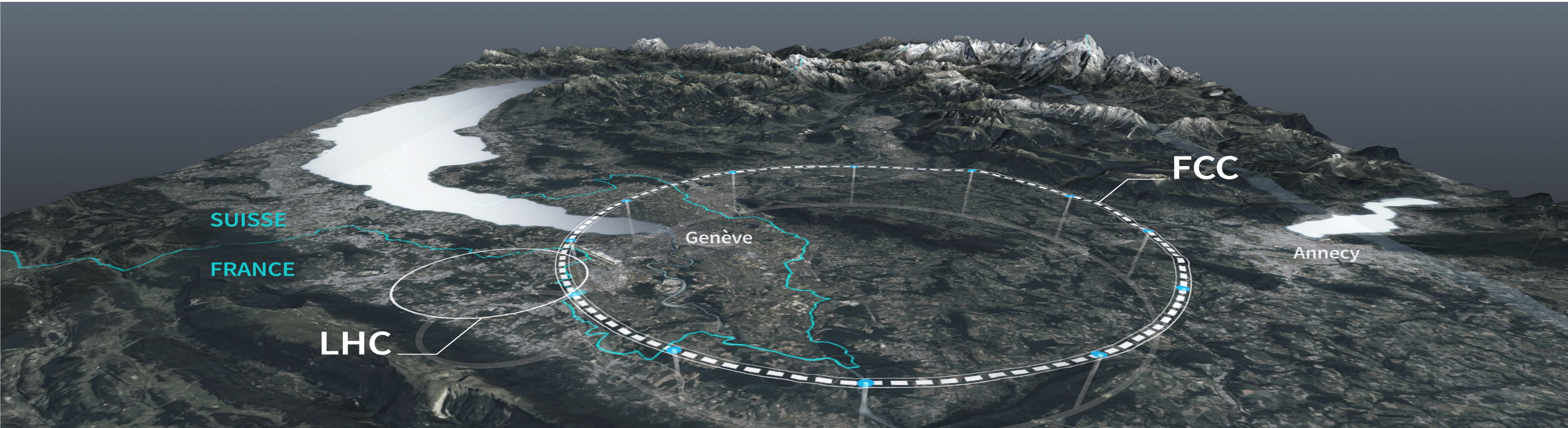

Monochromatization : a new operation mode of FCC-ee

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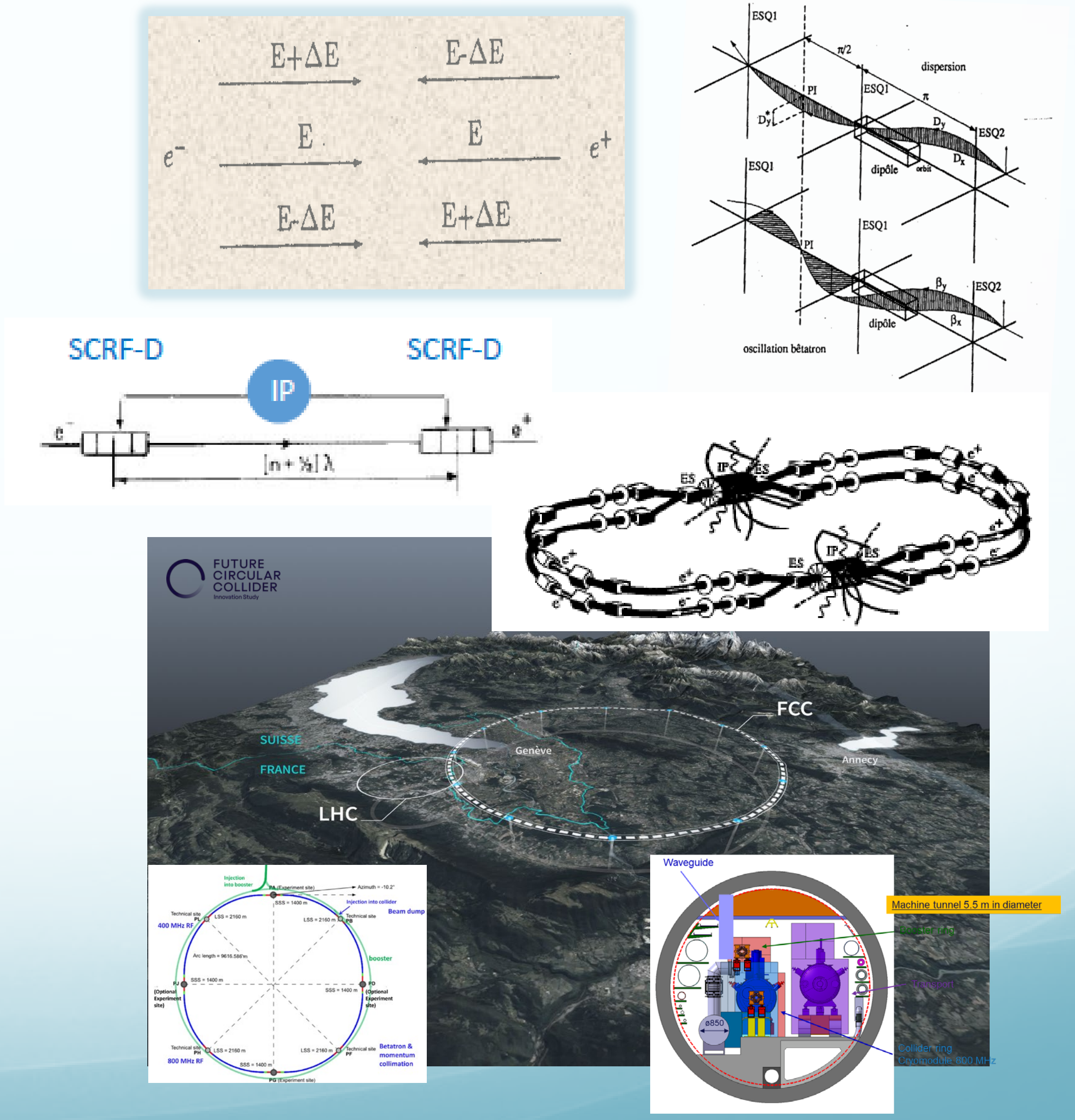
FCPPN/L2024

13th June 2024

Outline

- Monochromatization concept in e^+e^- colliders
  - Low-energy
  - High-energy: FCC-ee
- FCC-ee monochromatization physics motivation and performance studies
- FCC-ee monochromatization schemes and implementation studies
- Summary and Perspectives



CM Energy Resolution in Colliders

Reducing the **spread of the centre-of mass (CM) energies** (σ_ω) of colliding beams is a way to **increase** the **collision energy resolution**, that is of particular interest when operating the collider on a **narrow particle resonance** or at the threshold of its pair production.

spread of the CM energies

beam energy

$$\sigma_w = \sqrt{2}E_b\sigma_\delta \longrightarrow \sigma_w \propto \frac{1}{\sqrt{\rho J_\varepsilon}} \xrightarrow{\downdownarrows \sigma_w}$$

relative beam energy spread

$$\sigma_\delta^2 = \frac{55\hbar c E_b^2}{32\sqrt{3}\left(mc^2\right)^3}\frac{I_2}{I_3}\frac{1}{J_\varepsilon}$$

$1/\rho$

Relative energy spread is **mainly** due to Synchrotron Radiation (**SR**) emitted when an ultra-relativistic particle passes through a bending magnet (ρ)

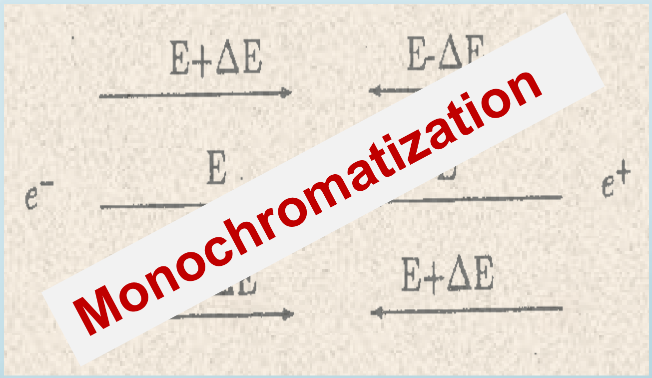
usual way

$$\begin{cases} \rho >>> & \text{bending radius} \\ 0.5 \le J_\varepsilon = 3 - J_x \le 2.5 \end{cases}$$

longitudinal partition number

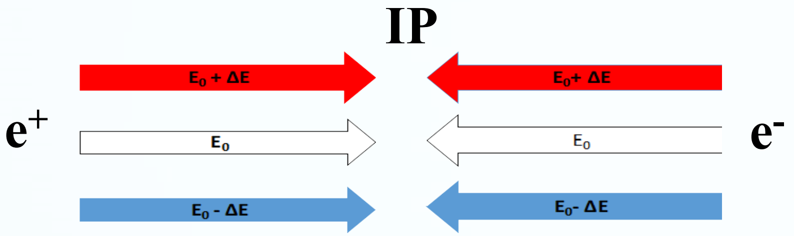
alternative way

Monochromatization consists in reducing the spread of the CM energies, **without** necessarily **reducing** the inherent **energy spread** of the two individual beams



Monochromatization Principle

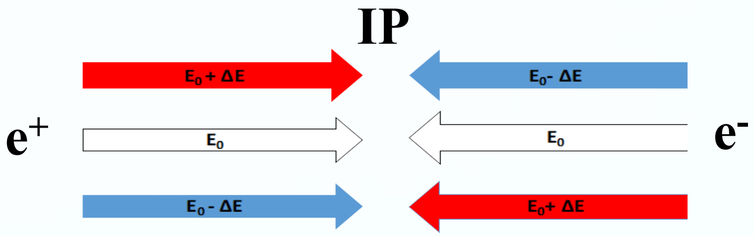
Standard



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

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

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

betatronic beam sizes at the IP

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

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 Principle

Standard

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

correlation between

IP

e$^+$

Proposed by A. Renieri in 1975 for ADONE.
Smart idea, conceptually very simple, but never tested experimentally !!!!!!

