MDI status and overview

M. Boscolo (INFN-LNF) for the MDI Team


Future Circular Collider Conference
Amsterdam, 11 April 2018
Introduction: MDI Group activity

• MDI WG launched on January 2016 with monthly meetings: http://indico.cern.ch/category/5665/

• Topics discussed in the MDI group: IR design, Synchrotron Radiation and Masking, Other accelerator backgrounds, Magnetic integration, luminosity measurements, beam-pipe dimension and masking, choice of I*, IR magnet parameters, trapped mode analysis, space and location of luminosity monitors, magnet integration, overall detector layout, etc..

• 1st MDI workshop*, Jan. 2017 at CERN, to review baseline design
• 2nd MDI workshop*, Jan. 2018 at CERN, to start with the assembly concept

• First milestone: ready with the conceptual design of the IR as required for the summary volume, naturally .. details come in the next phase

* http://indico.cern.ch/event/596695
* https://indico.cern.ch/event/694811
Outline

• IR Optics
• IR layout
• Synchrotron Radiation study
• HOM absorber design
• Luminosity monitor
• Background studies
• Solenoid Compensation scheme
• Mechanical design and assembly concept
• Conclusion
IR Optics & parameters: constraints and requirements

- **Crab waist** scheme: large crossing angle 30 mrad

- $\beta^*_x = 0.15\ m$ (45.6 GeV) and $\beta^*_x = 1\ m$ (182.5 GeV)
- $\beta^*_y = 0.8\ mm$ (45.6 GeV) and $\beta^*_y = 1.6\ mm$ (182.5 GeV)
- $\sigma^*_x = 6\ \mu m$ (45.6 GeV) and $\sigma^*_x = 38\ \mu m$ (182.5 GeV)
- $\sigma^*_y = 28\ nm$ (45.6 GeV) and $\sigma^*_y = 68\ nm$ (182.5 GeV)
- Asymmetric **energy acceptance at top energy** -2.8/+2.4 % and +/-1.3 % at 45.6 GeV for acceptable beamstrahlung lifetime (about 20 minutes)

- $E_{\text{critical}} < 100\ keV$ for incoming beam to IP from 500 m (based on LEP experience)

- 2 IPs
- FCC-hh footprint (FCC-ee booster)
Challenge of the FCC-ee IR

- The FCC-ee collider is a challenging machine, with unprecedented high $e^+e^-$ c.m. energy, luminosity and circumference.
- We have a flexible IR layout, common for wide range of energies.
- The crab-waist collision scheme has been chosen for the IR design.
- 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 request of $\varepsilon_y \approx \text{pm}$ scale requires a dedicated solenoid compensation scheme.
- Luminosity monitor aims at a precision measurement of $\approx 10^{-4}$ (at the Z energy).
- Luminosity and beam induced background sources into the detector are being considered for the different running energies together with masks, shieldings and collimators.

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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
Interaction Region Layout

Unique and flexible design at all energies

2018 updates on:
- Lumical
- Shielding (W)
- QC1
- Compensating solenoid
- Lumical electronics
- Lumical cables
- HOM absorbers
- W shielding

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Vacuum chamber

Geometry of the IR vacuum chamber optimized from the wake fields and trapped modes point of view.

DIMENSION
- Central beam pipe has 3 cm diameter
- Entering and exiting beam pipe through QC1 (3cm diameter)
- Pipe size increases to 4cm diameter in QC2
- Size outside QC2 is 7 cm diameter (but 6 cm in plot)

SR MASK TIPS
- +/-12 mm radius at Z= +/-2.1 m and +/-5.44 m
- +/-18 mm radius at Z= +/- 8.27 m
- Vert. 10 mm; 5 mm thickness

MATERIAL
- Be from about +/-80 cm to accommodate LumiCal
- Cu afterwards
- warm beam pipe, liquid cooled (similarly to SuperKEKB) to cope with SR and HOM heating

Be and Cu pipes may be welded together but similar solution to SuperKEKB using also Ti being considered.
Synchrotron Radiation

