FCC-ee Collider Optics

K. Oide (UNIGE/CERN)

June 6, 2023 @ FCC Week 2023

Many thanks to M. Benedikt, M. Hofer, 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

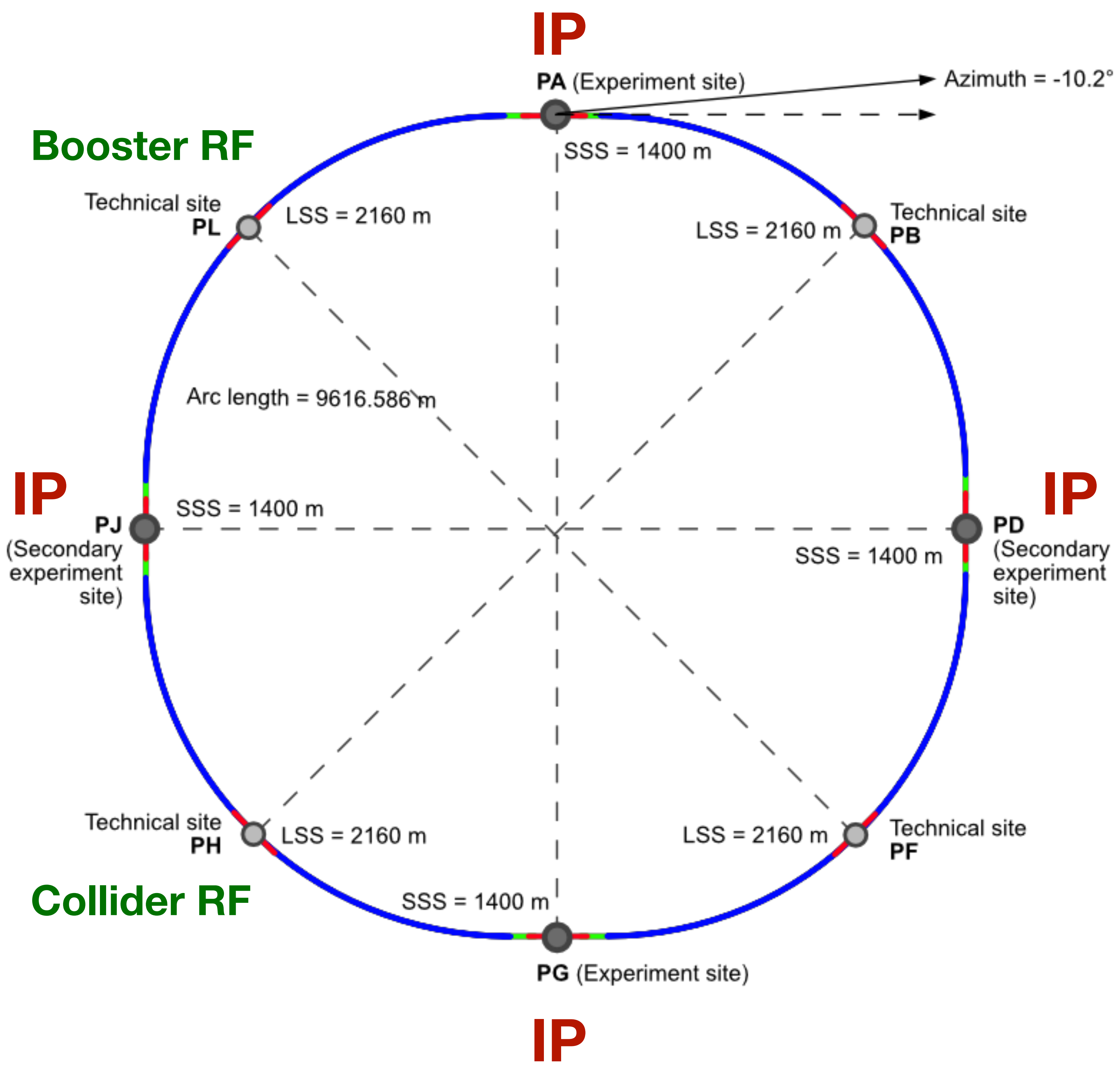


Table 1 Parameters of the layout in meter.

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.

05 – 09 June FCC WEEK 2023

CDR

COLLIDER DESIGN AND PERFORMANCE

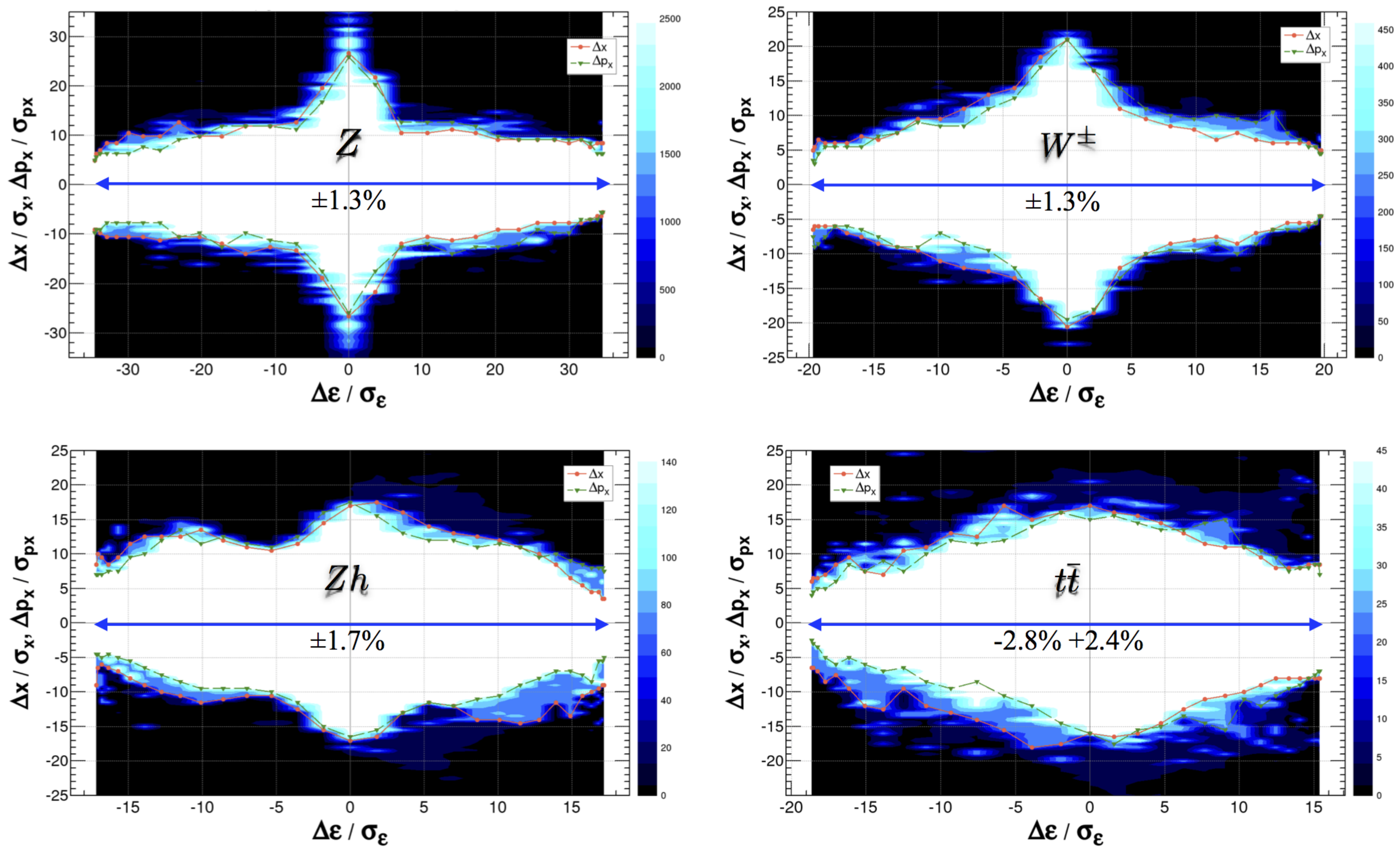
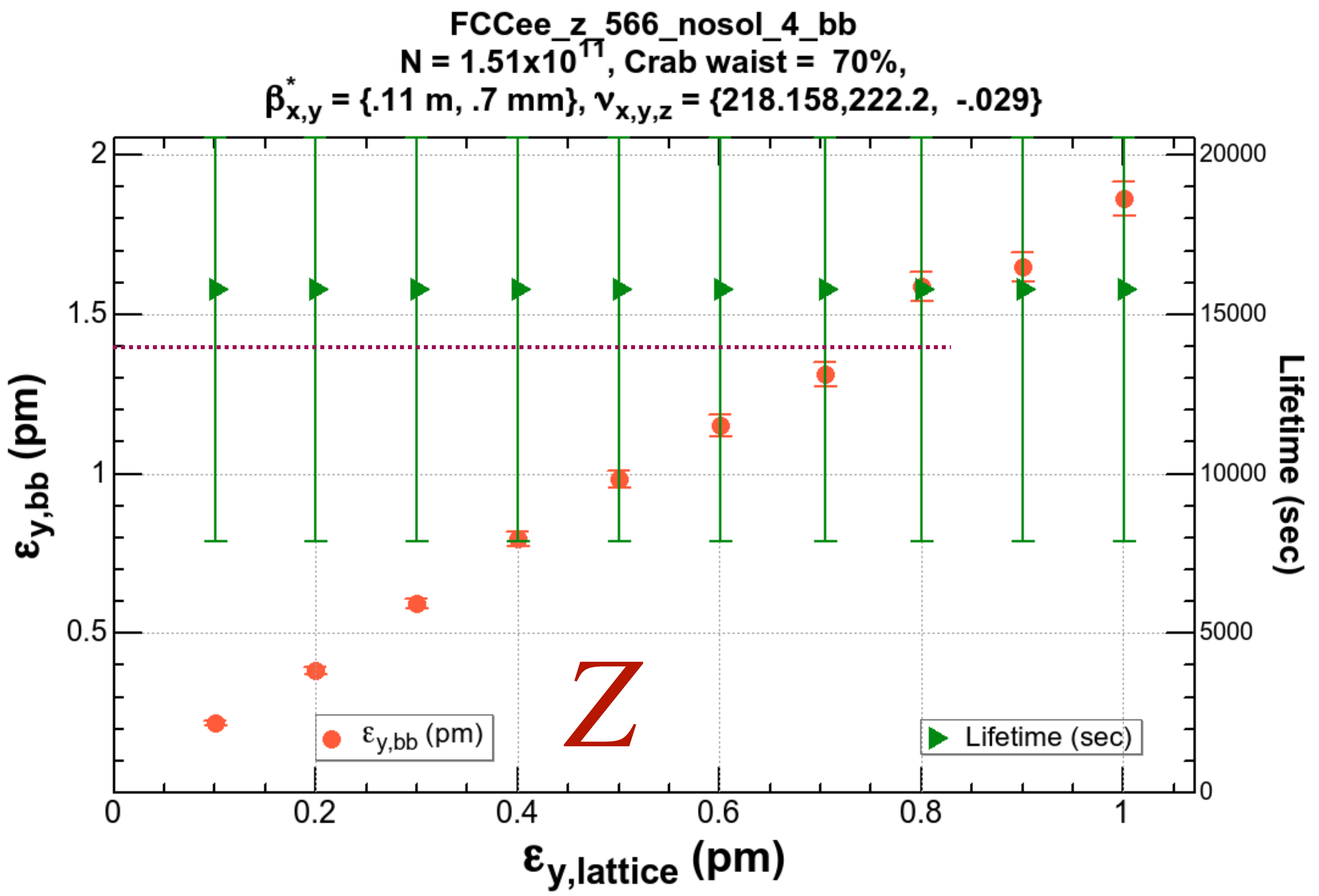
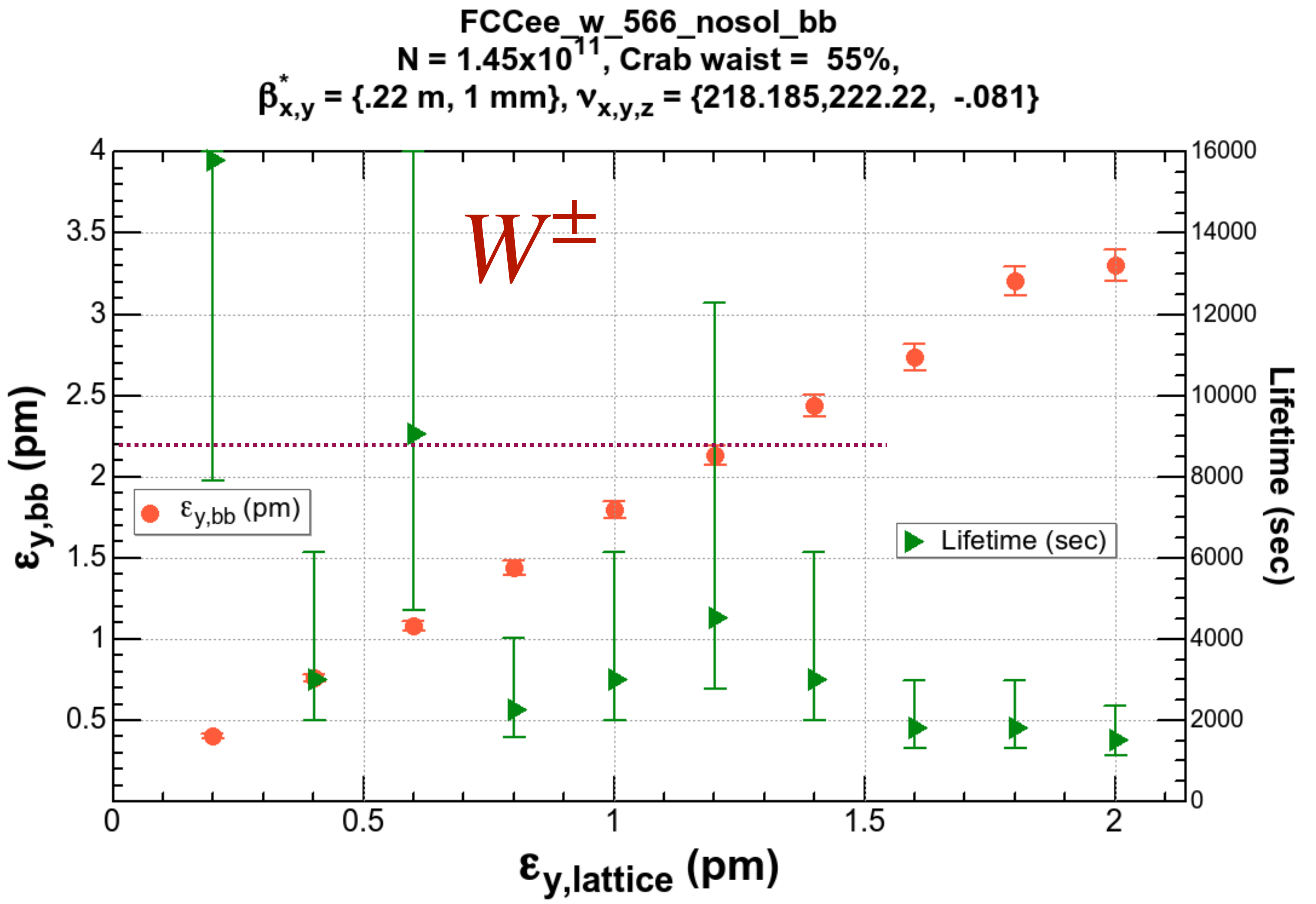