$x\beta \quad y\beta$

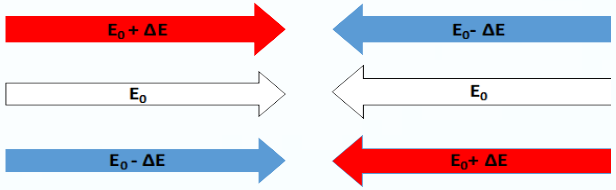
betatronic beam sizes at the IP

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

dispersive beam size at the IP

Monochromatization

IP



e$^-$

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

Opposite correlations between transverse spatial position and energy deviation

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

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

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

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

Monochromatization in Low-energy Colliders

At **low-energy e⁺e⁻ colliders**, with **flat beam schemes** ($\sigma^*_y <<< \sigma^*_x$) and where the energy spread is meanly due to SR ("beamstrahlung"(BS) is not important)**, we could optimize this scheme by playing with the beam-beam parameters and the emittances to avoid luminosity losses:**

$$\sigma^*_y <<< \sigma^*_x \quad \text{with} \begin{cases} \beta^*_y <<< \beta^*_x \\ \varepsilon_y <<< \varepsilon_x \end{cases}$$

beam emittances

$$\Longrightarrow \quad \begin{aligned} D^*_{x+} &= D^*_{x-} = 0 \\ D^*_{y+} &= -D^*_{y-} = D^*_y \end{aligned}$$

Vertical dispersion different from zero

$$\Longrightarrow \quad \begin{aligned} \sigma^*_y &\simeq \sigma_\varepsilon D^*_y \\ \xi_y &<< \xi_x \simeq \xi_{\max} \end{aligned}$$

beam-beam parameter

$$\xi_{x,y} = \frac{N_b r_e \beta^*_{x,y}}{2\pi\gamma\sigma^*_{x,y}\left(\sigma^*_x + \sigma^*_y\right)}$$

$$\Longrightarrow \quad L \simeq \frac{I\gamma}{2er_e}\frac{\xi_x}{\beta^*_x}$$

$$\frac{2\pi\gamma}{N_b r_e}\varepsilon_x \xi_x \frac{\beta^*_y}{\beta^*_x} \le 1$$

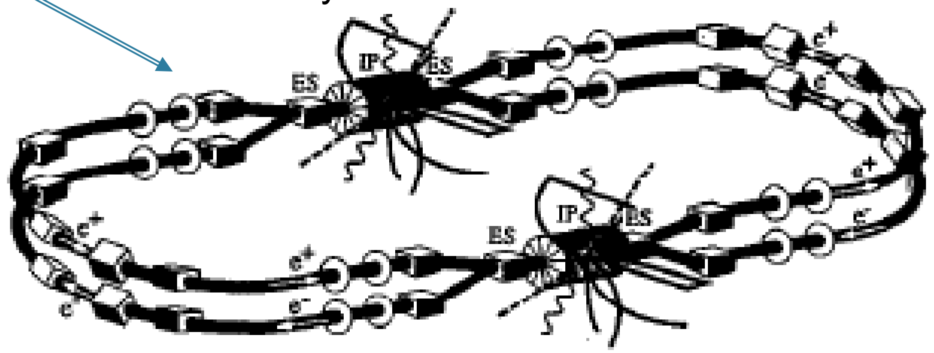
with low-horizontal emittance

we could **gain** in **energy resolution keeping** the **luminosity** constant and the **beam-beam** in the **standard** limits !!!!!!

Monocromatization Design Studies for low-energy e⁺e⁻ colliders:

- VEPP4: one ring, electrostatic quads ($\tau -$ charm)
- SPEAR: one ring, electrostatic quads, λ~8
- LEP: one ring, electrostatic quads (limited strength) and alternative RF magnetic quads, λ~3 (optics limitations)
- B-factory: Superconducting RF resonators
- $\tau -$ charm factory: two rings, vertical dipoles, λ~7.5

$\tau -$ charm factory with monochromatization scheme



A. Faus-Golfe, J. Le Duff, Versatile DBA and TBA lattices for a tau charm factory with and without beam monochromatization. Nucl. Instrum. Methods A 372, 6–18 (1996)

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 collider arcs ($\sigma_\delta = \sigma_{\delta,SR}$). Alternatively in **high-energy e$^+$e$^-$**, we must consider 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 $\boxed{D^*_{x,y}=0}$		**Monochromatization BS** $\boxed{\begin{array}{l} D^*_{x+} = -D^*_{x-} = D^*_x \\ D^*_{y+} = -D^*_{y-} = D^*_y \end{array}}$
$\sigma_{\delta,tot} = \sqrt{\frac{1}{2}\sigma^2_{\delta,SR} + \sqrt{\frac{1}{4}\sigma^4_{\delta,SR} + A\frac{\sigma^2_{\delta,SR}}{\sigma^2_{z,SR}}}}$ $A = \frac{275}{36\pi^{3/2}}\frac{n_{IP}\tau_E}{4T_{rev}}\frac{r_e^5 N_b^3 \gamma^2}{\alpha\sigma^{*3}_{x,SR}}$	**Energy spread**	$\sigma^2_{\delta,tot} = \sigma^2_{\delta,SR} + \frac{B}{D^{*3}_x \sigma^5_{\delta,tot}}$ Coupled system to be solved numerically $B \approx 50\frac{n_{IP}\tau_E}{T_{rev}}\frac{r_e^5 N_b^3 \gamma^2}{\left(\alpha_c C/\left(2\pi Q_s\right)\right)^2}$
$\varepsilon_{x,tot} \approx \varepsilon_{x,SR}$	**Horizontal emittance**	$\varepsilon_{x,tot} \approx \varepsilon_{x,SR} + \frac{2B}{D^*_x \beta^*_x \sigma^5_{\delta,tot}}$
$\sigma_{z,tot} = \frac{\alpha_c C}{2\pi Q_s}\sigma_{\delta,tot}$	**Bunch length**	$\sigma_{z,tot} = \frac{\alpha_c C}{2\pi Q_s}\sigma_{\delta,tot}$

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)

FCC-ee Monochrom Physics Motivation and Performance

- In recent years interest in **monochromatization** has been renewed, as **FCC-ee** could directly produce the Higgs boson in *s*-channel annihilation **$e^+e^- \rightarrow H$** *at* **125 GeV.** This production mode is only possible if the default collision energy spread (~ 50 MeV) can be reduced to a level comparable with the natural width of the **Higgs boson Γ_H = 4.2 MeV**, offering the only known path to measuring the **electron-Yukawa coupling (y_e).**

S. Jadach, R.A. Kycia, Phys. Lett. B 755, 58 (2016. DOI: 10.1016/j.physletb.2016.01.065

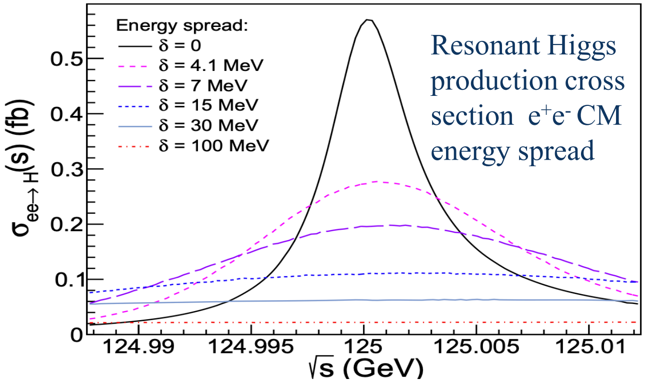
- **FCC-ee self-consistent parametric studies** at **125 GeV** has been realized to identify the best scenario with $D^*_x \neq 0$.

