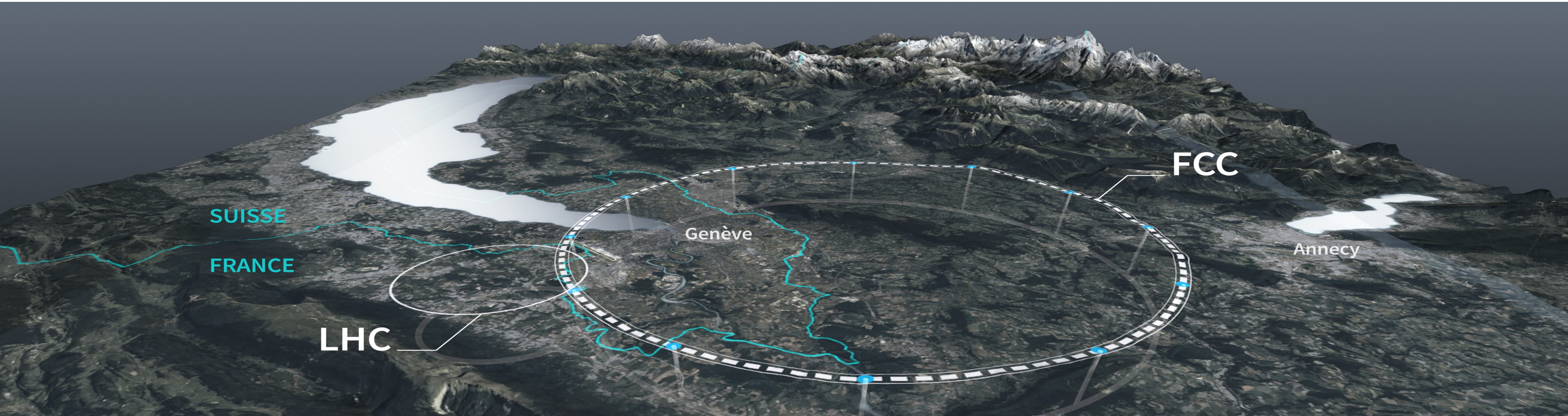

Monochromatization Optics for FCC-ee Lattices

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CEPC Workshop 2023

25 October 2023

Outline

- Introduction: Physics Requirements
- Transverse Monochromatization Principle
- FCC-ee Monochromatization Self-consistent Parameters
- FCC-ee Monochromatization Schemes
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  - Symmetric
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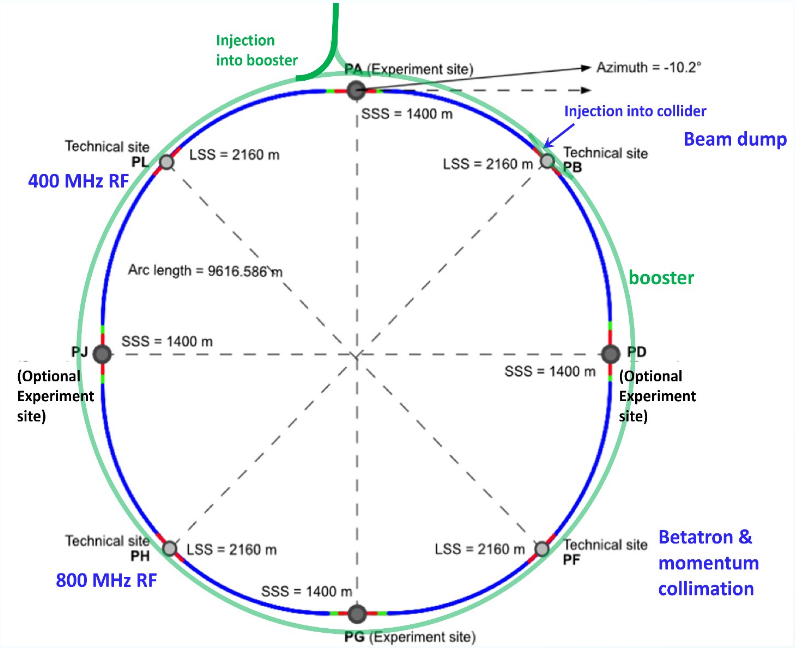
  - Symmetric
- Summary and Outlook

Introduction: Physics Requirements

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

      Z, $W^{\pm}$, Zh **and** $t\bar{t}$
  - 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.



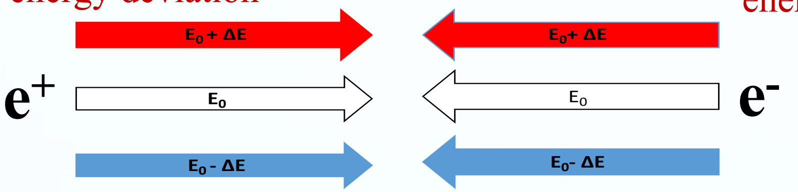
- **Requirements:**
  - Reduce the CM energy spread from 50 MeV to 5 MeV, which is comparable to the resonant width of the standard model Higgs Boson itself (4.2 MeV)

Transverse Monochromatization Principle

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

correlation between transverse spatial position and energy deviation

IP



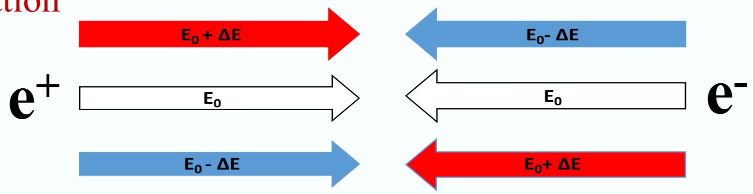
Monochromatization

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

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

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

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

Monochromatization factor

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

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

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

Revolution frequency

Number of bunches

Particles per bunch

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

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

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 increase of the relative frequency of the events at the center of of the distribution but **luminosity loss !!!!**

Monochromatization Self-consistent Parameters

Taking into account the baseline optics layout and parameters of the FCC-ee, featuring a large crossing angle of 30 mrad at the IP, a parametric study of monochromatization for FCC-ee has been made at 125 GeV collision energy. The results calculated with the simulation code Guinea-Pig are summarized below.

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	0.001
Monochromatization factor (λ)	/	8.1209	11.6705

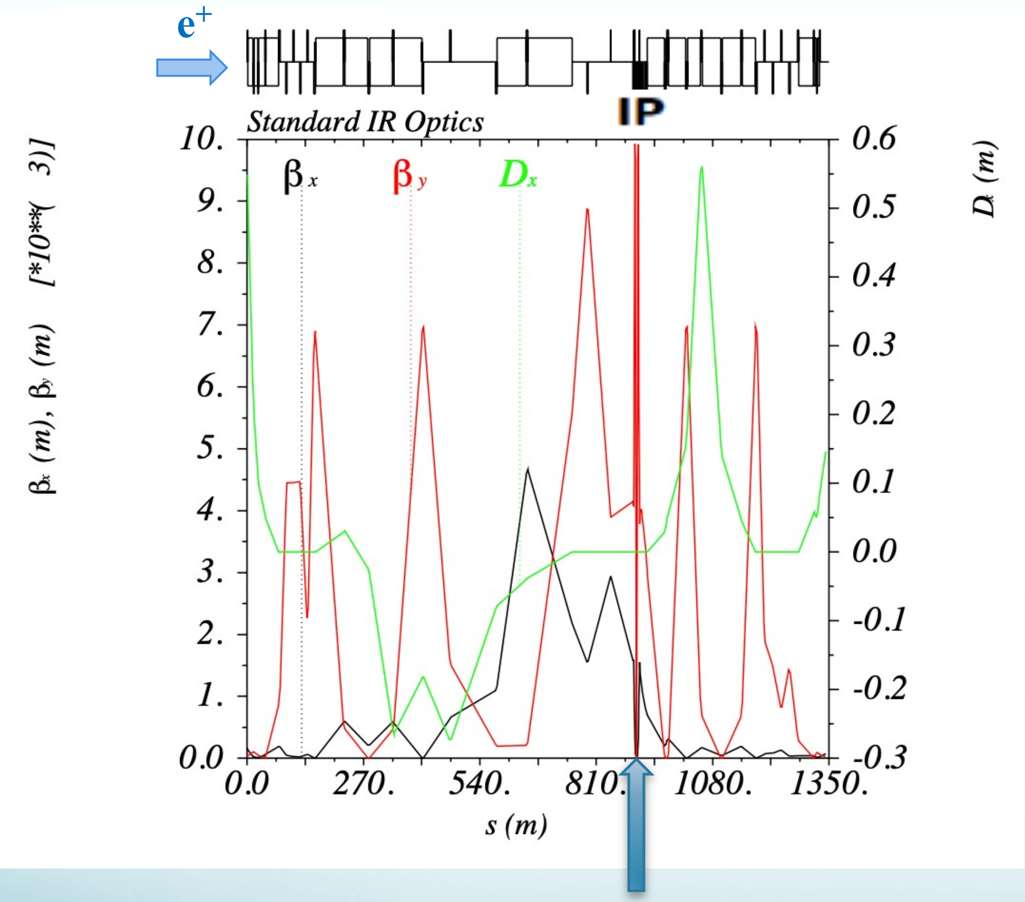
Monochromatization factor

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

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.

