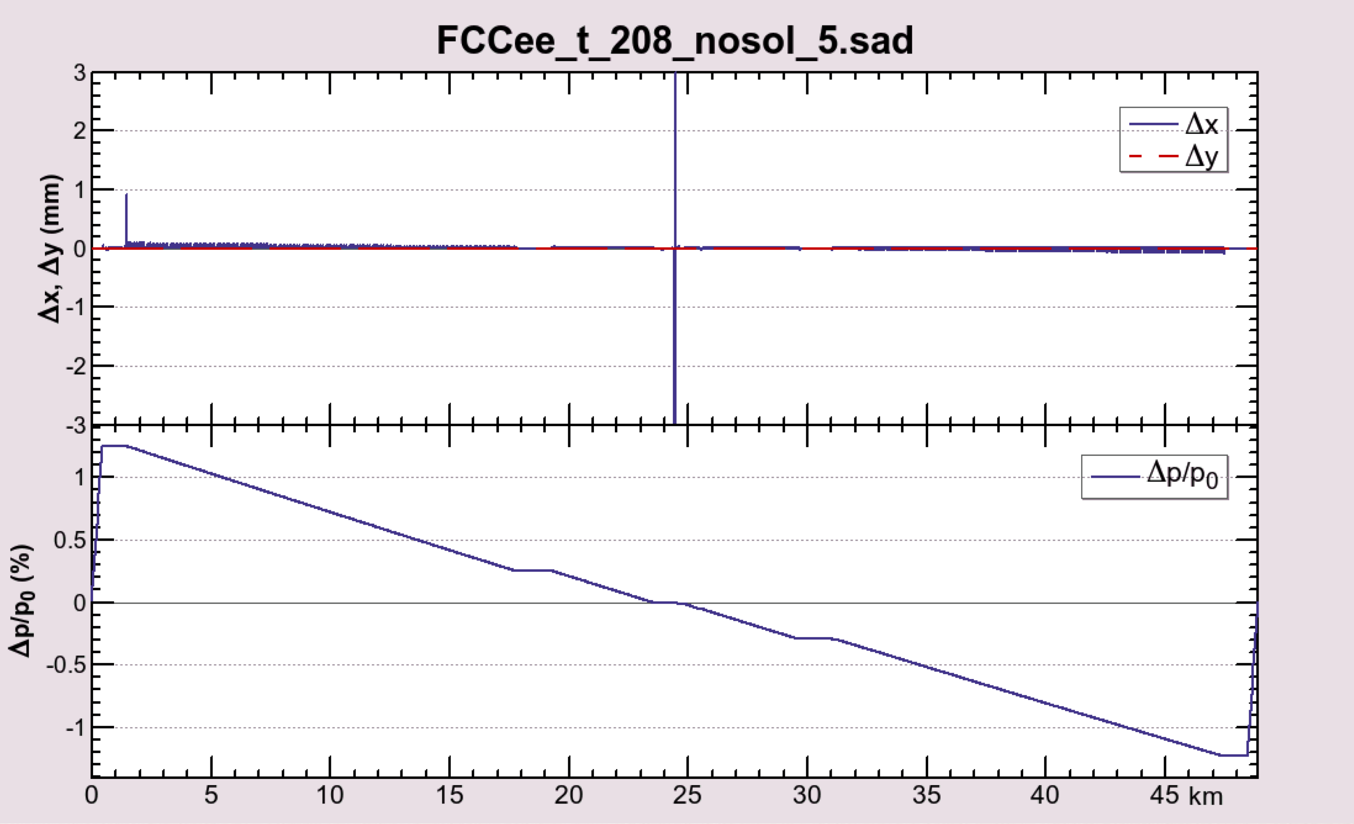
- The usage of the straights on the both sides of the RF is to be determined.
- If the nominal strengths of quads are symmetrical in the common section, it matches to the optics of both beam.
- This section is compatible with the RF staging scenario. For lower energy, the common RF and cross over will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

The Sawtooth & Tapering (FCC-ee @ 182.5 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).

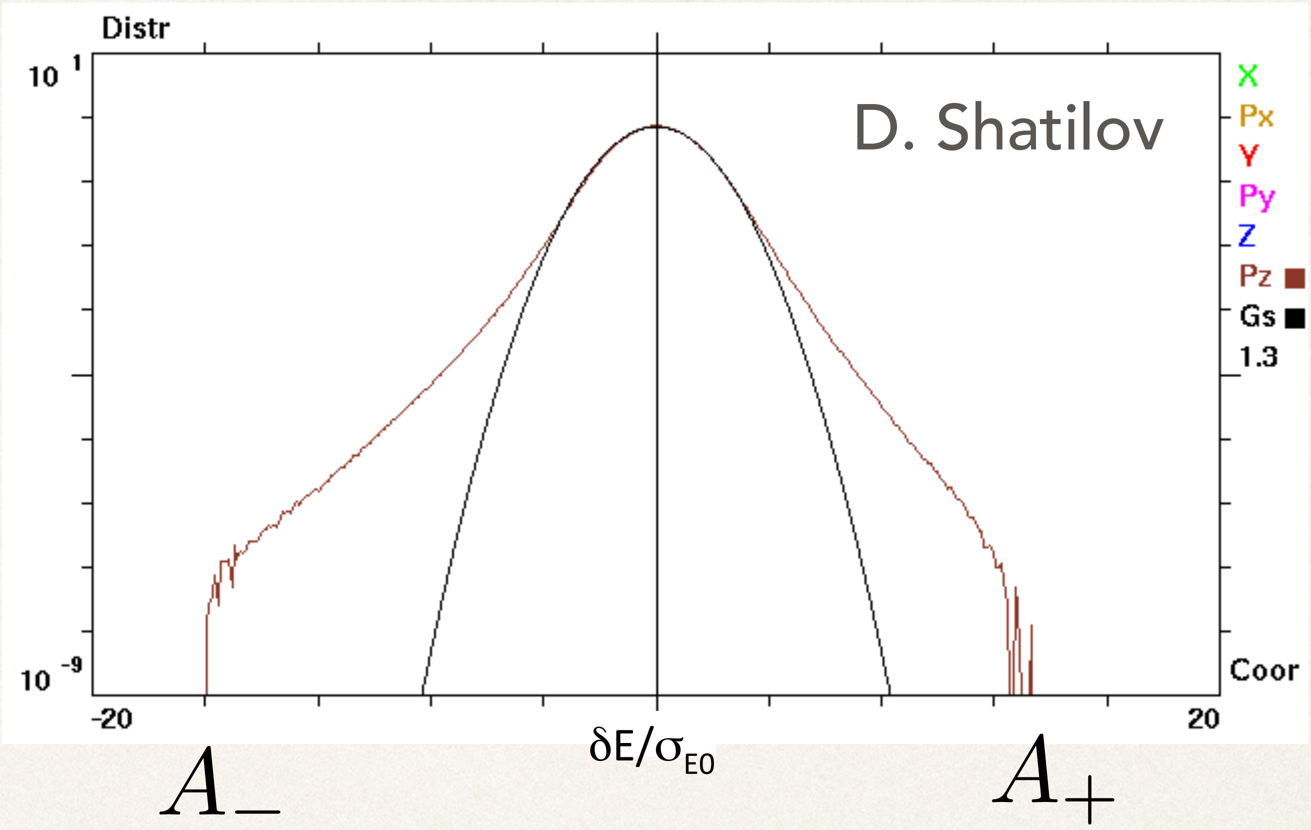
Asymmetric acceptance (ttbar)

