Collider Optics

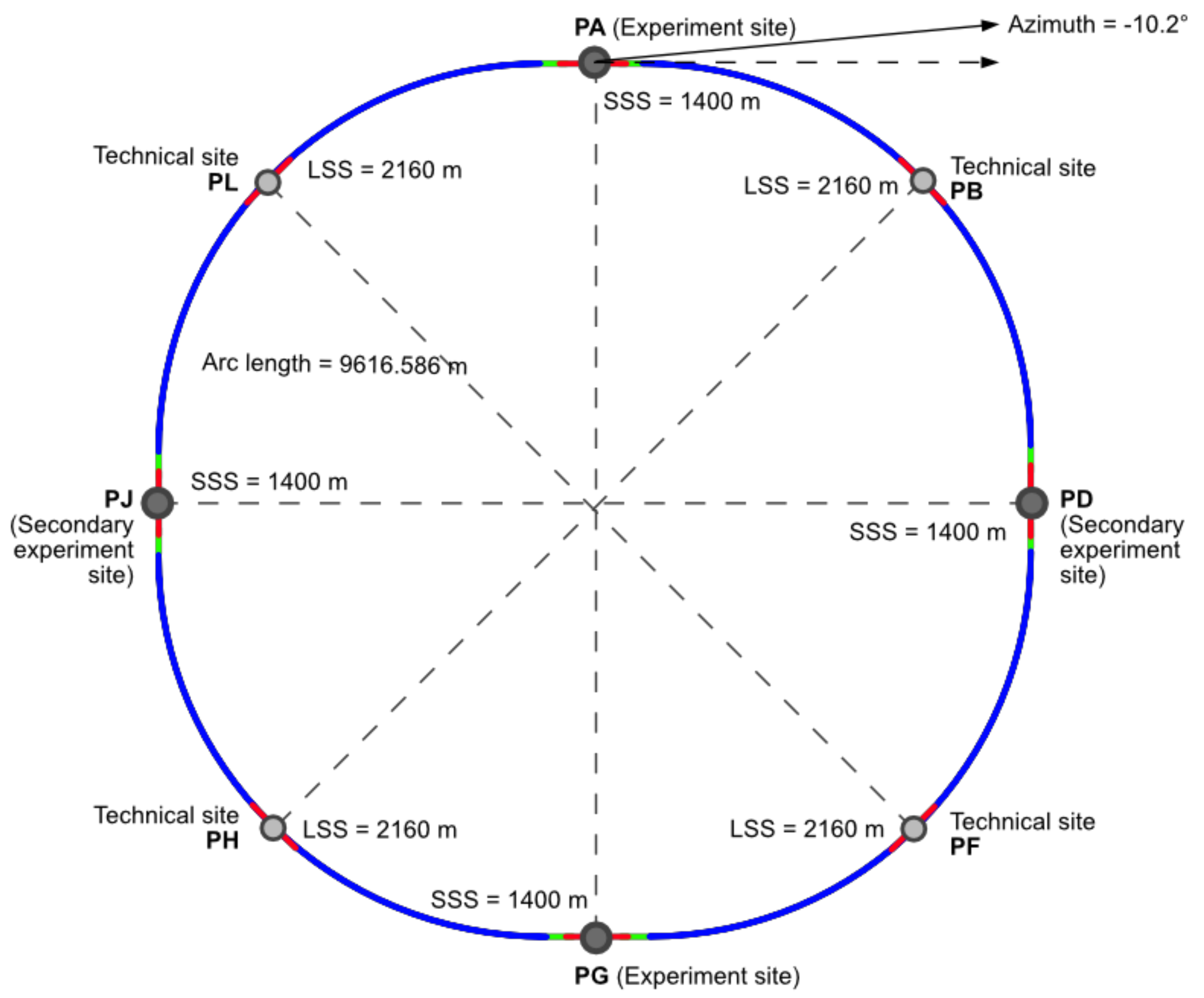
K. Oide (UNIGE/CERN)

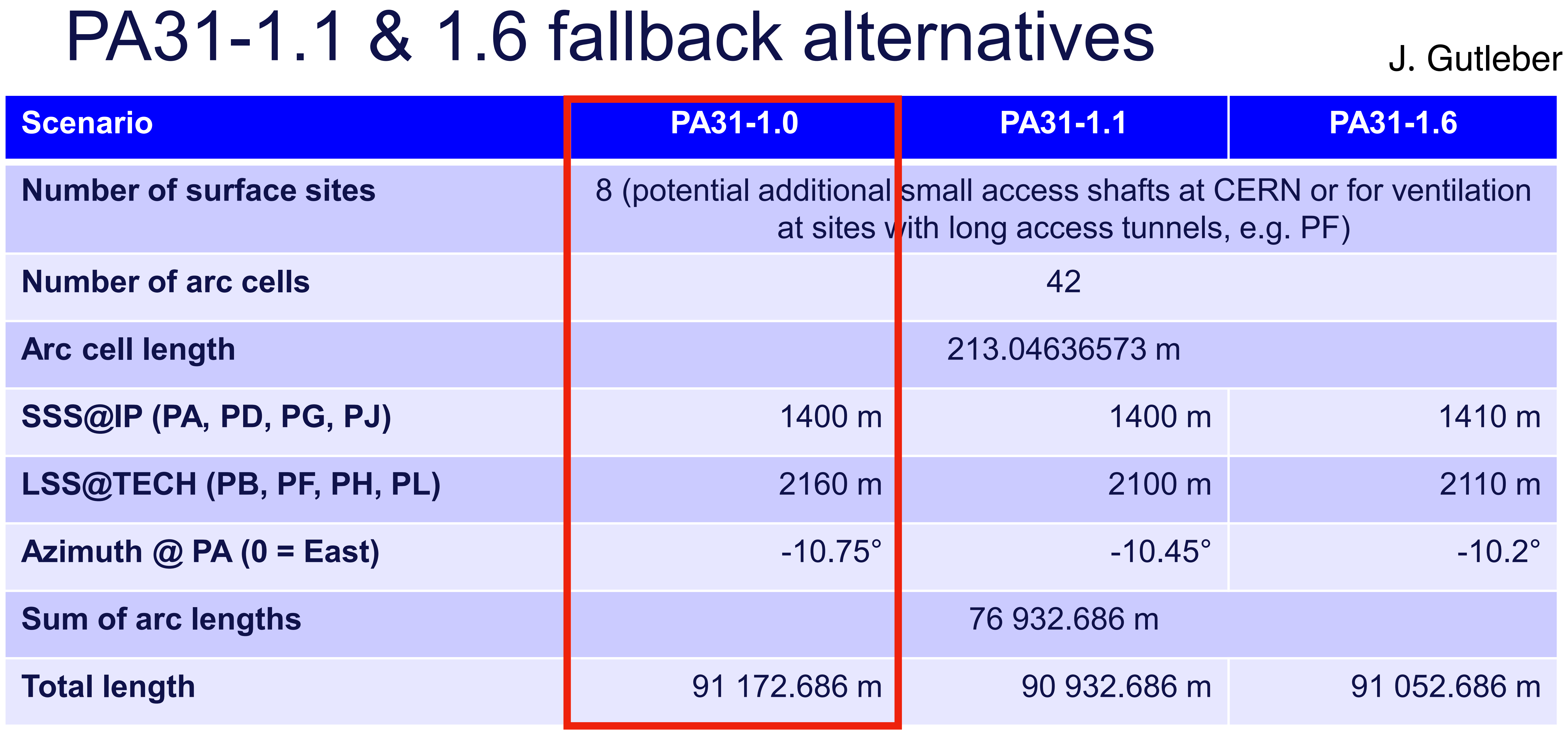
Dec. 06, 2022 @FCCIS 2022 Workshop

Many thanks to M. Benedikt, M. Hofer, M. Koratzinos, T. Raubenheimer, D. Shatilov, F. Zimmermann, and all FCC-ee/FCCIS colleagues
Work supported by the FCC Feasibility Study (**FCC-GOV-CC-0004, EDMS 1390795 v.2.0**)

The 4 IP layout

- The new layout “31” series has been presented by J. Gutleber in the last optics meeting.
  - 8 surface sites, 4 IP.
  - complete period-4 + mirror symmetries.
- Let us choose “PA31-1.0” for the baseline, for the time being.
  - The adaptation to other variants, if necessary, will be minor.
  - An update “PA31-2.0” has been proposed with a change in the length of IP straights. The optics will adapt it soon with several other changes.





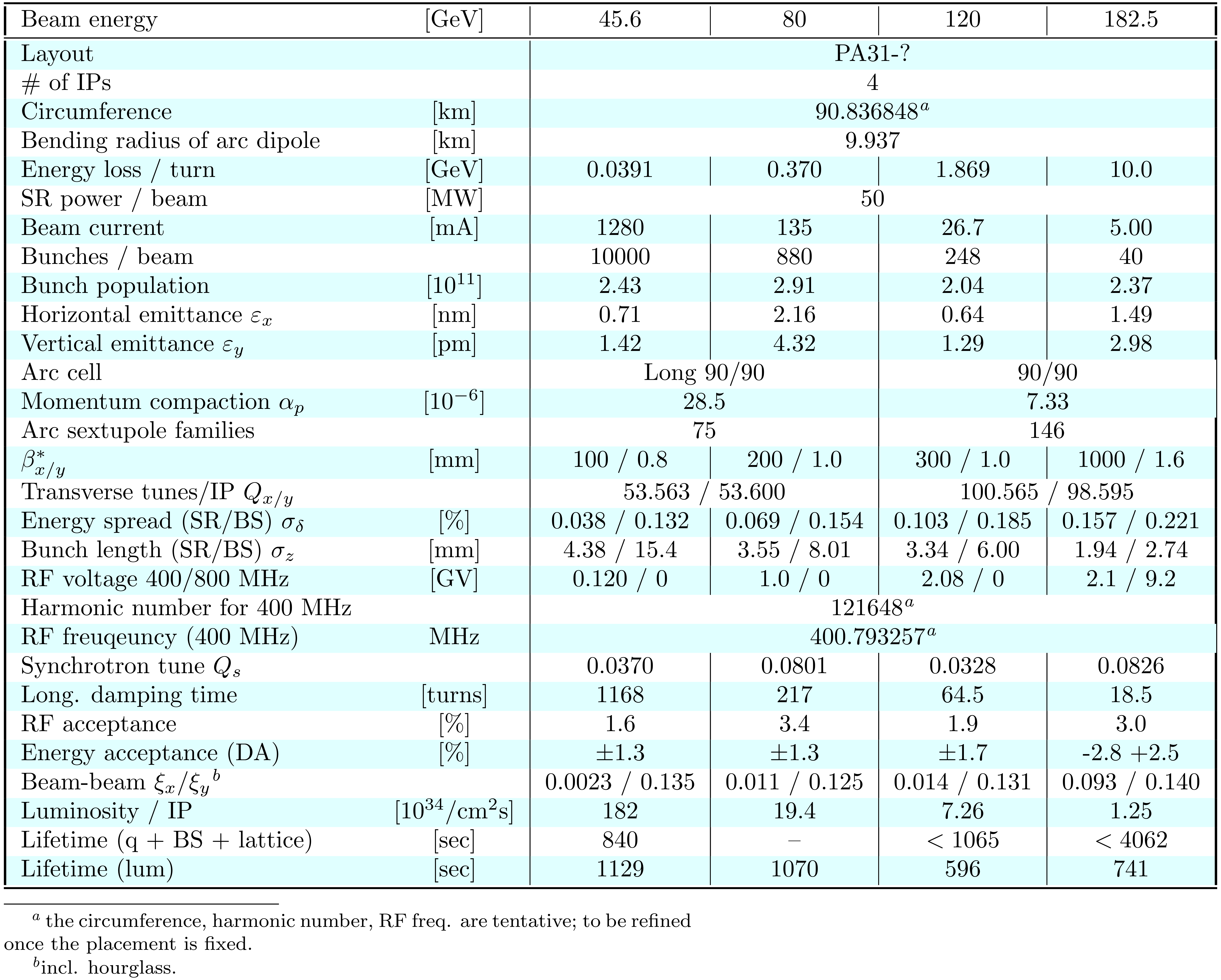
PA31-1.1 & 1.6 fallback alternatives

J. Gutleber

Scenario	PA31-1.0	PA31-1.1	PA31-1.6
Number of surface sites	8 (potential additional small access shafts at CERN or for ventilation at sites with long access tunnels, e.g. PF)		
Number of arc cells	42		
Arc cell length	213.04636573 m		
SSS@IP (PA, PD, PG, PJ)	1400 m	1400 m	1410 m
LSS@TECH (PB, PF, PH, PL)	2160 m	2100 m	2110 m
Azimuth @ PA (0 = East)	-10.75°	-10.45°	-10.2°
Sum of arc lengths	76 932.686 m		
Total length	91 172.686 m	90 932.686 m	91 052.686 m

Further reduction of circumference is planned to solve several placement issues (J. Gutleber, M. Benedikt).

“latest” (Dec. 06, 2022) parameters



Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-?			
# of IPs		4			
Circumference	[km]	90.836848[a]			
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		10000	880	248	40
Bunch population	[10^{11}]	2.43	2.91	2.04	2.37
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]	100 / 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	[%]	0.038 / 0.132	0.069 / 0.154	0.103 / 0.185	0.157 / 0.221
Bunch length (SR/BS) σ_z	[mm]	4.38 / 15.4	3.55 / 8.01	3.34 / 6.00	1.94 / 2.74
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.1 / 9.2
Harmonic number for 400 MHz		121648[a]			
RF freuqeuncy (400 MHz)	MHz	400.793257[a]			
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	3.0
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y[b]		0.0023 / 0.135	0.011 / 0.125	0.014 / 0.131	0.093 / 0.140
Luminosity / IP	[10^{34}/cm^{2}s]	182	19.4	7.26	1.25
Lifetime (q + BS + lattice)	[sec]	840	–	< 1065	< 4062
Lifetime (lum)	[sec]	1129	1070	596	741

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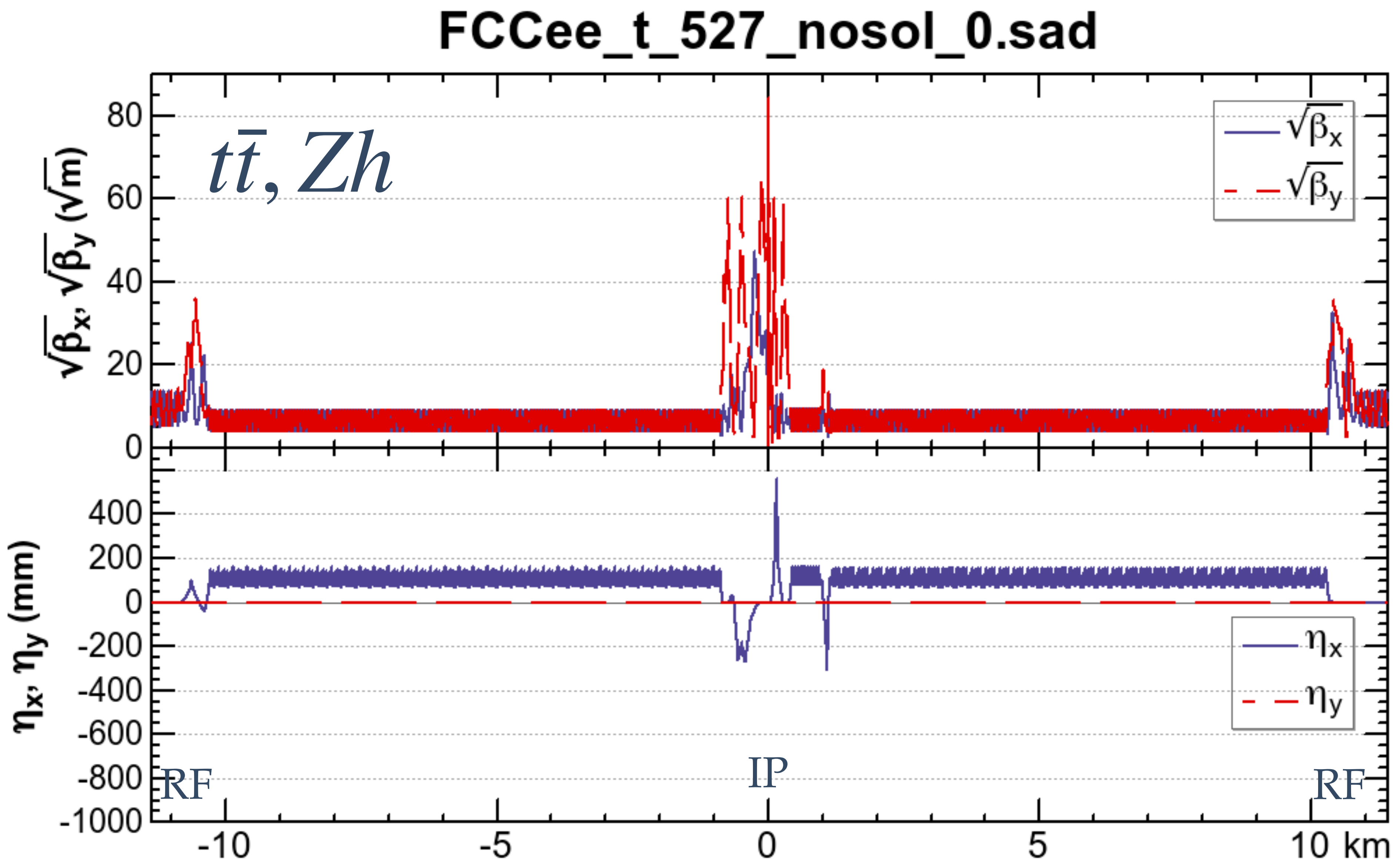
[a] the circumference, harmonic number, RF freq. are tentative; to be refined once the placement is fixed.

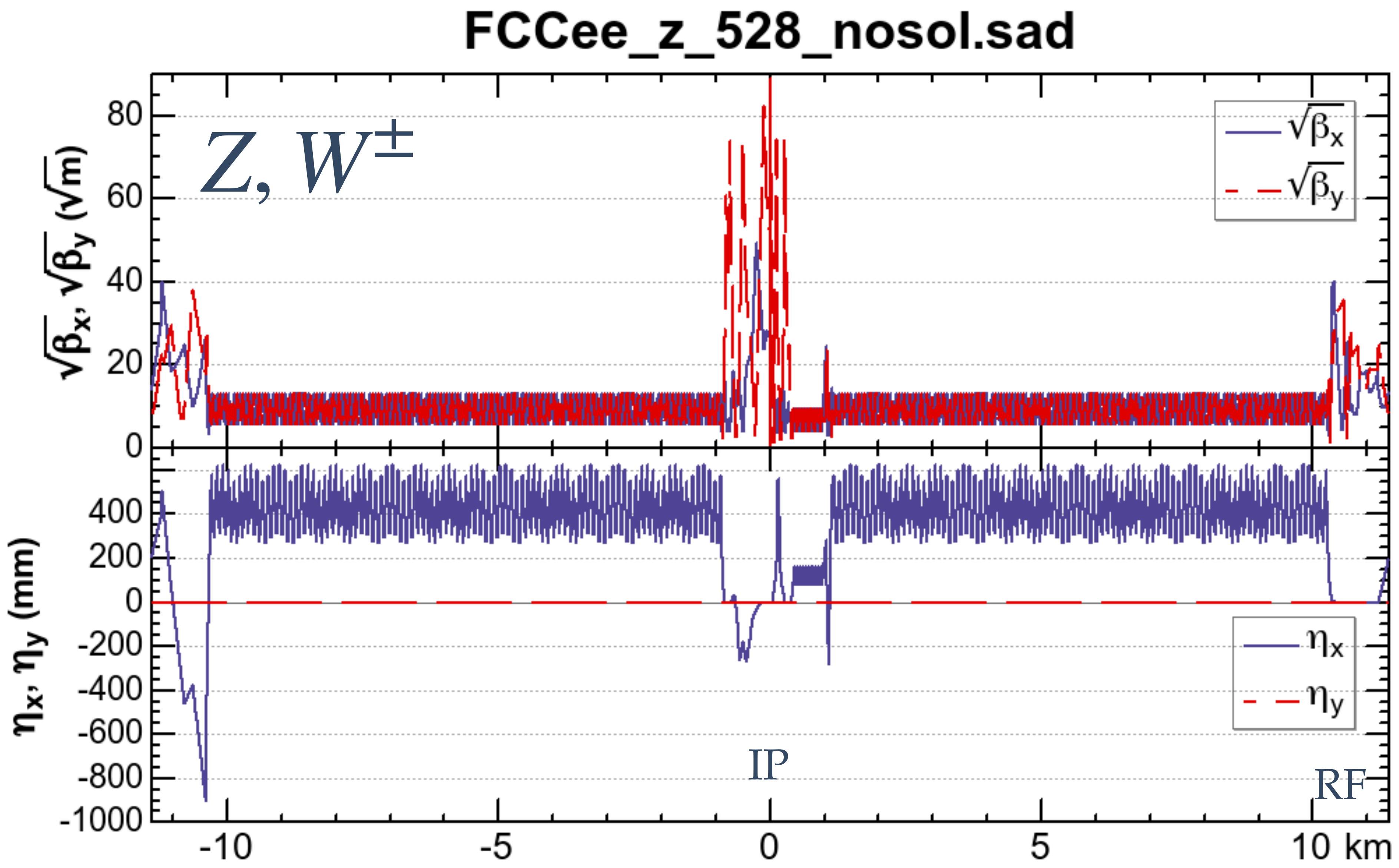
[b] incl. hourglass.

