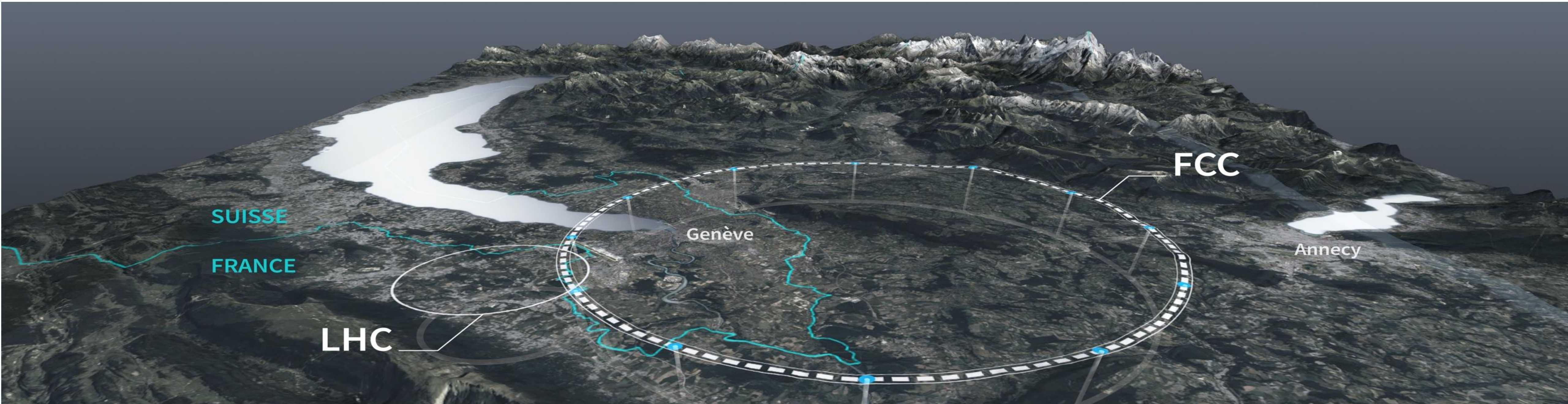

Monochromatization for the FCC-ee

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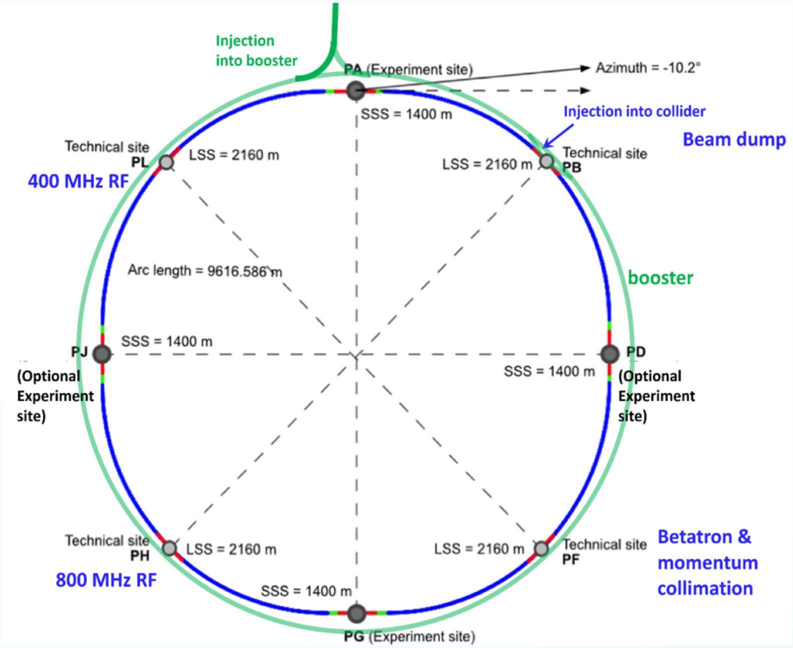
Outline

- Introduction and motivation
- Transverse Monochromatization Principle
- FCC-ee Monochromatization Optics Design
- Summary and Outlook

Introduction: Physics Requirements

- **FCC-ee modes:**
  - The FCC-ee standard modes:
    - Four different energy operation modes:

      $\boldsymbol{Z}$, $\boldsymbol{W^{\pm}}$, $\boldsymbol{Zh}$ **and** $\boldsymbol{t\bar{t}}$
  - The optional fifth mode: ***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.



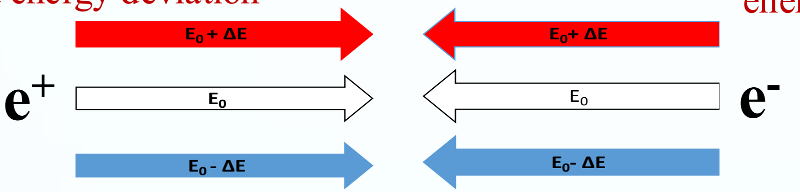
- **Requirements:**
  - Reduce the CM energy spread from 50 MeV to 5 MeV, which is comparable to the resonant width of the standard model Higgs Boson itself (4.2 MeV)

Transverse Monochromatization Principle

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

correlation between transverse spatial position and energy deviation

IP

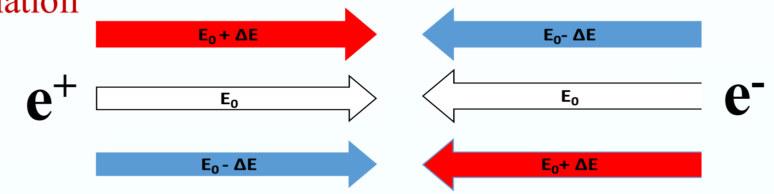


Monochromatization

$D^*_{x+} = - D^*_{x-} = D^*_x$
$D^*_{y+} = - D^*_{y-} = D^*_y$

Opposite correlations between transverse spatial position and energy deviation

IP



Dispersion function at the IP created by bending dipoles, when different from zero contribute to the beam size

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

Monochromatization factor

CM energy spread $\sigma_w = \sqrt{2}E_b\sigma_\delta$ $\quad$ $\sigma_w = \dfrac{\sqrt{2}E_b\sigma_\delta}{\lambda}$

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

Revolution frequency

Number of bunches

Particles per bunch

Luminosity $L_0 = \dfrac{k_b f_r N_+ N_-}{4\pi\sigma^*_{x\beta}\sigma^*_{y\beta}}$ $\quad$ $L = \dfrac{L_0}{\lambda}$

Betatronic beam sizes at the IP

Dispersive beam size at the IP

$$\sigma^*_{x,y} = \sqrt{\beta^*_{x,y}\epsilon_{x,y} + \left(D^*_{x,y}\sigma_\delta\right)^2}$$

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

Transverse Monochromatization principle

According to the formula of monochromatization factor, we can choose to introduce horizontal dispersion or vertical dispersion to the IP. Because the vertical beam size at the IP is much smaller than horizontal beam size, about ten times smaller vertical dispersion is needed to get the same monochromatization factor compared with the horizontal one.