E = 182.5 GeV

σ_{E0} = 0.00153, σ_E = 0.00193,

Black line: Gauss with $\sigma_E = 1.3\ \sigma_{E0}$

Energy acceptance: 2.5% = 16.3 σ_{E0}

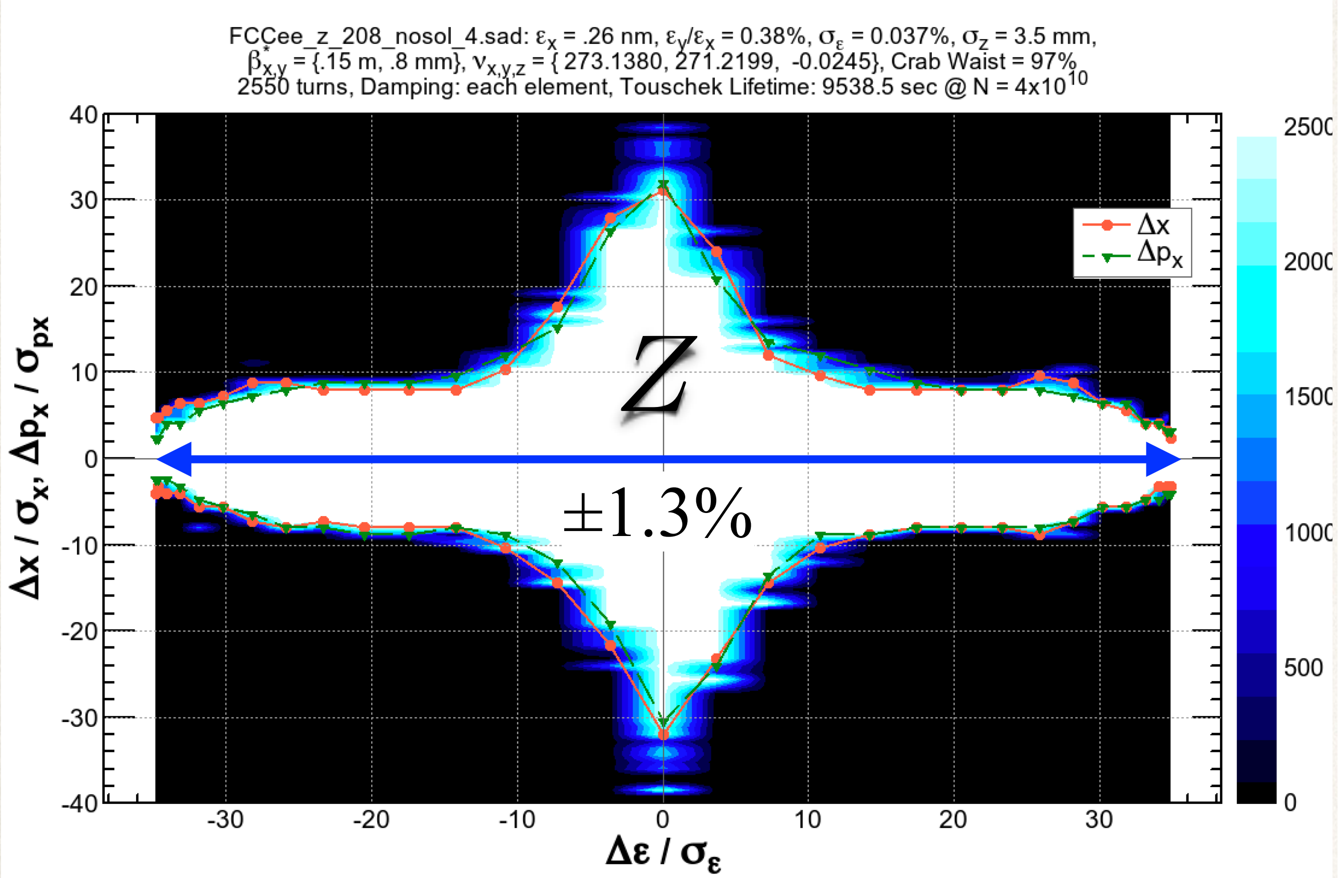


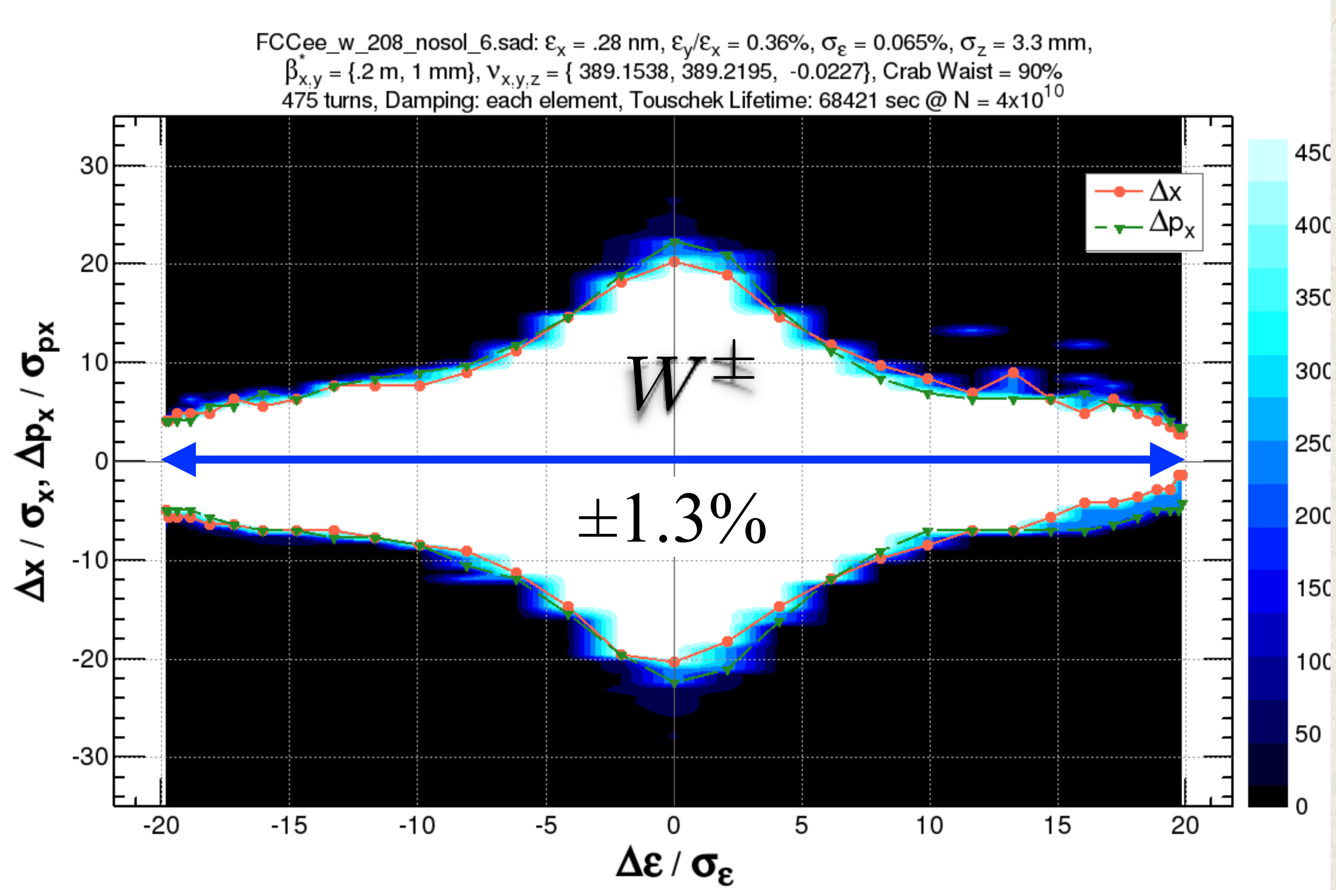
- The expected energy distribution of the beam has asymmetric tail due to beamstrahlung (D. Shatilov, as above).
- Thus the required momentum acceptance should be asymmetric: Wider aperture in the negative side.
- The aperture of the positive side can be expressed as the summation of damping and diffusion terms in a half synchrotron period:

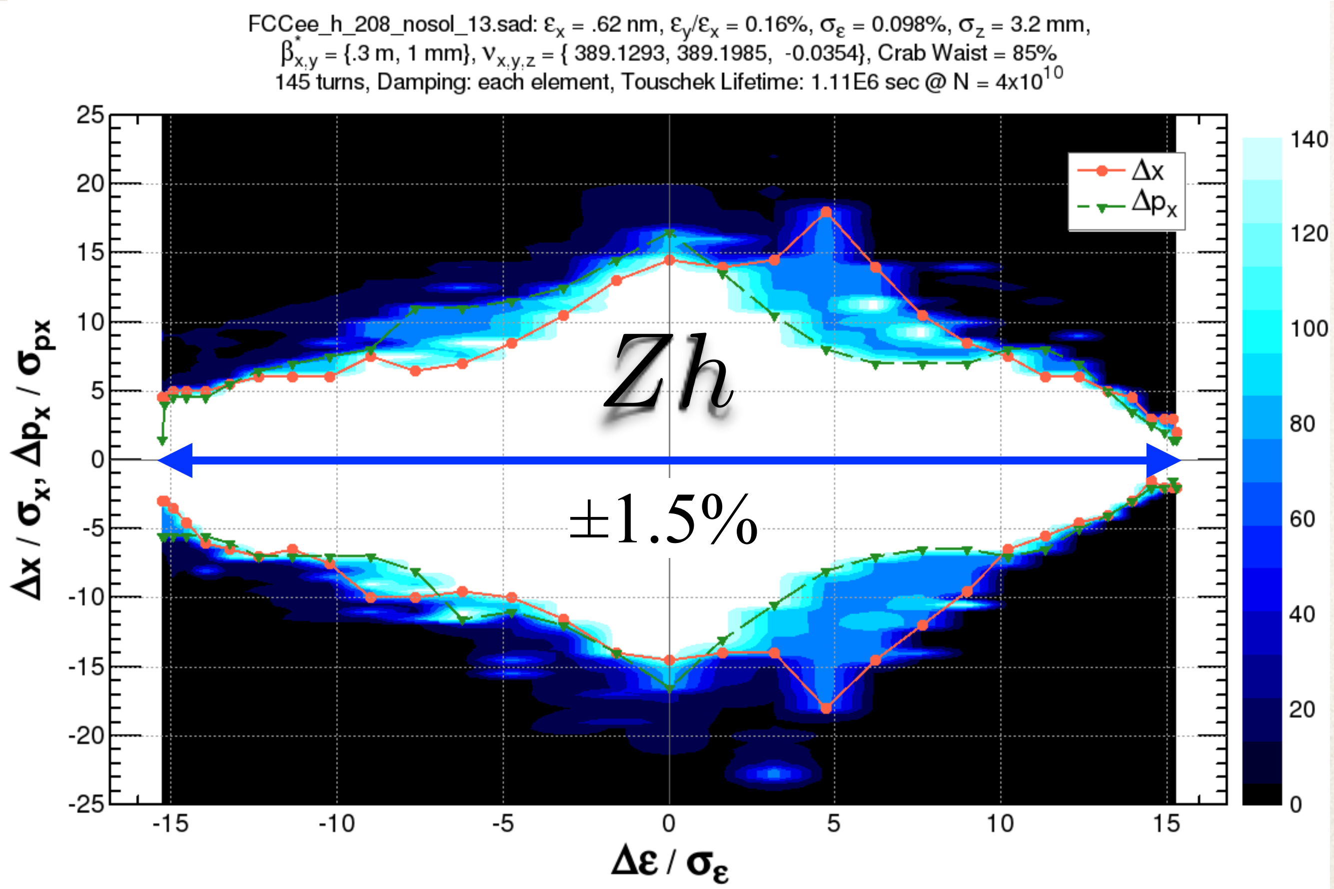
$$A_+ \approx -A_- \exp(-\alpha_z/2\nu_s) + 3\sigma_{\delta,\mathrm{BS}}\sqrt{1-\exp(-\alpha_z/\nu_s)}$$