Synchrotron Radiation is the main constraint for IR design and it drives the IR optics and layout

General requirement for the optics based on LEP experience:

1. Weak bends $E_{\text{critical}} < 100$ keV (LEP2 was 72 keV)
2. Weak bends far from IP (LEP2 was 260 m from IP)
3. Keep $E_{\text{cr}} \lesssim 1$ MeV in whole ring, to minimize n-production (LEP2 0.72 MeV)

Up-to-date lattices and layouts are studied in detail using several tools (MDISim, SYNC_BKG, SYNRAD+) that complement each other, allowing the study of SR from different approaches

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### SR photon rates

<table>
<thead>
<tr>
<th></th>
<th>Energy (GeV)</th>
<th>Critical energy (keV)</th>
<th>number of bunches</th>
<th>Current (mA)</th>
<th>Incident $\gamma$/xing (500$\mu$m from tip)</th>
<th>Incoming on central pipe/xing</th>
<th>$\gamma$ rate on central pipe (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt+</td>
<td>182.5</td>
<td>113.4</td>
<td>33</td>
<td>5.41</td>
<td>3.32E+09</td>
<td>1195</td>
<td>1.18E+08</td>
</tr>
<tr>
<td>tt</td>
<td>175</td>
<td>100</td>
<td>40</td>
<td>6.4</td>
<td>3.06E+09</td>
<td>1040</td>
<td>1.25E+08</td>
</tr>
<tr>
<td>h</td>
<td>125</td>
<td>36.4</td>
<td>328</td>
<td>29</td>
<td>1.05E+09</td>
<td>10.3</td>
<td>1.01E+07</td>
</tr>
<tr>
<td>W</td>
<td>80</td>
<td>9.56</td>
<td>1300</td>
<td>147</td>
<td>6.11E+08</td>
<td>0.18</td>
<td>7.02E+05</td>
</tr>
<tr>
<td>Z</td>
<td>45.6</td>
<td>1.77</td>
<td>16640</td>
<td>1390</td>
<td>9.62E+07</td>
<td>1.92E-04</td>
<td>9.58E+03</td>
</tr>
</tbody>
</table>

- No SR from dipoles or from quads hits directly the central beam pipe (cylinder +/- 12.5 cm in Z with a 1.5 cm radius)
- Non-Gaussian beam tails, considered out to +/-20 $\sigma_x$ and +/-60$\sigma_y$
- On-axis beam
- Quadrupole radiation that may strike mask surfaces included

- Photons tracked into CLD detector showing low occupancy (with W shielding)  
  
  [A. Kolano talk]
• Similar sawtooth ridged vacuum chamber proposed inside the FF quads (R. Kersevan)
SR MDISim- Geant4 simulation

- detailed study for SR collimator to intercept far bends photons in progress
- photon and energy spectra provided for full simulation in detector

more details by M. Lueckhof poster session on Tuesday
IR trapped modes and HOM absorbers

The two beam pipes combine into one in the interaction point, here they can generate e.m. waves, depending on their frequency there can be trapped modes in the IR, that might heat the IR.

The best design is model No. III with a smooth beam pipe:

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Trapped mode frequency [GHz]</th>
<th>Near revolution harmonic numbers</th>
<th>Mode loss factor [V/pC]</th>
<th>Mode decay time [ns]</th>
<th>Power of a trapped mode [kW]</th>
<th>Bunch 5 mm [kW]</th>
<th>Bunch 2.5 mm [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>5.774</td>
<td>14 and 15</td>
<td>0.38</td>
<td>5.51</td>
<td>8.71</td>
<td>2.42</td>
<td>10.77</td>
</tr>
<tr>
<td>III</td>
<td>3.459</td>
<td>8 and 9</td>
<td>0.08</td>
<td>9.2</td>
<td>2.91</td>
<td>0.45</td>
<td>2.10</td>
</tr>
</tbody>
</table>

• The trapped modes analysis was completed*
• The HOM absorbers have been designed for the FCC-ee IR