Parameters	Unit	Horizontal Dispersion	Vertical Dispersion
Beam energy(E)	GeV	62.5	
Horizontal, vertical emittance($\varepsilon_{x,y}$)	nm	0.51, 0.002	
Energy spread(σ_δ)	%	0.052	
Beam length(σ_δ)	mm	3.3	
IP Beta function($\beta^*_{x,y}$)	mm	90, 1	
IP RMS beam size ($\sigma_{x,y}$)	μm	55, 0.045	
Crossing Angle(θ_c)	mrad	30	
Vertical beam-beam parameter(ξ_y)	/	0.106	
Beam current(I_0)	mA	395	
Bunch population(N_b)	10^{11}	0.6	
Bunches per beam(n_b)	/	13420	
IP Dispersion ($D^*_{x,y}$)	m	0.105	0.01
Monochromatization factor (λ)	/	8.1209	11.6705

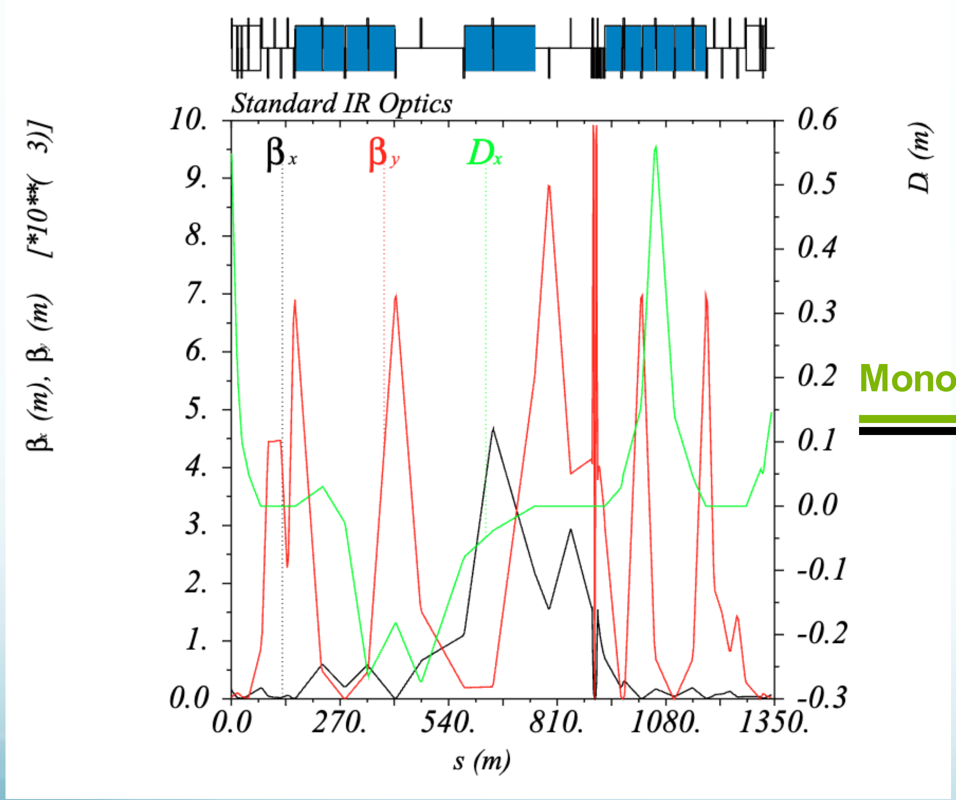
Monochromatization factor

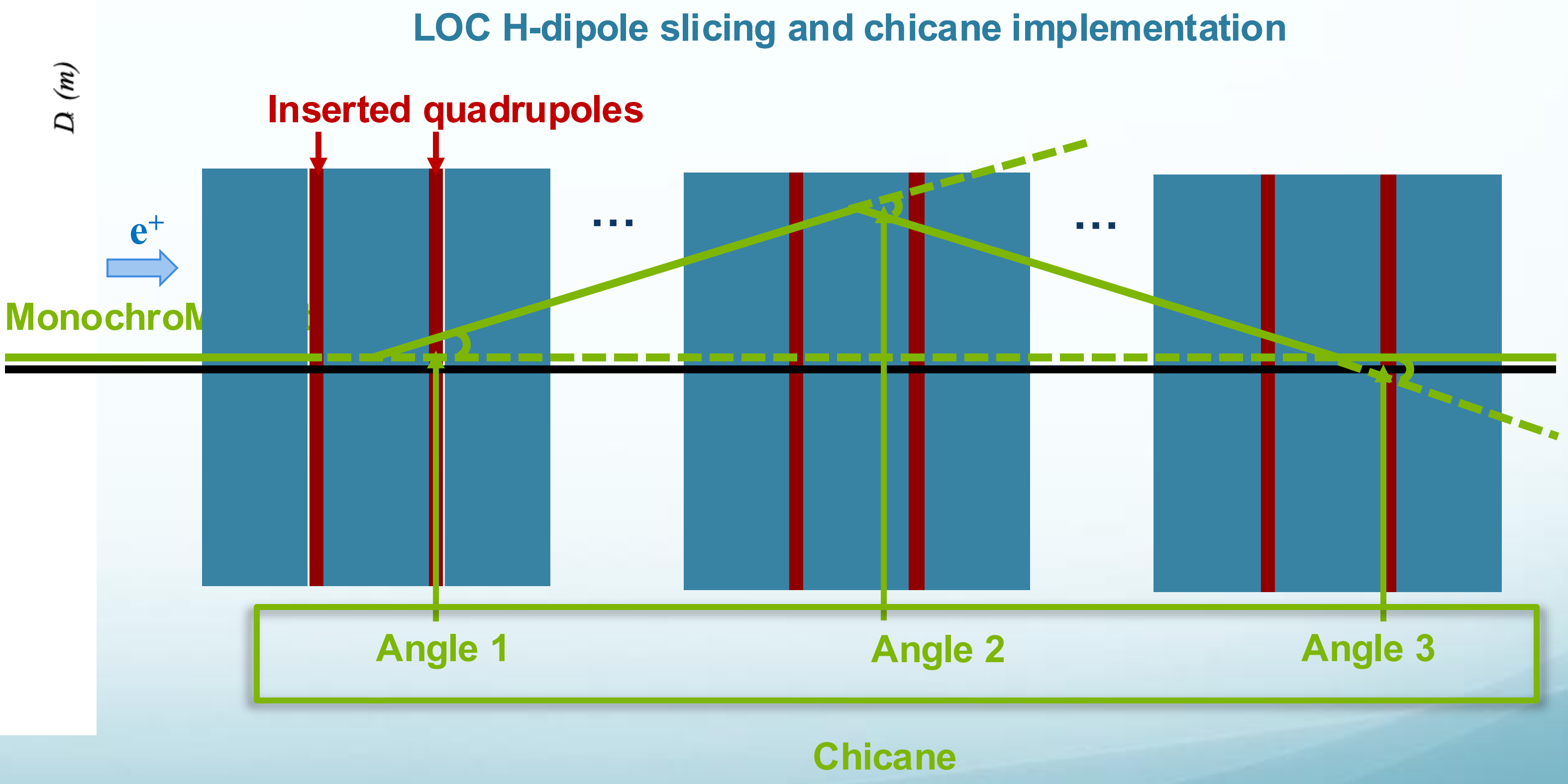
$$\lambda = \left(1 + \sigma_\delta^2 \left(\frac{D_x^{*2}}{\sigma_{x\beta}^{*2}} + \frac{D_y^{*2}}{\sigma_{y\beta}^{*2}}\right)\right)^{1/2}$$

