Update on dipole field quality and DA at injection for FCC-hh

B. Dalena

Acknowledgements: A. Chance, R. De Maria, E. Maclean, A. Mereghetti, T. Persson, T. Pugnat, F. Schmidt
Outline

• Summary of Amsterdam DA results for table v3
• Understanding Amsterdam results:
  I. FCC RF acceptance and $\Delta p/p$
  II. SixTrack DA values
• First DA results for table v42
• Conclusion and perspectives
Puzzling Amsterdam DA results

Main dipole field quality table v3, $b_2=50$ unit, $Q'=2$

<table>
<thead>
<tr>
<th>Min DA [$\sigma$]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.8</td>
<td>no phases</td>
</tr>
<tr>
<td>34.1</td>
<td>IPA-IPG col phases</td>
</tr>
<tr>
<td>15.3</td>
<td>+tripD1D2 errors</td>
</tr>
<tr>
<td>3.7</td>
<td>+IPA-IPG col phases, tripD1D2 errors</td>
</tr>
<tr>
<td>5.1</td>
<td>+IPA-IPG col phases, tripD1D2 errors -15/720 A octupole strength</td>
</tr>
<tr>
<td>7.0</td>
<td>+IPA-IPG col phases, tripD1D2 errors -30/720 A octupole strength</td>
</tr>
</tbody>
</table>

• Very big DA and large uncertainty for main dipole field errors only
• Very small DA for main dipole + triplet errors at injection
• DA increase with negative octupoles polarity
I. RF acceptance

Evolution of energy in SixTrack for initial $\Delta p/p$ of $7.5 \times 10^{-4}$

$$\left(\frac{\Delta p}{p_0}\right)_{max} = \sqrt{\frac{2V_{RF}}{\pi h |\eta| c p_0}}$$

<table>
<thead>
<tr>
<th>V_{RF} [MV]</th>
<th>P_0 [TeV]</th>
<th>$\Delta p/p$ max $10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC</td>
<td>16</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>50</td>
</tr>
<tr>
<td>LHC</td>
<td>8</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>7</td>
</tr>
</tbody>
</table>

$\Rightarrow$ FCC @ injection $3.2 \times 10^{-4}$ (2/3 of max RF acc)

$\Rightarrow$ FCC @ collision $1.15 \times 10^{-4}$ (2/3 of max RF acc)
II.  DA with dipole errors only (table v3)

**SixTrack output**

<table>
<thead>
<tr>
<th>Angle/seed</th>
<th>achaos</th>
<th>achaos1</th>
<th>alost1</th>
<th>alost2</th>
<th>Firstamp</th>
<th>lastamp</th>
</tr>
</thead>
</table>

DA values I used up to now came from alost1
- Unless particular values of distance of two very close particles and max slope of this distance alost1=alost2
- For FCC alost1 is always negative and with large spread (|alost1| > 30 σ)
- For FCC alost2 is positive for all the seeds

Δp/p of 7.5 \(10^{-4}\)

⇒ DA below the target at injection
### DA with dipole, triplet errors and MO (table v3)

**SixTrack output**

<table>
<thead>
<tr>
<th>Angle/seed</th>
<th>achaos</th>
<th>achaos1</th>
<th>alost1</th>
<th>alost2</th>
<th>Firstamp</th>
<th>lastamp</th>
</tr>
</thead>
</table>

- alost1 and alost2 values in this case are more similar
- alost1 has still some negative values $< 4 \sigma$

**Graphs**

- **ARC DIPOLE, TRIPLET**
  - Triplet has no significant impact on DA at injection

- **ARC DIPOLE, TRIPLET, MO l=-30/720A**
  - Octupoles slightly increase DA at injection

Δ$p/p$ of $7.5 \times 10^{-4}$
More correct Amsterdam results (table v3)

<table>
<thead>
<tr>
<th></th>
<th>Min DA [σ]</th>
<th>∆p/p = 7.5e⁻⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>arc dipoles</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>arc + triplet</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>arc + triplet + oct -30A</td>
<td>6.0</td>
<td></td>
</tr>
</tbody>
</table>

- DA below the target at injection
- Triplet has no significant impact on DA at injection
- Main Octupoles increase DA at injection
- All theses values are for particles out of RF acceptance
Detuning with amplitude and momentum (table v3)

\[ Q_z(\epsilon_x, \epsilon_y) = Q_{z0} + \left( \frac{\partial Q_z}{\partial \epsilon_x} \epsilon_x + \frac{\partial Q_z}{\partial \epsilon_y} \epsilon_y \right) + \frac{1}{2!} \left( \frac{\partial^2 Q_z}{\partial \epsilon_x^2} \epsilon_x^2 + 2 \frac{\partial^2 Q_z}{\partial \epsilon_x \partial \epsilon_y} \epsilon_x \epsilon_y + \frac{\partial^2 Q_z}{\partial \epsilon_y^2} \epsilon_y^2 \right) + \ldots \]

\[ Q_z \left( \frac{\delta p}{p_0} \right) = Q_{z0} + Q'_z \left( \frac{\delta p}{p_0} \right) + \frac{1}{2!} Q''_z \left( \frac{\delta p}{p_0} \right)^2 + \frac{1}{3!} Q'''_z \left( \frac{\delta p}{p_0} \right)^3 + \ldots \]

