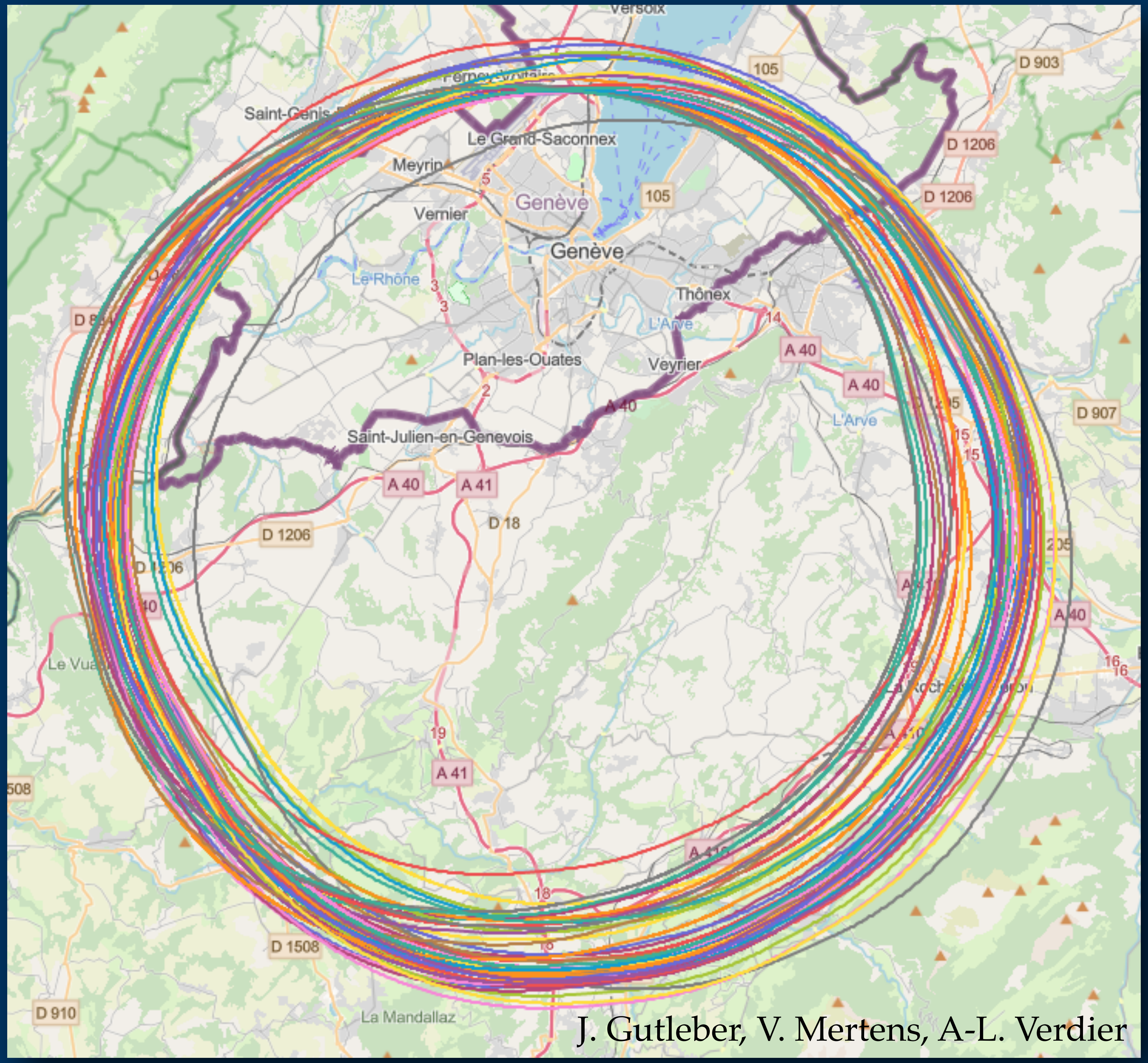


FUTURE CIRCULAR COLLIDER

Open points on FCC-ee collider optics

K. Oide

Dec. 2, 2021 @ FCC ABP Day

Many thanks to M. Benedikt, M. Hofer, T. Raubenheimer, D. Shatilov, Zimmermann, and all FCC-ee/FCCIS colleagues

Characteristics of FCC-ee optics

FUTURE CIRCULAR COLLIDER

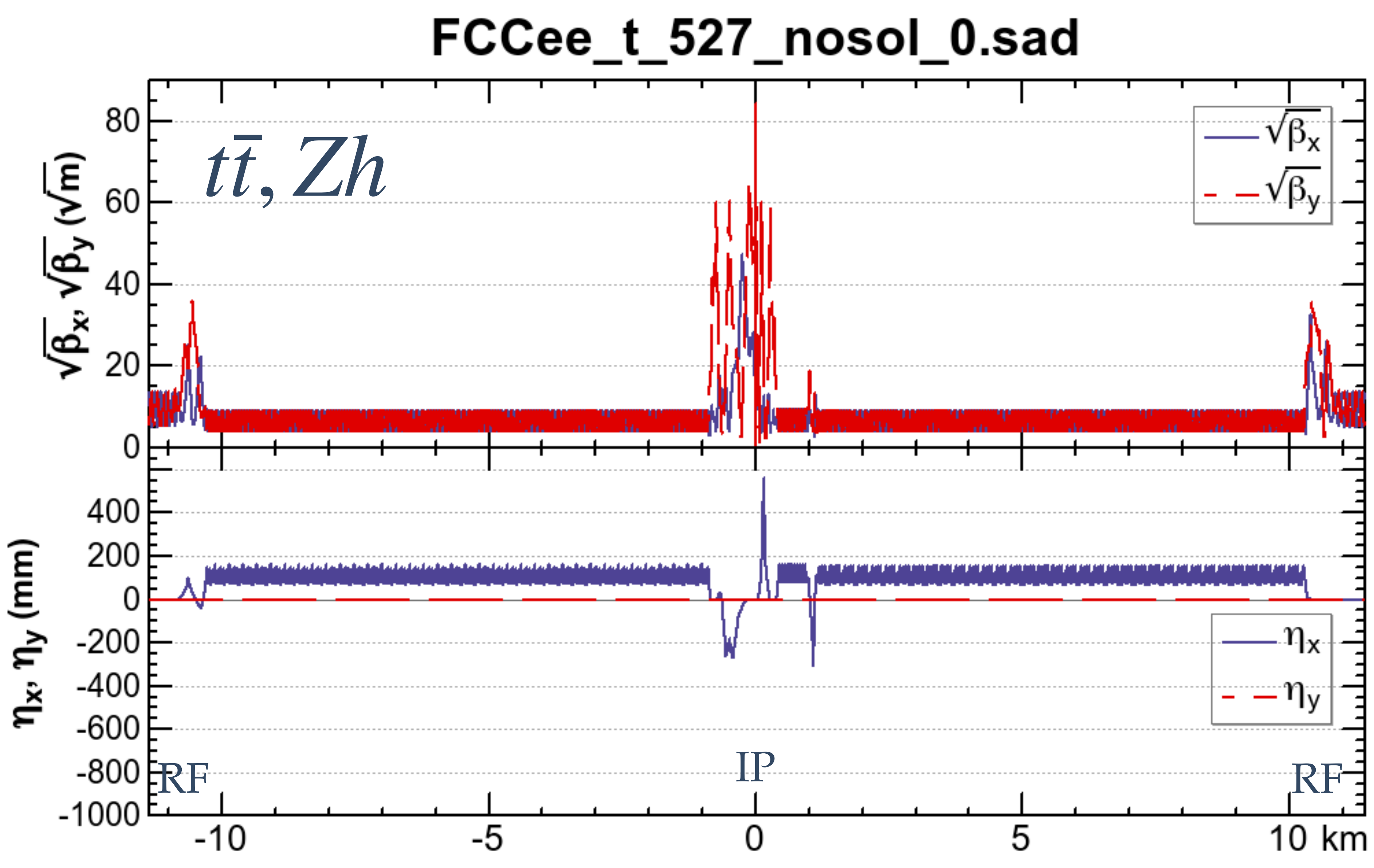
- Very high nonlinearities in lattice compared to hadron machines
  - short damping time (20 - 1200 turns)
  - small $\beta*$ (0.8 - 1.6 mm)
  - high synchrotron tune (0.03 - 0.08)
  - wide momentum acceptance (1.3% - 2.8%) with strong sextupoles in many families (75 - 146).
  - Crab waist collision by sextupoles at the both sides of the IP.

