Arc Optics and Geometry

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Acknowledgements:

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Outline

➤ Introduction
➤ Arc optics
➤ Ring geometry
➤ Physical aperture
➤ Summary
1. Introduction

High Energy LHC (HE-LHC) as proton-proton collider utilizing FCC-hh magnet technology

- 26.659 km ring fitting the LHC tunnel
- Centre-of-Mass beam energy from 14 to 27 TeV
- Magnets in arcs:
  * LHC: 8.33 T dipole, 223 T/m arc quadrupole, 4430 T/m² sextuple with 56 mm aperture
  * FCC-hh: 16 T dipole, 400 T/m quadrupole, 7800 T/m² sextuple with 50 mm aperture
- Simple scaling of the present LHC to 27 TeV CM energy yields the magnet fields exceeding the FCC specifications (next page)
1. Introduction

➤ Scale LHC to 27 TeV CM energy

- V6.503 as an example: $\beta^*=55$ cm at IP 1&5
- With baseline $\beta^*=25$ cm for HE-LHC, arc sextupoles will definitely exceed FCC specification
- Almost no optics flexibility
2. Arc optics

➤ Design considerations for arc optics of HE-LHC

- To fit the LHC tunnel with ring separation from 194 mm (LHC) to 204 mm (FCC-hh and HE-LHC baseline)

From LHC Design Report
2. Arc optics

- Design considerations for arc optics of HE-LHC
  - To reduce quadrupole and sextupole strengths
  - * Reduce arc FODO cell phase advance $\mu_c$ and/or increase cell length $L_c$

<table>
<thead>
<tr>
<th>90 deg $\rightarrow$ 60 deg</th>
<th>Longer cell $L_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weaker quads $\rightarrow$ factor of $\sqrt{2}$ ($\sim \sin(\mu/2)$)</td>
<td>Weaker quads $\sim 1/L_c$</td>
</tr>
<tr>
<td>Weaker sextupoles $\rightarrow$ factor of 3 (for arcs correction)</td>
<td>Weaker sextupoles $\sim 1/L_c^3$</td>
</tr>
<tr>
<td>Lower cell chromaticity $\rightarrow$ factor of $\sqrt{3}$ ($\sim \tan(\mu/2)$)</td>
<td>Same cell chromaticity</td>
</tr>
<tr>
<td>Similar peak $\beta$-functions</td>
<td>Larger peak $\beta \sim L_c$</td>
</tr>
<tr>
<td>Larger dispersion $\rightarrow$ factor of 2</td>
<td>Larger dispersion $\sim L_c^2$</td>
</tr>
</tbody>
</table>

Y. Nosochkov, FCC week 2017

\[
\sin\left(\frac{\Phi}{2}\right) = \frac{1}{4} K_1 L_{\text{cell}}
\]

\[
\beta_{\pm} = \frac{2 (1 \pm K_1 L_{\text{cell}}/4)}{K_1 \sqrt{1 - (K_1 L_{\text{cell}}/4)^2}}
\]

\[
\eta_{\pm} = \frac{4}{\rho K_1^2} \left(1 \pm K_1 L_{\text{cell}}/8\right)
\]

\[
K_{2\pm} = \frac{K_1}{\eta_{\pm}} \quad \text{Only for chromaticity correction in arc cells.}
\]
2. Arc optics

➢ Design considerations for arc optics of HE-LHC

● To reduce sensitivity to field errors: Resonance free lattice
  * Choose phase advance condition per arc: $N_c \mu_c = 2k\pi$
  * Cancellation of non-linear resonances => To improve dynamic aperture
    Cancellation condition (A. Verdier, PAC’99):
    $N_c(n_x \mu_{xc} + n_y \mu_{yc}) = 2k\pi \& (n_x \mu_{xc} + n_y \mu_{yc}) \neq 2k'\pi$
    $N_c$: number of cell; $\mu_{xc}$, $\mu_{yc}$: Phase advance per cell
  * 60-deg cell:
    Lowest order resonances: $n_x - n_y = 0$ and $n_x + n_y = 6$
  * 90-deg cell:
    Lowest order resonances: $n_x - n_y = 0$ and $n_x + n_y = 4$
2. Arc optics

➤ Design considerations for arc optics of HE-LHC

- To reduce sensitivity to field errors: Resonance free lattice
  - Choose phase advance condition per arc: \( N_c \mu_c = 2k\pi \)
  - Cancellation of non-linear resonances => To improve dynamic aperture
- Example: Injection optics for \( E = 450 \) GeV (by Y.N.)
  \( N_c = 24, \mu_c = 60 \) deg with basic IRs and tune (49.28, 47.31)
  RDTs by PTC and FMA tracking by SAD
2. Arc optics

➤ Design considerations for arc optics of HE-LHC

- To reduce sensitivity to field errors: Resonance free lattice
  * Choose phase advance condition per arc: $N_c \mu_c = 2k\pi$
  * Cancellation of non-linear resonances => To improve dynamic aperture
  * Example: Injection optics for $E=450$ GeV (by Y.N.)
    $N_c=18$, $\mu_c=60$ deg with basic IRs and tune $(37.28, 39.31)$
    RDTs by PTC and FMA tracking by SAD
2. Arc optics

