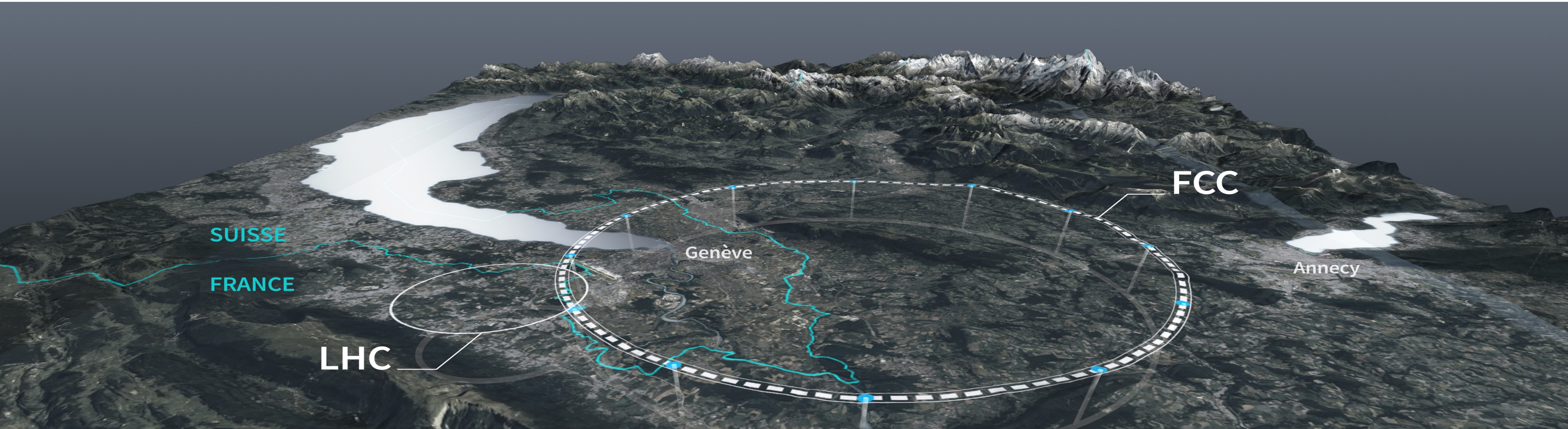

Monochromatization Optics Design for FCC-ee

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Outline

- FCC-ee Monochromatization Concept
- Monochromatization Basic Formulas
- FCC-ee V22 Standard Optics
- FCC-ee Monochromatization IR Optics Design
- FCC-ee Monochromatization Ring Optics
- Performance Check of FCC-ee Monochromatization Optics
- Summary and Outlook

FCC-ee Monochromatization Concept

- **The optional fifth mode of FCC-ee: *s*-channel Higgs production mode**

The measurement of the electron Yukawa coupling, in dedicated runs at 125 GeV with center-of-mass (CM) energy spread (5-10 MeV). But the natural collision energy spread, due to the synchrotron radiation, is about 50 MeV.

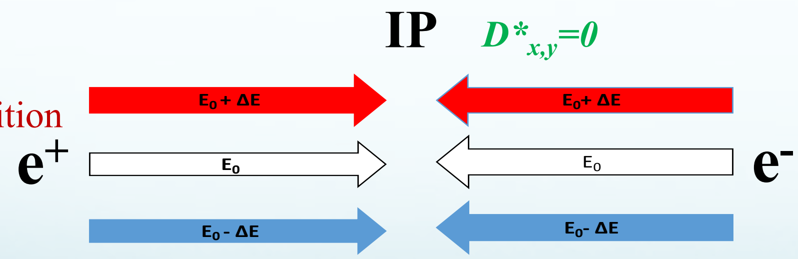
- **Physics Requirements**

Reduce the CM energy spread from 50 MeV to 5 MeV, which is comparable to the resonant width of the standard model Higgs Boson itself (4.2 MeV)

- **Monochromatization method: transverse monochromatization principle**

Standard Mode

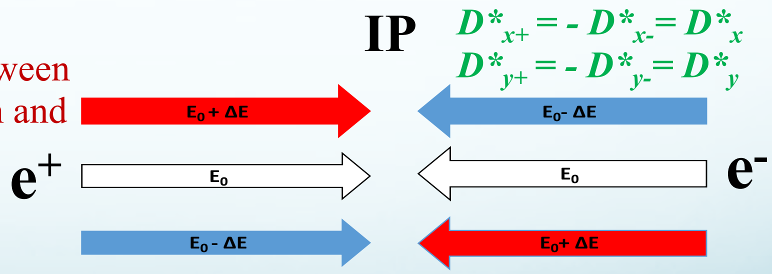
correlation between transverse spatial position and energy deviation



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**

$D^*_{x,y}=0$ — **Standard Mode**

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

CM energy spread

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

Standard Mode (Beam energy E_b, Energy spread σ_δ):

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

Monochromatization Mode:

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

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.

Standard Mode (Revolution frequency f_{rev}, Bunches per beam n_b, Particles per bunch N_b, Betatronic beam sizes at IPs $\sigma_x^*\sigma_y^*$):

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

Monochromatization Mode (Dispersive beam sizes at IPs):

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

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

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 of Beamstrahlung [1]**

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

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

Energy spread

Energy spread with BS

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

Energy spread without BS — Bunch length without BS

Couple 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

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

Fine structure constant — Beam size without BS

# of IP — Electron radius

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

Revolution time — Synchrotron tune

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

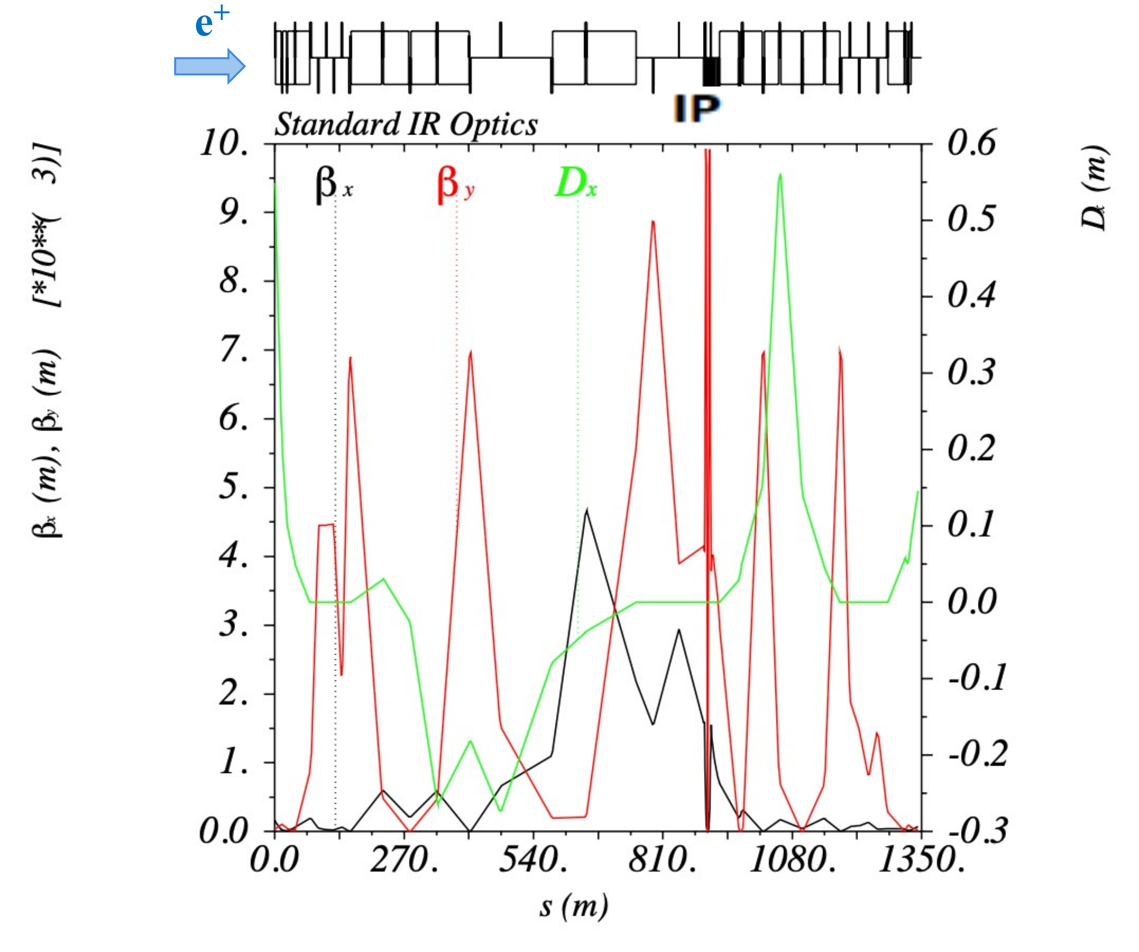
$$\sigma_{z.tot} = \frac{\alpha_c C}{2\pi Q_s}\sigma_{\delta,tot}$$

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

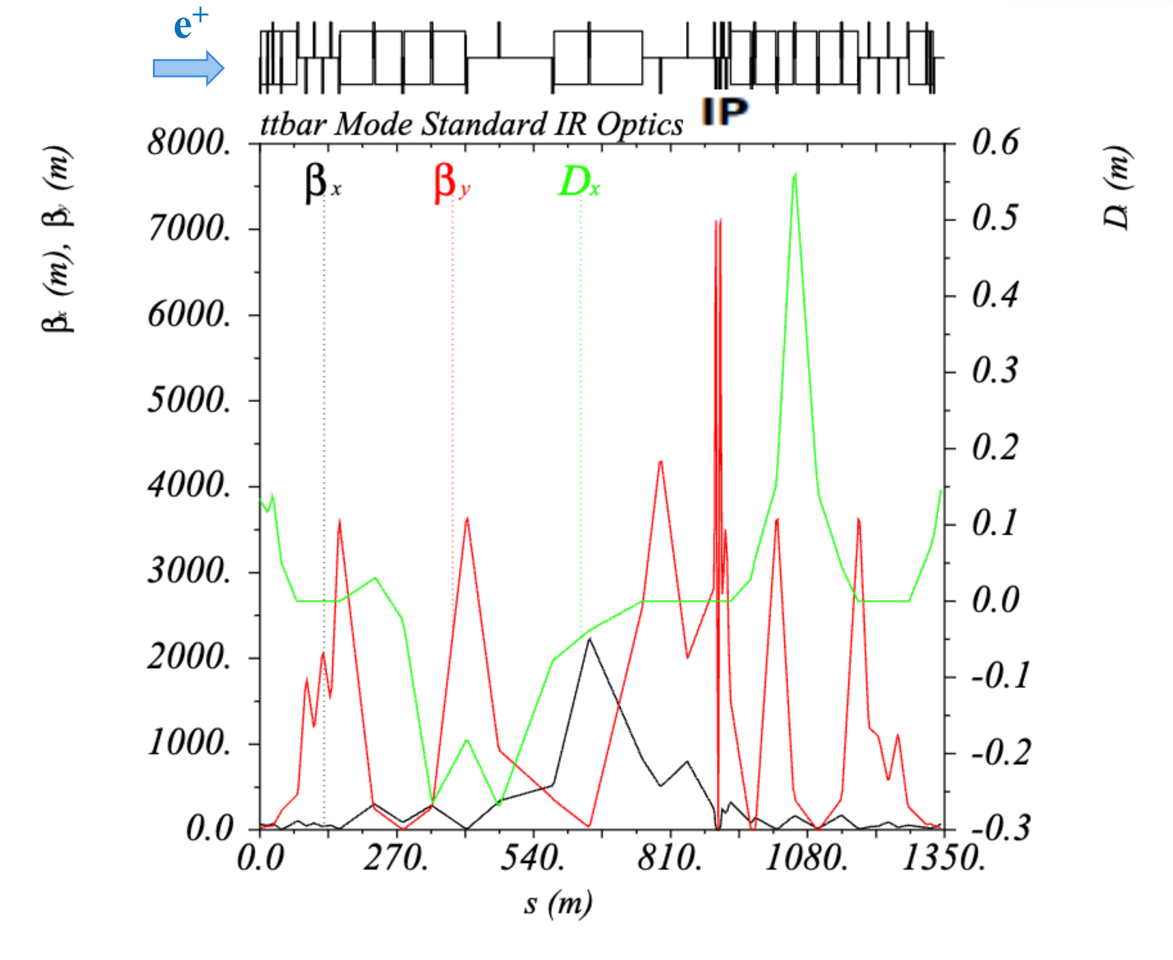
[1] M. A. Valdivia García, F. Zimmermann, Towards an optimized monochromatization for direct Higgs production in future circular e+ e- Colliders, in CERN-BINP Workshop for Young Scientists in e+e- Colliders, pp. 1–12 (2017)

FCC-ee V22 Standard Optics[2]