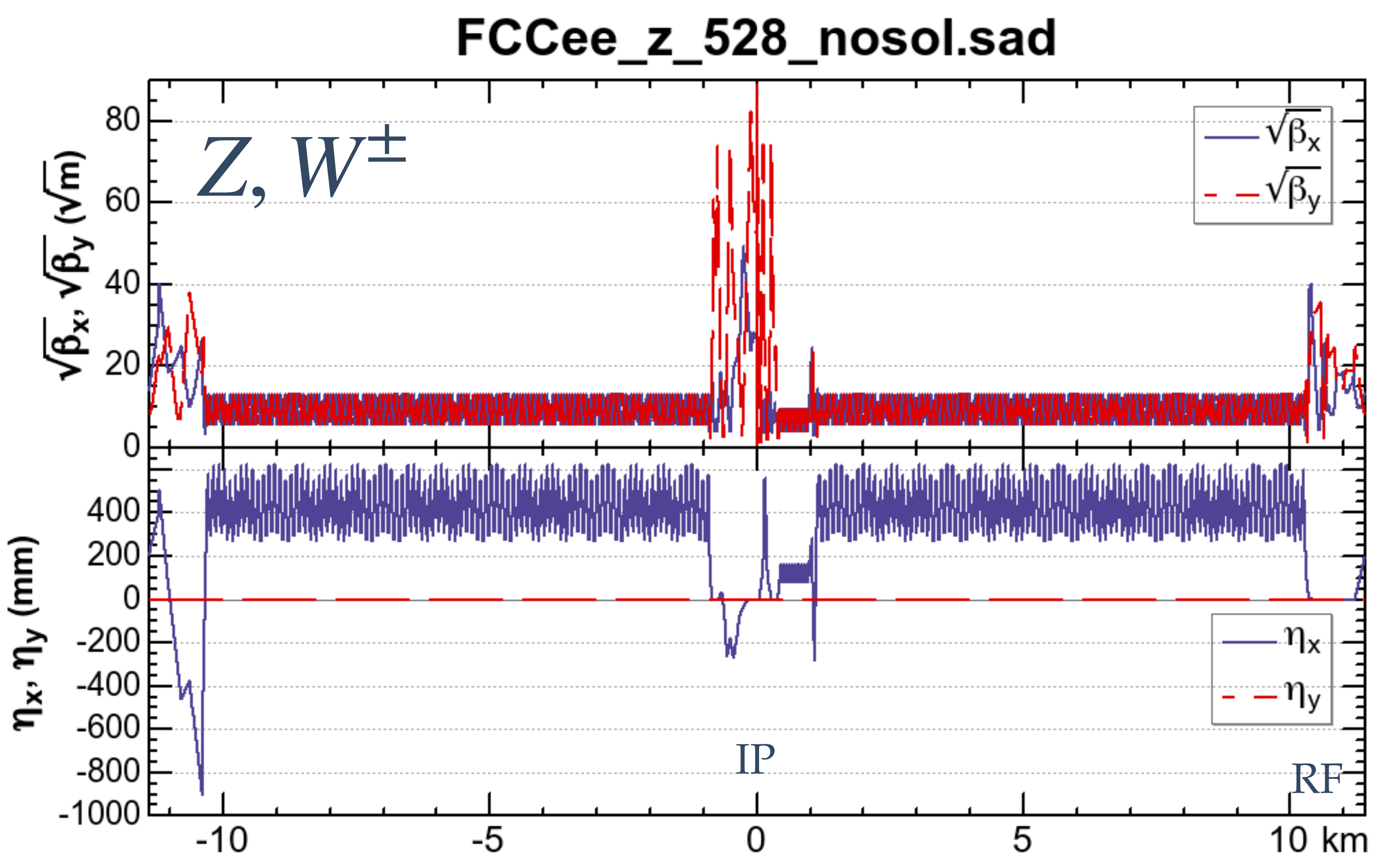
- Strong beam-beam effects
  - beam-beam parameter reaches 0.15.
  - the first beamstralung-dominated collider: x3 enlargements of bunch length & momentum spread
  - balance between two beams is essential (very narrow stable area, unrecoverable once broken).

Open Issues

- Dynamic aperture
  - Machine errors and corrections have significant impacts on the dynamic aperture, even the resulting linear optics look OK.
    - how can we recover this?
    - what kind of diagnostics and correctors are required?
    - what about the effects by storing high currents, esp. at Z?
  - Beam-beam performance, estimation with lattice + errors
    - Estimation of beam halo formation is important for collimation strategy.
    - Full simulation of topup injection
  - Possible beam blowup due to lattice nonlinearities (chromatic coupling, synchrobeta emittance)
    - beam-beam can make things worse…
  - estimation of effects due to global deformation of the tunnel and beam line.
- Missing components in the present lattice:
  - Better arc cell structure using combined quad-sext HYS magnets
  - BPMs & correctors, with diagnostics strategy
  - collimation strategy and collimators incl. impedance.
  - injection/extraction scheme, optics, devices, incl. transport lines
  - polarimeters
  - IP solenoid + compensation solenoid with realistic profile
  - realistic length of each magnet, esp. dipoles
  - longitudinal profile of each magnet, effective lengths, interference between magnets
  - technically reasonable spaces between magnets
  - feedback system: bunch-by-bunch + narrow band
- and many more…

Ring optics (1/4 ring)