Ring optics (1/4 ring)



FCCee_t_527_nosol_0.sad

180 Short 90/90 FODO cells / arc.
8 arcs / ring



FCCee_z_528_nosol.sad

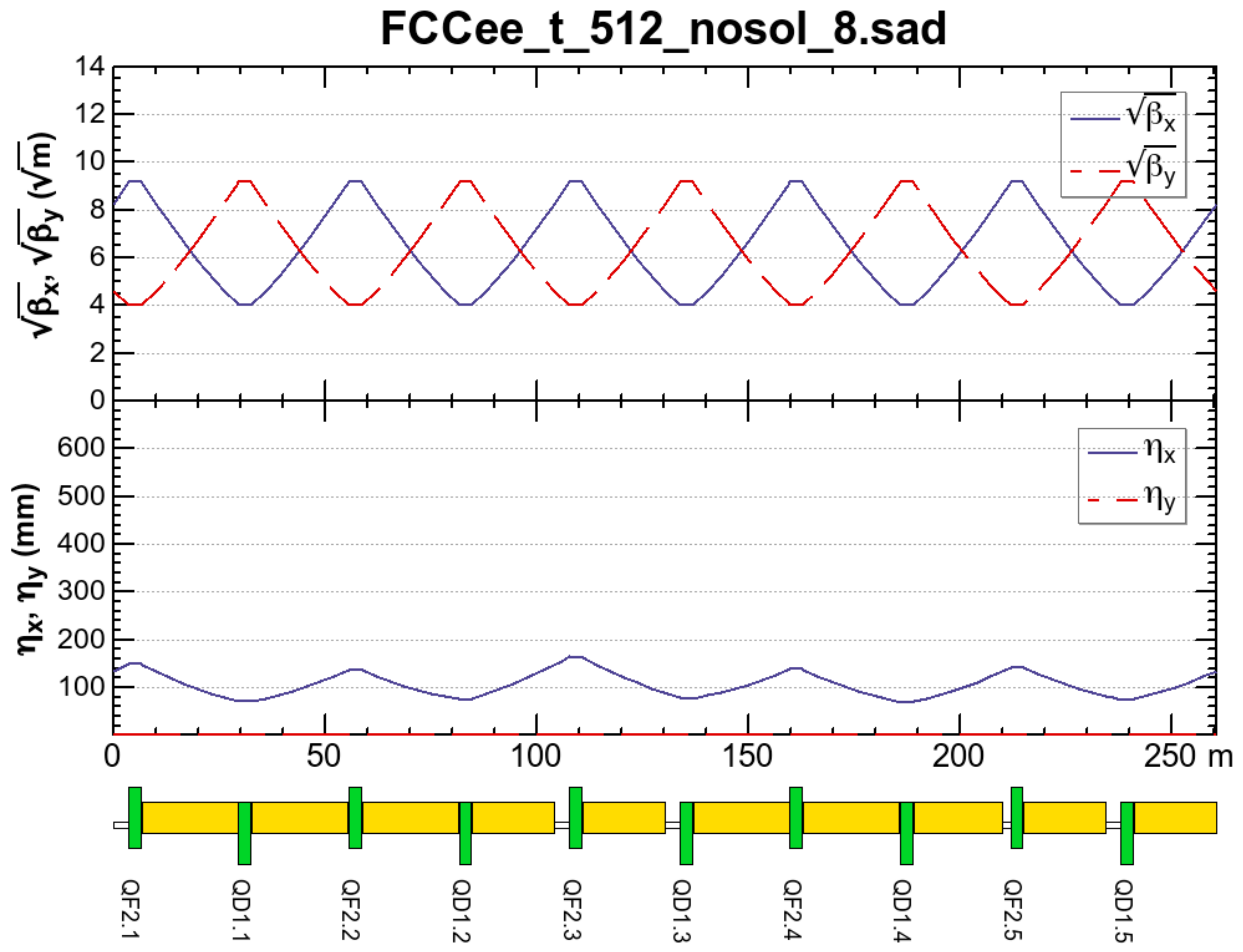
90 Long 90/90 FODO cells / arc.
8 arcs / ring

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

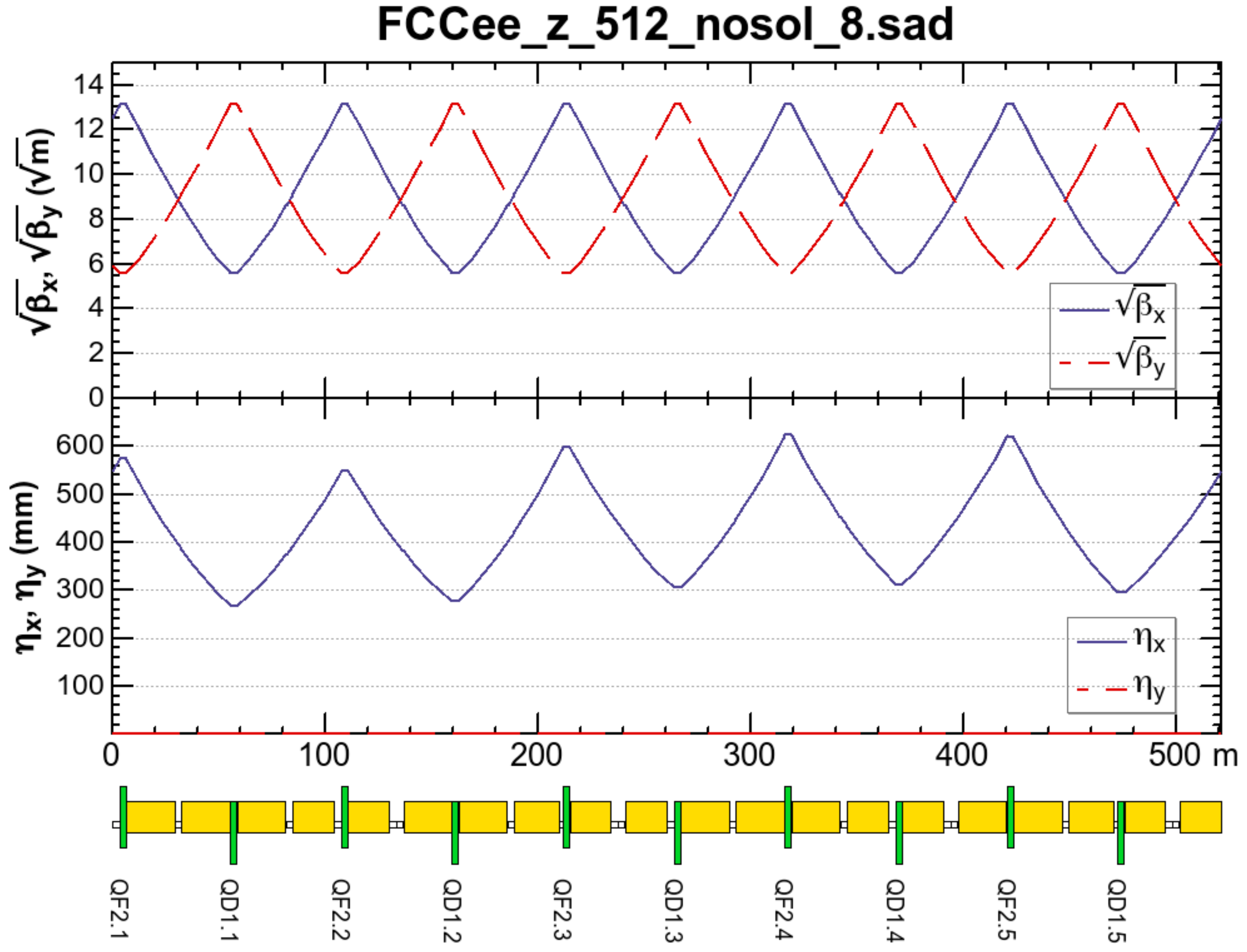
The beam optics shown here and later are not always the latest ones in details.

The arc cell optics (1 period = 5 FODOs)

Short 90/90: $t\bar{t}$, Zh



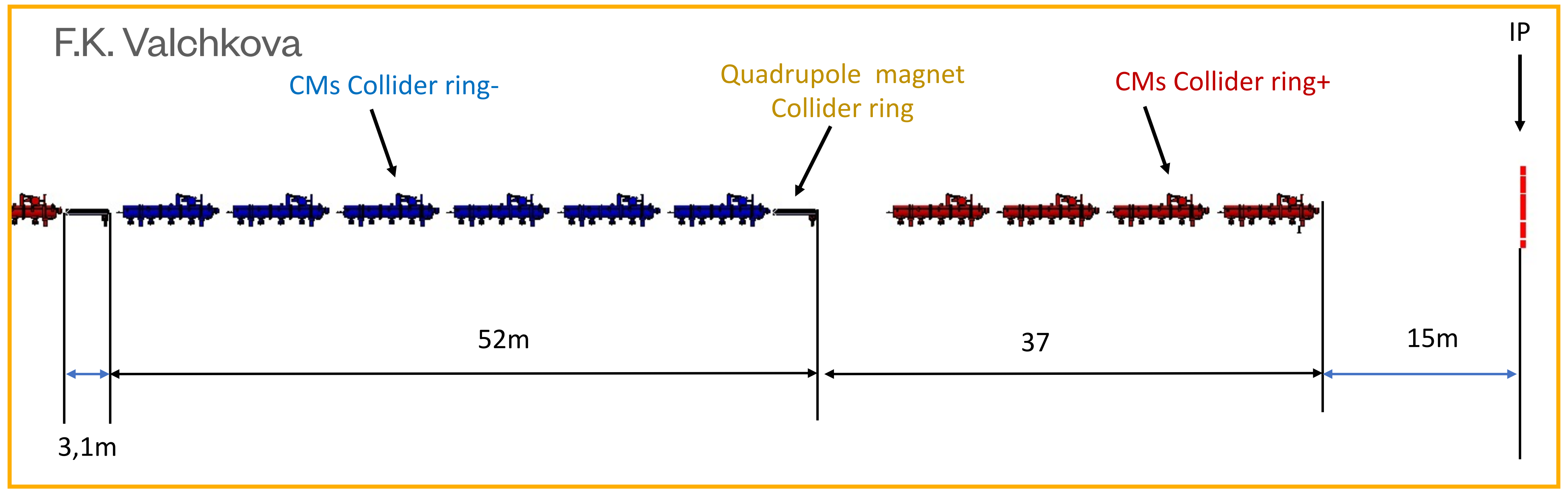
Long 90/90: Z, W



- For long 90/90:
  - The QDs for short 90/90 of the outer ring are turned off.
    - However, their BPMs and correctors are usable for additional orbit/optics correction power.
  - The polarity of QFs for short 90/90 are reversed alternatively to serve as QDs. These should have an easy mechanism in the wiring for switching.
- The arc dipoles should be divided into 3 pieces for installation. Then the field at their connection may matter.

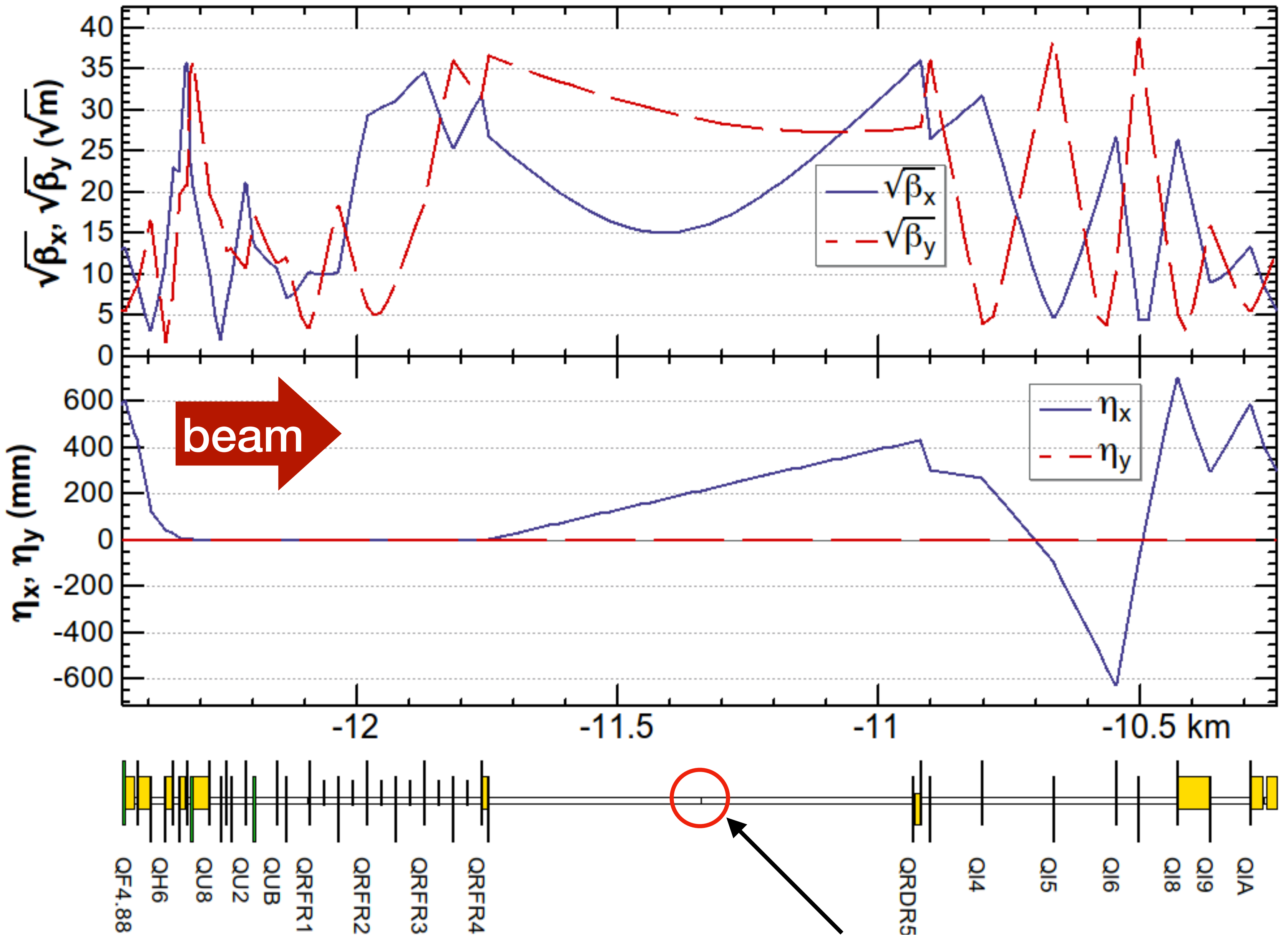
Layout in long straight sections BFHL

- The sections BFHL are used for beam inside/outside exchange, RF, injection, extraction, collimation, etc.
- RF is installed only one of these sections, for all energies.
- For RF cryomodules, each space between quads 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.
- Designed an RF section for Z/W and non-RF Zh/tt, which has a crossing point in the middle. The right part of the section is rebuilt at the transition to Zh/tt RF.



