K. Oide (UNIGE)

June 1, 2022

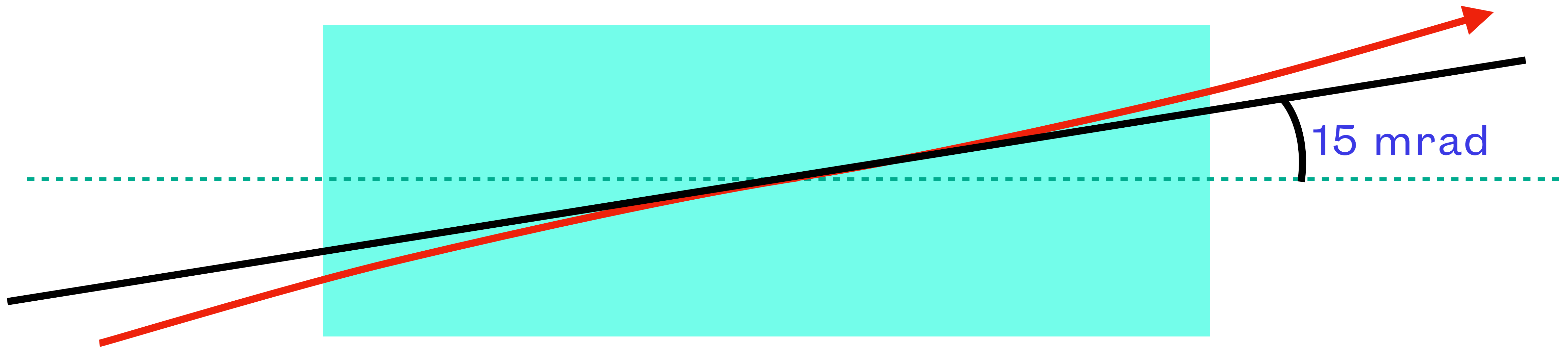
Many thanks to A. Blondel, M. Hofer, M. Koratzinos, N. Muchnoi,
D. Shatilov, and all FCC-ee/FCCIS colleagues

Polarimeter and wigglers integration status

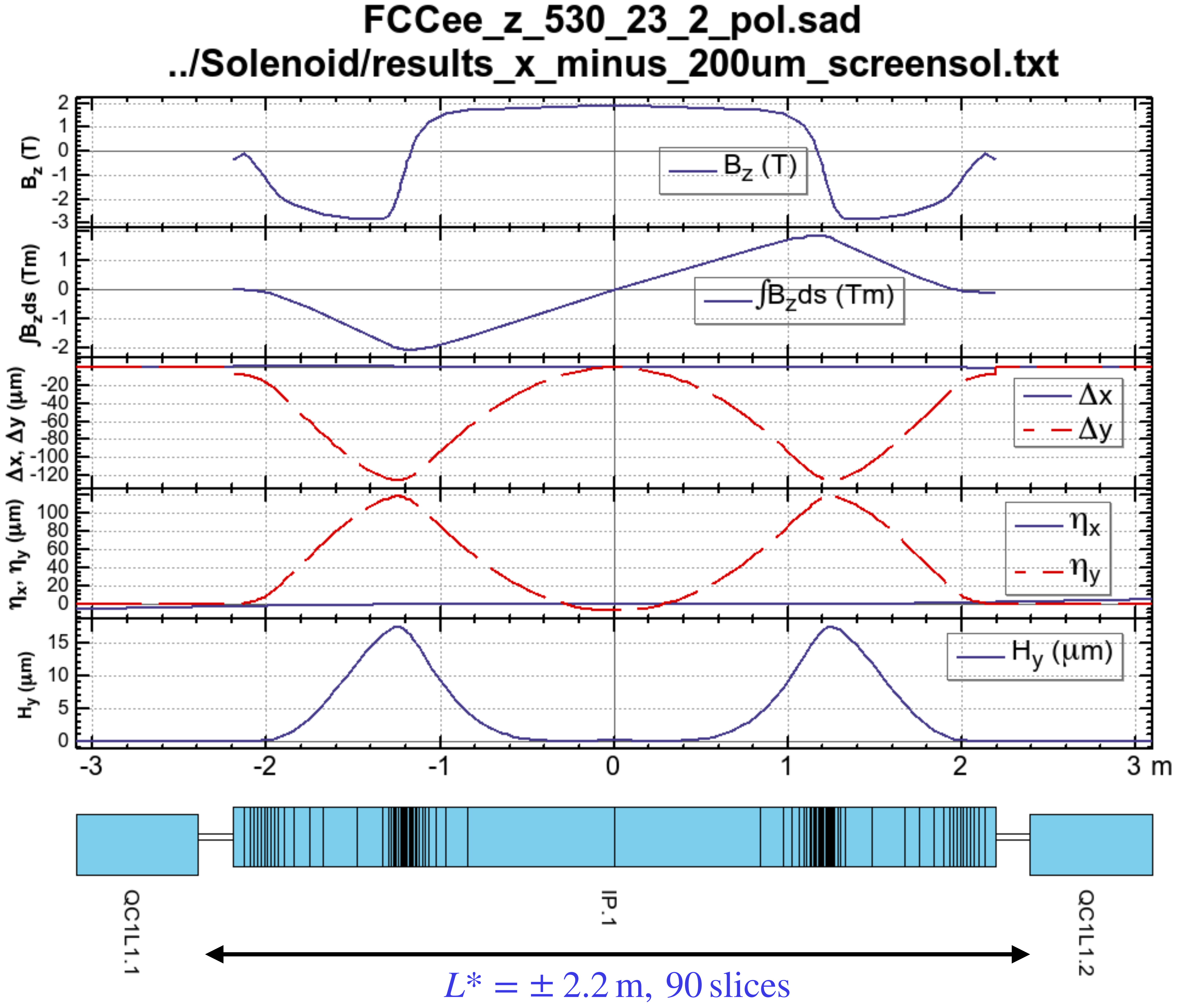
Optics including a realistic solenoid (M. Koratzinos)

30 May - 03 June FCC WEEK 2022

- A realistic solenoid + multipole field given by M. Koratzinos has been included into the latest 4 IP lattice.
- 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 corrected to the no-solenoid case by tweaking the outer quads.
- The highest contribution to the vertical emittance comes from the middle transition ($s \sim \pm 1.2\,\mathrm{m}$) of B_z.



~CDR, 2IP optics



Parameters (4 IP, new layout)

$\beta_x^* = 10\,\mathrm{cm}$ @Z

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 / 0.219
Bunch length (SR/BS) σ_z	[mm]	4.38 / 15.4	3.55 / 8.01	3.34 / 6.00	2.00 / 2.80
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	4.0 / 7.25
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	3.1
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	0.091 / 0.139
Luminosity / IP	[10^{34}/cm^{2}s]	182	19.4	7.26	1.24
Lifetime (q + BS)	[sec]	–		1065	5090
Lifetime (lum)	[sec]	1129	1070	596	752

[a] incl. hourglass.

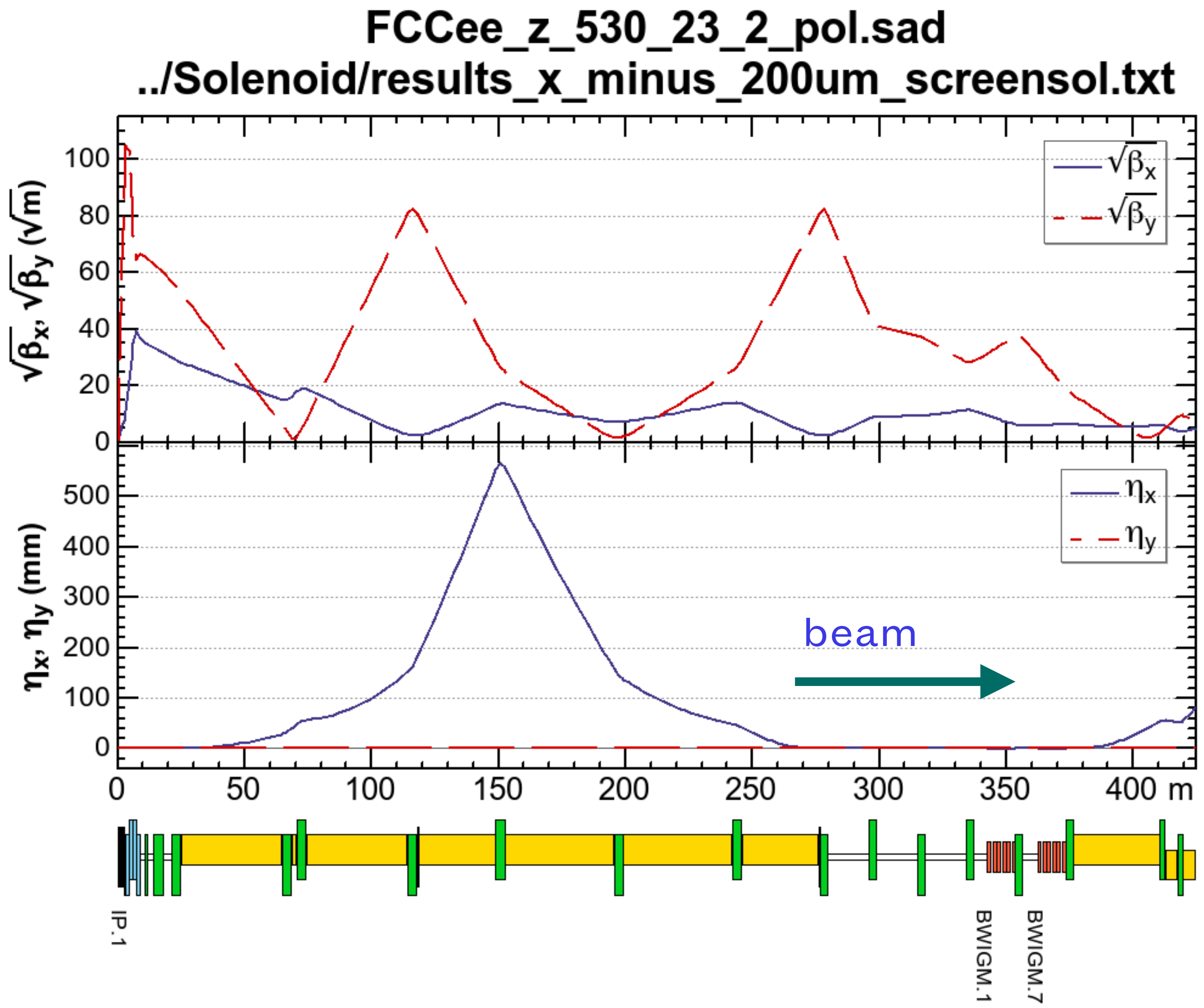
$\beta_x^* = 15\,\mathrm{cm}$ (Nov . 29)