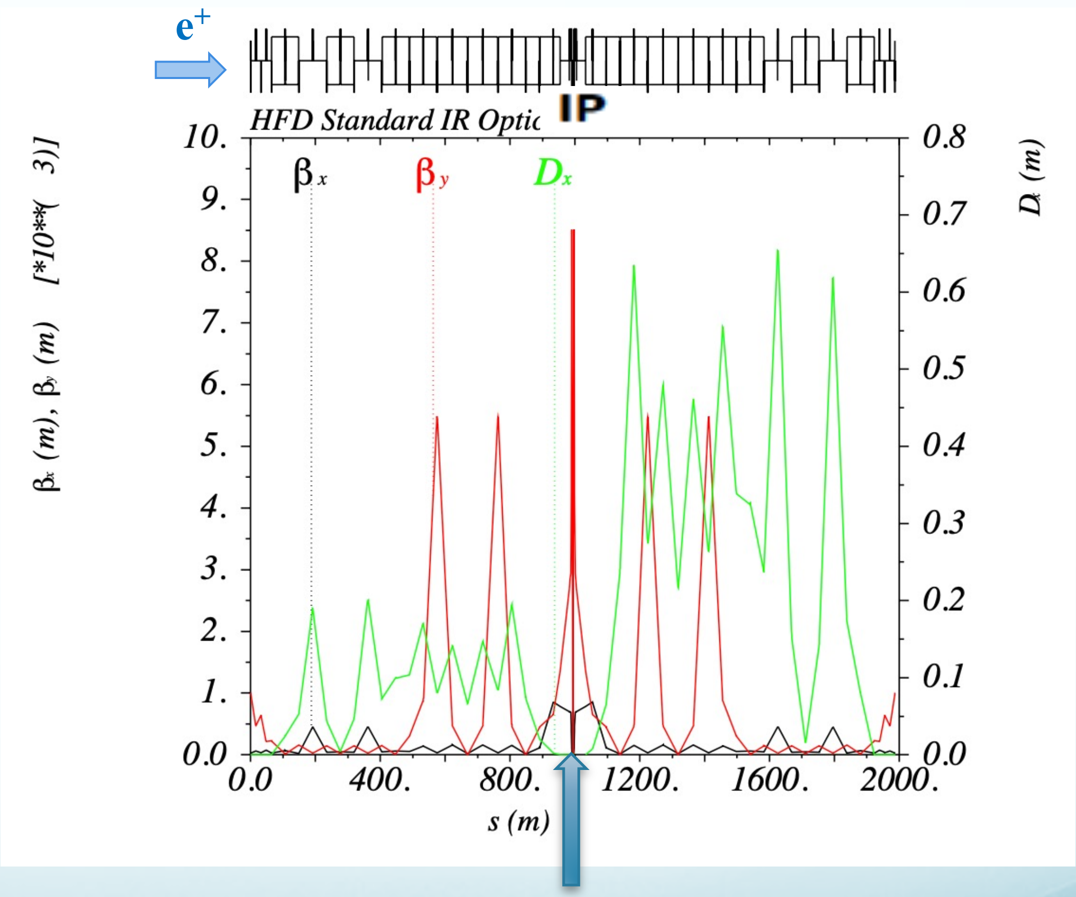
FCC-ee Monochromatization Schemes

Scheme for Asymmetrical Standard IR Optics (K. Oide)



Creating horizontal dispersion (D^*_x = 0.105 m)

Scheme for Symmetrical Standard IR Optics (P. Raimondi)

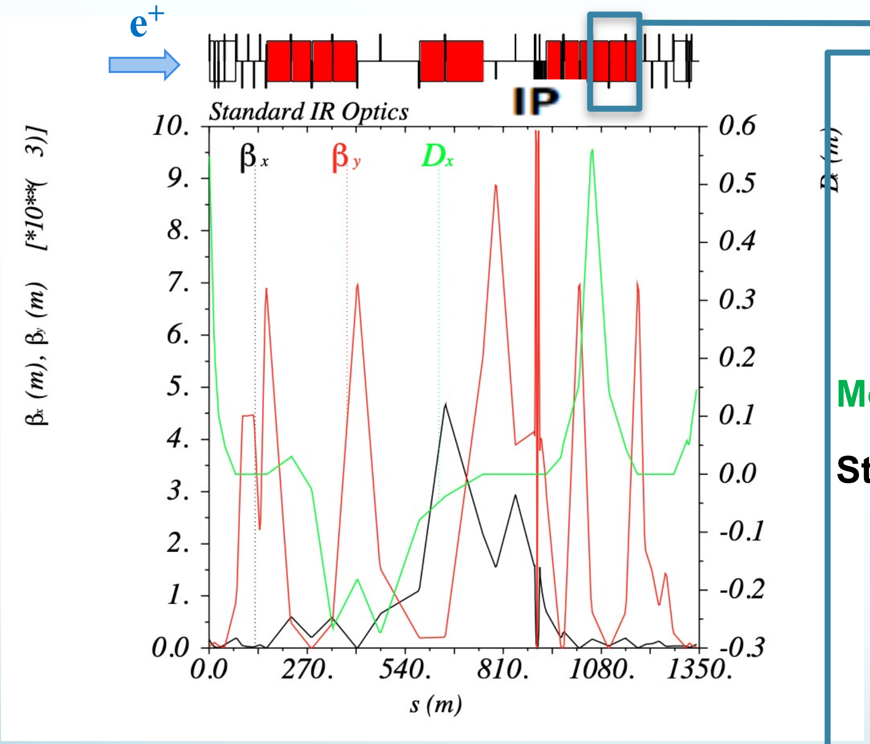


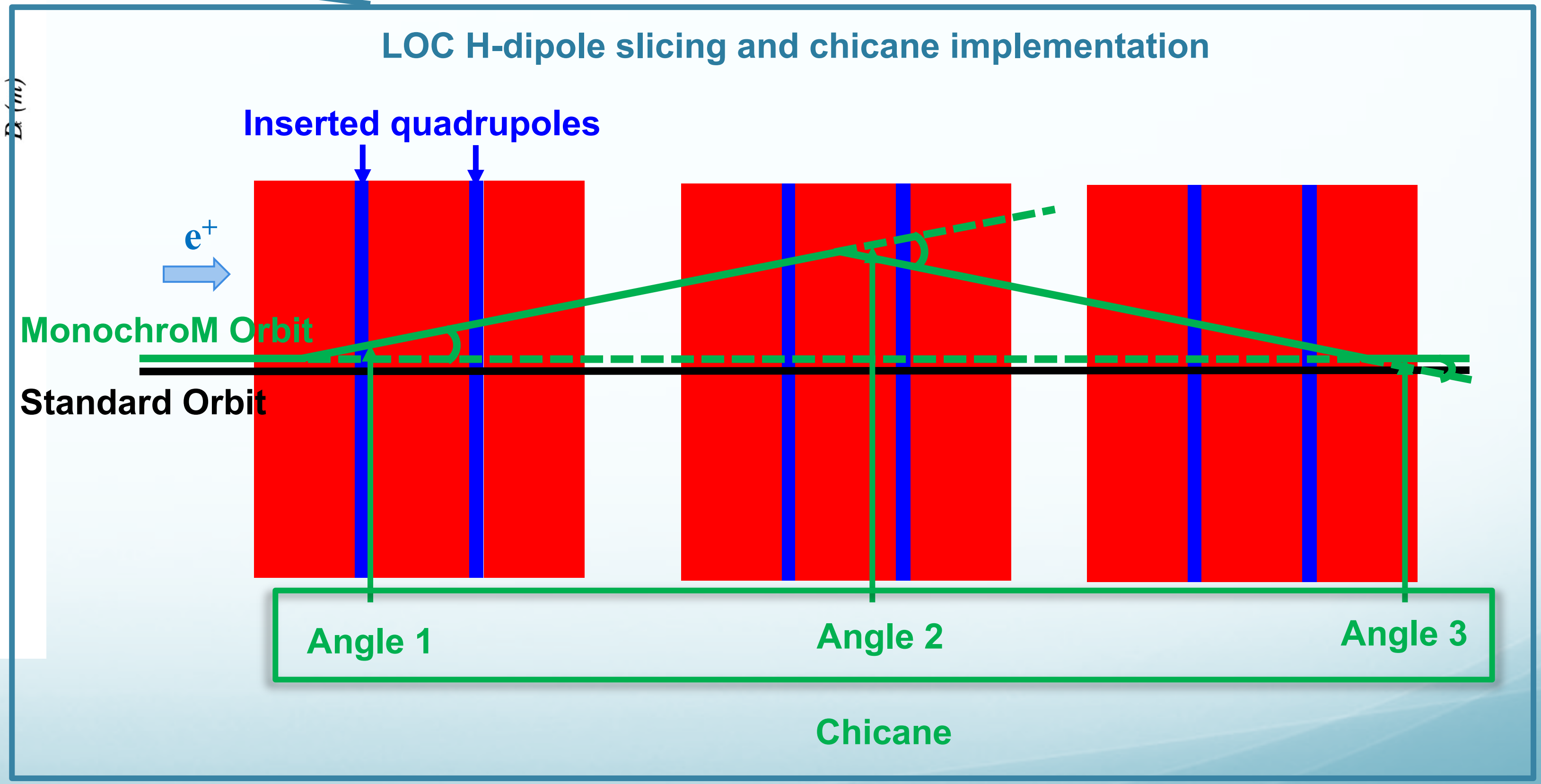
Creating vertical dispersion (D^*_y = 0.001m)

Asymmetrical Monochromatization IR Optics Design

- **Scheme for Asymmetrical IR Optics**

All local vertical chromaticity horizontal dipoles (LOC H-dipole) in standard IR Optics are cut into three pieces and quadrupoles are inserted between them. 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.

