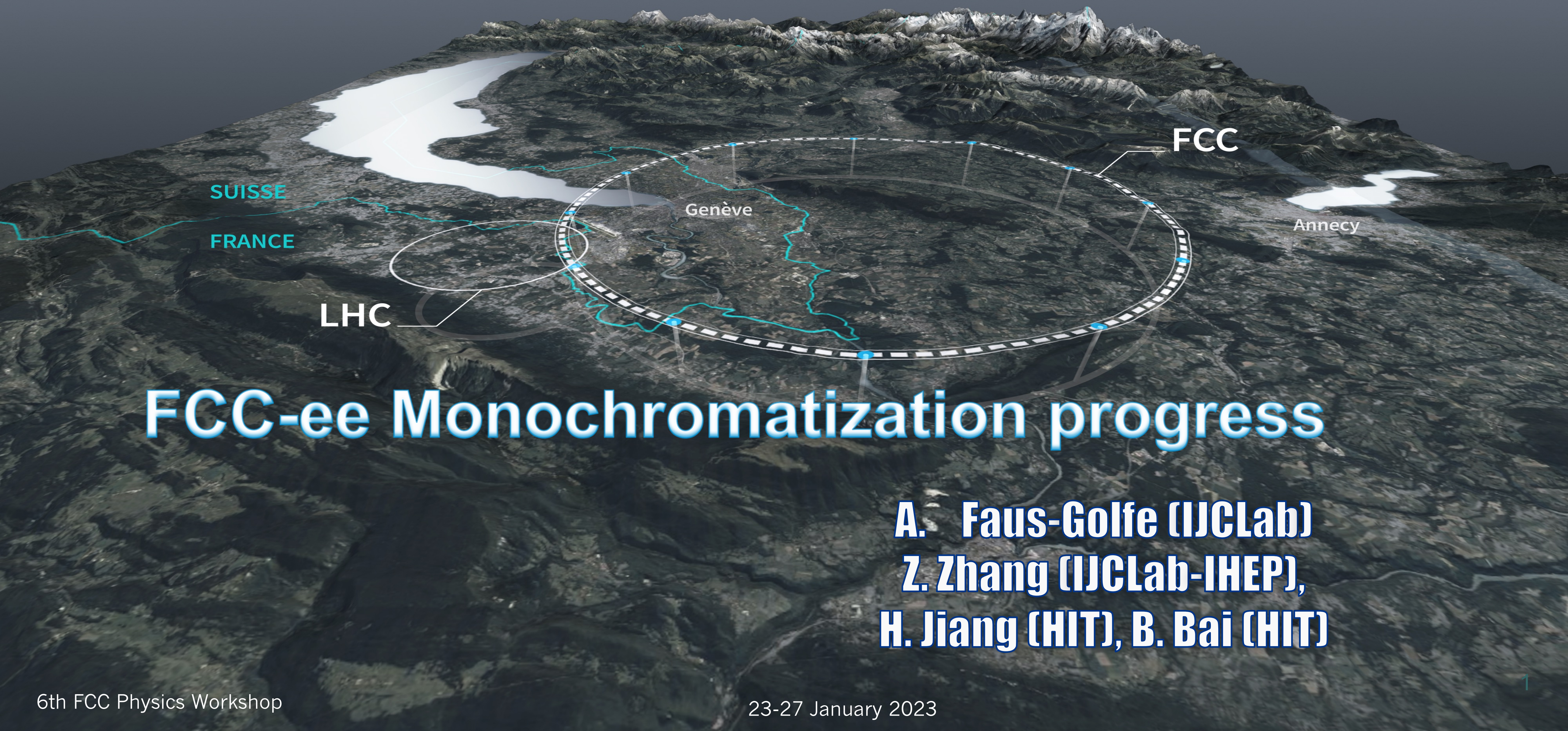


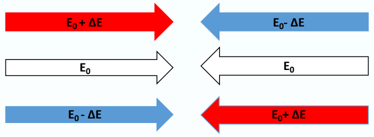
FCC-ee Monochromatization progress

A. Faus-Golfe (IJCLab)
Z. Zhang (IJCLab-IHEP),
H. Jiang (HIT), B. Bai (HIT)

6th FCC Physics Workshop
23-27 January 2023

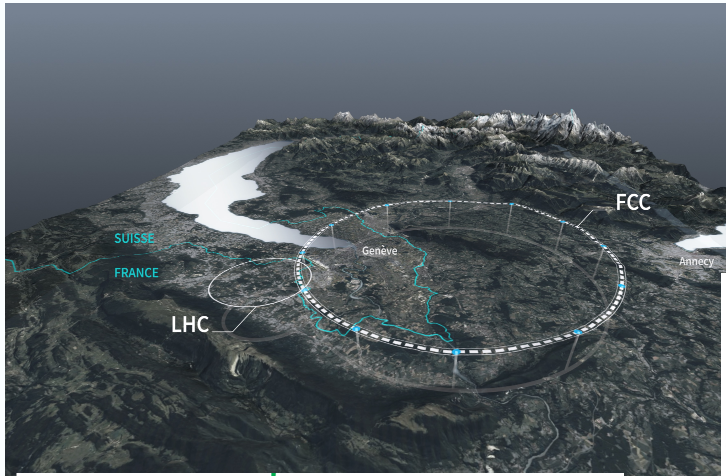
FUTURE CIRCULAR COLLIDER
Innovation Study

