IR optics design and challenges

K. Oide (UNIGE/CERN/KEK)

Nov. 16, 2023 @ FCCIS MDI and IR mockup workshop @ Frascati

Many thanks to M. Benedikt, M. Boscolo, 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)

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

FUTURE CIRCULAR COLLIDER

CDR

COLLIDER DESIGN AND PERFORMANCE

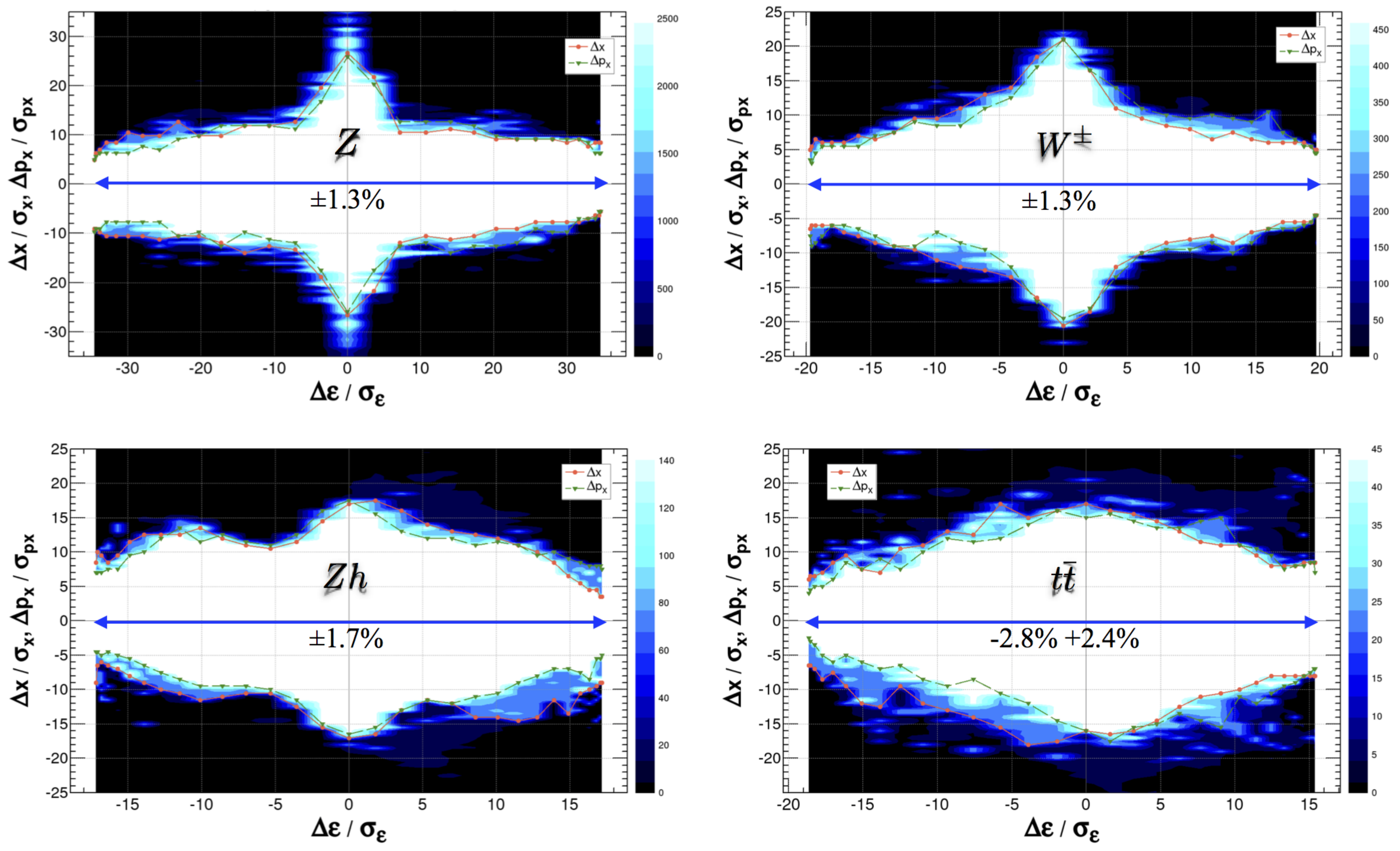
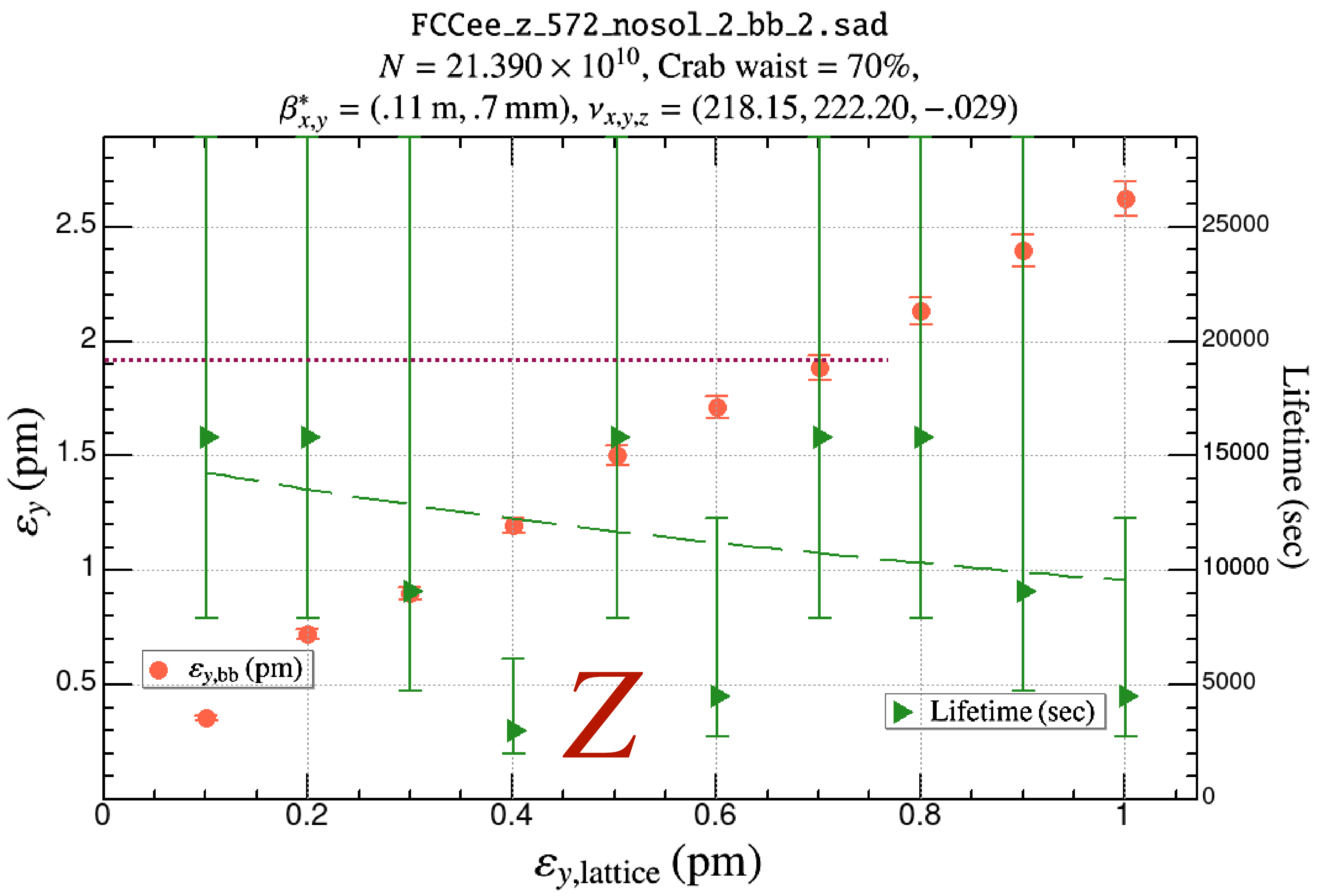
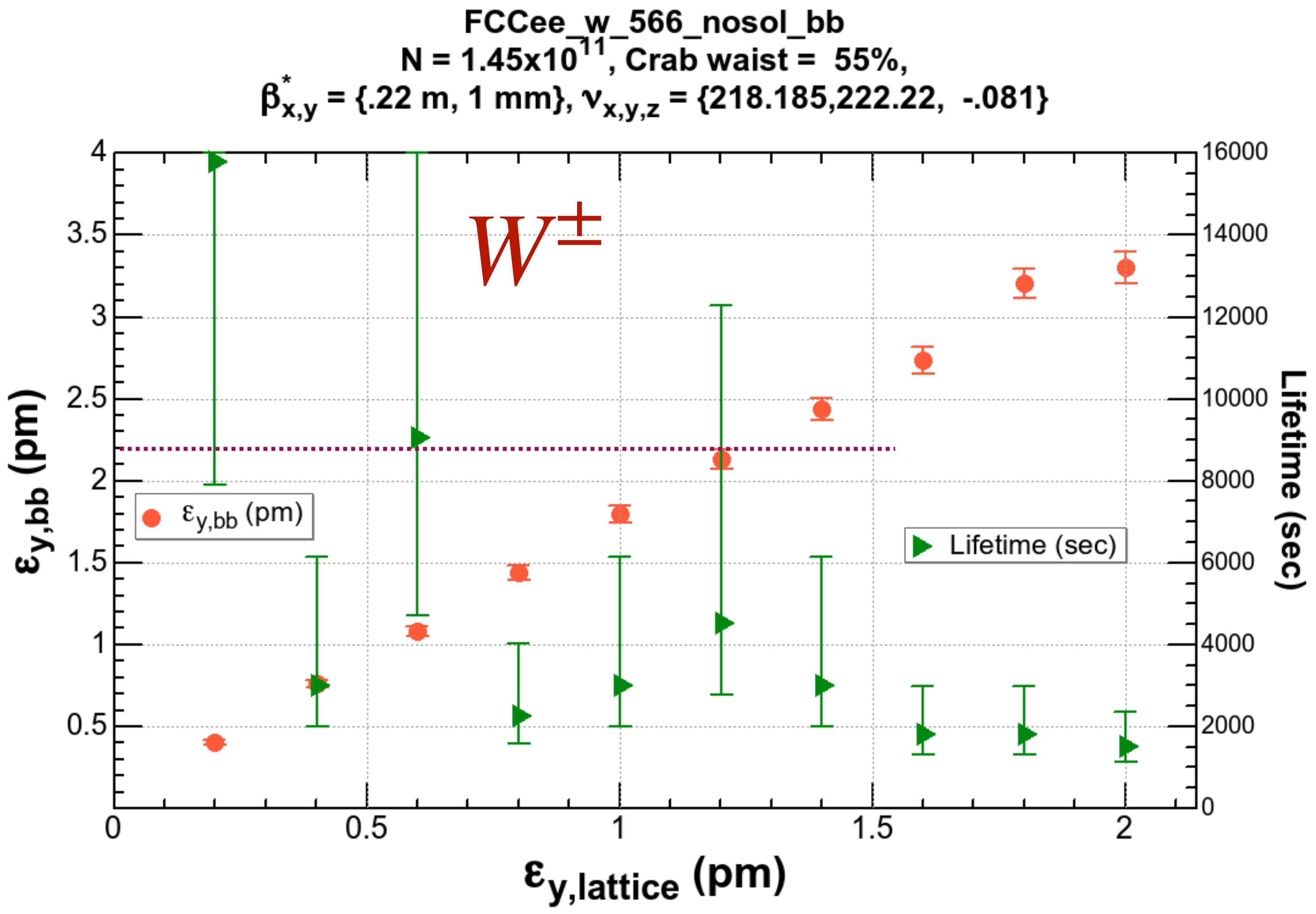


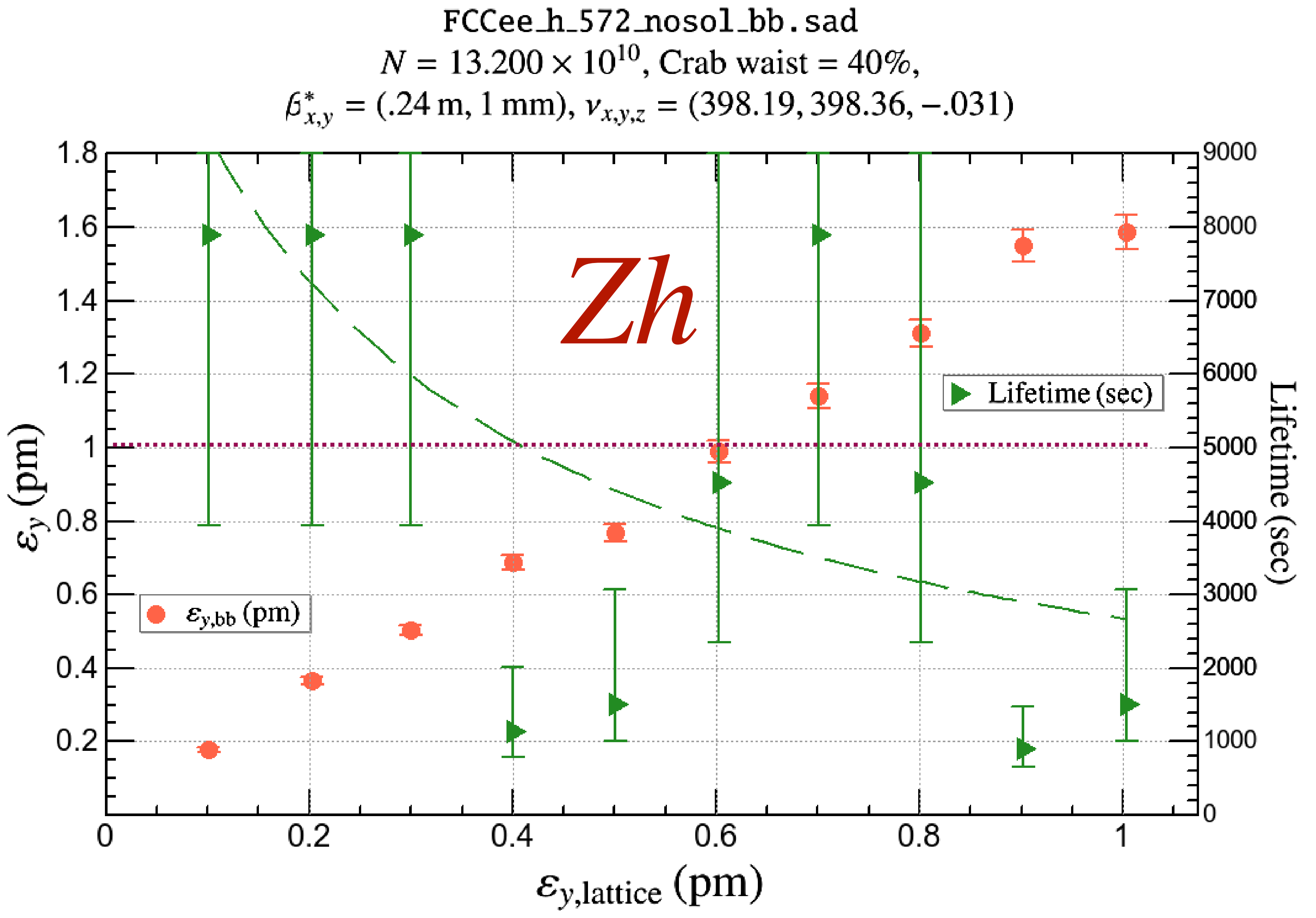
Figure 2.9: Dynamic apertures in z-x plane after sextupole optimisation with particle tracking for each energy. The initial vertical amplitude for the tracking is always set to $J_y/J_x = \varepsilon_y/\varepsilon_x$. The number of turns corresponds to about 2 longitudinal damping times. The resulting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

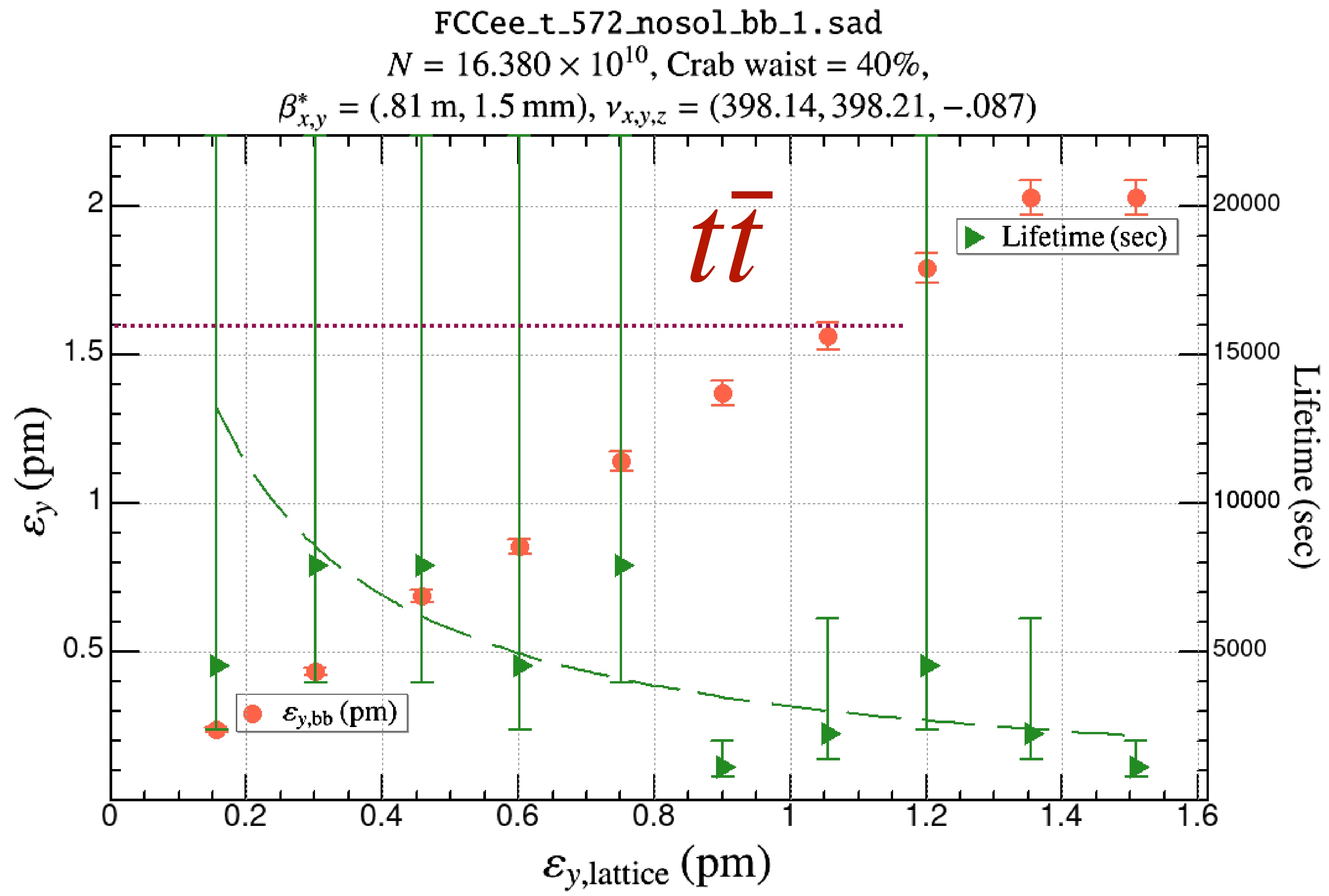
- The lattice dynamic aperture (DA) was optimized to ensure the required momentum acceptance which is estimated by beam-beam (BB) simulations without lattice.
- It has been noticed that the lattice lifetime must be evaluated by itself beyond the DA, esp. at Z with enlarged energy spread by beamstrahlung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







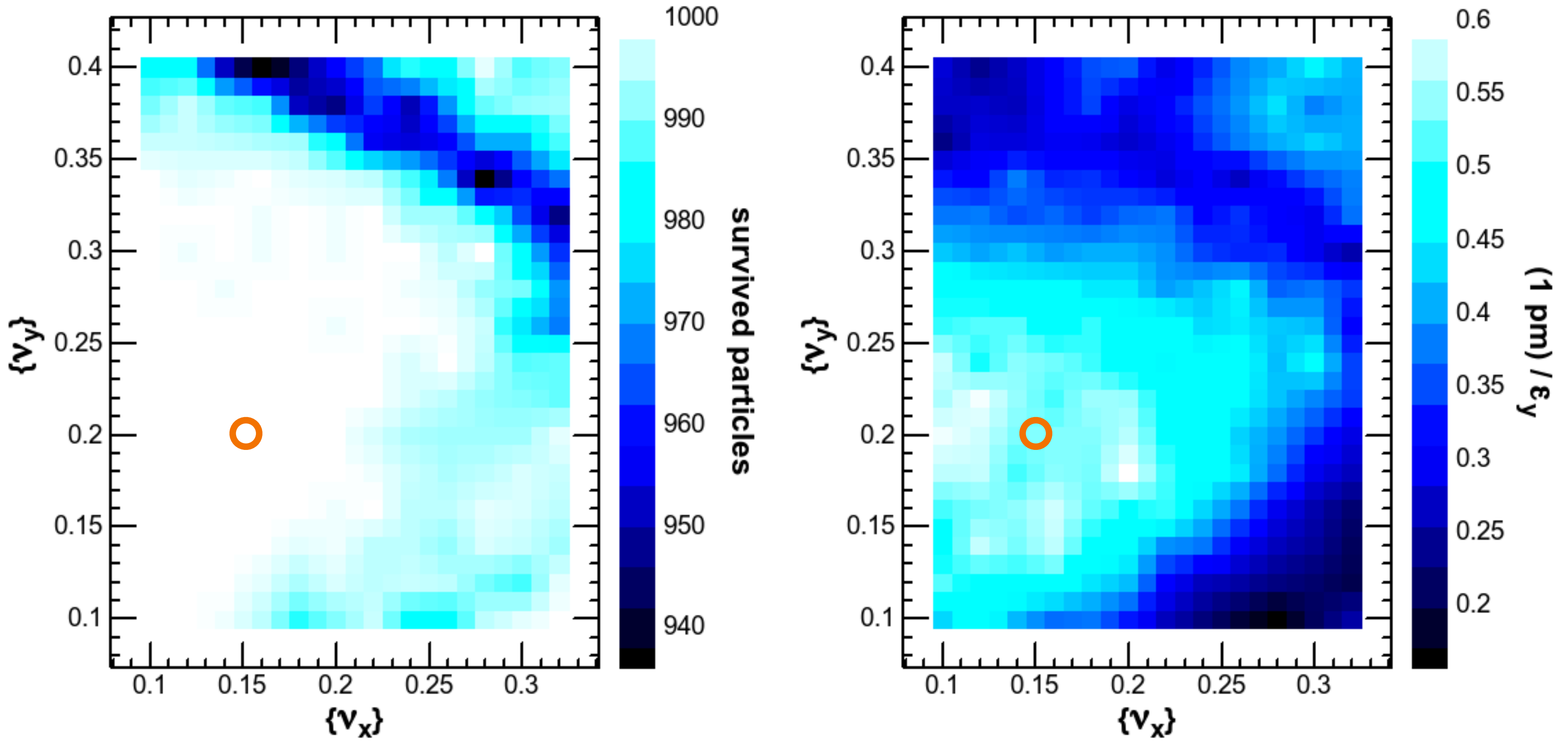


- The vertical emittance after collision (red) and the lifetime (green) against the lattice vertical emittance for each collision energy.
- The purple dashed line shows the goal vertical emittance at collision.
- SR in all elements, weak-strong beam-beam, beamstrahlung are included.
- No machine error is included.
- These results, and also the DA,have been reproduced by independent simulations by P. Kicsiny: https://indico.cern.ch/event/1335891/contributions/5632544/attachments/2745020/4776609/pkicsiny_fccee_optics_meeting_2023_11_02.pdf

