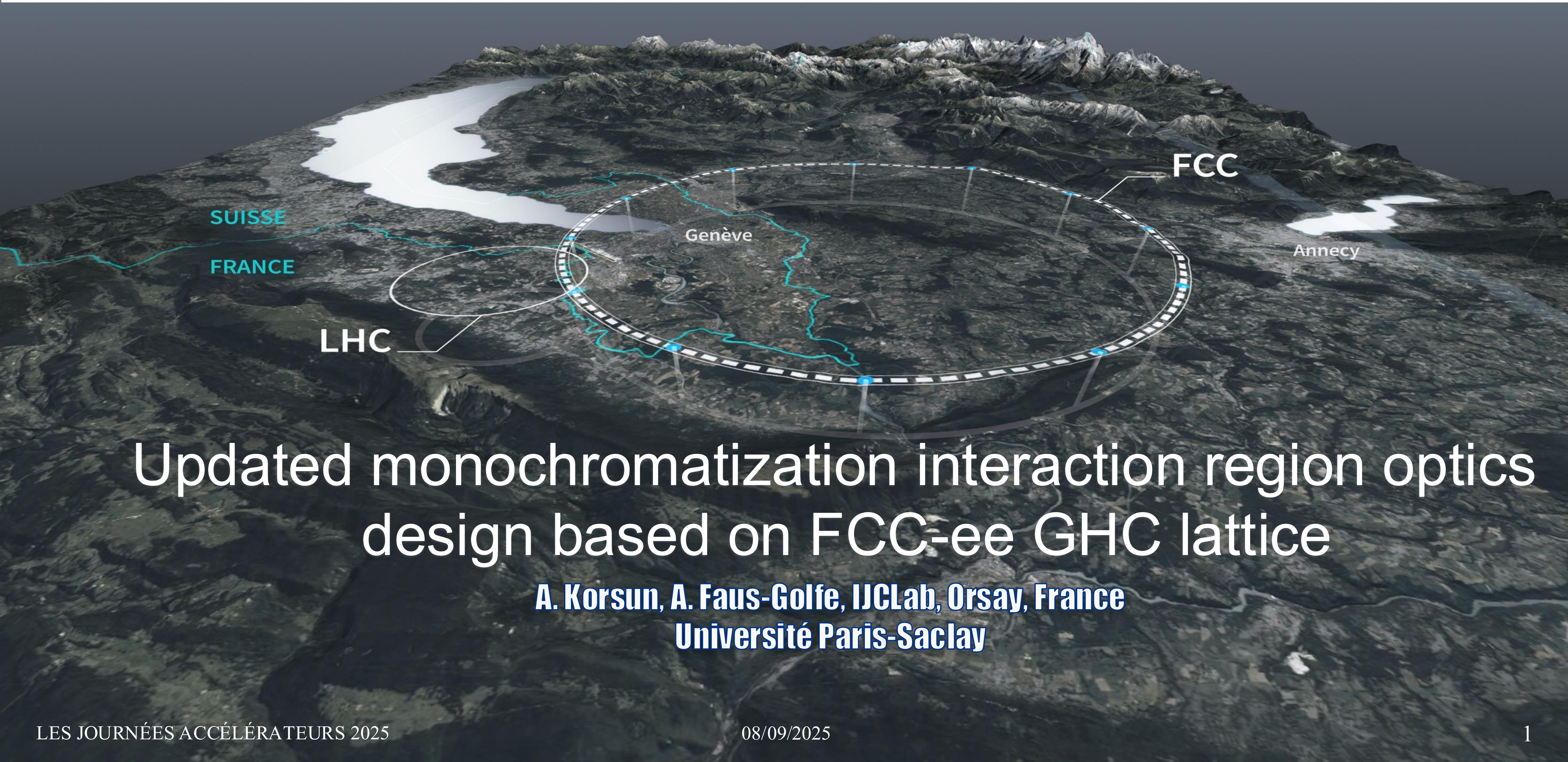

Updated monochromatization interaction region optics design based on FCC-ee GHC lattice

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Université Paris-Saclay

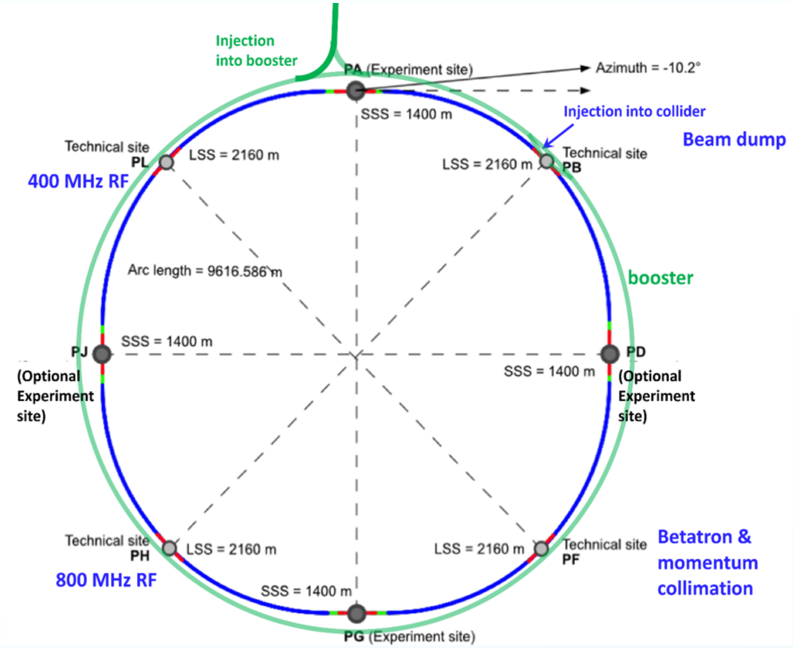
Outline

- Introduction and motivation
- Monochromatization Principle
- FCC-ee Monochromatization IR Optics Design
- Performance Check of FCC-ee MonochroM Optics
- Summary and outlook