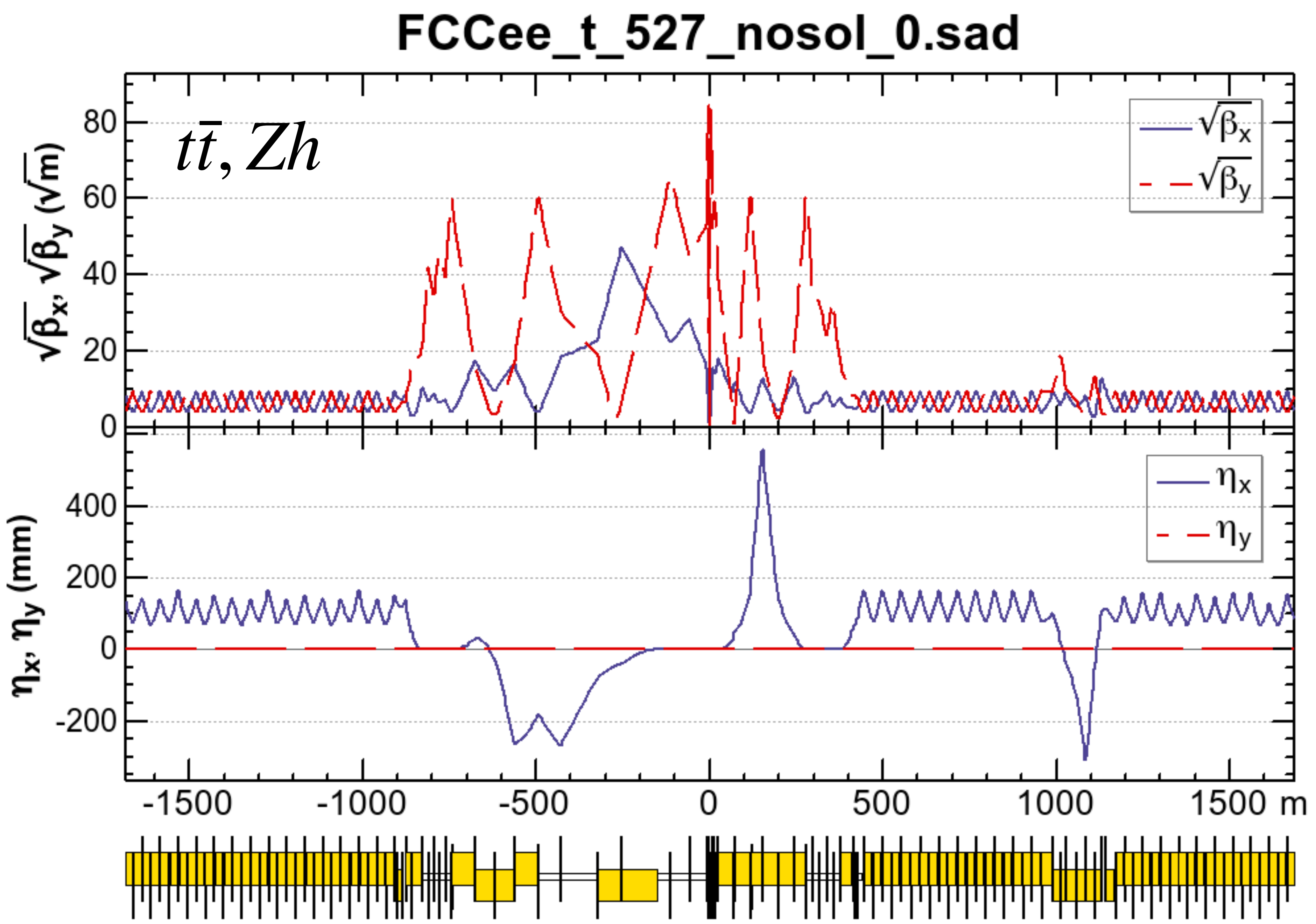


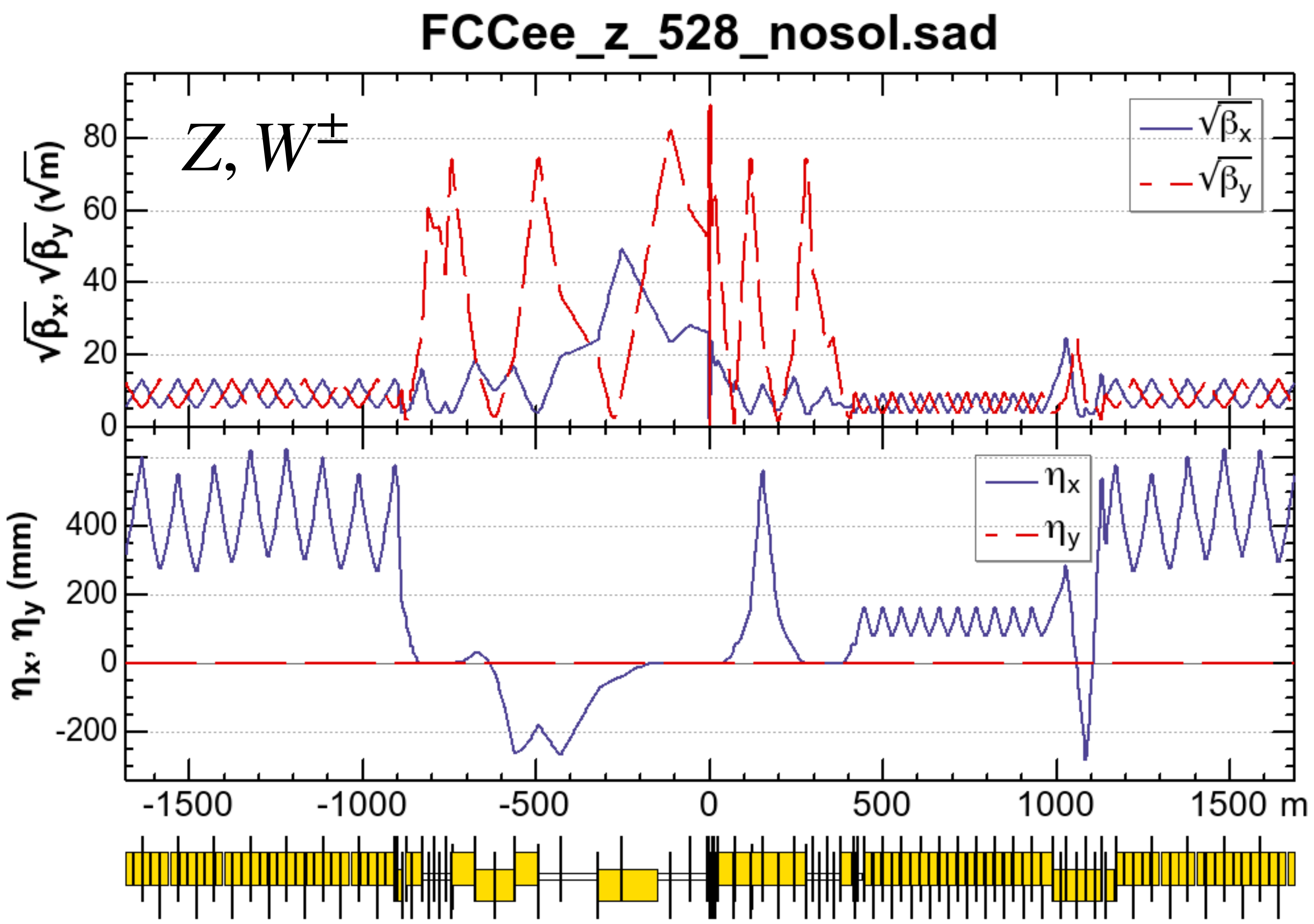


- Remarks:
  - Polarimeter, injection/extraction, collimation, BPMs, correctors are not included yet.
  - Details need technical advices for the actual requirements for spacing, field profile, etc.