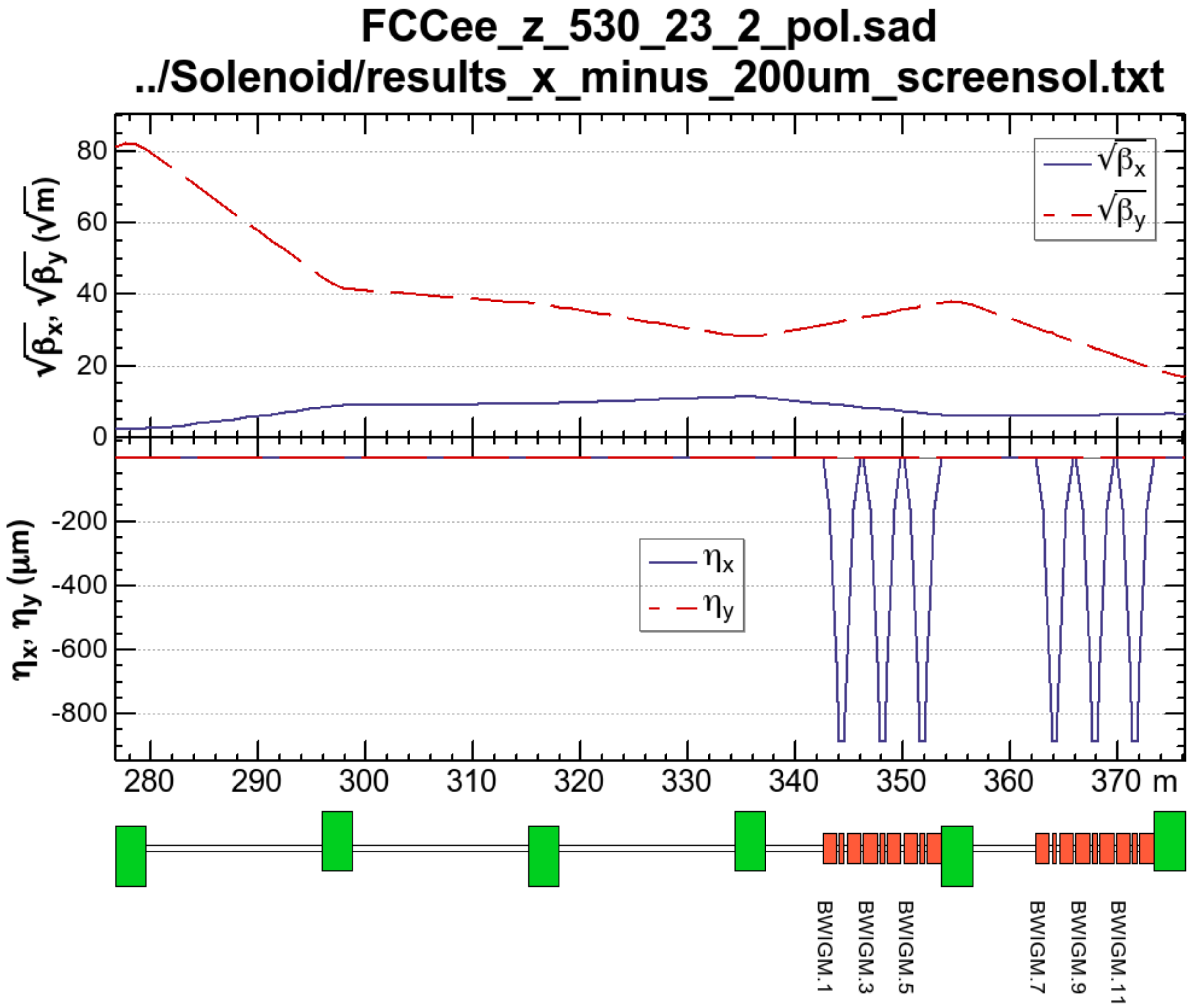
Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		9600	880	248	36
Bunch population	[10^{11}]	2.53	2.91	2.04	2.64
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]	150 / 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	[%]	0.039 / 0.130	0.069 / 0.154	0.103 / 0.185	0.157 / 0.229
Bunch length (SR/BS) σ_z	[mm]	4.37 / 14.5	3.55 / 8.01	3.34 / 6.00	2.02 / 2.95
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	4.0 / 7.25
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	3.1
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y [a]		0.0040 / 0.152	0.011 / 0.125	0.014 / 0.131	0.096 / 0.151
Luminosity / IP	[10^{34}/cm^{2}s]	189	19.4	7.26	1.33
Lifetime (q + BS)	[sec]	–		1065	2405
Lifetime (lum)	[sec]	1089	1070	596	701

[a] incl. hourglass.

- By squeezing β_x^*, bunches/ring (bunch population), bunch length, energy spread also change. All affect the luminosity.
- $\xi_y \lesssim 0.14$ is set as a criterion (also set at $t\bar{t}$ this time).
- The betatron tunes are not yet chosen perfectly considering the instability.

Polarization wigglers (M. Hofer)





- Polarization wigglers can be placed at the straight section "LA*", lcated at downstream of each IP.
  - Parameters follow CDR's: can be readjusted, taking the critical energy, etc., into account (M. Hofer).

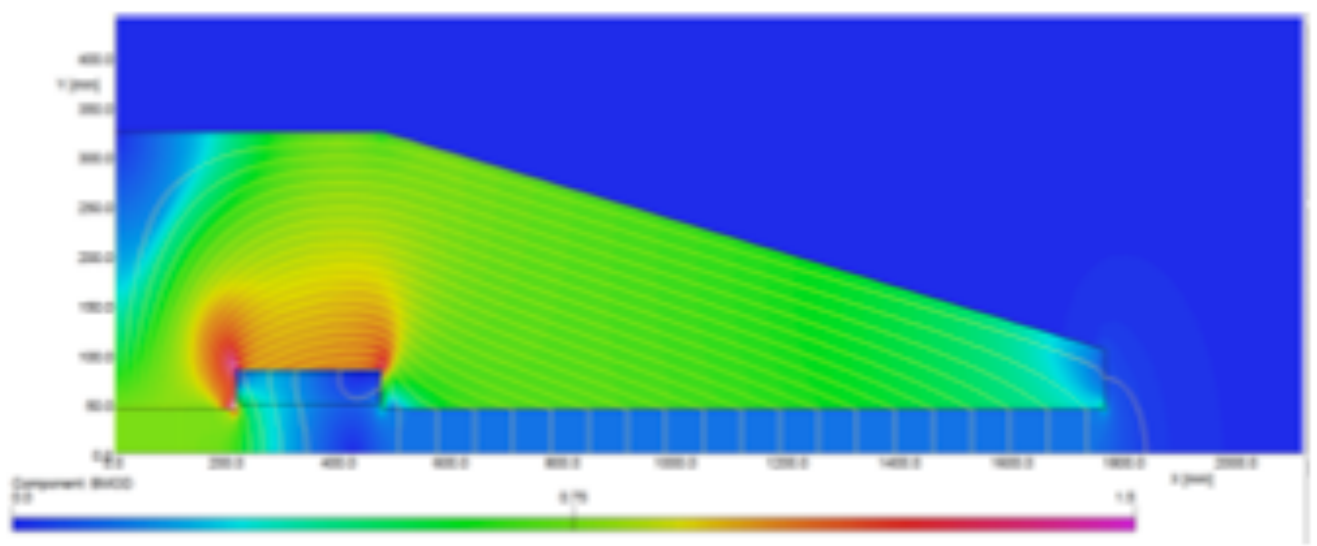
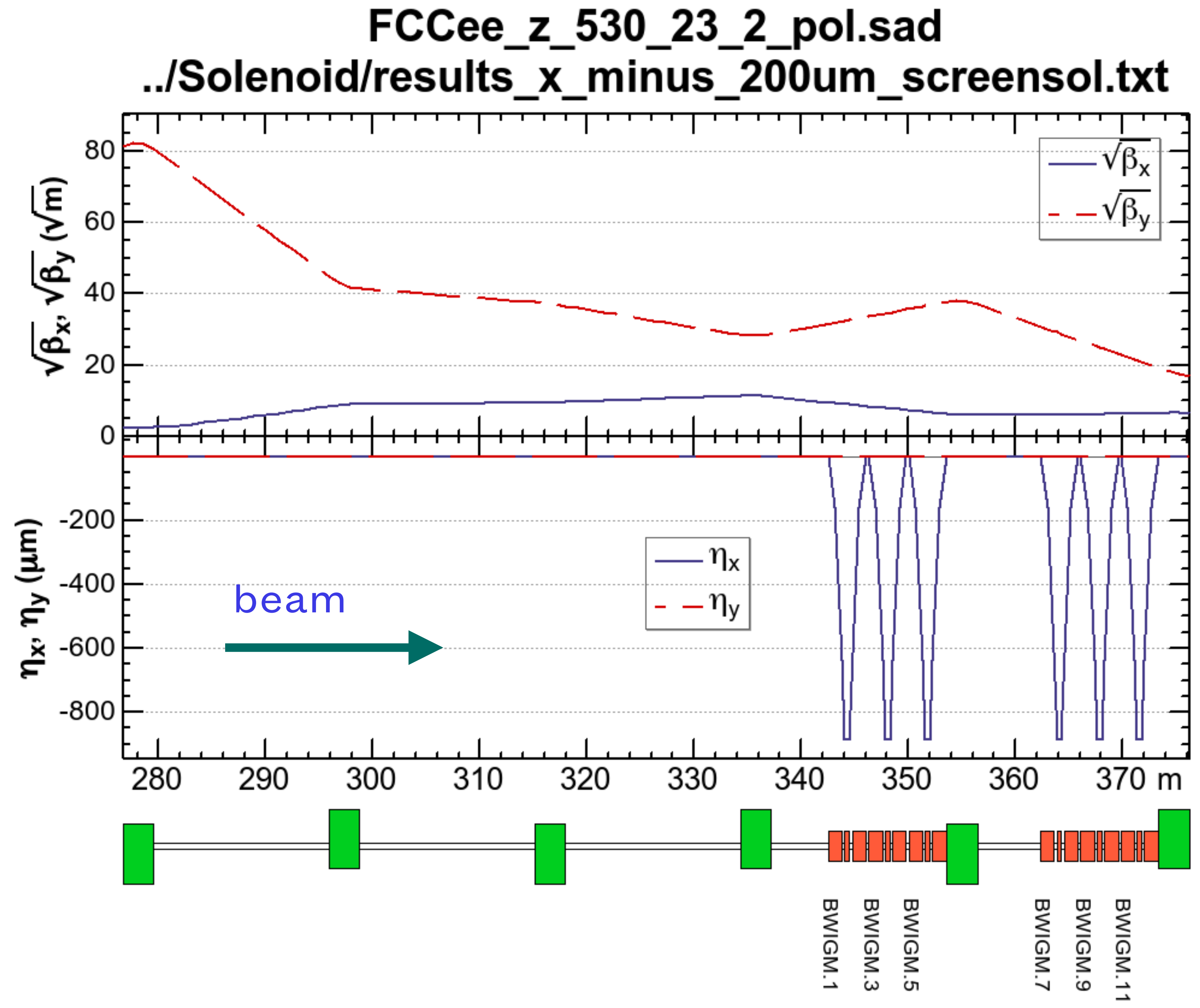


Figure 3.10: Magnetic design of a half unit of the polarisation wiggler. In this representation the beam will travel in the z-direction.