Introduction: Physics Requirements

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

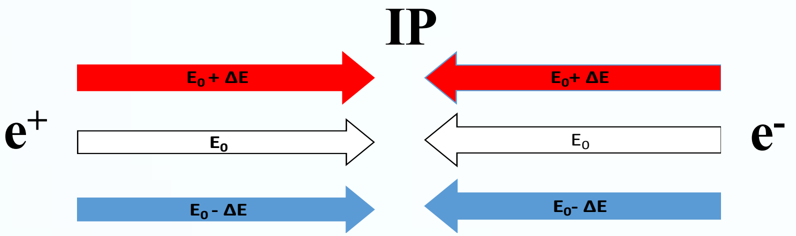
      $\boldsymbol{Z}$, $\boldsymbol{W^{\pm}}$, $\boldsymbol{Zh}$ **and** $\boldsymbol{t\bar{t}}$
  - The optional fifth mode: ***s***-channel Higgs production mode
    - The measurement of the electron Yukawa coupling, in dedicated runs at 125 GeV with center-of-mass (CM) energy spread (5-10 MeV). But the 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)

Monochromatization Principle

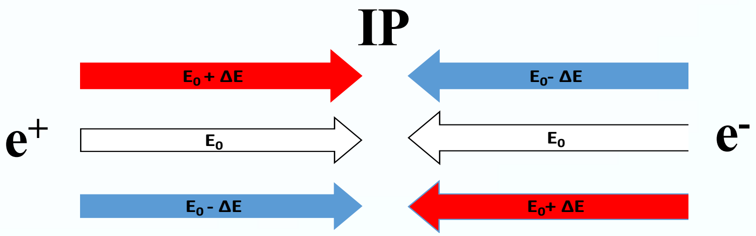
Standard



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

correlation between transverse spatial position and energy deviation

Monochromatization



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

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

Opposite correlations between transverse spatial position and energy deviation

$w = 2(E_b + \Delta E)$	**CM energy**	$w = 2E_b + O(\Delta E)^2$
$\sigma_w = \sqrt{2}E_b\sigma_\delta$	**Spread of the CM energies**	$\sigma_w = \frac{\sqrt{2}E_b\sigma_\delta}{\lambda}$
$\lambda = 1$	**Monochromatization factor**	$\lambda = \left(1 + \sigma_\delta^2\left(\frac{D_x^{*2}}{\sigma_{x\beta}^{*2}} + \frac{D_y^{*2}}{\sigma_{y\beta}^{*2}}\right)\right)^{1/2}$
$L_0 = \frac{k_b f_r N_+ N_-}{4\pi\sigma^*_{x\beta}\sigma^*_{y\beta}}$	**Luminosity**	$L = \frac{L_0}{\lambda}$

betatronic beam sizes at the IP

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

dispersive beam size at the IP

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 in High-energy Colliders

In the previous case for low-energy e⁺e⁻ colliders, the **relative energy spread** is mainly given by **SR** in the colliders arcs ($\sigma_\delta = \sigma_{\delta,SR}$). Alternatively in **high-energy e⁺e⁻**, we have to take into account also the **SR** created by the strong opposing EM field during collision or "**beamstrahlung**"(**BS**) ($N\gamma \propto 1/\sigma_z\,(\sigma^*_x + \sigma^*_y)$), with σ_z the bunch length).

Standard BS

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

Monochromatization BS

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

Coupled system to be solved numerically

Energy spread

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

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

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

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

Horizontal emittance

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

$$\varepsilon_{x,tot} \approx \varepsilon_{x,SR} + \frac{2B}{D^*_x\beta^*_x\sigma^5_{\delta,tot}}$$

Bunch length

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

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

BS at **high-energy** with $D_x^*=0$, has more **impact** on **energy spread** in standard mode than in monochromatization mode.

BS with **monochromatization** at **high-energy**, **avoids** the **blow up** of the relative beam energy spread, which is significant in standard mode with $D_x^*=0$.

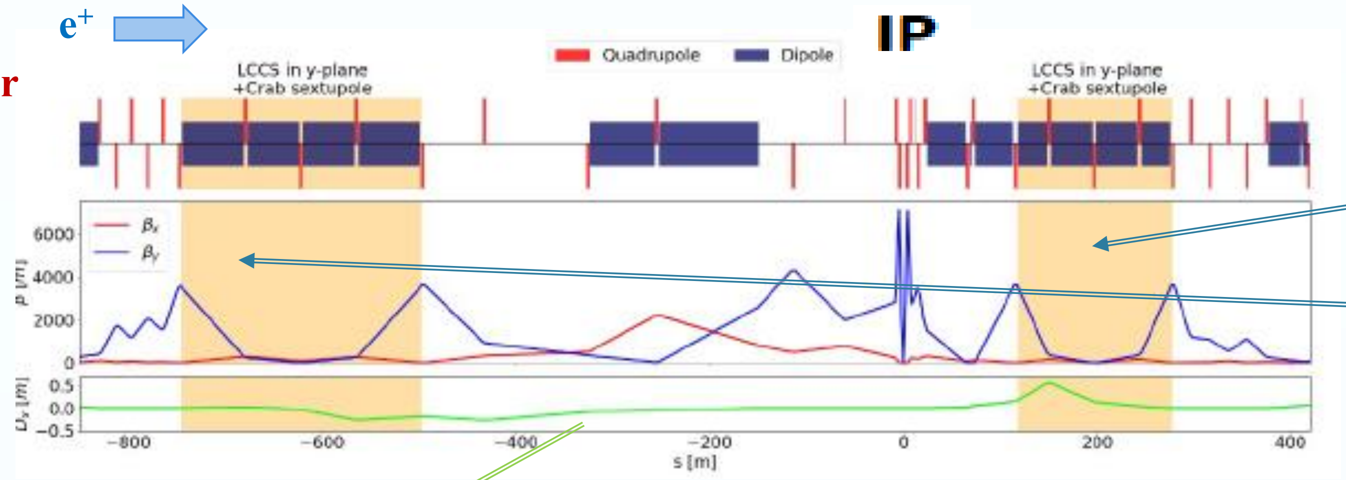
M. A. Valdivia García, F. Zimmermann, Towards an optimized monochromatization for direct Higgs production in future circular e+ e- Colliders, in CERN-BINP Workshop for Young Scientists in e+e- Colliders, pp. 1–12 (2017)

Monochrom Implementation in FCC-ee GHC IR

Despite the **simplicity** of the **monochromatization concept**, the **creation** and the **control** of the necessary **H/V dispersion** function of opposite signs at the IP could be **rather difficult to implement**.