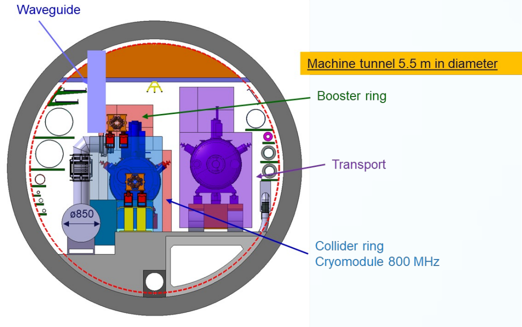
Monochromatization

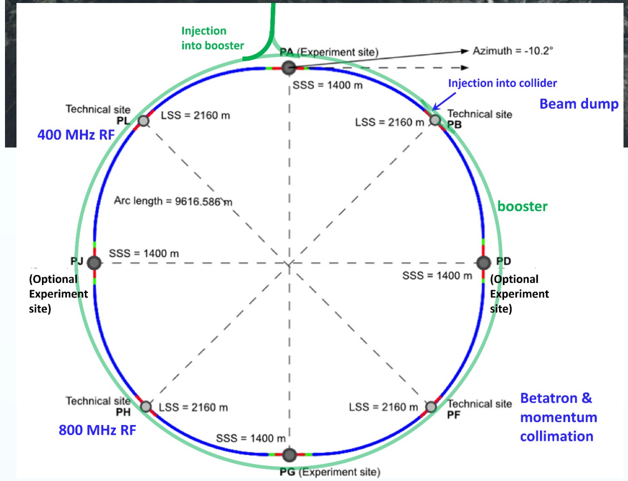


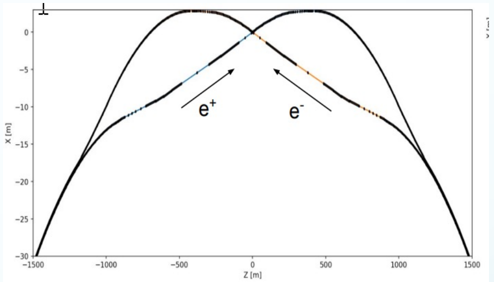
Outline

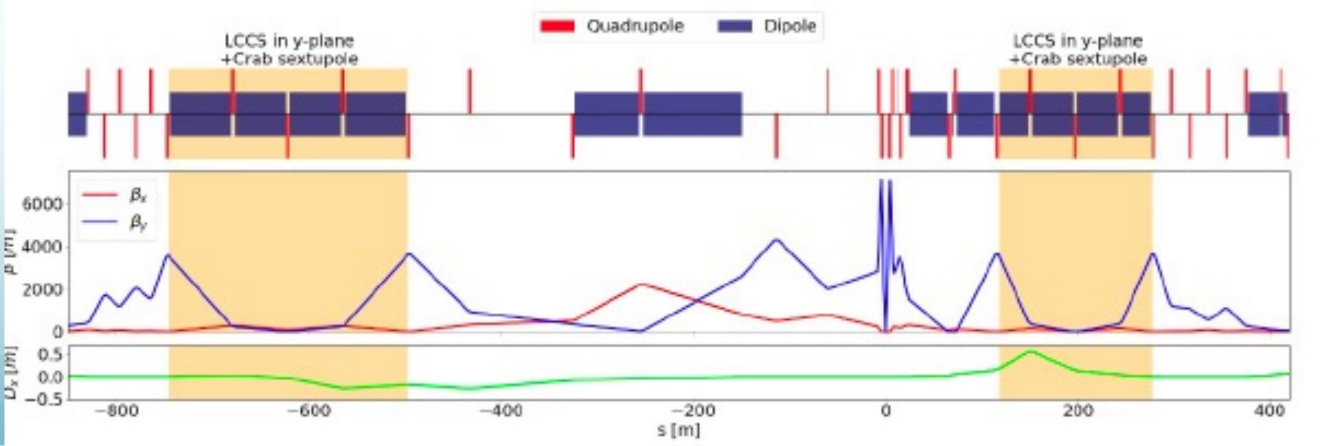
- Monochromatization concept recap
  - Low-energy
  - High-energy: FCC-ee
- FCC-ee Monochromatization performance studies
- FCC-ee Monochromatization schemes and implementation studies
- Summary and Perspectives











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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.

beam energy

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

relative beam energy spread

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

$$1/\rho$$

spread of the CM energies

$$\sigma_w \propto \frac{1}{\sqrt{\rho J_\varepsilon}}$$

$$\downdownarrows\sigma_w$$

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

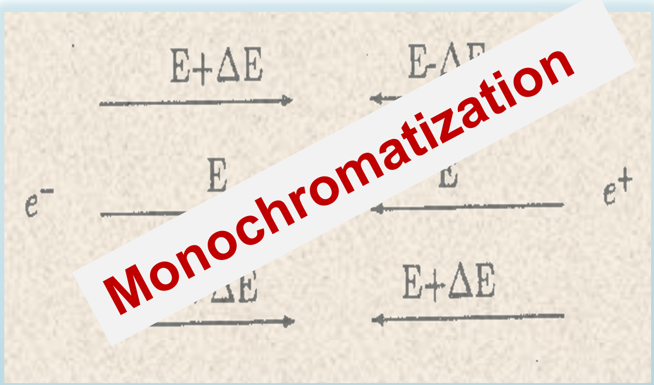
usual way

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

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



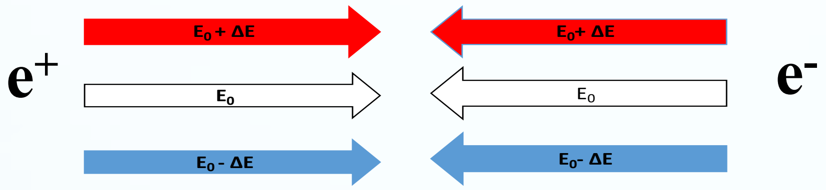
Monochromatization principle

Standard

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

correlation between transverse spatial position and energy deviation

IP



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

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

Number of bunches

Particles per bunch

Revolution frequency

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

Luminosity

betatronic beam sizes at the IP

dispersive beam size at the IP

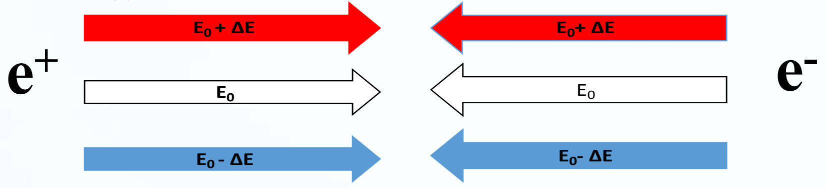
$$\sigma^*_{x,y} = \sqrt{\beta^*_{x,y}\epsilon_{x,y} + \left(D^*_{x,y}\sigma_\delta\right)^2}$$

Monochromatization principle

Standard

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

correlation between transverse spatial position and energy deviation



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

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Number of bunches

Revolution frequency

Particles per bunch

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

Luminosity

betatronic beam sizes at the IP

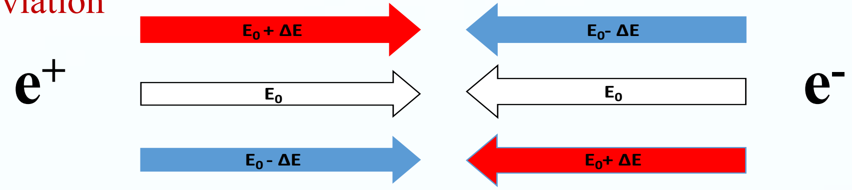
Monochromatization

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

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

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

Opposite correlations between transverse spatial position and energy deviation



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

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

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

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

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

dispersive beam size at the IP

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

Monochromatization principle

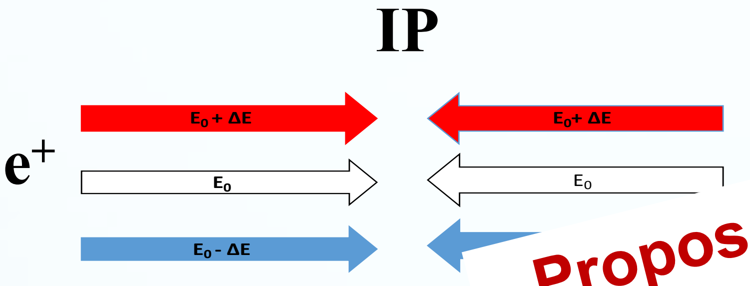
Standard $D^*_{x,y}=0$

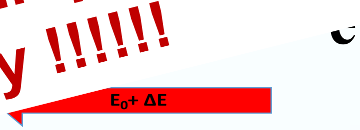
Monochromatization

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

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

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





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

$$w = 2E_b + 0(\epsilon)^2$$

CM

Monochromatization factor

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

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

A. Renieri. Possibility of Achieving Very High-Energy Resolution in electron-Positron Storage Rings. LNF Report, LNF-75/6-R, 2 (1975)

Revolu

resolution, and sometimes increase of the relative frequency of the events at the centre of of the distribution.

Lu

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

Betatronic beam sizes at the IP

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

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:**

$$\sigma^*_y <<< \sigma^*_x$$

$$\text{with} \begin{cases} \beta^*_y <<< \beta^*_x \\ \varepsilon^*_y <<< \varepsilon^*_x \end{cases}$$

beam emittances

→

$$D^*_{x+} = D^*_{x-} = 0$$
$$D^*_{y+} = -D^*_{y-} = D^*_y$$

Vertical dispersion different from zero

→

$$\sigma^*_y \simeq \sigma_\varepsilon D^*_y$$
$$\xi_y << \xi_x \simeq \xi_{max}$$

beam-beam parameter

$$\xi_{xy} = \frac{N_b r_e \beta^*_{xy}}{2\pi\gamma\sigma^*_{xy}(\sigma^*_x + \sigma^*_y)}$$

→

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

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

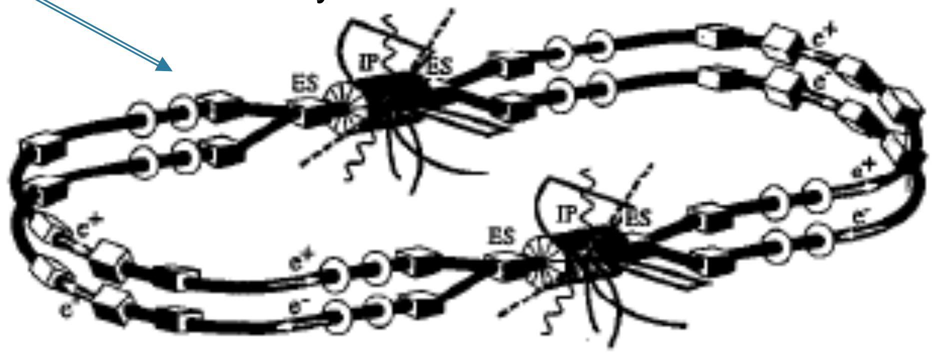
with low-horizontal emittance

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 (τ–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
- τ–charm factory: two rings, vertical dipoles, λ~7.5

τ–charm factory with monocromatization 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 colliders arcs ($\boldsymbol{\sigma_\delta = \sigma_{\delta,SR}}$). 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). Since the relative energy spread is given by:

$$\sigma^2_{\delta,coll} = \sigma^2_{\delta,SR} + \sigma^2_{\delta,BS}$$

With **monochromatization** at **high-energy**, we have to consider the fact that monochromatization **avoids** the **blow up** of the relative beam energy spread to a larger value of $\boldsymbol{\sigma_{\delta,coll}}$ due to the additional contribution from BS, which is significant in collisions with $D_x^*=0$.