* A. Novokhatski et al., PR-AB 20 111005 (2017)
FCC ee IR beam pipe with water-cooled HOM absorbers

HOM absorber design for 10 kW power

Efficiency of Damping Trapped and Propagating Modes
• Goal: absolute luminosity measurement to $10^{-4}$
• Bhabha cross section 12 nb at Z-pole with acceptance 65-85 mrad
• The LumiCals are centered on the outgoing beamlines with their faces perpendicular to the beamlines
• The LumiCal design fits with the HOM design; 3D mechanical design of the MDI in progress
• Extra shielding below the LumiCal might be added

The distance between the two calorimeters has to be measured to 110 µm

- Idea to be pursued: Align the tracker wrt IP with dimuon events, then align the tracker with the LumiCal using laser tracks

more details in M. Dam talk
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

<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>

IR Loss map

Z position where a primary electron is lost after a BG interaction

Ready for full simulation in detector and lumical
Beam-beam effects and beamstrahlung

→ Beam-beam effect studies (analytic and simulations (BBWS inserted in SAD))

→ Beamstrahlung simulations at Z and Top energies (Loss maps + lifetime)

→ Collimation studies will be considered to protect the IR from beam losses (e.g: Beamstrahlung, radiative Bhabhas, etc..)

→ Emittance blowup due to residual x-y couplings and dispersions at IP

→ Corrections of residuals are being considered to understand better the beam-beam effects in the simulation

\[ \beta_{y,design} = 2 \text{ mm} \]
\[ \epsilon_{y,design} = 2.7 \text{ pm} \]
\[ \beta_{y,dynamic} = 1.64 \text{ mm} \]
\[ \epsilon_{y,design} = 3.83 \text{ pm} \]
Higher thresholds in the IR with a heat load up to 15x lower compared to the 2.5ns beam

- In the arcs, lower thresholds but heat load within acceptable limit ($\approx 100 \, \text{W/m}$) for SEY < 1.3

### 15 ns beam

<table>
<thead>
<tr>
<th></th>
<th>Arc dipole</th>
<th>Arc quad</th>
<th>Arc drift</th>
<th>QC1L1</th>
<th>QC1L2</th>
<th>QC1L3</th>
<th>QC2L1</th>
<th>QC2L1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multipacting threshold*</td>
<td>1.0</td>
<td>&lt;1.0</td>
<td>1.0</td>
<td>1.3</td>
<td>1.4</td>
<td>1.5</td>
<td>1.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

- **SEY measurement after the 4th activation cycle of 24h**

- **E. Belli**
Solenoid Compensation Scheme

• Design was optimized at 1st MDI workshop Jan.’17:
  \( \varepsilon_y \) blow-up 0.3 pm with: \( L^* = 2.2 \text{m}, B_{\text{det}} = 2 \text{T}, \) Lumical before 1.25 m and 140 mrad angular acceptance from beam axis

• This solution increased the angular acceptance from 100 mrad to 140 mrad (only the lumical occupied this extra space)

• Detector group requires the angular acceptance of 100 mrad.

• Slight rearrangement of the solenoid compensation scheme allows to fulfill this requirement on the opening angle with an increase of \( \varepsilon_y \) by 0.34 pm (SAD, K.Oide with field map from M. Koratzinos)

• Space for cryostat not considered here
Baseline of Final Focus and solenoid compensation Layout

QC1R1_1: L = 0.7 m, K1 = -75 / -75 T/m, R = 0.015 m

• QC1R1_2: L = 1.4 m, K1 = -173 / -166 T/m, R = 0.0175 m
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~0)

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

**detector solenoid** dimensions $3.76m$ (inner radius) ($3.818m$) × $4m$ (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

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Mechanical assembly at IR

• We started discussing this task at the 2nd MDI workshop, February 2018
• Experience from SuperKEKB is very important
  ▪ K. Kanazawa presented “SuperKEKB mechanical assembly at IR”
  ▪ M. Masuzawa presented “SuperKEKB vibration measurement and collision feedback”

