Arc design and lattice integration

Antoine CHANCE

CEA Paris-Saclay/DRF/Irfu/DACM

FCC week 2018

with many thanks to B. Dalena, D. Boutin, W. Bartmann, E. Cruz-Alaniz, M. Hofer, R. Martin, J. Molson, D. Schoerling, D. Schulte, …
1 From FCC week 2017 to 2018
2 Arc lattice
3 Ring lattice
4 Correction scheme
5 Alternatives
6 Conclusions
Status at the FCC week 2017:

- The ring lattice has been updated to fit with the new layout.
- The lattice is available on the git repository
- The dispersion suppressor has been modified to insert collimators.
- The aperture model is being updated to take into account the last beam screen geometry.
- A new spurious dispersion scheme has been integrated.
- The coupling and tune correction is under integration.
- Alternatives for the arc FODO cell have been provided (60 degrees and longer cell).

Perspectives:

- Inserting octupoles (with optimized location) for Landau damping.
- To refine tune and chromaticity corrections (by freezing phase advances between IPs).
- To refine alternatives for the arc cells.
- To integrate other correction schemes (skew sextupoles, ...).
- Options of combined multipole lenses.
What changes since FCC week 2017: layout

- 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:
  - see R. Martin "Experimental insertions".
    - $L = 1.5 \text{ km} \rightarrow L = 1.4 \text{ km}$.
      - LAR a bit longer.
      - $B_{MB} \downarrow$
    - Alternative inner triplet.
      - $B_{MB} = 15.71 \text{ T} \rightarrow B_{MB} = 15.96 \text{ T}$
Integration strategy

- A python script was written to generate the MAD-X files for the integration of the different lattices and of the insertions.
- The FODO cells of the arcs are generated according to some input parameters (e.g. range of the cell length).
- The dispersion suppressors are generated.
- The matching macros are generated.
- Some matching sections between the dispersion suppressors and insertions can be added.
- The insertions are optimized by different groups.
- The global tune is matched with the phase advance of the FODO cells in the long arcs.
  - Phase advances of the FODO cells in the SAR: 90°.
  - Phase advances of the FODO cells in the LAR: 90 + \( \epsilon_{x,y} \)°.
  - Phase trombones can now be used to match the phase advances between insertions.
- The chromaticity is corrected by two sextupole families.
→ see Dalena’s talk at the FCC week 2015 in Washington.
→ see CERN-ACC-2015-035 First results for a FCC-hh ring optics design

### Parameters

- Circumference $3.75 \times \text{LHC} \approx 100 \text{ km}$.
- Maximum dipole field: 16 T.
- Magnetic dipole length: $14.3 \text{ m} \rightarrow$ is calculated to fill the FODO cell.
- Phase advance per FODO cell: $90^\circ$.
- Maximum gradient in the QPole: $400 \text{ T/m} \rightarrow 360 \text{ T/m}$.
- $\varnothing=50 \text{ mm}$.
- Spacing dipole-dipole: $1.36 \text{ m} \rightarrow 1.5 \text{ m}$.
- Min. spacing QPole-dipole: $3.67 \text{ m} \rightarrow$ Min. spacing dipole-SSS: $1.3 \text{ m}$.
- Spacing QPole-sextupole: $0.4 \text{ m} \rightarrow 0.35 \text{ m}$.
- Length sextupole: $1.2 \text{ m}$
- Length orbit corrector: $1.0 \text{ m} \rightarrow 1.2 \text{ m}$
- Length $b_3$ corrector: $0.11 \text{ m}$
Impact of $b_2$

- Because of saturation effects in the main dipoles, $b_2 = \pm 50$ at collision.
- Integrated strength of one dipole for $b_2 = 50$: $\frac{b_2 L_d}{\rho R_{\text{ref}}} \approx 0.4 \times 10^{-3}$ to be compared with one quadrupole: $14 \times 10^{-3}$.
- Integrated strength of 6 dipoles is 17% of one quadrupole!

$b_2 = 0$

- $L_{MQ} = 7.2$ m
- $G_D = -317$ T/m
- $G_F = +315$ T/m
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$b_2 = -50$ inner side

- $L_{MQ} = 7.2$ m
- $G_D = -267$ T/m
- $G_F = +358$ T/m
- The quadrupoles MQs are enlarged to handle the extra gradient.
- $b_2 = 0$ at collision enables to reduce the quadrupole length to 6.4 m.
Because of saturation effects in the main dipoles, $b_2 = \pm 50$ at collision.