To this end, we introduce the **effective monochromatization factor λ_{eff},** that compares the true **collision energy spread without and with monochromatization** (mc):

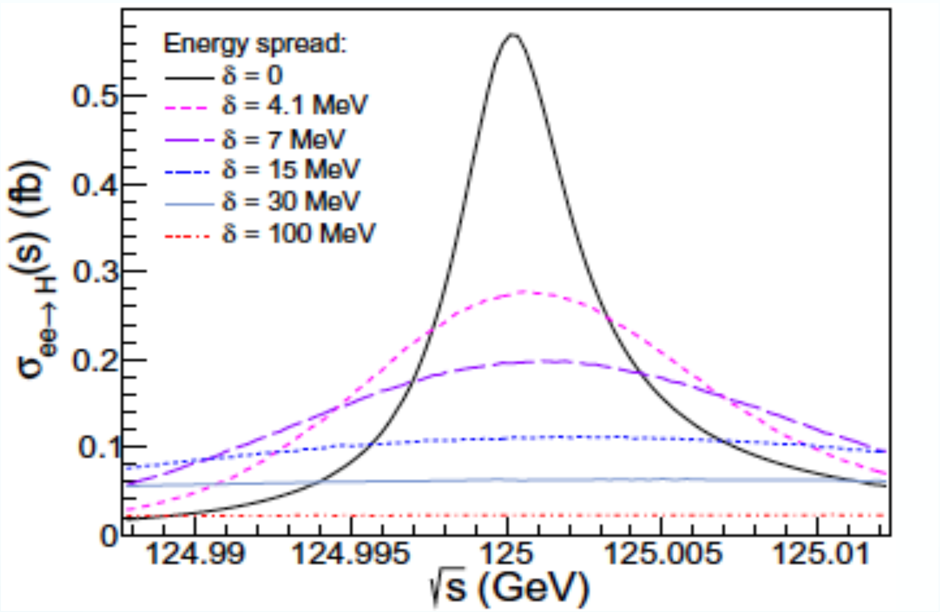
$$\lambda_{eff} = \frac{\sigma_{w,D^*=0}}{\sigma_{w,mc}} = \frac{\sigma_{\delta,coll}}{\sigma_{\delta,SR}} \left(\frac{D_x^{*2}\sigma^2_{\delta,SR}}{\epsilon_x \beta_x^*} + 1 \right)^{1/2}$$

In FCC-ee, λ_{eff} is more than two times larger than λ.

Monochromatization in FCC-ee

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

Resonant Higgs production cross section for several values of the e+e- center-of-mass energy spread.

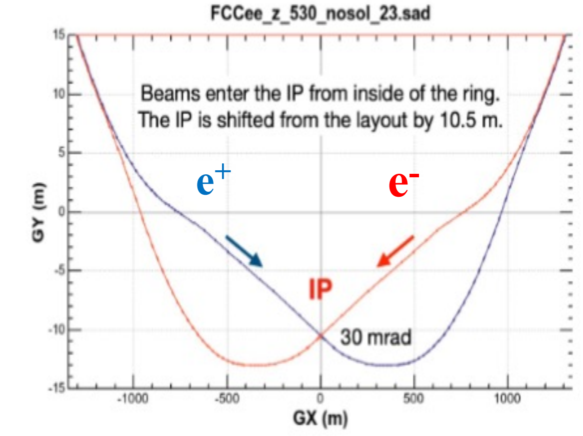


In recent years interest in **monochromatization** has been renewed, as **FCC-ee** could directly produce the Higgs boson in *s*-channel annihilation $e^+e^- \to H$. This production mode is only possible if the default collision energy spread (~ 50 MeV) can be reduced to a level comparable with the natural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

In comparison to the **previous monocromatization designs**, for the first time given the **high-energies** in **FCC-ee** the **BS become significant** contributing to **increase the energy spread**. In these conditions is convenient to introduce the dispersion in the horizontal plane (D_x^*). Wide σ_x^* **reduce** the **BS** while preserve small σ_y^* for attaining high-luminosity. Furthermore in FCC-ee, horizontal dispersion is created more easily (horizontal dipoles), since the beams are crossed in this plane.

Monochromatization in FCC-ee

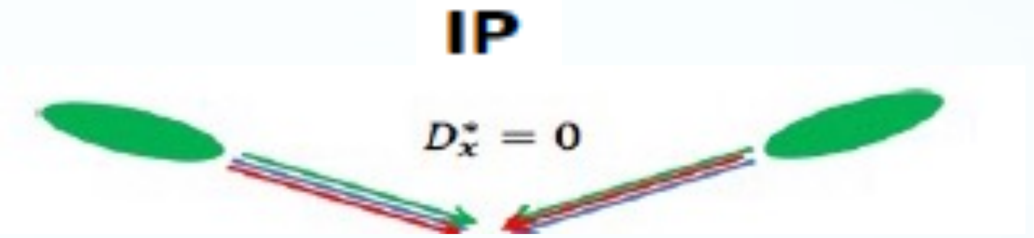
Given the **FCC-ee IR design** which features a **large IP crossing angle**, (θ_c=30 mrad), required to separate the two beams to harmful effects of parasitic collisions.

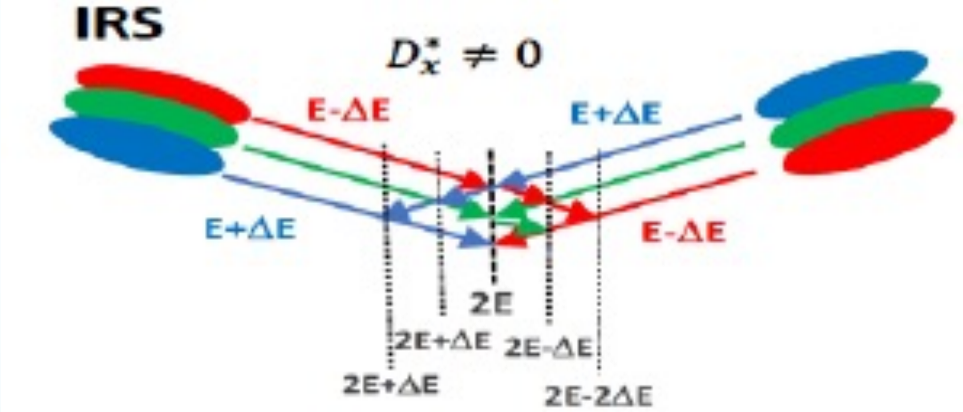


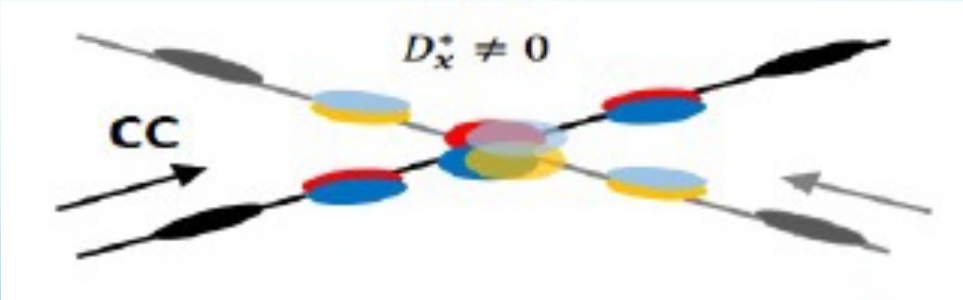
Two **monochromatization schemes** are possible. **Crossing angle** monochromatization scheme featuring **IP dispersion of opposite signs** for the colliding beams:

- Without crab crossing or **Integrated Resonances Scan (IRS)**

- **With crab crossing (CC)** head-on

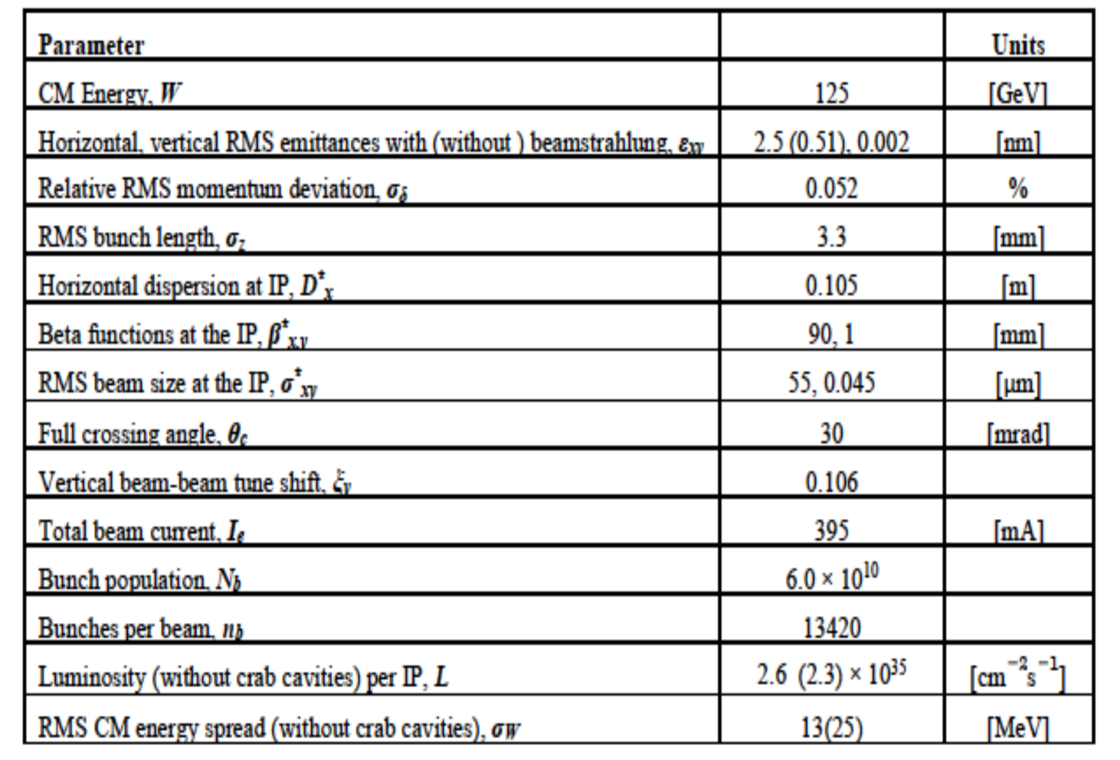






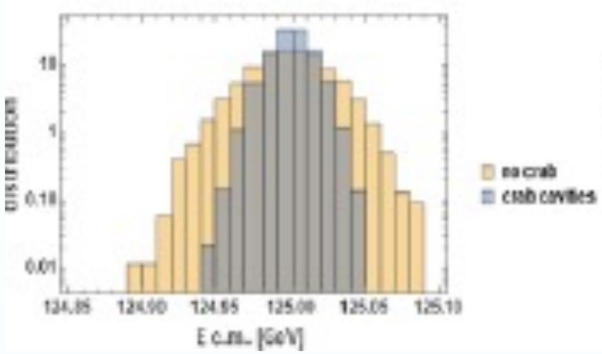
Monocromatization in FCC-ee

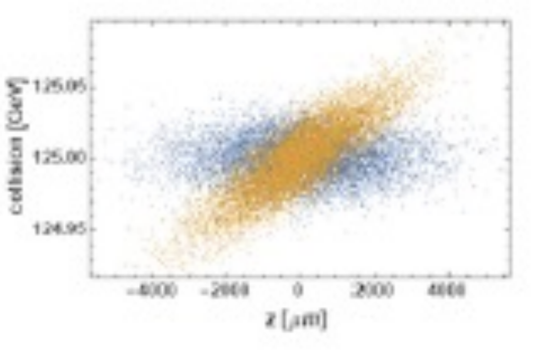
Example **IP parameters and performance** for typical **monochromatization scenario** for **FCC-ee**



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	$2.6\ (2.3) \times 10^{35}$	$[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$
RMS CM energy spread (without crab cavities), σ_W	13(25)	[MeV]

Monochromatization beam-beam simulations





CM distribution with and without crab cavities

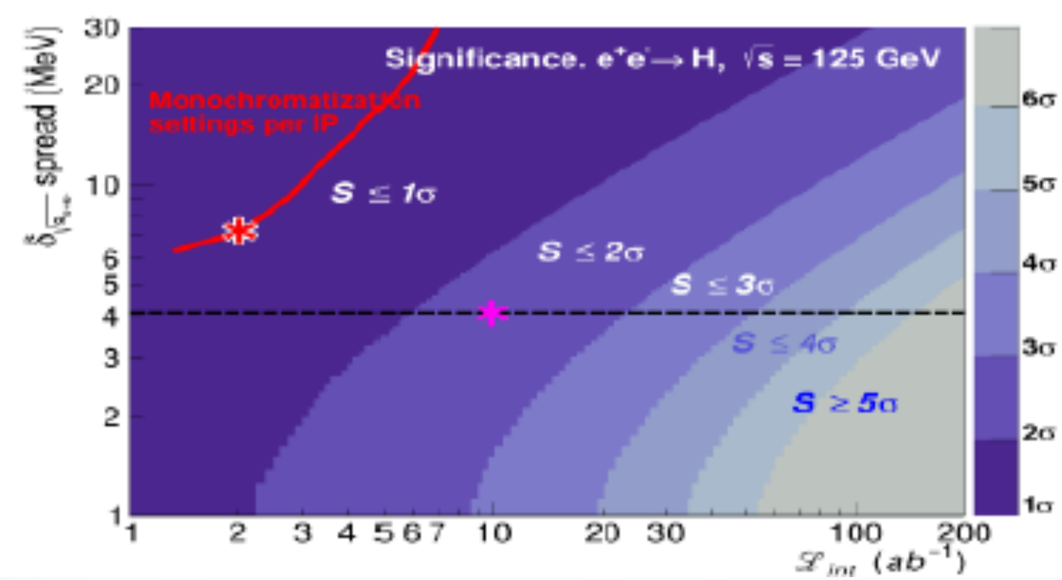
Correlation between collision energy and longitudinal position