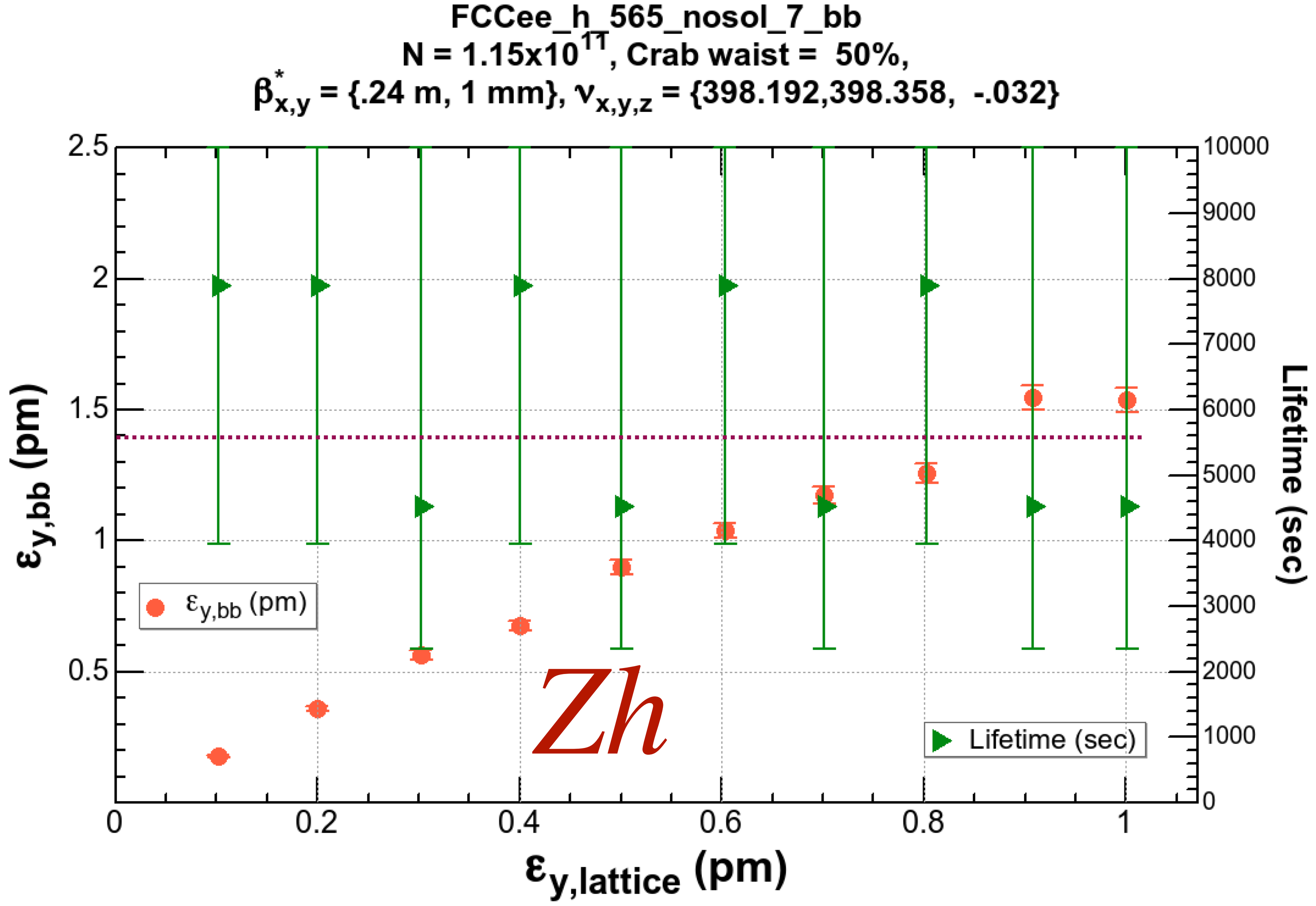
Figure 2.9: Dynamic apertures in z-x plane after sextupole optimisation with particle tracking for each energy. The initial vertical amplitude for the tracking is always set to $J_y/J_x = \varepsilon_y/\varepsilon_x$. The number of turns corresponds to about 2 longitudinal damping times. The resulting 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 $t\bar{t}$ is "asymmetric" to match the distribution with beamstrahlung.

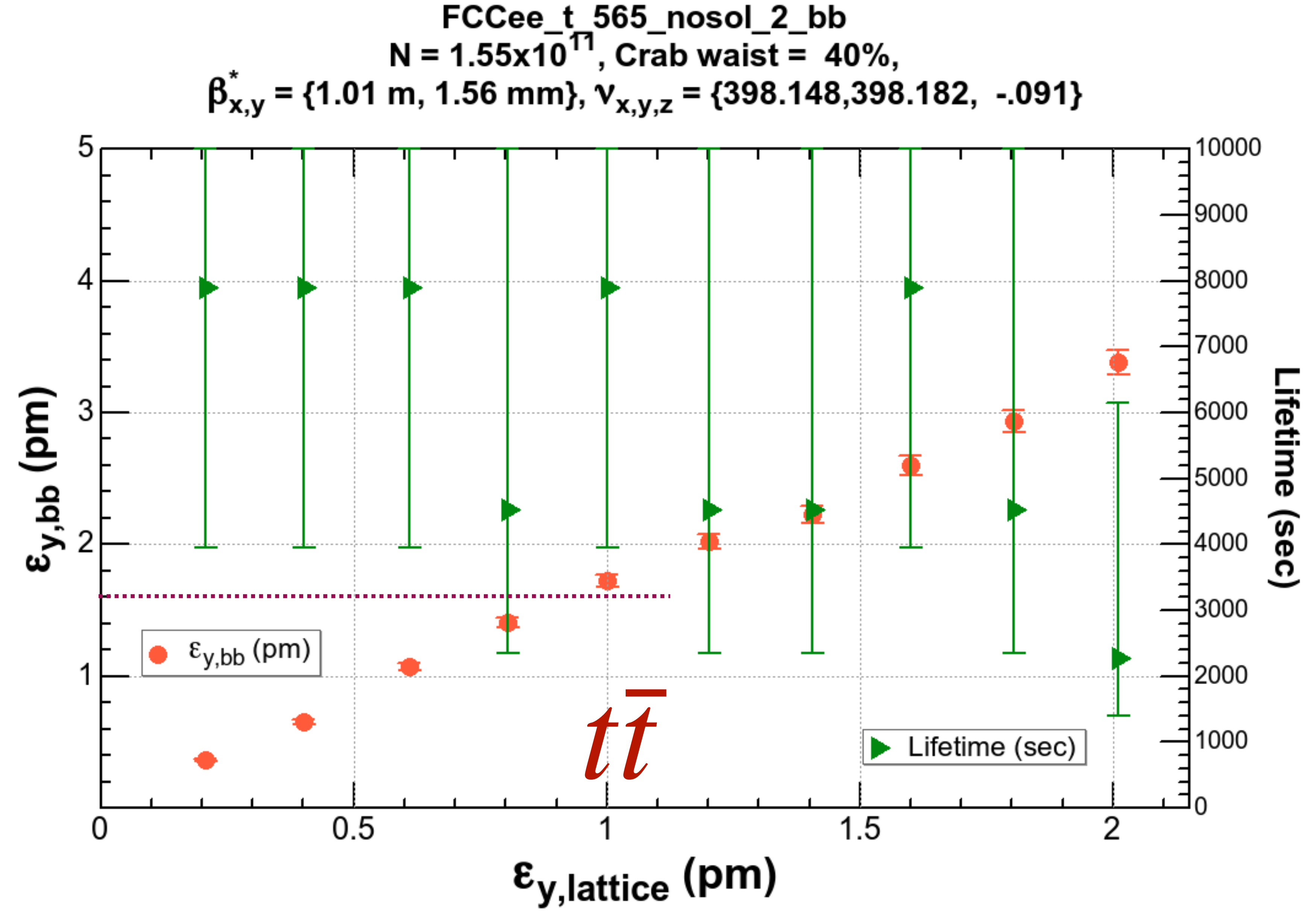
- The lattice dynamic aperture (DA) was optimized to ensure the required momentum acceptance which is estimated by beam-beam (BB) simulations without lattice.
- It has been noticed that the lattice lifetime must be evaluated by itself beyond the DA, esp. at Z with enlarged energy spread by beamstrahlung (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