• Mechanical assembly is important as baseline for detailed studies (impedance, tracking, integration, consistency) and it is the starting point for technical designs, next step after conceptual design
• Necessarily this study may bring to modification of the layout, due to space constraints
• This can be considered as a future step after the Conceptual Design Report phase.
• It will be also important to prove the feasibility of the FCC-ee MDI design
Alternative Preliminary new design

- Completely different approach for solenoid compensation: two separated compensating solenoids

- It is promising for few advantages like
  - space saving
  - Much smaller vertical emittance blow-up

- physics require 100 mrad opening angle
- Also flanges, bellows, cryostat, bpm need to be added

more details in next talk by E. Levichev
Solenoids with correctors (S. Syniatkin)
Conclusions

- We have a baseline conceptual design of FCC-ee-MDI for all energies considered for the CDR.
- Much work has been done and continues on detailed, flexible simulation tools.
- Still space for improved and alternative design of course.

- Last year in 1st MDI workshop baseline design layout was reviewed and discussed:
  - $L^*$, opening angle acceptance, solenoid compensation scheme, LumiCal space, IR HOM and trapped modes analysis, vacuum chamber
- This year we added important elements to the MDI design discussion and new topics addressed:
  - Mechanical design and assembly concept, HOM absorber design, cryostat, water cooling system, remote vacuum connection, flanges, bellows, vacuum pump, vibration studies, orbit correction, fast luminosity monitor for machine tuning, BPMs

As a next step:
- together with improvements on simulation level
- MDI Integration and assembly concept
- Progress on IR magnets design
- Prototyping?
Back-up
<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>W⁺W⁻</th>
<th>ZH</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam energy</strong></td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>175</td>
</tr>
<tr>
<td><strong>Luminosity / IP</strong></td>
<td>230</td>
<td>28</td>
<td>8.5</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>Beam current</strong></td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>6.4</td>
</tr>
<tr>
<td><strong>Bunches per beam</strong></td>
<td>16640</td>
<td>2000</td>
<td>328</td>
<td>59</td>
</tr>
<tr>
<td><strong>Average bunch spacing</strong></td>
<td>19.6</td>
<td>163</td>
<td>994</td>
<td>2763</td>
</tr>
<tr>
<td>10¹¹</td>
<td>1.7</td>
<td>1.5</td>
<td>1.8</td>
<td>2.2</td>
</tr>
<tr>
<td>10¹¹</td>
<td>0.27</td>
<td>0.84</td>
<td>0.63</td>
<td>1.34</td>
</tr>
<tr>
<td>10¹¹</td>
<td>1.0</td>
<td>1.7</td>
<td>1.3</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>βₓ / βᵧ</strong></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>
</tr>
<tr>
<td><strong>beam size at IP</strong></td>
<td>6.4 / 28</td>
<td>13 / 41</td>
<td>13.7 / 36</td>
<td>36.7 / 66</td>
</tr>
<tr>
<td><strong>Energy spread</strong></td>
<td>0.038 / 0.132</td>
<td>0.066 / 0.131</td>
<td>0.099 / 0.165</td>
<td>0.144 / 0.196</td>
</tr>
<tr>
<td><strong>Bunch length</strong></td>
<td>3.5 / 12.1</td>
<td>3 / 6.0</td>
<td>3.15 / 5.3</td>
<td>2.75 / 3.82</td>
</tr>
<tr>
<td><strong>Energy loss per turn</strong></td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
<td>7.8</td>
</tr>
<tr>
<td><strong>RF Voltage /station</strong></td>
<td>0.1</td>
<td>0.75</td>
<td>2.0</td>
<td>4/5.4</td>
</tr>
<tr>
<td><strong>Longitudinal damping time</strong></td>
<td>1273</td>
<td>236</td>
<td>70.3</td>
<td>23.1</td>
</tr>
<tr>
<td><strong>Acceptance RF / energy (DA)</strong></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>
</tr>
<tr>
<td><strong>Rad. Bhabha/ actual Beamstr. Lifetime</strong></td>
<td>68 / &gt; 200</td>
<td>59 / &gt;200</td>
<td>38 / 18</td>
<td>37/ 24</td>
</tr>
<tr>
<td><strong>Beam-beam parameter</strong></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>
</tr>
<tr>
<td><strong>Interaction region length</strong></td>
<td>0.42</td>
<td>0.85</td>
<td>0.9</td>
<td>1.8</td>
</tr>
</tbody>
</table>
BPM