⇒ Detuning is larger with momentum than with amplitude!
⇒ \( Q''' \) and \( Q'' \) are present
Detuning with momentum table v3

\[ Q_z \left( \frac{\delta p}{p_0} \right) = Q_{z0} + Q'_z \left( \frac{\delta p}{p_0} \right) + \frac{1}{2!} Q''_z \left( \frac{\delta p}{p_0} \right)^2 + \frac{1}{3!} Q'''_z \left( \frac{\delta p}{p_0} \right)^3 + \ldots \]

\[ Q''_z \propto 3\beta b_4 + \ldots \]

\[ Q'''_z \propto 12\beta b_5 + \ldots \]

Fitting with a 3rd order polynomial for seed giving minimum DA

\[ \Rightarrow Q''' \text{ is stronger than } Q'' \]

With Octupoles ON \( Q'' \) dominates and out of the RF acceptance the octupoles reduce the tune spread due to different seeds of main dipole errors
Effect of the main octupoles @ $\delta p/p = 7.5e^{-4}$

Arc errors only

Arc, IRs errors and octupoles $I=-30$ A

Lost

Stable
DA at injection for August 2018 optics and table v3

- New optics: new insertions, $b_{2S} = 0$ at collision and $b_{2S} = 20$ units at injection, no phase advance fixed between the two high luminosity IRs at injection
- Improvements in the matching macros for thin lattice
- Improvements in the mask file to generate SixTrack inputs

- Initial amplitude of particles lost used to evaluate DA ($a_{lost2}$)
- Energy corresponding to the max RF acceptance considered

<table>
<thead>
<tr>
<th></th>
<th>Min DA $[\sigma]$ $\Delta p/p = 0$</th>
<th>Min DA $[\sigma]$ $\Delta p/p = 4.7e^{-4}$</th>
<th>Min DA $[\sigma]$ $\Delta p/p = 7.5e^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>arc dipoles</td>
<td>5.8</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>arc + triplet</td>
<td>14.4</td>
<td>4.9</td>
<td>4.7</td>
</tr>
<tr>
<td>arc + triplet + oct -30A</td>
<td>7.9</td>
<td>3.2</td>
<td>6.7</td>
</tr>
</tbody>
</table>
Tables v42 (half artificial pinning)

- New asymmetric coil design (INFN-LASA & INFN GENOVA)
- New strand magnetization for persistent current effects

Susana Izquierdo Bermudez, Davide Tommasini
01-10-2018

- Initial amplitude of particles lost used to evaluate DA (alost2)
- Energy corresponding to 2/3 of the max RF acceptance considered
- Main Octupoles current of -15A @ injection (Sergey ARSENJEV communication)

<table>
<thead>
<tr>
<th></th>
<th>Min DA [σ] (\Delta p/p=0)</th>
<th>Min DA [σ] (\Delta p/p=3.2e^{-4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>arc</td>
<td>16.21</td>
<td>9.2</td>
</tr>
<tr>
<td>arc+triplet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>arc+triplet+oct</td>
<td>10.55</td>
<td>6.3</td>
</tr>
</tbody>
</table>
DA w/o systematic $b_5$ of table v42

DA evaluated for $b_{55} = 0$ units

- Minimum DA with arc errors only above the target of $12\,\sigma$
- Minimum DA with arc, main IRs errors and octupoles current of -15A above primary collimators settings

<table>
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<th></th>
<th>Min DA [$\sigma$] $\Delta p/p=0$</th>
<th>Min DA [$\sigma$] $\Delta p/p=3.2e^{-4}$</th>
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</tr>
<tr>
<td>arc+triplet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>arc+triplet+oct</td>
<td>10.55</td>
<td>8.1</td>
</tr>
</tbody>
</table>

17/10/2018

B. Dalena, 4th EuroCirCol meeting
Detuning with momentum $w$ and $w/o b_5$ (table v42)

With $b_{5S} = 0$ we have only $Q''$ left and both $w$ and $w/o$ octupole max detuning is $< 0.01 \times 3.2 \times 10^{-4}$ dp/p

$\Rightarrow$ Correction of $b_4$ from Table v42 not required
Conclusion and perspectives

- Amsterdam results have been understood and corrected
  - DA at injection due to dipole field quality (table v3) below the target
  - Strong decapole component induces large detuning with momentum
- New asymmetric design and new strand magnetization (table v42) improve DA but decapole component correction is also required in order to be above the target of 12 $\sigma$ at injection

- $b_5$ correction scheme
- Impact of main quadrupoles on DA
- Impact of linear imperfection on DA
- Working point at injection
Effect of the main octupoles @ $\delta p/p = 7.5 \times 10^{-4}$

Arc errors only

Arc, IRs errors and octupoles $I = -30$ A