Monochromatization factor

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



IR GHC: Local Chromaticity Correction Section (LCCS) with Crab Sextupoles (CS) in the vertical to produce a crab waist collision

➢ $D^*_x \neq 0$ generation at the IP

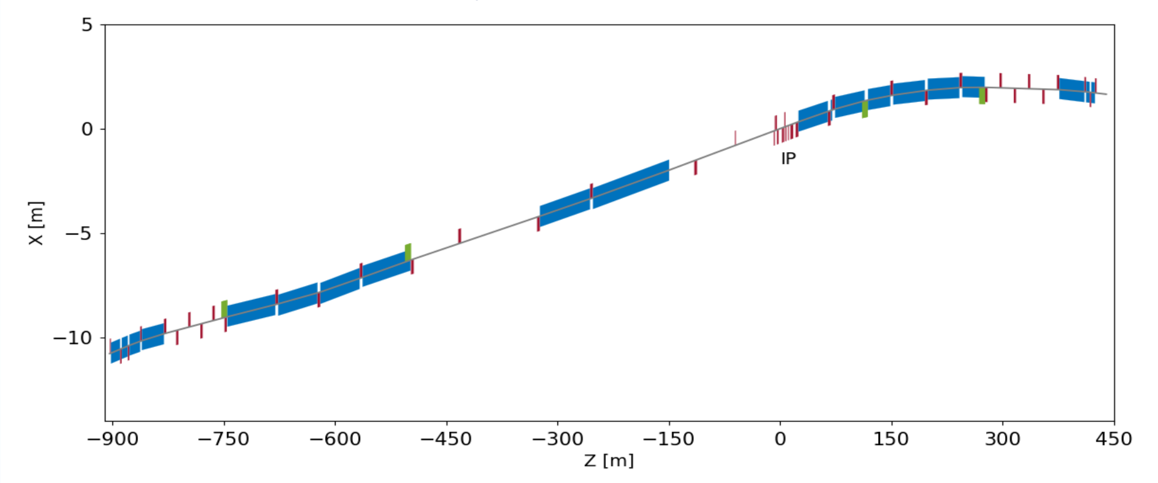
In FCC-ee IR region, the **large crossing angle of 30 mrad** in the H-plane and the **local chromaticity correction system (LCCS)** are achieved using **H-dipoles** at both sides of the IP, creating some **H-dispersion** D^*_x ($D_x \neq 0$ in the LCCS and $D_x = 0$ close to the IP for high-luminosity). $D^*_x \neq 0$ can be generated **(~10 cm)** by intentionally **mismatching D_x** in the LCCS.

➢ $D^*_y \neq 0$ generation at the IP

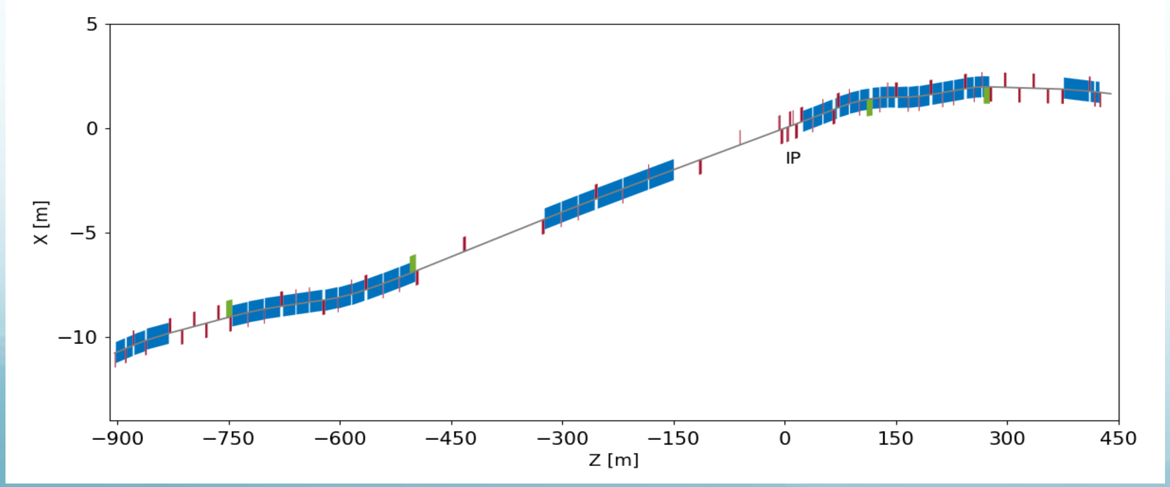
Because $\sigma^*_{y\beta} \lll \sigma^*_{x\beta}$, about **100 times smaller D^*_y (~mm)** is needed to get the same monochromatization factor. Therefore, $D^*_y \neq 0$ could be generated by implementing **skew quadrupoles** around IP. These quadrupoles could be located where the chromatic sextupole (CS) pairs are located in the LCC system.

