Experimental Interaction Region

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On behalf of EuroCirCol WP3 EIR design team:
CERN, CI, EPFL, INFN, JAI, TU

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The team

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• Overview
• Final Focus optics
  – Longer triplet FF
  – Shorter triplet FF & Flat beam FF
  – Low luminosity IR FF
  – Correction schemes
• Energy deposition and protection
• Machine Detector Interface
  – Proton cross talk / muon cross talk
  – SR background
• Beam-beam effects
• Conclusions and outlook
We have two parameter sets:
- Beam current is the same
- But luminosity differs

\[ \mathcal{L} \propto \frac{N}{\epsilon \frac{1}{\beta_y}} N n_b f_r \]

They have the same current but the ultimate set has more challenging collision parameters.

The “baseline” in EuroCirCol should be capable to run with the ultimate parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh Baseline</th>
<th>FCC-hh Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity ( L ) ([10^{34}\text{cm}^{-2}\text{s}^{-1}])</td>
<td>5</td>
<td>20-30</td>
</tr>
<tr>
<td>Background events/bx</td>
<td>170 (34)</td>
<td>&lt;1020 (204)</td>
</tr>
<tr>
<td>Bunch distance ( \Delta t ) [ns]</td>
<td>25 (5)</td>
<td></td>
</tr>
<tr>
<td>Bunch charge ( N ) ([10^{11}])</td>
<td>1 (0.2)</td>
<td></td>
</tr>
<tr>
<td>Fract. of ring filled ( \eta_{\text{fill}} ) [%]</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Norm. emitt. [(\mu\text{m})]</td>
<td>2.2(0.44)</td>
<td></td>
</tr>
<tr>
<td>Max ( \xi ) for 2 IPs</td>
<td>0.01 (0.02)</td>
<td>0.03</td>
</tr>
<tr>
<td>IP beta-function ( \beta ) [m]</td>
<td>1.1</td>
<td>0.3</td>
</tr>
<tr>
<td>IP beam size ( \sigma ) [(\mu\text{m})]</td>
<td>6.8 (3)</td>
<td>3.5 (1.6)</td>
</tr>
<tr>
<td>RMS bunch length ( \sigma_z ) [cm]</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Crossing angle [(\sigma')]</td>
<td>12</td>
<td>Crab. Cav.</td>
</tr>
<tr>
<td>Turn-around time [h]</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

Slide from Daniel Schulte
The experimental interaction region (EIR) is one of the key areas that define the performance of the Future Circular Collider (FCC-hh), housed in a 97.75 km perimeter racetrack tunnel filled with 16 T SC magnets, includes four EIRs -- two for nominal/high luminosity and two for low-luminosity experiments.

Each of the EIR straight sections is 1400 m long, while in low-luminosity EIR sections the experiments are combined with injection sections.

FCC-hh layout and key parameters of the main and low-luminosity EIR:

- **Main EIR:**
  - Inj. + Exp.
  - L = 1.4 km
  - $L^* = 45 \text{m}$
  - $\beta^* = 0.3 \text{m}$

- **Low-luminosity EIR:**
  - Inj. + Exp.
  - L = 1.4 km
  - $L^* = 25 \text{m}$
  - $\beta^* = 3 \text{m}$
In the main EIR the present $L^*$ is 45m – is can accommodate the baseline detector (unshielded solenoid with balanced conical / cylindrical solenoid) or the alternative longer detector (twin shielded solenoid with dipole spectrometers).

