Mechanical design of the FCC-ee interaction region (MDI)

A. Bogomyagkov, E. Levichev, S. Pivovarov, S. Sinyatkin
Budker Institute of Nuclear Physics
Novosibirsk, Russia
IR (MDI) task and systems

Main task of MDI is to provide design (maximum) luminosity and design (minimum) detector background in the whole FCC-ee energy range.

Components:

- Magnet (FF quadrupoles, solenoids, correctors)
- Vacuum (pipes, bellows, pumps, flanges, RVC (Remote Vacuum Connector)-flange)
- Cryogenic (cryostats, pipelines)
- HOM absorbers
- Beam diagnostics (BPMs, luminometer)
- Detector protection shield, SR masks, etc.
- Water cooling pipes
- Geodesic alignment marks
- Mechanical supports: framework, stands, bars, carcass, etc.
- ...
Mechanical design tasks and constrains

Mechanical system should

• Integrate all accelerator systems in solid block(s) providing required precision of the components (magnets, BPMs, masks, etc.) positioning wrt to the design beam trajectory
• Integrate accelerator block(s) with detector providing required precision of the accelerator components wrt detector
• Allows easy and reliable assembling/disassembling of the accelerator and detector parts preventing equipment damage (power/signal cables and wires, water tubes, cryogenic lines, etc.)
• Withstands dynamical processes (magnets and detector field up/down, quenches, cooling, warming, vibration, etc.) conserving design coordinates of all accelerator elements with required tolerance
Factors influencing MDI design

• Very stringent beam parameters (energy, current, beam size, etc.) and their tolerances. Consequently, requirements on the accelerator components tolerances (position accuracy, excitation current accuracy, field quality, etc.) are very tough as well.
• Crab Waist collision method. FF magnets are very close to the IP deep inside the detector and hardly can be inspected, adjusted, repaired etc. during operation without dismounting. All components should be rather compact.
• Strong field (superconducting) FF magnets.
• Strong electromagnet forces between the detector field and FF magnet components.
• Detector background requirements.
• 100 mrad blind detector solid angle.
Baseline MDI schematic view I

Inside the detector (≈±4.5 m)
Baseline MDI schematic view II

Interaction Region layout

- Compensating solenoid
- LumiCal
- LumiCal electronics
- LumiCal cables
- Neg Pumps
- Tungsten shield
- Beam pipe
- HOM absorbers
- QC1 final focus

M. Sullivan (SLAC)
Super KEKB MDI example
Typical dimensions:
Cryostat wall thickness ≈ 60 mm
Solenoid steel support ≈ 40 mm
Bellow+BPM ≈ 135 mm
RVC flange ≈ Ø220 mm
Beam parameters

Baseline beam parameters for FCC-ee (FCC CDR v.2, 2019)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$Z$-pole</th>
<th>$WW$</th>
<th>$H(ZH)$</th>
<th>$\tilde{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>$\varepsilon_x$ [nm-rad]</td>
<td>0.27</td>
<td>0.28</td>
<td>0.63</td>
<td>1.45</td>
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<tr>
<td>$\varepsilon_y$ [pm-rad]</td>
<td>1</td>
<td>1</td>
<td>1.3</td>
<td>2.7</td>
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<tr>
<td>$\beta_x^*$ [m]</td>
<td>0.15</td>
<td>0.2</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>$\beta_y^*$ [mm]</td>
<td>0.8</td>
<td>1</td>
<td>1</td>
<td>1.6</td>
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<tr>
<td>Number of bunches</td>
<td>16640</td>
<td>1300</td>
<td>328</td>
<td>33</td>
</tr>
<tr>
<td>$\mathcal{L}$ [10^{34}cm^{-2}s^{-1}]</td>
<td>230</td>
<td>32</td>
<td>8</td>
<td>1.5</td>
</tr>
</tbody>
</table>

$\sigma_x^* = 6.4 \mu m$ (neuron width)

$\sigma_y^* = 28.3 \text{ nm}$
Luminosity vs vertical beams separation

For 10% luminosity loss, the vertical separation at IP should be $d_y < 10 \text{ nm}$