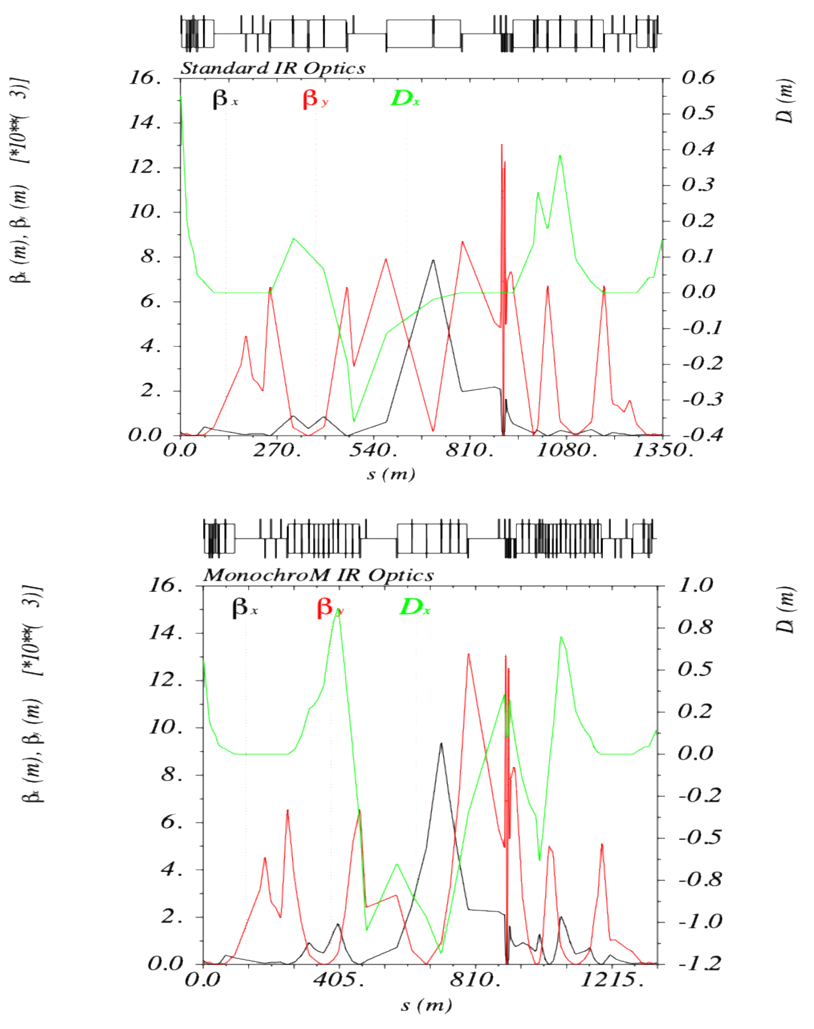
FCCee H Monochromatization optic design

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



  - Monochromatization Survey Plot





Parameters table for GHC Z V23 lattice

Parameters	Units	Standard	Standard_625	Monochrom_h_4ip	Monochrom_v_opt	Monochrom_v
Beam Energy E	GeV	45.6	62.5	62.5	62.5	62.5
# of IPs	/	4	4	4	4	4
Circumference	m	90658.816	90658.816	90658.816	90658.816	90658.816
Energy Loss/turn	MeV	39.4	138.1791153	143.0311645	137.1381791	138.1791153
SR power loss	MW	50.0	50.0	50.0	50.0	50.0
Beam current	mA	1270	360	350	360	360
Bunches/beam n_b	/	15880	12000	12000	12000	12000
Bunch population N_b	10^{11}	1.51	0.56	0.56	0.56	0.56
Horizontal emittance (SR/BS) ε_x	nm	0.71 / 0.71	1.317 / 1.317	1.68 / 4.12	1.32 / 1.32	1.31 / 1.31
Vertical emittance (SR/BS) ε_y	pm	1.4 / 1.4	2.64 / 2.64	3.32 / 3.32	4.8 / 85	4 / 533.9
Momentum compaction α_c	10^{-6}	28.6	28.0	27.4	27.9	27.9
$\beta^*_{x/y}$	mm	110 / 0.7	110 / 0.7	110 / 0.7	1500 / 0.7	110 / 0.7
$D^*_{x/y}$	m	0 / 0	0 / 0	0.105 / 0	0 / 0.001	0 / 0.001
Energy Spread (SR/BS) σ_δ	%	0.039 / 0.089	0.0537 / 0.074	0.0547 / 0.0558	0.0537 / 0.0564	0.0537 / 0.0689
MonochroM Factor (SR/BS) λ	/	1 / 1	1 / 1	2.7 / 1.96	9.31 / 2.51	10.23 / 1.5
CM energy spread (SR/BS) σ_W	MeV	25.3 / 57.4	47.47 / 65	17 / 27	5 / 29.9	4 / 40
Bunch length (SR/BS) σ_z	mm	5.6 / 13	5.4 / 7.25	5.32 / 5.34	5.4 / 5.5	5.4 / 6.8
Sychrotron tune Q_s	/	0.0288	0.041069085	0.041350116	0.041069108	0.041069085
Longitudinal damping time	turns	1158	452	437	456	452
Luminosity (SR/BS)	10^{34}cm^{-2} s^{-1}	360 / 140	28.9 / 18	20 / 9.35	2 / 1.35	2.3 / 0.9

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 V23**	**MonochroM ZH V23**	**MonochroM ZV V23**
RMS CM energy spread σ_w (with crab cavity)	[MeV]	64.90	27.17	29.90
Luminosity per IP (with crab cavity)	[10^{34}cm^{-2}s^{-1}]	18	9	1.35

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

Parameters		**Standard TES V22**	**MonochroM TH V22**	**MonochroM TV V22**
RMS CM energy spread σ_w (with crab cavity)	[MeV]	67.25	29.59	15.85
Luminosity per IP (with crab cavity)	[10^{34}cm^{-2}s^{-1}]	57.9	12.01	1.57

Summary and Outlook

- ✓ Parametric analysis for monochrome optimization (future optimization using ML)
- ✓ Design optics update of the monochromatization IR optics in the whole ring GHC lattice (future LCC lattice)
- ✓ Dynamic aperture and beam-beam studies in the case of the monochrom scheme with Xsuite tracking (brute force)
- ✓ Scanned beam-beam studies with the Circulant Matrix Model (semi-analytical)
- ➢ Exploration of possible experimental implementation on SuperKEKB, BEPC, and BEPCII