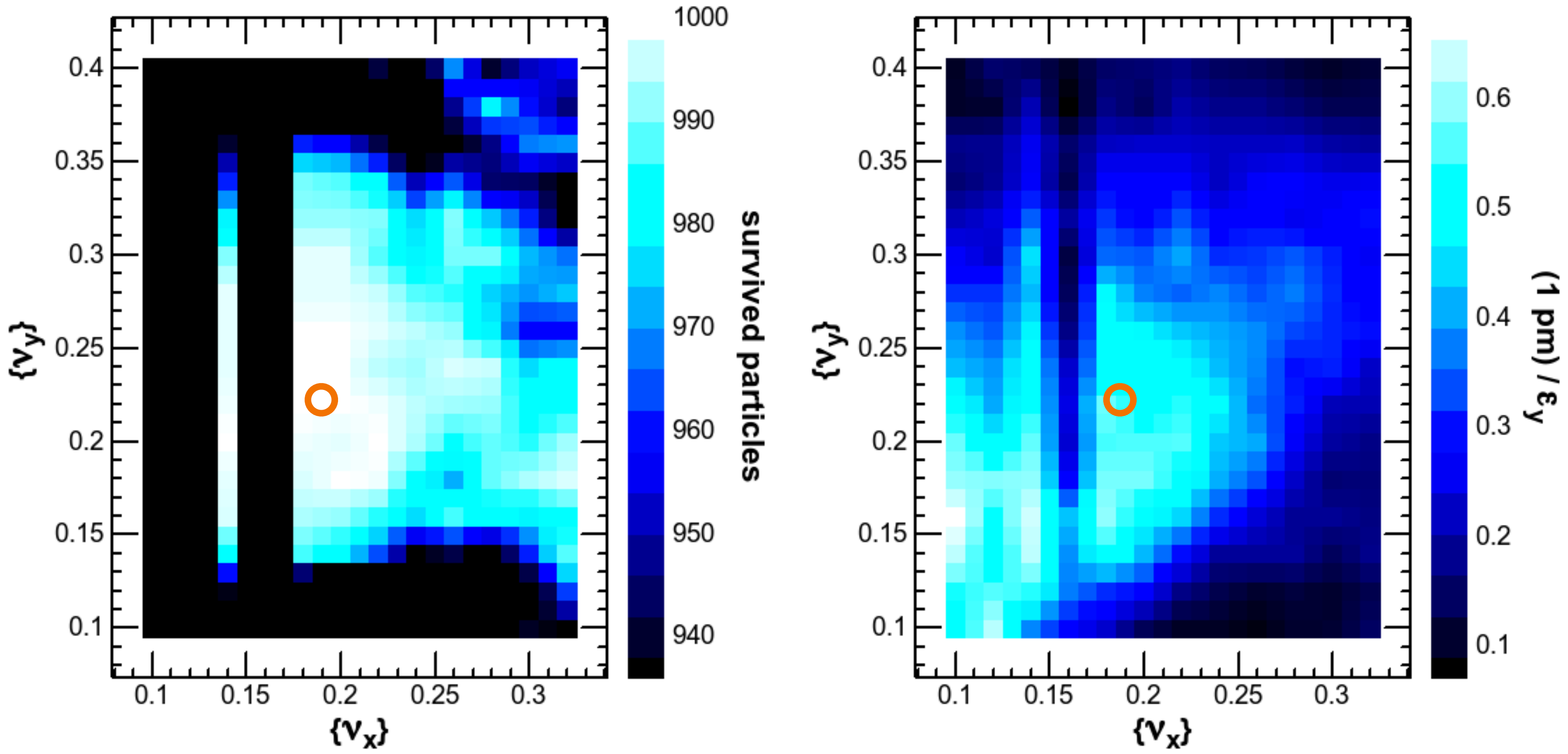
Tune scan (lattice + beam-beam + beamstrahlung)

FUTURE CIRCULAR COLLIDER

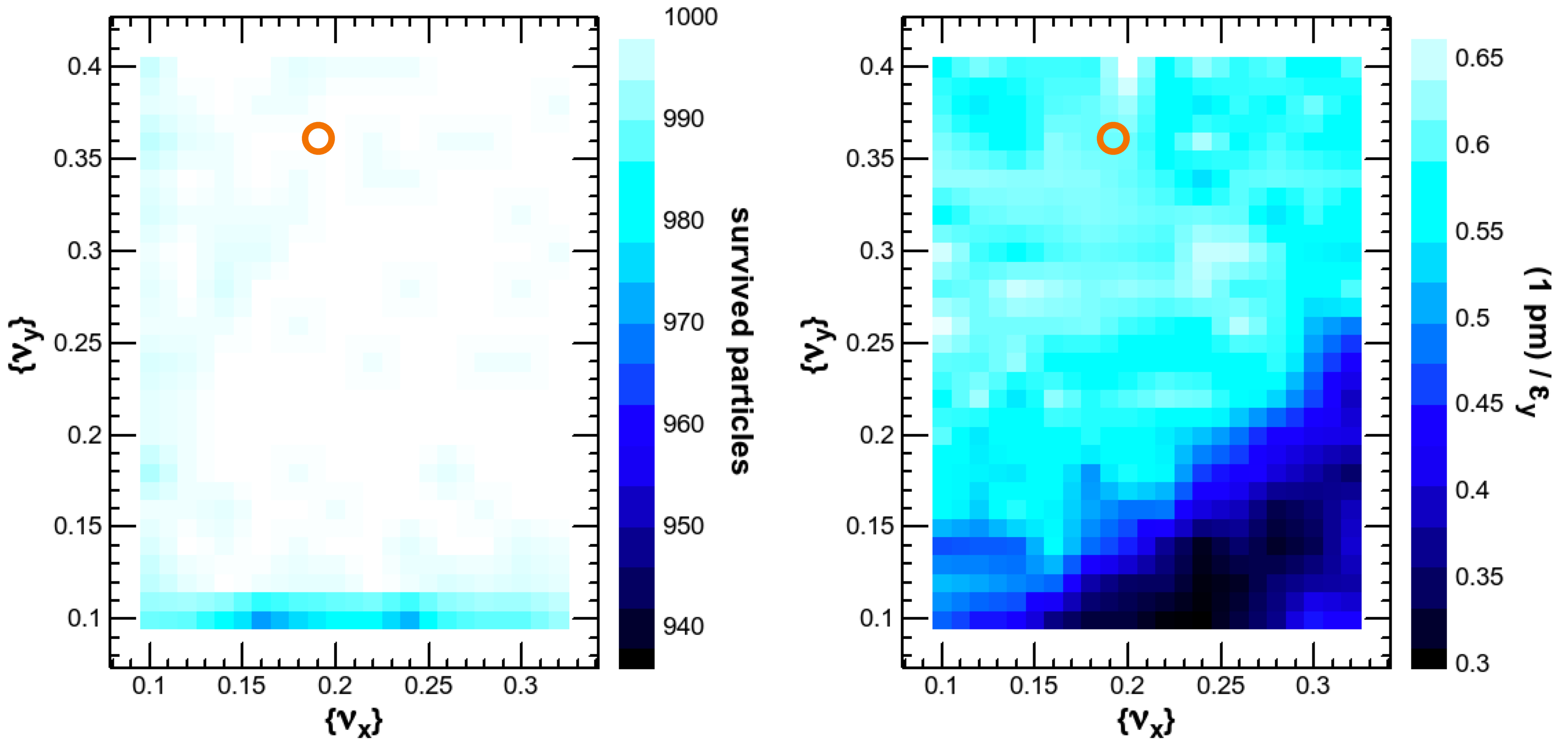
FCCee_z_566_nosol_4_ts
N = 1.51x10^{11}, Crab waist = 70%,
$\beta^*_{x,y}$ = {.11 m, .7 mm}, ν_z = -.02867, $\varepsilon_{y,\mathrm{lattice}}$ = .99936 pm



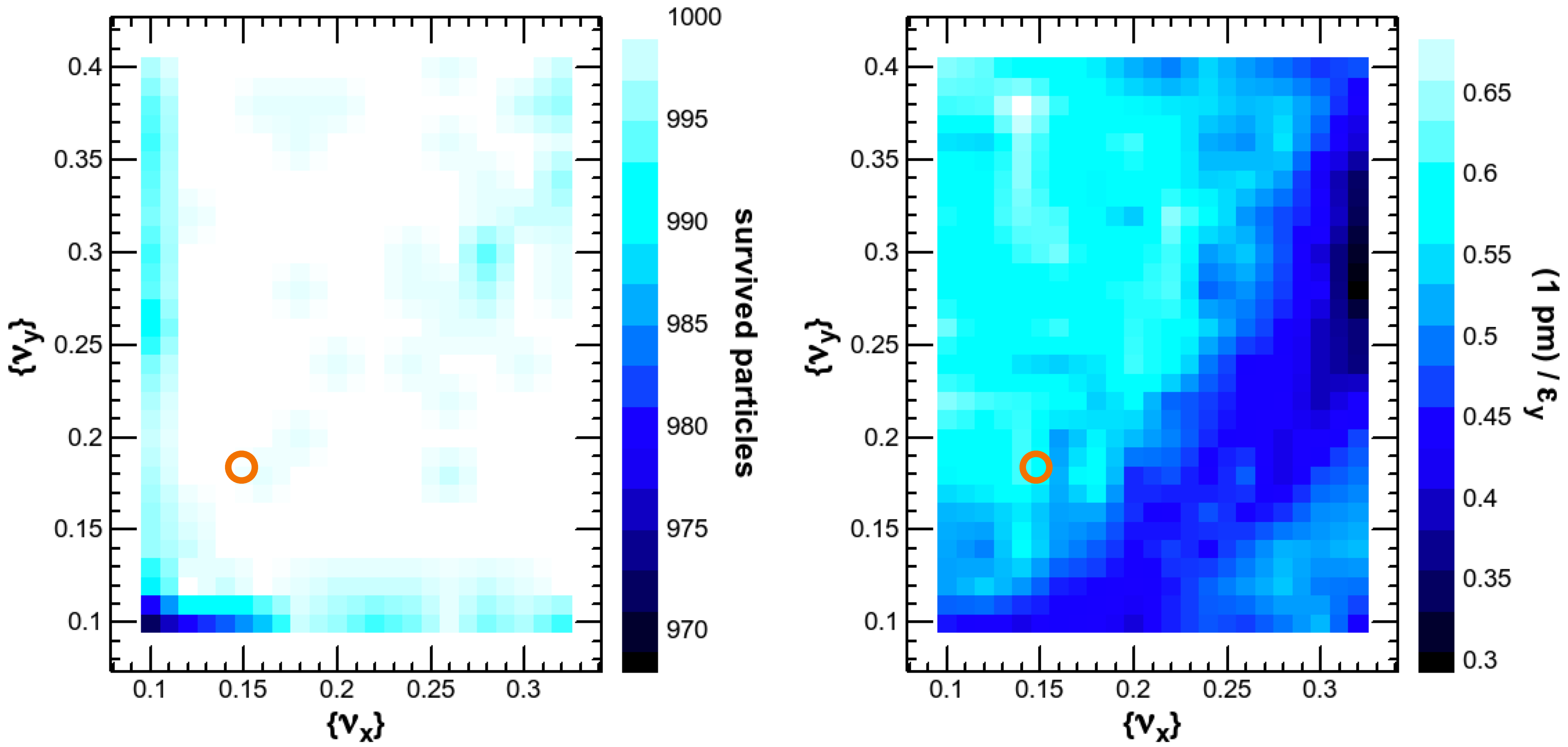
FCCee_w_566_nosol_ts
N = 1.45x10^{11}, Crab waist = 55%,
$\beta^*_{x,y}$ = {.22 m, 1 mm}, ν_z = -.08101, $\varepsilon_{y,\mathrm{lattice}}$ = 1.00046 pm



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

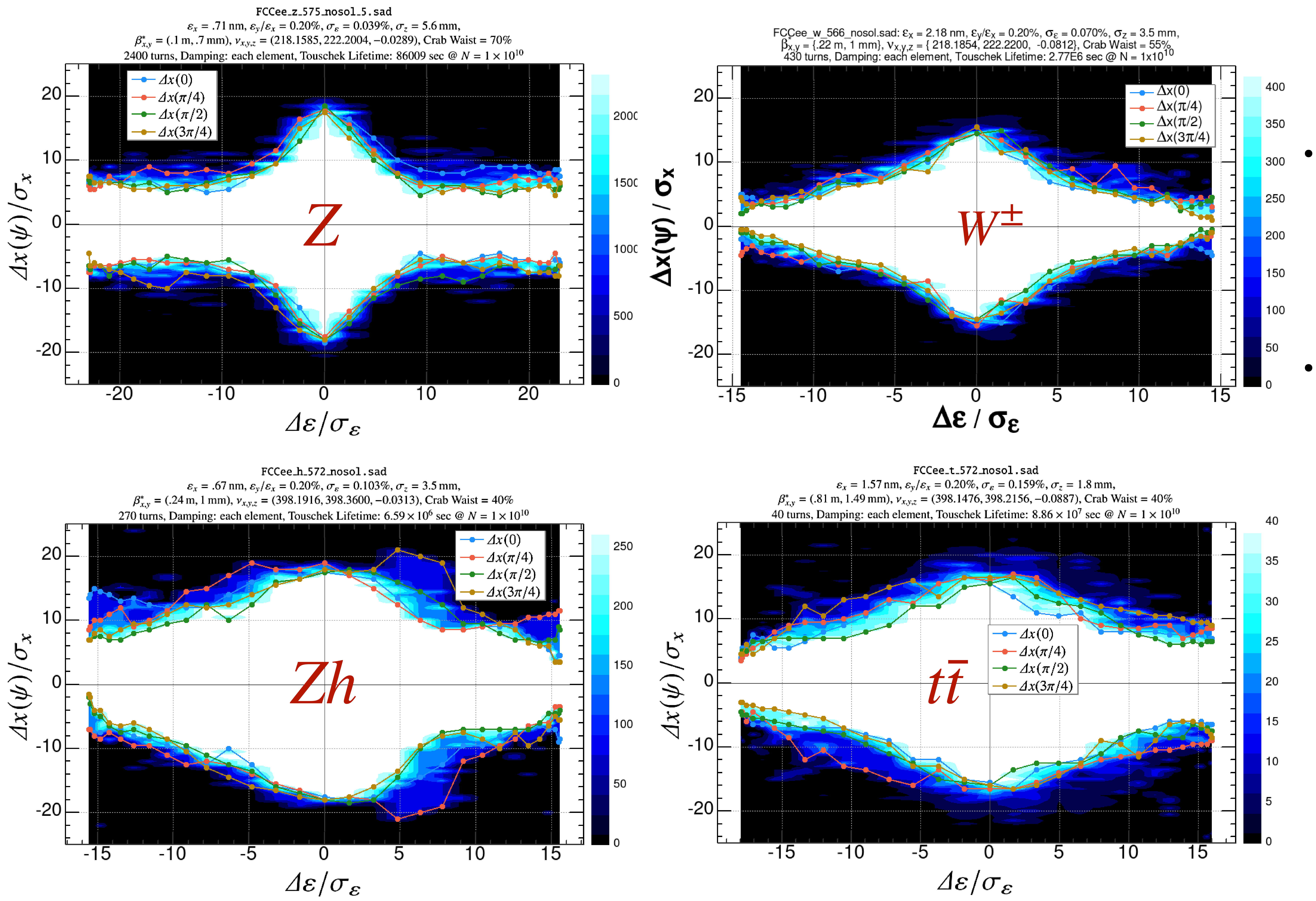


FCCee_t_565_nosol_2_ts
N = 1.55x10^{11}, Crab waist = 40%,
$\beta^*_{x,y}$ = {1.01 m, 1.56 mm}, ν_z = -.08966, $\varepsilon_{y,\mathrm{lattice}}$ = 1.08717 pm



- 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%).

A slightly modified parameter set after MTR

FCC-ee collider parameters as of July 30, 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]	10.021			
Energy loss / turn	[GeV]	0.0391	0.374	1.88	10.29
SR power / beam	[MW]	50			
Beam current	[mA]	1279	137	26.7	4.9
Colliding bunches / beam		11200	1780	380	56
Colliding bunch population	$[10^{11}]$	2.14	1.45	1.32	1.64
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.67	1.57
Ver. emittance at collision ε_y	[pm]	1.9	2.2	1.0	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.85	1.25	0.65	1.1
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	800 / 1.5
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.360	398.148 / 398.216
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.109	0.070 / 0.109	0.103 / 0.152	0.159 / 0.201
Bunch length (SR/BS) σ_z	[mm]	5.60 / 15.5	3.46 / 5.09	3.40 / 5.09	1.85 / 2.33
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	0.089
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	3.1
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP	[mrad]	±15			
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y[a]		0.0022 / 0.097	0.013 / 0.128	0.010 / 0.088	0.066 / 0.144
Piwinski angle $(\theta_x\sigma_{z,\mathrm{BS}})/\sigma^*_x$		26.4	3.7	5.4	0.99
Lifetime (q + BS + lattice)	[sec]	10000	4000	3500	3000
Lifetime (lum)[b]	[sec]	1330	970	660	650
Luminosity / IP	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	141	20	6.3	1.38
Luminosity / IP (CDR)	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	230	28	8.5	1.8

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

- Small modifications have been made @$Z/t\bar{t}$, according to the changes described above.
- Not yet looked at $W^\pm$.
- Still not far from the official ones (below) for the mid-term review.

Running mode	Z	W	ZH	$t\bar{t}$
Number of IPs	4	4	4	4
Beam energy (GeV)	45.6	80	120	182.5
Bunches/beam	11200	1780	440	60
Beam current [mA]	1270	137	26.7	4.9
Luminosity/IP $[10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$	141	20	5.0	1.25
Energy loss / turn [GeV]	0.0394	0.374	1.89	10.42
Synchrotron Radiation Power [MW]	100			
RF Voltage 400/800 MHz [GV]	0.08/0	1.0/0	2.1/0	2.1/9.4
Rms bunch length (SR) [mm]	5.60	3.47	3.40	1.81
Rms bunch length (+BS) [mm]	15.5	5.41	4.70	2.17
Rms horizontal emittance ε_x [nm]	0.71	2.17	0.71	1.59
Rms vertical emittance ε_y [pm]	1.9	2.2	1.4	1.6
Longitudinal damping time [turns]	1158	215	64	18
Horizontal IP beta β^*_x [mm]	110	200	240	1000
Vertical IP beta β^*_y [mm]	0.7	1.0	1.0	1.6
Beam lifetime (q+BS+lattice) [min.]	50	42	100	100
Beam lifetime (lum.) [min.]	22	16	14	12
Int. annual luminosity / IP $[\mathrm{ab}^{-1}/\mathrm{yr}]$	17†	2.4†	0.6	0.15‡

† The integrated luminosity in the first two years is assumed to be half this value to account for the machine commissioning and beam tuning;
‡ The integrated luminosity in the first year. at a lower beam energy of about 173 GeV is assumed to be about 65% this value to account for the machine commissioning and beam tuning. The smaller time for commissioning compared with the lower energy running reflects the LEP/LEP-2 experience.

F. Zimmermann

Some variants may be possible for higher luminosity or fewer bunches

(suggested by T. Raubenheimer)

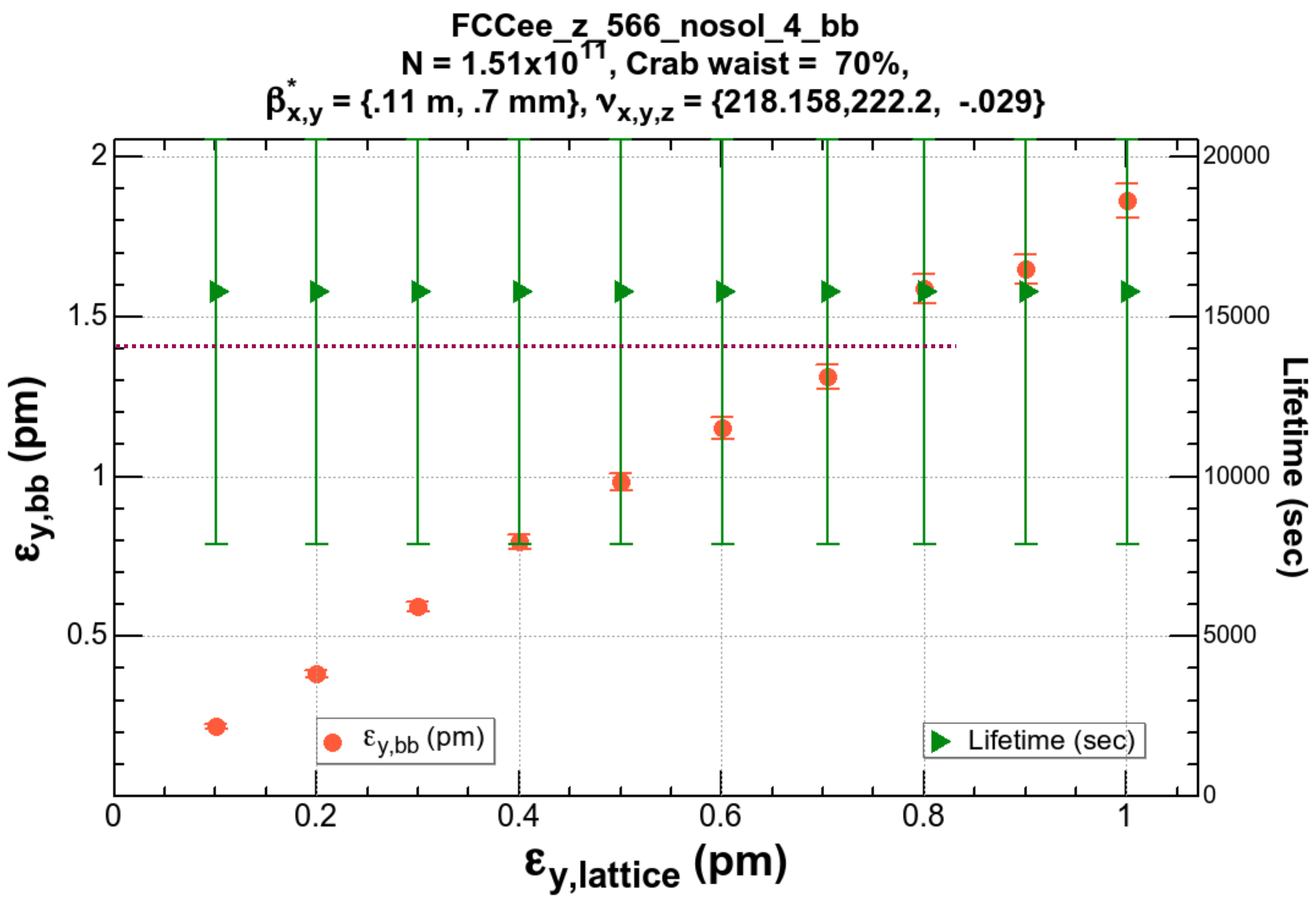
A few variants in parameters, as of June 14, 2023.