- 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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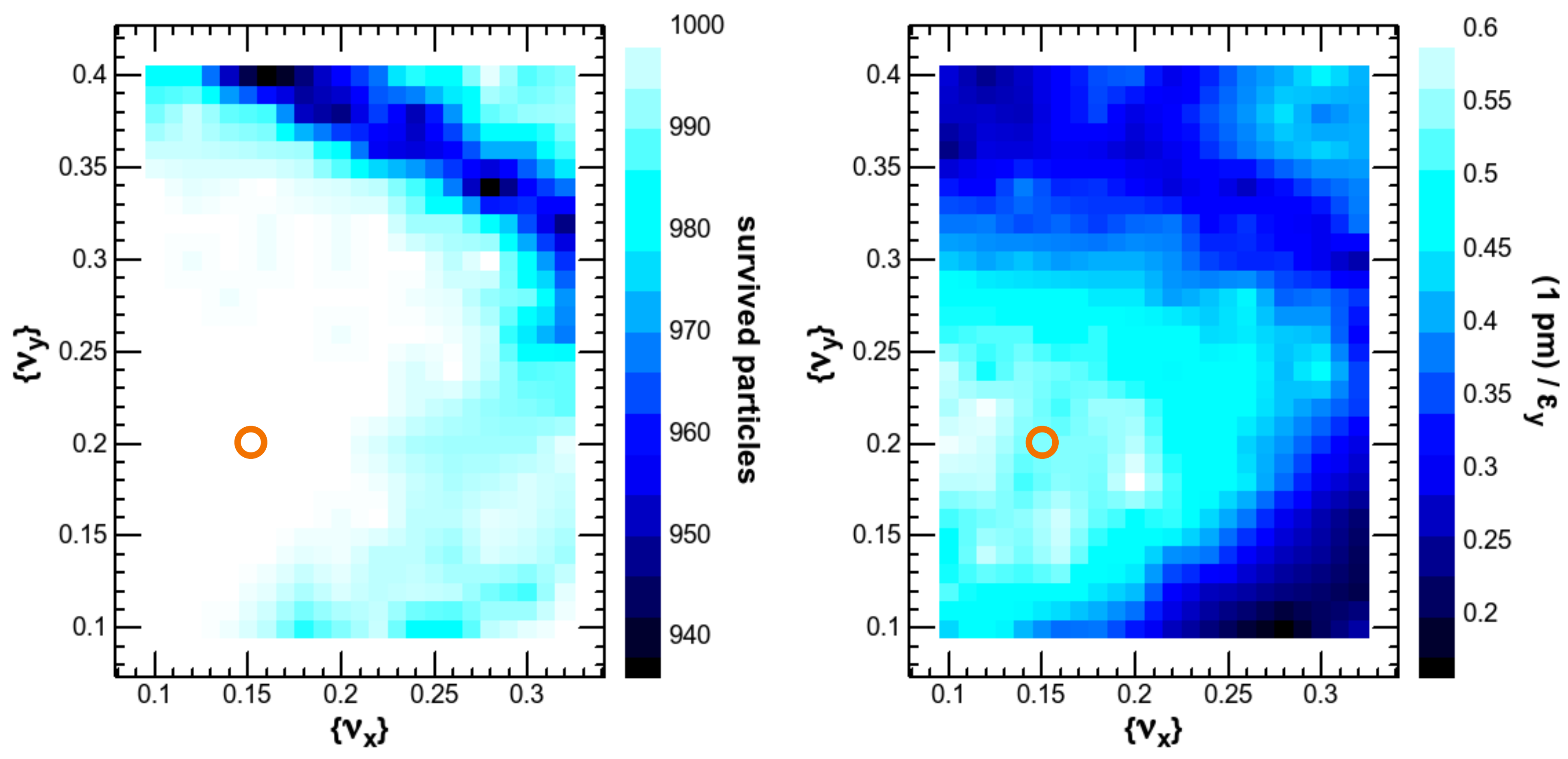
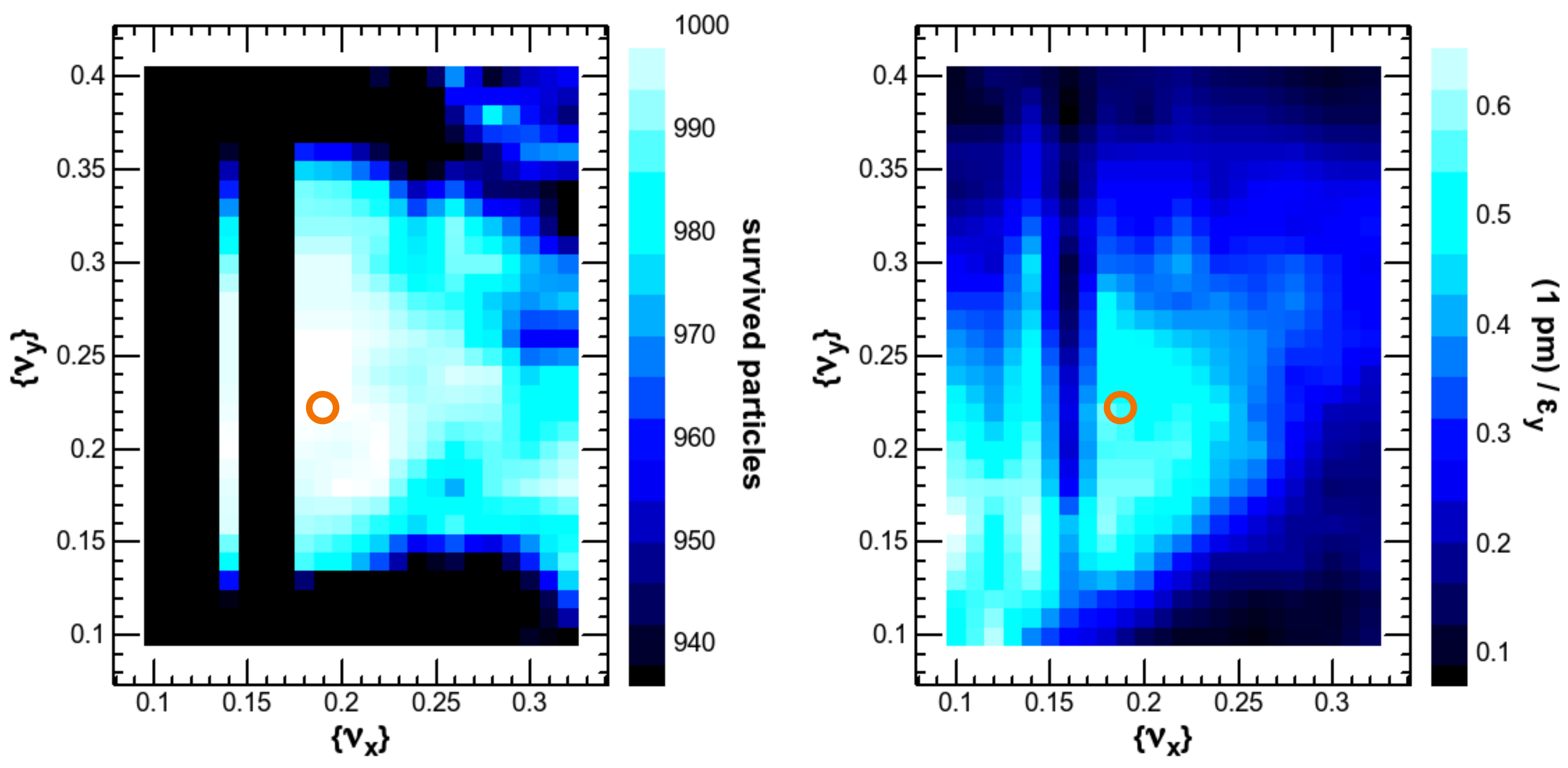
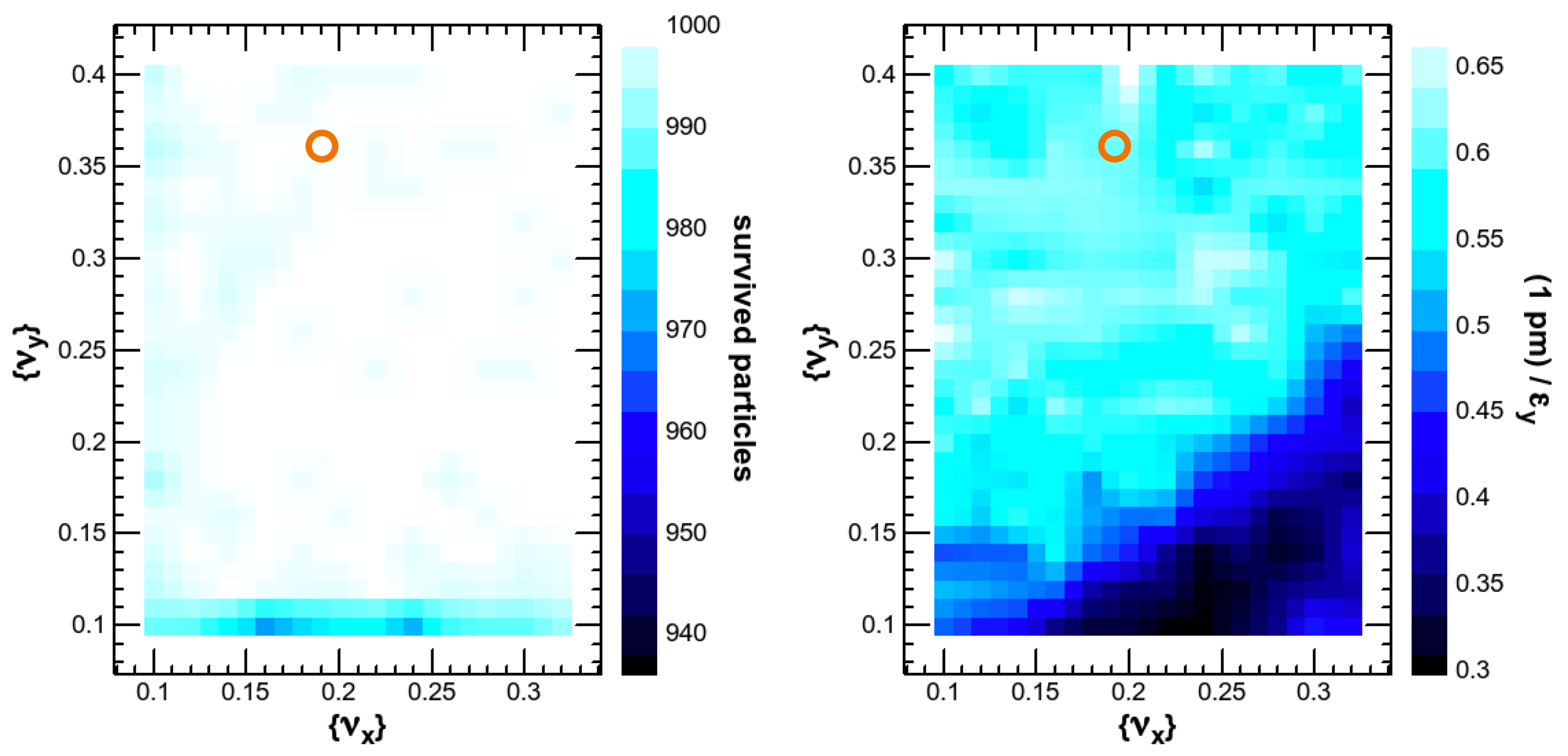
FCCee_z_566_nosol_4_ts
N = 1.51x10^{11}, Crab waist = 70%,
$\beta^*_{x,y}$ = {.11 m, .7 mm}, ν_z = -.02867, $\varepsilon_{y,\mathrm{lattice}}$ = .99936 pm



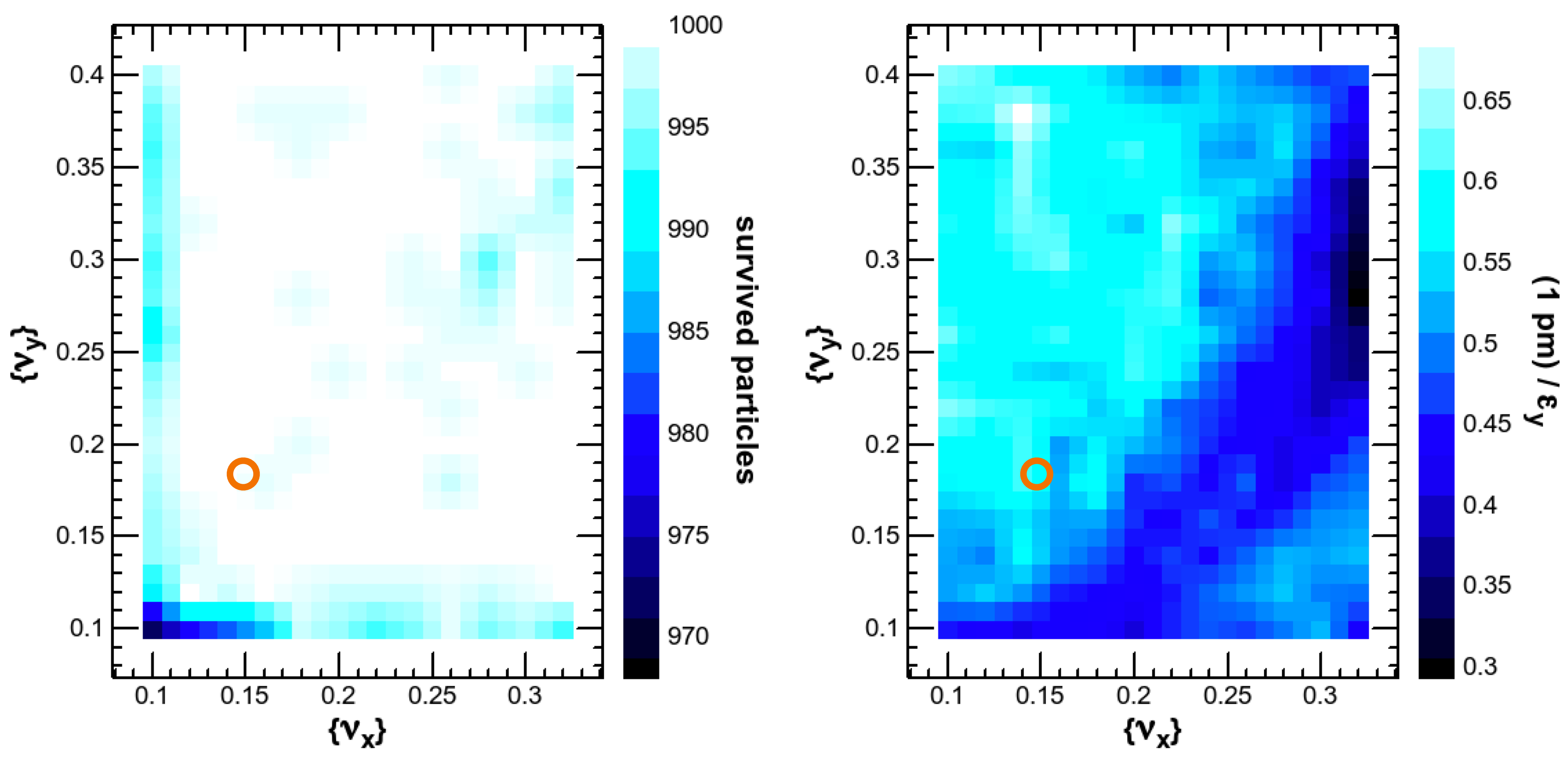
FCCee_w_566_nosol_ts
N = 1.45x10^{11}, Crab waist = 55%,
$\beta^*_{x,y}$ = {.22 m, 1 mm}, ν_z = -.08101, $\varepsilon_{y,\mathrm{lattice}}$ = 1.00046 pm



FCCee_h_565_nosol_7_ts
N = 1.15x10^{11}, Crab waist = 50%,
$\beta^*_{x,y}$ = {.24 m, 1 mm}, ν_z = -.03123, $\varepsilon_{y,\mathrm{lattice}}$ = 1.00490 pm

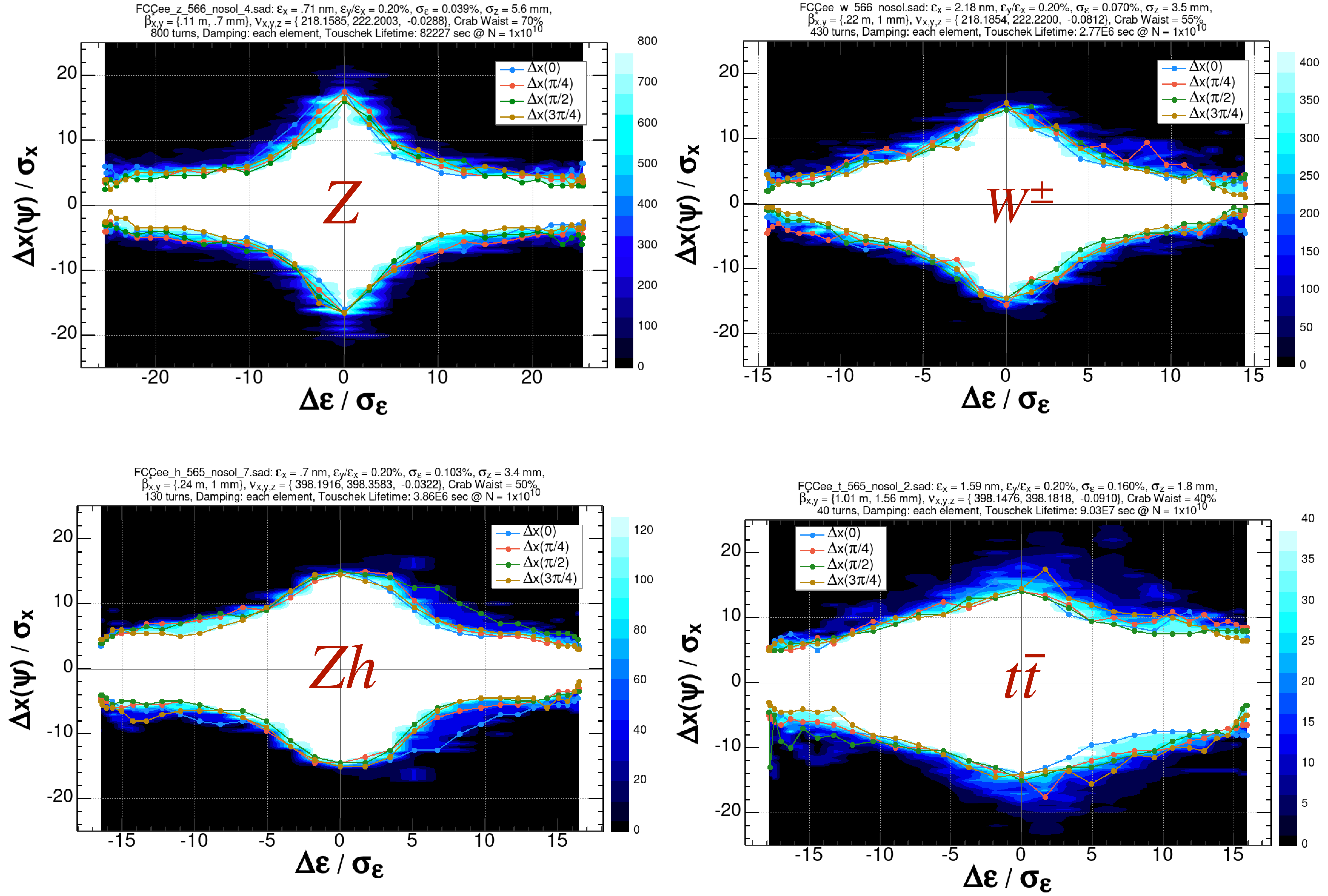


FCCee_t_565_nosol_2_ts
N = 1.55x10^{11}, Crab waist = 40%,
$\beta^*_{x,y}$ = {1.01 m, 1.56 mm}, ν_z = -.08966, $\varepsilon_{y,\mathrm{lattice}}$ = 1.08717 pm



- 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*)



- 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	[$10^{34}/\mathrm{cm}^2\mathrm{s}$]	140	20	5.0	1.25
Luminosity / IP (CDR, 2 IP)	[$10^{34}/\mathrm{cm}^2\mathrm{s}$]	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.