Parameters checked analytically

- ## 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.

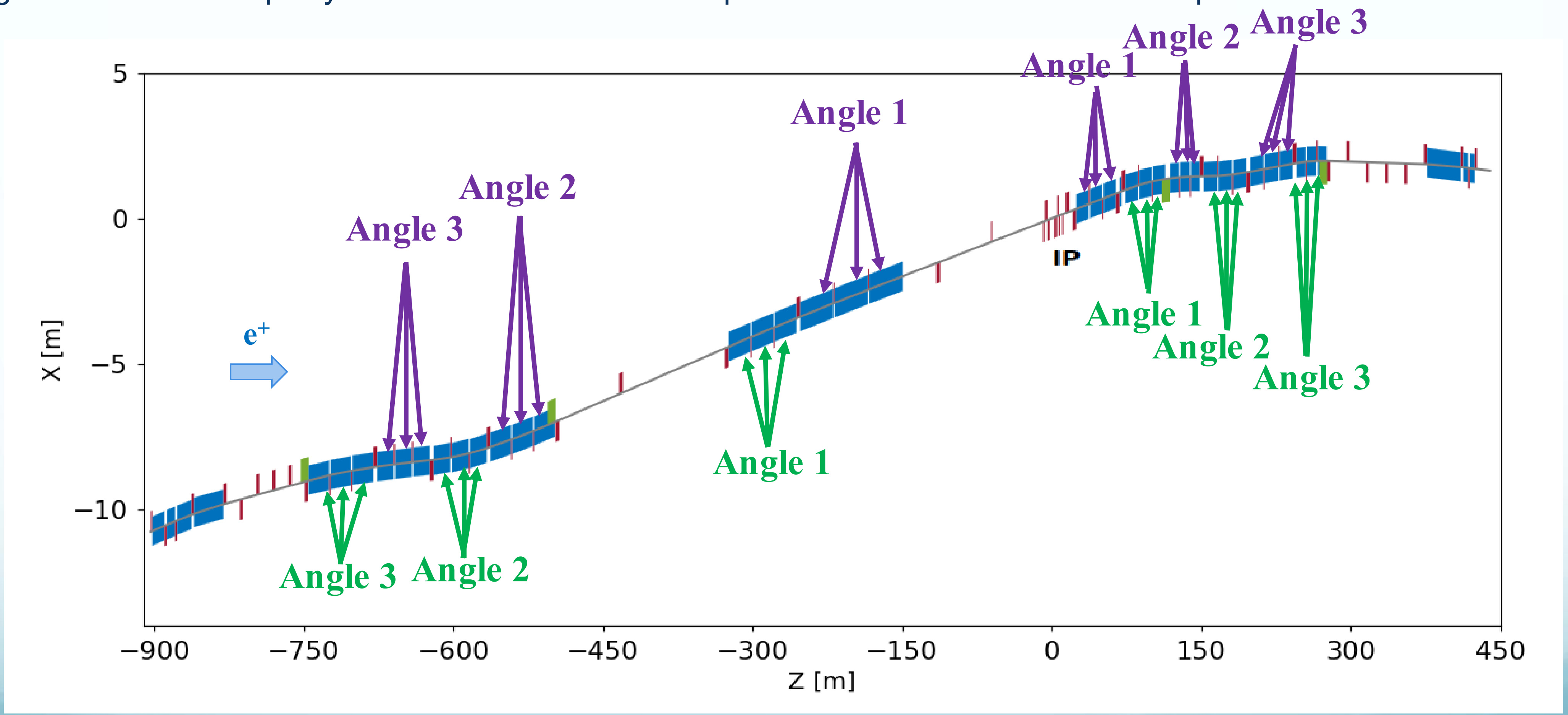




FCC-ee Monochromatization IR Optics Design

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

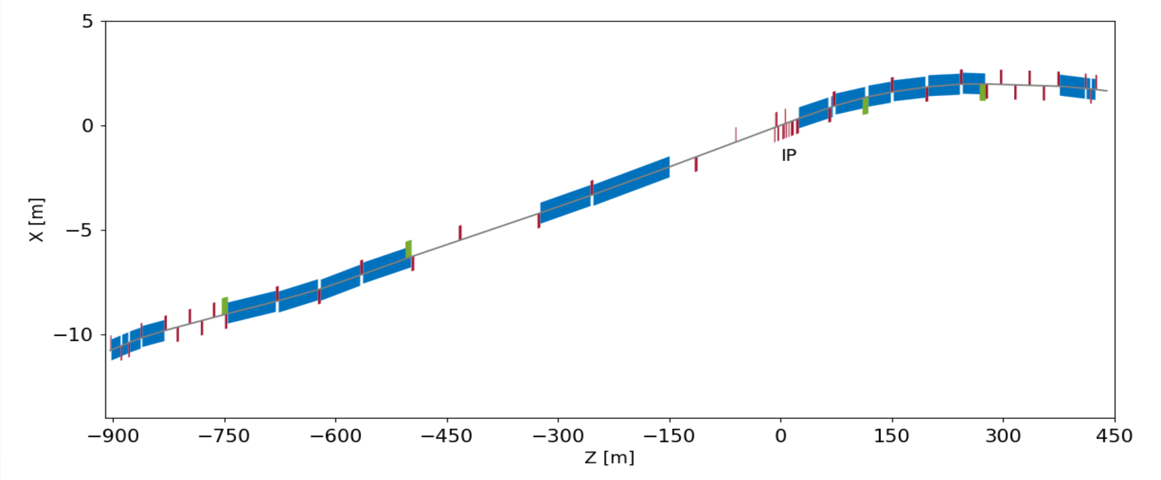
To mitigate horizontal emittance blowup[3], two long chicanes are implemented to each upstream and downstream. And each angle of chicane is equally distributed to all the three pieces of each LOC horizontal dipole.

