Overview of MDI issues toward the TDR

M. Boscolo (INFN-LNF)

Thanks to N. Bacchetta, H. Burkhardt, M. Sullivan

Future Circular Collider Conference
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FCC-ee MDI design challenges

- We have a **flexible layout, common for the wide range of energies**, from Z pole to tt$_{\text{bar}}$
- **Crab-waist** collision scheme is adopted.
- **Synchrotron Radiation** needs special care especially at the top energy and also due to the large crossing angle (total 30 mrad). This topic is a **main driver of the IR layout**.
- **Small emittances**: $\varepsilon_x \approx \text{nm}$, $\varepsilon_y \approx \text{pm}$:
  - very good machine alignment, vibration studies
  - The large crossing angle with the pm scale vertically requires a very good **solenoid compensation scheme**.
- **Luminosity monitor** aims at a precision measurement of $\approx 10^{-4}$ at 45.6 GeV.
- FCC-ee is the first circular collider **Beamstrahlung dominated**, with a strong impact on the beam parameters choice and requirements (i.e. optimal $\beta^*$, asymmetric energy acceptance at top energy $-2.8/+2.4\%$ beamstrahlung lifetime of about 20 minutes.

The MDI WG has developed a layout that matches the requirements both of the machine and detector.
Interaction Region Layout

L* = 2.2 m distance from IP to first quadrupole
2 T detector
## FCC-ee parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Z</th>
<th>W⁺W⁻</th>
<th>ZH</th>
<th>ttbar</th>
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<td>Luminosity / IP</td>
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<td>#</td>
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<td>328</td>
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<td>Average bunch spacing</td>
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<td>1.34</td>
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<td>Vertical emittance εᵧ</td>
<td>pm</td>
<td>1.0</td>
<td>1.7</td>
<td>1.3</td>
<td>2.7</td>
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<td>βₓ / βᵧ</td>
<td>m / mm</td>
<td>0.15 / 0.8</td>
<td>0.2 / 1.0</td>
<td>0.3 / 1.0</td>
<td>1.0 / 1.6</td>
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<td>beam size at IP: σₓ / σᵧ</td>
<td>μm / nm</td>
<td>6.4 / 28</td>
<td>13 / 41</td>
<td>13.7 / 36</td>
<td>36.7 / 66</td>
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<td>Energy spread: SR / total (w BS)</td>
<td>%</td>
<td>0.038 / 0.132</td>
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<td>3 / 6.0</td>
<td>3.15 / 5.3</td>
<td>2.75 / 3.82</td>
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<td>Energy loss per turn</td>
<td>GeV</td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
<td>7.8</td>
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<td>RF Voltage / station</td>
<td>GV</td>
<td>0.1</td>
<td>0.75</td>
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<td>4/5.4</td>
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<td>Longitudinal damping time</td>
<td>turns</td>
<td>1273</td>
<td>236</td>
<td>70.3</td>
<td>23.1</td>
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<tr>
<td>Acceptance RF / energy (DA)</td>
<td>%</td>
<td>1.9 / ±1.3</td>
<td>2.3 / ±1.3</td>
<td>2.3 / ±1.7</td>
<td>3.5/ (-2.8; +2.4)</td>
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<td>min</td>
<td>68 / &gt; 200</td>
<td>59 / &gt;200</td>
<td>38 / 18</td>
<td>37/ 24</td>
</tr>
<tr>
<td>Beam-beam parameter ξₓ / ξᵧ</td>
<td></td>
<td>0.004 / 0.133</td>
<td>0.01 / 0.141</td>
<td>0.016 / 0.118</td>
<td>0.088 / 0.148</td>
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<tr>
<td>Interaction region length</td>
<td>mm</td>
<td>0.42</td>
<td>0.85</td>
<td>0.9</td>
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The next steps can be subdivided in the following macro-areas, all inter-connected:

1. **Beam physics (optics, beam dynamics, collective effects)**
2. **Experimental environment & luminometer**
3. **Software**
4. **Engineering (mechanical, magnets, diagnostics, vacuum, cooling, ...)**

Input and strong collaboration from all areas of expertise are crucial to optimize the promising studies presented in the CDR and finalize them for the TDR phase.

