The implementation of monochromatization to FCC-ee

H. Jiang, A. Faus-Golfe, Z. Zhang (IJCLab)
K. Oide (KEK), F. Zimmermann (CERN)

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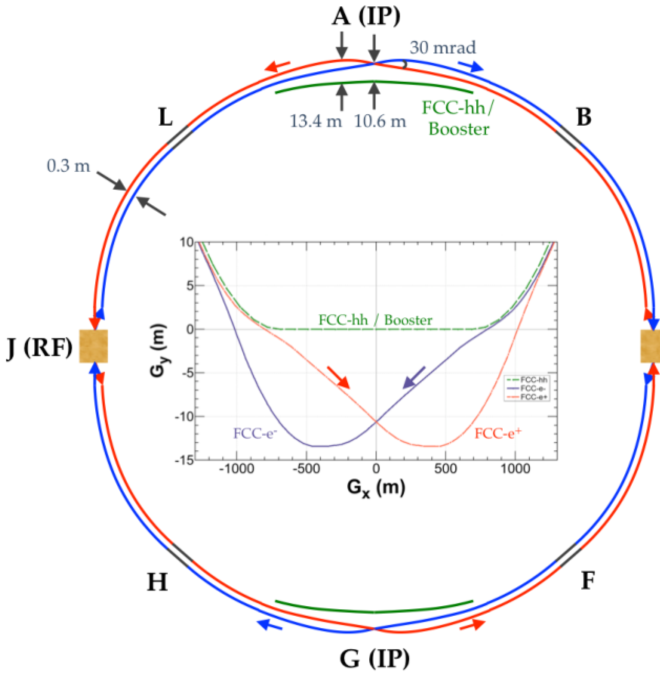
Outline

- Introductions
- Monochromatization (mono)
- The most promising mono-schemes for FCC-ee
- The drawbacks of the mono-schemes
- The continuing optimization of the mono-schemes

- FCC-ee modes:
  - The FCC-ee standard modes:
    - Four different energy operation modes: Z, WW,H(ZH) and ttbar.
  - 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 50MeV.
- **Requirements:**
  - reduce the CM energy spread from 50MeV to 5MeV, which is comparable to the resonant width of the standard model Higgs Boson itself (4.2MeV) [1]
- There is a great interest from the particle-physics community:
  - The only known pathway to measure the Yukawa coupling, an important property of the Higgs boson, and to understand the origin of the electron mass



- [1]Abada, A., Abbrescia, M., AbdusSalam, S.S. et al. FCC-ee: The Lepton Collider.

The CM energy expression：

1.Standard modes

- the energy of zero-dispersion is equal to the case of the same value dispersion at the IP:

$$w = 2(E_0 + \Delta E)$$

2.Monochromatization

- dispersion has opposite sign at the IP:

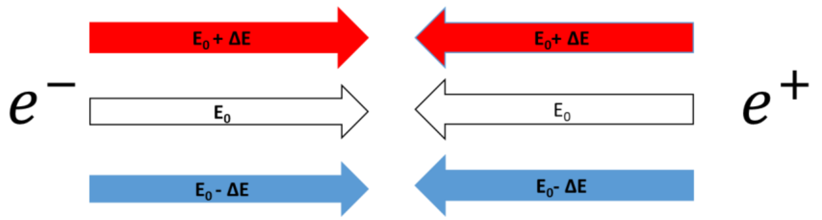
$$w = 2E_0 + O(\Delta E)^2$$

The CM collision energy spread for mono-schemes

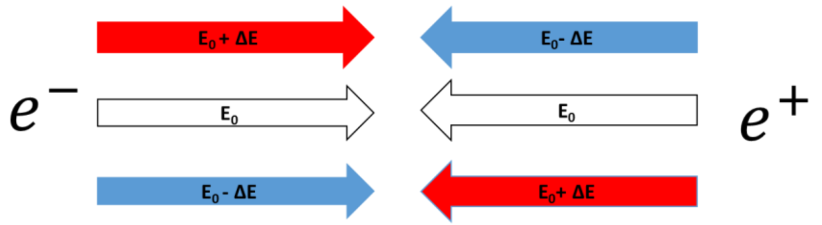
$$\left(\frac{\sigma_W}{W}\right)_{\mathrm{c.m.}} = \frac{\Delta E}{\sqrt{2}}\frac{1}{\lambda}$$