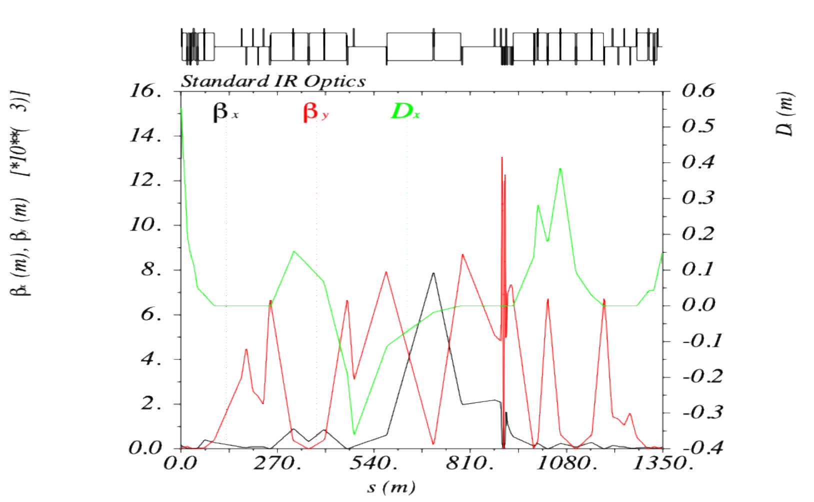


[3] Z.Zhang, A. Faus-Golfe, F. Zimmermann et al. "Monochromatization optics for FCC-ee lattices", CEPC Workshop 2023, https://indico.ihep.ac.cn/event/19316/contributions/142896/

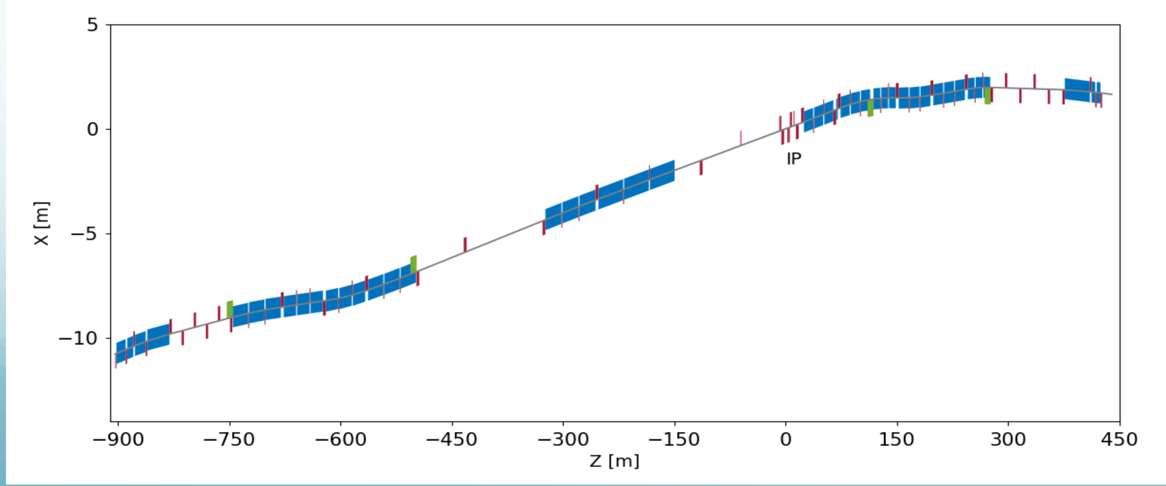
FCCee Monochromatization optic design

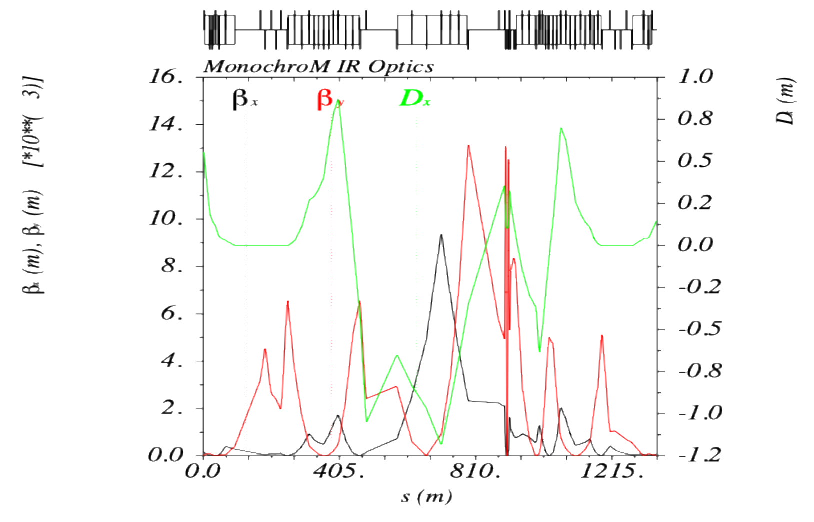
- **Comparison between Standard Survey and Monochromatization Survey**
  - Standard Survey Plot