Older and the newer detector in the same scale:

- ALBA-2016
  - Now baseline
  - 25m

- Rome-2016
  - Now alternative

$FF$ optics and $L^*$
Detectors and main EIR FF L* 

6T, 12m bore solenoid, 10Tm dipoles, shielding coil

- 65 GJ Stored Energy
- 28m Diameter
- >30m shaft
- Multi Billion project

4T, 10m bore solenoid, 4T forward solenoids, no shielding coil

- 14 GJ Stored Energy
- Rotational symmetry for tracking!
- 20m Diameter (≈ ATLAS)
- 15m shaft
- ≈ 1 Billion project

Detectors shown roughly in the same scale
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### Main EIR FF optics - triplets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil Radius (mm)</td>
<td>95</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Aperture Ø (mm)</td>
<td>72</td>
<td>119</td>
<td>119</td>
</tr>
<tr>
<td>Gradient (T/m)</td>
<td>115</td>
<td>94</td>
<td>94</td>
</tr>
<tr>
<td>Shielding (mm)</td>
<td>48</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Length (m)</td>
<td>15</td>
<td>13.2</td>
<td>15</td>
</tr>
</tbody>
</table>

**Versions of main EIR FF optics under study are:**

- the longer triplet version
- and the so-called flat optics with shorter triplet

### Main EIR inner triplets, long and short triplet optics version – inner coil radius, clear aperture, gradient, thickness of shielding and length of individual quadrupole

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>Length (m)</td>
<td>15</td>
</tr>
<tr>
<td>Shielding (mm)</td>
<td>44.2</td>
</tr>
<tr>
<td>Gradient (T/m)</td>
<td>106</td>
</tr>
<tr>
<td>Aperture Ø (mm)</td>
<td>86</td>
</tr>
<tr>
<td>Coil Radius (mm)</td>
<td>98.3</td>
</tr>
</tbody>
</table>
The present design of the longer triplet FF provides the most flexibility in terms of $\beta^*$ reach and the best performance in terms of energy deposition protection.

Large apertures of the quadrupoles allow reaching $\beta^*$ below 0.1 m (with 15 mm shielding) or significantly increasing shielding still with good $\beta^*$ reach of 0.2 m.

However, this optics is 1500 m long.

The possibility of reducing its length to the allocated 1400 m is currently under study.
Longer triplet FF – Beam Stay Clear

- Triplet aperture still allows for $\beta^*$ below 0.1m at beam stay clear of $15.5\sigma$ and with 15mm thick shielding inside quadrupole apertures
- Alternative option with thick shielding of 48mm still allows to reach $\beta^* = 0.2$m
Main EIR – shorter triplet FF

• Since the length of the inner triplet translates into the total length of EIR FF with a large multiplication factor, the shorter by ten meters triplet of the other FF option fits comfortably to the allocated 1400 m space.

• Dedicated code has been used to optimize this optics to be compatible with round beam collisions as well as for flat beam collisions with $\beta^* x/y = 1.0/0.2$ m which can be suitable for the option of operation without crab cavities.

See poster of Léon van Riesen-Haupt
Short triplet FF - Beam Stay Clear

Round

Flat

21\sigma

19.6\sigma
• Can balance, at the design stage, between amount of shielding and $\beta^*$ reach

See poster of Léon van Riesen-Haupt
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Low Lumi EIR FF - triplets

The optics of low-luminosity EIR, where FF is co-located with injection, take into account additional requirements imposed from the need to protect the cold elements from mis-kicked injected beams.

Low Lumi EIR inner triplet – inner coil radius, clear aperture, gradient, thickness of shielding and length of individual quadrupole

M. Hofer, et al
Low Lumi EIR optics

- In the new, more compact FCC-hh layout injection and the low luminosity experiment are combined in Points B & L
- The straight section length remains at 1.4 km
- A layout for these insertion has been designed, which uses a L* of 25 m and achieves $\beta^* = 3$ m
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Studies have been done to test the effect of different errors on the interaction region. These include alignment errors in the triplet, matching section and separation/recombination dipoles, and field errors on the triplet.

For the case of alignment errors, studies have been done to test how well the orbit is restored in comparison to the original one, and the strength of the correctors needed.

For the case of field errors non-linear correctors have been implemented into the lattice to minimize the resonance driving terms arising from the errors of the triplet. Dynamic aperture studies are then performed to study the impact of this correction.