CDR

Parameter with pol. wigglers

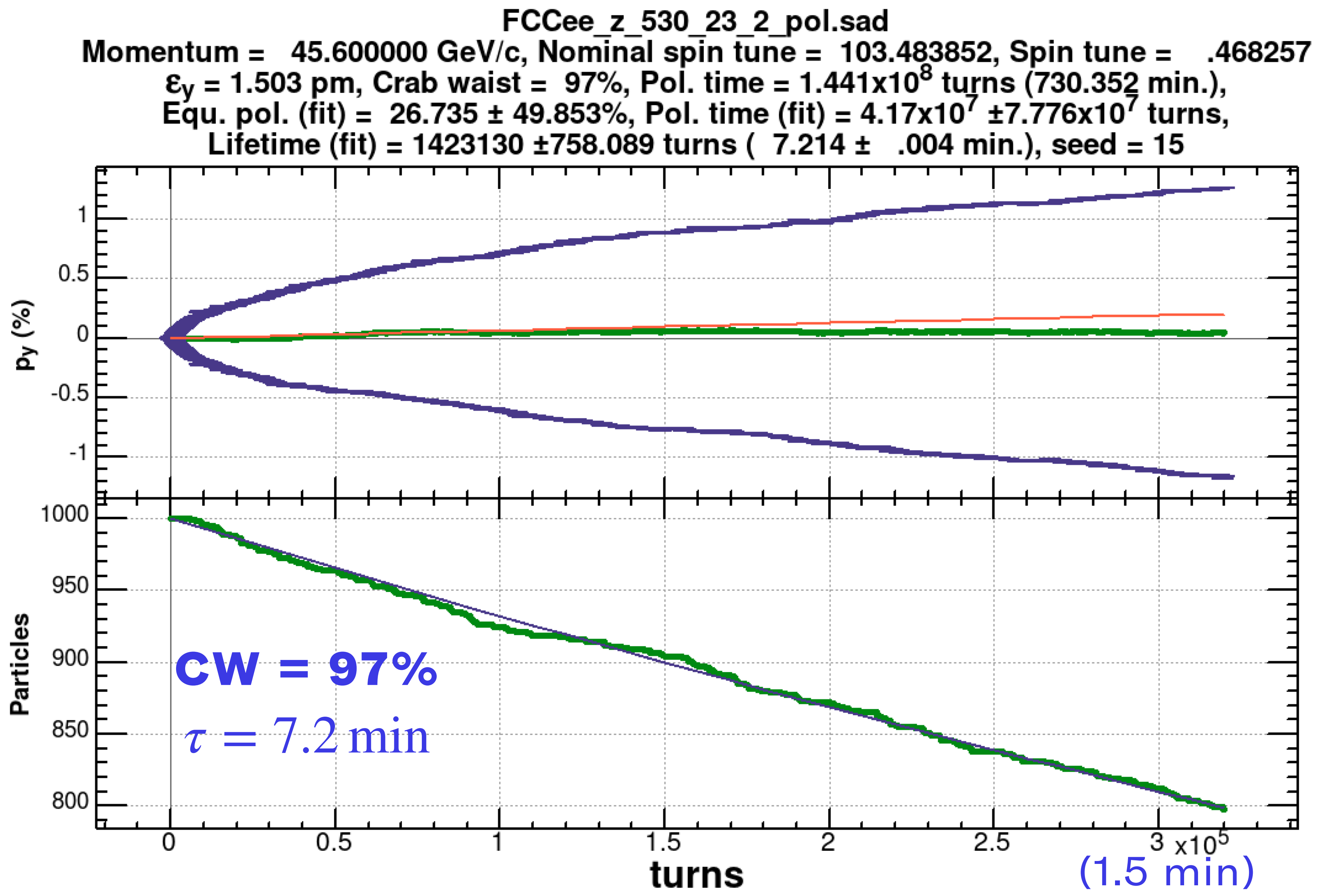


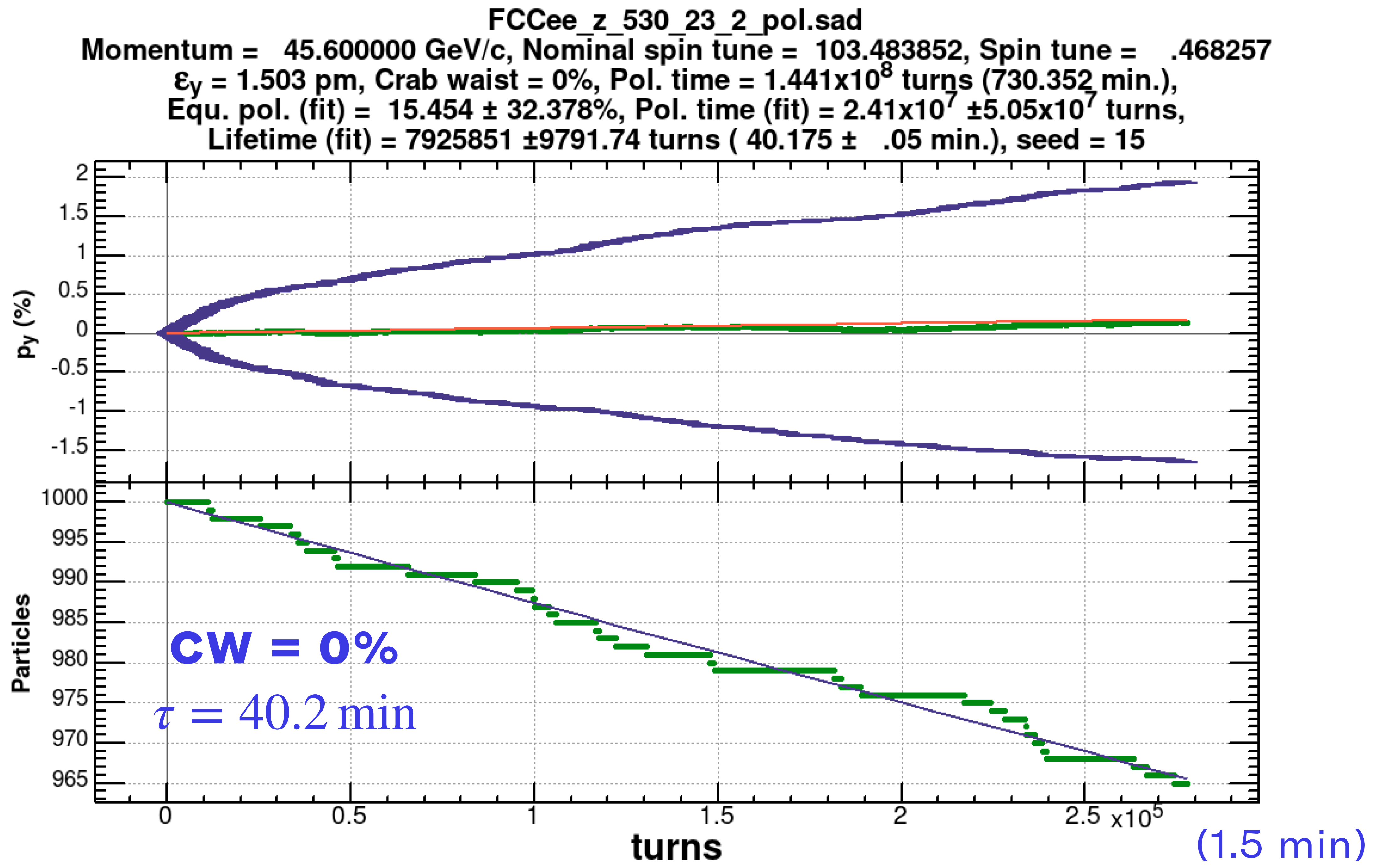
Beam energy	[GeV]	45.6	
Wiggler poles/ring (long/short)		-	48 / 24
Wiggler field	[T]	-	-0.1167 / 0.6
Wiggler length	[m]	-	1.29 / 0.43
Energy loss / turn	[MeV]	39.3	54.8
Horizontal emittance ε_x	[nm]	0.702	0.563
Vertical emittance ε_y	[pm]	0.426	0.305
Energy spread (SR) σ_δ	[%]	0.040	0.137
Bunch length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

- The parameters for the pol. wigglers follow CDR.
- It is interesting that the resulting beam parameters such as σ_z, σ_ε become very similar to those of colliding bunches with beamstrahlung:

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

Tracking simulation for beam lifetime (+polarization)





- Tracking simulations have been performed for Z lattices with pol. wigglers, with solenoid with the latest 4 IP optics.
- The vertical emittance is generated by random vertical misalignments of arc sextupoles. The associated orbit distortion and β-beats are small. This should be almost the best situation.
- 1000 particles, SR in all magnets, no beam-beam.
- An ideal tapering.
- For the initial condition, each particle has zero vertical polarization with a random pol. angle in x-z plane.
- The tracking takes about 1 day on hpc-batch for one sample, for about 3×10^5 turns.