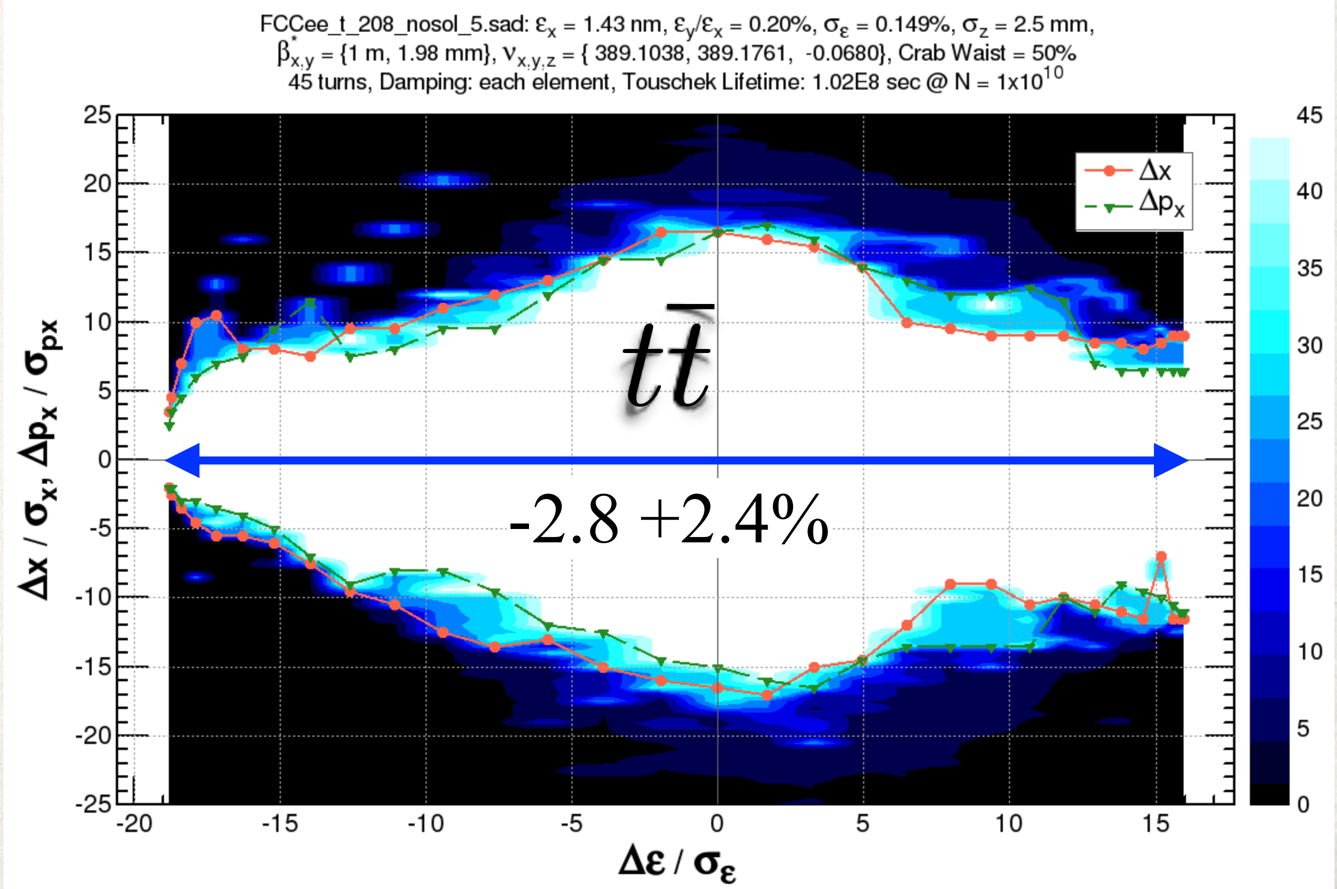
with the damping rate α_z.

Dynamic Aperture


FCCee_z_208_nosol_4.sad: ε_x = .26 nm, $\varepsilon_y/\varepsilon_x$ = 0.38%, σ_ε = 0.037%, σ_z = 3.5 mm,
$\beta^*_{x,y}$ = {.15 m, .8 mm}, $\nu_{x,y,z}$ = { 273.1380, 271.2199, -0.0245}, Crab Waist = 97%
2550 turns, Damping: each element, Touschek Lifetime: 9538.5 sec @ N = 4×10^{10}

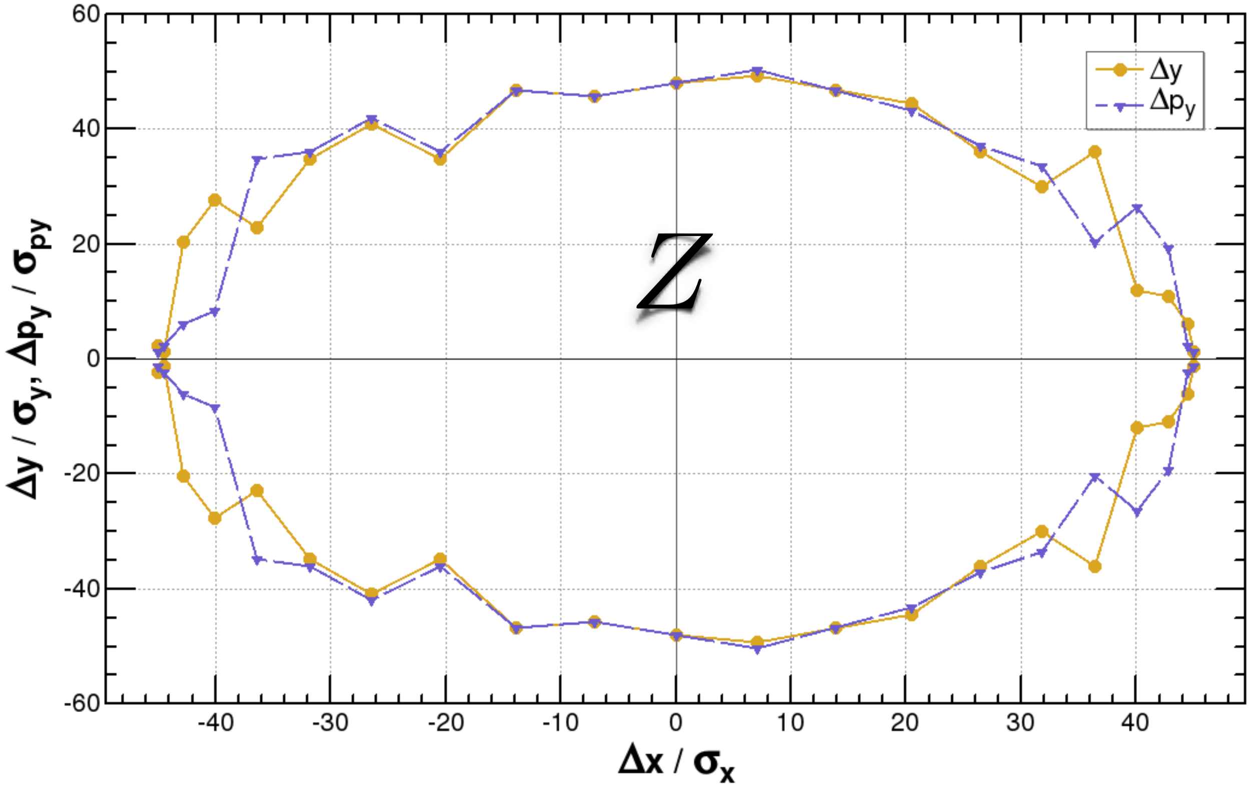

FCCee_w_208_nosol_6.sad: ε_x = .28 nm, $\varepsilon_y/\varepsilon_x$ = 0.36%, σ_ε = 0.065%, σ_z = 3.3 mm,
$\beta^*_{x,y}$ = {.2 m, 1 mm}, $\nu_{x,y,z}$ = { 389.1538, 389.2195, -0.0227}, Crab Waist = 90%
475 turns, Damping: each element, Touschek Lifetime: 68421 sec @ N = 4×10^{10}


FCCee_h_208_nosol_13.sad: ε_x = .62 nm, $\varepsilon_y/\varepsilon_x$ = 0.16%, σ_ε = 0.098%, σ_z = 3.2 mm,
$\beta^*_{x,y}$ = {.3 m, 1 mm}, $\nu_{x,y,z}$ = { 389.1293, 389.1985, -0.0354}, Crab Waist = 85%
145 turns, Damping: each element, Touschek Lifetime: 1.11E6 sec @ N = 4×10^{10}