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, DOI: 10.1140/epjp/s13360-021-02151-y

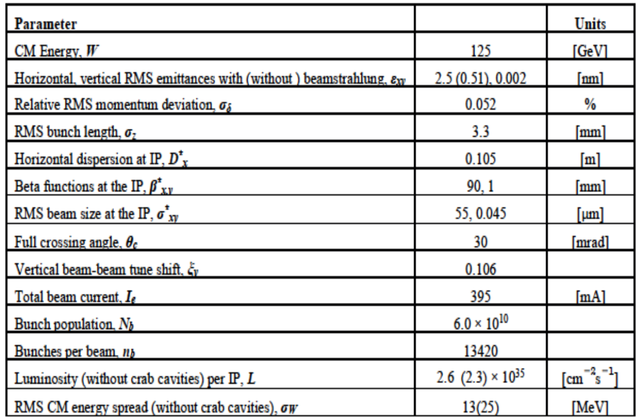
- Associated **upper limits contours** (95% CL) on the **electron Yukawa coupling** (y_e) has been calculated.

Red curves show the range of parameters presently reached in self-parametric FCC-ee monochromatization studies. The red star indicates the best signal strength monochromatization point in the plane (the pink star over the $\delta\sqrt{s} = \Gamma H$ = 4.2 MeV dashed line, indicates the ideal baseline point assumed in default analysis). All results are given per IP and per year.

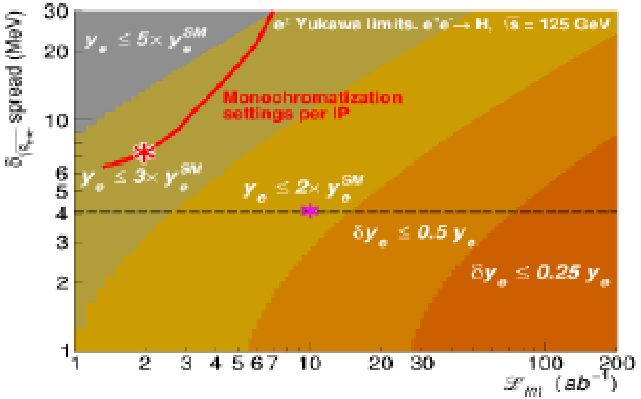
D. d'Enterria, A. Poldaru, G. Wojcik, Measuring the electron Yukawa coupling via resonant s-channel Higgs production at FCC-ee, arXiv:2107.02686v1 [hep-ex] 6 Jul 2021



Resonant Higgs production cross section e^+e^- CM energy spread

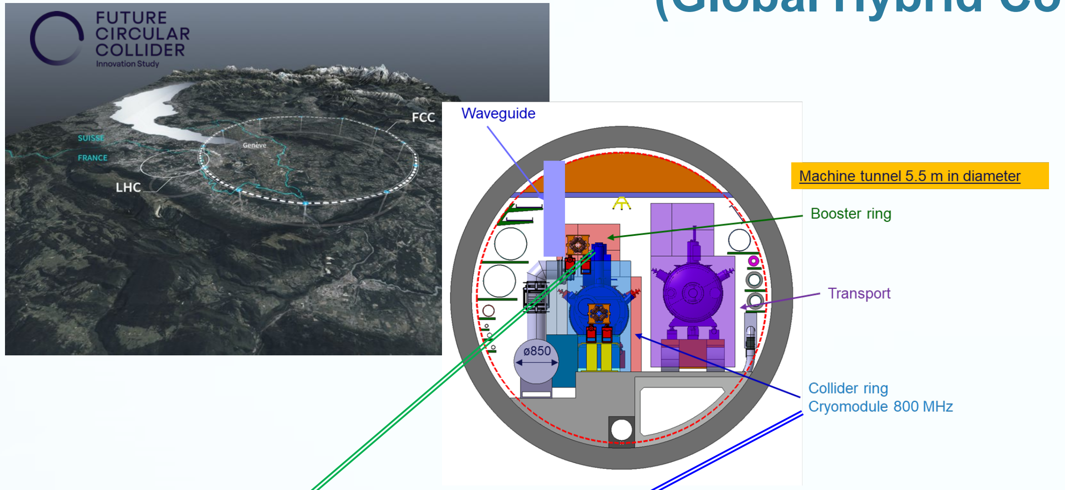


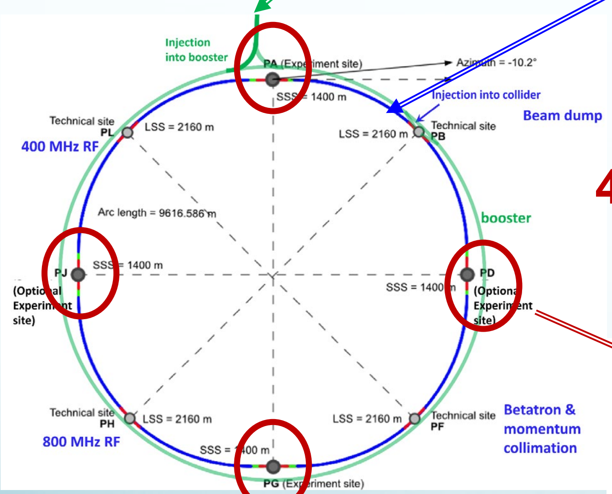
Parameter		Units
CM Energy, W	125	[GeV]
Horizontal, vertical RMS emittances with (without) beamstrahlung, ε_{xy}	2.5 (0.51), 0.002	[nm]
Relative RMS momentum deviation, σ_δ	0.052	%
RMS bunch length, σ_z	3.3	[mm]
Horizontal dispersion at IP, D^*_x	0.105	[m]
Beta functions at the IP, $\beta^*_{x,y}$	90, 1	[mm]
RMS beam size at the IP, σ^*_{xy}	55, 0.045	[µm]
Full crossing angle, θ_c	30	[mrad]
Vertical beam-beam tune shift, ξ_y	0.106	
Total beam current, I_e	395	[mA]
Bunch population, N_b	6.0×10^{10}	
Bunches per beam, n_b	13420	
Luminosity (without crab cavities) per IP, L	$2.6\ (2.3) \times 10^{35}$	[$cm^{-2}s^{-1}$]
RMS CM energy spread (without crab cavities), σ_W	13(25)	[MeV]



The FCC-ee GHC Standard Lattice & Performances

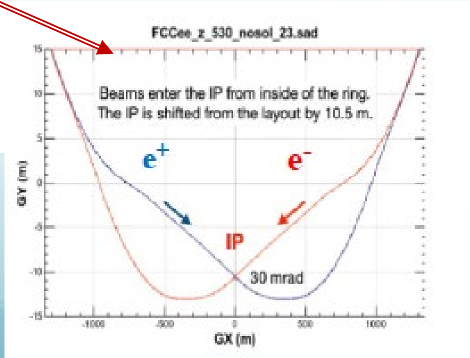
(Global Hybrid Correction)





4 IPs

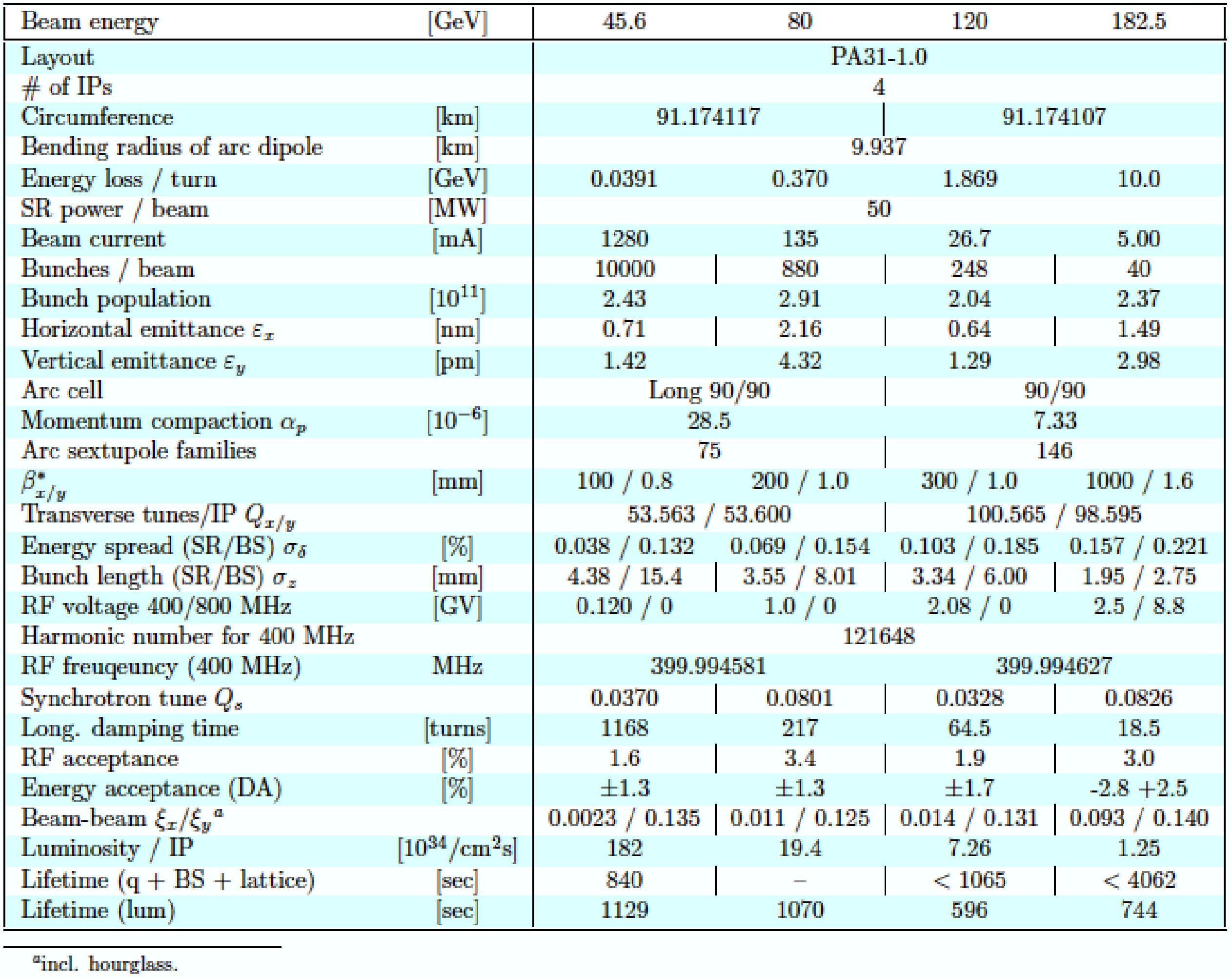
Long weak dipoles and antisymmetric IR to avoid SR