IR optics

FUTURE CIRCULAR COLLIDER



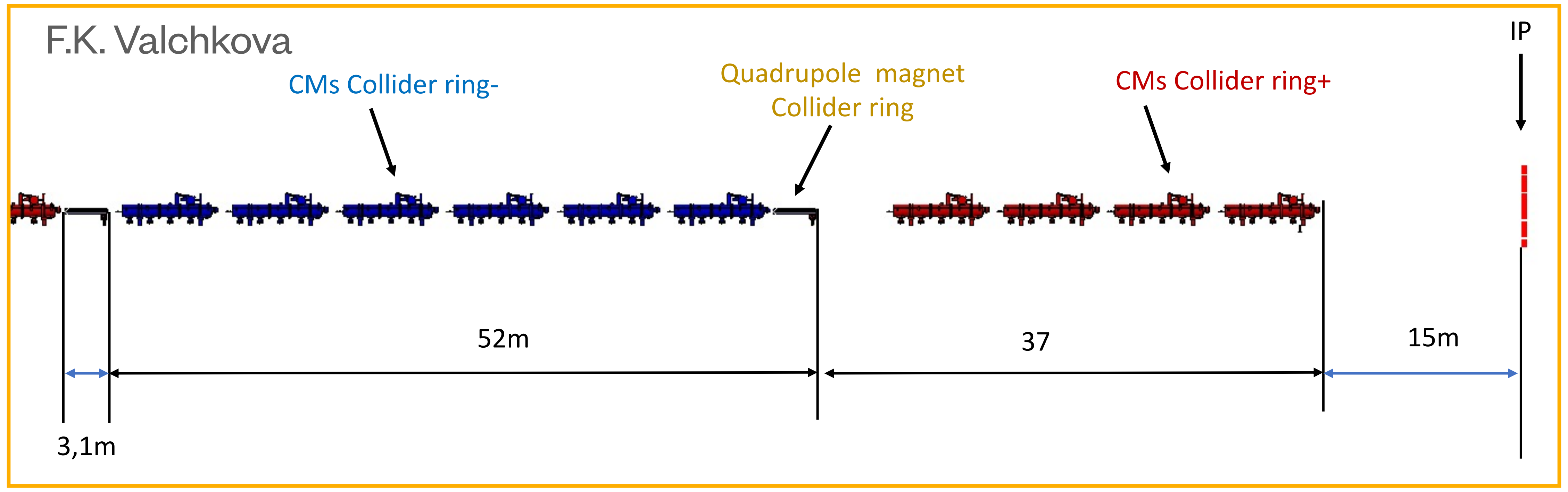


LA*

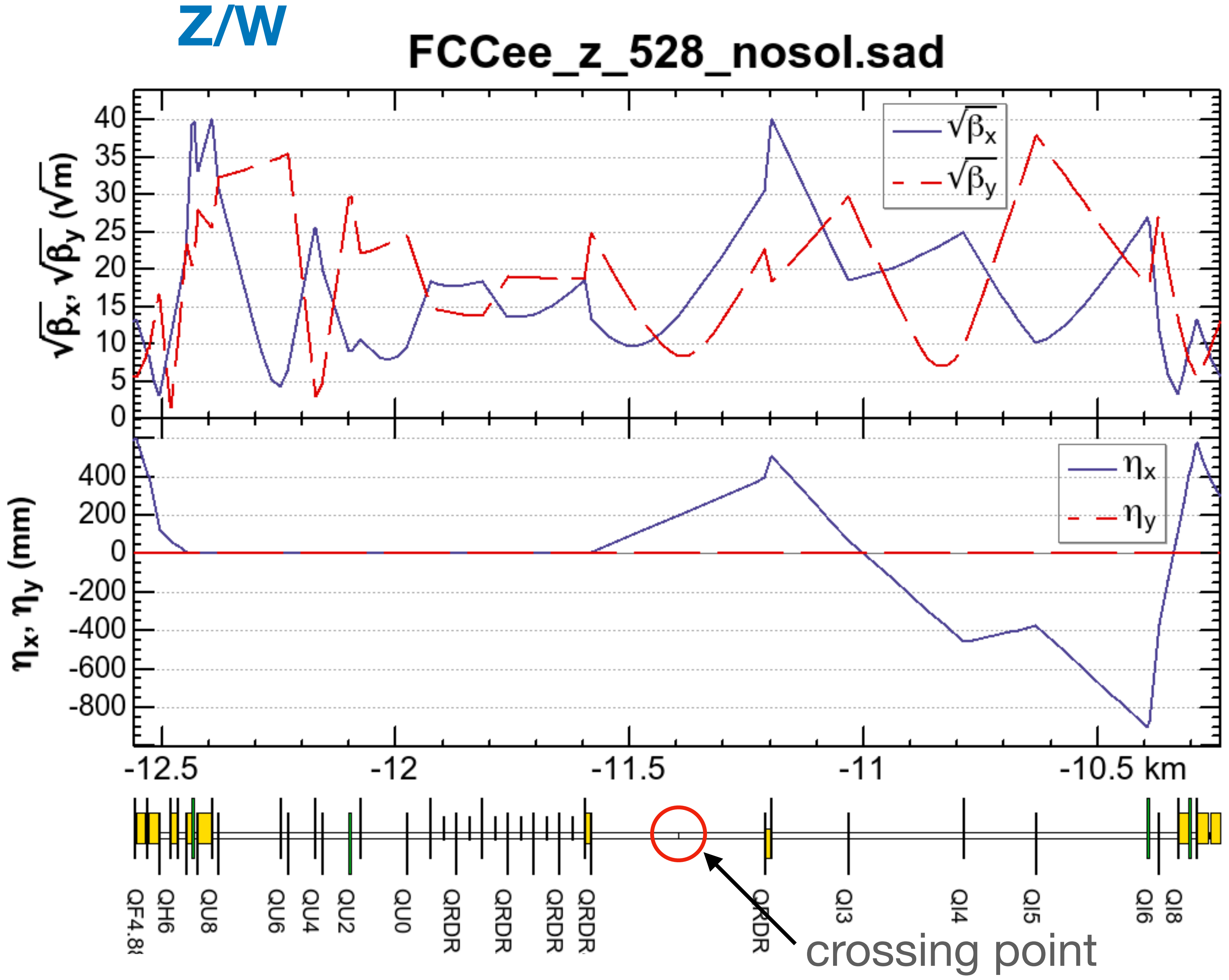
- The IR optics basically inherit conditions set at the CDR and later:
  - SR strengths
  - QC1/2 lengths
  - Now LA* are longer than 15.5 m for pol. wigglers (M. Hofer), shown in later page.
- Some dipoles have unrealistic lengths (> 100 m).

Layout in the RF section ($t\bar{t}$)

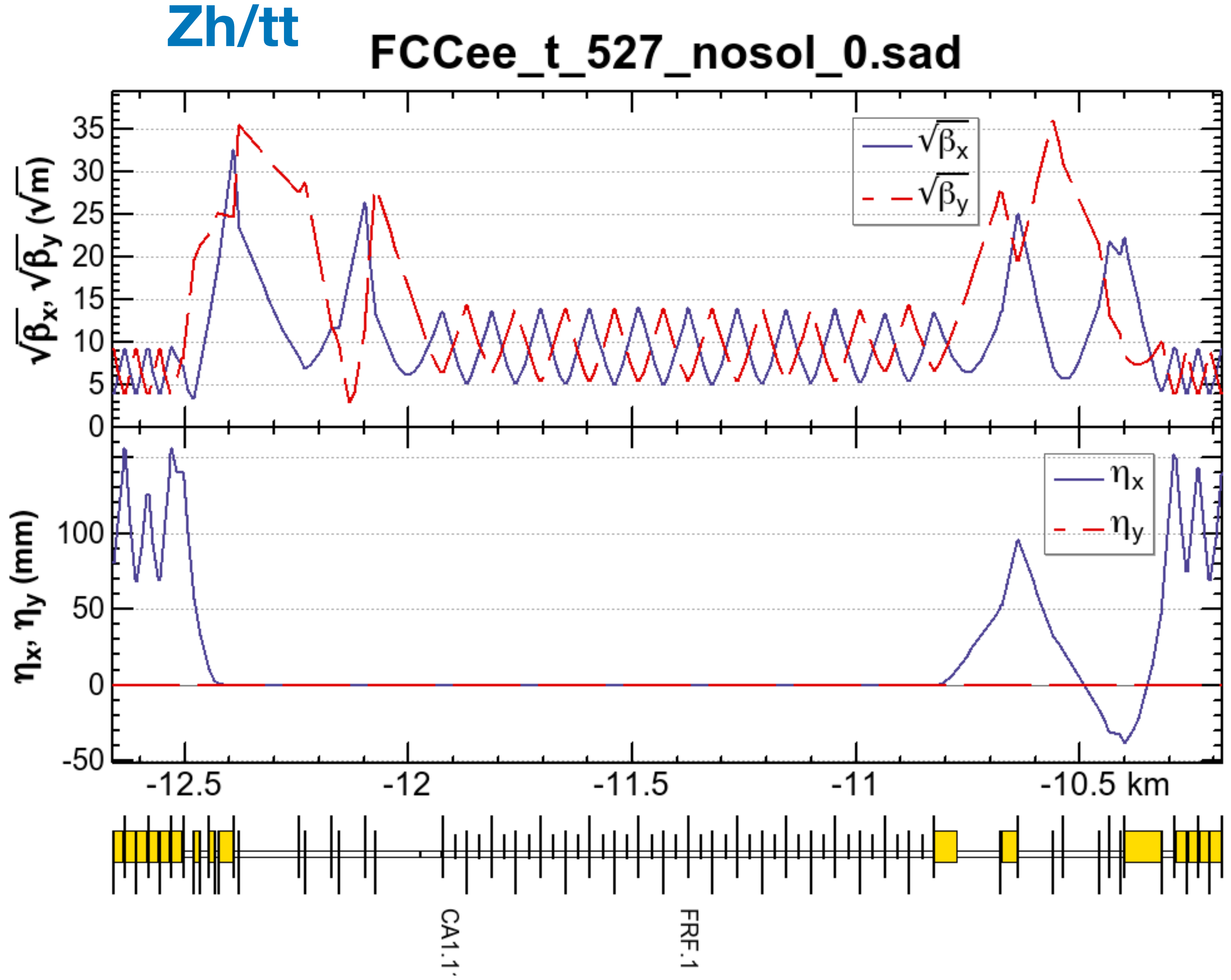
- Each space for RF is extended from 40 m to 52 m according to the request by F.K. Valchkova.
- The center of RF ("FRF") section is now shifted from the geometric center of the section to produce $\lambda_{\mathrm{RF400}}/2$ path difference from the IP between $e^{\pm}$, which is the condition of the common RF to ensure the collision at the IP.
  - The harmonic number for 400 MHz is 121648 with $f_{\mathrm{RF}} = 399.994627\ \mathrm{MHz}$ for Zh/tt.
- Designed an RF section for Z/W, which has a crossing point in the middle. The right part of the section is rebuilt at the transition to Zh/tt.



