First evaluation of Dynamic Aperture at injection for FCC-hh

B. Dalena

Thanks to: D. Boutin, A. Chancé, R. De Maria, S. Fartoukh, R. Martin, J. Payet, E. Todesco, K. N. Sjobaek...
Outline

• Arcs design
  – Feedback from magnet designers

• Dipole’s field errors and Dynamic Aperture

• First tolerances on systematic $b_3$ and correctors integrated strength
  – Feedback from magnet designers

• First consideration on systematic $b_5$
• MD and b3 correctors (MCS) have same length as LHC (12 MD and 12 MCS)
  – minimum distance between two dipole checked (see E. Todesco talk)
• 2 focusing and 2 defocusing sextupole families
• No octupole and decapole correctors are integrated so far
• No skew quadrupoles and skew sextupoles
• Each quad is equipped with a trim (before the quad, not showed in the sketch)
• Relative position of the BPM and the orbit corrector with respect to the MQ are different from LHC
  – see D. Boutin talk
### Arcs design: magnets status

<table>
<thead>
<tr>
<th>element</th>
<th>Length [m]</th>
<th>Max strength</th>
<th>units</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Dipole</td>
<td>14.3</td>
<td>16-ε</td>
<td>T</td>
<td>2% less field is a non negligible gain!</td>
</tr>
<tr>
<td>b3 corrector</td>
<td>0.11</td>
<td>0.0043</td>
<td>m⁻²</td>
<td>up to 3 times LHC MCS field is fine</td>
</tr>
<tr>
<td>quadrupole</td>
<td>6.29</td>
<td>370</td>
<td>T/m</td>
<td>with Nb₃Sn can reach 400 T/m (6 m long magnet)</td>
</tr>
<tr>
<td>sextupole</td>
<td>0.5</td>
<td>16000.</td>
<td>T/m²</td>
<td>4.8 (10^{-2}) m⁻² max we can reach with present technology (1.5 m long magnet) ⇒ (\beta^* \leq 0.3)m requires longer sextupoles or special chromaticity correction scheme</td>
</tr>
<tr>
<td>orbit corrector</td>
<td>0.647</td>
<td>3.6</td>
<td>Tm</td>
<td>feasible up to 4 Tm with NbTi technology</td>
</tr>
</tbody>
</table>

- \(\sigma_{quad}=0.35\)mm
- \(\sigma_{b1}=0.001\) main field
Dynamic aperture is evaluated with SixTrack adapted for FCC!
(SixTrack website, cern.ch/sixtrack-ng)
Inputs long-term DA study:
- 60 seeds
- 30 particle pairs
- Emit norm 2.2e-6 m.rad
- $E_0 = 3.3$ TeV
- $Q' = 2$
- $\frac{dp}{p} = 0.00075$ (LHC)
- $\frac{dp}{p}$ max = 0.002
- $\sigma$ step = 2, $\sigma \in [2-40]$ explored
- 5 angles $\in [0,90^\circ]$

without dipoles errors DA > 80 $\sigma$

with first dipoles errors: “systematic” $b_3$ uncorrected (chromaticity due to $b_3$ corrected)

<table>
<thead>
<tr>
<th>MS Integrated strength</th>
<th>$b_3 = 0$</th>
<th>$b_{3S} = -5$ error table</th>
<th>$b_{3S} = 15$</th>
</tr>
</thead>
<tbody>
<tr>
<td>KSF $[10^{-2} m^{-2}]$</td>
<td>0.9</td>
<td>2.9</td>
<td>-5.2</td>
</tr>
<tr>
<td>KSD$[10^{-2} m^{-2}]$</td>
<td>-1.8</td>
<td>1.4</td>
<td>-11.5</td>
</tr>
</tbody>
</table>

$\Rightarrow b_{3S} = -5$ units is not a problem for DA at 3.3TeV
$\Rightarrow$ good compensation of $b_{3S}$ by the $\sim 90^\circ$ phase advance, DA reduction dominated by random errors
$\Rightarrow b_{3S} = 15$ units intolerable without correction (strong sextupoles and minimum DA $\sim 8\sigma$)
$\Rightarrow$ effect of different horizontal phase advance in the long arcs: up to $3\sigma$ of average DA (at $15^\circ$)
DA with errors: collision