E. Cruz-Alaniz
Alignment Errors & Linear Correctors

- Misalignment errors have been added to the quadrupoles on the triplet, matching section and the separation/recombination dipoles.
- The corrector scheme used for these studies include correctors next to the triplet, matching section and dispersion suppressor, as well as BPM’s installed along the IR.

- Method: use the CORRECT method in MADX, followed by calculating the max orbit deviation in the IR and the strength of the correctors needed, and then repeating the procedure for 100 seeds.
- All the studies have a max deviation below 0.7 mm and require a strength of the correctors for the non-crossing orbit below 1.5 Tm for all cases (achievable). Some of the correctors in the crossing orbit require larger strengths (up to 8 Tm) but are compensated by the length of the correctors.
Field Errors & non-linear Correctors

- Non linear correctors added to the lattice to compensate for the errors errors in the triplet

- Method: adjust strengths of the correctors such that the resonance driving terms arising from the errors in the triplet are set to zero. Each pair of non-linear correctors corrects resonance driving terms arising from two different resonance lines chosen by its proximity to the working point.

- The effect of the implementation of non-linear correctors gave encouraging results, increasing the dynamic aperture from $1.9\sigma$ (without correctors) up to $10.1\sigma$ (with $a3/b3/a4/b4/b6$ correctors)
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Main IR Layout

- Interaction region parameters:
  - $L^*$ 45 m, 89 $\mu$rad half crossing angle

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Q1</th>
<th>Q2A-B</th>
<th>Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td>coil inner diameter [mm]</td>
<td>205</td>
<td>248</td>
<td>248</td>
</tr>
<tr>
<td>length [m]</td>
<td>30.8</td>
<td>26.4</td>
<td>30.8</td>
</tr>
<tr>
<td>gradient [T/m]</td>
<td>107</td>
<td>86</td>
<td>89</td>
</tr>
</tbody>
</table>

3 m long copper TAS at 2 m from Q1, 50 mm ID aperture

**Shielding**, 2 cases considered: 15 mm and 55 mm thick tungsten (INERMET180) shielding inside the cold bore with tentative gaps in the interconnects
Total Power for $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$:

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Power [kW] vertical crossing</th>
<th>Power [kW] horizontal crossing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Shielding</td>
</tr>
<tr>
<td>Q1</td>
<td>2.7</td>
<td>2.0</td>
</tr>
<tr>
<td>C1</td>
<td>0.14</td>
<td>0.11</td>
</tr>
<tr>
<td>Q2A</td>
<td>0.5</td>
<td>0.34</td>
</tr>
<tr>
<td>Q2B</td>
<td>2.15</td>
<td>1.6</td>
</tr>
<tr>
<td>Q3</td>
<td>1.8</td>
<td>1.4</td>
</tr>
<tr>
<td>C2</td>
<td>0.17</td>
<td>0.11</td>
</tr>
</tbody>
</table>

- maximum power per meter is on Q1 and it is 23 W/m, similar to LHC

Peak power density for $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$:
- the maximum on the quadrupole inner coils is at the end of Q1 for both crossing schemes and it is equal to $2.3 \text{ mWcm}^{-3}$ ($1.8 \text{ mWcm}^{-3}$) for vertical crossing (horizontal crossing):
  - for $30 \times 10^{34}$ cm$^{-2}$s$^{-1}$ we expect $13.8 \text{ mWcm}^{-3}$ ($11.8 \text{ mWcm}^{-3}$) for v-(h-)crossing.
15 mm Case: Peak Dose

Peak dose for 5 ab\(^{-1}\):

Max dose value reduced by 40% wrt to previous layout with L* 36 m and 100 mm coil aperture.