Z mode lattices with Long 90/90 arc cells



ttbar mode lattices with 90/90 arc cells

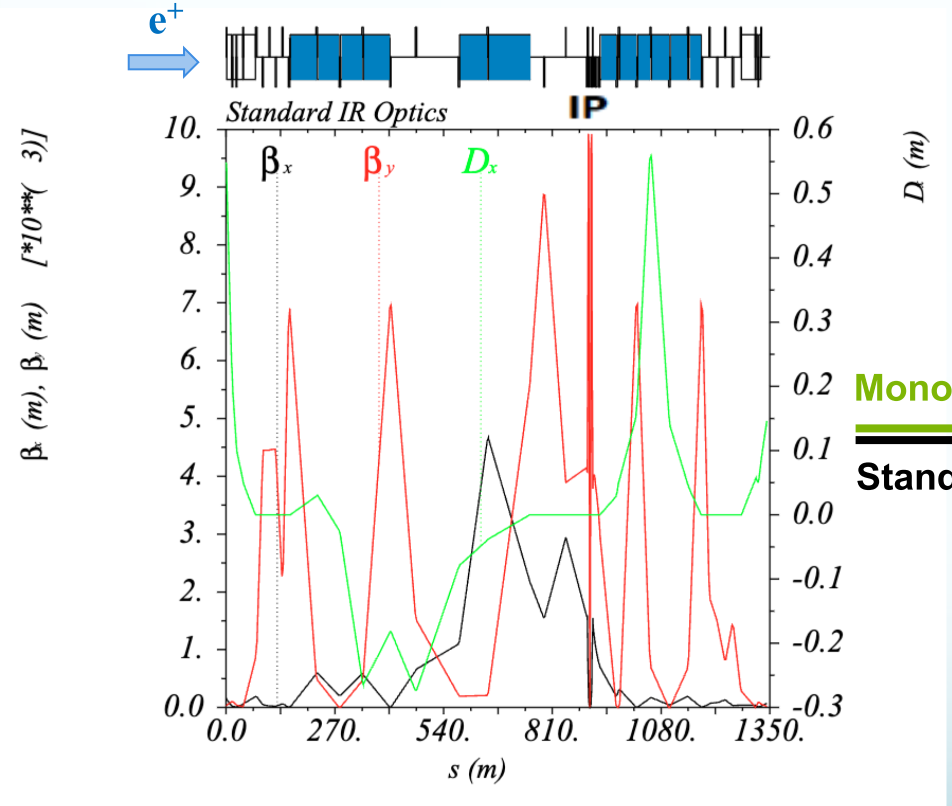


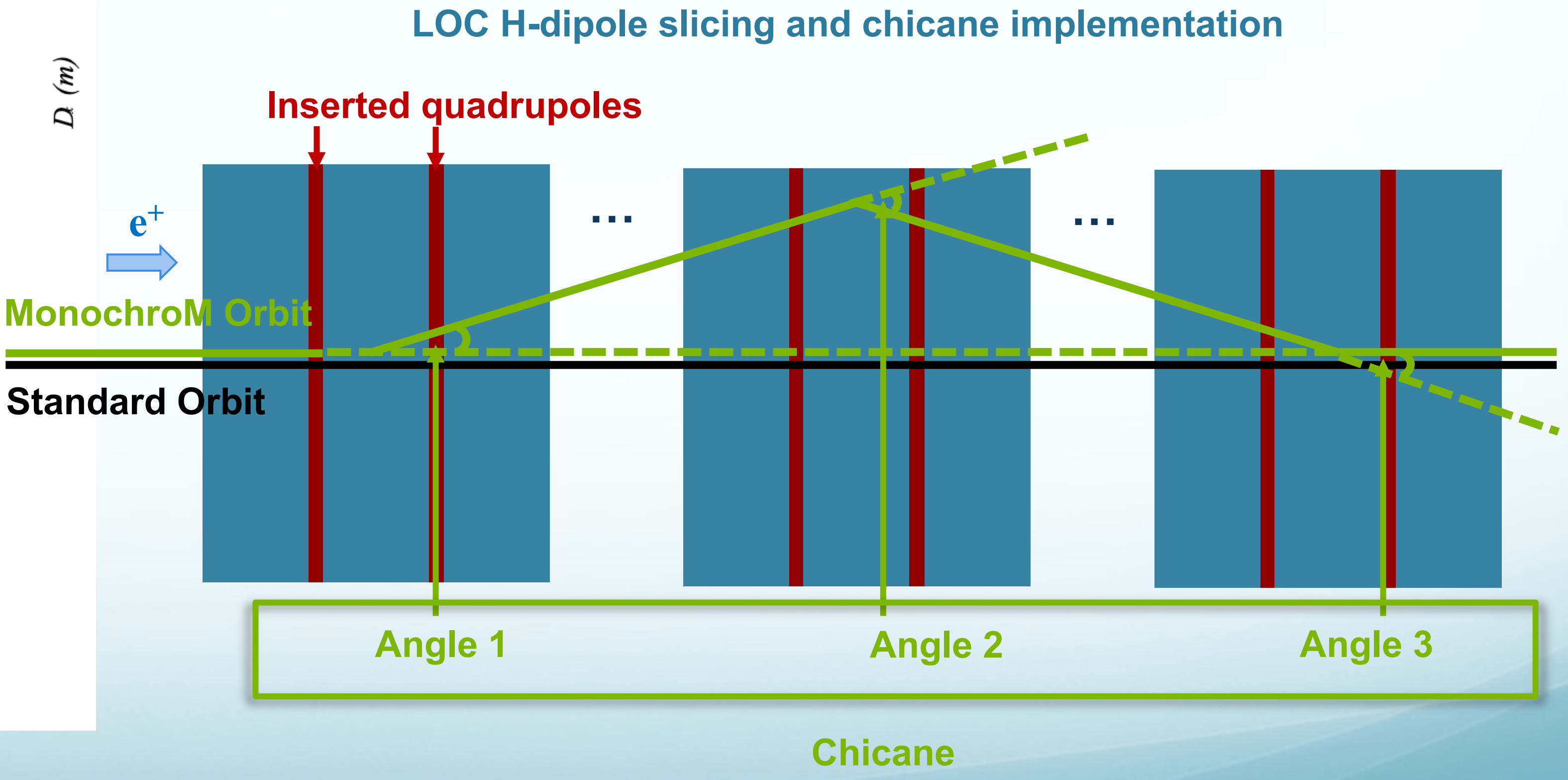
[2] J. Keintzel, A. Abramov, M. Benedikt, M.Hofer, K.Oide et al. "FCC-ee lattice design", eeFACT2022, doi:10.18429/JACoW-eeFACT2022-TUYAT0102

FCC-ee Monochromatization IR Optics Design

- **Scheme for Horizontal Dispersion Generation at the IP**

All local vertical chromaticity horizontal dipoles (LOC H-dipole) (blue) in standard IR Optics are cut into three pieces and quadrupoles (red) are inserted between them. Additional chicanes are implemented LOC H-dipole in each upstream and downstream to create the dispersion at the IP while keeping the orbit.

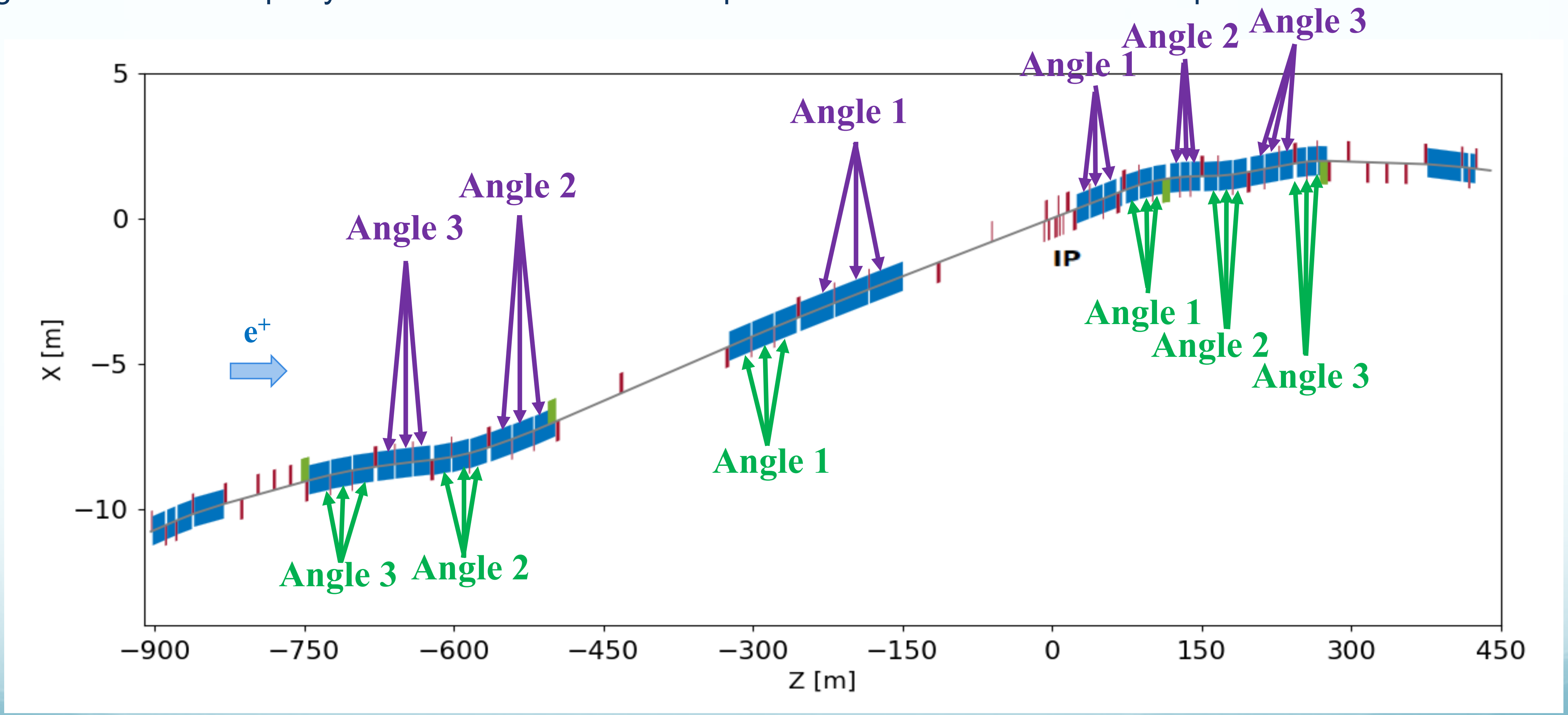




FCC-ee Monochromatization IR Optics Design

- **Scheme for Horizontal Dispersion Generation at the IP**

To mitigate horizontal emittance blowup[3], two long chicanes are implemented to each upstream and downstream. And each angle of chicane is equally distributed to all the three pieces of each LOC horizontal dipole.

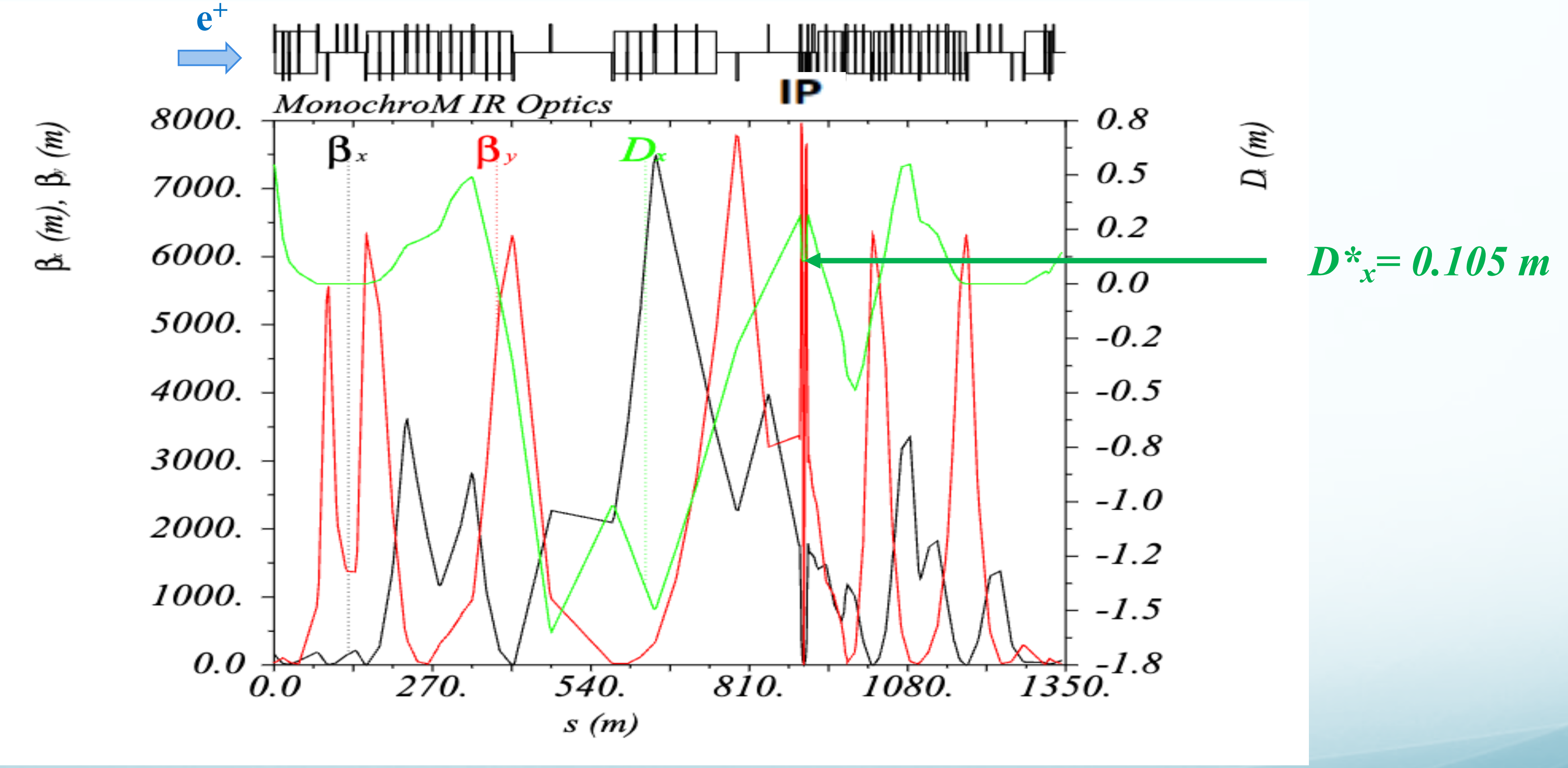


[3] Z.Zhang, A. Faus-Golfe, F. Zimmermann et al. "Monochromatization optics for FCC-ee lattices", CEPC Workshop 2023, https://indico.ihep.ac.cn/event/19316/contributions/142896/

FCC-ee Monochromatization IR Optics Design

- **Horizontal Dispersion Generation IR Optics Design Result base on Z mode Lattice**

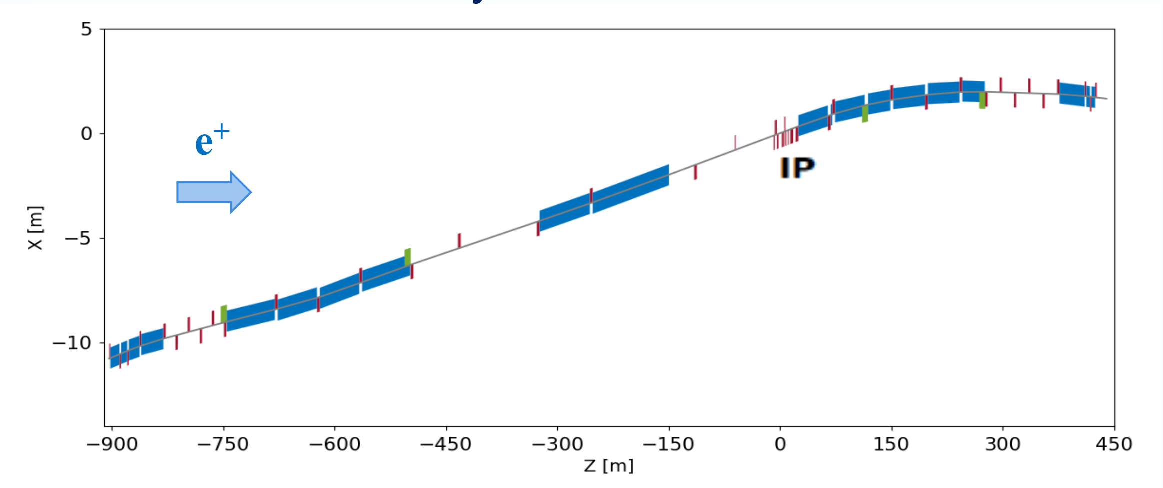
The beam parameters at the IP are matched to FCC-ee Monochromatization self-consistent parameters[4] while keeping the beam parameters at the entrance and exit of the IR are same with those of standard mode. The phase advance of sextupoles and crab sextupoles is also matched to be same with that of standard mode.