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	

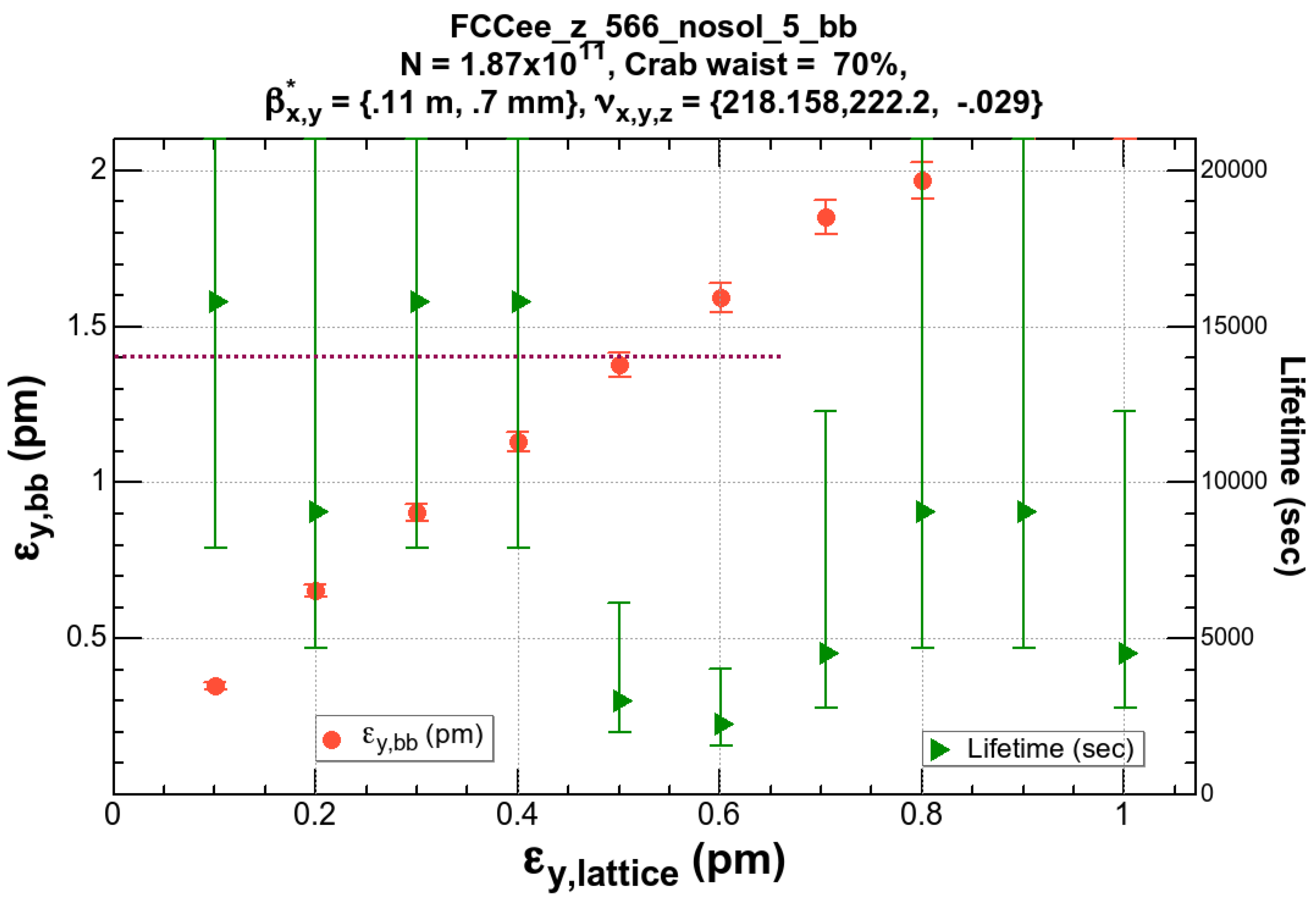
[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section

- 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).

Some variants may be possible for higher luminosity or fewer bunches



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



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

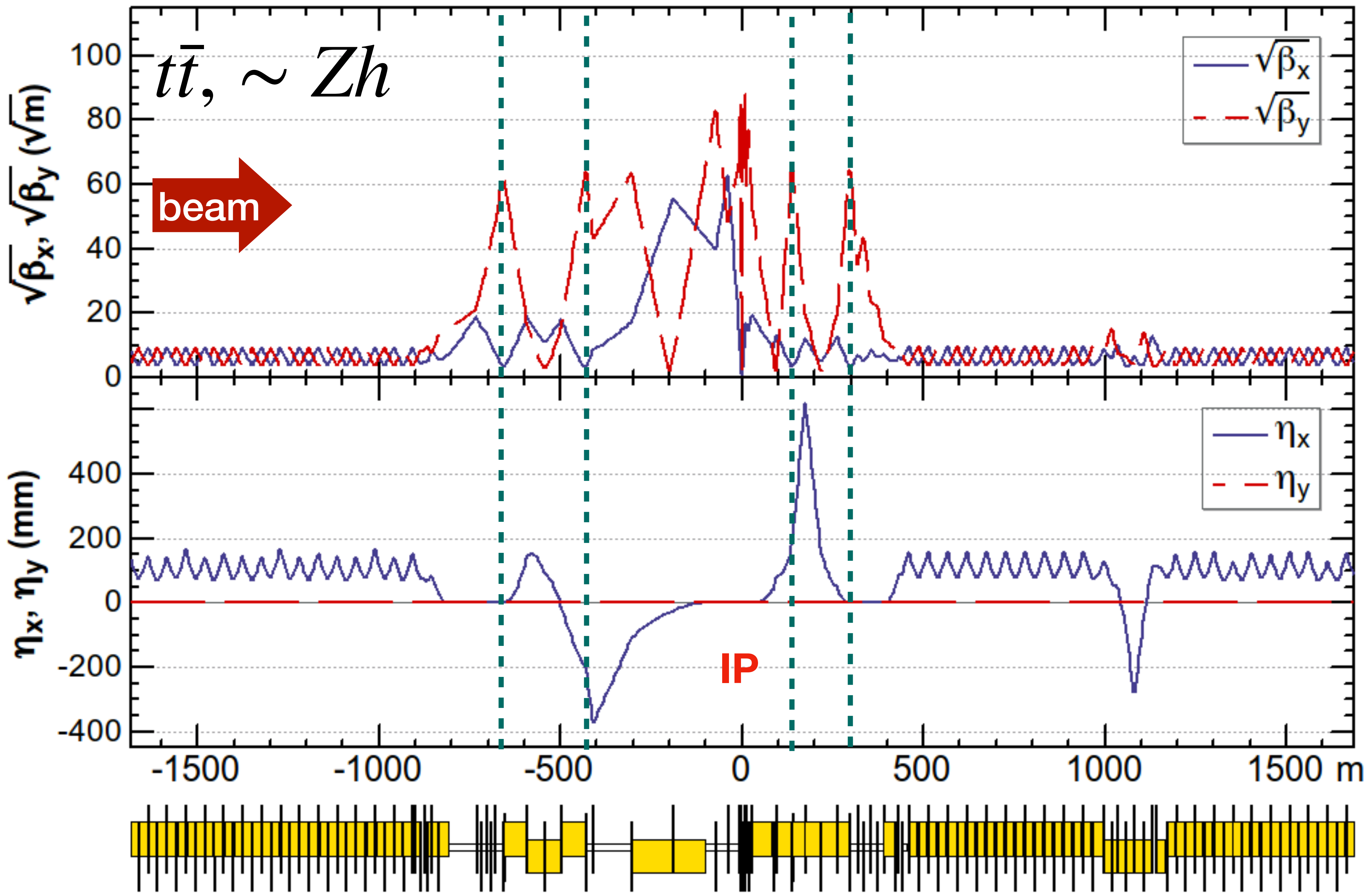
- If we push the luminosity further by increasing the bunch charge (right plot),
  - Indeed, the luminosity gets higher by 10%, but
  - lifetime drops to 1/5 (~3000 s),
  - the required lattice vertical emittance reduces from 0.75 pm to 0.52 pm.
  - note that these have not taken the errors/corrections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

IR optics (SLSS ADGJ)

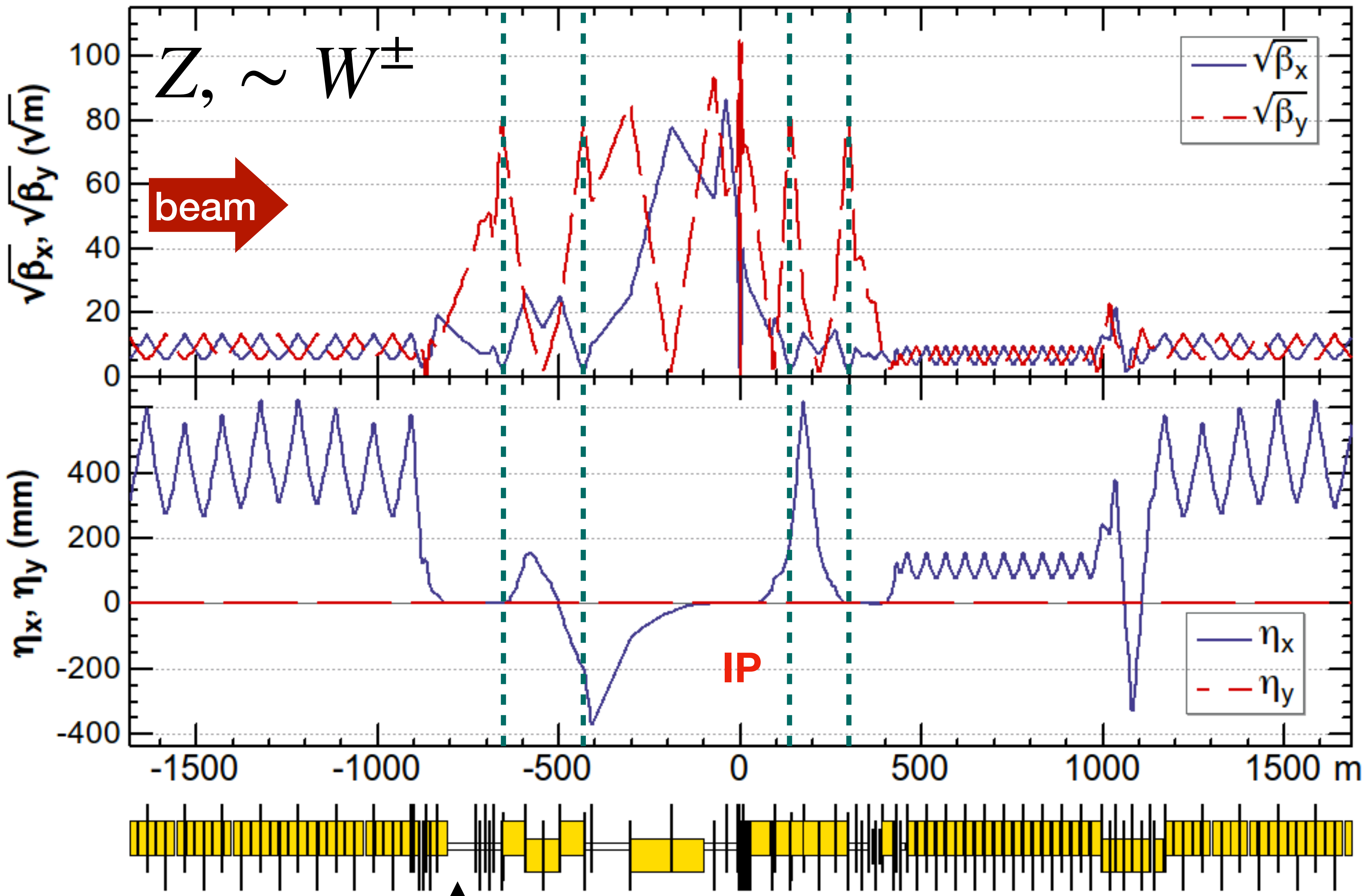
The beam optics shown here and later are not the latest ones in details.

FUTURE CIRCULAR COLLIDER

FCCee_t_546_nosol.sad



FCCee_z_546_nosol_1.sad

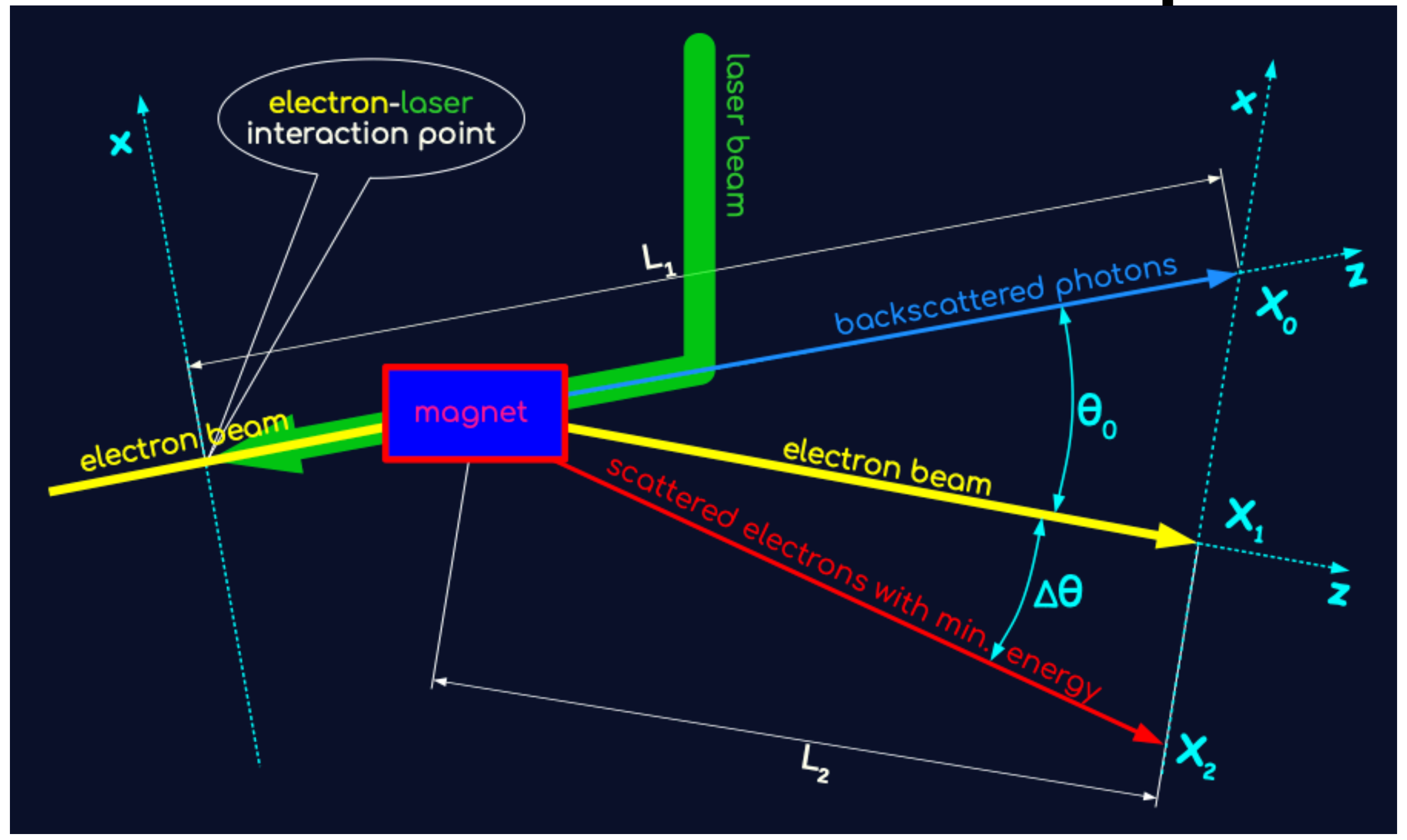


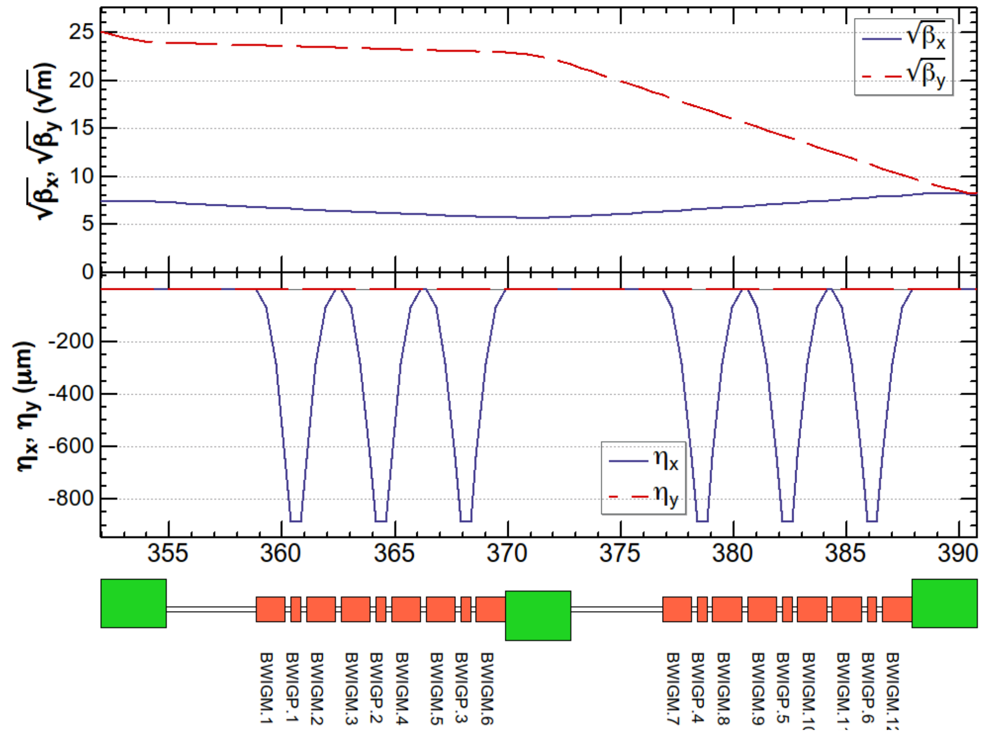
6

polarimeter
N. Muchnoi

pol. wiggler

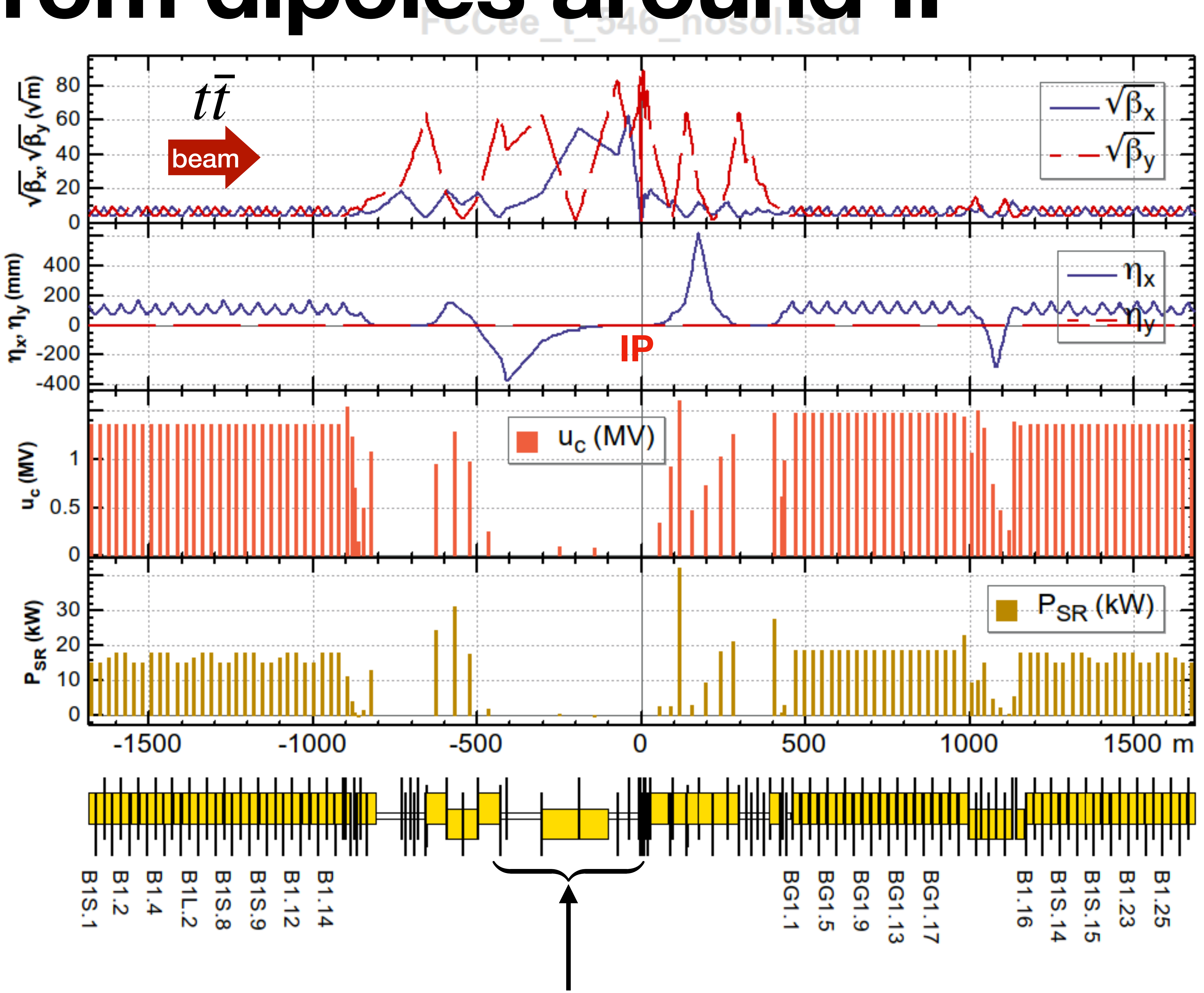
- The beam optics are highly asymmetric between upstream/downstream due to crossing angle & suppression of the SR from upstream to the IP.
- Crab waist/vertical chromaticity correction sextupoles are located at the vertical dashed lines.
- The matching sections may be used for polarimeters (upstream)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





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

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 $t\bar{t}$.

