FCCee systems: requirements for beam instrumentation
Main ring and MDI region

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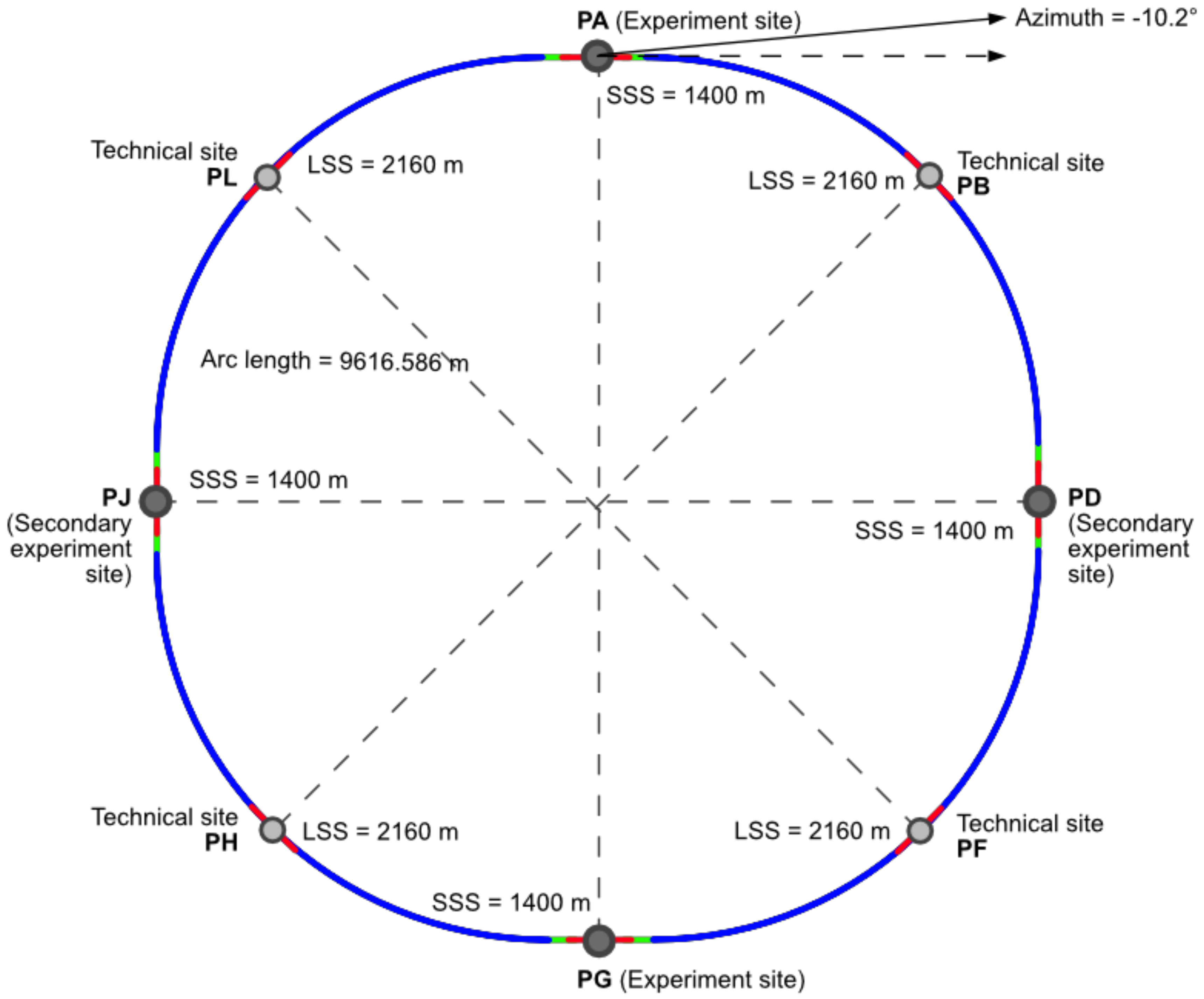
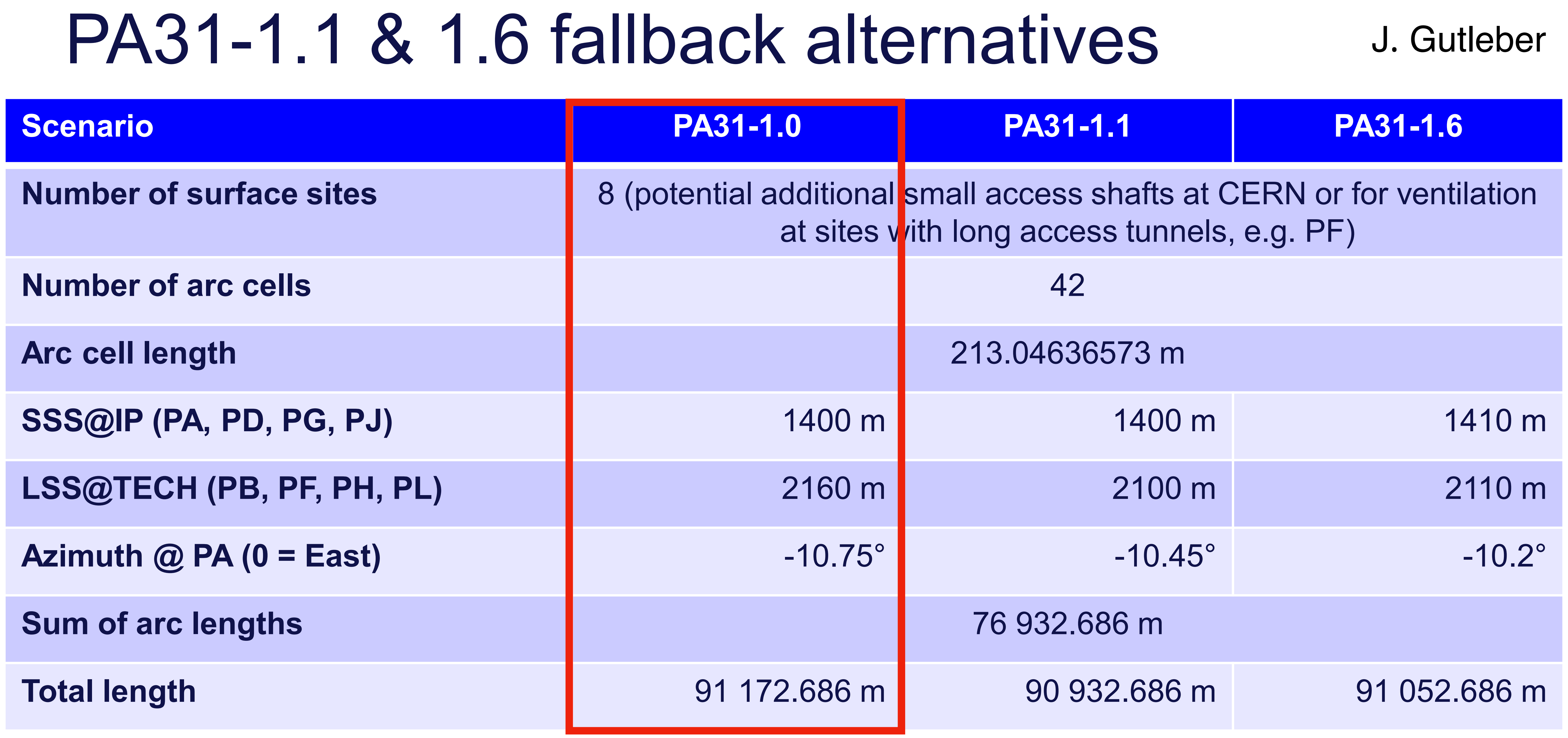
Nov. 21, 2022 @1st FCCee Beam Instrumentation Workshop

Many thanks to T. Charles, M. Hofer, T. Lefevre, S. Mazzoni, T. Raubenheimer, M. Wendt, F. Zimmermann, and all FCC-ee/FCCIS colleagues

The 4 IP layout

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



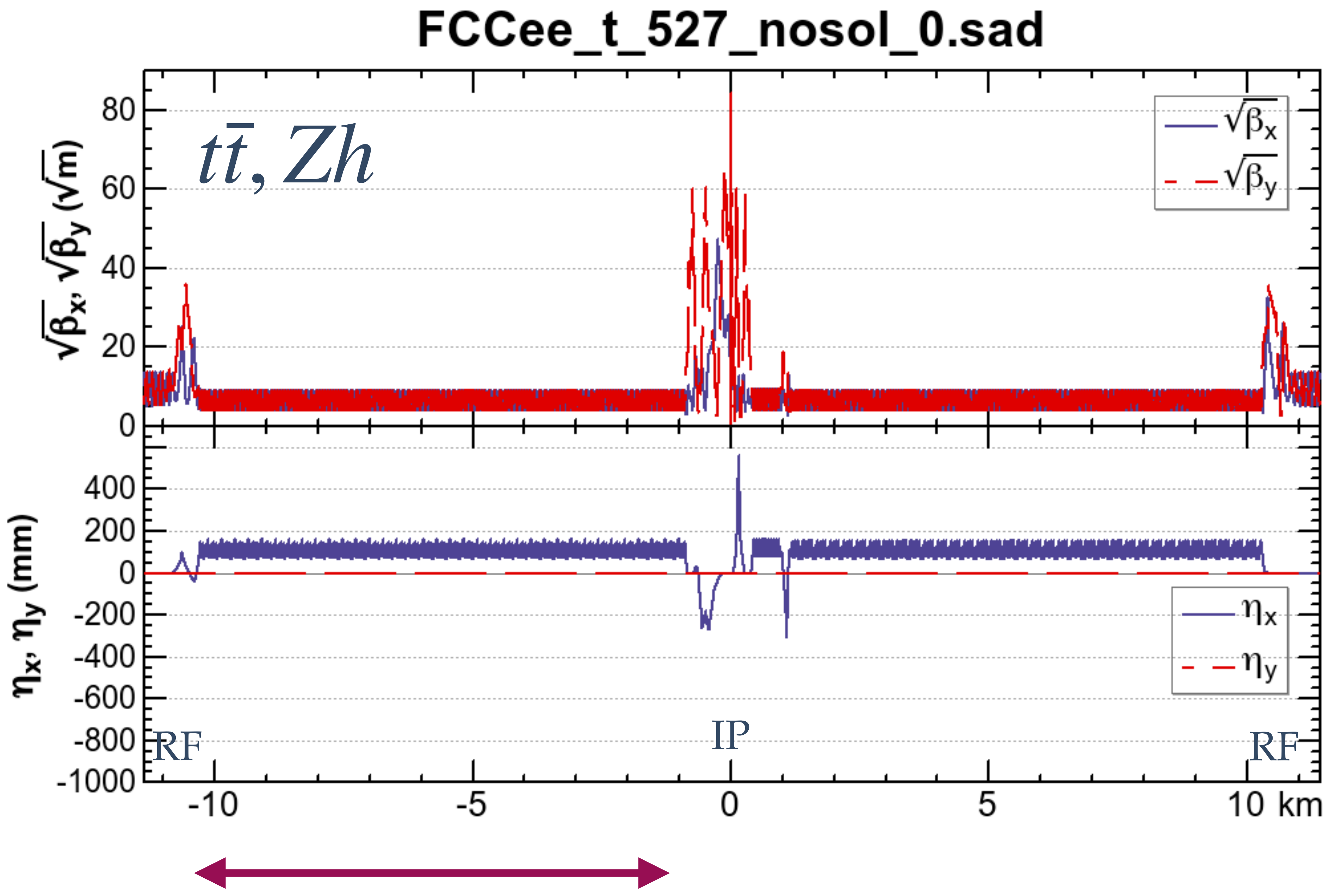


PA31-1.1 & 1.6 fallback alternatives

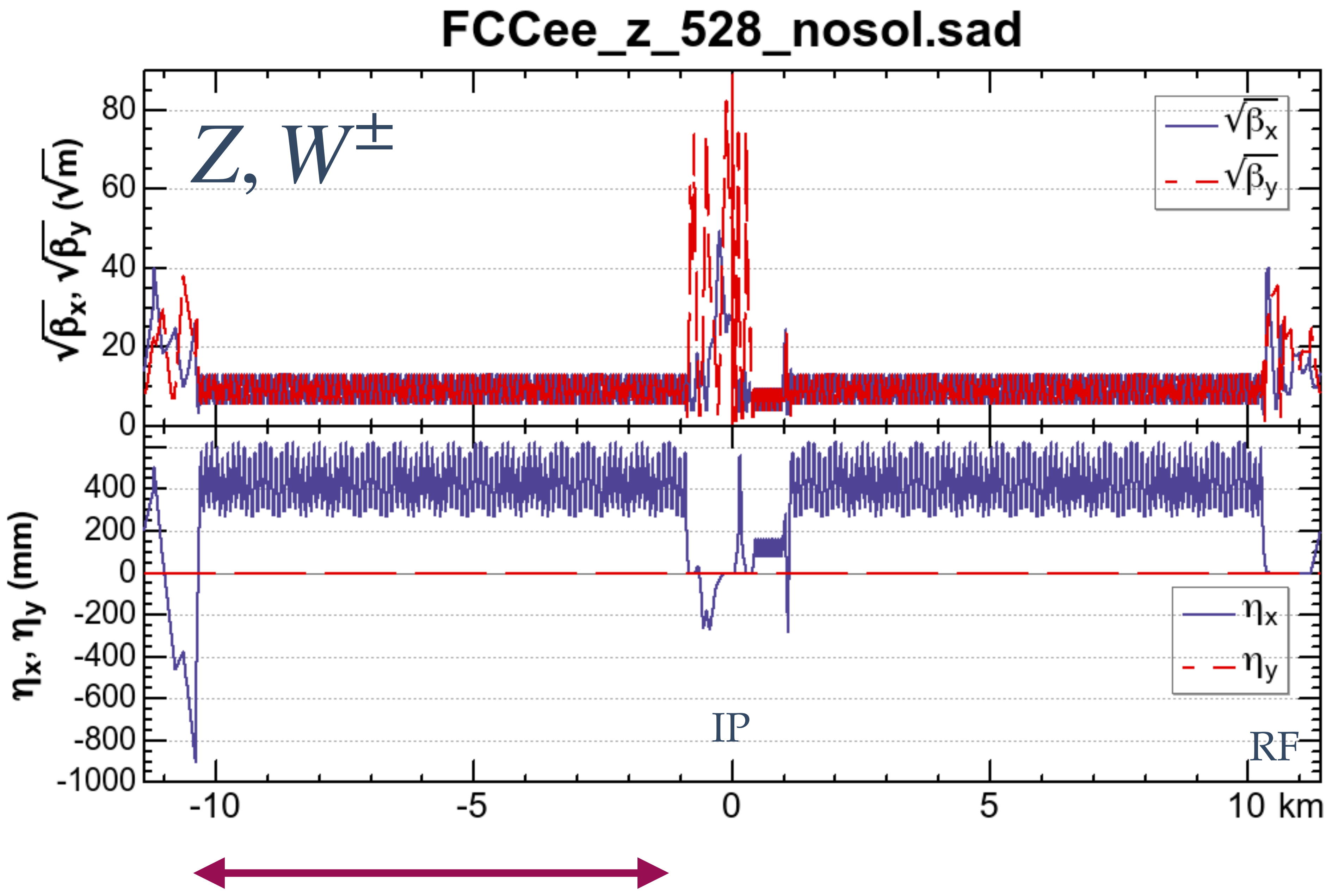
J. Gutleber

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

Ring optics (1/4 ring)