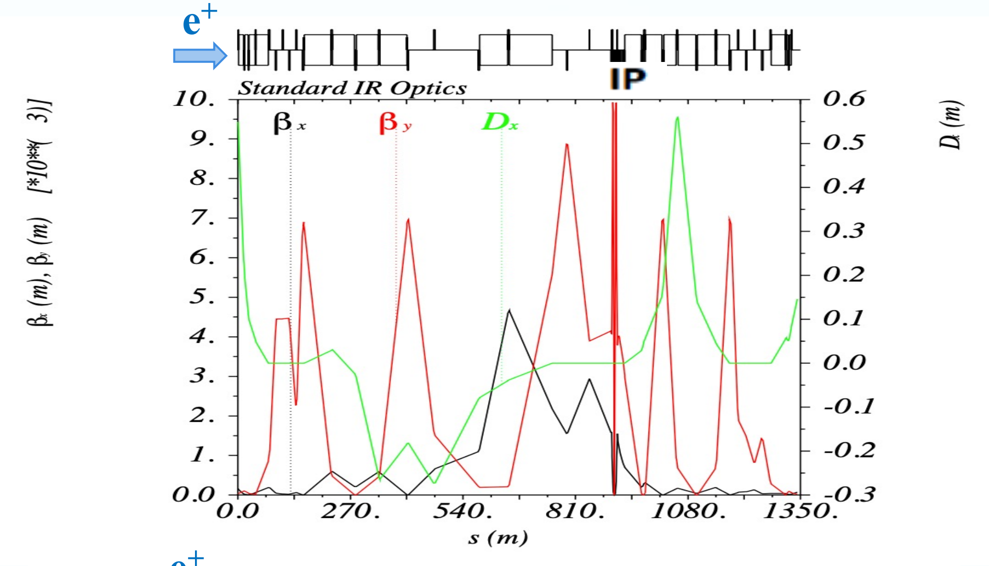


[4] A. Faus-Golfe, M. Valdivia Garcia, F. Zimmermann, The challenge of monochromatization Direct s-channel Higgs production: e+e− → H, Eur. Phys. J. Plus (2022) 137:31, https://doi.org/10.1140/epjp/s13360-021-02151-y

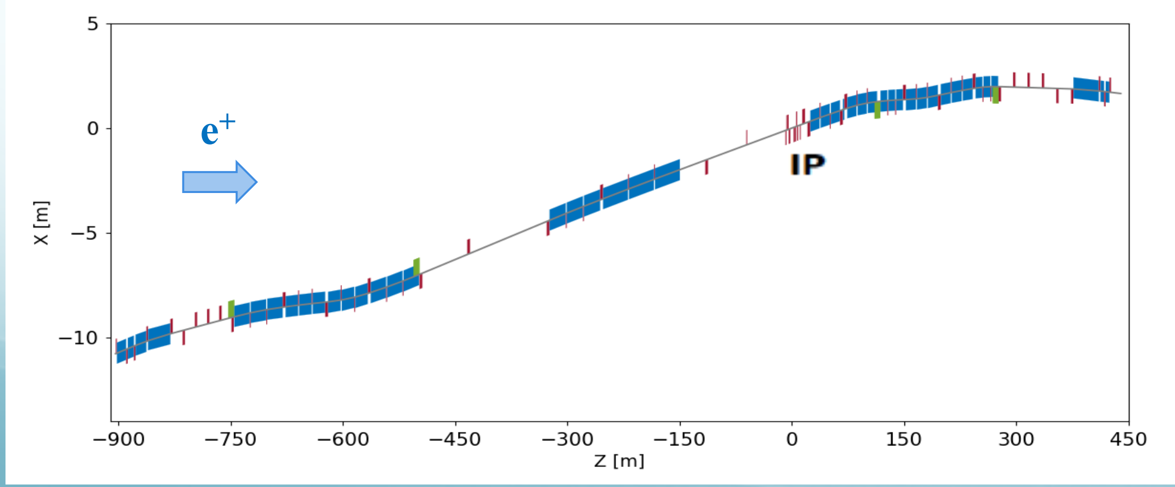
FCC-ee Monochromatization IR Optics Design

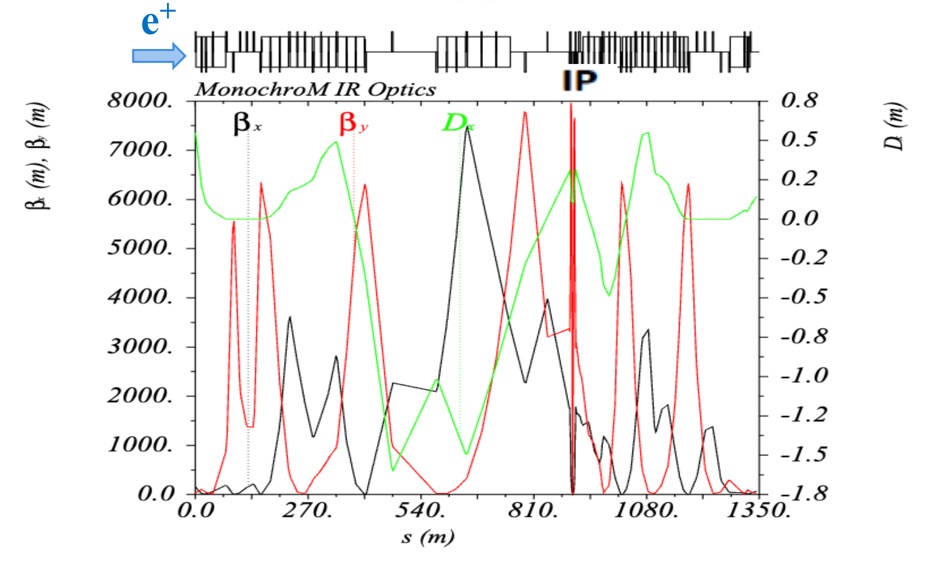
- **Comparison between Standard Orbit and Monochromatization Orbit base on Z mode Lattice**
  - Standard Survey Plot





  - Monochromatization Survey Plot

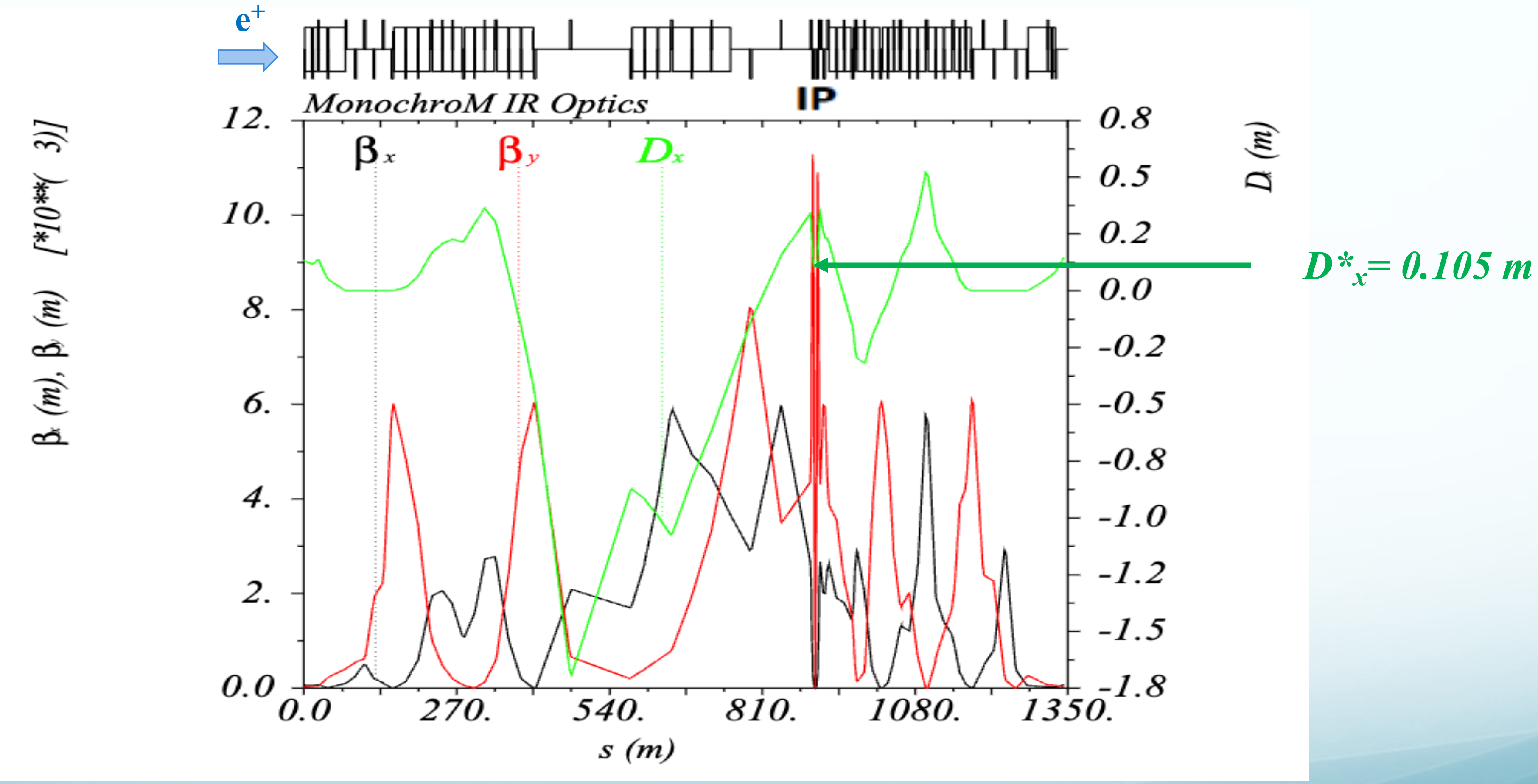




FCC-ee Monochromatization IR Optics Design

- **Horizontal Dispersion Generation IR Optics Design Result base on ttbar mode Lattice**

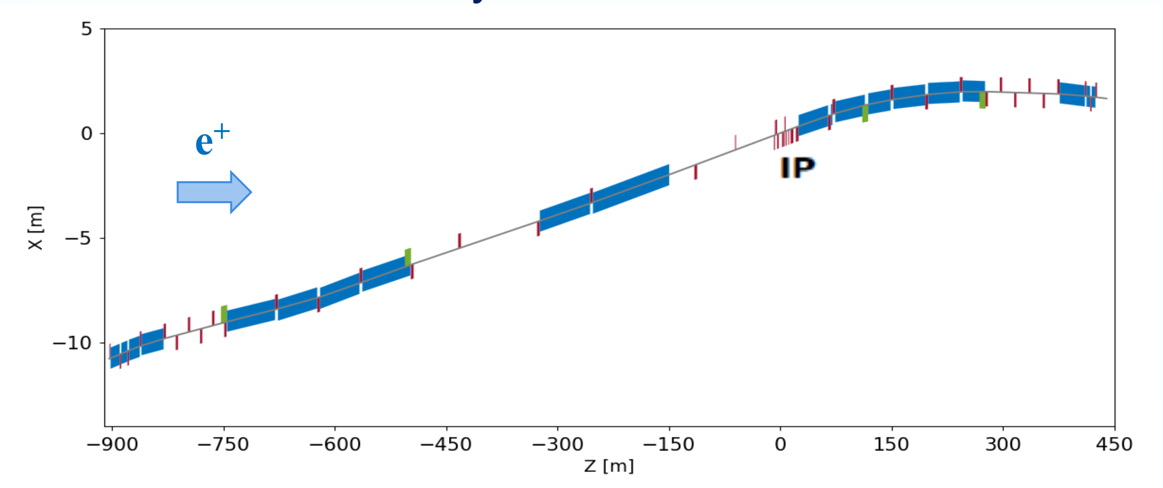
With the same scheme, the horizontal Dispersion Generation IR optics design base on ttbar mode lattice is also completed in the code MADX[5].

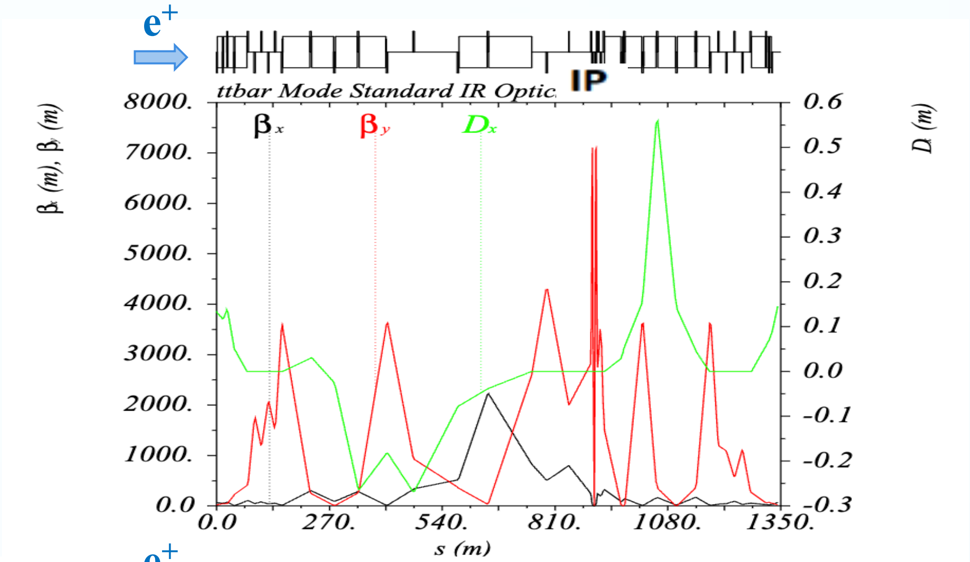


[5] MADX - Methodical Accelerator Design. http://madx.web.cern.ch/madx/

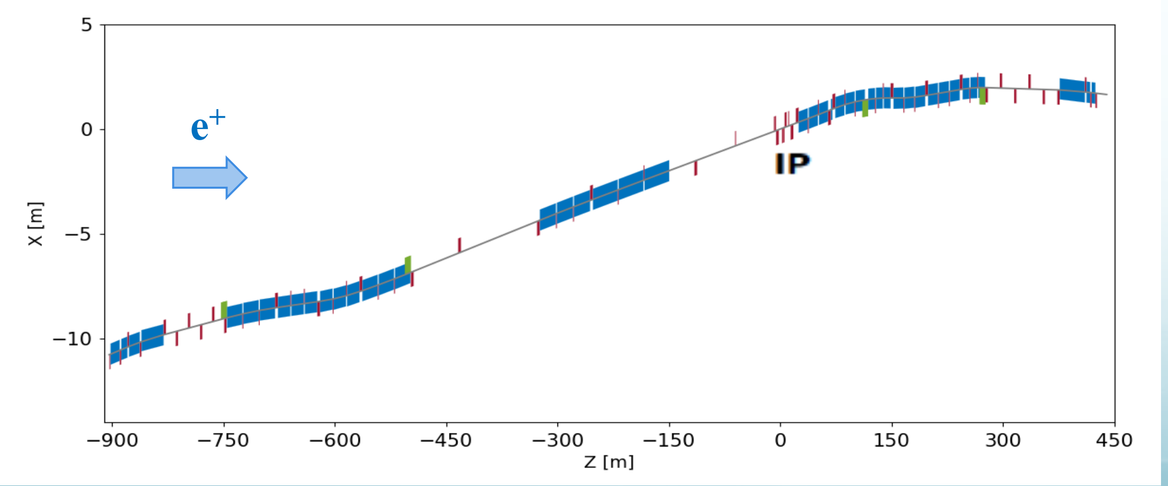
FCC-ee Monochromatization IR Optics Design