Z/W,
Zh/tt (no RF)

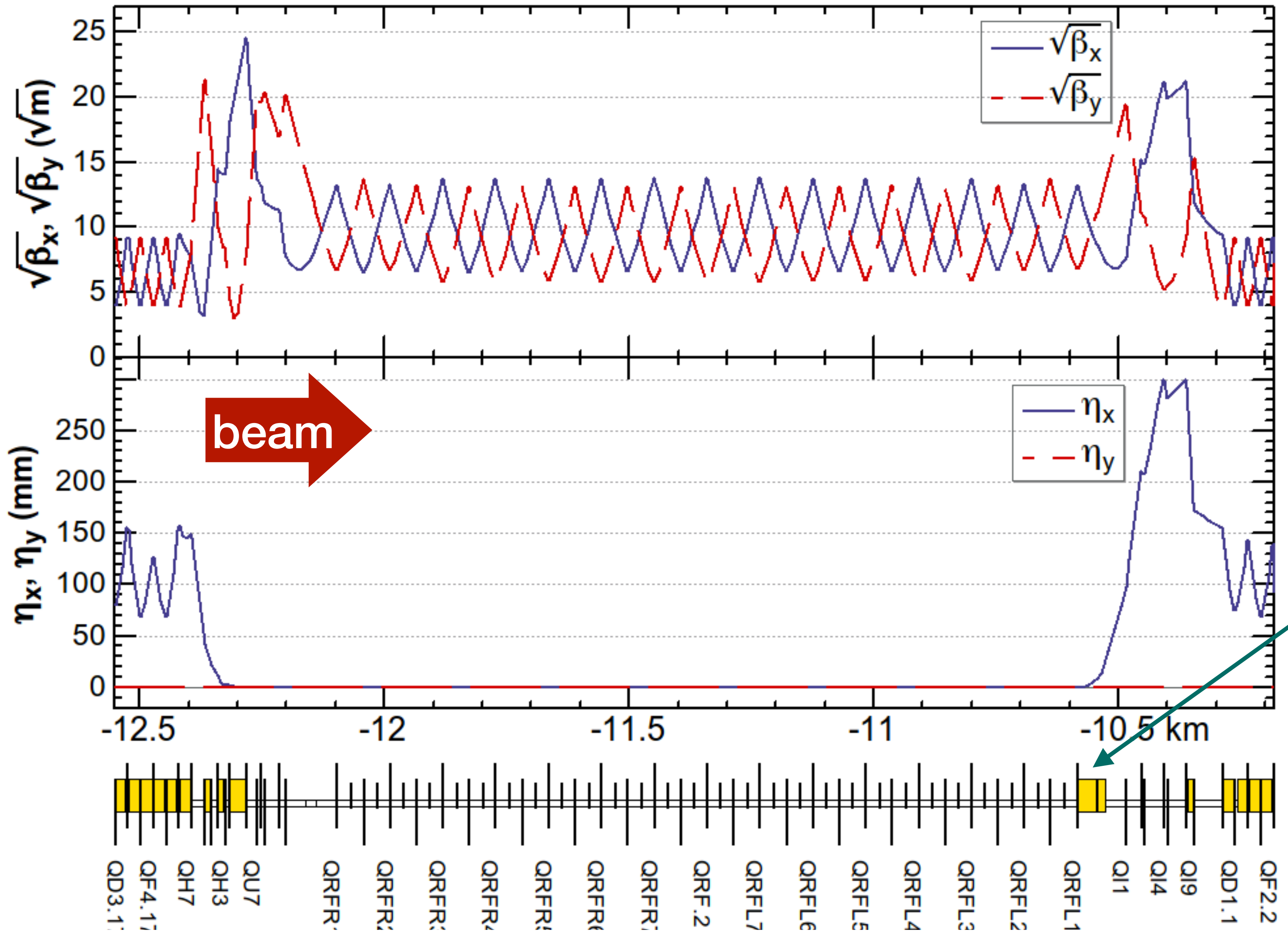
FCCee_z_546_nosol_1.sad



RF
(single beam)

crossing point

Zh/tt (RF) **FCCee_t_546_nosol.sad**

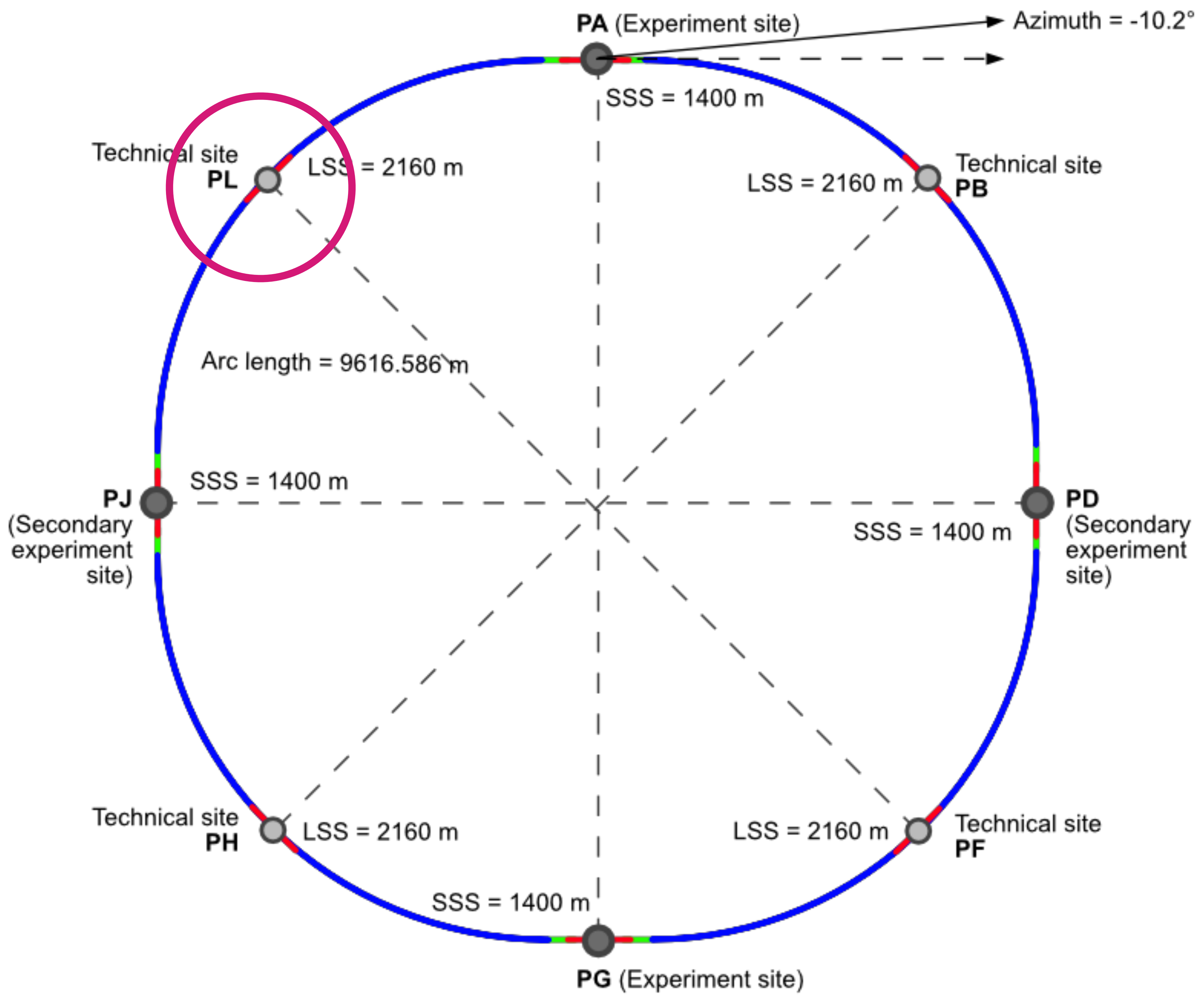


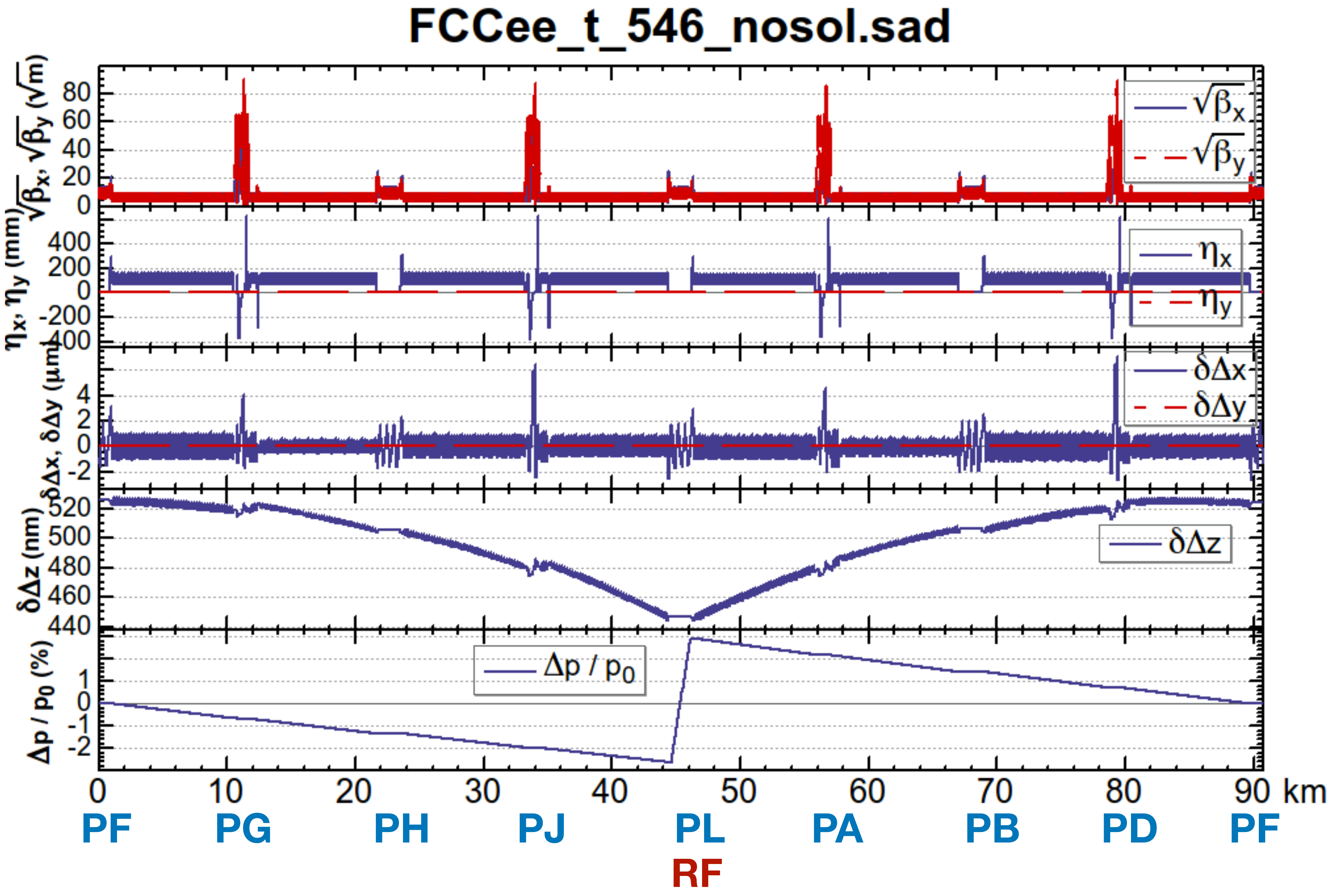
Separator; combination of electrostatic & magnetic

Only outgoing beam is deflected

RF cryomodules common to e+e-

Energy sawtooth for RF@PL ($t\bar{t}$)





- The energy sawtooth reaches -2.5%+3.0% energy deviation on the closed orbit around the ring ($t\bar{t}$, above).
  - Note that there is an asymmetry due to the SR loss itself.
- If we apply tapering over all magnets in the ring, the residual closed orbit & optics change, etc., will be tiny enough.

Layout in the interaction region

- Both IPs of FCC-ee and FCC-hh now completely overlap.
  - **The IP transversely deviates from the layout line by about 10.5 m outward.**
- Beams always enter the IP from inside of the ring.
  - Thus they must cross to each other in the long straight sections BFHL.
- The placement of the booster has not been perfectly determined.
  - It must bypass the FCC-ee detector by more than 8 m separation from the IP.

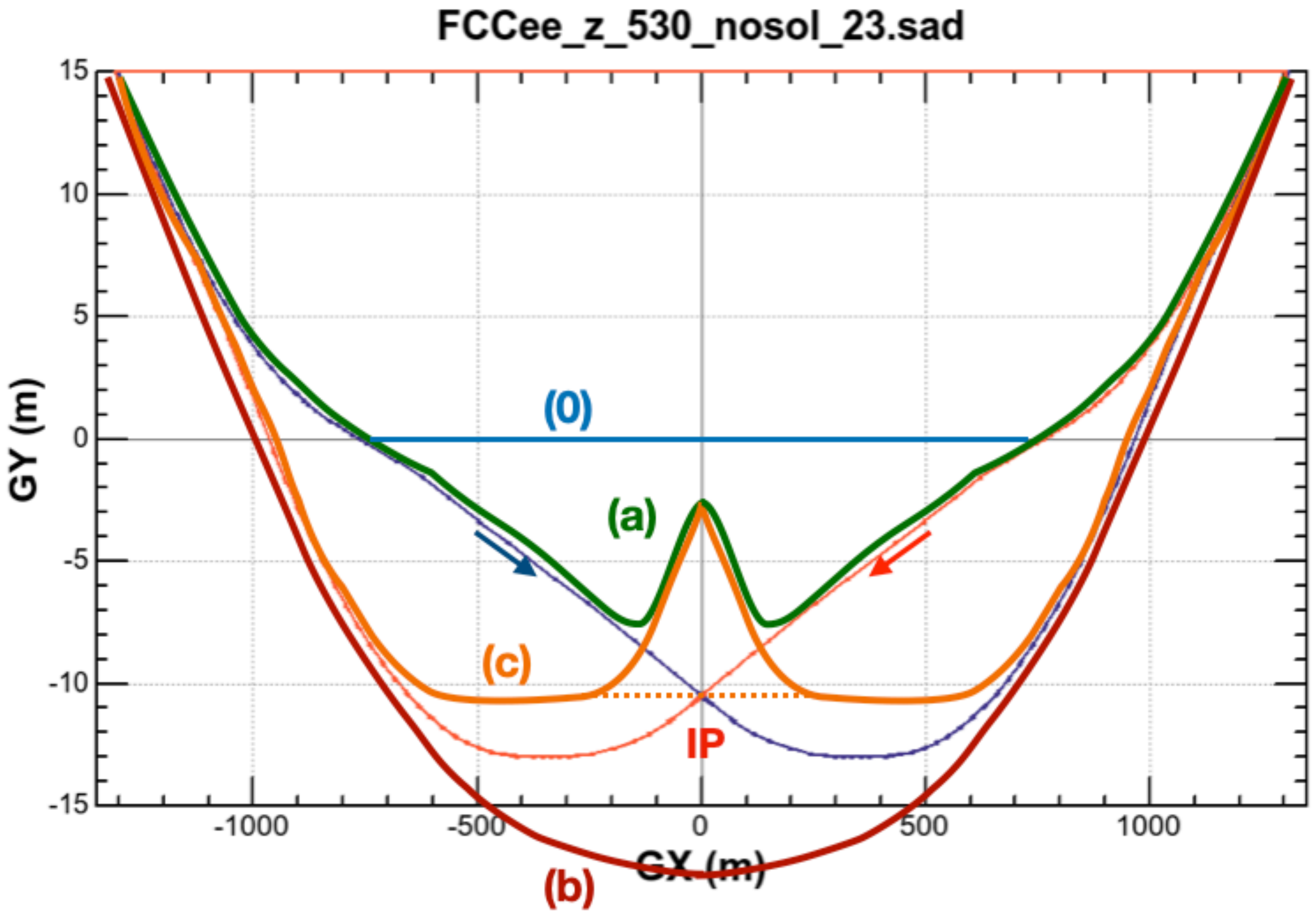
    Several choices (and more) are conceivable:

    (0) Layout line

    (a) stay inside of the inner collider ring with a bypass chicane within about ±200 m of the IP.

    (b) going outside of the detector

    (c) follow the FCC-hh beam line with a bypass chicane.
  - If the booster is placed on the same plane as the colliders, (c) has to cross the colliders at several locations.
  - To avoid the crossing, (a) and (b) have to stay inside or outside of the colliders, respectively.
- The choice will be made considering the size of the associated tunnel, synchrotron radiation towards the detector, etc.

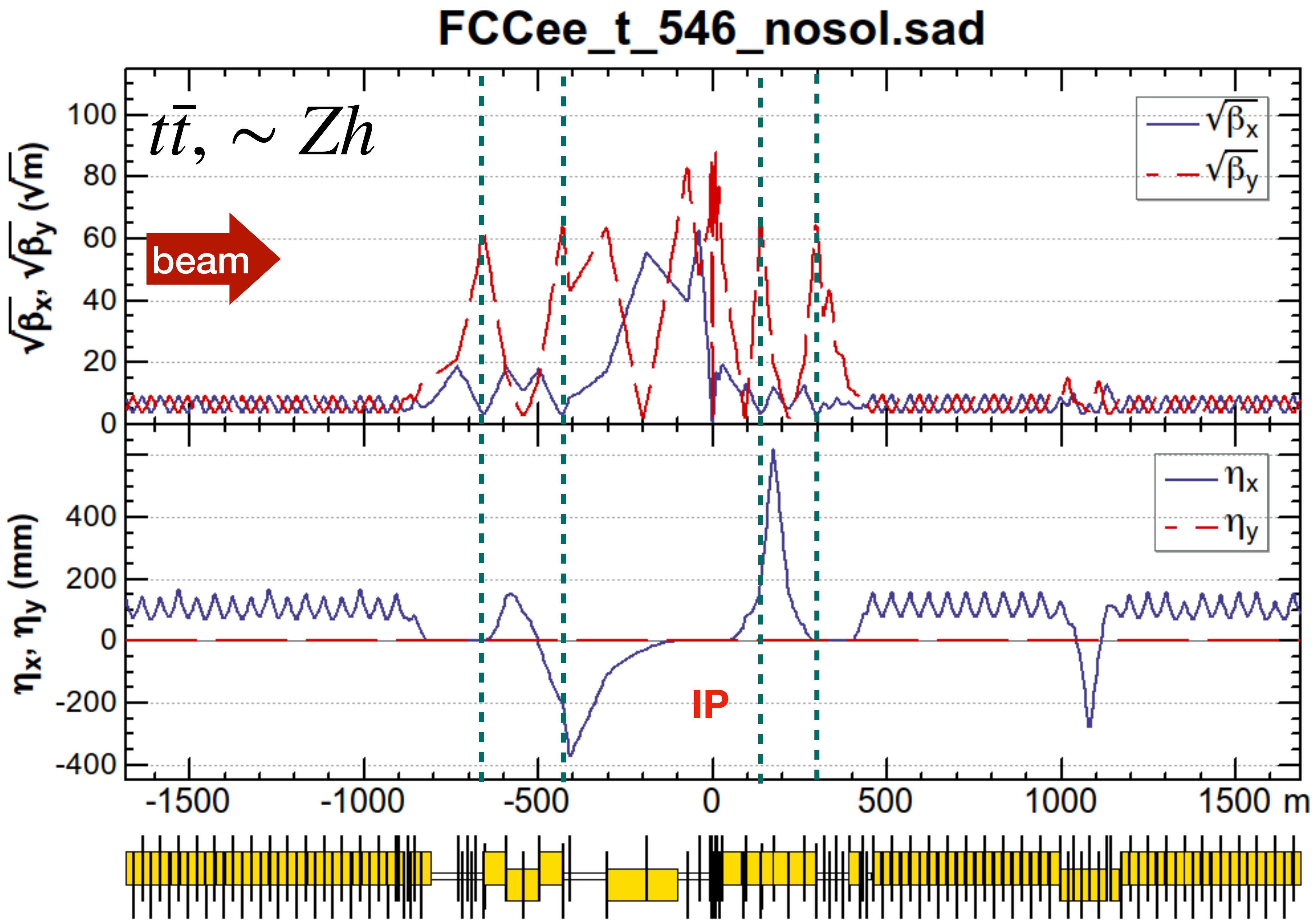


"Bypass of the booster near the detector still an open question."