Z/W



Zh/tt



Parameters

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		9600	880	248	36
Bunch population	[10^{11}]	2.53	2.91	2.04	2.64
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	150 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.130	0.069 / 0.154	0.103 / 0.185	0.157 / 0.229
Bunch length (SR/BS) σ_z	[mm]	4.37 / 14.5	3.55 / 8.01	3.34 / 6.00	2.02 / 2.95
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	4.0 / 7.25
Harmonic number for 400 MHz		121648			
RF freuqeuncy (400 MHz)	MHz	399.994581		399.994627	
Synchrotron tune Q_s		0.0370	0.0801	0.0328	0.0826
Long. damping time	[turns]	1168	217	64.5	18.5
RF acceptance	[%]	1.6	3.4	1.9	3.1
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y[a]		0.0040 / 0.152	0.011 / 0.125	0.014 / 0.131	0.096 / 0.151
Luminosity / IP	[10^{34}/cm^{2}s]	189	19.4	7.26	1.33
Lifetime (q + BS)	[sec]	–		1065	2405
Lifetime (lum)	[sec]	1089	1070	596	701

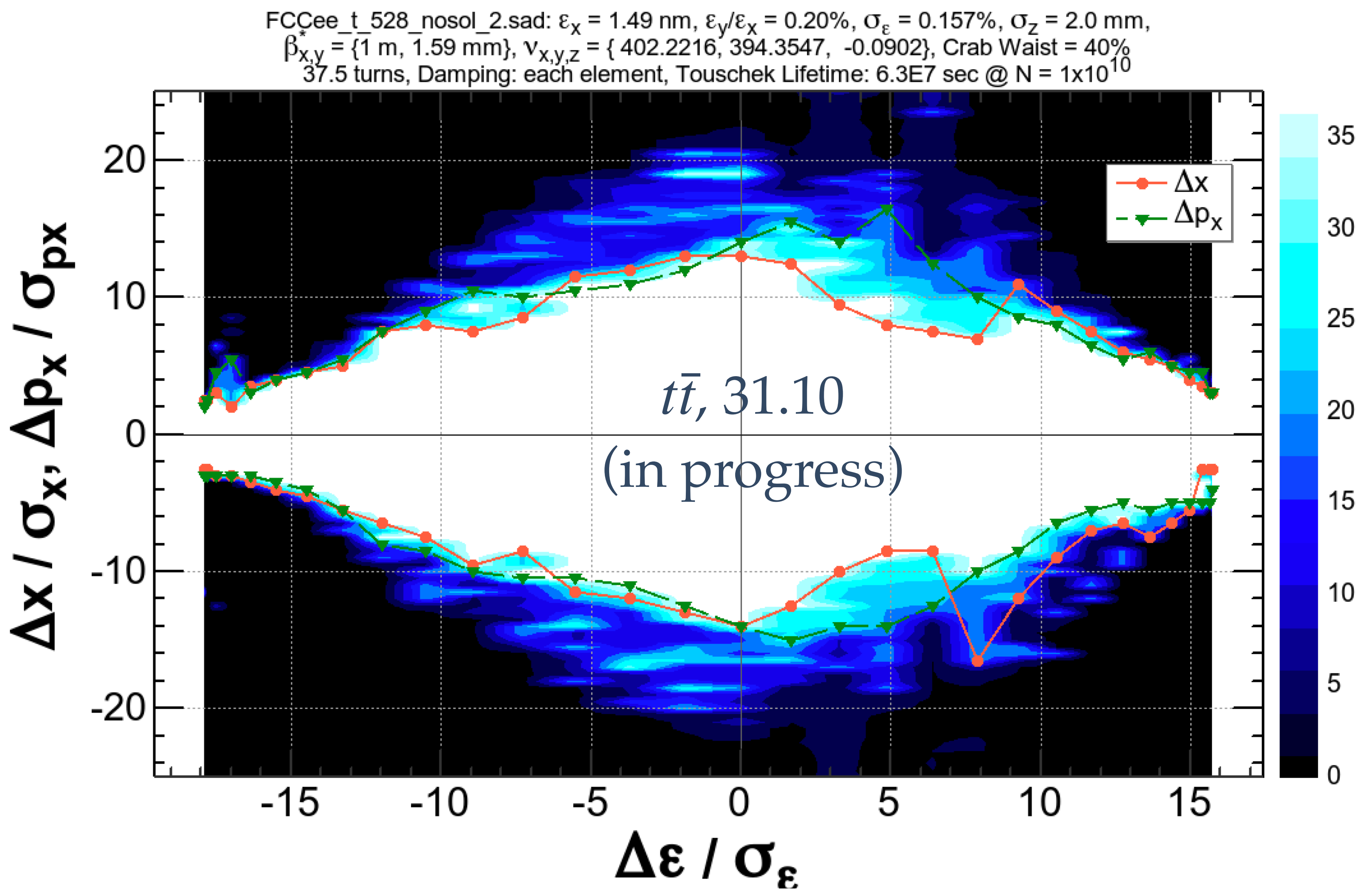
[a] incl. hourglass.