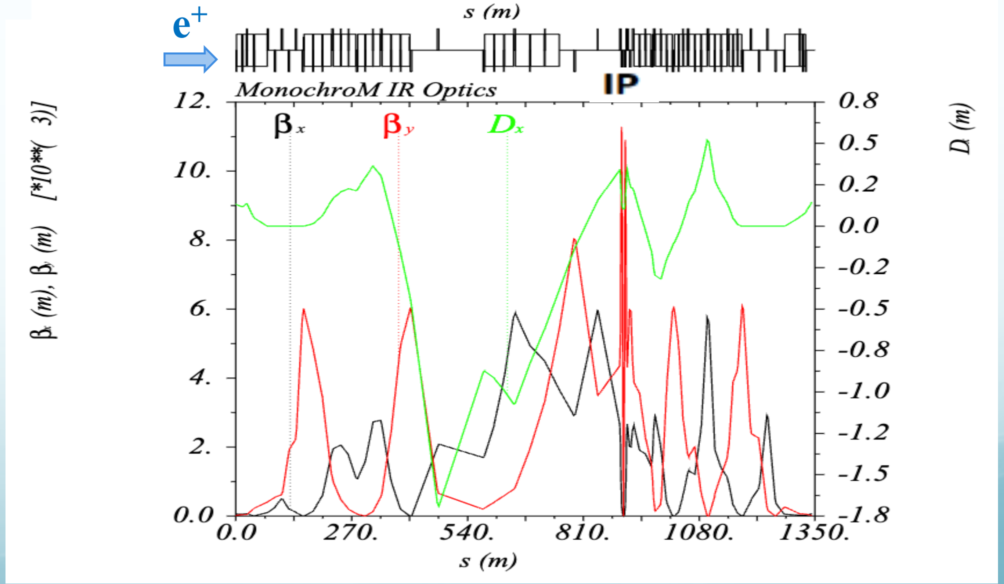
- **Comparison between Standard Orbit and Monochromatization Orbit base on ttbar mode Lattice**
  - Standard Survey Plot





  - Monochromatization Survey Plot



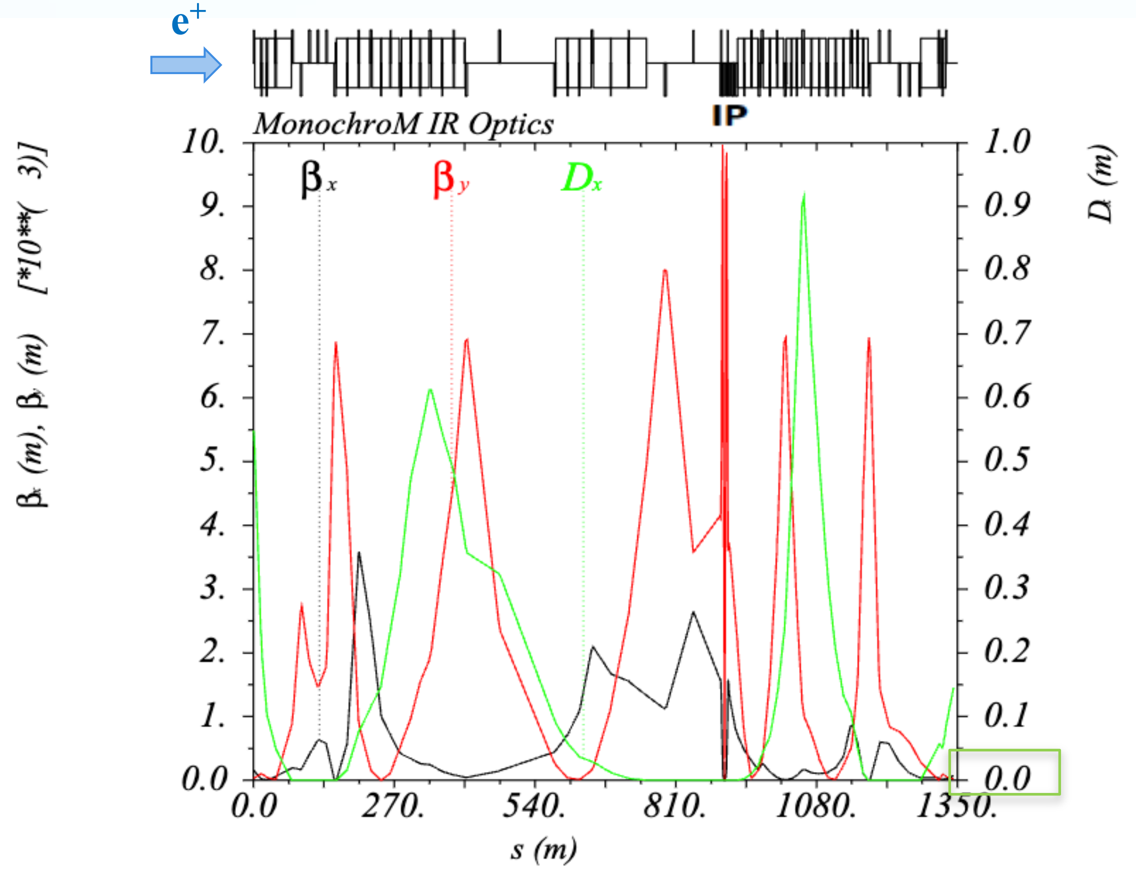


FCC-ee Monochromatization IR Optics Design

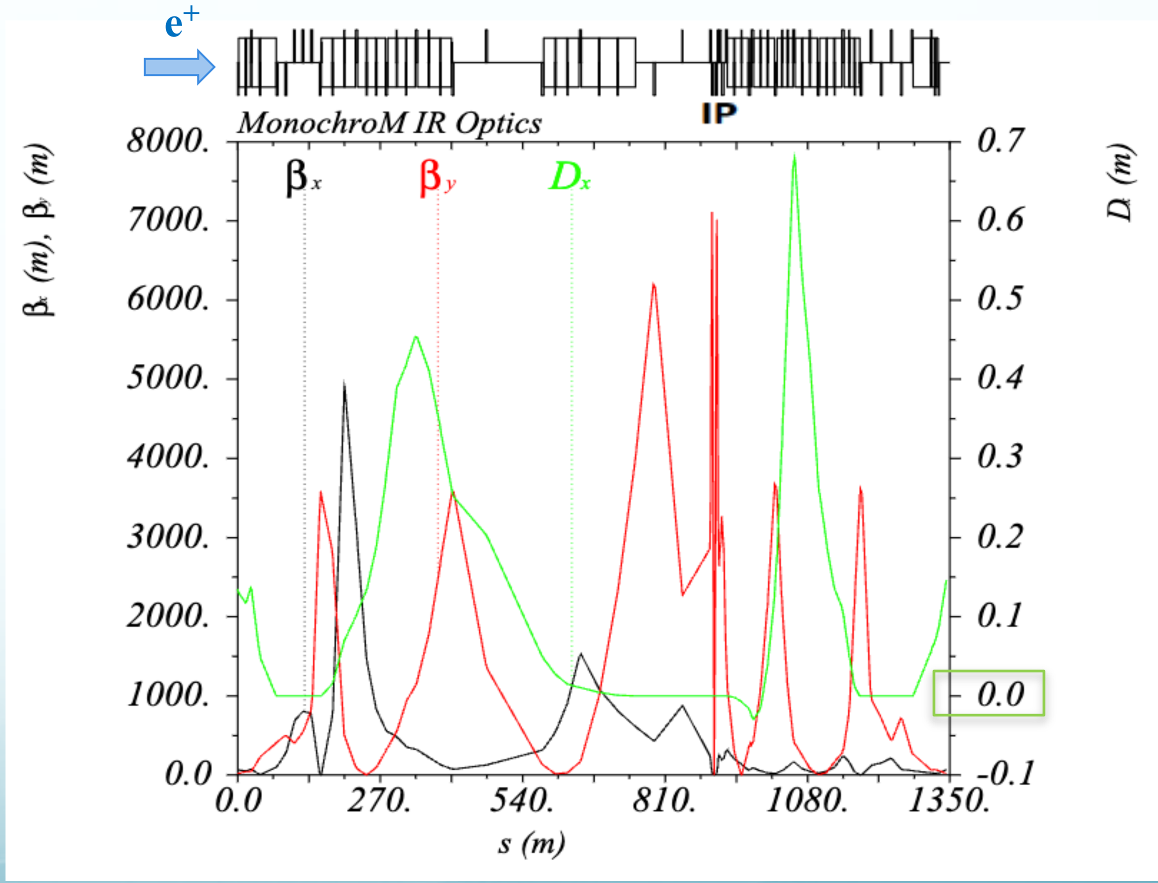
- **Standard Mode with Monochromatization Orbit**

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.

- *MonochroM-standard mode base on Z mode lattice*



- *MonochroM-standard mode base on ttbar mode lattice*

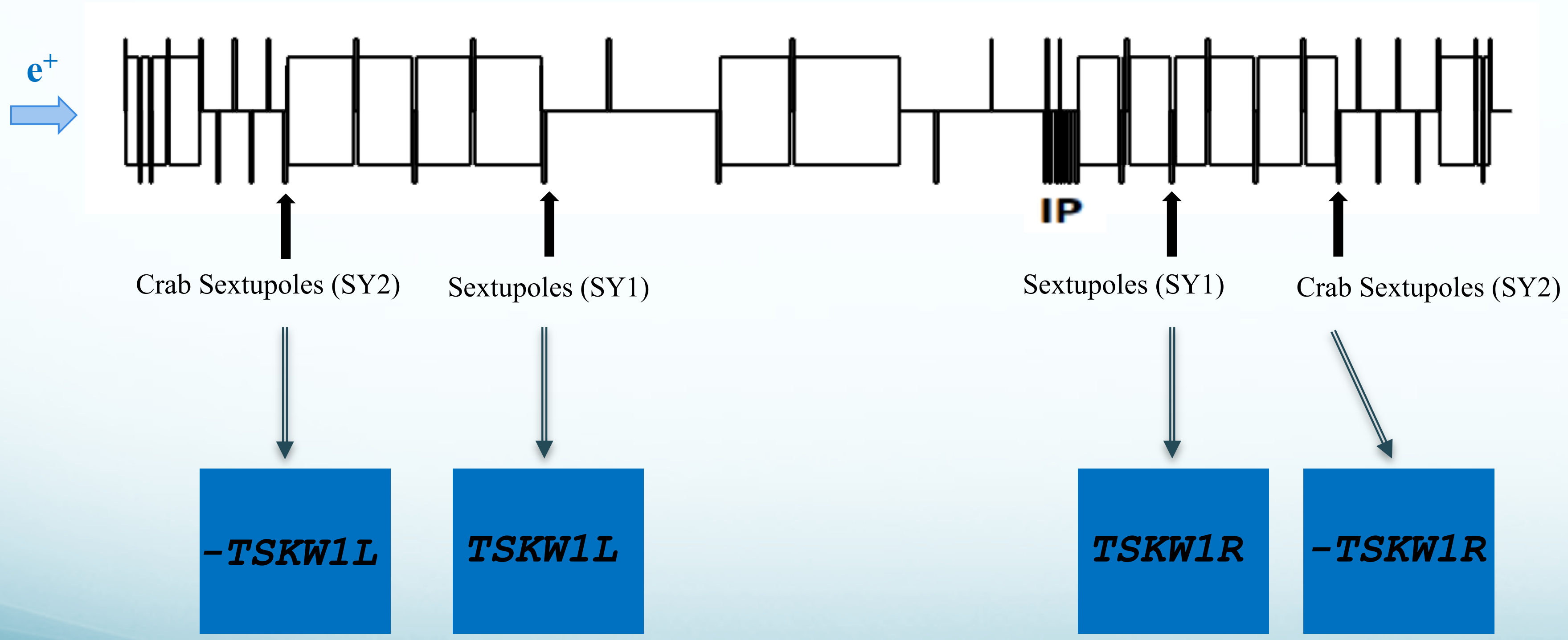


FCC-ee Monochromatization IR Optics Design

- **Scheme of Vertical Dispersion Generation at the IP**

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.