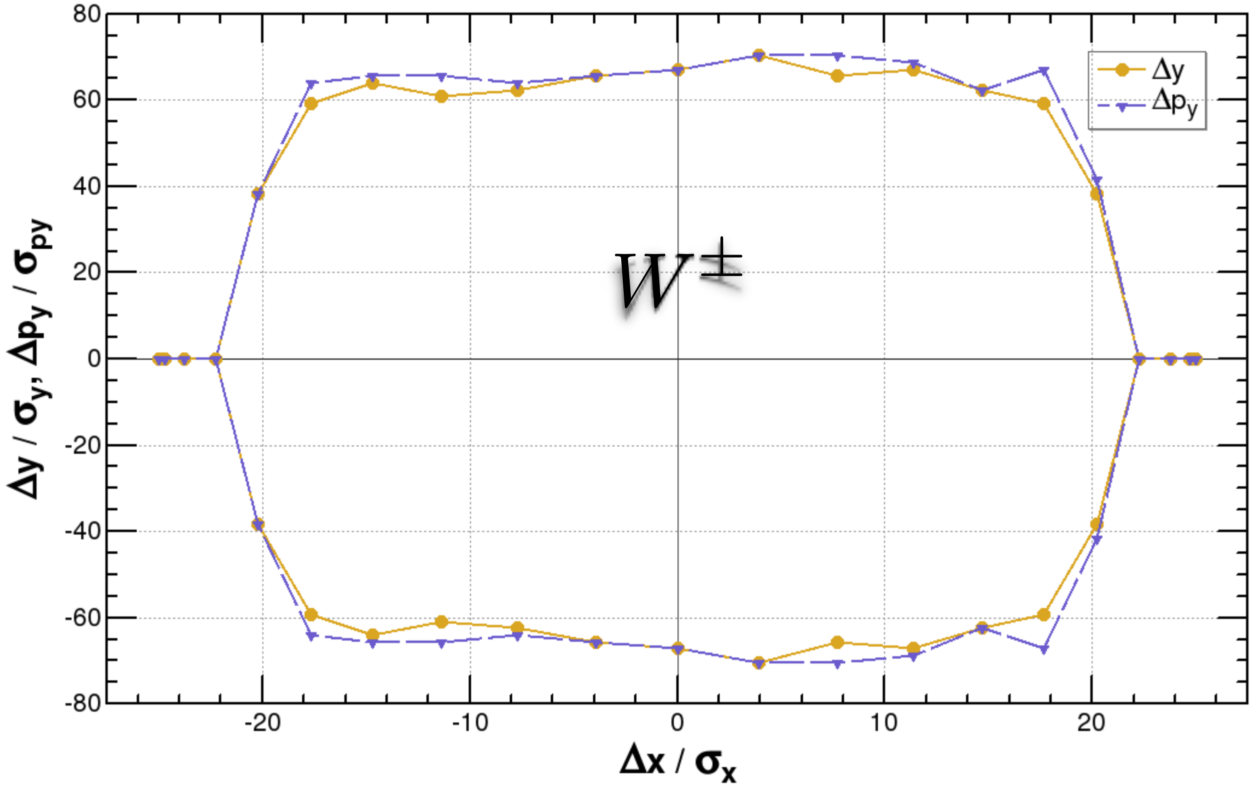

FCCee_t_208_nosol_5.sad: ε_x = 1.43 nm, $\varepsilon_y/\varepsilon_x$ = 0.20%, σ_ε = 0.149%, σ_z = 2.5 mm,
$\beta^*_{x,y}$ = {1 m, 1.98 mm}, $\nu_{x,y,z}$ = { 389.1038, 389.1761, -0.0680}, Crab Waist = 50%
45 turns, Damping: each element, Touschek Lifetime: 1.02E8 sec @ N = 1×10^{10}

Dynamic Aperture (cont'd : on-momentum transverse)

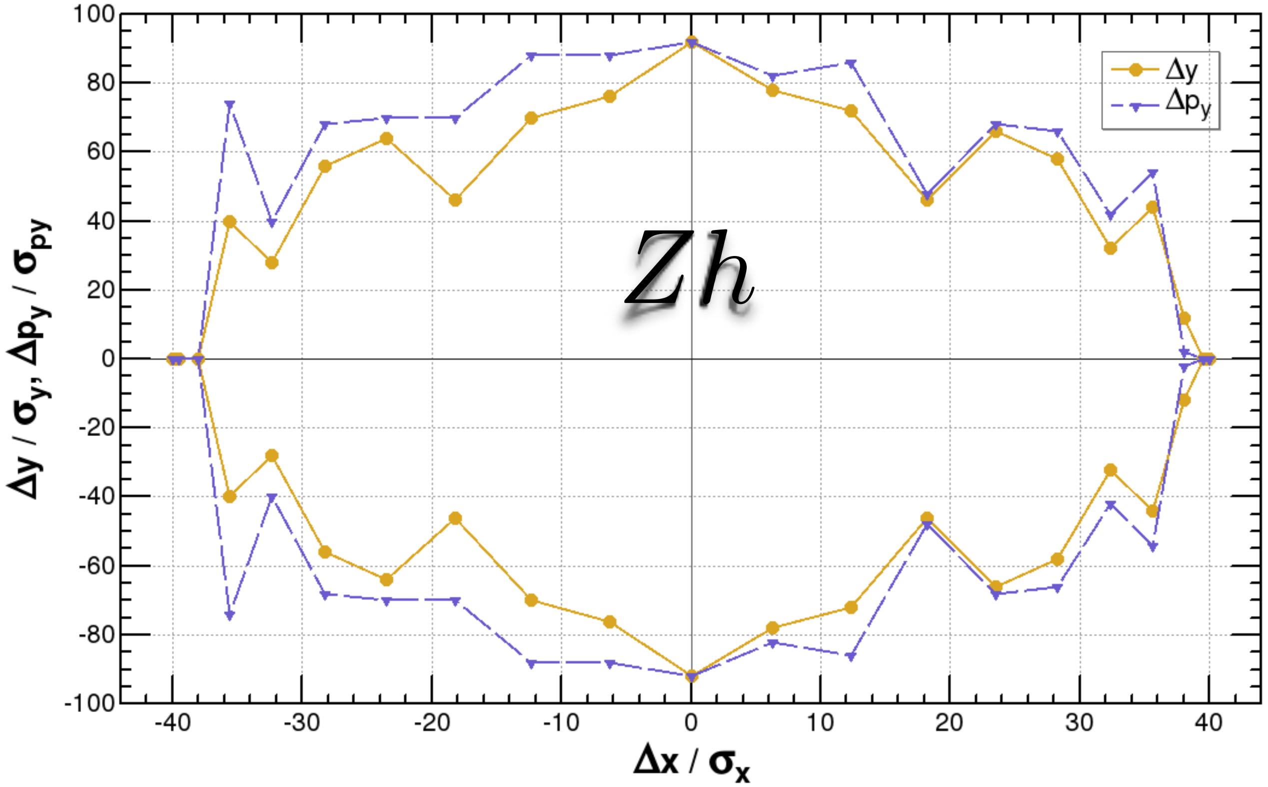
FCCee_z_208_nosol_4.sad: ε_x = .26 nm, $\varepsilon_y/\varepsilon_x$ = 0.38%, σ_ε = 0.037%, σ_z = 3.5 mm,
$\beta^*_{x,y}$ = {.15 m, .8 mm}, $\nu_{x,y,z}$ = { 273.1380, 271.2199, -0.0245}, Crab Waist = 97%
2550 turns, Damping: each element, $\Delta p/p$ = 0%



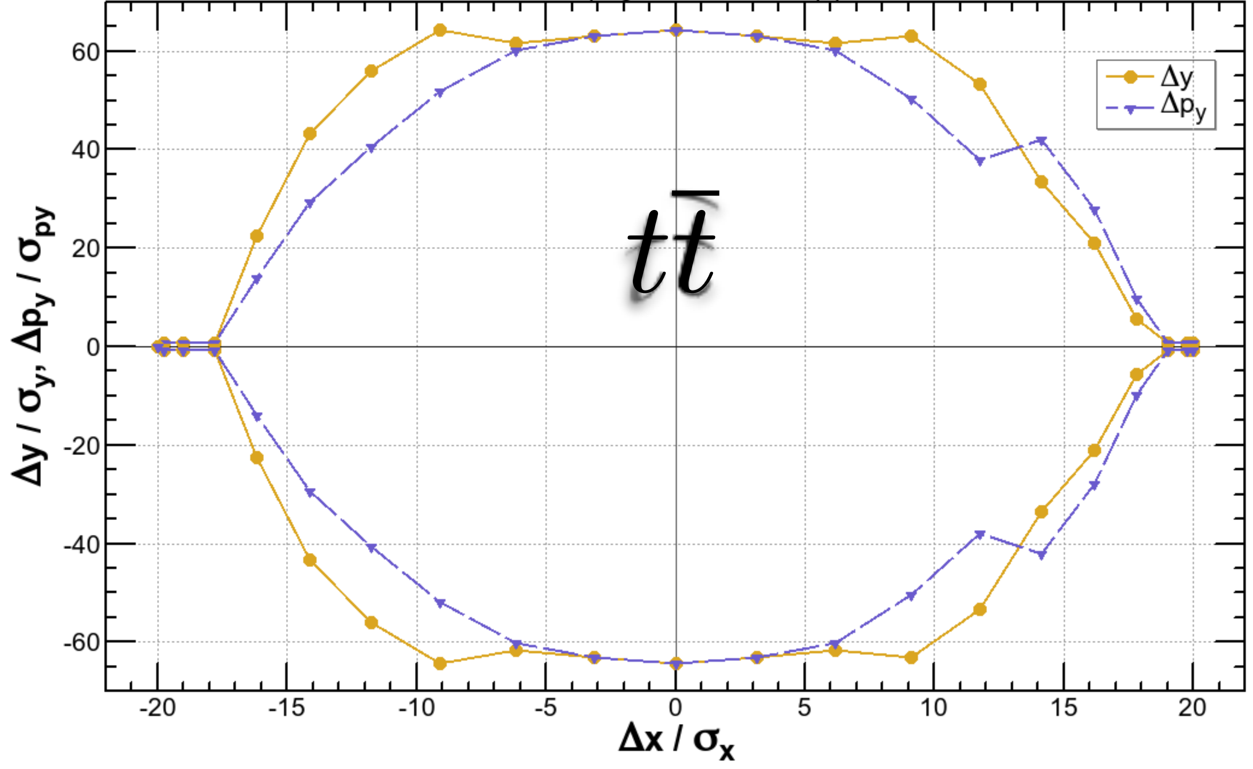
FCCee_w_208_nosol_6.sad: ε_x = .28 nm, $\varepsilon_y/\varepsilon_x$ = 0.36%, σ_ε = 0.065%, σ_z = 3.3 mm,
$\beta^*_{x,y}$ = {.2 m, 1 mm}, $\nu_{x,y,z}$ = { 389.1538, 389.2195, -0.0227}, Crab Waist = 90%
475 turns, Damping: each element, $\Delta p/p$ = 0%



FCCee_h_208_nosol_13.sad: ε_x = .62 nm, $\varepsilon_y/\varepsilon_x$ = 0.40%, σ_ε = 0.098%, σ_z = 3.2 mm,
$\beta^*_{x,y}$ = {.3 m, 1 mm}, $\nu_{x,y,z}$ = { 389.1300, 389.2000, -0.0354}, Crab Waist = 85%
145 turns, Damping: each turn, $\Delta p/p$ = 0%