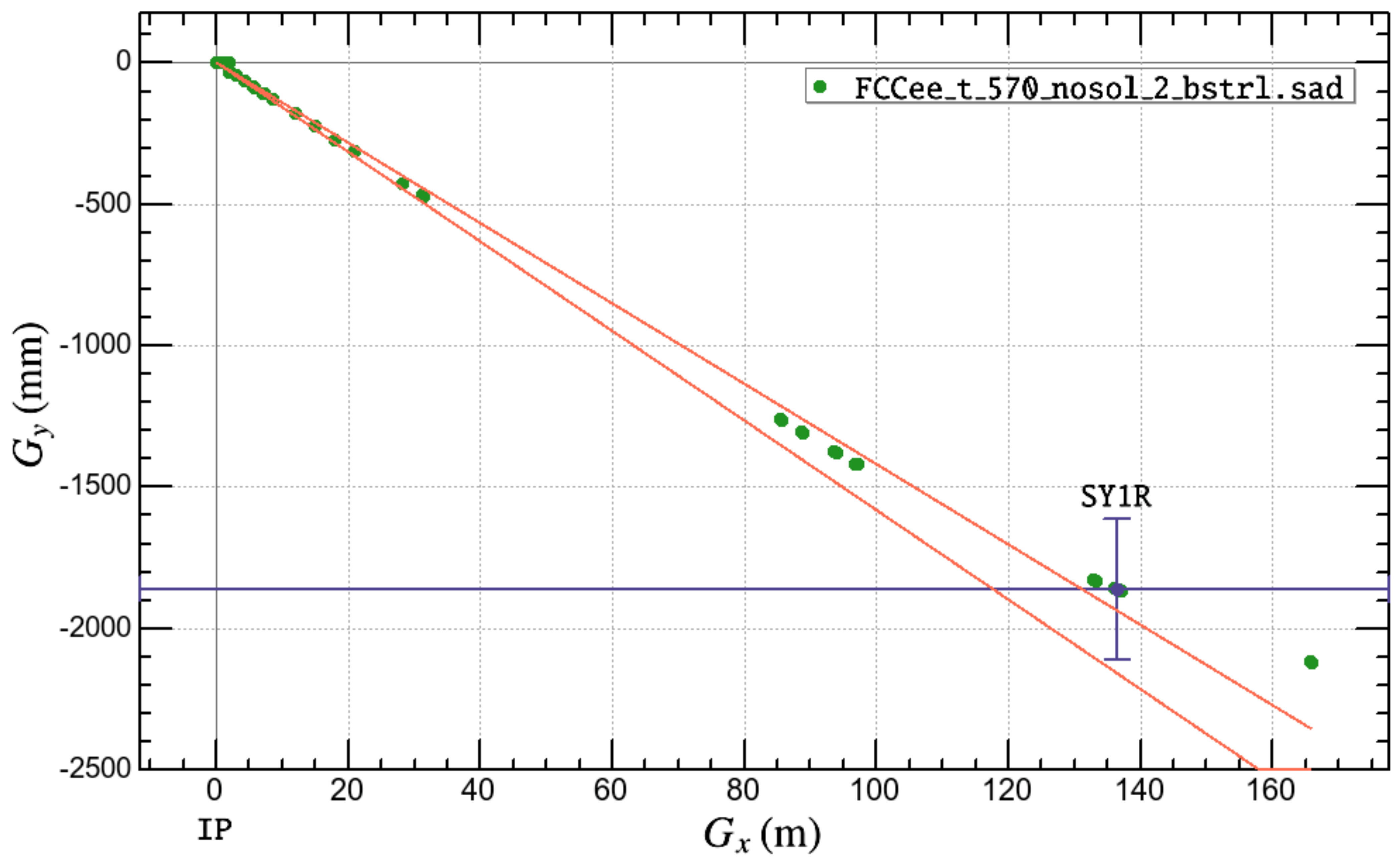
We must be extremely careful on the SR: Belle killed their silicon vertex detector only in two months beam operation at maximum 500 mA in 1999.

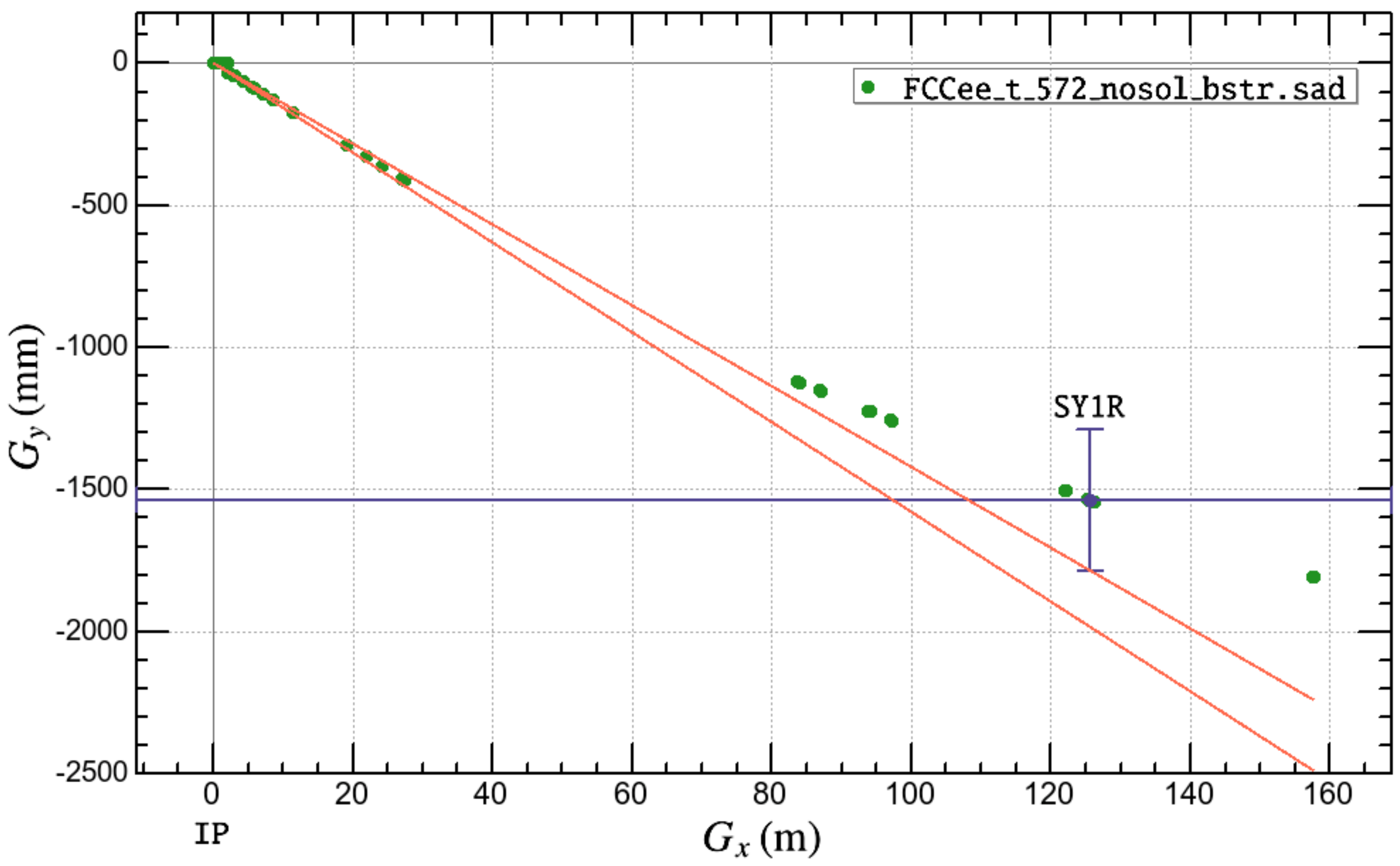
It's not only an issue of critical energy.vWe should not ignore any leaked/reflected SR through SR masks, as their acceptance cannot be 100%.

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

Shifting location of SY1R for clearance of the outgoing beamstrahung (requested by A. Foussat)

- It is necessary to make the clearance for the outgoing beamstrahlung, downstream the IP.
    - Special designs have been made for quadrupoles.
    - As SY1R is a superconducting sextupole, a clearance larger than 250 mm is required from beam center to the edge of the BS fan $\left(\pm 10 \times \sqrt{\varepsilon_x/\beta_x^*}\right)$

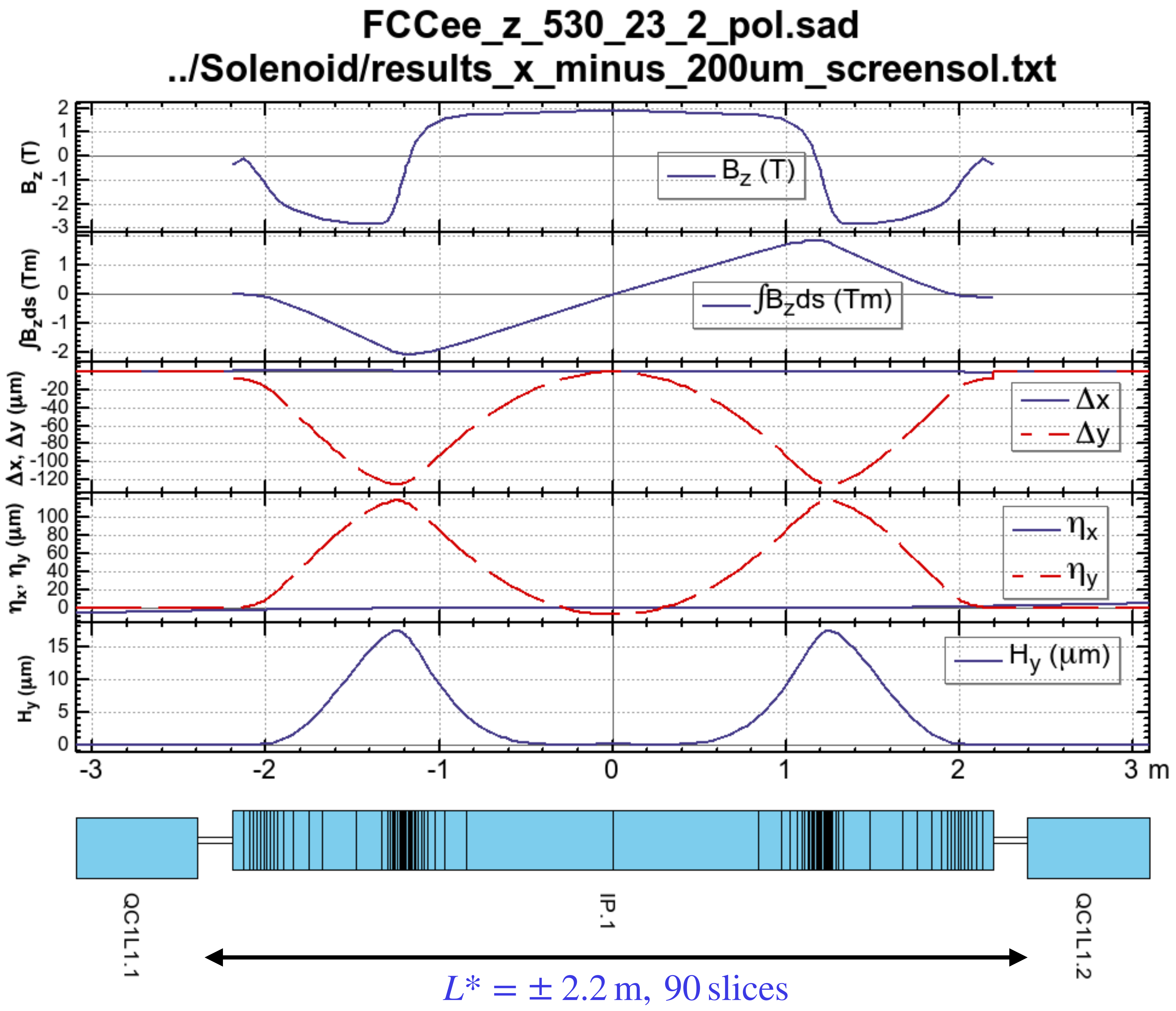


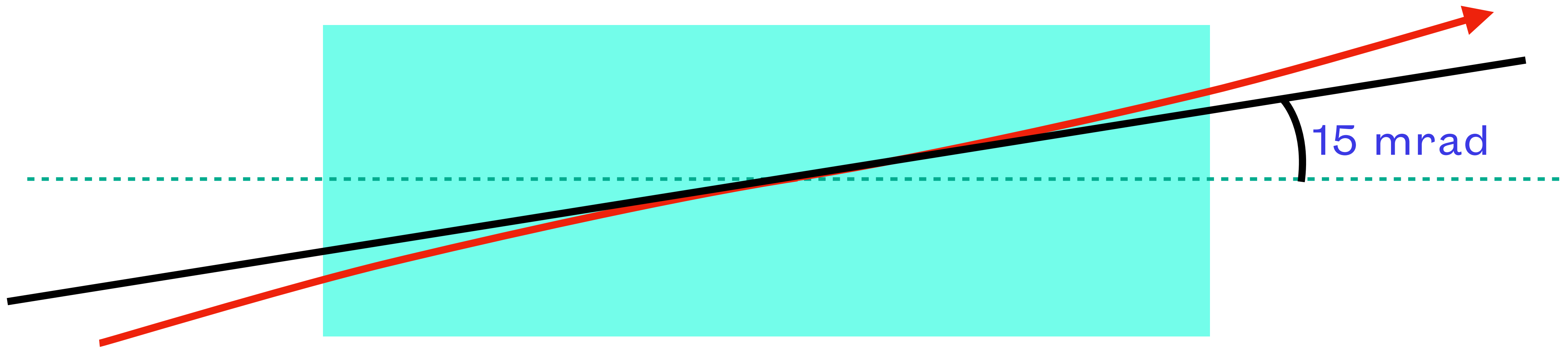


Optics including a realistic solenoid (M. Koratzinos)

FUTURE CIRCULAR COLLIDER

- 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.

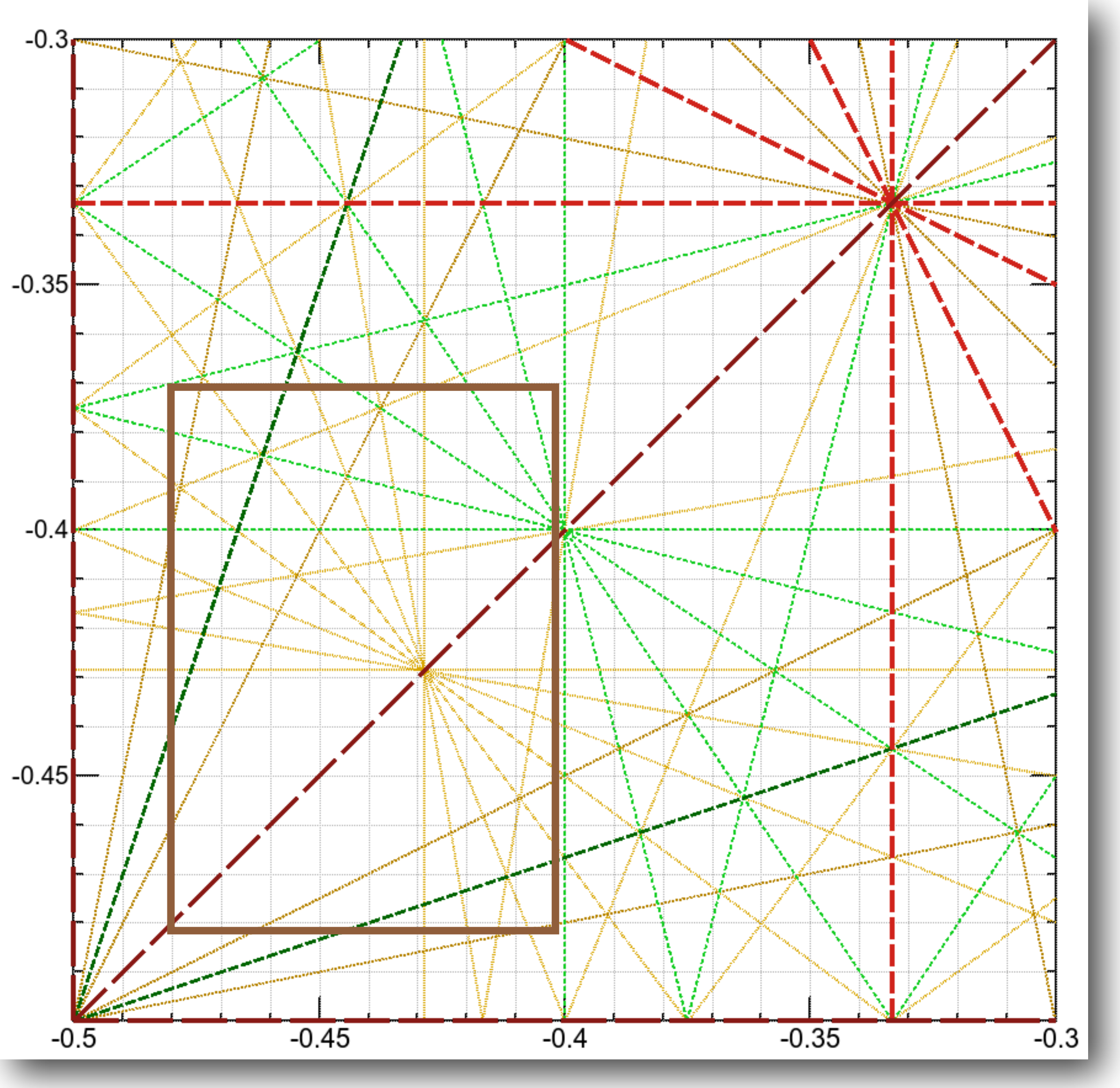




The beam optics shown here and later are not the latest ones in details.

SuperKEKB LER tune survey

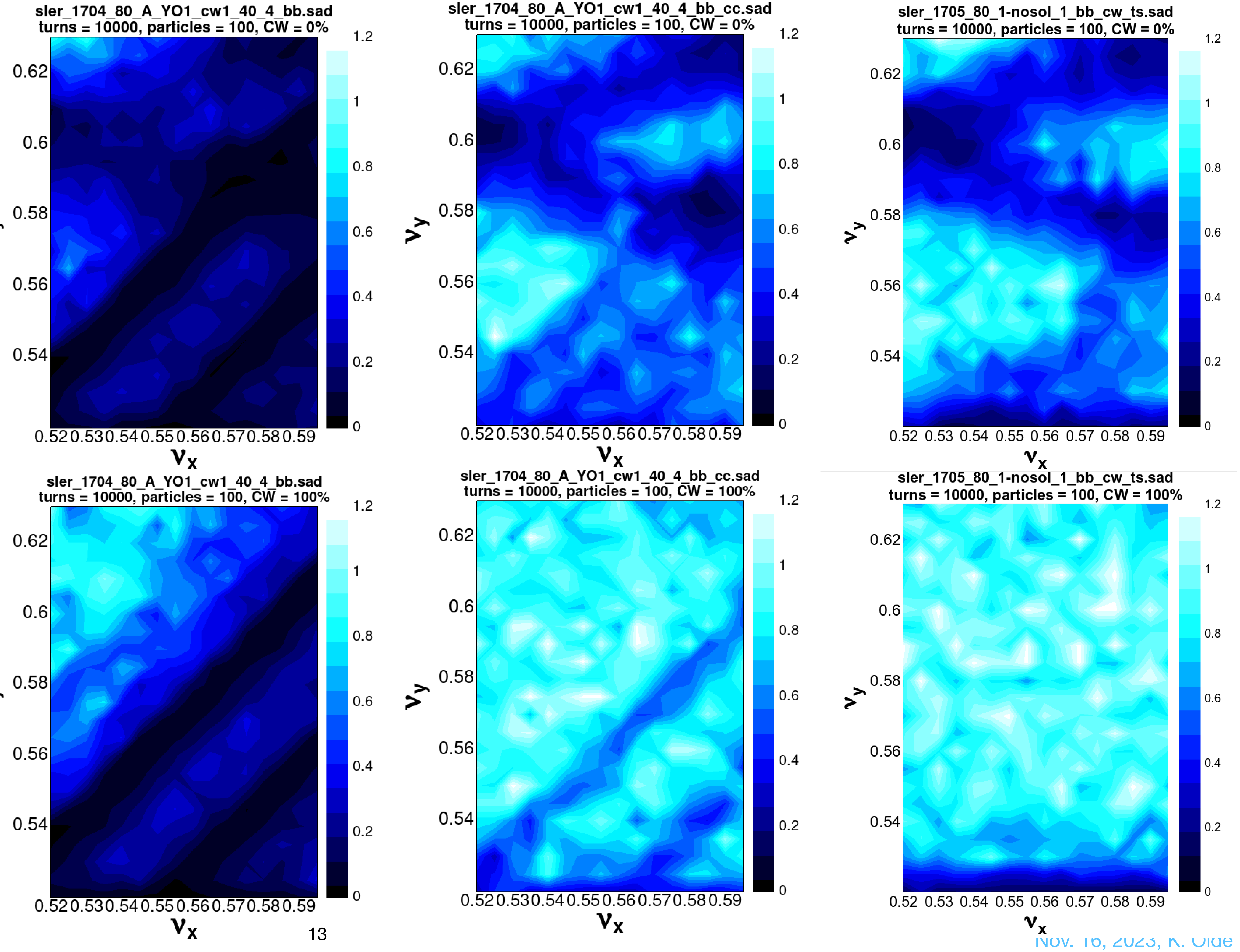
$\varepsilon_{y0}/\varepsilon_y$



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

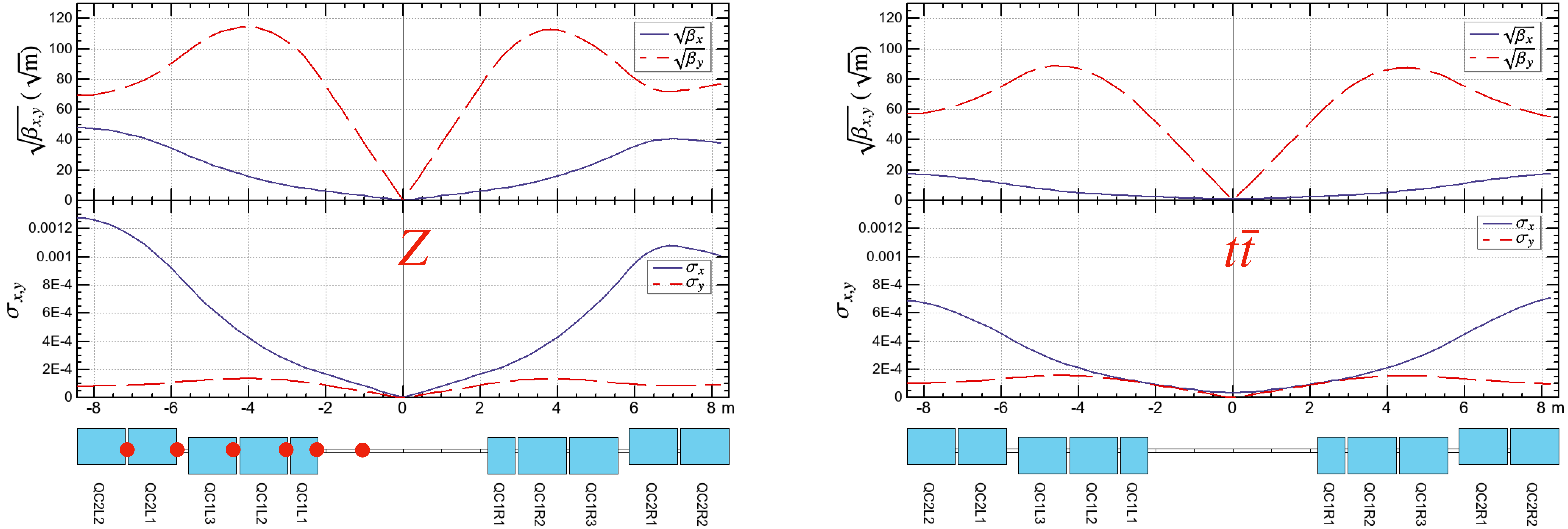
CW = 0%

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.