Beam lifetime with pol. wigglers

Wiggler & Solenoid		ON					
Vertical emittance	[pm]	1.5					
β_x^*	[m]	0.1				0.15	
Sexts optimization[a]		SC		SW		C	
Crab waist	[%]	97	0	97	0	97	0
Lifetime	[min]	7.2	40.2	4.5	53.9	15	1800

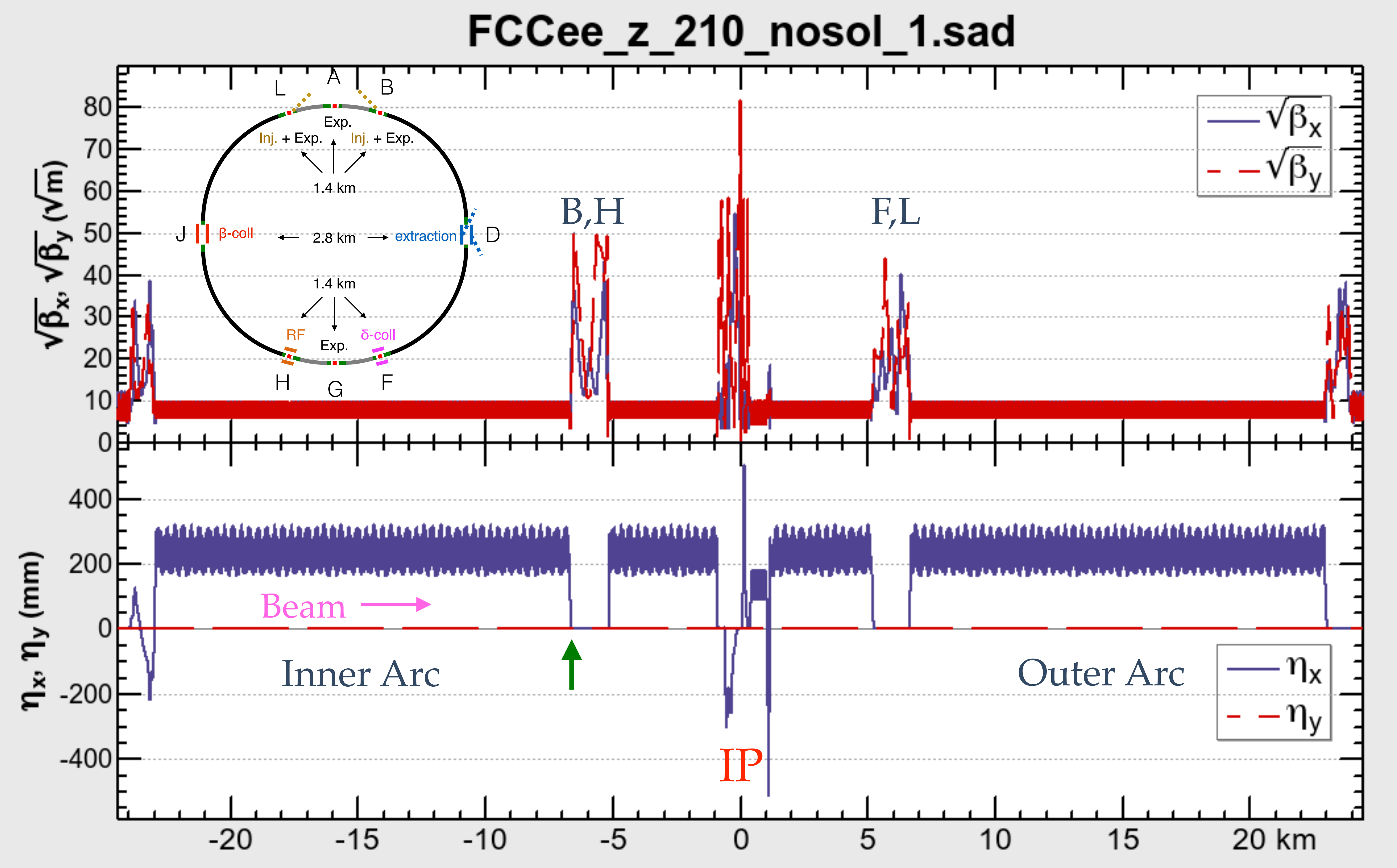
[a] including S: solenoid, C: crab 97%, W: pol. wigglers.

- The polarization wiggler has an impact on the beam lifetime.
- The $\beta_x^* = 10$ cm optics is more affected than the $\beta_x^* = 15$ cm optics.
- Turning off the crab sexts improves the lifetime (S. Shatilov).
- The lifetime depends on the optimization of the sexts.
  - It will not be practical to switch the sextupole settings except crab sexts during an operation: Corrections are needed in the entire ring.
- However, the colliding beams will suffer, due to a similar energy spread as the wigglers. (The luminosity lifetime is 17 minutes at Z).

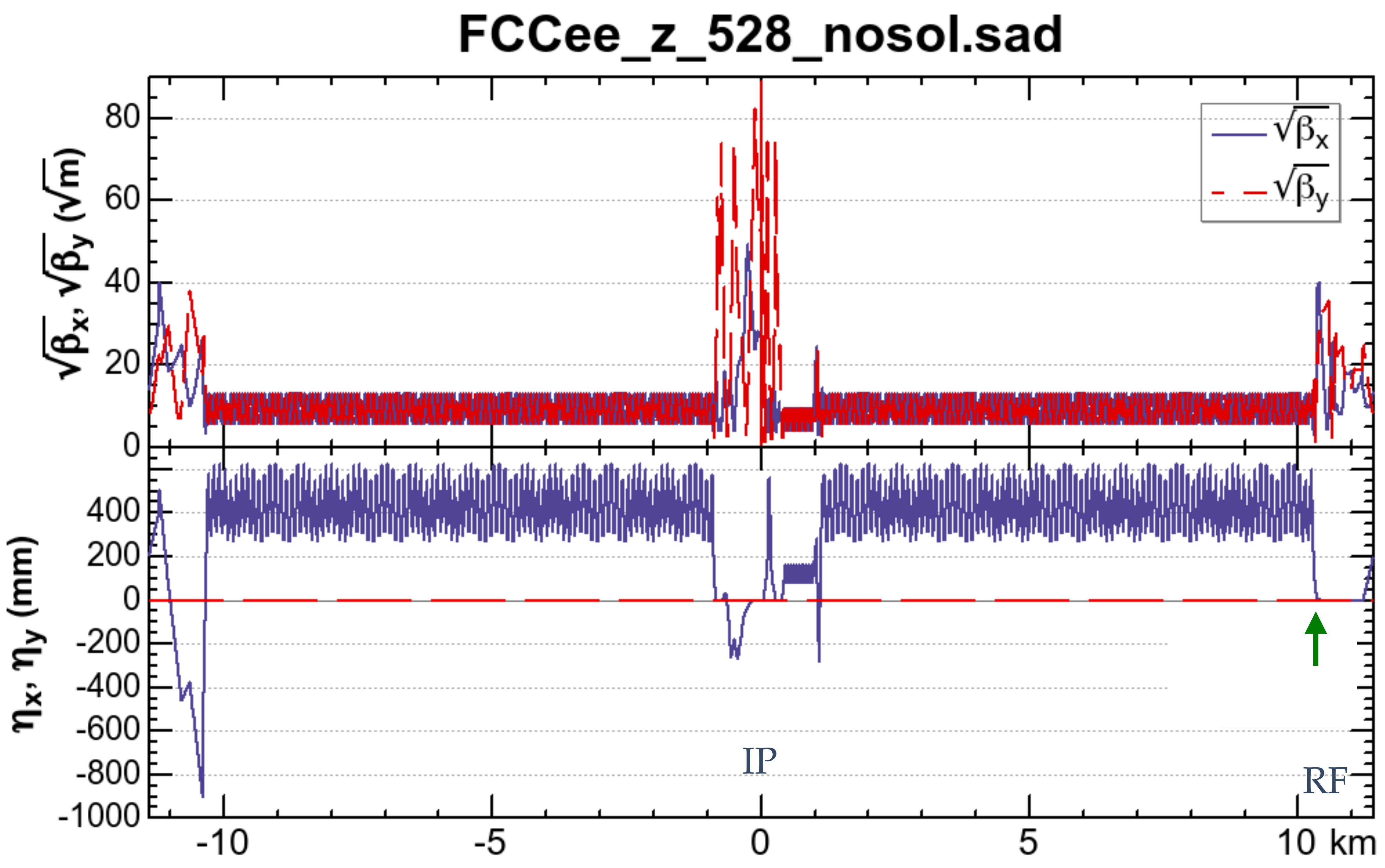
Placement of polarimeter

- CDR assigned one of the intermediate straight sections (B, F, H, L) for the polarimeter.
- Now with the new 4-IP compatible tunnel layout, *no such straight sections exist*.
- Candidates using a straight upstream of an IP have been looked first by M. Hofer as shown later.
- Another candidate may be the end of arc, upstream of an RF straight.

Location for the spectrometer (CDR)



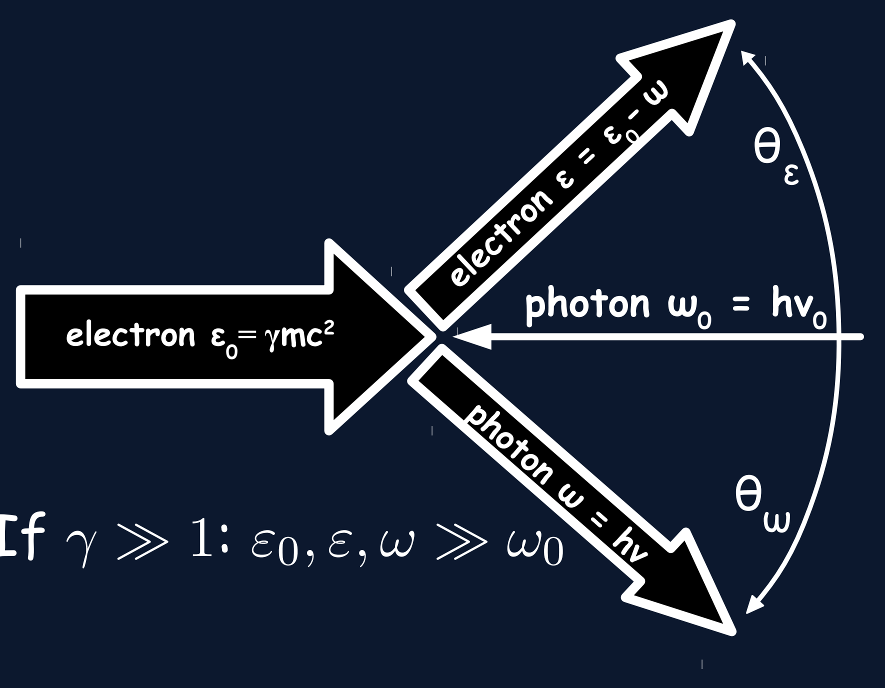
4-IP compatible new layout



Requirements (N. Muchnoi)

First proposed by:
Determination of the transverse polarization of high-energy electrons
V.N. Baier (Novosibirsk, IYF), Valery A. Khoze (Novosibirsk, IYF)
Published in: Sov.J.Nucl.Phys. 9 (1969), 238-240, Yad.Fiz. 9 (1969), 409-41

Inverse Compton Scattering



If $\gamma \gg 1$: $\varepsilon_0, \varepsilon, \omega \gg \omega_0$

Scattering parameter

$$u = \frac{\omega}{\varepsilon} = \frac{\theta_\varepsilon}{\theta_\omega} = \frac{\omega}{\varepsilon_0 - \omega} = \frac{\varepsilon_0 - \varepsilon}{\varepsilon}$$

is in the range

$$u \in [0, \kappa]\text{, where } \kappa = \frac{4\omega_0\varepsilon_0}{(mc^2)^2}\sin^2(\alpha/2)$$

$\kappa \simeq 1.63$ if $\varepsilon_0 = 45.6$ GeV, $\omega_0 = 2.33$ eV.

Scattering angles: $\theta_\omega = \frac{1}{\gamma}\sqrt{\frac{\kappa}{u} - 1}$; $\quad \theta_\varepsilon = \frac{u}{\gamma}\sqrt{\frac{\kappa}{u} - 1}$.