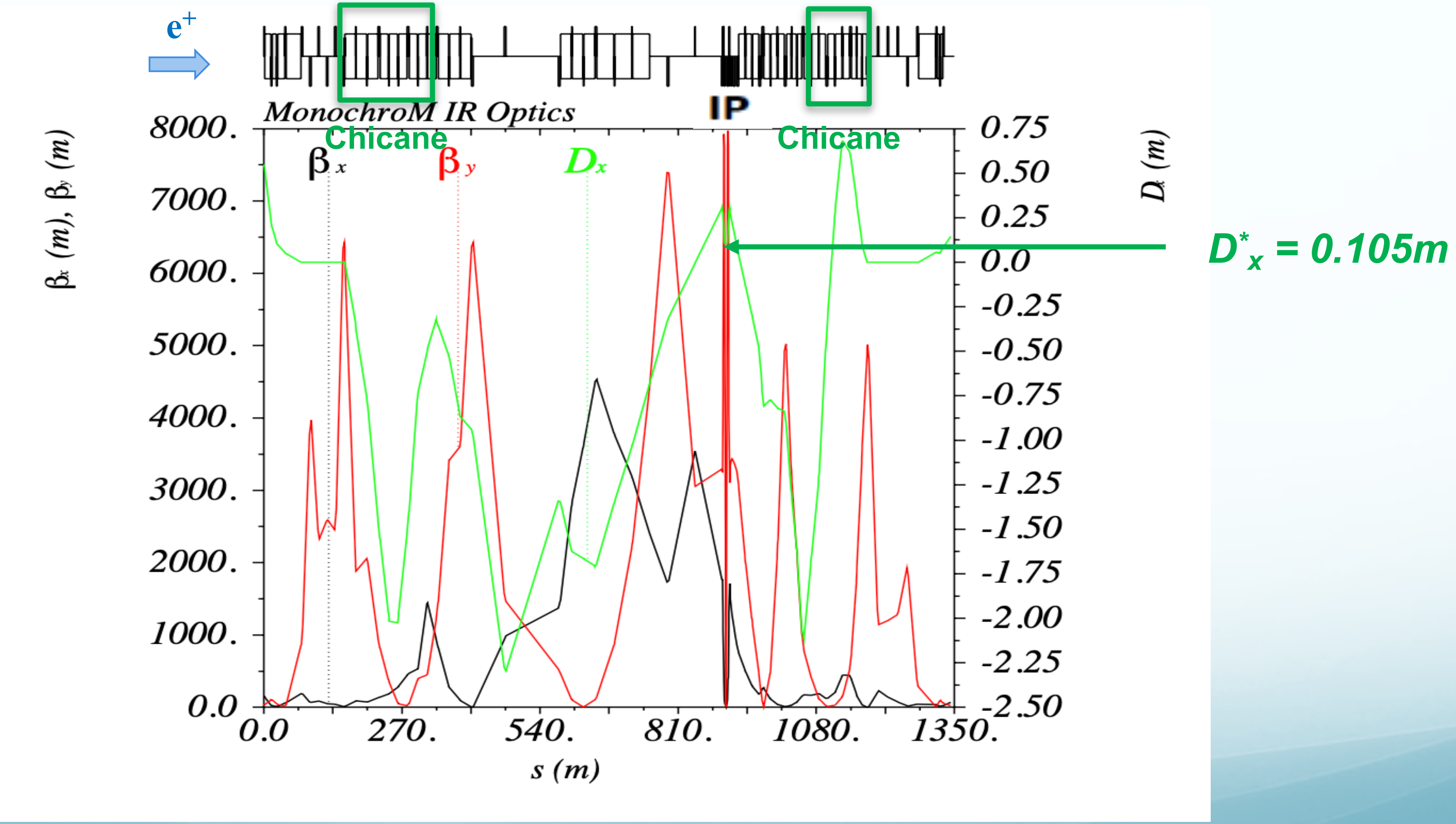




Asymmetrical Monochromatization IR Optics Design

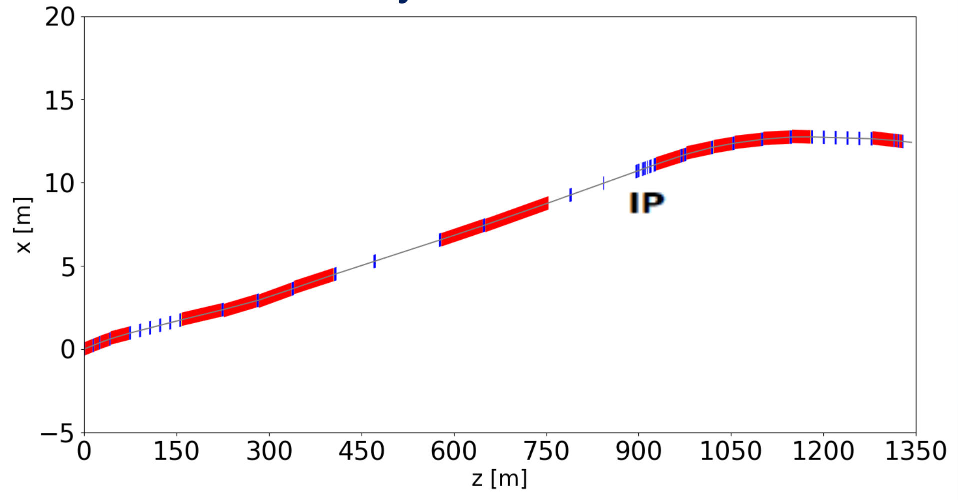
- **Asymmetrical Monochromatization IR Optics**

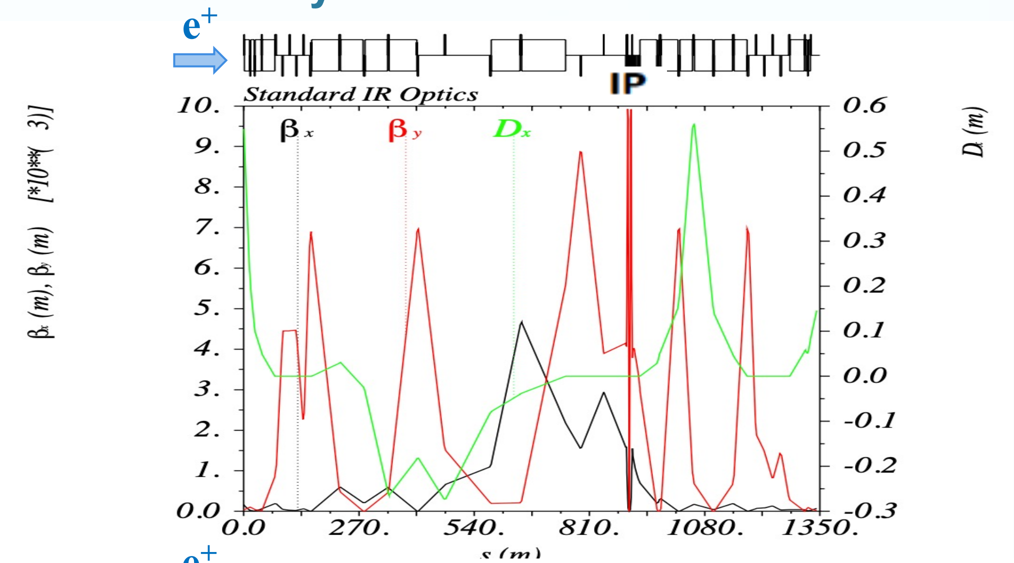
The beam parameters at the IP are matched to be same with the FCC-ee monochromatization self-consistent parameters and the beam parameters at the entrance and exit of the IR are same with those of standard mode.



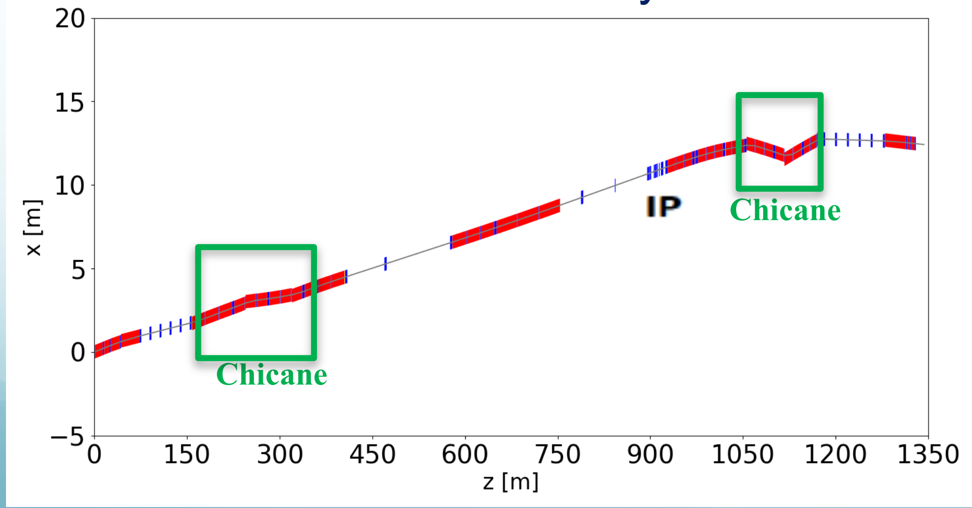
Asymmetrical Monochromatization IR Optics Design

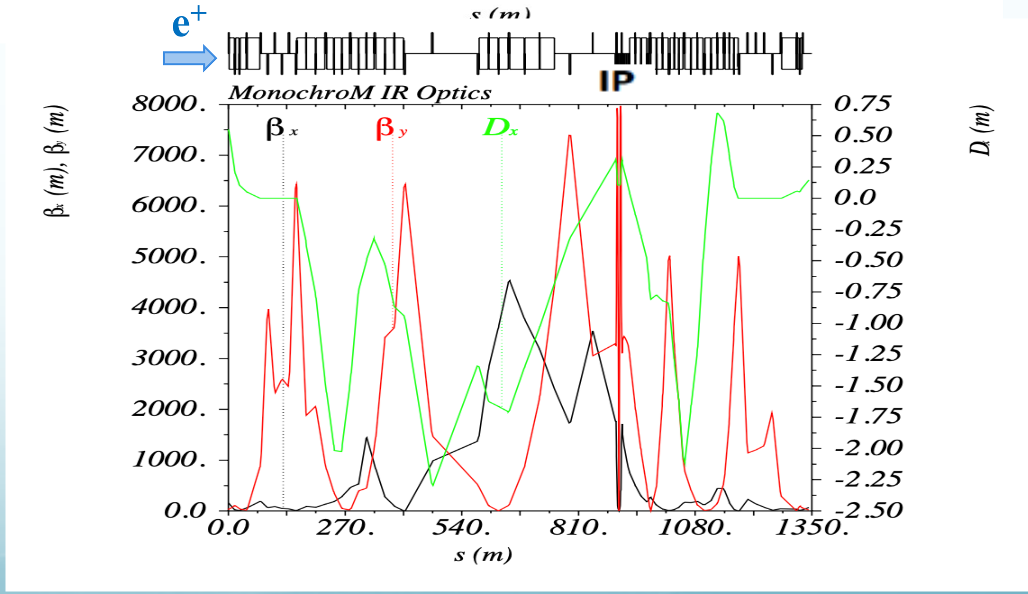
- **Comparison between Standard Survey and Monochromatization Survey**
  - Standard Survey Plot