Final quadrupoles QC{12}*



- Each slice of QC{12}* *must* equipped with at least one BPM.
  - These are the most important/sensitive locations in the ring.
  - If the present lattice may not provide enough spacing between slices, we have to modify the lattice to incorporate these BPMs.

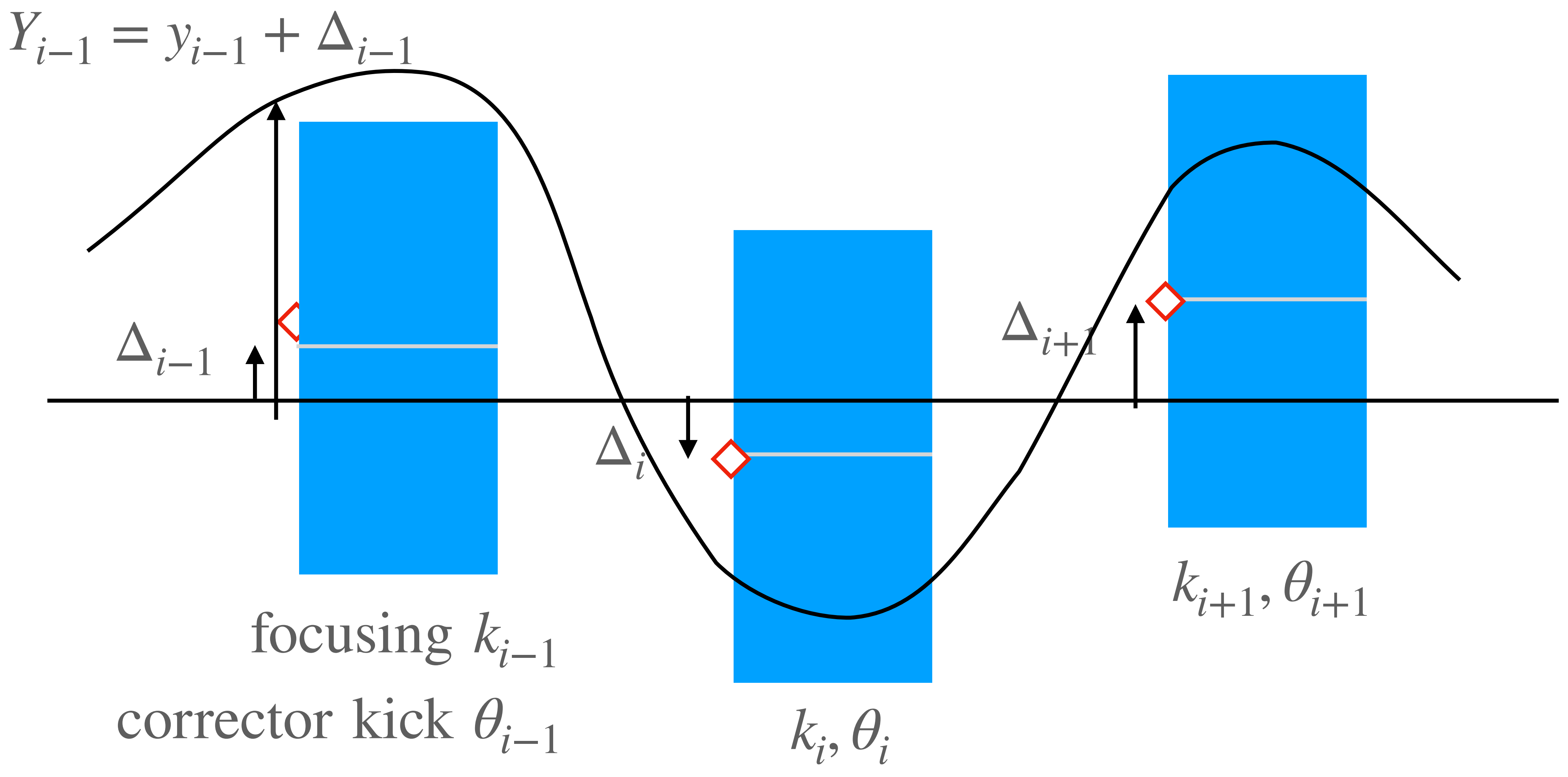
Estimation of quadrupole misalignment (2)

FUTURE CIRCULAR COLLIDER

If we combine this with the equation for $(i+1,i)$, we can derive the relation between three successive offsets as:

$$f_{a,i}\Delta_{i-1} + \Delta_i + f_{b,i}\Delta_{i+1} = c_{a,i}y_{i-1} + c_{0,i}y_i + c_{b,i}y_{i+1} + v_{a,i}\theta_{i-1} + v_{0,i}\theta_i\ ,$$

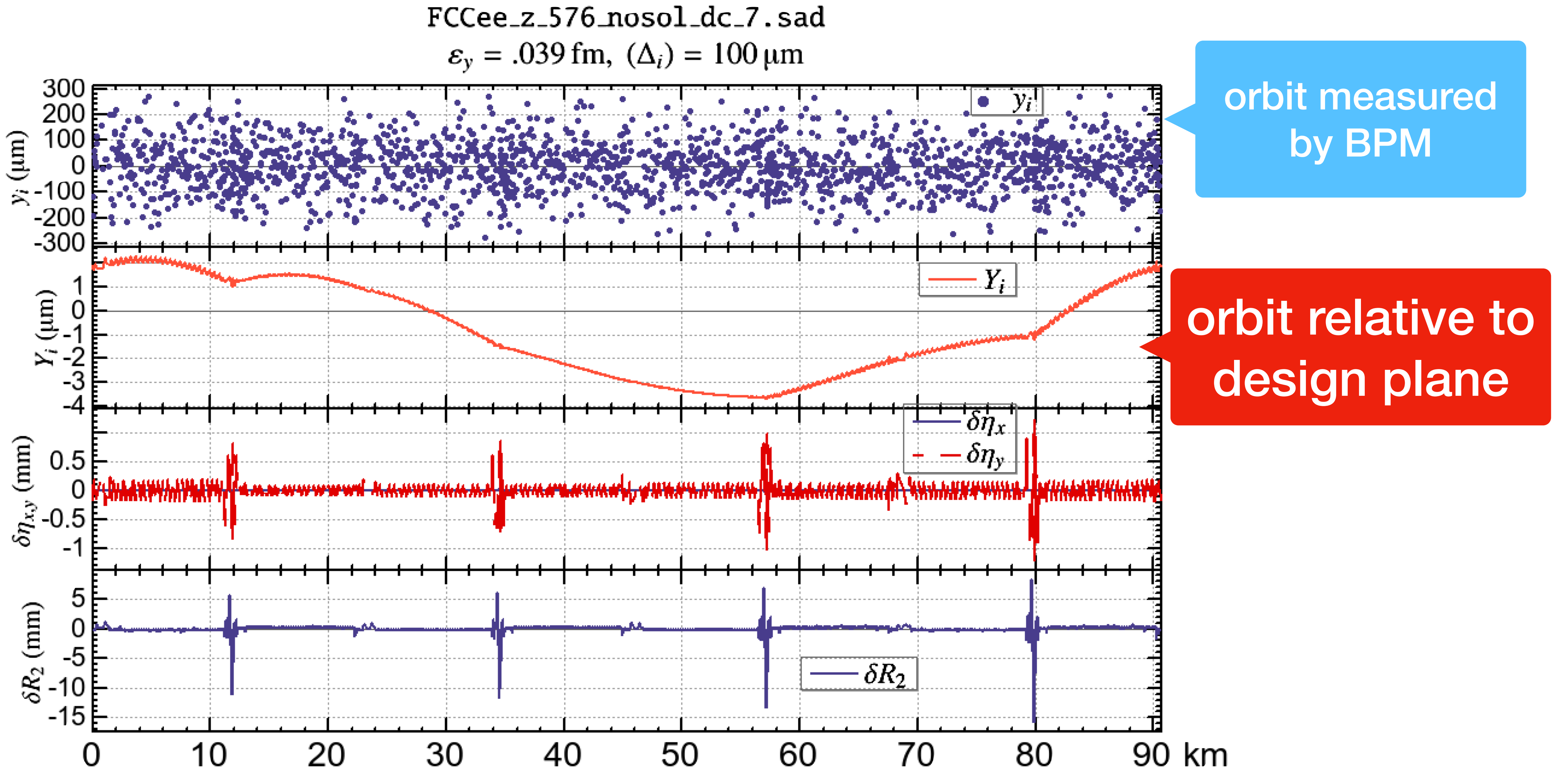
where coefficients $f_{a,i}$, $f_{b,i}$, $c_{a,i}$, $c_{0,i}$, $c_{b,i}$, $v_{a,i}$, $v_{0,i}$ are all expressed in terms of the matrices M and K. The rhs of above is determined by the measured orbit y_i and the corrector setting θ_i. So we can solve the above equation for $\Delta_i, i=(1..n)$, once an orbit is measured. Actually this equation is expressed by solving a nearly bi-diagonal matrix.



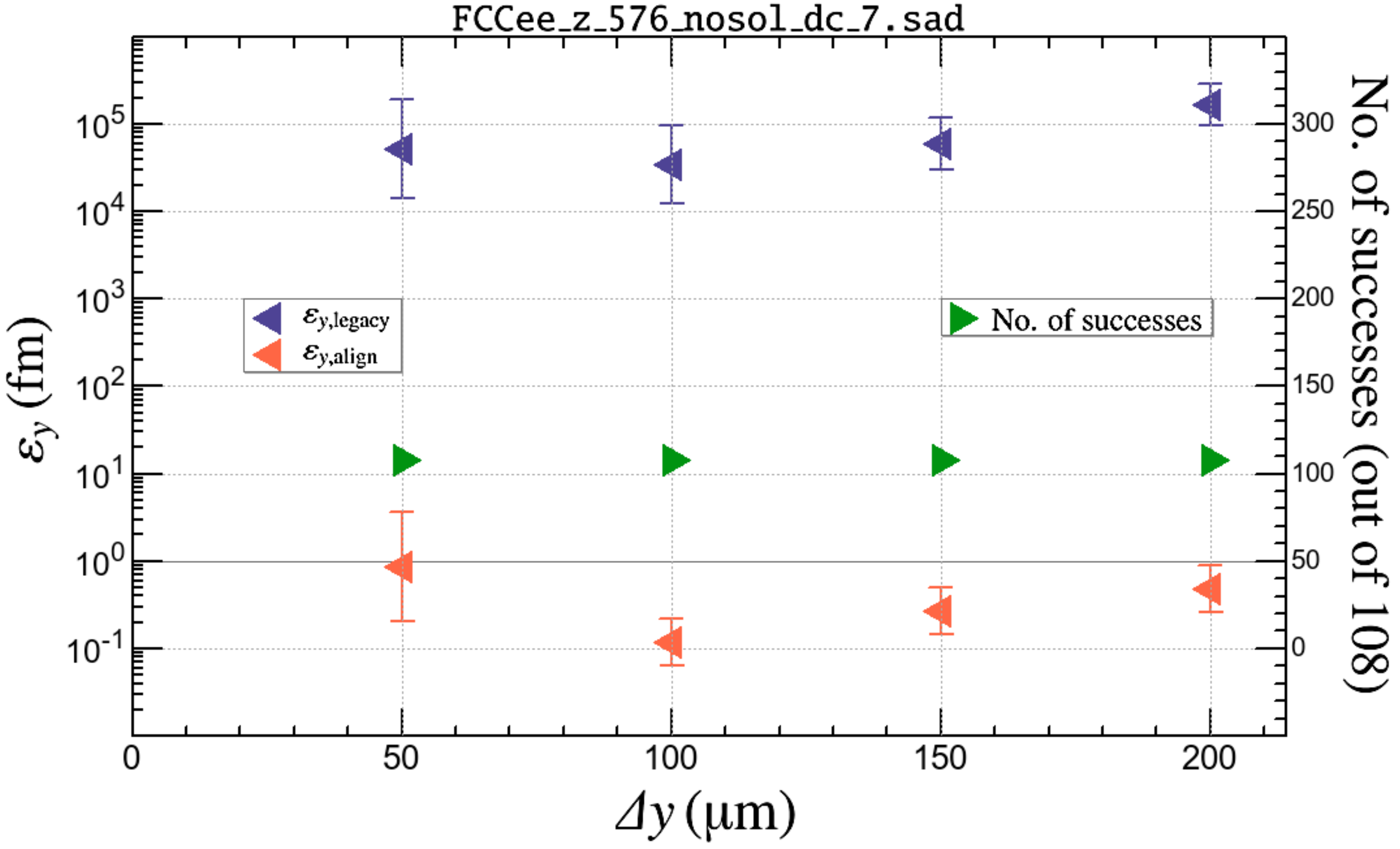
Estimation of quadrupole misalignment (3)

- If we solve the equation above, we can determine all misalignments of quadrupoles.
- For the lattice at Z, the solution looks nearly perfect; it is possible to reach vertical emittance below 1 fm, under up to 200 μm misalignments of quadrupoles (together with BPMs).
- Here all sextupoles are nested on nearby quads, except for crab/YCCS ones (SY*), which are set to zero here.

$$f_{a,i}\Delta_{i-1} + \Delta_i + f_{b,i}\Delta_{i+1}$$
$$= c_{a,i}y_{i-1} + c_{0,i}y_i + c_{b,i}y_{i+1} + v_{a,i}\theta_{i-1} + v_{0,i}\theta_i\ ,$$



Results do not depend on the magnitude of misalignments.



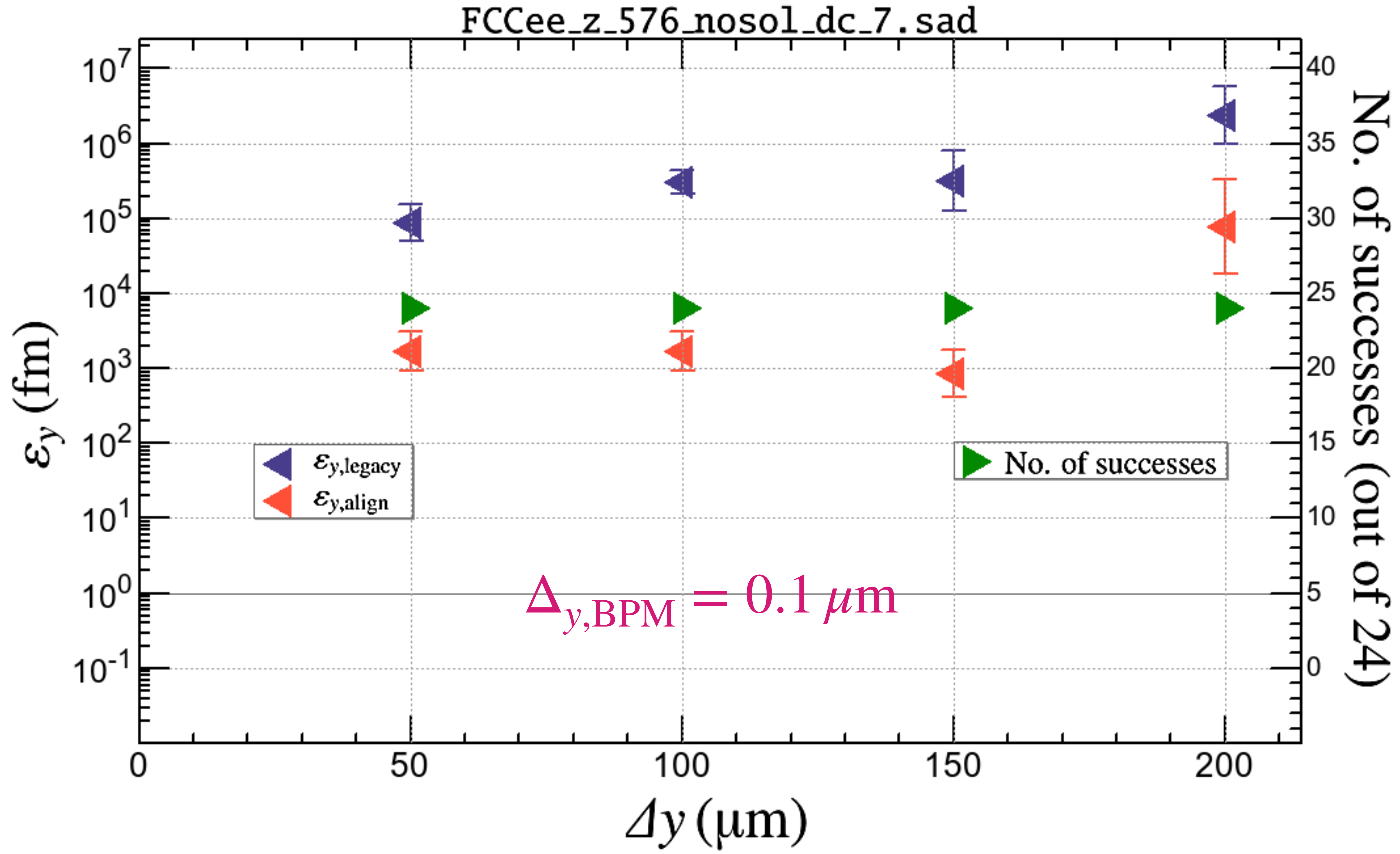
Estimation of quadrupole misalignment (4)

$$f_{a,i}\Delta_{i-1} + \Delta_i + f_{b,i}\Delta_{i+1}$$
$$= c_{a,i}y_{i-1} + c_{0,i}y_i + c_{b,i}y_{i+1} + v_{a,i}\theta_{i-1} + v_{0,i}\theta_i \,,$$

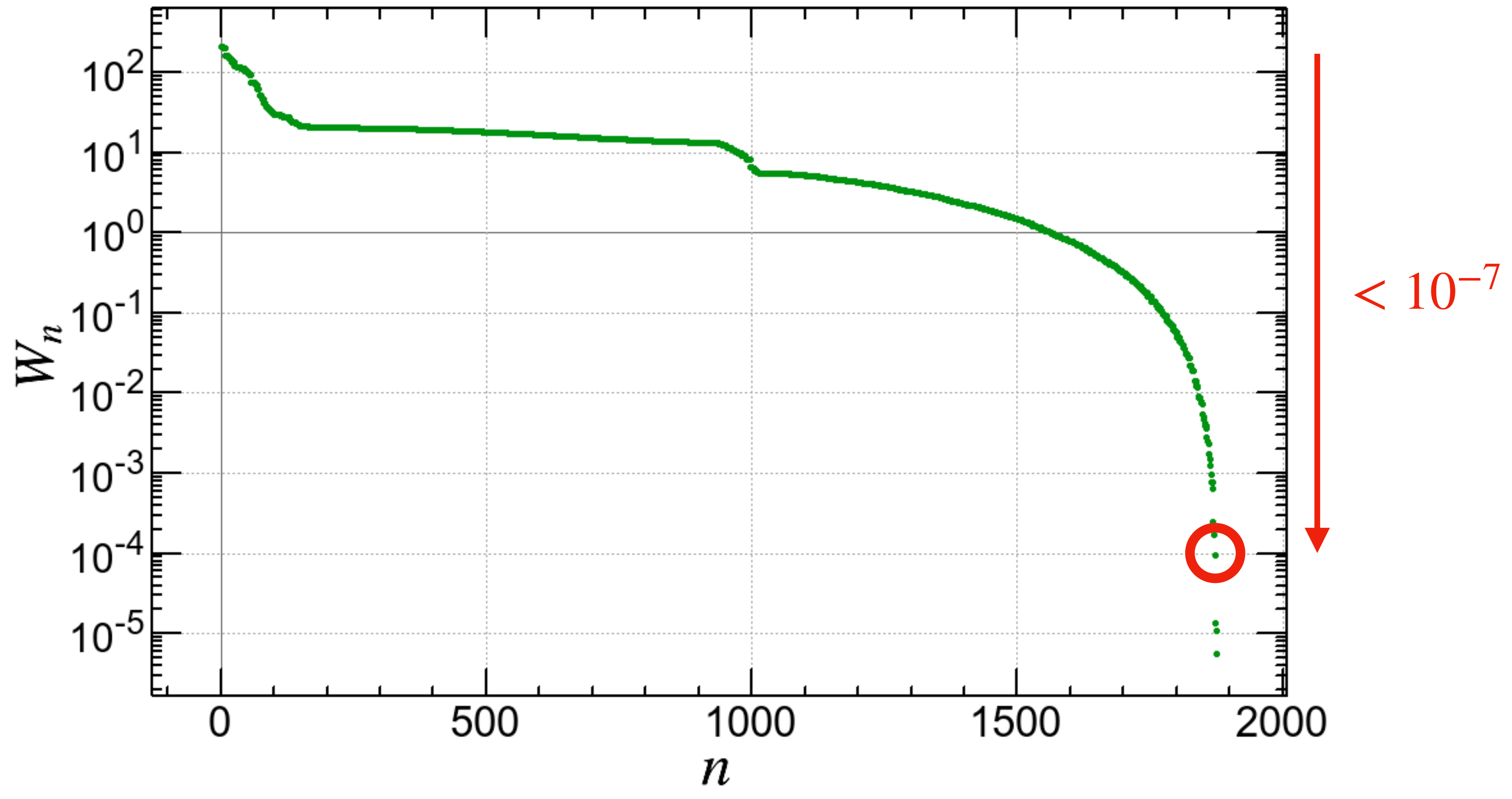
- However, the result above is only true with zero BPM measurement/alignment errors.
- If we add BPM errors, the estimation results in huge vertical emittance.

To reach 1 μm accuracy by a BPM with 100 μm single-shot resolution BPM, we need 10^6 turns (= 5 minutes) with 10000 bunches in the ring. Besides, the BPM offset to the quad center must have the same accuracy.