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

4 operation modes: *Z, WW, ZH, ttbar*

FCC-ee V22 GHC Performance Table



Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		10000	880	248	40
Bunch population	[10^{11}]	2.43	2.91	2.04	2.37
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	100 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.038 / 0.132	0.069 / 0.154	0.103 / 0.185	0.157 / 0.221
Bunch length (SR/BS) σ_z	[mm]	4.38 / 15.4	3.55 / 8.01	3.34 / 6.00	1.95 / 2.75
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.5 / 8.8
Harmonic number for 400 MHz		121648			
RF freuqeuncy (400 MHz)	MHz	399.994581		399.994627	
Synchrotron tune Q_s		0.0370	0.0801	0.0328	0.0826
Long. damping time	[turns]	1168	217	64.5	18.5
RF acceptance	[%]	1.6	3.4	1.9	3.0
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y[a]		0.0023 / 0.135	0.011 / 0.125	0.014 / 0.131	0.093 / 0.140
Luminosity / IP	[10^{34}/cm^{2}s]	182	19.4	7.26	1.25
Lifetime (q + BS + lattice)	[sec]	840	–	< 1065	< 4062
Lifetime (lum)	[sec]	1129	1070	596	744

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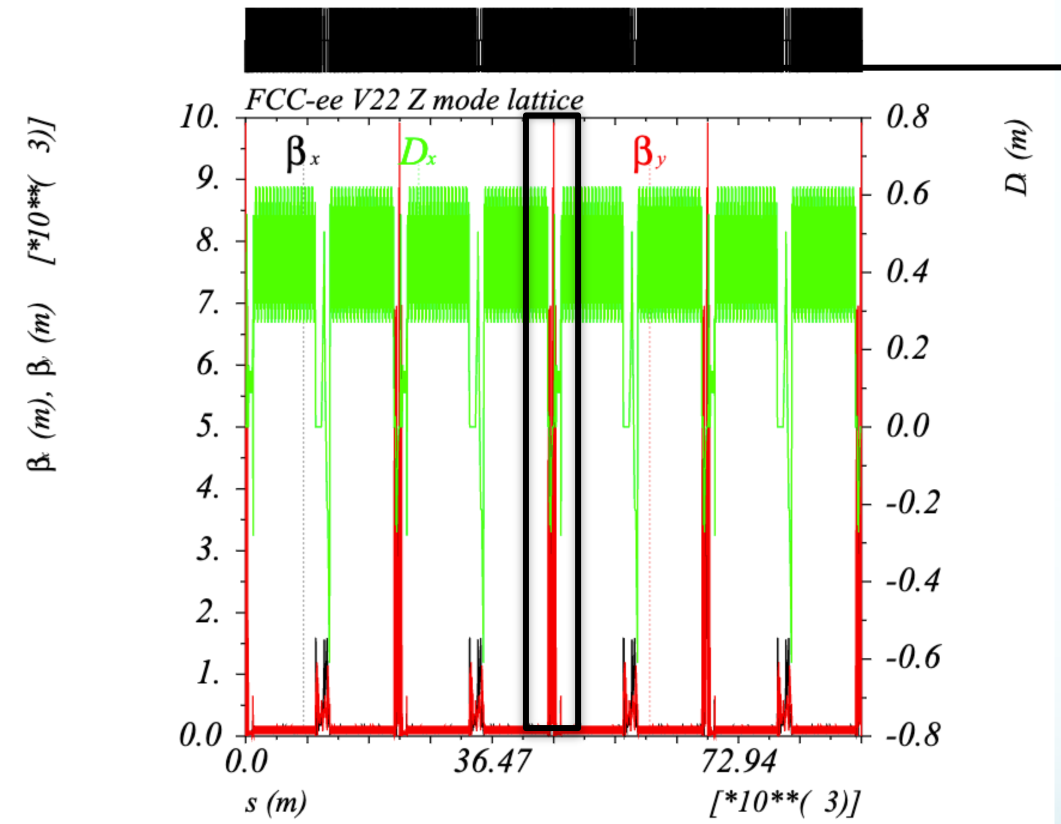
[a] incl. hourglass.

FCC-ee GHC V22 Standard Optics

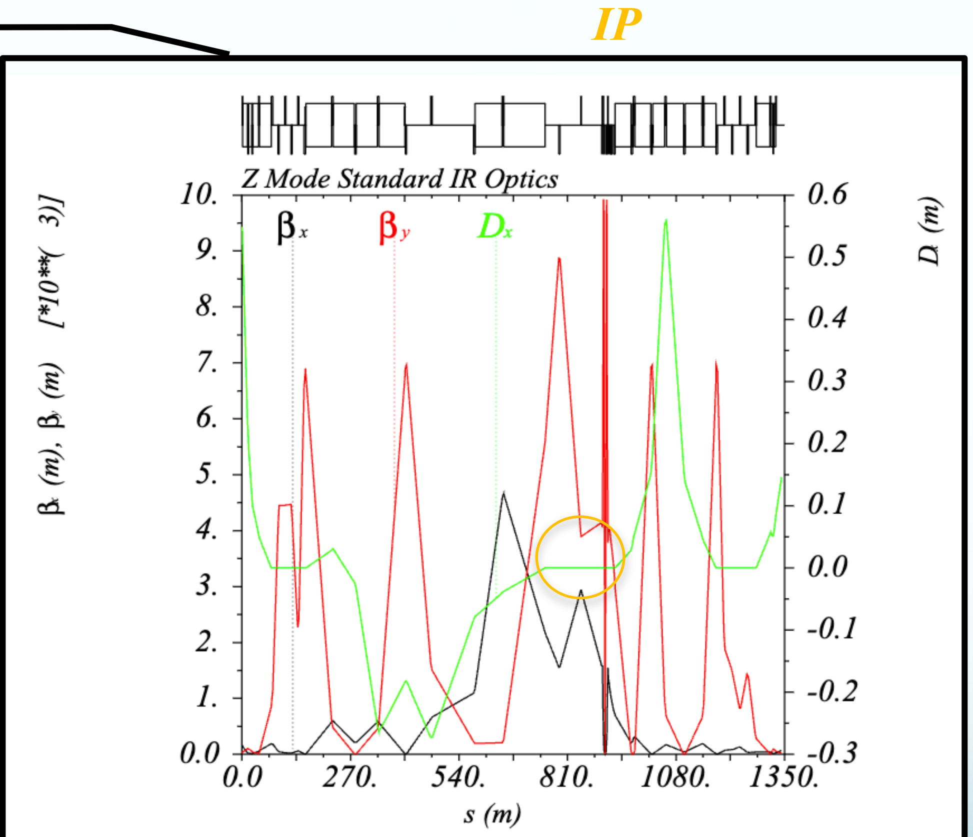
Z mode lattice with Long 90/90 arc cells



