FCC-ee Collider Optics
+ correction of sextupole misalignments

K. Oide (UNIGE/CERN)

June 26, 2023 @ Optics Tuning and Corrections for Future colliders workshop

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

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The 4 IP layout

FUTURE CIRCULAR COLLIDER

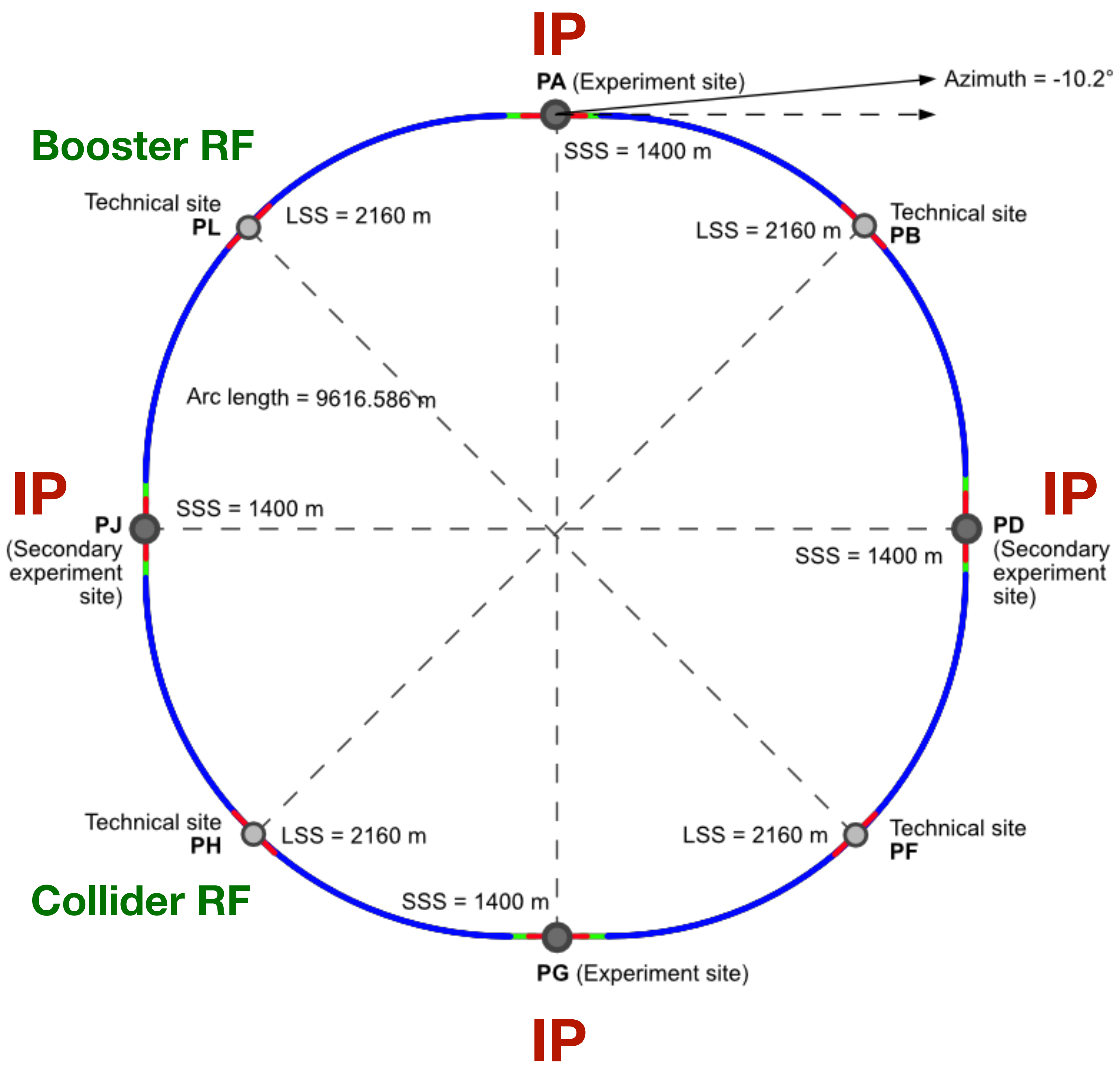

Table 1 Parameters of the layout in meter.

Layout	circumference	arc	LLSS	SLSS (IP)
PA31-3.0	90657.400	9616.175	2032.000	1400.000
CDR	97765		2760	1450

- 4 IP-capable, a perfect period-4, symmetric layout.
- IPs are at SLSS PA, PD, PG, PJ.
- The IP shifts radially from the layout line (10.2 m outside in the latest lattice).
- The collider RF is concentrated at the LLSS PH.
- The booster RF is located at LLSS PL.
- Other LLSS are for injection, extraction, collimation.

At the CDR, the lattice dynamics aperture and beam-beam effects were evaluated separately.

CDR

Collider Design and Performance

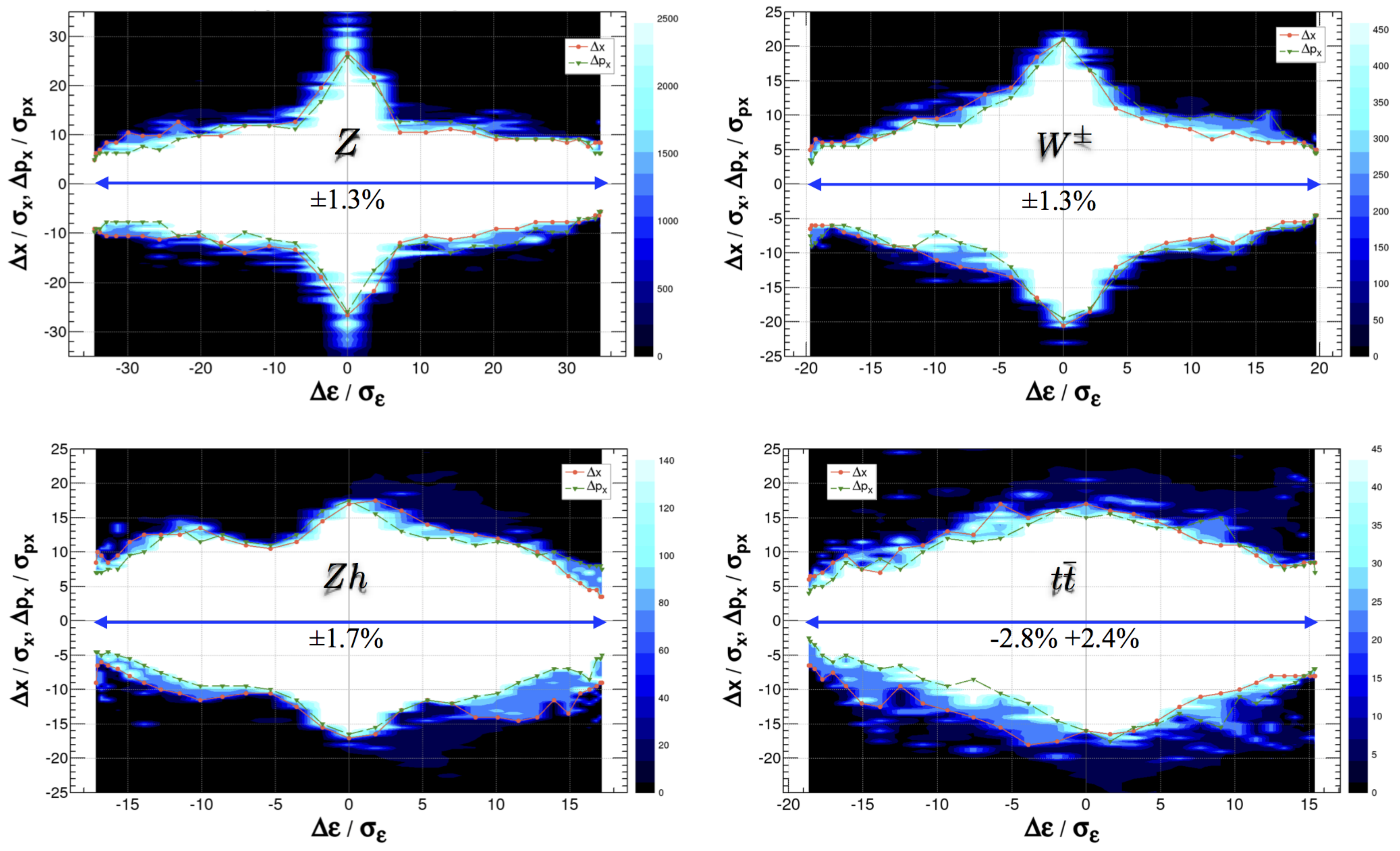

Figure 2.9: Dynamic apertures in z-x plane after sextupole optimisation with particle tracking for each energy. The initial vertical amplitude for the tracking is always set to $J_y/J_x = \varepsilon_y/\varepsilon_x$. The number of turns corresponds to about 2 longitudinal damping times. The resulting momentum acceptances are consistent with the luminosity optimisation shown in Table 2.1. Effects in Table 2.3 are taken into account. The momentum acceptance at $\mathrm{t\bar{t}}$ is "asymmetric" to match the distribution with beamstrahlung.

- The lattice dynamic aperture (DA) was optimized to ensure the required momentum acceptance which is estimated by beam-beam (BB) simulations without lattice.
- It has been noticed that the lattice lifetime must be evaluated by itself beyond the DA, esp. at Z with enlarged energy spread by beamstrahlung (BS) (K. Oide, FCC Week 2022).
- Then D. Shatilov revealed that the lifetime reduces drastically at Z, esp. for 1 RF/ring, by simulations as well as frequency-map analysis including the lattice, BB and BS.
- Then evaluations including lattice, BB, BS all together have been performed this year to determine the tunes, β*, lattice vertical emittance,…

Lifetime & beam blowup with lattice + beam beam & beamstrahlung

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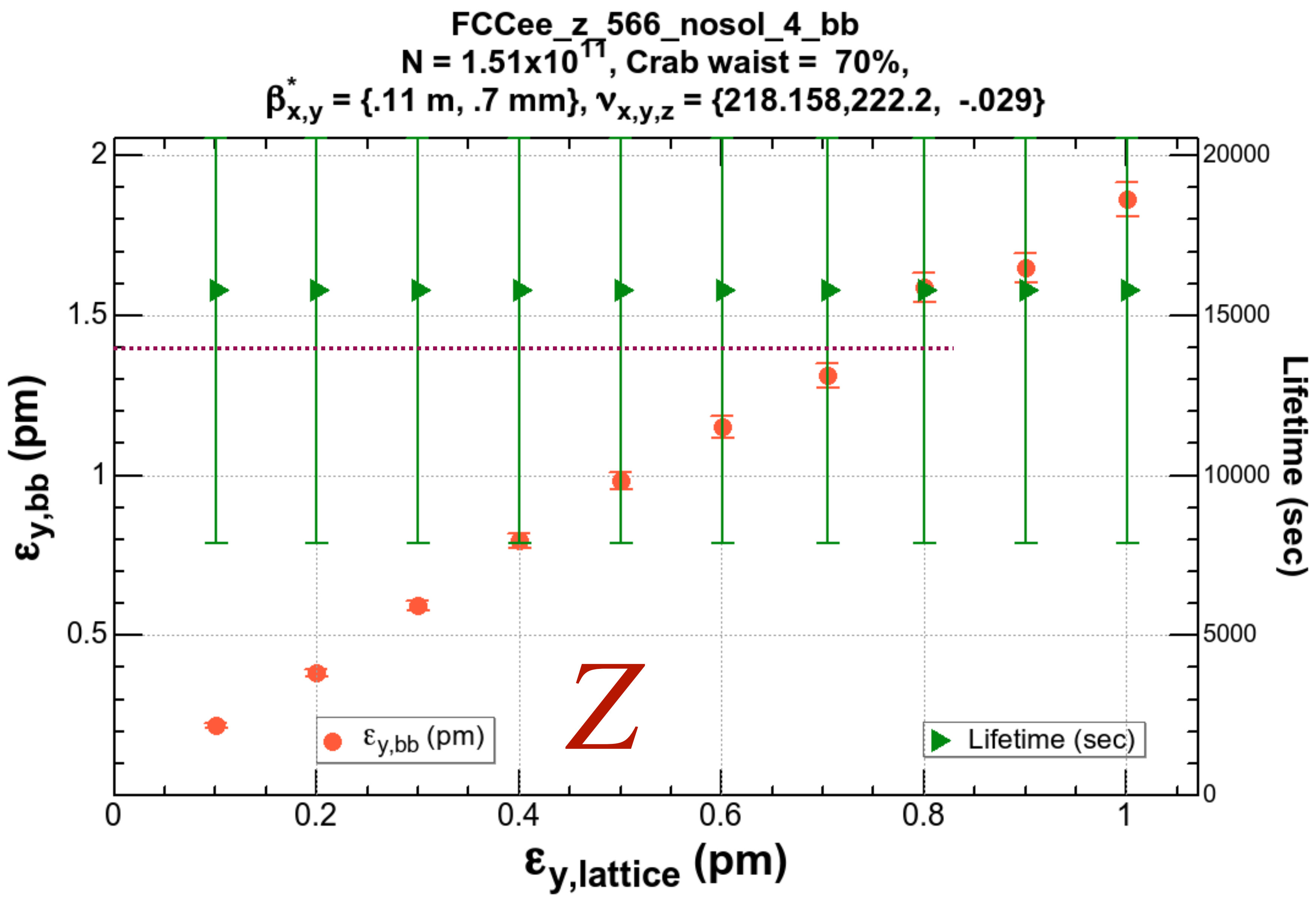