➤ Design considerations for arc optics of HE-LHC

- **To reduce sensitivity to field errors:** Resonance free lattice
  * Choose phase advance condition per arc: $N_c \mu_c = 2k\pi$
  * Cancellation of non-linear resonances => To improve dynamic aperture
  * Example: Injection optics for $E=450$ GeV (by Y.N.)
    $N_c=20$, $\mu_c=90$ deg with basic IRs and tune (56.28, 57.31)
    RDTs by PTC and FMA tracking by SAD
2. Arc optics

➤ Design considerations for arc optics of HE-LHC

- To reduce sensitivity to field errors: Resonance free lattice
  
  * Choose phase advance condition per arc: $N_c \mu_c = 2k\pi$
  
  * Cancellation of non-linear resonances => To improve dynamic aperture
  
  * Example: Injection optics for LHC (V6.503)
    $N_c = 23$, $\mu_c = \sim 90$ deg with basic IRs and tune (64.28, 59.31)
    RDTs by PTC and FMA tracking by SAD
2. Arc optics

Details in talk “Dynamic aperture” by Y. Nosochkov

General features for arcs of HE-LHC lattice model

- C = 26658.8832 m same as in LHC
- Same quad and sext. lengths as in LHC
- Same magnet-to-magnet distances as in LHC cell
- Similar layout of dispersion suppressors as in LHC
- Odd and even arcs with opposite quad polarity - same as in LHC
- Arc length close to LHC with adjustment in better fitting tunnel geometry
2. Arc optics

➤ Options for arc cells

- 23x 90-deg arc cell
- 20x 90-deg arc cell
- 18x 60-deg arc cell
- 24x 60-deg arc cell
- 17x 90-deg arc cell
- 18x 90-deg arc cell
2. Arc optics

Parameters for arc cells of *injection optics*

- FCC: 16 T dipole, 400 T/m quad., 7800 T/m² sext. with 50 mm aperture

<table>
<thead>
<tr>
<th>Arc cell phase</th>
<th>LHC</th>
<th>17x90</th>
<th>18x60</th>
<th>18x90</th>
<th>20x90</th>
<th>24x60</th>
</tr>
</thead>
<tbody>
<tr>
<td>~90/90</td>
<td>90/90</td>
<td>60/60</td>
<td>90/90</td>
<td>90/90</td>
<td>60/60</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Arc cell length [m]</th>
<th>LHC</th>
<th>17x90</th>
<th>18x60</th>
<th>18x90</th>
<th>20x90</th>
<th>24x60</th>
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<tbody>
<tr>
<td>107</td>
<td>144.4</td>
<td>137.2</td>
<td>124.8</td>
<td>102.9</td>
<td></td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>K1 [m⁻²]</th>
<th>LHC</th>
<th>17x90</th>
<th>18x60</th>
<th>18x90</th>
<th>20x90</th>
<th>24x60</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.009</td>
<td>0.0064</td>
<td>0.0048</td>
<td>0.0068</td>
<td>0.0076</td>
<td>0.0064</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>β_max/min [m]</th>
<th>LHC</th>
<th>17x90</th>
<th>18x60</th>
<th>18x90</th>
<th>20x90</th>
<th>24x60</th>
</tr>
</thead>
<tbody>
<tr>
<td>181/32</td>
<td>241/43</td>
<td>234/80</td>
<td>229/41</td>
<td>208/37</td>
<td>175/61</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>η_max/min [m]</th>
<th>LHC</th>
<th>17x90</th>
<th>18x60</th>
<th>18x90</th>
<th>20x90</th>
<th>24x60</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2/1.1</td>
<td>4/2</td>
<td>6.9/4.1</td>
<td>3.6/1.8</td>
<td>3.0/1.5</td>
<td>3.8/2.3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dipole length [m]</th>
<th>LHC</th>
<th>17x90</th>
<th>18x60</th>
<th>18x90</th>
<th>20x90</th>
<th>24x60</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Dipole field [T] @13.5TeV</th>
<th>LHC</th>
<th>17x90</th>
<th>18x60</th>
<th>18x90</th>
<th>20x90</th>
<th>24x60</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.06</td>
<td>15.94</td>
<td>15.59</td>
<td>15.92</td>
<td>16.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quad. grad. [T/m] @13.5TeV</th>
<th>LHC</th>
<th>17x90</th>
<th>18x60</th>
<th>18x90</th>
<th>20x90</th>
<th>24x60</th>
</tr>
</thead>
<tbody>
<tr>
<td>405</td>
<td>289</td>
<td>215</td>
<td>304</td>
<td>340</td>
<td>288</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sext. grad. [T/m²] @13.5TeV</th>
<th>LHC</th>
<th>17x90</th>
<th>18x60</th>
<th>18x90</th>
<th>20x90</th>
<th>24x60</th>
</tr>
</thead>
<tbody>
<tr>
<td>4826</td>
<td>2035</td>
<td>~870</td>
<td>2470</td>
<td>2943</td>
<td>1997</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Filling factor</th>
<th>LHC</th>
<th>17x90</th>
<th>18x60</th>
<th>18x90</th>
<th>20x90</th>
<th>24x60</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.802</td>
<td>0.809</td>
<td>0.827</td>
<td>0.809</td>
<td>0.791</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2. Arc optics