Antoine Chance @ FCC-BI Workshop

https://indico.cern.ch/event/1209598/contributions/5092242/attachments/2551153/4394714/2022_11_21_heb_status.pdf

IR optics (sect. ADGJ)



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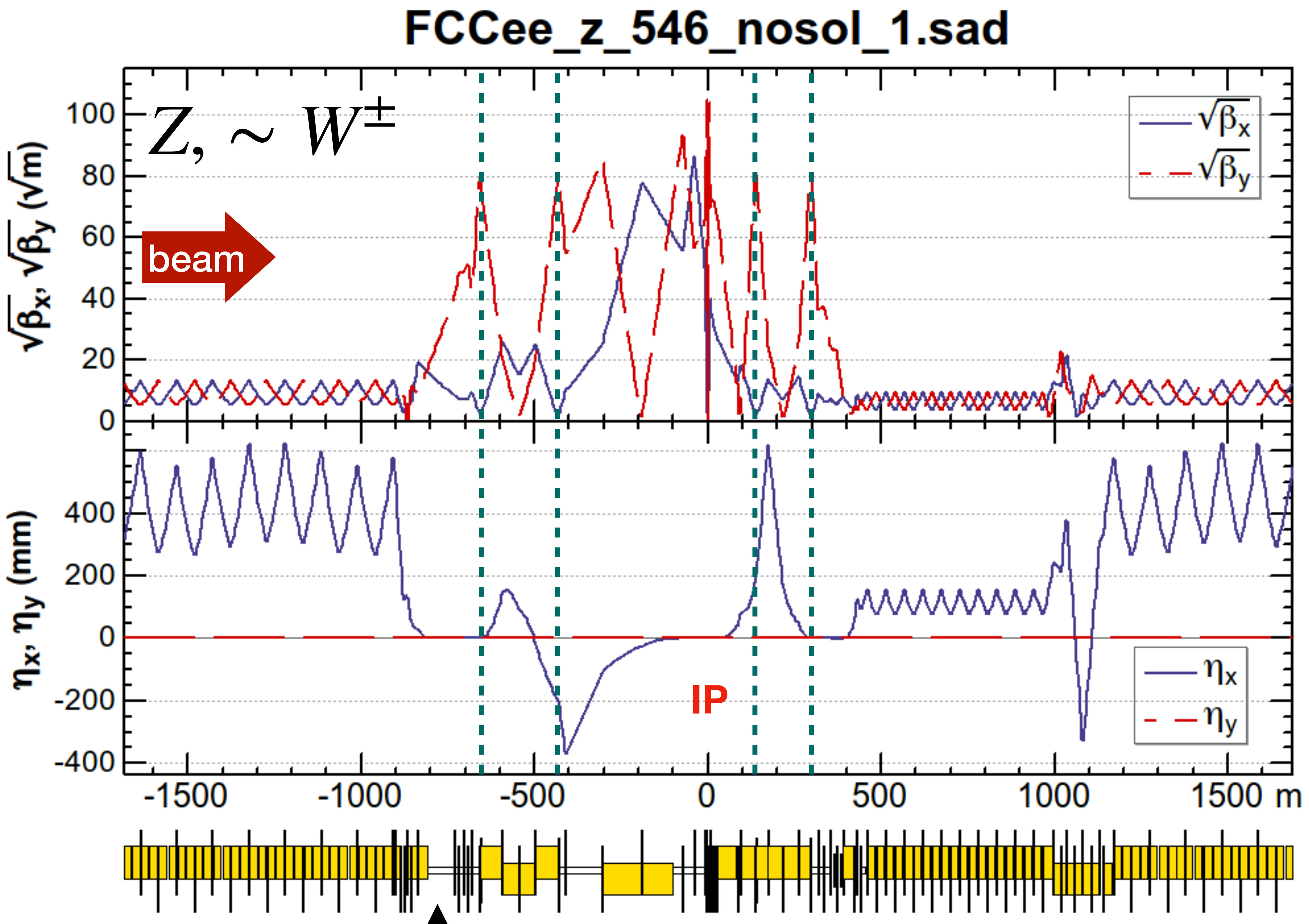
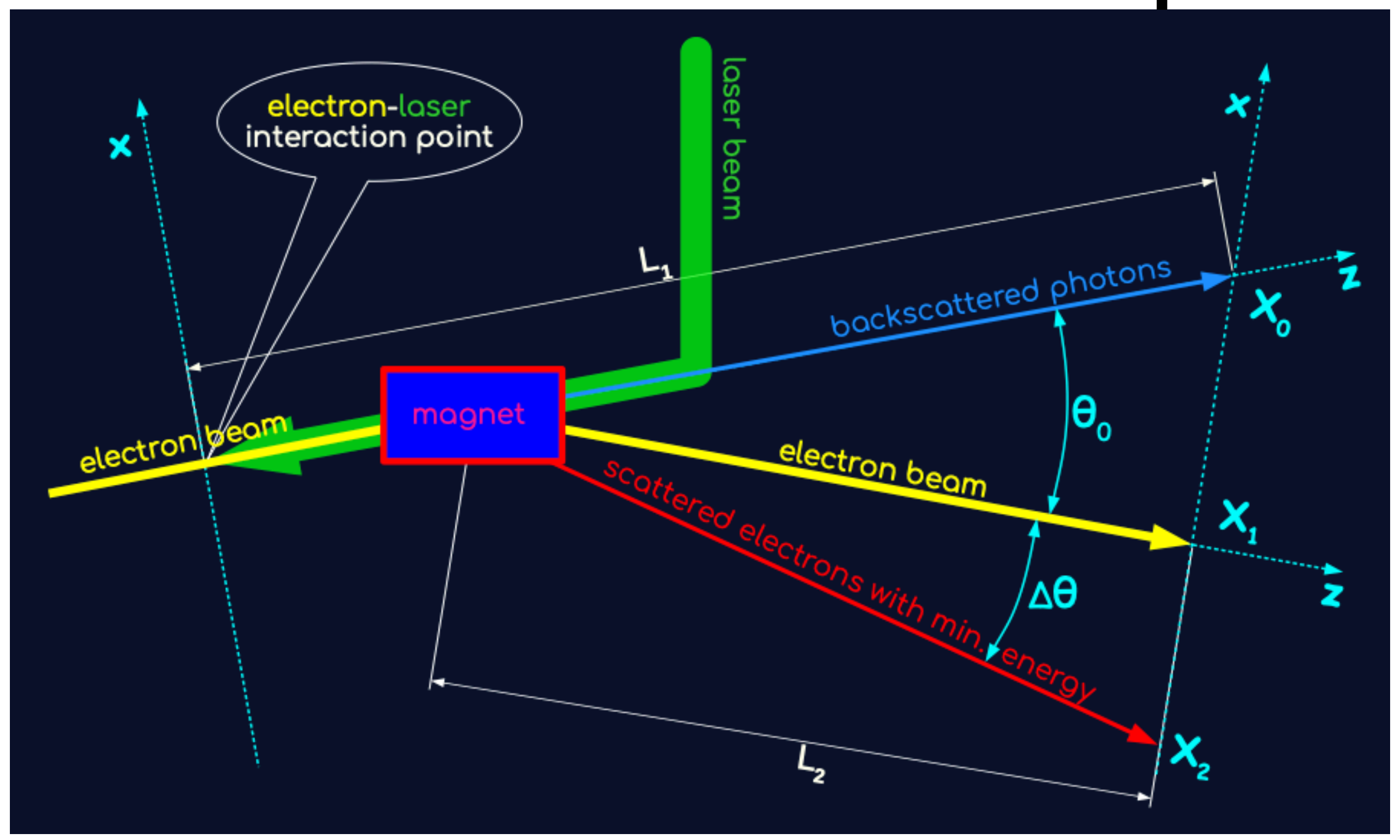
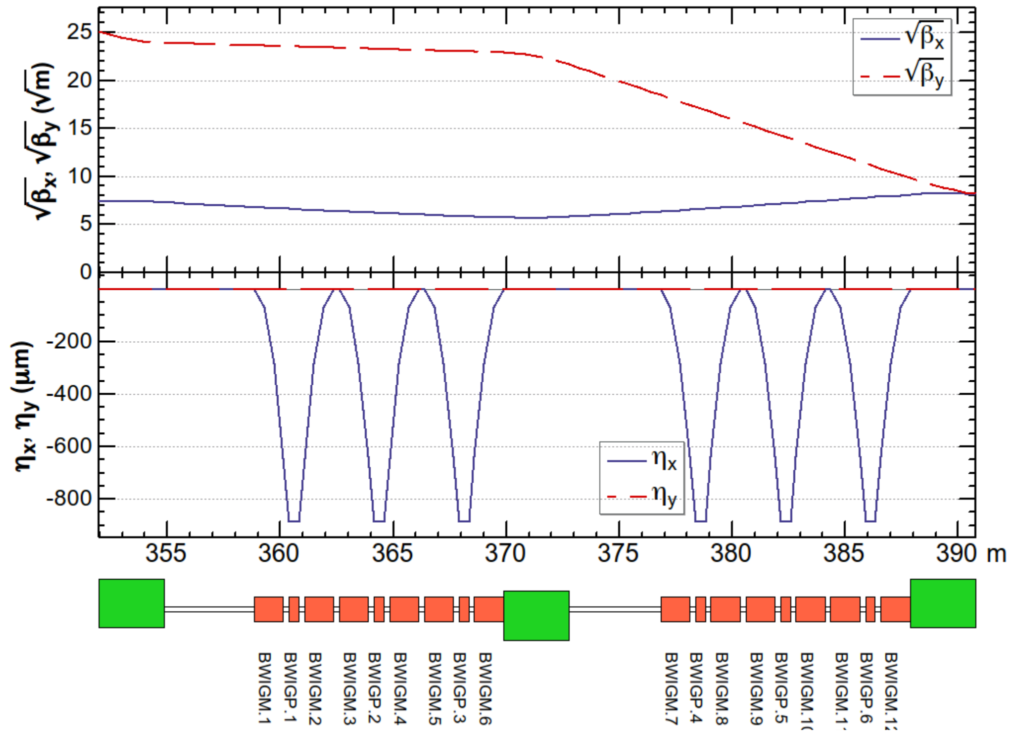


polarimeter
N. Muchnoi

pol. wiggler

- The beam optics are highly asymmetric between upstream/downstream due to crossing angle & suppression of the SR from upstream to the IP.
- Crab waist/vertical chromaticity correction sextupoles are located at the vertical dashed lines.
- The matching sections may be used for polarimeters (upstream) and polarization wigglers (downstream) (A. Blondel, M. Hofer).





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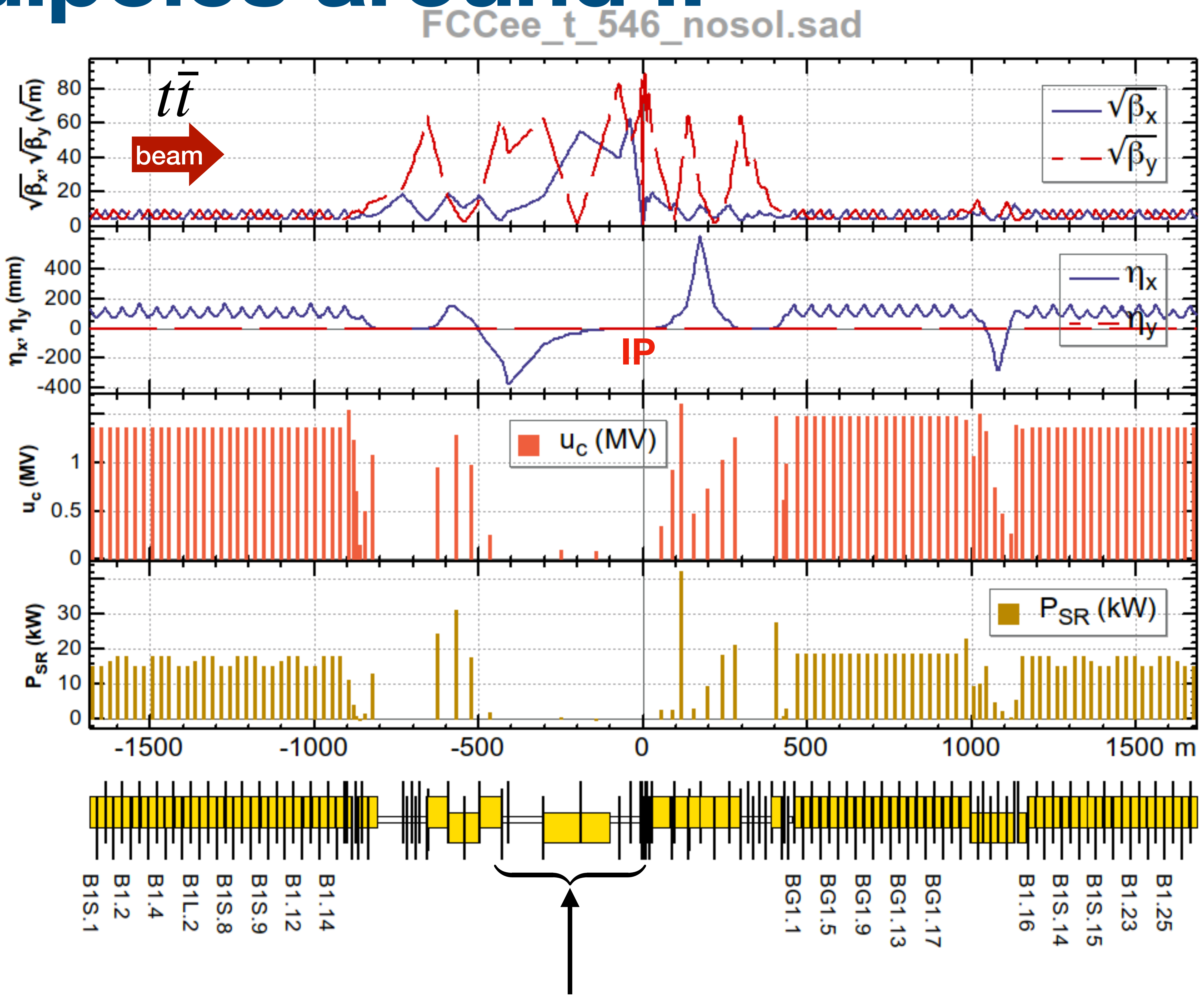
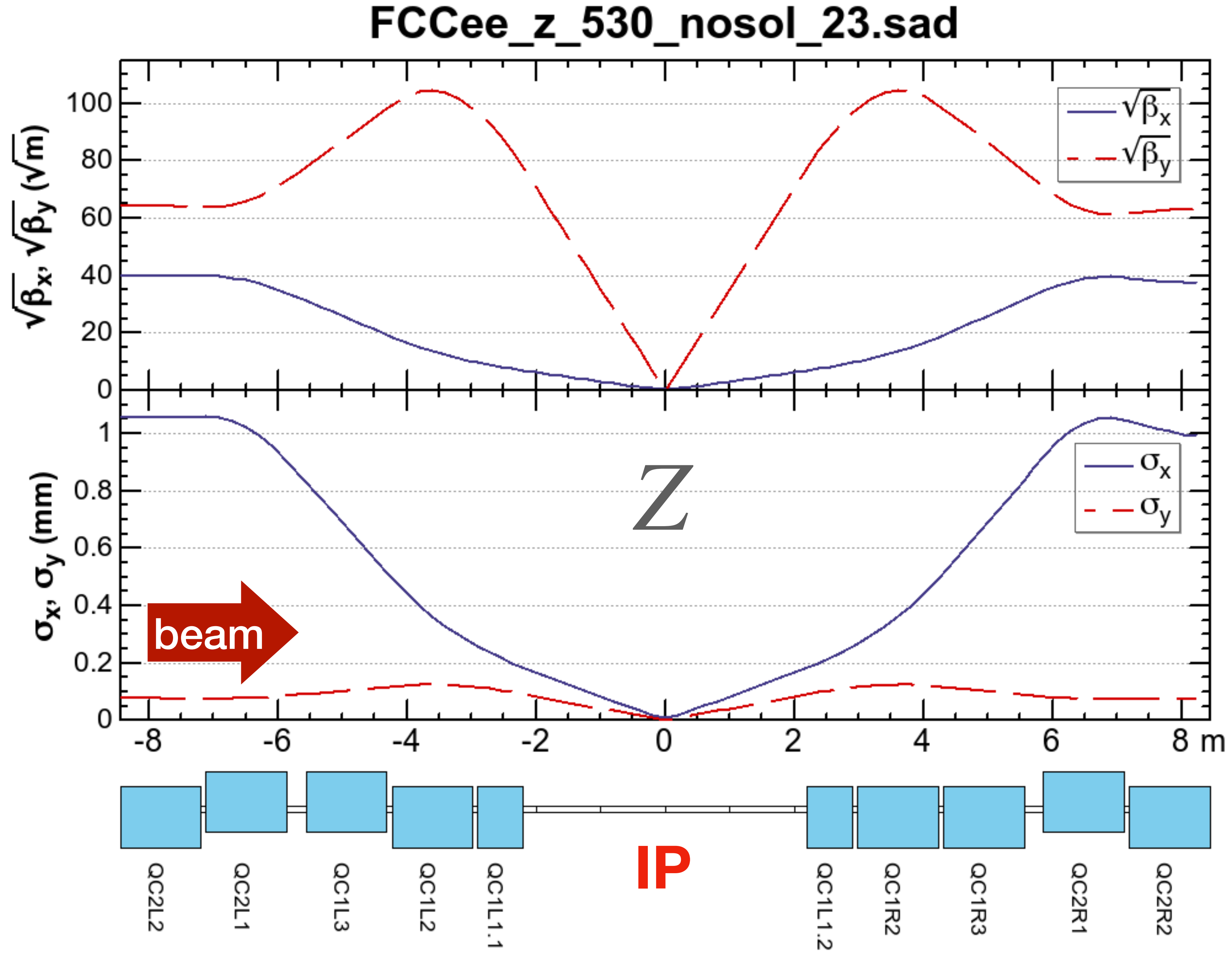
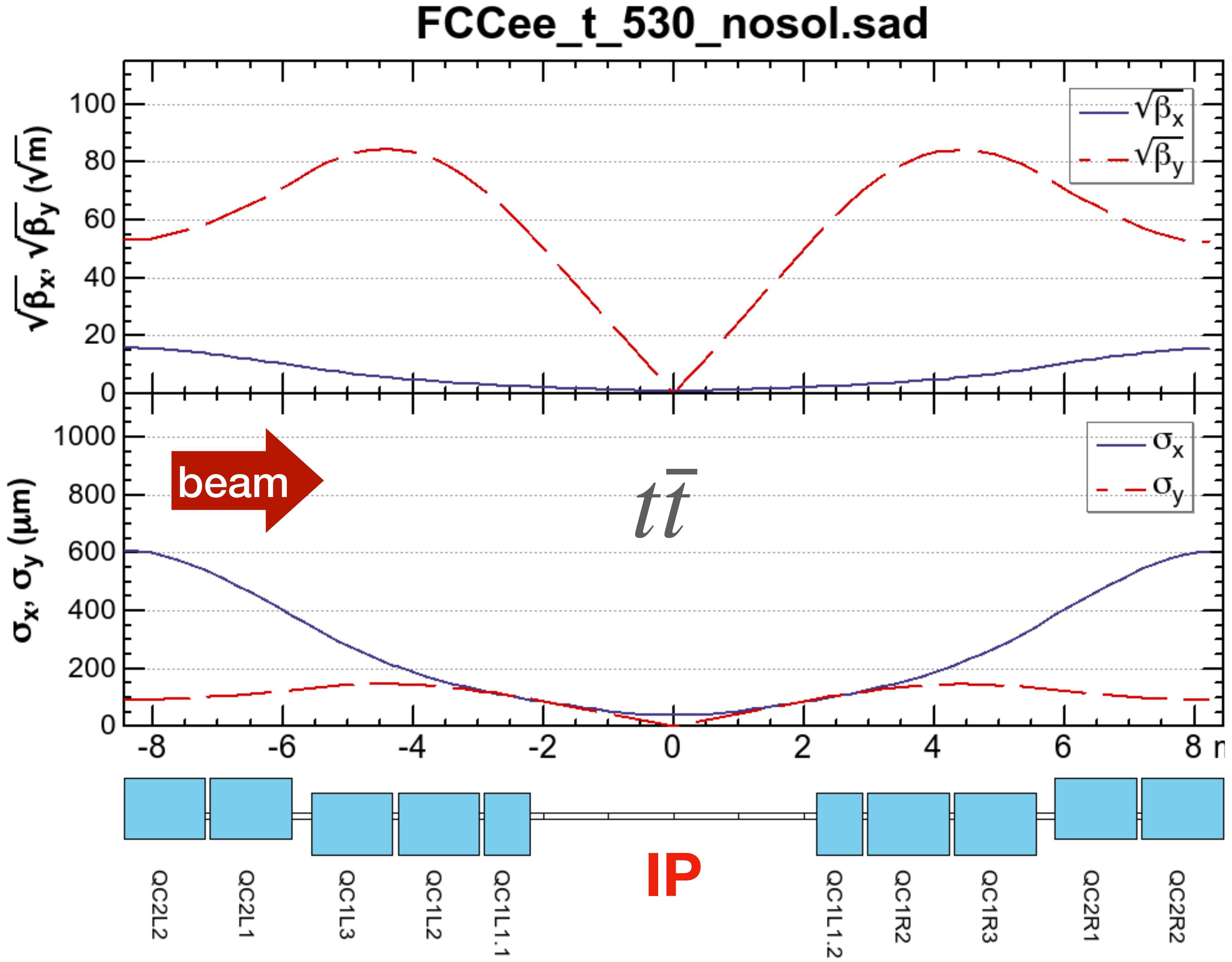
SR from dipoles around IP



- The critical energy of the SR from dipoles upstream the IP is suppressed below 100 keV up to $\sim 400\,\mathrm{m}$ from IP at $t\bar{t}$.