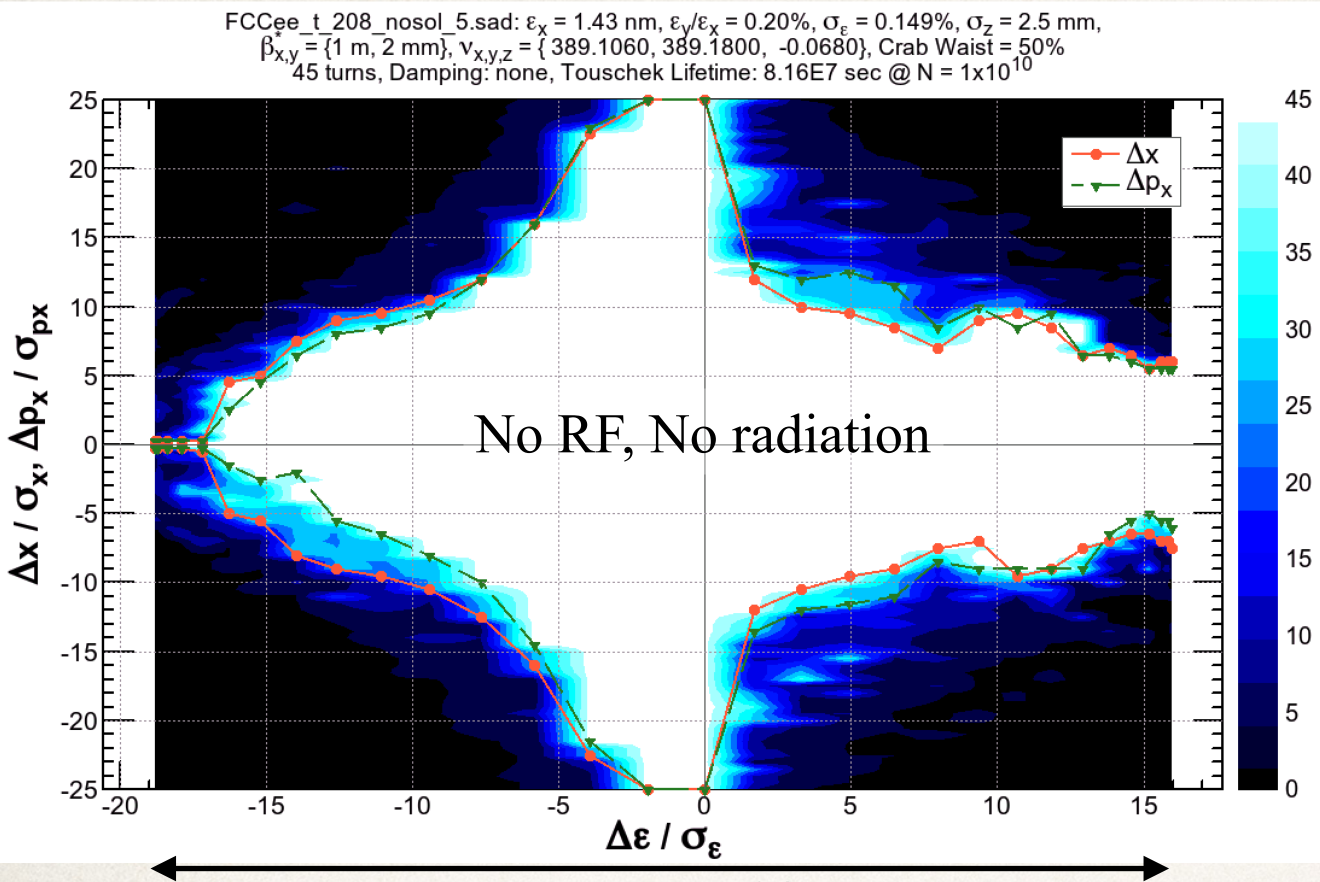
FCCee_t_208_nosol_5.sad: ε_x = 1.43 nm, $\varepsilon_y/\varepsilon_x$ = 0.20%, σ_ε = 0.149%, σ_z = 2.5 mm,
$\beta^*_{x,y}$ = {1 m, 1.98 mm}, $\nu_{x,y,z}$ = { 389.1038, 389.1761, -0.0680}, Crab Waist = 50%
45 turns, Damping: each element, $\Delta p/p$ = 0%



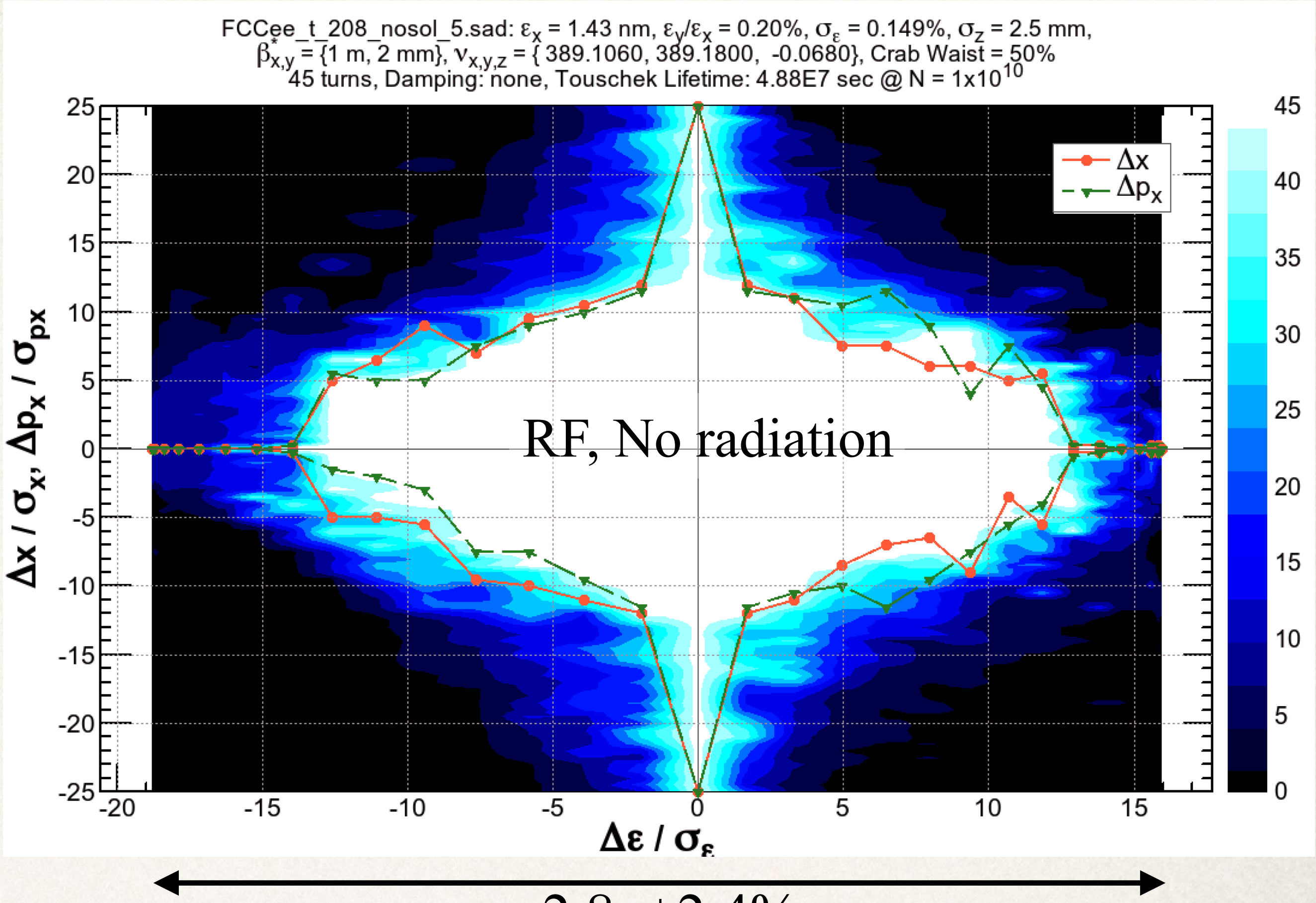
Effects included in the dynamic aperture survey

Effects	Included?	Significance
Synchrotron motion	Yes	**Essential**
Radiation loss in dipoles	Yes	**Essential** – improves the aperture
Radiation loss in quadrupoles	Yes	**Essential** – reduces the aperture esp. at $t\bar{t}$
Radiation fluctuation	after optimization	**Essential**
Tapering	Yes	**Essential**
Crab waist	Yes	transverse aperture is reduced by $\sim 20\%$
Maxwellian fringes	Yes	small
Kinematical terms	Yes	small
Solenoids	Evaluated separately	minimal, if locally compensated
Beam-beam effects and beamstrahlung for stored beam	after optimization (D. Zhou, D. El Kechen)	affects the lifetime for $\beta_y^* = 1$ mm at $t\bar{t}$
Beam-beam effects for injected beam	on going	
Higher order fields / errors / misalignments	on going	**Essential**, development of correction/tuning scheme is necessary