Monochromatization factor: λ

Standard modes

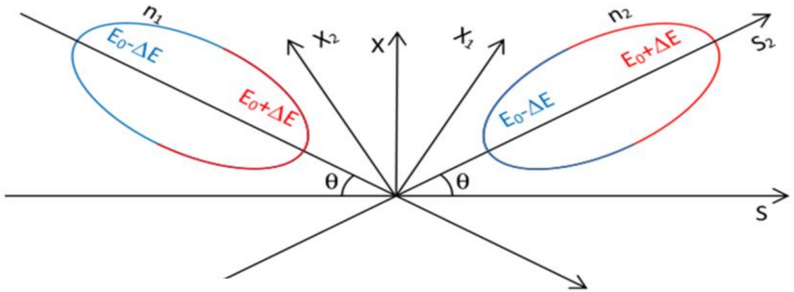


Monochromatization

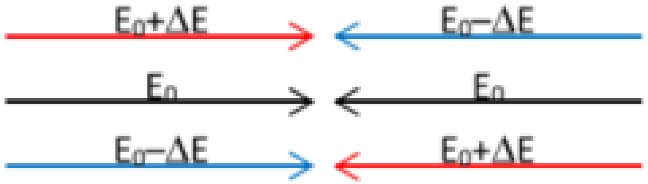


Improving the CM energy resolution

- The less feasible schemes:
  1. RF-Monochromatization scheme(A. A. ZHOLENTS et al.) [2]
     It requires an operation of the RF cavities in a transverse deflecting mode, E_{210} . Reduces the energy spread of each beam prior to the collision. Unacceptable due to the very high voltage of RF cavities.
  2. Large crossing angle (0.5rad) scheme (V. I. Telnov)[3]
     unacceptable due to the small crossing angle 30mrad and long interaction region at FCC-ee
  3. Longitudinal scheme (A. Bogomyagkov et al.) [4]
     The longitudinal correlation requires high voltage and high frequency RF system, it is hard to build.



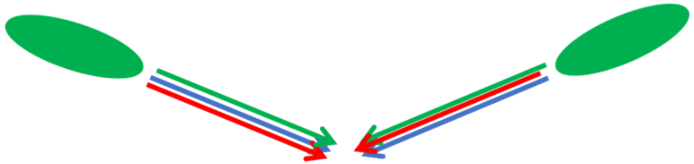
- The most promising scheme for FCC_ee
  - Transversal scheme：



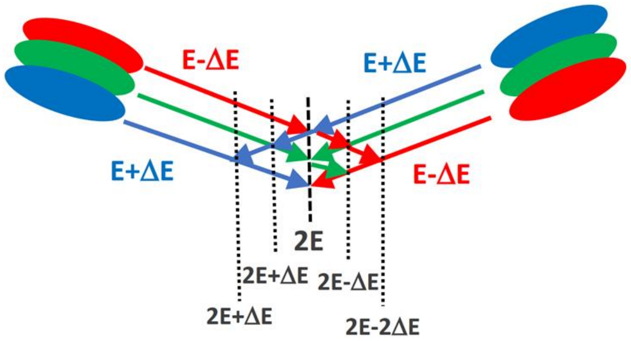
[2] A. A. Zholents, "Sophisticated Accelerator Techniques for Colliding Beam Experiments", Nuclear Instruments and Methods in Physics Research A265
[3] V. Telnov, "Monochromatization of e+e− colliders with a large crossing angle" 31.08.
[4]A. Bogomyagkov and E. Levichev, "Collision Monochromatization in e+e− Colliders", Phys. Rev. Accel. Beams 20, 051001 (2017).

