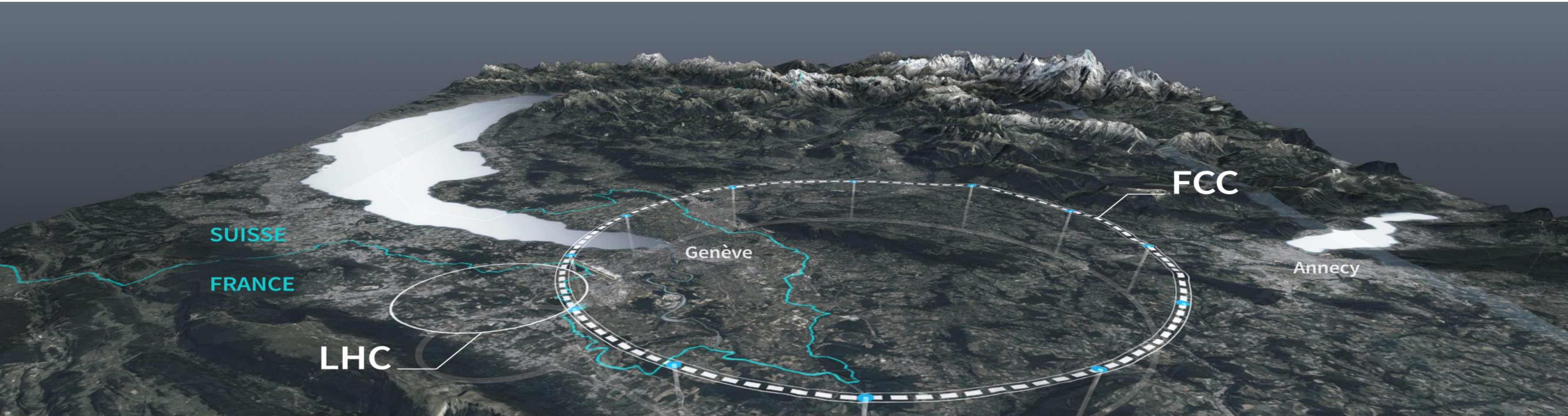

Progress on Monochromatization Studies

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Outline

- FCC-ee Monochromatization Concept
- Monochromatization Basic Formulas
- FCC-ee V22 Standard Optics
- FCC-ee Monochromatization Optics Design
  - Monochromatization Optics Design based on Z mode Lattice
  - Monochromatization Optics Design based on ttbar mode Lattice
- Summary and Outlook

FCC-ee Monochromatization Concept

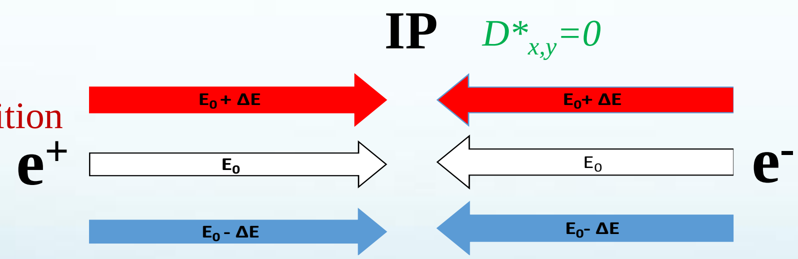
- **A 5th mode of FCC-ee operation : Monochromatic *s*-channel Higgs mode**

The measurement of the electron Yukawa coupling should be possible in dedicated runs at 125 GeV if the center-of-mass (CM) beam energy spread is comparable to the resonant width of the standard model Higgs Boson itself that is 4.2 MeV. For achieving this, the CM energy spread has to be reduced from 50 MeV (natural collision energy spread, due to the synchrotron radiation at these energies) to 5-10 MeV.

- **Monochromatization method: transverse monochromatization principle**

Standard Mode

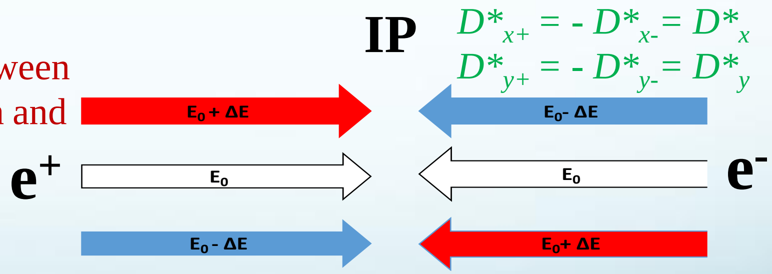
correlation between transverse spatial position and energy deviation



CM energy $w = 2(E_b + \Delta E)$

Monochromatization Mode

Opposite correlations between transverse spatial position and energy deviation



CM energy $w = 2E_b + O(\Delta E)^2$

Monochromatization Basic Formulas

- **Monochromatization Analytical Formulas**

Standard Mode $D^*_{x,y}=0$

Monochromatization Mode $D^*_{x,y} \neq 0$

CM energy spread

Non-zero dispersion at IPs means a non-zero monochromatization factor, therefore reducing the CM energy spread.

Beam energy

$$\sigma_w = \sqrt{2} E_b \sigma_\delta$$

Energy spread

$$\sigma_w = \frac{\sqrt{2} E_b \sigma_\delta}{\lambda}$$

Monochromatization factor

$$\lambda = \sqrt{1 + \sigma_\delta^2 \left(\frac{D_x^{*2}}{\varepsilon_x \beta_x^*} + \frac{D_y^{*2}}{\varepsilon_y \beta_y^*} \right)}$$

Luminosity

Non-zero dispersion at IPs increases the beam sizes at IPs, therefore causing the luminosity loss.

Bunches per beam

Revolution frequency

Particles per bunch

$$L_0 = \frac{f_{rev} n_b N_b{}^2}{4\pi \sigma_x^* \sigma_y^*}$$

Betatronic beam sizes at IPs

$$L = \frac{L_0}{\lambda}$$

Dispersive beam sizes at IPs

$$\sigma_{x,y}^* = \sqrt{\varepsilon_{x,y} \beta_{x,y}^* + D_{x,y}^*{}^2 \sigma_\delta{}^2}$$

Emittance   Beta function at IPs

Enhancement of energy resolution, and sometimes increase of the relative frequency of the events at the center of of the distribution but **luminosity loss !!!!**

Monochromatization Basic Formulas

- **Semi-analytical Formulas with Beamstrahlung [1]**

Standard Mode $D^*_{x,y}=0$

Monochromatization Mode $D^*_{x,y}\neq 0$

Energy spread

Standard mode (Energy spread with BS; Energy spread without BS; Bunch length without BS):

$$\sigma_{\delta,tot} = \sqrt{\frac{1}{2}\sigma_{\delta,SR}^2 + \sqrt{\frac{1}{4}\sigma_{\delta,SR}^4 + A\frac{\sigma_{\delta,SR}^2}{\sigma_{z,SR}^2}}}$$

Monochromatization mode — Coupled system to be solved numerically.

$$\sigma_{\delta,tot}^2 = \sigma_{\delta,SR}^2 + \frac{B}{D_x^{*3}\sigma_{\delta,tot}^5}$$

Beamstrahlung has more impact on energy spread of standard mode than that of monochromatization mode.

Longitudinal damping time; Fine structure constant; Beam size without BS:

$$with\ A = \frac{275}{36\pi^{\frac{3}{2}}}\frac{n_{IP}\tau_E}{4T_{rev}}\frac{r_e^5 N_b^3\gamma^2}{\alpha\sigma_{x,SR}^{*3}}$$

# of IP; Electron radius; Revolution time; Synchrotron tune:

$$with\ \ B \approx 50\frac{n_{IP}\tau_E}{T_{rev}}\frac{r_e^5 N_b^3\gamma^2}{(\alpha_c C/(2\pi Q_s))^2}$$

Horizontal emittance

Horizontal emittance with BS; Horizontal emittance without BS:

$$\varepsilon_{x,tot} \approx \varepsilon_{x,SR}$$

$$\varepsilon_{x,tot} \approx \varepsilon_{x,SR} + \frac{2B}{D_x^*\beta_x^*\sigma_{\delta,tot}^5}$$

Bunch length

Momentum compaction factor; Circumference:

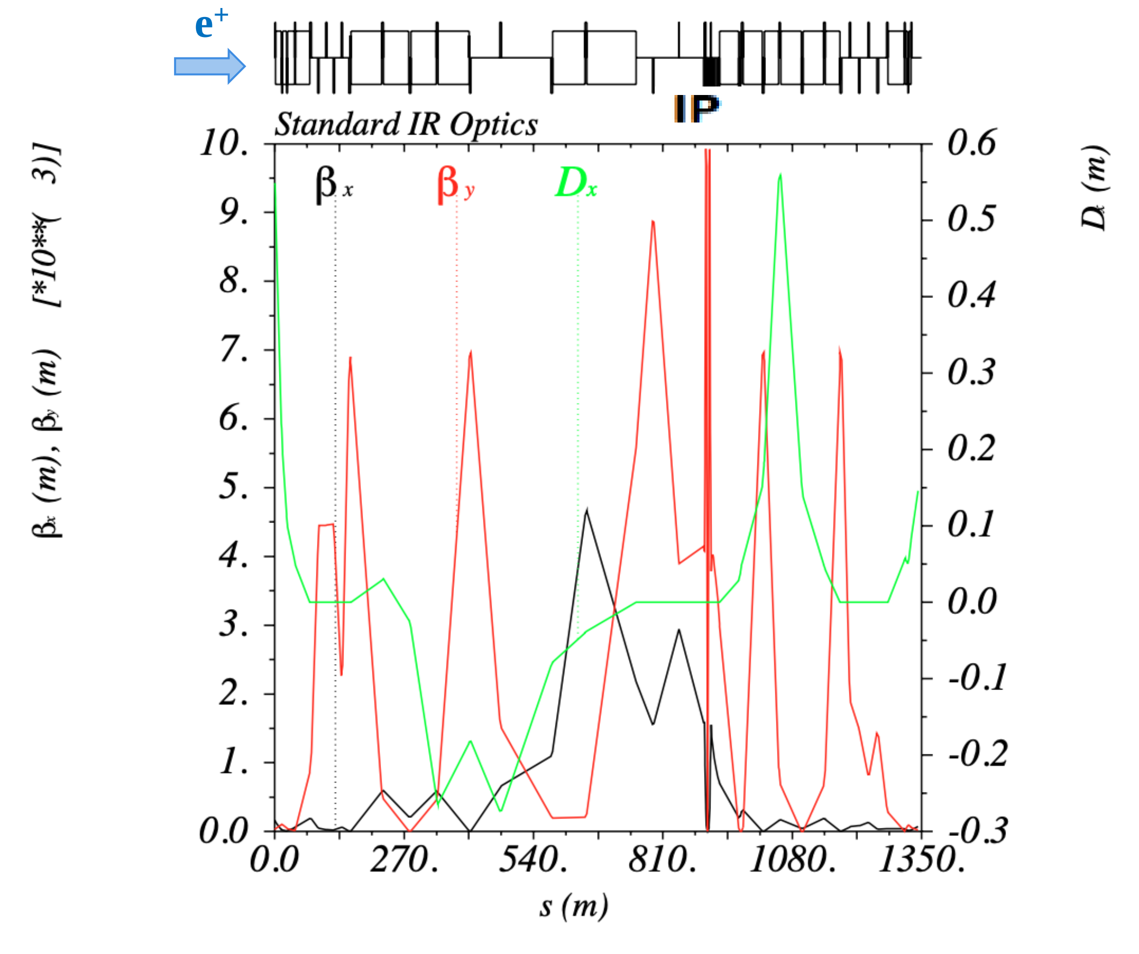
$$\sigma_{z.tot} = \frac{\alpha_c C}{2\pi Q_s}\sigma_{\delta,tot}$$

$$\sigma_{z.tot} = \frac{\alpha_c C}{2\pi Q_s}\sigma_{\delta,tot}$$

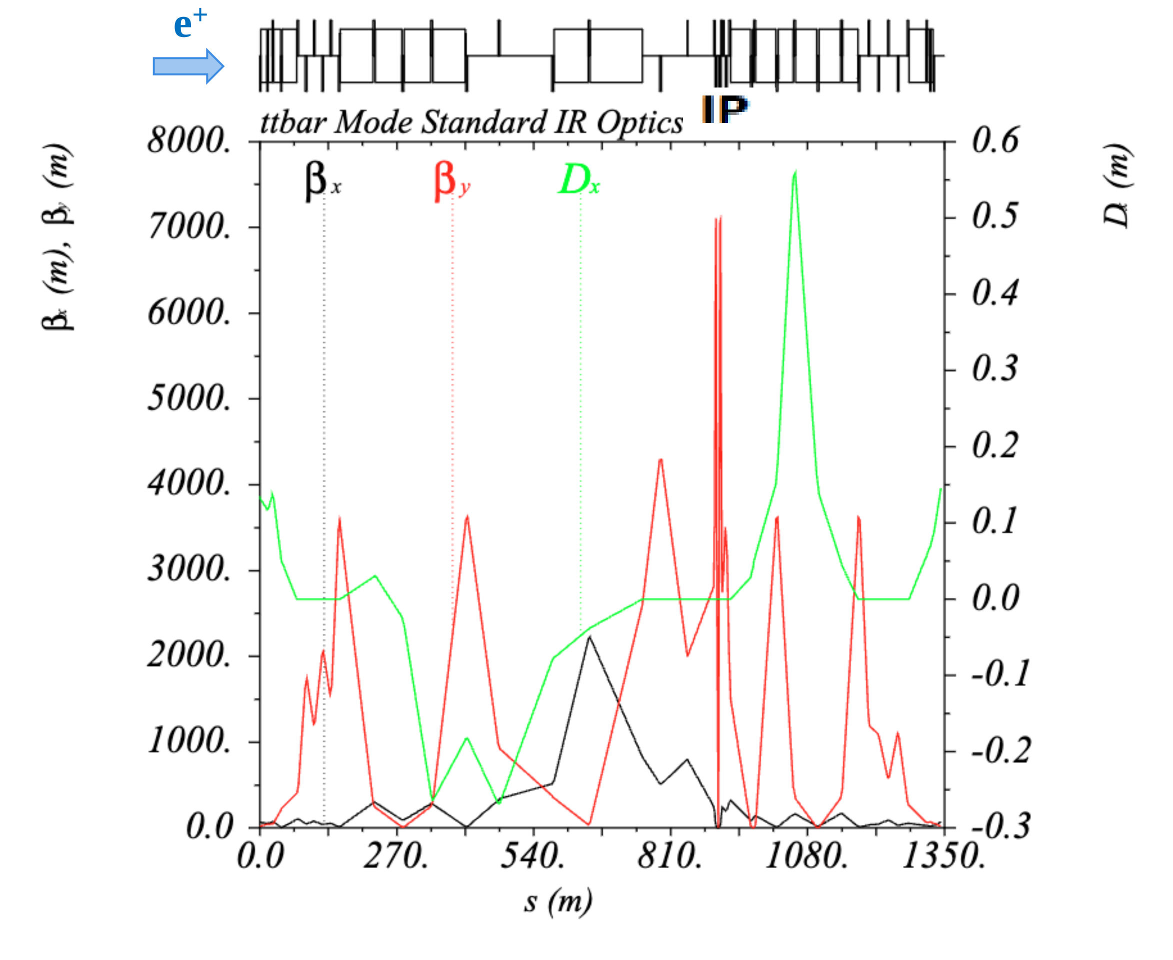
[1] M. A. Valdivia García, F. Zimmermann, Towards an optimized monochromatization for direct Higgs production in future circular e+ e- Colliders, in CERN-BINP Workshop for Young Scientists in e+e- Colliders, pp. 1–12 (2017)