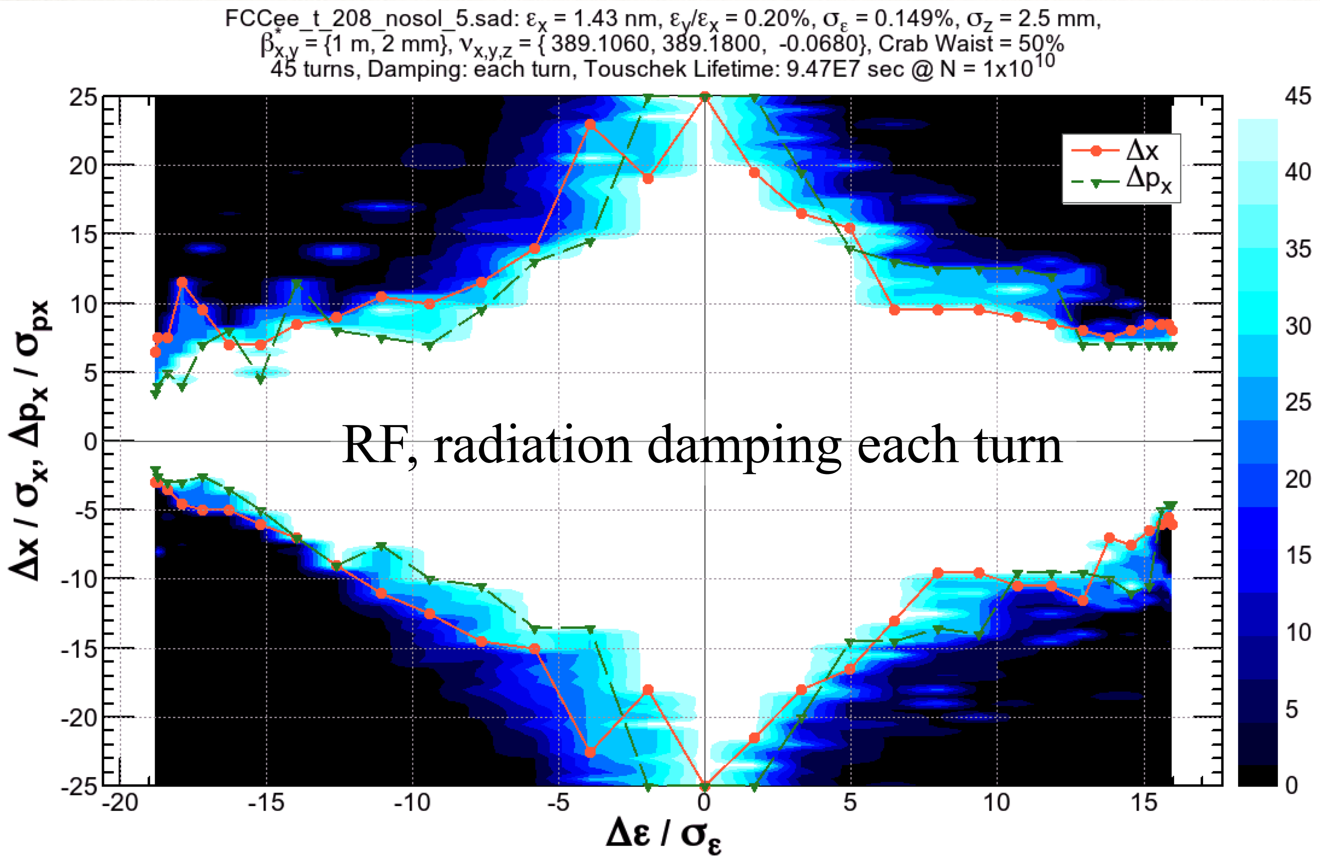
Several effects on the dynamic aperture (ttbar)

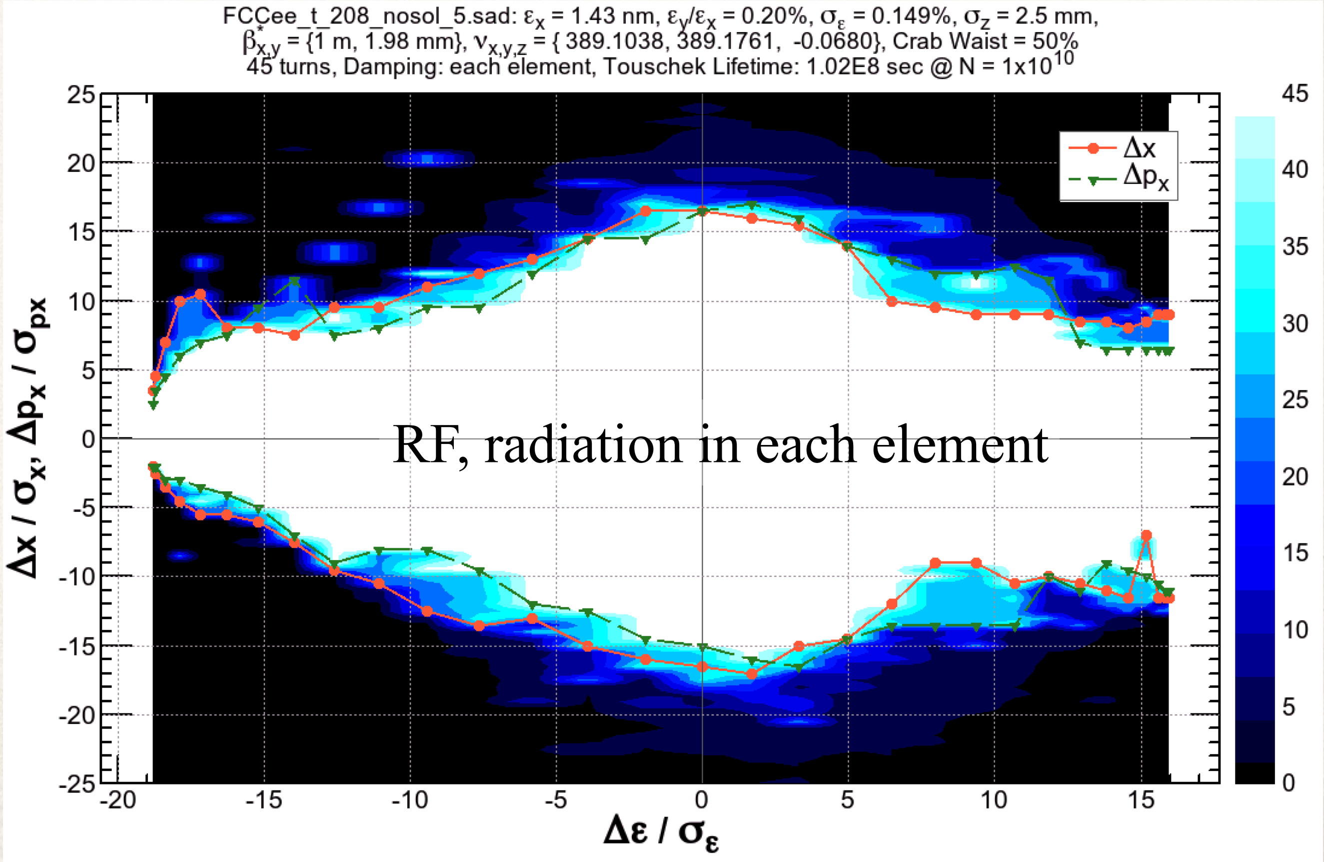


-2.8, +2.4%

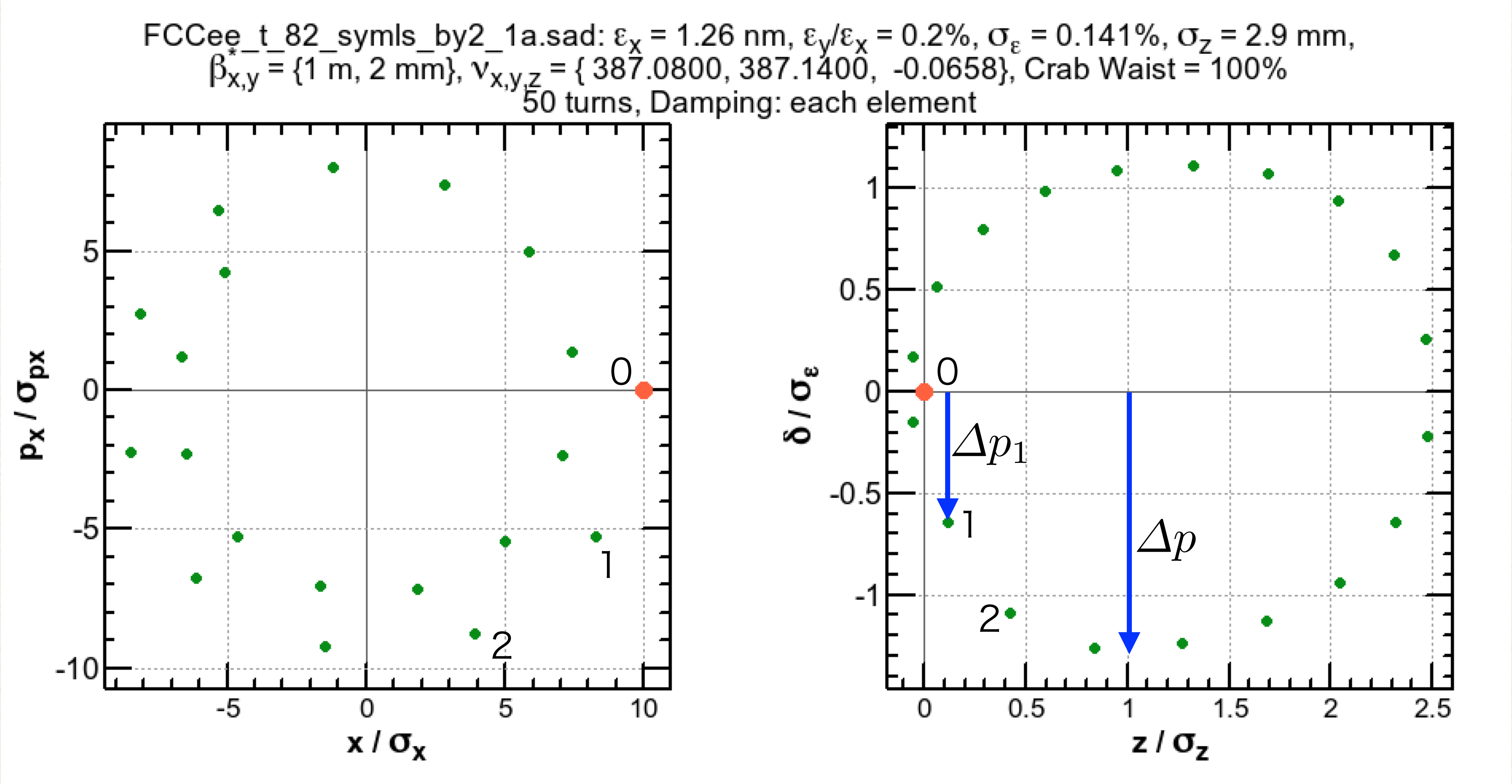


-2.8, +2.4%





Synchrotron radiation in quadrupoles



- Horizontal betatron oscillation (left) causes a synchrotron motion (right) due to the energy loss by the synchrotron radiation in arc quadrupoles.