Energy: 45.6 GeV, E_x=0.71 nm, E_y=1.42 pm

IR Crab waist type Z mode Lattice

Highly asymmetric IR lattice around the IP to mitigate the SR impact



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

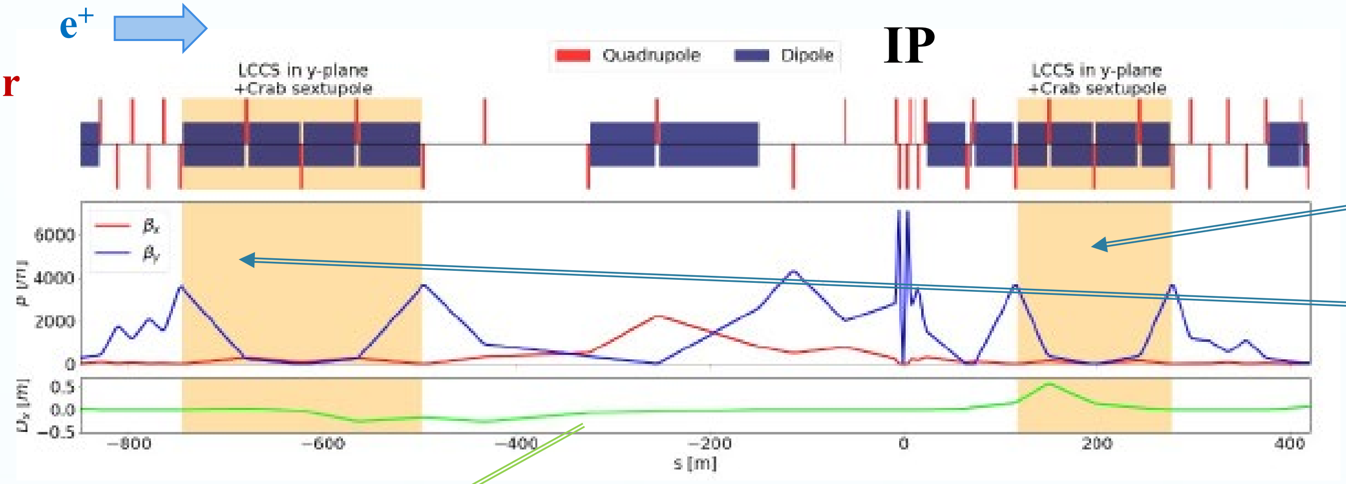
J. Keintzel, A. Abramov, M. Benedikt, M.Hofer, K.Oide et al. "FCC-ee lattice design", eeFACT2022, doi:10.18429/JACoW-eeFACT2022-TUYAT0102

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

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



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

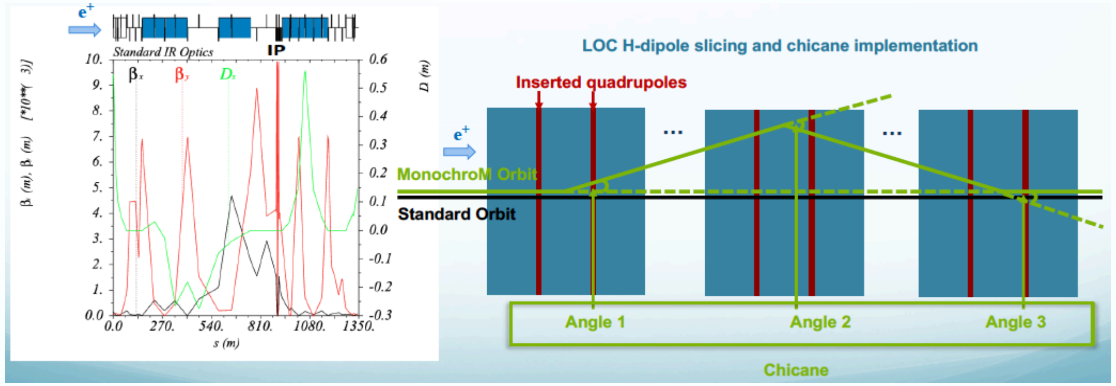
In FCC-ee IR region, the **large crossing angle of 30 mrad** in the H-plane and the **LCCS** is made possible with **H-dipoles** at the two sides of the IP creating some **H-dispersion** D^*_x ($D_x \neq 0$ in the LCCS and $D_x = 0$ close to the IP for high-luminosity). $D^*_x \neq 0$ could be generated **(~10 cm)** by **mismatching** $\boldsymbol{D_x}$ in the LCCS.

➢ $D^*_y \neq 0$ generation at the IP

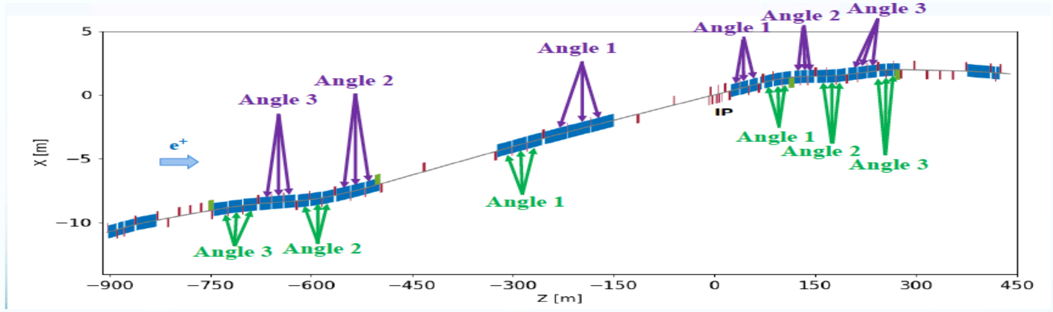
Because $\sigma^*_{y\beta} \lll \sigma^*_{x\beta}$, about **100 times smaller** $\boldsymbol{D^*_y}$ **(~mm)** is needed to get the same monochromatization factor. Therefore $\boldsymbol{D^*_y \neq 0}$ could be generated by implementing **skew quadrupoles** around IP. These quadrupoles could be located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

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

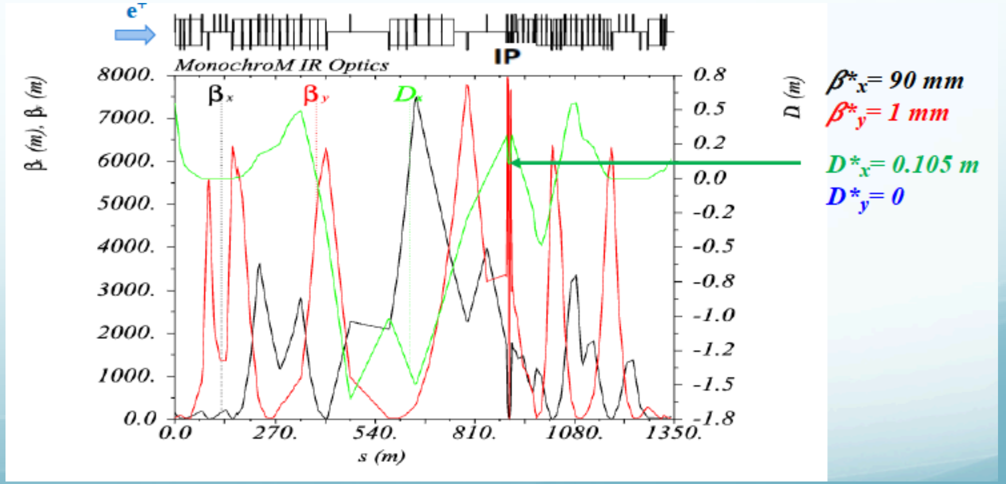
Step 1: All LCCS H-dipoles (blue) are cut into three pieces and quadrupoles (red) are inserted between them for matching flexibility. Additional chicanes are implemented in each upstream and downstream LCCS H-dipole to create the dispersion at the IP while keeping the orbit.



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.



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.



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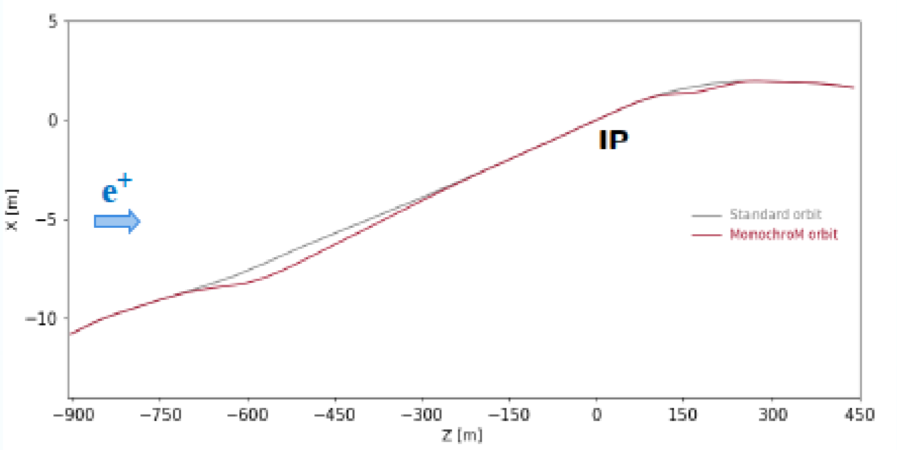
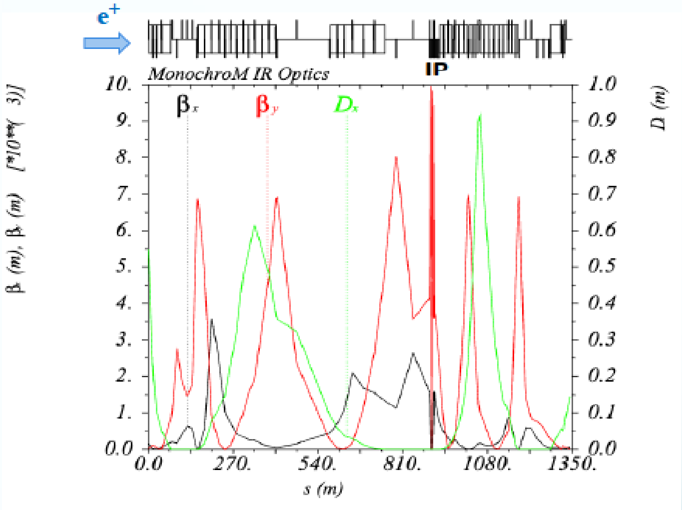
* A. Faus-Golfe, M. Valdivia Garcia, F. Zimmermann, The challenge of monochromatization Direct s-channel Higgs production: e+e− → H, Eur. Phys. J. Plus (2022) 137:31, https://doi.org/10.1140/epjp/s13360-021-02151-y