  - Monochromatization Survey Plot



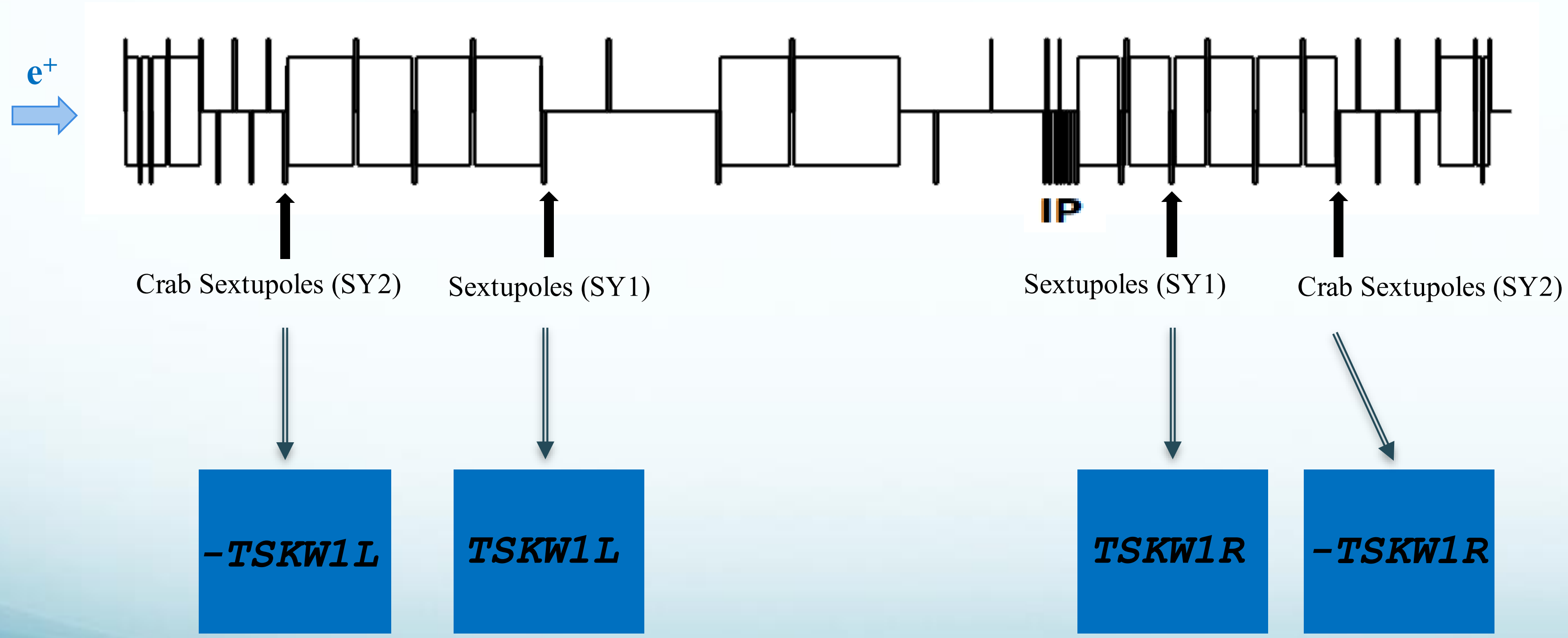


FCC-ee Monochromatization IR Optics Design

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

Since 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.