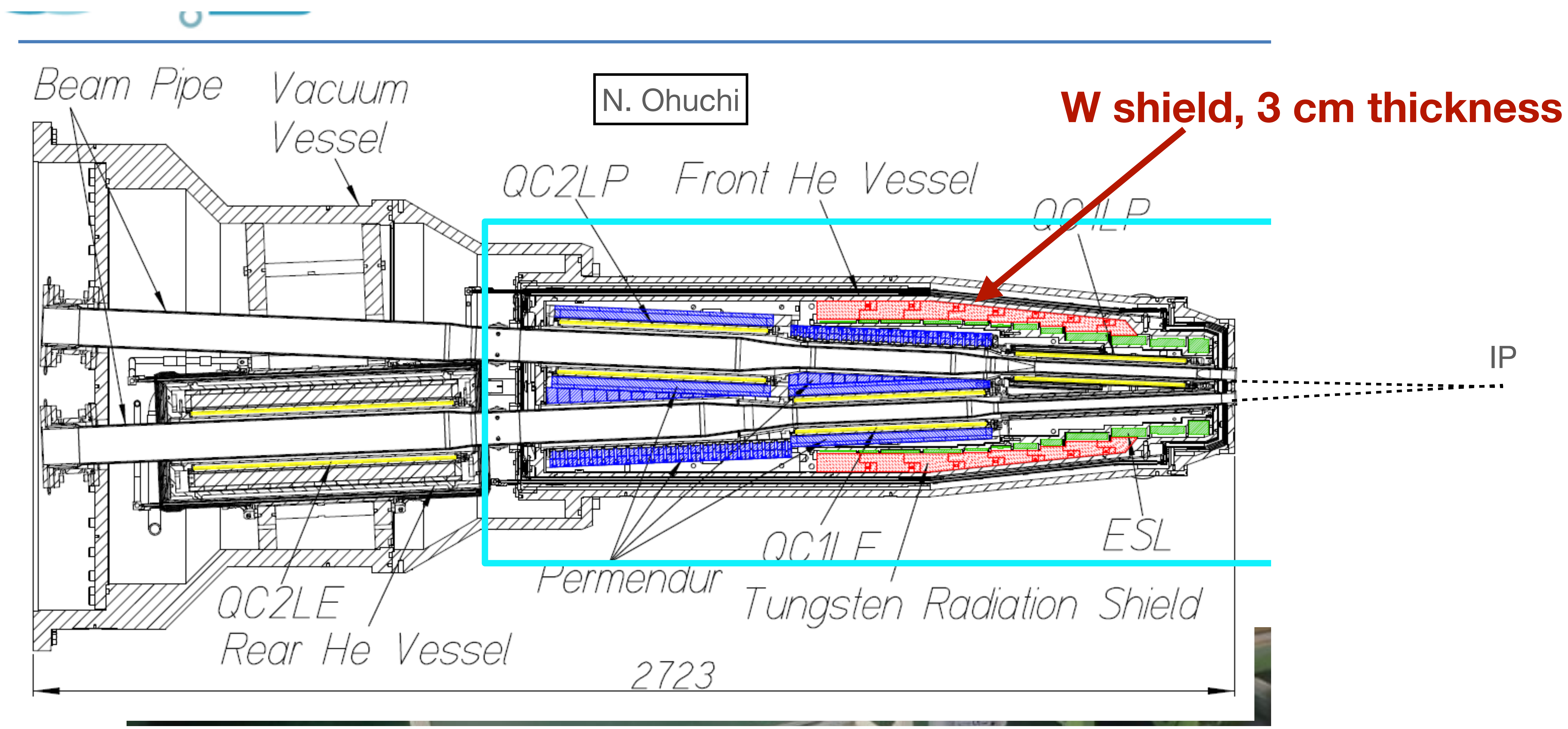
all singular values of the bi-diagonal matrix



Singular values of the bi-diagonal matrix



Some differences between SuperKEKB's



- Noticeable differences exist concerning the shielding for the detectors, from possible backgrounds by beam-gas & beam tail hitting beam pipe.
  - heavy metal inside the counter solenoid, at 1-2m from the IP.
  - FCC-ee has an almost transparent beam pipe for LumiCal in the same area.

Summary

FUTURE CIRCULAR COLLIDER

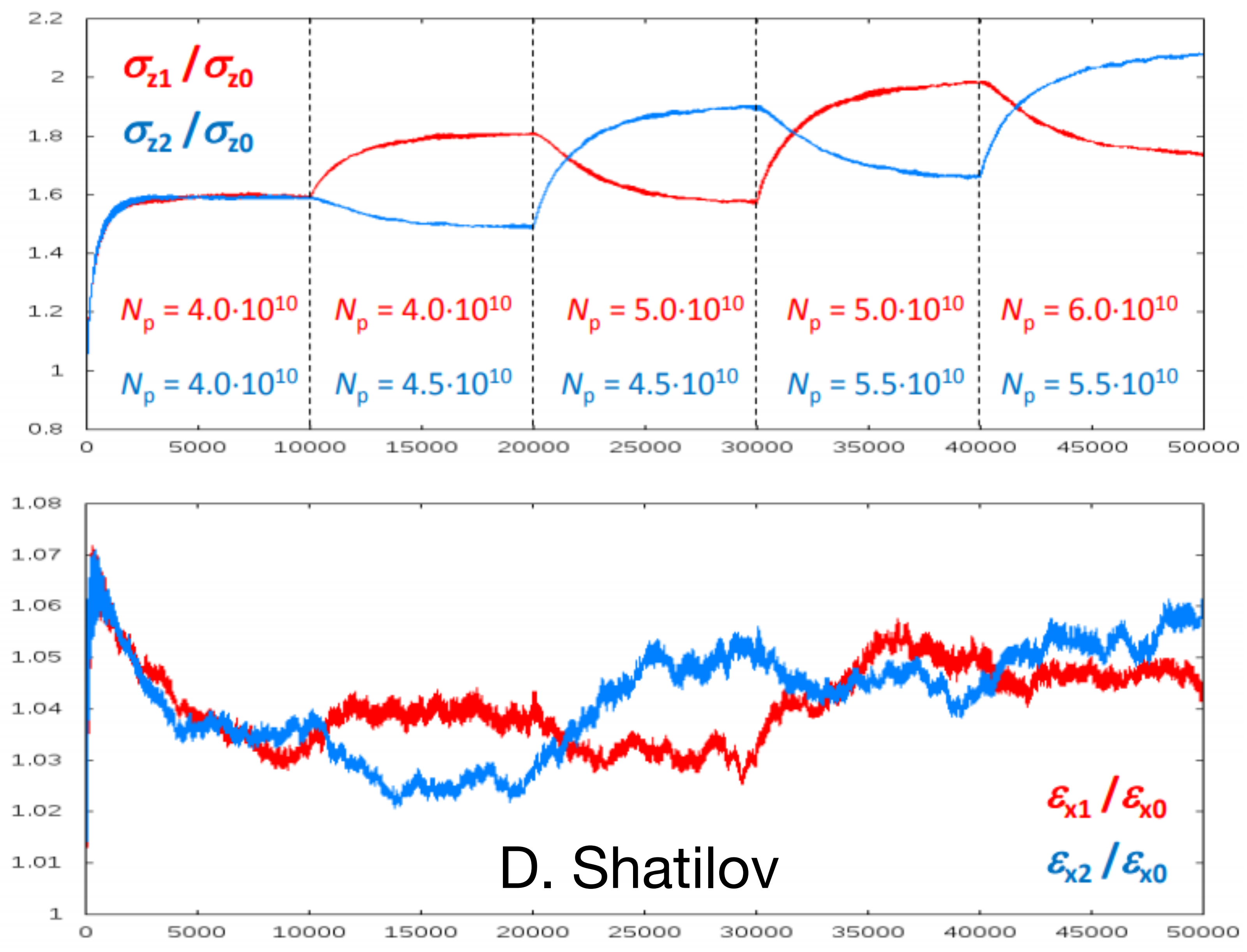
- The baseline optics design has been shown having characteristics:
  - Low magnitude of upstream SR.
  - complete compensation of solenoid field
  - integration of polarimeter at each IP
  - allocation of magnets not to intervene the outgoing beamstrahlung

- Several concerns around the IP :
  - BPM at each segment of QC{12}* .
  - Any shielding needed for the detectors within 1-2m from the IP?

Backups

Injection

- From scratch:
  - "Bootstrap" (D. Shatilov) is necessary to maintain the balance between bunch charges of two beam.
    - Charge imbalance by ±5% (Z) - ±3% (others) is allowed between *four* colliding bunches.
- Top-up:
  - Maintain the charge imbalance within the allowed range.
    - Thus the amount of injected charge must be different bunch by bunch, with *0 to 100%* deviation, since the lifetime can be different for each bunch.
- Pilot bunches:
  - Esp. at Z and W, non-colliding pilot bunches have special rolls:
    - At the beginning of each fill, first the polarizing wigglers are turned on. Then pilot bunches are injected.
    - Wait for ≳ 1 hour to polarize pilot bunches.
    - Turn off wigglers
    - Start filling colliding bunches with the bootstrapping.
- Once one beam is aborted, it is not possible to maintain the other beam. The other beam must be aborted ASAP.



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

- Bunch charge does not change from the linac through BR. It is accumulated only in the collider.
- Booster has a copy of collider bunch pattern, and injects all bunches to the collider in one turn.
- The booster operates alternatively on e+ & e-.
- For the injection from scratch, collider can accumulate the maximum bunch charge from linac up to 50% of the collision bunch charge.
- Beyond 50%, the injected bunch charge is limited by the flip-flop condition (6 - 10% of the collision bunch charge).
- Once the collision starts, the necessary bunch charge injected each time will be all different for each bunch, with 0 - 100% variation.

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	11200	1780	380	56
Collider particles / bunch N_b [10^{10}]	21.4	14.5	13.2	16.4
Allowable charge imbalance Δ [±%]	5	3		
Injector particles / bunch N_{max} [10^{10}]	≦ 2.5			
Bootstrap particles / bunch [10^{10}] $= 2N_b\Delta$	2.14	0.87	0.792	0.984
# of BR ramps (up to 1/2 stored current, with N_{max})	3	3	3	4
# of BR ramps (bootstrap with $2N_b\Delta$)	5	4	4	5
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	5600	890	190	28
Linac repetition frequency [Hz] f_{rep}	**200**	**100**	50	
Collider filling time from scratch [s]	228.8	72.8	30.8	39.42
Collider filling time for top-up [s] $= n_p/f_{rep} + t_{ramp}$	**28.6**	**10.4**	**6.3**	**4.66**
Lum. lifetime (4 IP) [s]	1330	970	660	650
Lattice+BS lifetime (4 IP) [s]	10000	4000	3500	3000
(real lattice lifetime)/(design lattice lifetime)	0.25	0.25	0.25	0.25
Collider lifetime (4 IP) τ_2 [s]	868.1	492.4	376.2	348.2
Collider top-up interval (between e+ and e-)(4 IP) [s] $= \tau_2\Delta$	**43.4**	**14.8**	**11.3**	**10.4**

Vibration of quadrupoles

https://indico.cern.ch/event/1186798/contributions/5062667/attachments/2533360/4362351/Vib_Oide_221025.pdf

1.3 Non-resonant vibration

Next let us look at the off-resonant contribution of Eq. (7). If we roughly approximate the tune-dependent term by 1, the integrated power spectrum in a range $\omega \geq \omega_c$ is given by

$$\langle \Delta y^{*2} \rangle = \frac{N_q \beta^* \beta_q k_q^2}{4} \int_{\omega_c}^{\infty} S(\omega) \frac{d\omega}{2\pi} = \frac{N_q \beta^* \beta_q k_q^2 \sigma}{24\pi\omega_c^3} . \tag{15}$$

In the case for the previous measurement, we estimate $\sigma \sim 1.6 \times 10^{-12}\,\mathrm{m^2/Hz}$, then

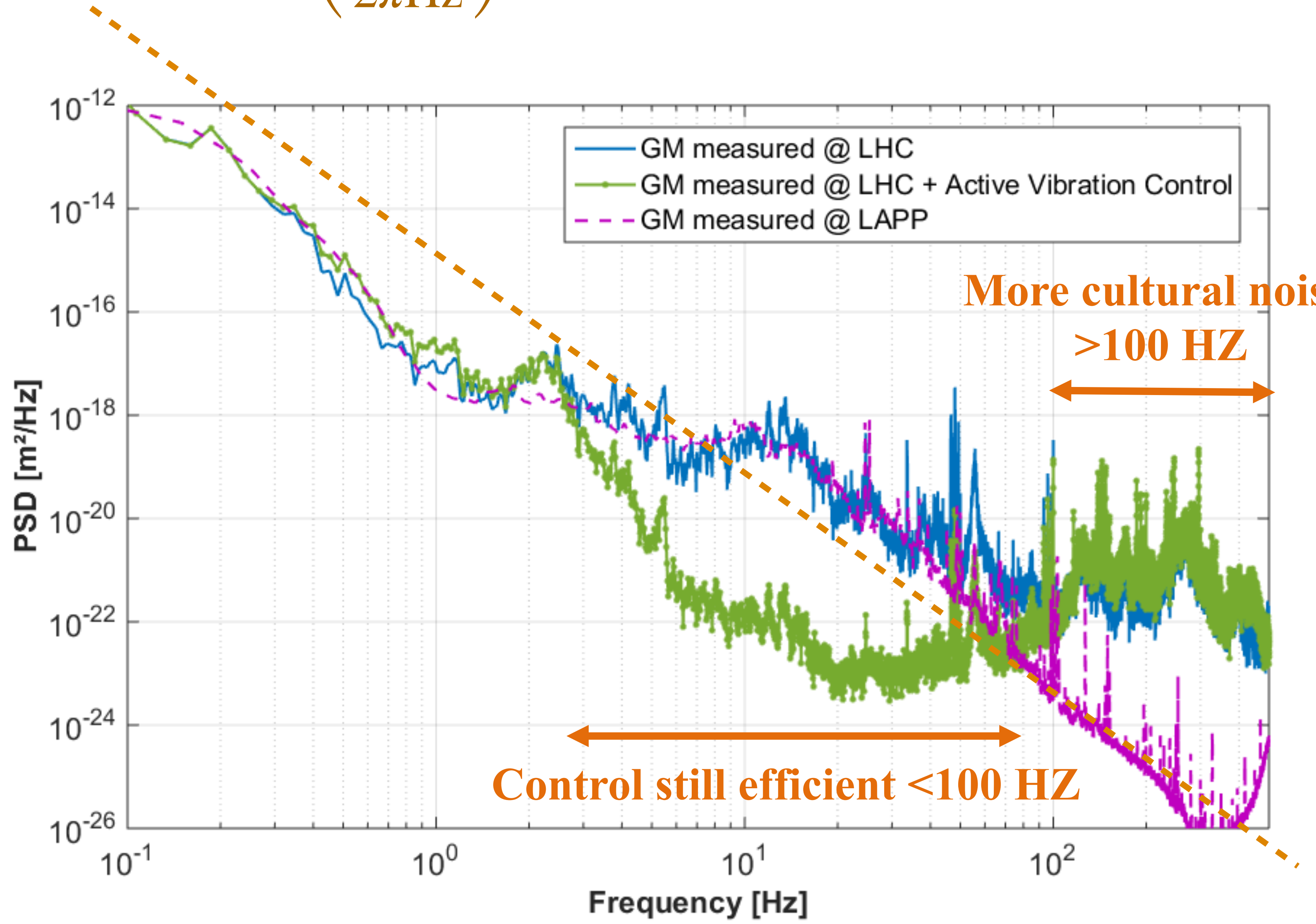
$$\sqrt{\Delta y^{*2}} \sim 32.9\,\mathrm{nm} \tag{16}$$

for $\omega_c = 2\pi \times 1\,\mathrm{Hz}$. The assumption here is that below the critical frequency ω_c, an orbit feedback suppresses the beam oscillation perfectly. Thus the expected vibration reaches to the vertical beam size at the IP. Among the vibration, the dominant contribution comes from the final quads "QC{12}*". If we exclude them, the expected vibration becomes

$$\sqrt{\Delta y^{*2}}_{\text{excl. QC\{12\}*}} \sim 5.8\,\mathrm{nm} . \tag{17}$$

This value means that the contribution from other quads is small, but still not negligible. Suppressing the vibration of the final quads as well as an orbit feedback system working beyond 1 Hz will be crucial.

$S(\omega) \sim 10^{-15} \left(\frac{\omega}{2\pi\mathrm{Hz}}\right)^{-4}\ \mathrm{m^2/Hz}$



M. Serluca, et al.

https://indico.cern.ch/event/694811/contributions/2863859/attachments/1595533/2526938/2018_02_06_FCCee_MDI_workshop_Serluca.pdf

Correlation between $e^{\pm}$

Let us discuss the vertical displacement of a bunch at the IP, arriving at $t = 0$. The vertical displacement of a positron Δy_+^* at the IP caused by a quadrupole for positrons, located at vertical phase advance ϕ_q from the IP, vibrating with an amplitude Δy_q and an angular frequency ω_q is written as:

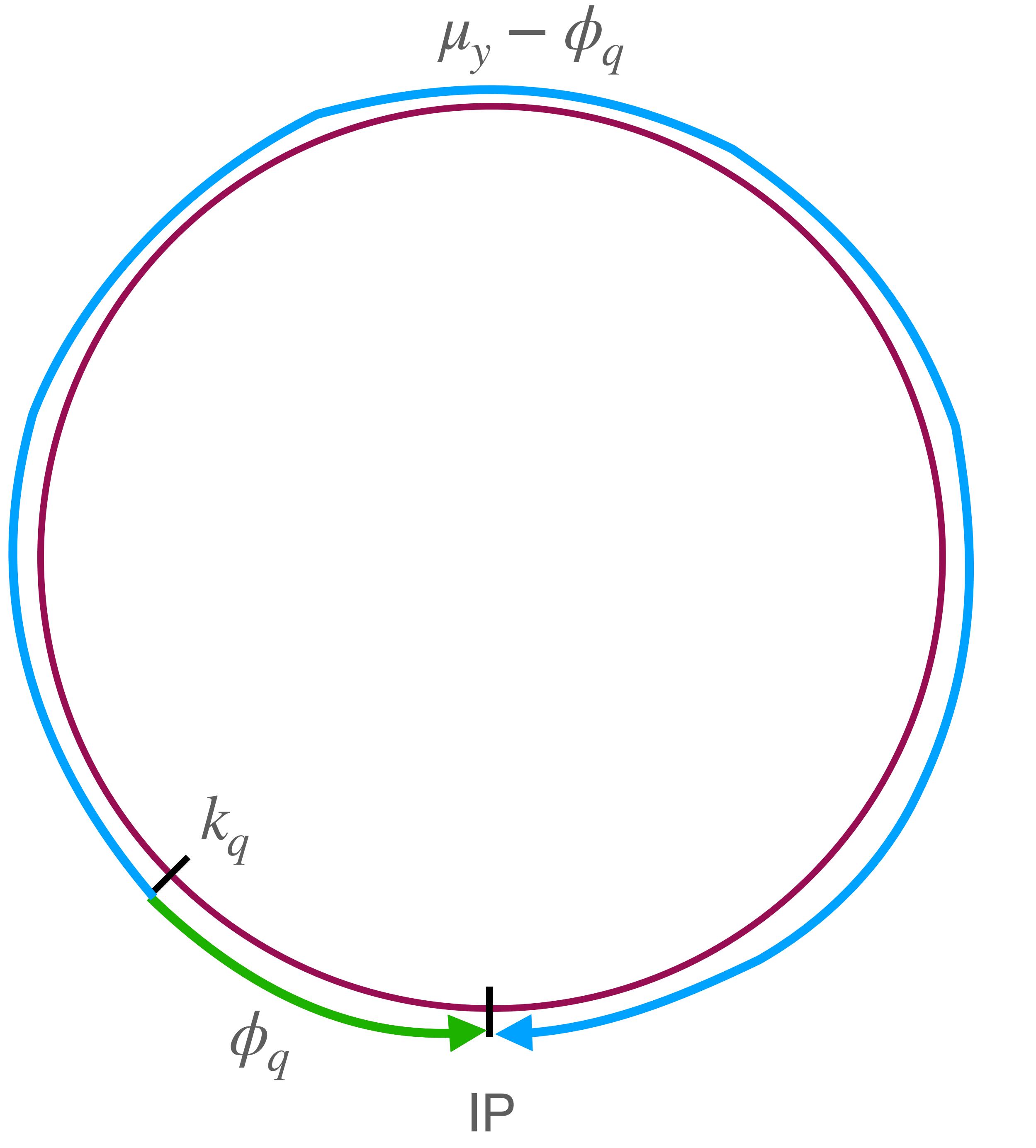
$$\begin{aligned}\Delta y_+^* &= \sum_n \sqrt{\beta^* \beta_q} \exp(-nT_0/\tau_y - i\omega_q t_{q+}) \sin(\phi_q + n\mu_y) k_q \Delta y_q \\ &= \sum_n \sqrt{\beta^* \beta_q} \exp(-n\alpha_y + i(n + n_q)\mu_q) \sin(\phi_q + n\mu_y) k_q \Delta y_q \,,\end{aligned} \quad (1)$$

where μ_y, T_0 & τ_y, are the vertical betatron angular tune, the revolution & damping times, and $\alpha_y \equiv T_0/\tau_y$, $\mu_q \equiv \omega_q T_0$, $n_q \equiv \phi_q/\mu_y$. β^*, β_q, k_q are the beta functions at the IP and the quadrupole, and the focusing strength of the quadrupole. We can assume that $t_{q+} \approx -(n + n_q)T_0$.

The current design of the collider optics employs a twin-aperture quadrupole magnet for arc quadrupoles. Although both quadrupoles for $e^{\pm}$ are mechanically tight coupled, they have opposit focusing/defocusing, having different *betas*. So we do not have to care about their interference on the vibration. Another source of the vibration is the final focusing quad QC1, having the same strength and polarity for two beams. The motion of the electron beam caused by the same quad is written as

$$\Delta y_-^* = \sum_n \sqrt{\beta^* \beta_q} \exp(-n\alpha_y + i(n + 1 - n_q)\mu_q) \sin(\phi_q + n\mu_y) k_q \Delta y_q \,, \quad (2)$$

by replacing $\phi_q \to \mu_y - \phi_q$ in Eq. (1), and the source time is given by $t_{q-} \approx -(n + 1 - n_q)T_0$.