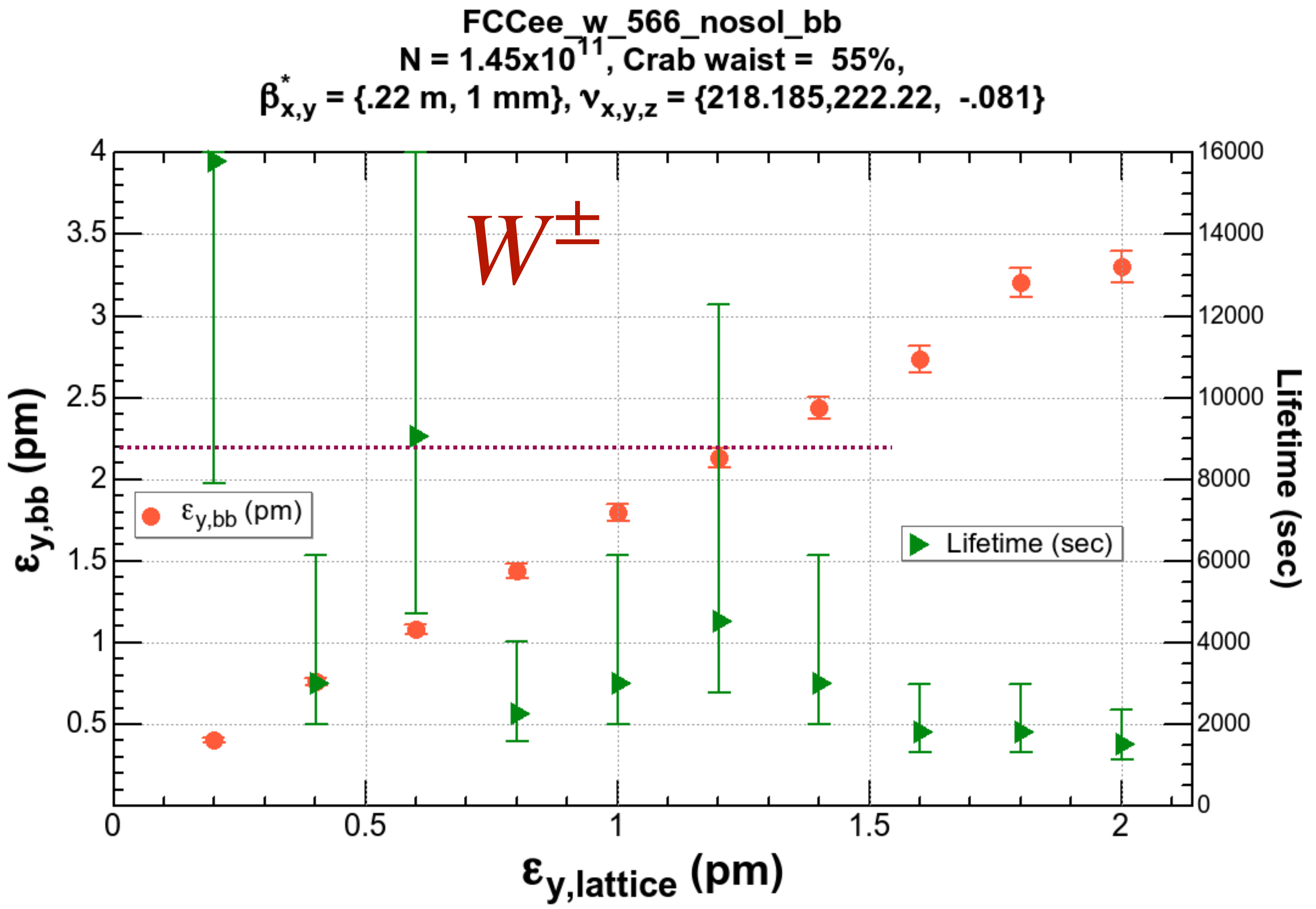

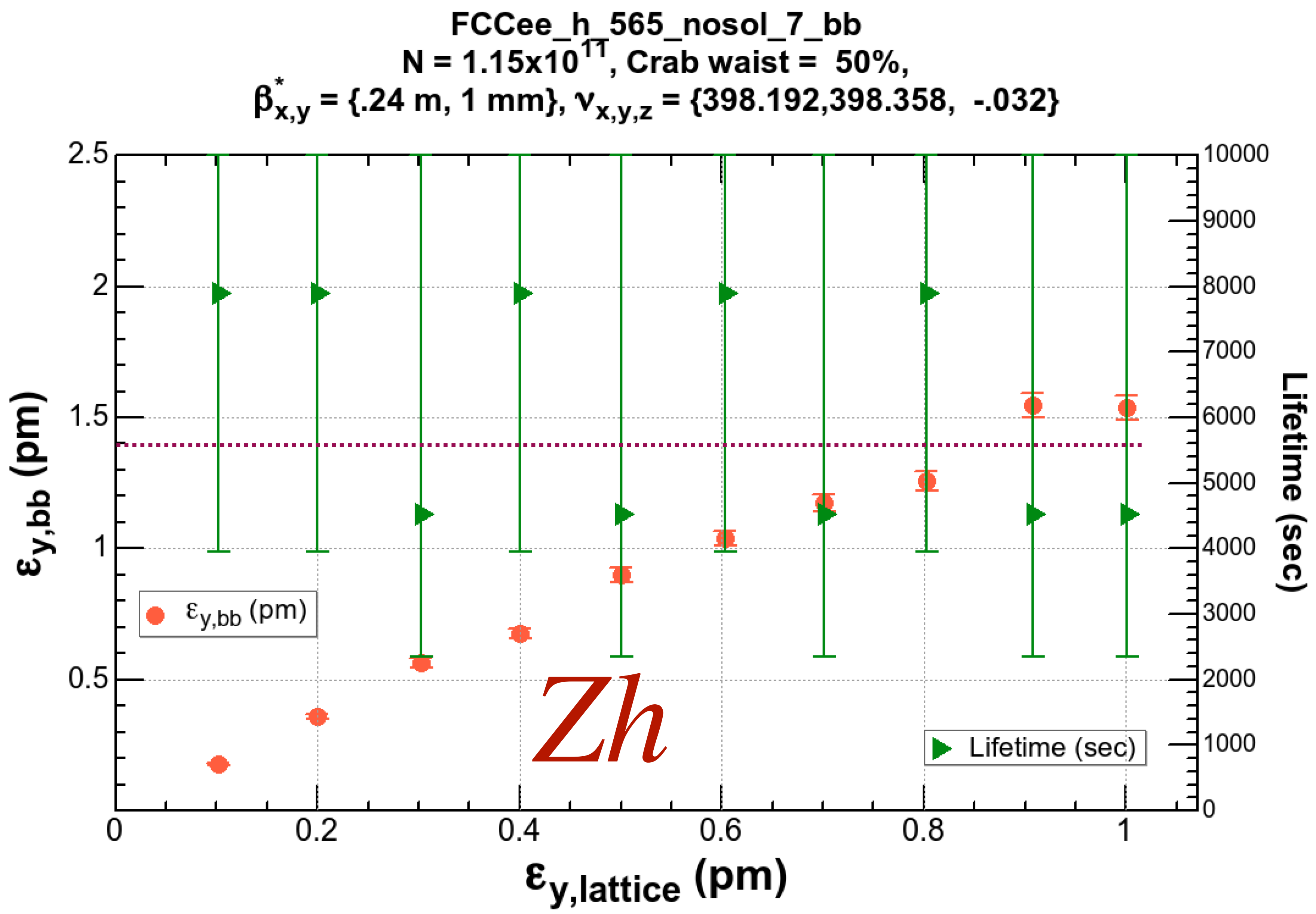

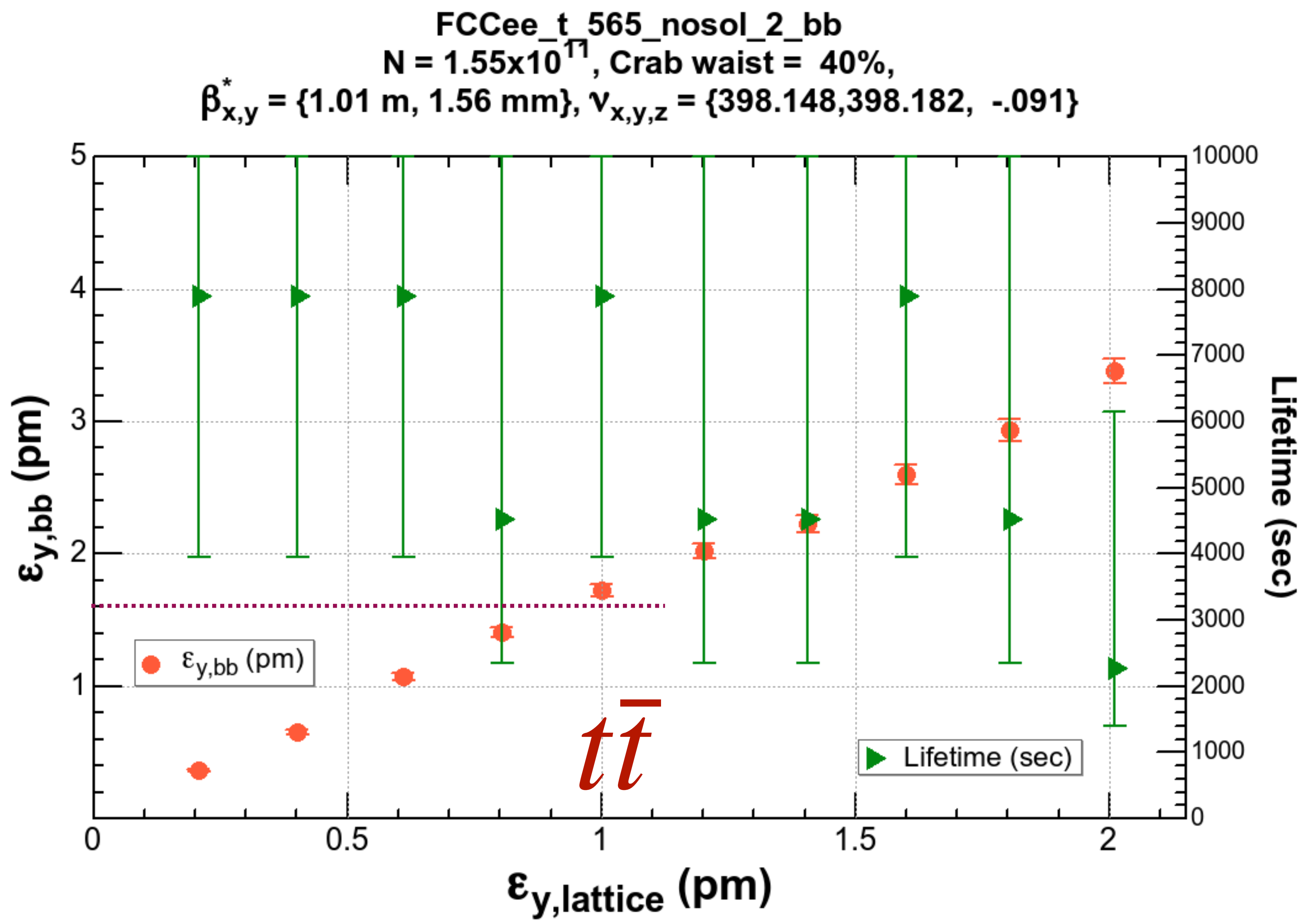

- The vertical emittance after collision (red) and the lifetime (green) against the lattice vertical emittance for each collision energy.
- The purple dashed line shows the goal vertical emittance at collision.
- SR in all elements, weak-strong beam-beam, beamstrahlung are included.
- No machine error is included.

Tune scan (lattice + beam-beam + beamstrahlung)

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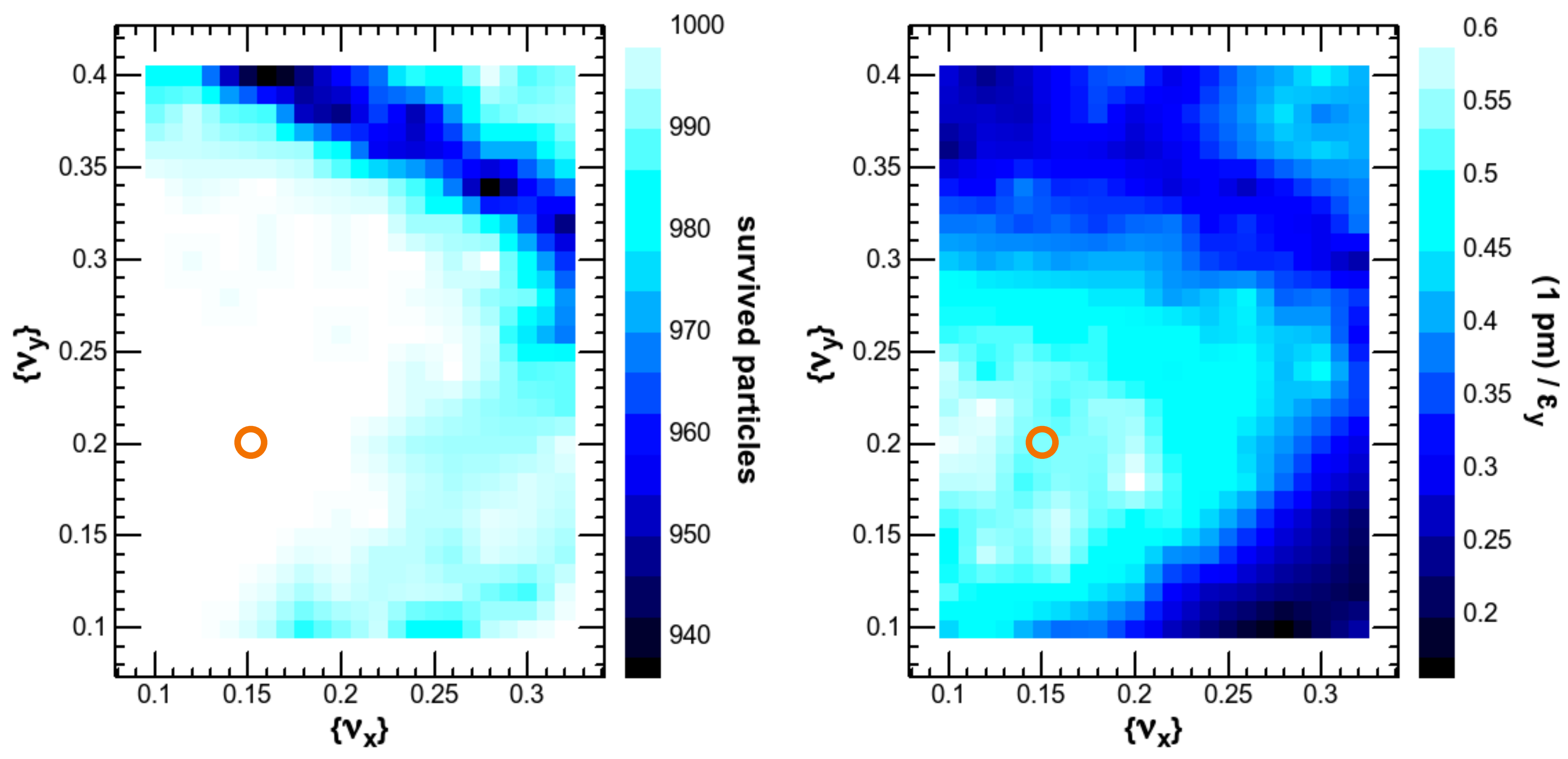
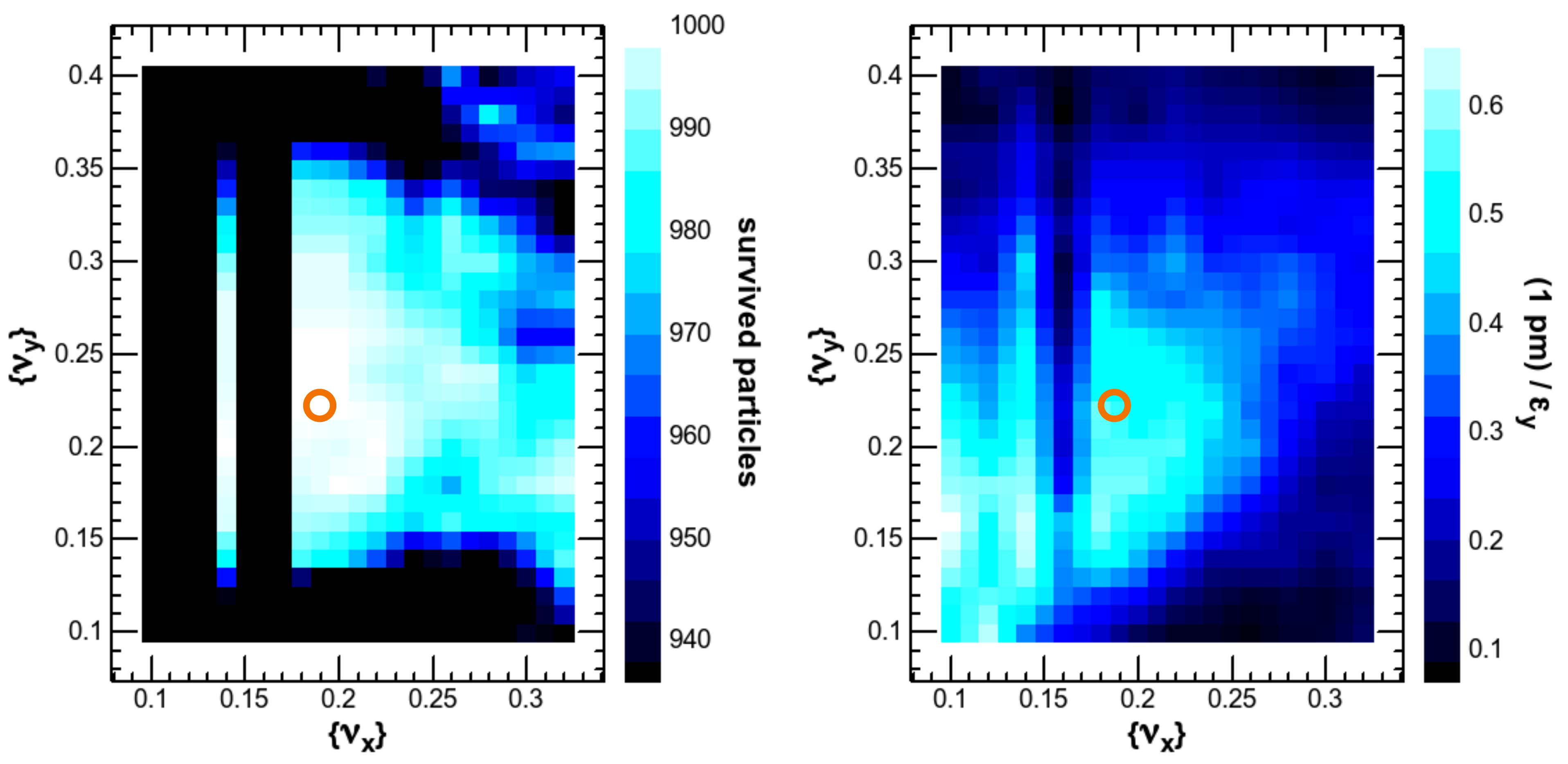
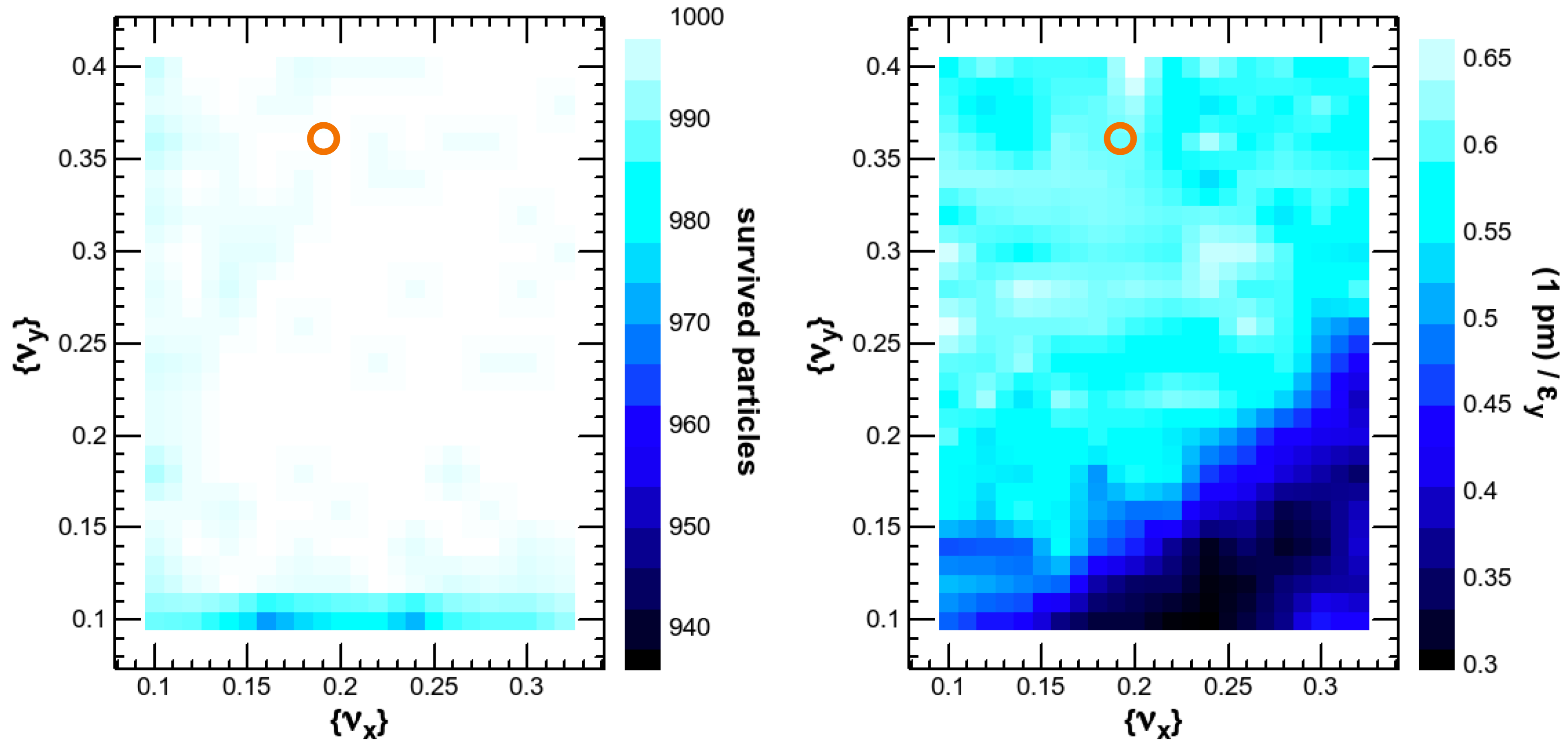
FCCee_z_566_nosol_4_ts
$N = 1.51\times10^{11}$, Crab waist = 70%,
$\beta^*_{x,y}$ = {.11 m, .7 mm}, ν_z = -.02867, $\varepsilon_{y,\mathrm{lattice}}$ = .99936 pm



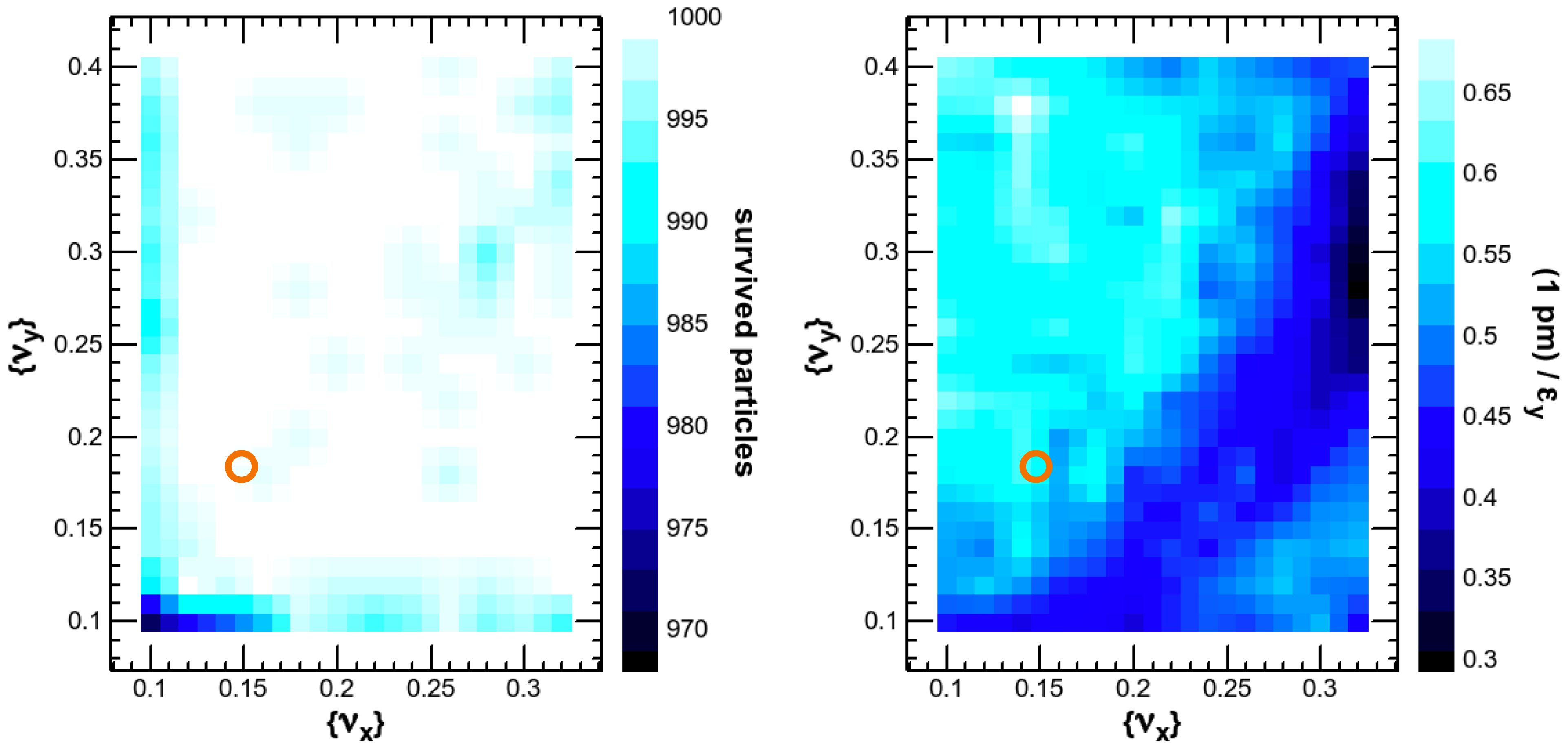
FCCee_w_566_nosol_ts
$N = 1.45\times10^{11}$, Crab waist = 55%,
$\beta^*_{x,y}$ = {.22 m, 1 mm}, ν_z = -.08101, $\varepsilon_{y,\mathrm{lattice}}$ = 1.00046 pm



FCCee_h_565_nosol_7_ts
$N = 1.15\times10^{11}$, Crab waist = 50%,
$\beta^*_{x,y}$ = {.24 m, 1 mm}, ν_z = -.03123, $\varepsilon_{y,\mathrm{lattice}}$ = 1.00490 pm



FCCee_t_565_nosol_2_ts
$N = 1.55\times10^{11}$, Crab waist = 40%,
$\beta^*_{x,y}$ = {1.01 m, 1.56 mm}, ν_z = -.08966, $\varepsilon_{y,\mathrm{lattice}}$ = 1.08717 pm



- Each plot shows the particle loss (left) and vert. emittance after collision (right) with each lattice. The circles show the current working point.
- A strong "chromatic-crab" resonance line $\nu_x + 2\nu_y - \nu_z = N$ is observed with Z & W lattices.
- At higher energies (Zh, $t\bar{t}$), the chromatic-crab resonance seems weaker or invisible.
    - is it due to faster damping or the lattice itself?
- Very strong synchrotron sidebands $\nu_x + \nu_z = N$, $\nu_x + 2\nu_z = N$ are seen at $W^\pm$.