Final quadupoles QC{12}

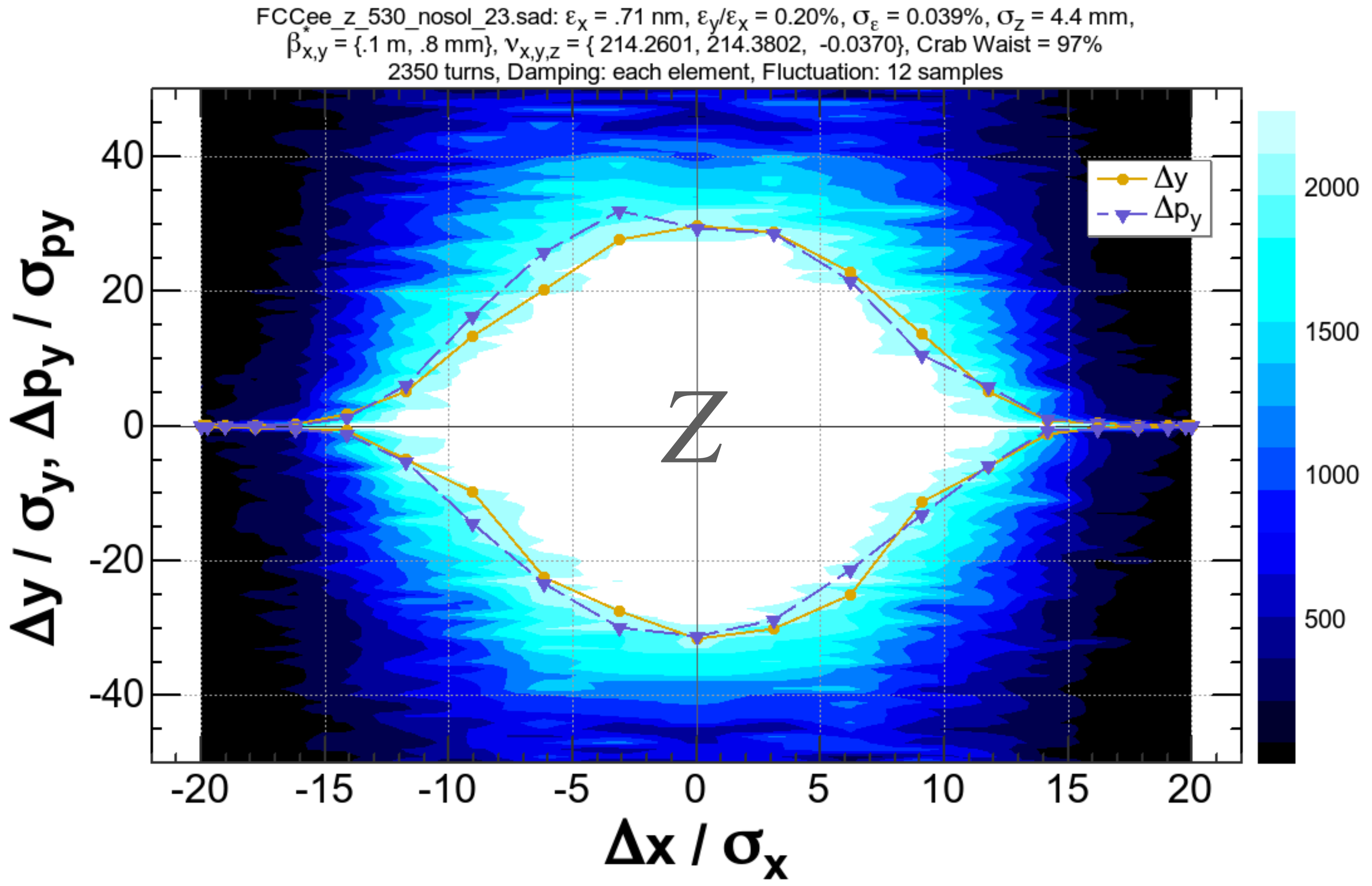

FCCee_z_530_nosol_23.sad


FCCee_t_530_nosol.sad

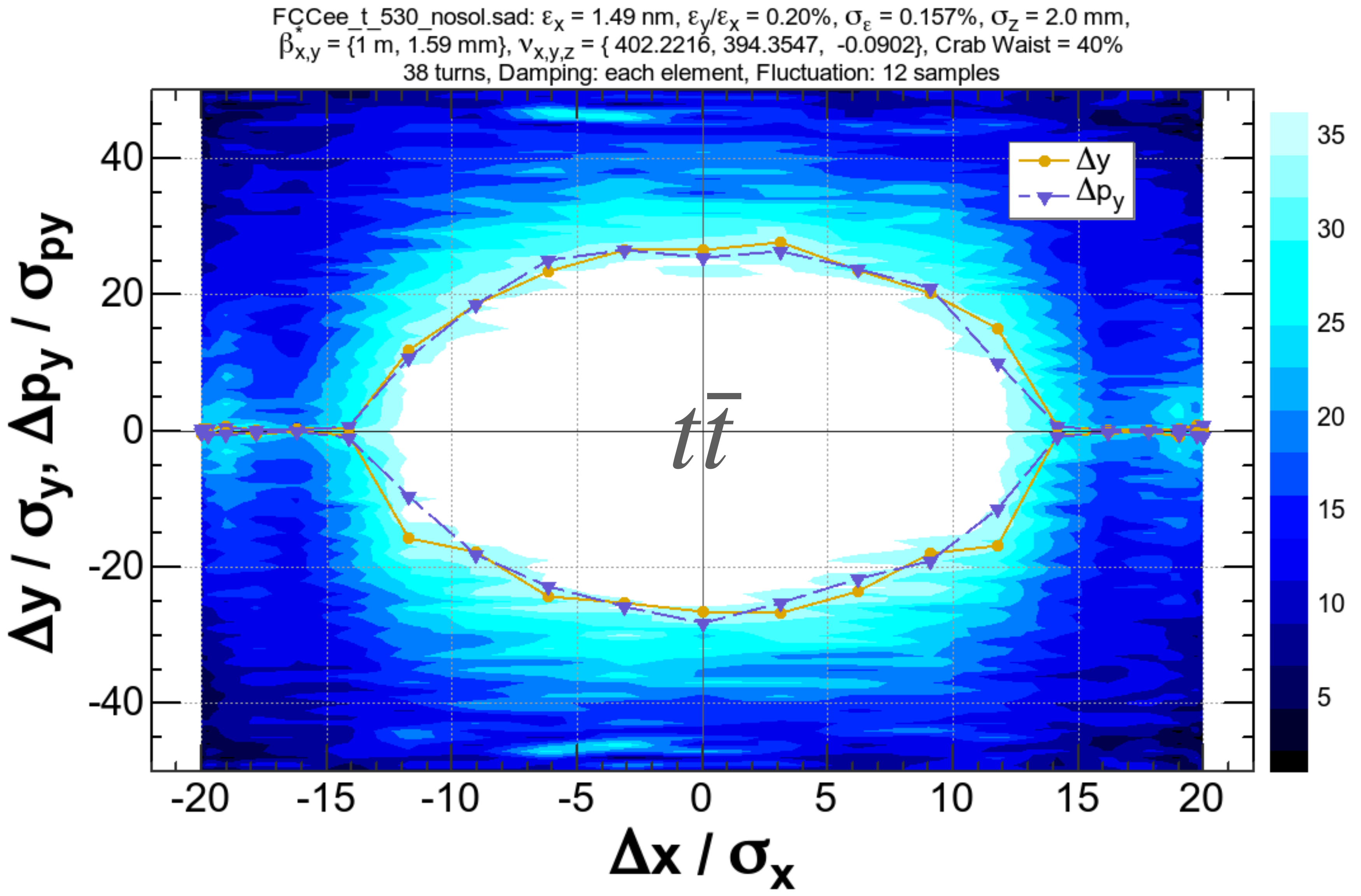
			z_530	t_530
	L (m)	s (m)	B' (T/m)	
QC2L2	1.25	-8.440	-1.654	76.954
QC2L1	1.25	-7.110	30.848	32.886
QC1L3	1.25	-5.560	0.567	-89.722
QC1L2	1.25	-4.230	-41.472	-98.144
QC1L1.1	0.7	-2.900	-41.500	-97.996
QC1L1.2	0.7	2.200	-41.500	-97.996
QC1R2	1.25	2.980	-41.500	-99.892
QC1R3	1.25	4.310	-2.489	-88.582
QC2R1	1.25	5.860	39.756	27.356
QC2R2	1.25	7.190	-5.071	96.462

- The final quadrupoles are split into slices.
- Each slice may change the gradient/polarity depending on the beam energy.
- The maximum gradient is 100 T/m (x tapering).
- At Z, too high gradient degrades the DA.

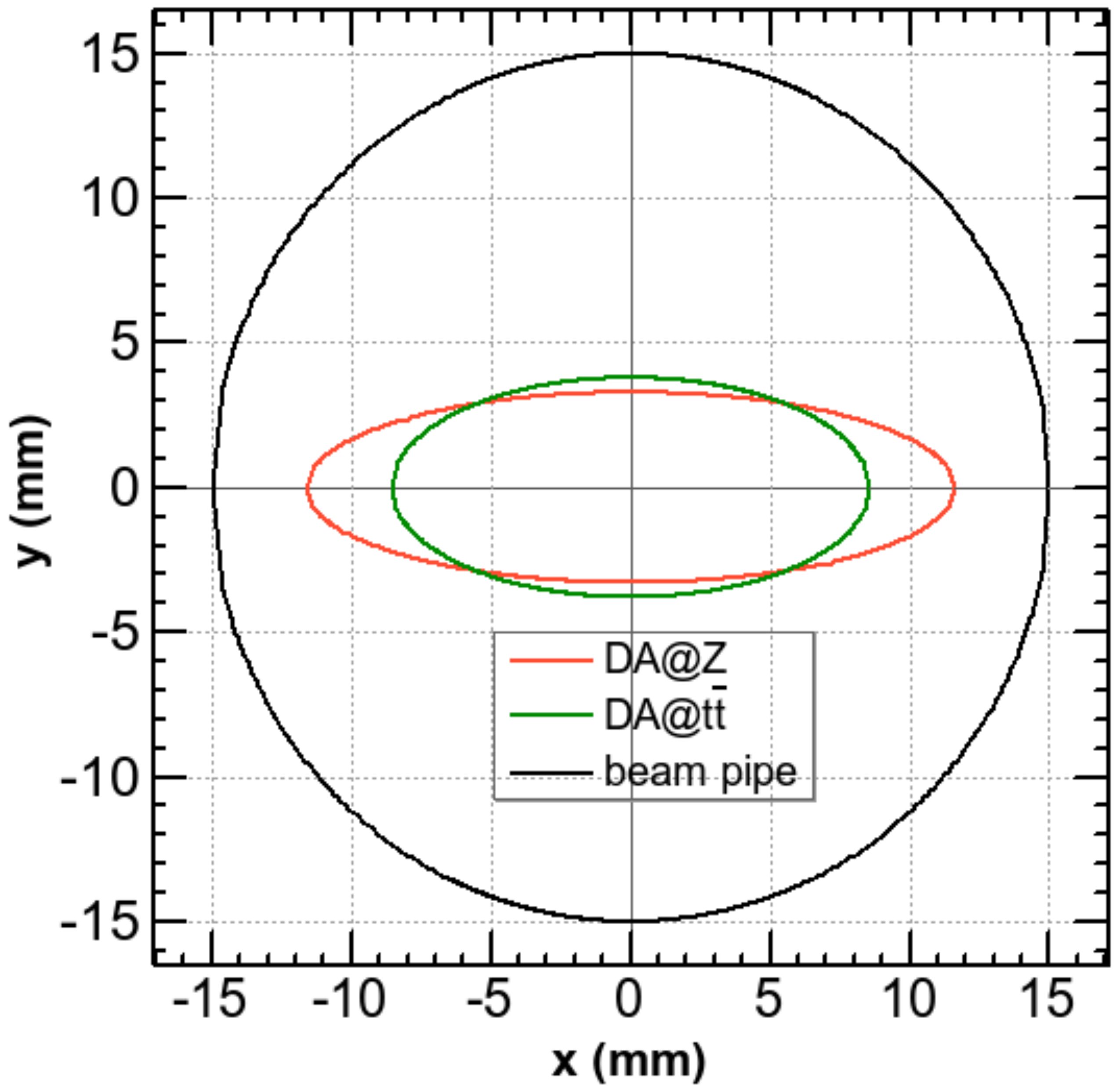
Dynamic aperture @ QC1



FCCee_z_530_nosol_23.sad: ε_x = .71 nm, $\varepsilon_y/\varepsilon_x$ = 0.20%, σ_ε = 0.039%, σ_z = 4.4 mm,
$\beta^*_{x,y}$ = {.1 m, .8 mm}, $\nu_{x,y,z}$ = { 214.2601, 214.3802, -0.0370}, Crab Waist = 97%
2350 turns, Damping: each element, Fluctuation: 12 samples



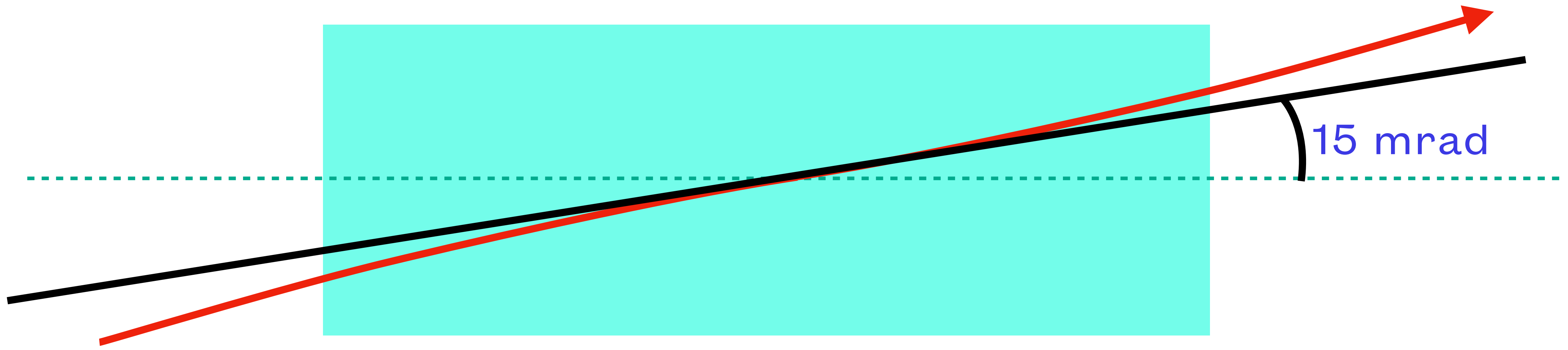
FCCee_t_530_nosol.sad: ε_x = 1.49 nm, $\varepsilon_y/\varepsilon_x$ = 0.20%, σ_ε = 0.157%, σ_z = 2.0 mm,
$\beta^*_{x,y}$ = {1 m, 1.59 mm}, $\nu_{x,y,z}$ = { 402.2216, 394.3547, -0.0902}, Crab Waist = 40%
38 turns, Damping: each element, Fluctuation: 12 samples

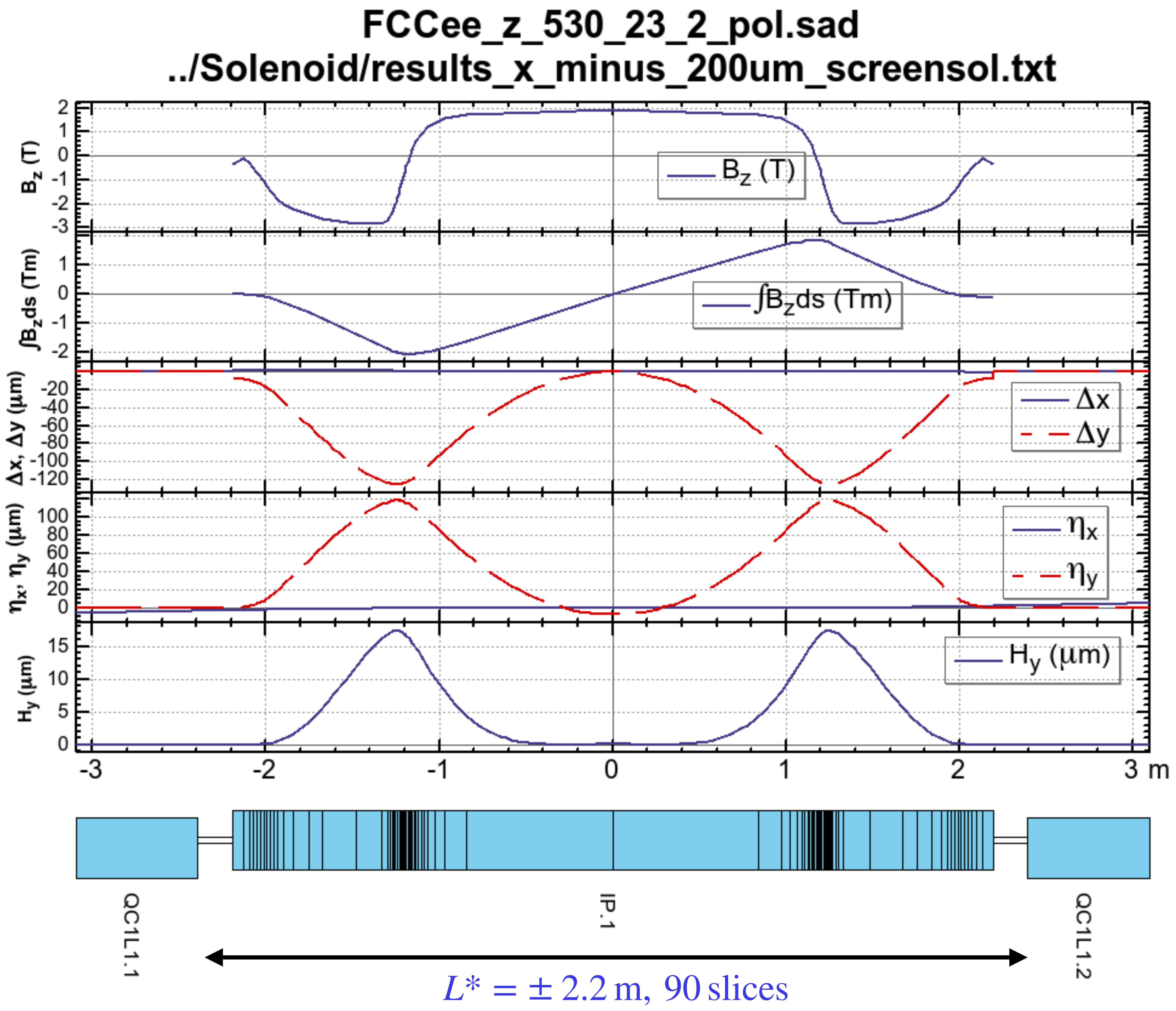


- The dynamic apertures above are evaluated with SR & tapering for 2x long. damping time at Z&$t\bar{t}$.
- The strength of QC1 affects the vertical DA via SR fluctuation @Z.
- The dynamic aperture in the final quad QC1* is much smaller than the beam pipe radius in both x&y (left plot).
  - This may imply that the necessary collimation depth can be larger than the DA, somewhere between the DA and the pipe radius.
    - This may mean that the collimators will not affect the beam lifetime.