Our goal is to have a feasible and engineered design that meets optics, beam dynamics and high current requirements, foresees tolerable radiation and meets as well the mechanical requirements in terms of integration, stability, assembly.
MDI & Beam physics issues

FCC-ee accelerator design is continuously evolving and improving

- Goal is to optimize the design with 4 IPs: beam-beam optimization implies an evolution of beam parameters, and MDI layout will follow the optics updates that will come also for other beam dynamics studies that may come
  - Beam-beam blow-up issues (D. El Khechen)
- Optics variations take into account that FCC-hh footprint is not a constraint now
- Optimization of beam pipe aperture, study the reduction of the central Be pipe

- Synchrotron Radiation (SR) at the IR, major issue for the MDI design, well under control as reported in CDR, but work is not done, on-going study

- Beam backgrounds simulations: single beam and IP processes
  - Beam losses from all main processes (beam-gas, thermal photons, ...)
  - Collimation system for betatron and momentum cleaning (possibly outside the MDI area, but useful to control losses in the experiments)
- Heat load evaluation from RW impedance and SR at IR (strictly connected with engineering issues)
- Collective effects at IR
Synchrotron Radiation in the IR

- To fulfil the requirement that $E_{\text{critical from dipoles}} < 100 \text{ keV}$ from $\sim 500m$ from IP, special optics has been developed
  [ref.: K. Oide et al, PRAB 19, 111005 (2016)]
- SR studied with SYNC_BKG, MDISim (MADX/ROOT/Geant4) and SYNRAD+
- Different **countermeasures** undertaken to protect IR & detector
  - SR mask tips in front of QC1 and QC2
  - 1 cm Tantalum shielding
  - 5 μm Gold coating in the central chamber

**Countermeasures are effective:**
- No SR from dipoles or from quads hits directly the central beam pipe
- SR impact on Vertex detector (VXD) and Tracker barrel (TB) small

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

mask tips prevent FF quad radiation from striking nearby beam pipe elements
SR bkg comes only from the last soft bend radiation striking the mask tips

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Synchrotron Radiation in the IR

Still a lot of work to be done:

• **Refine simulations** (also following the optics changes)
• **More detailed studies** with improvements on the simulation level:
  • tracking in IR with beams tilted in solenoid
  • fringe fields overlapping with quads
  • X-ray reflection not yet included in Geant4 (and check for giant dipole resonance)
• Add **SR collimators** upstream the IR
• Neutron production from high-energy tails in FF quads: study has to continue
• Carefully evaluate the **SR from final focus quadrupoles** especially at the top energy: hard photons are produced, lost at ~50/60 m downstream the IP
• Primaries under control, **secondary sources** to be simulated more carefully

✓ M. Luckhof will present last results with MDISim (this session)
✓ M. Sullivan evaluated the impact on SR with a smaller beam pipe (this session)
Single Beam induced backgrounds

✓ Progress on Thermal photon scattering (talk by H. Burkhardt, this session)

- Inelastic beam-gas simulation performed with MDISim, scattered particles tracked into the lumical, negligible background source
- Elastic beam-gas scattering just started with custom process generator & MADX-PTC (LNF)
- Touschek scattering: expected not to be relevant but check of IR beam losses planned Touschek lifetime ~15/30 hrs at Z, MADX/SAD
IP backgrounds: $e^+e^-$ pairs simulation with GuineaPig

Impact of backgrounds evaluated in detectors CLD & IDEA

- **Coherent Pairs Creation** (CPC): Photon interaction with the collective field of the opposite bunch
  - *Negligible* for FCC-ee: strongly focused on the forward direction

- **Incoherent Pairs Creation** (IPC): real or virtual photon scattering
  - *Dominant* effect: virtual $\gamma$ scattering