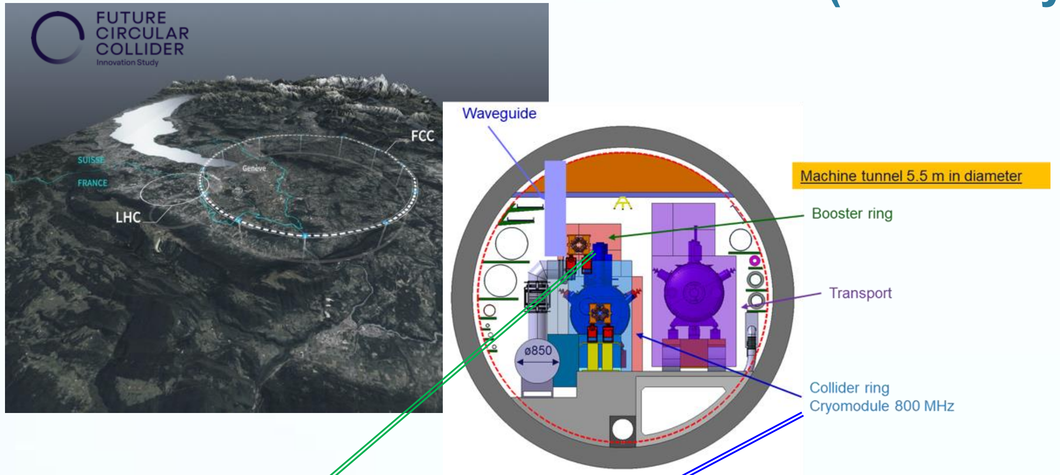
Thanks for you attention!

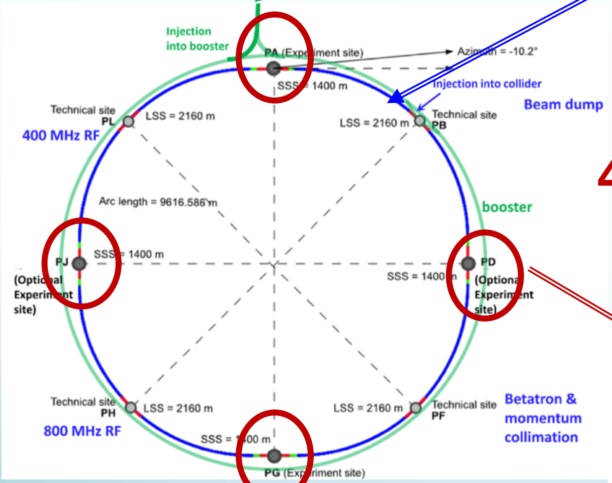
Back-up

The FCC-ee GHC Standard Lattice & Performances

(Global Hybrid Correction)

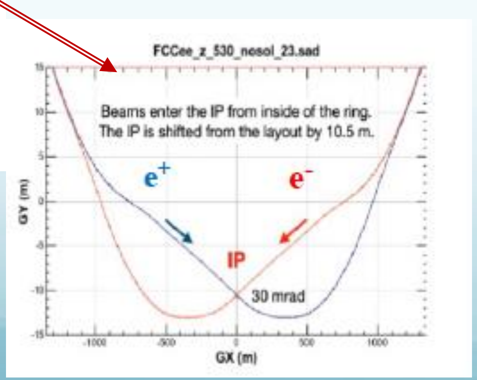
4 operation modes: Z, WW, ZH, ttbar





4 IPs

Long week dipoles and antisymmetric IR to avoid SR

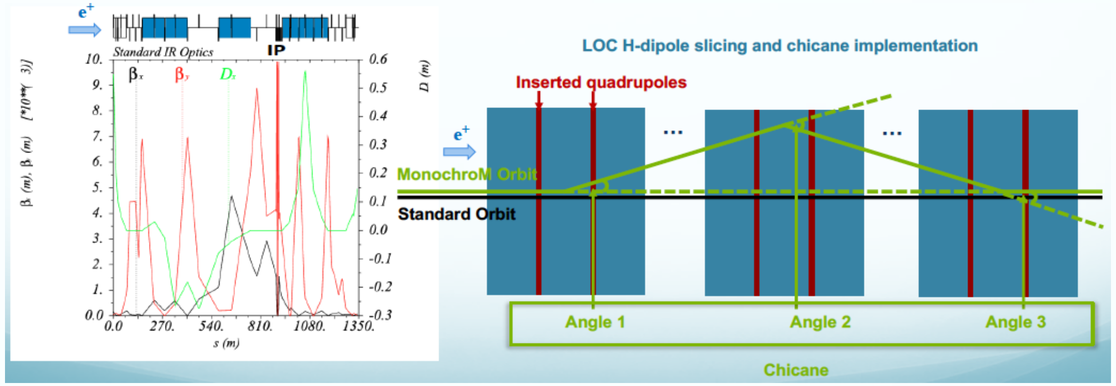


Large crossing angle (θ_c=30 mrad) at IP are required to separate the two beams to harmful effects of parasitic collisions

