Monochromatization Optics for FCC-ee Lattices

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Outline

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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

**Monochromatization**

- Opposite correlations between transverse spatial position and energy deviation

**IP**

- **e^+**
  - \( E_0 + \Delta E \)
  - \( E_0 \)
  - \( E_0 - \Delta E \)

- **e^-**
  - \( E_0 + \Delta E \)
  - \( E_0 \)
  - \( E_0 - \Delta E \)

- Dispersive beam size at the IP

**CM energy**

\[ w = 2(E_b + \Delta E) \]

**CM energy spread**

\[ \sigma_w = \sqrt{2} E_b \sigma_\delta \]

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

**Revolution frequency**

\[ k_e f_r \]

**Number of bunches**

\[ N_+ N_- \]

**Particles per bunch**

\[ 4\pi \sigma_{x\beta}^* \sigma_{y\beta}^* \]

**Luminosity**

\[ L_0 = \frac{k_e f_r N_+ N_-}{4\pi \sigma^*_{x\beta} \sigma^*_{y\beta}} \]

\[ L = \frac{L_0}{\lambda} \]

**Betatronic beam sizes at the IP**

\[ \sigma_{x,y}^* = \sqrt{\beta_{x,y} \epsilon_{x,y} + (D_{x,y}^* \sigma_\delta)^2} \]

**Dispersion function**

- \( D_{x,y}^* = - D_{x,y}^* = D_x^* \)
- \( D_{x,y}^* = - D_{x,y}^* = D_y^* \)

**Enhancement of energy resolution**, and sometimes increase of the relative frequency of the events at the center 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.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Horizontal Dispersion</th>
<th>Vertical Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy ( (E) )</td>
<td>GeV</td>
<td></td>
<td>62.5</td>
</tr>
<tr>
<td>Horizontal, vertical emittance ( (\varepsilon_{x,y}) )</td>
<td>nm</td>
<td></td>
<td>0.51, 0.002</td>
</tr>
<tr>
<td>Energy spread ( (\sigma_{\delta}) )</td>
<td>%</td>
<td></td>
<td>0.052</td>
</tr>
<tr>
<td>Beam length ( (\sigma_{\delta}) )</td>
<td>mm</td>
<td></td>
<td>3.3</td>
</tr>
<tr>
<td>IP Beta function ( (\beta_{x,y}) )</td>
<td>mm</td>
<td></td>
<td>90, 1</td>
</tr>
<tr>
<td>IP RMS beam size ( (\sigma_{x,y}) )</td>
<td>( \mu ) m</td>
<td></td>
<td>55, 0.045</td>
</tr>
<tr>
<td>Crossing Angle ( (\theta_{c}) )</td>
<td>mrad</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Vertical beam-beam parameter ( (\xi_{y}) )</td>
<td>/</td>
<td></td>
<td>0.106</td>
</tr>
<tr>
<td>Beam current ( (I_{b}) )</td>
<td>mA</td>
<td></td>
<td>395</td>
</tr>
<tr>
<td>Bunch population ( (N_{b}) )</td>
<td>( 10^{11} )</td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>Bunches per beam ( (n_{b}) )</td>
<td>/</td>
<td></td>
<td>13420</td>
</tr>
<tr>
<td>IP Dispersion ( (D_{x,y}) )</td>
<td>m</td>
<td>0.105</td>
<td>0.001</td>
</tr>
<tr>
<td>Monochromatization factor ( (\lambda) )</td>
<td>/</td>
<td>8.1209</td>
<td>11.6705</td>
</tr>
</tbody>
</table>

**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 ($D^*_x = 0.105 \text{ m}$)

Scheme for Symmetrical Standard IR Optics (P. Raimondi)

Creating vertical dispersion ($D^*_y = 0.001 \text{ m}$)
Scheme for Asymmetrical Standard IR Optics

- **First Optics Design**

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 half-chicane is implemented in the last dipole in each upstream and downstream to create the dispersion at the IP to match the dispersion in the arcs.
The dispersion at the IP is successfully matched to 0.105m, but the orbit is changed at the position of the two half-chicane.