Resolution:
\(\Delta z = 10\ \text{cm}, \Delta \phi = 2\ \text{deg}, 2\text{-}3\ \text{mm}\)
15 mm Case: Peak Dose

Peak dose for 5 ab$^{-1}$:

Assuming a peak dose limit of 30 MGy, the triplet can survive an entire high luminosity Run. For 30 ab$^{-1}$ the dose would be 150 MGy.
**15 mm Case: DPA**

**DPA for 5 \( \text{ab}^{-1} \)**

**HL-LHC:** max DPA for 5 \( \text{ab}^{-1} \) is \( \sim 3 \times 10^{-4} \)

<table>
<thead>
<tr>
<th>Particles</th>
<th>Contribution to DPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrons &lt; 20 MeV</td>
<td>78%</td>
</tr>
<tr>
<td>residual nuclei</td>
<td>19%</td>
</tr>
<tr>
<td>protons</td>
<td>1.5%</td>
</tr>
<tr>
<td>electrons</td>
<td>1%</td>
</tr>
</tbody>
</table>

Resolution:

\( \Delta z = 10 \text{ cm}, \Delta \phi = 2 \text{ deg}, 2 - 3 \text{ mm} \)

**Neutron Fluence:**

**HL-LHC:** \( 3 \times 10^{17} \text{ cm}^{-2} \) max neutron fluence for 5 \( \text{ab}^{-1} \)
Total power for $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [kW]:

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Total</th>
<th>Shielding</th>
<th>Cold Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>4.1</td>
<td>3.7</td>
<td>0.37</td>
</tr>
<tr>
<td>C1</td>
<td>0.061</td>
<td>0.056</td>
<td>0.005</td>
</tr>
<tr>
<td>Q2A</td>
<td>0.76</td>
<td>0.7</td>
<td>0.07</td>
</tr>
<tr>
<td>Q2B</td>
<td>2.3</td>
<td>2.1</td>
<td>0.17</td>
</tr>
<tr>
<td>Q3</td>
<td>2.5</td>
<td>2.3</td>
<td>0.18</td>
</tr>
<tr>
<td>C2</td>
<td>0.13</td>
<td>0.12</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Ratio of the power on the cold mass wrt the 15 mm thick shielding case:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>0.5</td>
</tr>
<tr>
<td>C1</td>
<td>0.11</td>
</tr>
<tr>
<td>Q2A</td>
<td>0.5</td>
</tr>
<tr>
<td>Q2B</td>
<td>0.3</td>
</tr>
<tr>
<td>Q3</td>
<td>0.4</td>
</tr>
<tr>
<td>C2</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Peak power density for $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$:

for baseline luminosity the maximum peak power is $0.3 \text{ mW cm}^{-3}$.

Resolution: $\Delta z = 10 \text{ cm}$, $\Delta \phi = 2 \text{ deg}$, radial average is considered along the innermost coil (Q: 18 mm, C: 5 mm)

The expected peak power density for $30 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ is $\sim 2 \text{ mW cm}^{-3}$
Peak dose for 5 ab\(^{-1}\):  
- The peak dose is \(\sim 5\) MGy for 5 ab\(^{-1}\) \(\rightarrow 30\) MGy for 30 ab\(^{-1}\)  
- The triplet can survive for the whole data-taking

DPA for 5 ab\(^{-1}\):  
- The shielding increase has a small impact on DPA  
- After 30 ab\(^{-1}\) DPA are \(4.2\times 10^{-3}\) \(\rightarrow\) challenging  
- Studies and discussions are on-going to determine the limits of the coil material
To do lists:

- magnets are too long:
  - Q1 and Q3: 30.8 m
  - Q2A and Q2B: 26.4 m
- they need to be split to reach a maximum value of 15 m and a 2 m gap between each pair has to be included

> simulations will be repeated with the new layout as soon as it is finalized

M. I. Besana
Shorter triplet FF

Q1
106 T/m

Abs: 4.4 cm

Q2
111 T/m

Abs: 3.3 cm

Q3
97 T/m

Abs: 2.4 cm
Shorter triplet FF

Peak dose for round optics (0.3 m).

Peak dose for flat optics (1.2, 0.15).

Peak dose (50 % hor, 50% vertical cross.)