Optics including a realistic solenoid (M. Koratzinos)

- A realistic solenoid + multipole field given by M. Koratzinos has been included into the latest 4 IP lattice.
  - Both MAD-X and SAD can include the same solenoid field map, *independently* (H. Burkhardt, L.V. Riesen-Haupt).
- The L* region (IP±2.2 m) is divided into 90 slices with *unequal thicknesses* ≥5 mm, *along the tilted straight line (±15 mrad),* not along the solenoid axis.
- No leak of vertical dispersion and x-y coupling to the outside region.
  - $\alpha, \beta,$ and hor. dispersion leak outside.
  - The leaked optics and hor. dispersion are adjusted to the no-solenoid case by tweaking several outer quads.
- The associated vertical emittance is 0.43 pm at Z.
- The highest contribution to the vertical emittance comes from the middle transition ($s \sim \pm 1.2\,\mathrm{m}$) of B_z.

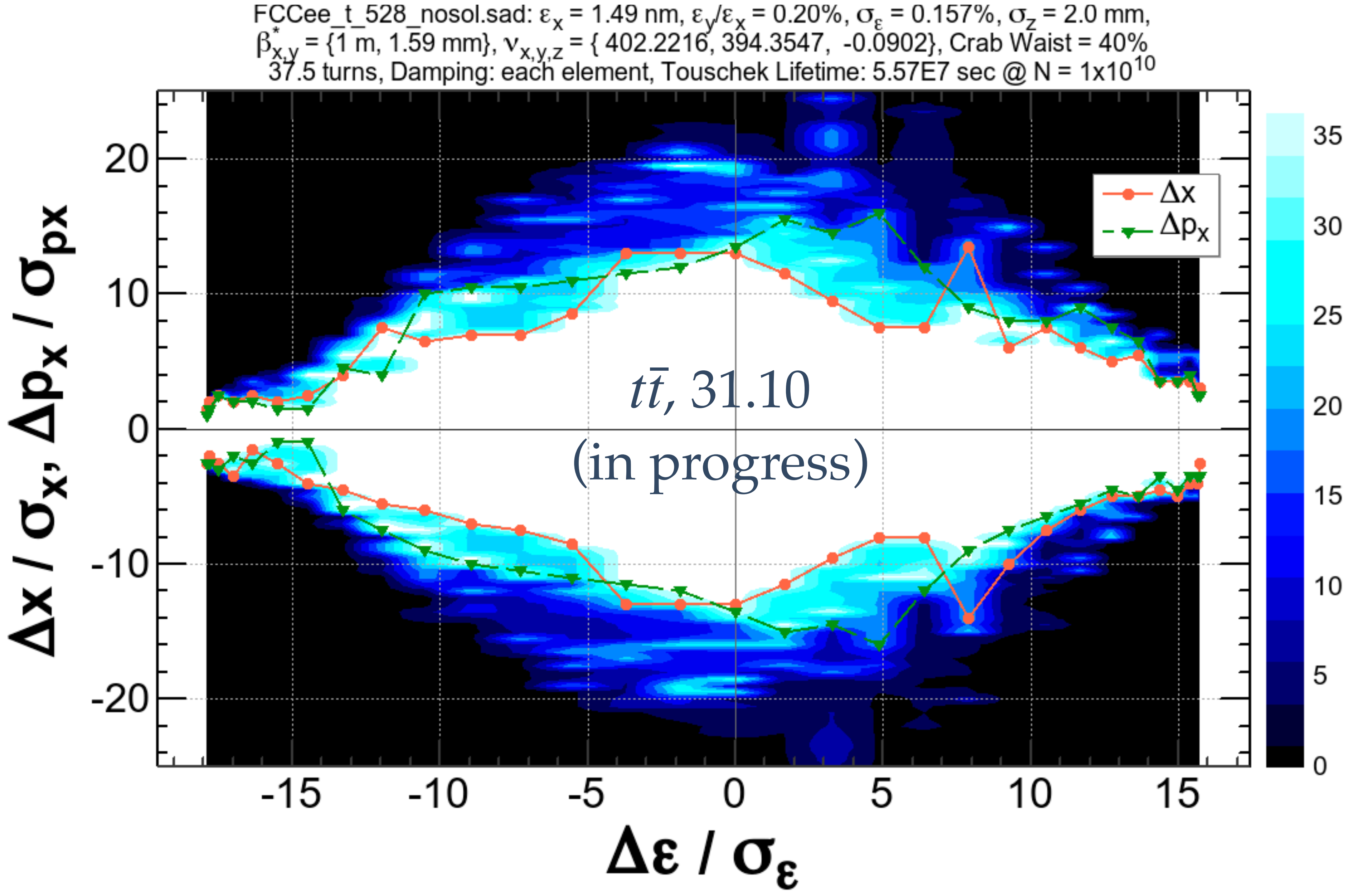


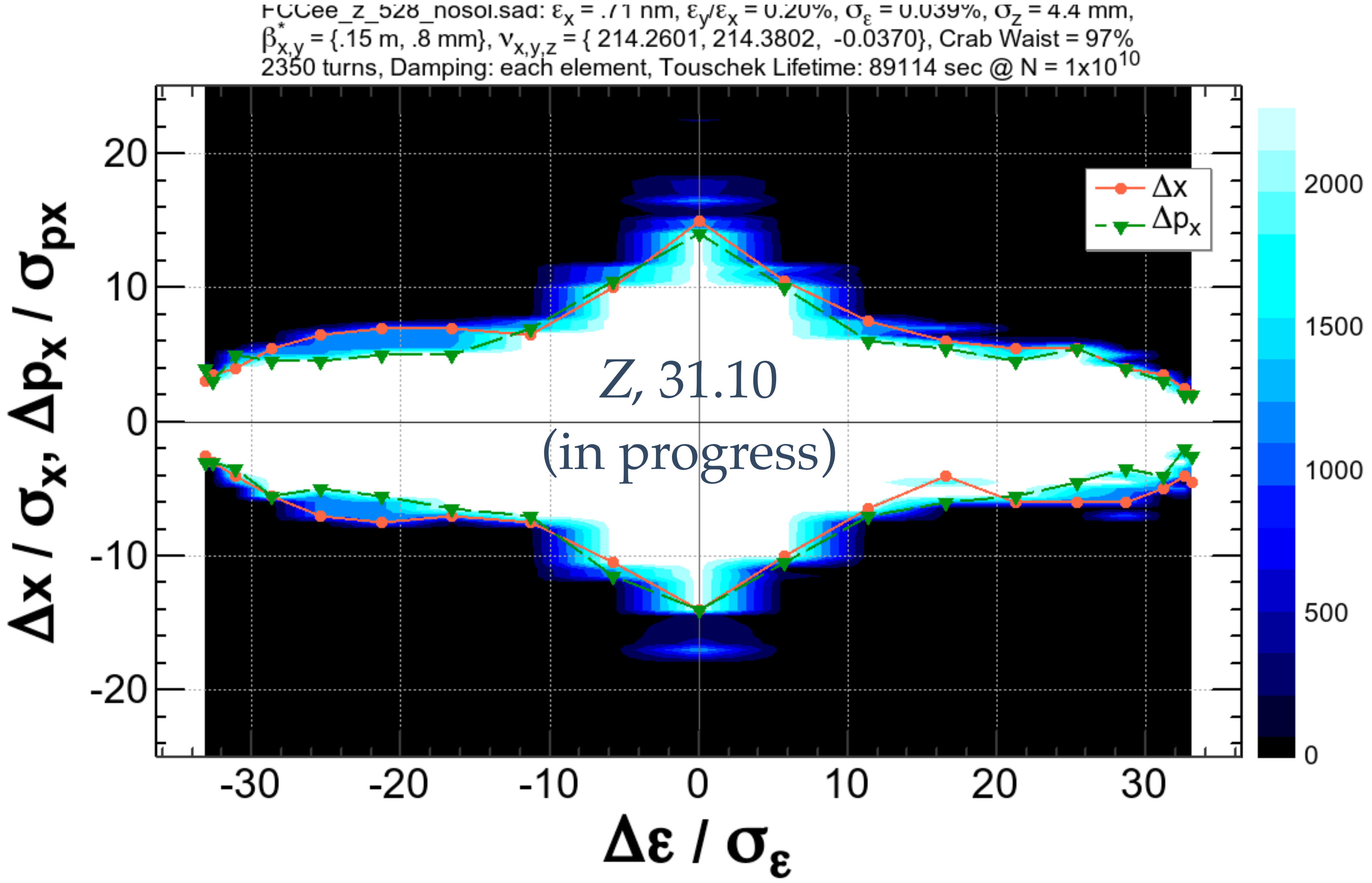


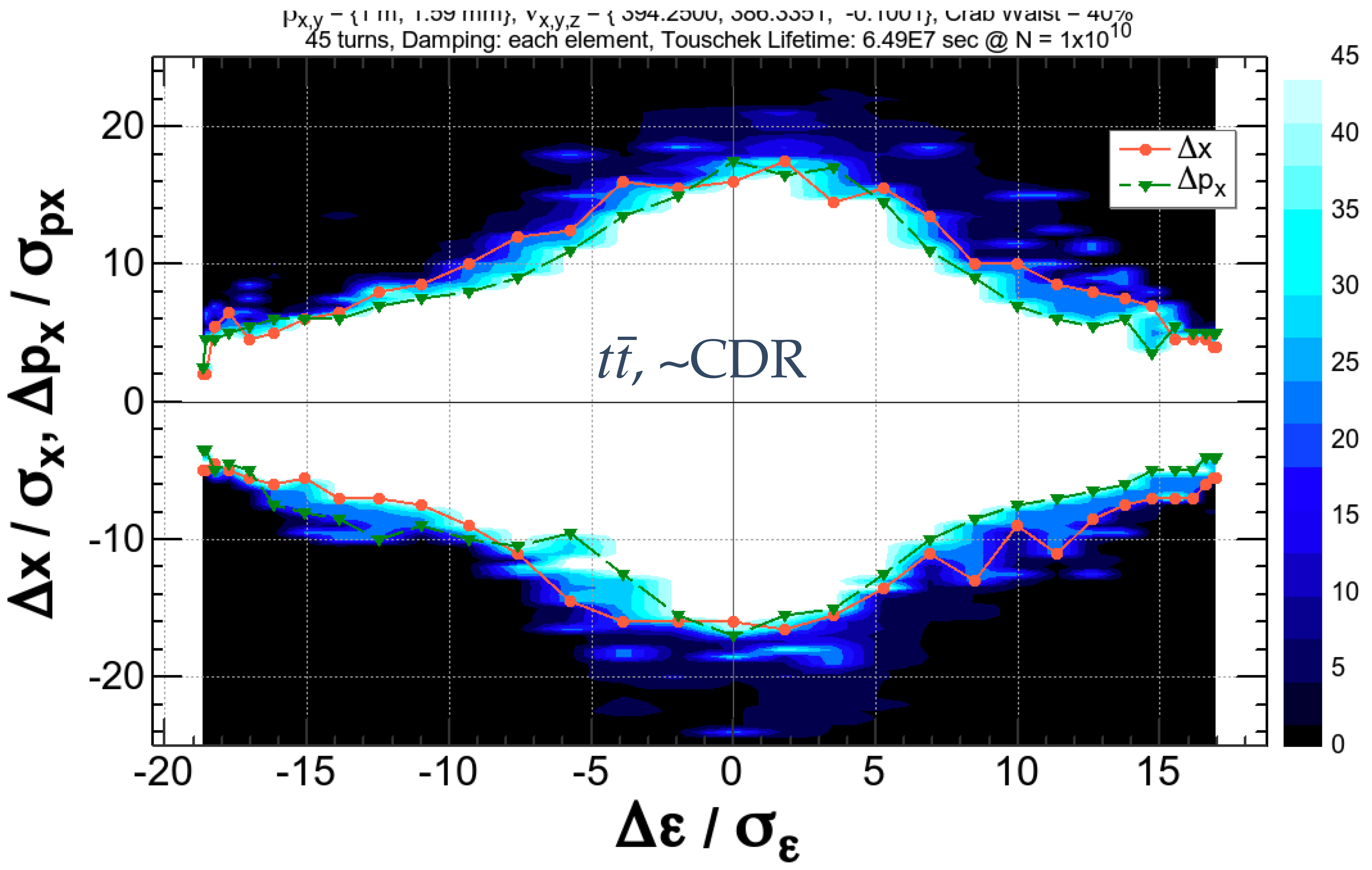
Dynamic aperture

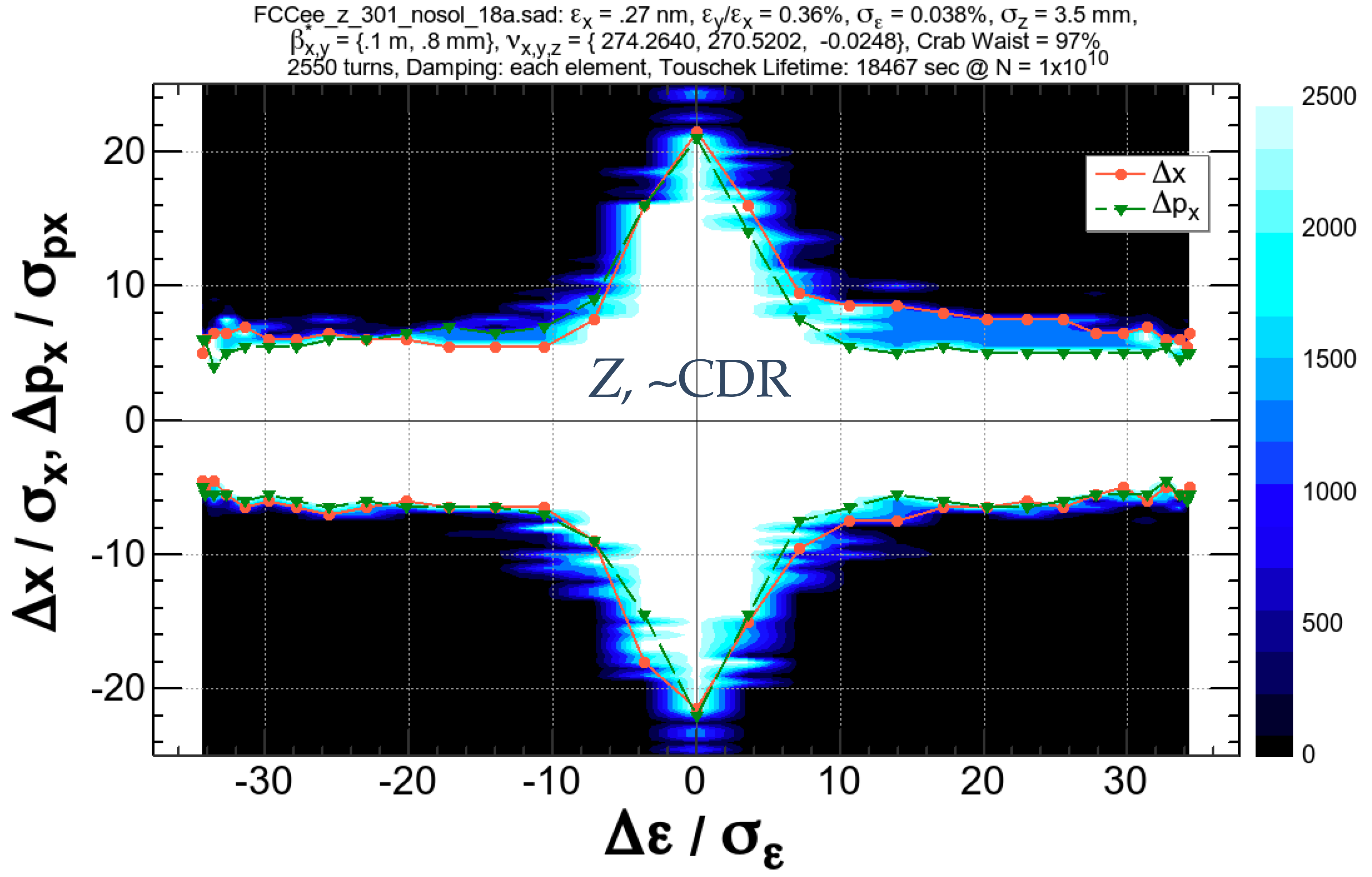
These are with the old RF sections and tunes.
DA with new RF sections and tunes are in progress…

FUTURE
CIRCULAR
COLLIDER


FCCee_t_528_nosol.sad: ε_x = 1.49 nm, $\varepsilon_y/\varepsilon_x$ = 0.20%, σ_ε = 0.157%, σ_z = 2.0 mm,
$\beta^*_{x,y}$ = {1 m, 1.59 mm}, $\nu_{x,y,z}$ = { 402.2216, 394.3547, -0.0902}, Crab Waist = 40%
37.5 turns, Damping: each element, Touschek Lifetime: 5.57E7 sec @ N = 1×10^{10}

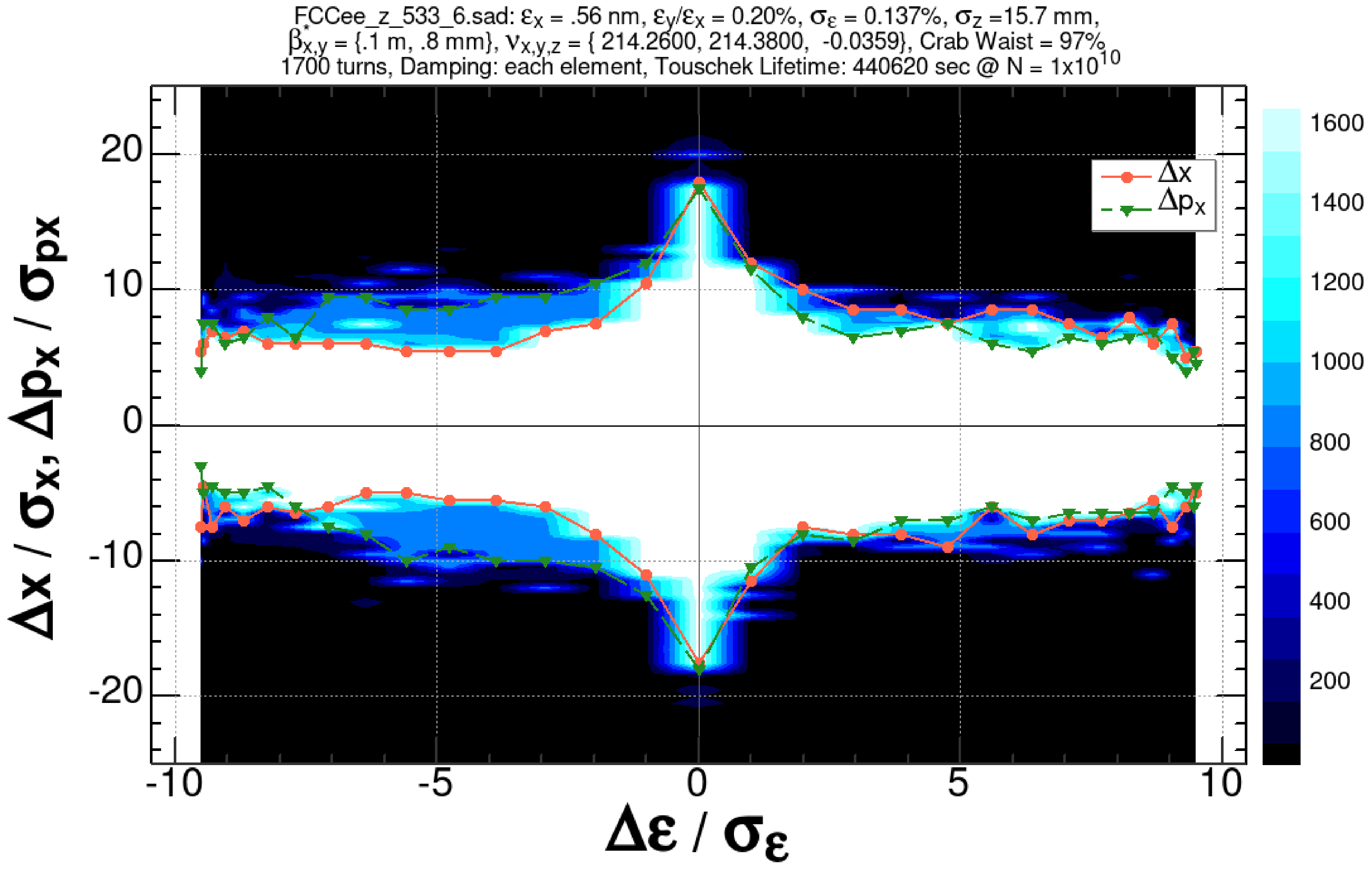

FCCee_z_528_nosol.sad: ε_x = .71 nm, $\varepsilon_y/\varepsilon_x$ = 0.20%, σ_ε = 0.039%, σ_z = 4.4 mm,
$\beta^*_{x,y}$ = {.15 m, .8 mm}, $\nu_{x,y,z}$ = { 214.2601, 214.3802, -0.0370}, Crab Waist = 97%
2350 turns, Damping: each element, Touschek Lifetime: 89114 sec @ N = 1×10^{10}