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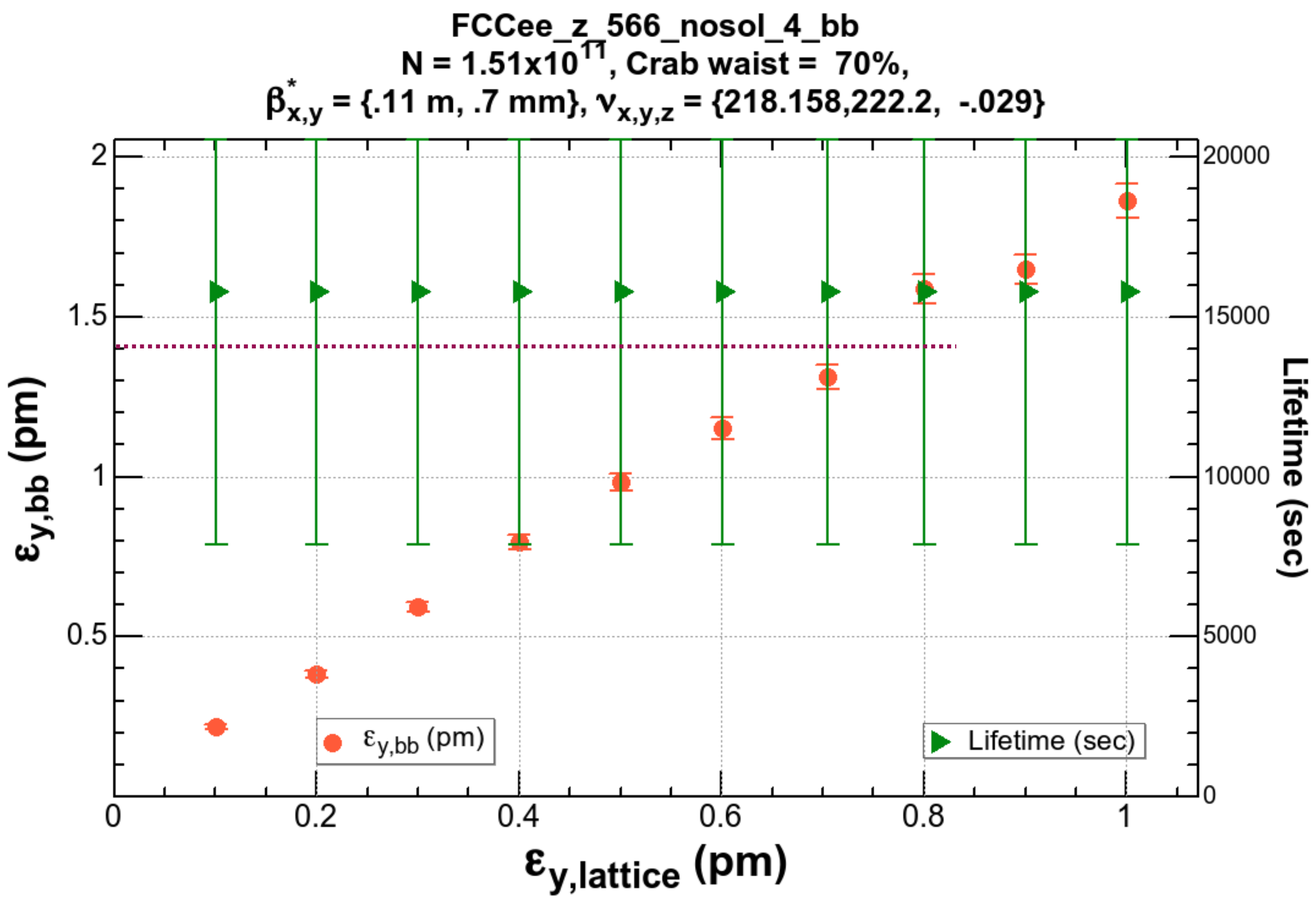
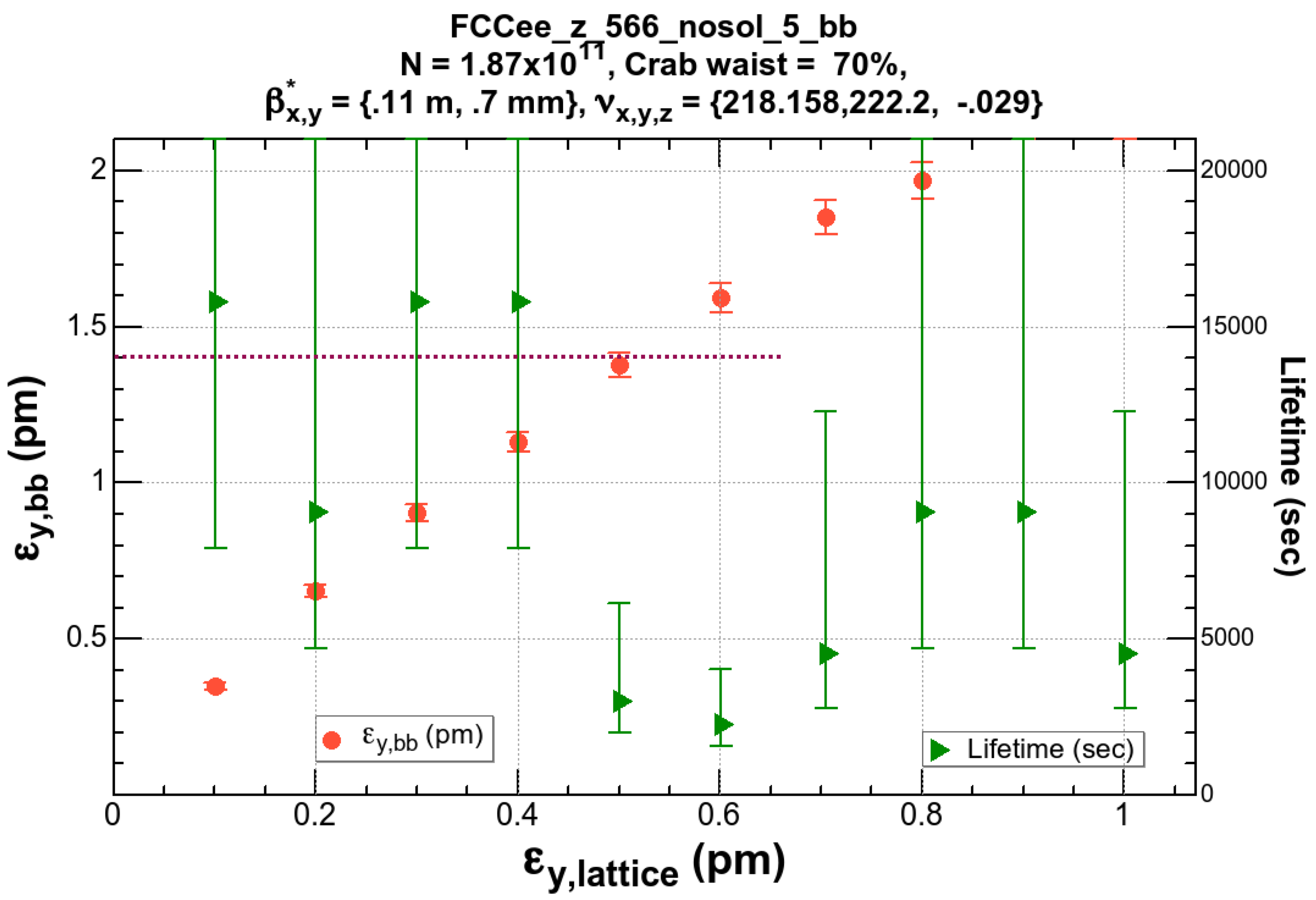
If we push the luminosity further ($@Z$)…



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



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

- 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…

2 IP/4 IP @Z

Table 1: FCC-ee collider parameters for Z as of Apr. 25, 2023.

Beam energy	[GeV]	45.6	
Layout		PA31-3.0	
# of IPs		4	2
Circumference	[km]	90.658816	
Bending radius of arc dipole	[km]	9.936	
Energy loss / turn	[GeV]	0.0394	
SR power / beam	[MW]	50	
Beam current	[mA]	1270	
Colliding bunches / beam		15880	12000
Colliding bunch population	[10^{11}]	1.51	2.00
Horizontal emittance at collision ε_x	[nm]	0.71	
Vertical emittance at collision ε_y	[pm]	1.4	
Lattice vertical emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.75	0.8
Arc cell		Long 90/90	
Momentum compaction α_p	[10^{-6}]	28.6	
Arc sextupole families		75	
$\beta^*_{x/y}$	[mm]	110 / 0.7	
Transverse tunes $Q_{x/y}$		214.158 / 214.200	
Chromaticities $Q'_{x/y}$		0 / +5	
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.089	0.039 / 0.092
Bunch length (SR/BS) σ_z	[mm]	5.60 / 12.7	5.60 / 13.1
RF voltage 400/800 MHz	[GV]	0.079 / 0	
Harmonic number for 400 MHz		121200	
RF freuqeuncy (400 MHz)	MHz	400.786684	
Synchrotron tune Q_s		0.0288	
Long. damping time	[turns]	1158	
RF acceptance	[%]	1.05	
Energy acceptance (DA)	[%]	±1.0	
Beam crossing angle at IP	[mrad]	±15	
Crab waist ratio	[%]	70	
Beam-beam ξ_x/ξ_y [a]		0.0023 / 0.096	0.0029 / 0.124
Lifetime (q + BS + lattice)	[sec]	15000	3000
Lifetime (lum) [b]	[sec]	1340	2090
Luminosity / IP	[10^{34}/cm^{2}s]	140	180

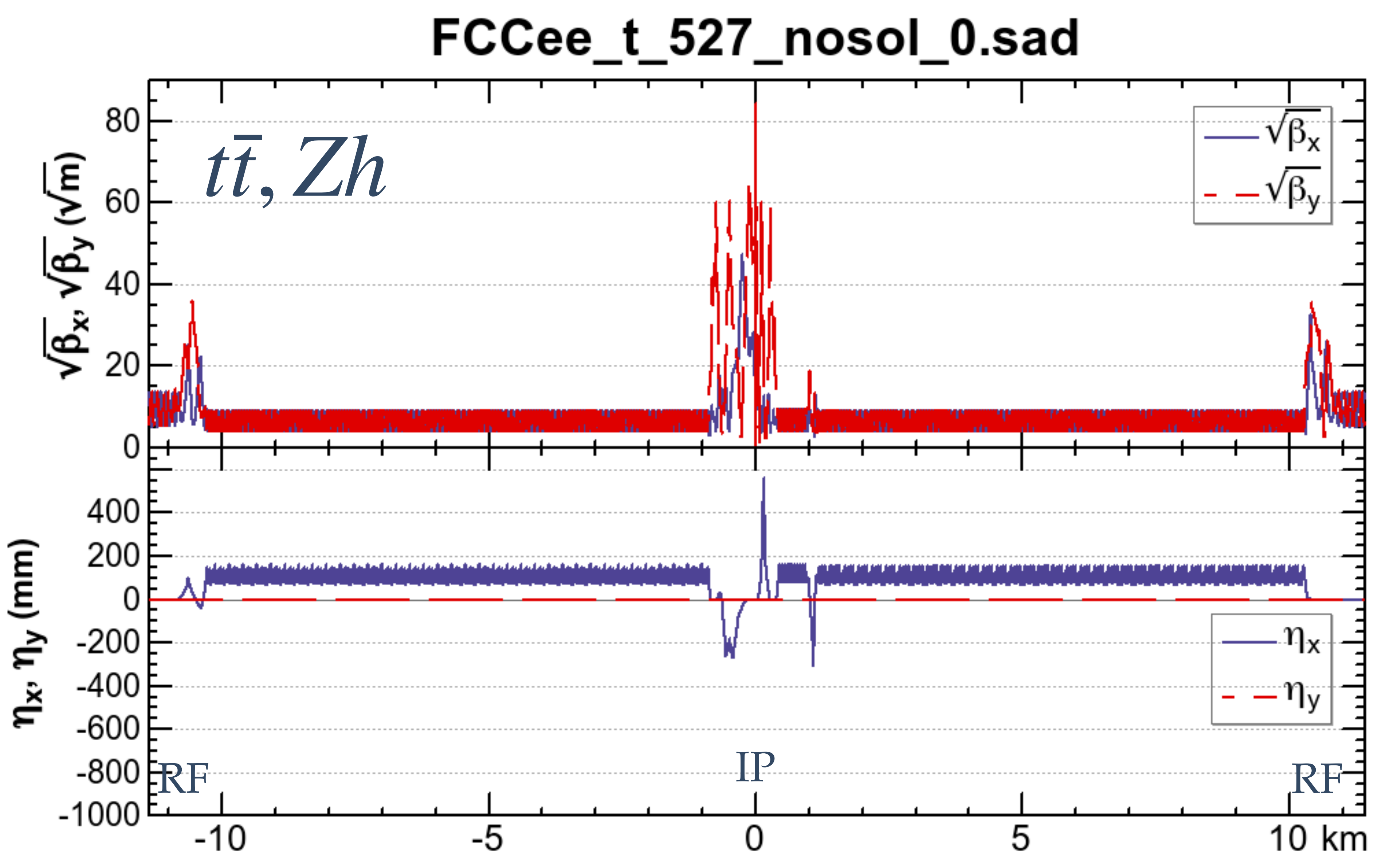
[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section