J. L. Abelleira
Low L IR Layout

- Interaction region parameters:
  - $L^* = 25 \, m$
  - crossing angle of $19 \, \mu rad$, both vertical and horizontal crossing considered
- Magnets:
  - orbit correctors with the same coil aperture
  - A $10 \, mm$ thick tungsten (INERMET180) shielding considered all along the triplet
    - free aperture: $18.25 \, mm$ inner radius
    - $70 \, cm$ long tentative gaps in the interconnects
  - Tungsten mask in front of Q1A:
    - $13.25 \, mm$ inner radius & $8 \, cm$ outer radius
    - almost $80 \, cm$ long

<table>
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<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td>coil aperture radius [mm]</td>
<td>32</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>length [m]</td>
<td>10</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>gradient [T/m]</td>
<td>265</td>
<td>270</td>
<td>260</td>
</tr>
</tbody>
</table>
Low Lumi Energy Deposition

- **Total Power** for $5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ on the inner triplet cold mass = 404 W
  - maximum power per meter on Q1A for both crossing schemes: ~14.4 W/m

- **Peak power density** for $5 \times 10^{33} \text{ cm}$:

- **Peak dose** for 500 fb$^{-1}$:
  - Higher value, but still large statistical uncertainty
  - Peak dose below 20 MGy, for 500 fb$^{-1}$, below present baseline limits

Maximum power at the beginning of Q1A

The effect of the gaps in the interconnects is clearly visible
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Inelastic protons are mostly lost before the next detector, transmission is minimal.

Protons at IPA = 1142177
Protons at IPB = 4263

Particles at IPB PER BX [nom]: 1.457946
Particles at IPB PER BX [ult]: 8.747676
Power [W] at IPB [nom]: 367.969721204
Power [W] at IPB [ult]: 2207.81832722
Mean energy of protons at IPB [GeV]: 49889.6530665

All collision debris generated using DPMJET-III in FLUKA.
Inelastic Protons Lost in DS

H. Rafique, R. B. Appleby, A. M. Krainer

DS losses identified as a concern. Mitigated using existing TCLD DS collimator design and nominal jaw openings. No violation of betatron collimation hierarchy.

\[ \sim 10^7 \text{ [p/s/m] in DS} \]
Muons can travel far in dense materials. Theoretical calculations estimate a range of ~3km. This has been confirmed using FLUKA simulations. Muons should not reach the next IP.

**Muon Detector Cross-Talk**

H. Rafique, R. B. Appleby, J. L. Abelleira

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![Muon E at a given s post IPA](image1.png)

**Theoretical range of muons scored at s = 10 m post IPA**

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![10⁶ muon histories scored at given s in FLUKA](image2.png)

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**no muons**
Synchrotron Radiation Backgrounds for the FCC-hh experiments*

However, at FCC-hh energies this effect starts to be visible!

- About 100W of SR power are emitted by the last 4 bending magnets:

  \[ P \propto \gamma^4 \rightarrow P \propto m^{-4} \]
  \[ P_p \sim 10^{-13} \times P_e \]

- **MDISim** was used to import the beam pipe geometry, magnetic fields and beam characteristics obtained with MAD-X into GEANT4 to perform a full simulation of SR creation and tracking.

- For the two cases with and without the crossing angle scheme we expect about **15-30W** to enter the TAS and thus the Interaction Region.

- About **1W** is expected to hit the inner Beryllium pipe.

- Spectrum of photons entering the TAS with (red) and without (blue) the crossing angle scheme:
  - \( \Rightarrow \) The amount of these photons traversing the Be Pipe is **negligible**.

- This study has been performed also with **SYNRAD+**, with similar results.
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Beam-beam effects DA

- DA criteria from LHC 7.2 $\sigma$ is ensured for a crossing angle of 180 $\mu$rad corresponding to a separation of 15.5 $\sigma$ at long-range encounter
- No margins left for multipolar errors and for stability requirements (octupoles and RF-Q)
- Larger angles will be required and magnets tolerances defined
- Two low luminosity (but high BB) are under study and set “transparent to main”

Studies presented @ IPAC2017: TUPVA026, TUPVA027, TUPVA030, THPAB056, THPAB042

Min dynamic aperture for different beam-beam normalized separations for round optics.