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

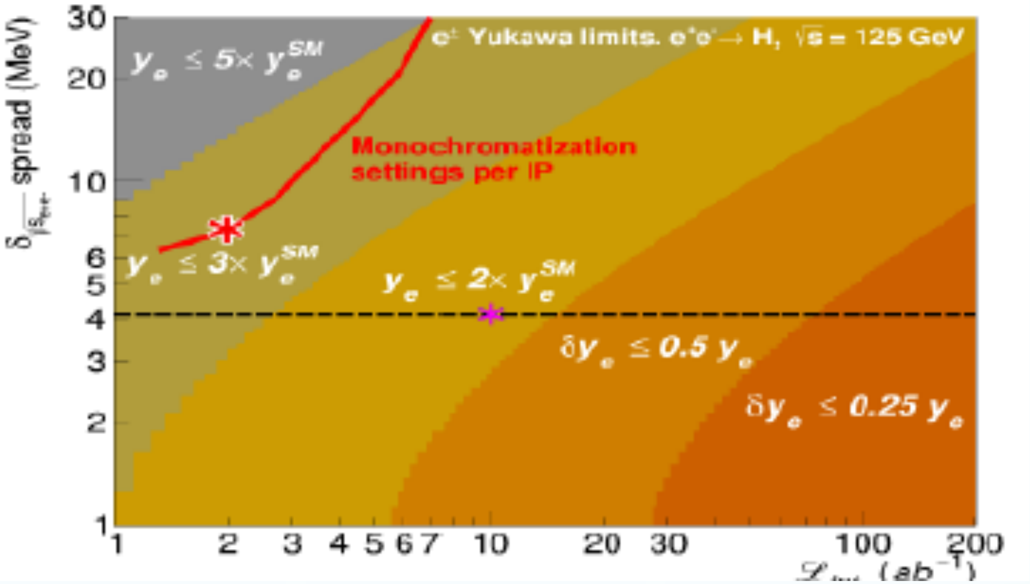
Monochromatization scheme works well both **with and without crab cavities**. In the latter case, the local RMS energy spread at the IP is the same, e.g., 13 MeV, but the total RMS spread is higher and a resonance scan is automatically performed, since the average collision energy W varies with longitudinal position.

Monochromatization in FCC-ee

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.



Significance contours (in std. dev. units σ) in the CM energy spread vs. integrated luminosity plane for the resonant σ_{e+e}−→H cross section at s = mH.

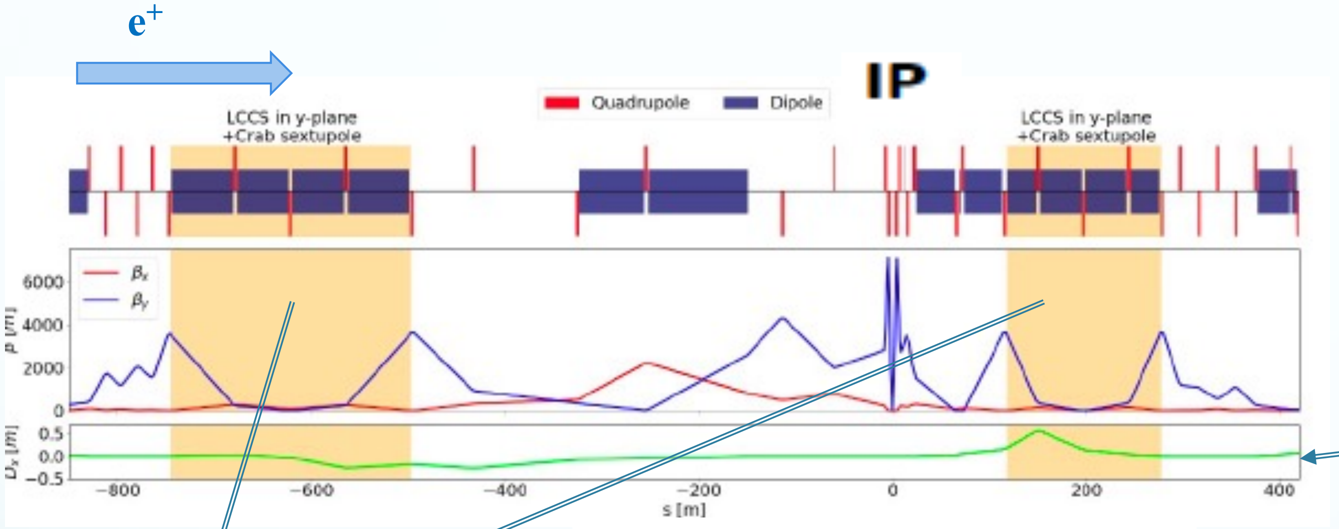


Associated upper limits contours (95% CL) on the electron Yukawa coupling y_e.

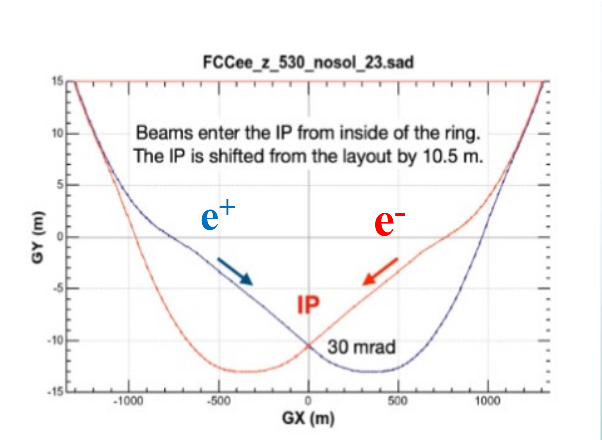
The red curves show the range of parameters presently reached in FCC-ee monochromatization studies. The red star indicates the best signal strength monochromatization point in the plane (the pink star over the δ√s = ΓH = 4.2 MeV dashed line, indicates the ideal baseline point assumed in default analysis). All results are given per IP and per year.

Monochromatization in FCC-ee

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



Local Chromaticity Correction Section (LCCS) with Crab Sextupoles (CS) to produce a crab waist collision



In FCC-ee IR region, the **large crossing angle of 30 mrad** in the horizontal plane and the **Local Chromaticity Correction Section (LCCS)** is made possible with **horizontal dipole magnets** at the two sides of the IP creating some **horizontal dispersion** (D^*_x) :

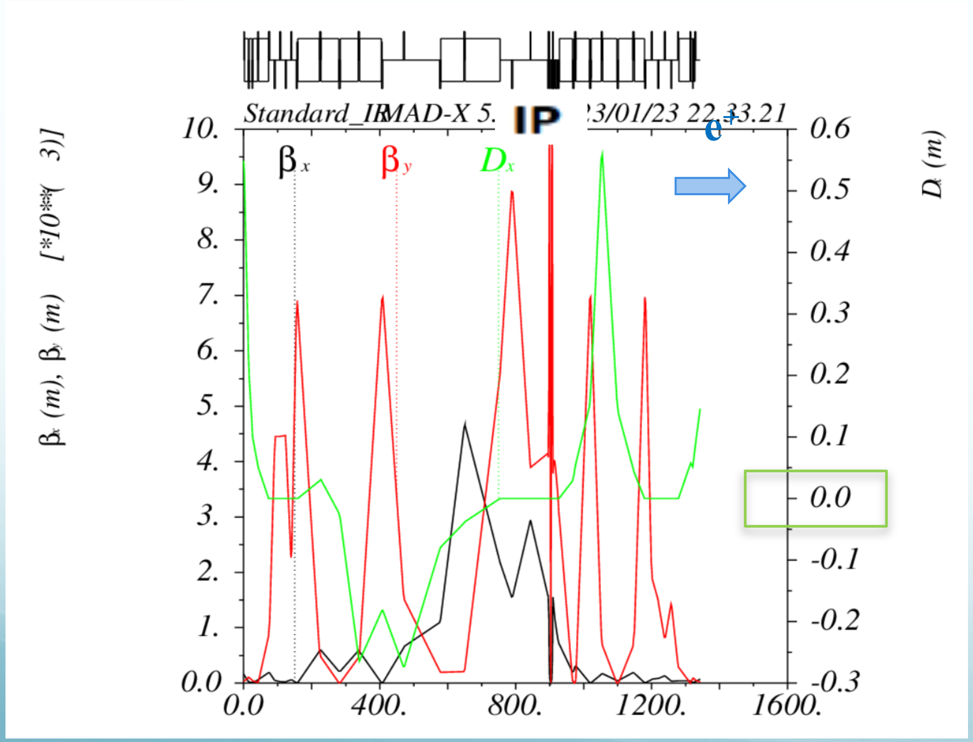
- $D^*_x \neq 0$ in the LCCS
- $D^*_x = 0$ close to the IP for high-luminosity