Note: $\max(\theta_\varepsilon) = 2\omega_0/mc^2$ (when $u = \kappa/2$). It is $\simeq 10\ \mu$rad for green light.

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Scattered electrons

Beam bending angle: $\vartheta_0 \equiv \gamma\theta_0 = \frac{\int B_\perp(l)\,dl}{mc/e}$, $\qquad \frac{mc}{e} = 1.704509024 \cdot 10^{-3}$[T m].

A scattered electron with energy $\varepsilon = \frac{\gamma mc^2}{1+u}$ bends more: $\qquad \vartheta(u) = \vartheta_0(1+u)$.

Electron angles by scattering and bending, relative to ϑ_0, in units of $1/\gamma$:

$$\vartheta_x \equiv \vartheta(u) - \vartheta_0 + \gamma\theta_x = u\vartheta_0 - u\sqrt{\kappa/u - 1}\cos(\varphi),$$
$$\vartheta_y \equiv \gamma\theta_y = -u\sqrt{\kappa/u - 1}\sin(\varphi).$$

Two solutions for u:

$$u^\pm = \frac{\kappa + 2\vartheta_0\vartheta_x \pm \sqrt{\kappa^2 - 4(\vartheta_x^2 + \vartheta_y^2(1+\vartheta_0^2) - \kappa\vartheta_0\vartheta_x)}}{2(1+\vartheta_0^2)}.$$

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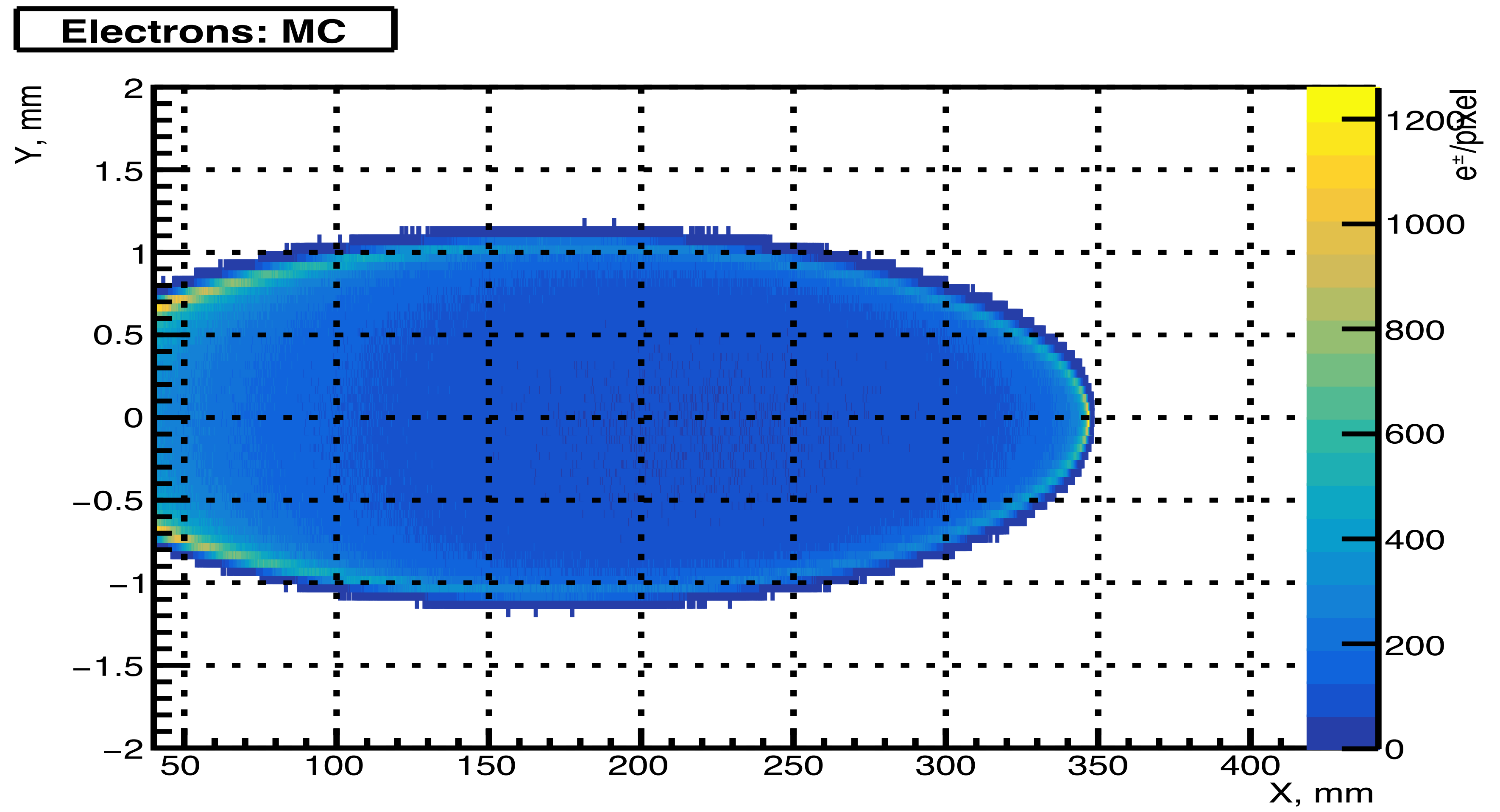
According to above expressions by N. Muchnoi, the maximum deflected angle for electrons is written as

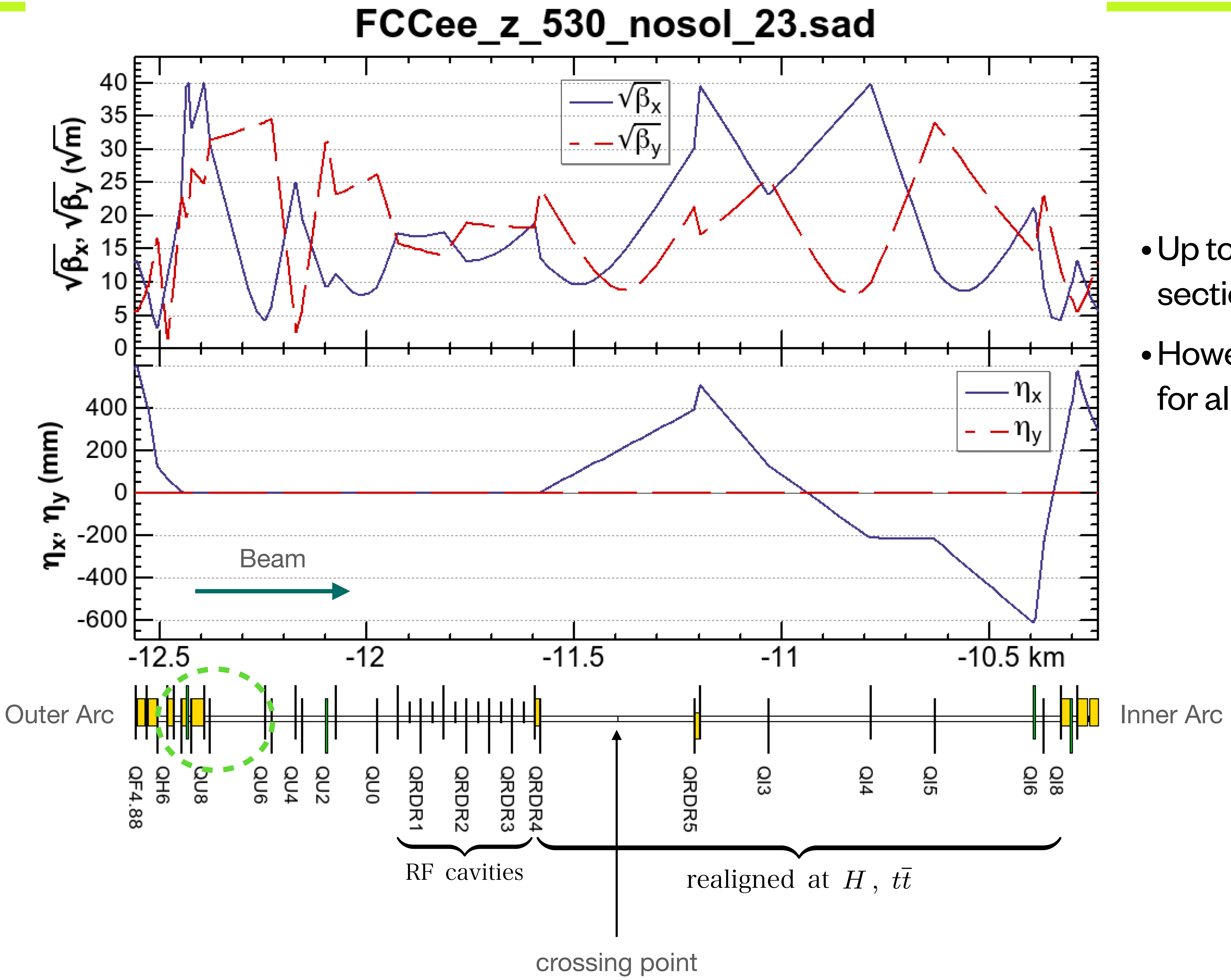
$$\Delta\theta_{x,\max} \approx u_{\max}\theta_0 = \kappa\theta_0\,, \qquad \kappa \approx 1.63\,@\,45.6\,\mathrm{GeV}\,.$$