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



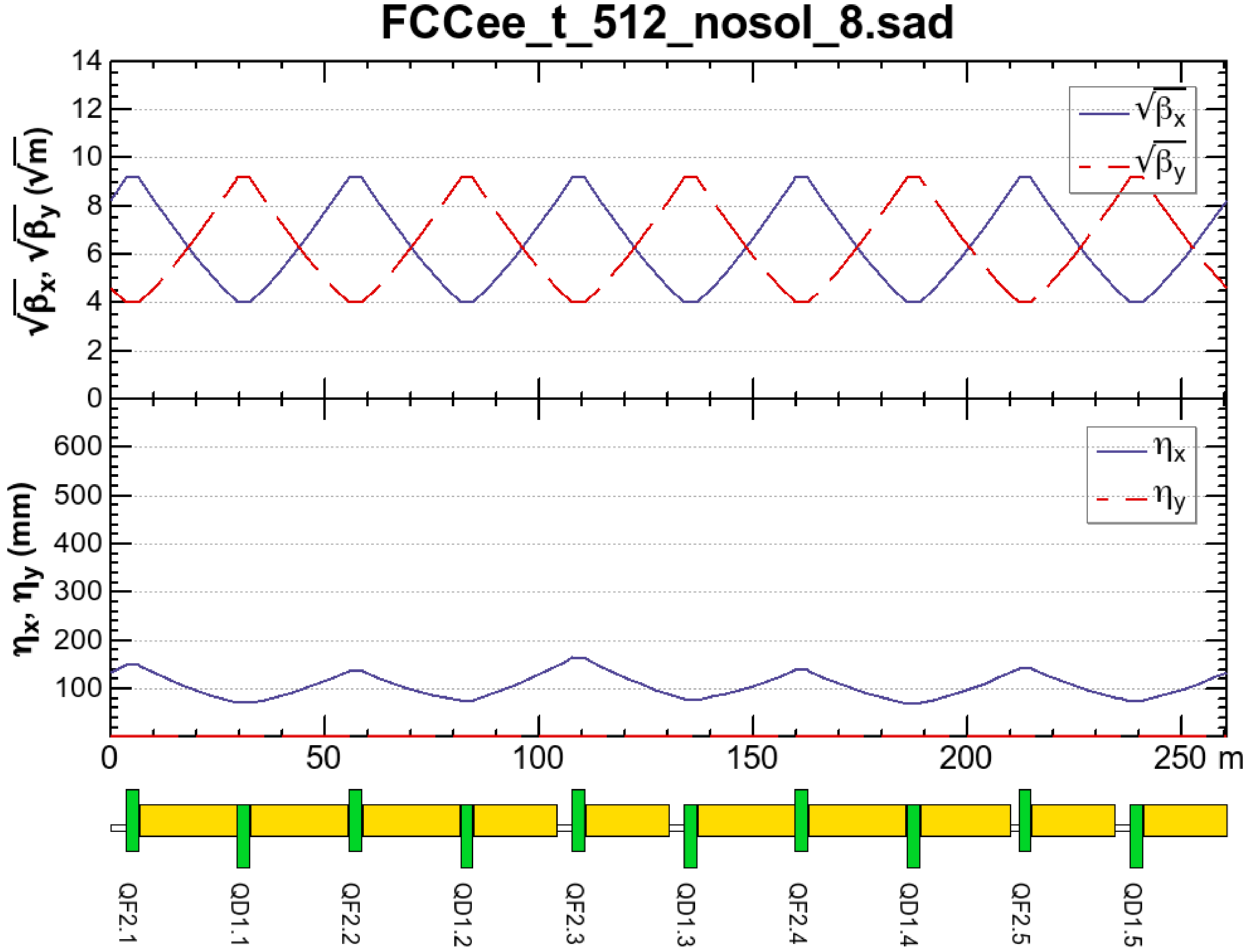
90 Long 90/90 FODO cells / arc.
8 arcs / ring

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

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

The arc cell optics (1 period = 5 FODOs)

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



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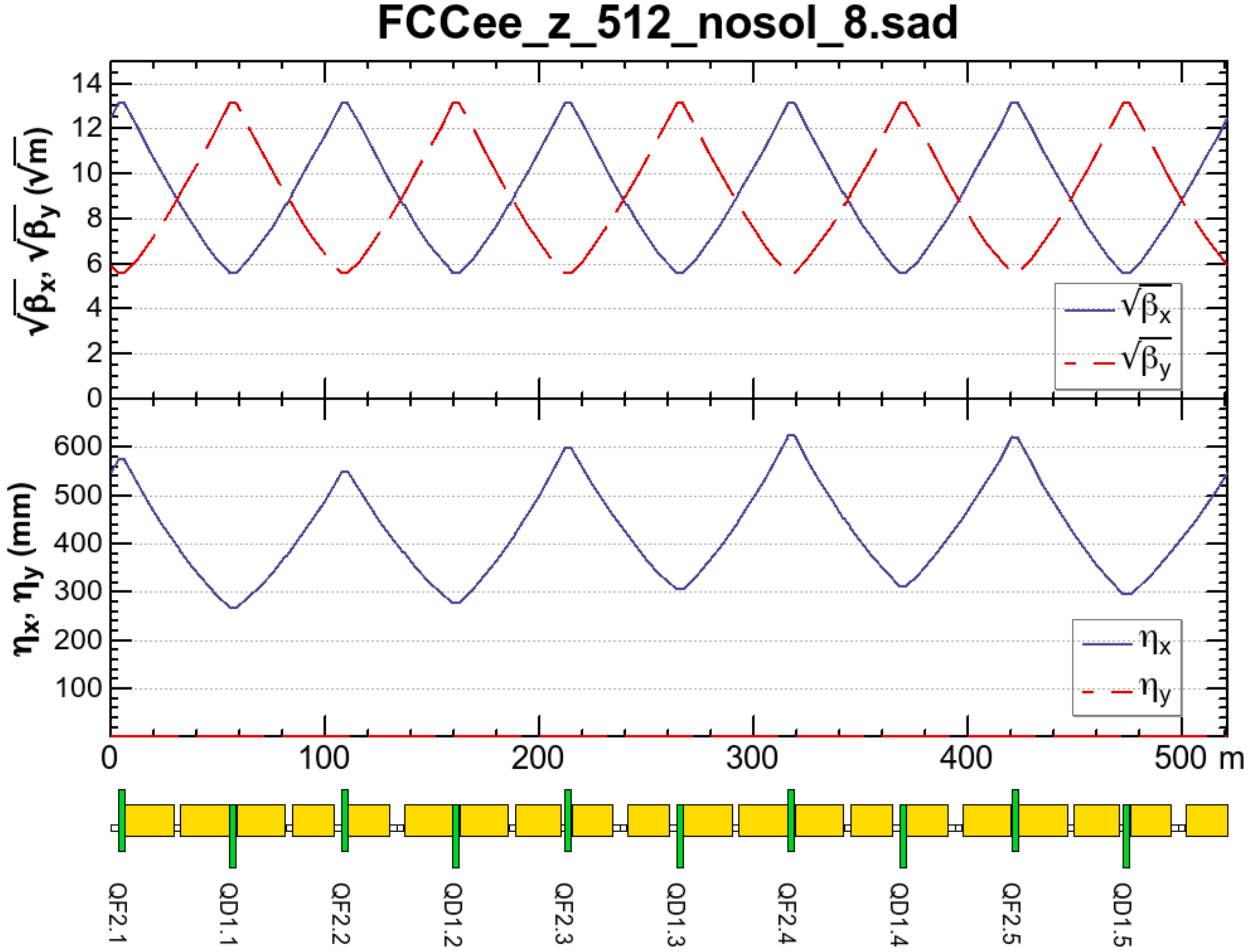
Long 90/90: Z, W



FCCee_z_512_nosol_8.sad

- 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.

“latest” parameters

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		10000	880	248	40
Bunch population	[10^{11}]	2.43	2.91	2.04	2.37
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.038 / 0.132	0.069 / 0.154	0.103 / 0.185	0.157 / 0.221
Bunch length (SR/BS) σ_z	[mm]	4.38 / 15.4	3.55 / 8.01	3.34 / 6.00	1.95 / 2.75
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.5 / 8.8
Harmonic number for 400 MHz		121648			
RF freuqeuncy (400 MHz)	MHz	399.994581		399.994627	
Synchrotron tune Q_s		0.0370	0.0801	0.0328	0.0826
Long. damping time	[turns]	1168	217	64.5	18.5
RF acceptance	[%]	1.6	3.4	1.9	3.0
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y[a]		0.0023 / 0.135	0.011 / 0.125	0.014 / 0.131	0.093 / 0.140
Luminosity / IP	[$10^{34}/\mathrm{cm}^2\mathrm{s}$]	182	19.4	7.26	1.25
Lifetime (q + BS + lattice)	[sec]	840	–	< 1065	< 4062
Lifetime (lum)	[sec]	1129	1070	596	744

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[a] incl. hourglass.

Layout in the interaction region

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

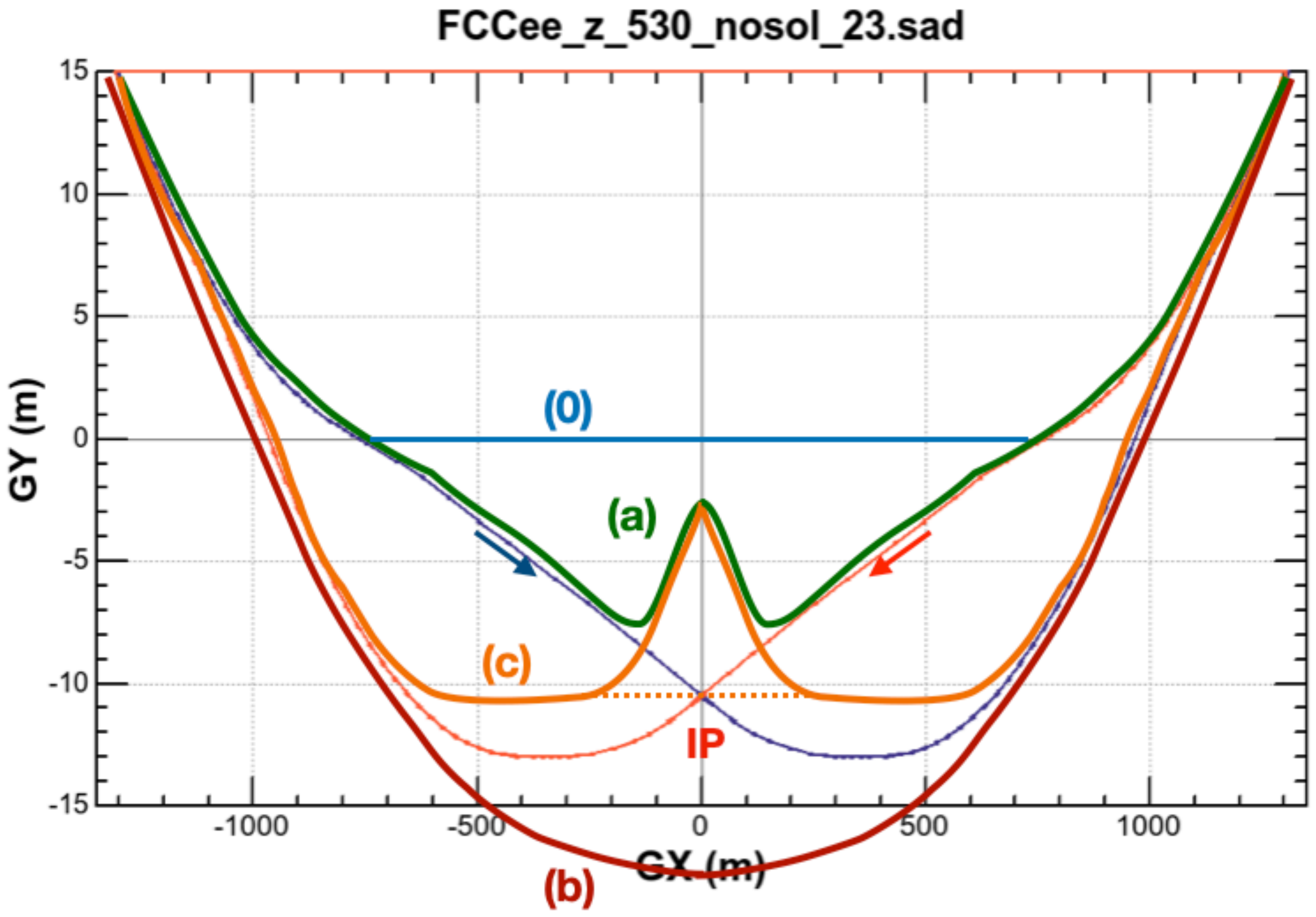
    Several choices (and more) are conceivable:

    (0) Layout line

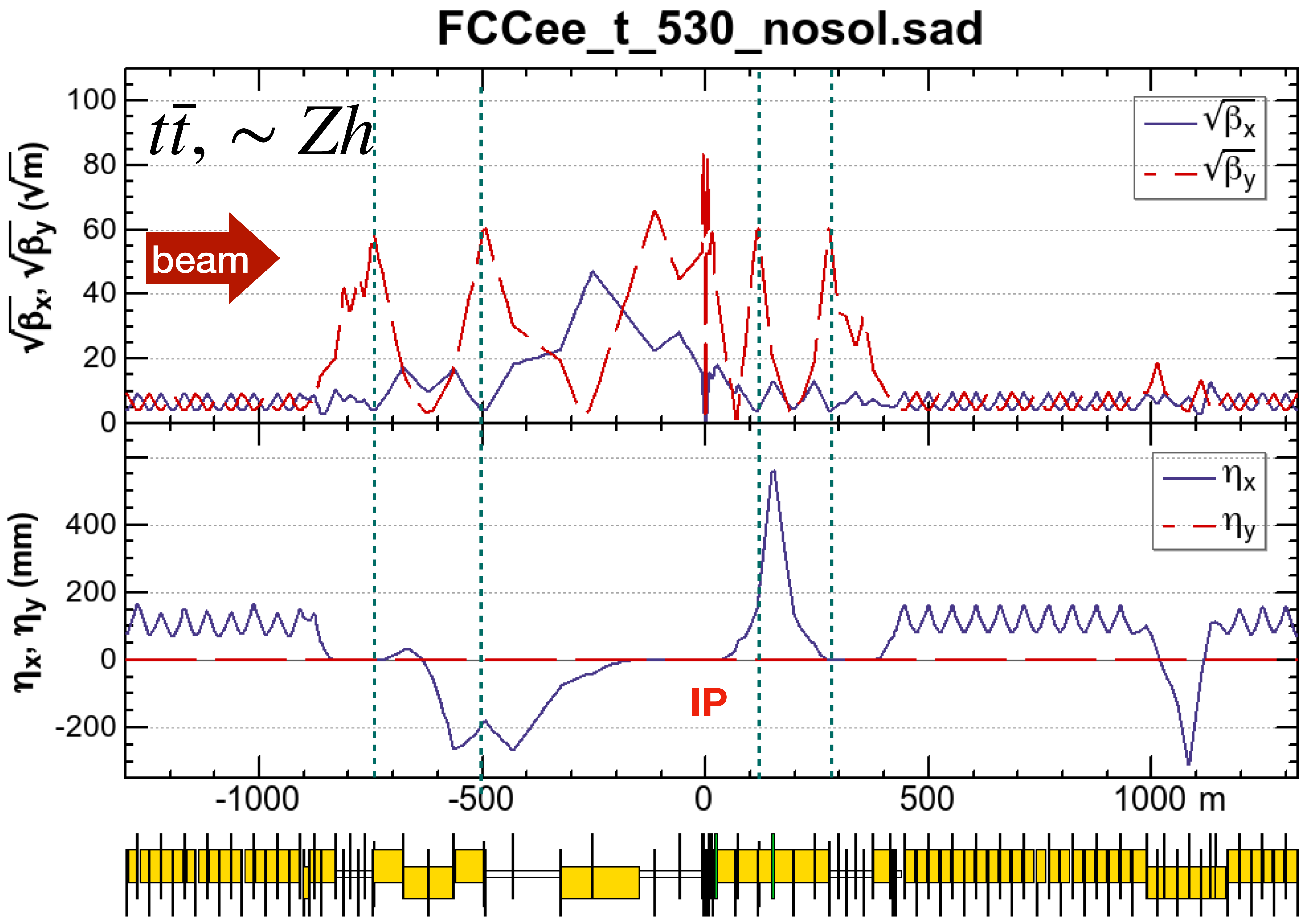
    (a) stay inside of the inner collider ring with a bypass chicane within about ±200 m of the IP.