IP backgrounds: $\gamma\gamma$ to hadrons

- Direct production of hadrons, or indirect, where one or both photons interact hadronically
- Simulation with a combination of Guinea Pig and Phythia
- The effect of this background source is confirmed to be small

- **Beamstrahlung** loss map through the ring to be continued
- **Radiative Bhabha** loss map to be continued
- Beamstrahlung photons produced at IR
Experimental environment & luminometer

- **Keep refining the studies** on the impact of the various backgrounds on the detector performance and impact on the luminometer, for example:
  - detector performance with smaller beam pipe
  - collimation system to minimize SR
  - track particles in detector from all backgrounds processes

✓ Impact of beam-beam effects on luminosity measurement (E. Perez)

All of above is dynamic as the detector description becomes more refined and the engineering of the IR progresses

Software

- Essential part of FCC studies is using, interfacing and further developing standard programs of general interest, in particular MAD-X, ROOT, GEANT4 (combined in MDISim) and SAD
- This activity is strictly connected with the beam backgrounds simulations and with the tracking into the detector and luminometer
- We need to close the loop between MDISim and the Geant4 detector model
- ...
Engineering: toward the TDR

- Mechanical design and integration
- IR magnets: Final focus quads and anti-solenoids
- Engineered design of IR components like: diagnostics (BPM), flanges, bellows to be included in the mechanical design
- HOM absorbers  ✔️ A. Novokhatzki, this session
- Beam pipe cooling system
- Cryostat support and remote vacuum connection
- Lumical support and alignment
- Vibration control

### Alignment tolerances

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_x$ (µm)</th>
<th>$\sigma_y$ (µm)</th>
<th>$\sigma_\phi$ (µrad)</th>
</tr>
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<tbody>
<tr>
<td>arc quads</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>IP quads</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>sextupoles</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>BPMs</td>
<td>20</td>
<td>20</td>
<td>150</td>
</tr>
</tbody>
</table>

Some are standard features, other require a custom study
Some concerns on the assembly

- Remote vacuum connection
- Central chamber support
- Cooling pipe space for central detectors
- Space for lumical, cryostat, NEG pump, HOM absorbers, shielding

Mechanical design & integration

Goal:
- Try to converge on a design of the IR with sufficient details to constitute a real engineering baseline
- Understand installation procedures, mechanical detector interfaces, detector and machine elements accessibility for maintenance/upgrades
- Mechanical stability and position precisions of some detector elements (i.e. Lumical) is a relevant element to consider in the design
- Better define the general strategy for services in and out of the detector
BINF group started this engineering activity -> next talk by E. Levichev

BINF is focusing on computer simulation, design and testing of several most critical components of FCC-ee IP region:
(1) The anti-solenoid with individual correctors
(2) The remotely connecting flange
(3) Multi-layers beam vacuum chamber
(4) The first FF quadrupole
Final Focus quadrupole: CCT project

✓ more details by M. Koratzinos, this session

What has been achieved so far:
• Conceptual design
• Final magnetic design
• Final mechanical design
• Manufacturing
• Set up of the winding table (motorized)

To be performed:
• Winding of the magnet
• Test at warm
• Test at cold
• Impregnation
• Test at cold of impregnated magnet

Timescales:
The timescale of the project critically depends firstly on the manufacturing of the test (rotating) probe and secondly on the availability of a small cryostat for cold testing
• Winding of the magnet July 2019 – one week
• Test at warm: starting when testing probe would be ready – one week
• Test at cold: starting when cryostat would be ready – one week
• Impregnation: one week
• Test at cold of impregnated magnet: starting at next available slot of cryostat
MDI sessions

1. Overview of MDI issues toward the TDR (M. Boscolo)
2. Mechanical design of the interaction region (E. Levichev)
3. Final focus quadrupoles and solenoids (M. Koratzinos)
4. Beam-beam blow-up issues (D. El Khechen)
5. Impact of beam-beam effects on luminosity measurement (E. Perez)