Inputs long-term DA study:
- 60 seeds
- 30 particle pairs
- Emit norm 2.2e-6 m.rad
- \( E_0 = 50 \) TeV
- \( Q' = 2 \)
- \( \frac{dp}{p} = 0.00027 \) (LHC)
- \( \frac{dp}{p} \) max = 0.002
- \( \sigma \) step = 2, \( \sigma \in [2-40] \) explored
- 5 angles \( \in [0,90^\circ] \)

without dipoles errors minimum DA > 54 \( \sigma \)

with first dipoles errors: “systematic” \( b_3 \) uncorrected (chromaticity due to \( b_3 \) corrected)

<table>
<thead>
<tr>
<th>MS integrated strength</th>
<th>( b_3 = 0 )</th>
<th>( b_{3S} = 20 ) error table</th>
</tr>
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<tbody>
<tr>
<td>KSF ([10^{-2} \text{ m}^2])</td>
<td>2.4</td>
<td>-5.8</td>
</tr>
<tr>
<td>KSD([10^{-2} \text{ m}^2])</td>
<td>-4.8</td>
<td>-17.9</td>
</tr>
</tbody>
</table>

\( \Rightarrow \) \( b_{3S} = 20 \) units intolerable without correction (minimum DA 8 \( \sigma \) and too stronger sextupoles)

\( \Rightarrow \) need to correct \( b_{3S} \) (with \( b_{3S} = 0 \) units, minimum DA \( \sim 28 \) \( \sigma \))

\( \Rightarrow \) effect of different straight sections: smaller than at injection (different multipoles play a role)
### b3 and MCS strength: collision

Based on S. Fartoukh and O. Bruning, **LHC project report 501**

**MCS integrated strength for** $B = 0.471$ T, $L_{MCS} = 0.11$ m

\[
(K^+_2 L)_{mcs} = \frac{L_{mcs}}{B \rho} \cdot \frac{\partial^2 B_y}{\partial x^2} = 2 \times \frac{0.3}{p \text{[GeV]}} \times \frac{\left(Bl_{(x=R_{ref})}\right) \text{[Tm]}}{R_{ref}^2}
\]

- Integrated strength to correct one $b_{3S}$ unit of $b_{3s}$
  \[
  (K^+_2 L)_{mb} = 2 \times \alpha \frac{b_{3S}}{R_{ref}^2}
  \]
  \[
  \alpha = 2 \pi / N_{dipole}
  \]

**LHC MCS correct**

- @ LHC $|b_{3S}| < 3 \text{ [10}^{-4}\text{]}$ equal to 70% of MCS max integrated strength
- $\Rightarrow$ FCC $|b_{3S}| < 3 \text{ [10}^{-4}\text{]}$ equal to 70% of 2 integrated strength of LHC MCS
  (to have same tolerance of LHC at FCC)

- 3 units of $b_3$ are reasonable at 50 TeV if we allow 6-7 units of $b_3$ at injection (3.3 TeV)
- 3 times stronger MCS is feasible and can correct up to 6 units of $b_3$ at 50 TeV
  - see E. Todesco talk

**Table:**

<table>
<thead>
<tr>
<th>Coll [10-4 m-2]</th>
<th>Inj [10-4 m-2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>154.</td>
<td>2390.</td>
</tr>
<tr>
<td>21.5</td>
<td>326.</td>
</tr>
</tbody>
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<tr>
<td>35.3 x $b_{3S}$</td>
</tr>
<tr>
<td>9.42 x $b_{3S}$</td>
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<tr>
<td>4.35</td>
<td>67.7</td>
</tr>
<tr>
<td>2.3</td>
<td>34.6</td>
</tr>
</tbody>
</table>
Average $b_{3S}$ for each of the 8 arcs is corrected with spool pieces MCS, one at every dipole (same scheme of HL-LHC by S. Fartoukh).