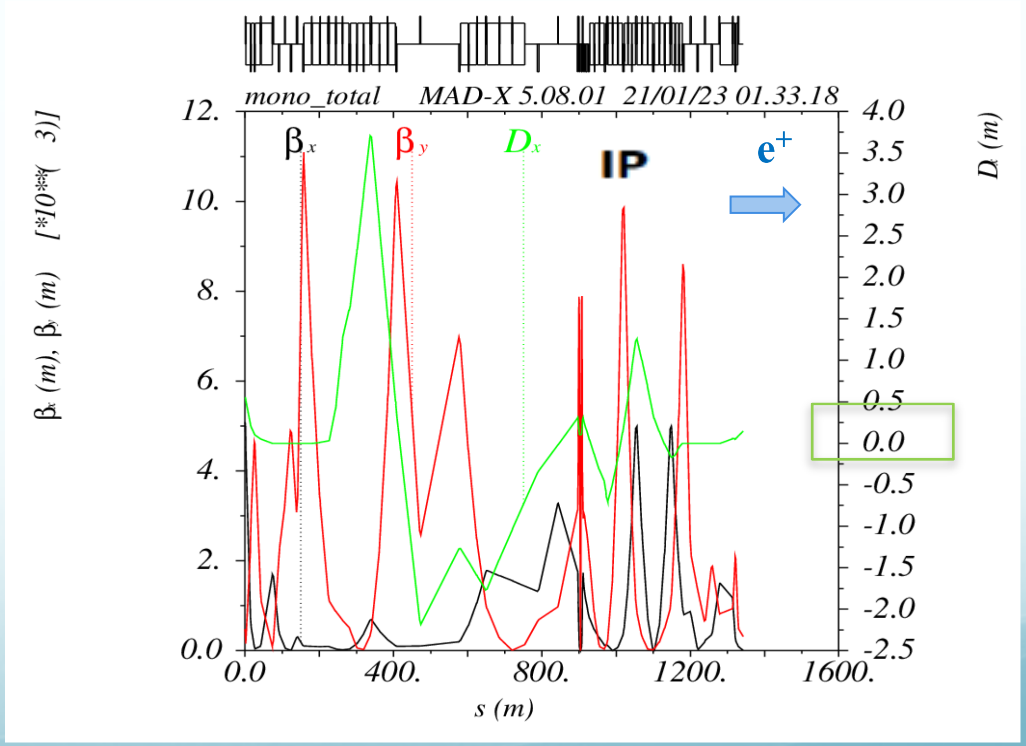
Large crossing angle (θ_c=30 mrad) at IP are required to separate the two beams to harmful effects of parasitic collisions

Monochromatization implementation in FCC-ee

Different implementation schemes are possible:

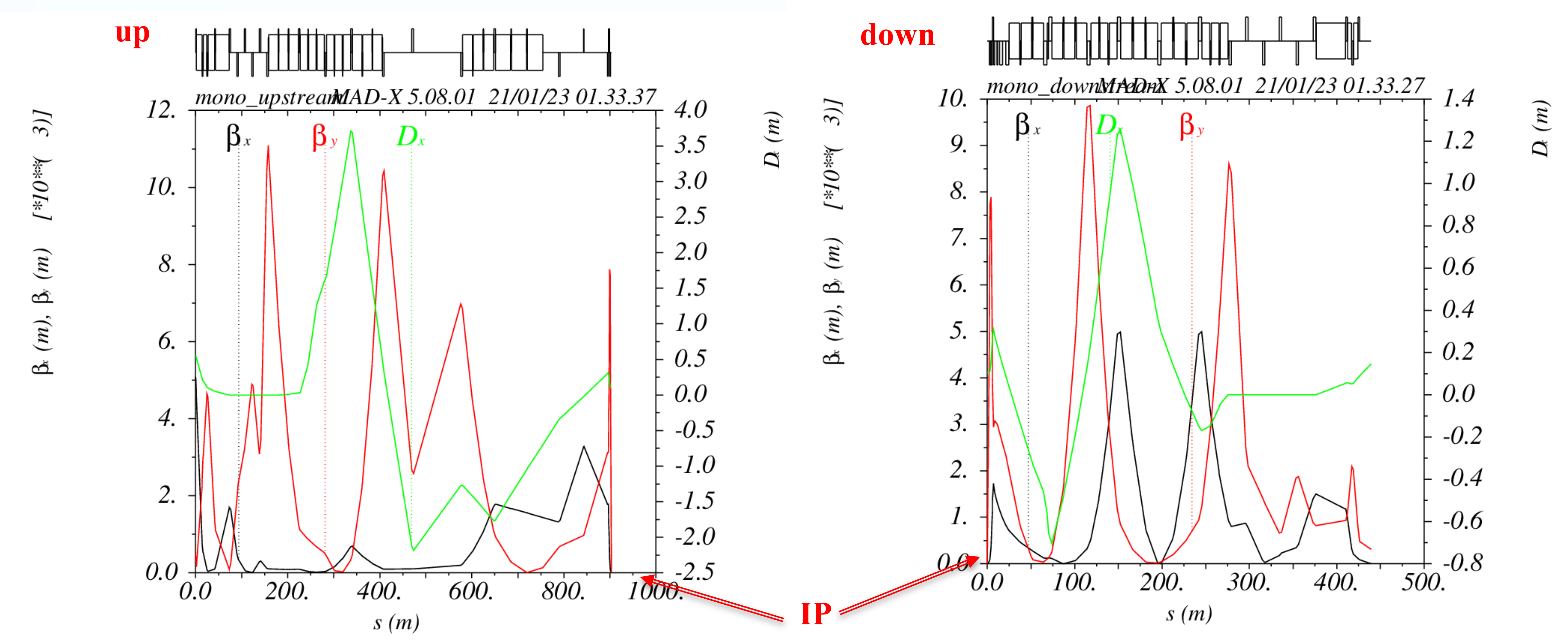
- Monochromatization with horizontal dispersion created by the already **existing horizontal dipoles** of the **IR** (crossing angle + LCCS).
  - $D^*_x = 0$ Standard Optics
  - $D^*_x = 0.1$ m Monochromatization Optics