    (b) going outside of the detector

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

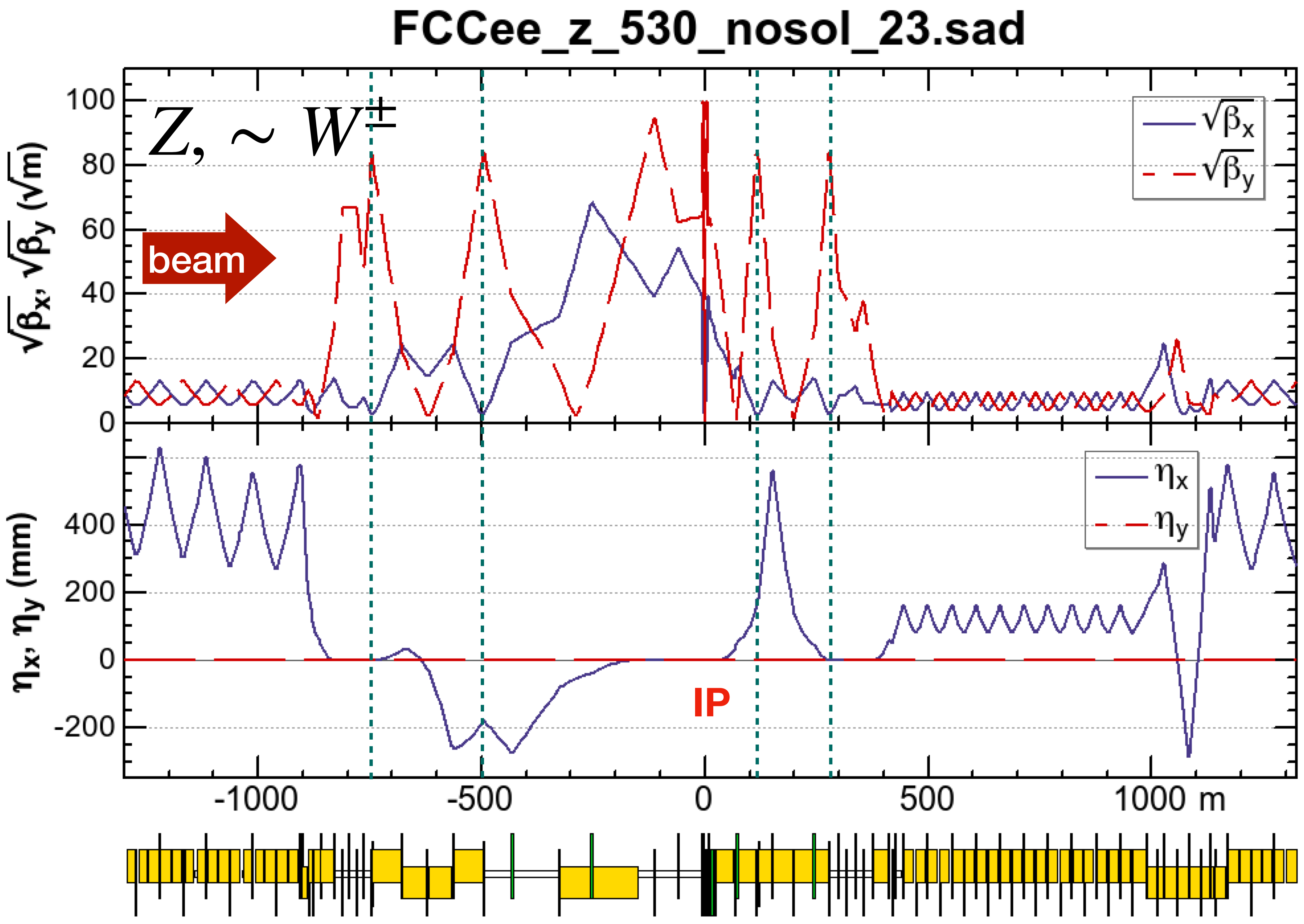


IR optics



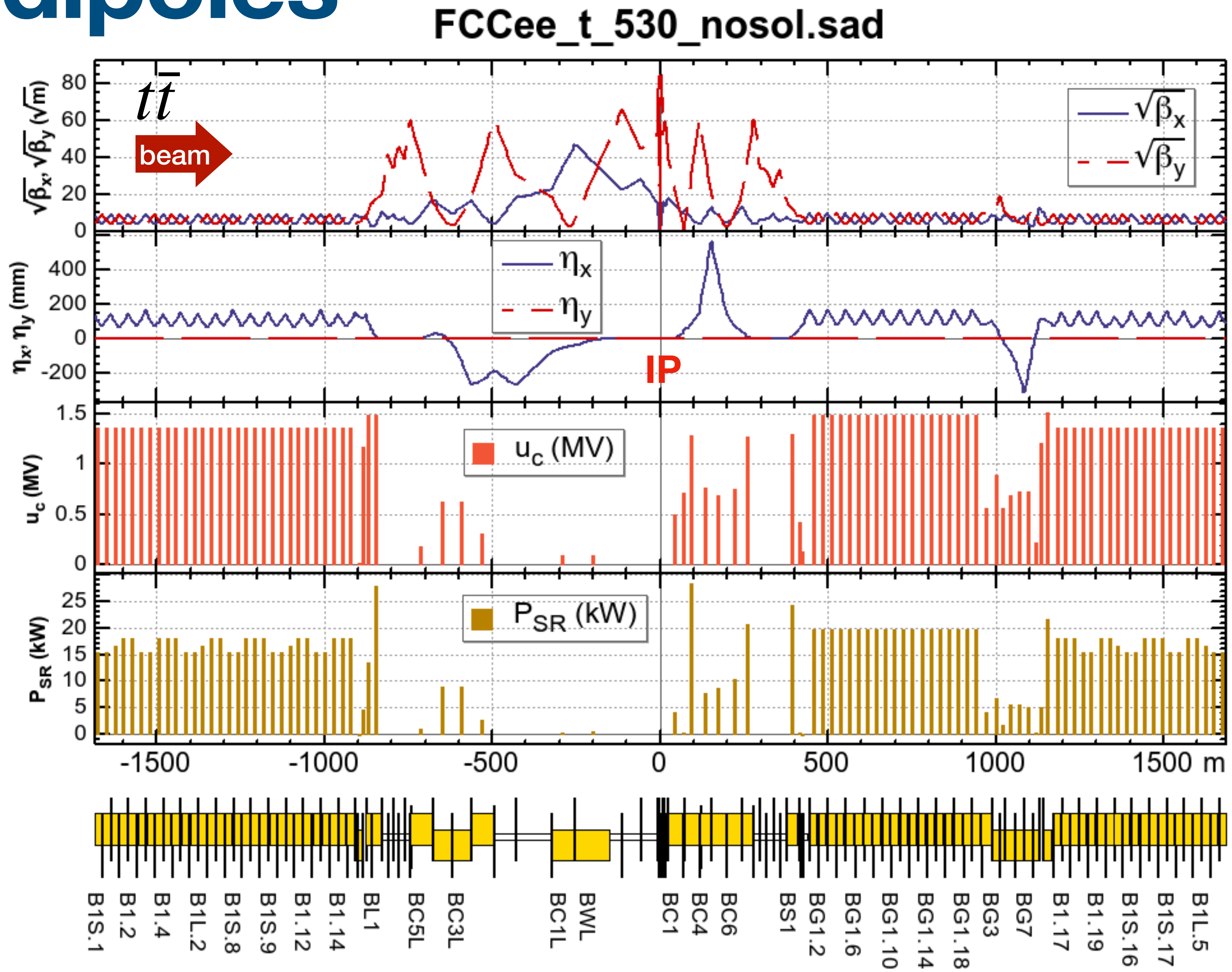
polarimeter
(to be finalized)

pol. wiggler



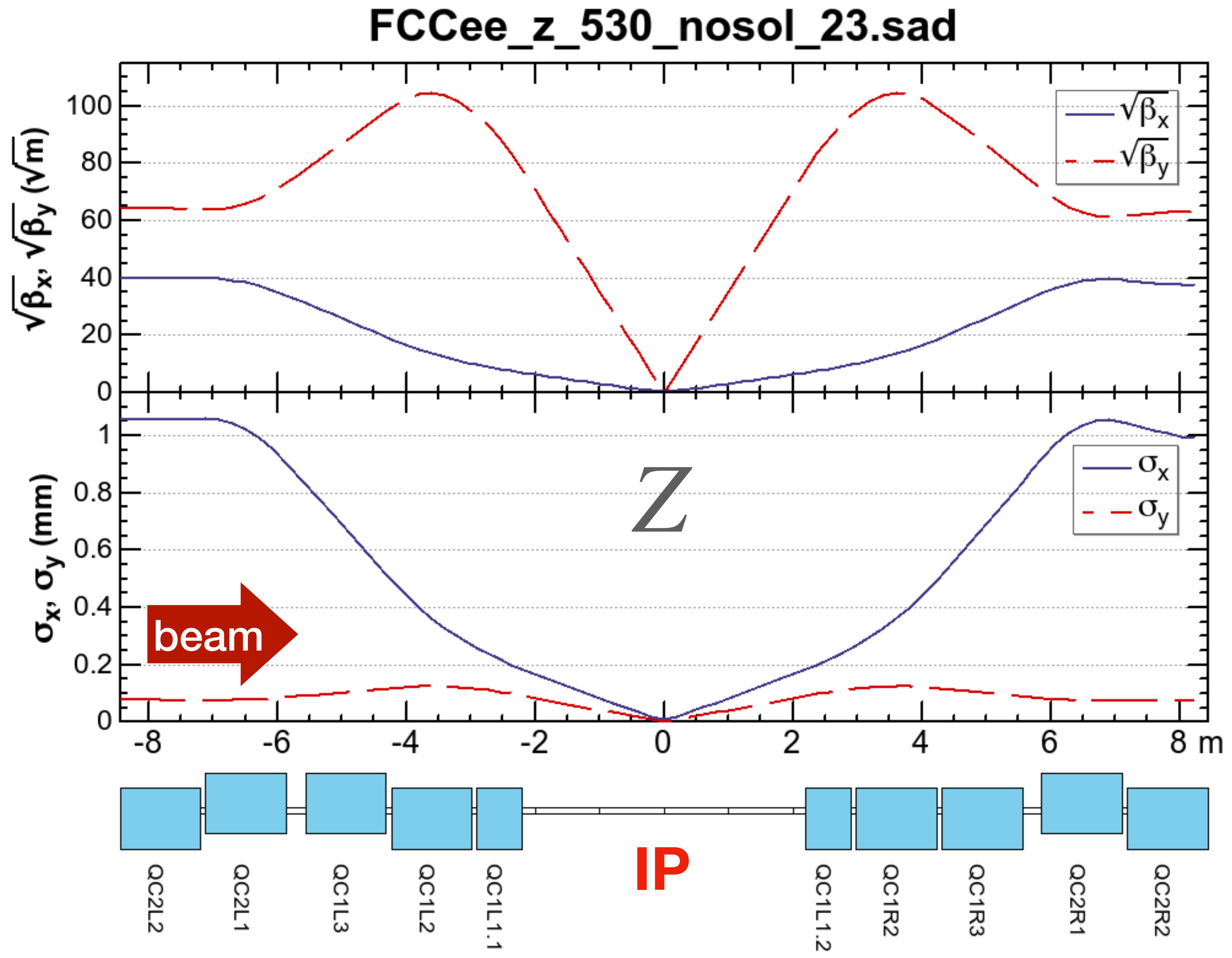
- The beam optics are highly asymmetric between upstream/downstream due to crossing angle & suppression of the SR from upstream to the IP.
- Crab waist/vertical chromaticity correction sextupoles are located at the dashed lines.
- The matching sections may be used for polarimeters (upstream) and polarization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

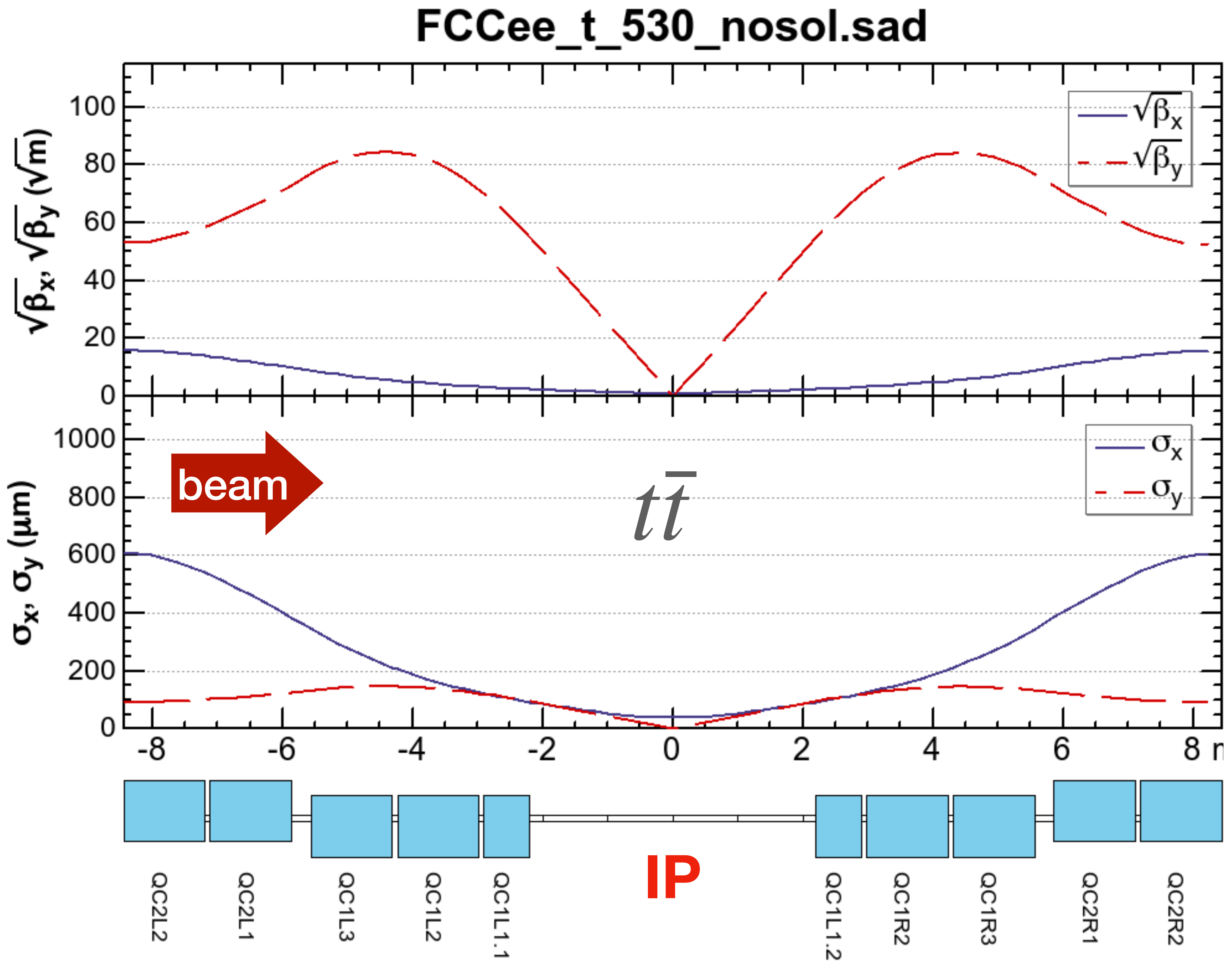
SR from dipoles



- The critical energy of the SR from dipoles upstream the IP is suppressed below 100 keV up to $\sim 500\,\mathrm{m}$ from IP at $t\bar{t}$.