If we need a 35 cm horizontal spread of electrons as shown by Muchnoi, at $L = 100$ m downstream of the laser hit point, we need

$$\theta_0 = (35\,\mathrm{cm})/(\kappa L) = 2.14\,\mathrm{mrad}\,.$$

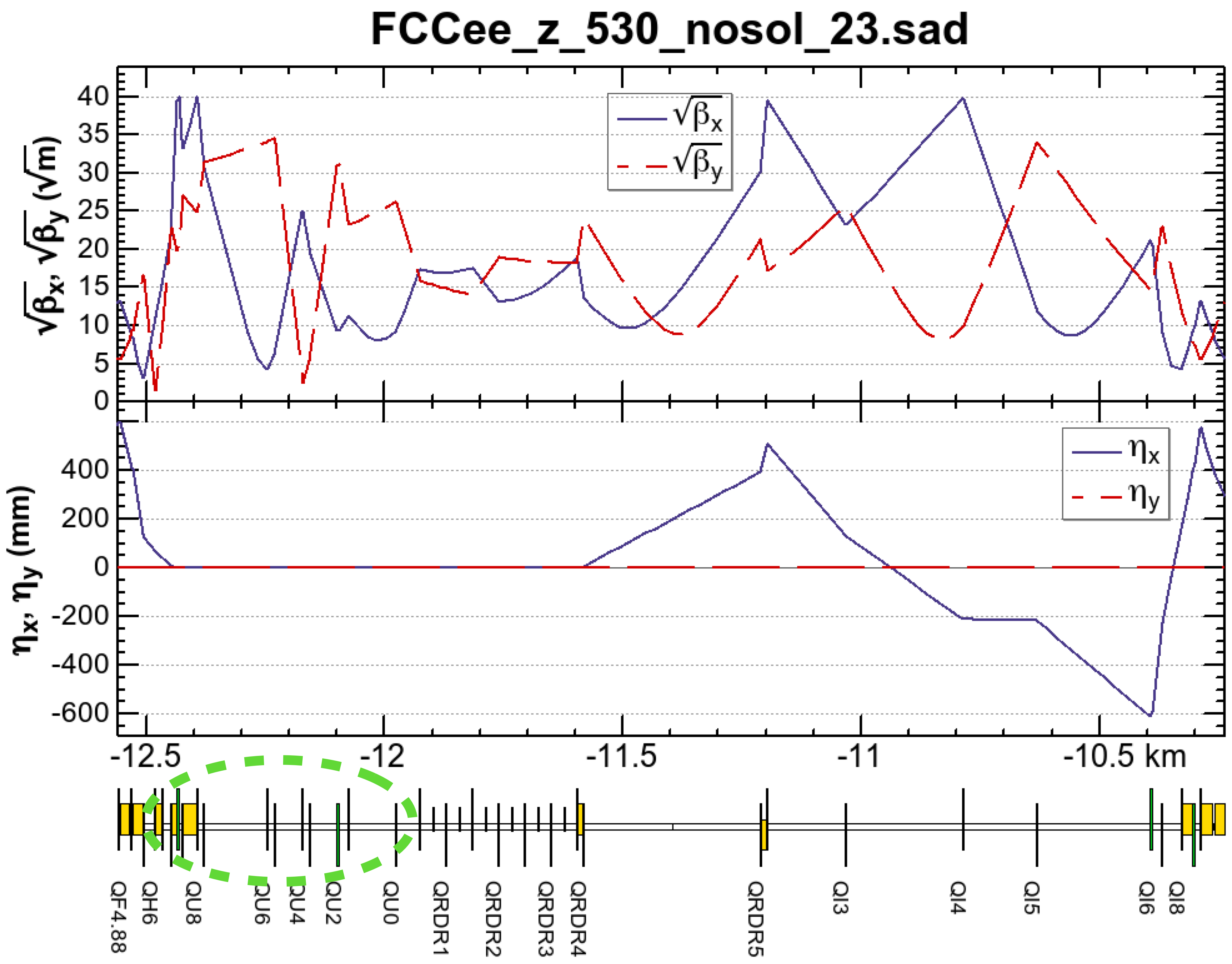


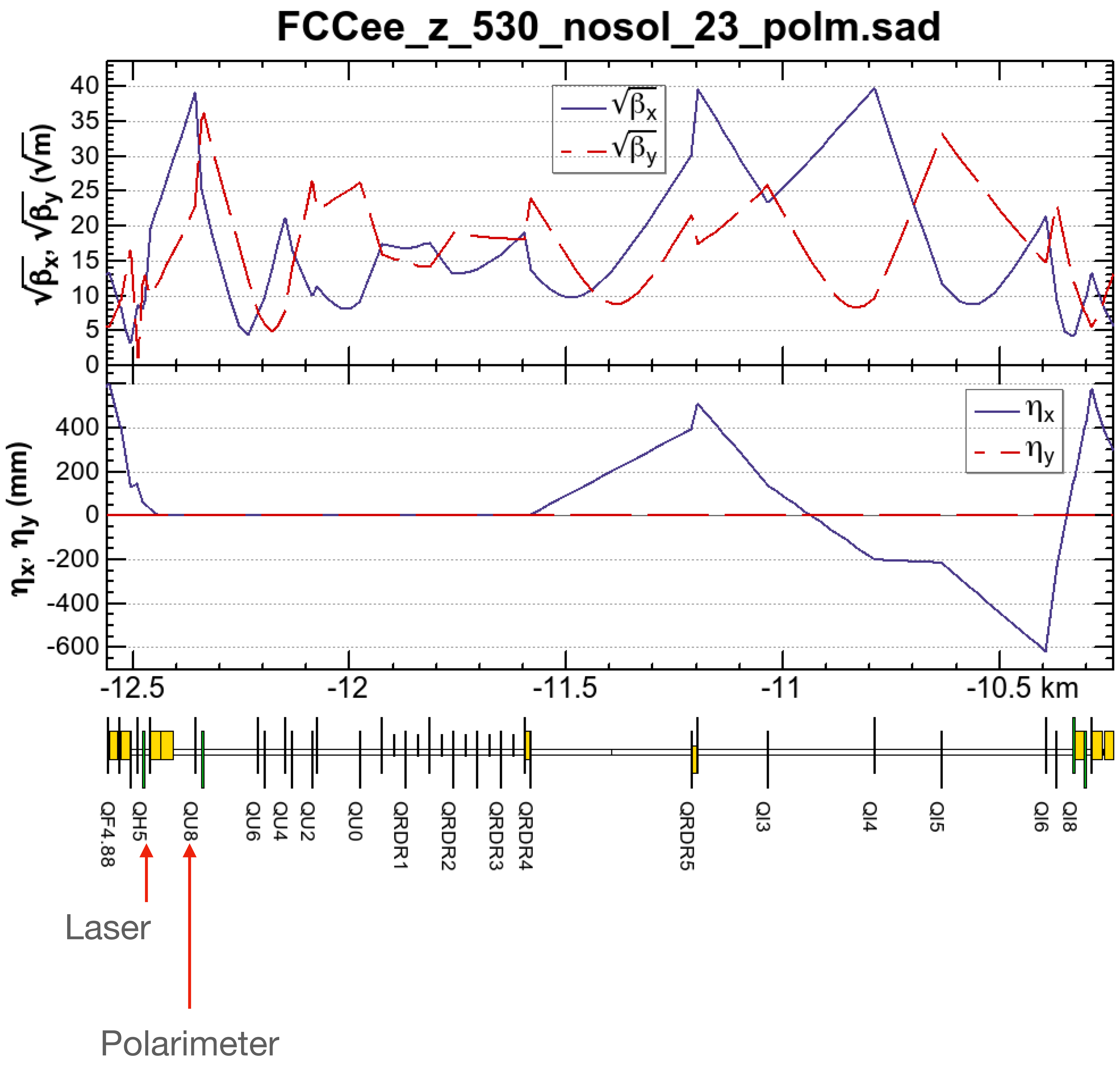
Beam optics of the RF section at Z, W



- Up to H, cavities are filled in only one of the RF sections.
- However, we want to make the optics identical for all sections to preserve the periodicity.