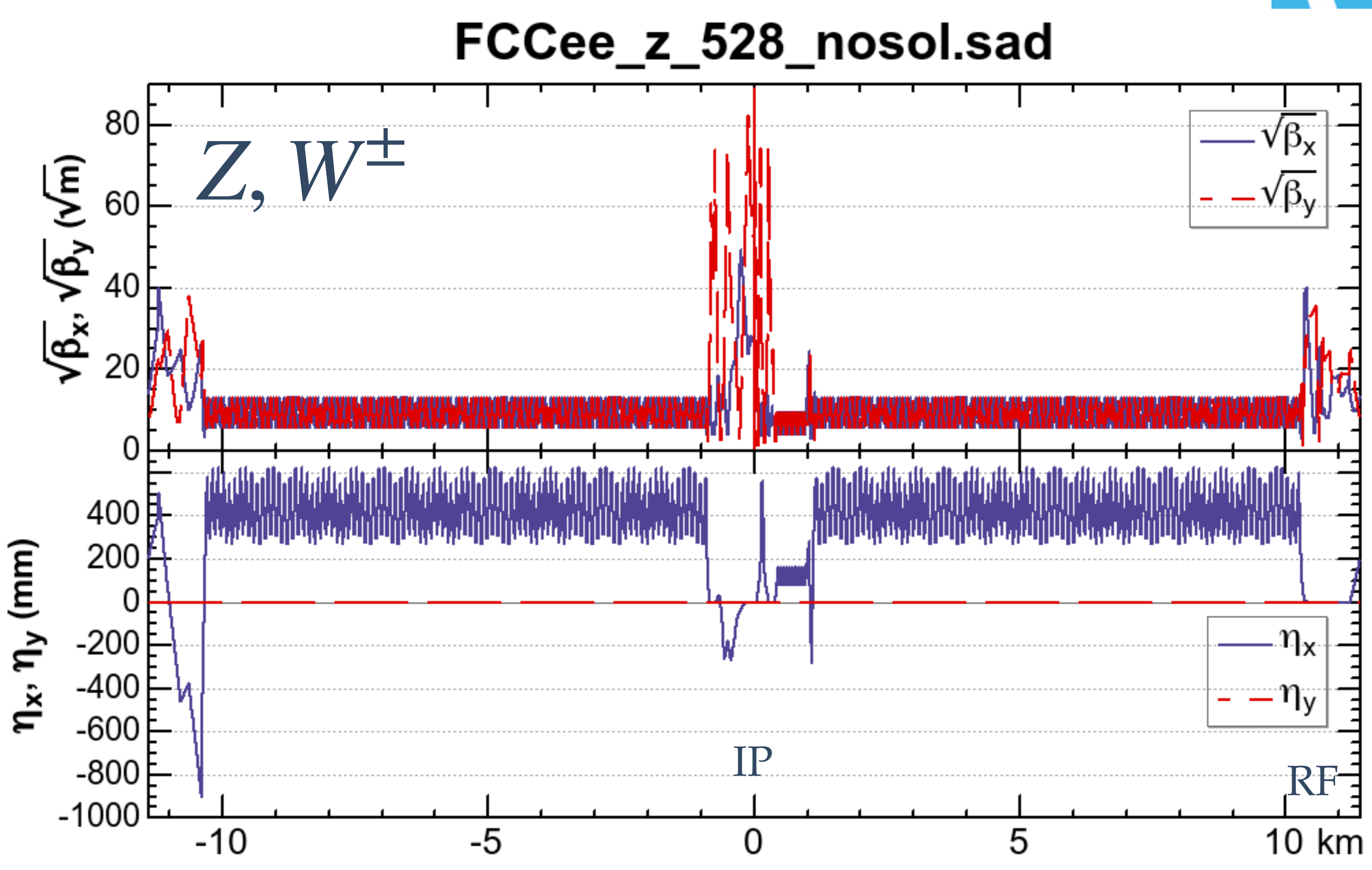
- An example of 2 IP parameters are obtained with the same lattice as the 4 IP, just by turning off the collision alternatively.
- Thus it may not be practical, as at the off-collision IPs, the detectors are still exposed to the beam backgrounds.
- So far a detuned lattice at off-collision IPs has not shown a better lifetime than the 4 IP lattice. It needs more time if this option should be pursued further.
- Luminosity/IP is 29% better than 4 IP in this example due to more damping per IP and higher beam-beam parameter in this example.

Injection time for each specie (20 GeV Linac, 4 IP)

	Z	WW	ZH	tt
Collider energy [GeV]	45.6	80	120	182.5
Collider & BR bunches / ring	16000	1800	450	60
Collider particles / bunch N_b [10^{10}]	15.1	14.5	11.5	15.5
Allowable charge imbalance Δ [±%]	5	3		
Injector particles / bunch $N_{\max}$ [10^{10}]	≦ 4.0			
Bootstrap particles / bunch [10^{10}] $= 2N_b\Delta$	1.51	0.87	0.69	0.93
# of BR ramps (up to 1/2 stored current, with $N_{\max}$)	3	3	3	4
# of BR ramps (bootstrap with $2N_b\Delta$)	4	4	4	4
BR ramp time (up + down) t_{ramp} [s]	0.6	1.5	2.5	4.1
Linac bunches / pulse	2			
Linac pulses needed n_p	8000	900	225	30
Linac repetition frequency [Hz] f_{rep}	200	100	50	
Collider filling time from scratch [s]	**284.2**	**73.5**	**49**	**35.2**
Collider filling time for top-up [s] $= n_p/f_{\text{rep}} + t_{\text{ramp}}$	**40.6**	**10.5**	**7**	**4.7**
Lum. lifetime (4 IP) [s]	1340	970	840	730
Lattice+BS lifetime (4 IP) [s]	15000	4000	6000	6000
(real lattice lifetime)/(design lattice lifetime)	0.25	0.25	0.25	0.25
Collider lifetime (4 IP) τ_2 [s]	987.2	492.4	538.5	491.0
Collider top-up interval (between e+ and e-)(4 IP) [s] $= \tau_2\Delta$	**49.4**	**14.8**	**16.2**	**14.7**

Ring optics (1/4 ring)





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

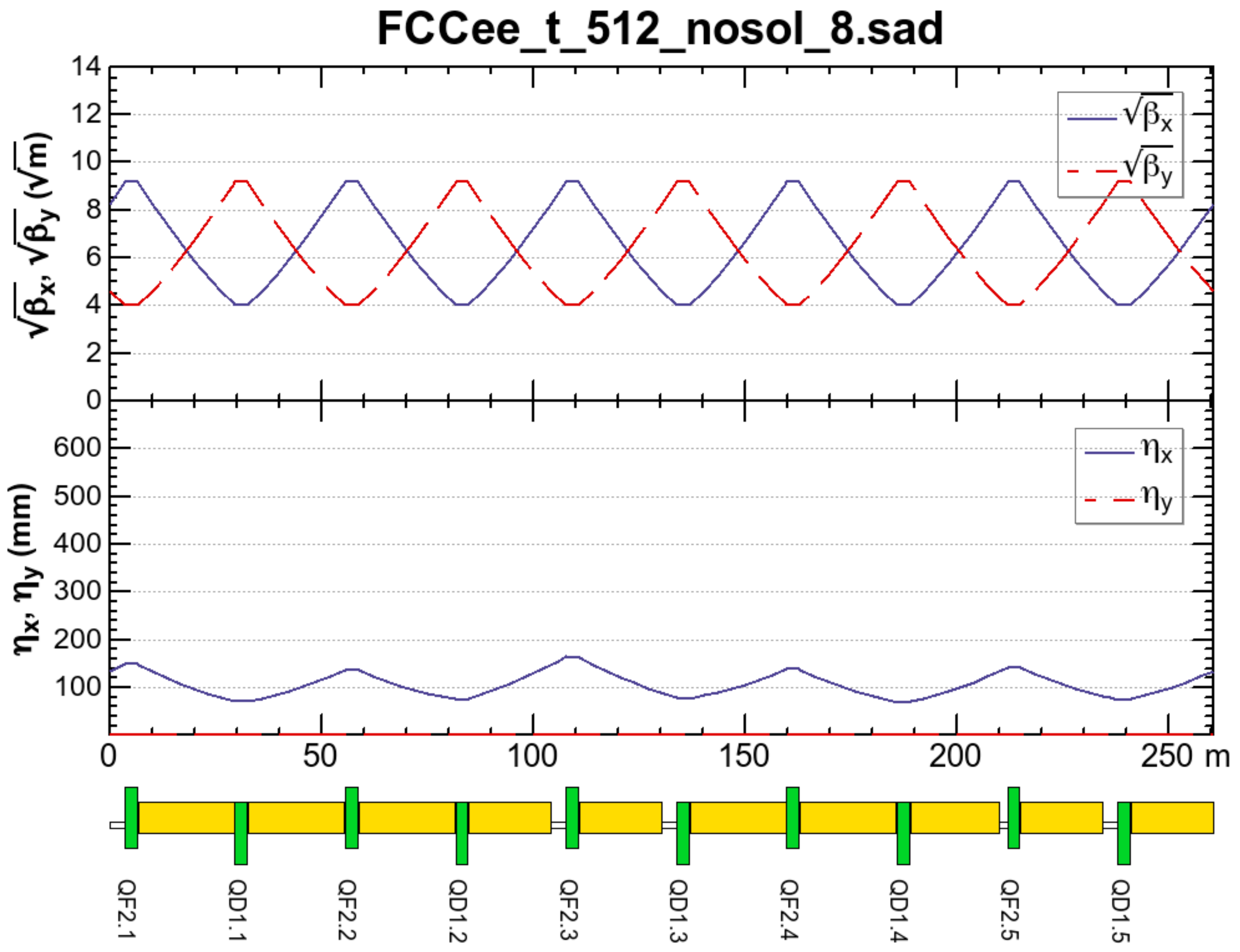
90 Long 90/90 FODO cells / arc.
8 arcs / ring

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

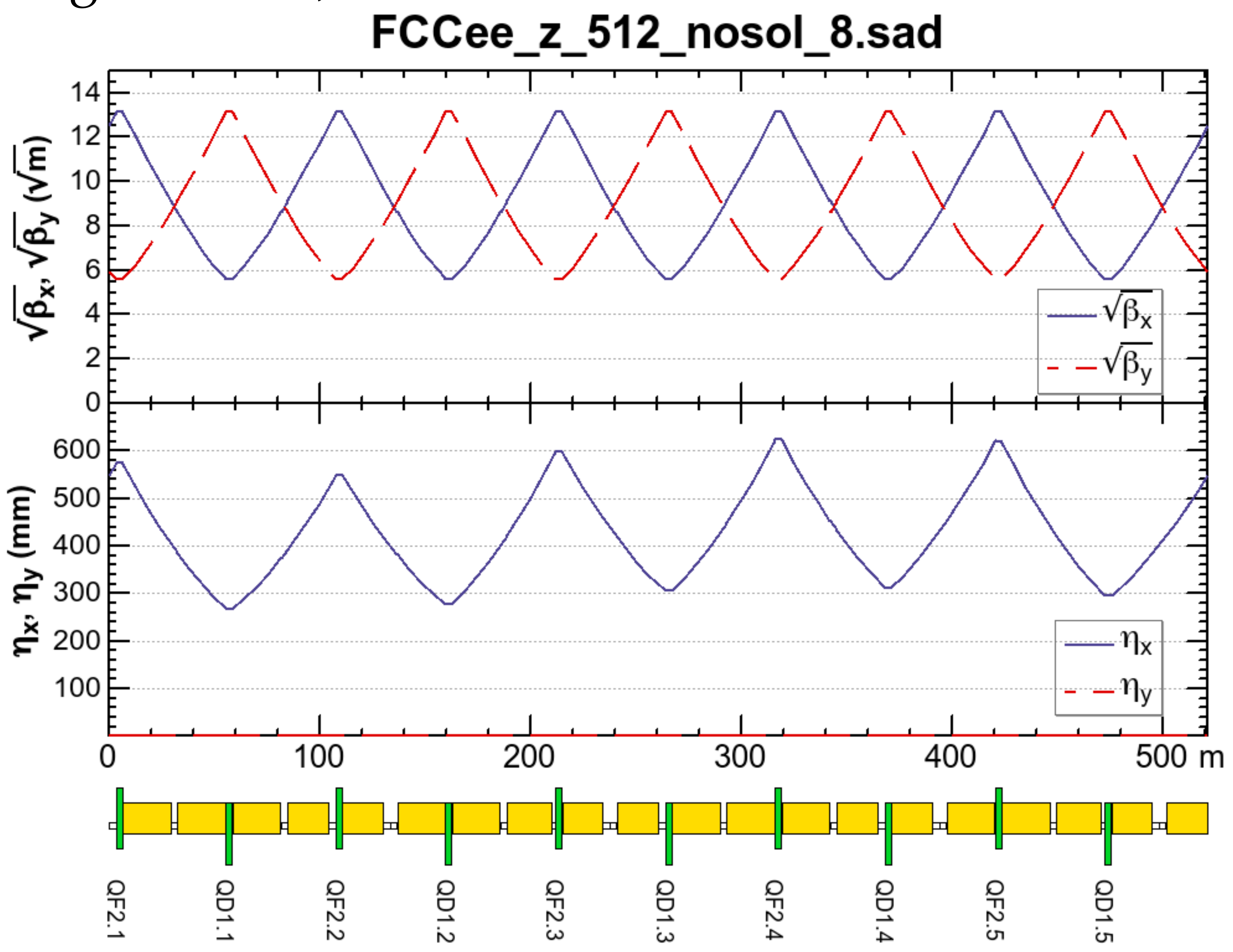
The beam optics shown here and later are not always the latest ones in details.

The arc cell optics (1 period = 5 FODOs)

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



Long 90/90: Z, W

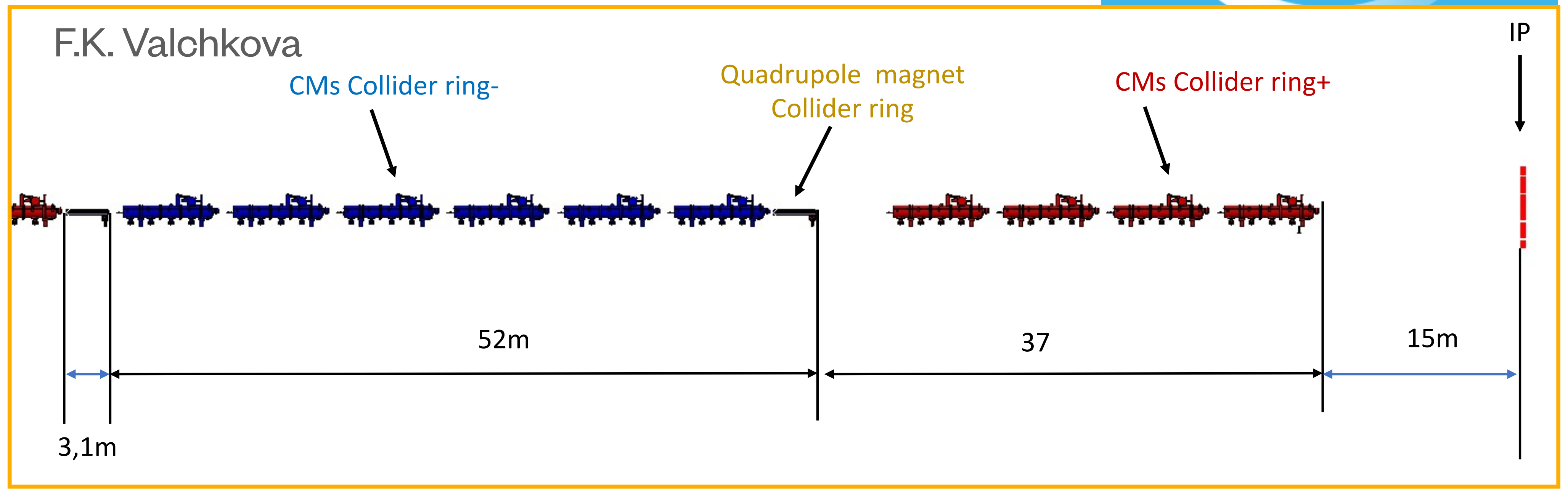


- For long 90/90:
  - The QDs for short 90/90 of the outer ring are turned off.
    - However, their BPMs and correctors are usable for additional orbit/optics correction power.
  - The polarity of QFs for short 90/90 are reversed alternatively to serve as QDs. These should have an easy mechanism in 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.