  - Monochromatization Survey Plot



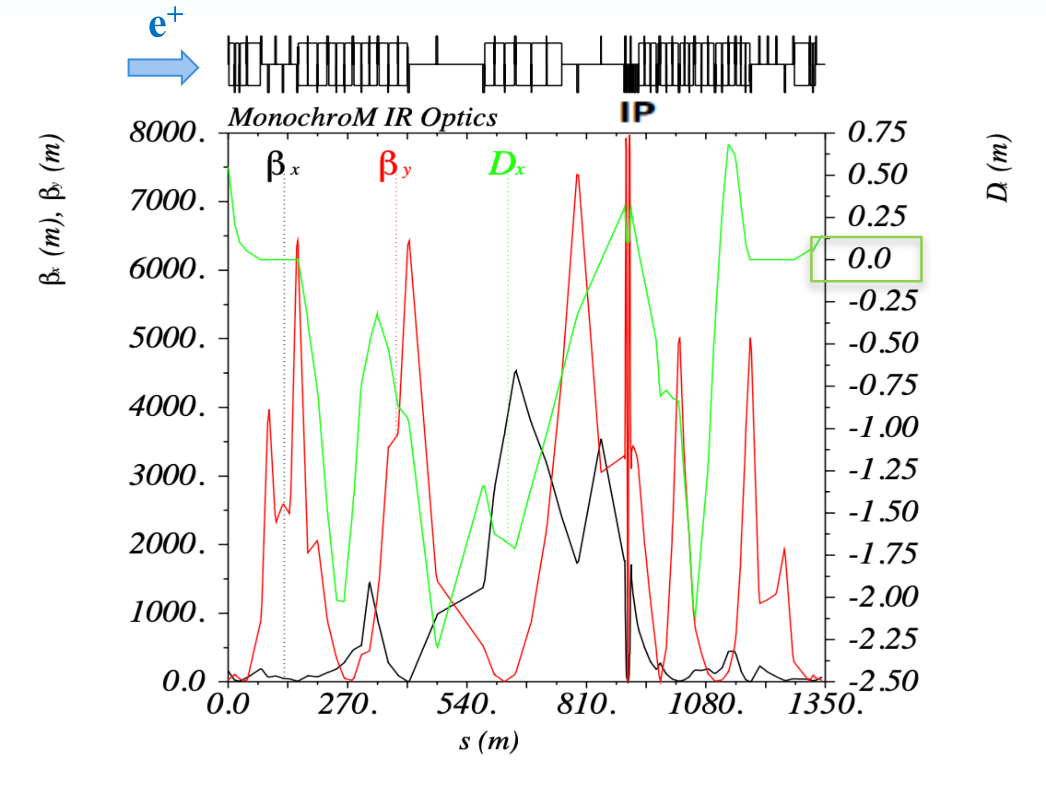


Asymmetrical Monochromatization IR Optics Design

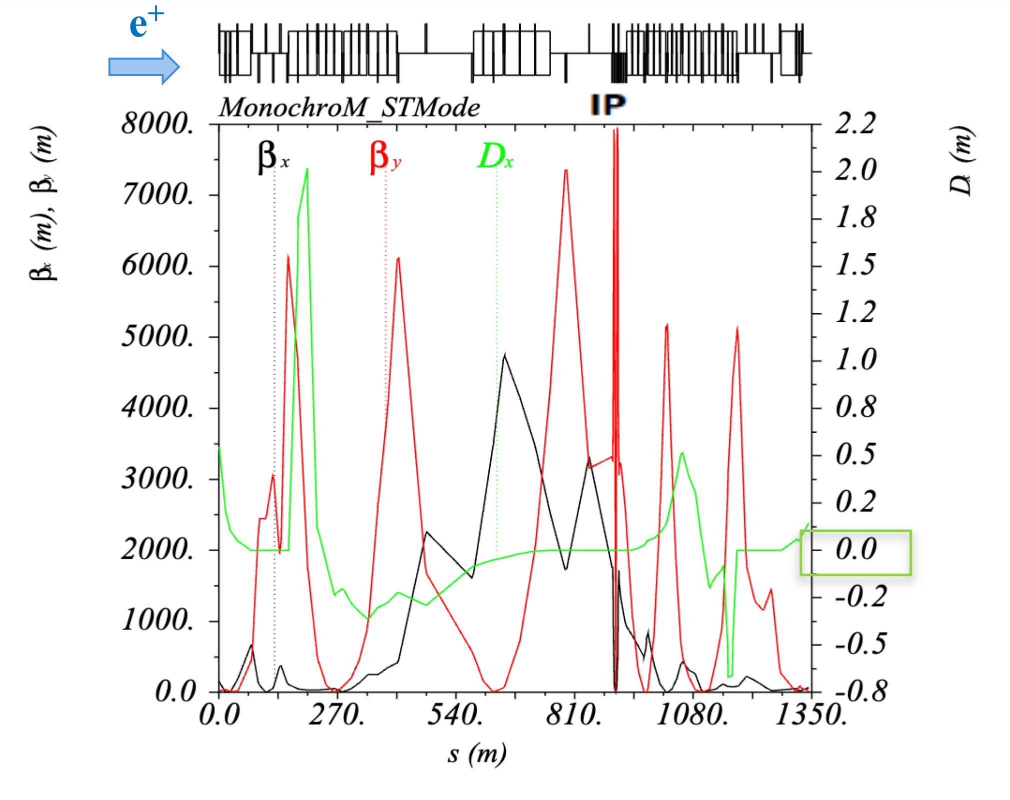
- **Standard Mode with Monochromatization orbit**

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.

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



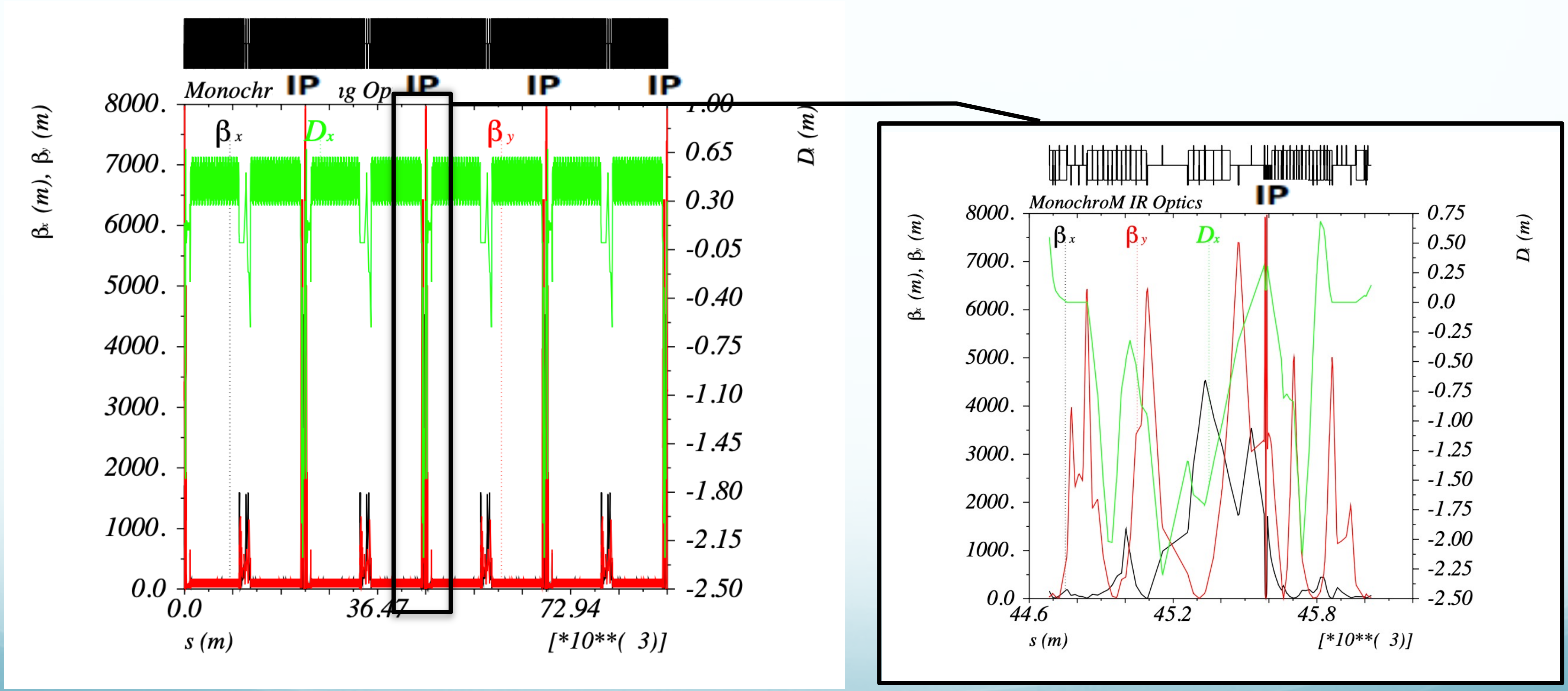
- $D^*_x = 0$ Standard mode



Asymmetrical 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.