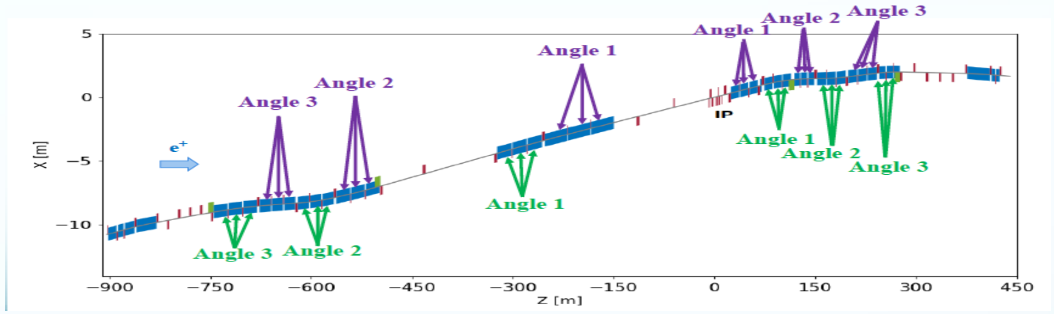
FCC-ee GHC Performance Table for V22

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	9.936			
Energy loss / turn	[GeV]	0.0394	0.374	1.89	10.42
SR power / beam	[MW]	50			
Beam current	[mA]	1270	137	26.7	4.9
Colliding bunches / beam		15880	1780	440	60
Colliding bunch population	[10^{11}]	1.51	1.45	1.15	1.55
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.71	1.59
Ver. emittance at collision ε_y	[pm]	1.4	2.2	1.4	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.75	1.25	0.85	0.9
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	1000 / 1.6
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.358	398.148 / 398.182
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.089	0.070 / 0.109	0.104 / 0.143	0.160 / 0.192
Bunch length (SR/BS) σ_z	[mm]	5.60 / 12.7	3.47 / 5.41	3.40 / 4.70	1.81 / 2.17
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.091
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	2.9
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP $\pm\theta_x$	[mrad]	±15			
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		21.7	3.7	5.4	0.82
Crab waist ratio	[%]	70	55	50	40
Beam-beam $\xi_x/\xi_y{}^a$		0.0023 / 0.096	0.013 / 0.128	0.010 / 0.088	0.073 / 0.134
Lifetime (q + BS + lattice)	[sec]	15000	4000	6000	6000
Lifetime (lum)^b	[sec]	1340	970	840	730
Luminosity / IP	[10^{34}/cm^{2}s]	140	20	5.0	1.25
Luminosity / IP (CDR, 2 IP)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

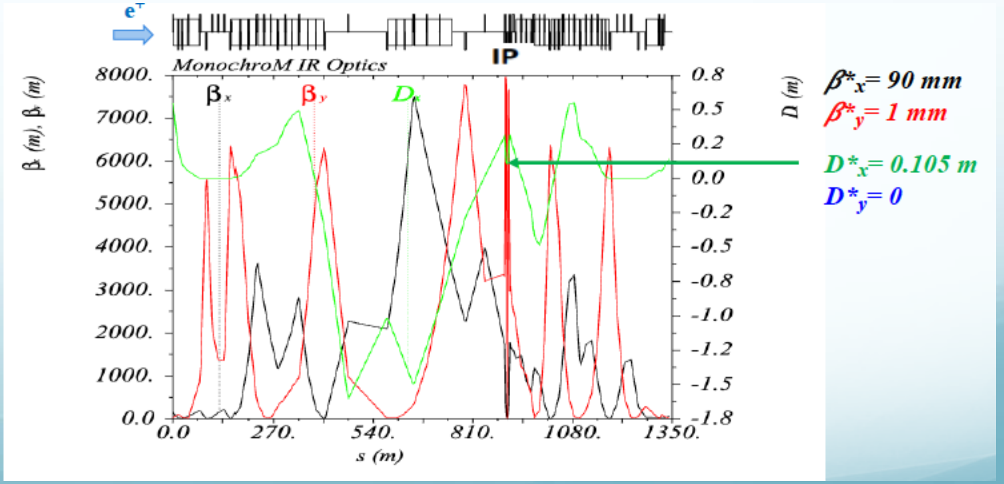
H-Monochrom Implementation in FCC-ee GHC IR (I)



Step 1: All LCCS H-dipoles (blue) are cut into three pieces and quadrupoles (red) are inserted between them for matching flexibility. Additional chicanes are implemented in each upstream and downstream LCCS H-dipole to create the dispersion at the IP while keeping the orbit.



Step 2: To mitigate the horizontal emittance blowup, 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 LCCS H-dipole.



$\beta^*_x = 90\ mm$

$\beta^*_y = 1\ mm$

$D^*_x = 0.105\ m$

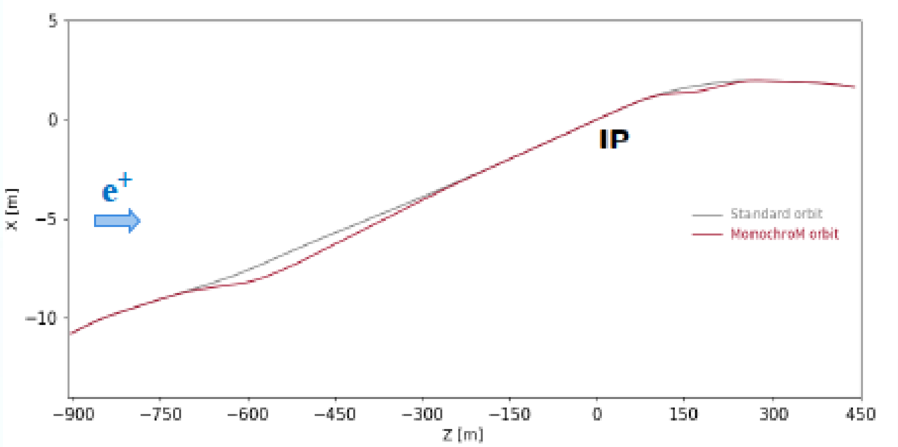
$D^*_y = 0$

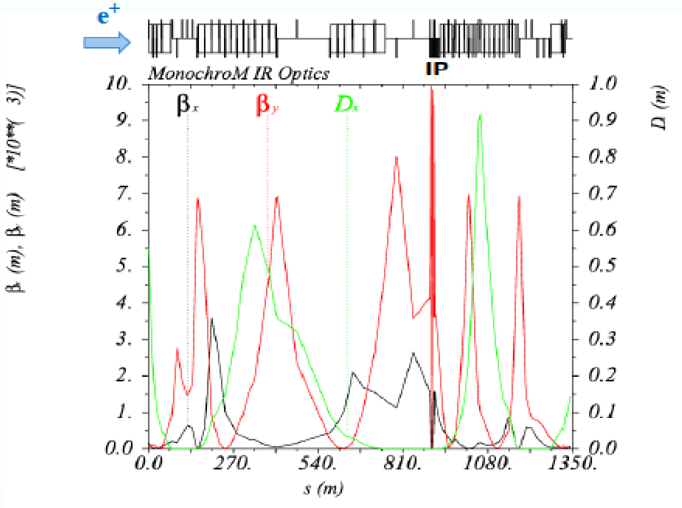
Step 3: The IP beam parameters are matched to FCC-ee Monochrom self-consistent parameters* while keeping the beam parameters at the entrance and exit of the IR similar to those of standard mode, including phase advances between sextupoles and crab sextupoles.