Final quadupoles QC{12}

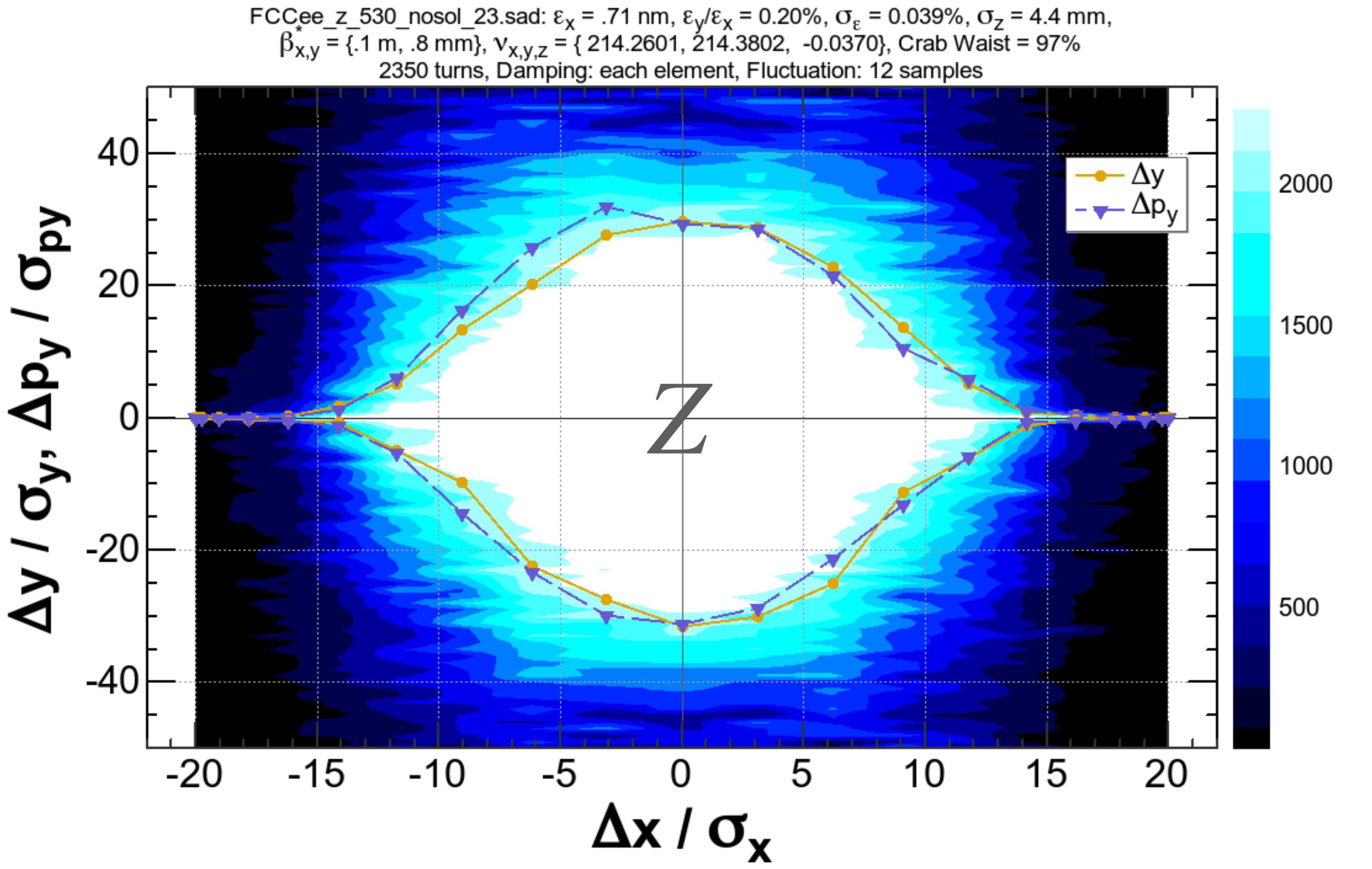


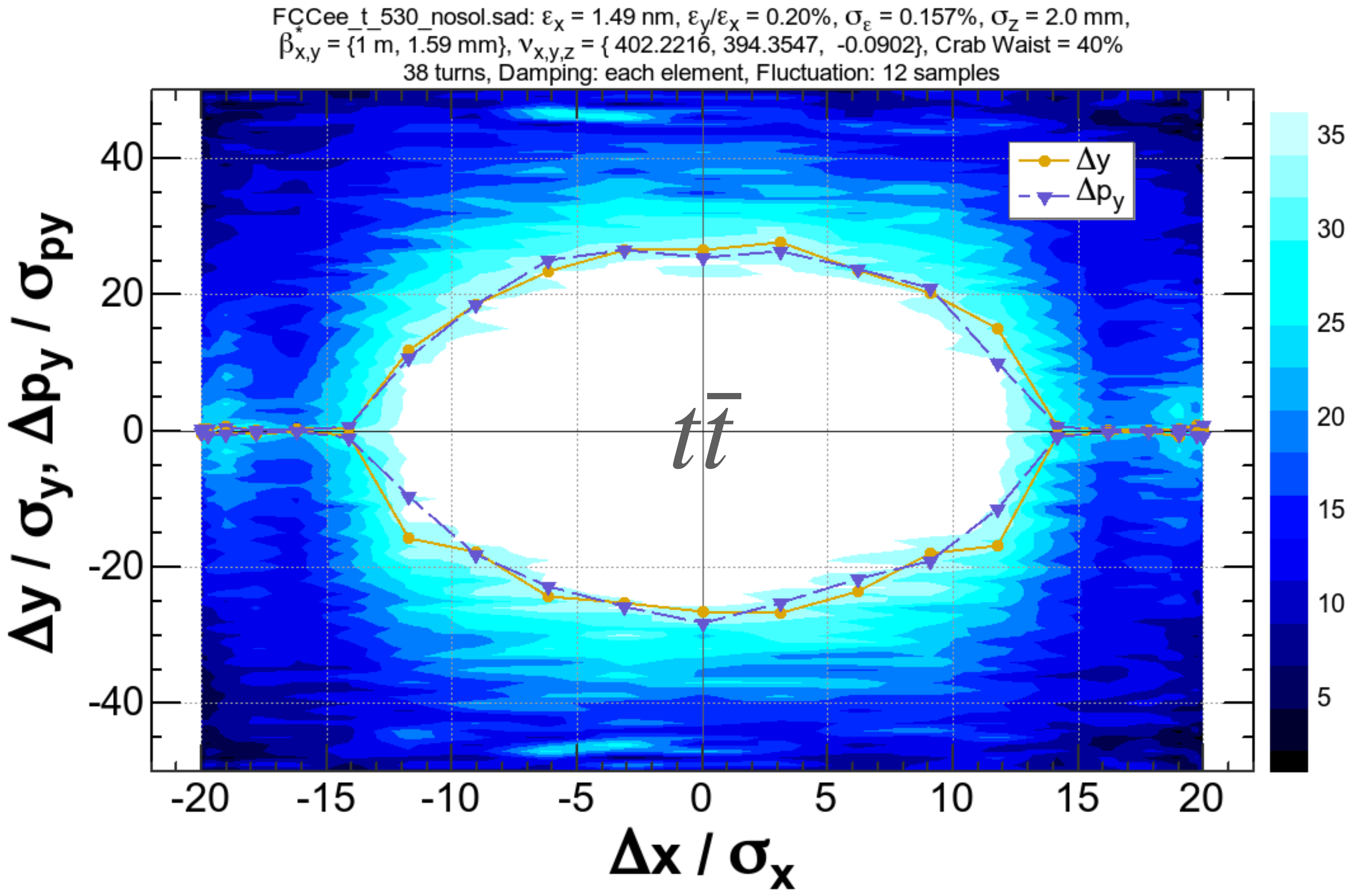


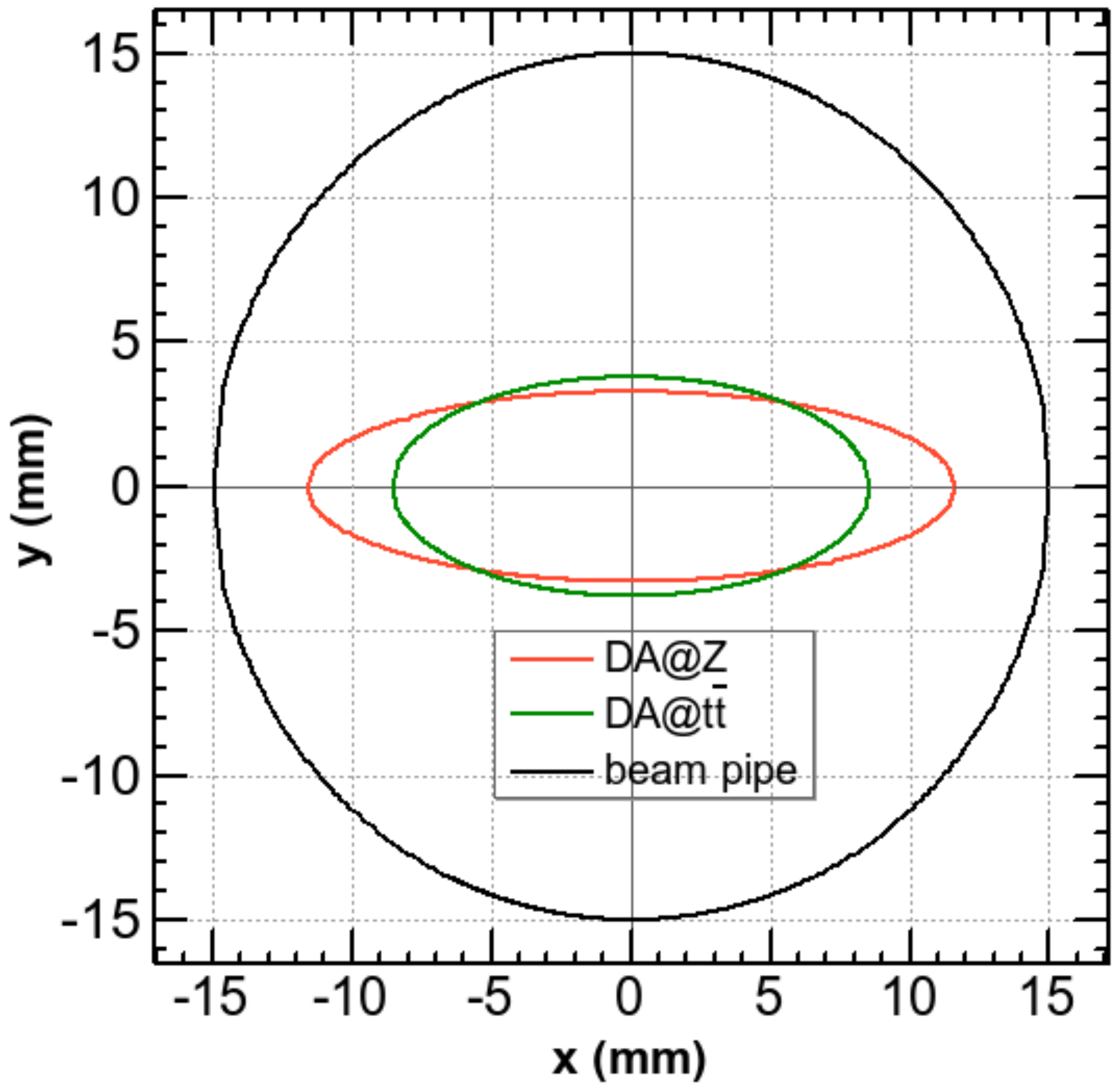
			z_530	t_530
	L (m)	s (m)	B' (T/m)	
QC2L2	1.25	-8.440	-1.654	76.954
QC2L1	1.25	-7.110	30.848	32.886
QC1L3	1.25	-5.560	0.567	-89.722
QC1L2	1.25	-4.230	-41.472	-98.144
QC1L1.1	0.7	-2.900	-41.500	-97.996
QC1L1.2	0.7	2.200	-41.500	-97.996
QC1R2	1.25	2.980	-41.500	-99.892
QC1R3	1.25	4.310	-2.489	-88.582
QC2R1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

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

Dynamic aperture @ QC1





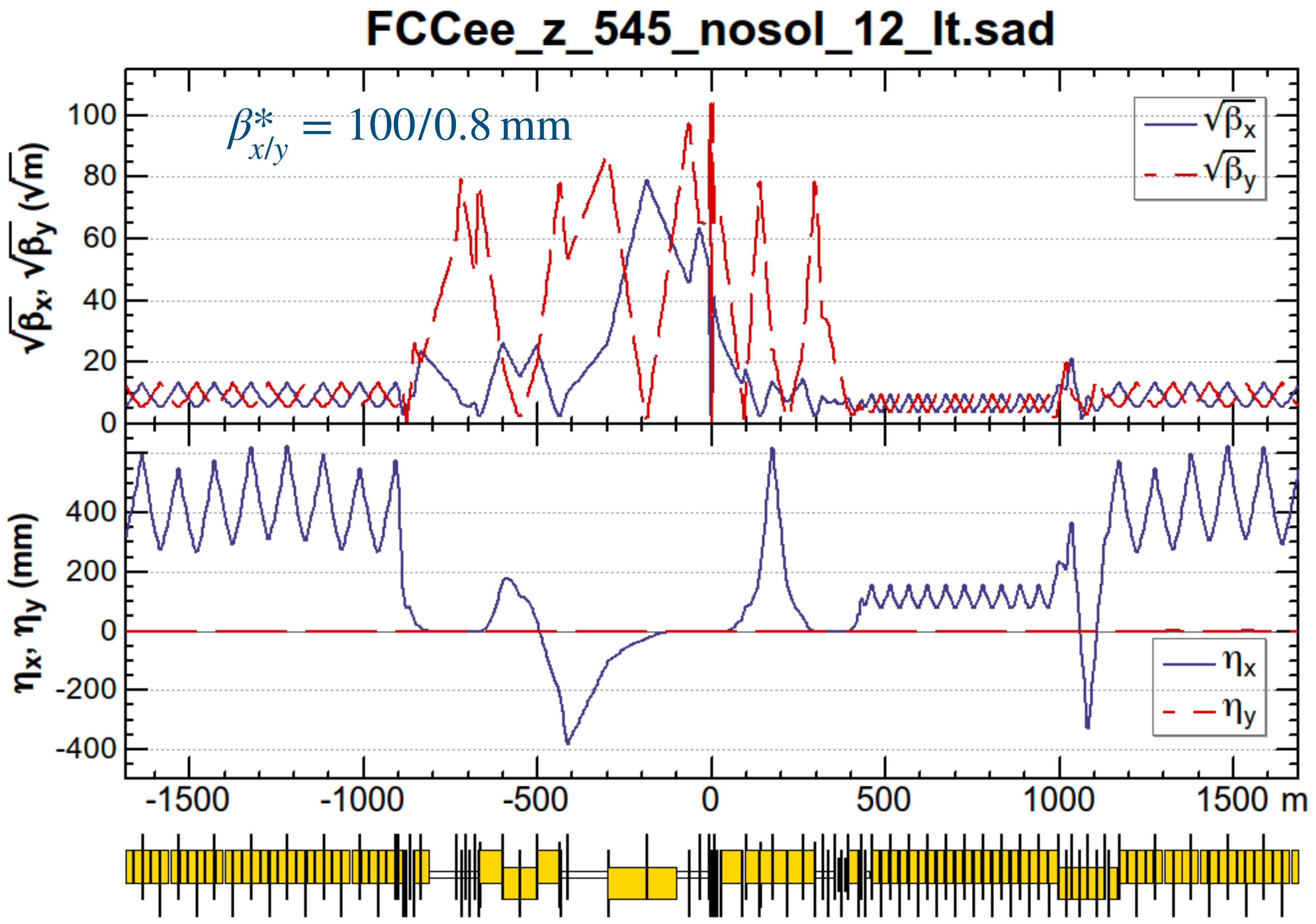


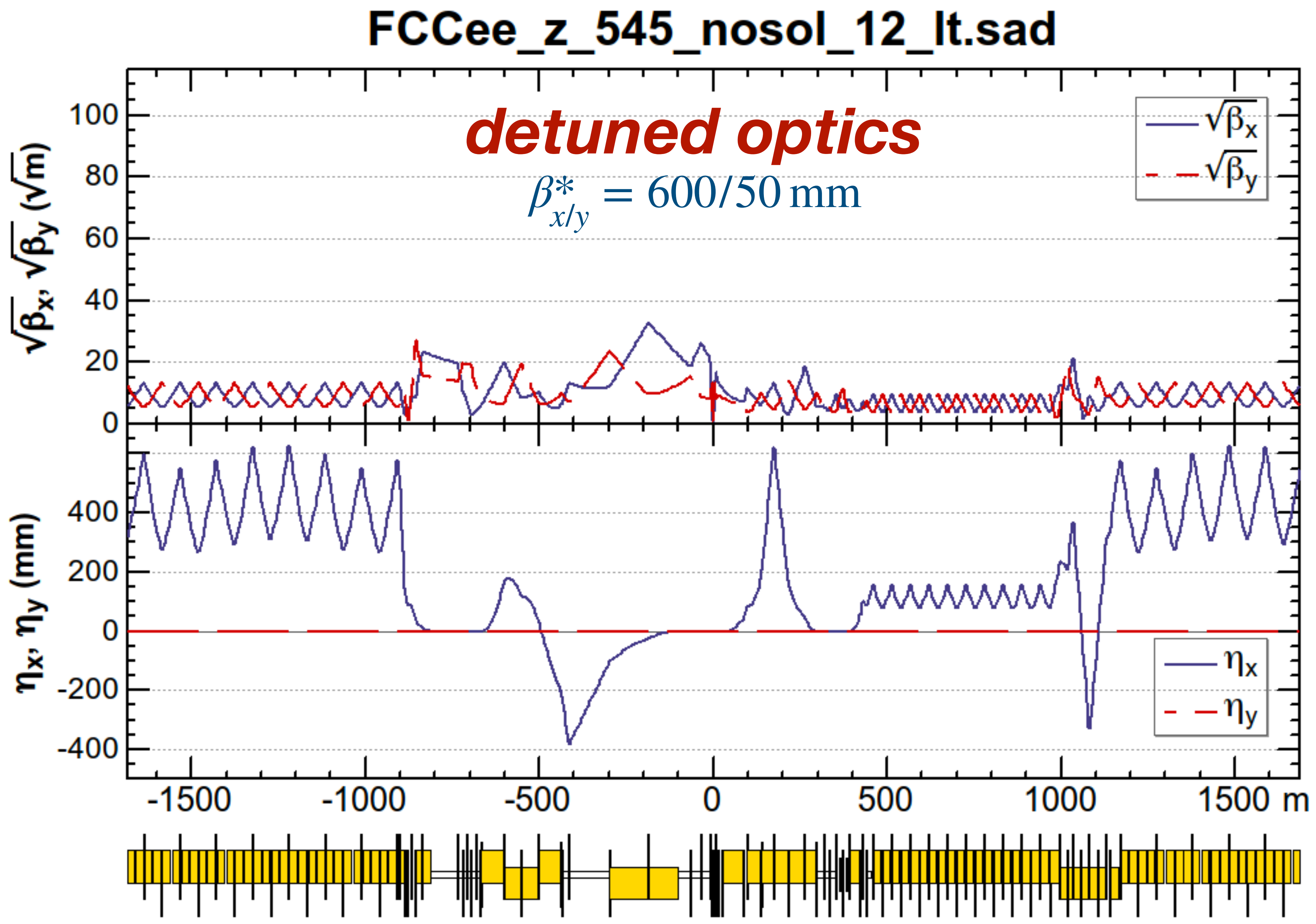
- The dynamic apertures above are evaluated with SR & tapering for 2x long. damping time at Z&$t\bar{t}$.
- The strength of QC1 affects the vertical DA via SR fluctuation @Z.
- The dynamic aperture in the final quad QC1* is much smaller than the beam pipe radius in both x&y (left plot).
  - This may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