Asymmetrical Monochromatization Ring Optics

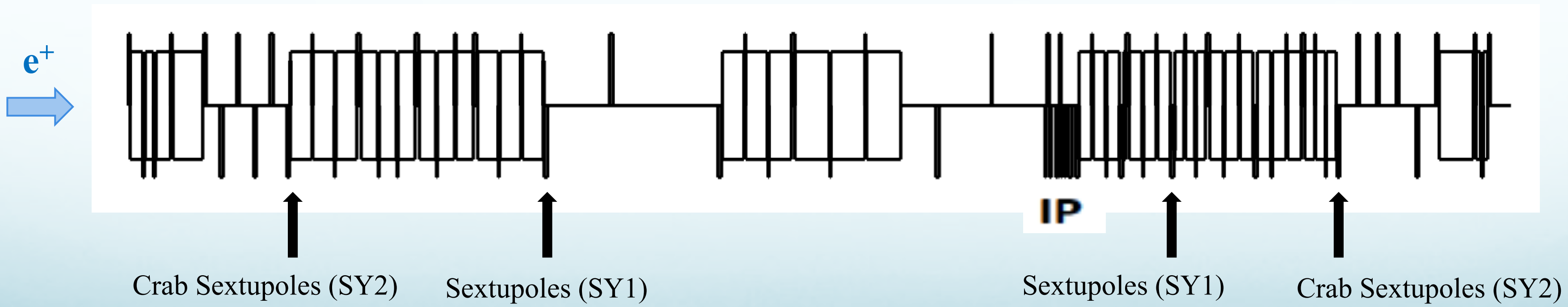
- **Local Chromaticity Correction**
  - Load monochromatization ring lattice, and extract sequence from IP to crab sextupole.
  - Turned off all the sextupoles including crab sextupoles SY2.
  - Match the vertical chromaticity from IP to crab sextupoles to 0 using the sextupoles SY1.
  - Calculate the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



Asymmetrical 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 214.27 and 214.3900332 same as the standard mode while keeping the beam parameters at the IRs.

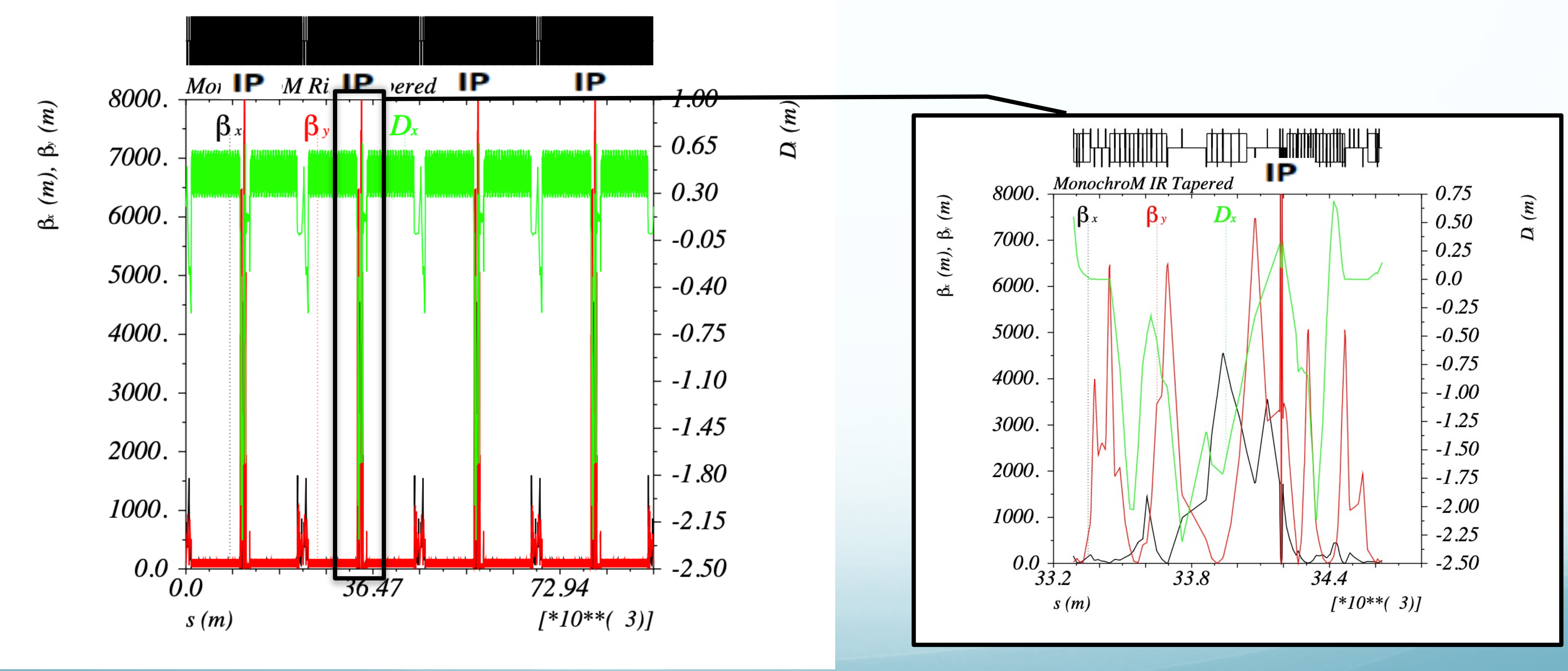
- **Emittance Check**

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.

Asymmetrical Monochromatization Ring Optics

- **Emittance Check**

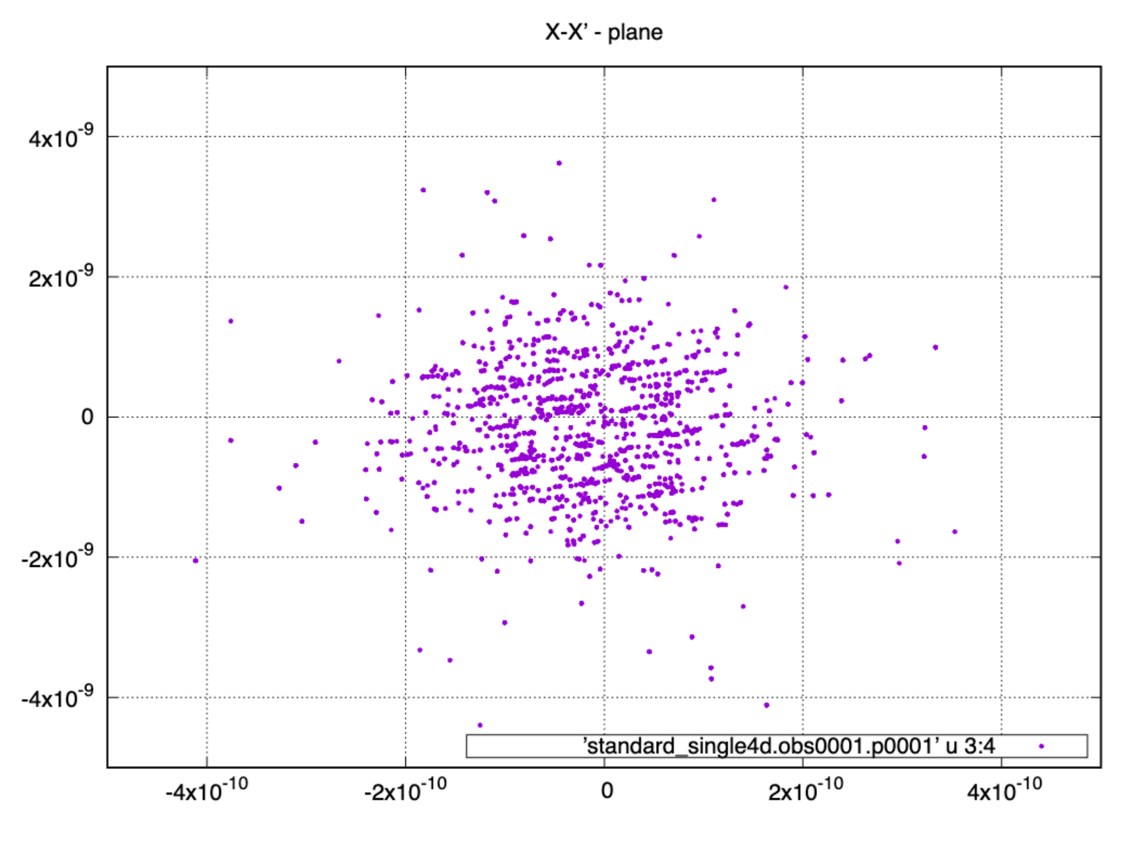
The beam parameters are same with those parameters before tapering. The horizontal emittance calculated in MADX and Xsuite increase from 7e-10 to 4e-7 compared with the standard mode. The emittance optimization is in progress.