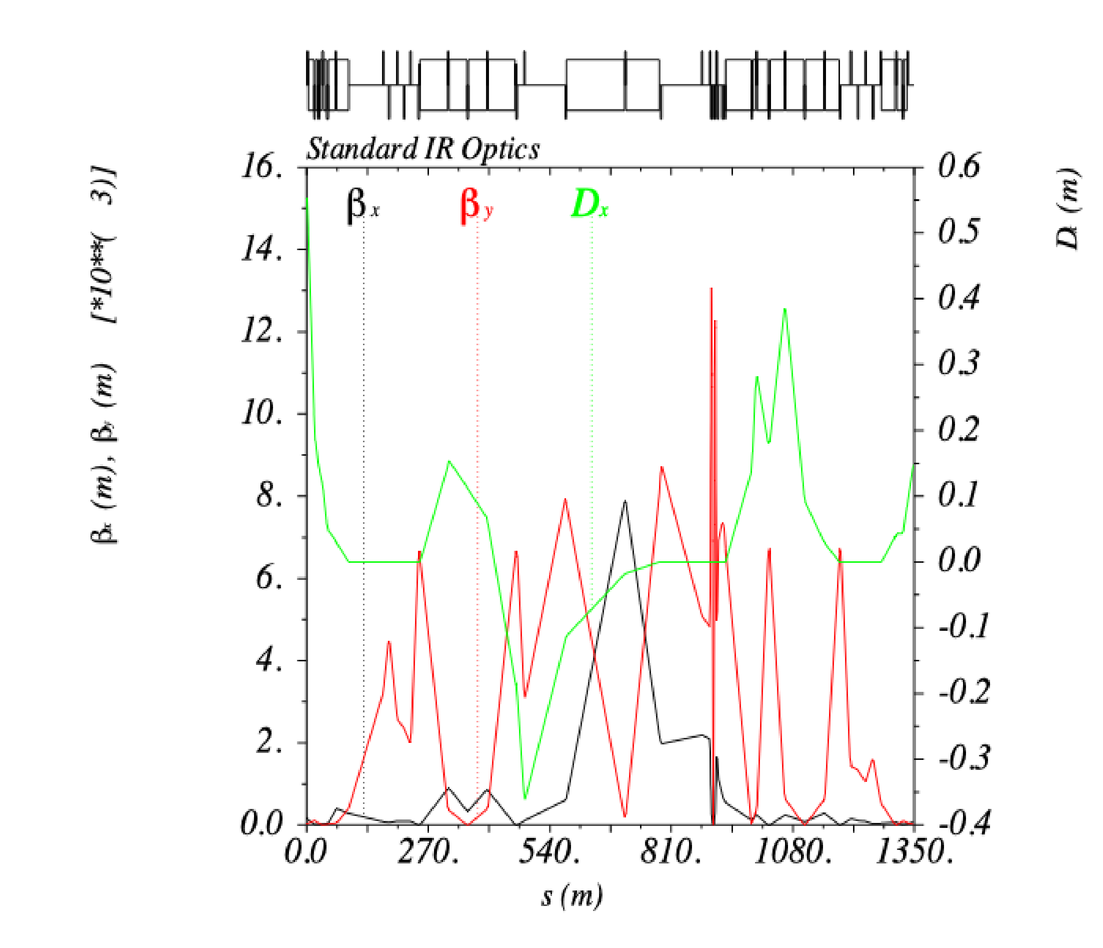
Monochromatization factor

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

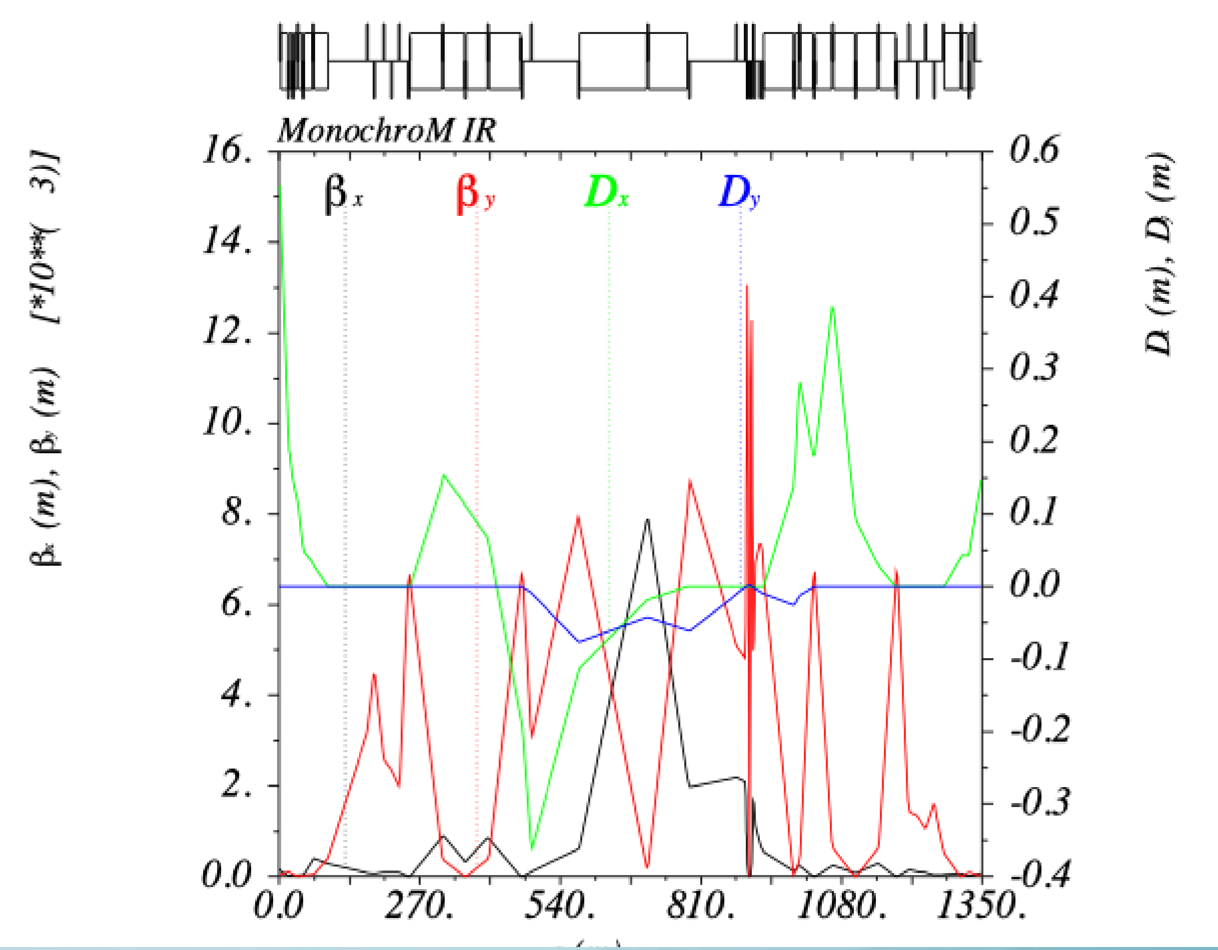
FCC-ee Monochromatization IR Optics Design