Requirements on BI

- along a typical commissioning scenario -

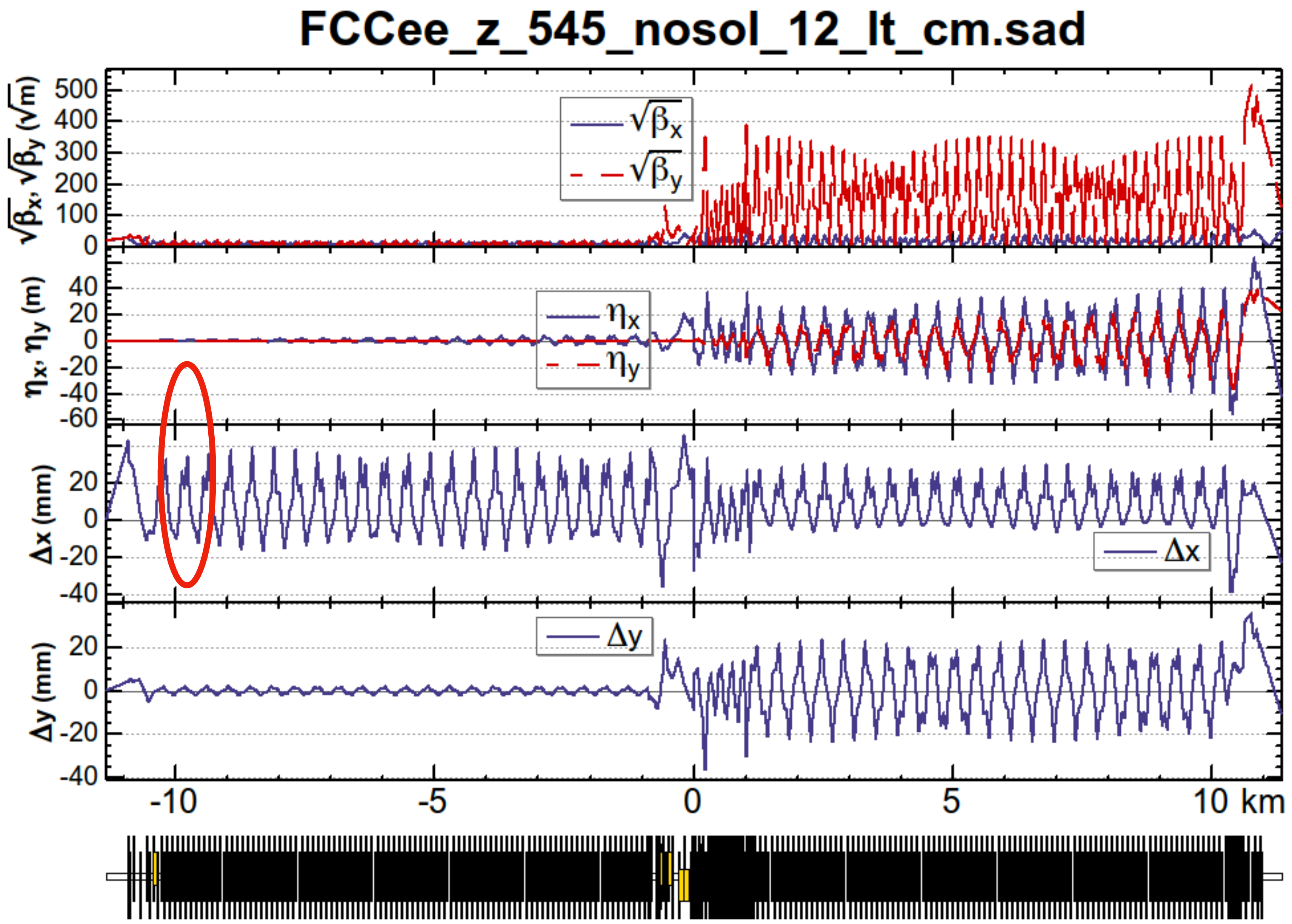
- **Feb. 3, 2048 (Mon.) 09:00 The very first beam was injected from the Booster to the collider rings.**
  - The injector chain (gun, linac, e+ source, damping ring, booster ring, transfer lines) has been tuned, sufficient to provide both beams for the commissioning (~2 nC/bunch) by the end of last month.
  - Both e+ and e- rings can be commissioned in parallel.
  - Z mode optics, E_{beam} = 45.6 GeV.
  - Sextupoles & RF are off, on-axis injection.
  - A detuned optics is set to the main rings:



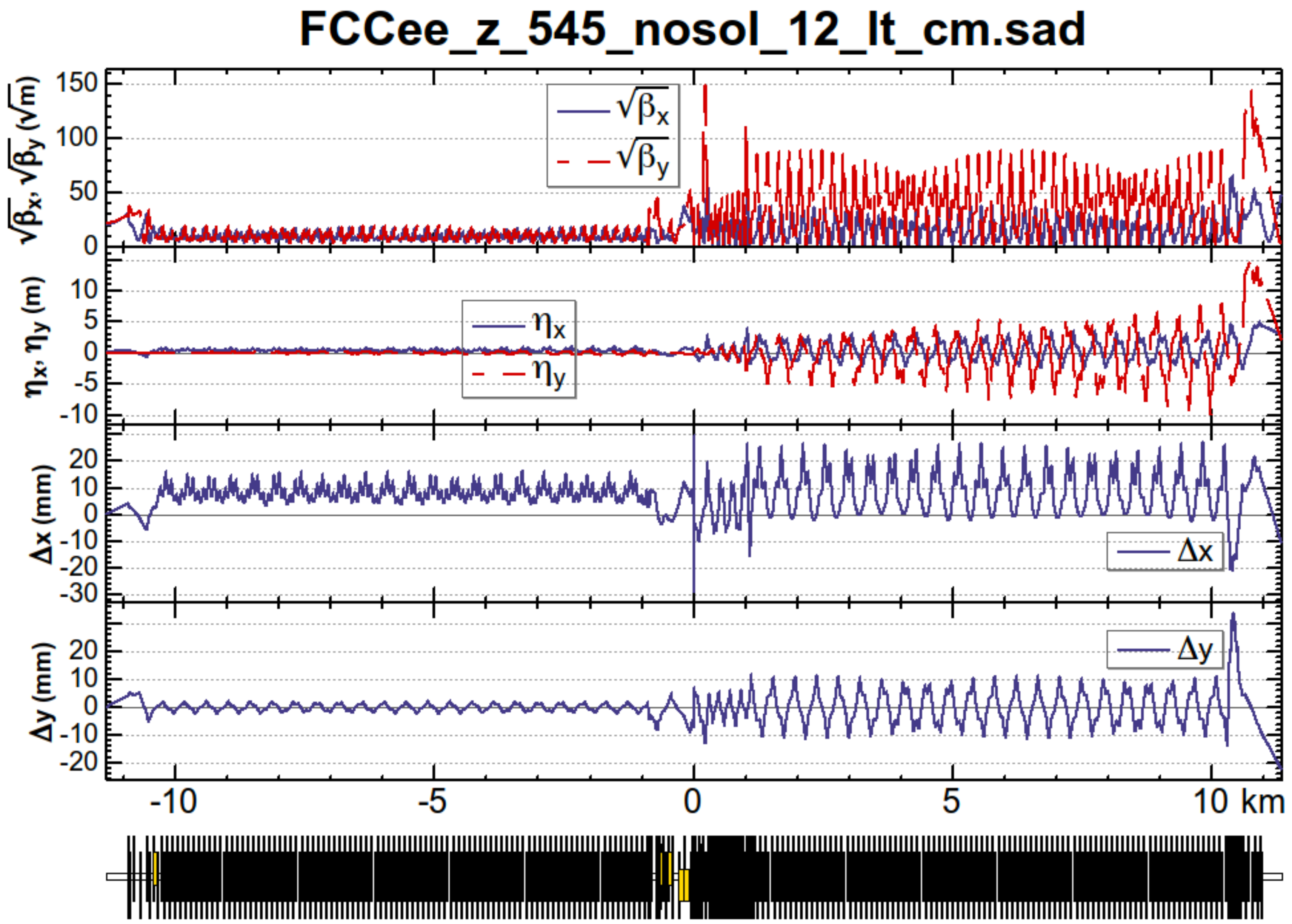


Toward a single turn

- **Feb. 3, 2048 (Mon.) 09:10 A large beam loss was detected by beam loss monitor at the injection straight, about 100 m downstream from the injection point.**
- **Feb. 3, 2048 (Mon.) 10:30 A large horizontal deviation of the injected beam is detected by BPMs in the injection straight.**
  - **The initial BPM tuning (timing, etc.) too about an hour.**



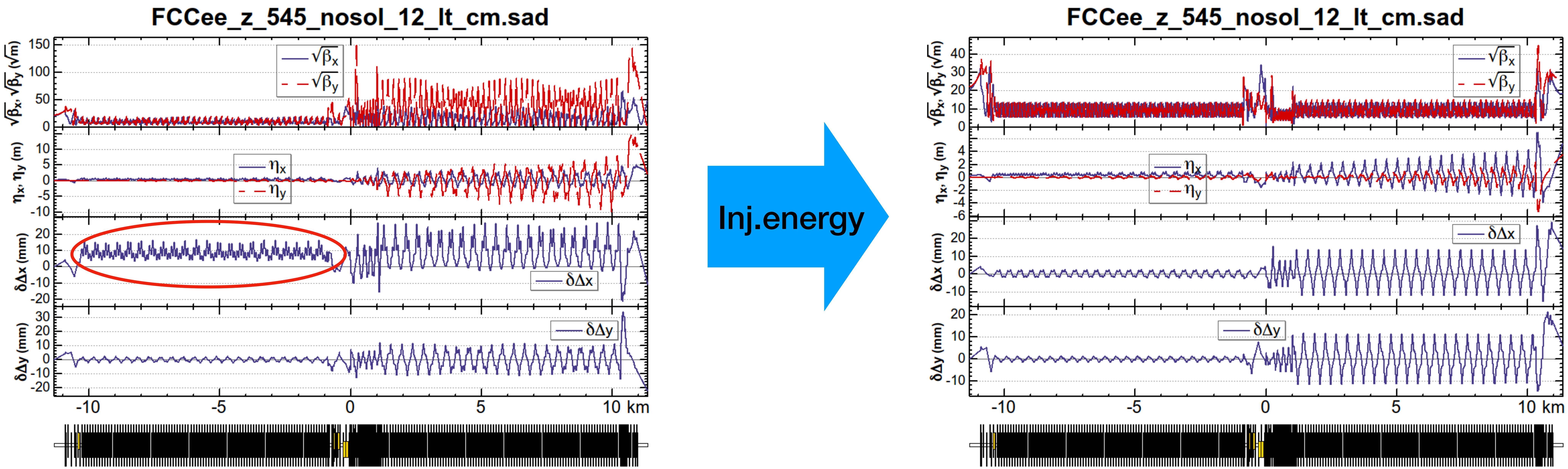
kicker tuning



- **Feb. 3, 2048 (Mon.) 11:30 am: The beam reached the first IP by manual tuning of the inj. kicker, looking at loss monitors & BPMs from the inj. straight through the first arc.**
  - The kicker timing accuracy can be loose at this moment, as the kicker has a very long flat-top for 300 μs.

Injection energy

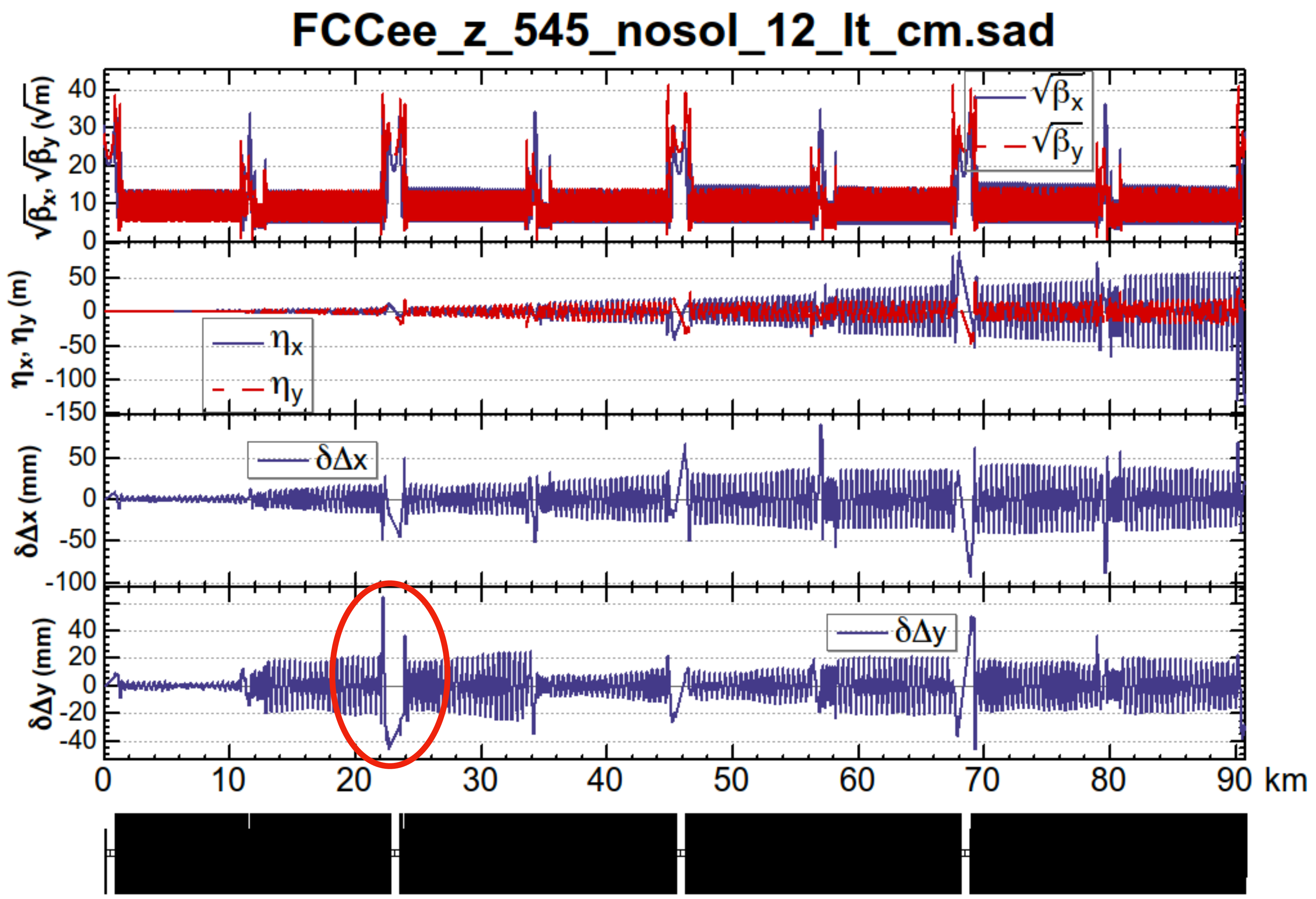
- **Feb. 3, 2048 (Mon.) 12:30 Noticed a systematic hor. offset through the first arc:**
    - By comparing with the design dispersion, it corresponds to $\Delta p/p \approx +2\,\%$.
    - As another ring tells a similar amount, the booster flat-top energy was reduced by 1.9%.



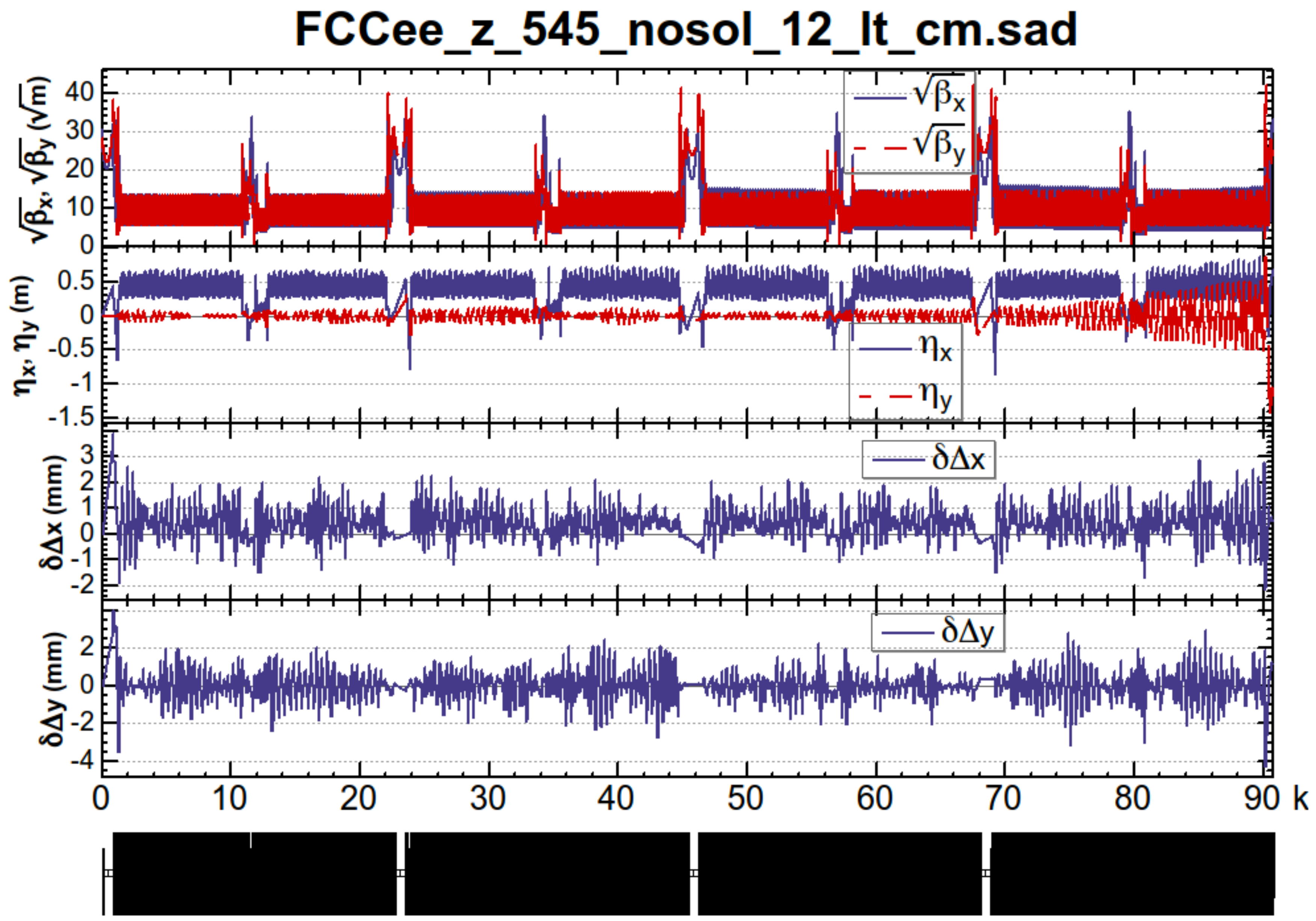
- To tell a 0.1% momentum deviation, the arc BPM must have better than $0.6 \times \sqrt{90} = 5.7\,\mathrm{mm}$ accuracy.
- A precise energy/timing matching between Booster and collider will be done looking at the synchrotron motion after beam storage.
- The exact energy calibration must wait for the spin tune measurement.