$\beta_y^* = 0.7\,\mathrm{mm}$, $\mu_y = 222.2 \times 2\pi$,

$\phi_q = \pi/2$, $T_0 = 0.3\,\mathrm{ms}$, $\alpha = 4.28 \times 10^{-4}$,

$\beta_q = 12000\,\mathrm{m}$, $k_q = 0.2\,/\mathrm{m}$

Correlation between $e^{\pm}$ (2)

Then we sum up above over n from 0 to infinity, we obtain the difference between the positron and electron bunches as:

$$\Delta y^*(\infty) = A(f)\Delta y_q \,, \tag{3}$$

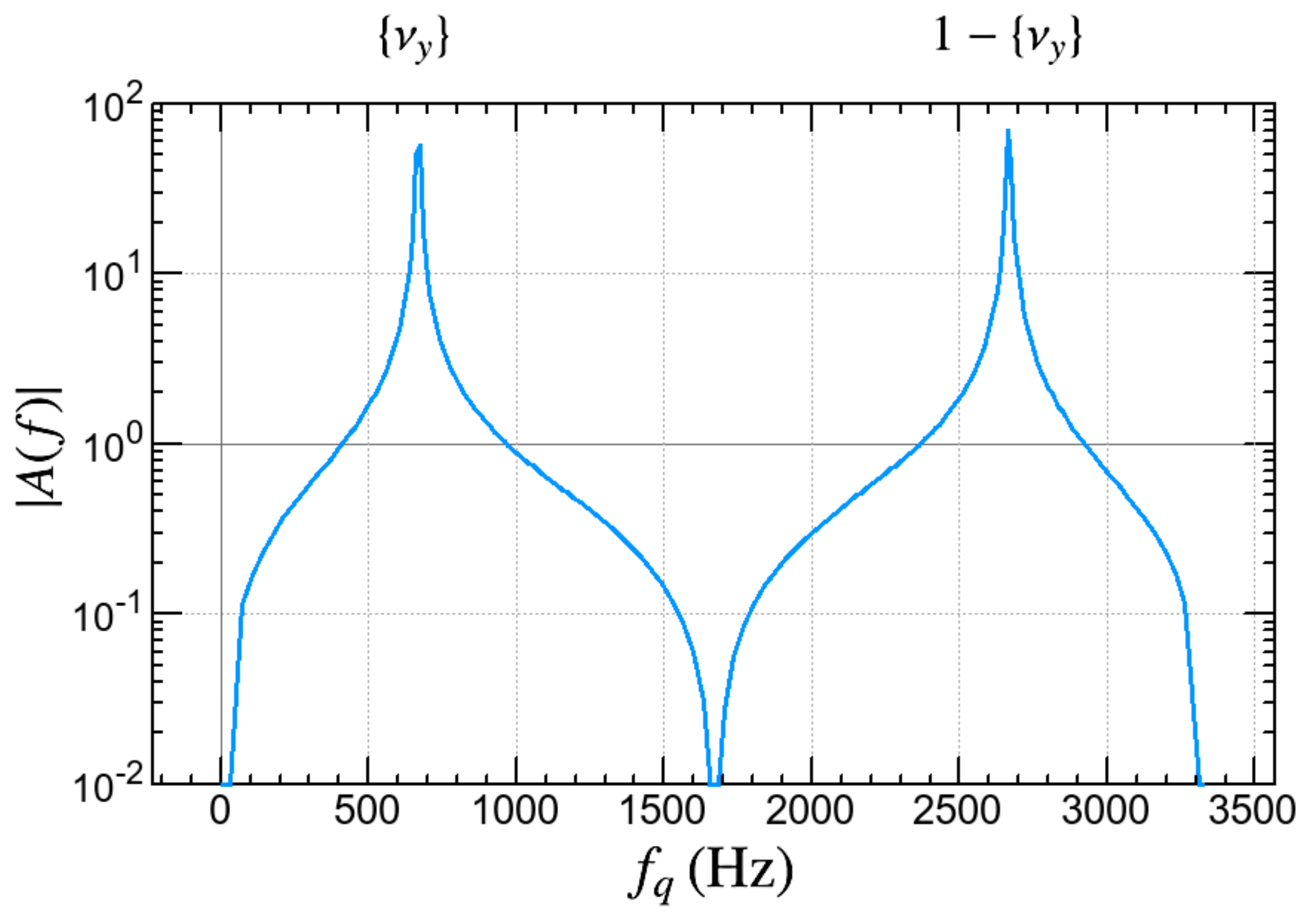
where f is the vibration frequency of the quadrupole $f = \omega_q/2\pi$, and $A(f)$ is the attenuation factor can be analytically obtained from above. We do not write $A(f)$ here as it is a little bit lengthy.

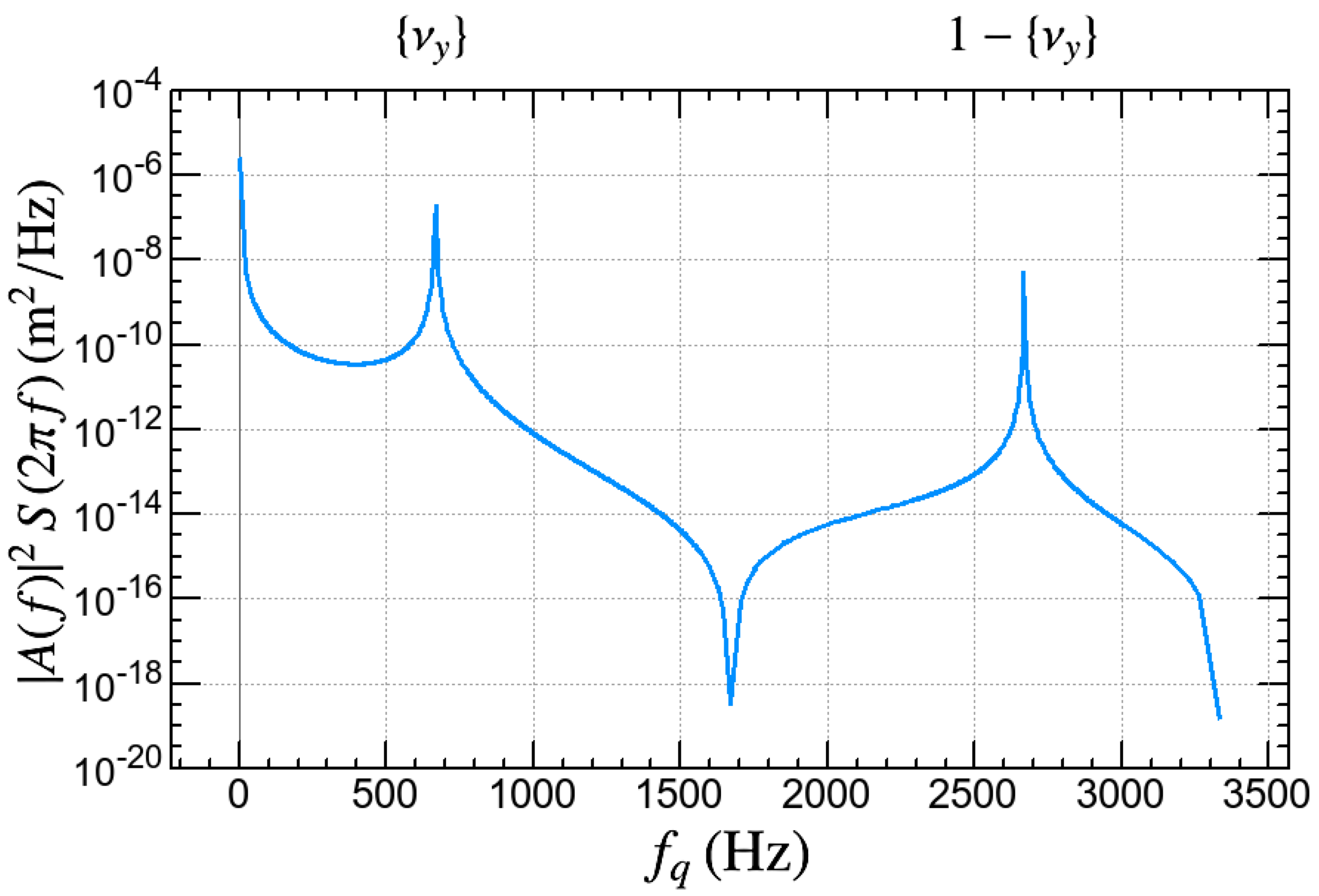
The right plot shows $A(f)$ for the final quad `QC1L1` with the optics for Z. Two peaks are seen at the fraction of tune, $\{\nu_y\}$ and $1 - \{\nu_y\}$.

By integrating the product of $A(f)^2$ and the ground motion $S(\omega)$, from a critical frequency ω_c up to the revolution frequency. we obtain the magnitude of the vertical difference:

$$\begin{aligned}\langle \Delta y^{*2} \rangle &= \int_{f_c}^{1/T0} A(f)^2 S(2\pi f) df \\ &= (96\,\mathrm{pm})^2 \,,\end{aligned} \tag{4}$$

for $fc = 1\,\mathrm{Hz}$. This number seems small even if we take all 8 similar quads into account.





Summary

- Lattices of FCC-ee collider rings 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.
    - Further optimization and modifications are expected on lattice, tunes, β^*, crab waist ratio, bunch charge (ξ_y),…
- No machine error has been assumed so far. Errors/correction/tuning are the next step. Please see my presentation tomorrow.
- The requirements on the injector linac are shown. Even with 1/4 lattice lifetime, the repetition rates of the linac are below 200 Hz (Z), 100 Hz (W), and 50 Hz (Zh,tt).
- The e+e- correlation on the vibration has been estimated.

The 4 IP layout

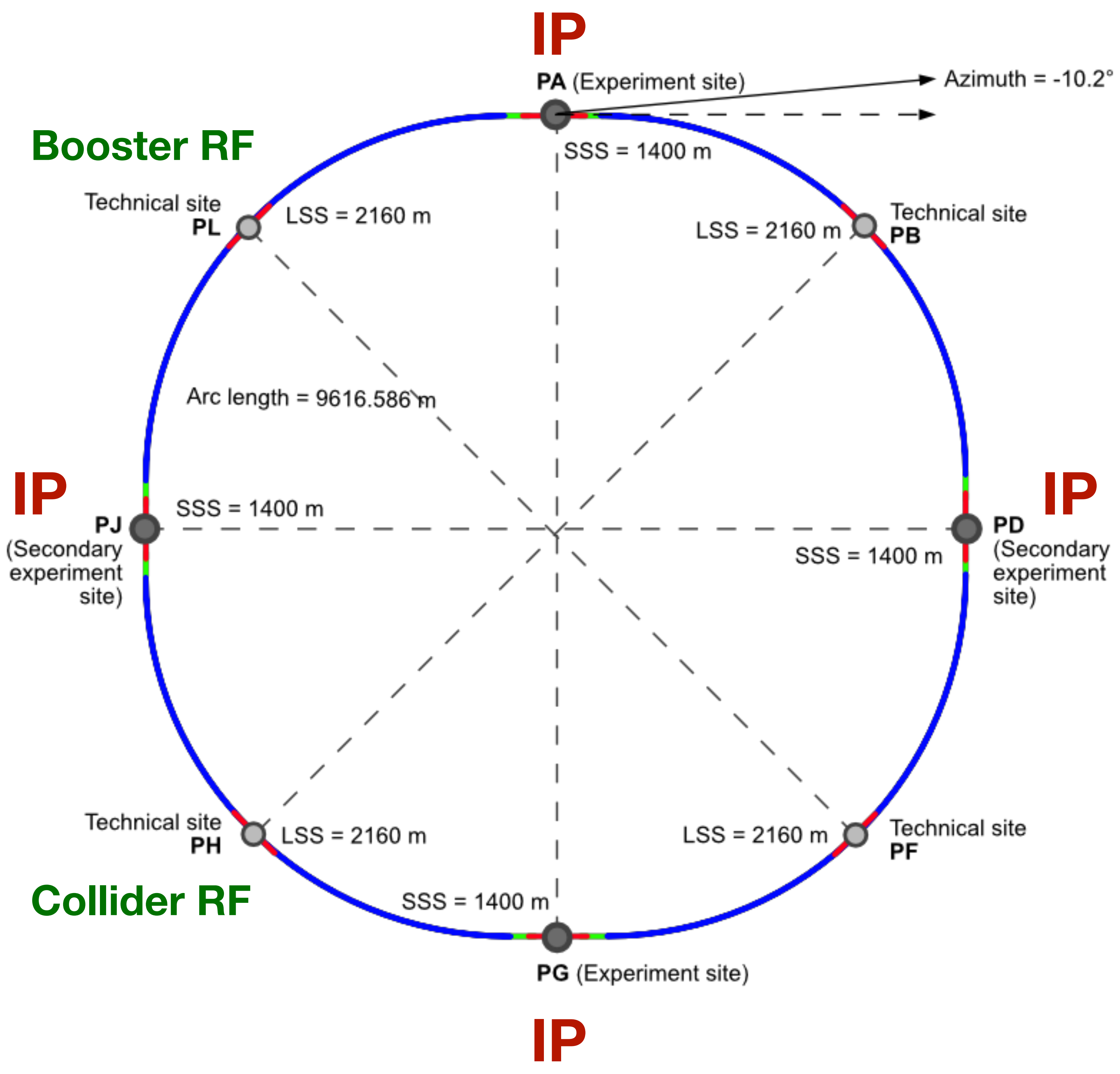


Table 1 Parameters of the layout in meter.

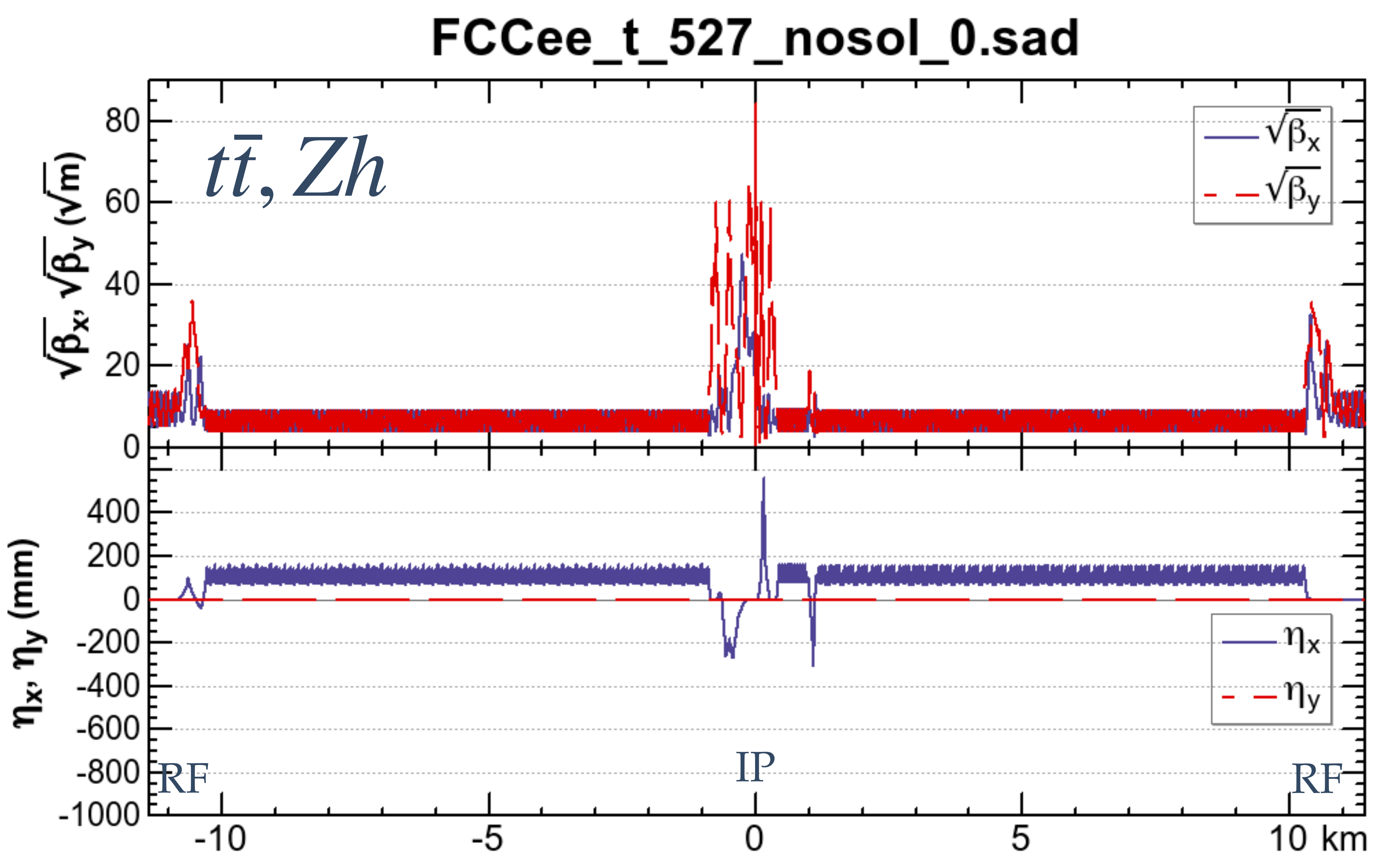
Layout	circumference	arc	LLSS	SLSS (IP)
PA31-3.0	90657.400	9616.175	2032.000	1400.000
CDR	97765		2760	1450

- 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.

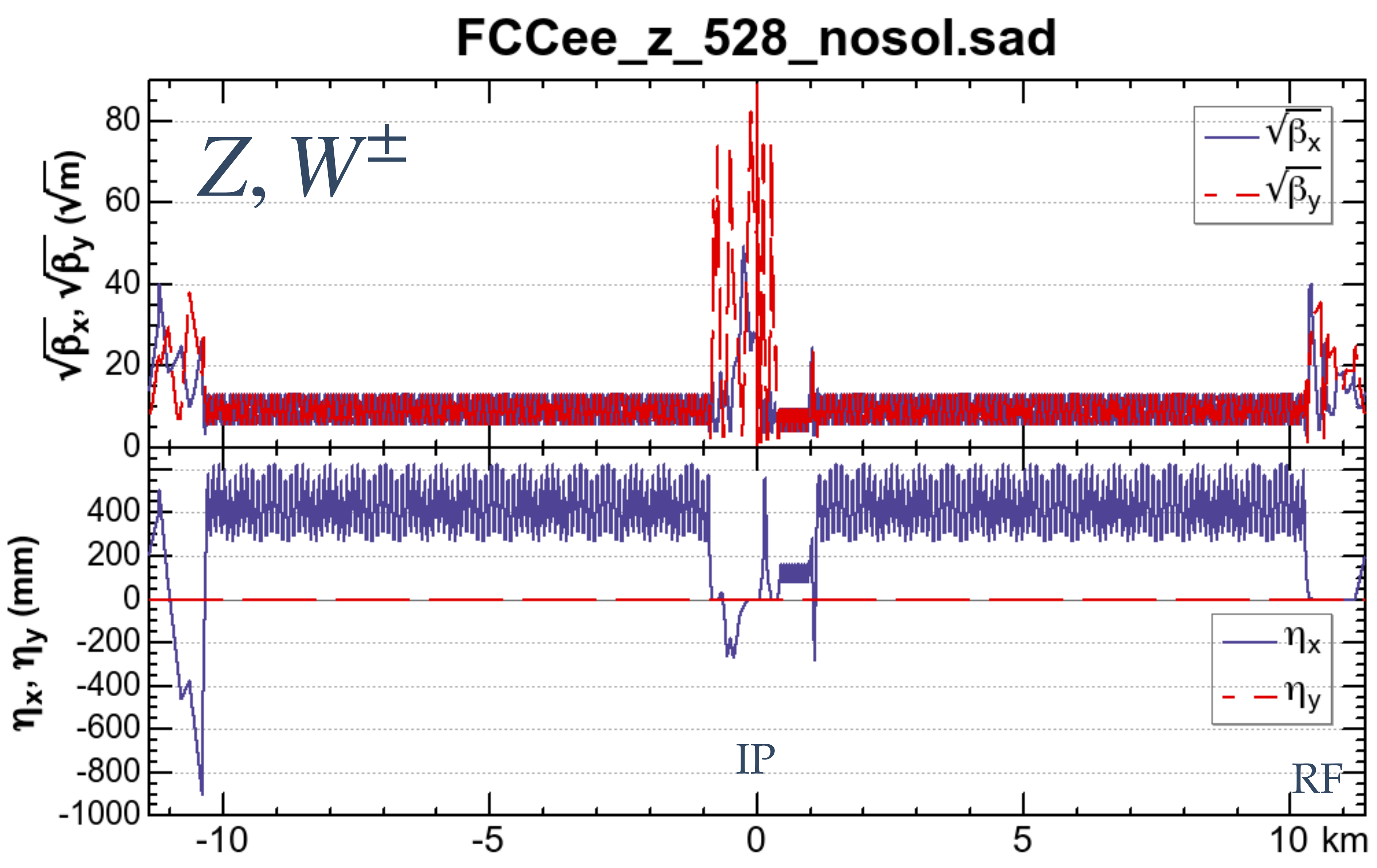
History of Final Focus

Machine	Year	Local CCS plane	arc sexts families	remarks
PEP-II LER	1998	X		
KEKB LER	1999	Y	52	
SuperKEKB LER/HER	2015	X & Y	51	X-CCS has not been effective up to now, as β_x^* is much larger than design (8 cm vs 3 cm).
FCC-ee		Y	75 (Z/W) 146 (H/tt)	
CEPC		X & Y	32 ?	
SLC	1987	X & Y interleaved		
FFTB	1995	X & Y		X-CCS was not effective, as β_x^* was much larger than design (100 mm vs 10 mm).
ATF2	2008	X & Y		X-CCS has not been effective until now, as β_x^* is much larger than design.

Ring optics (1/4 ring)



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



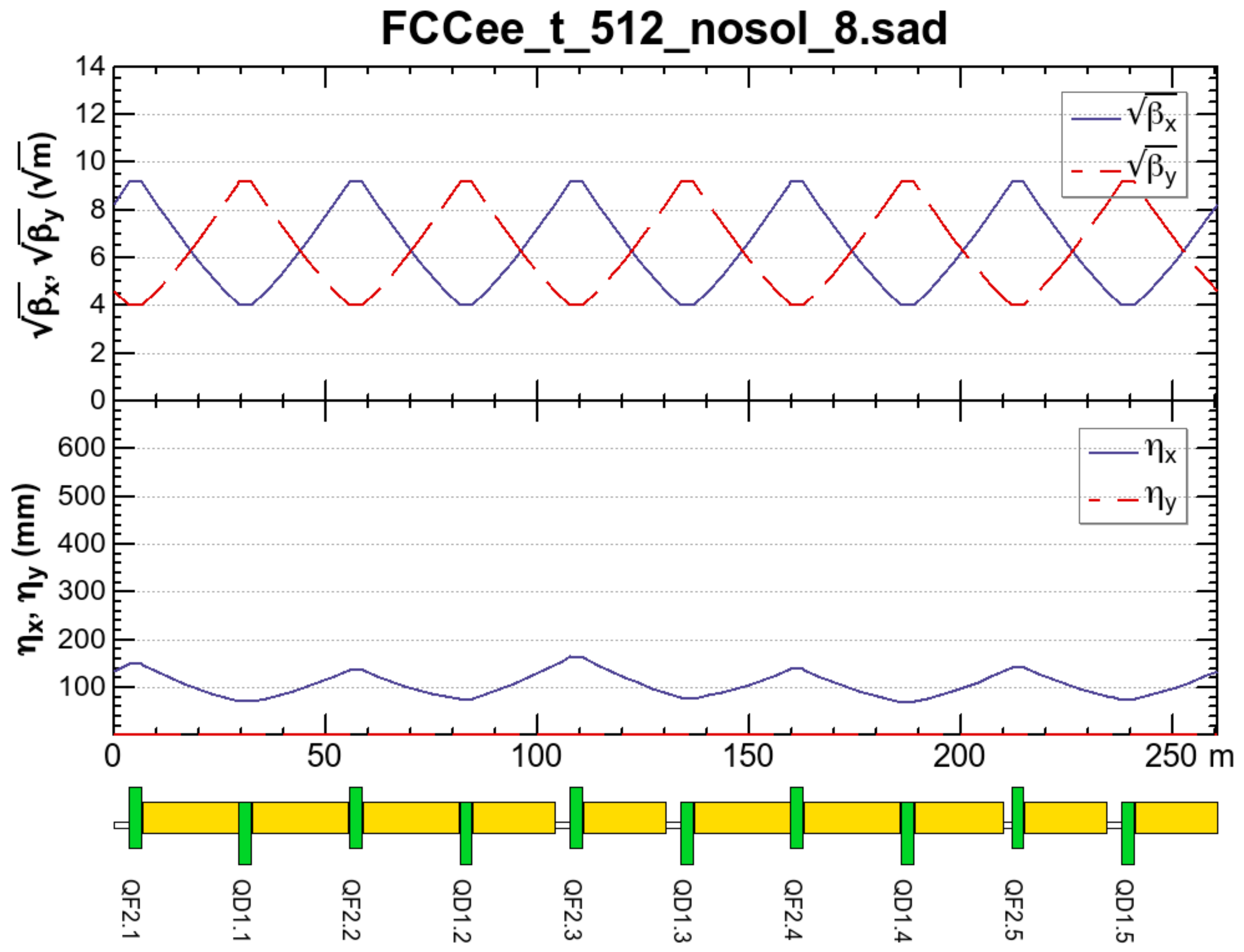
90 Long 90/90 FODO cells / arc.
8 arcs / ring

- The separation between two beams in the arc is 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.

