OVERVIEW, PLAN, AND OPEN QUESTIONS

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for the MDI group

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Outline

The design of the interaction region must comply with various important constraints, imposed by high beam energy, high luminosity, need for polarization, and crossing scheme.

An **overview of the MDI design** with recent results and ongoing studies
• layout and mechanical model
• beam backgrounds study

Plan & Open question
Collision scheme for $e^+e^-$ circular colliders

**Crab-waist** based on two ingredients:
- concept of **nano-beam scheme** (vertical squeeze of the beam at IP and large horizontal crossing angle, reduced instantaneous overlap area, allowing for a smaller $\beta_y^*$)
- crab-waist sextupoles

**Smaller beams at IP → higher $\mathcal{L}$ & higher backgrounds**
(IP bkgs and beam losses in the final focus quads due to the very high $\beta$-function)

These ingredients determine the complex MDI design
- Tight and packed interaction region → small $L^*$, QC1 inside detector, mechanical constraints
- Beam pipe design, as splitting in two pipes is very close to the IP
- Robustness against machine backgrounds (from IP and environment)
- Radiation damage and occupancy and fake hits
- Higher trigger rate, DAQ and computing

Ref. First Successful validation test performed at DAFNE (2008) link
SuperKEKB successfully implemented the FCC-ee virtual crab-waist, i.e. w/o new sextupoles [2020, K. Oide]
FCC-ee IR optics design

driven by synchrotron radiation:
\( E_{\text{critical}} < 100 \text{ keV} \) from 450 m from the IP
(from LEP experience)

\( \rightarrow \) Asymmetric IR optics

<table>
<thead>
<tr>
<th>IR parameters</th>
<th>Table</th>
<th>Z</th>
<th>W^+W^-</th>
<th>ZH</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta_x^* )</td>
<td>m</td>
<td>0.15</td>
<td>0.2</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>( \beta_y^* )</td>
<td>mm</td>
<td>0.8</td>
<td>1.0</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>( \sigma_x^* )</td>
<td>( \mu )m</td>
<td>6.4</td>
<td>13</td>
<td>13.7</td>
<td>38.2</td>
</tr>
<tr>
<td>( \sigma_y^* )</td>
<td>nm</td>
<td>28</td>
<td>41</td>
<td>36</td>
<td>68</td>
</tr>
<tr>
<td>( \sigma_z )</td>
<td>mm</td>
<td>12.1</td>
<td>6</td>
<td>5.3</td>
<td>2.54</td>
</tr>
<tr>
<td>( z^*_{\text{int}} )</td>
<td>mm</td>
<td>0.42</td>
<td>0.85</td>
<td>0.9</td>
<td>1.8</td>
</tr>
</tbody>
</table>

in collision

interaction length

Flexible design with final focus doublet
in slices to adapt for the different beam energies
FCC-ee Interaction Region

[ArXiv:2105.09698]

- **Flexible** design, one IR for all energies
- **Compact** design: QC1 and compensation solenoids inside detector
- **Squeezed beams at IP**, tens of nm in $\sigma_y^*$
  - challenges in several aspects, from magnets to vibrations mitigation, alignment and monitoring system, feedback for beam orbit and luminosity
- **High intensity and high energy beam**

- **Synchrotron radiation**: detector sustainability top priority
- **Solenoid compensation scheme** preserves $\varepsilon_y \approx$ pm
- **Luminosity detector** @Z: absolute meas. to $10^{-4}$ (low angle Bhabha),
- **Robustness against machine bkgs, occupancy**
- **Optimization of the central beam pipe design, material, thickness**
- **Keep low material budget**: minimise mass of electronics, cables, cooling

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$L^* = 2.2 \text{ m}$

$B = 2 \text{ T}$
Low impedance central beam pipe

Smaller central pipe  20 mm diameter

The double effect of smoothing the geometry and a smaller central pipe reduces the local heating power by a factor ten wrt the CDR design.

Heat load due to resistive wakefields vs bunch length for a $r=1\text{cm}$ Be central beam pipe.