Dynamic aperture (*z*-*x*)

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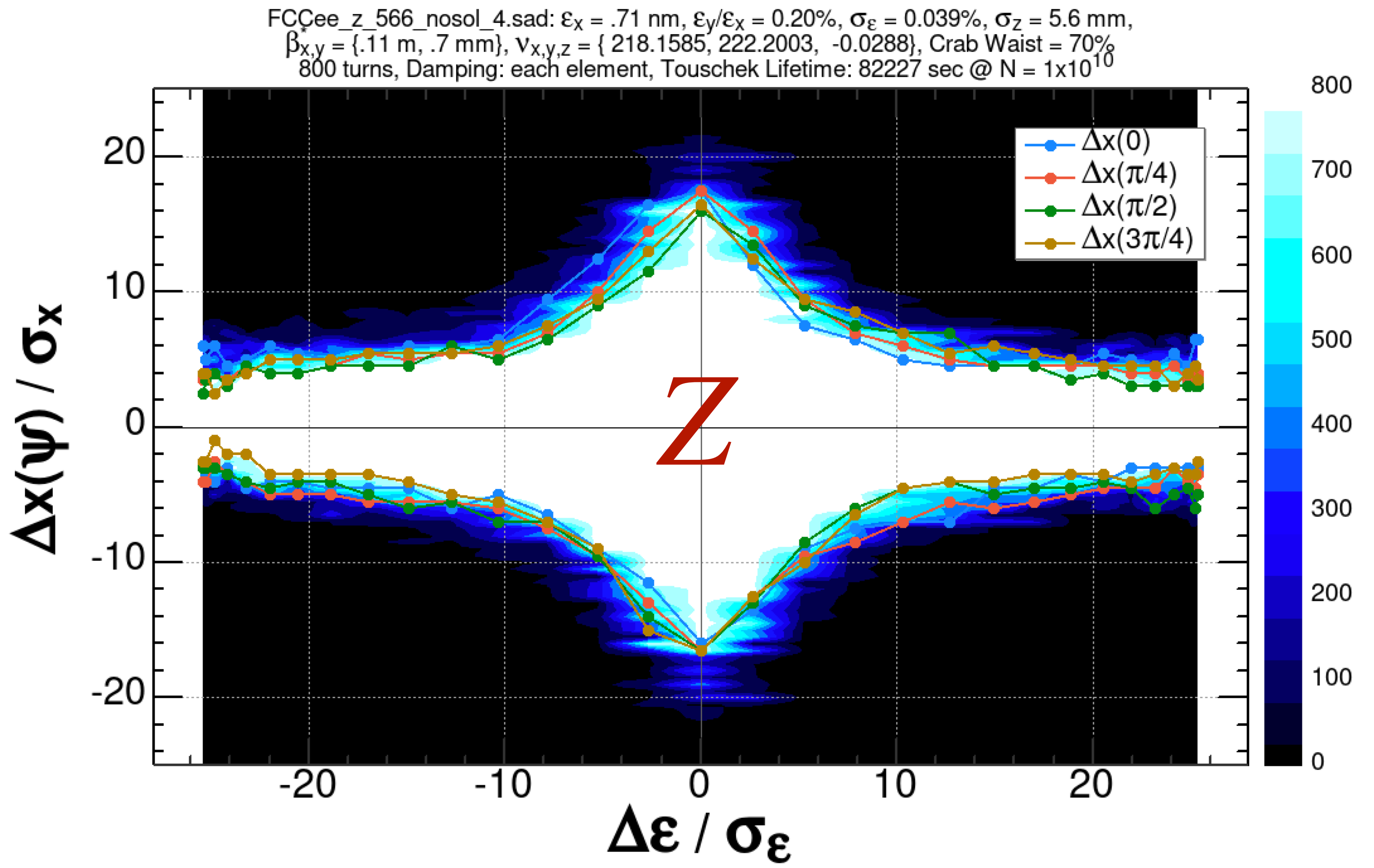

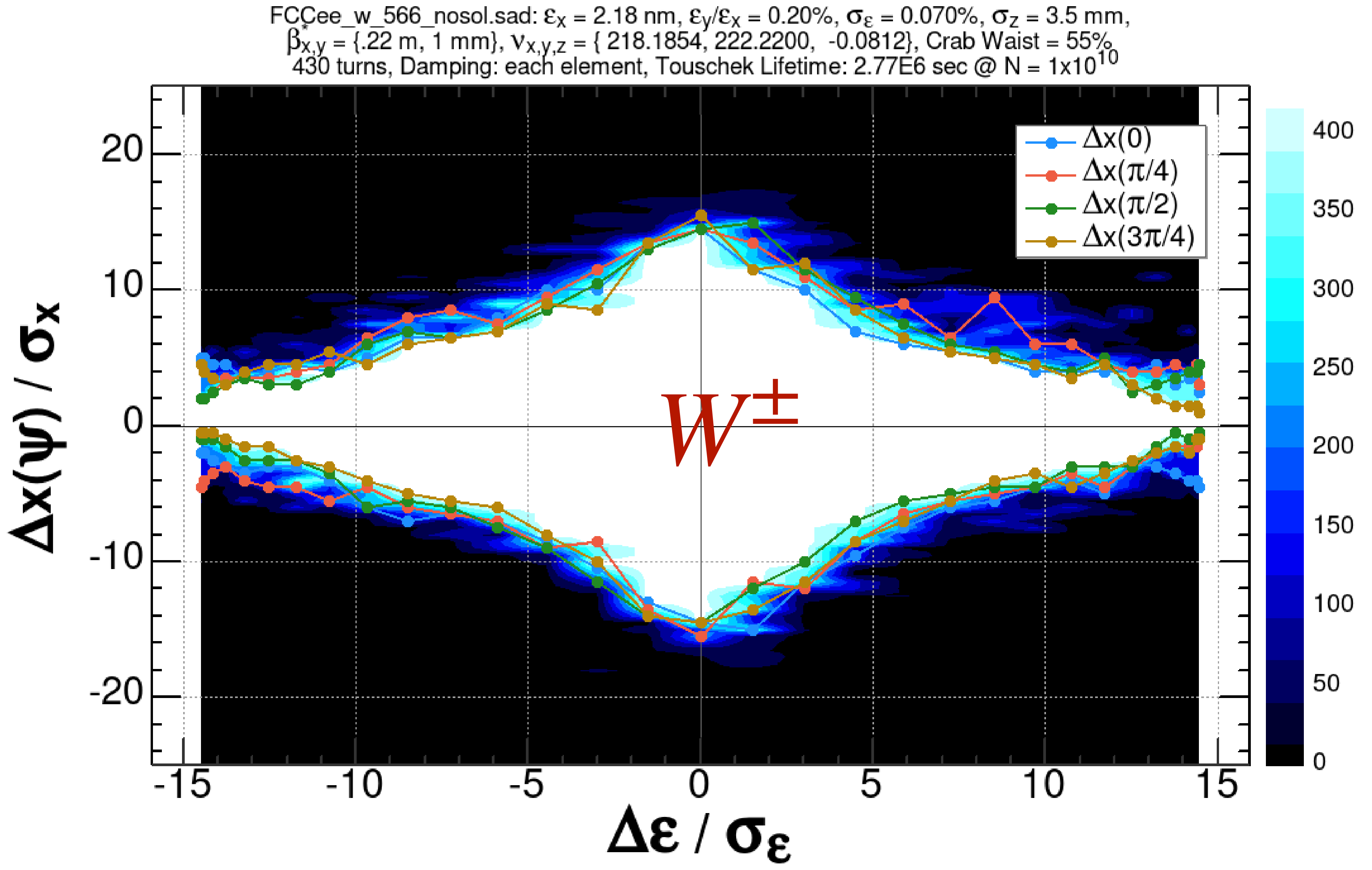

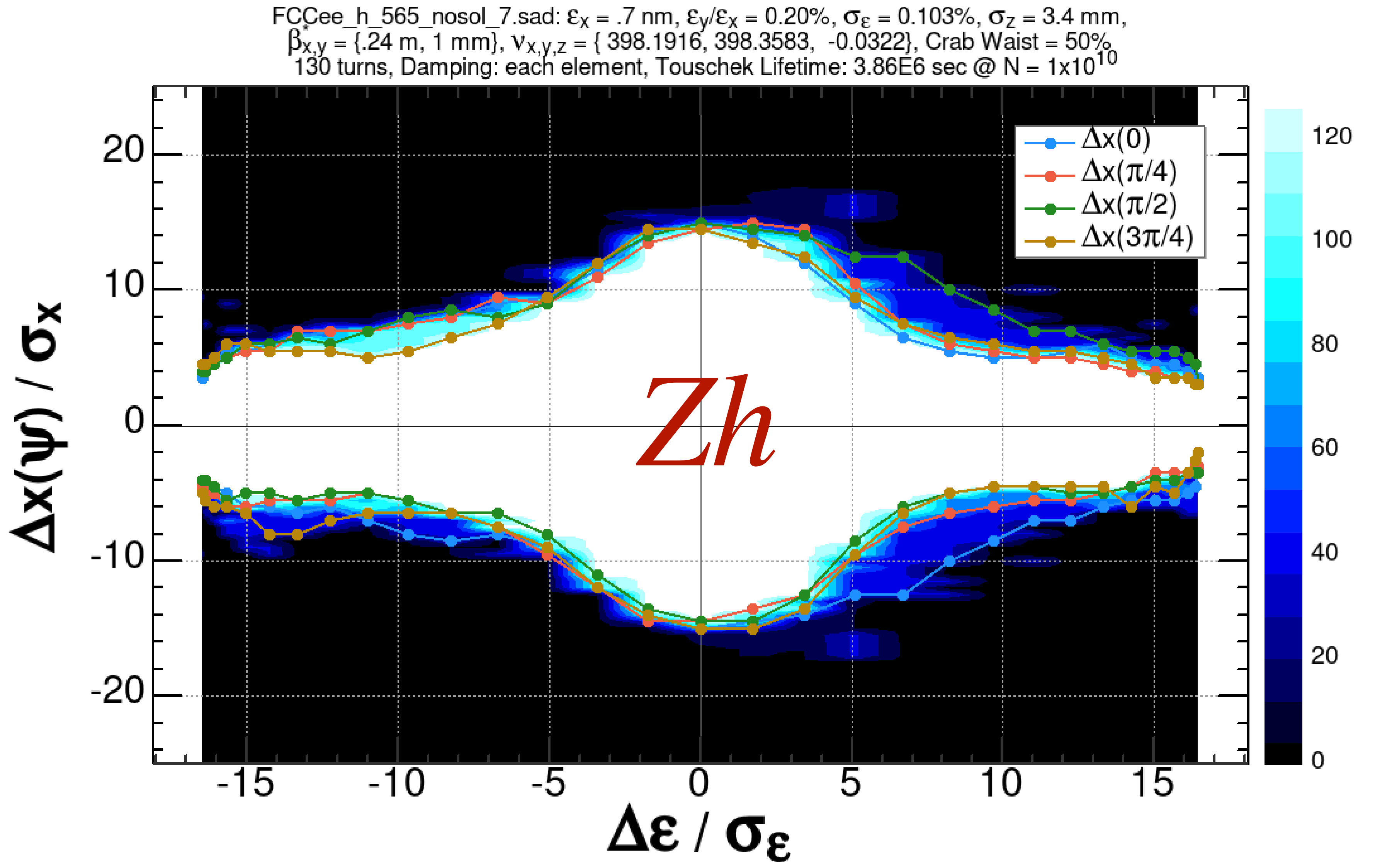

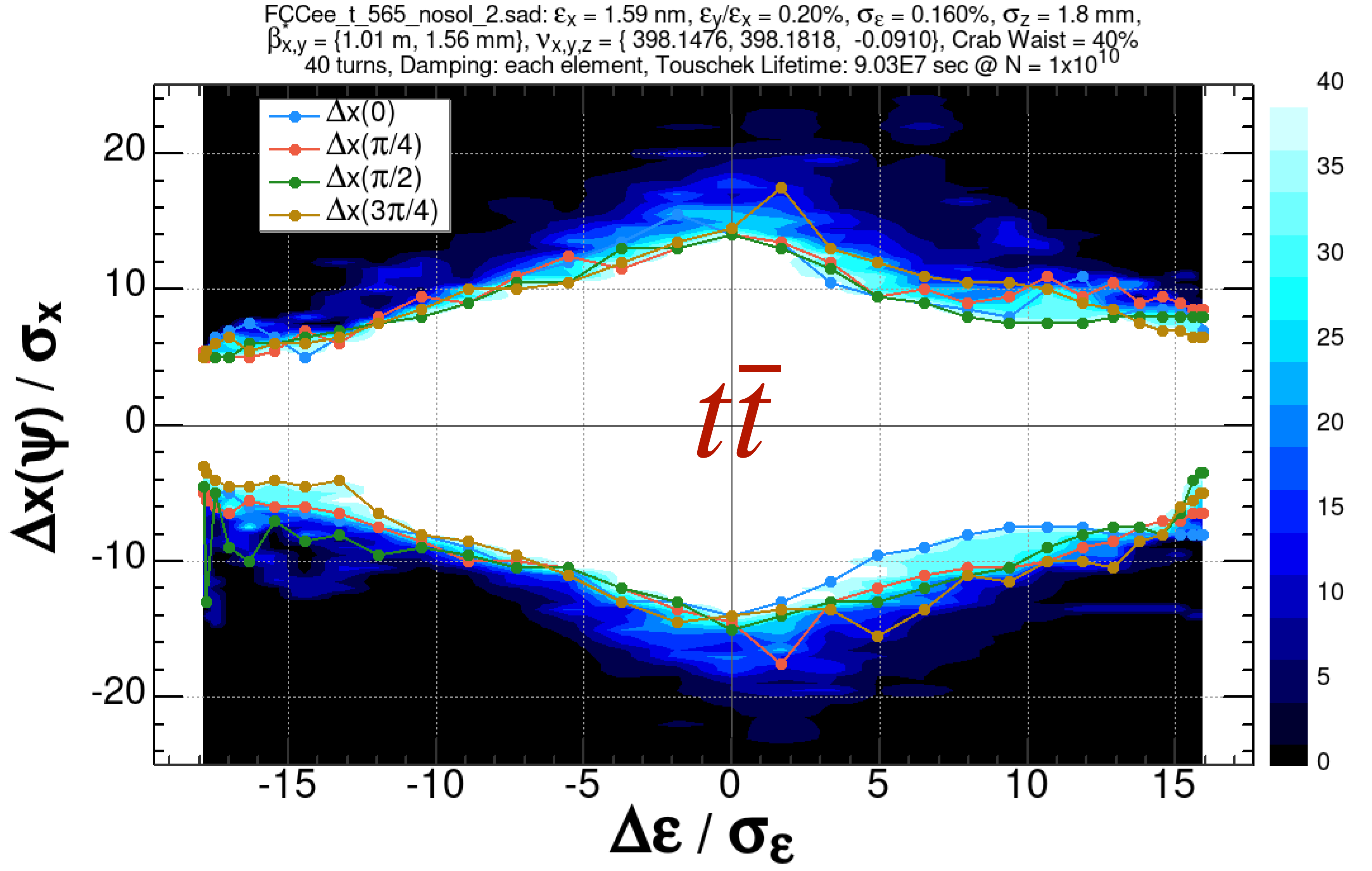

- At the CDR, the dynamic aperture (DA) and beam-beam were estimated separately. Then the estimation of the beam lifetimes was not good enough, esp. including the beamstrahlung.
- Thus it had not been noticed until recent that at some betatron tunes, the beam lifetime suffered a lot by beam-beam & beamstrahlung.
- Also the blowup of the vertical emittance, or the required lattice emittance, were not properly estimated at the CDR.
- All such issues are addressed this time, but the resulting luminosity is reduced by more than 15%, on top of the reductions due to the shorter circumference (-7%) and less damping between IPs (-7%).

Parameters

FCC-ee collider parameters as of June 3, 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	9.936			
Energy loss / turn	[GeV]	0.0394	0.374	1.89	10.42
SR power / beam	[MW]	50			
Beam current	[mA]	1270	137	26.7	4.9
Colliding bunches / beam		15880	1780	440	60
Colliding bunch population	[10^{11}]	1.51	1.45	1.15	1.55
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.71	1.59
Ver. emittance at collision ε_y	[pm]	1.4	2.2	1.4	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.75	1.25	0.85	0.9
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	1000 / 1.6
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.358	398.148 / 398.182
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.089	0.070 / 0.109	0.104 / 0.143	0.160 / 0.192
Bunch length (SR/BS) σ_z	[mm]	5.60 / 12.7	3.47 / 5.41	3.40 / 4.70	1.81 / 2.17
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.091
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	2.9
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP $\pm\theta_x$	[mrad]	±15			
Piwinski angle $(\theta_x\sigma_{z,\mathrm{BS}})/\sigma^*_x$		21.7	3.7	5.4	0.82
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y [a]		0.0023 / 0.096	0.013 / 0.128	0.010 / 0.088	0.073 / 0.134
Lifetime (q + BS + lattice)	[sec]	15000	4000	6000	6000
Lifetime (lum) [b]	[sec]	1340	970	840	730
Luminosity / IP	[10^{34}/cm^{2}s]	140	20	5.0	1.25
Luminosity / IP (CDR, 2 IP)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section

- Parameters such as tunes, β^*, crab waist ratio are chosen to maximize the luminosity keeping the lifetime longer than 4000 sec without machine errors.
- The choice of the parameters including the sextupole settings still has a room for further optimization.
- Including injection/extraction/ collimation optics will need additional optimization.

nus = 0.075 @W may be acceptable
(I. Koop, 8/6/23)

$$\frac{\nu_0\sigma_\delta}{\nu_s} < 1.5$$

Some variants may be possible for higher luminosity or fewer bunches
(suggested by T. Raubenheimer)

A few variants in parameters, as of June 14, 2023.

Beam energy	[GeV]	45.6			182.5	
Layout		PA31-3.0				
# of IPs		4				
Energy loss / turn	[GeV]	0.0394			10.42	
Beam current	[mA]	1270			4.9	
Colliding bunches / beam		15880	12800	11200	60	56
Colliding bunch population	[10^{11}]	1.51	1.87	2.14	1.15	1.55
Hor. emittance at collision ε_x	[nm]	0.71			1.59	
Ver. emittance at collision ε_y	[pm]	1.4	1.4	1.9	1.6	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.75	0.52	0.77	0.9	1.0
Arc cell		Long 90/90			90/90	
Momentum compaction α_p	[10^{-6}]	28.6			7.4	
$\beta^*_{x/y}$	[mm]	110 / 0.7			1000 / 1.6	800 / 1.5
Transverse tunes $Q_{x/y}$		218.158 / 222.200			398.148 / 398.182	
Chromaticities $Q'_{x/y}$		0 / +5			0 / 0	
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.089	0.039 / 0.101	0.039 / 0.109	0.160 / 0.192	0.160 / 0.204
Bunch length (SR/BS) σ_z	[mm]	5.60 / 12.7	5.60 / 14.4	5.60 / 15.5	1.81 / 2.17	1.81 / 2.30
RF voltage 400/800 MHz	[GV]	0.079 / 0			2.1 / 9.38	
Synchrotron tune Q_s		0.0288			0.091	
Long. damping time	[turns]	1158			18.3	
RF acceptance	[%]	1.05			2.9	
Energy acceptance (DA)	[%]	±1.0			-2.8/+2.5	±2.5
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		21.7	24.4	26.5	0.82	0.97
Crab waist ratio	[%]	70			40	
Beam-beam ξ_x/ξ_y[a]		0.0023 / 0.096	0.0022 / 0.1062	0.0022 / 0.0973	0.073 / 0.134	0.068 / 0.146
Lifetime (q + BS + lattice)	[sec]	15000	3000	3000	6000	1000
Lifetime (lum)[b]	[sec]	1340	1220	1330	730	640
Luminosity / IP	[10^{34}/cm^{2}s]	140	154	141	1.25	1.42
Luminosity / IP (CDR, 2 IP)	[10^{34}/cm^{2}s]	230			1.8	

[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section

- Some variants of parameters will be possible, if we still have a room for lifetime.
- For higher luminosity (Z, tt), on going for Zh.
- For fewer bunches (Z).