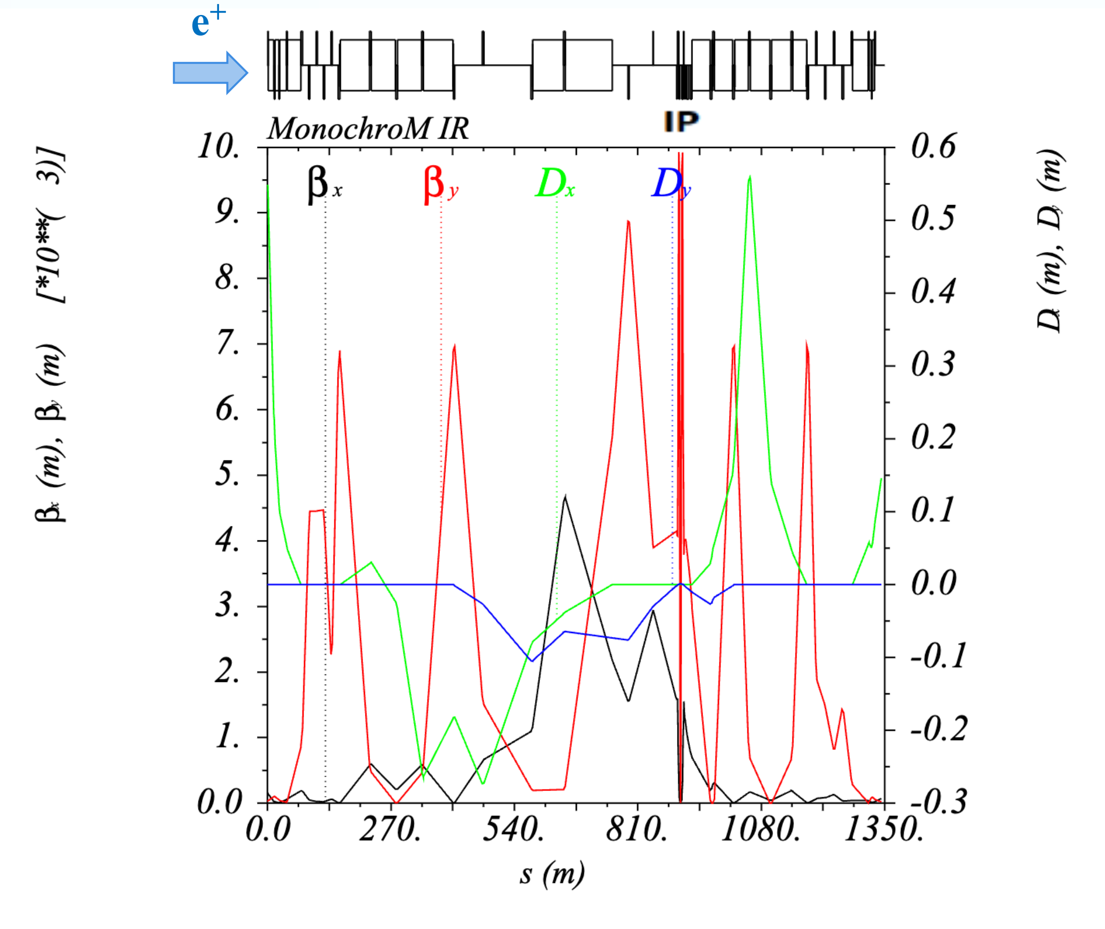
Monochromatization factor

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

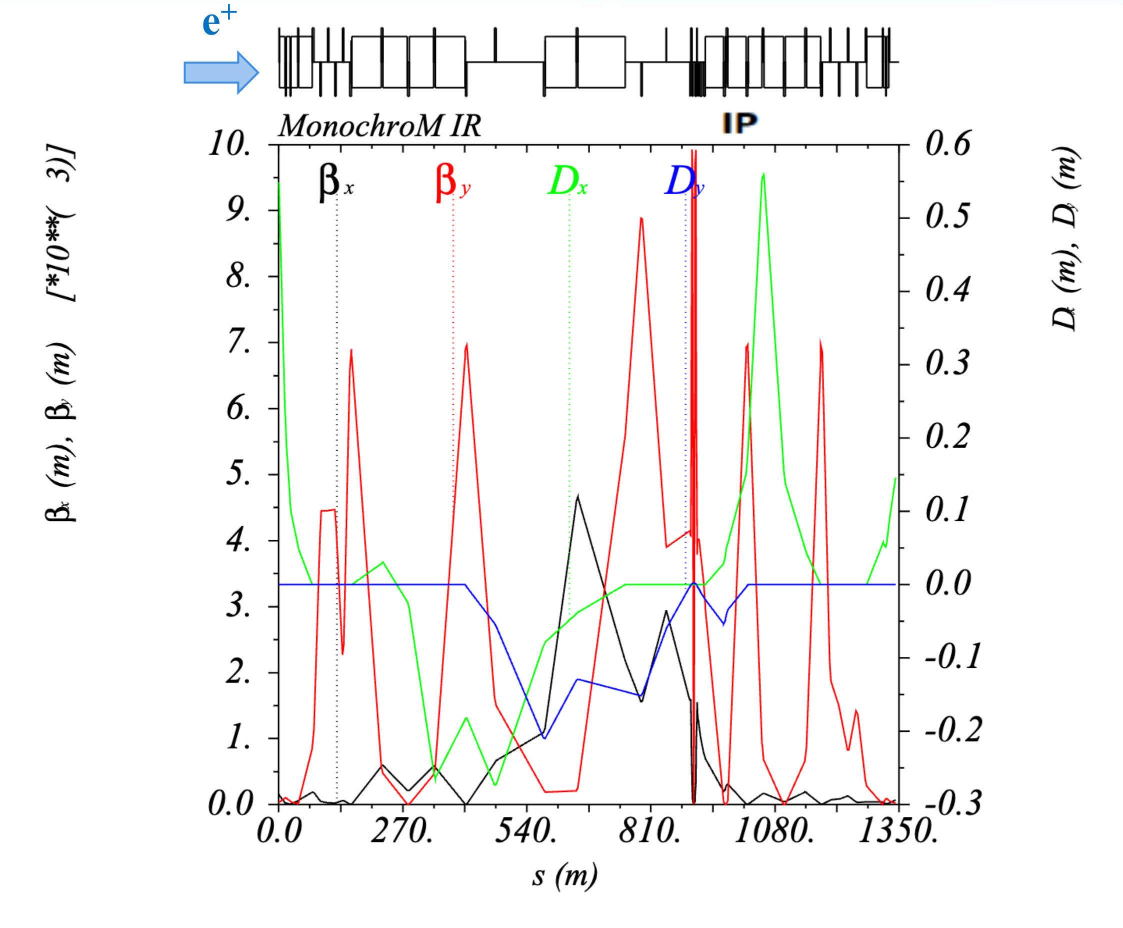
FCC-ee Monochromatization IR Optics Design

- **Monochromatization Optics Design Result based on Z mode Lattice**

- $D^*_y = 1$ mm



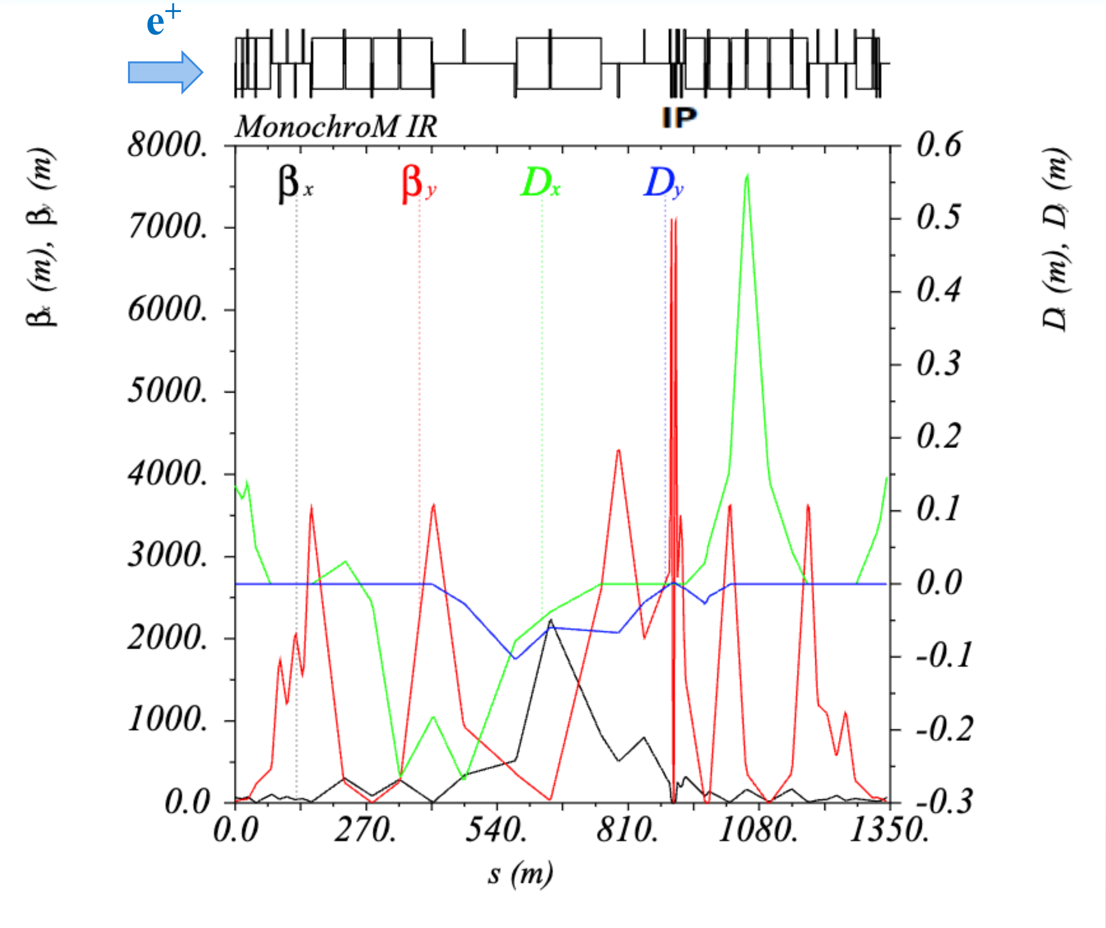
- $D^*_y = 2$ mm



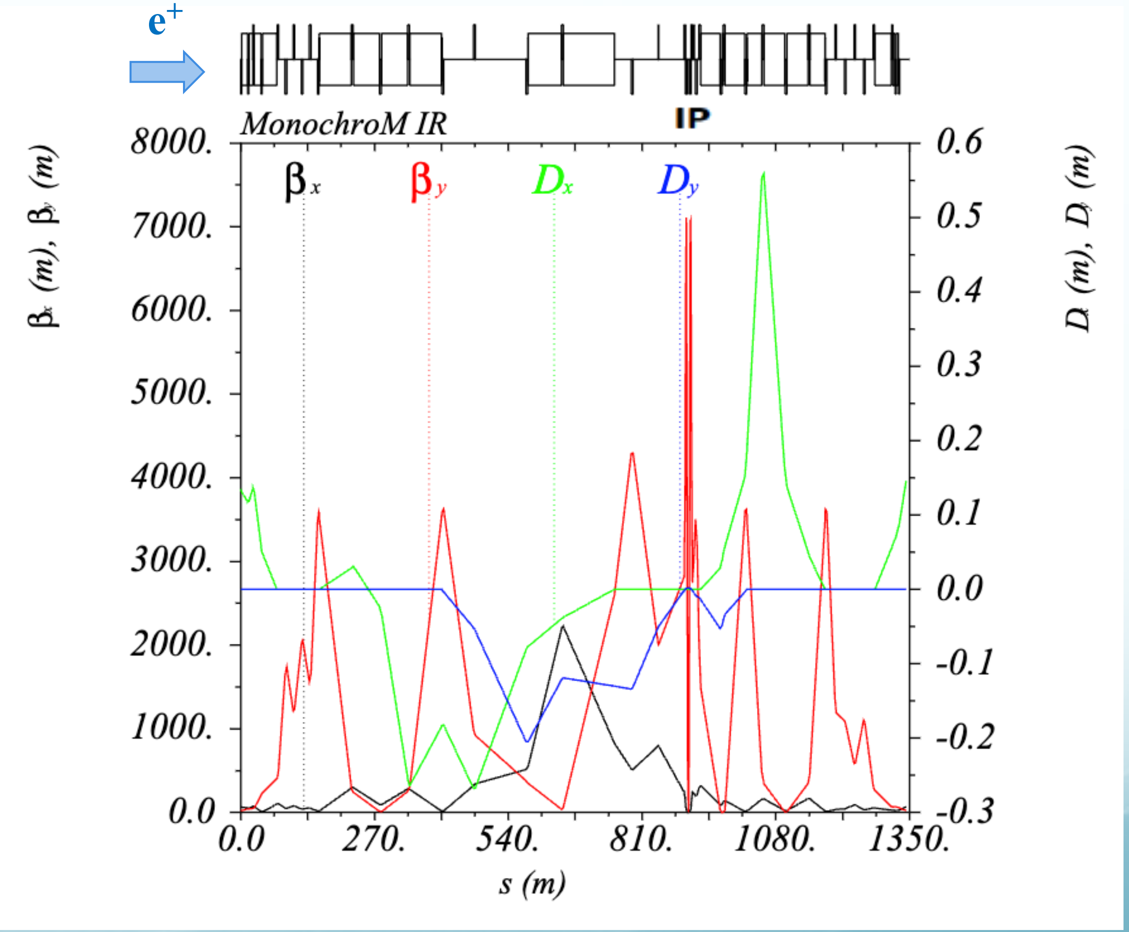
FCC-ee Monochromatization IR Optics Design

- **Monochromatization Optics Design Result based on ttbar mode Lattice**

- $D^*_y = 1$ mm



- $D^*_y = 2$ mm

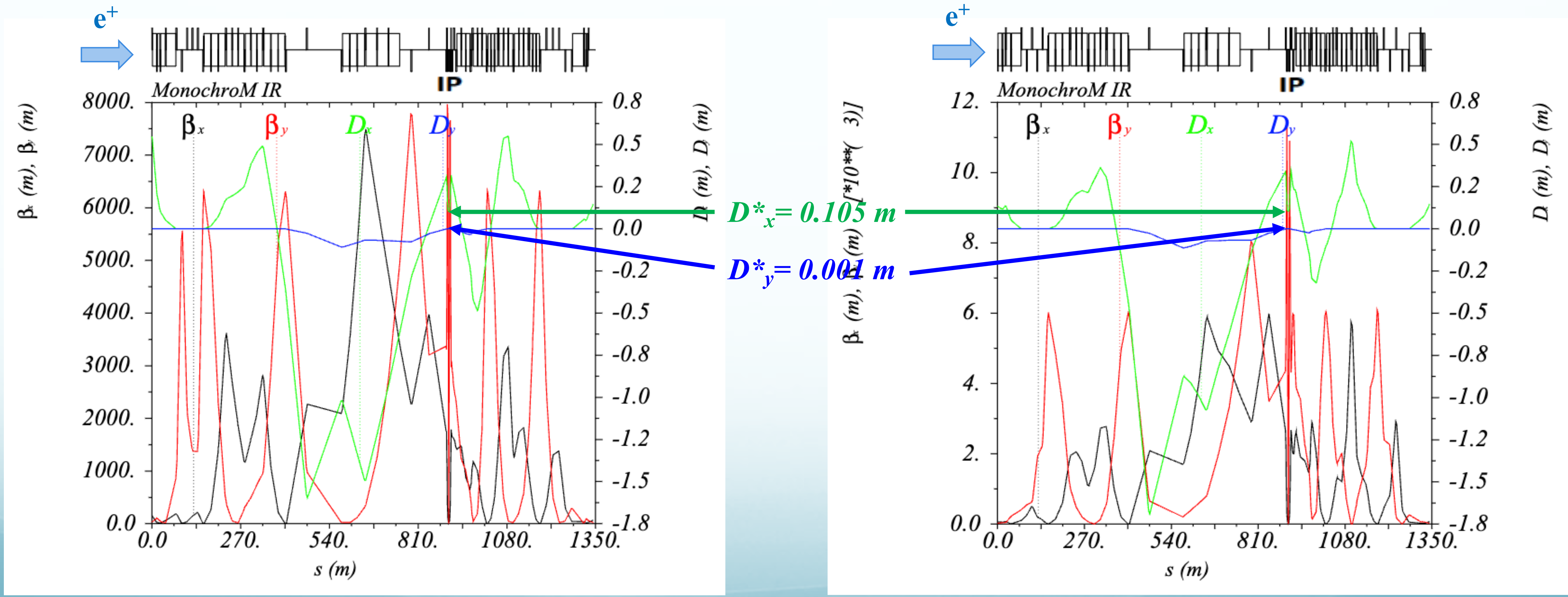


FCC-ee Monochromatization IR Optics Design

- **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.

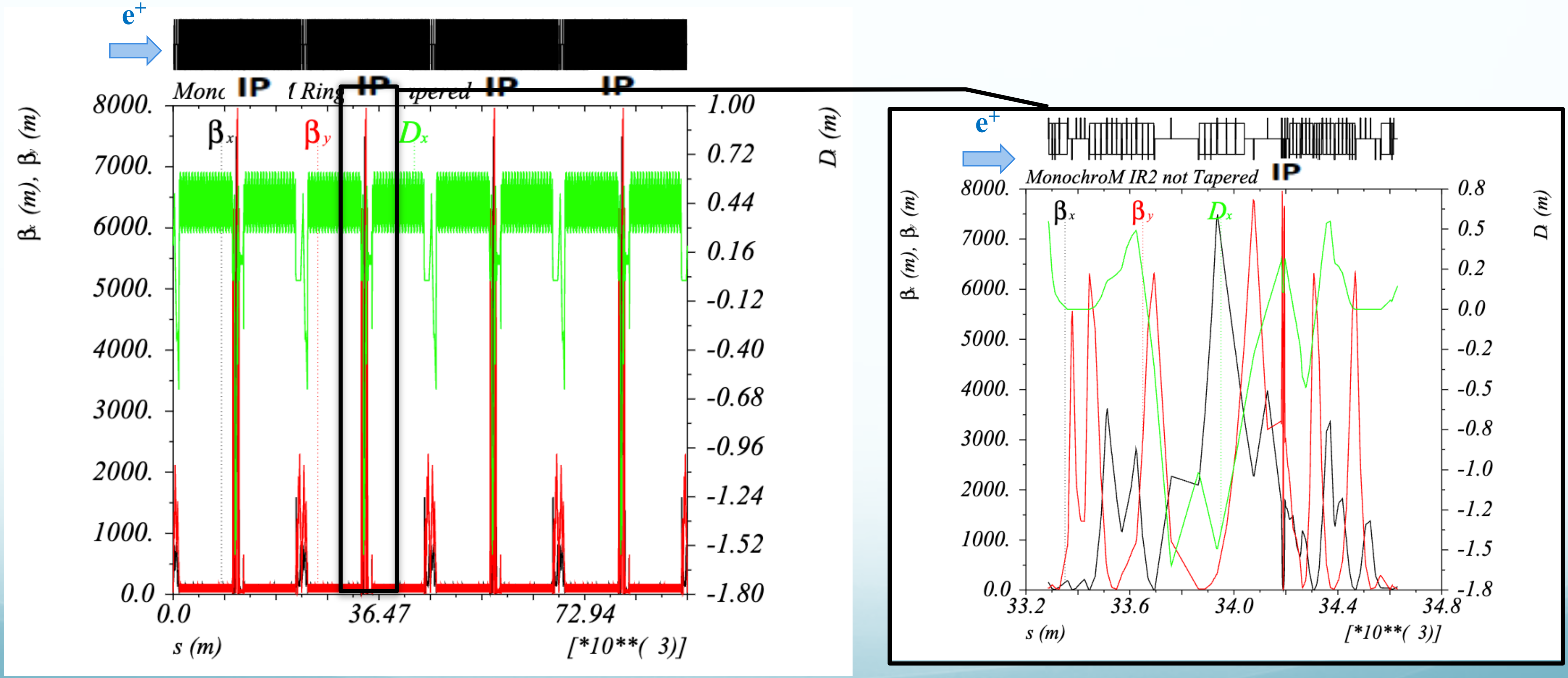
- *Mixing dispersion generation base on Z mode lattice*
- *Mixing dispersion generation base on ttbar mode lattice*