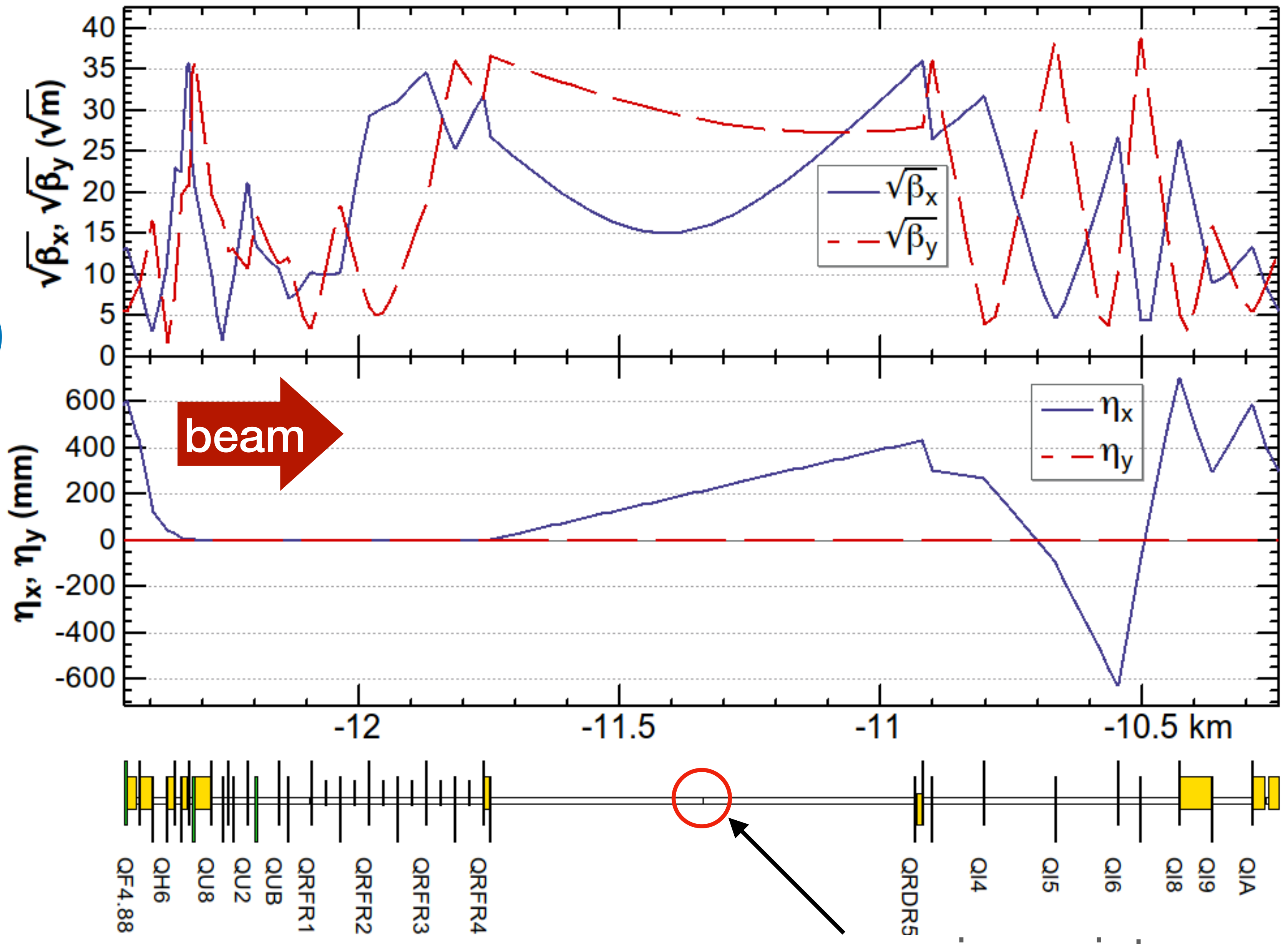
Layout in long straight sections BFHL

- 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.



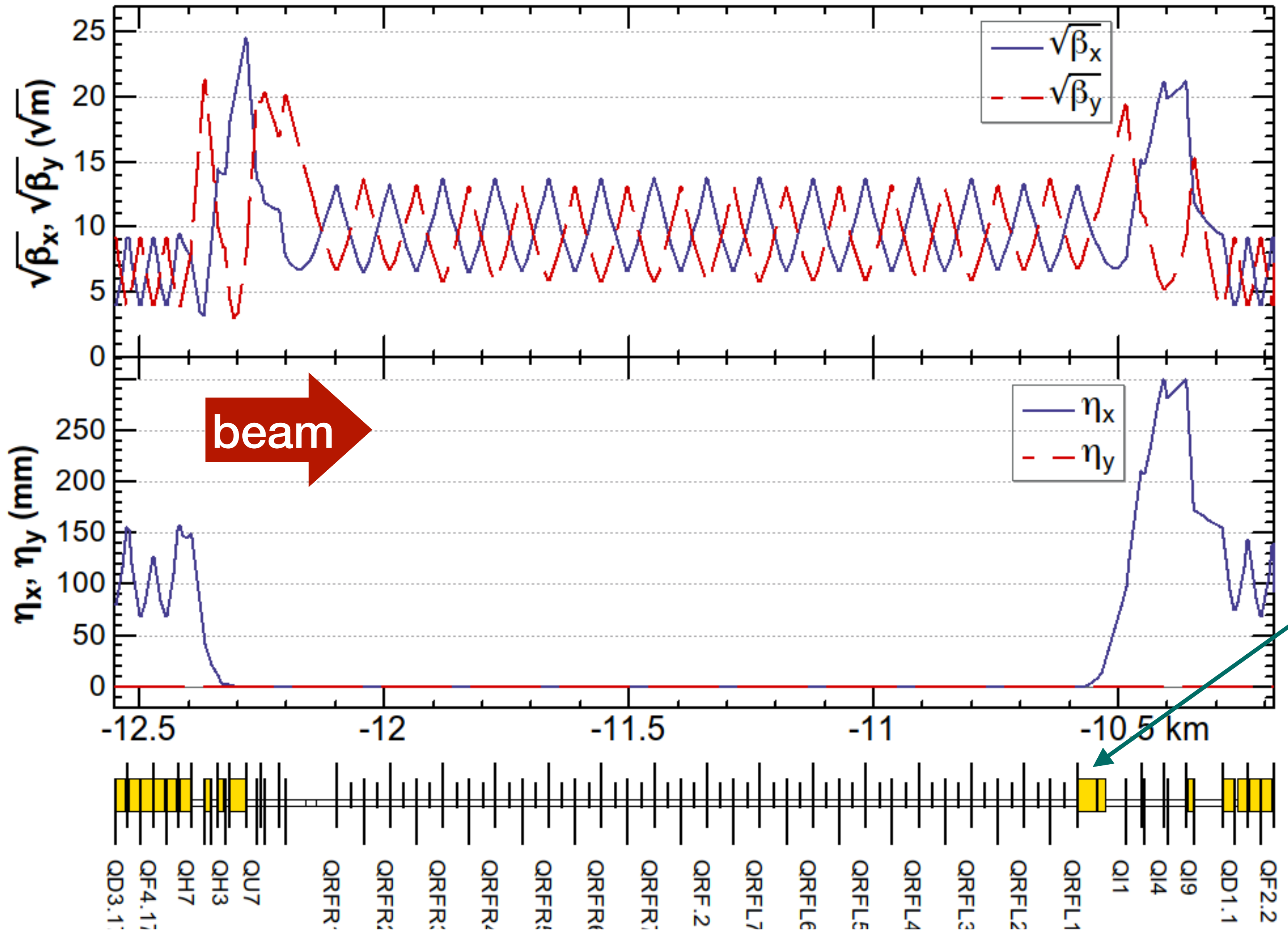
The beam optics shown here and later are not always the latest ones in details.

Z/W, Zh/tt (no RF)



RF (single beam)

Zh/tt (RF)

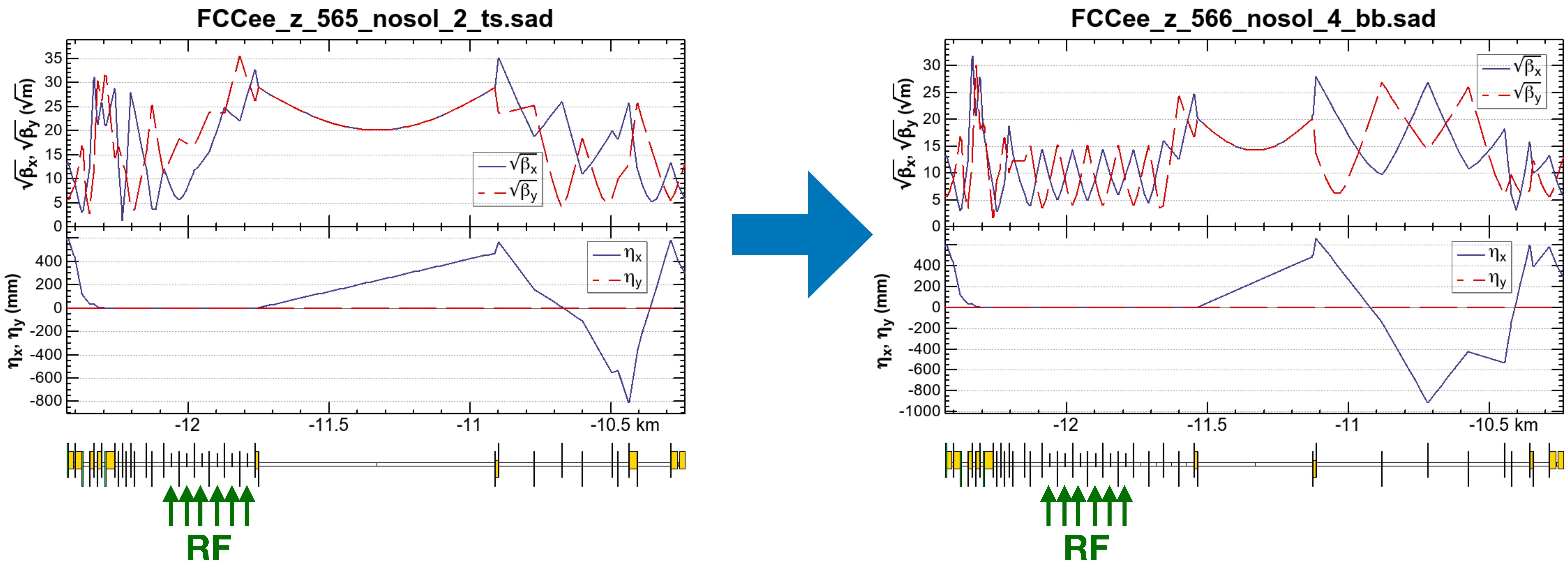


Separator; combination of electrostatic & magnetic

Only outgoing beam is deflected

RF cryomodules common to e+e-

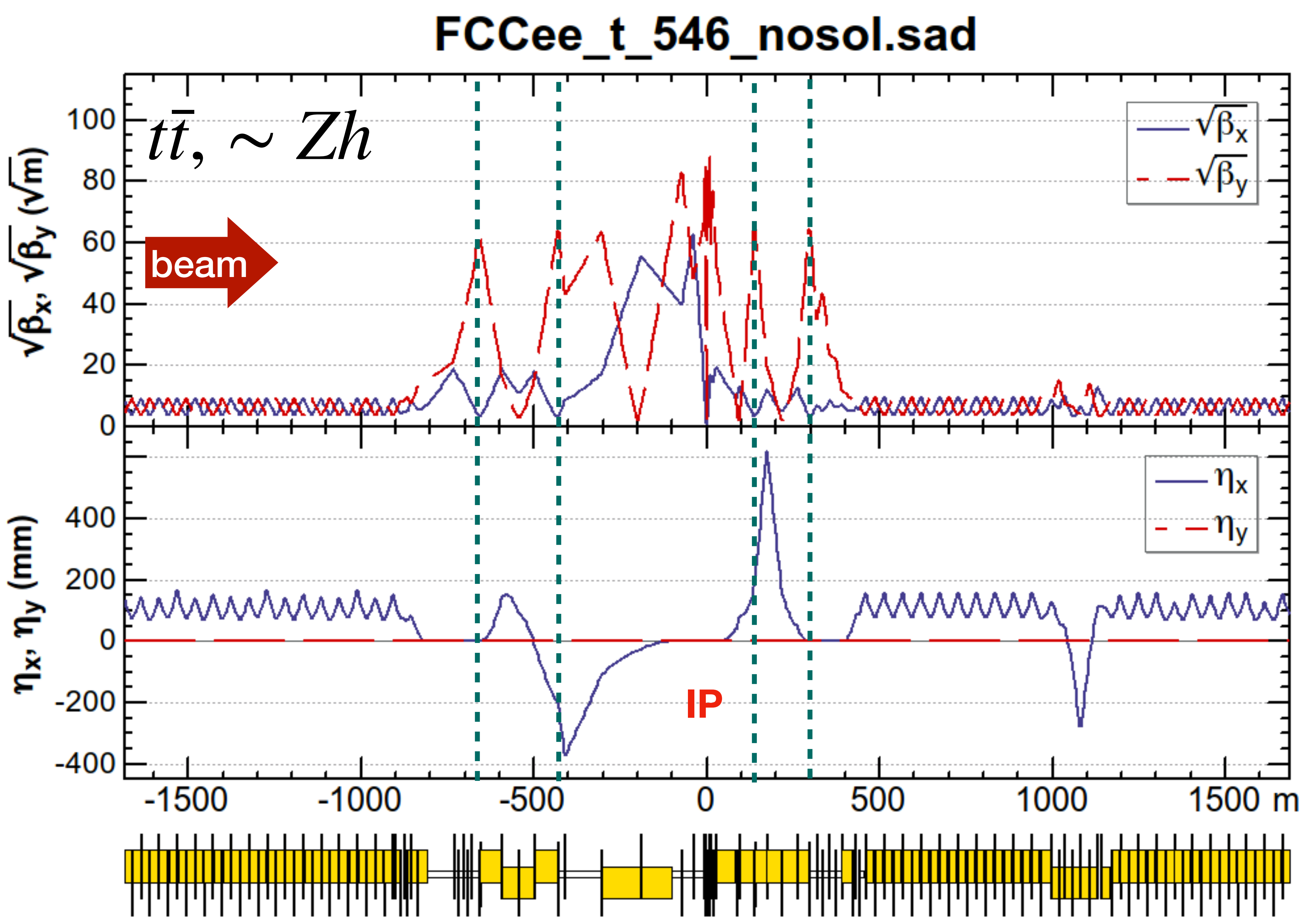
Modification of the crossing section (LLSS)



- 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.