Single-pass orbit correction

- **Feb. 3, 2048 (Mon.) 13:00 Beam reached the 2nd RF straight, then lost.**
    - Large horizontal & vertical orbits in the 2nd straight are observed.



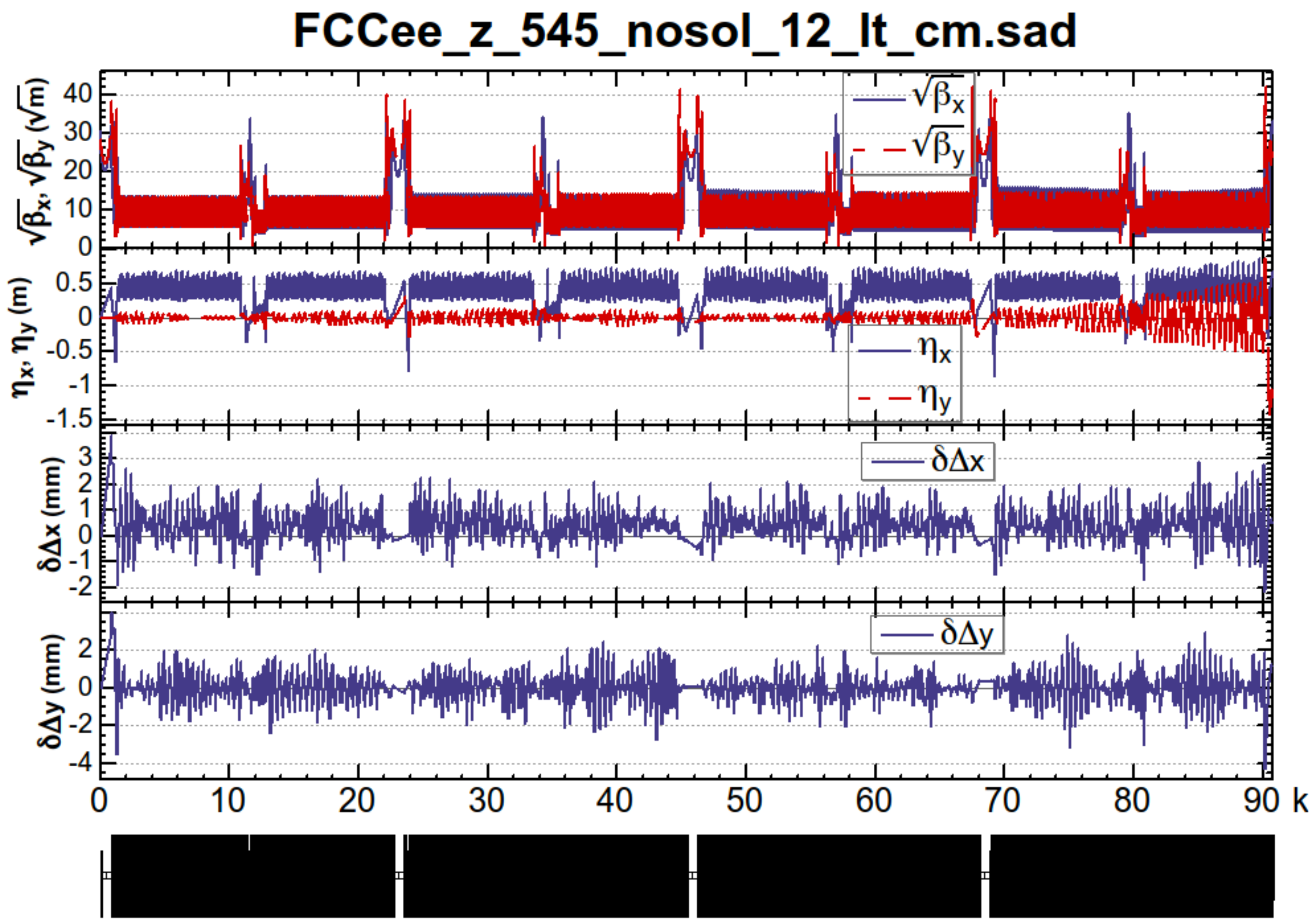
Single-pass orbit correction



- **Single-pass orbit correction based on the model optics has been applied 5 times.**
    - SVD (tolerance = 0.02) using all quads and correctors.

Beam has been stored!

- **Feb. 3, 2048 (Mon.) 14:00 The beam has started to circulate.**
    - The closed orbit has been observed.
    - Tune measurement has become possible by BPMs.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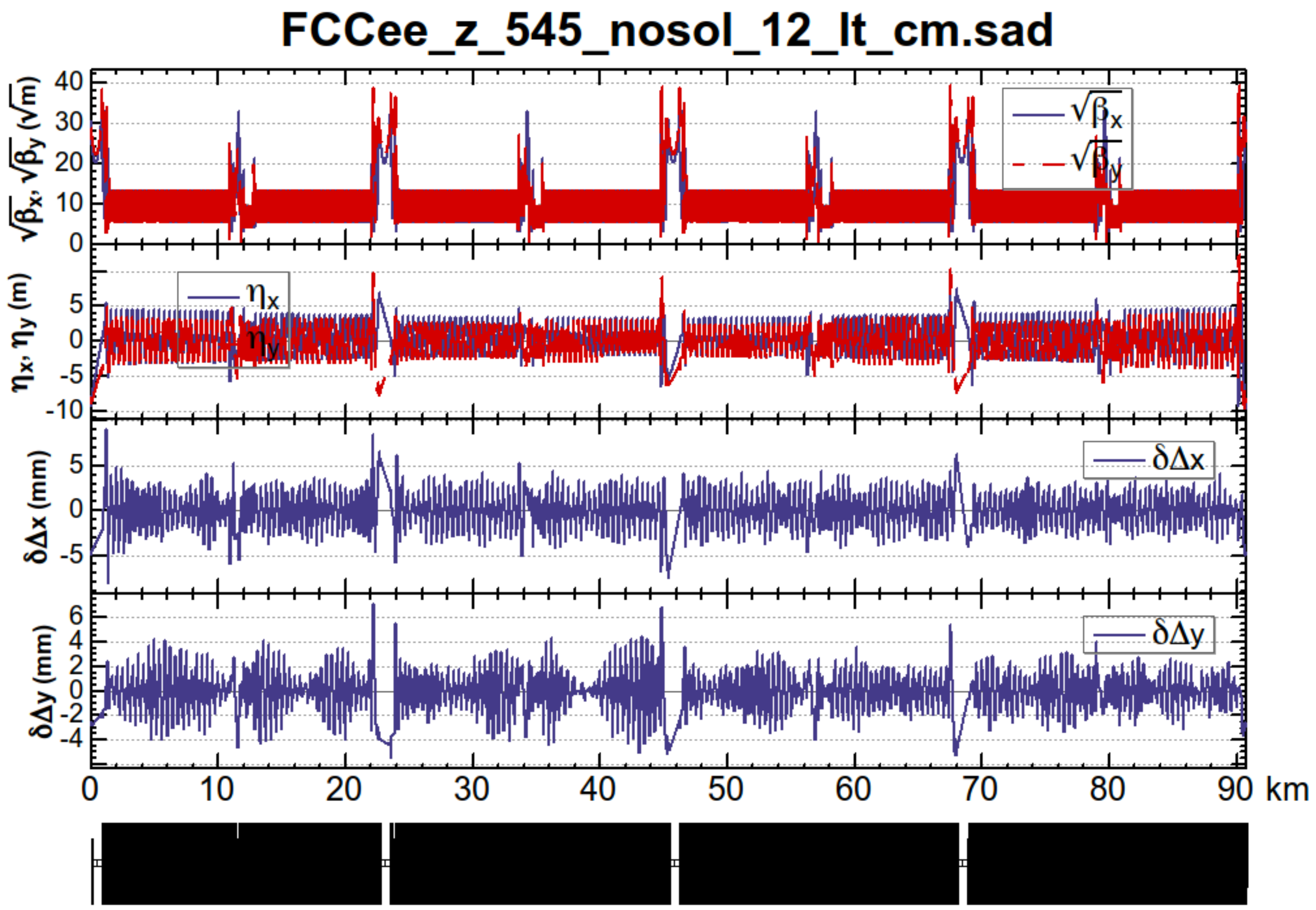
Beam is stored!


FCCee_z_545_nosol_12_lt_cm.sad

- It has been known that the integer part of the vertical tune was smaller than the design by 2.

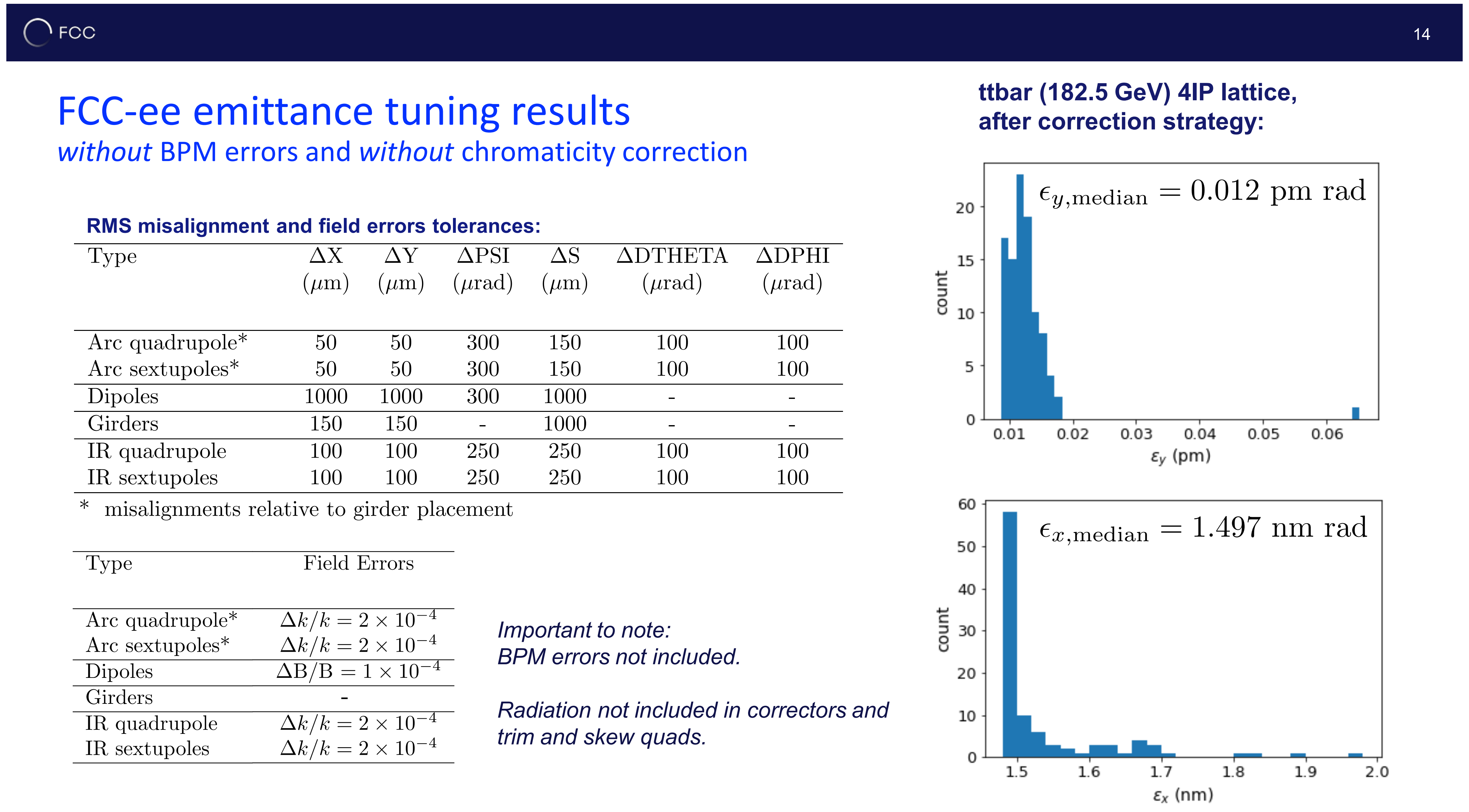
Sextupoles & RF are turned on

- **Feb. 3, 2048 (Mon.) 16:00 Sextupoles are turned on in 5 steps, by repeating orbit/tune corrections.**
- **Feb. 3, 2048 (Mon.) 18:00 RF are turned on.**
  - Injection phase as well as the injection energy offset is optimized by looking at the synchrotron motion detected by the BPM.
    - **Some BPM must tell the bunch phase (Δz) to observe the synchrotron phase space.**
  - **Now closed orbit correction is applied continuously.**
  - **The ring dispersion and chromaticity can be measured by shifting the RF frequency.**
  - **The kicker is set to the accumulation mode for scrubbing with high current.**
  - **The abort kickers are commissioned.**
  - **Synchrotron light and X-ray monitor tells a rough estimation of the emittance.**
  - ....