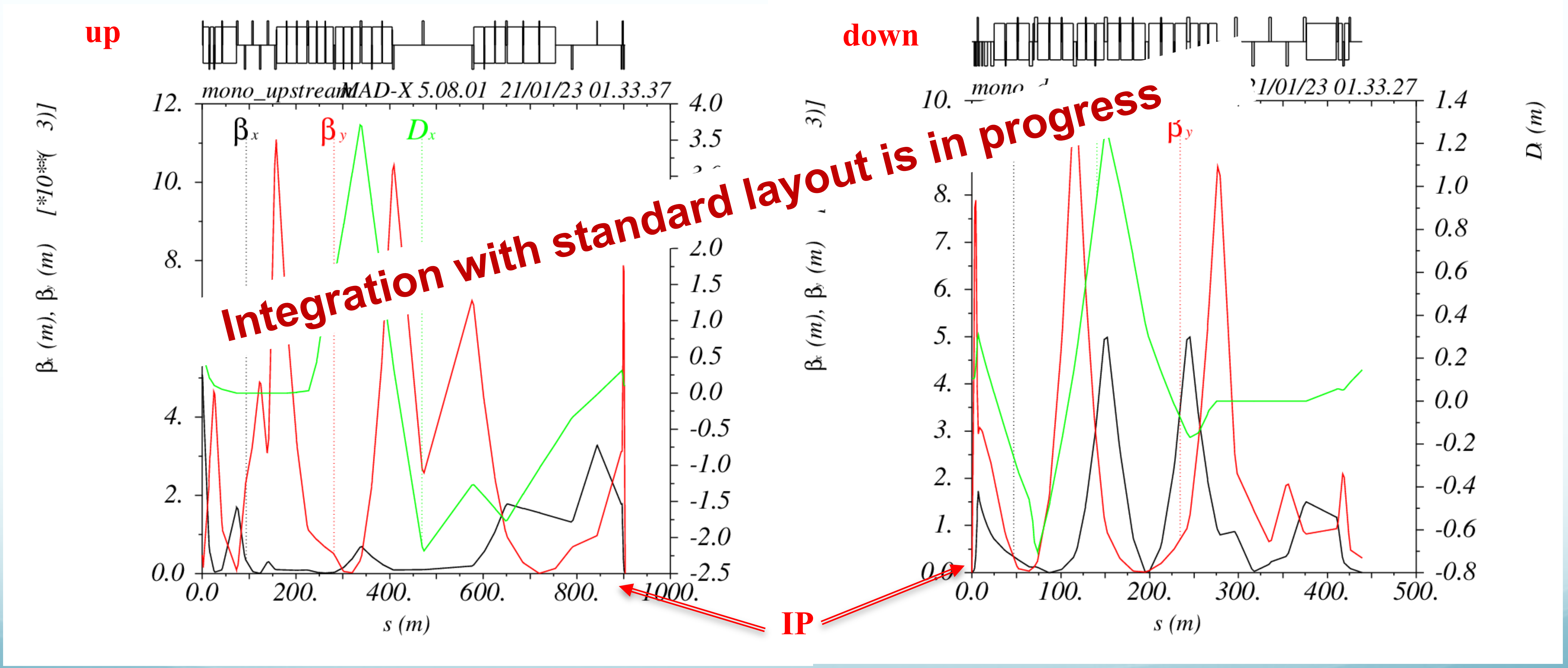
Monochromatization in FCC-ee

- $D^*_x = 0.1$ m Monochromatization Optics



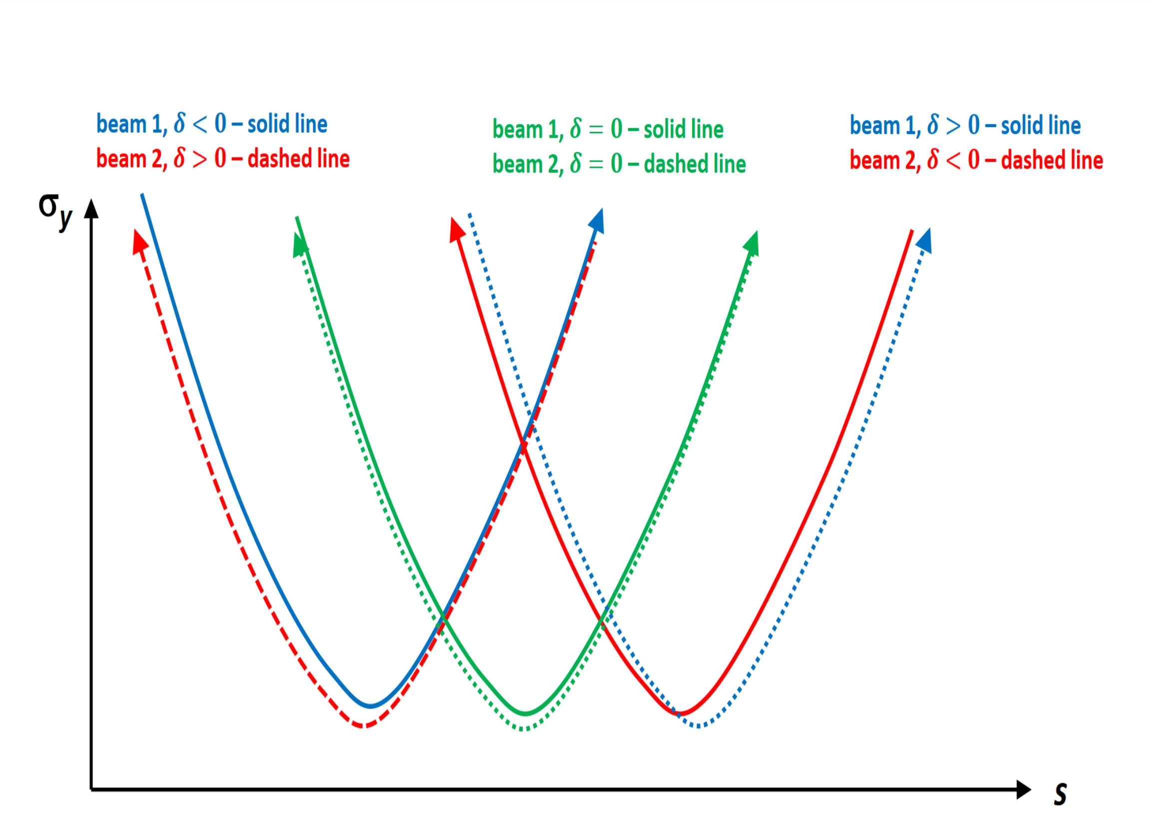
Monochromatization in FCC-ee

- $D^*_x = 0.1$ m Monochromatization Optics



Integration with standard layout is in progress

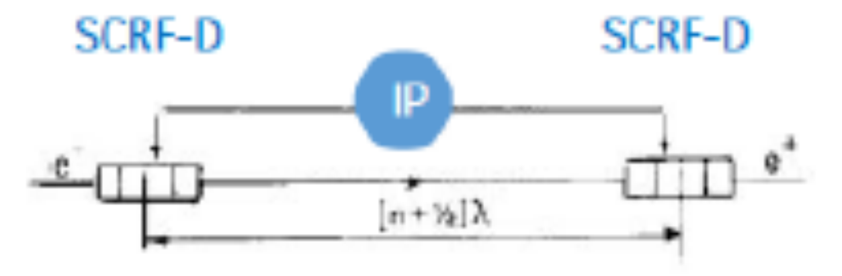
- Monochromatization could be obtained by operating with a **residual nonzero local vertical chromaticit**y (RLC). This enables the focal length of the final quadrupoles to change with the momentum deviation of a beam particle, and establishes a dependence between the vertical beam size waist and momentum offset. An effective monochromatization could be obtained, without adding any new hardware. The resulting monochromatization factor will be enhanced for smaller β_y^*, but limited λ possible.

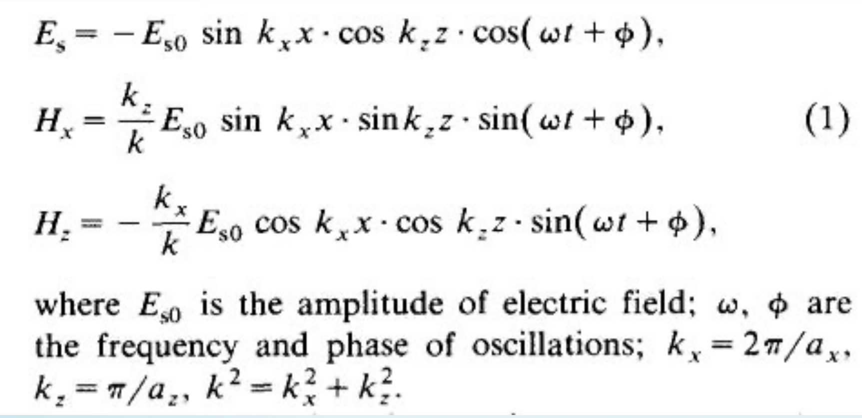


Waist location for beam 1 with momentum offset δ, can be made to coincide with the waist location for beam 2 with momentum offset -δ, leading to an effective monochromatization, without adding any new hardware.

P. Raimondi, F. Zimmermann, private communication

- Monochromatization with **dispersion inside the deflecting RF cavities (SCRF-D)** on either side of the collision point.





$$E_s = -E_{s0}\ \sin\ k_x x \cdot \cos\ k_z z \cdot \cos(\omega t + \phi),$$

$$H_x = \frac{k_z}{k} E_{s0}\ \sin\ k_x x \cdot \sin k_z z \cdot \sin(\omega t + \phi), \qquad (1)$$

$$H_z = -\frac{k_x}{k} E_{s0}\ \cos\ k_x x \cdot \cos\ k_z z \cdot \sin(\omega t + \phi),$$

where E_{s0} is the amplitude of electric field; ω, ϕ are the frequency and phase of oscillations; $k_x = 2\pi/a_x$, $k_z = \pi/a_z$, $k^2 = k_x^2 + k_z^2$.