Ring optics (1/4 ring)

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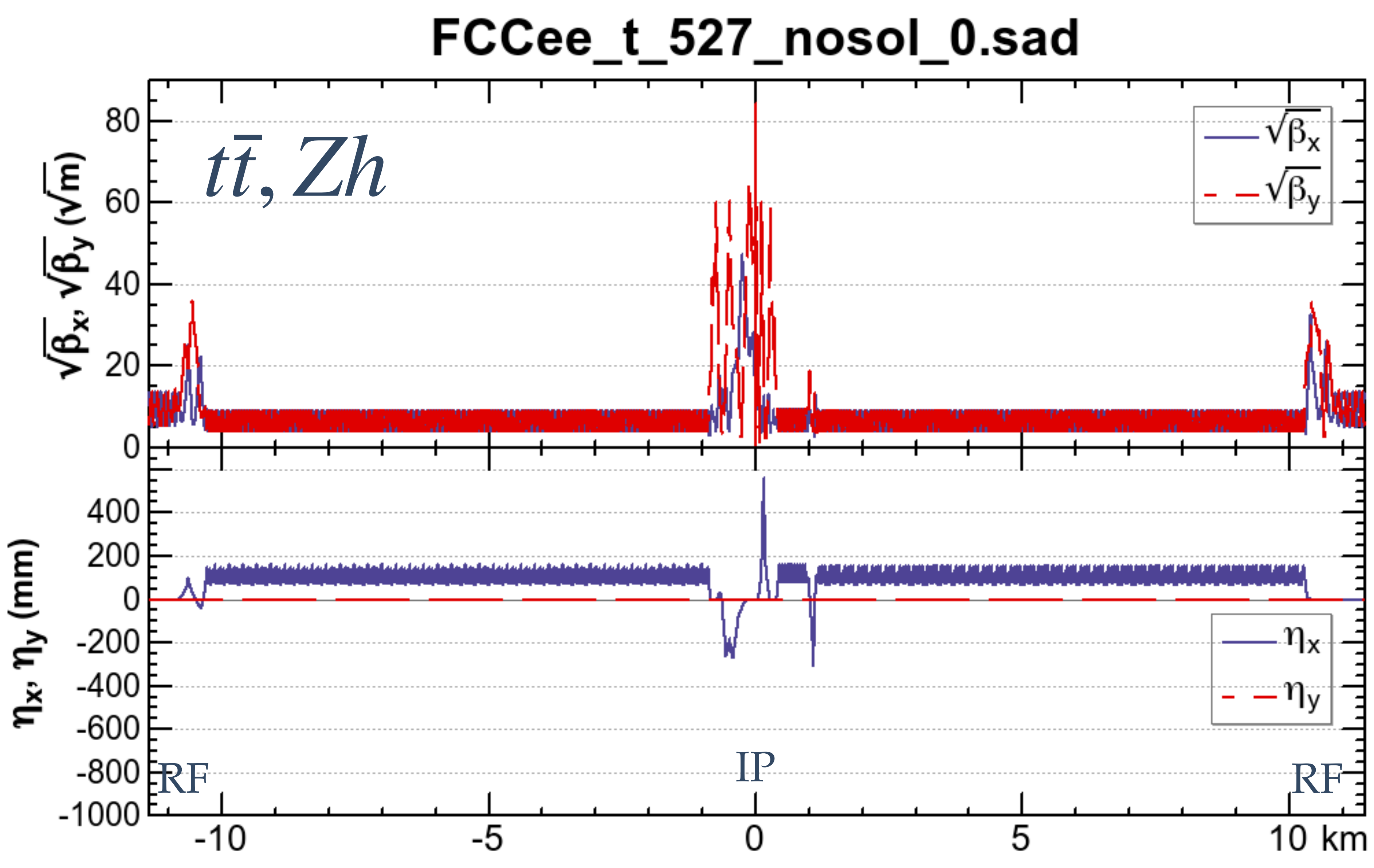
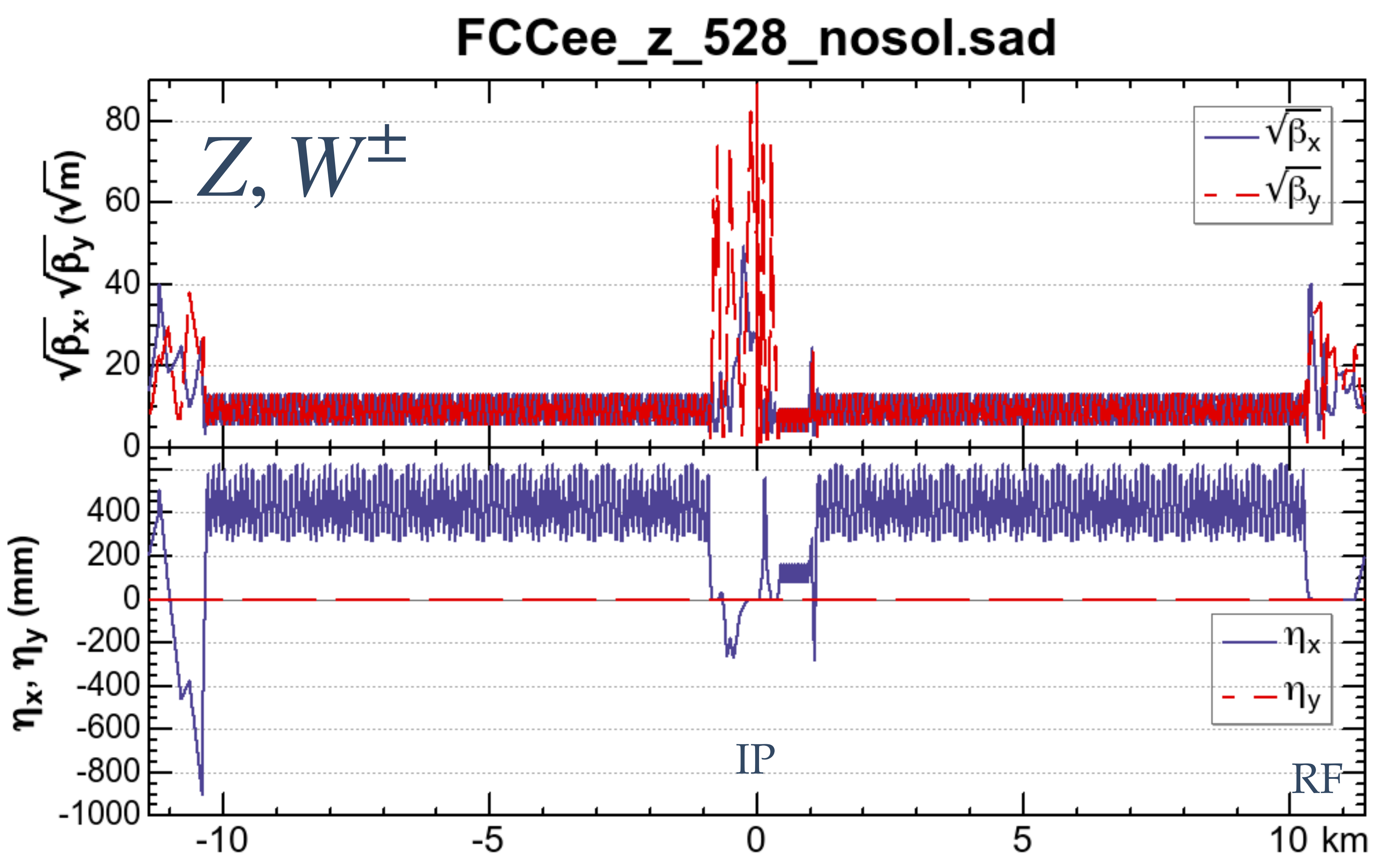




180 Short 90/90 FODO cells / arc.
8 arcs / ring

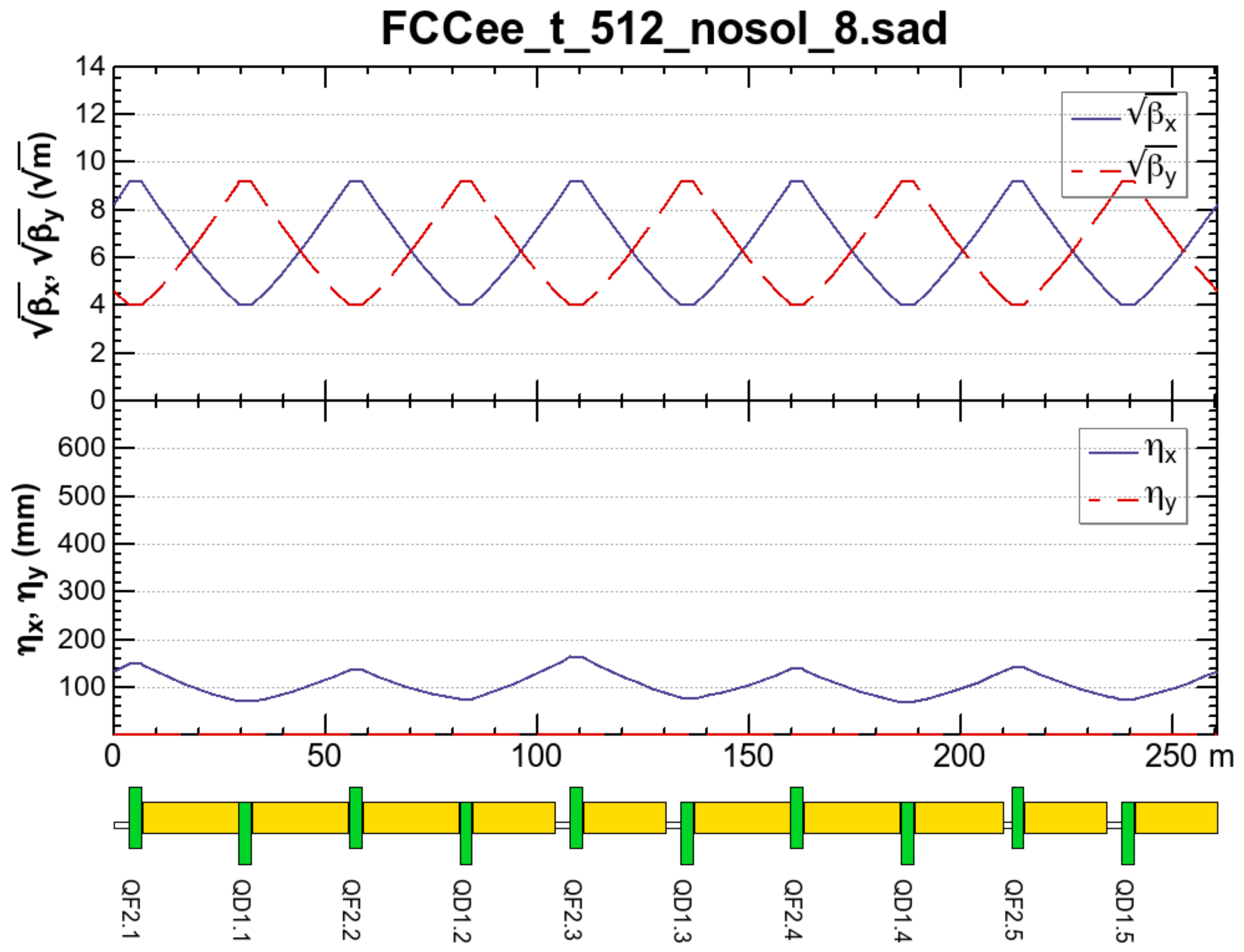
90 Long 90/90 FODO cells / arc.
8 arcs / ring

- The separation between two beams in the arc is enlarged from 30 cm (CDR) to 35 cm.
- The beam pipe radius in the most parts of the ring *may shrink* from 35 mm to 30 mm.

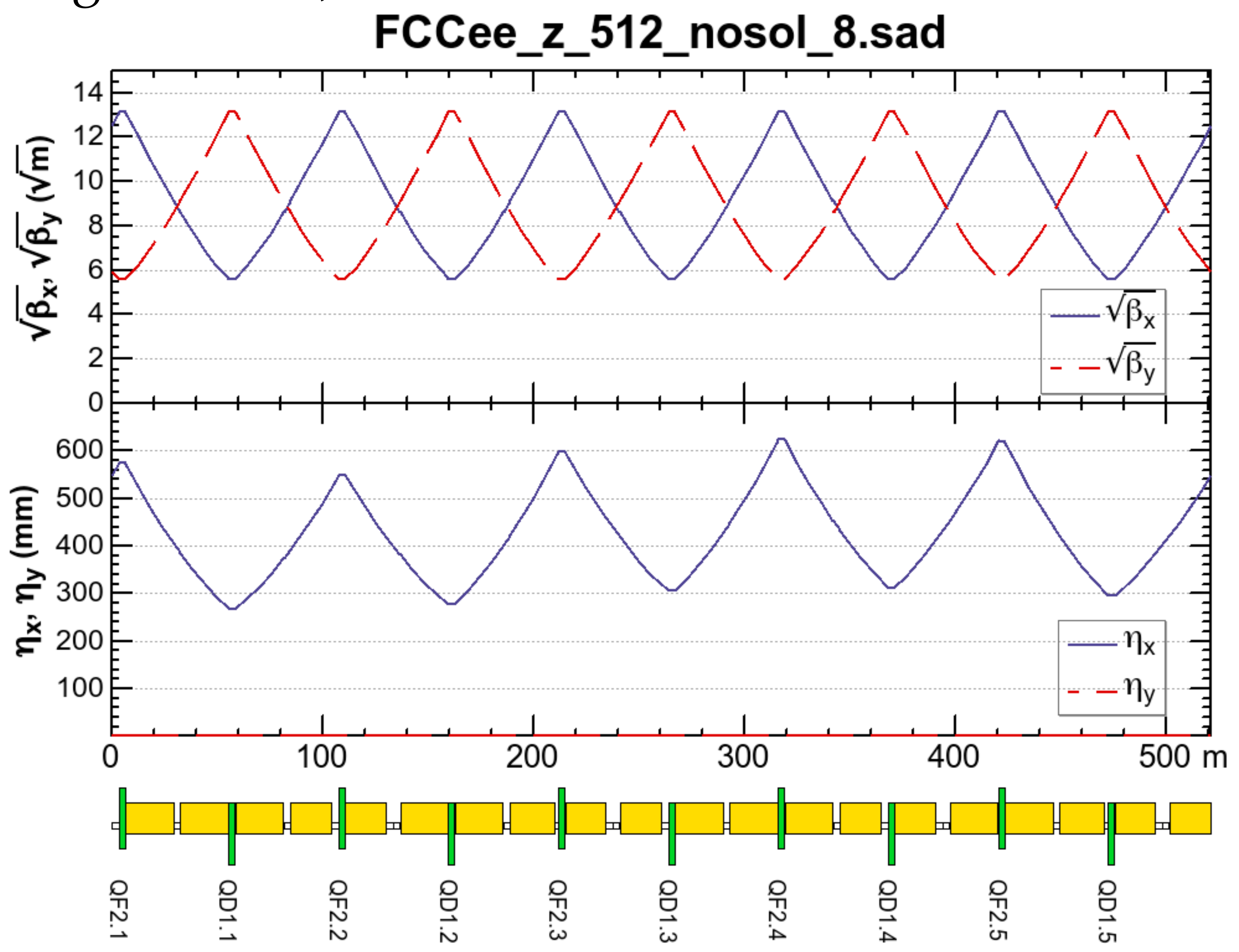
The beam optics shown here and later are not always the latest ones in details.

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.

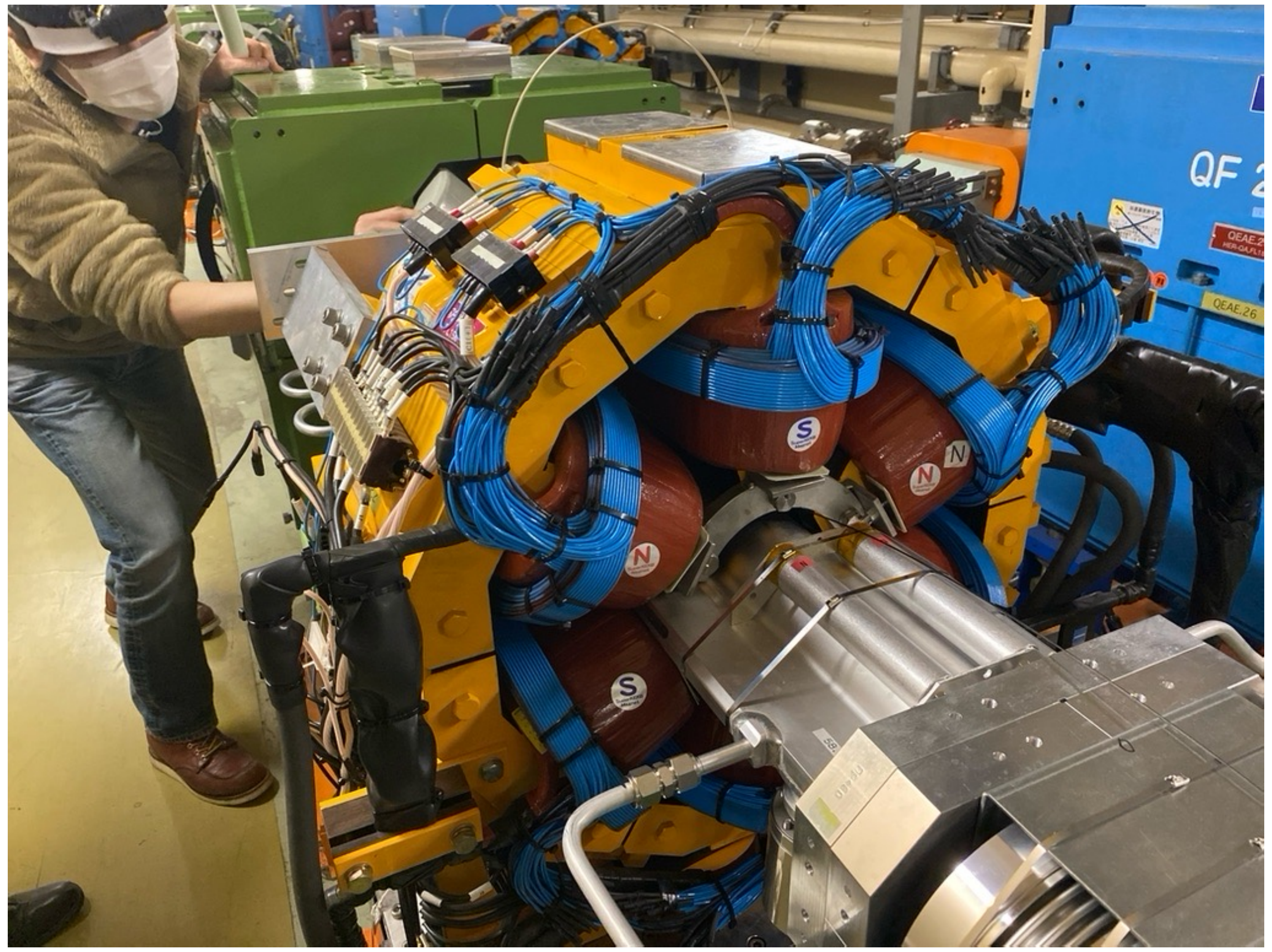
The beam optics shown here and later are not always the latest ones in details.

Expected further studies/modifications

- Removal of “chromatic-crab” resonance at Z & $W^{\pm}$.
- Errors, corrections & tuning including beam-beam & beamstrahlung.

- Rectify the lengths of dipoles to be technically more conformal. Divide some of them into shorter pieces.
- Injection/extraction/collimation optics at LLSS FGHL.
- Change the placement of IP downstream magnets to have enough space for beamstrahlung photons (esp. SY1 crab sext).
- vertical chicane in the crossing optics at FGHL.
- A circumference adjuster at each of FGHL to correct the initial misalignment and change of circumference due to tidal force.
- Adopt HTS short straight section with combined function dipole+quad+sext (15% higher luminosity).
- Detailed optimization for the SR around the IP incl. masking.
- Reflect the alignment strategy on magnets and/or girders.
- Employ field profiles estimated by magnet design.
- Place BPMs and correctors.
- …and more…

Tuning performance on x-y coupling/v. dispersion due to misalignments of sextuples



Trim windings (blue coils) on an arc sextupole @SuperKEKB.

- Motivation: each sextupole magnet in FCC-ee will have trim winding on its each pole to generate normal/skew quadrupole components, which can in principle cancel the misalignment of the sextupole magnet.
- Let us examine how well the misalignment is correctable, by measurements on *x*-*y* coupling and vertical dispersion by BPMs all around the ring.

Some definitions (modified L.C. Teng's)

The transformation matrix from the physical coordinate (x, p_x, y, p_y) to the x-y decoupled coordinate (X, P_X, Y, P_Y) is written as (.=0):

$$\mathrm{R} = \begin{pmatrix} \mu\mathrm{I} & \mathrm{J}\mathrm{r}^T\mathrm{J} \\ \mathrm{r} & \mu\mathrm{I} \end{pmatrix} = \begin{pmatrix} \mu & . & -R_1 & R_2 \\ . & \mu & R_3 & -R_1 \\ R_1 & R_2 & \mu & . \\ R_3 & R_4 & . & \mu \end{pmatrix}$$

with a submatrix

$$\mathrm{r} = \begin{pmatrix} R_1 & R_2 \\ R_3 & R_4 \end{pmatrix} ,$$

where

$$\mu^2 + \det(\mathrm{r}) = 1,$$
$$\mathrm{I} \equiv \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} ,$$
$$\mathrm{J} \equiv \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} .$$

The inverse of R is obtained by reversing the sign of r:

$$\mathrm{R}^{-1} = \begin{pmatrix} \mu\mathrm{I} & -\mathrm{J}\mathrm{r}^T\mathrm{J} \\ -\mathrm{r} & \mu\mathrm{I} \end{pmatrix} = \begin{pmatrix} \mu & . & R_4 & -R_2 \\ . & \mu & -R_3 & R_1 \\ -R_1 & -R_2 & \mu & . \\ -R_3 & -R_4 & . & \mu \end{pmatrix}$$

.

Let M stand for the physical transfer matrix of a ring, then the transformation in the decoupled coordinate is diagonalized as

$$\mathrm{RMR}^{-1} = \begin{pmatrix} \mathrm{M}_X & 0 \\ 0 & \mathrm{M}_Y \end{pmatrix} .$$

The Twiss parameters are defined for the 2 by 2 matrices T_X and T_Y.