FCC-ee Monochromatization Ring Optics

- **Implementation of Monochromatization IR Optics**

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



FCC-ee Monochromatization Ring Optics

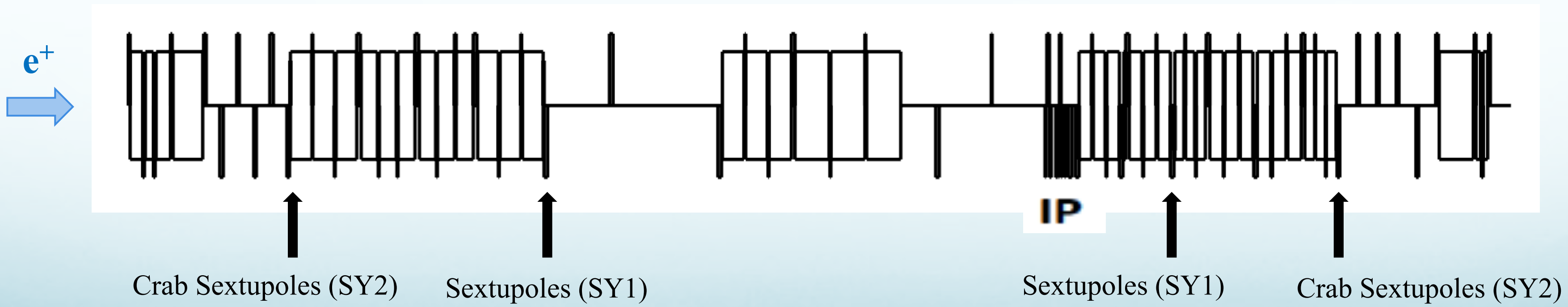
- **Local Chromaticity Correction**
  - Load monochromatization ring lattice, and extract sequence from IP to crab sextupoles.
  - Turned off all the sextupoles including crab sextupoles SY2.
  - Match the vertical chromaticity from IP to crab sextupoles to 0 using the sextupoles SY1.
  - Calculate the strength of crab sextupoles (SY2) with the following formula [6]:

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

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.



[6] K. Oide, M. Aiba, S. Aumon, M. Benedikt, A. Blondel et al. "Design of beam optics for the future circular collider e+e- collider rings", Physical Review Accelerators and Beams, 19, 111005 (2016)

FCC-ee Monochromatization Ring Optics

- **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 be same with the standard mode while keeping the beam parameters at the IRs.

- **Emittance Check**

Switching on the RF cavities and considering the energy loss due to 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.

FCC-ee Monochromatization Ring Optics

- **FCC-ee Monochromatization Optics Design Result**

Finishing all the corrections for all the monochromatization optics, we have now 7 kinds of monochromatization optics design based on K. Oide's V22 FCC-ee Z mode lattices and ttbar lattices.

Abbreviation of optics	Orbit changed or not	*Dx**	*Dy**
standard_625	No	0	0
monochrom_h_4ip	Yes	0.105 m	0
monochrom_h_2ip	Yes	0.105 m	0
monochrom_h_d0	Yes	0	0
monochrom_v_1	No	0	0.001 m
monochrom_v_2	No	0	0.002 m
monochrom_mix	Yes	0.105 m	0.001 m

These totally 14 kinds of lattice are all transferred from MADX sequence file to Xsuite[7] .json file and are re-matched in Xsuite.

[7] Xsuite. https://xsuite.readthedocs.io/

Performance Check of FCC-ee Monochromatization Optics

- **Parameters of FCC-ee V22 Monochromatization Optics Performance base on Z mode Lattice (o/w BS)**

Parameters	Units	Standard	Standard_625	Monochrom_h_4ip	Monochrom_h_2ip	Monochrom_h_d0	Monochrom_v_1	Monochrom_v_2	Monochrom_mix
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	4	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	137.9	142.7	140.2	142.7	137.8	137.7	142.7
SR power loss	MW	50.0	54.5	56.4	55.4	56.4	54.4	54.4	56.4
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	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Horizontal emittance (SR/BS) ε_x	nm	0.71 / 0.71	1.33 / 1.33	2.09 / 4.94	1.71 / 4.73	1.66 / 1.66	1.32 / 1.32	1.32 / 1.32	2.03 / 4.88
Vertical emittance (SR/BS) ε_y	pm	1.42 / 1.42	2.65 / 2.65	4.17 / 4.17	3.42 / 3.42	3.33 / 3.33	2.65 / 2.65	2.63 / 2.63	4.06 / 4.06
Momentum compaction α_c	10^{-6}	28.2	28.0	27.4	27.7	27.6	27.9	27.9	27.4
$\beta^*_{x/y}$	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	%	0.0392 / 0.2804	0.0537 / 0.0910	0.0548 / 0.0559	0.0543 / 0.0554	0.0548 / 0.0852	0.0537 / 0.0910	0.0537 / 0.0911	0.0548 / 0.0559
MonochroM Factor (SR/BS) λ	/	1 / 1	1 / 1	4.32 / 2.96	4.70 / 2.99	1 / 1	11.72 / 19.80	23.44 / 39.75	9.66 / 9.26
CM energy spread (SR/BS) σ_W	MeV	25.3 / 180.8	47.47 / 80.42	11.22 / 16.70	10.21 / 16.36	48.46 / 75.28	4.05 / 4.06	2.03 / 2.03	5.02 / 5.33
Bunch length (SR/BS) σ_z	mm	4.38 / 30.96	4.09 / 6.80	4.15 / 4.16	4.13 / 4.14	4.17 / 6.36	4.10 / 6.81	4.10 / 6.82	4.15 / 4.16
Sychrotron tune Q_s	/	0.037	0.054	0.053	0.054	0.054	0.054	0.054	0.053
Longitudinal damping time	turns	1168	453	438	446	438	454	454	438
Luminosity (SR/BS)	10^{34}cm^{-2} s^{-1}	5476 / 5476	206.9 / 206.9	28.69 / 27.23	32.12 / 30.35	164.8 / 164.8	17.68 / 10.46	8.89 / 5.24	3.24 / 3.13

Performance Check of FCC-ee Monochromatization Optics

- **Parameters of FCC-ee V22 Monochromatization Optics Performance base on ttbar mode Lattice (o/w BS)**

Parameters	Units	Standard	Standard_625	Monochrom_h_4ip	Monochrom_h_2ip	Monochrom_h_d0	Monochrom_v_1	Monochrom_v_2	Monochrom_mix
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	4	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	10000.0	137.6	143.5	140.5	143.4	137.6	137.6	143.4
SR power loss	MW	50.0	54.3	56.7	55.5	56.7	54.3	54.3	56.7
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	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Horizontal emittance (SR/BS) ε_x	nm	1.49 / 1.49	0.17 / 0.17	1.48 / 4.31	0.84 / 3.97	0.35 / 0.35	0.17 / 0.17	0.17 / 0.17	1.48 / 4.31
Vertical emittance (SR/BS) ε_y	pm	2.98 / 2.98	0.34 / 0.34	2.96 / 2.96	1.68 / 1.68	0.71 / 0.71	0.35 / 0.35	0.35 / 0.35	2.96 / 2.96
Momentum compaction α_c	10^{-6}	6.99	7.30	6.92	7.12	7.06	7.31	7.31	6.92
$\beta^*_{x/y}$	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	%	0.1569 / 0.2180	0.0537 / 0.0861	0.0552 / 0.0563	0.0545 / 0.0556	0.0552 / 0.0714	0.0537 / 0.0861	0.0537 / 0.0861	0.0552 / 0.0563
MonochroM Factor (SR/BS) λ	/	1 / 1	1 / 1	5.12 / 3.16	6.65 / 3.25	1 / 1	22.81 / 36.55	45.58 / 73.08	11.38 / 10.82
CM energy spread (SR/BS) σ_W	MeV	404.91 / 562.75	47.46 / 76.10	9.54 / 15.73	7.24 / 15.14	48.81 / 63.08	2.08 / 2.08	1.04 / 1.04	4.29 / 4.60
Bunch length (SR/BS) σ_z	mm	2.03 / 2.70	3.86 / 6.18	4.05 / 4.13	3.95 / 4.03	4.09 / 5.28	3.86 / 6.18	3.86 / 6.18	4.05 / 4.13
Sychrotron tune Q_s	/	0.082	0.015	0.014	0.014	0.014	0.015	0.015	0.014
Longitudinal damping time	turns	18.5	454	436	445	436	454	454	436
Luminosity (SR/BS)	10^{34}cm^{-2} s^{-1}	2.21 / 2.21	353.2 / 353.2	34.1 / 32.3	46.19 / 43.53	173.5 / 173.5	15.49 / 9.66	7.750 / 4.834	3.227 / 3.116

Lower CM energy spread compared to Z mode

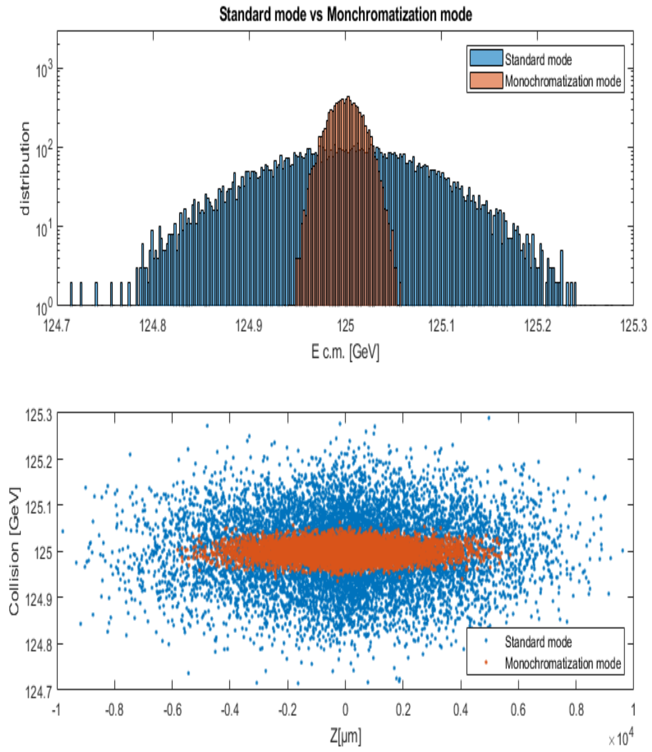
Performance Check of FCC-ee Monochromatization Optics

- **Luminosity and CM Energy Spread Calculations in Guinea-pig (with BS)**

The following figures show the Guinea-pig calculation result of FCC-ee monochromatization optics base on Z mode lattice with crab cavities (head-on) compared with that of the scaled standard mode.

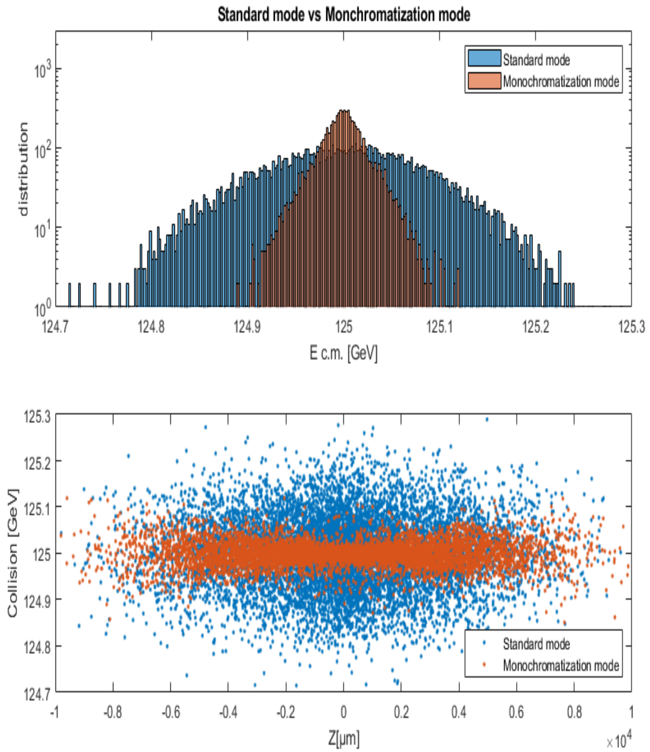
Standard_625/head-on: Luminosity: 1.20×10^{36} $cm^{-2}s^{-1}$, CM energy spread: 80.12 MeV

- *monochrom_h_4ip/head-on*



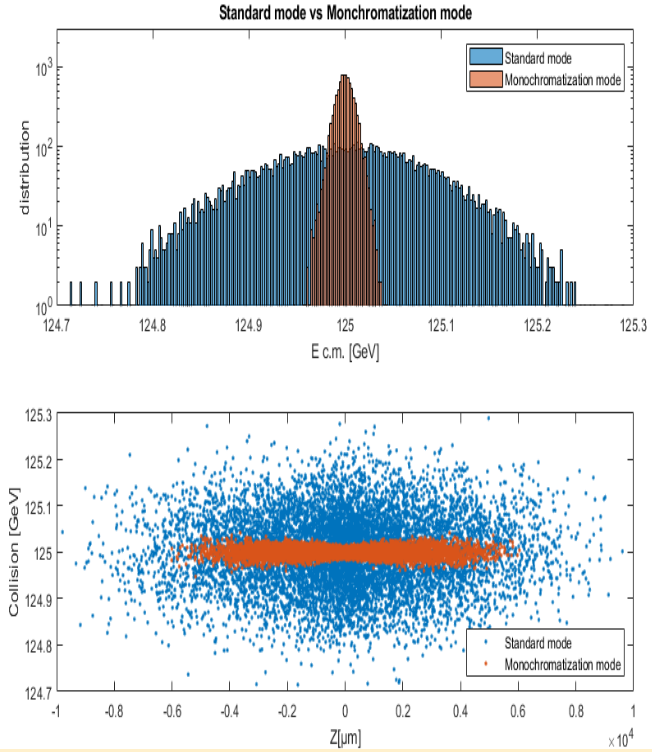
Luminosity: 2.80×10^{35} $cm^{-2}s^{-1}$
CM energy spread: 17.11 MeV

- *monochrom_v_1/head-on*



Luminosity: 2.23×10^{35} $cm^{-2}s^{-1}$
CM energy spread: 18.15 MeV

- *monochrom_mix/head-on*



Luminosity: 1.35×10^{35} $cm^{-2}s^{-1}$
CM energy spread: 8.61 MeV

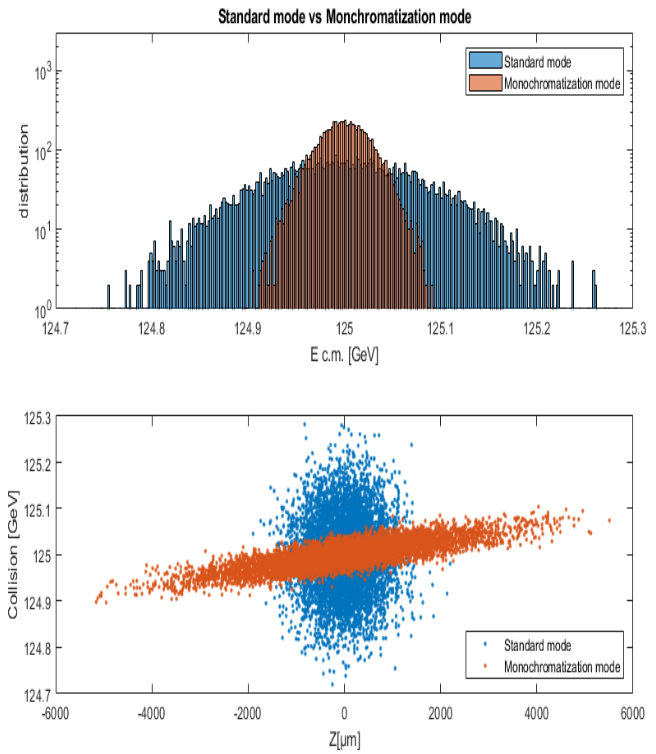
Performance Check of FCC-ee Monochromatization Optics

- **Luminosity and CM Energy Spread Calculations in Guinea-pig (with BS)**

The following figures show the Guinea-pig calculation result of FCC-ee monochromatization optics base on Z mode lattice without crab cavities (crossing-angle) compared with that of the scaled standard mode.