\[
\begin{array}{|c|c|c|c|}
\hline
\text{MS integrated strength} & b_3 = 0 & b_{3S} = 20 \text{ error table} & b_{3S} = 3 + \text{correctors} \\
\hline
\text{KSF} [10^{-2} \text{ m}^2] & 2.4 & -5.8 & 2.4 \\
\text{KSD} [10^{-2} \text{ m}^2] & -4.8 & -17.9 & -4.8 \\
\hline
\end{array}
\]

⇒ ~81% of 2 times the strength of LHC MCS fully correct $b_{3S}=3$ units (minimum DA ~28 σ)

If 3 times stronger MCS are feasible and correct up to 6 units of $b_3$ at 50 TeV (see E. Todesco talk)
⇒ possibility to reduce the number of MCS?
Average $b_{3S}$ for each of the 8 arcs is corrected with spool pieces MCS, one at every dipole (as in collision).

|$b_{3S}$ for each of the 8 arcs is corrected with spool pieces MCS, one at every dipole (as in collision).$

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$\Rightarrow$ **23% of 2 times the strength of LHC MCS fully correct $b_{3S} = 15$ units** (minimum DA > 12 $\sigma$)

$\Rightarrow$ E. Todesco (see talk) proposed 6-7 units of $b_{3S}$ at injection

$\Rightarrow$ as far as DA is concerned with MCS even 15 units of $b_{3S}$ are fine, feed-down effects on random $b_2$ to be checked, in presence of misalignment
Inputs long-term DA study:
- 60 seeds
- 30 particle pairs
- Emit norm 2.2e-6 m.rad
- \( E_0 = 3.3 \text{ TeV} \)
- \( Q' = 2 \)
- \( \frac{dp}{p} = 0.00075 \text{ (LHC)} \)
- \( \frac{dp}{p} \text{ max} = 0.002 \)
- \( \sigma \text{ step} = 2, \sigma \in [2-40] \text{ explored} \)
- 5 angles \( \in [0,90^\circ] \)

\( \Rightarrow b_5^S = 1 \text{ unit reduces average DA of } 3 \sigma \text{ at } 15^\circ \)
\( \Rightarrow \text{similar effect is produced by different horizontal phase advance in the long arcs} \)

\( \Rightarrow \text{As far as DA is the criteria (> 12 } \sigma \text{ at injection), we do not need the } b_5 \text{ correctors} \)
  \( \Rightarrow \text{need to look at the impact of } b_5^S \text{ on } Q''' \text{ (i.e. tune vs } \delta p/p) \)
  \( \Rightarrow \text{need to look at the feed-down effect on } b_4 \text{ (tune spread)} \)
Conclusion

✓ First dipole’s errors table gives good DA (12σ) at injection
  • 5 units of systematic $b_3$ at 3.3 TeV are well compensated as far as DA is considered as criteria
  • 15 units of systematic $b_3$ reduce DA to < 10 σ and too strong sextupoles required
  • ~23% of 2 times the strength of LHC MCS fully correct $b_{3S}=15$ units at 3.3 TeV
  • at present 6-7 units of $b_3$ at injection (3.3 TeV) are proposed (see E. Todesco talk)
  ⇒ 3.3 TeV is not the lower limit for injection energy (as far as DA is concerned)

✓ First dipole’s errors table gives DA < 10 σ in collision
  • 3 units of systematic $b_3$ has been fixed as target at 50 TeV
  • ~81% of 2 times the strength of LHC MCS fully correct $b_3=3$ units at 50 TeV
  • with 3 times the strength of LHC MCS can correct up to 6 units of $b_3$ at 50 TeV (see E. Todesco talk)
  ⇒ possibility to reduce spool pieces ?