FCC-ee V22 Standard Optics ($D^*_{x,y}=0$)

Z mode lattices with Long 90/90 arc cells



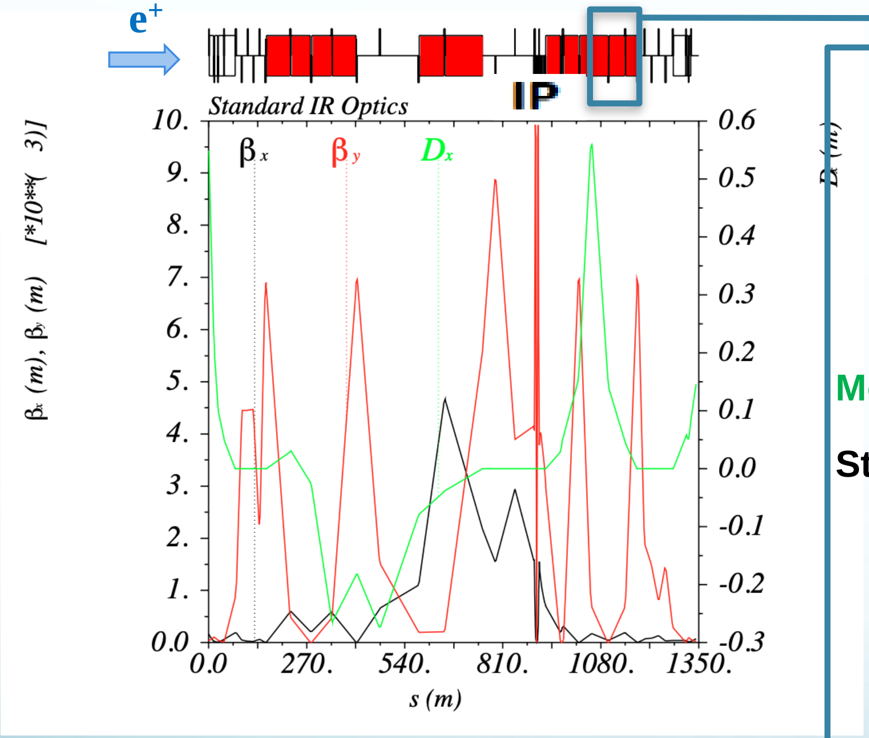
ttbar mode lattices with 90/90 arc cells

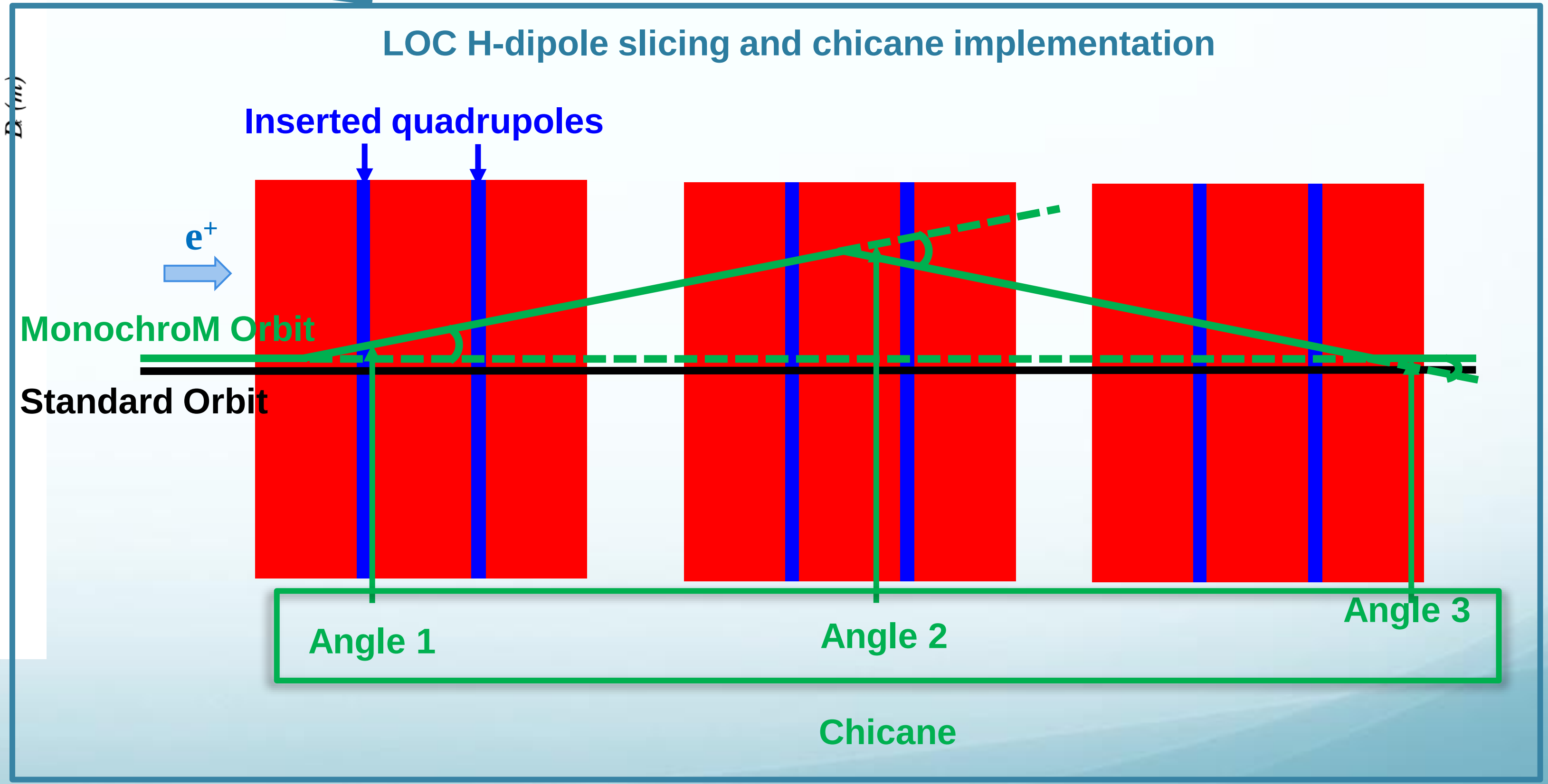


Horizontal Dispersion Generation based on Z mode Lattice

- **Scheme for Monochromtization IR Optics Design**

All local vertical chromaticity horizontal dipoles (**LOC H-dipole**) in standard IR Optics are cut into three pieces and quadrupoles are inserted between them to gain in flexibility. One chicane is implemented in the last three LOC H-dipole in each upstream and downstream to create the dispersion at the IP while keeping the orbit.

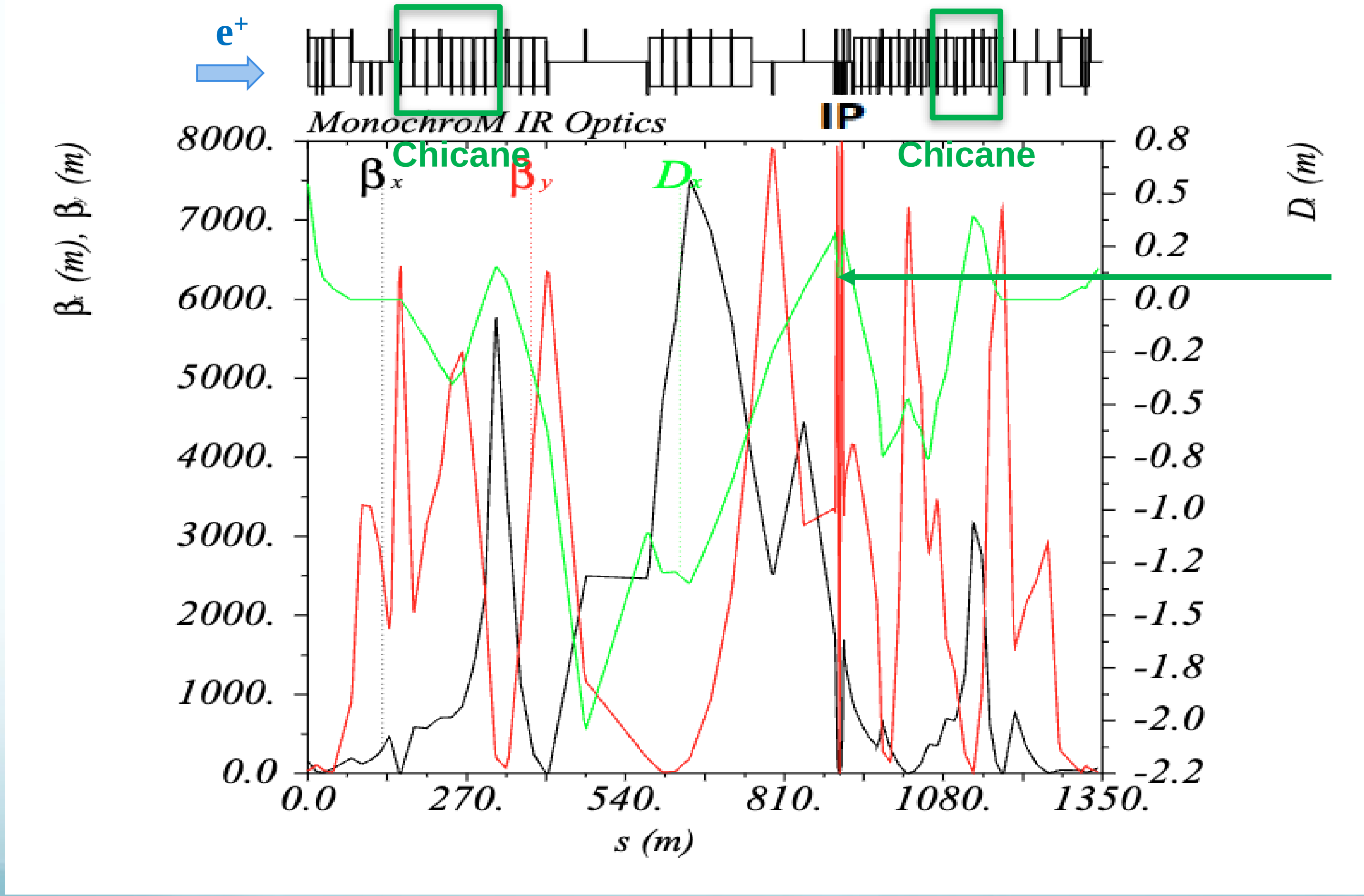




IP Horizontal Dispersion Generation based on Z mode Lattice

- **Monochromatization IR Optics Design Result**

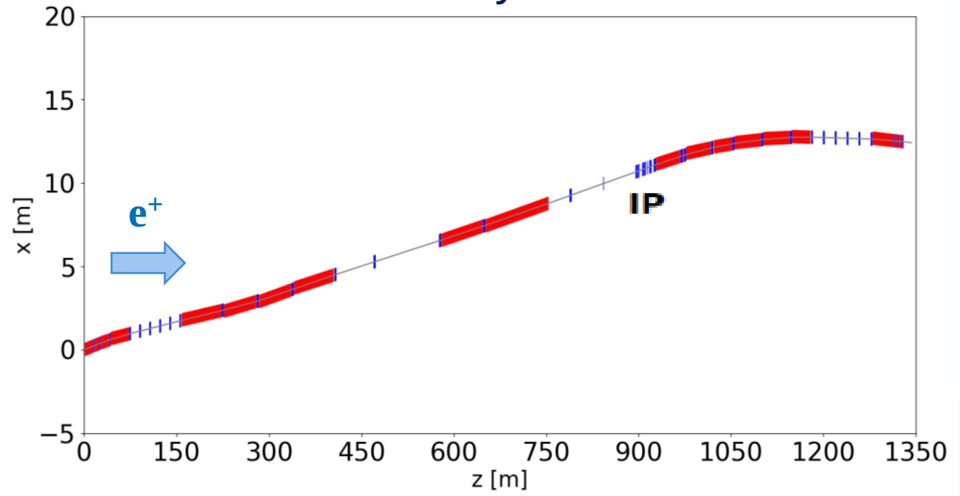
The beam parameters at the entrance and exit of the IR are same with those of standard mode. The phase advance of sextupoles and crab sextupoles is also matched to be same with that of standard mode to keep the correction scheme.