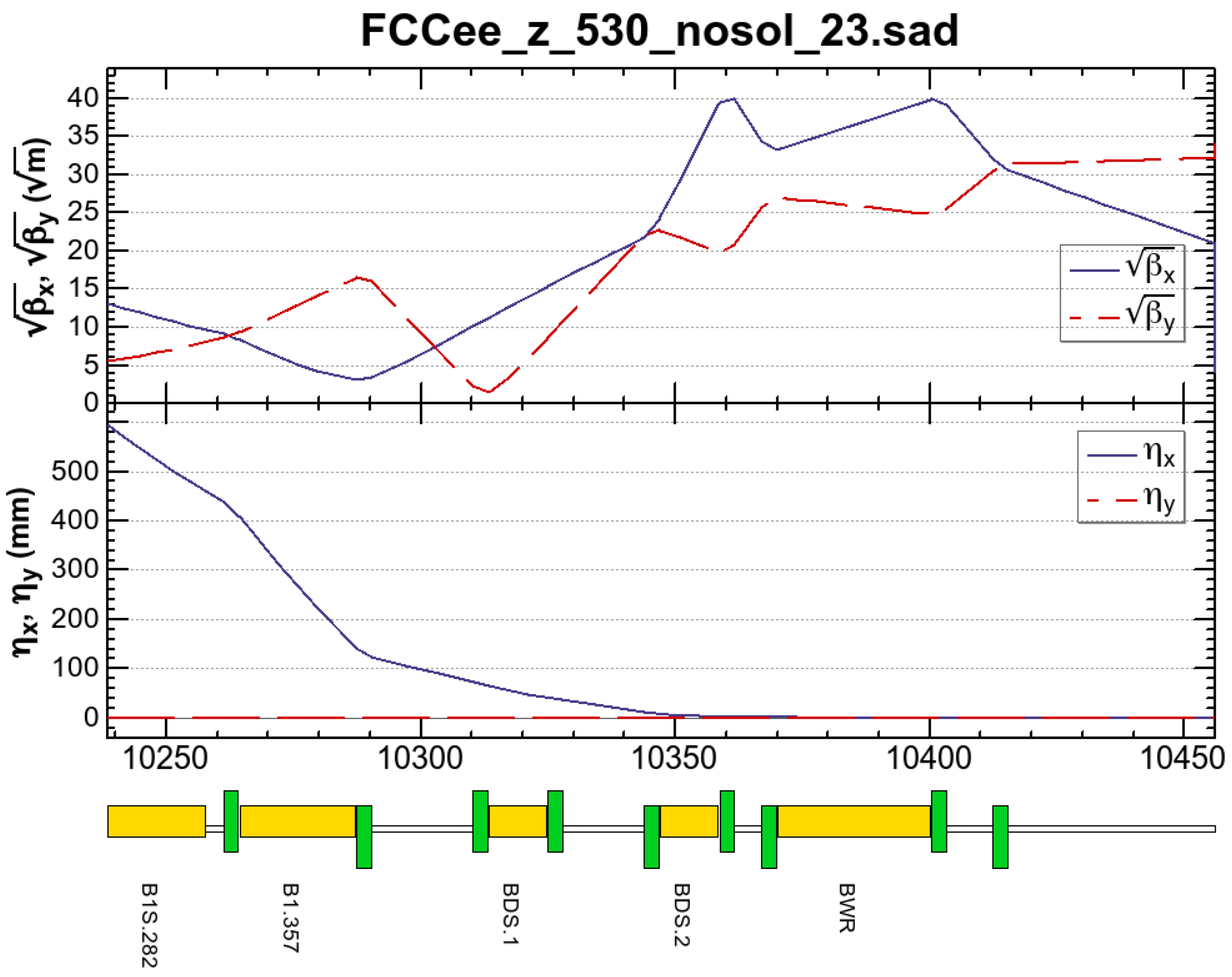
Tweak the RF section for polarimeter

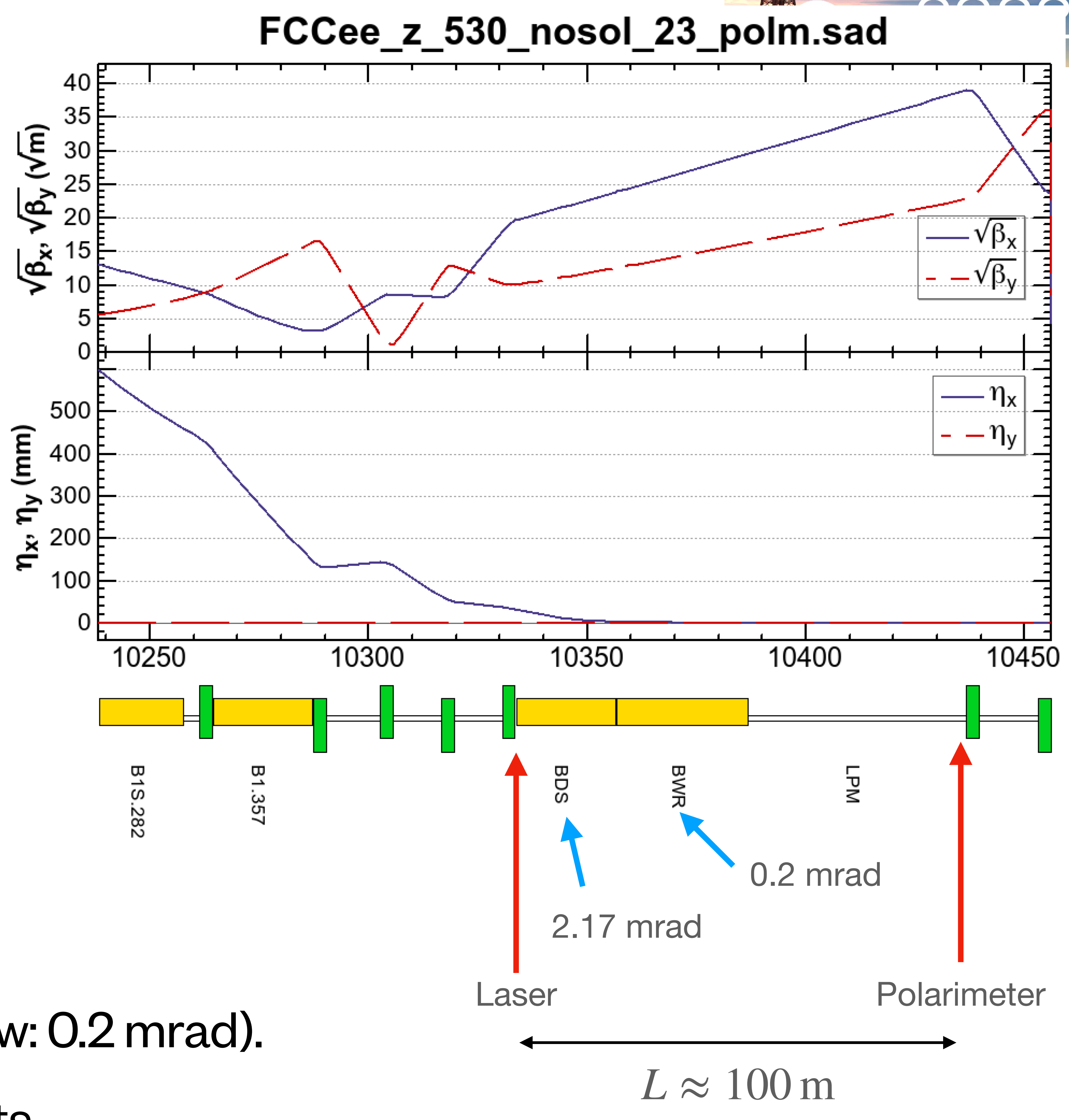




- The upstream of the RF sections is rearranged to install the polarimeter.
- The exact ring geometry is not yet precisely adjusted.

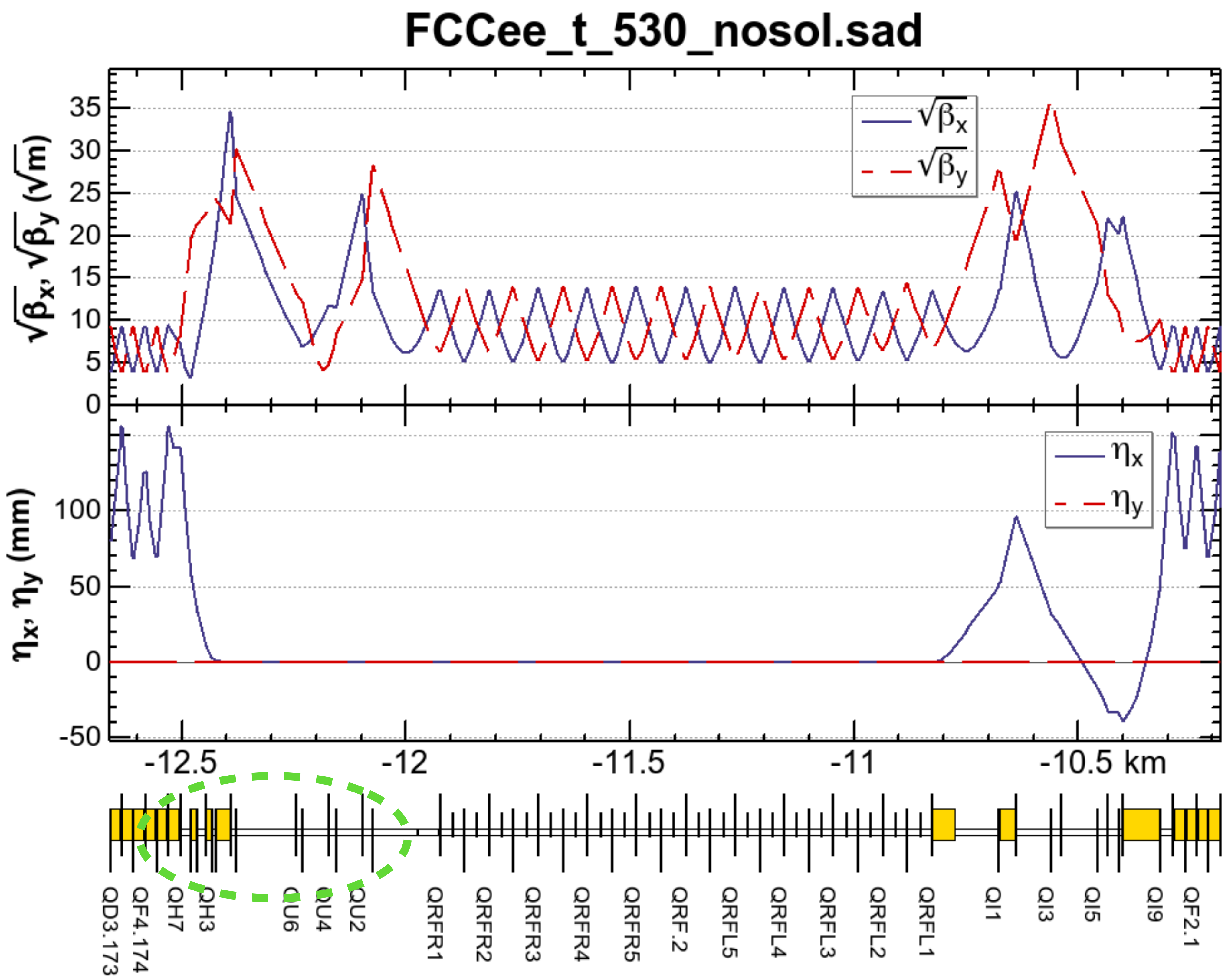
Closer look

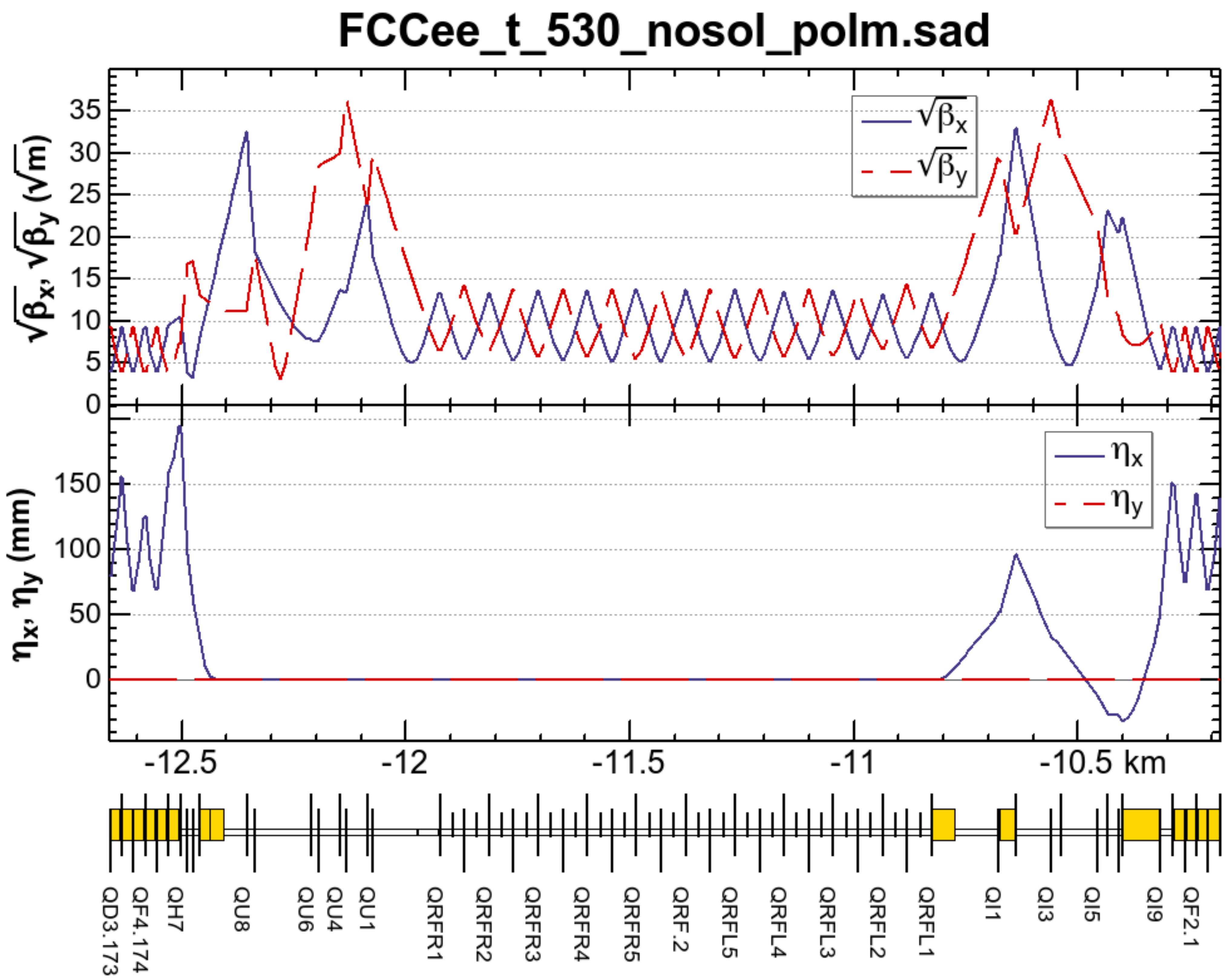




- BDS: dispersion suppressor dipole (2.17 mrad total).
- BWR: weak bend to avoid SR hit on RF cavities (old: 0.1 mrad, new: 0.2 mrad).
- Optics for H/$t\bar{t}$ should have the compatible layout of components.