6. Synchrotron radiation background studies (M. Luckhof)
7. Beam losses at IR (H. Burkhardt)
8. Improvement of detector performance with smaller central IP beam pipe (E. Leogrande)
9. HOM and heating with smaller central IP beam pipe (A. Novokhatski)
10. Synchrotron radiation with smaller central IP beam pipe (M. Sullivan)
Concluding remarks

- **FCC-ee MDI baseline conceptual design is solid** with many details being studied as described in the CDR.
- Much work has been done and continues on detailed, flexible simulation tools.
- A lot of space for improvements and optimizations on the simulation level especially for beam backgrounds, SR and high current issues.
- Prototype of final focus quad QC1 with CCT design in progress at CERN.
- With this MDI layout we can now progress on the **MDI mechanical design and integration** as well as on other important engineering issues.

Input and strong collaboration from all areas of expertise are crucial to optimize these promising studies and finalize the FCC-ee design for the next phase.
Thanks to all that are part of this effort on the MDI design!

Some related references

• CDR
• MDI meetings: https://indico.cern.ch/category/5665/
• 1st MDI workshop http://indico.cern.ch/event/596695
• 2nd MDI workshop https://indico.cern.ch/event/694811
• K. Oide et al, *Design of beam optics for the future circular e+e- collider rings*, PR-AB 19, 111005 (2016) link:
• E. Belli et al, PR-AB 21, 111002 (2018) link
• M Boscolo et al, *Machine detector interface for the e+e- future circular collider*, 62th ICFA ABDW on high luminosity circular e+e- colliders, eeFACT18, Hong Kong (2019) link
Back-up
• The energy spectrum of the SR from the final focus magnets is much higher than the spectrum from the last bend magnet
Downstream bend

- Distance from IP is 29 m (38 m long)
- Bend strength is 328 Gauss
  - Critical energy is higher (668 keV)
  - Luminosity window?
- Radiation from the Final Focus magnets
  - Final Focus Quad radiation is about 2 kW
  - Quad radiation has high critical energies (~few MeV)
    - Possible source of neutrons in the detector?
• 3 BPMs in the IR:
  – 1 before QC1
  – 1 between first and second section of QC1
  – 1 between QC1 and QC2

• **Special BMPs** in IR needed due to space constraint: smaller than standard ones (~1 cm long instead of 4-5cm)

Superkekb BPMs

[Image: BPM-bellows tube between IP chamber and QCS]

transversely fixed to the beam pipe, but longitudinally free to move with temperature variations

[Image: BPM-bellows tube]
Vacuum chamber inside the cryostat

Rough estimation shows for the SCTF MDI vacuum chamber ~100 W/m thermal load due to HOMs and image currents. The task is to develop, produce and test a prototype for the multilayer vacuum chamber inside the cryostat providing tolerable heating of FF magnets.

- Inner vessel 0.7 mm thick with copper coating, $T=300$K
- 0.7 mm cooling water gap against HOM & IC
- Vacuum tube 0.7 mm with mirror-like coating (Cu or Au), $T=300$K
- 0.9 mm vacuum gap
- Outer 1 mm vessel coated by Cu, $T=4.2$K
- Superconducting coil on a mandrel

Remote flange prototype
Baseline (with M. Koratzinos’ dimensions)
3D conceptual design Interaction Region.

Cryostat “walls” thickness.
- Outer SS wall 10 mm
- 10 mm vacuum
- Thermal shield 3 mm
- Inner wall 6 mm
- In total: ~40...45 mm

Correct. sol.(4)
Anti-sol.
Two bellows
BPM
Connection Be-Cu
Remote flange
HOM Absorber
LumiCal
Cooling
Connection Be-Cu

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QC1 : CCT approach

Quadrupole with embedded local edges correction and crosstalk correction

Pros:
• Excellent field quality (<0.1 unit for all multipoles) at all field strengths (no saturation problems)
• The design can have embedded correctors (x and y dipole correctors, skew quadrupole correctors, etc.)
• Strengths up to 150T/m possible
• Potentially cheaper than traditional designs

Cons:
• Needs prototyping

Inner bore: 40mm (diameter)
Fits outside the warm water-cooled beam pipe of inner diameter 30mm