• 3 BPMs in the IR:
  – 1 before QC1
  – 1 between first and second section of QC1
  – 1 between QC1 and QC2

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

**Superkekb BPMs**

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

0.5mm wire, critical current @3T is 300A, physical length ~20cm
QC1L1 single coil edge correction

- Integrated multipoles before (centre) and after correction (right)

Before correction

After correction

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QC1L1 double coil crosstalk correction

before

after

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## Comparison of Site Vibration

<table>
<thead>
<tr>
<th>Location</th>
<th>Maximum pp (nm)</th>
<th>FWHM (nm)</th>
<th>Average RMS (nm)</th>
<th>SD σ (nm)</th>
<th>Selected Data Quiet RMS (nm)</th>
<th>Noisy RMS (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic Station Moxa</td>
<td>7</td>
<td>17</td>
<td>0.6</td>
<td>0.1</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Salt Mine Asse</td>
<td>12</td>
<td>35</td>
<td>0.5</td>
<td>0.1</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>CERN LHC Tunnel</td>
<td>21</td>
<td>53</td>
<td>1.8</td>
<td>0.8</td>
<td>0.9</td>
<td>2.9</td>
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<tr>
<td>Spring-8 Harima</td>
<td>22</td>
<td>40</td>
<td>2.0</td>
<td>0.4</td>
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<td>2.5</td>
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<td>FNAL Batavia</td>
<td>23</td>
<td>49</td>
<td>2.9</td>
<td>0.9</td>
<td>2.2</td>
<td>4.0</td>
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<td>LAPP Annecy</td>
<td>35</td>
<td>59</td>
<td>3.3</td>
<td>1.6</td>
<td>1.9</td>
<td>7.0</td>
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<td>IHEP Beijing</td>
<td>49</td>
<td>18</td>
<td>8.4</td>
<td>0.5</td>
<td>8.1</td>
<td>9.0</td>
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<td>SLAC Menlo Park</td>
<td>60</td>
<td>105</td>
<td>4.8</td>
<td>1.2</td>
<td>4.1</td>
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<td>APS Argonne</td>
<td>68</td>
<td>56</td>
<td>10.5</td>
<td>1.0</td>
<td>9.8</td>
<td>11.0</td>
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<td>ALBA Cerdanyola</td>
<td>87</td>
<td>125</td>
<td>18.3</td>
<td>9.5</td>
<td>9.1</td>
<td>42.0</td>
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<td>DESY TESLA</td>
<td>104</td>
<td>160</td>
<td>17.4</td>
<td>8.4</td>
<td>9.3</td>
<td>35.9</td>
</tr>
<tr>
<td>DESY XFEL Osdorf</td>
<td>150</td>
<td>195</td>
<td>28.9</td>
<td>11.9</td>
<td>19.5</td>
<td>48.4</td>
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<td>64.0</td>
<td>40.4</td>
<td>88.5</td>
<td>75.6</td>
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<td>ESRF Grenoble</td>
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<td>175</td>
<td>71.6</td>
<td>34.9</td>
<td>40.2</td>
<td>137.2</td>
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<tr>
<td>DESY XFEL Schenefeld</td>
<td>180</td>
<td>245</td>
<td>38.7</td>
<td>16.6</td>
<td>35.1</td>
<td>70.0</td>
</tr>
<tr>
<td>DESY HERA</td>
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</tbody>
</table>

M. Masuzawa, “Superkekb vibration measurement and collision feedback” 2nd MDI workshop 2018
Superkekb HOM estimate
much lower (even if higher beam current
and lower vacuum chamber)