Optics for $H/t\bar{t}$





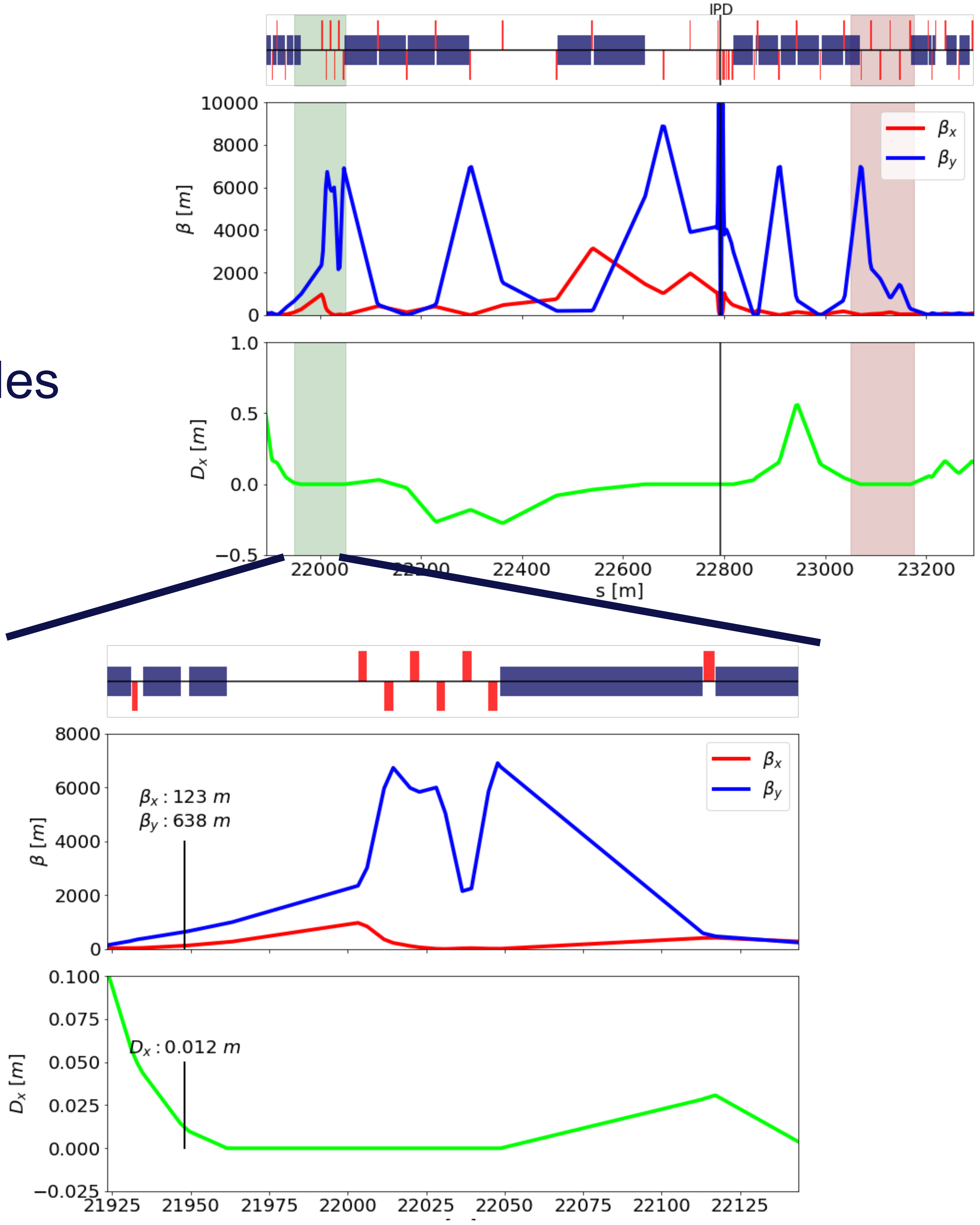
- The modified lattice is indeed compatible for $H/t\bar{t}$.
  - No need to move quads upstream of the RF cavities, except one (QU0) located at the electrostatic separator.

Possibility for the IP upstream (M. Hofer)

30 May - 03 June FCC WEEK 2022

Polarimeter in 4-IP lattice

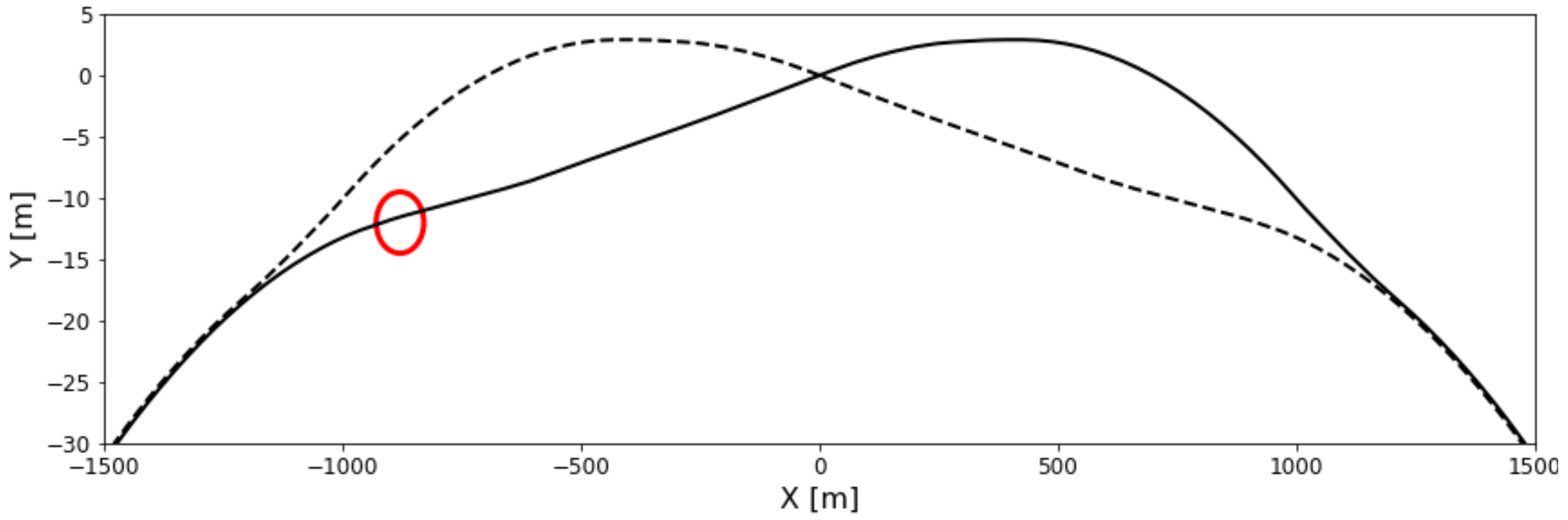
- Modification compatible with Z and $t\bar{t}$ optics
- Phase advance between IP and first arc sextupoles is partly used to optimize dynamic aperture
  - These changes could have implications on optics matching and Dynamic aperture
- More drift space could be recovered by moving crab sextupole and dipoles closer to IP
  - Change in the geometry could affect background in the detector



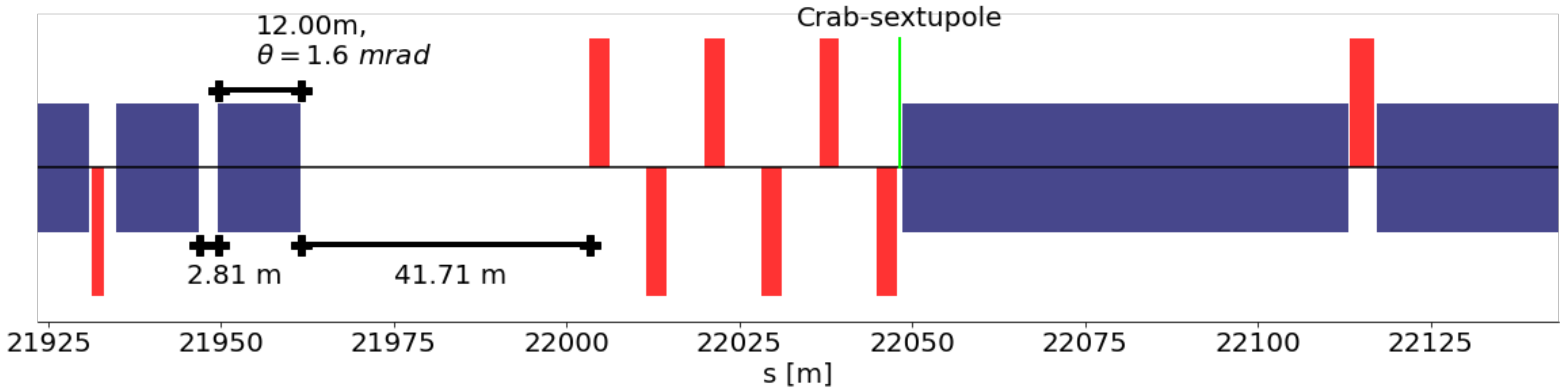
Possibility for the IP upstream (M. Hofer)

Polarimeter in 4-IP lattice

- By moving a few quadrupoles, free space after spectrometer dipole created
  - Drift space is less than half of baseline solution
  - Sufficient space on either side for detectors



- Shorter drift space not impossible, but changes required [see ref]:
  1. Change laser wavelength from 532nm to 266nm
  2. Changes on the detector (smaller pixels)



Summary

- The effect of polarization wigglers placed downstream of each IP has been looked at by particle trackings.
  - A more or less realistic field of the detector/compensation solenoids are included.
- Impact on the beam lifetime due to the large energy spread caused by the wigglers can be an issue.
  - For pilot bunches, it can be recovered by turning off the crab sextupoles.
  - However, the lifetime for colliding beams maymatter, as they have the similar energy spread by the beamstrahlung as the wigglers.
    - The effect is larger in $\beta_x^* = 10\,\mathrm{cm}$ optics than $\beta_x^* = 15\,\mathrm{cm}$.
    - It can be worsened by machine errors.
- There are at least two candidates for the location of the polarimeter:
  - Upstream in the RF straight section:
    - The measurement is done though a weak bend to protect the RF.
    - The separation of two beams must compatible with requirements from the RF.
  - Upstream of an IP:
    - No interference with the other beam.
    - Relatively short available space and small bending angle.
    - May need a short wavelength laser.
    - Otherwise pushing components toward the IP by $\sim 50\,\mathrm{m}$ will be necessary.