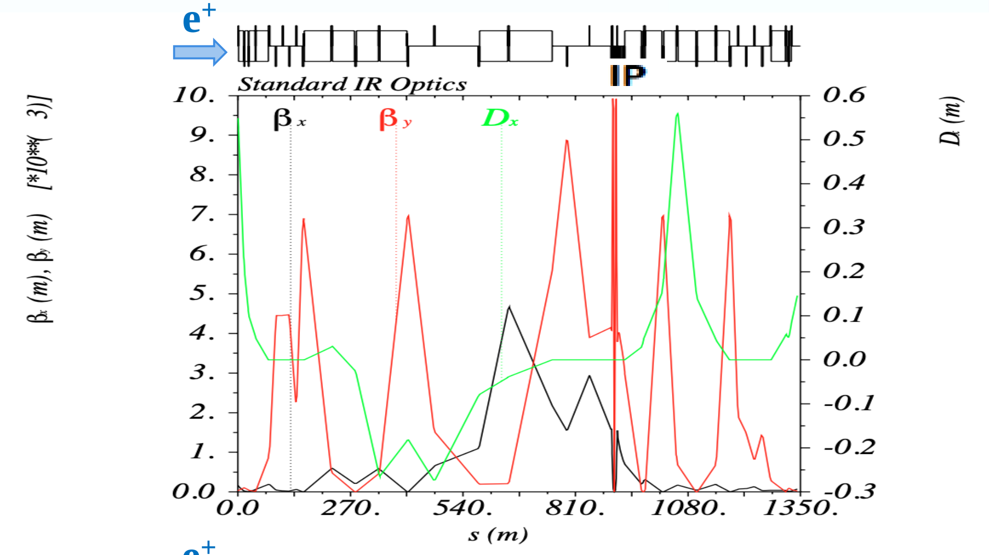


$D_x^* = 0.105\, m$

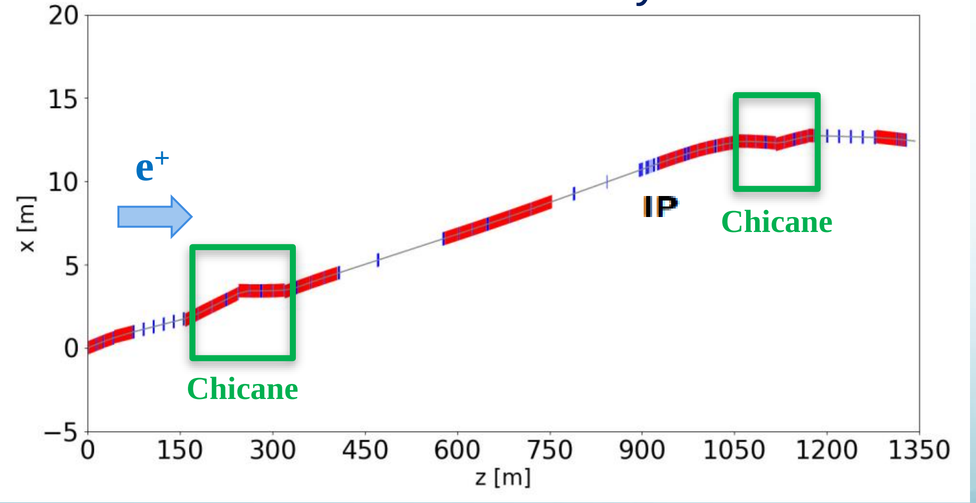
IP Horizontal Dispersion Generation based on Z mode Lattice

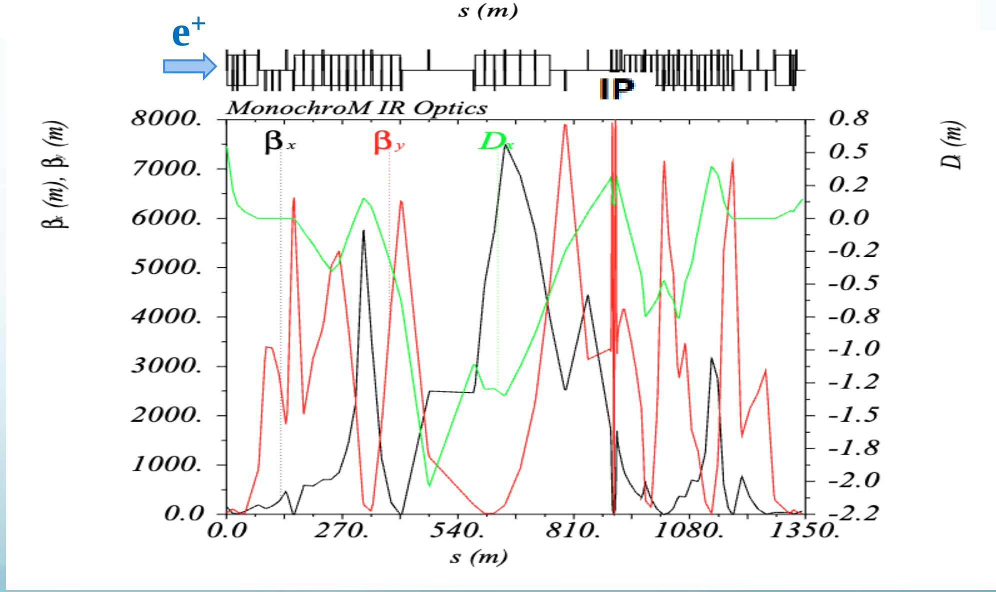
- **Comparison between Standard Orbit and Monochromatization Orbit**
  - V22 Standard Survey Plot





  - Monochromatization Survey Plot



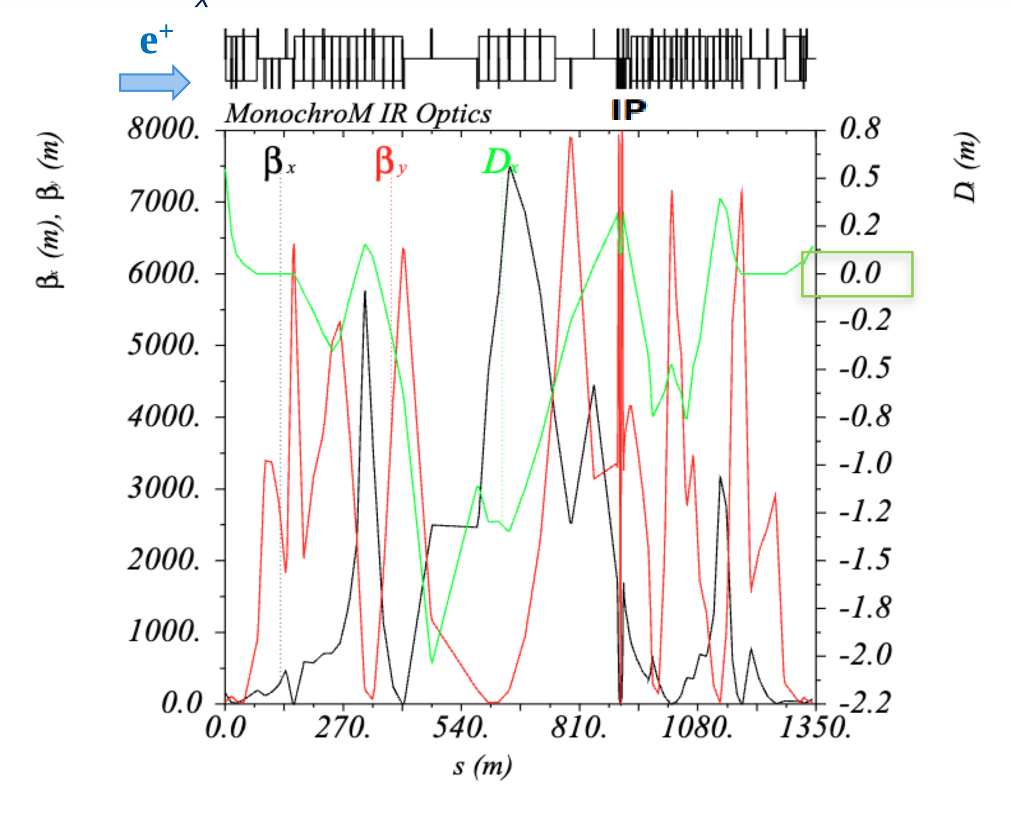


IP Horizontal Dispersion Generation based on Z mode Lattice

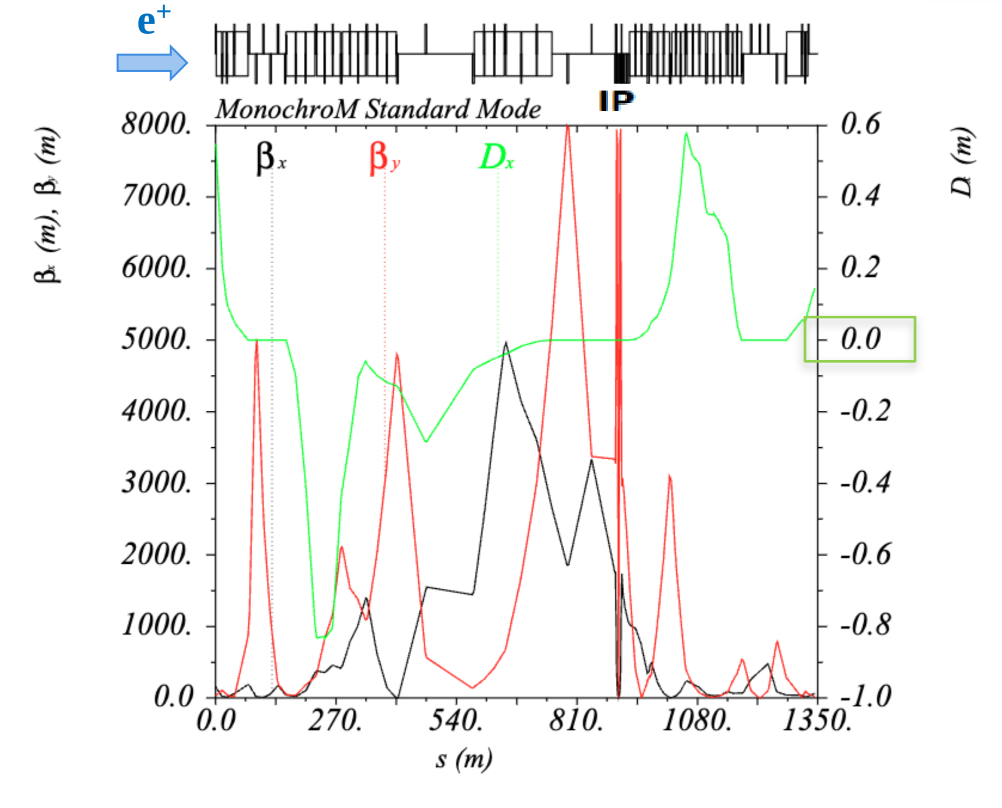
- **Standard Mode with Monochromatization Orbit**

Frozen the angle of all the dipoles of monochromatization optics (keeping the monochromatization orbit), matching only with the strength of all the quadrupoles to get the dispersion at the IP back to zero.

- $D^*_x = 0.105$ m Monochromatization mode



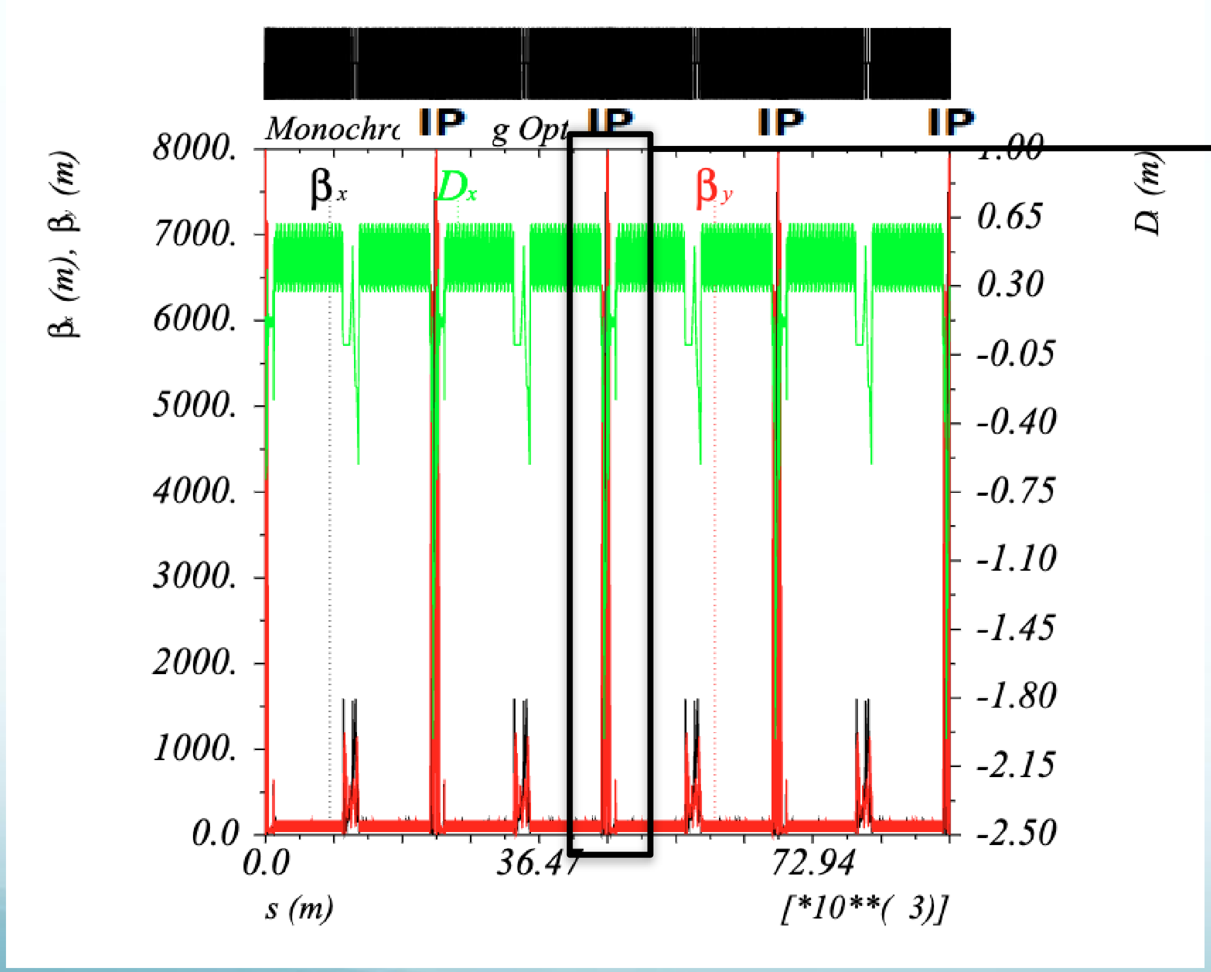
- $D^*_x = 0$ Standard mode

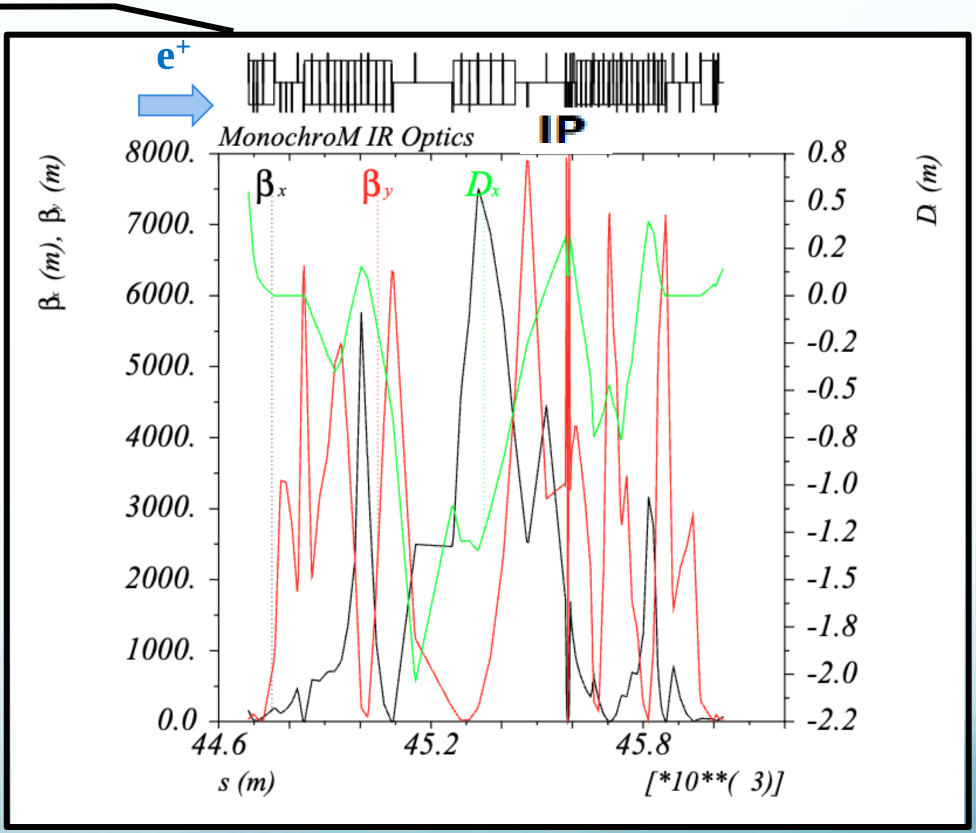


IP Horizontal Dispersion Generation based on Z mode Lattice

- **Implementation of Monochromatization IR Optics in the Global lattice**

The designed monochromatization IR lattice is implemented to all four IPs of the whole ring to replace standard IR lattices.