$\sigma_z=12$ mm in collision at $Z$

Heating power is 260 W for the two beams, most of this power will travel out away from the IP
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No need of HOM absorbers
CDR IR pipe model with HOM absorbers

Higher Order Modes absorbers were foreseen in the CDR design to absorb the trapped mode found by CST simulations.

The HOM fields, which are generating by the beam in the Interaction Region pass through the longitudinal slots into the absorber box.

[A. Novokhatski et al. PR-AB 20, 111005 (2017)]
Low impedance central beam pipe

No need of HOM absorbers

• The distributed trapped modes have very small shunt impedance and even at the resonance they produce less than 200 W for the two beams.

• To remove the remaining heat, we will use paraffin as liquid coolant that will flow within the room temperature pipe in the central chamber, and water outside.
Central pipe composition

Inner radius 10 mm

Thickness 1.7mm \((X/X_0 = 0.59\%)\)

<table>
<thead>
<tr>
<th>Material</th>
<th>thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlBeMet162</td>
<td>0.35 mm</td>
</tr>
<tr>
<td>Paraffin (PF200)</td>
<td>1 mm</td>
</tr>
<tr>
<td>AlBeMet162</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Au</td>
<td>5 (\mu m)</td>
</tr>
</tbody>
</table>

AlBeMet162: 62% beryllium and 38% aluminum alloy

Central pipe CDR values: inner radius 15 mm
1.2 mm Be + 0.5 mm \(H_2O\) for \(X/X_0 = 0.47\%\)
Vertex resolution vs the first vertex layer radius

Radial distance \((r)\) of the very first vertex layer

- Improvement in the vertex resolution from 17 to 12 mm of about 25%, better especially for central B’s.

- Vertex performance mildly dependent on slight variations of \(X/X_0\)

IDEA Delphes configuration

More central B’s are shown in red, and more forward B’s in blue (defined according to \(\cos(\theta)\) values)

Donal Hill, MDI meeting #33
Preliminary assembly of the MDI

Thanks to M. Koratzinos for magnets and cryostat

Section

proposed design cryostat: yellow “skeleton” shape
Final Focus quadrupole canted cos-theta design

[M. Koratzinos, this session]

Iron-free design, it can provide an excellent field quality
One prototype designed, manufactured, assembled and tested at warm at CERN

- Conductor technology NbTi
- The maximum field gradient is 100 T/m.
- QC1 inner diameter of beam pipe 30 mm
- (minimum distance between the magnetic centers of e+/e- for QC1L1 is only 66 mm)
QC1 will be embedded in the screening solenoid and cryostat, all inside the detector

Foreseen next steps:
- Cold test on the prototype
- Cryostat
- Proper shielding to avoid quenches
- Supports for vibration mitigation studies
Alignment

Strategy under study

Two systems to monitor the MDI:
- external monitoring system
- Internal monitoring system

The interface would be monitored from the outside of the experiment. This will allow the alignment of the interfaces of the two sides of the detector. The interface would serve as a origin to compute the deformations of the cryostat and/or skeleton and the position of the inner elements.

Requirements on distance measurements

- **Lumical** lumical-IP at 50 µm, two faces lumical at 100 µm
- **Final focus quads and sextupoles** radially 75 µm, longitudinally 100 µm
- **BPM** radially 40 µm, relative to quad displacement 100 µm
Beam Background studies

MDI induced detector backgrounds estimation study restarted to deepen the studies presented in the CDR with the following objectives:

• Get full control of the relevant tools for detector background estimation, provide a unified vision and simplified and well documented access.
• Investigate the impact of the debris in the MDI, optimize the shielding in the MDI area
• A complete and flexible description of the geometry of the relevant components (in DD4hep format)
• A solution for interplay with CAD based formats

Final goal is to assess the control of detector backgrounds with reliable estimates in collaboration with the detector group

Collimation scheme to protect detector from sudden beam loss events is also as important in collaboration with the collimation group
Beam Background studies

Synchrotron radiation background

- complementary codes (MDISim, Synch_bkg, SYNRAD+)
- study in progress to optimise shielding, SR absorbers, vacuum chamber and radiation produced at IR also by non gaussian beam tails

Generation and tracking of beam scattered particles

- IP backgrounds
- Single beam backgrounds (thermal photons, beam-gas studied for the CDR)