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

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

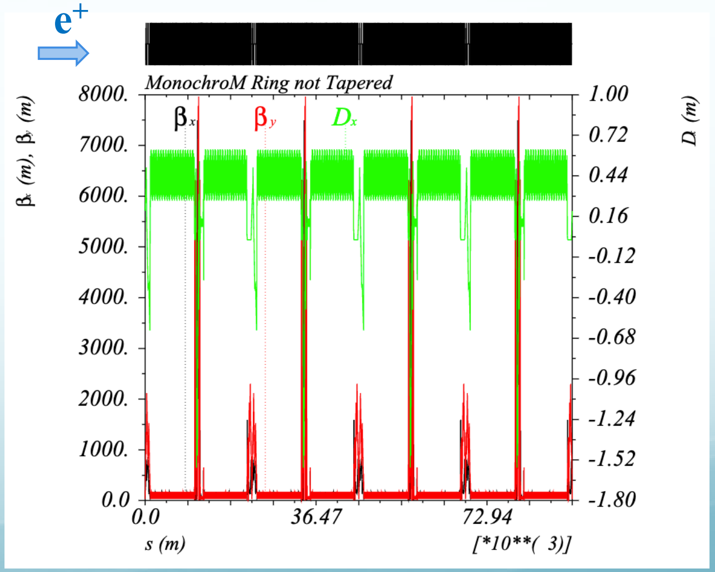




β^*_x= 100 mm β^*_y= 0.8 mm D^*_x= 0 D^*_y= 0

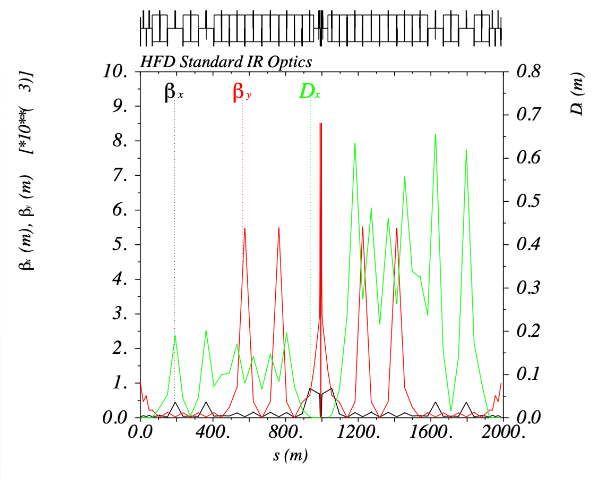
Step 5: IR Monochrom is implemented in the four IPs and global matching:

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



V-Monochrom Implementation in FCC-ee GHC IR

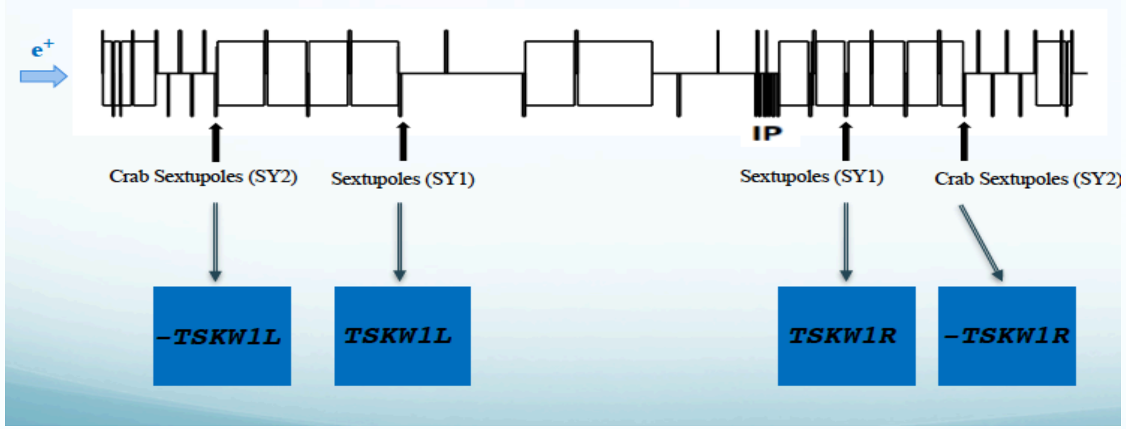
Step 1: Therefore $D^*_y \neq 0$ could be generated by implementing **skew quadrupoles** around IP. These quadrupoles could be located where the CS pairs are located in the LCC system.

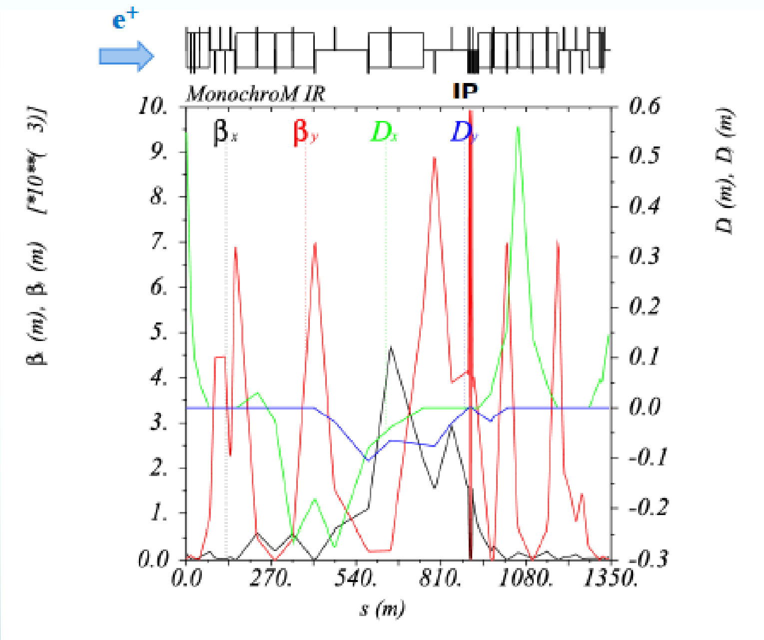


Inspired in **Local Chromaticity Correction** (LCC) IR optics solenoid compensation scheme

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



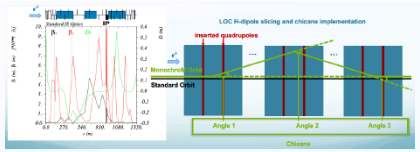


$\beta^*_x = 100$ mm $\beta^*_y = 0.8$ mm $D^*_x = 0$ $D^*_y = 1$ mm

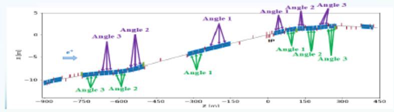
HV-Monochrom Implementation in FCC-ee GHC IR

D^*_x

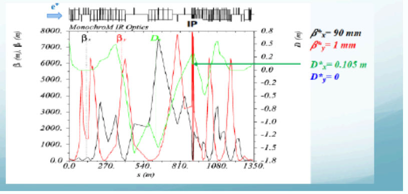
Step 1: All LCCS H-dipoles (blue) are cut into three pieces and quadrupoles (red) are inserted between them for matching flexibility. Additional chicanes are implemented in each upstream and downstream LCCS H-dipole to create the dispersion at the IP while keeping the orbit.



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.



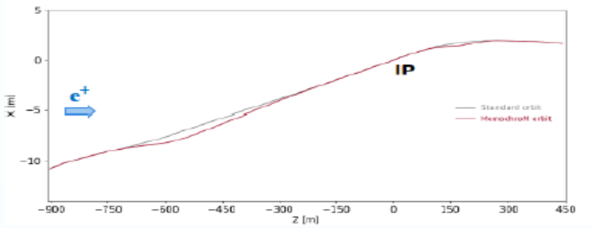
Step 3: The IP beam parameters are matched to FCC-ee Monochrom self-consistent parameters* while keeping the beam parameters at the entrance and exit of the IR similar to those of standard mode, including phase advances between sextupoles and crab sextupoles.