IP Horizontal Dispersion Generation based on Z mode Lattice

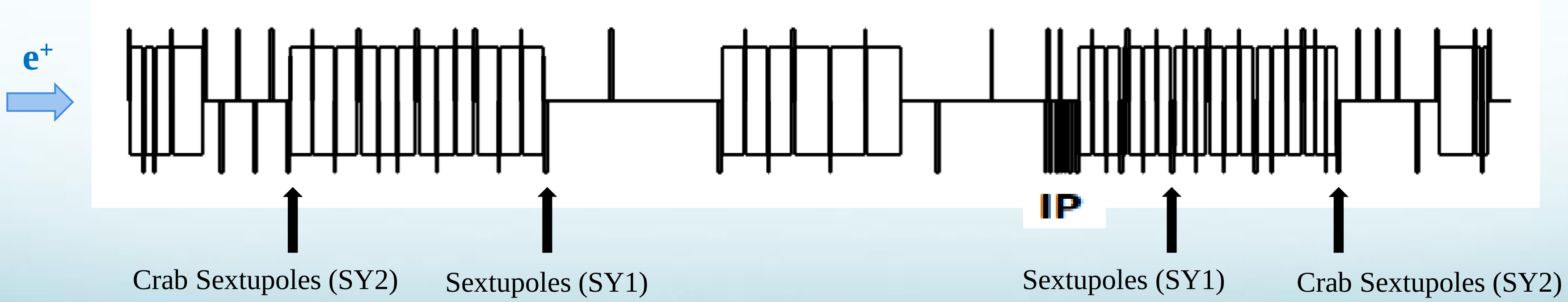
- **Local Chromaticity Correction**
  - Load monochromatization ring lattice, and extract sequence from IP to crab sextupole.
  - Turned off all the sextupoles including crab sextupoles SY2.
  - Match the vertical chromaticity from IP to crab sextupoles to 0 using the sextupoles SY1.
  - Calculate the strength of crab sextupoles (SY2) with the following formula:

$$K2SY2 = K2SY1 - crab_{factor} \cdot crab_{strength}$$

The crab strength is given by:

$$crab_{strength} = \frac{1}{L_{SY2} * \theta_{CROSS} * BY_{IP} * BY_{CS}} * \sqrt{\frac{BX_{IP}}{BX_{CS}}}$$

The crab factor is determined from Beam-beam studies, at Z it's 97%, W 87%, so ~90% for Higgs mode seems a good starting guess. (The crab factor is set as 1 temporarily.)



IP Horizontal Dispersion Generation based on Z mode Lattice

- **Global Chromaticity Correction**

With the matched strength of the SY1 and the strength of SY2 calculated by the formula, the global chromaticity correction is done by matching the strength of all the sextupoles in the arc.

There are two kinds of sextupoles in the arc, focus sextupoles and defocus sextupoles. The strength of all the focus sextupoles is multiplied by the coefficient kn_sf, while the strength of all the defocus sextupoles is multiplied by the coefficient kn_sd.

The horizontal chromaticity (DQ1) and vertical chromaticity (DQ2) are matched to 5 with the two coefficient, because positive chromaticity is benefit for the beam stability.

- **Tune Correction**

By varying the strength of quadrupoles around the RF cavities in the arc, the horizontal tune Q1 and vertical tune Q2 are matched to 214.27 and 214.3900332 same as the standard mode while keeping the beam parameters at the IRs.

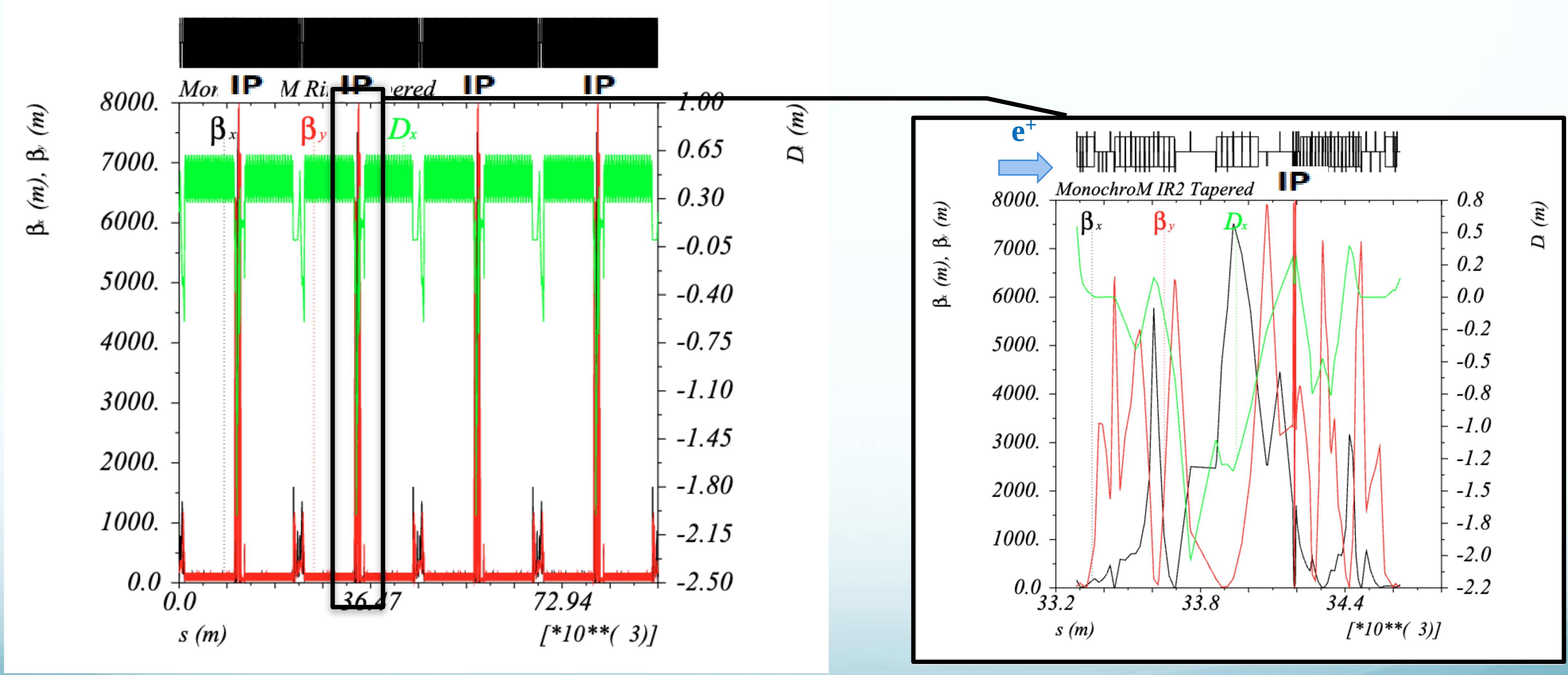
- **Emittance Check**

Opening the RF cavities on and considering the energy loss of synchrotron radiation, the longitudinal energy difference (pt) are matched to zero by varying the voltage and the phase of the RF cavities in tapering twiss model.

IP Horizontal Dispersion Generation based on Z mode Lattice

- **Emittance Check**

The beam parameters are same with those parameters before tapering. The horizontal emittance are calculated in MADX.



IP Horizontal Dispersion Generation based on Z mode Lattice

- **Parameters of FCC-ee Preliminary Monochromatization Optics Design to Generate IP Horizontal Dispersion**

The monochromatization factor is only 1.6 because the horizontal emittance blow up causes a beam size blowup at the IPs.

Parameter	Units	FCCee Z (V22)	FCCee Z 62.5 (scaled)	FCCee MonochroM (Dx=0.105m)	FCCee MonochroM (Dx=0)
Beam Energy E	GeV	45.6	62.5	62.5	62.5
# of IPs	/	4	4	4	4
Circumference	m	91174.117	91174.117	91174.117	91174.117
Energy Loss/turn	MeV	39.1	137.87	191.2335648	191.457973
SR power loss	MW	50.048	54.45865	75.5372581	75.62589932
Beam current	mA	1280	395	395	395
Bunches/beam n_b	/	10000	13420	13420	13420
Bunch population N_b	10^{11}	2.43	0.559	0.559	0.559
Horizontal emittance (SR/BS) ε_x	nm	0.71 / 0.71	1.325 / 1.325	76.3 / 76.31	36 / 36
Vertical emittance (SR/BS) ε_y	pm	1.42 / 1.42	2.65 / 2.65	152.6 / 152.6	72 / 72
Momentum compaction factor (αc)	10^{-6}	28.2	28.0	27.5	27.8
$\beta^*_{x/y}$	mm	100 / 0.8	100 / 0.8	90 / 1	90 / 1
$D^*_{x/y}$	m	0 / 0	0 / 0	0.105 / 0	0 / 0
Energy Spread (SR/BS) σ_δ	%	0.038 / 0.275	0.0537 / 0.0595	0.099459 / 0.099460	0.099459 / 0.099469
MonochroM Factor (SR/BS) λ	/	1 / 1	1 / 1	1.60878 / 1.60873	1 / 1
CM energy spread (SR/BS) σ_W	MeV	24.505 / 177.332	47.465 / 52.590	54.644 / 54.646	87.911 / 87.919
Bunch length (SR/BS) σ_z	mm	4.38 / 30.37	25.36 / 28.11	39.22 / 39.20	39.44 / 39.45
RF frequency	Hz	399994581	399994581	399994581	399994581
Sychrotron tune Q_s	/	0.03702531	0.008738557	0.010114505	0.010175363
Longitudinal damping time	turns	1168	907	653	653
Horizontal beam-beam (SR/BS) ξ_x	/	1.71409 / 1.71409	0.15410 / 0.15410	0.00103504 / 0.00103497	0.00567 / 0.00567
Vertical beam-beam (SR/BS) ξ_y	/	3.4282 / 3.4282	0.3082 / 0.3082	0.0039248 / 0.0039246	0.01336 / 0.01336
LUMINOSITY (SR/BS)	$10^{34}cm^{-2}\ s^{-2}$	5440 / 5440	206.9 / 206.9	2.105 / 2.105	7.18 / 7.18

Reduced Current

Emittance blow up

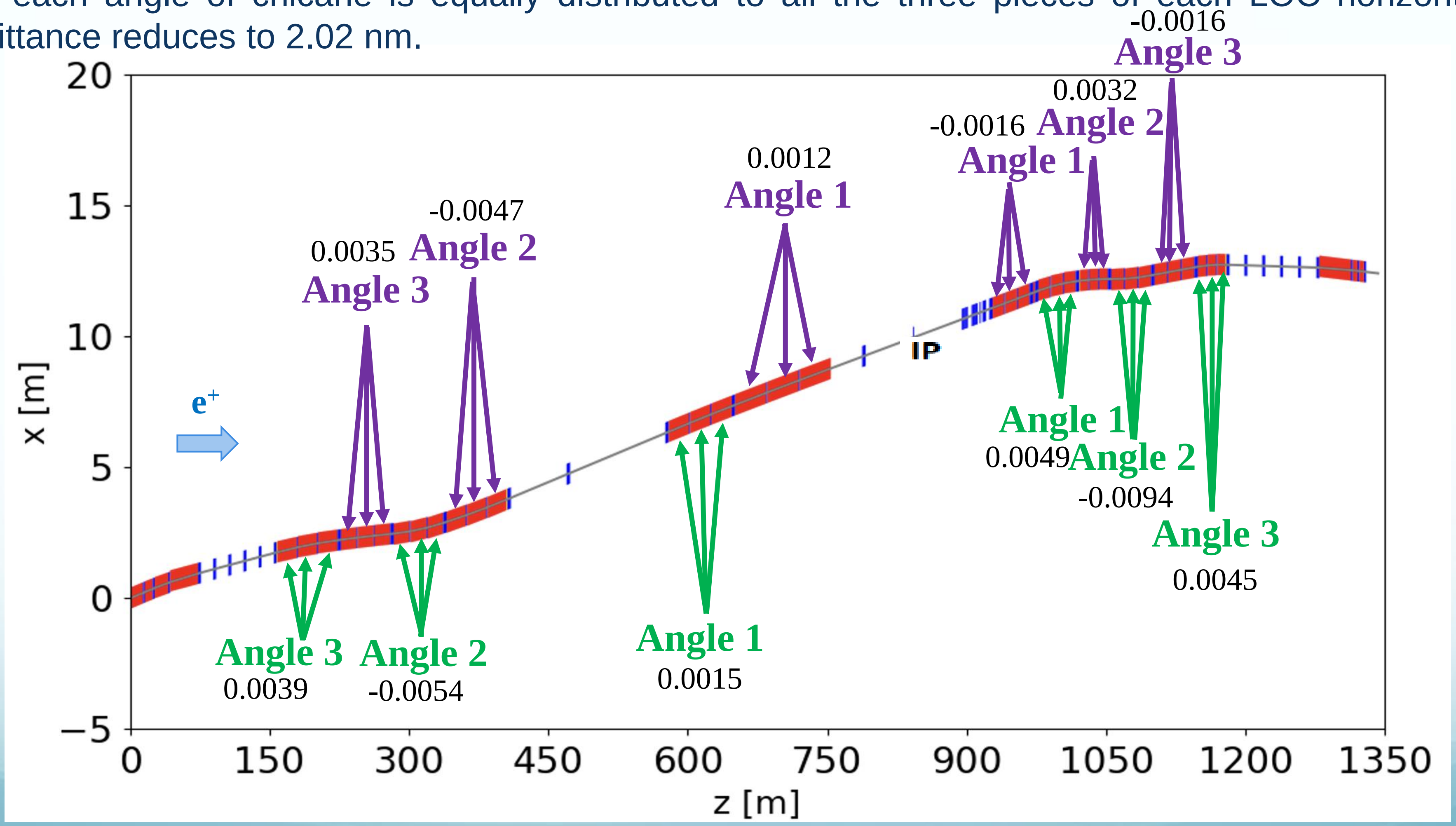
Energy spread blow up

Not enough MonochromM Factor

IP Horizontal Dispersion Generation based on Z mode Lattice

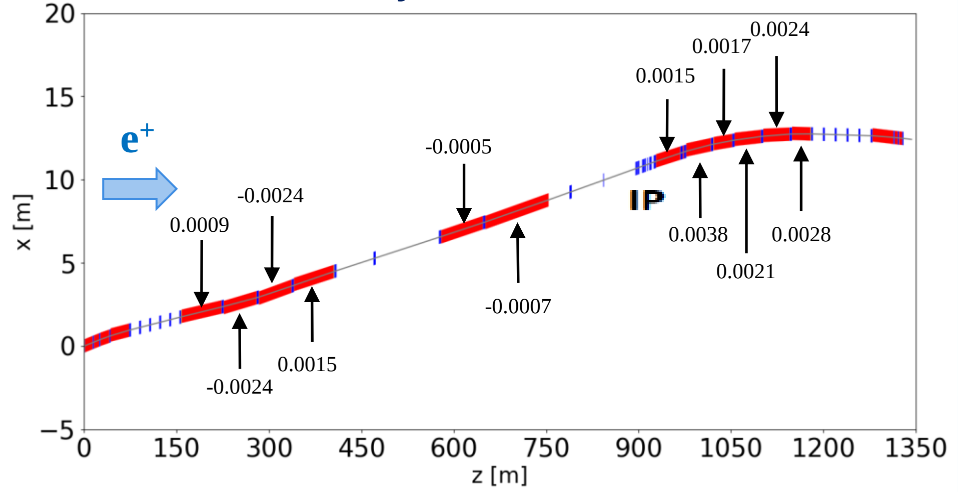
- **Optimization of Horizontal Emittance**