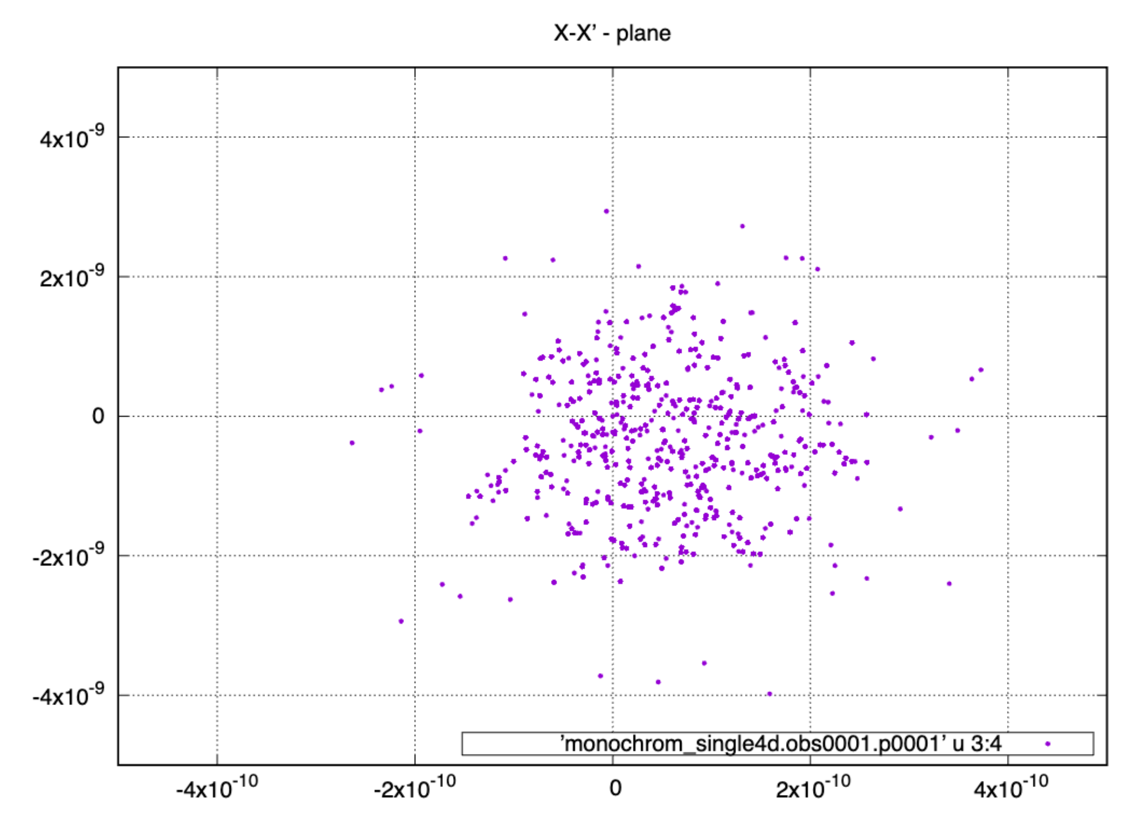
Asymmetrical Monochromatization Ring Optics

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

- 1000 Turns Single Particle Tracking for Standard Mode

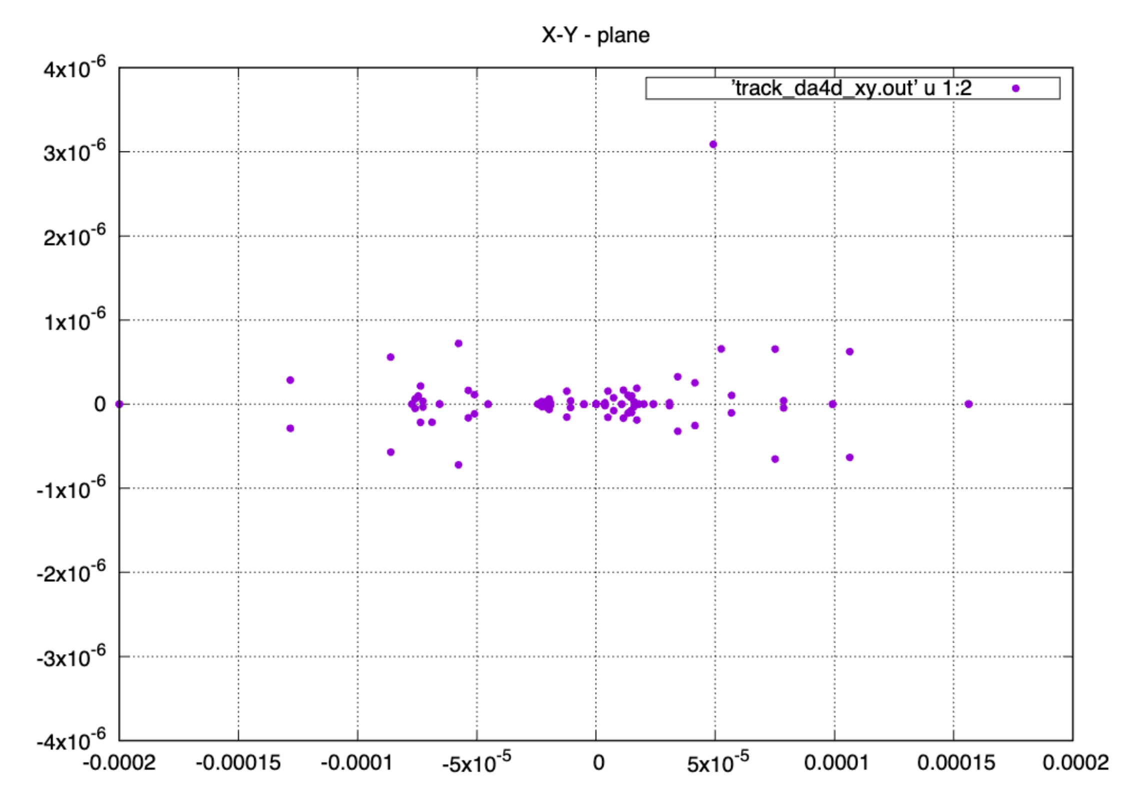


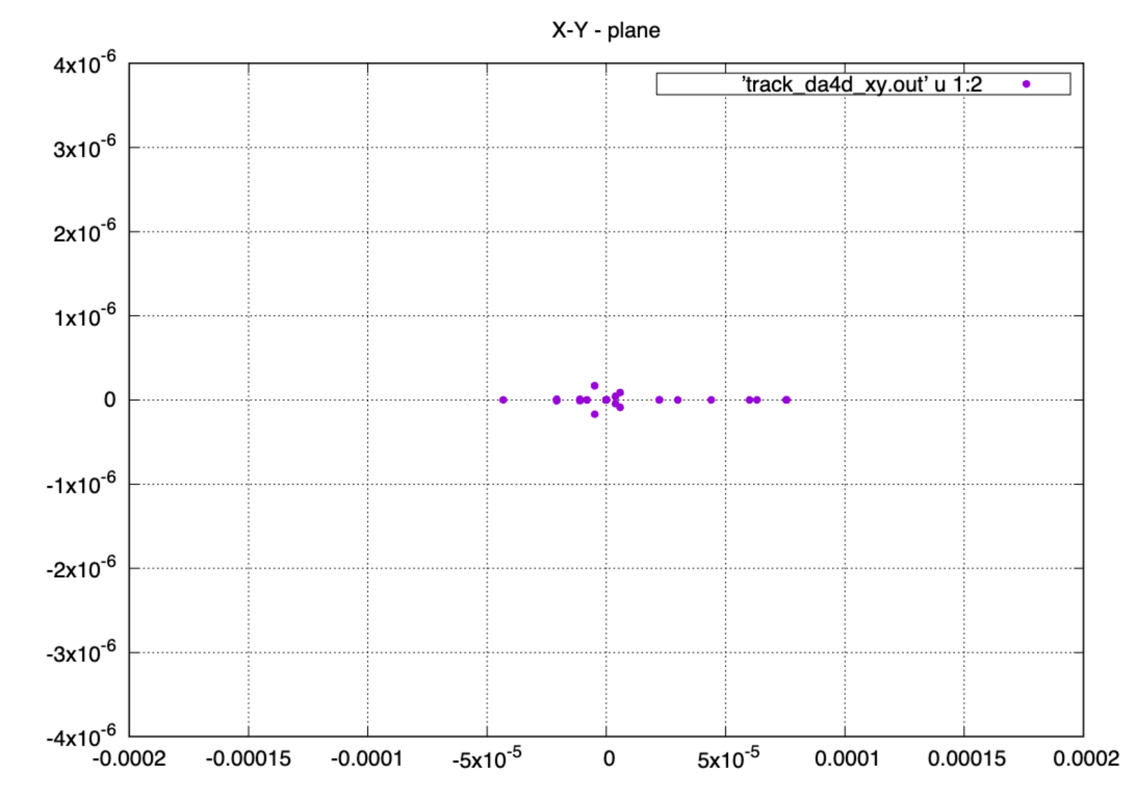
- 1000 Turns Single Particle Tracking for Monochromatization Mode



Asymmetrical Monochromatization Ring Optics

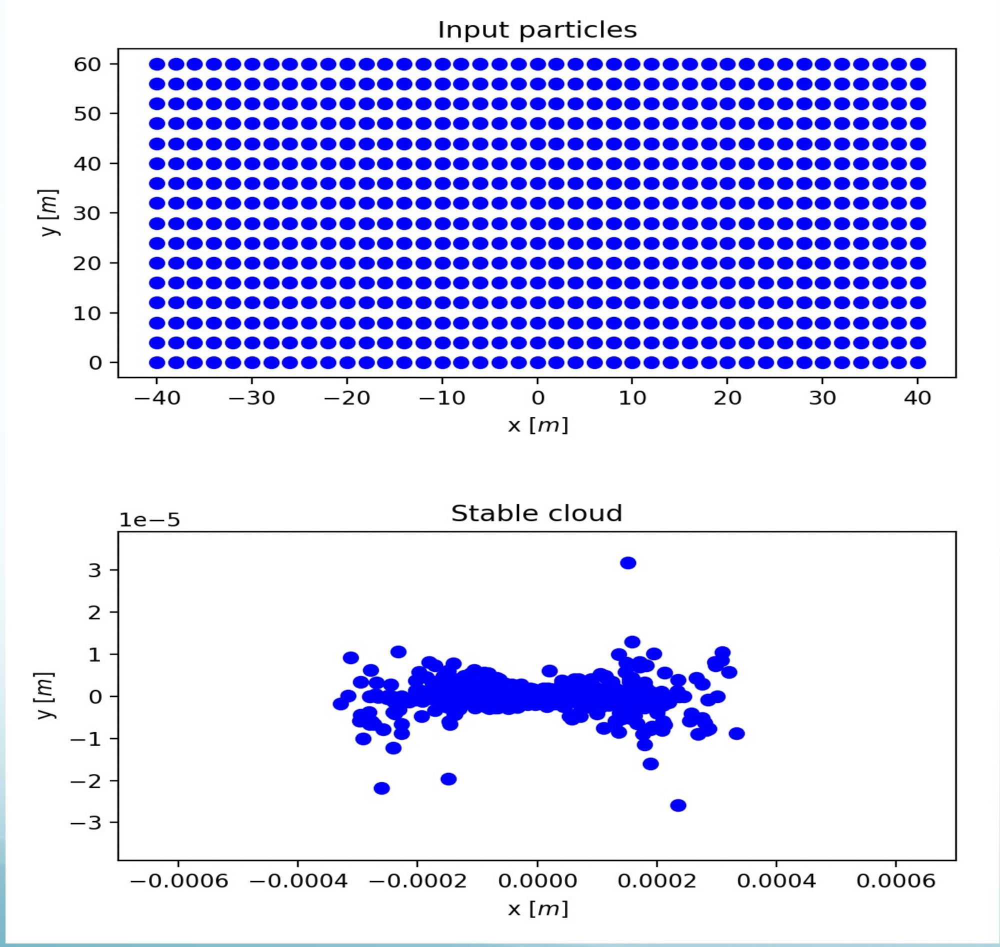
- **Dynamic Aperture Tracking in MADX-PTC**
  - 1000 Turns DA Tracking for Standard Mode
  - 1000 Turns DA Tracking for Monochromatization Mode