Active beam adjusting feedback is needed.

\[
\mathcal{L} = \mathcal{L}_0 \exp \left( -\frac{d_y^2}{\sigma_y^2} \right)
\]

<table>
<thead>
<tr>
<th>$E$, GeV</th>
<th>$Z$</th>
<th>$W$</th>
<th>$H$</th>
<th>tt</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$230 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>175</td>
<td>182.5</td>
</tr>
<tr>
<td>$\sigma_y$, nm</td>
<td>28</td>
<td>41</td>
<td>36</td>
<td>76</td>
<td>82</td>
</tr>
<tr>
<td>$d_y$, nm</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$\Delta \mathcal{L} / \mathcal{L}_0$, %</td>
<td>-99</td>
<td>-88</td>
<td>-94</td>
<td>-46</td>
<td>-41</td>
</tr>
</tbody>
</table>
Luminosity vs vertical crossing angle

\[ L = L_0 - L_0 \frac{\sigma_s^2}{8\sigma_y^2(1 + \varphi^2)} \frac{3 + \cos 4\theta}{(\cos \theta)^4} \theta_y^2 \]

For 10% luminosity loss, the vertical crossing angle at the IP \( \theta_y < 10-20 \text{ \(\mu\)rad} \)

<table>
<thead>
<tr>
<th>( E, \text{GeV} )</th>
<th>( Z )</th>
<th>( W )</th>
<th>( H )</th>
<th>( \text{tt} )</th>
<th>( \text{ttH} )</th>
</tr>
</thead>
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<tr>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>175</td>
<td>182.5</td>
<td></td>
</tr>
</tbody>
</table>

\( \mathcal{L}, 10^{34} \text{cm}^{-2}\text{s}^{-1} \)

\( 230 \quad 34 \quad 8.5 \quad 1.9 \quad 1.7 \)

\( \sigma_{py}, \text{\(\mu\)rad} \)

\( 35 \quad 41 \quad 36 \quad 48 \quad 51 \)

\( \theta_y, \text{\(\mu\)rad} \)

\( 25 \quad 25 \quad 25 \quad 25 \quad 25 \)

\( \Delta L/L_0, \% \)

\( -7 \quad -14 \quad -20 \quad -23 \quad -20 \)

In horizontal plane

\( d_x < 20-60 \text{ \(\mu\)m} \)

\( \theta_x < 1-2 \text{ mrad} \)

But still active beam adjusting feedback is needed.
FF quadrupoles shift

\[ E = 182.5 \text{ GeV} \]

\[ \beta_{y_{\text{max}}} = 6960 \text{ m} \quad \beta_{y_{\text{IP}}} = 1.6 \text{ mm} \]

\[ \beta_{x_{\text{max}}} = 225 \text{ m} \quad \beta_{x_{\text{IP}}} = 1 \text{ m} \]

\[ \Delta y(QD) = 1 \mu\text{m} \rightarrow \Delta y(IP) \approx -1 \mu\text{m} \]

\[ \Delta x(QF) = 1 \mu\text{m} \rightarrow \Delta x(IP) \approx -6 \mu\text{m} \]

CDR requirements

<table>
<thead>
<tr>
<th>Magnet type</th>
<th>Hor. displacement ( \Delta x ) ( \mu \text{m} )</th>
<th>Vert. displacement ( \Delta y ) ( \mu \text{m} )</th>
<th>Tilt ( \Delta \theta ) ( \mu \text{rad} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc quadrupoles</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Sextupoles</td>
<td>100</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>IP quadrupoles</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>
SSW measurement system in the IR

- Two magnet-cryostats of QCSR/R were aligned to the beam lines with the targets of the cryostats.
- A BeCu single wire of φ0.1 mm, which was aligned to the design beam line, was stretched through QCSR and QCSL cryostat bores.
- The measurements were performed with operating the Belle SC solenoid at 1.5 T, and ESL and ESR1 solenoids.
  - The measured data include the displacement by the electro-magnetic forces between solenoids and magnetic components in the cryostats.
SSW measurement summary