- **Feb. 3, 2048 (Mon.) 20:00 Declare the Victory! Toast!**
- **Feb. 4, 2048 (Tue.) is dedicated for beam-based BPM alignment & calibration.**
  - One can compensate several kinds of BPM errors such as deviation of the electric transmission or amplifier gain of each electrode. See, eg.," Calibration of KEK B beam position monitors", Kotaro Satoh, Masaki Tejima(KEK, Tsukuba) (May, 1997) 17th IEEE Particle Accelerator Conference (PAC 97): Accelerator Science, Technology and Applications

Optics/Emittance tuning

- **Feb. 5, 2048 (Wed.) 09:00 am: The tuning process started, based on the scheme studied by T. Charles more than 25 years ago!**
- eg. https://indico.cern.ch/event/1186798/contributions/5062640/attachments/2532968/4358650/FCC_EIC_MDI_workshop_2022_Charles.pdf



FCC-ee emittance tuning results

without BPM errors and *without* chromaticity correction

RMS misalignment and field errors tolerances:

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔDTHETA (μrad)	ΔDPHI (μrad)
Arc quadrupole*	50	50	300	150	100	100
Arc sextupoles*	50	50	300	150	100	100
Dipoles	1000	1000	300	1000	-	-
Girders	150	150	-	1000	-	-
IR quadrupole	100	100	250	250	100	100
IR sextupoles	100	100	250	250	100	100

* misalignments relative to girder placement

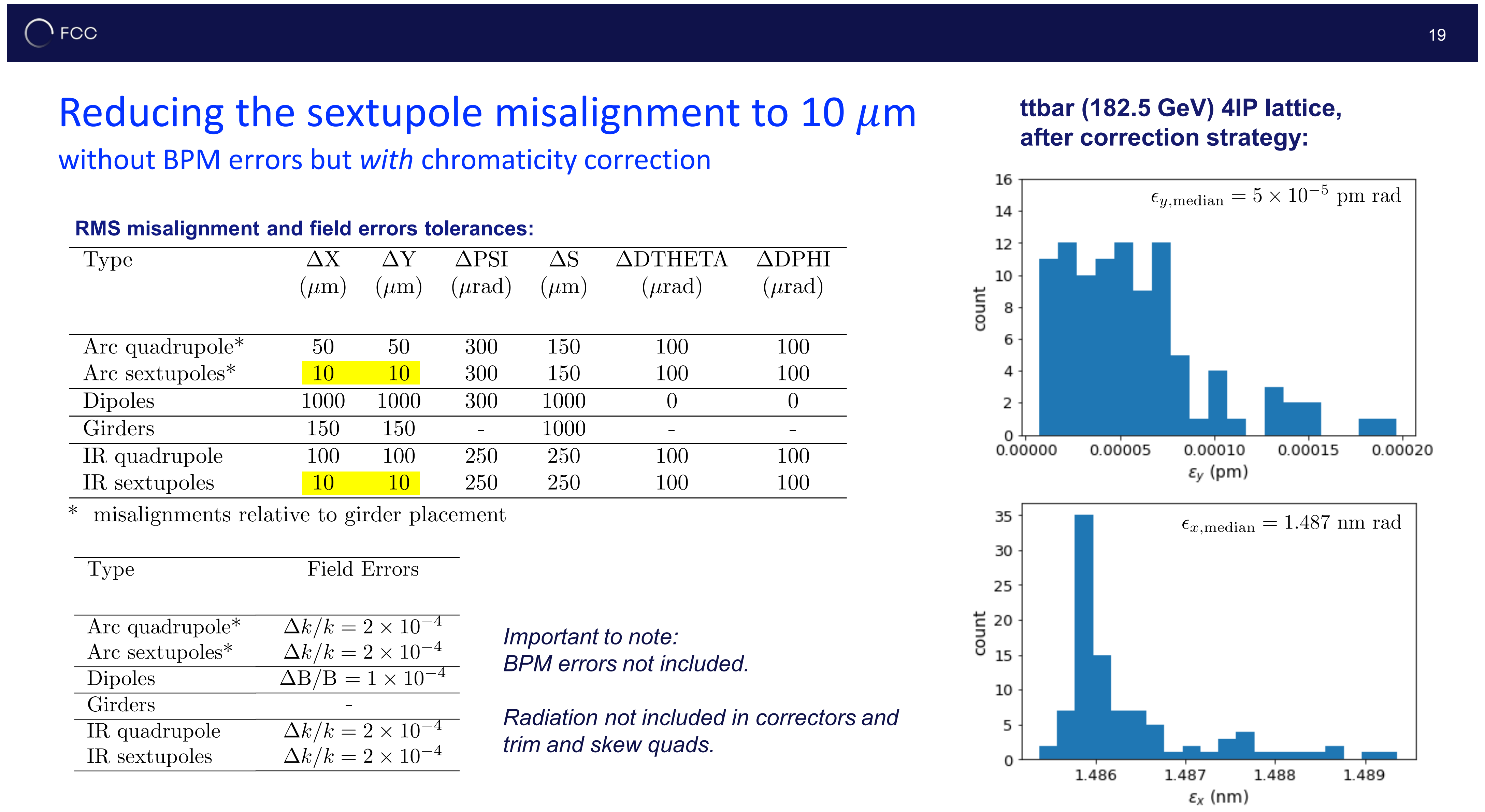
Type	Field Errors
Arc quadrupole*	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	$\Delta B/B = 1 \times 10^{-4}$
Girders	-
IR quadrupole	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	$\Delta k/k = 2 \times 10^{-4}$

Important to note:
BPM errors not included.

Radiation not included in correctors and trim and skew quads.

ttbar (182.5 GeV) 4IP lattice, after correction strategy:

T. Charles



Reducing the sextupole misalignment to 10 μm

without BPM errors but *with* chromaticity correction

RMS misalignment and field errors tolerances:

Type	ΔX (μm)	ΔY (μm)	ΔPSI (μrad)	ΔS (μm)	ΔDTHETA (μrad)	ΔDPHI (μrad)
Arc quadrupole*	50	50	300	150	100	100
Arc sextupoles*	10	10	300	150	100	100
Dipoles	1000	1000	300	1000	0	0
Girders	150	150	-	1000	-	-
IR quadrupole	100	100	250	250	100	100
IR sextupoles	10	10	250	250	100	100

* misalignments relative to girder placement

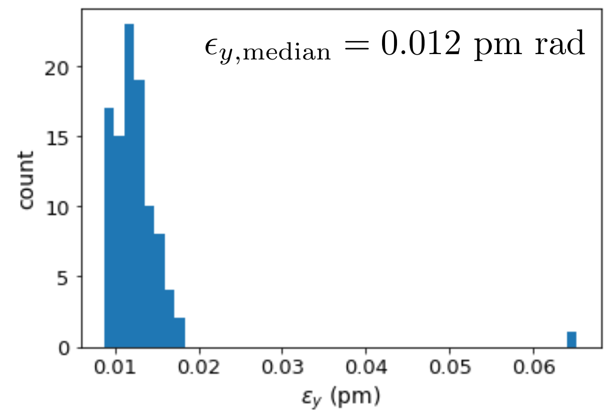
Type	Field Errors
Arc quadrupole*	$\Delta k/k = 2 \times 10^{-4}$
Arc sextupoles*	$\Delta k/k = 2 \times 10^{-4}$
Dipoles	$\Delta B/B = 1 \times 10^{-4}$
Girders	-
IR quadrupole	$\Delta k/k = 2 \times 10^{-4}$
IR sextupoles	$\Delta k/k = 2 \times 10^{-4}$

Important to note:
BPM errors not included.

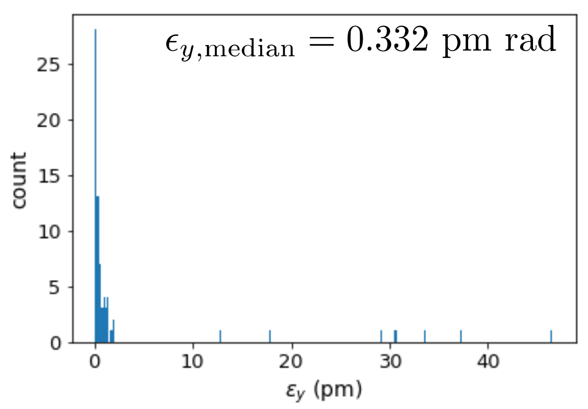
Radiation not included in correctors and trim and skew quads.

ttbar (182.5 GeV) 4IP lattice, after correction strategy:

No chromaticity correction:



Chromaticity correction:

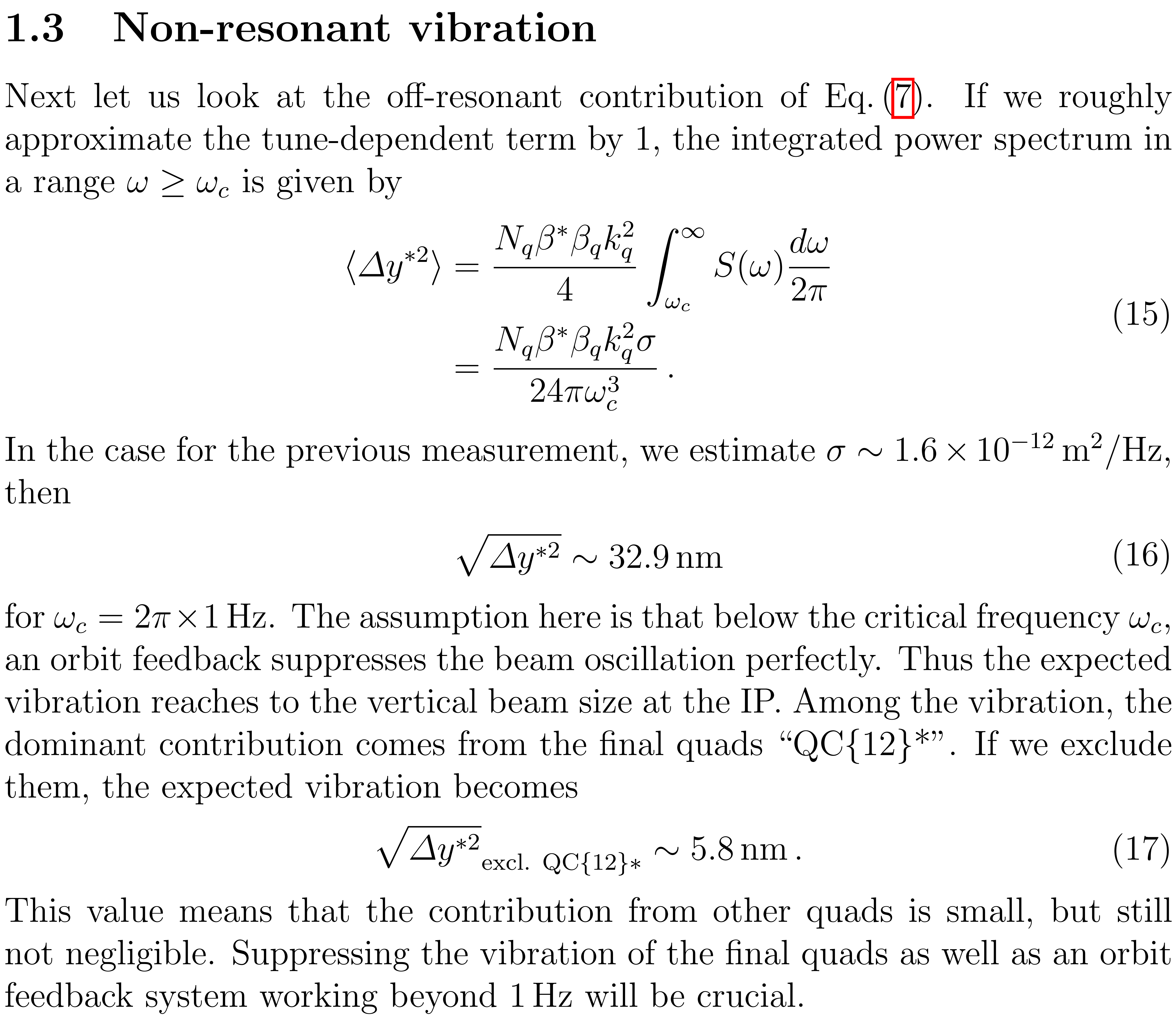


Large proportion of seeds start to fail

- **The requirements on BPMs to estimate the optical functions are not specified yet.**
- **Measurements are based on relative orbit change or phase difference, so the absolute accuracy for the BPM offset is not required.**

Requirements for optics/emittance tuning

- **Measurement error δ of $\Delta\beta/\beta \sim \Delta\mu$ roughly corresponds to $\Delta y/y_m$, where Δy and y_m are the BPM resolution and the amplitude of the orbit difference or the oscillation. If we can use $y_m = 15\sigma_y = 0.2\,\mathrm{mm}$ (@Z) at the arc quads, the 1% precision on δ means $\Delta y = 2\,\mu\mathrm{m}$.**
- **If a measurement is done in n_t turns with n_b bunches involved, the necessary BPM resolution for single bunch, single pass will be $\sqrt{n_t n_b}\Delta y$.**
  - **For 300 turns (= 0.1 s) & 100 bunches, $\sqrt{n_t n_b}\Delta y \approx 240\,\mu\mathrm{m}$, which does not seem too difficult to achieve.**
  - **If we want to measure the optics using pilot bunches, 300 turns & 1 bunch requires $\boxed{\sqrt{n_t n_b}\Delta y \approx 24\,\mu\mathrm{m}.}$**



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

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

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

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

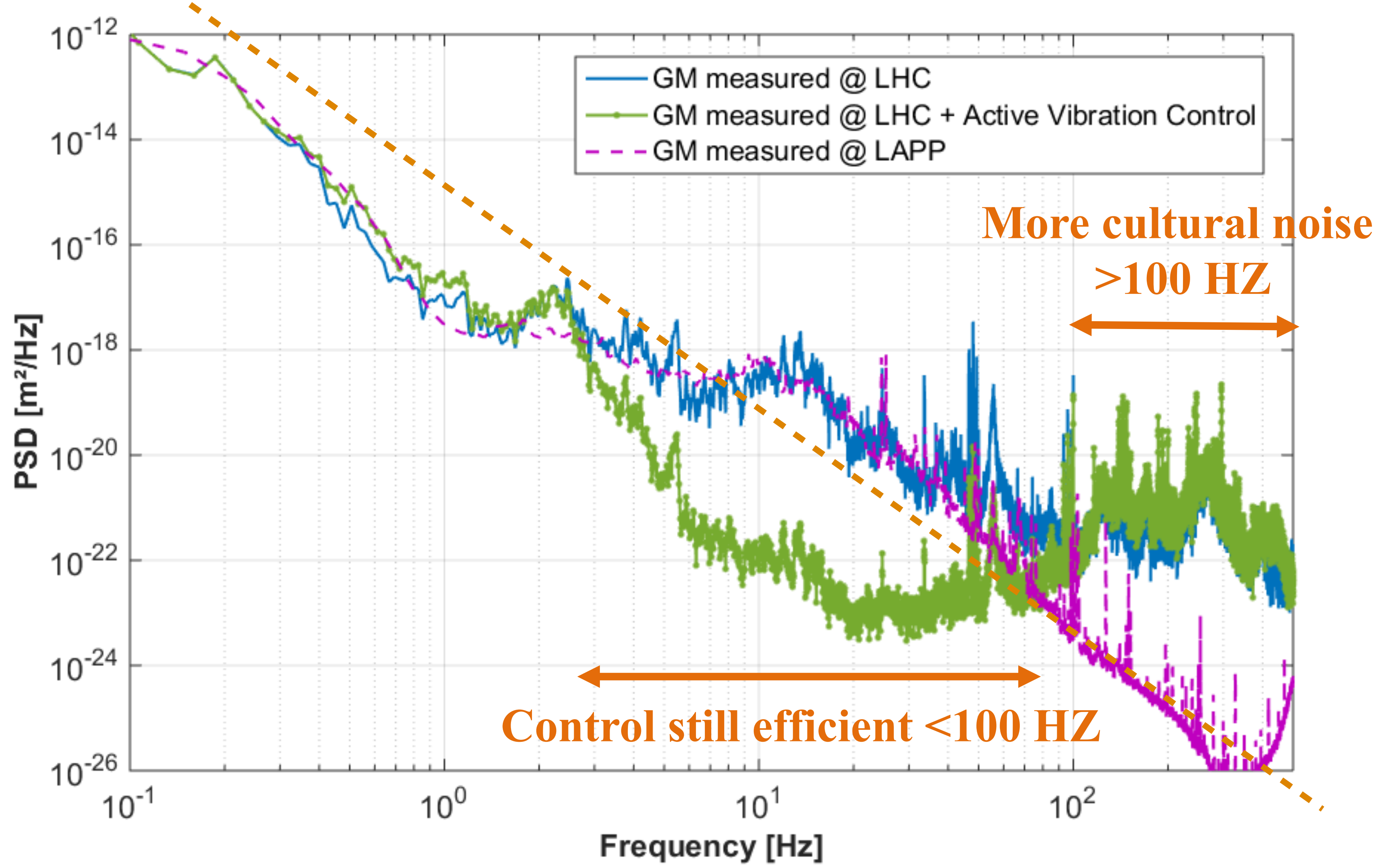
for $\omega_c = 2\pi \times 1\,\mathrm{Hz}$. The assumption here is that below the critical frequency ω_c, an orbit feedback suppresses the beam oscillation perfectly. Thus the expected vibration reaches to the vertical beam size at the IP. Among the vibration, the dominant contribution comes from the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

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

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



More cultural noise >100 HZ

Control still efficient <100 HZ

M. Serluca, et al.

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

Maintaining the collision

1.4 Beam-beam deflection (SLC, B-factories)

If two beams have relative vertical offset at the IP by Δy^*, each beam receive a beam-beam kick at the IP:

$$\Delta p_y^* = \pm \frac{2\pi\xi_y}{\beta_y^*}\Delta y^* \,, \qquad (18)$$

where ξ_y is the vertical beam-beam parameter. If we plugin the numbers for Z:

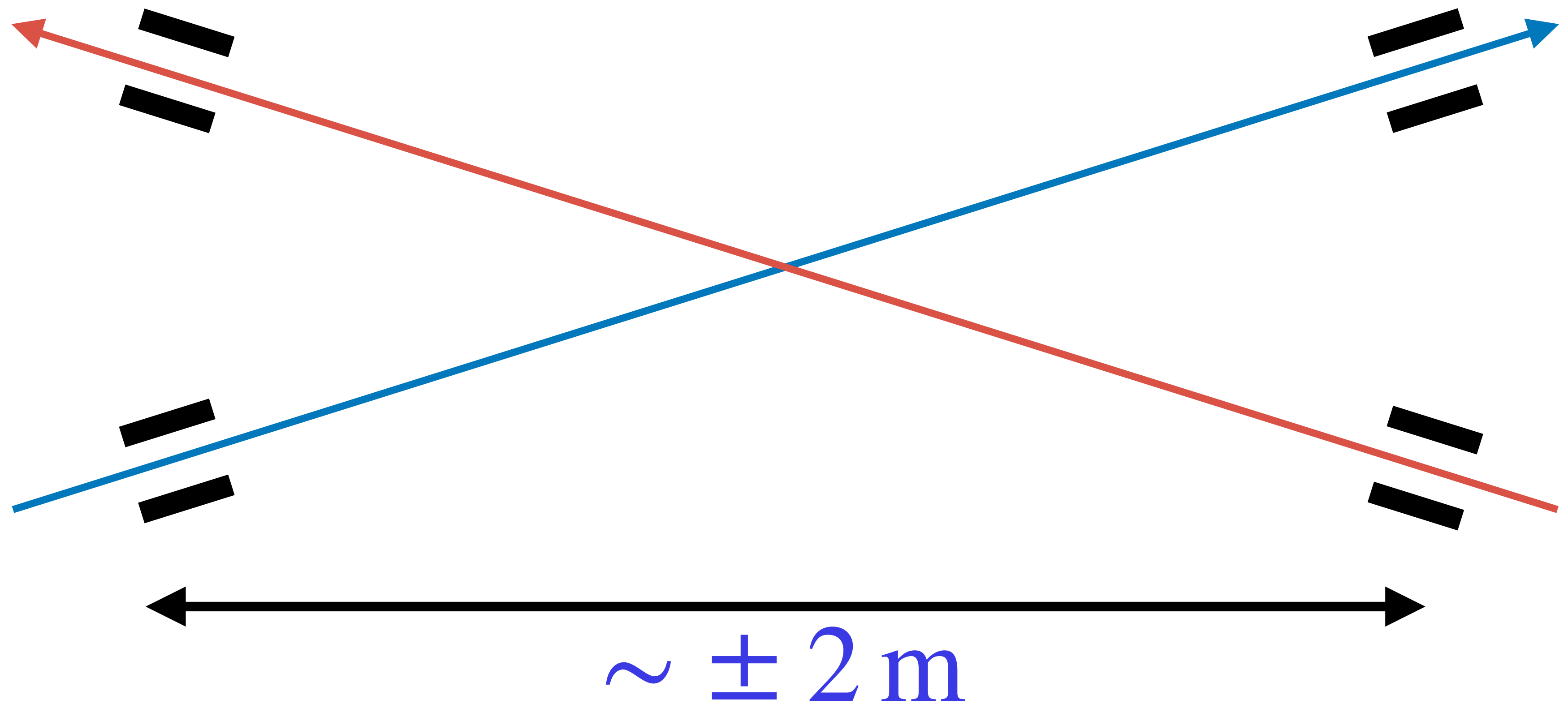
$$\xi_y = 0.135\,, \qquad \beta_y^* = 0.8\,\mathrm{mm}, \qquad \Delta y^* = \frac{1}{10}\sigma_y^* = 3.4\,\mathrm{nm}\,, \qquad (19)$$

the beam-beam kick becomes

$$\Delta p_y^* = 3.6\,\mu\mathrm{rad}\,. \qquad (20)$$

If we have BPMs for both beams at ±2 m from the IP, this kick is well larger than the resolution of the BPMs, at least for the average over the bunches.

Thus the beam-beam deflection has been the primary method to detect and correct the relative offset of two beams at the IP for a linear or double ring colliders.



By combining the readings of four BPMs at the both sides of IP for both beams, it is possible to extract the beam-beam deflection.

Requirements for detection of beam-beam deflection

The beam-beam kick Δy^* is measured by four BPM readings located at $\pm L$ from the IP:

$$\Delta p_y^* = k(y_2^* - y_1^*) = k\frac{y_{1L} + y_{1R} - y_{2L} - y_{2R}}{2(kL-1)}\,, \tag{1}$$

where $k = 2\pi\xi_y/\beta_y^*$. In the case of Z, $\beta_y^* = 0.8\,\mathrm{mm}$ and $\xi_y = 0.14$ give $k \approx 1100\,/\mathrm{m}$, so $kL \gg 1$, which reduces the above equation to

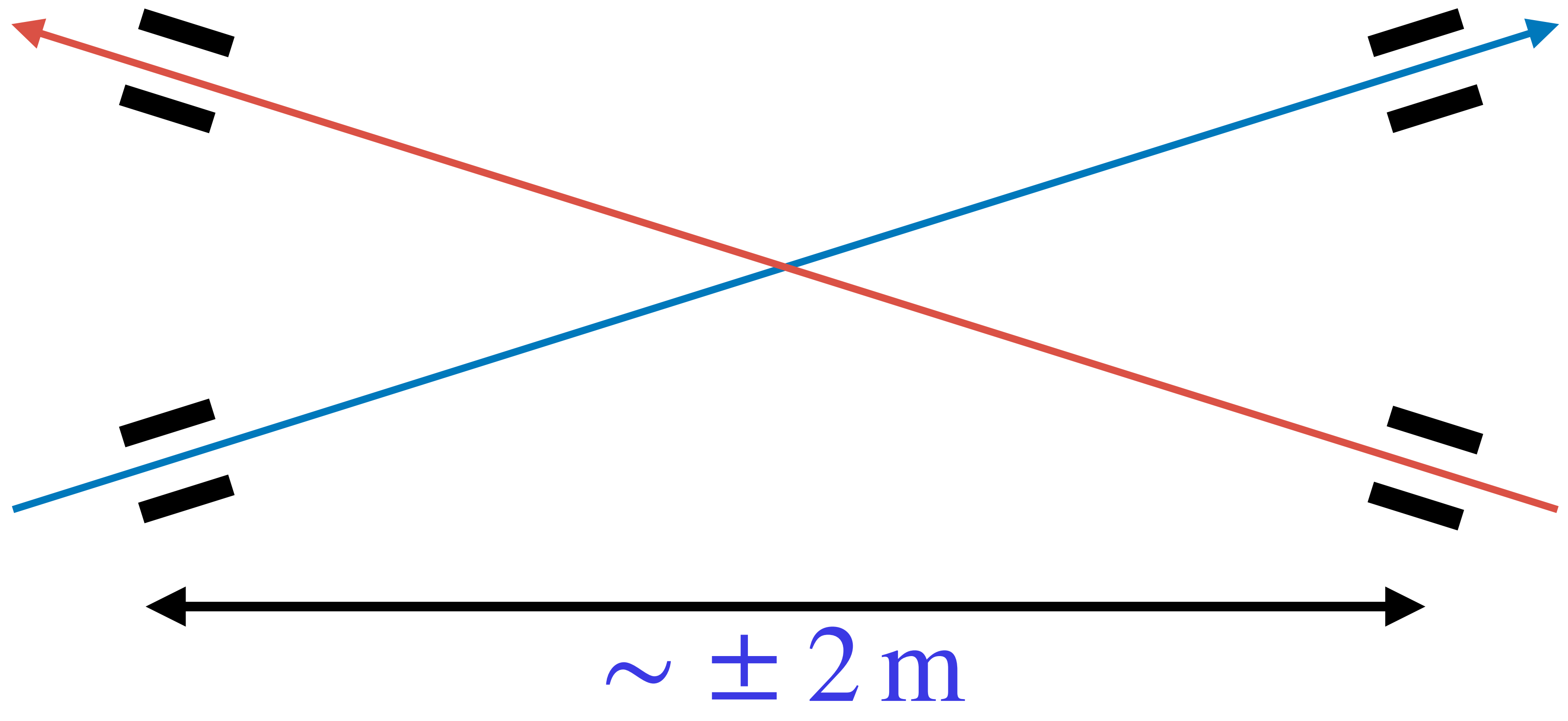
$$\Delta p_y^* = k(y_2^* - y_1^*) \approx \frac{y_{1L} + y_{1R} - y_{2L} - y_{2R}}{2L}\,. \tag{2}$$

Thus the resolution for $\delta_{\Delta p_y^*}$ is simply given by the resolution of the BPM δ_y as

$$\delta_{\Delta p_y^*} = \frac{\delta_y}{L}\,, \tag{3}$$

which gives $\delta_y = 7.2\,\mu\mathrm{m}$ with $L = 2\,\mathrm{m}$.

We need to detect the beam-beam deflection at $10\,\mathrm{Hz}$. At Z, we have 10^4 bunches/beam, then we have $\sim 3 \times 10^6$ crossings in $0.1\,\mathrm{s}$. So the single-pass, single-bunch BPM resolution can be $\sqrt{3 \times 10^6} \approx 1700$ times worse than above, which is $12.5\,\mathrm{mm}$. As for $t\bar{t}$, however, as we have 40 bunches per beam, the multiplication factor is reduced to $\sqrt{12000} \approx 110$. Then the required resolution is reduced to $0.8\,\mathrm{mm}$.

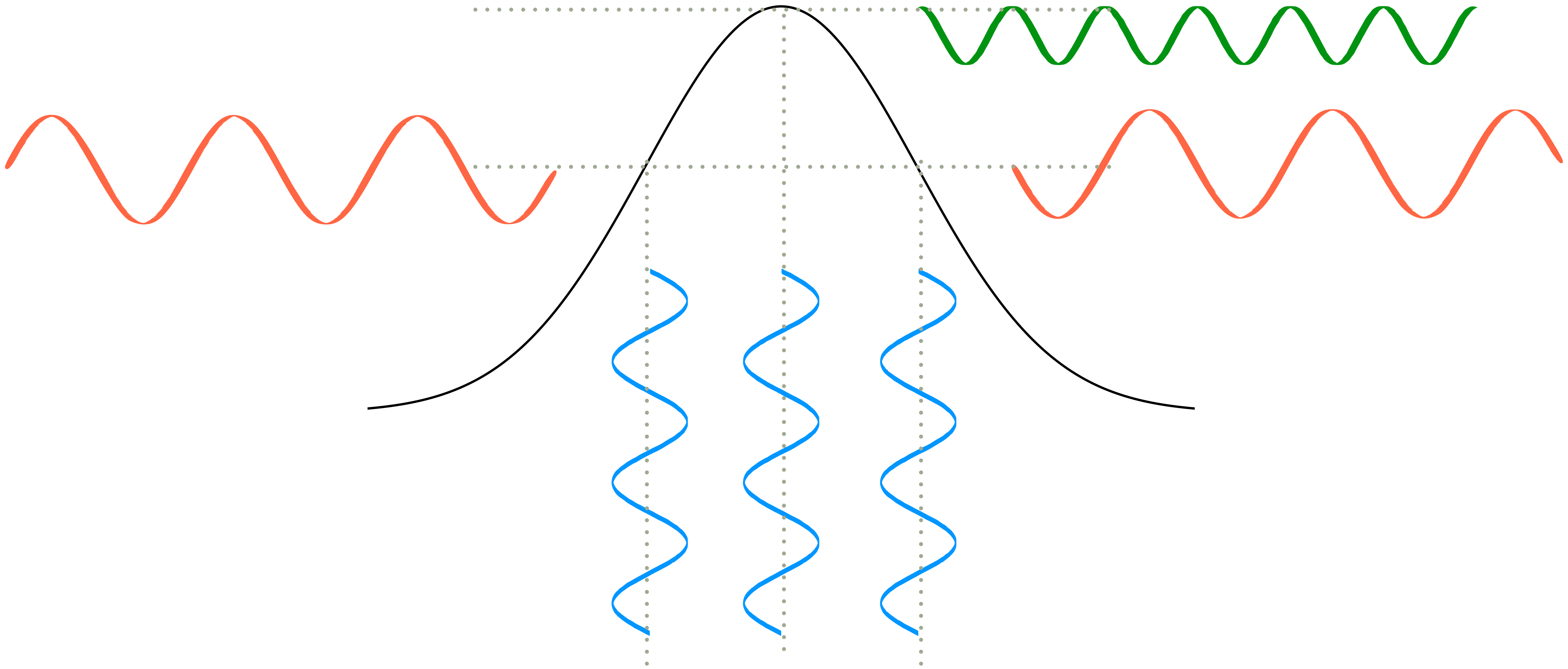


By combining the readings of four BPMs at the both sides of IP for both beams, it is possible to extract the beam-beam deflection.

Maintaining the collision (2)

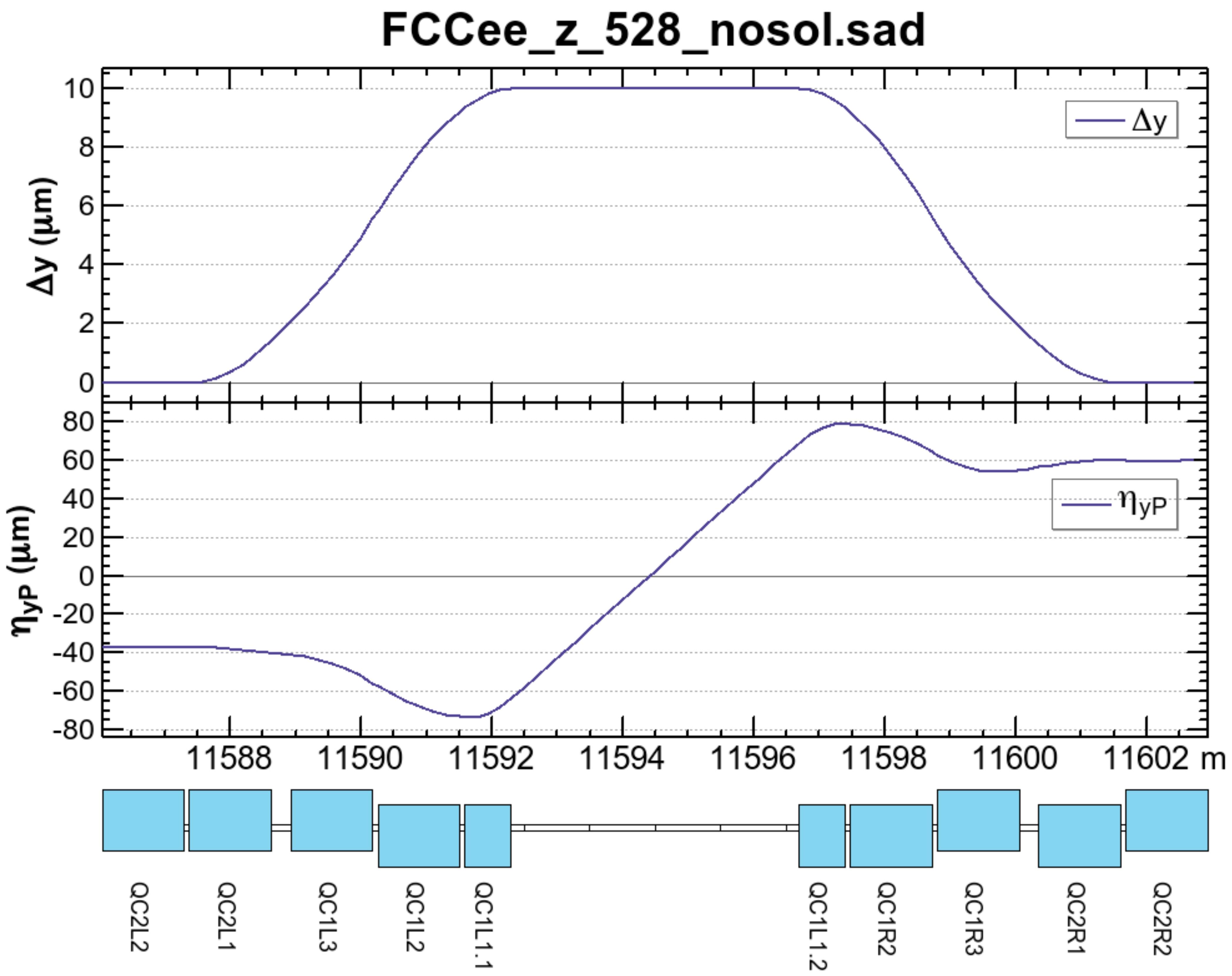
1.5 Dithering

As the horizontal beam-beam parameter is very small in low energies ($\xi_x = 0.004$ at Z), the beam-beam deflection is not appropriate for the detection of horizon offset at the IP. In such a case, a method called *dithering*, developed at PEP-II, is applicable, It shakes one beam with a single frequency, then detect the modulation of luminosity at that frequency, then by nullifying that component, the optimum offset is obtained.



An example of vertical bump at IP

- A simplest vertical bump orbit to control the IP offset can be produced by the skew dipole corrector winding of QC{12}{LR}1.
- This example does not close the dispersion.
- However, the associated vertical emittance generated by the dispersion leak is only 2.6 am by the 10 μm vertical offset at the IP. So the dispersion leak is not a practical issue.
- If this corrector is used for the IP feedback, its frequency response can be an issue, due to reduction by the beam pipe.



Requirements discussed here

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instruments	accuracy	resolution	conditions
BPM* for initial injection, all ring	1 mm	-	2 nC/bunch single-pass, single-bunch
BPM$^{\$}$ for optics/emittance tuning (all ring)	-	24 µm	2 nC/bunch single-pass, single-bunch pilot bunch
BPM for beam-beam deflection	-	0.8 mm	design intensity/luminosity (tt)
Loss monitor	?	?	necessary for initial injection 1 for every 100 m
SRM, XRM, beam core		eventually 1/10 of the design emittance	
SRM, hallo			useful for luminosity/lifetime tuning
Bunch by bunch feedback			
narrow band, 0-turn feedback			for resistive wall coupled bunch instability
pilot bunch kickers			for spin depolarization, dispersion measurement of pilot bunch, etc.

* Some BPMs must be able to detect the bunch timing for synchrotron motion.

$ The resolution assumes the scaling with sqrt(number of bunches * number of turns).

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Thank you!