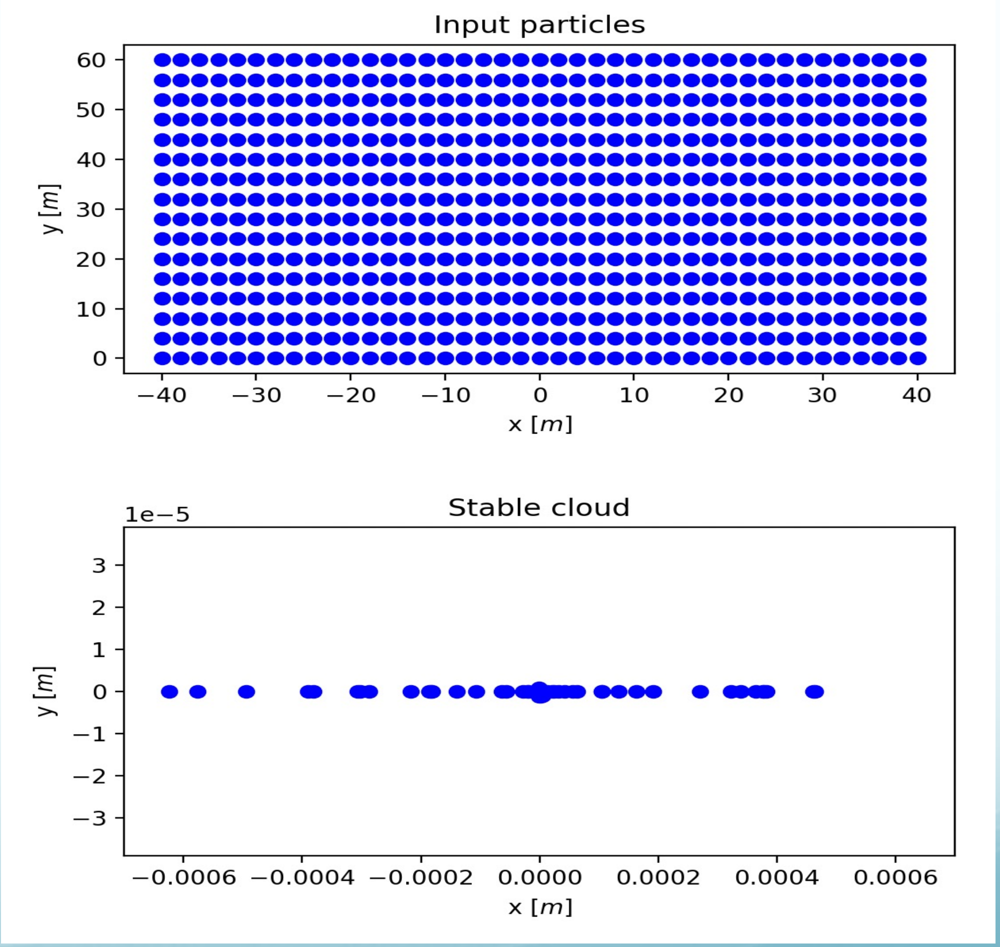


Asymmetrical Monochromatization Ring Optics

- **Dynamic Aperture Tracking in Xsuite**
  - 1000 Turns DA Tracking for Standard Mode



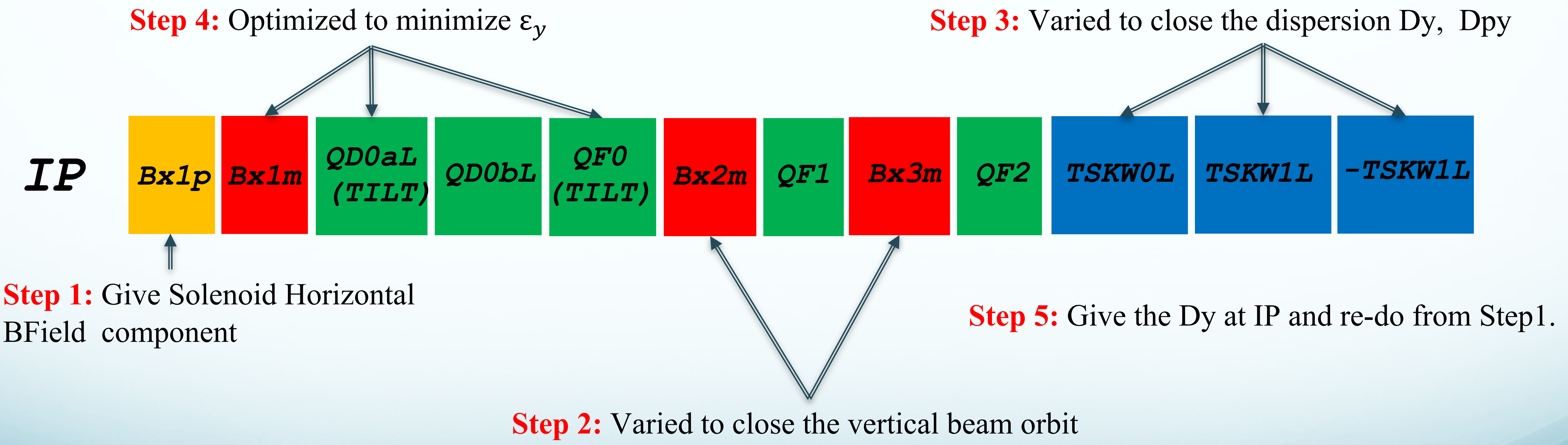
  - 1000 Turns DA Tracking for Monochromatization Mode



Symmetrical Monochromatization IR Optics Design

- **Preliminary Scheme**

Creating the vertical dispersion by adjusting the correctors (red) and skew quadrupoles (blue) around the IP solenoid (yellow). It will take the following five steps to get the vertical dispersion at the IP.