- **Standard Survey Plot**

- **Monochromatization Survey Plot**
Scheme for Asymmetrical Standard IR Optics

- First Optics Design Orbit Closing
  One another kind of chicane is implemented in the last dipoles in each upstream and downstream to chose the orbit.
The survey plot shows that the monochromatization orbit is different from the standard one only at the position of the two chicanes. However, the angle of chicane is too high for the synchrotron radiation control.

- **Standard Survey Plot**

- **Monochromatization Survey Plot**
Scheme for Asymmetrical Standard IR Optics

- Optimization of Chicane Angle

In order to reduce the angle of chicane, the chicane is implemented in the last three dipoles instead of one.
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.

\[ D_x = 0.105\text{m} \]
Asymmetrical Monochromatization IR Optics Design

- Comparison between standard survey and monochromatization survey

- Standard Survey Plot

- Monochromatization Survey Plot
Asymmetrical Monochromatization IR Optics Design

- Entrance Survey Point Check and Beam Parameter Check

  - Standard

    - Entrance survey point check
      - X = 14.7731827
      - Angle = 0.013272

  - Monochromatization

    - Entrance survey point check
      - X = 14.77329905
      - Angle = 0.013272

- Entrance beam parameters check
  - \( \beta_x = 156.6587437 \)
  - \( \alpha_x = -2.264602028 \)
  - \( \beta_y = 35.30306244 \)
  - \( \alpha_y = 0.617284605 \)
  - \( D_x = 0.5488569734 \)
  - \( D_{px} = 0.007526257585 \)

- Entrance beam parameters check
  - \( \beta_x = 156.658721 \)
  - \( \alpha_x = -2.264601911 \)
  - \( \beta_y = 35.30305802 \)
  - \( \alpha_y = 0.6172849609 \)
  - \( D_x = 0.5488569538 \)
  - \( D_{px} = 0.007526259165 \)
Asymmetrical Monochromatization IR Optics Design

- **Exit Survey Point Check and Beam Parameter Check**
  
  **Standard**
  
  ![](image1.png)
  
  Exit survey point check
  
  $X = 2.4083046330304256$
  
  Angle $= -0.0024383648753176683$

  ![](image2.png)
  
  Exit beam parameter check
  
  $\beta_x = 70.69329$
  
  $\alpha_x = -2.0980736970165381$
  
  $\beta_y = 21.4996407$
  
  $\alpha_y = 0.81240088314360692$
  
  $D_x = 0.14579546$
  
  $D_{px} = 0.00429520279$

- **Monochromatization**

  ![](image3.png)
  
  Exit survey point check
  
  $X = 2.408308143765483$
  
  Angle $= -0.0024383648753180066$

  ![](image4.png)
  
  Exit beam parameter check
  
  $\beta_x = 70.69328967393588$
  
  $\alpha_x = -2.0980736921462215$
  
  $\beta_y = 21.499640414866093$
  
  $\alpha_y = 0.8124009880050117$
  
  $D_x = 0.14579548213956553$
  
  $D_{px} = 0.0042952063751779106$
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.

  - \( D'_x = 0.105 \, \text{m} \) Monochromatization mode

- **Next step**
  Implementation of the monochromatization IR optics in the whole ring and simplification of the dipoles slicing.
Scheme for Symmetrical Standard IR Optics

- 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.

**Step 1:** Give Solenoid Horizontal BField component

**Step 2:** Varied to close the vertical orbit

**Step 3:** Varied to close the dispersion Dy, Dpy

**Step 4:** Optimized to minimize $\varepsilon_y$

**Step 5:** Give the Dy at IP and re-do from Step1.
Solenoid Implementation

Vertical orbit and vertical dispersion was closed after implementing the solenoid.
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 optics design for positron
  - Survey plot and beam parameters check
  - Standard Mode with monochromatization orbit
    - Implementation of the monochromatization IR optics in the whole ring 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
Thanks for you attention!