New lattice design

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4th EuroCirCol meeting @ KIT
17th October 2018
Status at the FCC week 2018

- New arc FODO cells:
  - FODO cells a bit longer.
  - $b_2$ up to 50 units in the main dipoles.
  - More realistic magnet fields.
    - Courtesy D. Schoerling’s group
  - Longer inter-dipole distance.
    - $1.36 \text{ m} \rightarrow 1.5 \text{ m}$
    - $B_{MB} \uparrow$

- New experimental insertion region:
  - $L = 1.5 \text{ km} \rightarrow L = 1.4 \text{ km}$.
    - LAR a bit longer.
    - $B_{MB} \downarrow$
  - Alternative inner triplet.
  - $B_{MB} = 15.71 \text{ T} \rightarrow B_{MB} = 15.96 \text{ T}$
Main changes

- **New intra-beam distance**: 204 mm → 250 mm

  ⇒ **New $b_2$ value in the dipoles**: 0 at collision and 20 units at injection.

  - $b_2$ may decrease even more with new magnet design.

- **Insertions have been updated**:

  - Updated interaction region with enlarged intra-beam distance.
  - Updated injection + low-luminosity region.
  - New extraction section.
  - Momentum collimation section with enlarged dispersion (increase by 25% at collision and by 60% at injection).

- Reduction of the optical functions in the dispersion suppressors to enlarge the physical aperture.

- No more missing dipole at the middle of TSS to get empty place (civil engineering has put a local cavern nearby).

- **New method to set the global tune and phase advances between IPs** by playing with FODO cells of long arcs.

- Bug correction on the aperture calculation (thanks to Roman Martin).
The FODO cell is 213.03 m long.

- The distance inter-dipole is 1.5 m.
- The main dipole MD is 14.069 m long.
- The maximum dipole field is 15.94 T with an aperture of 50 mm.
- MCS has the same length as in LHC: 0.11 m.
- The maximum quadrupole gradient is 318 T/m in the arcs (against 360 T/m before thanks to $b_2$ reduction). MQs could be shortened.
- The maximum corrector field is 4 T.
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## Arc lattice: magnets

<table>
<thead>
<tr>
<th>Magnet type</th>
<th>Distance (m)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB-MB</td>
<td>1.5</td>
<td>May be longer if stronger MCS required</td>
</tr>
<tr>
<td>MB-SSS</td>
<td>1.3</td>
<td>Does not include BPMs</td>
</tr>
<tr>
<td>MQ-Other</td>
<td>0.35</td>
<td>Other magnetic elements in SSS</td>
</tr>
<tr>
<td>Other-Other</td>
<td>0.35</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Magnet type</th>
<th>Number</th>
<th>Max. Strength</th>
<th>Length</th>
<th>SC material</th>
<th>LHC nominal strength (56 mm aperture)</th>
<th>LHC nominal strength scaled to 50 mm aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Dipole (MB)</td>
<td>4672</td>
<td>16 T</td>
<td>14.1 m</td>
<td>Nb$_3$Sn</td>
<td>8.33 T</td>
<td>8.33 T</td>
</tr>
<tr>
<td>Main Quadrupole (MQ)</td>
<td>744</td>
<td>360 T/m</td>
<td>7.2 m</td>
<td>Nb$_3$Sn</td>
<td>223 T/m</td>
<td>250 T/m</td>
</tr>
<tr>
<td>Trim Quadrupole (MQT)</td>
<td>88</td>
<td>220 T/m</td>
<td>0.5 m</td>
<td>Nb-Ti</td>
<td>123 T/m</td>
<td>140 T/m</td>
</tr>
<tr>
<td>Skew Quadrupole (MQS)</td>
<td>96</td>
<td>220 T/m</td>
<td>0.5 m</td>
<td>Nb-Ti</td>
<td>123 T/m</td>
<td>140 T/m</td>
</tr>
<tr>
<td>Main Sextupole (MS)</td>
<td>696</td>
<td>7000 T/m$^2$</td>
<td>1.2 m</td>
<td>Nb-Ti</td>
<td>4430 T/m$^2$</td>
<td>5560 T/m$^2$</td>
</tr>
<tr>
<td>Main Octupole (MO)</td>
<td>480</td>
<td>200,000 T/m$^3$</td>
<td>0.5 m</td>
<td>Nb-Ti</td>
<td>63,000 T/m$^3$</td>
<td>90,000 T/m$^3$</td>
</tr>
<tr>
<td>Sextupole Corrector (MCS)</td>
<td>9344</td>
<td>3000 T/m$^2$</td>
<td>0.11 m</td>
<td>Nb-Ti</td>
<td>1630 T/m$^2$</td>
<td>2050 T/m$^2$</td>
</tr>
<tr>
<td>Dipole Corrector (MCB)</td>
<td>792</td>
<td>4 T</td>
<td>1.2 m</td>
<td>Nb-Ti</td>
<td>3 T</td>
<td>3 T</td>
</tr>
<tr>
<td>DIS Trim Quadrupole (MQTL)</td>
<td>48</td>
<td>220 T/m</td>
<td>2.0 m</td>
<td>Nb-Ti</td>
<td>129 T/m</td>
<td>145 T/m</td>
</tr>
<tr>
<td>DIS Quadrupole (MQDA)</td>
<td>48</td>
<td>360 T/m</td>
<td>9.7 m</td>
<td>Nb$_3$Sn</td>
<td>129 T/m</td>
<td>145 T/m</td>
</tr>
</tbody>
</table>
Insertions: main experiments