The transversal mono-schemes with crossing angle and crab cavities

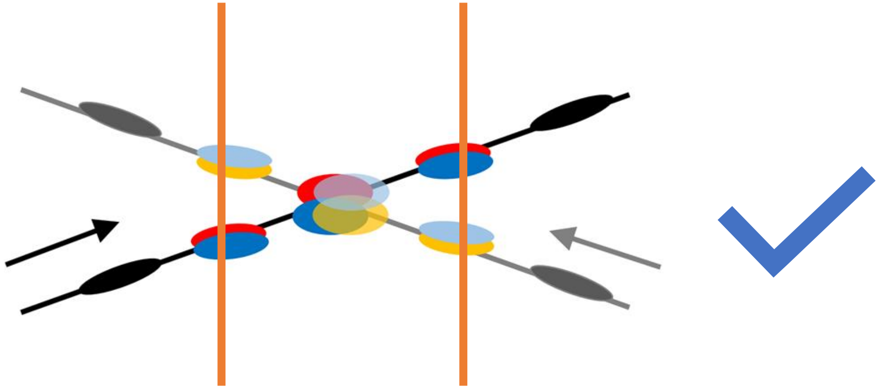
Standard collision mode:



Transversal mono-schemes:



Without crab cavities



Head-on collision with crab cavities

The principles of transversal mono-schemes

- The parameters of the mono-schemes:
  - The monochromatization factor

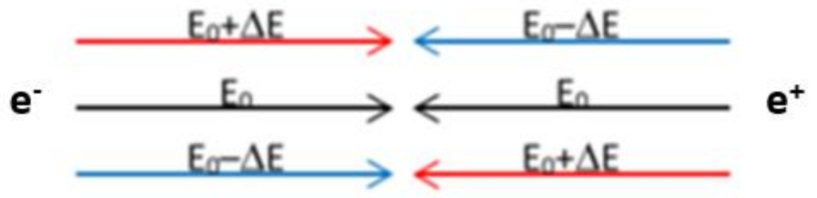
$$\lambda = (1 + \sigma_\varepsilon^2(\frac{D_x^{*2}}{\sigma_{x\beta}^{*2}} + \frac{D_y^{*2}}{\sigma_{y\beta}^{*2}}))^{1/2}$$

  - The monochromatization factor for FCC-ee($D_y^* = 0$)

$$\lambda = \sqrt{1 + \frac{D_x^{*2}\sigma_\varepsilon^2}{\epsilon_x \beta_x^*}}$$

  - The needed dispersion value at IP estimated from [5]

$$D_x^*(e^+) = -D_x^*(e^-) = -0.105m$$



Parameter	Symbol	Unit	Value
Center-of-mass energy	W	GeV	125
Horizontal, vertical rms emittance with (without) beamstrahlung	$\varepsilon_{x,y}$	nm	2.5 (0.51), 0.002
Relative rms momentum deviation	σ_δ	%	0.052
Rms bunch length	σ_z	mm	3.3
Horizontal dispersion at interaction point	D_x^*	m	0.105
Interaction-point beta function	$\beta_{x,y}^*$	mm	90, 1
Rms beam size at the interaction point	$\sigma_{x,y}^*$	µm	55, 0.045
Full crossing angle	θ_c	mrad	30
Vertical beam-beam tune shift	ξ_y		0.106
Total beam current	I_e	mA	395
Bunch population	N_b	10^{10}	6.0
Bunches per beam	n_b		13420
Luminosity (luminosity without crab cavities) per IP	L	$cm^{-2}s^{-1}$	2.6×10^{35} (2.3×10^{35})
Rms center-of-mass energy spread (total spread w/o crab cavities)	σ_W	MeV	13 (25)

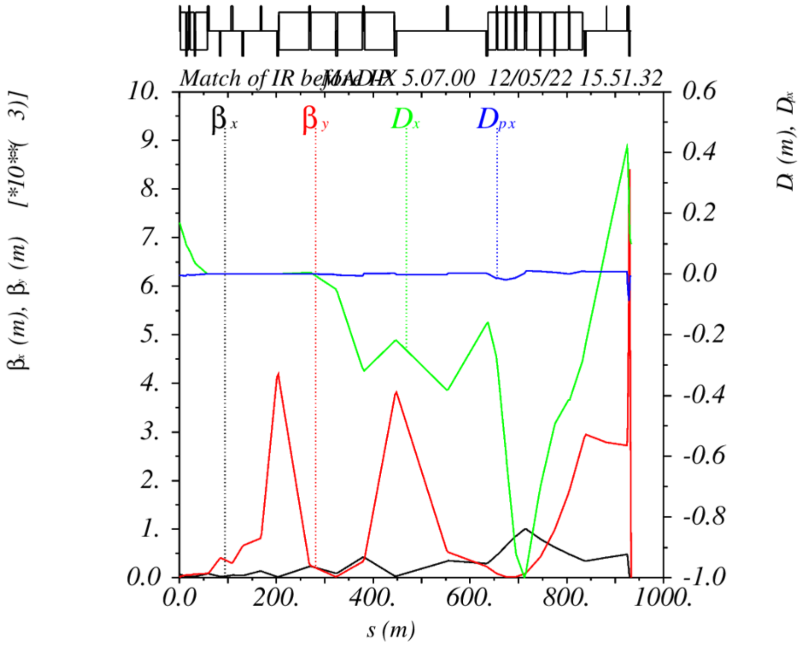
[5] Faus-Golfe, A., Valdivia Garcia, M.A. & Zimmermann, F. The challenge of monochromatization. Eur. Phys. J. Plus 137, 31 (2022)