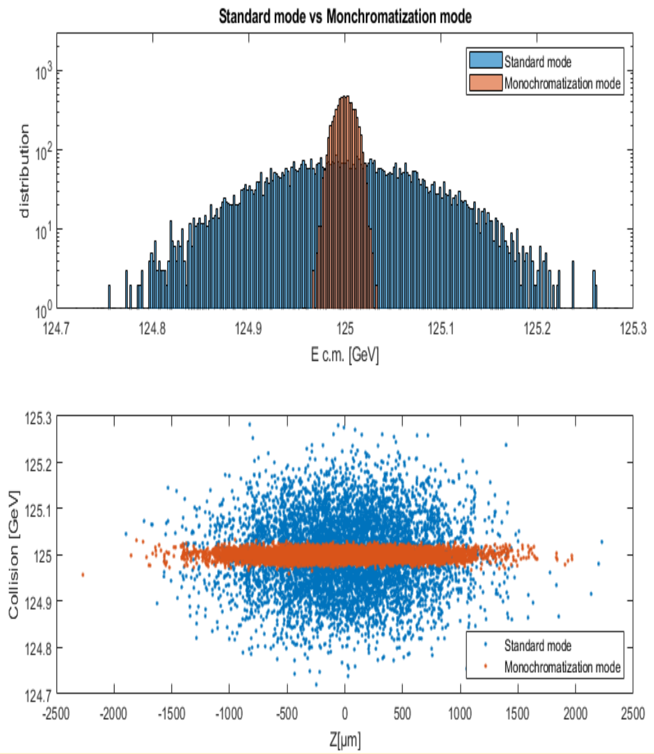
Standard_625/crossing-angle: Luminosity: 4.50×10^{35} cm^{-2}s^{-1}, CM energy spread: 80.33 MeV

- *monochrom_h_4ip/crossing-angle*



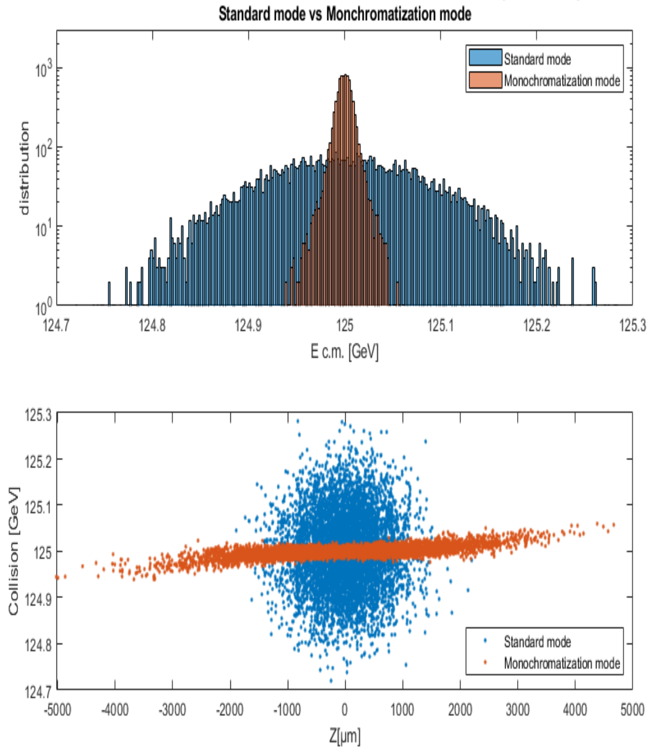
Luminosity: 2.43×10^{35} cm^{-2}s^{-1}
CM energy spread: 26.61 MeV

- *monochrom_v_1/crossing-angle*



Luminosity: 2.53×10^{34} cm^{-2}s^{-1}
CM energy spread: 10.66 MeV

- *monochrom_mix/crossing-angle*



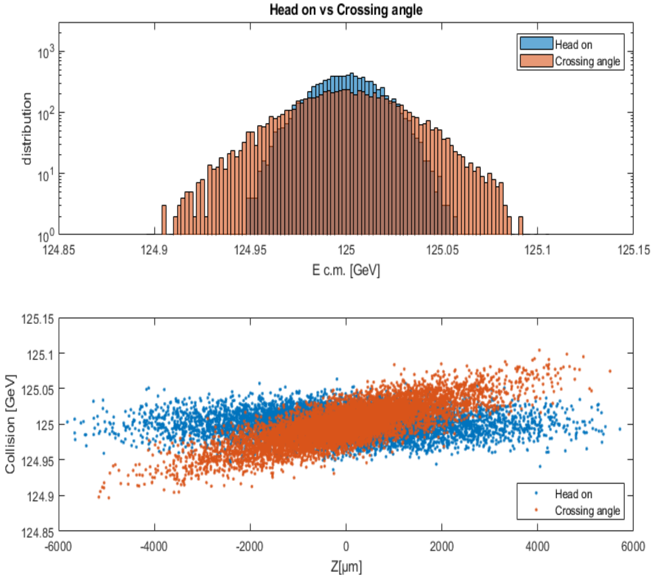
Luminosity: 6.46×10^{34} cm^{-2}s^{-1}
CM energy spread: 7.31 MeV

Performance Check of FCC-ee Monochromatization Optics

- **Luminosity and CM Energy Spread Calculations in Guinea-pig (with BS)**

The following figures show the comparison of the Guinea-pig calculation result with/without crab cavities of FCC-ee monochromatization optics design base on Z mode lattice.

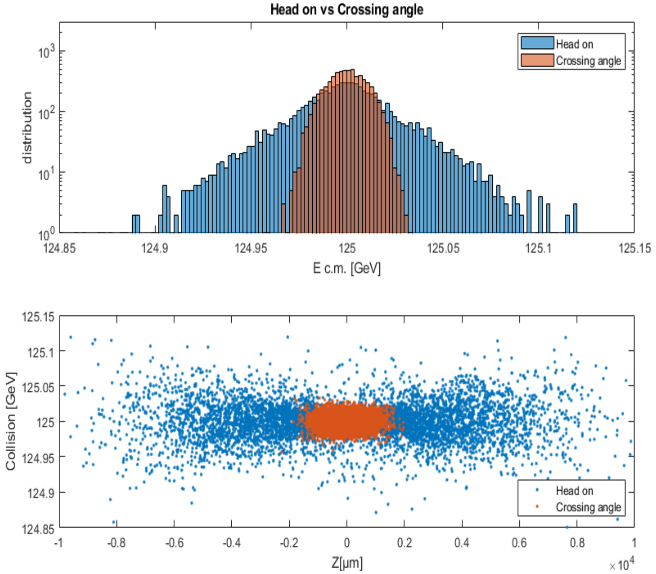
- *monochrom_h_4ip*



Luminosity (w/o crab cavity) : 2.80×10^{35} / 2.43×10^{35} $cm^{-2}s^{-1}$
CM energy spread (w/o crab cavity) : 17.11 / 26.61 MeV

***Advantage:** Higher luminosity with crossing angle*
***Disadvantage:** CM energy spread blows up with crossing angle*

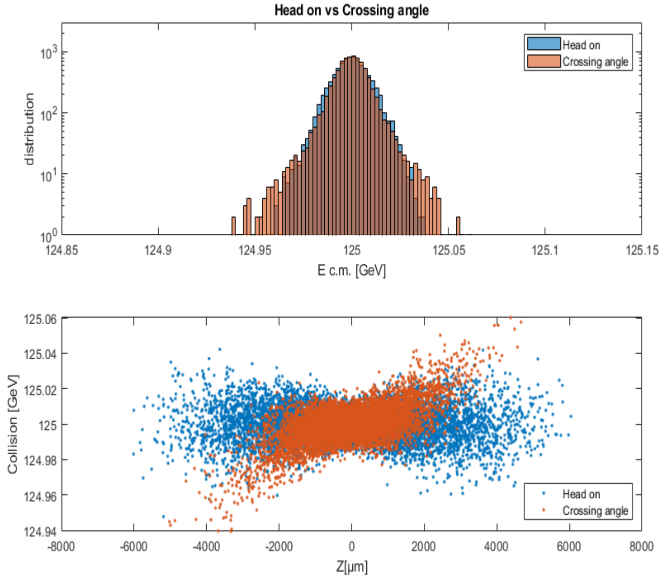
- *monochrom_v_1*



Luminosity (w/o crab cavity) : 2.23×10^{35} / 2.53×10^{34} $cm^{-2}s^{-1}$
CM energy spread (w/o crab cavity) : 18.15 / 10.66 MeV

***Advantage:** CM energy spread reduces with crossing angle*
***Disadvantage:** Luminosity loss with crossing angle like standard mode*

- *monochrom_mix*



Luminosity (w/o crab cavity) : 1.35×10^{35} / 6.46×10^{34} $cm^{-2}s^{-1}$
CM energy spread (w/o crab cavity) : 8.61 / 7.31 MeV

***Advantage:** Lowest CM energy spread and less luminosity loss with crossing angle than that of monochrom_v_1*
***Disadvantage:** Possibly causing coupling problem*

Performance Check of FCC-ee Monochromatization Optics

- **Luminosity and CM Energy Spread Calculations in Guinea-pig (with BS)**
  - *FCC-ee Monochromatization Optics based on Z mode lattice*

Parameters	Units	Standard	Standard_625	Monochrom_h_4ip	Monochrom_h_2ip	Monochrom_h_d0	Monochrom_v_1	Monochrom_v_2	Monochrom_mix
Luminosity (w/o crab cavity)	$10^{34}cm^{-2} s^{-1}$	449 / 99.3	120 / 45.0	28.0 / 24.3	31.2 / 27.8	99.8 / 42.7	22.3 / 2.53	9.92 / 1.28	13.5 / 6.46
CM energy spread (w/o crab cavity)	MeV	180.38 / 182.85	80.12 / 80.33	17.11 / 26.61	16.31 / 26.18	76.65 / 75.52	18.15 / 10.66	9.12 / 9.66	8.61 / 7.31

  - *FCC-ee Monochromatization Optics based on ttbar mode lattice*

Parameters	Units	Standard	Standard_625	Monochrom_h_4ip	Monochrom_h_2ip	Monochrom_h_d0	Monochrom_v_1	Monochrom_v_2	Monochrom_mix
Luminosity (w/o crab cavity)	$10^{34}cm^{-2} s^{-1}$	1.83 / 1.52	399 / 122	33.7 / 29.4	45.3 / 40.6	210 / 91.2	21.2 / 2.98	9.08 / 1.45	14.8 / 6.43
CM energy spread (w/o crab cavity)	MeV	547.02 / 542.7	75.94 / 76.65	15.86 / 25.88	15.32 / 25.10	63.43 / 64.39	9.10 / 4.94	5.94 / 4.51	7.64 / 6.36

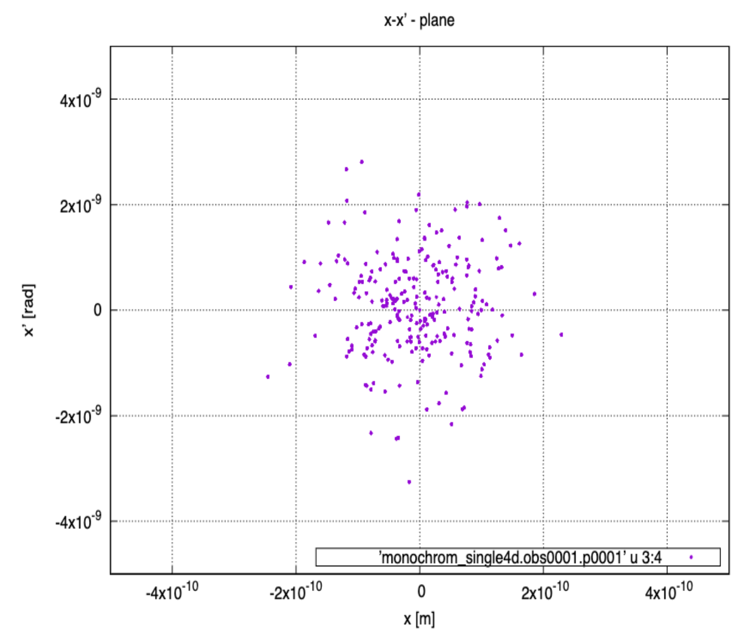
Monochromatization optics base on ttbar mode lattice have lower CM energy spread compared to that based on Z mode lattice

Performance Check of FCC-ee Monochromatization Optics

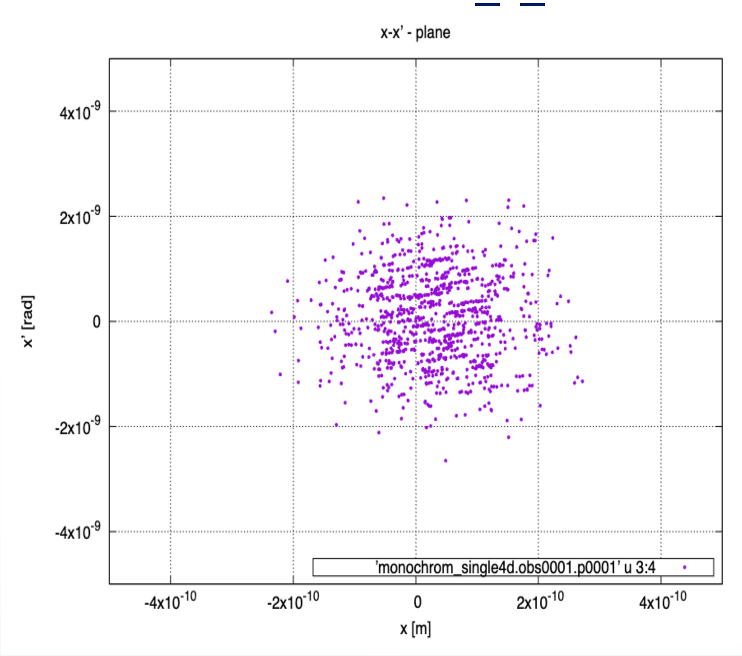
- **Preliminary Single Particle Tracking in MADX-PTC**