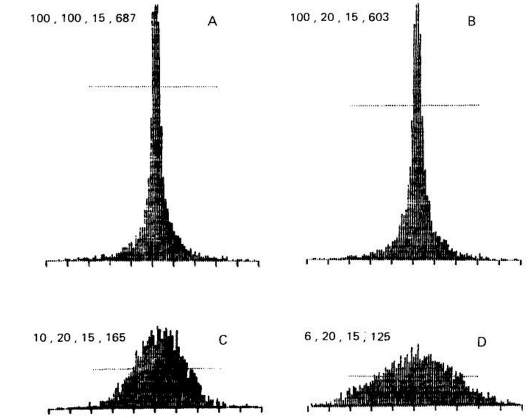


Fig. 5. Histograms of the luminosity distribution in the total energy of electron and positron collisions. The step of the histograms is 0.01 σ_t, where $\sigma_t = \sqrt{2}\,\sigma_{\Delta E/E}$ and there are 10 steps between two graduation lines. The parameters of the rf-monochromatization scheme, used in the numerical simulation, are given on each plot in the following order: κ_0, a_x/σ_{xs}, λ/σ_1. The fourth number shows the number of particles in the peak. The upper parts of the first two histograms lying above a certain level are not shown on the plot. An additional horizontal line on all the plots shows the half height of the peak.

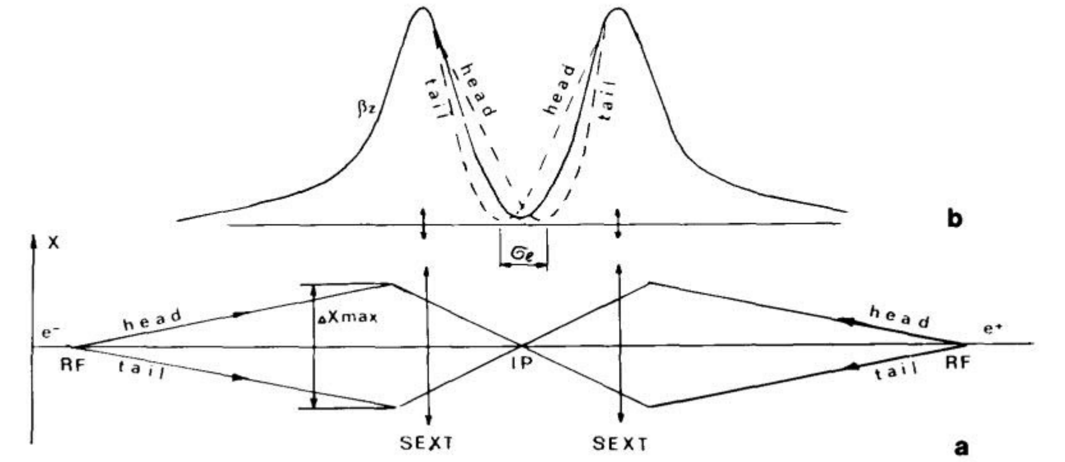


Fig. 6. a) The trajectories of the head and the tail of the bunch in the region between AS. b) The behaviour of β_z-function.

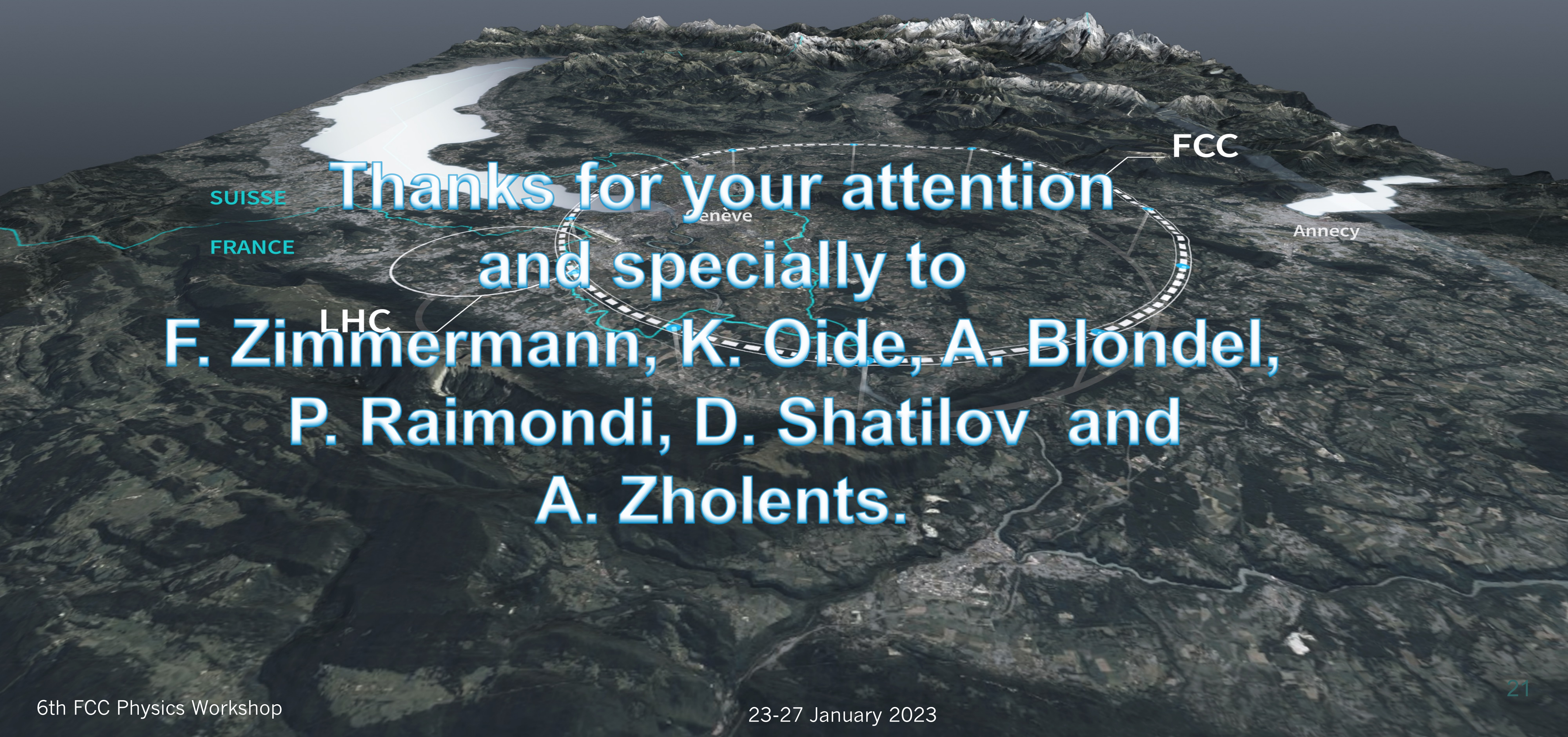
A.A. Zholents, Sophisticated accelerator techniques for colliding beam experiments. Nucl. Instrum. Methods A 265, 179–185 (1988)

Summary

- 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.
- Given the fact monochomatization has never been tested experimentally, a flexible lattice with two modes of operation with/without monocromatization is advisable.
- Monocromatization optics with IR LCCS Dipoles has been matched with D^*_x = 0.1 m, results are promising, integration in FCC-ee lattice is in progress.

Perspectives

- Further studies in FCC-ee monochromatization implementation will be made on:
  - Beam performance and main physics self-consistent parameters for monochromatized collisions and new monochromatic collision operation mode (125 MeV and 45 MeV).
  - Opics studies for monochromatization with IR LCCS dipoles (D_x^* limitations), integration and compatibility with baseline mode.
  - Non-linear beam dynamics studies including BS and SR issues for monochromatization with IR LCCS dipoles.
  - Feasibility study of crab cavities for monochromatization.
  - Alternative modes of monochromatization and combinations.
  - .....
- Performance simulation studies and possible experimental implementation for monochromatization concept in SuperKEKB are starting.



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