Relevant for MDI are especially IR loss map
Beam tails for lifetime and backgrounds source

First case-study GuineaPig++ performed integrated in FCCSW key4hep, goal: events reconstruction for detector backgrounds sim.
study Beamstrahlung photons
Radiative Bhabha BBBrems
tracking spent beam radiation from radiative Bhabha
Two Detector concepts

Based on CLIC detector design
- Silicon-based vertex and tracker
- Coil outside calorimeter

New, innovative
- Silicon vertex detector
- Dual-readout calorimeter
- Short-drift, ultra-light wire chamber
- Thin and light solenoid coil inside calorimeter system

B = 2 T
Synchrotron Radiation with smaller central beam pipe – Z case

Central pipe with 20 mm diameter and cylindrical length shorten from ±12.5 cm to ±9 cm

The mask tip is increased from 10 to 7 mm to shield the tapered section upstream the IP from the last bend and final focus quadrupole radiation.

On-axis beam, non-Gaussian beam tails to 20 $\sigma_x$ and 60 $\sigma_y$ have been considered.

The bend radiation can be masked away by reducing the mask radius from 10 mm to 7 mm from the beam line at -2.1 m.

The quadrupole radiation cannot be totally masked away even with a 5 mm radius mask at -2.1 m.

FF SR strikes here with 903 photons > 10 keV.
With the 7 mm mask tip this number becomes 18 >10 keV.

Without changing the mask tip, this surface gets 9 W of SR power and around $10^5$ incident photons > 10 keV.

With the mask tip at 7 mm this number goes to 0.2 photons >10 keV.
Synchrotron Radiation

Inset: Close up view of the IP area, with +/- 9 cm 20 mm ID Be pipe

51 localized SR absorbers

SYNRAD+: MDI area, [-601.7 ; + 238] m;
SR photon scattering ON
courtesy R. Kersevan
Beamstrahlung Radiation generated at the IP

[GuineaPig++]

- A significant flux of photons is generated at the IP in the very forward direction by Beamstrahlung, radiative Bhabha, and solenoidal and quadrupolar magnetic fields.
- **Beamstrahlung** interactions produce an **intense source of locally lost beam power**
- The impinging angle of the **Beamstrahlung** photons with the pipe is about 1 mrad for both beam energies.

Fluka or Geant4 simulation to design the proper shielding for this radiation is necessary.

<table>
<thead>
<tr>
<th>Beam energy</th>
<th>Beamstrahlung Radiation power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;E&gt; = 2$ MeV</td>
<td>45.6 GeV 387 kW</td>
</tr>
<tr>
<td>$&lt;E&gt; = 67$ MeV</td>
<td>182.5 GeV 89 kW</td>
</tr>
</tbody>
</table>
Open questions for mechanical model

Conceptual design of IR elements/systems: some are under study, others require optimisation, others are yet missing

- **Progress with the mechanical assembly** adding all the main components as they will be provided by the experts of the different systems.
- Introduce the weight of the components to design the supports and start with the structural studies. This will allow the optimization of the different options of different configurations of supports for vibration mitigation, in collaboration with LAPP.
- Space for the alignment system to fulfill the stringent requirements.
- **Thermal and mechanical simulations** Just started, with preliminary studies (cooling of central pipe, strength of simplified X pipe to vacuum load at several thicknesses)
- We will define the strategy for the integration.

Cryostat design
- IR beam diagnostic devices
- IR corrector magnets
- Shielding
- Vacuum system
- Remote vacuum connection
- Vertex detector ( & other IP detectors)
Background control, beam loss and radiation

Ongoing studies

• Synchrotron Radiation background: extensively studied, but still ongoing and planned refined studies
  • induced by non gaussian tails
  • backscattering photons
  • vacuum pipe modeling to absorb and intercept the SR photons, SR absorbers
  • induced in the IR by solenoidal fringing fields and FF quads

• Collimation strategy, and to provide for a safe machine and detector protection

• Beam losses from collisions processes: beamstrahlung, luminosity, including spent beam tracking, shielding optimization and evaluation of effect in detector

Some open questions

• Top-up injection background
• Neutron radiation in the IR area
• Tail collimation
• Beam abort system
Conclusion