IR optics (SLSS ADGJ)

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



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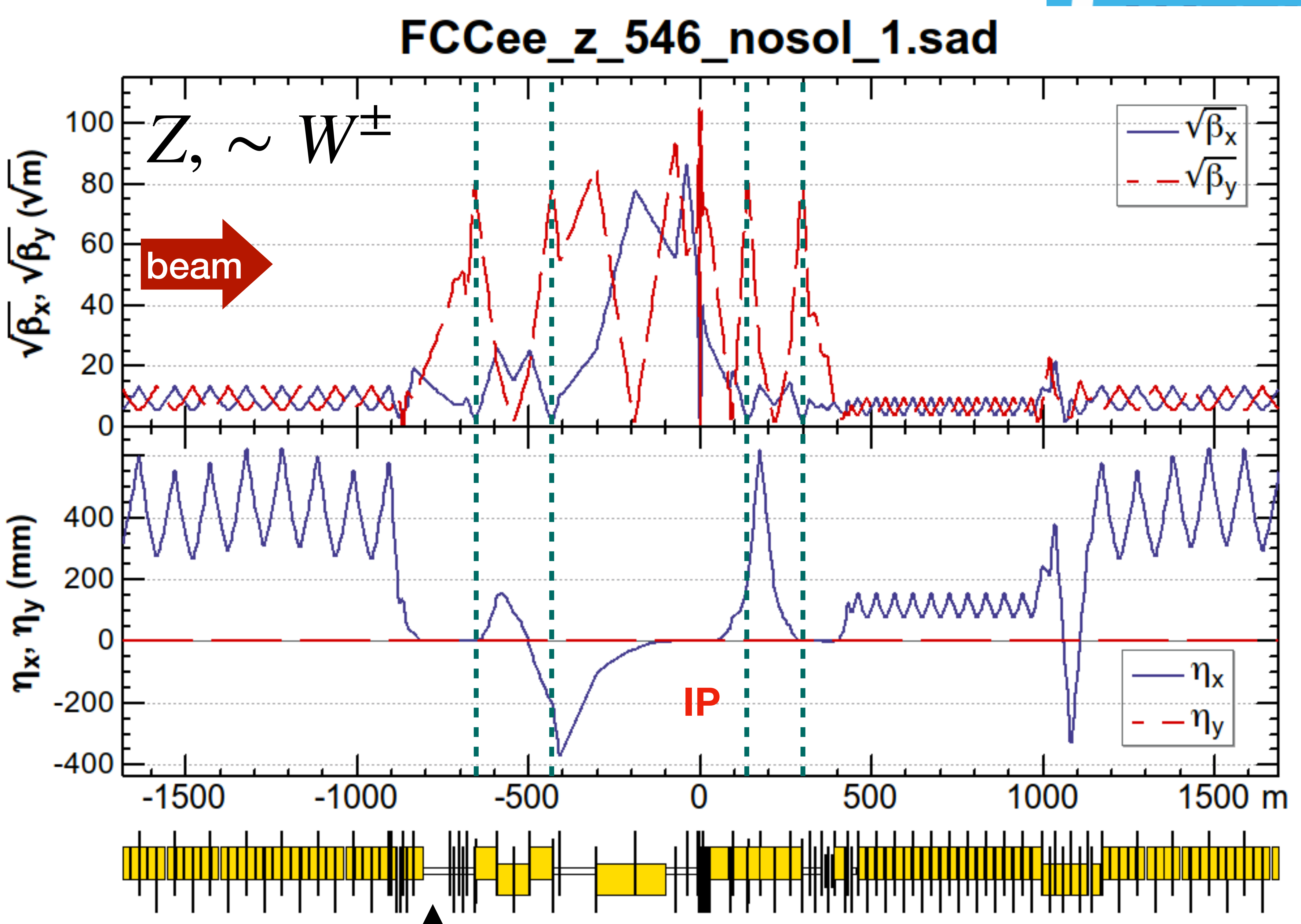
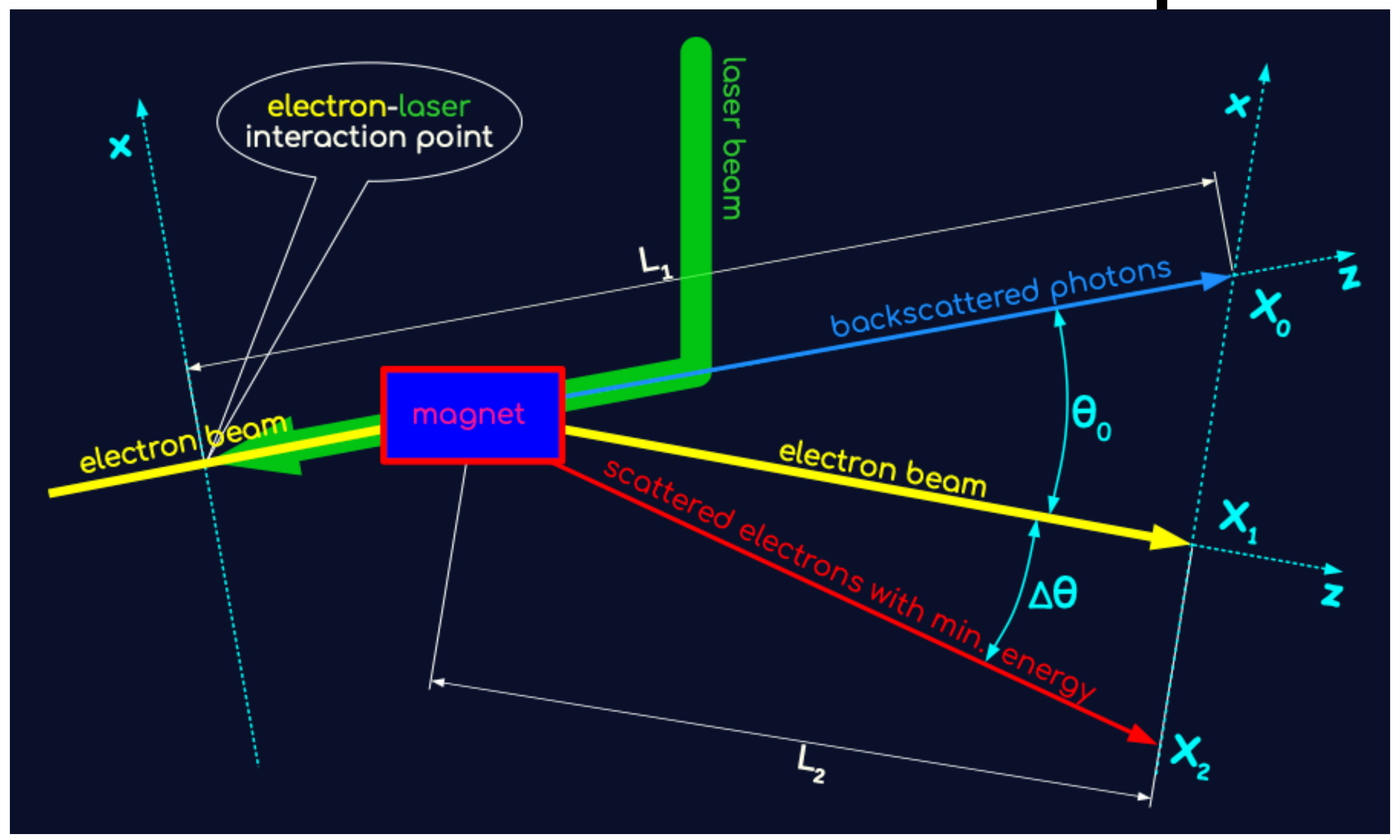
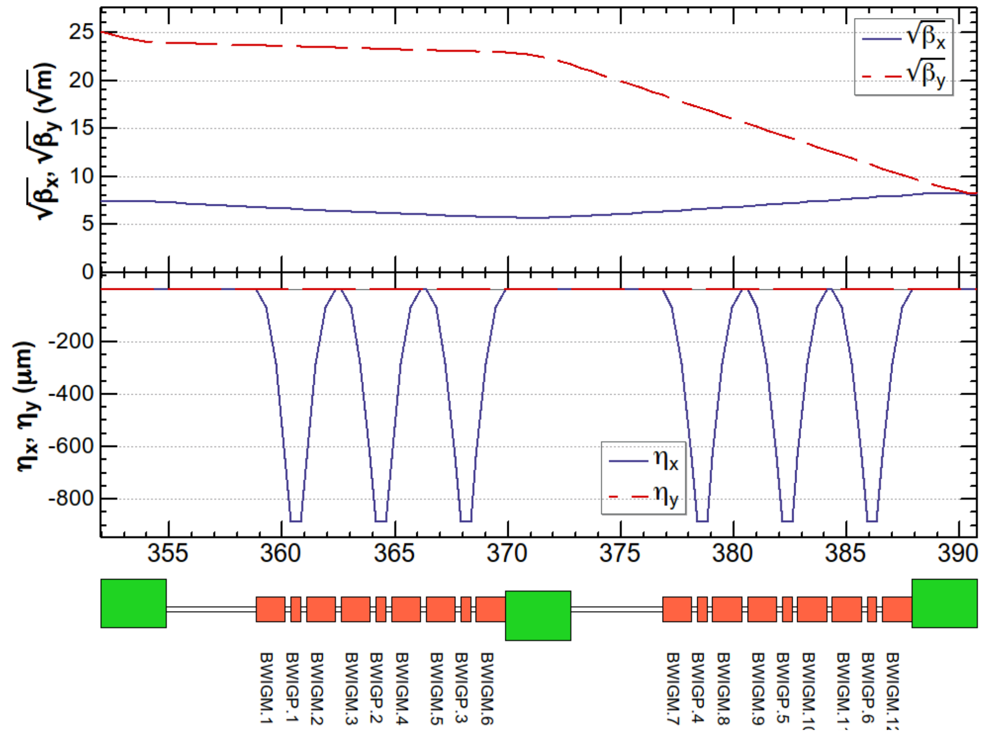


polarimeter
N. Muchnoi

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).

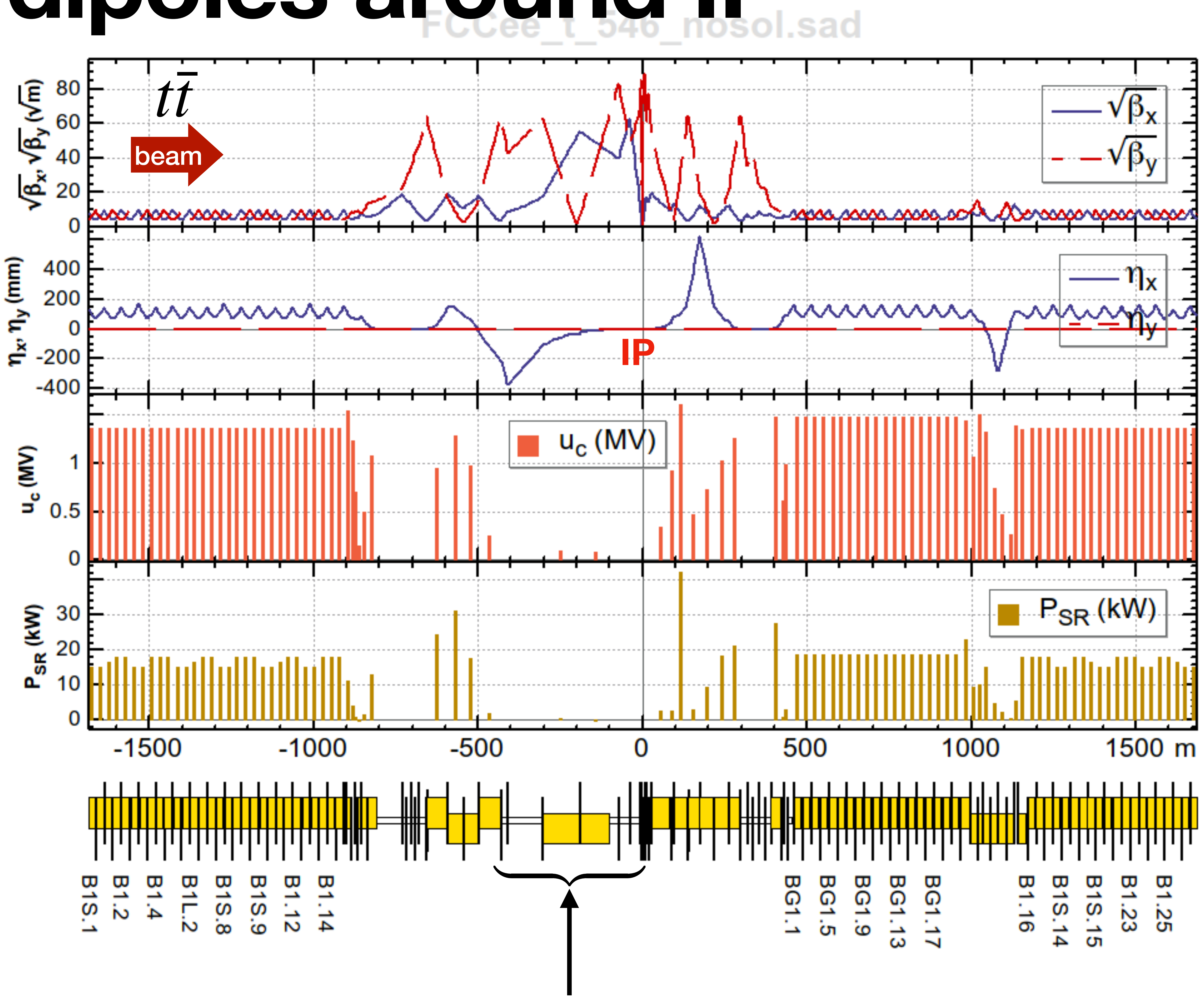




https://indico.cern.ch/event/1181966/contributions/5046175/attachments/2511830/4317657/muchnoi.pdf