1000-turn single particle tracking (4D) calculated with MADX-PTC (FCC-ee monochromatization optics base on Z mode lattice)

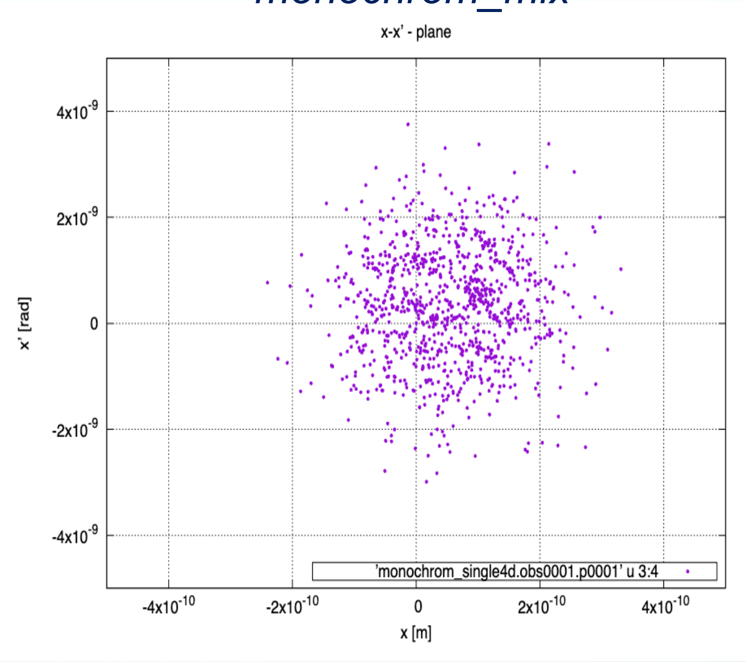
- *monochrom_h_4ip*



- *monochrom_v_1*



- *monochrom_mix*



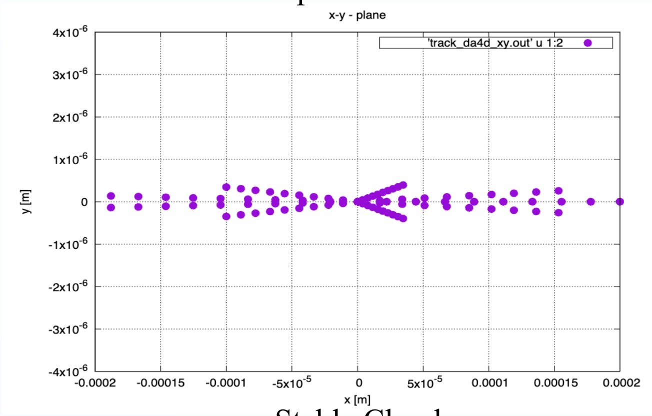
Performance Check of FCC-ee Monochromatization Optics

- **Preliminary Dynamic Aperture Particle Tracking in MADX-PTC**

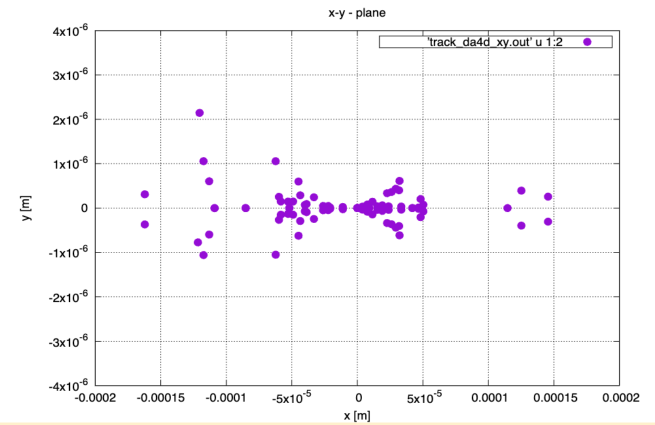
1000-turn dynamic aperture particle tracking (4D) calculated with MADX-PTC taking 100 particles without family sextupole optimization in the arc (FCC monochromatization optics base on Z mode lattice)

- *monochrom_h_4ip*

Input Particles



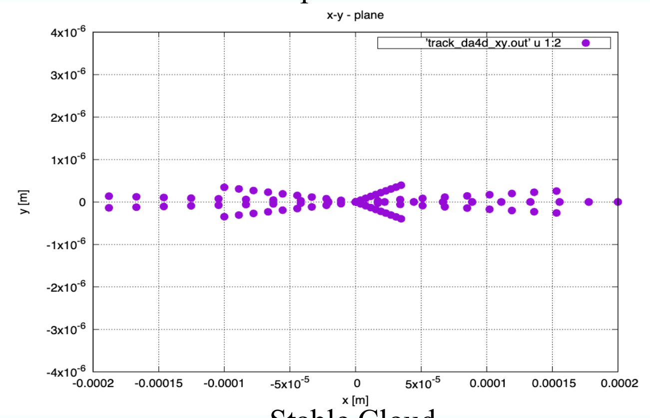
Stable Cloud



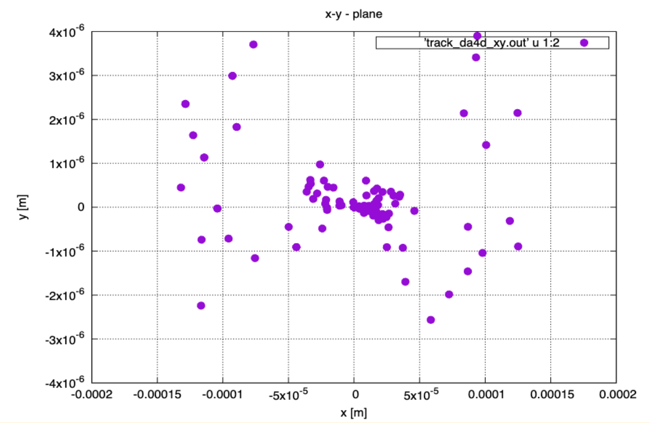
100% particles survive after 1000 turns

- *monochrom_v_1*

Input Particles



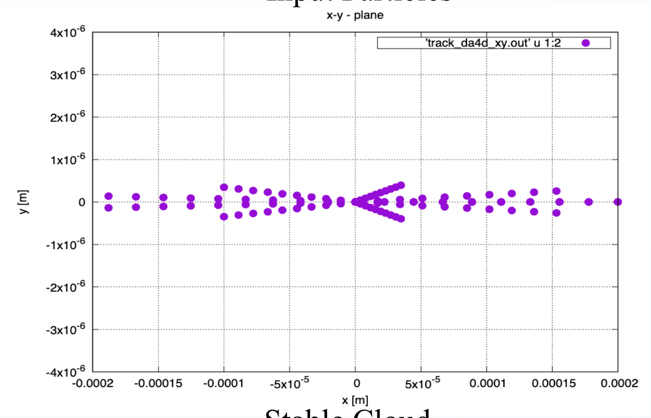
Stable Cloud



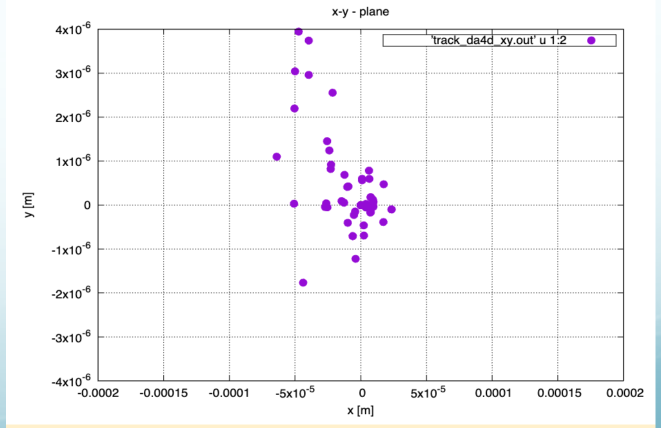
100% particles survive after 1000 turns

- *monochrom_mix*

Input Particles



Stable Cloud



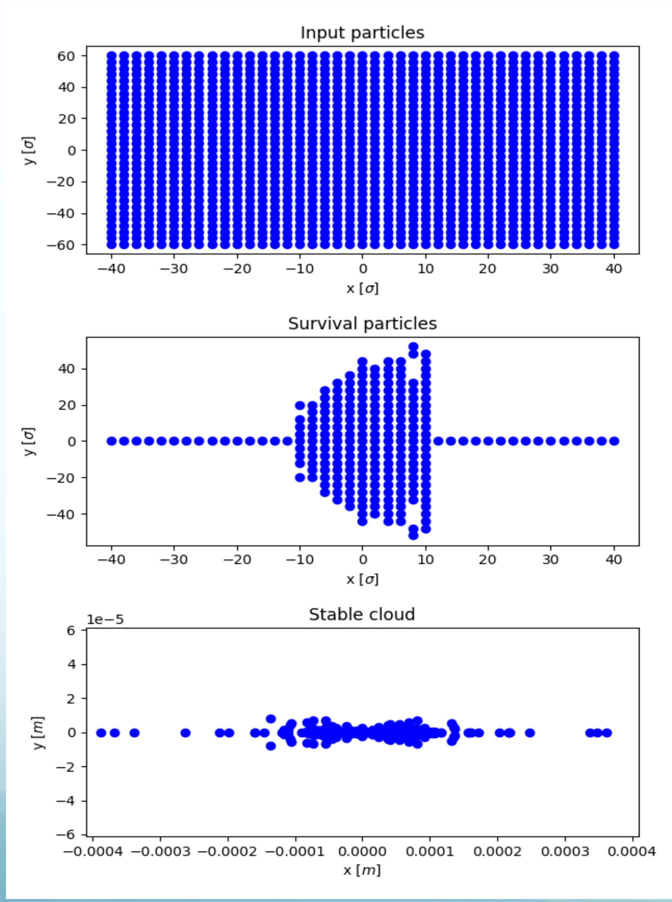
70% particles survive after 1000 turns

Performance Check of FCC-ee Monochromatization Optics

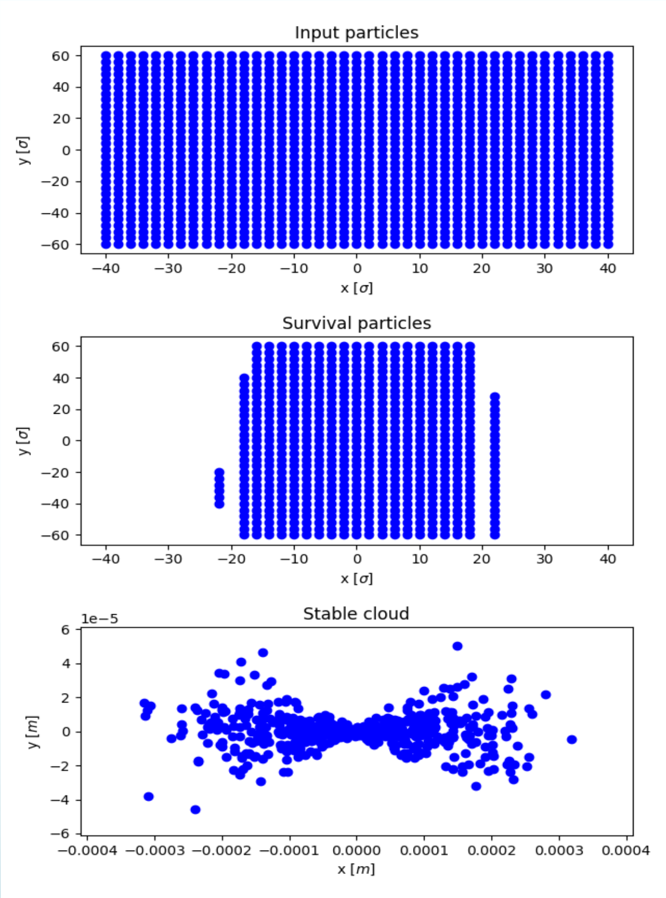
- **Preliminary Dynamic Aperture Particle Tracking in Xsuite**

1000-turn dynamic aperture particle tracking (4D) calculated with Xsuite without family sextupole optimization in the arc (FCC-ee monochromatization optics base on Z mode lattice).

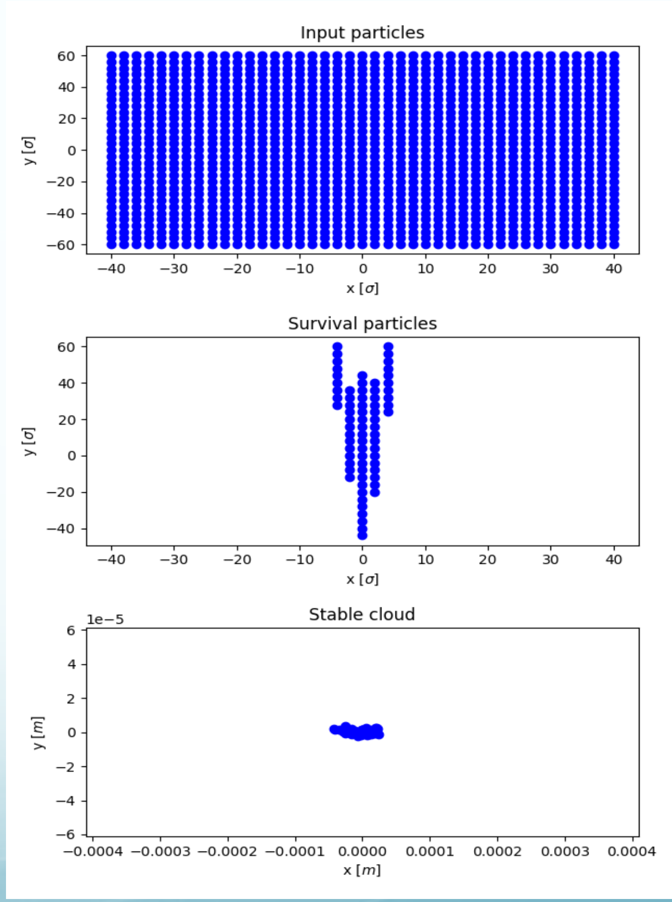
- *monochrom_h_4ip*



- *monochrom_v_1*



- *monochrom_mix*



Summary and Outlook

- ✓ The monochromatization IR optics design
- ✓ Chromaticity correction, tune correction and emittance check of monochromatization optics
- ✓ Luminosity and CM energy calculation in Guinea-Pig
- ✓ Single particle tracking and dynamic aperture particle tracking
- ➢ Dynamic aperture optimization is in progress
- ➢ Beam-beam calculation is in progress
- ➢ Monochromatization optics design for CEPC
- ➢ Experimental proof of monochromatization concept in running e^+e^- low energy colliders

Thanks for your attention!