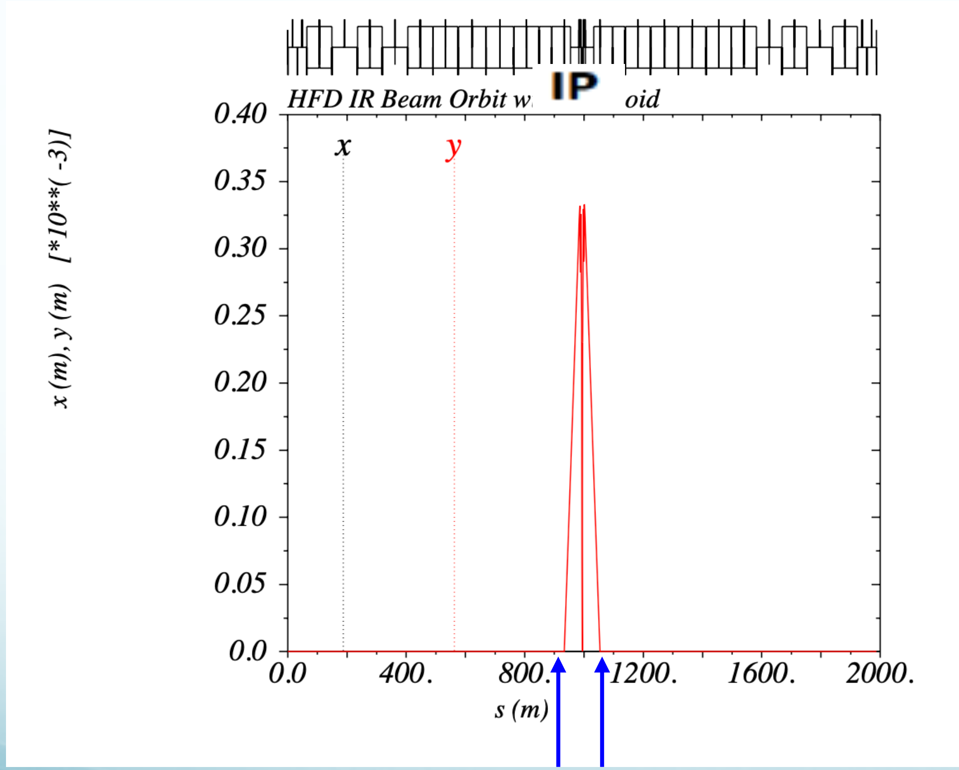


Symmetrical Monochromatization IR Optics Design

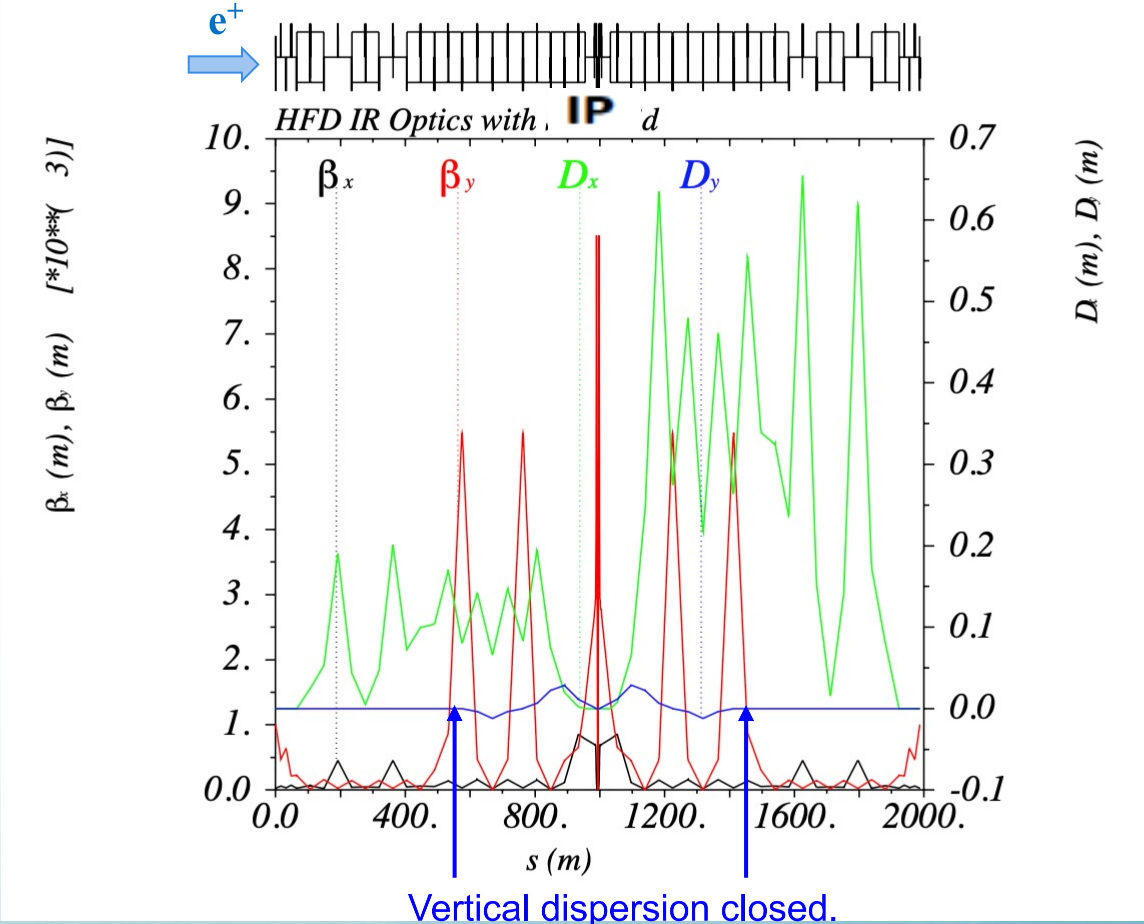
- **Solenoid Implementation**

Vertical beam orbit and vertical dispersion was closed after implementing the solenoid.

Vertical beam orbit



Vertical beam orbit back to 0 after Bx3m

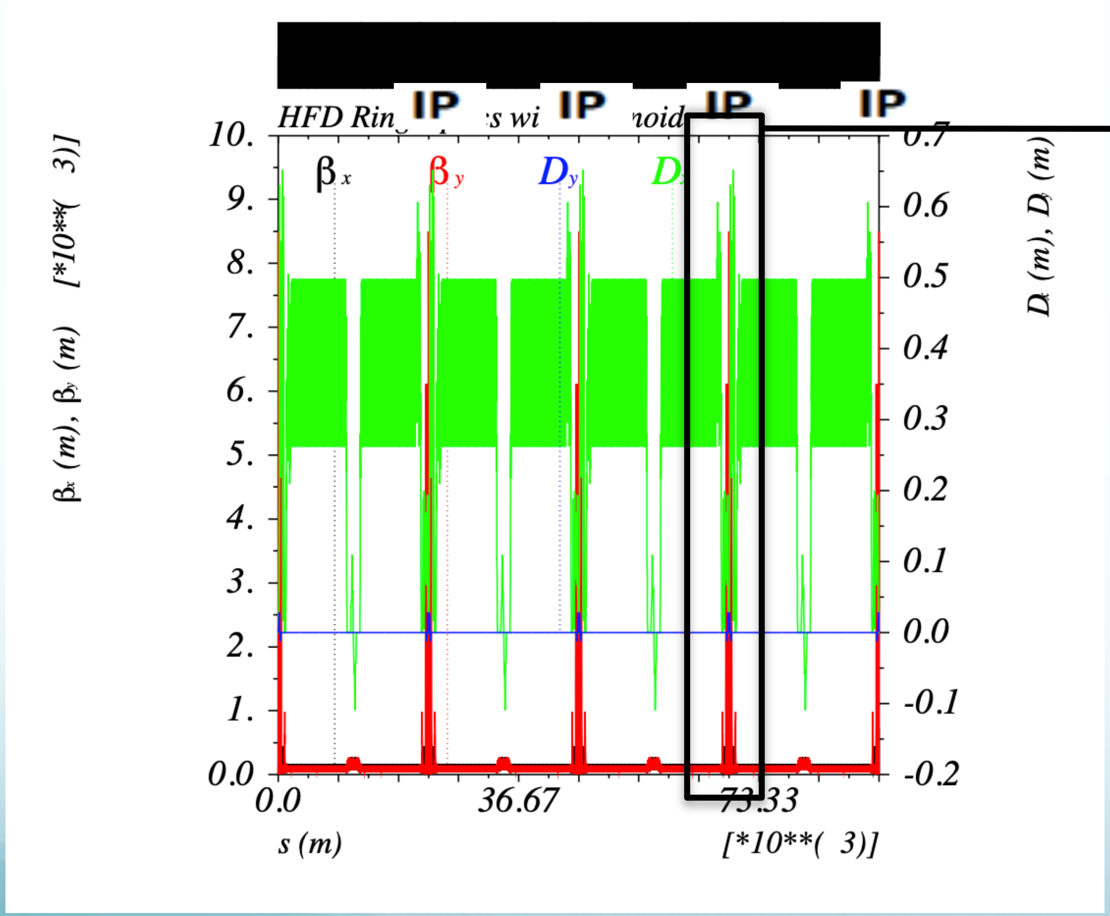


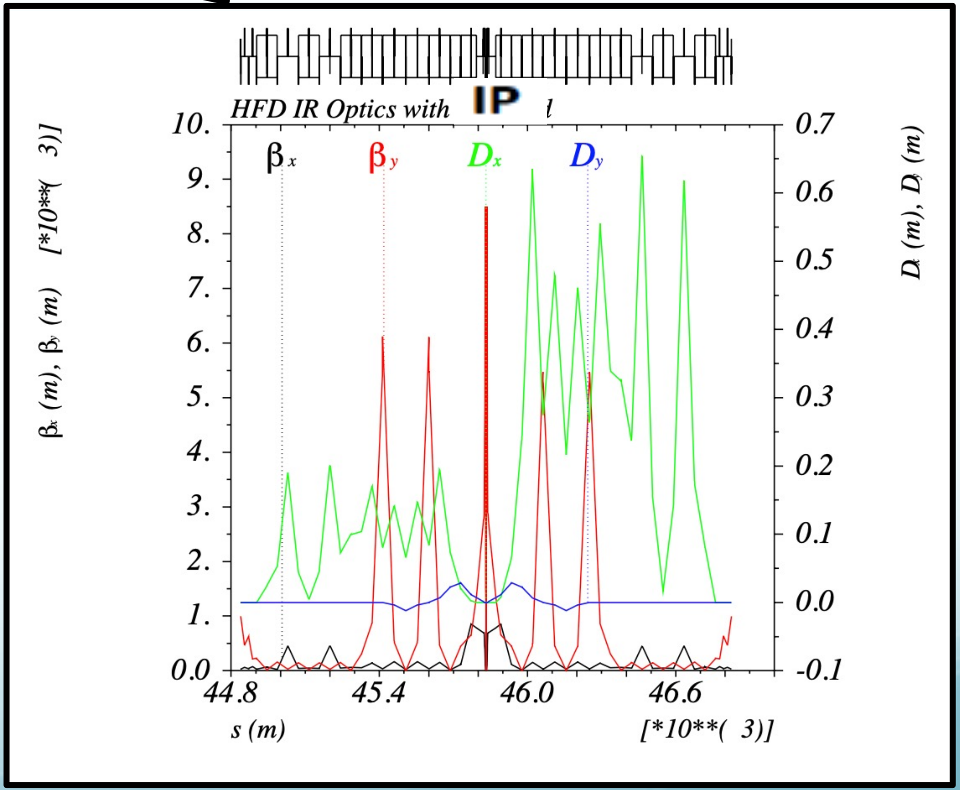
Vertical dispersion closed.

Symmetrical Monochromatization IR Optics Design

- **Calculation and minimization of the vertical emittance**

The IR lattice with solenoid was implemented in the whole ring successfully. A script for the minimization of the vertical emittance is being developed.





Summary and Outlook

- **Asymmetrical 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

➢ Emittance optimization and dynamic aperture tracking in Xsuite and MADX-PTC is in progress

➢ Luminosity calculation in Guinea-Pig is in progress

➢ Simplification of the dipoles slicing is in progress

- **Symmetrical IR Monochromatization Optics design**

✓ Solenoid implementation

✓ Closing vertical orbit and vertical dispersion

➢ Calculation and minimization of the vertical emittance is in progress

➢ Experimental proof of concept in DAFNE

➢ Monochromatization optics design for CEPC

Thanks for you attention!