- The Machine Detector Interface study is a key topic for the success of FCC-ee.
- Many exciting challenges for the design with state-of-the-art technologies and experience on past and present colliders.
- A lot of work has been done and ongoing.
- Interesting years ahead of us in the next years!
Thank you for your attention.
<table>
<thead>
<tr>
<th>particle type</th>
<th>e⁺e⁻</th>
<th>pp</th>
<th>e⁻⁻ ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>collider name</td>
<td>circular</td>
<td>linear</td>
<td>circular</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>GeV</td>
<td>LER (e+) 4</td>
<td>45.6, 120, 182.5</td>
</tr>
<tr>
<td>L (peak)</td>
<td>10⁻²⁴ cm⁻² s⁻¹</td>
<td>80</td>
<td>230, 8.5, 1.6</td>
</tr>
<tr>
<td>crossing angle</td>
<td>mrad</td>
<td>83</td>
<td>30</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>ns</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>L* (free region)</td>
<td>m</td>
<td>L 0.77</td>
<td>2.2</td>
</tr>
<tr>
<td>βₓ*</td>
<td>cm</td>
<td>L 3.2</td>
<td>15, 30, 100</td>
</tr>
<tr>
<td>βᵧ*</td>
<td>mm</td>
<td>L 0.27</td>
<td>0.8, 1, 1.6</td>
</tr>
<tr>
<td>Normalised emittance x</td>
<td>µm</td>
<td>L 25</td>
<td>24, 148, 479</td>
</tr>
<tr>
<td>Normalised emittance y</td>
<td>nm</td>
<td>L 68</td>
<td>89, 235, 1000</td>
</tr>
<tr>
<td>B_corrected</td>
<td>T</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>central pipe radius</td>
<td>cm</td>
<td>1</td>
<td>1.5 (1)</td>
</tr>
</tbody>
</table>

M. Boscolo, ECFA TF8 Symposium, 31/03/2021
SuperKEKB beam pipe & synchrotron radiation

Inner surface of Be pipe are coated with Au layer (10 µm) to protect detectors from SR

- φ20mm → φ10mm collimation on incoming beam pipes (no collimation on outgoing pipes, HOM can escape from outgoing beam pipe)
- Most of SR photons are stopped by the collimation on incoming pipe.
- Direct hits on IP beam pipe is negligible
- To hide IP beam pipe from reflected SR, “ridge” structure on inner surface of collimation part.
Heat load for 30 mm beam pipe

- Beryllium pipe takes **100 W/m** for a **12 mm bunch** but strongly increasing with shortening the bunch length.
- A gold coating can decrease the heat load by 30%

<table>
<thead>
<tr>
<th>bunch length [mm]</th>
<th>HEAT LOAD Two beams [W/m]</th>
<th>current [A]</th>
<th>Bunch spacing [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 x 1.39</td>
<td></td>
<td>19.50</td>
</tr>
<tr>
<td>12.10</td>
<td>63.45 69.18 81.68 96.57</td>
<td>125.23</td>
<td>349.64 1473.91</td>
</tr>
<tr>
<td>Material</td>
<td>Cu  Au  Al  Be  Ni  SS  NEG</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A. Novokhatski
Beamstrahlung

- SR in field of opposing beam, estimated at the Z with Guinea-Pig
- The IR will generate a very significant flux and power of hard X-rays lost mostly in the first downstream bend (49-55 m from IP)

<table>
<thead>
<tr>
<th>Classical SR and Guinea-Pig</th>
<th>$&lt;N_\gamma&gt;$</th>
<th>$&lt;E_\gamma&gt;$ keV</th>
<th>Power KW</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP magnets (quad, solenoid)</td>
<td>1.3</td>
<td>24</td>
<td>43 kW</td>
</tr>
<tr>
<td>Beamstrahlung</td>
<td>0.15</td>
<td>2000</td>
<td>417 kW</td>
</tr>
</tbody>
</table>

- ~460 kW hitting in a narrow ~5 m wide region
- wall power / length of order 100 kW/m

some MW / IP with spectrum extending into tenths of MeV strongly varying with bb-parameters and residual separation

H. Burkhardt