β^*_x = 90 mm
β^*_y = 1 mm
D^*_x = 0.105 m
D^*_y = 0

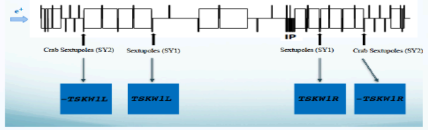
* A. Faus-Golfe, M. Valdivia Garcia, F. Zimmermann, The challenge of monochromatization Direct s-channel Higgs production: e+e− → H, Eur. Phys. J. Plus (2022) 137:31, https://doi.org/10.1140/epjp/s13360-021-02151-y

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



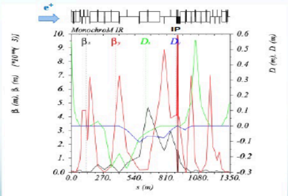
D^*_y

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.

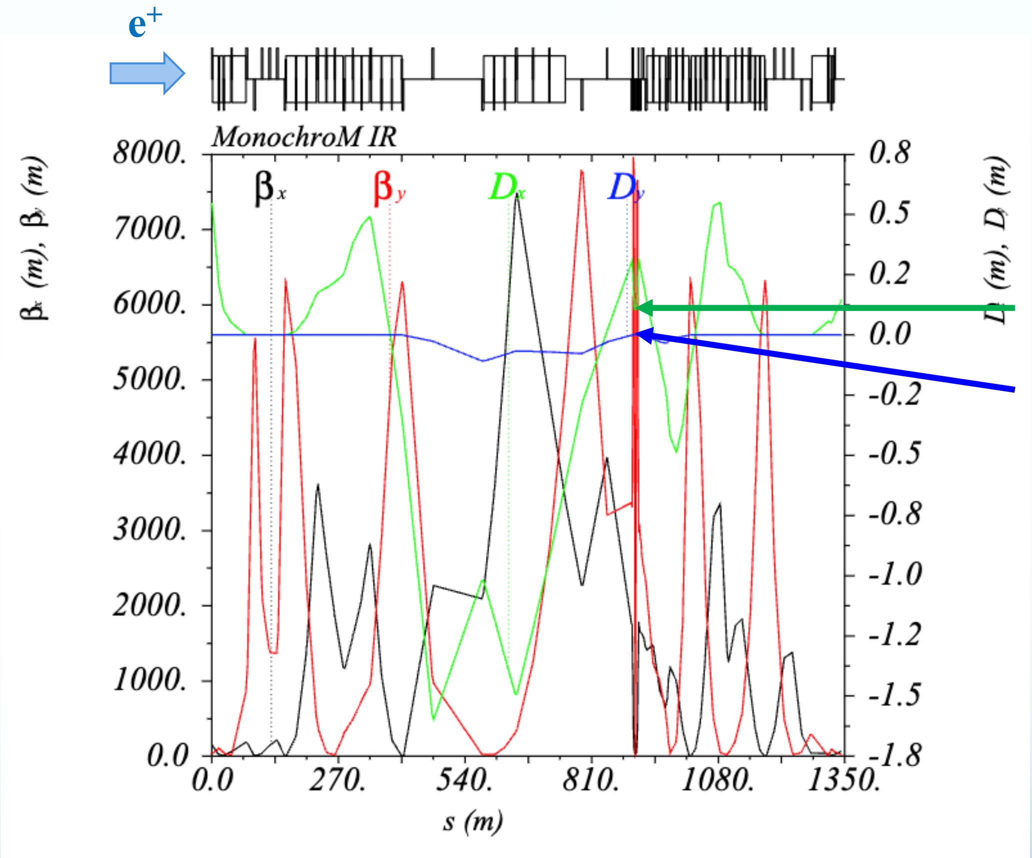


Step 2: IR Monochrom is implemented in the four IPs and global matching:

- LCCS chromaticity correction
- 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

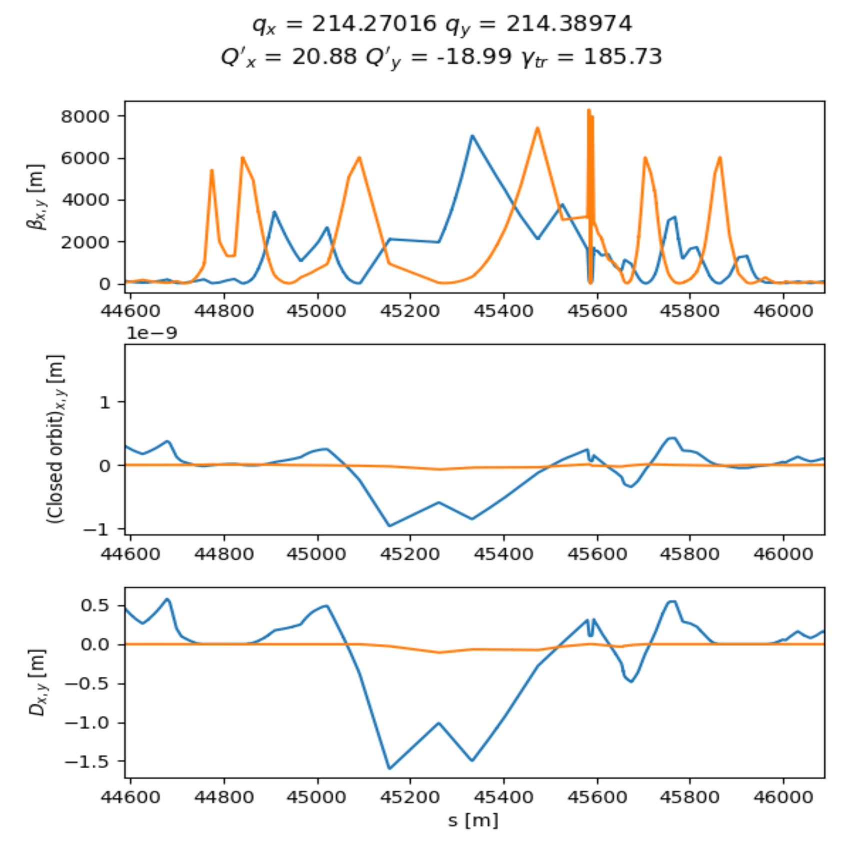


β^*_x= 90 mm
β^*_y= 1 mm
D^*_x= 0.105 m
D^*_y= 0.001 m

FCC-ee GHC Monochrom Lattices

7 kinds of **FCC-ee GHC V22 Monochrom** optics design based on **Z mode** and 7 lattices based on **ttbar mode** has been completed with different possible combination of **H**, **V**, **H/V** dispersions and number of **IPs**.

FCC-ee GHC	Orbit changed or not	D_x*	D_y*
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_hv	Yes	0.105 m	0.001 m



Xsuite Monochrom mixed based on Z mode lattice.

MADX - Methodical Accelerator Design. http://madx.web.cern.ch/madx/
Xsuite. https://xsuite.readthedocs.io/

FCC-ee GHC Monochrom Performance (I)

- **FCC-ee GHC Monochrom Optics Performance based on Z mode lattice (w/o BS effect)**

Parameters	Units	Standard	Standard_625	Monochrom_h_4ip	Monochrom_h_2ip	Monochrom_h_d0	Monochrom_v_1	Monochrom_v_2	Monochrom_hv
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

FCC-ee GHC Monochrom Performance (II)

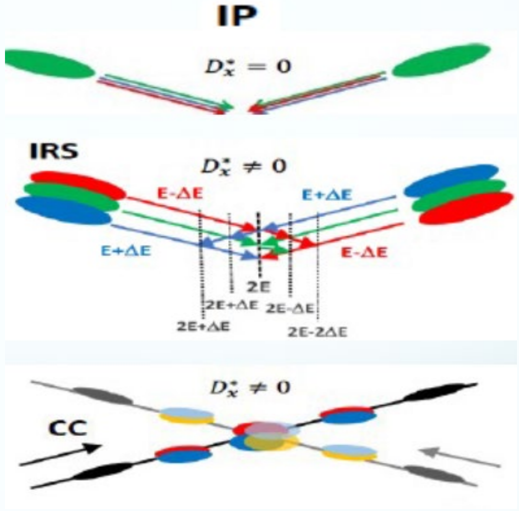
- **FCC-ee GHC Monochrom Optics Performance based on ttbar mode lattice (w/o BS effect)**

Parameters	Units	Standard	Standard_625	Monochrom_h_4ip	Monochrom_h_2ip	Monochrom_h_d0	Monochrom_v_1	Monochrom_v_2	Monochrom_hv
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

FCC-ee GHC Monochrom Luminosity and CM Energy Spread (I)

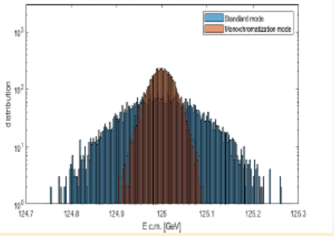
Luminosity and **CM Energy Spread** (with BS) calculated with Guinea-pig for FCC-ee GHC monochom based on **Z mode** lattice for: **monochrom crab cavities (CC)** and **monochrom (crossing or Integrated Resonances Scan IRS)** compared to **standard (crossing)**



➢ Monochrom CC vs Standard

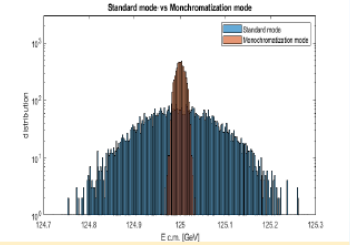
Standard_625/crossing-angle: Luminosity: 4.50×10^{35} cm^{-2}s^{-1}, CM energy spread: 80.33 MeV