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

  - $D^*_y = 0$ mm



  - $D^*_y = 1$ mm

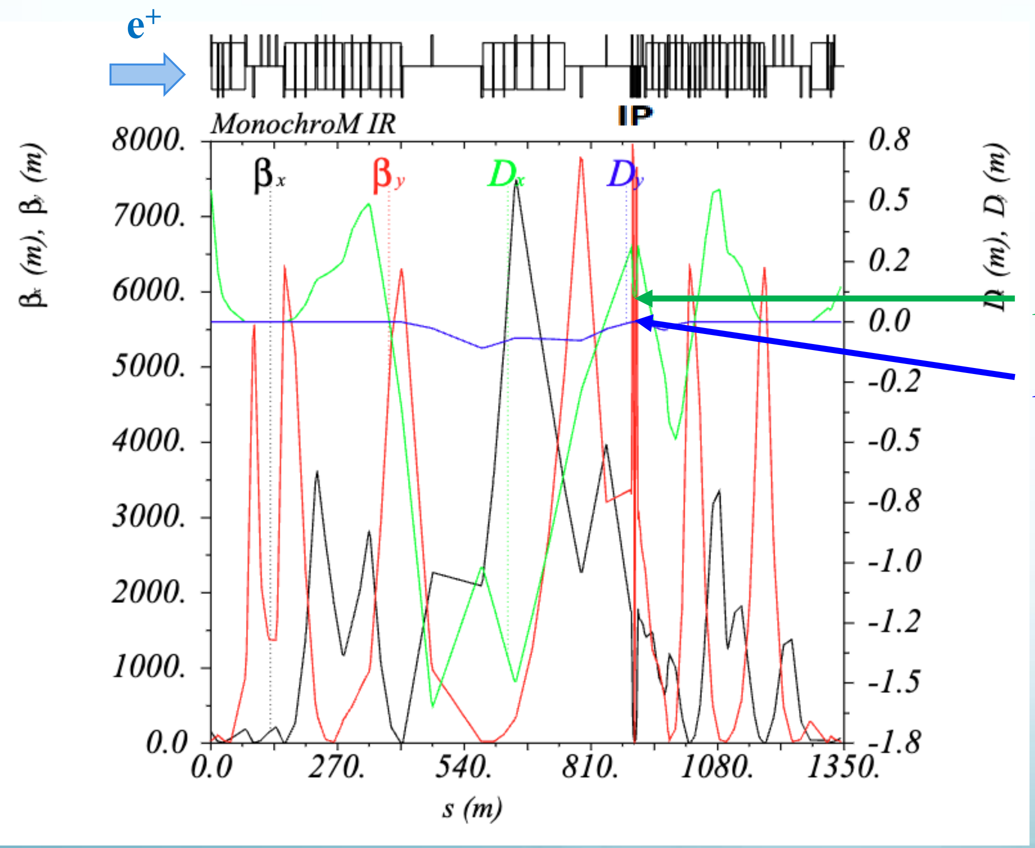


FCC-ee Monochromatization IR Optics Design

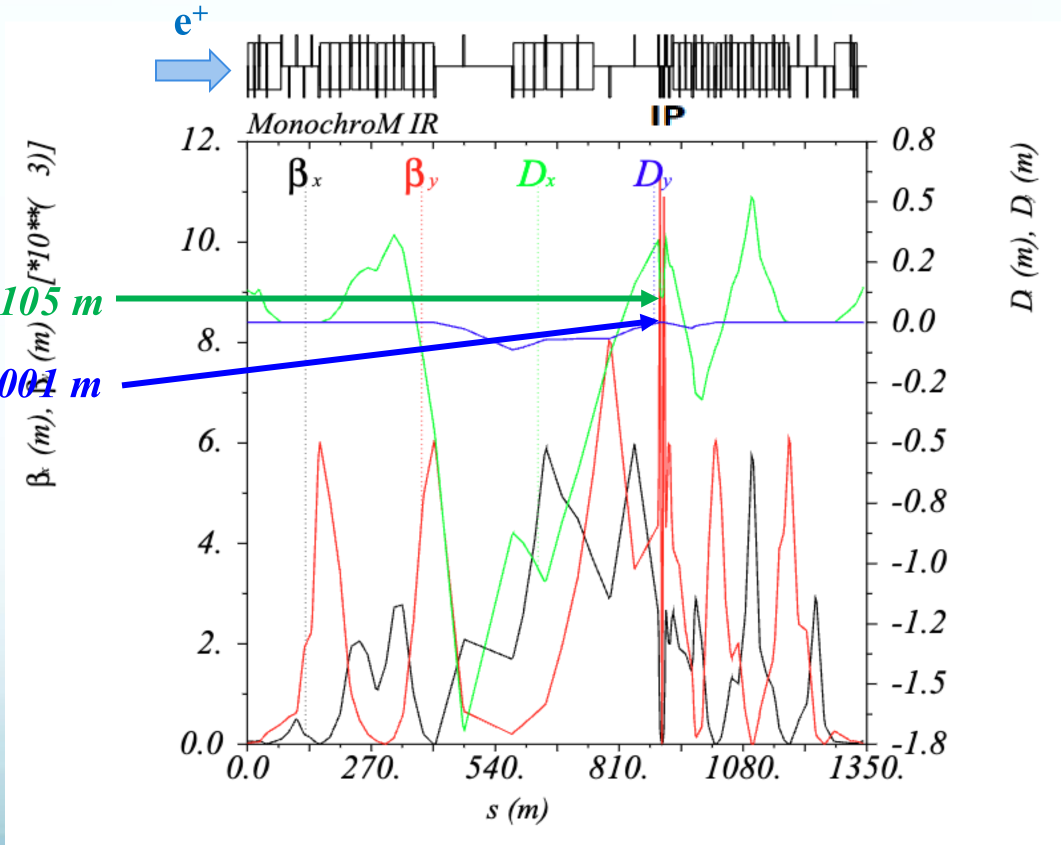
- **Scheme and Optics Design of Mixing Dispersion Generation**

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*



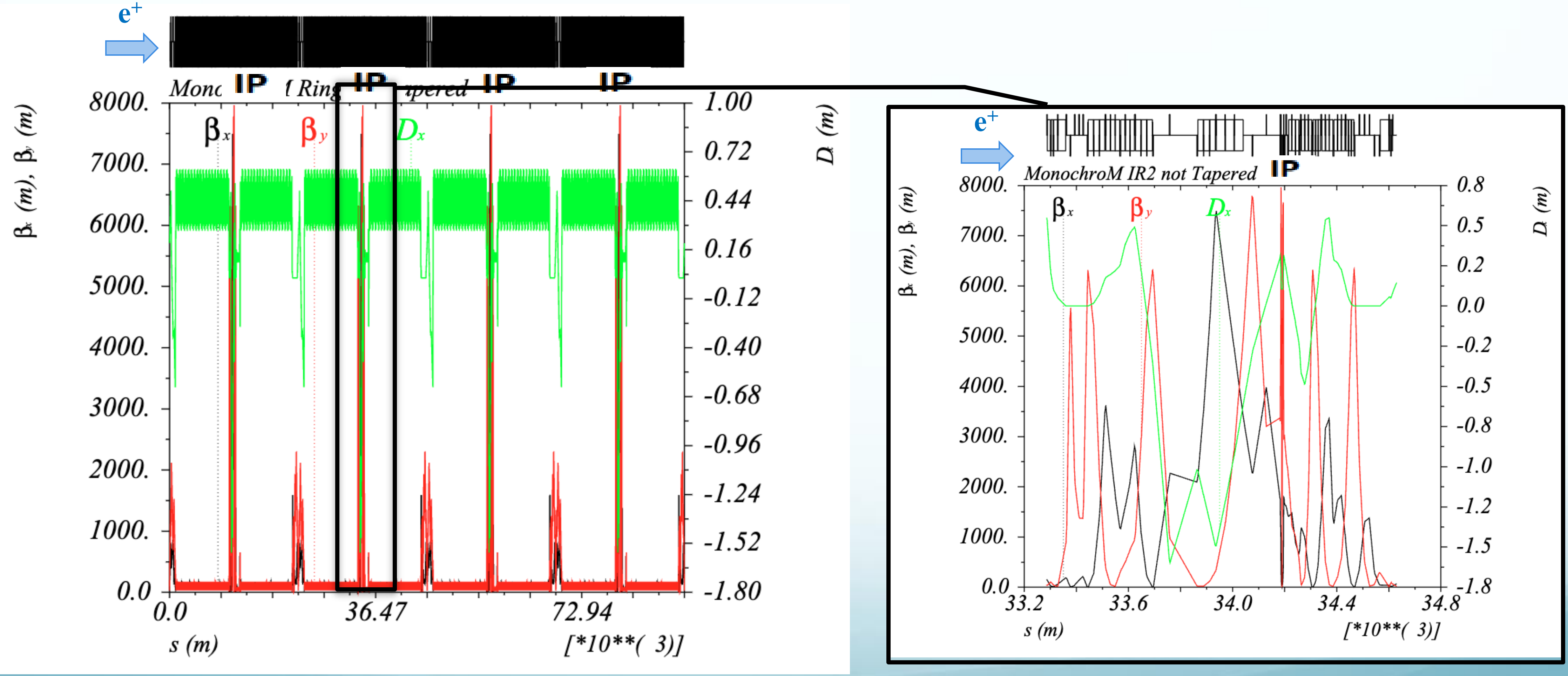
D^*_x= 0.105 m

D^*_y= 0.001 m

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

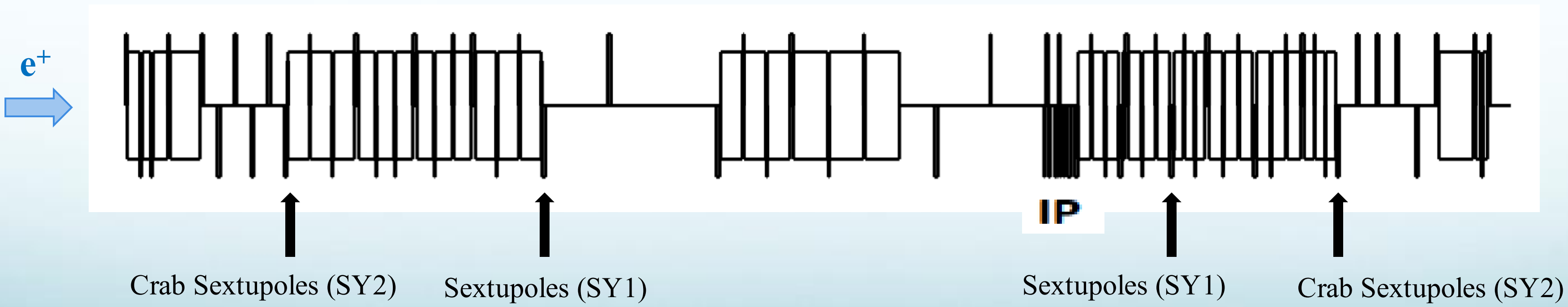
- **Local Chromaticity Correction**
  - Load monochromatization ring lattice, and extract sequence from IP to crab sextupoles.
  - Turned off all the sextupoles including crab sextupoles SY2.
  - Match the vertical chromaticity from IP to crab sextupoles to 0 using the sextupoles SY1.
  - Calculate the 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.