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- $G_F = +267$ T/m
- The quadrupoles MQs are enlarged to handle the extra gradient.
- $b_2 = 0$ at collision enables to reduce the quadrupole length at 6.4 m.
Impact of $b_2$ on the long arc

**No missing dipole**

- A dipole is removed for technical straight sections.
- Dispersion and betatron wave.

**1 missing dipole**

- Dispersion wave canceled by removing a 2nd dipole at 180°.
- Betatron wave not canceled.
- $\beta$-beating of 30% ($b_2 = 50$).

**2 missing dipoles at 180°**

- Use of 8 trim quadrupoles to cancel the $\beta$-beating, dispersion beating and tune split.
- Only 1-2% of residual $\beta$-beating.

**1 missing dipole with correction**

- A dipole is removed for technical straight sections.
- Dispersion and betatron wave.
⇒ 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 **15.96 T** with an aperture of 50 mm.
  - MCS has the same length as in LHC: **0.11 m**.
  - The maximum quadrupole gradient is **360 T/m**. MQs are lengthened in this aim.
  - The maximum corrector field is **4 T**.
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→ see Schoerling: "Other magnets parameters".
→ see Lorin: "Main quadrupoles".
→ see Louzguilti: "Lattice sextupoles and octupoles".

<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>
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</thead>
<tbody>
<tr>
<td>Main Dipole (MB)</td>
<td>4668</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>
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<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>
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<tr>
<td>Trim Quadrupole (MQT)</td>
<td>120</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>
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<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>
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<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>
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<tr>
<td>Sextupole Corrector (MCS)</td>
<td>9336</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>
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<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>
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<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>
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.

Reduction of the beam-stay clear by 1.5\(\sigma\) because of the sagitta.
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).
The selected dispersion suppressor is similar to LHC, best compromise between filling factor and flexibility.

Two collimators (TCLD) of 1 meter are inserted (the needed space is 5 meters for each TCLD).

Bottleneck for the machine aperture (location of betatron and dispersion peaks).
Collision optics integration

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Energy (TeV)</td>
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<tr>
<td>Circumference (km)</td>
<td>97.75</td>
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<tr>
<td>$\beta^*$ (m)</td>
<td>0.3</td>
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<tr>
<td>$L^*$ (m)</td>
<td>40</td>
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<tr>
<td>$\alpha$</td>
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<td>$\gamma_{tr}$</td>
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<td>$Q_y$ coll</td>
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<tr>
<td>$Q_y$ inj</td>
<td>108.31</td>
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<td>$Q'_x$</td>
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<tr>
<td>$Q'_y$</td>
<td>2</td>
</tr>
<tr>
<td>MB field (T)</td>
<td>15.96</td>
</tr>
<tr>
<td>MQ gradient (T/m)</td>
<td>359</td>
</tr>
<tr>
<td>MS gradient (T/m^2)</td>
<td>6998</td>
</tr>
</tbody>
</table>

Antoine CHANCE
Ring lattice
Arc design of FCC-hh
FCC week 2018 10th April
Insertions: main experiments

- Version 7 of the EIR.
- $L^* = 40 \text{ m}$.
- Courtesy: R. Martin et al..
  → see Martin: "Experimental insertions"
  → see Abelleira: "Flat beam alternative"

Considered $\beta^*$:
- $6.0 \text{ m (injection)}$
- $4.6 \text{ m (baseline injection)}$
- $1.1 \text{ m (baseline)}$
- $0.3 \text{ m (ultimate)}$
- $0.2 \text{ m (more ultimate)}$
- $0.15 \text{ m (ultimate ultimate)}$

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

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

- Injection in the same section as the additional experiments.
- \(L^* = 25\) m
  - see Martin: “Experimental insertions”
  - see Renner: “FCC-hh injection and extraction: insertions and requirements”

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

![Graphs showing injection and experiment sections](image-url)
Insertions: injection + low-\(L\) experiment

- Injection in the same section as the additional experiments.
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Inj.+Exp. section: LSS L (@ collision)

Inj.+Exp. section: LSS L (@ injection)
Dedicated section to $\beta$-cleaning

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

- see Molson: “Betatron collimation system insertions”
- see Bruce: “Collimation performance and issues”.

LHC-scaled $\delta$-cleaning insertion

- Courtesy: J. Molson
- Alternative under development at FNAL.
Insertions: RF+extraction

- 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 will be integrated soon.
- Courtesy: F. Burkart, W. Bartmann et al.

→ see Renner: “FCC-hh injection and extraction: insertions and requirements”
2 schemes are currently implemented to tune the ring:
- FODO cells of long are slightly detuned (90° + ϵ). DIS are rematched.
- Use of phase trombones in insertions. More straightforward but less realistic model.