- *monochrom_h_4ip/ crossing-angle*



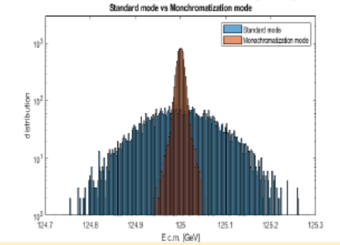
Luminosity: 2.43×10^{35} cm^{-2}s^{-1}
CM energy spread: 26.61 MeV

- *monochrom_v_1/ crossing-angle*



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

- *monochrom_mix/ crossing-angle*

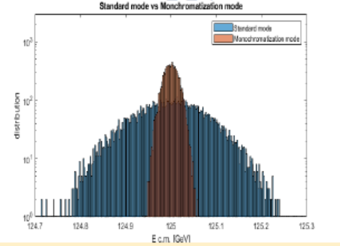


Luminosity: 6.46×10^{34} cm^{-2}s^{-1}
CM energy spread: 7.31 MeV

➢ Monochrom IRS vs Standard

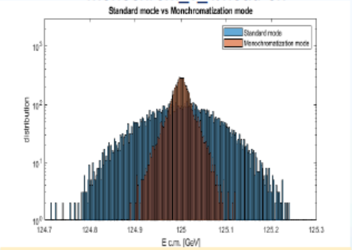
Standard_625/head-on: Luminosity: 1.20×10^{36} cm^{-2}s^{-1}, CM energy spread: 80.12 MeV

- *monochrom_h_4ip/head-on*



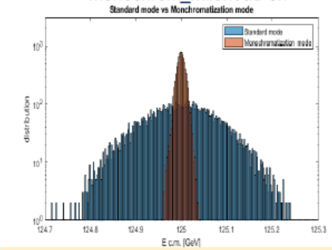
Luminosity: 2.80×10^{35} cm^{-2}s^{-1}
CM energy spread: 17.11 MeV

- *monochrom_v_1/head-on*



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

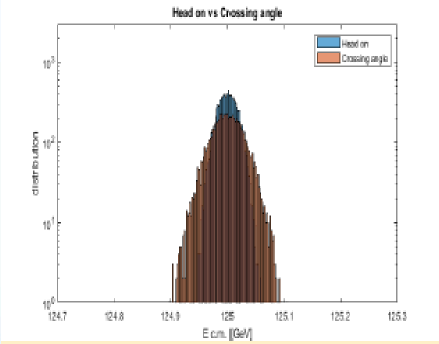
- *monochrom_mix/head-on*



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

➢ Monochrom CC vs IRS

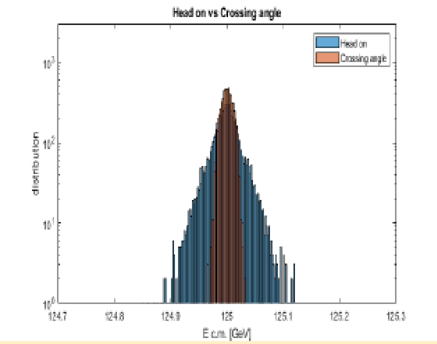
- *monochrom_h_4ip*



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*

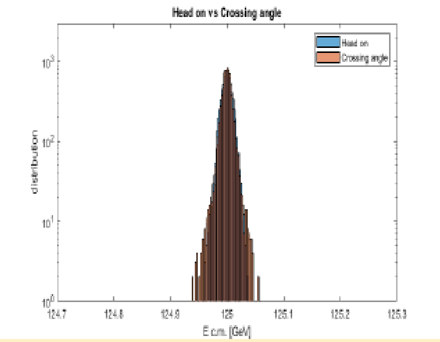
- *monochrom_v_1*



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: *Potentially face issues related to betatron coupling*

FCC-ee GHC Monochrom Luminosity and CM Energy Spread (II)

FCC-ee GHC Monochrom 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_hv
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 GHC Monochrom 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_hv
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

Monochrom optics based on ttbar mode lattice has lower CM energy spread than the one based on Z mode lattice

FCC-ee Monochrom Physics Performance

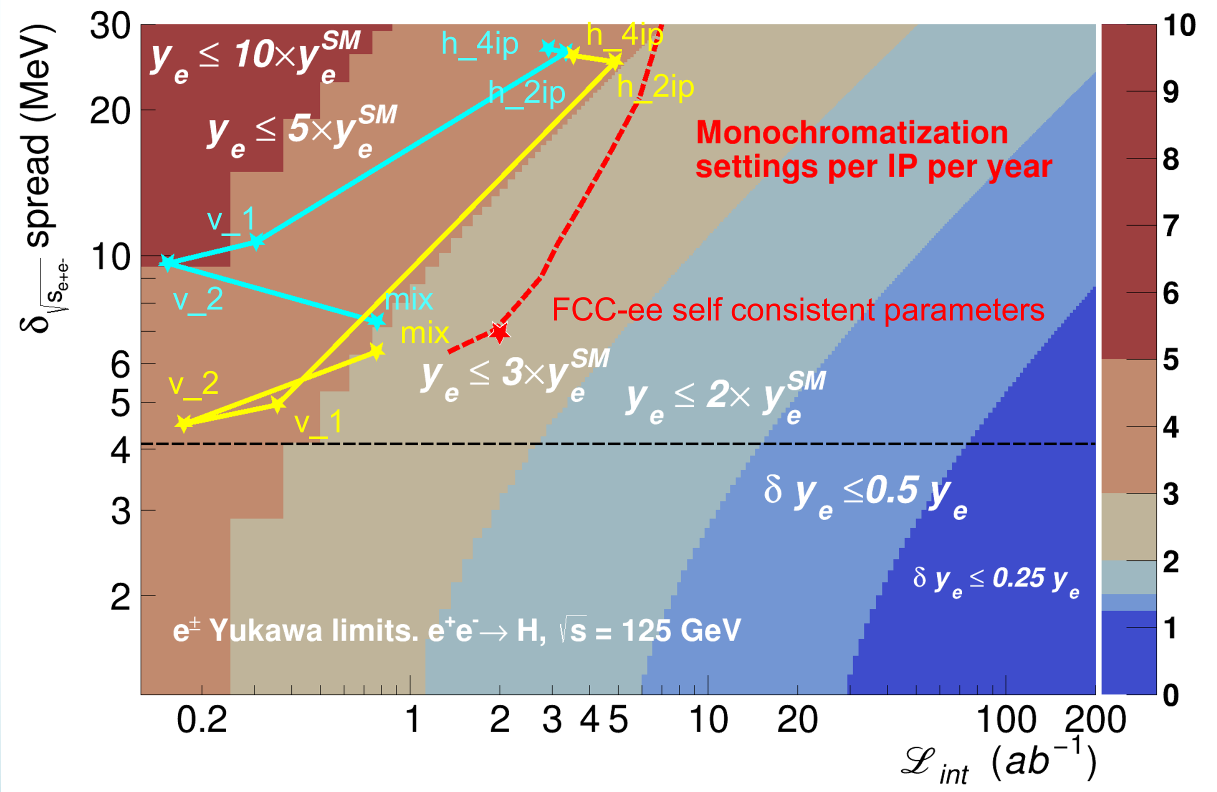
Associated upper limits contours (95% CL) on the electron Yukawa (y_e)

FCC-ee monochrom parametric studies (red line*), Z mode lattice based monochrom perfomance (light blue), ttbar mode lattice based monochrom performance (yellow).

The best performance is obtained with the **ttbar lattice** based **"mix" mode**, which reaches an upper limit of $y_e <$ 2.9*$y_e(SM)$ in the Higgs-electron coupling.

Re-optimization of the beam parameters should give better performances.

D. d'Enterria, A. Poldaru, G. Wojcik, Measuring the electron Yukawa coupling via resonant s-channel Higgs production at FCC-ee, arXiv:2107.02686v1 [hep-ex] 6 Jul 2021



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* 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

Summary and Perspectives

- Monochromatization is a **simple conceptual idea** but not easy to implement in a collider, if not integrated from the beginning in the optics IR design as a dedicated operation mode.

- However, the monochromatization principal research **never reached** a **maturity level** allowing **implementation** and **experimental testing**. A flexible lattice with two modes of operation with/without monocromatization is mandatory.

- Different **FCC-ee GHC Monochrom "realistic" optics** lattices has been completed for V22 featuring very promising performances.

- Further studies on FCC-ee GHC Monochrom lattices are needed: to evaluate the impact of the **beam-beam with** $D^*_{x,y} \neq 0$ and to optimize the DA for these new type of operation mode.

- Implementation and comparison with the LCC FCC-ee kind of lattice with more symmetric IRs will be carried out.

- Monochrom optics design for CEPC is ongoing (IR more symmetric)

- Experimental proof of monochromatization concept in running e+e- low energy colliders are under study for BEPCII (IHEP China), Daphne and maybe in SuperKEKB.

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