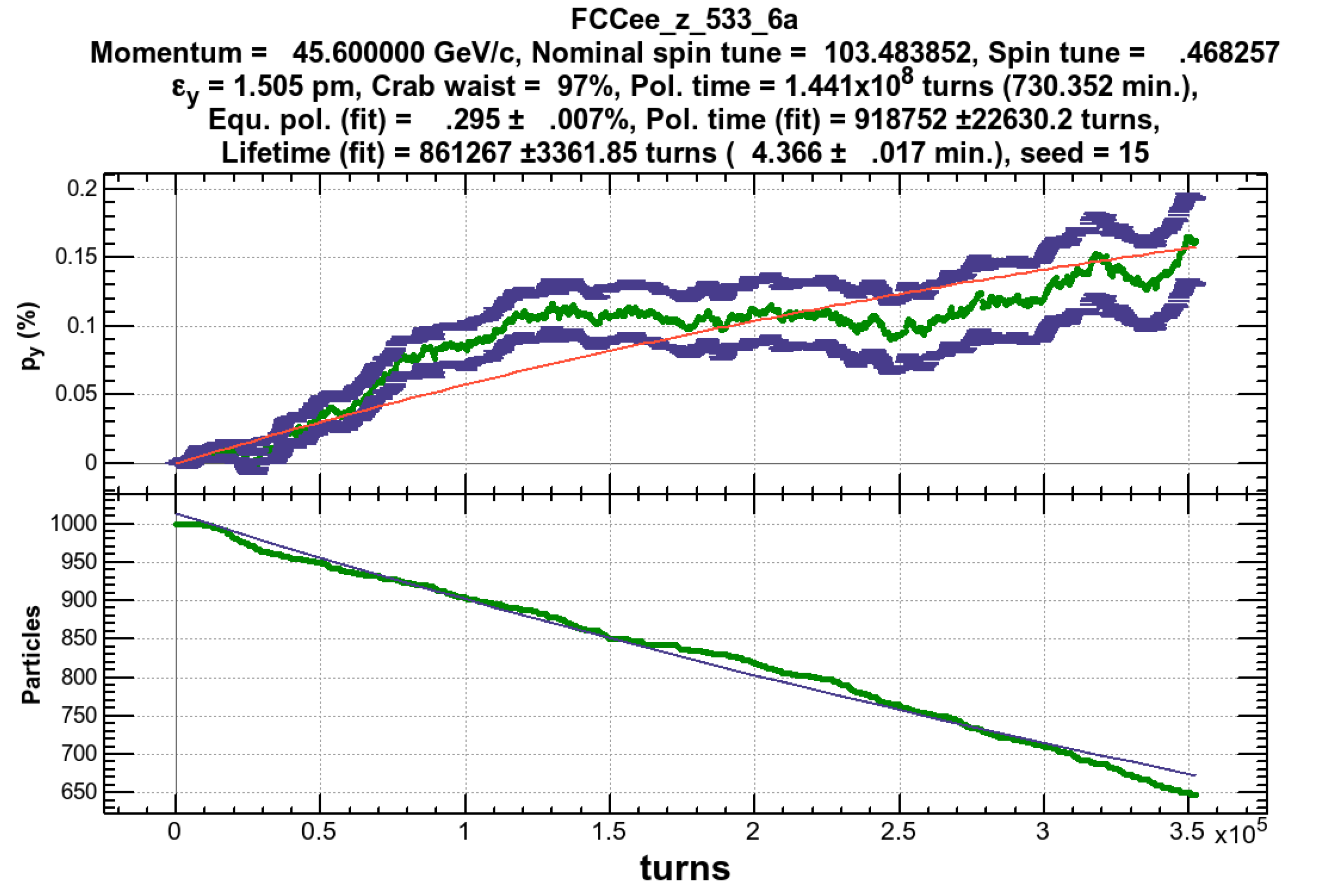

$\beta^*_{x,y}$ = {1 m, 1.59 mm}, $\nu_{x,y,z}$ = { 394.2500, 386.3351, -0.1001}, Crab Waist = 40%
45 turns, Damping: each element, Touschek Lifetime: 6.49E7 sec @ N = 1×10^{10}


FCCee_z_301_nosol_18a.sad: ε_x = .27 nm, $\varepsilon_y/\varepsilon_x$ = 0.36%, σ_ε = 0.038%, σ_z = 3.5 mm,
$\beta^*_{x,y}$ = {.1 m, .8 mm}, $\nu_{x,y,z}$ = { 274.2640, 270.5202, -0.0248}, Crab Waist = 97%
2550 turns, Damping: each element, Touschek Lifetime: 18467 sec @ N = 1×10^{10}

The dynamic aperture, seen by the legacy way, does not tell the lifetime

(A) $\tau = 4.37\,\mathrm{min}$

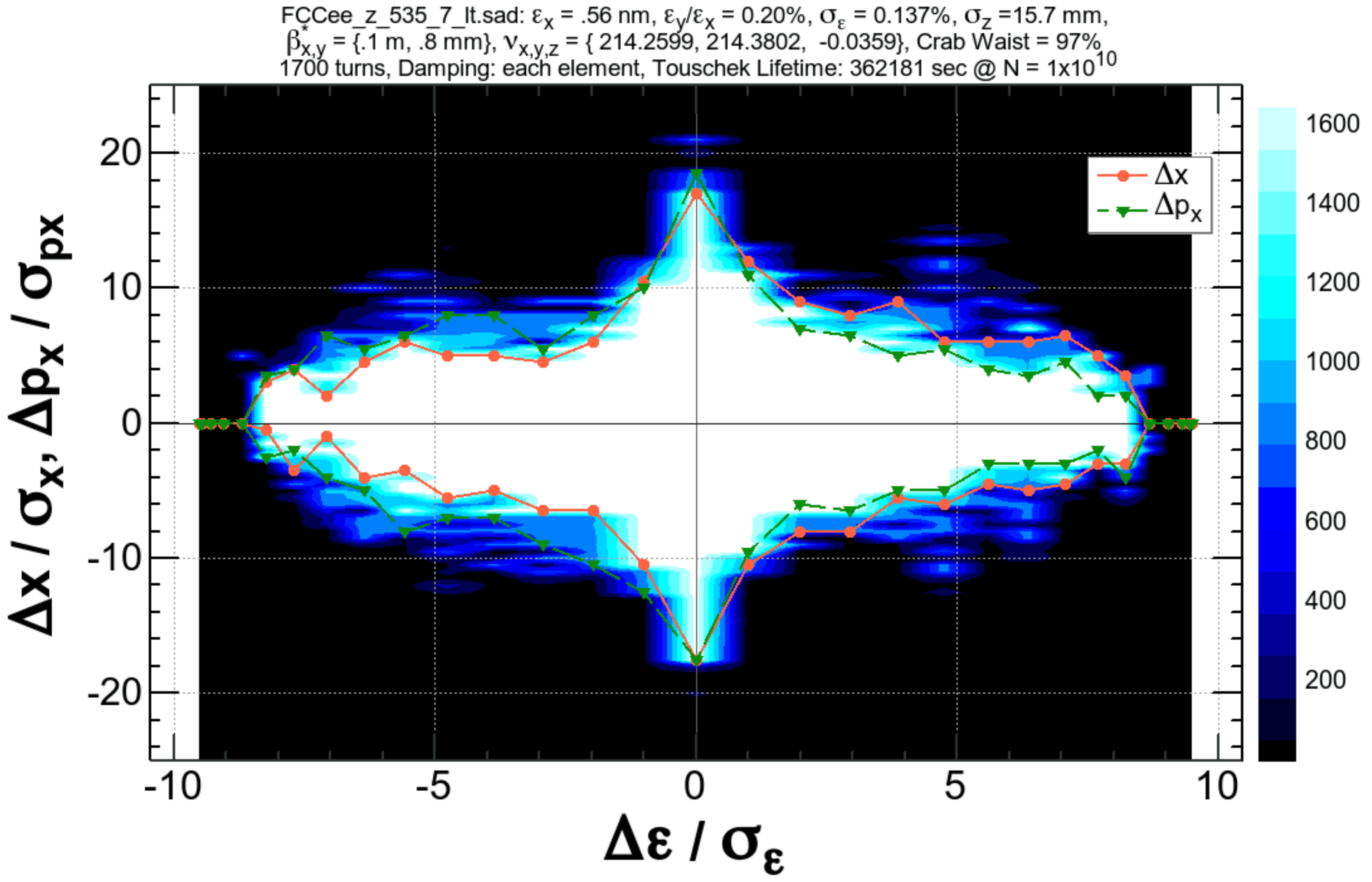

FCCee_z_533_6.sad: ε_x = .56 nm, $\varepsilon_y/\varepsilon_x$ = 0.20%, σ_ε = 0.137%, σ_z =15.7 mm, $\beta^*_{x,y}$ = {.1 m, .8 mm}, $\nu_{x,y,z}$ = { 214.2600, 214.3800, -0.0359}, Crab Waist = 97% 1700 turns, Damping: each element, Touschek Lifetime: 440620 sec @ N = $1\mathrm{x}10^{10}$

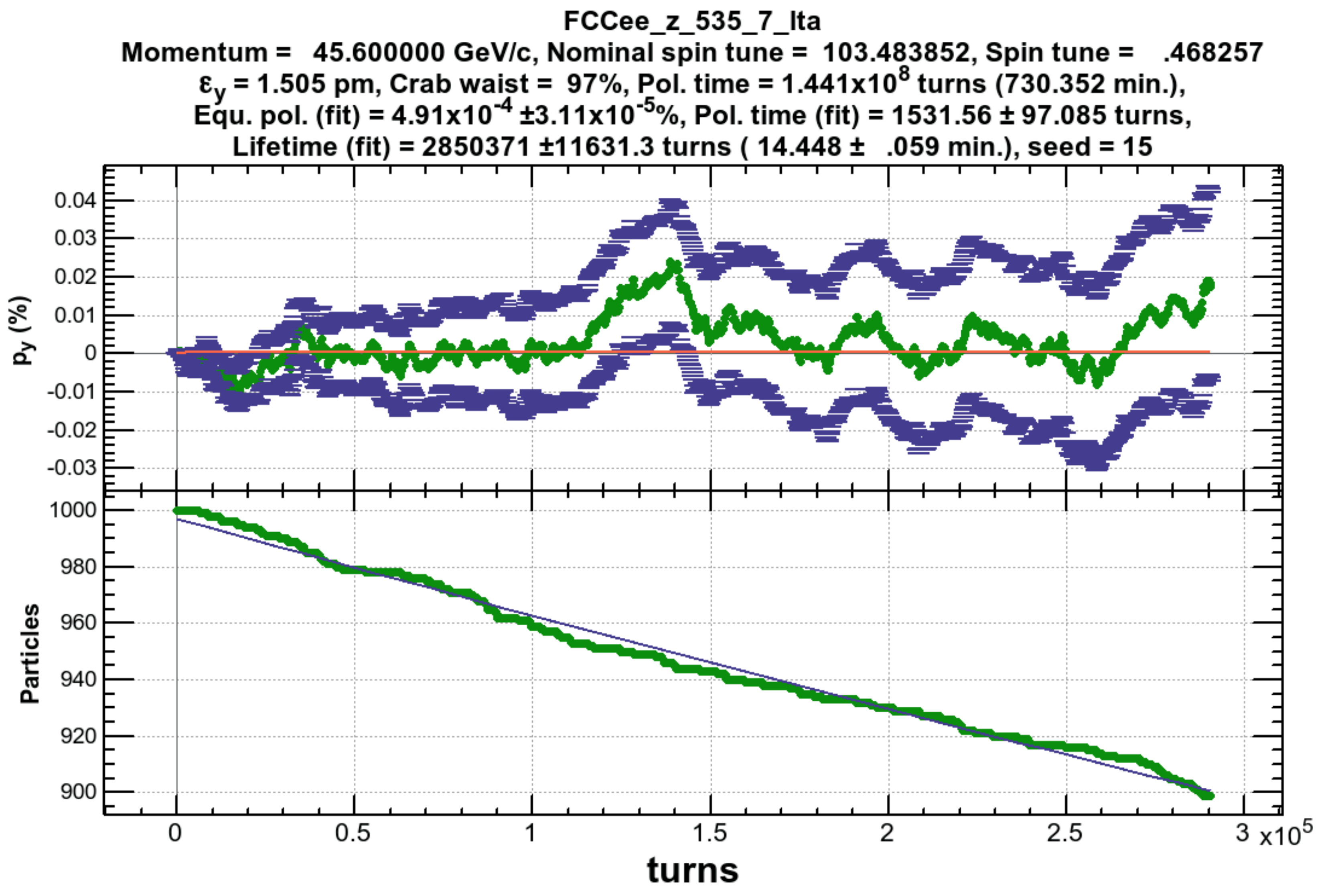

FCCee_z_533_6a

Momentum = 45.600000 GeV/c, Nominal spin tune = 103.483852, Spin tune = .468257 ε_y = 1.505 pm, Crab waist = 97%, Pol. time = $1.441\mathrm{x}10^8$ turns (730.352 min.), Equ. pol. (fit) = .295 ± .007%, Pol. time (fit) = 918752 ±22630.2 turns, Lifetime (fit) = 861267 ±3361.85 turns (4.366 ± .017 min.), seed = 15

- The example (A) seems to have a better DA than (B), but the lifetime is 1/3 of (B)!

(B) $\tau = 14.45\,\mathrm{min}$
(best lifetime so far)


FCCee_z_535_7_lt.sad: ε_x = .56 nm, $\varepsilon_y/\varepsilon_x$ = 0.20%, σ_ε = 0.137%, σ_z =15.7 mm, $\beta^*_{x,y}$ = {.1 m, .8 mm}, $\nu_{x,y,z}$ = { 214.2599, 214.3802, -0.0359}, Crab Waist = 97% 1700 turns, Damping: each element, Touschek Lifetime: 362181 sec @ N = $1\mathrm{x}10^{10}$

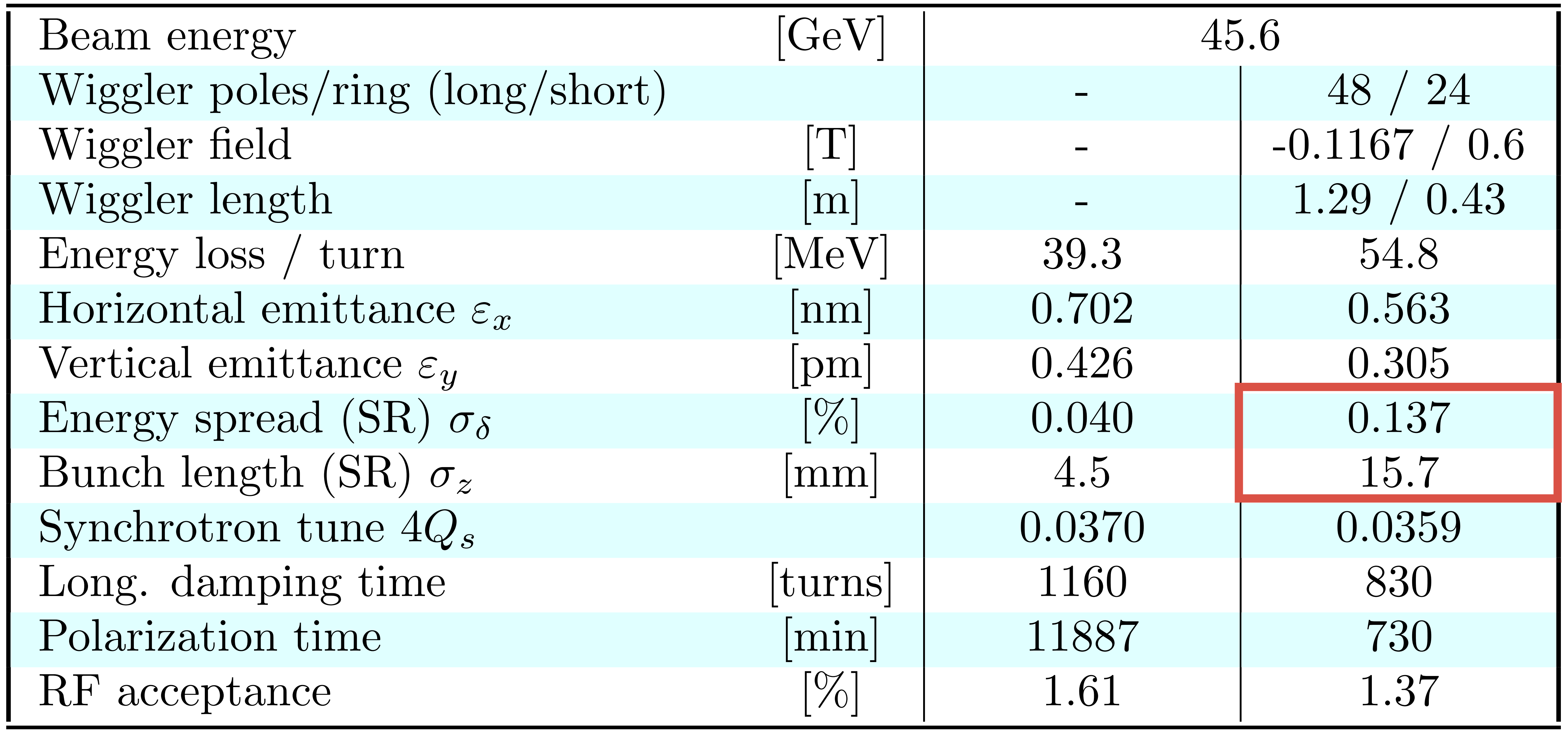

FCCee_z_535_7_lta

Momentum = 45.600000 GeV/c, Nominal spin tune = 103.483852, Spin tune = .468257 ε_y = 1.505 pm, Crab waist = 97%, Pol. time = $1.441\mathrm{x}10^8$ turns (730.352 min.), Equ. pol. (fit) = $4.91\mathrm{x}10^{-4}$ ±$3.11\mathrm{x}10^{-5}$%, Pol. time (fit) = 1531.56 ± 97.085 turns, Lifetime (fit) = 2850371 ±11631.3 turns (14.448 ± .059 min.), seed = 15

Methods in this study

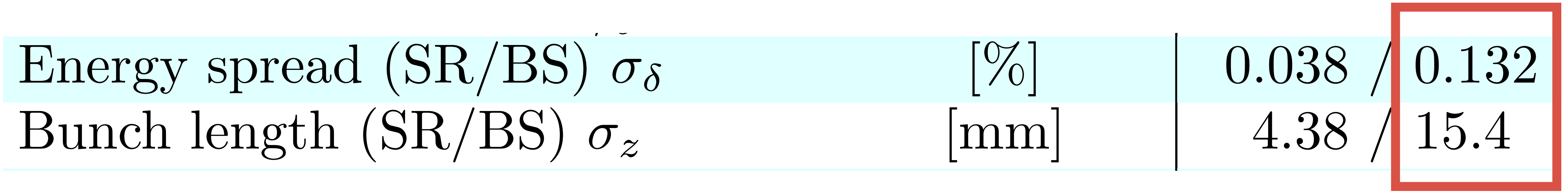
- Recent lattice for Z, 4IP, with solenoid (Mike's) and polarization wigglers.
- The momentum spread and the bunch length are enhanced by the pol. wigglers to very similar values by beamstrahlung.
- The vertical emittance, 1.5 pm, is generated by the solenoid and random vertical misalignments of arc sextupoles.
- Lifetime is determined by 6D tracking 1000 particles up to 6×10^5 tunrs (~ 1 day on SLURM).
- Radiation are turned on all elements. Tapering is applied.
- Spin polarization is also tracked.