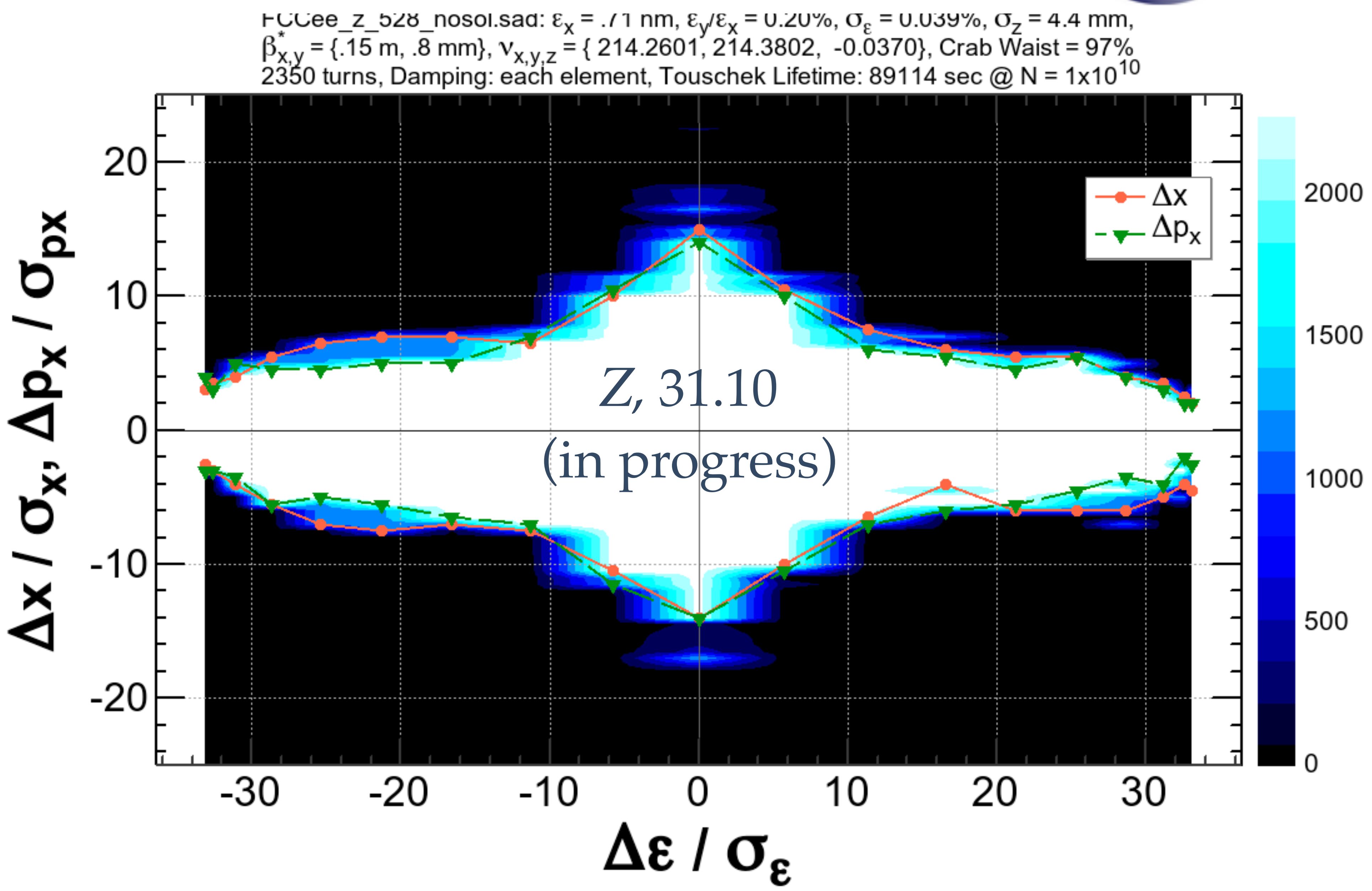
The luminosities and beam-beam related numbers are based on a simple model w/o beam-beam simulations.