- Measured magnetic center shifts to the design values and field angles to the horizontal planes of the 8 main quadrupoles as follows:

<table>
<thead>
<tr>
<th></th>
<th>QC1LP</th>
<th>QC2LP</th>
<th>QC1RP</th>
<th>QC2RP</th>
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</thead>
<tbody>
<tr>
<td>$\Delta x$, mm</td>
<td>0.01</td>
<td>-0.34</td>
<td>0.68</td>
<td>0.49</td>
</tr>
<tr>
<td>$\Delta y$, mm</td>
<td>-0.21</td>
<td>-0.69</td>
<td>-0.30</td>
<td>0.04</td>
</tr>
<tr>
<td>$\Delta \theta$, mrad</td>
<td>-1.67</td>
<td>-4.05</td>
<td>2.02</td>
<td>-1.73</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>QC1LE</th>
<th>QC2LE</th>
<th>QC1RE</th>
<th>QC2RE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta x$, mm</td>
<td>-0.21</td>
<td>0.13</td>
<td>0.25</td>
<td>0.08</td>
</tr>
<tr>
<td>$\Delta y$, mm</td>
<td>-0.29</td>
<td>-0.54</td>
<td>-0.37</td>
<td>-0.58</td>
</tr>
<tr>
<td>$\Delta \theta$, mrad</td>
<td>-1.60</td>
<td>-1.54</td>
<td>-0.14</td>
<td>-0.73</td>
</tr>
</tbody>
</table>

- Every alignment errors are able to be corrected by the corrector magnets.

Lessons for FCC-ee:
- Proper steering magnets should be placed at proper places.
- MDI symmetrical to the electromagnet forces is preferable to minimize displacement
- Measurement of the components’ position inside the detector is needed
- Measurement of the magnet field inside the detector is needed
CDR sketch of MDI

Very simple, no details

Fig. 2.20. A 3D sketch of the interaction region (IR) magnet system in the first 3 m from the interaction point (IP). Zero in the plot marks the location of the IP.
Attempt to look in detail

- Anti Sol
- HOM Absorb
- LumiCal

- Cryostat touches LumiCal
- Cryostat overlaps with vacuum chamber, flange, BPM, bellows

- Two bellows
- Remote flange
- BPM
Cryostat bent under the gravity force is 1 mm (3.3 tons components weight+2.5 tons cryostat). We need to support it in several points on the skeleton inside the detector. It should be adjusted to the detector design. Electro-magnetic forces should be taken into account.
MDI assembling 1-1

The IP vacuum chamber is inserted in the vertex. Two cryostats are assembled on table and...

≈4.5 m
MDI assembling 1-2

...moved in the detector. Remotely controlled flanges provide vacuum joint.

Super KEKB approach
Two cryostats with the IP chamber with the vertex are assembled on table as a single unit and...
MDI assembling 2-2

...the full assembly moves into the detector.

≈11-12 m

We plan for Novosibirsk Super Ct factory
Questions to the CDR baseline design

- Is 100 mrad solid angle possible for realistic design (magnets, solenoids, cryostat, etc.)?
- Is it possible to place BMPs, bellows, RVC flange, HOM absorbers, etc. inside the cryostat? How to connect their cables, cooling water tubes? How to connect draw bars to the RVC flange inside?
- Real sizes of the accelerator components inside the cryostat? Real size of the accelerator components outsize the cryostat? Real size of cryostat?
- How to assemble the MDI inside the detector with required accuracy?
- How to provide/control/adjust the components inside the cryostat inside the detector?
- Is there a skeleton inside the detector to support the cryostat(s)?
- Etc.
We need so detailed models/sketches/drawings to answer the questions.
Conclusion

IR/MDI is very critical system for the FCC-ee performance. To be sure in the IR/MDI mechanical design, we need

- 3D magnetic field map
- 3D force map
- Collect requirements for the MDI area from accelerator/detector experts
- Design separately all the systems/components (magnets, vacuum, cryo, ...)
- Integrate all the components is the blocks
- Integrate the accelerator blocks in the detector