June 6, 2023, K. Oide

SR from dipoles around IP

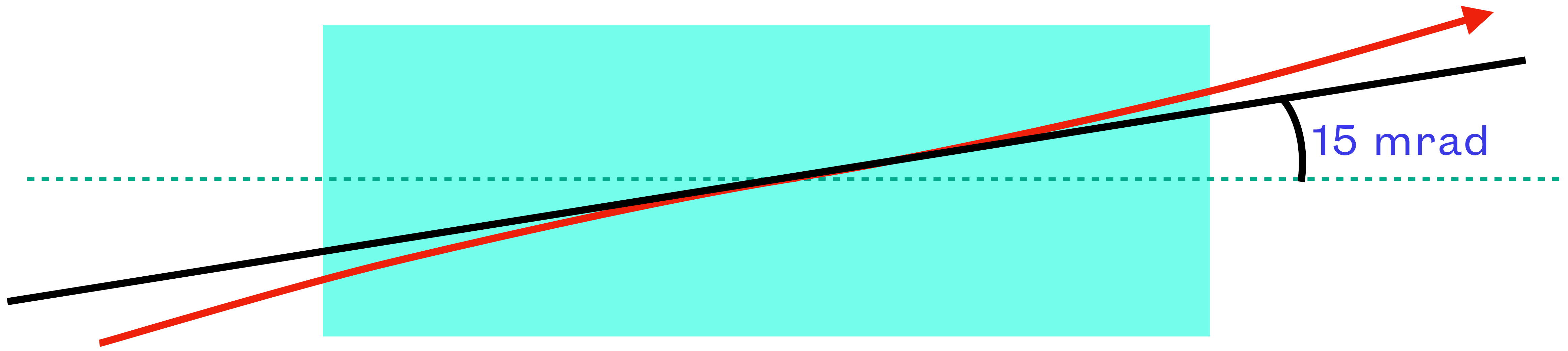


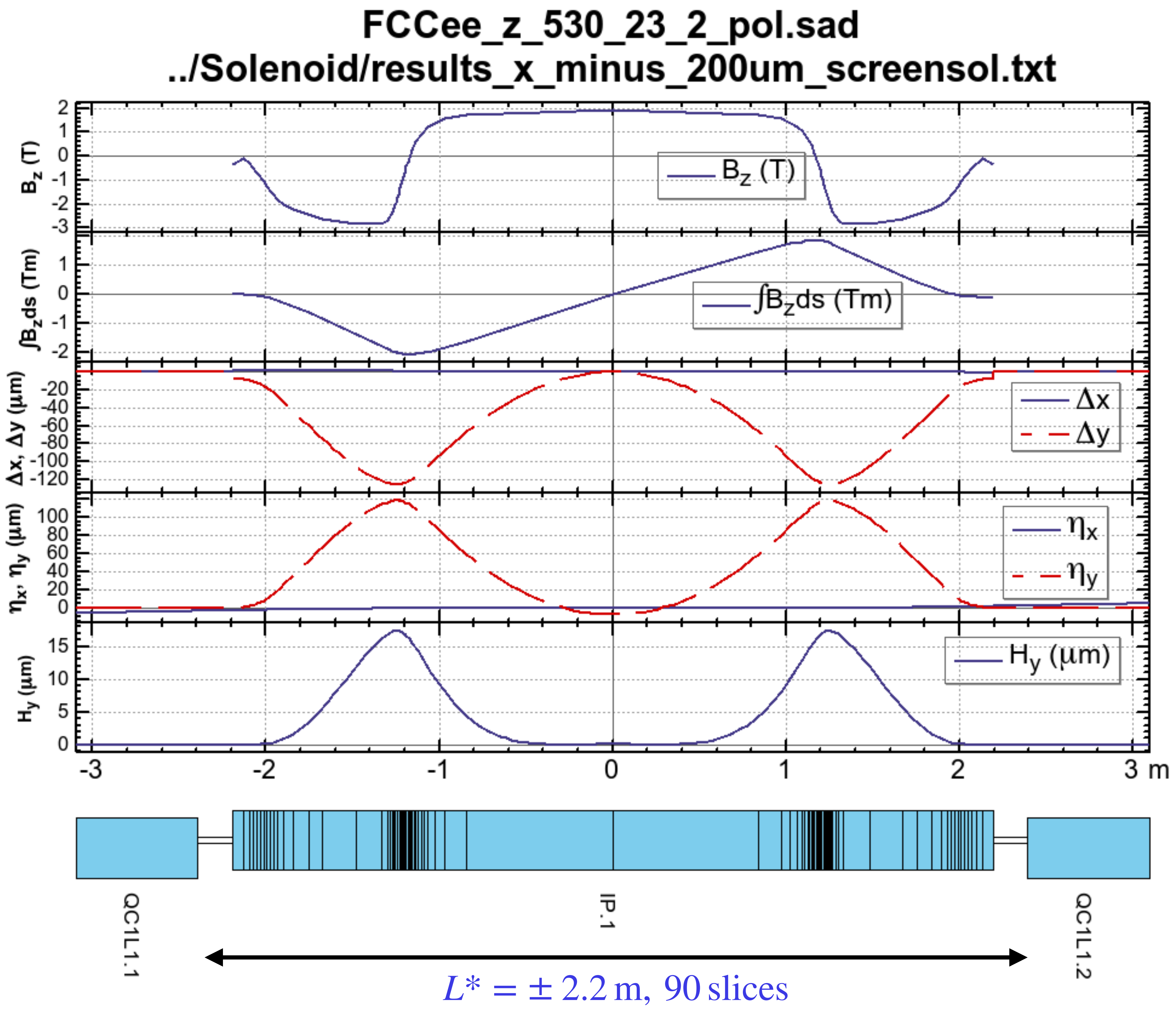
The beam optics shown here and later are not the latest ones in details.

- 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 $t\bar{t}$.

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.





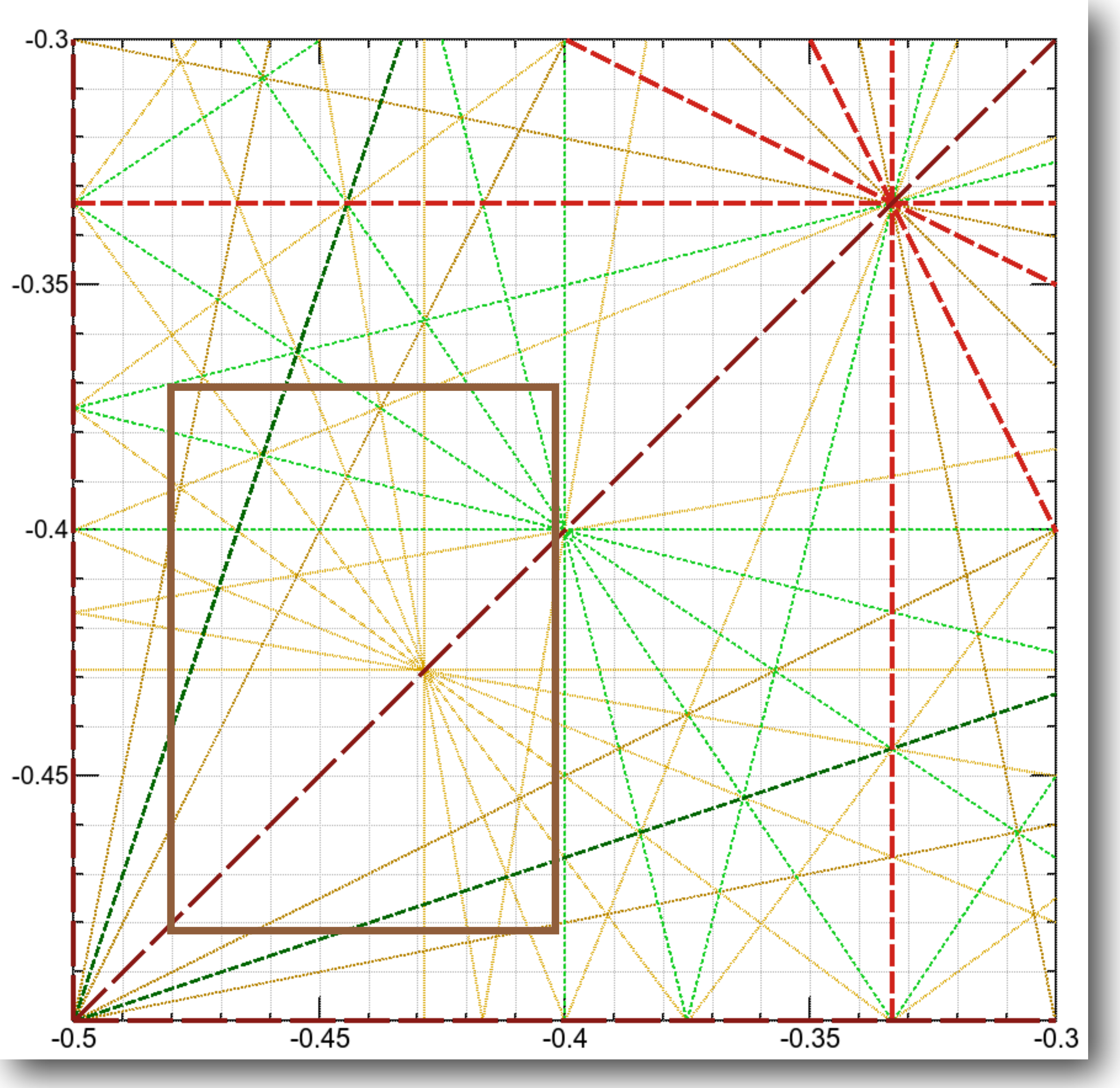
The beam optics shown here and later are not the latest ones in details.

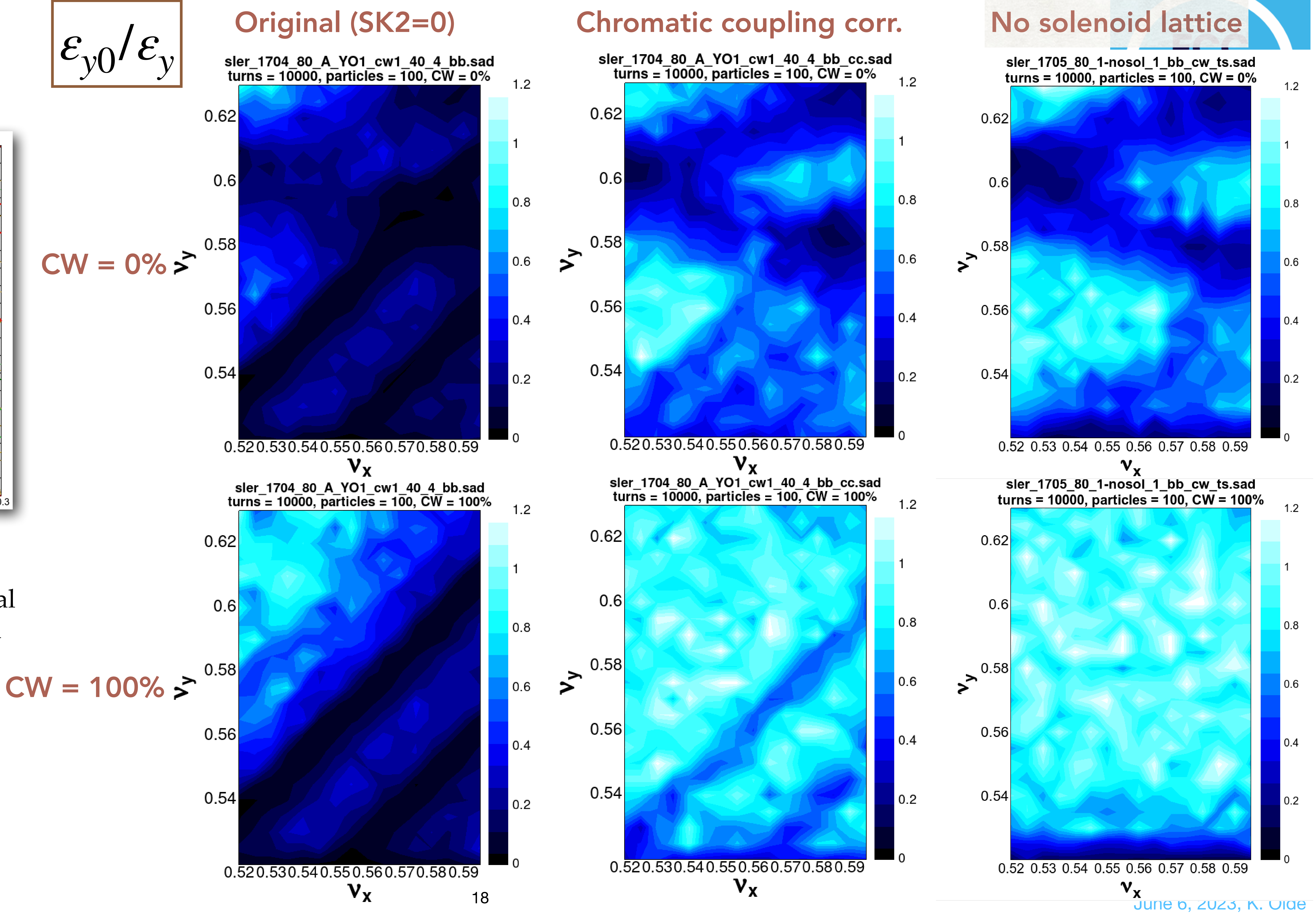
June 6, 2023, K. Oide

FCC WEEK 2023 05 – 09 June

SuperKEKB LER tune survey

$\varepsilon_{y0}/\varepsilon_y$





- 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.

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.
- 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+qiad+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…

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.
- Rough requirements for the injection charge & repetition are estimated.
- Further optimization and modifications are expected on lattice, tunes, $\beta*$, crab waist ratio, bunch charge (ξ_y),…