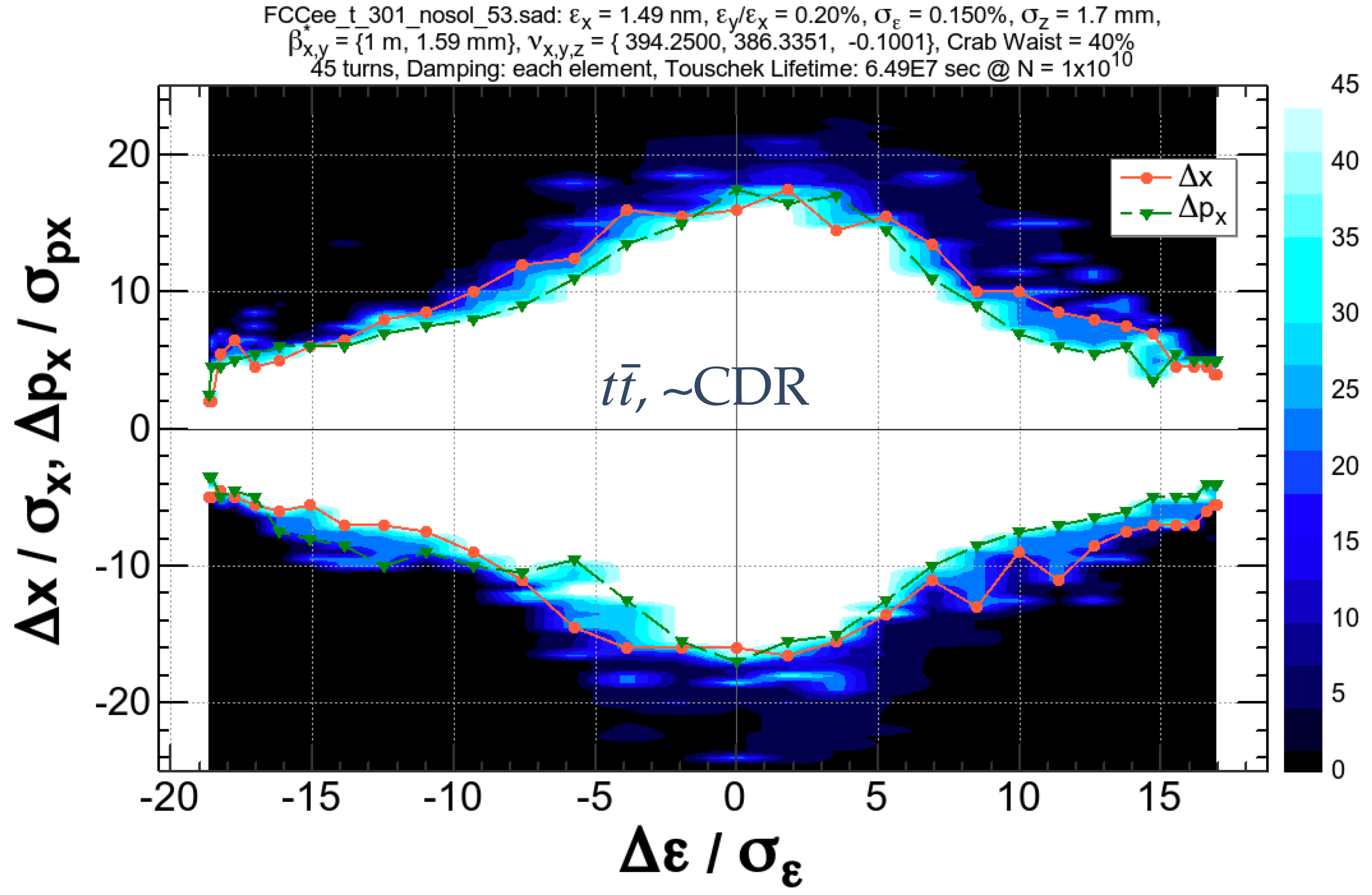
Dynamic aperture

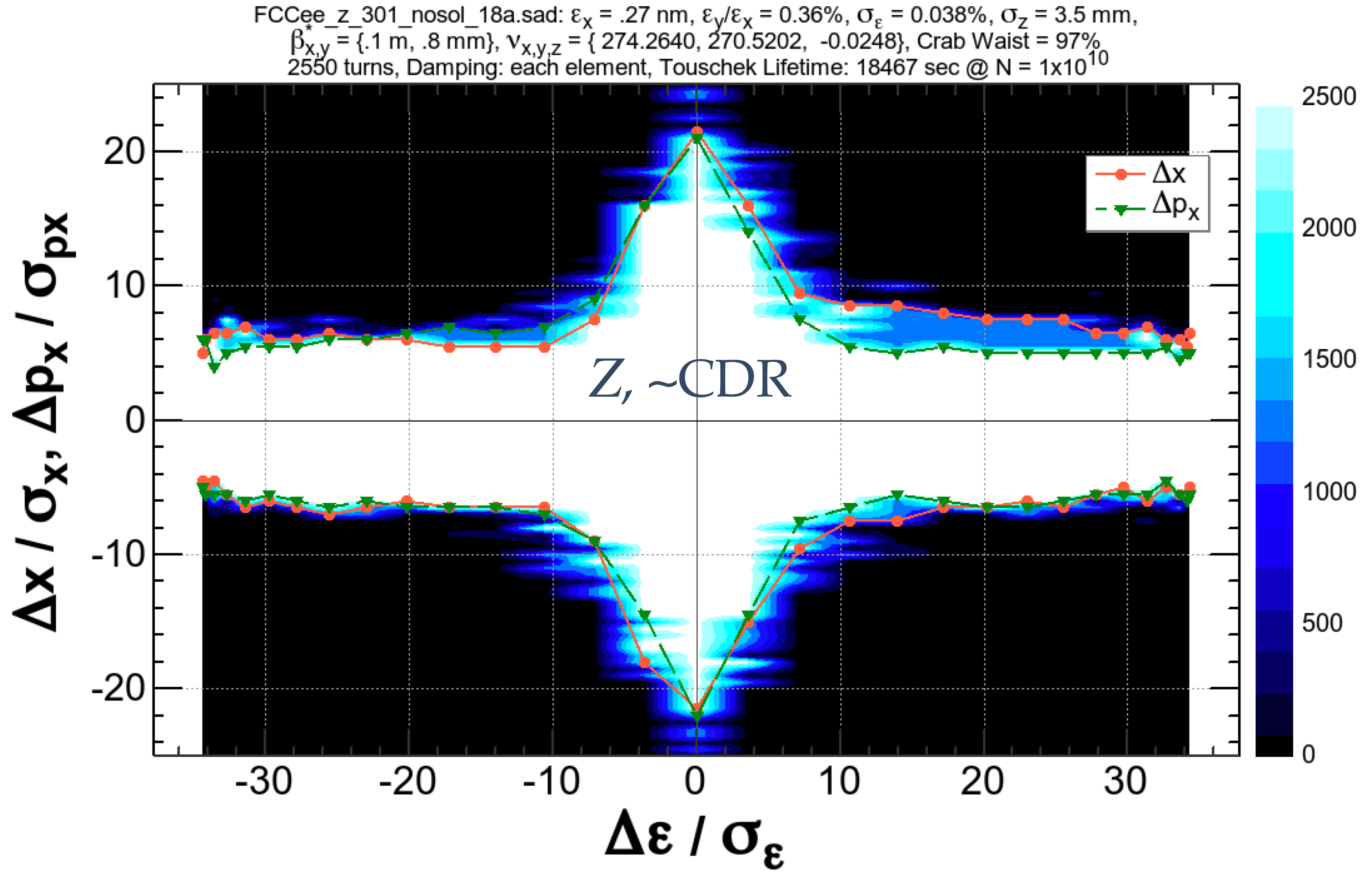
These are with the old RF sections and tunes.
DA with new RF sections and tunes are in progress…

FUTURE CIRCULAR COLLIDER

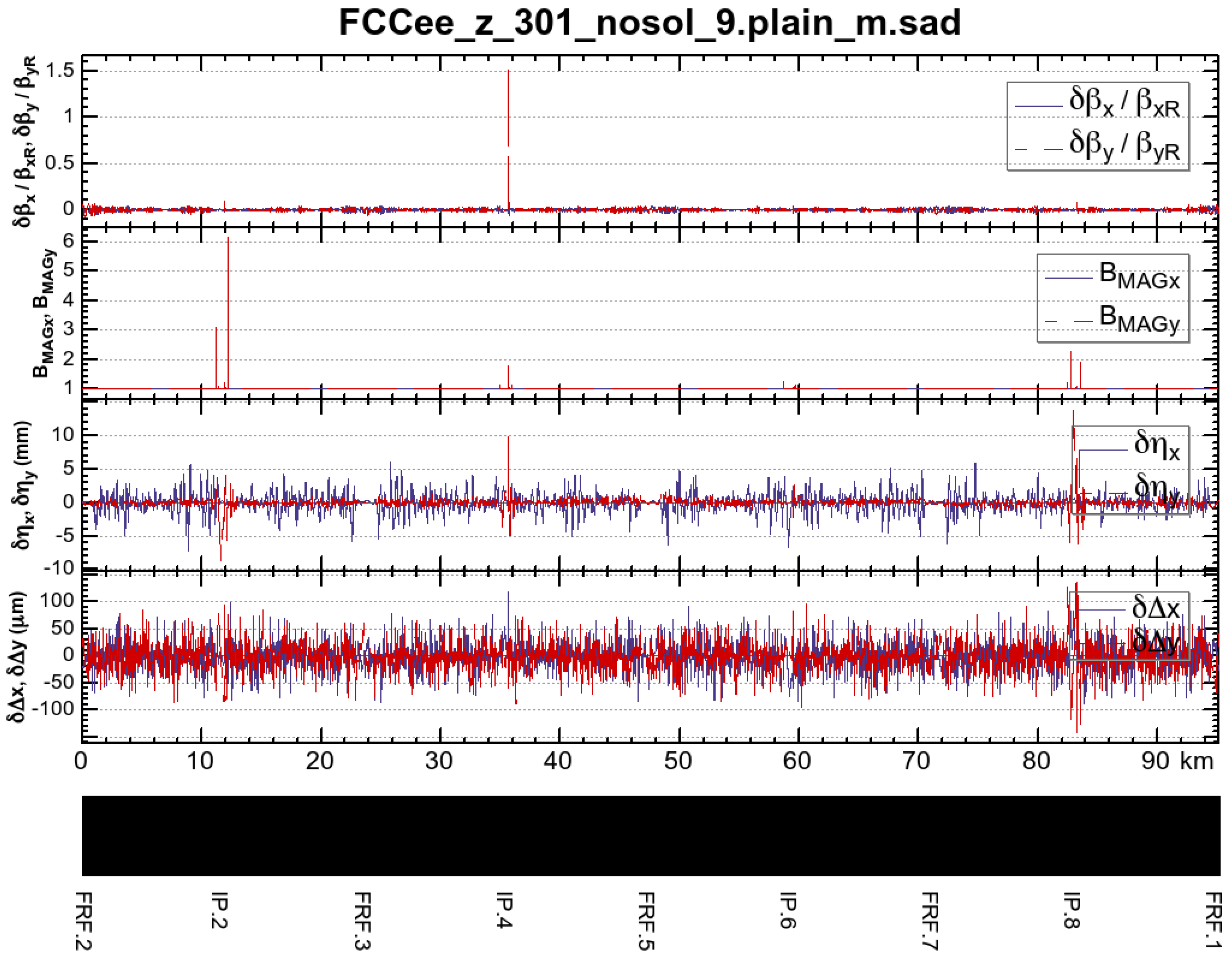








Impact of errors/corrections on DA



An example of errors and corrections by T. Charles, with an old 4IP lattice. New results will be in the next talk!

- The correction by T. Charles looks excellent!
  - Tunes are slightly shifted:
    - (274.26126, 270.52384) from (274.26400, 270.52000).
  - Emittances: (0.275 nm, 23.2 fm).

- Remarks:
  - The spike of $\Delta\beta_y/\beta_y$ at IP. 4 corresponds to a shift of waist.
  - If we look at B_{MAGy}, there are several locations with high B_{MAGy} esp. at crab sexts (see next page).
  - The residual orbit looks much smaller than the misalignment; probably the BPMs are placed on the ideal plane in this case?