* 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

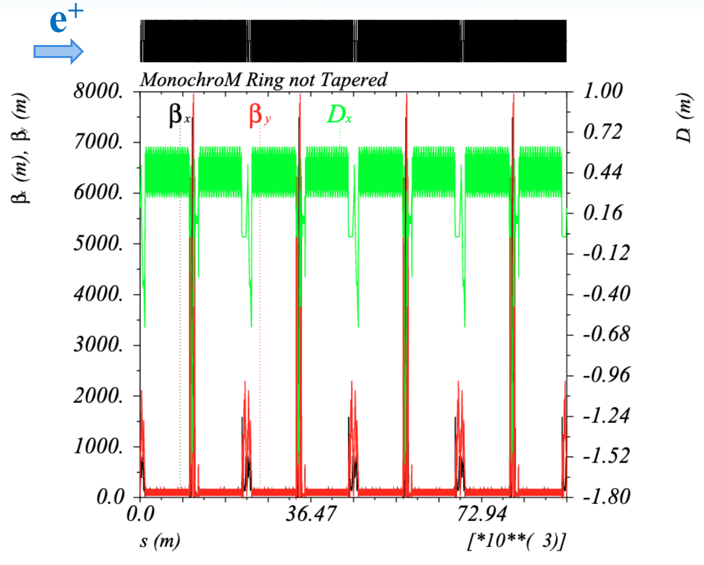
H-Monochrom Implementation in FCC-ee GHC IR (II)

Step 4: Compatibility orbit checking for the standard mode with D_x = 0.





β^*_x= 100 mm β^*_y= 0.8 mm D^*_x= 0 D^*_y= 0



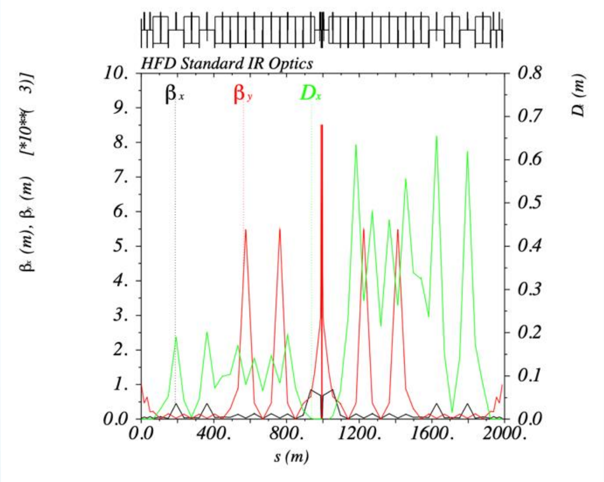
Step 5: IR Monochrom is implemented in the four IPs and global matching:

- LCCS chromaticity correction
- Global arc chromaticity correction
- Tune correction
- Emittance checks and SR-RF strategy compensation
- Preliminary Tracking and DA calculations

WEPR21

V-Monochrom Implementation in FCC-ee GHC IR

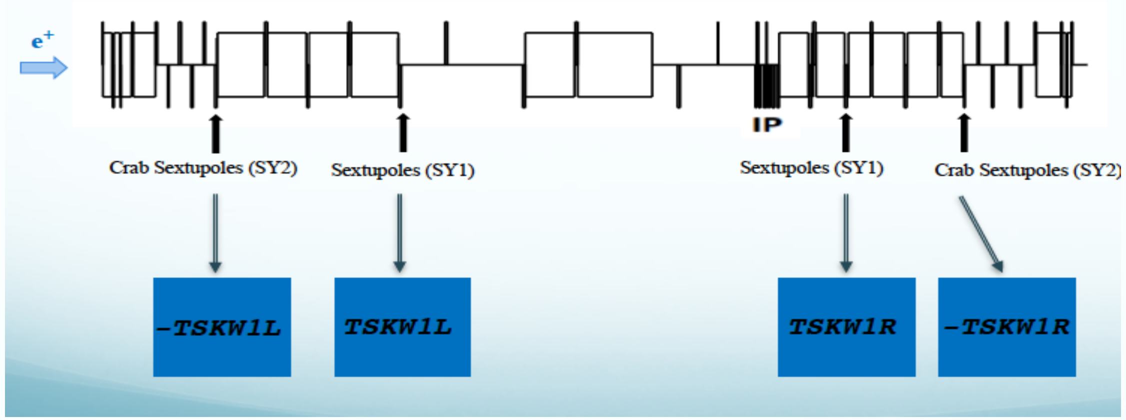
Step 1: Therefore $\mathbf{D^*_y \neq 0}$ could be generated by implementing **skew quadrupoles** around IP. These quadrupoles could be located where the CS pairs are located in the LCC system.

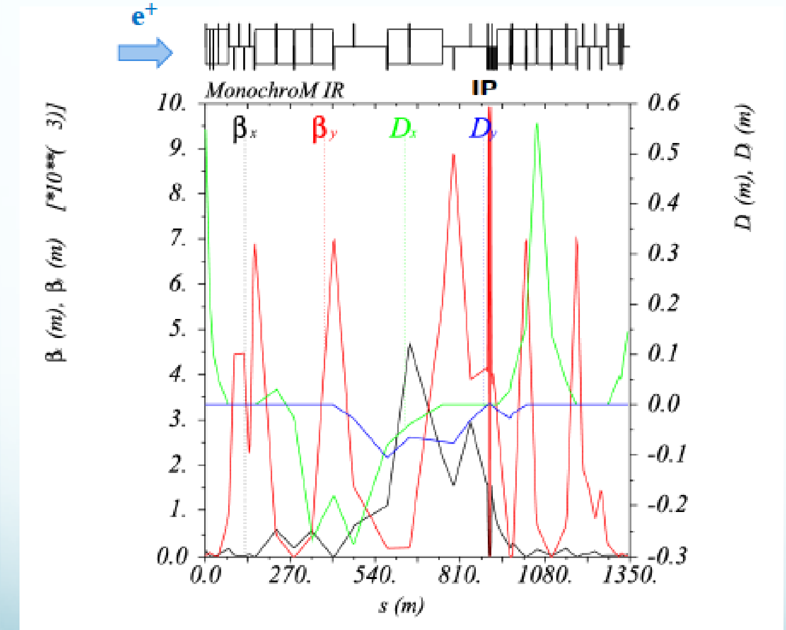


Inspired in **Local Chromaticity Correction** (LCC) IR optics solenoid compensation scheme

