HE-LHC IR Optics

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• LHC Infrastructure
  – LHC Tunnel Constraints
  – (Possibly) SPS injection at 450 GeV

• FCC-hh Technology
  – 13.5 TeV Beam Energy
  – Nb$_3$Sn Technology
  – Larger Beam separation

• Updated Arc Cell
  – 18 and 23 Cell Layout
  – New Dispersion Suppression Scheme
  – Update Correction Schemes
Requirements

- **Triplet**
  - Achieve 0.45 m $\beta^*$
  - 16.8 $\sigma$ Crossing Angle
  - 12.5 $\sigma$ Aperture
  - Sufficient shielding for 10 ab$^{-1}$ lifetime
  - Dose limit ~ 30-100 MGy
  - As short as possible

- **Separation Dipoles**
  - Achieve 250 mm separation

- **Matching Section**
  - Match rigid beam

- **Correction Schemes**
  - Dispersion Suppressor
  - Spurious dispersion correction
  - Dynamic aperture with triplet errors
• Triplet optimisation code
  – Collaboration between optics and energy deposition (Jose Abelleira)
  – “Alternative Optics” talk on Tuesday
• Based on experience of FCC-hh
  – Allow for Additional $\beta^*$ Margin
  – Uniform Beam Pipe
  – Magnet Length Limited to 15 m
• HL-LHC V1.2 Triplet as starting point
  – Use Magnet Separations
  – Initial estimate $\frac{13.5 \text{ TeV}}{7 \text{ TeV}} \approx 90 \%$ increase in length
  • Without considering increased shielding
• Converged on triplet with 2 cm shielding
• Only 35% longer than HL-LHC V1.2 triplet
  – 50% more magnetic length
• “Un-split” Q1 and Q3 magnet
  – Absorbed gap in inter magnet spacing
  – Safety margin
Results Continued

• Aperture of 18 $\sigma$
  – Larger than required 12 $\sigma$
  – Allow to further reduce $\beta^*$ by factor ~2 if needed

• Uniform magnetic aperture and shielding

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Q1</th>
<th>Quadrupole Q2</th>
<th>Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-magnets</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Sub-magnet Length (m)</td>
<td>12.9</td>
<td>10.5</td>
<td>12.9</td>
</tr>
<tr>
<td>Coil Radius (mm)</td>
<td>70.4</td>
<td>70.4</td>
<td>70.4</td>
</tr>
<tr>
<td>Gradient (Tm⁻¹)</td>
<td>145</td>
<td>145</td>
<td>145</td>
</tr>
<tr>
<td>Shielding (mm)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>
• FLUKA Simulation
  – Based on FCC-hh magnet model
• Energy deposition safely below 30 ab\(^{-1}\) margin
• Can reduce further by alternating crossing
• Extra room for shielding in Q1 and Q2 if needed
• 11 m $\beta^*$
• 16.8 $\sigma$ separation and crossing
Separation Dipoles

- Compact as possible
  - Compensate for longer triplet
- Increased beam rigidity
- Requires superconducting dipoles
- Radiation studies required

<table>
<thead>
<tr>
<th>Property</th>
<th>D1</th>
<th>D2</th>
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<tbody>
<tr>
<td>Aperture Type</td>
<td>Single</td>
<td>Double</td>
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<tr>
<td>Coil Radius (mm)</td>
<td>80</td>
<td>38.5</td>
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<tr>
<td>Shielding (mm)</td>
<td>21.5</td>
<td>9</td>
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<tr>
<td>Length (m)</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Field (T)</td>
<td>9.7</td>
<td>7.7</td>
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</table>
Energy Deposition

- Energy in D1 below 30 Mgy limit
- Large amount of deposition in D2
  - 9 mm not sufficient
• Possibility of installing shielding at an angle
  – Extrude cylinder shielding block
  – Allows 9 mm – 27 mm shielding
• Reduces dose
  – 40 MGy
• Further Reduction Possible
  – Split D2
Matching Section

• Based on HL-LHC Matching Section
  – Space reserved for crab cavities and instrumentation

  \[ V_{cc} \approx \frac{cE_{\text{beam}} \theta}{\pi f \sqrt{\beta \beta_{cc}}} \approx 10 \text{ MV} \]

  • Slightly higher than ~6.6 MV in HL-LHC
  – Layout of quadrupoles

• Adjusted Quadrupole Lengths
  – Match without strength constraints
  – Lengthen to achieve correct integrated strength

• Similar process for dispersion suppressor

• Matched for 23 and 18 cell lattice
**Matching Section**

- Twiss matched to arc
- Phase advance matched to 3\textsuperscript{rd} and 4\textsuperscript{th} sextupole
  - Instead of 1\textsuperscript{st} and 2\textsuperscript{nd}
- Small quadrupole increase
  - Distances between quadrupoles $\sim$ 20 m
  - Dispersion suppressor quadrupoles increase 25%

<table>
<thead>
<tr>
<th>Quadrupole</th>
<th>Length (m)</th>
<th>Increase (%)</th>
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<tbody>
<tr>
<td></td>
<td>LHC</td>
<td>HE-LHC</td>
</tr>
<tr>
<td>Q4</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Q5</td>
<td>4.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Q6</td>
<td>4.8</td>
<td>7.2</td>
</tr>
<tr>
<td>Q7</td>
<td>$2 \times 3.4$</td>
<td>$2 \times 5.1$</td>
</tr>
</tbody>
</table>
Spurious Dispersion

- Arises from crossing angle bumps
- LHC-like correction
  - Bump in arcs adjacent to EIR
  - Correction through quadrupoles and sextupoles
- Results in no dispersion in adjacent IRs
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Sixtrack studies
  - 23-Cell Lattice
  - $10^6$ turns

Double tuning applied
  - FCC experience (E. Cruz-Alaniz)

Triplet errors applied
  - Based on HL-LHC error table
  - $9\sigma$ DA

Corrections
  - Non-linear local correction
  - Coupling correction
  - $24\sigma$ DA
Double Tuning – IR4

- RF insertion
- Based on LHC
- Additional quadrupole
  - Extra freedom for tune
  - Change tune by changing optics
  - No beating in cavities
- Range of $\pi$ in both planes
  - Double tuning
  - Should be repeated with IR6
Double Tuning – IR4

• RF insertion
• Based on LHC
• Additional quadrupole
  – Extra freedom for tune
  – Change tune by changing optics
  – No beating in cavities
• Range of $\pi$ in both planes
  – Double tuning
  – Should be repeated with IR6
• Full HE-LHC EIR Design
• Triplet Optimised using FCC-hh Methods
  – Length and shielding optimised
  – Significantly shorter than expected
• Separation Dipole Design
  – Including radiation studies and shielding options
• Matching Section
  – For both lattices
  – Injection optics
• Dynamic Aperture
  – Meets requirements
  – Full set of correction tools