2 IPs only shows the need for 200$\mu$rad
• Alternatives: Flat optics are normally investigated assuming same normalized separation
• Flat optics for bunch trains need larger normalized separations!

DA loss can partially be compensated with tune corrections but not all!
The current tentative design of EIR is consistent with the overall FCC-hh design and its performance goals. In particular, we reiterate that:

- The separation of the points with experiments A, B and L is large enough to avoid significant background from one experiment into the other.
- The power deposited by SR in the experimental beam pipe is in the order of 1 W, which is considered negligible.
- Preliminary designs of the low luminosity EIR have been made matching the newly proposed collider layouts. Their luminosity is limited by $\beta^*$ and the envisaged triplet shielding adequate for providing triplet survivability for luminosity ten times below that of the main EIR.
- The main EIR length can be made to be 1400 m significantly decreasing the operational margins and flexibility. In particular the final quadrupoles might only survive one 5-year run, while with 1500 m three runs are at reach. This has an effect on the eventual choice of $L^*$ and also motivates R&D to develop materials more resilient to radiation.
The current tentative design of EIR is consistent with the overall FCC-hh design and its performance goals. In particular, we reiterate that:

- The separation of the points with experiments A, B and L is large enough to avoid significant background from one experiment into the other.

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- The main EIR length can be made to be 1400 m significantly decreasing the operational margins and flexibility. In particular the final quadrupoles might only survive one 5-year run, while with 1500 m three runs are at reach. This has an effect on the eventual choice of $L^*$ and also motivates R&D to develop materials more resilient to radiation.
The current tentative design of EIR is consistent with the overall FCC-hh design and its performance goals. In particular, we reiterate that:

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- The inner triplet design respects the manufacturing and installation requirements of the max length of quads 15 m and min separation of 2 m. These constraints affect the operational margins and triplet lifetime. It is important to explore further the margins on these values.

- The field quality of the final focusing triplets strongly affects the achievable DA and requires accurate corrections with dedicated coils, challenging machine operational phases before corrections are applied. It should be explored if better field quality can be achieved. Reducing $L^*$ even by 10% will have great benefits in terms of field quality tolerances, operational margins and triplet lifetime.

- Beams are separated in the common beam-pipe with a half crossing angle of about $90 \mu$rad. This is assessed sufficient but without considering the impact from the triplet non-linearities, octupoles and RFQs for Landau damping and the low luminosity experiments.

- Crab cavities are foreseen, which require 20 m of space.

- Alternative operational scenarios w/o crab cavities, using flat beams, have shown to yield integrated luminosity very close to the design goal but Beam-beam studies highlights limitations in the achievable separations.
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The presently chosen $L^*$ of 45 m is affecting the length of the EIR straight section (presently 1500 m for one of the EIR optics options, i.e. longer than 1400 m allocated).

A longer insertion can be allocated, but would either require significant modifications of civil engineering, or would decrease the arc length, which requires to increase the field in magnets in the arcs – this increases their cost or eat up the margins.

The value of $L^*$ is kept at 45 m to preserve the option of the dipole spectrometer in the detector, while the baseline detector is smaller and may use shorter $L^*$. Thus, keeping the option of dipole spectrometer in detector increases the cost of arc magnets. Dropping the option of dipole spectrometer, and better use of EIR space in the detector hall (where each extra meter translates into the total EIR length with a multiplication factor of around fifteen), may allow some reduction of $L^*$, reduction of length of FF and reducing the risks for arcs and arc magnets.

This global dependency will need to be addressed so that the overall performance/cost of the FCC-hh design will be further optimized.
Conclusions and outlook-3

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