Parameters with pol. wigglers



Beam energy	[GeV]	45.6	
Wiggler poles/ring (long/short)		-	48 / 24
Wiggler field	[T]	-	-0.1167 / 0.6
Wiggler length	[m]	-	1.29 / 0.43
Energy loss / turn	[MeV]	39.3	54.8
Horizontal emittance ε_x	[nm]	0.702	0.563
Vertical emittance ε_y	[pm]	0.426	0.305
Energy spread (SR) σ_δ	[%]	0.040	0.137
Bunch length (SR) σ_z	[mm]	4.5	15.7
Synchrotron tune $4Q_s$		0.0370	0.0359
Long. damping time	[turns]	1160	830
Polarization time	[min]	11887	730
RF acceptance	[%]	1.61	1.37

Parameters without pol. wigglers, with beamstrahlung



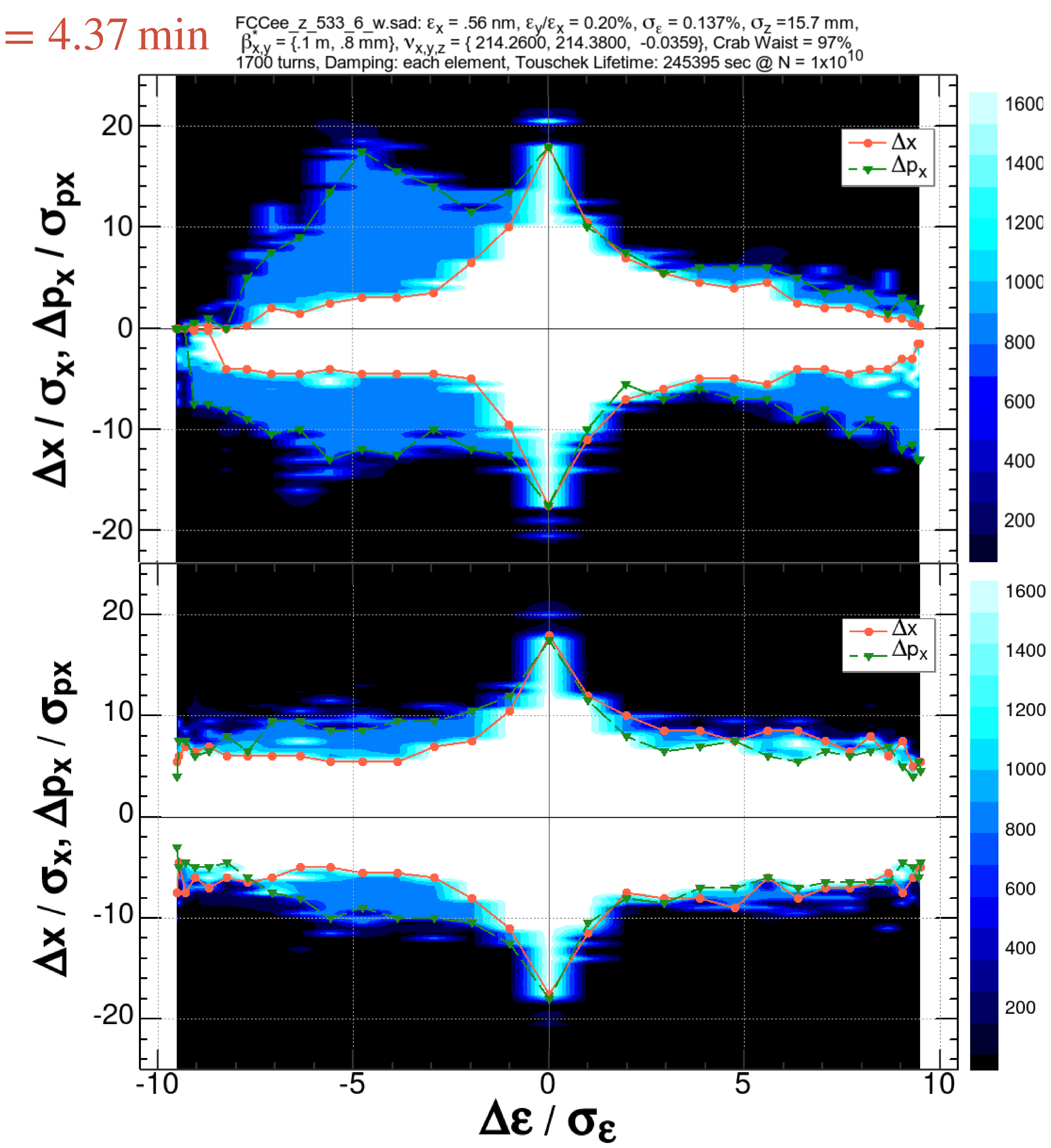
Energy spread (SR/BS) σ_δ	[%]	0.038 / 0.132
Bunch length (SR/BS) σ_z	[mm]	4.38 / 15.4

Conceivable reasons…

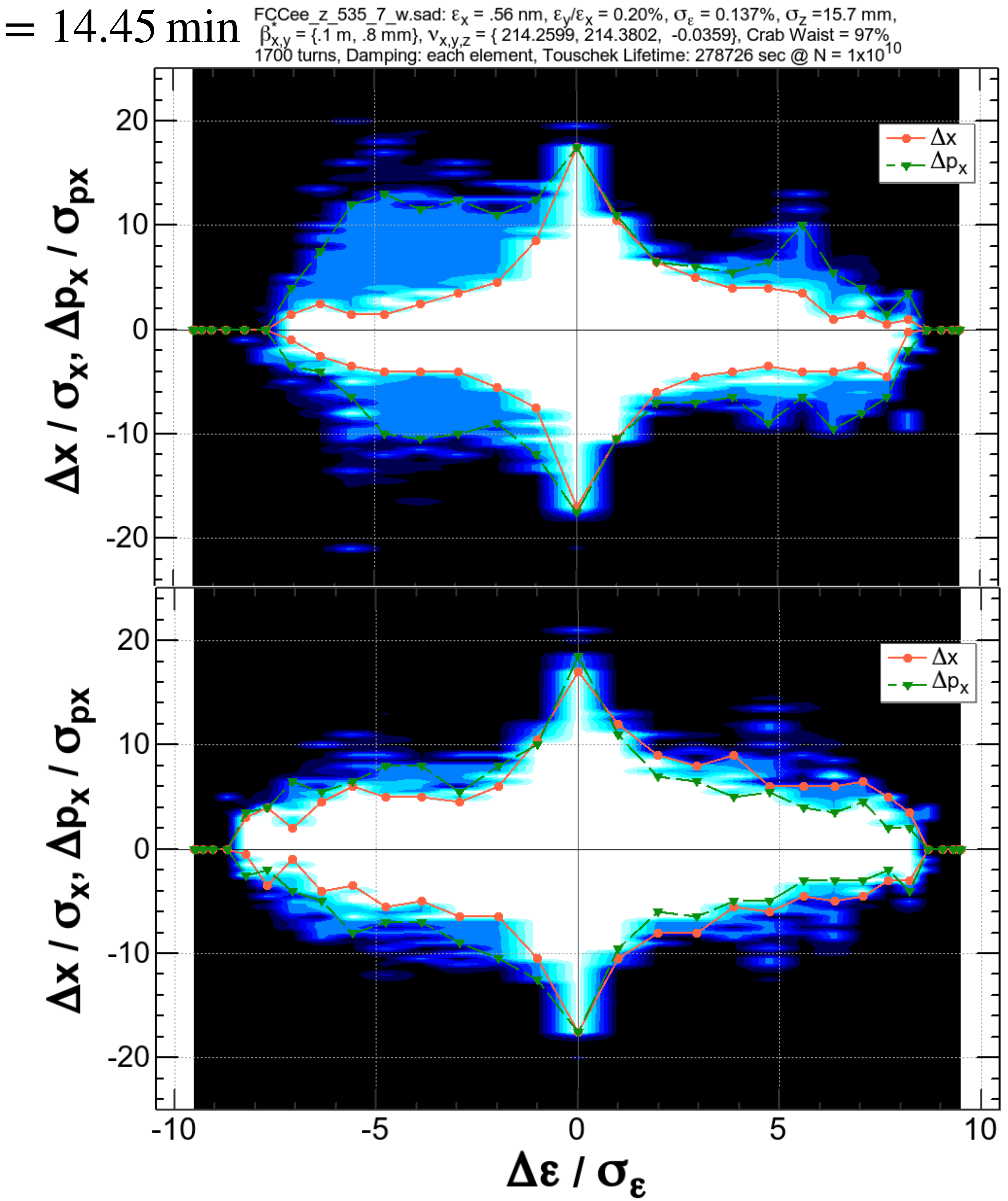
- The DA in the legacy view is looked & optimized at a particular location in the ring. The DA at other places can be different & unoptimized.
- For instance, the DA at the pol. wiggler looks as:

@wiggler

@RF



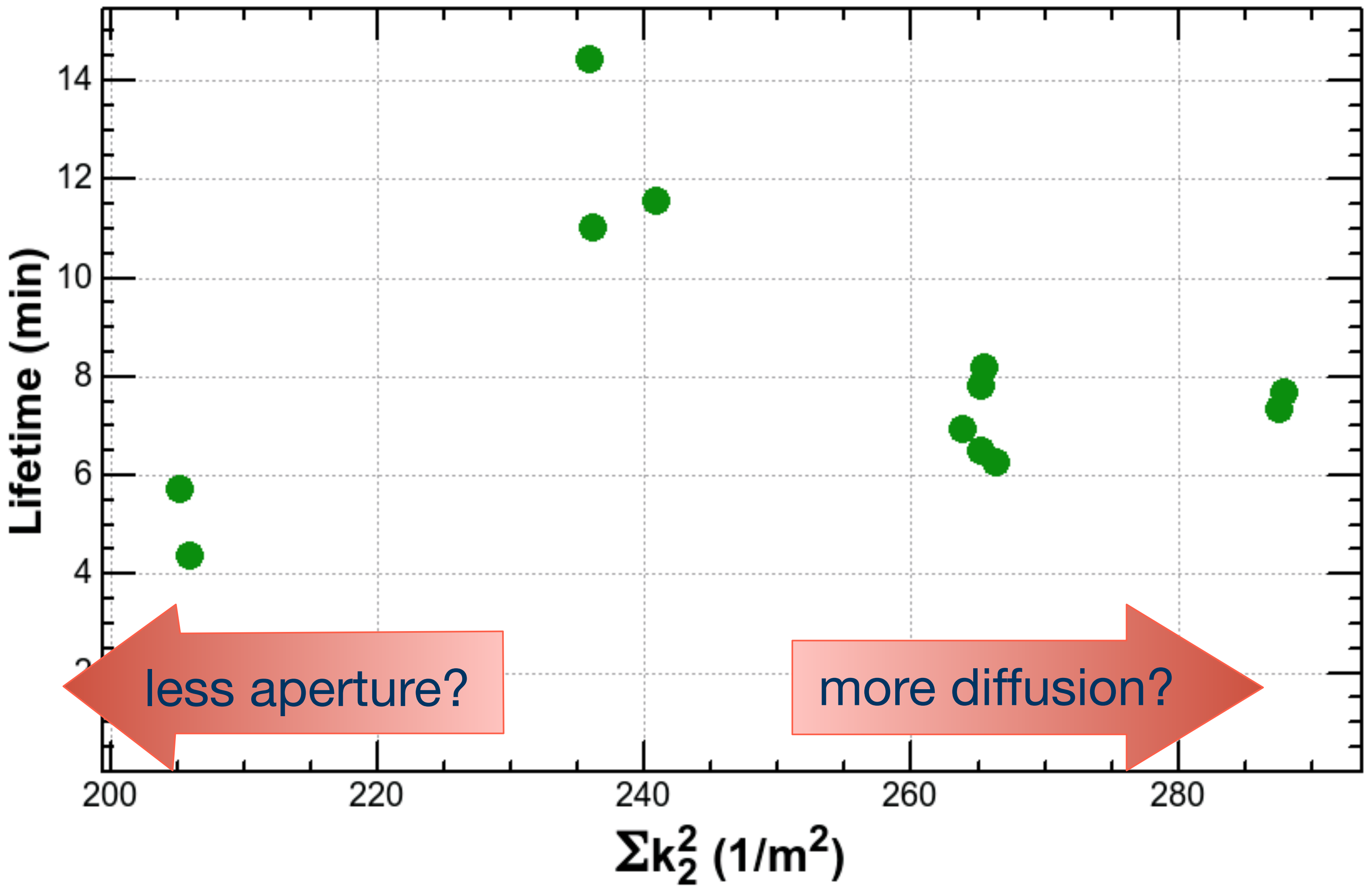
(A) $\tau = 4.37\ \mathrm{min}$



(B) $\tau = 14.45\ \mathrm{min}$

Conceivable reasons (2)

- The lifetime may not be determined only by the DA. For instance, the magnitude of diffusion due to lattice nonlinear should affect the lifetime, too.
- A possible index of the magnitude of diffusion is the *sum of sextupole strength squared* (SSSS, $\sum_i k_{2i}^2$) over arc sexupoles:

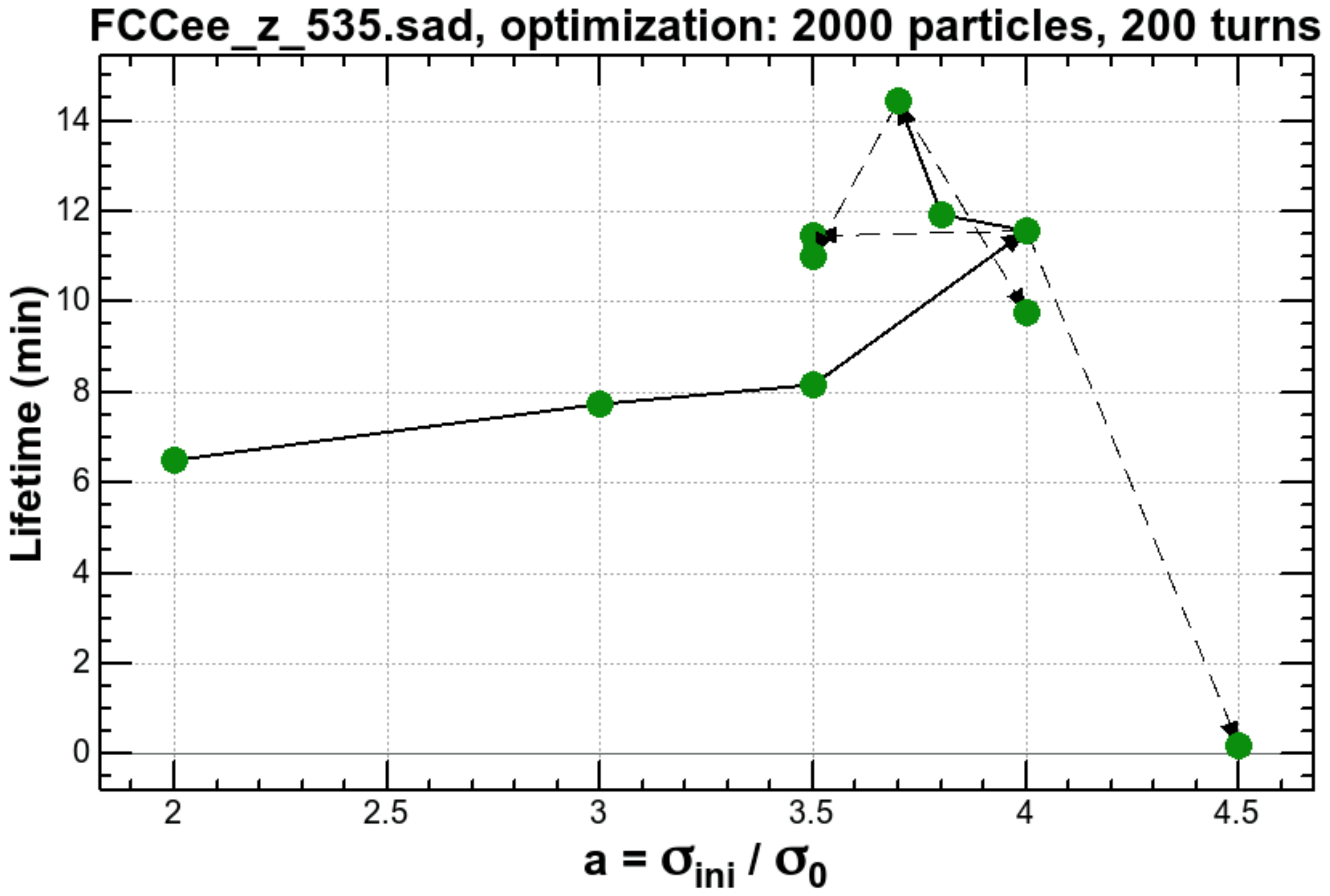


- The plot above may tell that there is an optimum SSSS?

Then we should optimize the lifetime itself

FUTURE
CIRCULAR
COLLIDER

- As the relation between the DA and the lifetime is not clear, why do not we optimize the lifetime itself?
- As the lifetime ($\gtrsim 2 \times 10^6$ turns) is very long for a tracking, we need some acceleration.
- A primitive way of the acceleration is to use a beam with bigger sizes than the equilibrium.
- Here we have used $a = \sigma_{\text{ini}}/\sigma_0$ times bigger beam in 6D than the equilibrium as the initial condition, then track 2000 particles for 200 turns.
  - The 1 cycle of optimization takes about 4 hours on SLURM.
- This method seems to work up to some extent (right



- The lifetime has been optimized by tracking with bigger initial beam.
- The initial beam size is $a = \sigma_{\text{ini}}/\sigma_0$ times larger than the equilibrium in all 6 dimensions.
- Optimization started at $a = 2$, then proceeded as the arrows.
- The dashed arrows are showing that the result got worse.
- So far $a = 3.7$ gives the best result.
- A weak constraint on SSSS has been applied in the optimization.

Coming modifications

- Change circumference, lengths of straight sections according to the placement study.
- Enlarge the separation of two beams in the arc from 30 cm to 35 cm.
- Refine the RF section to match the size of the cryomodules optimized for 400/800 MHz each.
- The crossing optics at FGHL using vertical chicane.
- Circumference adjuster at each FGHL to correct the initial misalignment and change due to tidal force.
- Injection/extraction/collimation optics at FGHL.
- Make lengths of some dipoles handleable, by dividing into shorter pieces.
- Reflect the alignment strategy on magnets and/or girders.
- Employ field profiles estimated by magnet design.
- Place BPMs and correctors.
- …and more…