Let us represent M in a form consisted of 2 by 2 submatrices as:

$$\mathrm{M} = \begin{pmatrix} \mathrm{P} & \mathrm{T} \\ \mathrm{S} & \mathrm{Q} \end{pmatrix}$$

then we can obtain:

$$\mathrm{r} = \frac{1 - 2\mu^2}{\mu(\mathrm{trP} - \mathrm{trQ})}(\mathrm{J}\mathrm{T}^T\mathrm{J} - \mathrm{S}) ,$$
$$\mu = \sqrt{\frac{1}{2}\left(1 + \frac{|\mathrm{trP} - \mathrm{trQ}|}{\sqrt{d}}\right)} ,$$
$$d \equiv 8\mathrm{detS} + 4\mathrm{tr(ST)} + (\mathrm{trP} - \mathrm{trQ})^2 .$$

If $d > 0$, the matrix M is stable, otherwise it is on a *sum resonance*.

Response of coupling parameters/dispersion to a skew quad

If there is a thin skew quadrupole having a transfer matrix

$$\mathrm{K} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k_s & 0 \\ 0 & 0 & 1 & 0 \\ k_s & 0 & 0 & 1 \end{pmatrix}$$

in a ring at phase advances $\Delta\psi_{x,y}$ from an observation point, the skew quad generates an x-y coupling at the observation point. By a matrix calculation, for instance, the response to R_2 at the observation point is written as:

$$\delta R_2 = \sqrt{\beta_x\beta_y\beta_{xk}\beta_{yk}}\frac{\sin\Delta\psi_x\sin(\mu_y-\Delta\psi_y)-\sin\Delta\psi_y\sin(\mu_x-\Delta\psi_x)}{2(\cos\mu_x-\cos\mu_y)}k_s+O[k_s^2]\,,$$

where $\beta_{x,y}$, $\beta_{xk,yk}$ are the horizontal and vertical β-functions at the observation point and the skew quad, respectively, with ring tunes $\mu_{x,y}$.

Similarly, the associated vertical dispersion at the observation point is written as

$$\delta\eta_y = \sqrt{\beta_y\beta_{yk}}\frac{\cos(\Delta\psi_y-\mu_y/2)}{2\sin(\mu_y/2)}\eta_{xk}k_s\,,$$

where η_{xk} is the horizontal dispersion at the skew quad.

Response of coupling parameters/dispersion to a skew quad (2)

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- Therefore we can analytically construct a response matrix A from all skew quads on the sexts to R_2 and η_y at all BPMs in the ring as:

$$\mathrm{A} = \begin{pmatrix} (\delta R_2/k_s) \\ (\delta \eta_y/k_s) \end{pmatrix}$$

- It may be more practical to put weights on R_2, η_y, and k_s to construct A. Here we choose them as $\sqrt{\varepsilon_x/\beta_x}$, σ_δ, and $\sqrt{\beta_{xk}\beta_{yk}}$, respectively. However, to avoid complication, we will omit these weights in expressions below.

- Once R_2 and η_y are measured at each BPM, the magnitude of each skew quad is simply obtained by solving

$$\mathrm{A}(k_s) = \begin{pmatrix} (\delta R_2) \\ (\delta \eta_y) \end{pmatrix} . \tag{1}$$

  Practically, the solution is simply obtained by a singular value decomposition (SVD).

- If there is no source of coupling/dispersion other than sextupole misalignments, the solution above will ***perfectly cancel*** the misalignments, unless there are no measurement errors.

- If there are measurement errors at BPMs, such errors will transfer to the skew strengths through the inversion of Eq. (1), then result in coupling/dispersion and vertical emittance.

Measurement of coupling/dispersion at BPMs

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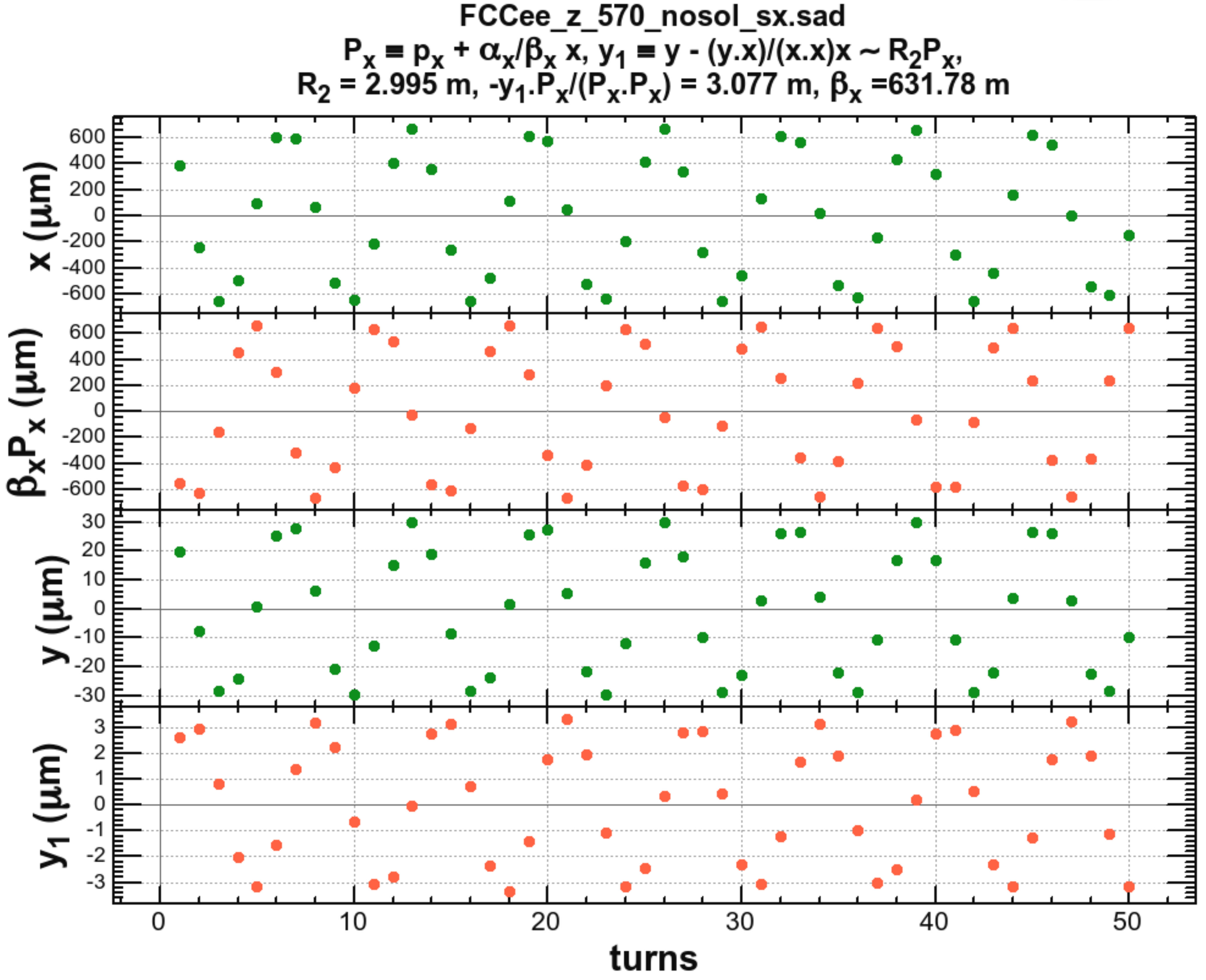
- There are many ways to measure the coupling at each BPM. One of them is to use turn-by-turn BPM to excite the horizontal betatron oscillation over many turns. It may be difficult for higher energies esp. at $t\bar{t}$ due to the very strong damping, but should be possible at Z, which requires the most stringent correction.

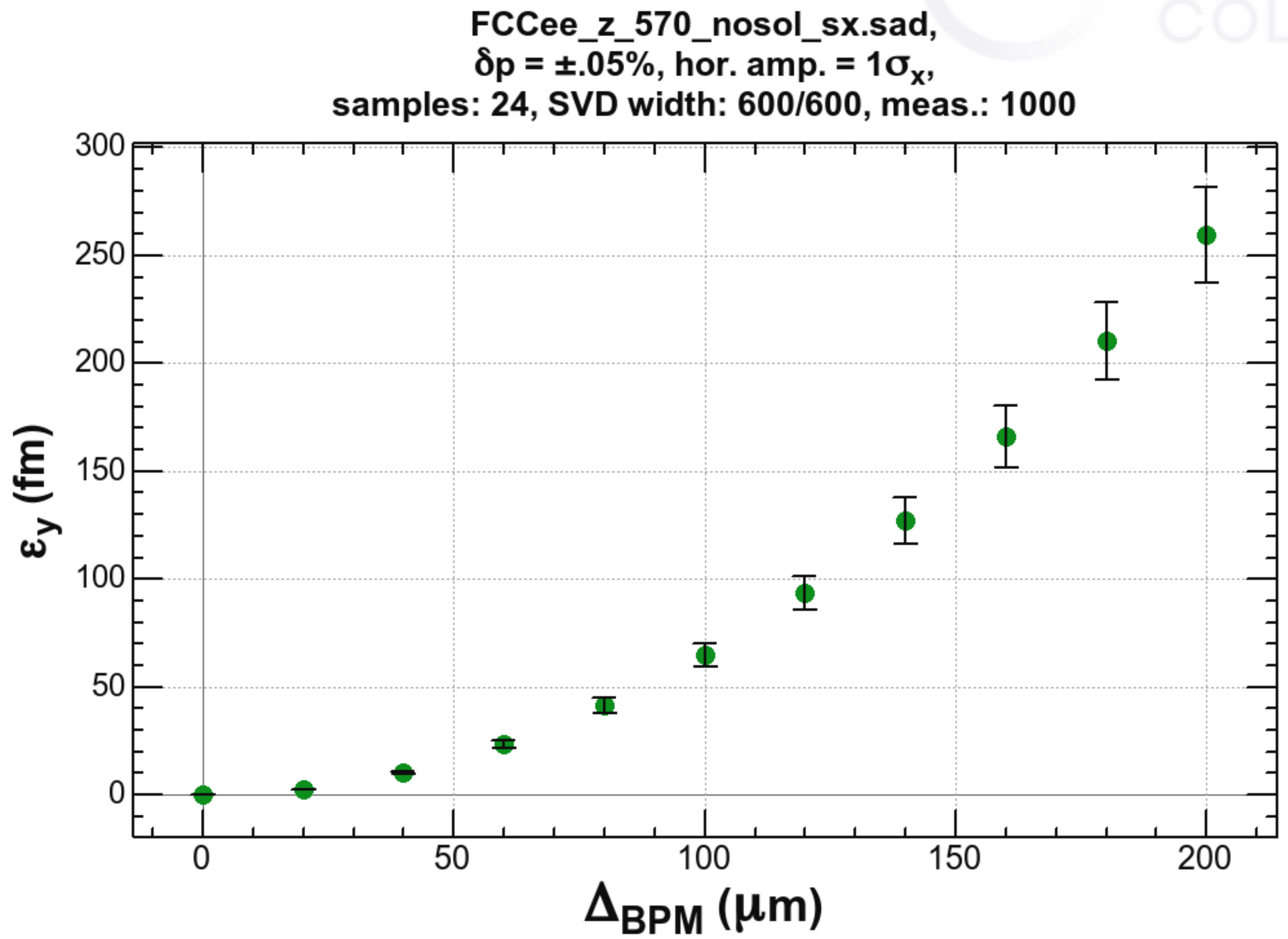
- Once such a horizontal oscillation is excited, the vertical signal at the same BPM will be observed due to the coupling. There are two components in the vertical signal, due to R_1 $(X \to y)$ and R_2 $(P_X \to y)$. Although both are detectable, *the signal by R_1 can be contaminated by a rotation error of the BPM*. As we do not know a way to eliminate such a rotation error, let us consider only R_2 here.

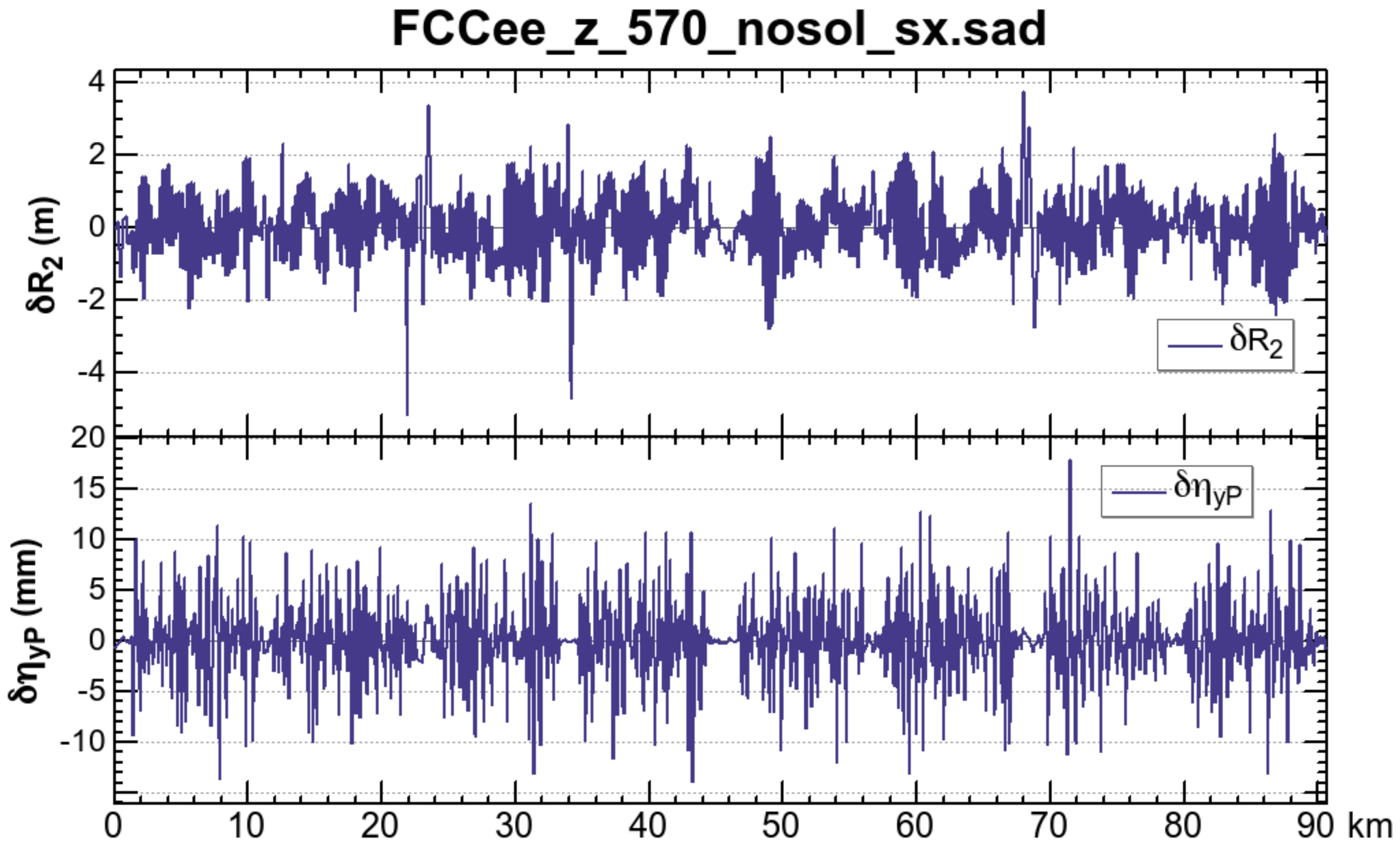


An example of turn-by-turn oscillation at a BPM. There is a coupling $R_2 \sim 3$ m at this BPM. A horizontal vibration by $1\sigma_x$ induce the vertical oscillation by $\sim 30\,\mu$m. The component y_1 which is orthogonal to x gives the measurement of R_2 ($y_1 \sim R_2 P_X$).

Measurement errors of coupling/dispersion at BPMs

- Let us assume the BPM can measure the turn-by-turn displacement of a bunch with a resolution Δ_{BPM} per turn per bunch.
- We excite a horizontal oscillation by an amplitude $n_x\sigma_x$.
- The associated vertical oscillation has an amplitude orthogonal to x by $R_2P_X \sim R_2x/\beta_x \sim R_2n_x\sigma_x/\beta_x$.
- Then the measurement error for N measurements (*ie.*, turns $\times$ bunches) is $\delta R_2 \sim \Delta_{\mathrm{BPM}}\beta_x/(n_x\sigma_x\sqrt{N})$.
- The vertical dispersion at the BPM is measured by the difference of orbits between two momenta ($\pm\delta p$).
- The measurement error of the dispersion is $\delta\eta_y \sim \Delta_{\mathrm{BPM}}/(2\delta p)$.
- The right upper plot shows the resulting vertical emittance associated with random measurement errors in R_2 and η_y, on the BPMSs at all quads, with $n_x = 1$, $N = 1000$, $\delta p = 0.05\%$. All singular values are inverted. Only arc sexts are taken into account.
- The right lower plots an example of resulting δR_2 and $\delta\eta_y$ with $\Delta_{\mathrm{BPM}} = 200\,\mu\mathrm{m}$, generating $\varepsilon_y = 240\,\mathrm{fm}$.





$\Delta_{\mathrm{BPM}} = 200\,\mu\mathrm{m},\ \varepsilon_y = 240\,\mathrm{fm}$

Discussions

- The correction of sext misalignment using coupling/dispersion measurements at BPMs seems OK, giving smaller vertical emittance than required ($\approx$ 300fm), even with a large BPM resolution $\Delta_{\mathrm{BPM}} = 200\,\mu$m.

- The right upper plot shows the result of (k_s), and equiv. displacement $(\Delta y) = (k_s)/(k_2)$, and the sext strengths (k_2) for the last example with $\Delta_{\mathrm{BPM}} = 200\,\mu$m. The "average" misalignment of sexts due to the measurement errors of coupling/dispersion is

$$\sqrt{\frac{\sum k_s^2}{\sum k_2^2}} \approx 370\,\mu\mathrm{m}$$

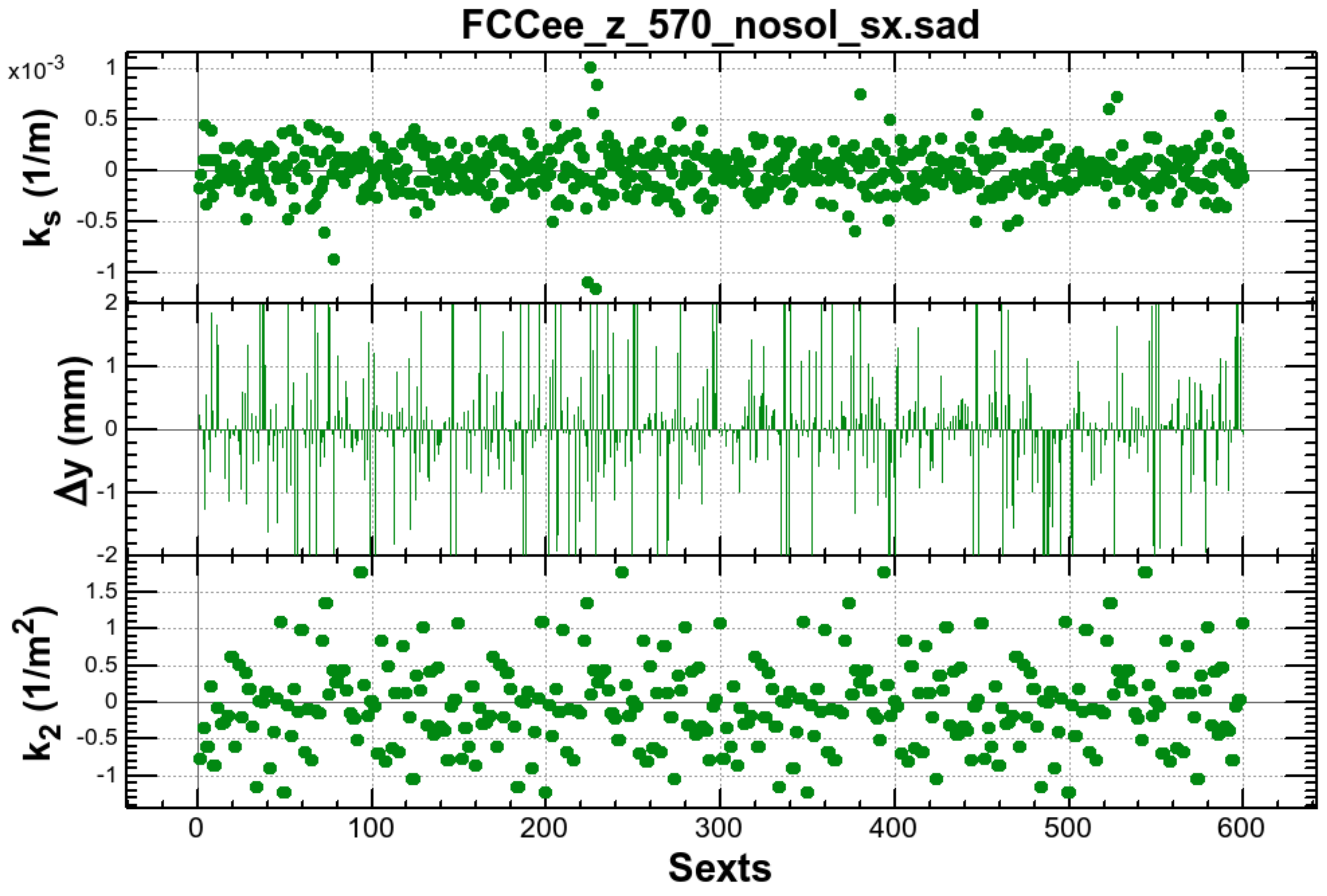
  in this case. This number somewhat sounds large.