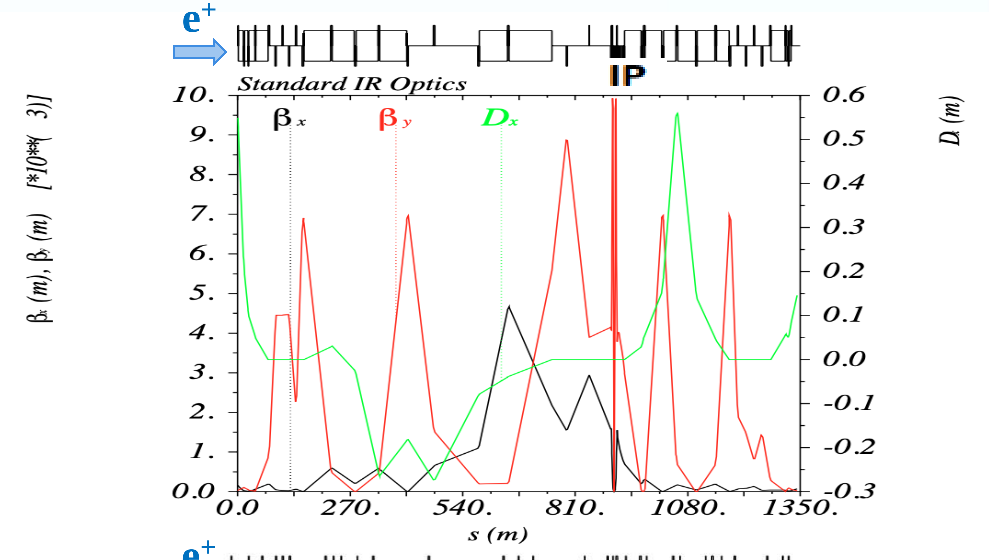
To optimize horizontal emittance, two longer chicanes are implemented to each upstream and downstream instead of one chicane. And each angle of chicane is equally distributed to all the three pieces of each LOC horizontal dipole. The horizontal emittance reduces to 2.02 nm.



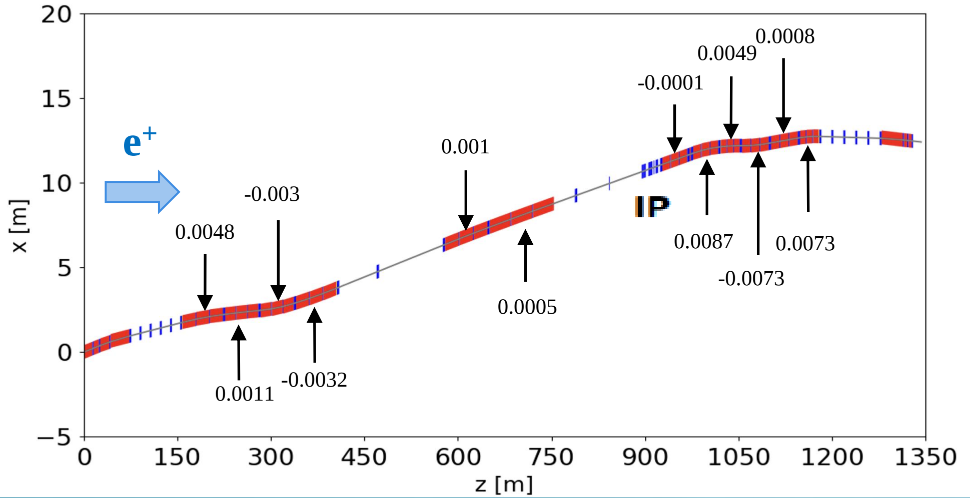
IP Horizontal Dispersion Generation based on Z mode Lattice

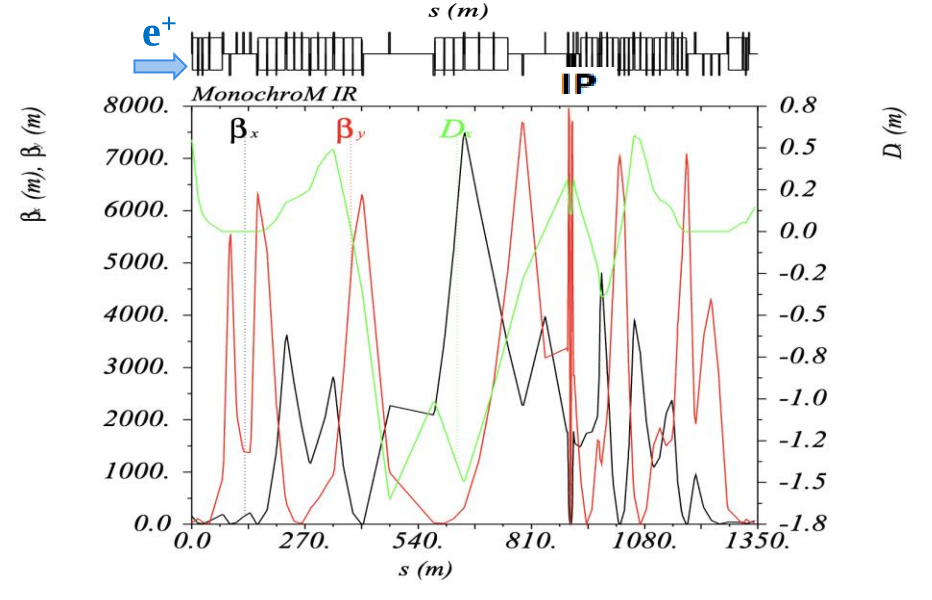
- **Comparison between Standard Orbit and Monochromatization Orbit**
  - Standard Survey Plot





  - Monochromatization Survey Plot

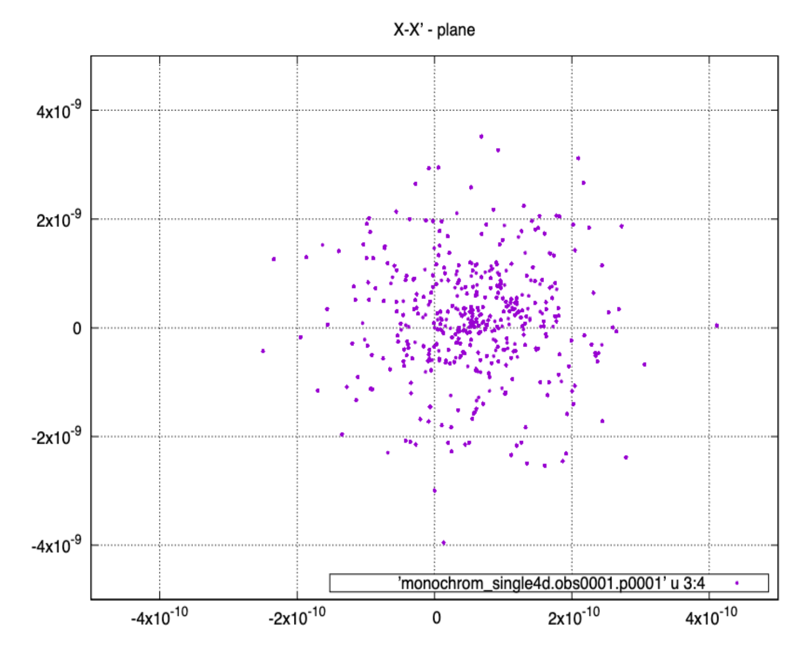




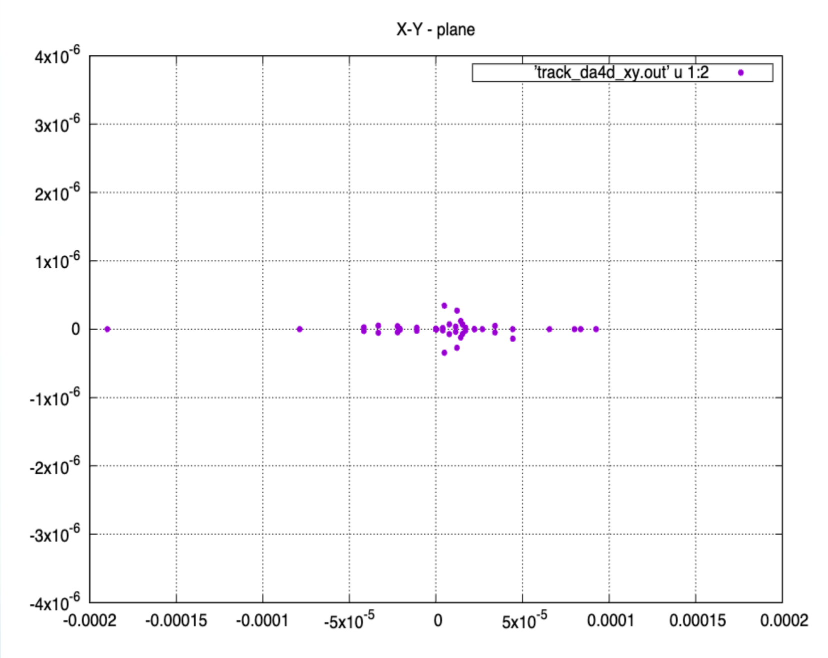
IP Horizontal Dispersion Generation based on Z mode Lattice

- **Single Particle Tracking and Dynamic Aperture Particle Tracking**

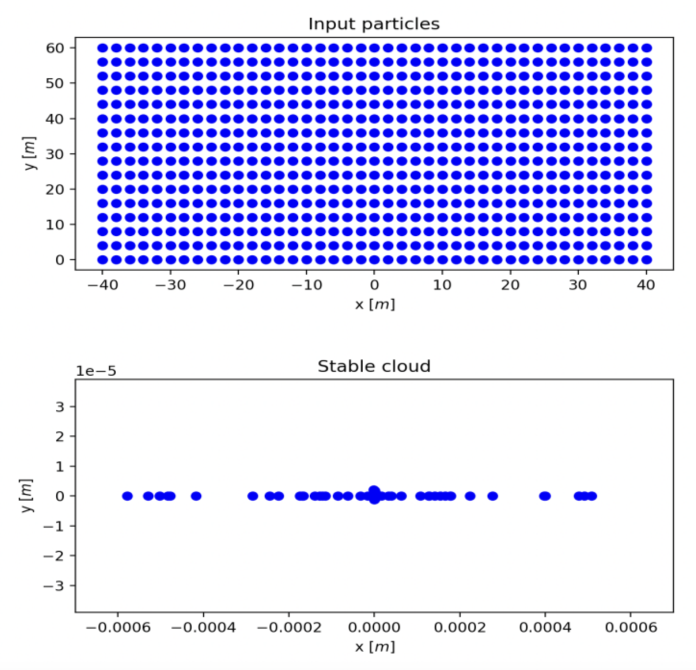
The single particle tracking (4d) was done in MADX-PTC. And dynamic aperture particle tracking was done in MADX-PTC and also in Xsuite. In DA particle tracking, we found that only 50% particles survived after 1000 turns without optimization of family sextupoles in the arc.



Single particle tracking in MADX-PTC



DA particle tracking in MADX-PTC



DA particle tracking in Xsuite

IP Horizontal Dispersion Generation based on Z mode Lattice

- **Parameters of FCC-ee Monochromatization Optimized Optics Design to Generate Horizontal Dispersion**

Parameters	Units	FCCee Z (V22)	FCCee Z 62.5 (scaled)	FCCee MonochroM Z 4ip (Dx=0.105m)	FCCee MonochroM Z 2ip (Dx=0.105m)	FCCee MonochroM Z(Dx=0m)
Beam Energy E	GeV	45.6	62.5	62.5	62.5	62.5
# of IPs	/	4	4	4	2	4
Circumference	m	91174.117	91174.117	91174.117	91174.117	91174.117
Energy Loss/turn	MeV	39.1	137.87	143.4740352	140.7424706	143.4740361
SR power loss	MW	50.048	54.45865	56.6722439	55.5932759	56.67224424
Beam current	mA	1280	395	395	395	395
Bunches/beam n_b	/	10000	13420	13420	13420	13420
Bunch population N_b	10^{11}	2.43	0.559	0.559	0.559	0.559
Horizontal emittance (SR/BS) ε_x	nm	0.71 / 0.71	1.325 / 1.325	2.0219 / 2.1019	1.710 / 1.752	1.526 / 1.526
Vertical emittance (SR/BS) ε_y	pm	1.42 / 1.42	2.65 / 2.65	4.044 / 4.044	3.42 / 3.42	3.052 / 3.052
Momentum compaction α_c	10^{-6}	28.2	28.0	28.0	28.2	28.1
$\beta^*_{x/y}$	mm	100 / 0.8	100 / 0.8	90 / 1	90 / 1	100 / 0.8
$D^*_{x/y}$	m	0 / 0	0 / 0	0.105 / 0	0.105 / 0	0 / 0
Energy Spread (SR/BS) σ_δ	%	0.038 / 0.275	0.0537 / 0.0595	0.05504 / 0.05507	0.05444 / 0.05445	0.05504 / 0.05758
MonochroM Factor (SR/BS) λ	/	1 / 1	1 / 1	4.40 / 4.32	4.72 / 4.66	1 / 1
CM energy spread (SR/BS) σ_W	MeV	24.51 / 177.33	47.46 / 52.59	11.06 / 11.26	10.21 / 10.32	48.65 / 50.89
Bunch length (SR/BS) σ_z	mm	4.38 / 30.37	25.36 / 28.11	35.79 / 35.80	35.87 / 35.88	35.88 / 37.53
RF frequency	Hz	399994581	399994581	399994581	399994581	399994581
Sychrotron tune Q_s	/	0.03702531	0.008738557	0.006245489	0.006210017	0.006262672
Longitudinal damping time	turns	1168	907	871	888	871
Horizontal beam-beam (SR/BS) ξ_x	/	1.7141 / 1.7141	0.1541 / 0.1541	0.00523 / 0.00522	0.00539 / 0.00538	0.1338 / 0.1338
Vertical beam-beam (SR/BS) ξ_y	/	3.4282 / 3.4282	0.3082 / 0.3082	0.05426 / 0.05417	0.05986 / 0.05982	0.2676 / 0.2676
Luminosity (SR/BS)	$10^{34} cm^{-2} s^{-2}$	5440 / 5440	206.9 / 206.9	29.05 / 29.01	32.05 / 32.02	179.6 / 179.6