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<th></th>
<th>Z</th>
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<th>ZH</th>
<th>tt</th>
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<td>Circumference</td>
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<td>Bending radius</td>
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<td>Free length to IP $l^*$</td>
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<td>Solenoid field at IP</td>
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<td>Full crossing angle at IP $\theta$</td>
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<tr>
<td>Arc cell phase advances</td>
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<td>90/90</td>
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<td>Horizontal $\beta_x$</td>
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<td>Horizontal size at IP $\sigma_x$</td>
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<tr>
<td>Pinswinski angle (SR/BS) $\phi$</td>
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<td>8.2/28.5</td>
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<td>3.4/5.8</td>
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<tr>
<td>Length of interaction area $L_z$</td>
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<td>0.42</td>
<td>0.85</td>
<td>0.90</td>
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<td>Hourglass factor $R_{HG}$</td>
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<td>0.89</td>
<td>0.88</td>
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<tr>
<td>Crab sextupole strength</td>
<td>[%]</td>
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<td>0.75</td>
<td>2.0</td>
</tr>
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<td>Synchrotron tune $Q_z$</td>
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<td>0.0506</td>
<td>0.0358</td>
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<tr>
<td>Longitudinal damping time</td>
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<td>Polarisation time $t_p$</td>
<td>[min]</td>
<td>15000</td>
<td>900</td>
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<td>Luminosity / IP</td>
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<td>269.199</td>
<td>389.199</td>
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<tr>
<td>Beam-beam $\xi_x/\xi_y$</td>
<td></td>
<td>0.004/0.133</td>
<td>0.010/0.113</td>
<td>0.016/0.118</td>
</tr>
<tr>
<td>Allowable $e^+e^-$ charge asymmetry</td>
<td>[%]</td>
<td>±5</td>
<td>±3</td>
<td></td>
</tr>
<tr>
<td>Lifetime by rad. Bhabha scattering</td>
<td>[min]</td>
<td>68</td>
<td>59</td>
<td>38</td>
</tr>
<tr>
<td>Actual lifetime due to beamstrahlung</td>
<td>[min]</td>
<td>&gt; 200</td>
<td>&gt; 200</td>
<td>18</td>
</tr>
</tbody>
</table>
## Comparison of Site Vibration

<table>
<thead>
<tr>
<th>Location</th>
<th>Peak to Peak distribution</th>
<th>without highest 5%</th>
<th>Selected Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum (nm)</td>
<td>FWHM (nm)</td>
<td>Average (nm)</td>
</tr>
<tr>
<td>Seismic Station Moxa</td>
<td>7</td>
<td>17</td>
<td>0.6</td>
</tr>
<tr>
<td>Salt Mine Asse</td>
<td>12</td>
<td>35</td>
<td>0.5</td>
</tr>
<tr>
<td>CERN LHC Tunnel</td>
<td>21</td>
<td>53</td>
<td>1.8</td>
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<tr>
<td>Spring-8 Harima</td>
<td>22</td>
<td>40</td>
<td>2.0</td>
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<tr>
<td>FNAL Batavia</td>
<td>23</td>
<td>49</td>
<td>2.9</td>
</tr>
<tr>
<td>LAPP Annecy</td>
<td>35</td>
<td>59</td>
<td>3.3</td>
</tr>
<tr>
<td>IHEP Beijing</td>
<td>49</td>
<td>18</td>
<td>8.4</td>
</tr>
<tr>
<td>SLAC Menlo Park</td>
<td>60</td>
<td>105</td>
<td>4.8</td>
</tr>
<tr>
<td>APS Argonne</td>
<td>68</td>
<td>56</td>
<td>10.5</td>
</tr>
<tr>
<td>ALBA Cerdanyola</td>
<td>87</td>
<td>125</td>
<td>18.3</td>
</tr>
<tr>
<td>DESY TESLA</td>
<td>104</td>
<td>160</td>
<td>17.4</td>
</tr>
<tr>
<td>DESY XFEL Oseldorf</td>
<td>150</td>
<td>195</td>
<td>28.9</td>
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<tr>
<td>DESY Zeuthen</td>
<td>105</td>
<td>235</td>
<td>64.0</td>
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<tr>
<td>ESRF Grenoble</td>
<td>155</td>
<td>175</td>
<td>71.6</td>
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<tr>
<td>DESY XFEL Schenefeld</td>
<td>180</td>
<td>245</td>
<td>38.7</td>
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<tr>
<td>DESY HERA</td>
<td>170</td>
<td>200</td>
<td>51.8</td>
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<td>KEK Tsukuba</td>
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<td>210</td>
<td>78.0</td>
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<tr>
<td>BESSY Berlin</td>
<td>245</td>
<td>160</td>
<td>72.8</td>
</tr>
<tr>
<td>SSRF Shanghai</td>
<td>550</td>
<td>1000</td>
<td>292</td>
</tr>
</tbody>
</table>