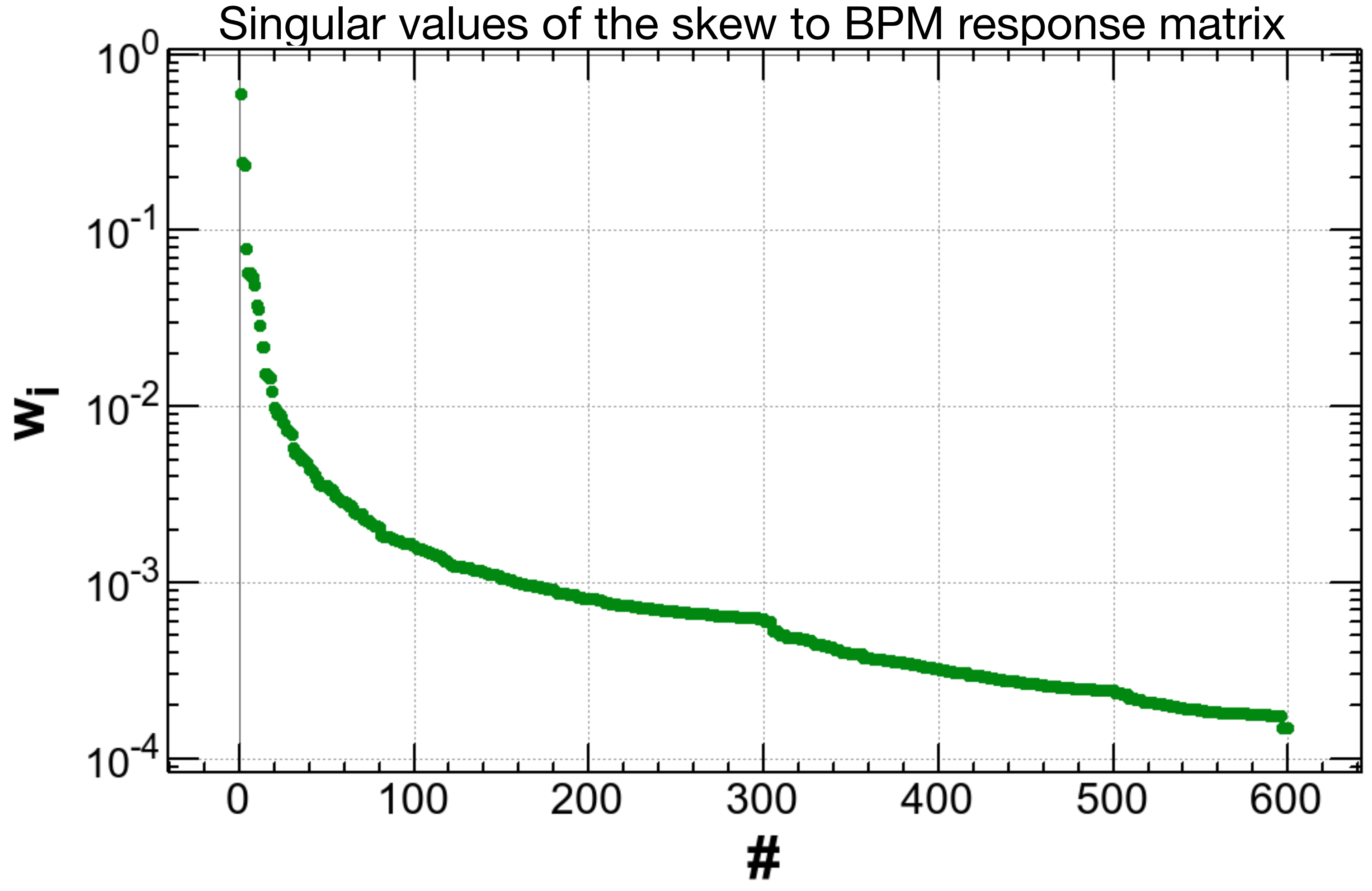
- The skew to coupling/dispersion response matrix ***does not depend on the sextupole setting***. Thus it is different from so-called tolerance on the misalignment of sextupoles.

- Even if the response matrix is incorrect, the correction can be done by iterations, and the resulting emittance will be similar.

- If there are other source of coupling/dispersion in the ring, more skew quads besides the skew on sexts are necessary for their correction. Otherwise the skews on sexts will deviate from the correct value for canceling the misalignment of the sext.

- In the case on the previous page, we have inverted all singular values of the response matrix, shown in the right lower plot.





Summary

- Lattices for four beam energies have been constructed.
    - The lifetime and emittance blowup are evaluated by tracking with SR from all components, beam-beam & beamstrahlung,
- The parameters are chosen to be consistent with the lattices and beamstrahlung.
    - The required lattice vertical emittance is about 1/2 of that at collision for all energies.
- No machine error has been assumed so far. Errors/correction/tuning are the next step.
- Examined a feasibility to correct sextupole misalignments using coupling/dispersion measurements by BPMs, and the result seems OK so far.
- Further optimization and modifications are expected on lattice, tunes, β^*, crab waist ratio, bunch charge (ξ_y),…

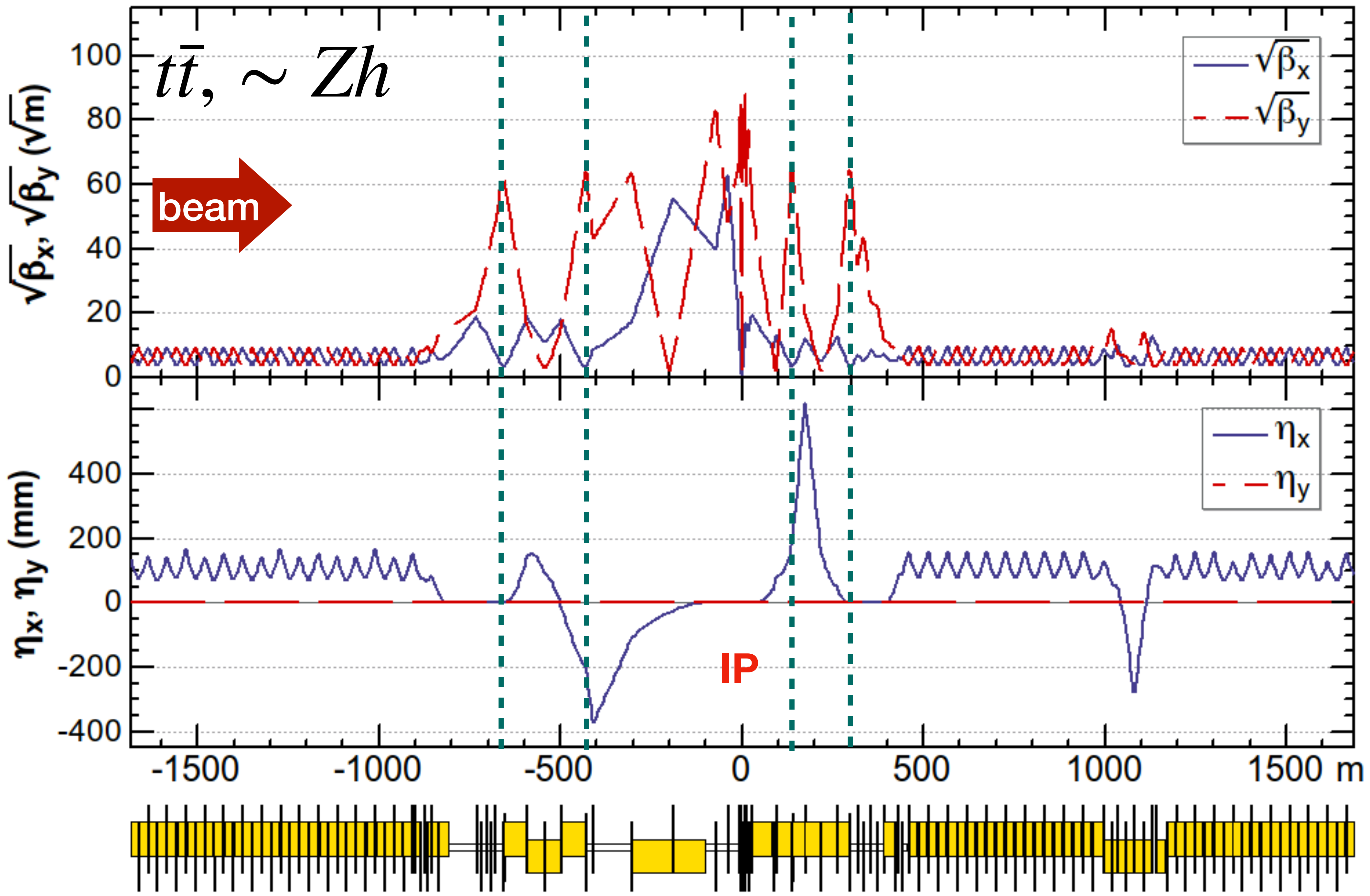
Backups

IR optics (SLSS ADGJ)

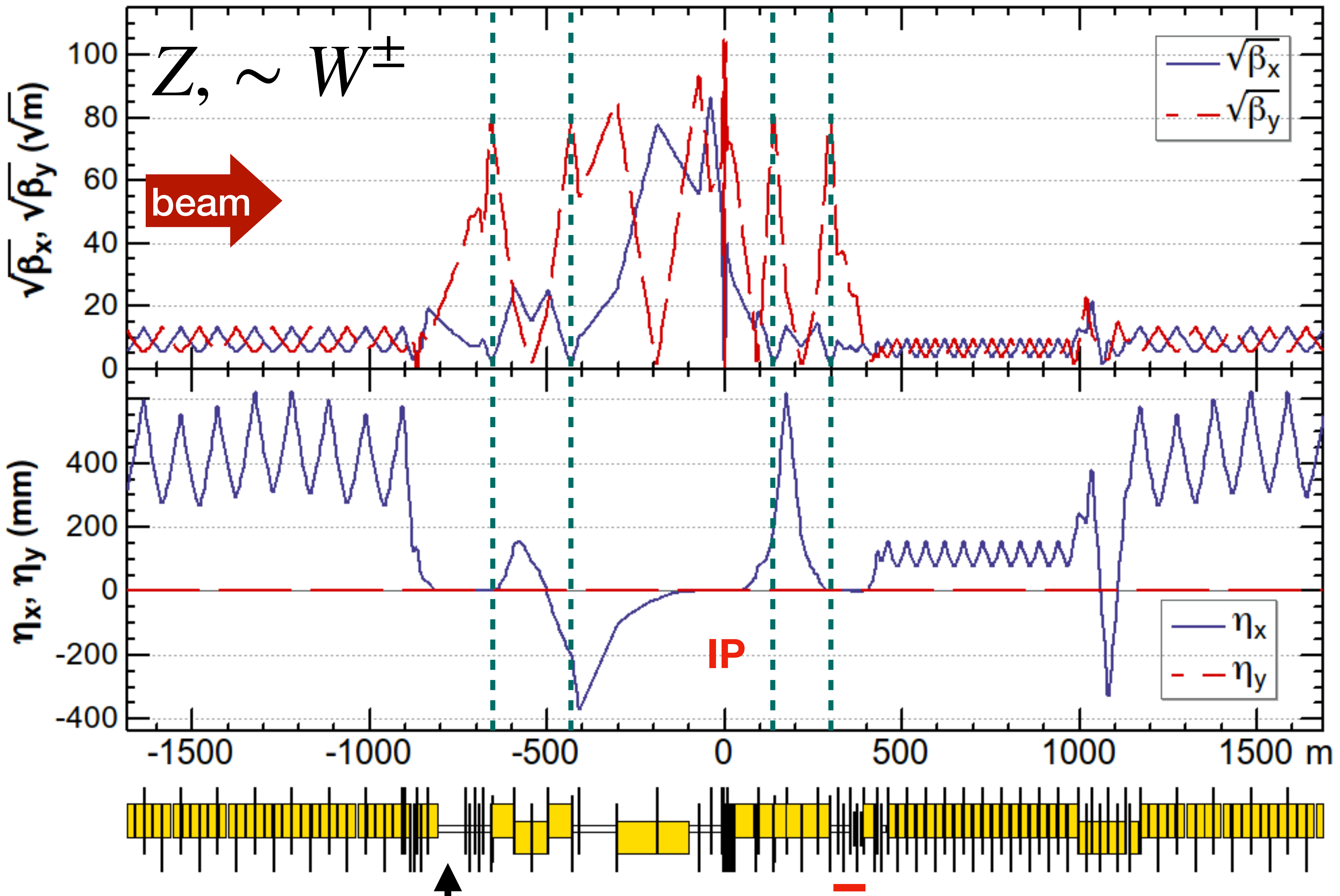
The beam optics shown here and later are not the latest ones in details.

FUTURE CIRCULAR COLLIDER

FCCee_t_546_nosol.sad



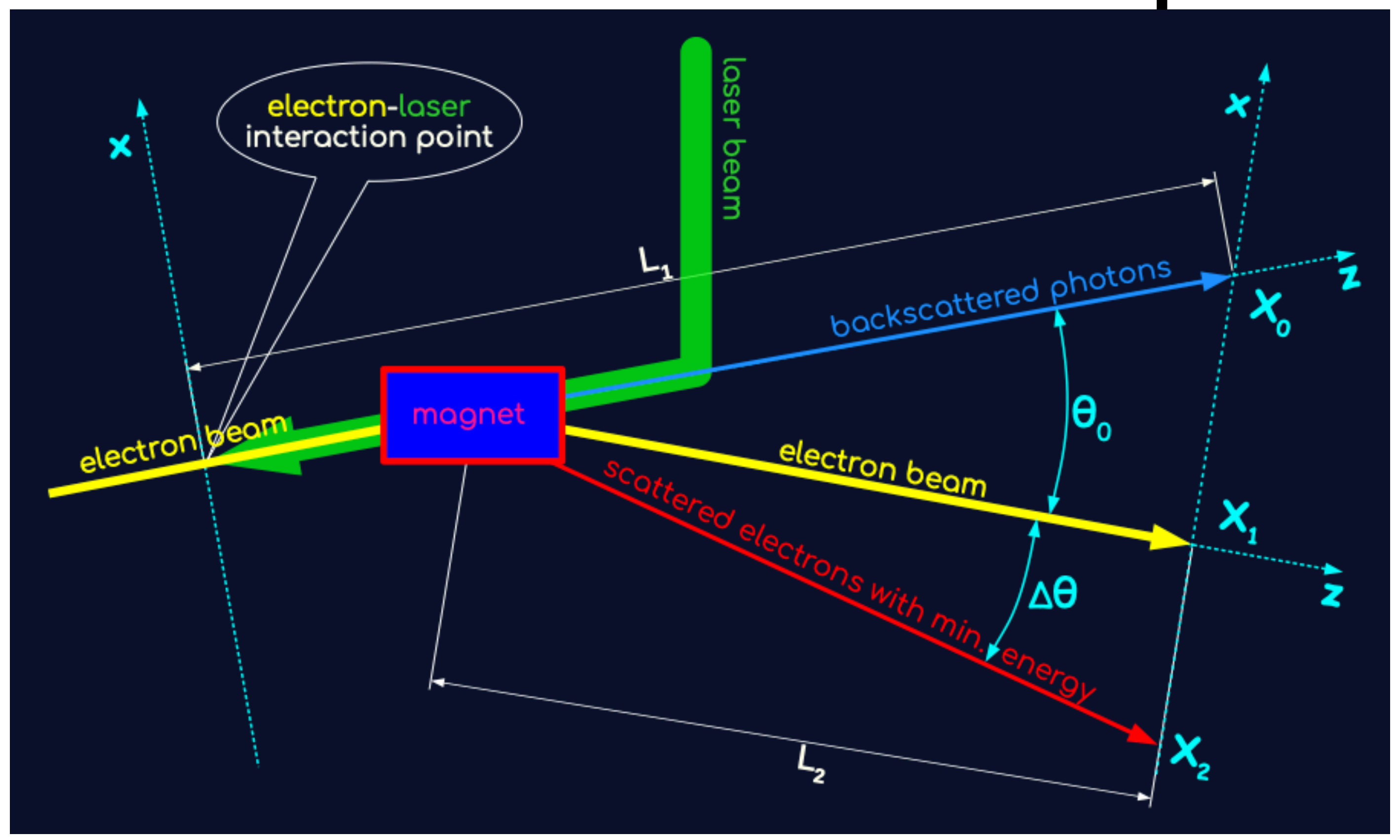
FCCee_z_546_nosol_1.sad

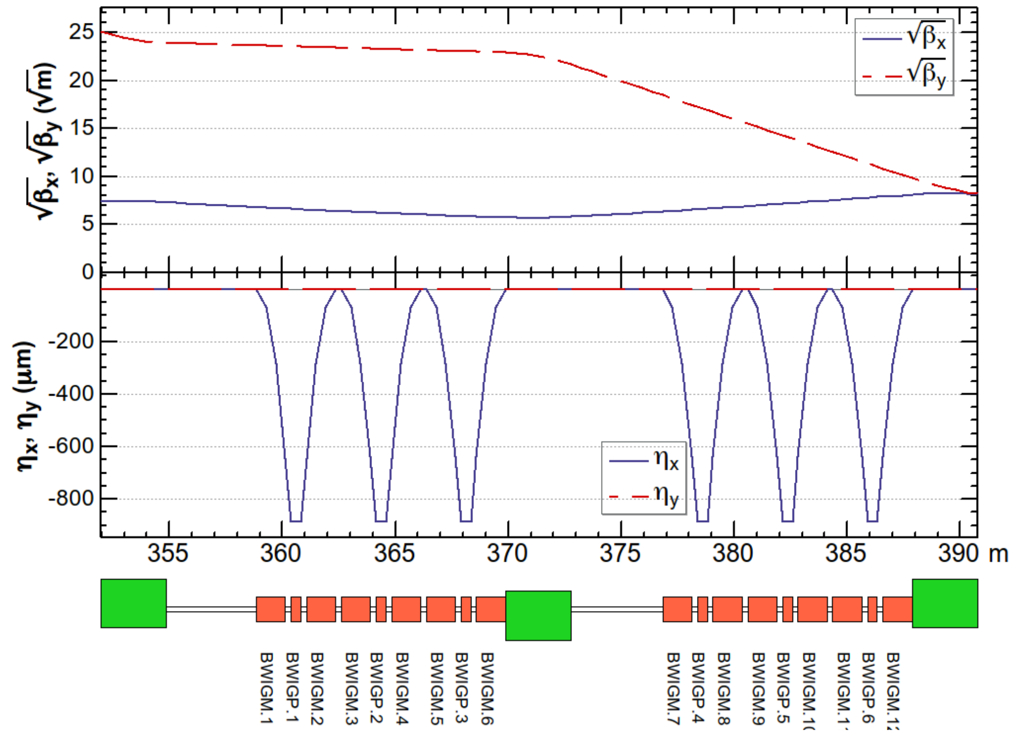


polarimeter
N. Muchnoi

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).