Studies have shown that phase advances between insertions have a major impact on dynamic aperture.
Modification of an insertion can imply a dramatic DA reduction.
- see Cruz-Alaniz: "Dynamic aperture at collision"
- see Dalena: "Dipole Field Quality and Dynamic Aperture for FCC-hh"

It is mandatory to understand the needs on the phase advances differences to freeze the first order optics.
Next steps are only possible if this issue is correctly addressed.
- BPMs and dipole correctors are integrated in the lattice to correct the orbit.
- Trim quadrupoles are integrated to correct the horizontal spurious dispersion, the $\beta$-beating (still under investigation) and the dispersion-beating.
- Skew quadrupoles are used to correct the coupling (sets of 4 skew quadrupoles separated by 90° each) and the vertical spurious dispersion.
  → see Boutin: "Alignment".
- The dynamic aperture studies have shown that:
  - Correcting $b_3$ components in dipoles is mandatory.
  - We can correct up to 4 units of $b_3$ at collision with MCS (max. strength 3000 T/m$^2$).
  - Currently, $b_4$ and $b_5$ do not need any correctors.
  - These values have been checked with updated table (source: D. Schoerling).
  → see Dalena: “Dipole Field Quality and Dynamic Aperture for FCC-hh”
- Octupoles have been integrated to the lattice for Landau damping and beam-beam correction.
  → see Tambasco: "Two beam stability and Landau damping"
  → see Pieloni: "Beam-beam effects".
Spurious dispersion correction ($\beta^* = 0.3$ m)

- SSC-like scheme.
  - see D. Ritson, and Y. Nosochkov, "The Provision of IP Crossing Angles for the SSC", Proceedings of PAC 93
- Works for the vertical dispersion with skew quadrupoles

![Graphs showing dispersion profiles for IPA, IPG, IPB, and IPL]
Alternative triplet for the experiment insertion has been integrated (and flat optics)
→ see Abelleira: “Flat beam alternative”

Phase advance of 60 degrees against 90 degrees (idea: E. Todesco).

- The integrated quadrupole gradient is multiplied by $\frac{\sin 30^\circ}{\sin 45^\circ} \approx 0.7$.
- With the same FODO cell length, the maximum quadrupole gradient is decreased from $360 \text{ T/m}$ to $220 \text{ T/m}$ ($b_2 = 0$) or $270 \text{ T/m}$ ($b_2 = 50$).
- With the same maximum gradient, the quadrupole can be shortened from $7.2 \text{ m}$ to $5.4 \text{ m}$.
- The FODO cell can then be shortened or dipole lengthened (by $0.3 \text{ m}$).
- The reached dipole field we can get is $15.61 \text{ T}$ (against $15.96 \text{ T}$ before).

The correction schemes must be modified.
- With a system of 6 trim quadrupoles with 60 degrees in between, possibility to correct beta-beating, dispersion beating, coupling (if skew), or tune as the system of 4 quadrupoles in the case of $90^\circ$ by phase advance.
- The dispersion is enlarged: **reduction of the aperture.**
Phase advance of 60 degrees

Apertures @3.3 TeV

\[ n_1 = 16.4 \rightarrow n_1 = 12.6 \text{ below the target!} \]

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<td>( \beta^* )</td>
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<td>( Q_y ) inj</td>
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<td>( Q'_x )</td>
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</tr>
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<tr>
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<td>T/m²</td>
</tr>
</tbody>
</table>
Current status:
- The arc cells have been updated to fit with magnet requirements.
- The quadrupole component $b_2$ of the main dipoles is taken into account in the lattice.
- The aperture model has been updated and integrated to take into account the last beam screen geometry.
- The bottleneck is the dispersion suppressors (too small aperture there).
- The ring lattice has been updated.
- The lattice is available on the git repository https://gitlab.cern.ch/fcc-optics/FCC-hh-lattice.git.
- Multipole correctors (trim, skew quadrupoles and octupoles) are integrated.
- Alternatives for the arc FODO cell have been provided (60 degrees).

Perspectives:
- To refine tune and chromaticity corrections (by freezing phase advances between IPs).
- To refine alternatives for the arc cells.
- To integrate other correction schemes (skew sextupoles,...).
- To be ready for the CDR ;-)}
Thank you for your attention!

Many thanks to all people who I have taken some material from and to all FCC-hh team. Thanks to Schoerling’s group for the multipole table of the dipoles and fruitful discussion on the arc layout.