Emittance reduced

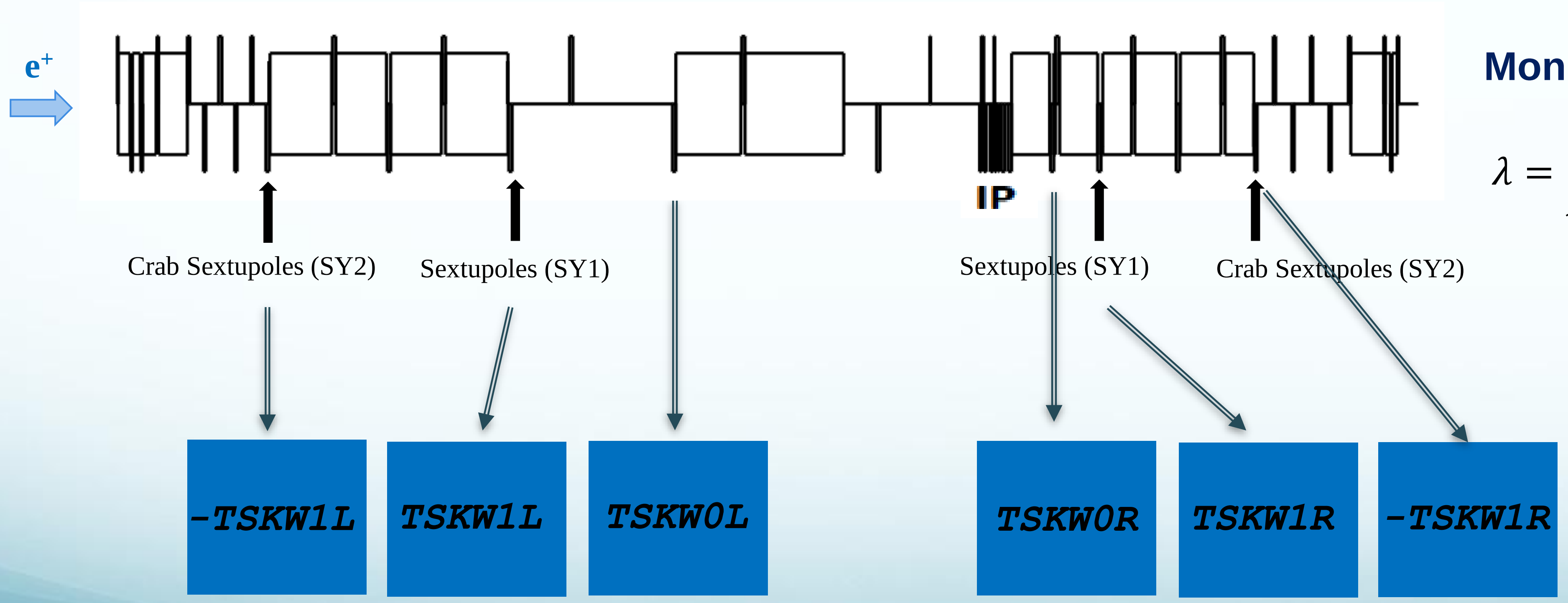
CM energy spread reduced

IP Vertical Dispersion Generation based on Z mode Lattice

- **Scheme of Introducing Vertical Dispersion**

Because the vertical beam size at the IP is much smaller than horizontal beam size, about 100 times smaller vertical dispersion (0.001m) is needed to get the same monochromatization factor compared with the horizontal one.

Creating vertical dispersion by implementing skew quadrupoles around IP. After introducing the vertical dispersion at the IP, match the vertical dispersion back to zero by varying the strength of these six skew quadrupoles.



Monochromatization factor

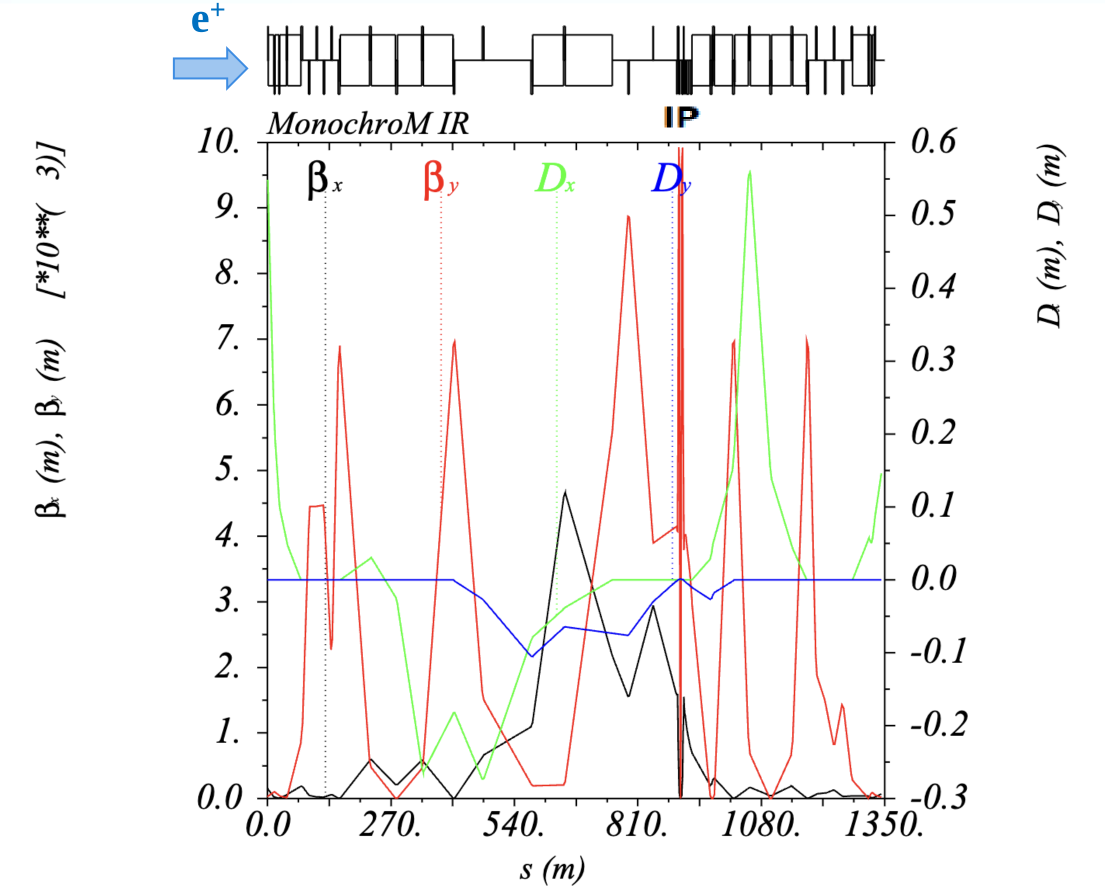
$$\lambda = \sqrt{1 + \sigma_{\delta,SR}^2 \left(\frac{D_x^{*2}}{\sigma_{x\beta}^{*2}} + \frac{D_y^{*2}}{\sigma_{y\beta}^{*2}} \right)}$$

IP Vertical Dispersion Generation based on Z mode Lattice

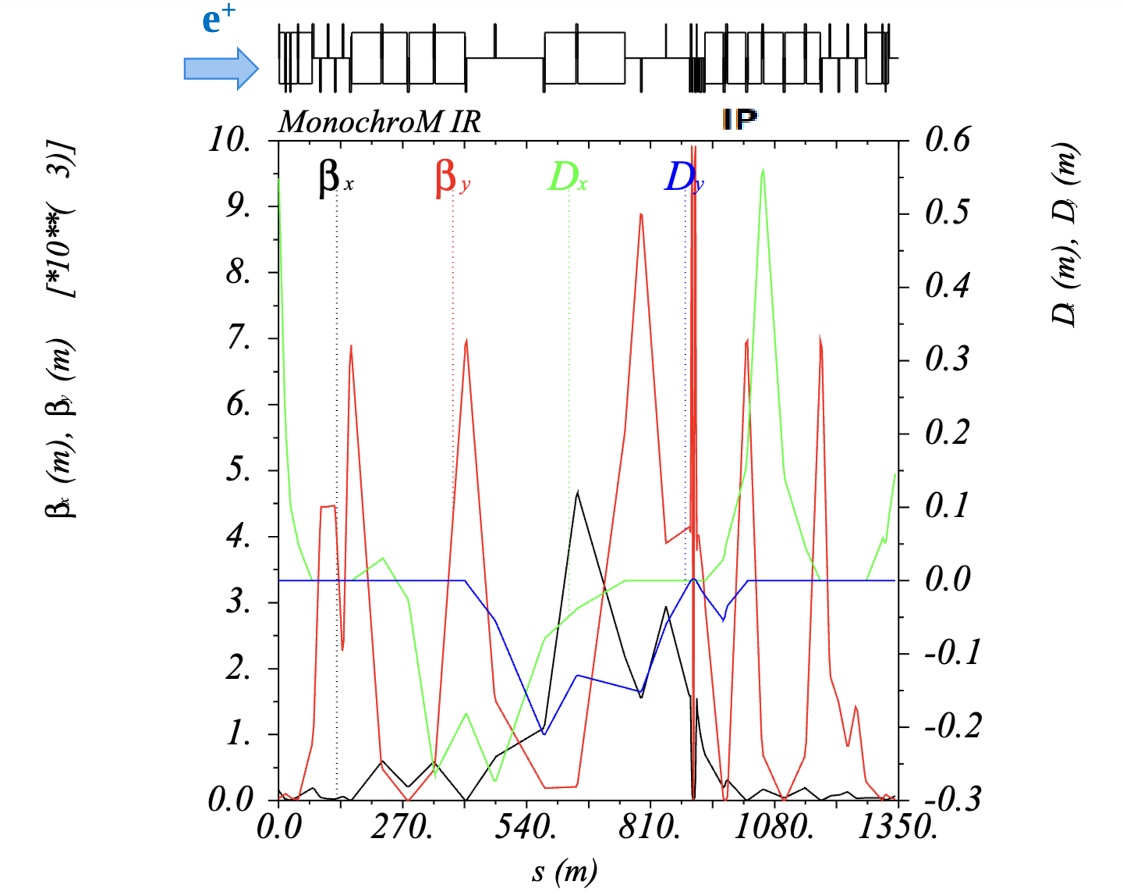
- **Monochromatization Optics Design Result**

V22 Scaled standard mode at 62.5 GeV : ε_x = 1.3 nm, ε_y = 2.6 pm

- D^*_y = 1 mm, ε_x = 1.322 nm, ε_y = 2.645 pm
- D^*_y = 2 mm, ε_x = 1.318 nm ε_y = 2.636 pm



Monochromatization factor (o/w BS): 11.7/13.6



Monochromatization factor (o/w BS): 23.4/27.7

IP Vertical Dispersion Generation based on Z mode Lattice

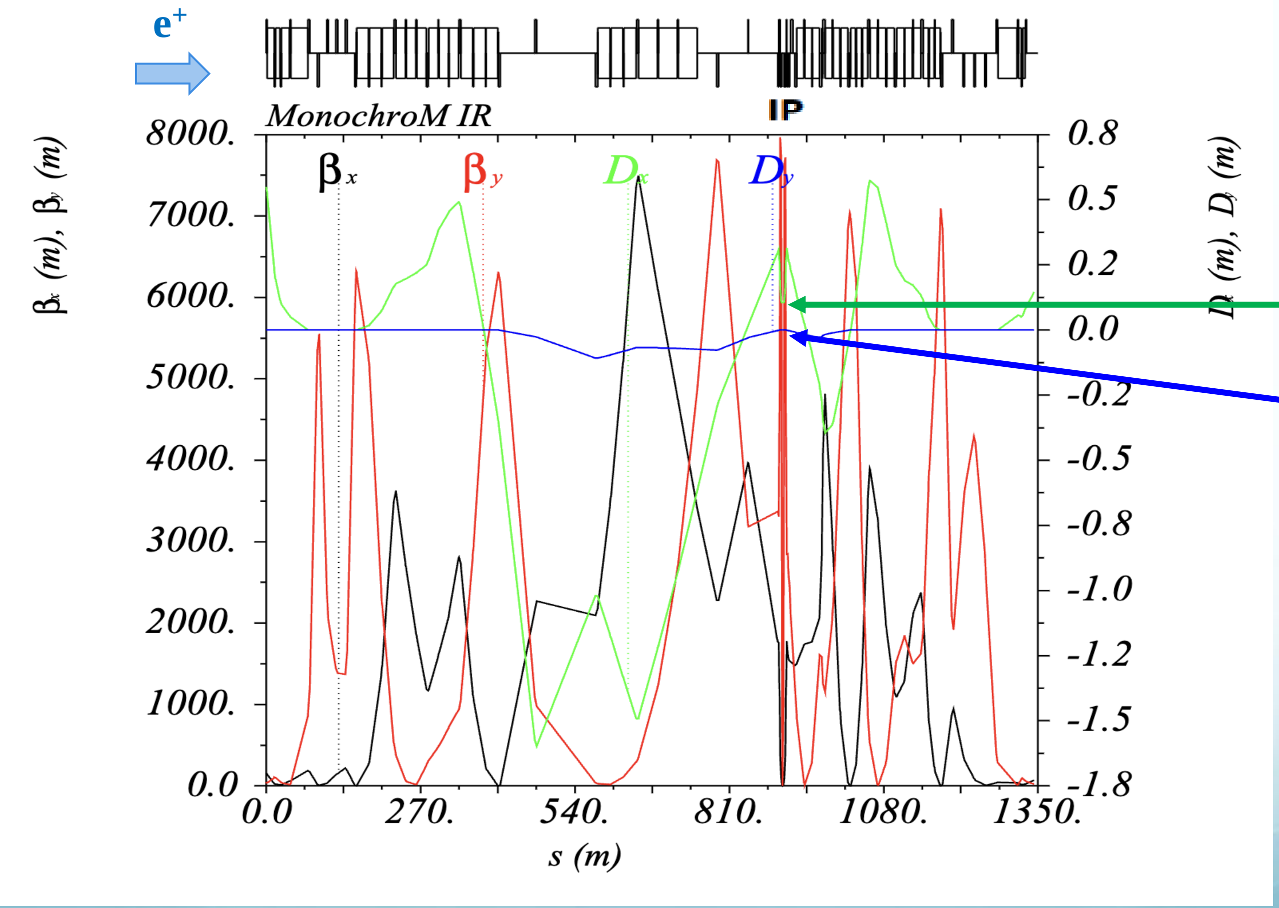
- **Parameters of FCC-ee Monochromatization Optics Design to Generate IP Vertical Dispersion**