Step 2: IR Monochrom is implemented in the four IPs and global matching:

- LCCS chromaticity correction
- Global arc chromaticity correction
- Tune correction
- Emittance checks and SR-RF strategy compensation
- Preliminary Tracking and DA calculations





$\beta^*_x = 100$ mm $\beta^*_y = 0.8$ mm $D^*_x = 0$ $D^*_y = 1$ mm

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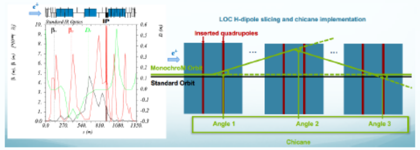
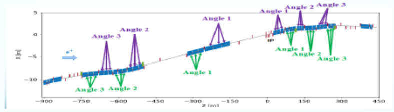
HV-Monochrom Implementation in FCC-ee GHC IR

D^*_x

Step 1: All LCCS H-dipoles (blue) are cut into three pieces and quadrupoles (red) are inserted between them for matching flexibility. Additional chicanes are implemented in each upstream and downstream LCCS H-dipole to create the dispersion at the IP while keeping the orbit.



Step 2: To mitigate the horizontal emittance blowup, 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 LCCS H-dipole.



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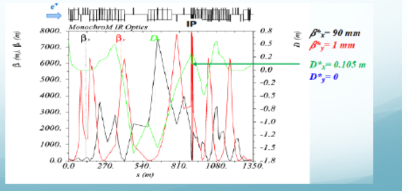

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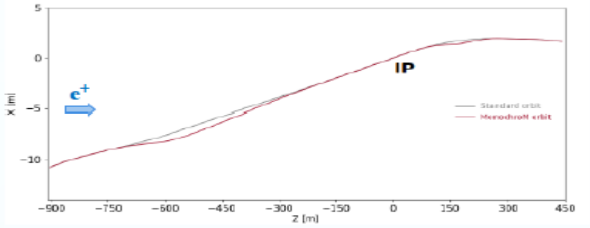
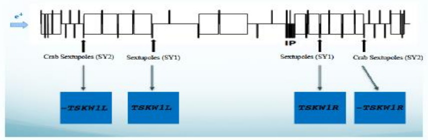


D^*_y

Step 1: Therefore $D^*_y \neq 0$ could be generated by implementing **skew quadrupoles** around IP. These quadrupoles could to be located where the CS pairs are located in the LCC system.



Step 2: IR Monochrom is implemented in the four IPs and global matching:

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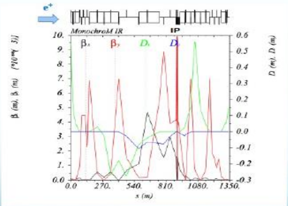
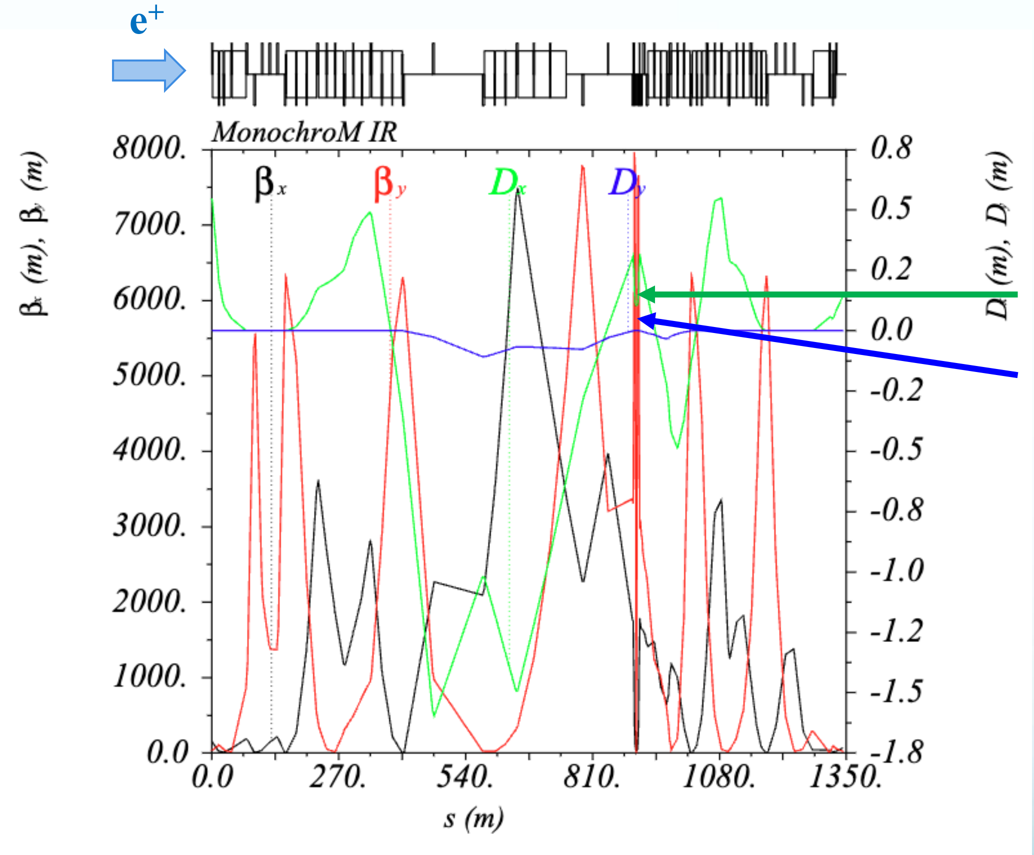
- Global arc chromaticity correction
- Tune correction
- Emittance checks
- Preliminary Tracking and DA calculations



β^*_x= 100 mm β^*_y= 0.8 mm D^*_x= 0 D^*_y= 1 mm



β^*_x= 90 mm

β^*_y= 1 mm

D^*_x= 0.105 m

D^*_y= 0.001 m

WEPR21