M. Masuzawa, “Superkekb vibration measurement and collision feedback” 2nd MDI workshop 2018
Asymmetric Interaction Region optics

**Optics improvements before FCCWEEK2018**

- Increase of beam energy at ttbar (182.5 GeV): lattice design and parameters set optimized
- Further reduction of $\beta^*$ at the IP at $Z, W^\pm, ZH, ttbar(\beta_y)$
- Momentum acceptance at ttbar increased

**Motivations** for these changes:
- to mitigate the coherent beam-beam instability also at $W^\pm, ZH$
- to mitigate 3D flip-flop

- Asymmetric optics suppresses SR toward the IP, $E_{\text{critical}} < 100$ keV from 450 m from the IP
- Local chromaticity correction scheme for $y$-plane (a-d), incorporated with crab sextupoles (a,d), needed for energy acceptance requirement (up to 2.8%)
Final Focus optics

- Flexible optics design: final focus quadrupoles are longitudinally split into three slices.
  - At the Z chromaticity is reduced for the smaller $\beta^*$, smaller beam size.

Only 1st slice of QC1 is defocusing horizontally

All 3 slices of QC1 are defocusing horizontally

M. Boscolo, FCCWEEK19
Baseline for Solenoid Compensation Scheme

- **screening solenoid** that shields the detector field inside the quads (in the FF quad net solenoidal field=0)
- **compensating solenoid** in front of the first quad, as close as possible, to reduce the $\varepsilon_y$ blow-up (integral $BL\sim0$)

`detector solenoid` dimensions $3.76m$ (inner radius) $(outer radius 3.818m) \times 4m$ (half-length)

`drift chamber` at $z=2m$ with 150 mrad opening angle (IDEA design)

$0.34 \, pm$ is the overall $\varepsilon_y$ blow-up for $2IPs$ @Z

The discussion on the mechanical integration is actually bringing to improvements of this scheme, due to space constraints
Beam induced backgrounds

Two main classes:

- **Synchrotron Radiation**
- **Beam particles effects** ($e^+, e^-, e^+e^-$)
  - Beamstrahlung
    - Incoherent/Coherent $e^+e^-$ Pair Creation
    - $\gamma\gamma$ to hadrons
  - beam-gas elastic and inelastic
  - Thermal photon Compton scattering
  - Radiative Bhabha

Impact of backgrounds studied in detector designs CLD & IDEA

PURPLE: collision induced backgrounds
GREEN: single beam backgrounds
Inelastic Beam Gas scattering in the IR

- MDISim was used to import in Geant4 beam pipe geometry + magnetic elements + beam characteristics

Z position where the BG interaction that will lead to particle loss happened

IR Loss map

<table>
<thead>
<tr>
<th>Case</th>
<th>Loss Rate +/-20m from IP [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>147</td>
</tr>
<tr>
<td>W</td>
<td>16</td>
</tr>
<tr>
<td>H</td>
<td>3</td>
</tr>
<tr>
<td>t</td>
<td>0.5</td>
</tr>
</tbody>
</table>

more details by F. Collamati