- Version 7 of the EIR.
- $L^* = 40$ m.
- BPMs and correctors have been integrated.
- Courtesy: R. Martin et al.
  
→ see Martin: “Overview of IR”
→ see Van Riesen-Haupt: “Alternative IR for FCC-hh and HE-LHC IR”

Considered $\beta^*$:
- 6.0 m (injection)
- 4.6 m (baseline injection)
- 1.1 m (baseline)
- 0.3 m (ultimate)
- 0.2 m (more ultimate)
- 0.15 m (ultimate ultimate)
- 1.2 m/0.15 m (alternative flat beam)

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- 1.2 m/0.15 m (alternative flat beam)

$\beta^* = 0.3 \text{ m alternative}$

$\beta^* = 4.6 \text{ m alternative}$
Insertions: injection + low-$L$ experiment

- Injection in the same section as the additional experiments.
- $L^* = 25$ m

- New version of the insertion implemented.
- Courtesy: M. Hofer et al.
- Considered $\beta^*$:
  - 27 m (injection)
  - 3 m (collision)

Inj.+Exp. section: LSS B (@ collision)

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- Considered $\beta^*$:
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Dedicated section to $\beta$-cleaning

The DIS is optimized to enhance the losses coming from $\beta$ and $\delta$ collimation.

→ see Molson: “FCC-hh collimation”

LHC-scaled $\delta$-cleaning insertion

Courtesy: J. Molson

Enlarged dispersion (max: 3 m at collision, 4 m at injection).
Insertions: collimation sections

- Dedicated section to $\beta$-cleaning
- The DIS is optimized to enhance the losses coming from $\beta$ and $\delta$ collimation.
  → see Molson: “FCC-hh collimation”

- LHC-scaled $\delta$-cleaning insertion
- Courtesy: J. Molson
- Enlarged dispersion (max: 3 m at collision, 4 m at injection).
RF section is made of FODO cells: it can be used to adjust phase advances between insertions.

The lattice of this section has been implemented.

Dedicated section for the extraction (2.8 km).

New version of this insertion has been integrated.