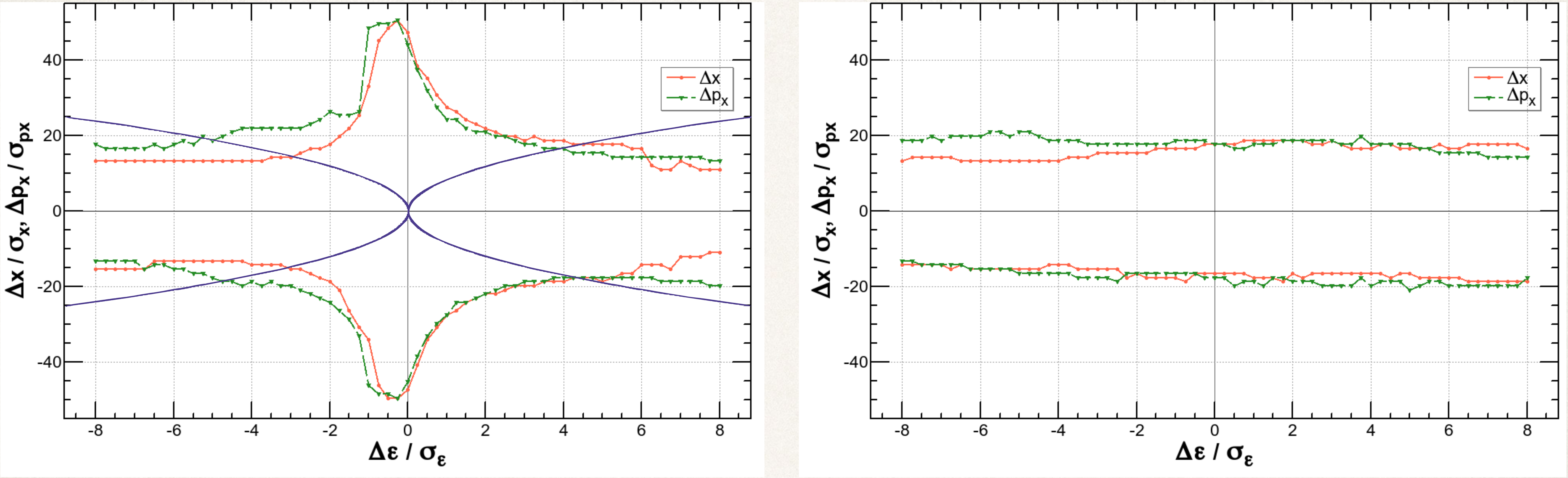
$$\Delta p = \frac{\Delta p_1}{2\pi\nu_s}\exp(-\alpha_z/4\nu_s) = \frac{\alpha_z}{\pi\nu_s J_z} R_{\mathrm{Q}} n^2 \varepsilon_x \exp(-\alpha_z/4\nu_s)\ ,$$

$$R_{\mathrm{Q}} = \frac{2\sqrt{2}}{\theta_c^2}\left(\frac{\sqrt{2}+1}{\ell_{\mathrm{QF}}} + \frac{\sqrt{2}-1}{\ell_{\mathrm{QD}}}\right) \quad (90^\circ\ \mathrm{FODO})$$

- Such particles can not stay on momentum: reduction of the dynamic aperture.

Synchrotron radiation in quadrupoles (cont'd)

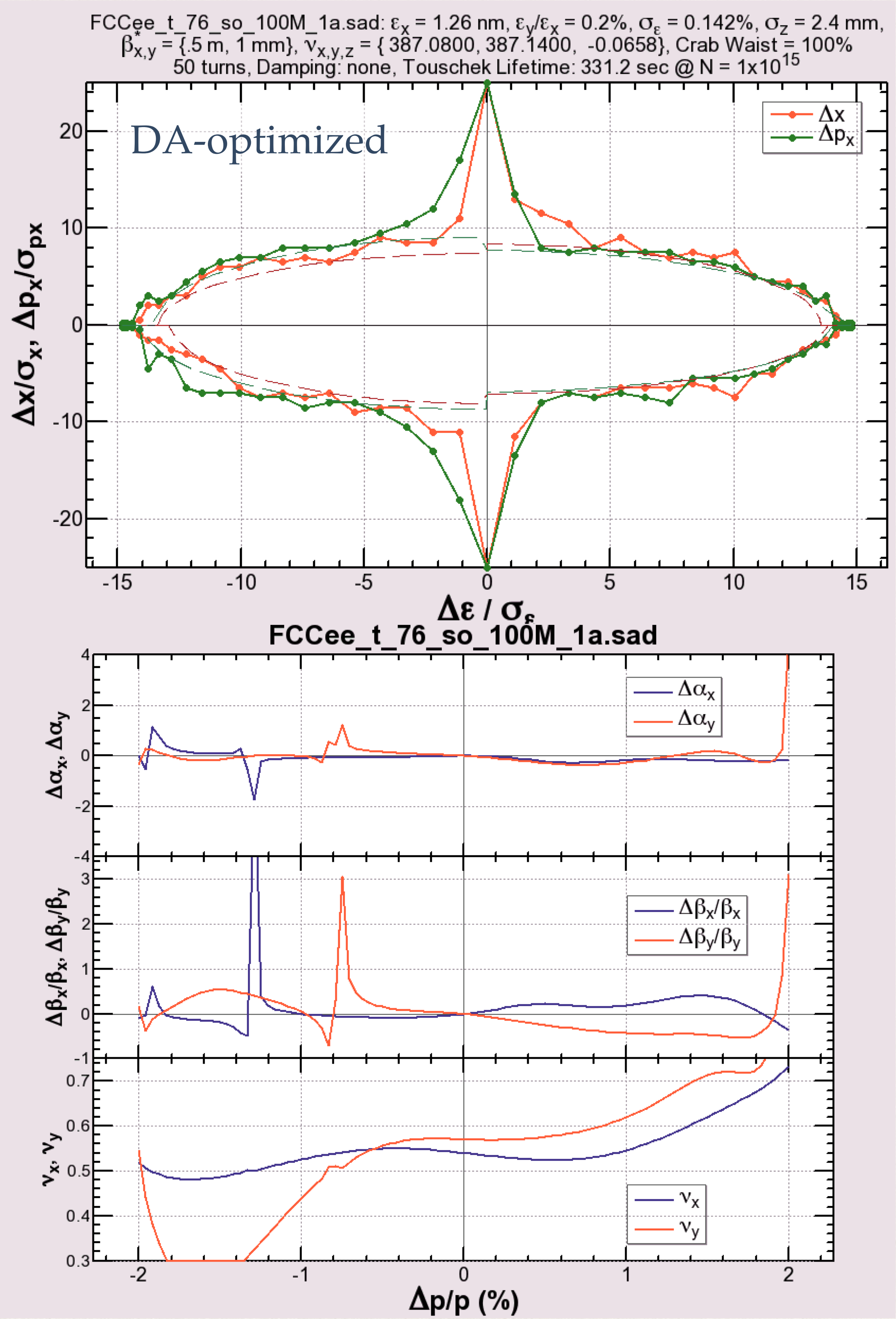
E = 175 GeV, $\beta_{x,y}$ = (1 m, 2 mm)

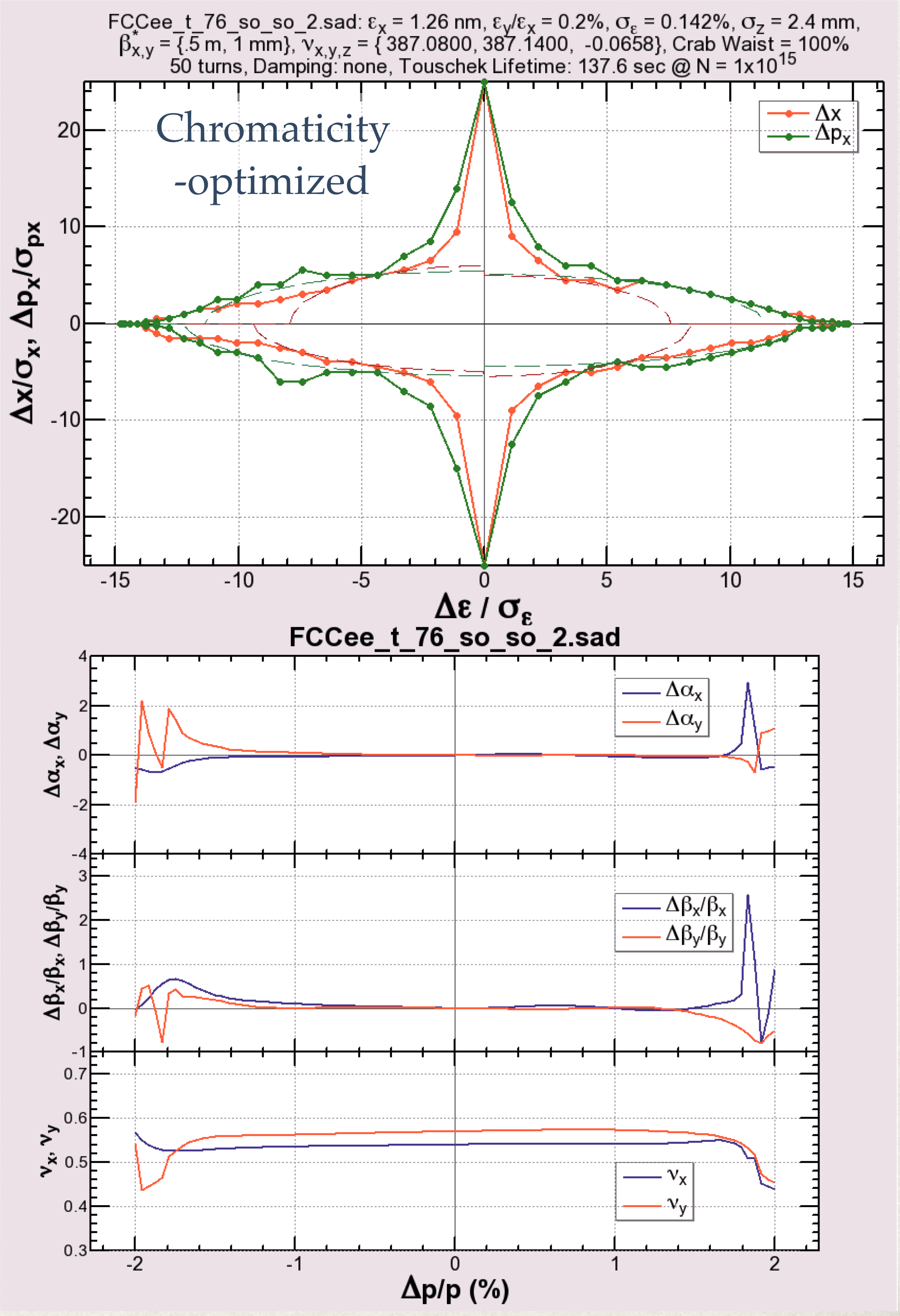


- The dynamic aperture without radiation loss in quadrupoles (left) has a sharp peak at on momentum.
- The peak is destroyed if the radiation in quads is turned on (right).
- The parabolas on the left show the amplitude of the synchrotron motion due to the radiation in the quadrupole. For a given transverse amplitude, if the parabola is beyond the DA, the particle with that amplitude will be lost.
- More effects will be presented by A. Bogomyagkov in this workshop.