Parameters	Units	FCCee Z (V22)	FCCee Z 62.5 (scaled)	FCCee MonochroM Z(Dy=1mm)	FCCee MonochroM Z(Dy=2mm)
Beam Energy E	GeV	45.6	62.5	62.5	62.5
# of IPs	/	4	4	4	4
Circumference	m	91174.117	91174.117	91174.117	91174.117
Energy Loss/turn	MeV	39.1	137.87	137.760264	137.760264
SR power loss	MW	50.048	54.45865	54.41530426	54.41530426
Beam current	mA	1280	395	395	395
Bunches/beam n_b	/	10000	13420	13420	13420
Bunch population N_b	10^{11}	2.43	0.559	0.559	0.559
Horizontal emittance (SR/BS) ε_x	nm	0.71 / 0.71	1.325 / 1.325	1.3223 / 1.323	1.318 / 1.318
Vertical emittance (SR/BS) ε_y	pm	1.42 / 1.42	2.65 / 2.65	2.646 / 2.646	2.636 / 2.636
Momentum compaction α_c	10^{-6}	28.2	28.0	28.4	28.4
$\beta^*_{x/y}$	mm	100 / 0.8	100 / 0.8	100 / 0.8	100 / 0.8
$D^*_{x/y}$	m	0 / 0	0 / 0	0 / 0.001	0 / 0.002
Energy Spread (SR/BS) σ_δ	%	0.038 / 0.275	0.0537 / 0.0595	0.05369 / 0.06356	0.05369 / 0.06360
MonochroM Factor (SR/BS) λ	/	1 / 1	1 / 1	11.71 / 13.85	23.40 / 27.72
CM energy spread (SR/BS) σ_W	MeV	24.51 / 177.33	47.46 / 52.59	4.05 / 4.06	2.03 / 2.03
Bunch length (SR/BS) σ_z	mm	4.38 / 30.37	25.36 / 28.11	17.90 / 21.17	17.90 / 21.18
RF frequency	Hz	399994581	399994581	399994581	399994581
Sychrotron tune Q_s	/	0.03702531	0.008738557	0.012384818	0.012384818
Longitudinal damping time	turns	1168	907	907	907
Horizontal beam-beam (SR/BS) ξ_x	/	1.7141 / 1.7141	0.1541 / 0.1541	0.1480 / 0.1468	0.1422 / 0.1400
Vertical beam-beam (SR/BS) ξ_y	/	3.4282 / 3.4282	0.3082 / 0.3082	0.0253 / 0.0211	0.0121 / 0.0101
Luminosity (SR/BS)	10^{34}cm^{-2} s^{-2}	5440 / 5440	206.9 / 206.9	17.69 / 14.96	8.885 / 7.503

IP Mixing Dispersion Generation based on Z mode Lattice

- **Scheme and Optics Design of Mixing IP Dispersion Generation**

Considering that beamstrahlung has less impact on the energy spread when there is non-zero horizontal dispersion at IPs, we introduce the horizontal dispersion and vertical dispersion at IPs at the same time. This means the skew quadrupoles are implemented to the horizontal dispersion monochromatization optics.



$D_x^* = 0.105\,m$

$D_y^* = 1\,mm$

IP Mixing Dispersion Generation based on Z mode Lattice

- **Parameters of FCC-ee Monochromatization Optics Design based on Z mode Lattice**

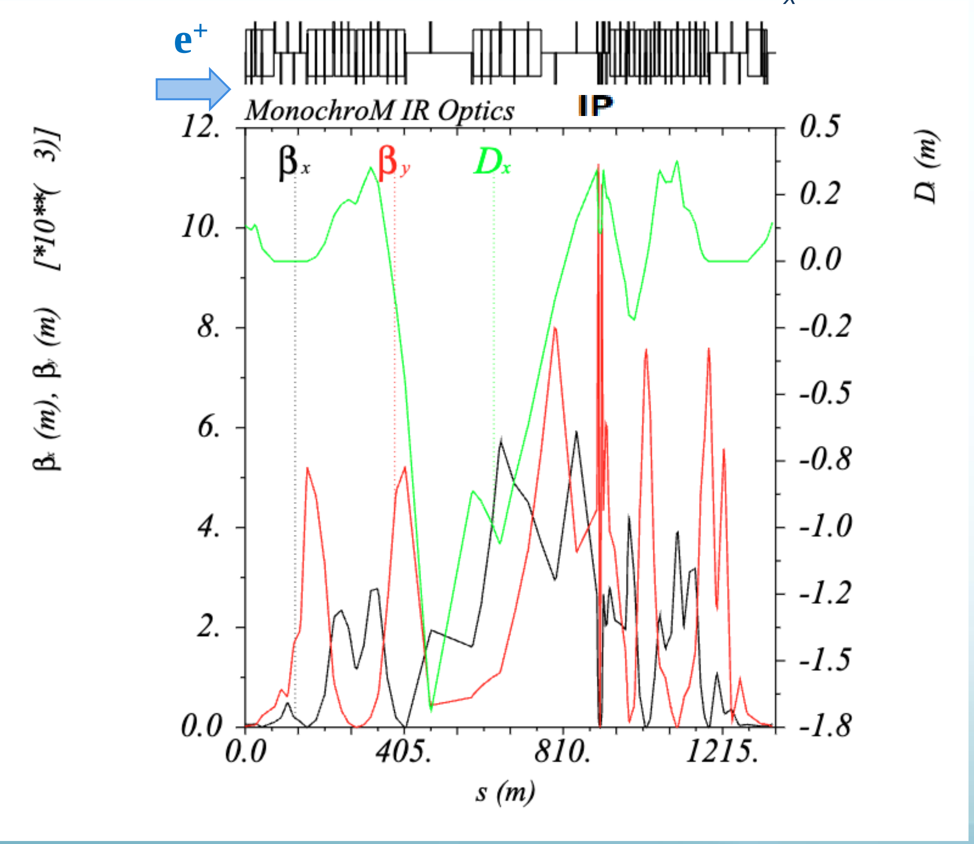
Parameters	Units	FCCee Z (V22)	FCCee Z 62.5	FCCee MonochroM Z 4ip(Dx=0.105m)	FCCee MonochroM Z 2ip(Dx=0.105m)	FCCee MonochroM Z (Dx=0m)	FCCee MonochroM Z (Dy=1mm)	FCCee MonochroM Z (Dy=2mm)	FCCee MonochroM Z MIX (Dx=0.105m,Dy=1mm)
Beam Energy E	GeV	45.6	62.5	62.5	62.5	62.5	62.5	62.5	62.5
# of IPs	/	4	4	4	2	4	4	4	4
Circumference	m	91174.117	91174.117	91174.117	91174.117	91174.117	91174.117	91174.117	91174.117
Energy Loss/turn	MeV	39.1	137.87	143.4740352	140.7424706	143.4740361	137.760264	137.760264	143.4740352
SR power loss	MW	50.048	54.45865	56.6722439	55.5932759	56.67224424	54.41530426	54.41530426	56.6722439
Beam current	mA	1280	395	395	395	395	395	395	395
Bunches/beam n_b	/	10000	13420	13420	13420	13420	13420	13420	13420
Bunch population N_b	10^{11}	2.43	0.559	0.559	0.559	0.559	0.559	0.559	0.559
Horizontal emittance (SR/BS) ε_x	nm	0.71 / 0.71	1.325 / 1.325	2.0219 / 2.1019	1.710 / 1.752	1.526 / 1.526	1.3223 / 1.323	1.318 / 1.318	2.105 / 2.204
Vertical emittance (SR/BS) ε_y	pm	1.42 / 1.42	2.65 / 2.65	4.044 / 4.044	3.42 / 3.42	3.052 / 3.052	2.646 / 2.646	2.636 / 2.636	4.21 / 4.21
Momentum compaction α_c	10^{-6}	28.2	28.0	28.0	28.2	28.1	28.4	28.4	28.0
$\beta^*_{x/y}$	mm	100 / 0.8	100 / 0.8	90 / 1	90 / 1	100 / 0.8	100 / 0.8	100 / 0.8	90 / 1
$D^*_{x/y}$	m	0 / 0	0 / 0	0.105 / 0	0.105 / 0	0 / 0	0 / 0.001	0 / 0.002	0.105 / 0.001
Energy Spread (SR/BS) σ_δ	%	0.038 / 0.275	0.0537 / 0.0595	0.05504 / 0.05507	0.05444 / 0.05445	0.05504 / 0.05758	0.05369 / 0.06356	0.05369 / 0.06360	0.05504 / 0.05508
MonochroM Factor (SR/BS) λ	/	1 / 1	1 / 1	4.40 / 4.32	4.72 / 4.66	1 / 1	11.71 / 13.85	23.40 / 27.72	9.52 / 9.48
CM energy spread (SR/BS) σ_W	MeV	24.51 / 177.33	47.46 / 52.59	11.06 / 11.26	10.21 / 10.32	48.65 / 50.89	4.05 / 4.06	2.03 / 2.03	4.71 / 4.72
Bunch length (SR/BS) σ_z	mm	4.38 / 30.37	25.36 / 28.11	35.79 / 35.80	35.87 / 35.88	35.88 / 37.53	17.90 / 21.17	17.90 / 21.18	35.78 / 35.80
RF frequency	Hz	399994581	399994581	399994581	399994581	399994581	399994581	399994581	399994581
Sychrotron tune Q_s	/	0.03702531	0.008738557	0.006245489	0.006210017	0.006262672	0.012384818	0.012384818	0.006245489
Longitudinal damping time	turns	1168	907	871	888	871	907	907	871
Horizontal beam-beam (SR/BS) ξ_x	/	1.7141 / 1.7141	0.1541 / 0.1541	0.00523 / 0.00522	0.00539 / 0.00538	0.1338 / 0.1338	0.1480 / 0.1468	0.1422 / 0.1400	0.0057 / 0.0057
Vertical beam-beam (SR/BS) ξ_y	/	3.4282 / 3.4282	0.3082 / 0.3082	0.05426 / 0.05417	0.05986 / 0.05982	0.2676 / 0.2676	0.0253 / 0.0211	0.0121 / 0.0101	0.00492 / 0.00491
Luminosity (SR/BS)	$10^{34} cm^{-2} s^{-2}$	5440 / 5440	206.9 / 206.9	29.05 / 29.01	32.05 / 32.02	179.6 / 179.6	17.69 / 14.96	8.885 / 7.503	3.326 / 3.321

IP Horizontal Dispersion Generation based on ttbar mode Lattice

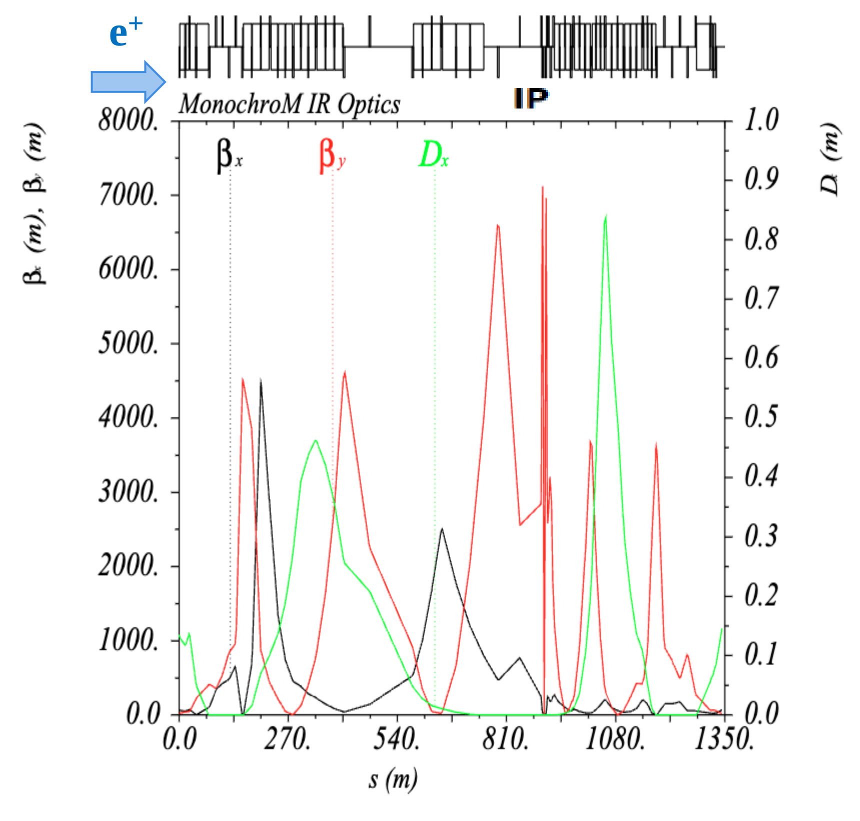
- **Monochromatization Optics Design Result**

With the same method for introducing IP horizontal dispersion based on Z mode lattices, the preliminary monochromatization IR optics design for ttbar mode is completed. The main difference between Z mode one and ttbar mode one is the different beam parameters at the IPs, the entrance and exit of the IR because Z mode lattice uses long 90/90 arc cell while ttbar mode lattice use 90/90 arc cell. The horizontal emittance calculated in MADX is 0.861 nm which is smaller than that of Z mode.