Courtesy: F. Burkart, W. Bartmann et al.
3 schemes are currently implemented to tune the ring:
- FODO cells of long are slightly detuned \((90° + \epsilon)\). DIS are rematched.
- Use of phase trombones in insertions.
- **Use of different phase advances in the long arcs** to tune the machine and phase advances between IPs (baseline).
- BPMs and dipole correctors are integrated in the lattice to correct the orbit. Additional BPMs in the IR have been added.
- Trim quadrupoles are integrated to correct the horizontal spurious dispersion, the \(\beta\)-beating and the dispersion-beating
- Skew quadrupoles are used to correct the coupling (sets of 4 separated by 90° each) and the vertical spurious dispersion.

\[\rightarrow\text{ see Boutin: "Correction scheme".}\]
- The dynamic aperture studies have shown that:
  - \(b_3 \text{ (coll + injection)}\) and \(b_5 \text{ (injection)}\) correctors are mandatory.
  - \(b_4\) does not need corrections

\[\rightarrow\text{ see Dalena: “Dynamic aperture studies of FCC-hh at injection”}\]

\[\rightarrow\text{ see Cruz-Alaniz: “Dynamic aperture studies of FCC-hh at collision”}\]
- Octupoles integrated for Landau damping and beam-beam correction.
Collision optics integration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>TeV</td>
</tr>
<tr>
<td>Circumference</td>
<td>km</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>m</td>
</tr>
<tr>
<td>$L^*$</td>
<td>m</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$\gamma_{tr}$</td>
<td>-</td>
</tr>
<tr>
<td>$Q_{X \text{ coll}}$</td>
<td>-</td>
</tr>
<tr>
<td>$Q_{Y \text{ coll}}$</td>
<td>-</td>
</tr>
<tr>
<td>$Q_{X \text{ inj}}$</td>
<td>-</td>
</tr>
<tr>
<td>$Q_{Y \text{ inj}}$</td>
<td>-</td>
</tr>
<tr>
<td>$Q'_{X}$</td>
<td>-</td>
</tr>
<tr>
<td>$Q'_{Y}$</td>
<td>-</td>
</tr>
<tr>
<td>MB field</td>
<td>T</td>
</tr>
<tr>
<td>MQ gradient</td>
<td>T/m</td>
</tr>
<tr>
<td>MS gradient</td>
<td>T/m$^2$</td>
</tr>
</tbody>
</table>
Contrary to LHC, the dipoles are assumed to be straight.

A margin of 1.2 mm is added to the horizontal tolerance to handle the sagitta.

Arc AB: \( b_2 = +20 \)

\( n_{1,\text{min}} = 16.8 \)

Arc BC: \( b_2 = -20 \)

\( n_{1,\text{min}} = 17.3 \)

Reduction of the beam-stay clear by 1.5\( \sigma \) because of the sagitta.

Target: 13.4\( \sigma \) at injection and 15.5\( \sigma \) at collision.
The selected dispersion suppressor is similar to LHC: best compromise between filling factor and flexibility.

- Two collimators (TCLD) of 1 meter are inserted to clean the beam at the arc entrance (the needed space is 5 meters for each TCLD).
- Bottleneck for the machine aperture (location of betatron and dispersion peaks).
- New constraints in the DIS to reduce betatron and dispersion peaks there.
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Interaction region aperture @ injection

EIR: LSS A

Low-lumi + injection section: LSS B

Low-lumi section: LSS L

EIR: LSS G
Insertions aperture @ injection

Extraction: ESS D

β collimation: ESS J

RF section: LSS H

δ collimation: LSS F
New lattice has been presented:

- $b_2$ is smaller in dipoles: 20 units at injection and 0 unit at collision.
- Updated insertions: larger intra-beam separation in the insertions, larger dispersion in the $\delta$ collimation section.
- Machine is now tuned with phase advances in the FODO cells of the long arcs.
- No missing dipole in the long arcs.
- Optical functions reduced in the DIS.

- Physical aperture is now within the specifications at injection.
- Magnet list has been updated.
- Alternative optics exists.
Next steps

- To check with collimation team that the new $\delta$ collimation insertion fits the expectations.
- To release on gitlab a new lattice (the last release is already obsolete).
- To finalize the magnet list: effort was focused on arcs. Collimation, extraction and RF insertions were not investigated as much.
- To integrate $b_5$ correctors.
- To consolidate the lattice files.
- CDR writing.
- CDR debugging.
- CDR checking.