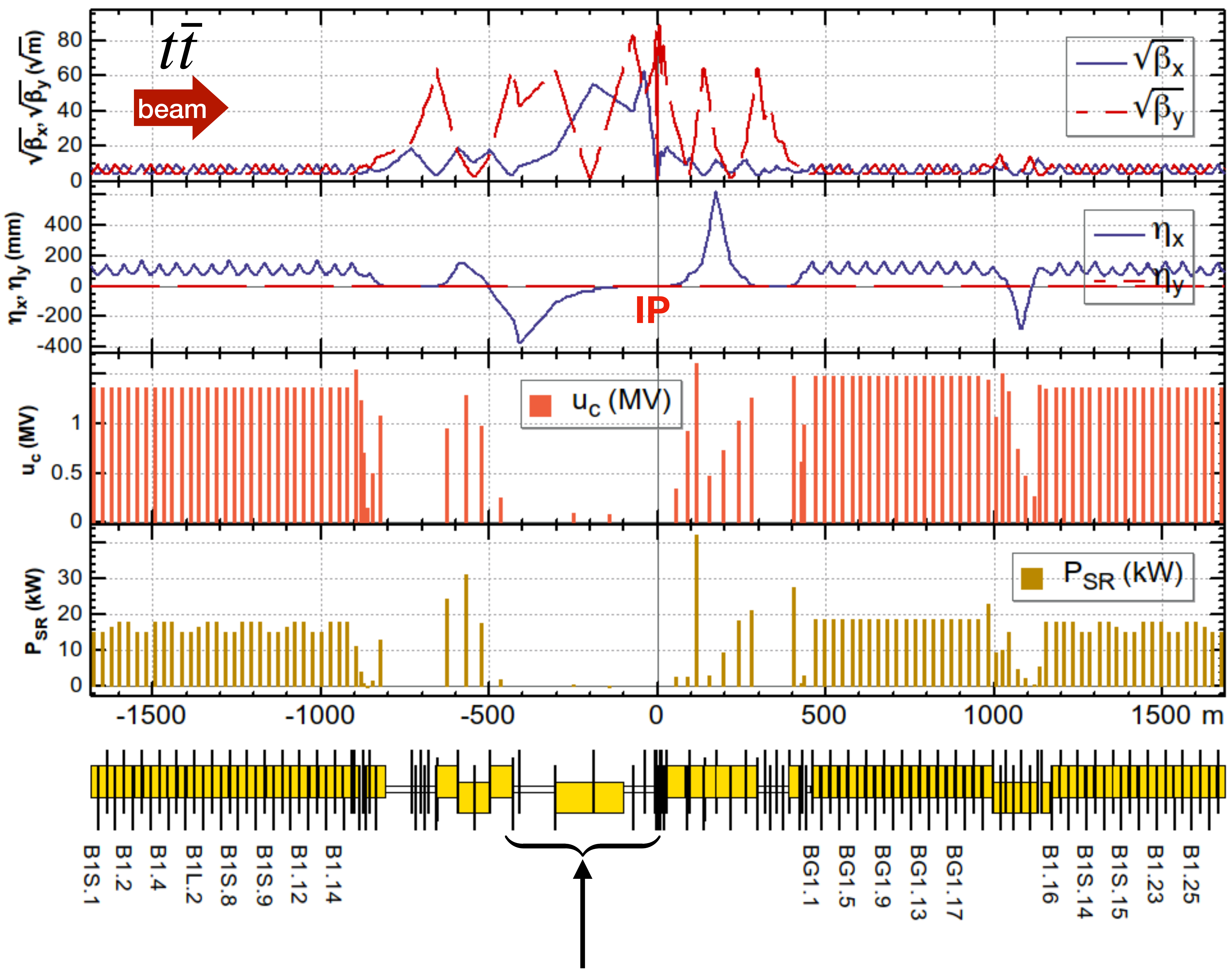




https://indico.cern.ch/event/1181966/contributions/5046175/attachments/2511830/4317657/muchnoi.pdf

June 26, 2023, K. Oide

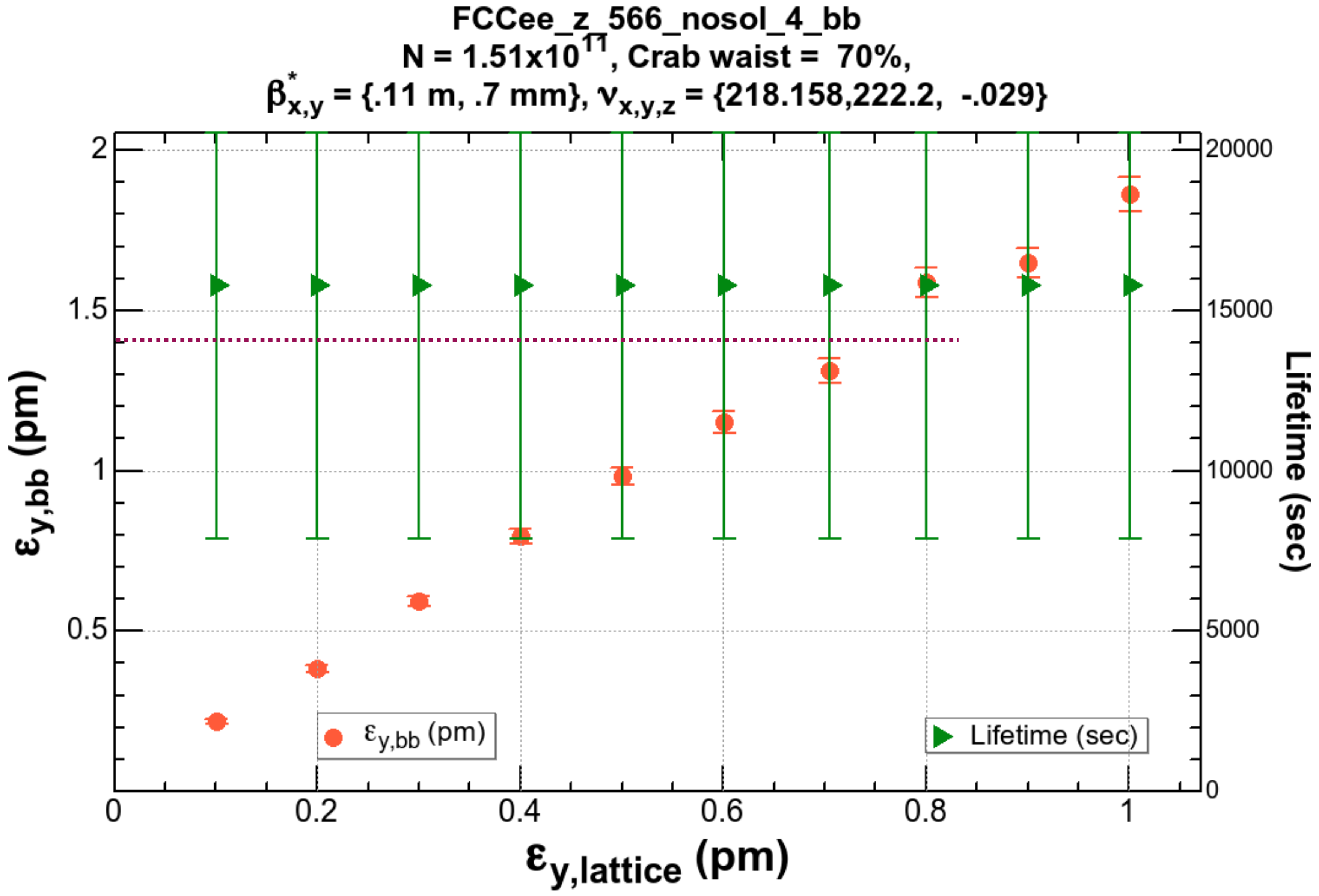
SR from dipoles around IP



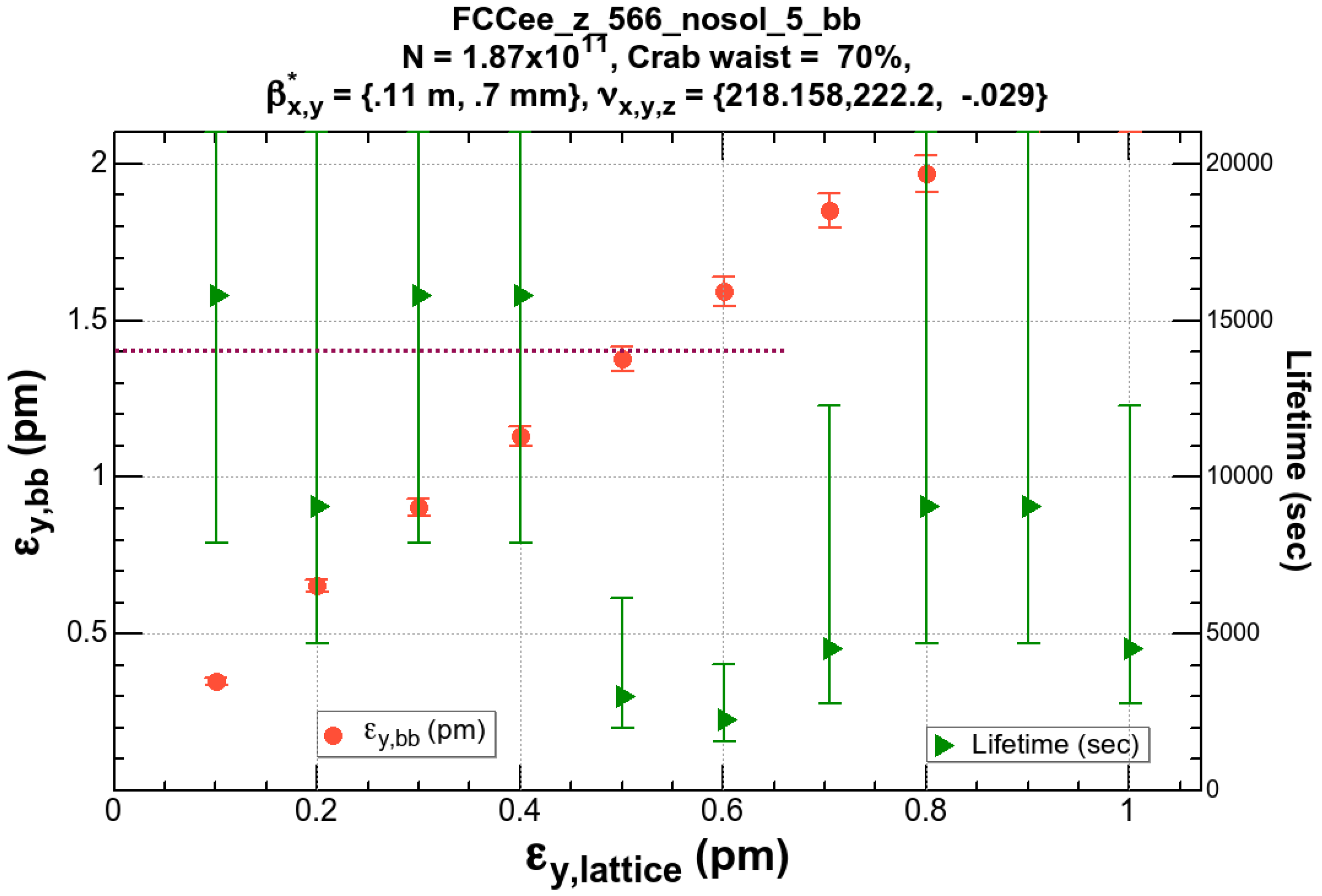
The beam optics shown here and later are not the latest ones in details.

- 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 $t\bar{t}$.

Some variants may be possible for higher luminosity or fewer bunches



$$\mathscr{L}/\mathrm{IP} = 140 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$$
$$N = 1.51 \times 10^{11}$$
$$\tau \gtrsim 15000\,\mathrm{s}$$
$$\varepsilon_{y,\mathrm{lattice}} = 0.75\,\mathrm{pm}$$



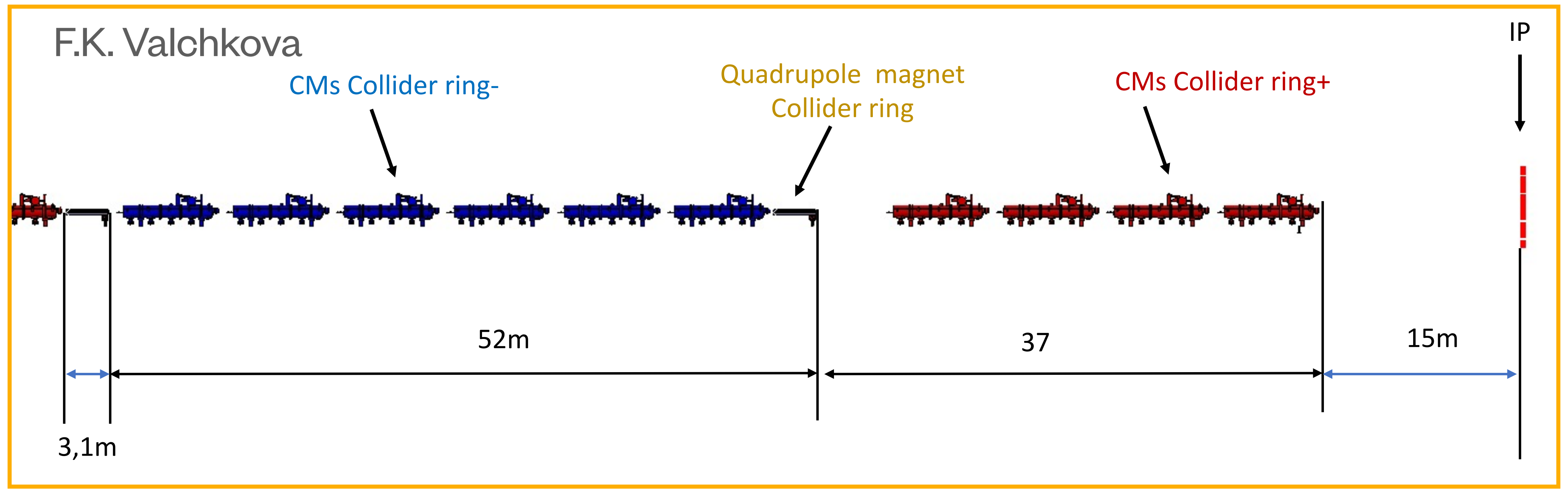
$$\mathscr{L}/\mathrm{IP} = 154 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$$
$$N = 1.87 \times 10^{11}$$
$$\tau \sim 3000\,\mathrm{s}$$
$$\varepsilon_{y,\mathrm{lattice}} = 0.52\,\mathrm{pm}$$

- If we push the luminosity further by increasing the bunch charge (right plot),
  - Indeed, the luminosity gets higher by 10%, but
  - lifetime drops to 1/5 (~3000 s),
  - the required lattice vertical emittance reduces from 0.75 pm to 0.52 pm.
  - note that these have not taken the errors/corrections into account yet…

Layout in long straight sections BFHL

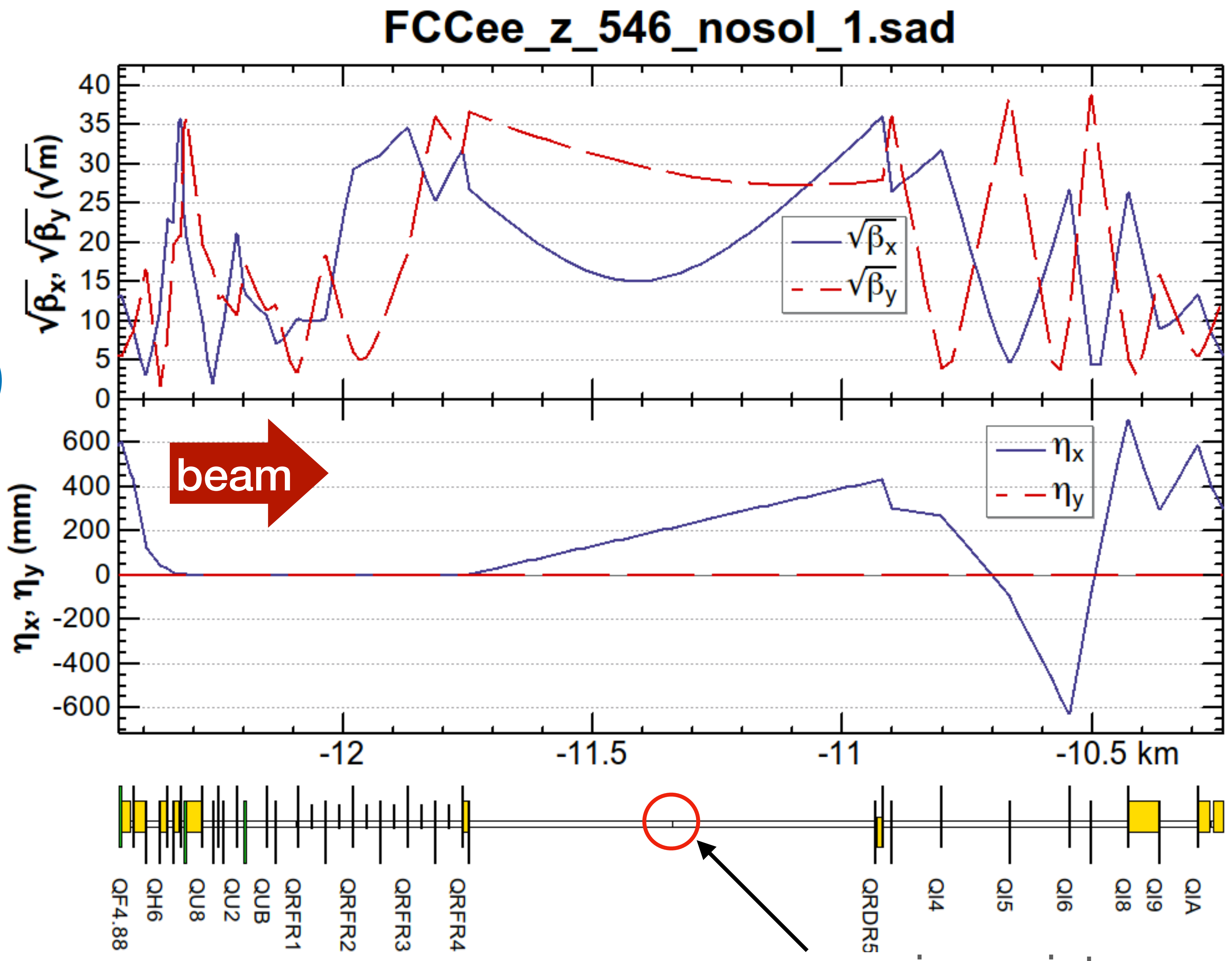
FUTURE CIRCULAR COLLIDER

- 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.



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

Z/W,
Zh/tt (no RF)

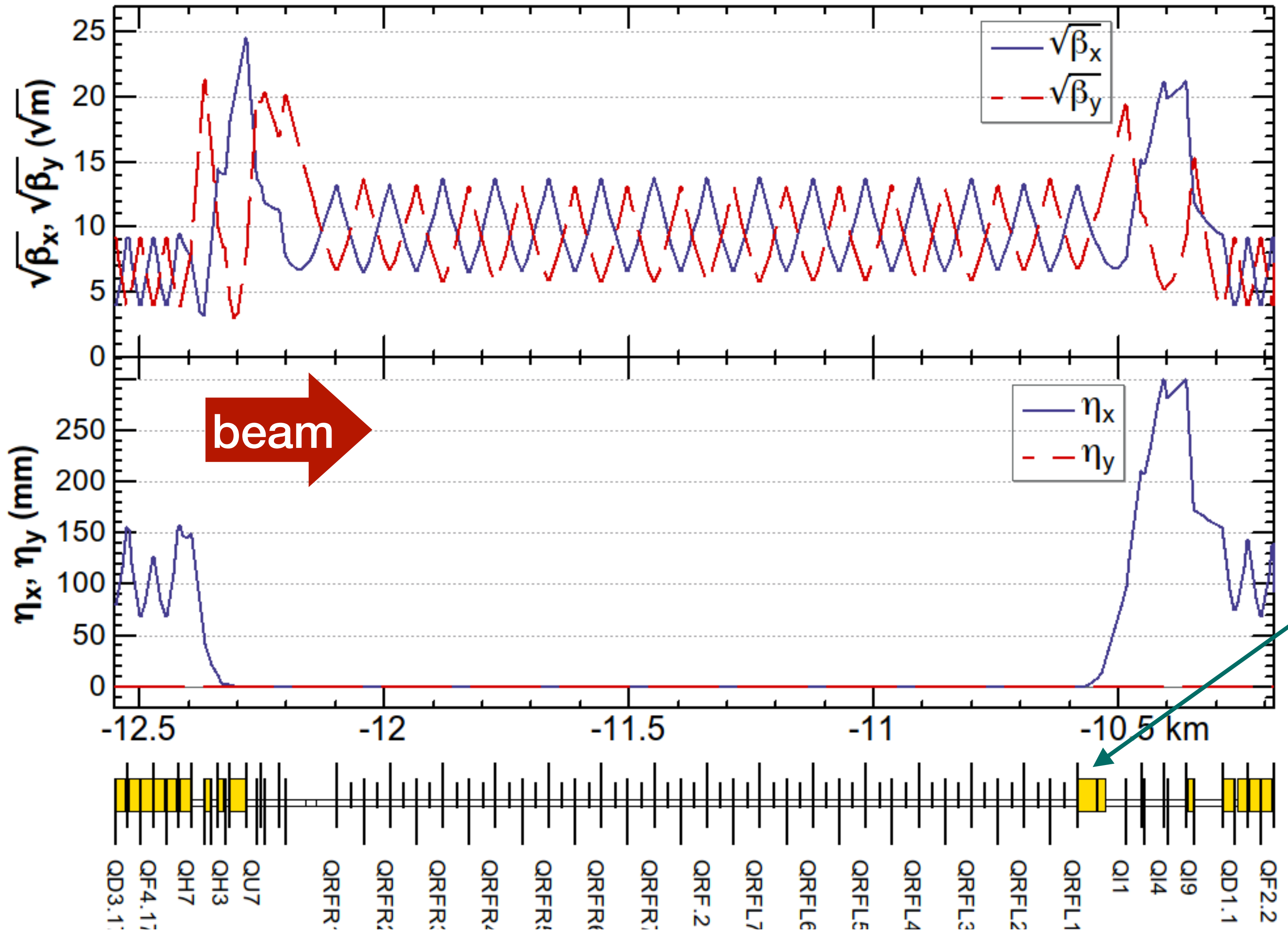


RF
(single beam)

crossing point

Zh/tt (RF)