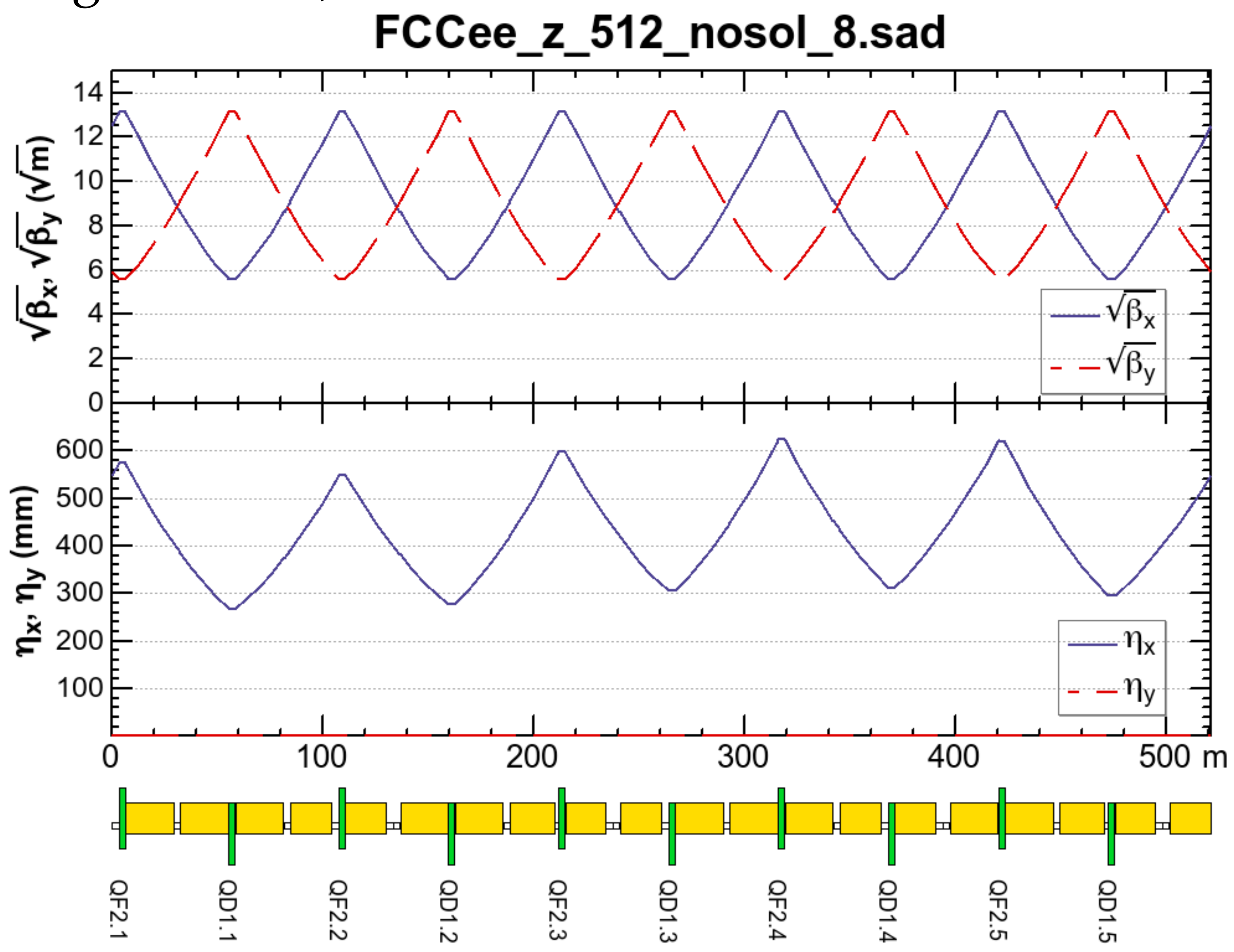
The beam optics shown here and later are not always the latest ones in details.

The arc cell optics (1 period = 5 FODOs)

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



Long 90/90: Z, W



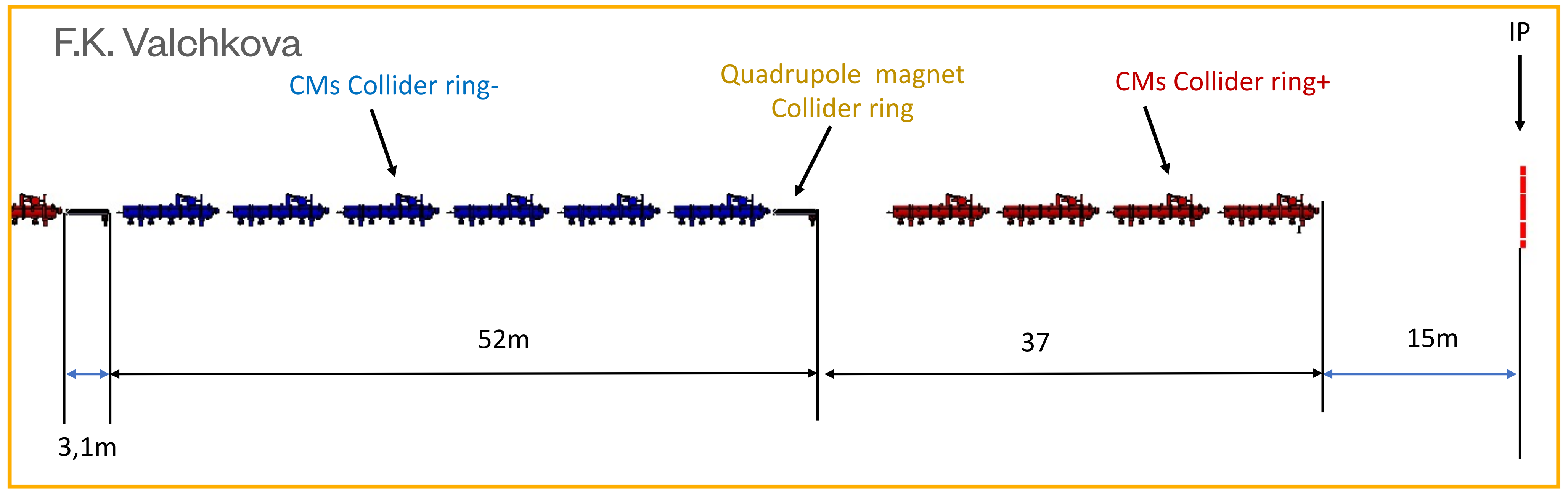
The beam optics shown here and later are not always the latest ones in details.

- 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

FUTURE CIRCULAR COLLIDER

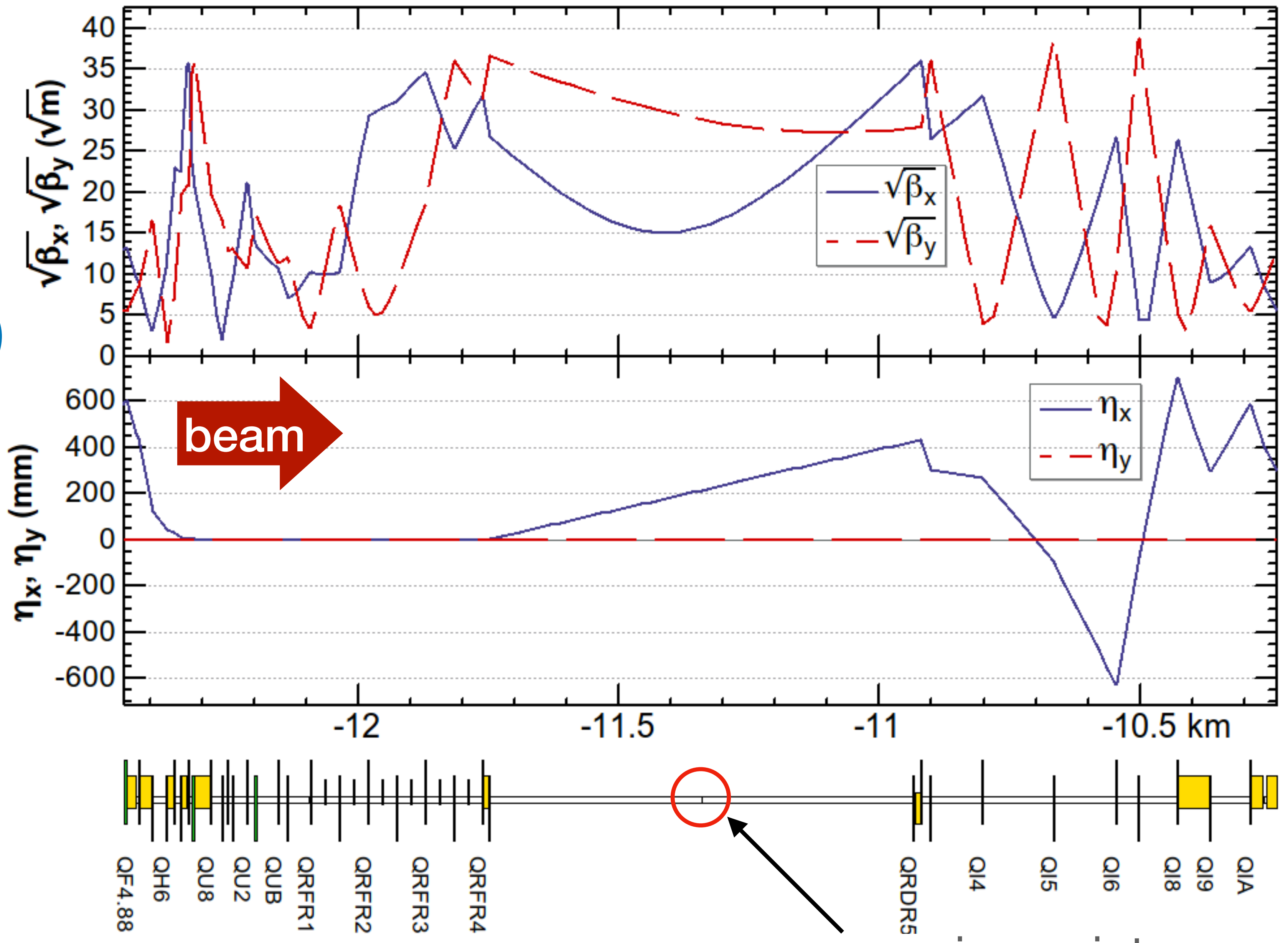
- The sections BFHL are used for beam inside/outside exchange, RF, injection, extraction, collimation, etc.
- RF is installed only one of these sections, for all energies.
- For RF cryomodules, each space between quads is extended from 40 m to 52 m according to the request by F.K. Valchkova.
- The center 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.

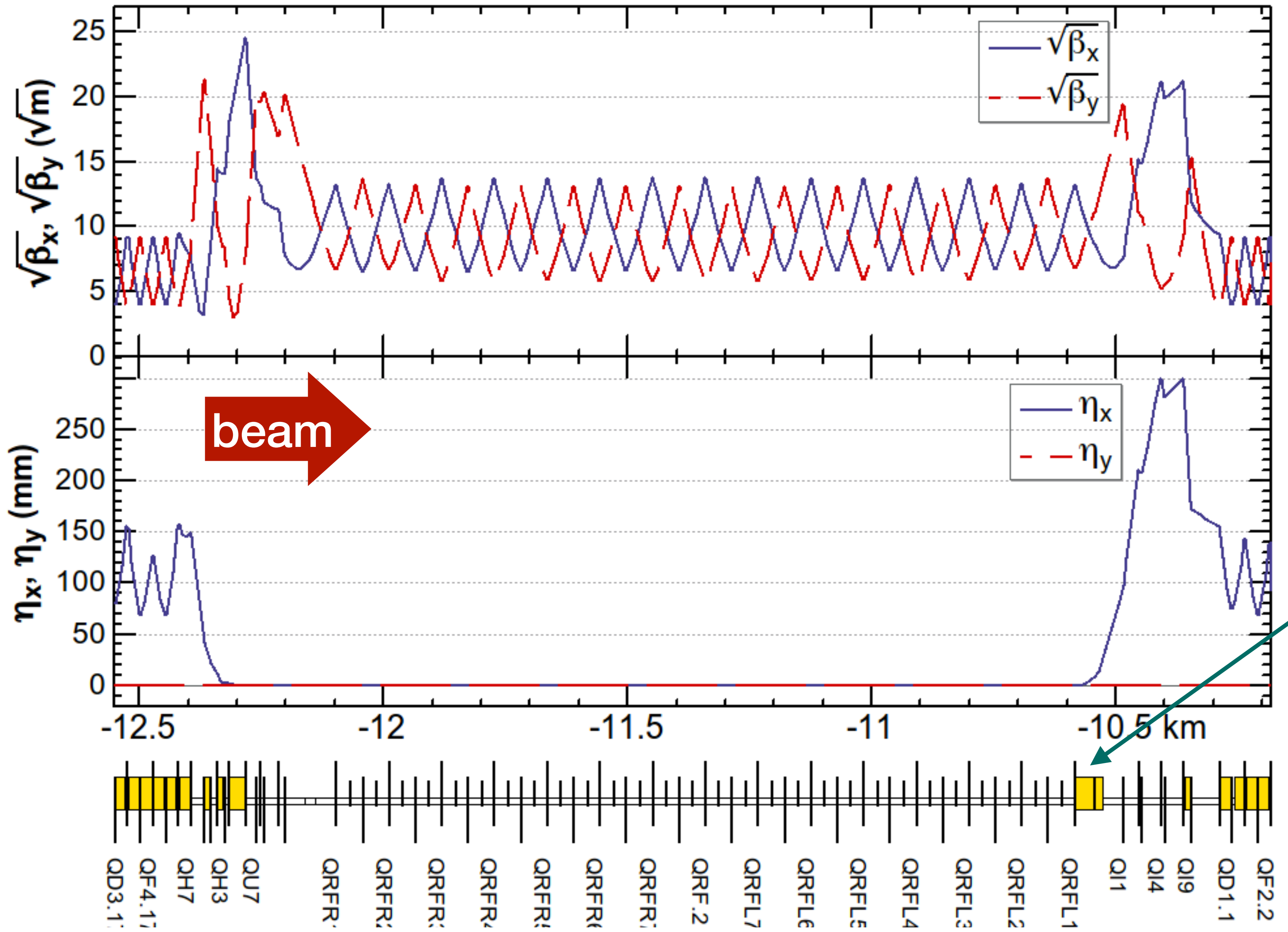
Z/W, Zh/tt (no RF)

FCCee_z_546_nosol_1.sad



RF (single beam)

Zh/tt (RF) FCCee_t_546_nosol.sad



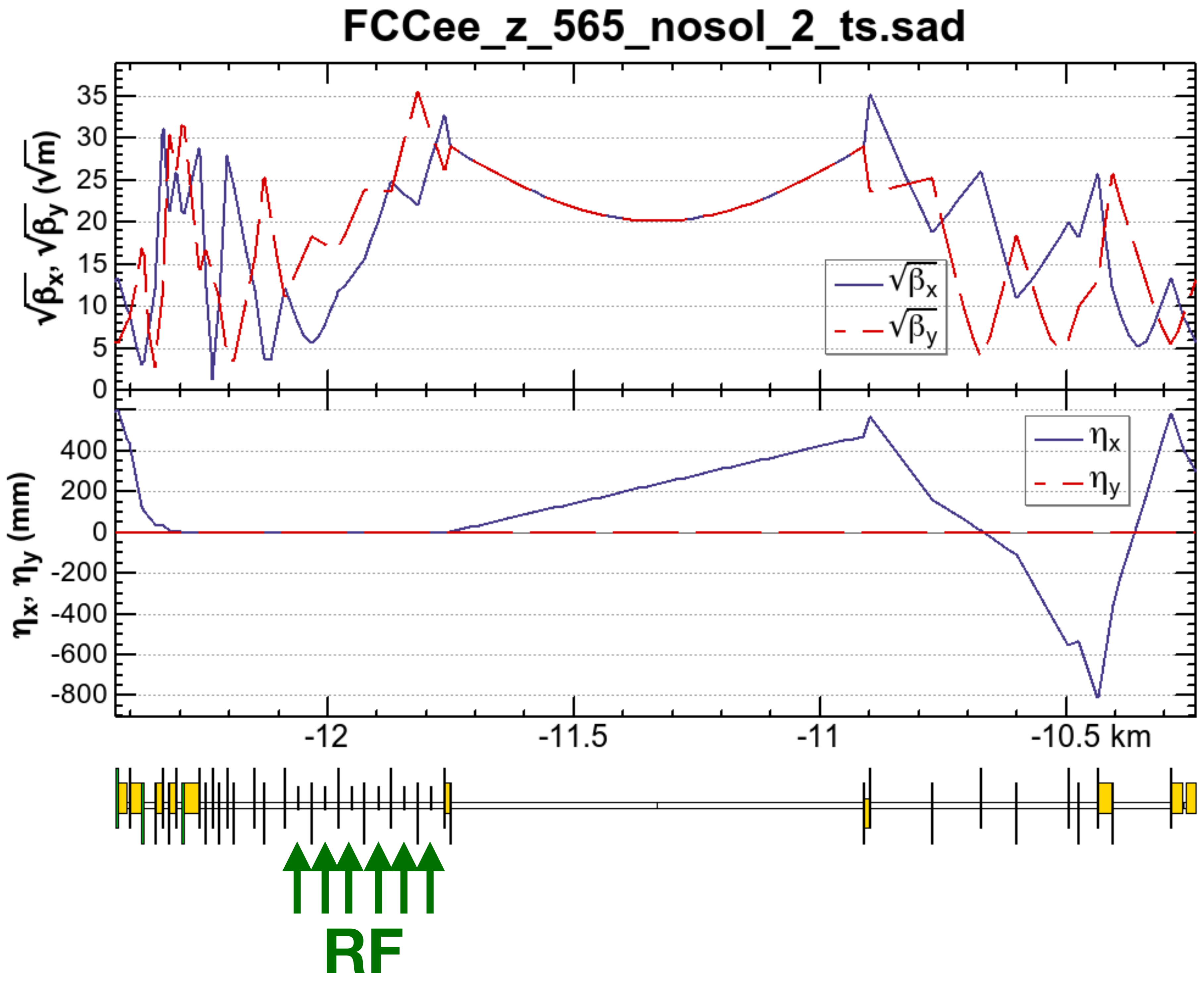
RF cryomodules common to e+e-

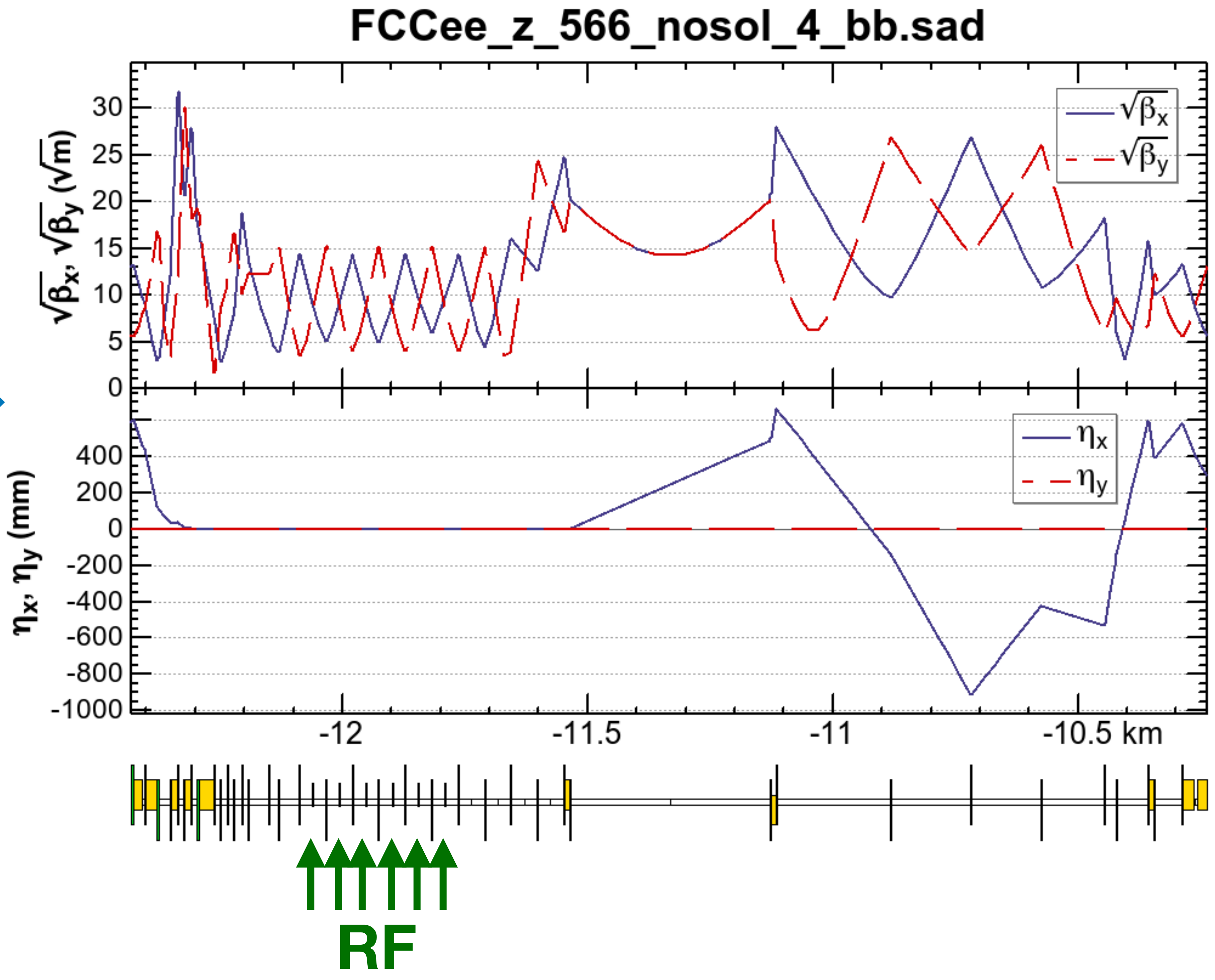
Separator; combination of electrostatic & magnetic

Only outgoing beam is deflected

Modification of the crossing section (LLSS)

FUTURE CIRCULAR COLLIDER





- 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.

Expected further studies/modifications in optics design

- 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).
    - Also for the crab/YCCS sexts (“SY*”).
- Detailed optimization for the SR around the IP incl. masking.
- Reflect the alignment strategy on magnets and/or girders.
- Employ field profiles with higher multipoles estimated by magnet design.
- Place BPMs and correctors.