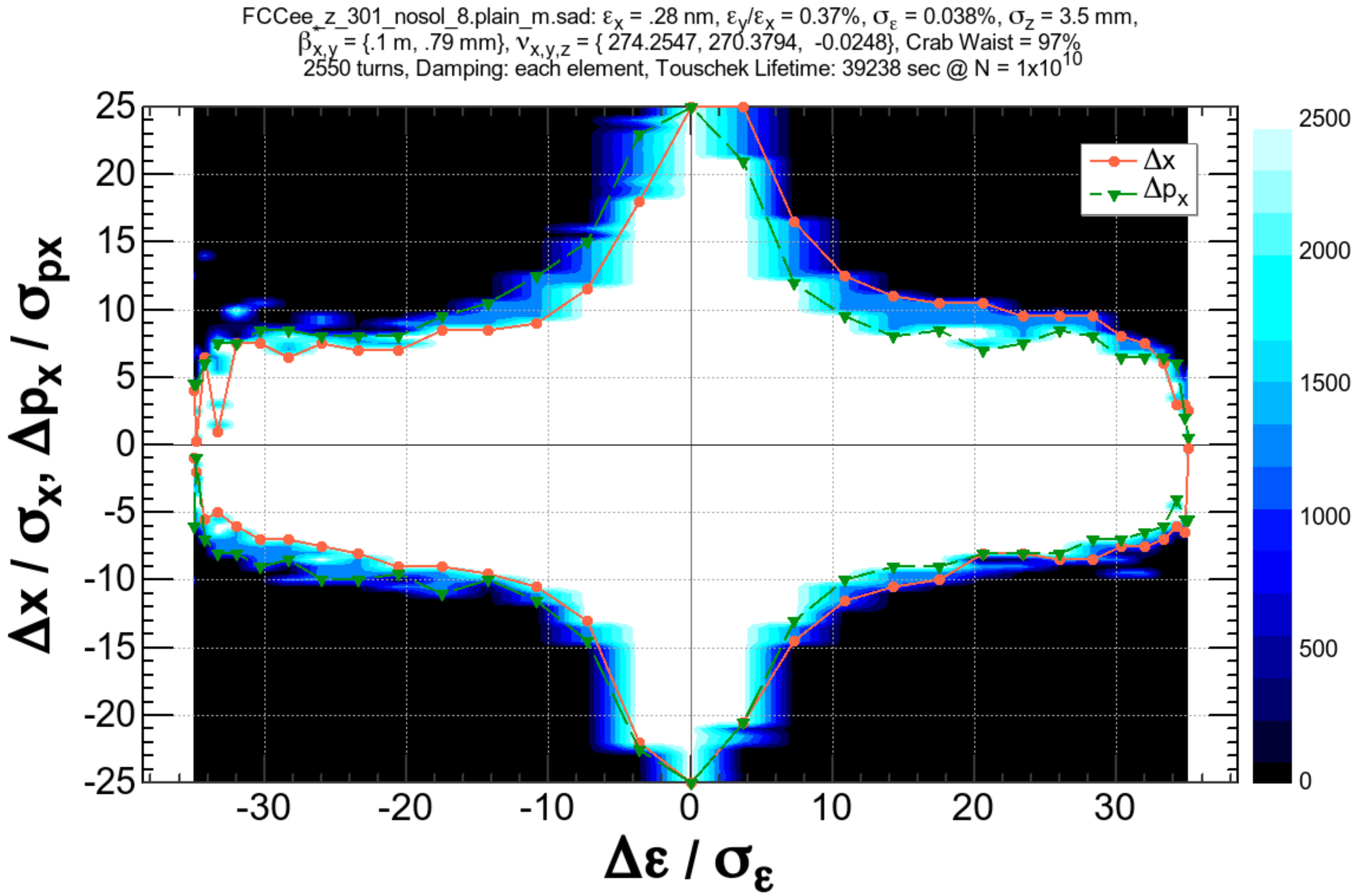
Reduction of DA by errors/corrections

FUTURE CIRCULAR COLLIDER

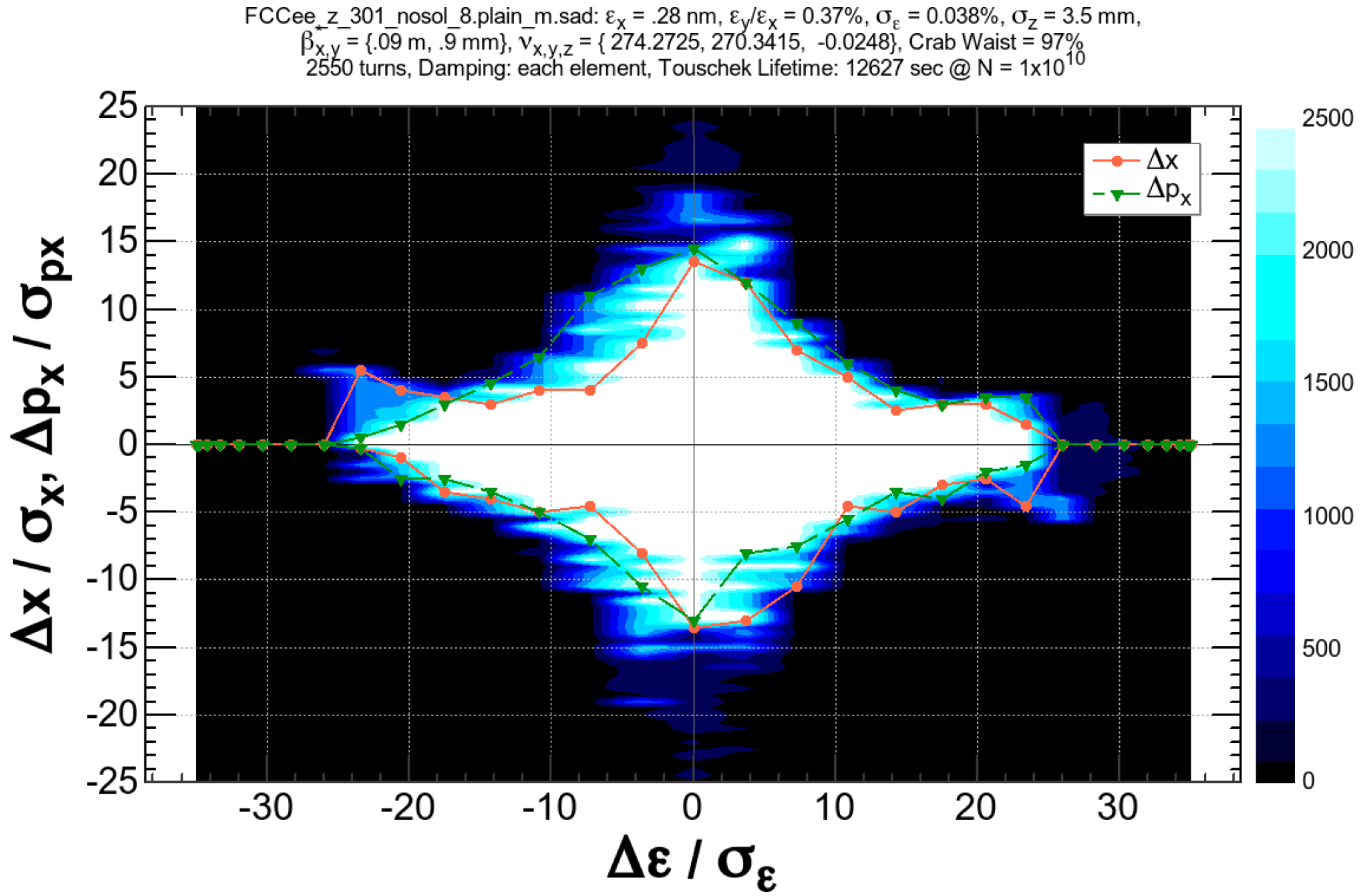
An example of errors and corrections by T. Charles, with an old 4IP lattice.

301_8

No error



Errors + corrections ("seed 1")



- The dynamic aperture shrinks with the errors and corrections ("seed 1") as seen in figures above.
  - The errors/corrections for 301_9 were simply applied on 301_8. The resulting vertical emittance raised to 0.2 pm.
- The corresponding momentum acceptance: ±1.3% (no error) → ±0.8%? (seed_1).
- Further optimization of sexts with errors/corrections may improve the DA