Performance Check of FCC-ee MonochroM Optics

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

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

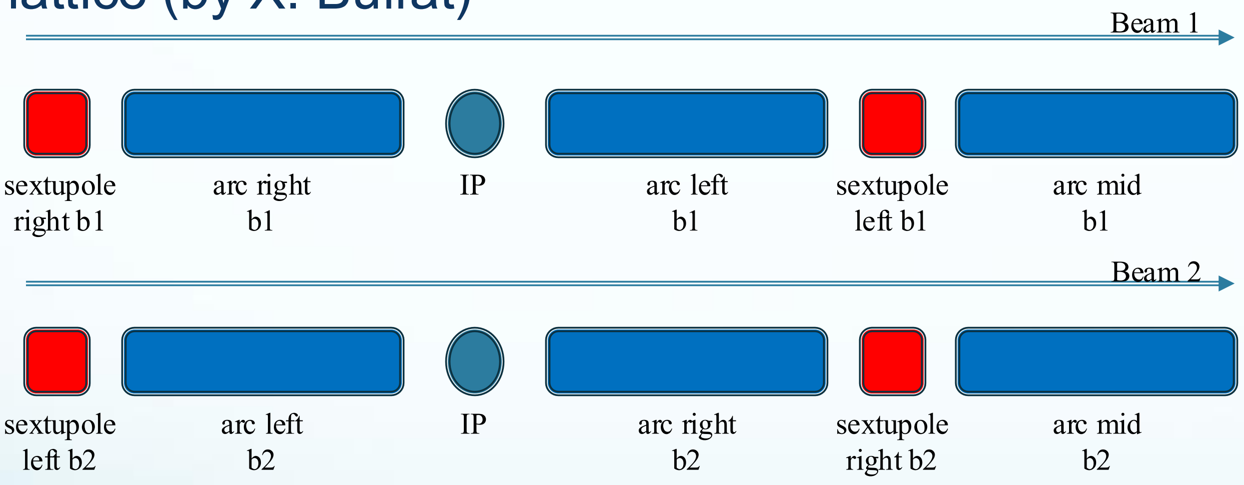
Parameters		Standard ZES V22	MonochroM ZH V22	MonochroM ZV V22	MonochroM ZHV V22
RMS CM energy spread σ_w (with crab cavity)	[MeV]	26.8	25.25	20.58	24.4
Luminosity per IP (with crab cavity)	[10^{34}cm^{-2}s^{-1}]	15.0	1.46	1.42	18.4

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

Parameters		Standard TES V22	MonochroM TH V22	MonochroM TV V22	MonochroM THV V22
RMS CM energy spread σ_w (with crab cavity)	[MeV]	27.10	20.23	21.24	20.23
Luminosity per IP (with crab cavity)	[10^{34}cm^{-2}s^{-1}]	17.9	1.37	1.42	1.37

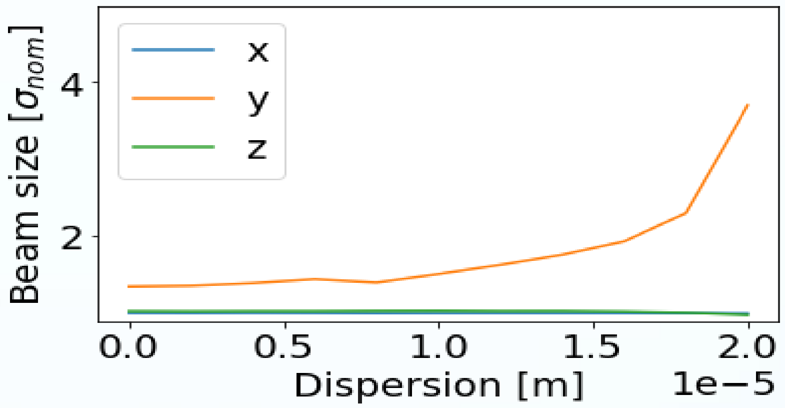
Ongoing beam-beam studies

- Performed with Xsuite using a simplified perfect lattice (by X. Buffat)

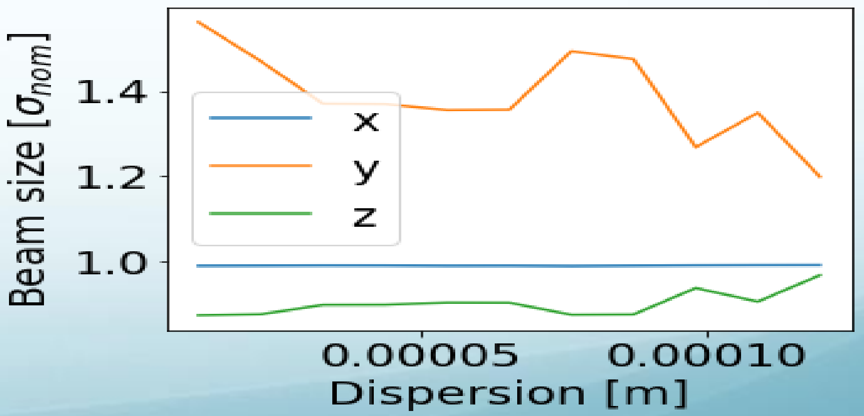


It doesn't take into account all the lattice effects

- Vertical dispersion



- Horizontal dispersion



Summary and Outlook

IR Monochromatization Optics design

- ✓ The monochromatization IR optics design for positron
- ✓ Implementation of the monochromatization IR optics in the whole ring
- ✓ Chromaticity correction, tune correction, and emittance check
- ➢ Optimization of emittance, dynamic aperture, and luminosity in progress

Beam-beam studies

- ✓ Preliminary studies of dispersion implementation effects
- ➢ Analysis of already obtained data from the simulations
- ➢ Extending the simulations to a wider range of dispersion
- ➢ Setting the weak-strong model to introduce the lattice effects

Thanks for you attention!