- MonochroM IR base on ttbar mode lattice $D^*_x = 0.105$ m



- Standard mode base on MonochroM Orbit $D^*_x = 0$

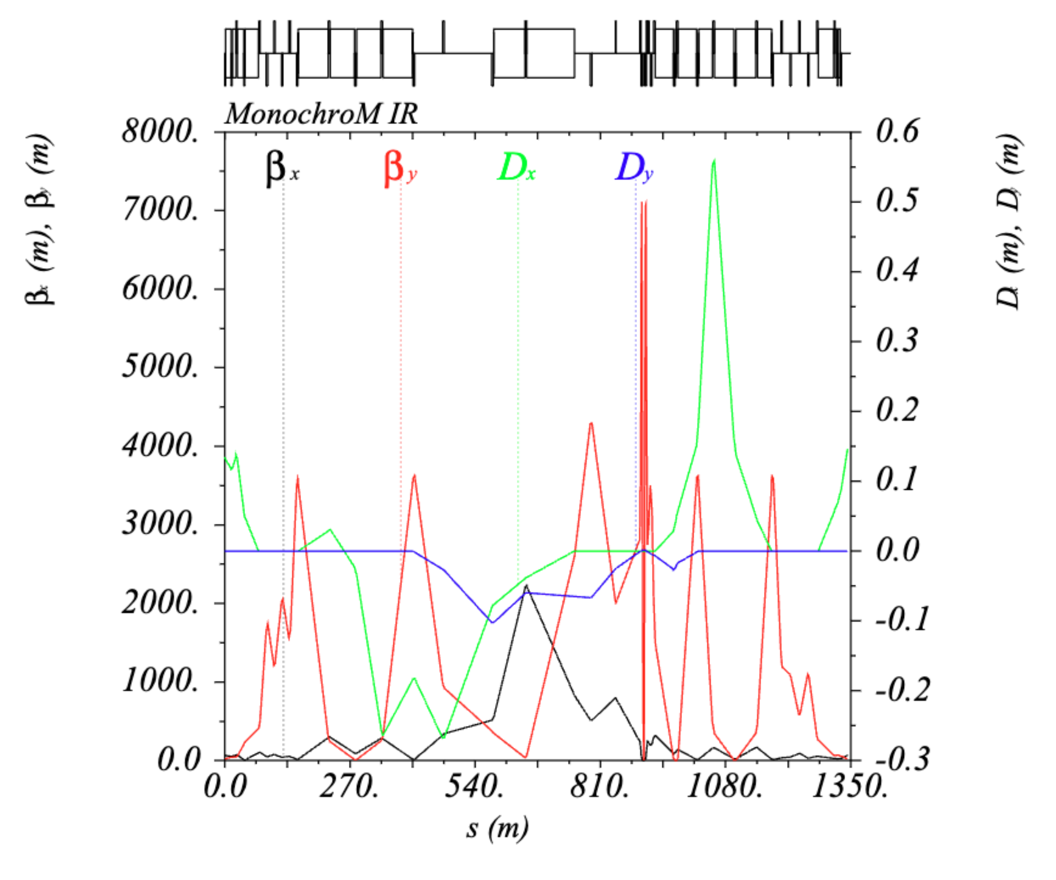


IP Vertical Dispersion Generation based on ttbar mode Lattice

- **Monochromatization Optics Design Result**

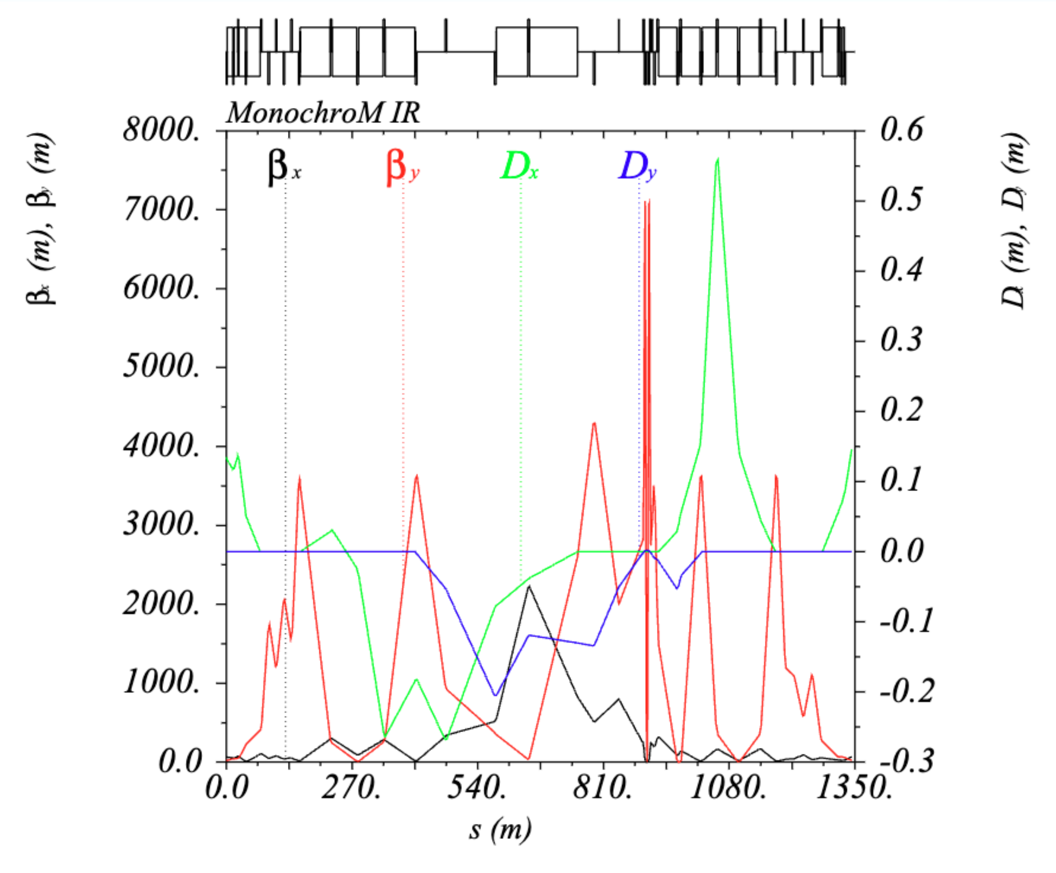
V22 Scaled standard mode at 62.5 GeV : ε_x = 0.17 nm, ε_y = 0.34 pm

- D^*_y = 1 mm, ε_x = 0.174 nm, ε_y = 0.347 pm



Monochromatization factor (o/w BS): 22.8/30.6

- D^*_y = 2 mm, ε_x = 0.174 nm ε_y = 0.347 pm

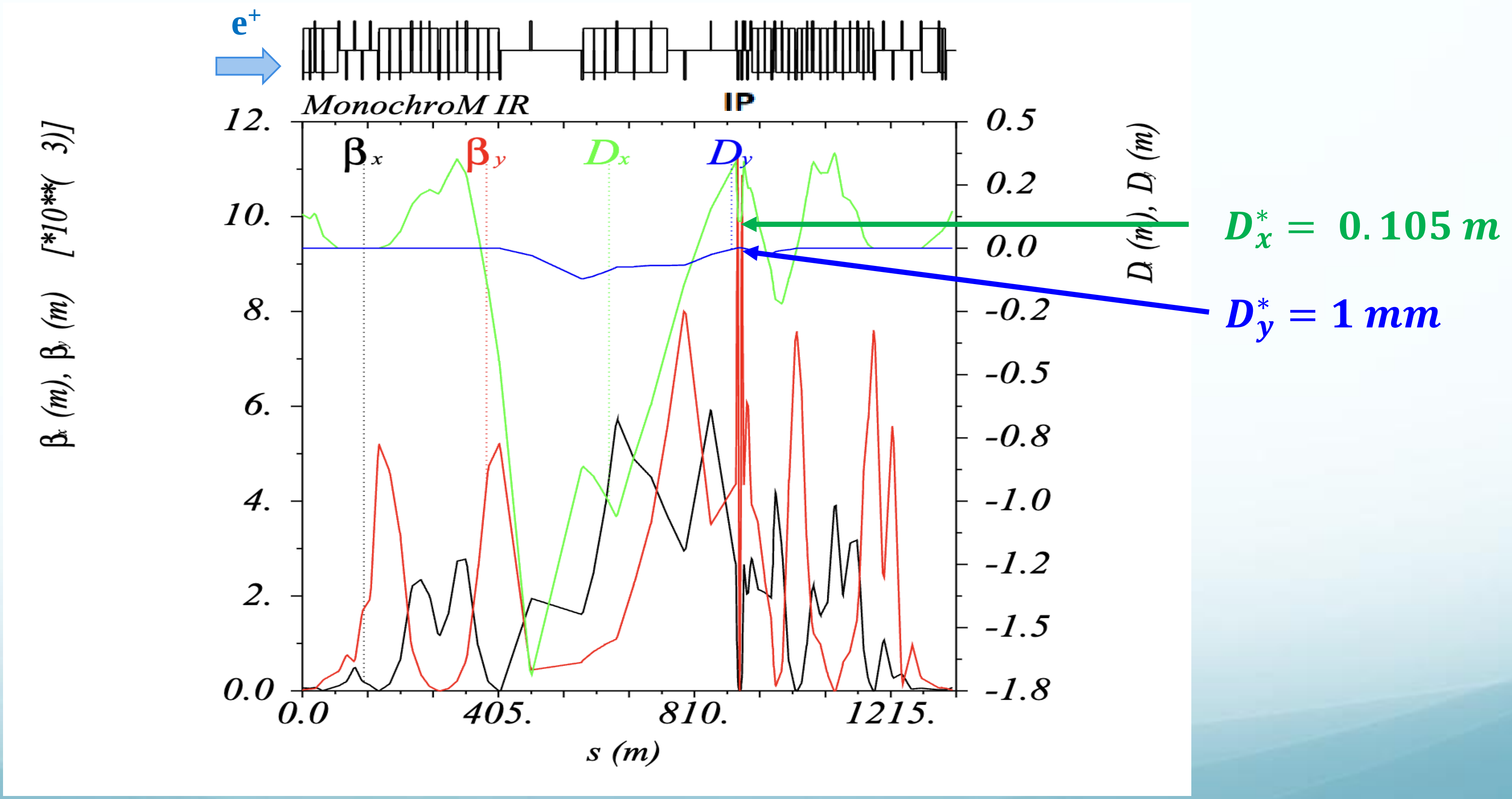


Monochromatization factor (o/w BS): 45.6/61.3

IP Mixing Dispersion Generation based on ttbar mode Lattice

- **Scheme and Optics Design of Mixing Dispersion Generation**

Considering that beamstrahlung has less impact on the energy spread when there is non-zero horizontal dispersion at IPs, we introduce the horizontal dispersion and vertical dispersion at IPs at the same time. This means the skew quadrupoles are implemented to the horizontal dispersion monochromatization optics.



IP Mixing Dispersion Generation based on ttbar mode Lattice

- **Parameters of FCC-ee Monochromatization Optics Design based on ttbar mode Lattice**

Parameter	Units	FCCee ttbar (V22)	FCCee ttbar 62.5 (scaled)	FCCee MonochroM ttbar 4ip (Dx=0.105m)	FCCee MonochroM ttbar 2ip (Dx=0.105m)	FCCee MonochroM ttbar (Dx=0m)	FCCee MonochroM ttbar (Dy=1mm)	FCCee MonochroM ttbar (Dy=2mm)	FCCee MonochroM ttbar MIX (Dx=0.105m,Dy=1mm)
Beam Energy E	GeV	182.5	62.5	62.5	62.5	62.5	62.5	62.5	62.5
# of IPs	/	4	4	4	2	4	4	4	4
Circumference	m	91174.117	91174.117	91174.117	91174.117	91174.117	91174.117	91174.117	91174.117
Energy Loss/turn	MeV	10000	137.57	142.8418588	140.2080326	142.8361848	137.5669772	137.5669772	142.8418588
SR power loss	MW	50	54.34015	56.42253421	55.38217289	56.42029298	54.33895598	54.33895598	56.42253421
Beam current	mA	5	395	395	395	395	395	395	395
Bunches/beam n_b	/	40	13420	13420	13420	13420	13420	13420	13420
Bunch population N_b	10^{11}	2.37	0.559	0.559	0.559	0.559	0.559	0.559	0.559
Horizontal emittance (SR/BS) ε_x	nm	1.49 / 1.49	0.174 / 0.174	0.861 / 1.492	0.521 / 0.852	0.334 / 0.344	0.174 / 0.174	0.174 / 0.174	0.888 / 1.519
Vertical emittance (SR/BS) ε_y	pm	2.98 / 2.98	0.348 / 0.348	1.722 / 1.722	1.042 / 1.042	0.668 / 0.668	0.347 / 0.347	0.347 / 0.347	1.776 / 1.776
Momentum compaction α_c	10^{-6}	6.99	7.30	7.00	7.16	7.04	7.32	7.32	7.00
$\beta^*_{x/y}$	mm	1000 / 1.6	1000 / 1.6	90 / 1	90 / 1	1000 / 1.6	1000 / 1.6	1000 / 1.6	90 / 1
$D^*_{x/y}$	m	0 / 0	0 / 0	0.105 / 0	0.105 / 0	0 / 0	0 / 0.001	0 / 0.002	0.105 / 0.001
Energy Spread (SR/BS) σ_δ	%	0.15689 / 0.21804	0.05369 / 0.06545	0.05501 / 0.05524	0.05437 / 0.05449	0.05501 / 0.06054	0.05369 / 0.07216	0.05369 / 0.07216	0.05501 / 0.05524
MonochroM Factor (SR/BS) λ	/	1 / 1	1 / 1	6.64 / 5.10	8.40 / 6.61	1 / 1	22.81 / 30.64	45.58 / 61.25	14.60 / 14.05
CM energy spread (SR/BS) σ_W	MeV	404.9 / 562.8	47.5 / 57.8	7.3 / 9.6	5.7 / 7.3	48.6 / 53.5	2.1 / 2.1	1.0 / 1.0	3.3 / 3.5
Bunch length (SR/BS) σ_z	mm	2.03 / 2.70	12.88 / 15.70	12.66 / 12.71	12.78 / 12.80	12.70 / 13.98	9.09 / 12.21	9.09 / 12.21	12.66 / 12.72
RF frequency	Hz	399994581	399994581	399994581	399994581	399994581	399994581	399994581	399994581
Sychrotron tune Q_s	/	0.081982082	0.004429944	0.00441462	0.004423262	0.004427741	0.006277935	0.006277935	0.00441462
Longitudinal damping time	turns	18.5	909	875	892	875	909	909	875
Horizontal beam-beam (SR/BS) ξ_x	/	0.1997 / 0.1997	1.1760 / 1.1760	0.005401 / 0.005270	0.005578 / 0.005504	0.6127 / 0.6127	1.1352 / 1.1201	1.0924 / 1.0648	0.005264 / 0.005221
Vertical beam-beam (SR/BS) ξ_y	/	0.1787 / 0.1787	1.0519 / 1.0519	0.08449 / 0.08346	0.1104 / 0.1097	0.5480 / 0.5480	0.04452 / 0.03270	0.02143 / 0.01555	0.006247 / 0.006196
Luminosity (SR/BS)	$10^{34}cm^{-2}\ s^{-2}$	2.211 / 2.211	352.2 / 352.2	45.22 / 44.67	59.08 / 58.68	183.5 / 183.5	15.49 / 11.53	7.75 / 5.77	3.37 / 3.35

Lower CM energy spread compared to Z mode

Summary and Outlook

- ✓ The monochromatization IR optics design
- ✓ Implementation of the monochromatization IR optics in the whole ring
- ✓ Chromaticity correction, tune correction and emittance check
- ✓ Emittance optimization and particle tracking in MADX-PTC and Xsuite
- ➢ Luminosity calculation in Guinea-Pig is in progress
- ➢ Beam-beam calculation is in progress
- ➢ Dynamic aperture optimization is in progress

Thanks for you attention!