Less chromaticity ≠ better dynamic aperture

$\beta^*_{x,y}$ = (0.5 m, 1 mm), no radiation damping

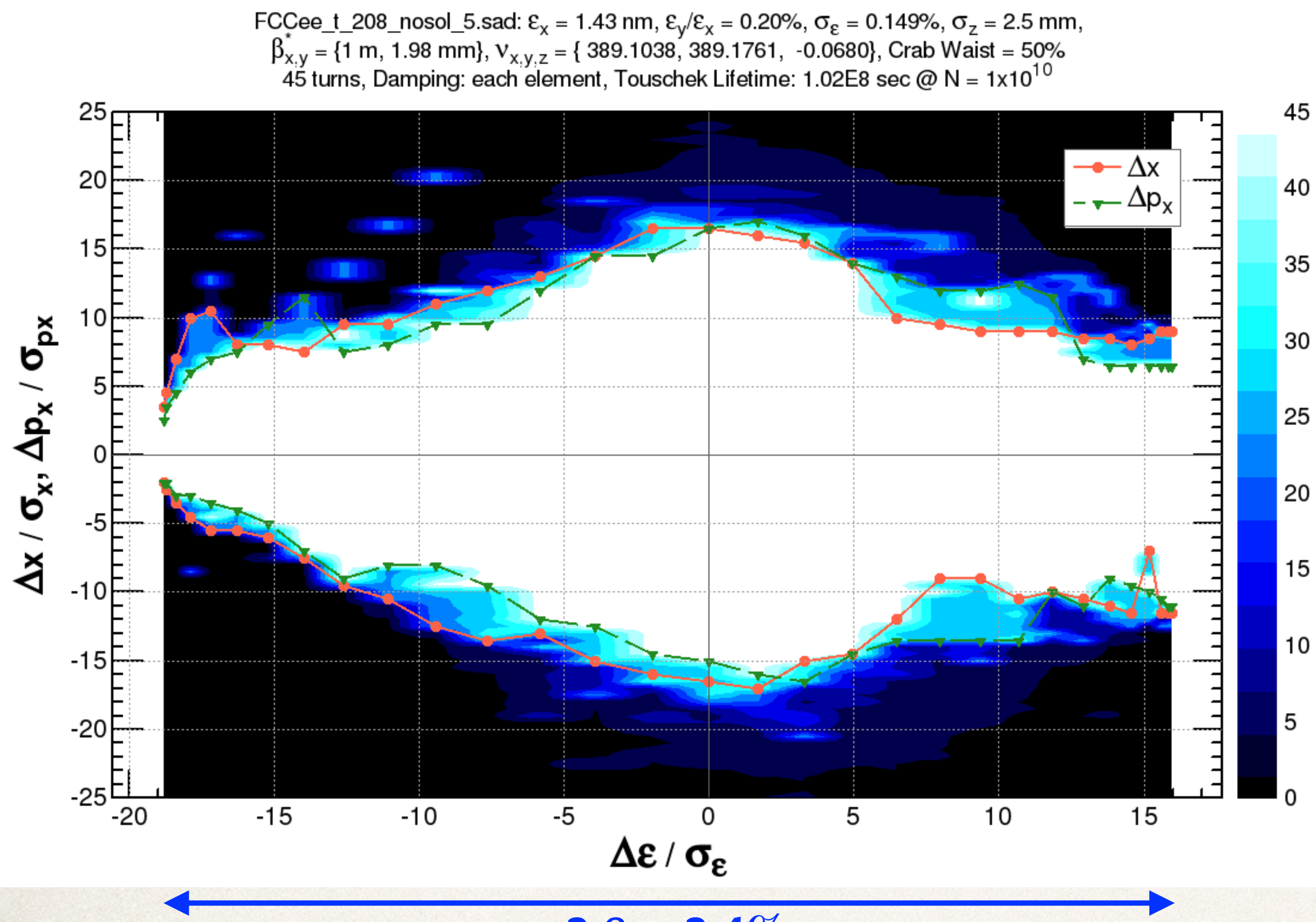




Effect of Radiation Fluctuation

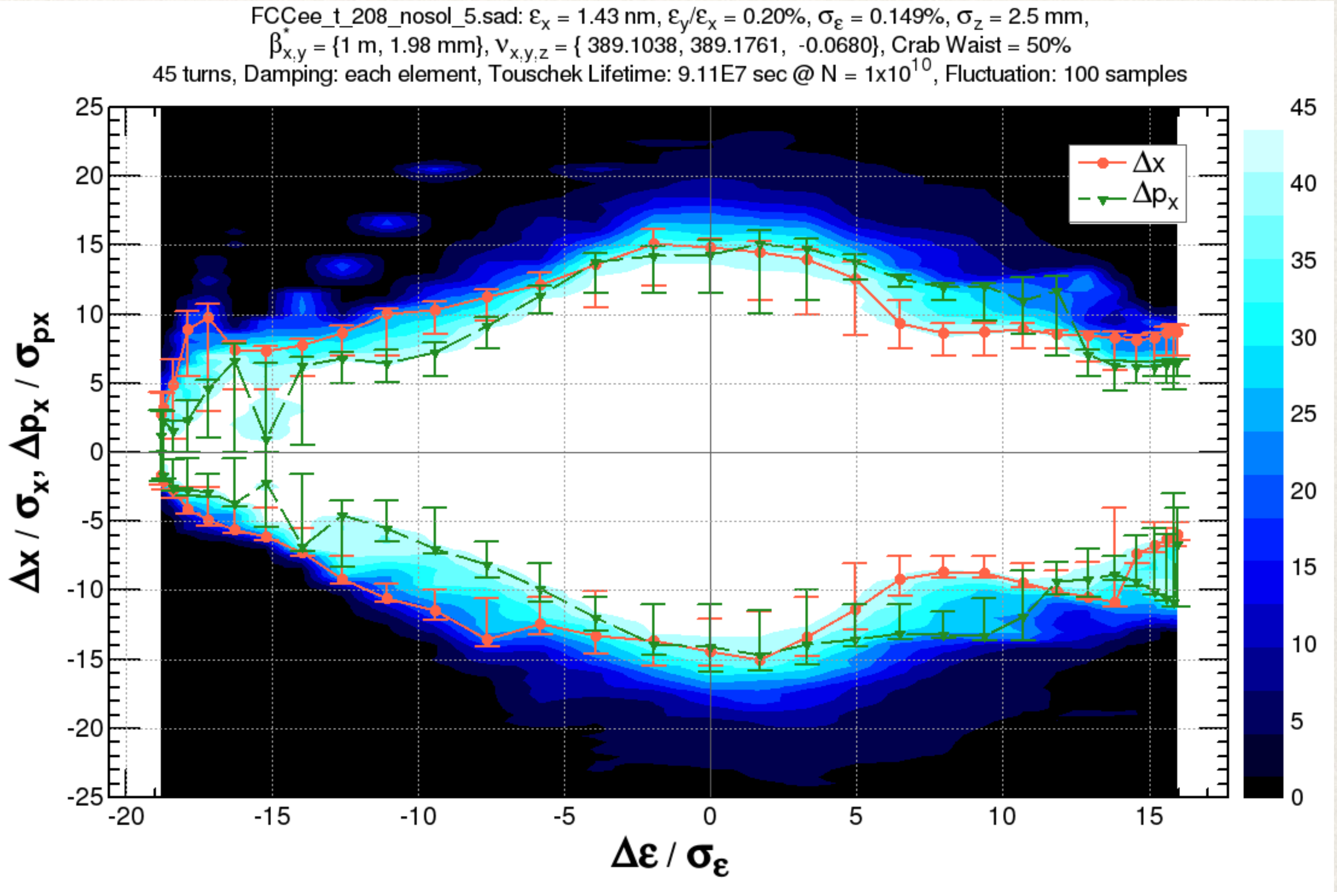
E = 182.5 GeV, $\beta^*_{x,y}$ = (1 m, 2 mm)

Radiation damping only



-2.8, +2.4%

Radiation damping + fluctuation



- (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.

Summary

- Modification of the beam optics for FCC-ee has been performed over the base line optics 2016:
  - Mitigation of the coherent beam-beam instability at Z
    - *By achieving smaller* β_x^* *at Z, W, Zh.*
    - *Applying 60°/60° cell in the arc, only at Z, compatible with 90°/90° cell at higher energies.*
  - The base energy for tuba is raised to 182.5 GeV, keeping the SR to IP below 100 keV.
  - Adopt the "Twin Aperture Quadrupole" scheme for arc quadrupoles.
  - Fit the footprint to a new FCC-hh layout.
- The resulting dynamic aperture is sufficient for the beamstrahlung and top-up injection.