FCCee_t_546_nosol.sad

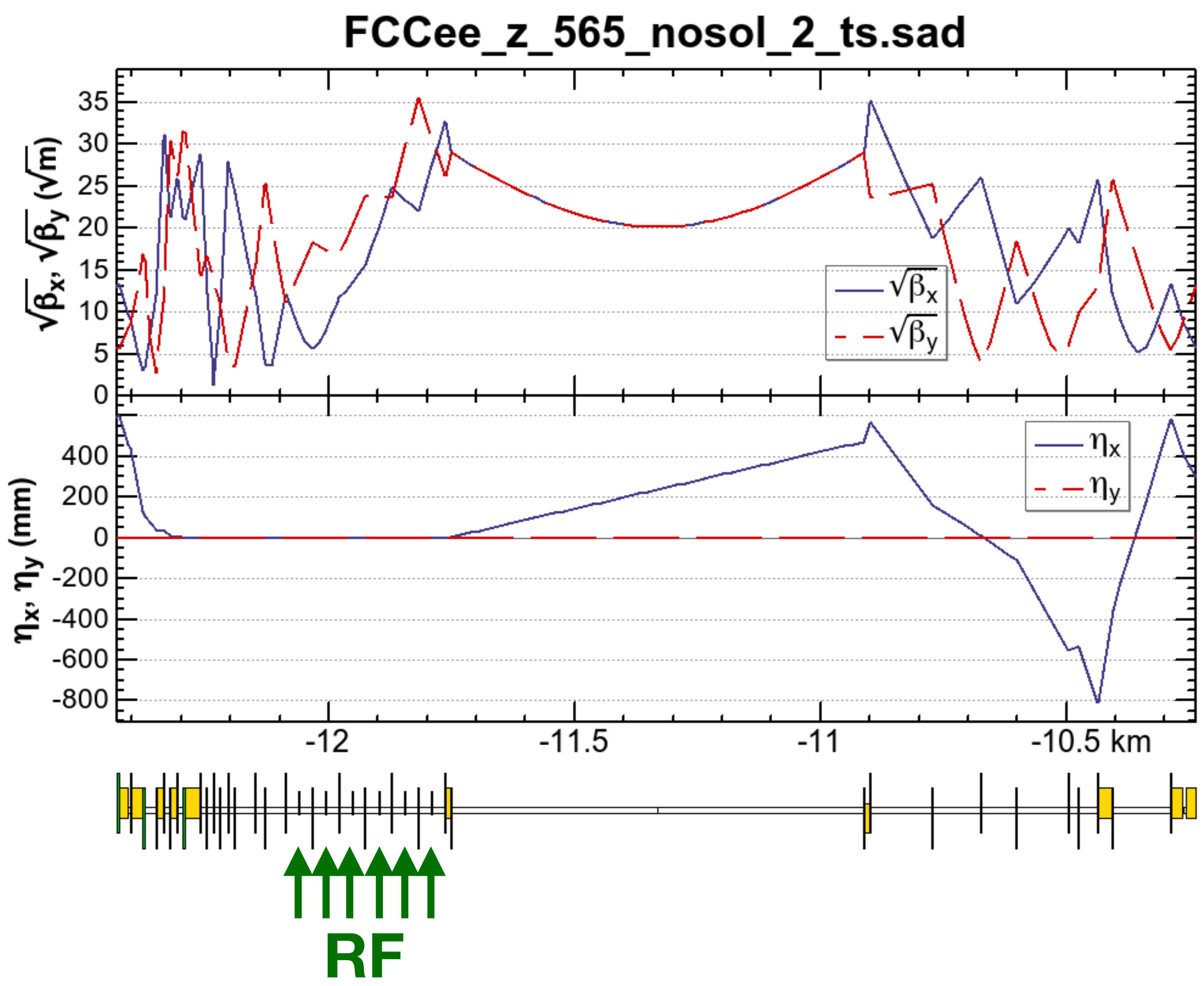


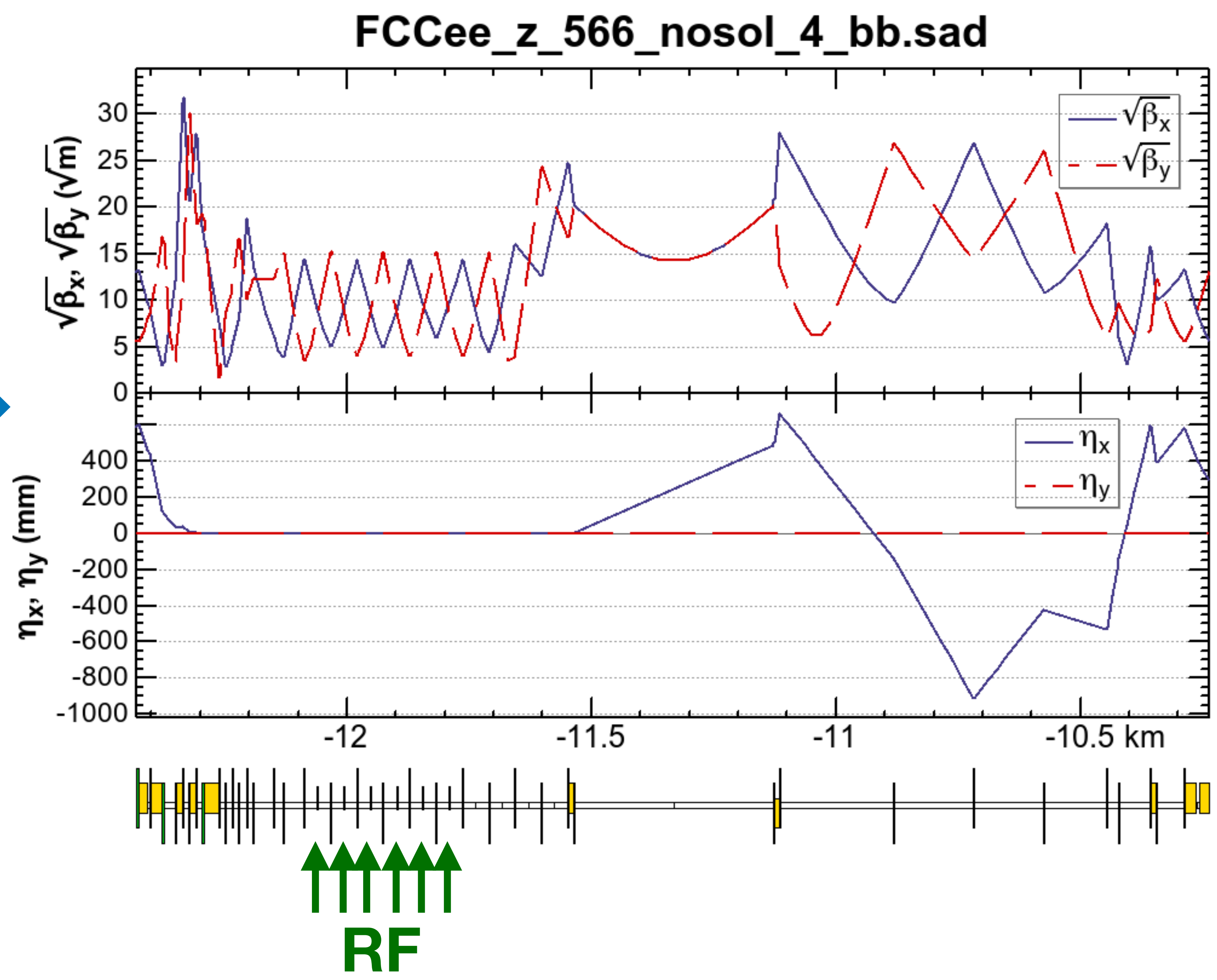
RF cryomodules common to e+e-

Separator; combination of electrostatic & magnetic

Only outgoing beam is deflected

Modification of the crossing section (LLSS)

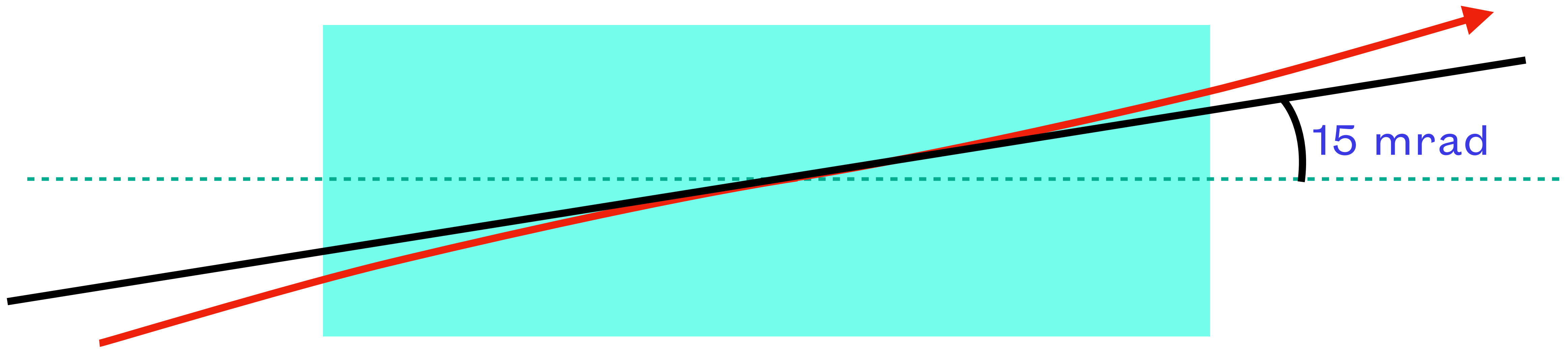


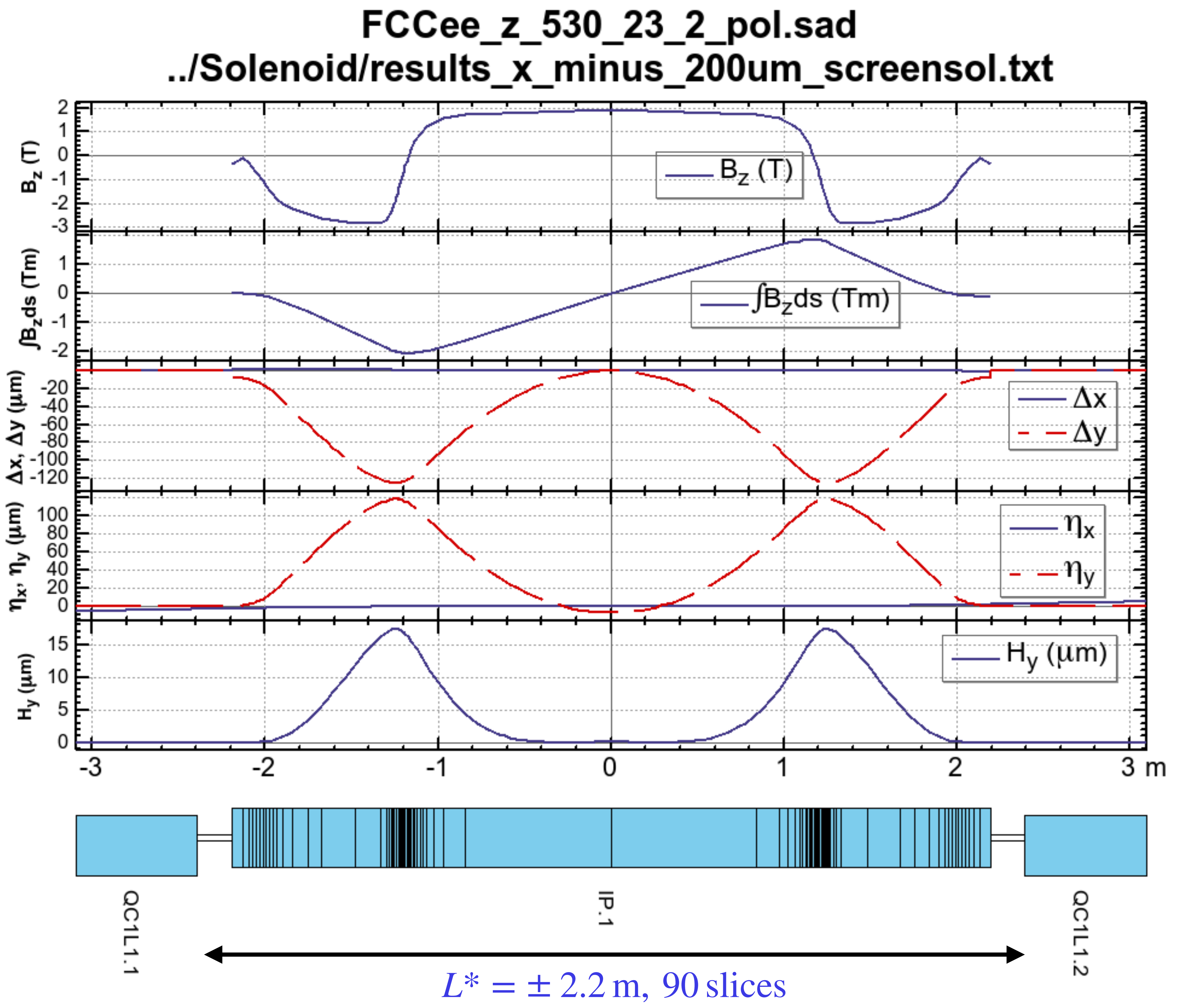


- Reduced the length of the crossing drift from ~800 m to ~400 m.
- The β-functions at the RF cavities become smaller and more regular.
- The phase advances of these sections increase by $\Delta\nu_{x,y} = (+1, +2)$.
- The resulting DA and lifetime seems improved.

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).
- In this SAD model, 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 ($s \sim \pm 1.2$ m) of B_z.

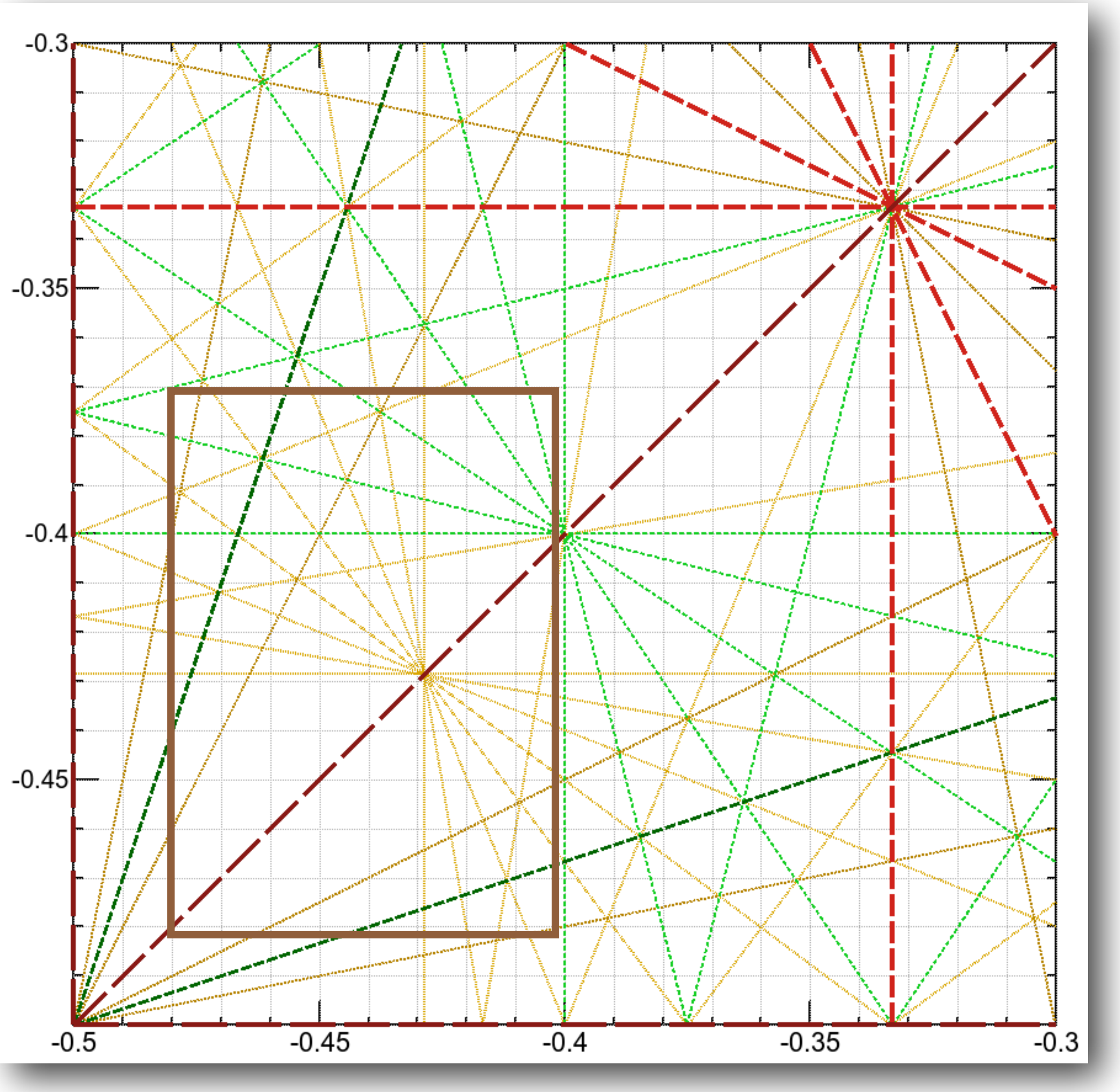




The beam optics shown here and later are not the latest ones in details.

SuperKEKB LER tune survey

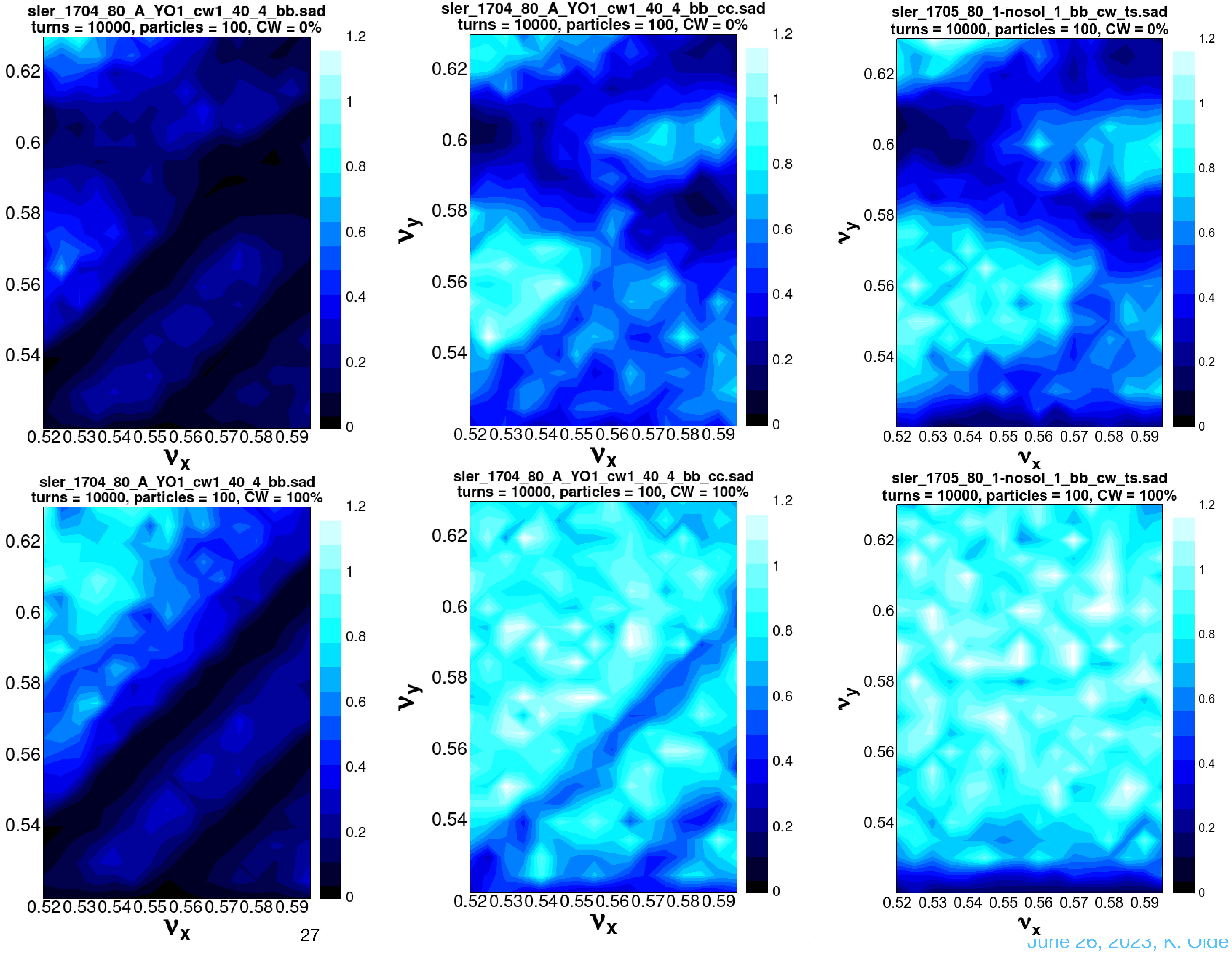
$\varepsilon_{y0}/\varepsilon_y$



Original (SK2=0) | Chromatic coupling corr. | No solenoid lattice

CW = 0%

CW = 100%



- A perfect compensation of the solenoid field is essential to suppress the beam-beam blowup in the case of SuperKEKB.
- In this plot, sextupoles are not re-optimized at each tune.