✓ As far as DA is the criteria (> 12 σ at injection), the $b_5$ correctors seems not to be needed
  ⇒ Look at impact of systematic $b_5$ on $Q'''$ and feed-down effect on $b_4$
- Misalignment and feed-down effects
- Tolerances on the uncertainty “U” and the random components (of higher multipoles as well)
- Effect of different optics (straight section and arcs phase advances)
SPARES
FCC-hh Layout

- Long arc \((L=16\text{ km}, R=13\text{ km})\)
- Short arc \((L=3.2\text{ km}, R=13\text{ km})\)
- DS \((L=0.4\text{ km}, R=17.3\text{ km})\)

6 short straight sections \((1.4\text{ km})\)
2 long straight sections \((4.2\text{ km})\)
CELL PARAMETERS

Input parameters:
• Minimum space between dipoles 1.36 m
• Dipole maximum field 16 T
• Dipole length 14.3 m
• Minimum space between quadrupole and dipoles 3.67 m
• Maximum gradient of the quadrupole 370 T/m
• $\Phi = 50$ mm, beam screen radius 20 mm
• Sextupole length 0.5 m
• Space between quadrupole and sextupole 1.0 m
• Phase advance per cell 90° x/y
• Circumference $3.75 \times \text{LHC} \sim 100$ km

$\# \text{ of sigma at } E_{\text{inj}} = 3.3 \text{ TeV}$

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Dispersion Suppressor and dipole Field

Circumference = 100.12 km

⇒ Full Bend DS: ~1% lower dipole field with respect to LHC-like DS
⇒ Half Bend DS: no solution below 16 T
Dispersion suppressor types & optics

Circumference = 100.12 km, beam screen radius = 20 mm

- Half Bend
- LHC-like
- Full Bend

Non matched solutions

⇒ Lcell ~215 m good for optics functions and number of sigma of the beam
⇒ LHC-like DS easiest to match to the insertions

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Closer look to dipoles and cells length

Circumference = 100.12 km, beam screen radius = 20 mm, LHC-like dispersion suppressor

\[ LD = [14.0 : 14.3] \text{ m} \text{ and } L_{\text{cell}} = 245 \text{ m} \]
\( \approx 2\% \) of dipole field is saved, losing \( \approx 15\% \) of beam sigma and having 2.5-4\% more dipoles

\[ LD = 14.8 \text{ m} \text{ and } L_{\text{cell}} = 219 \text{ m} \]
\( \approx 3\% \) of dipoles and 1\% of dipole field can be saved, losing \( \approx 3\% \) of beam sigma

\[ \Rightarrow \text{LD } \approx [14.0 : 14.3] \text{ m} \text{ and } L_{\text{cell}} = 245 \text{ m} \]
\( \approx 2\% \) of dipole field is saved, losing \( \approx 15\% \) of beam sigma and having 2.5-4\% more dipoles

\[ \Rightarrow \text{LD } = 14.8 \text{ m} \text{ and } L_{\text{cell}} = 219 \text{ m} \]
\( \approx 3\% \) of dipoles and 1\% of dipole field can be saved, losing \( \approx 3\% \) of beam sigma

B. Dalena, FCC week 2015
# Some Lattice parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bρ [T m]</td>
<td>166667</td>
</tr>
<tr>
<td>γ</td>
<td>53289</td>
</tr>
<tr>
<td>γ_transition</td>
<td>97</td>
</tr>
<tr>
<td>α</td>
<td>0.0001</td>
</tr>
<tr>
<td>β* [m]</td>
<td>1.1</td>
</tr>
<tr>
<td>Natural chromaticity x/y</td>
<td>-196/ -197.</td>
</tr>
<tr>
<td>Equilibrium emittance* [m rad]</td>
<td>1e-12</td>
</tr>
<tr>
<td>(\varepsilon_{\text{norm}}/\beta\gamma) [m rad]</td>
<td>4.1e-11</td>
</tr>
<tr>
<td>Transverse/Longitudinal Damping time** [h]</td>
<td>2/1</td>
</tr>
</tbody>
</table>

\[*\] \(\varepsilon_{eq} = \frac{C_q\gamma^2 I_5}{I_2\left(1 - \frac{I_4}{I_2}\right)}\)

\[**\] \(\tau_t = \frac{2E_0T_0}{U_0} \quad \tau_t = \frac{2E_0T_0}{U_0\left(2 + \frac{I_4}{I_2}\right)}\)

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