Constraints of the Optics for the Mono-Schemes

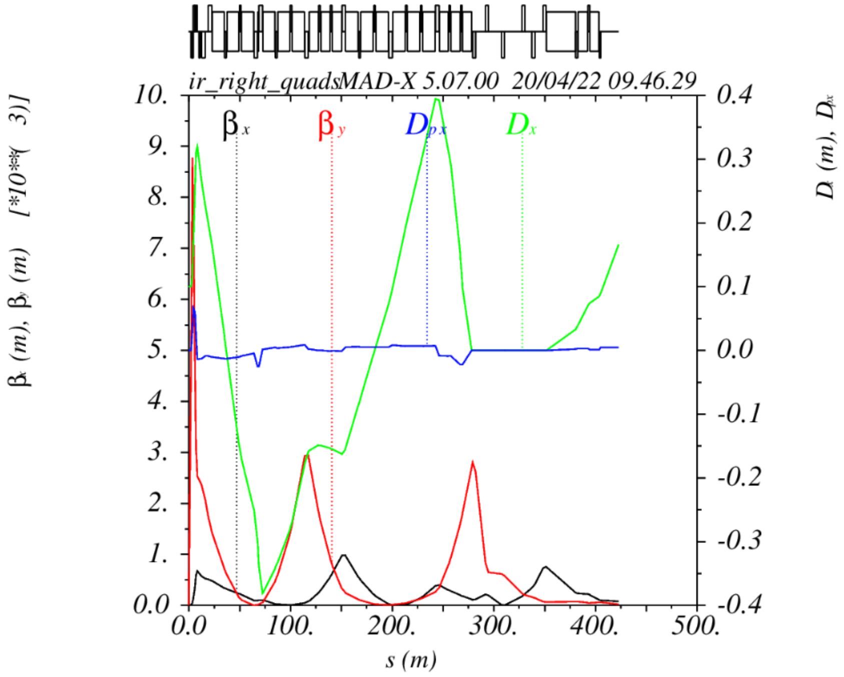
- Constraints:
  1. The beam size
     - The beta function
     - The dispersion function
  2. The monochromatization conditions:
     - D*x=0.105m
     - D*px=0
  3. The match with the rest of the ring
     - The Twiss functions.
  4. The same tunnel with standard mode
     - The same crossing angle for mono and standard mode.
     - The asymmetric IR
  5. The synchrotron radiation (SR limit photon energy below 100keV)
     - the dipole angles
  6. Phase advance and tune
  7. The crab cavities

- The flexible optics of FCC_ee means it easily switches from standard mode to mono.

Before the Interaction Point:



After the Interaction Point:



The Drawbacks of the mono-schemes

1. Beamstrahlung:

   If the dispersion function at the collision point is not zero, beamstrahlung will also increase the transverse emittances.

2. The luminosity loss:

   Trade off luminosity and energy spread

3. Inducing a large chromaticity:

   Redesign of the Local chromaticity correction

4. Beam dynamic aperture (DA) analysis

5. Beam-beam effects

Conclusion and Future Works

- We are designing a new IR optics to meet all the constraints at the last optimized IR optics.
- we are trying to solve all of the drawbacks before the implementation the mono-schemes to the FCC-ee.
- The theory is simple, and the studies begin at 1975, but it is never used in any real machine!

- Thanks for your attentions!