- Global parameters for injection optics
  - $C=26658.8832 \text{ m}$
  - Matching of 18x60 and 24x60 lattices not optimized

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>17x90</th>
<th>18x60</th>
<th>18x90</th>
<th>20x90</th>
<th>24x60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tune [x/y]</td>
<td>64.28/59.31</td>
<td>49.28/47.31</td>
<td><strong>37.23/36.06</strong></td>
<td>50.28/49.31</td>
<td>54.28/53.31</td>
<td><strong>46.1/45.8</strong></td>
</tr>
<tr>
<td>Nat. Chrom. [x/y]</td>
<td>-86.2/-81.5</td>
<td>-67.9/-68.0</td>
<td>-48.7/-48.4</td>
<td>-68.7/-70.5</td>
<td>-73.9/-74.9</td>
<td>-57.3/-57.7</td>
</tr>
<tr>
<td>Cor. Chrom. [x/y]</td>
<td>2/2</td>
<td>1/1</td>
<td>-</td>
<td>0.6/1</td>
<td>1/1</td>
<td>-</td>
</tr>
<tr>
<td>Mom. Compact.</td>
<td>3.22E-04</td>
<td>6.2E-04</td>
<td>1.14E-03</td>
<td>5.71E-04</td>
<td>4.75E-04</td>
<td>6.51E-04</td>
</tr>
<tr>
<td>$\beta^*$ (m) [x/y]</td>
<td>11/11</td>
<td>10/10</td>
<td>10/10</td>
<td>10/10</td>
<td>10/10</td>
<td>10/10</td>
</tr>
<tr>
<td>Beam separation at arcs (mm)</td>
<td>194</td>
<td>204</td>
<td>204</td>
<td>204</td>
<td>204</td>
<td>204</td>
</tr>
</tbody>
</table>
2. Arc optics

➢ 18x90 arc scheme chosen as the baseline with respect to overall performance
  ● Best filling factor and consequent lowest dipole field => Gain in operational margin
  ● Quadrupole strengths well below FCC limit
  ● Acceptable sextupole strengths (though exceed FCC limit)
  ● Physical aperture (To be discussed in next pages. Also details in talk by F. Zimmermann)
  ● Dynamic aperture (Details in talk by N. Nosochkov)
  ● Matching to IRs (Details in talks by M. Hofer and L. Riesen-Haupt)
2. Arc optics

➤ HE-LHC collision optics at 27 TeV CM energy

● V0.2 as an example:
  * 18x90 arcs, $\beta^*=25$ cm at IP 1&5

● Dipoles/quadrupoles below FCC specifications

● Sextupoles exceed FCC specification
  * Natural chrom.: (-69.8, -71.1)$_{\text{injection}}$ => (-246.6, -263.4)$_{\text{collision}}$
  * Solutions: Longer sext./Smaller $\mu_c$ per cell/Larger $\beta^*$

![Graphs of dipole field, quadrupole gradient, sextupole gradient]
2. Arc optics

➤ HE-LHC collision optics at 27 TeV CM energy

- V0.2 as an example:
  * 18x90 arcs, $\beta^*=25$ cm at IP 1&5

- Dipoles/quadrupoles below FCC specifications

- Sextupoles exceed FCC specification
  * Natural chrom.: $(-69.8, -71.1)_{\text{injection}} \Rightarrow (-246.6, -263.4)_{\text{collision}}$
  * Solutions: Longer sext./Smaller $\mu_c$ per cell/Larger $\beta^*$

![Sext. gradient](image1.png)

![Natural chromaticity](image2.png)
3. Ring geometry

➤ Compare the survey of LEP and (HE-)LHC

- Comparison of “average” ring
- Use similar strategy as in LHC for geometry optimization by T. Risselada

NOTE (T.R.):
1) Maximum offset in radial direction: <~11cm comparing to LEP survey
2) Good ring geometry for all candidates
3. Ring geometry

➤ Compare the survey of LEP and (HE-)LHC

- Ring separation at arcs: 204 mm
- The effort of geometry optimization was the price to pay for using the same main bends in the arcs and in the dispersion suppressors.

NOTE (T.R.):
1) Maximum offset in radial direction: <\sim 11\text{cm} comparing to LEP survey
2) Good ring geometry for all candidates
4. Physical aperture

➤ Estimate of physical aperture using “1-D” model

- n1 method: Indicate the geometrical acceptance
- Assumed parameters:
  - Tolerances in hardware misalignment and orbit distortion: $t_x=(2+1)$ mm
  - Tolerance for beta beating: $k_\beta=1.05$
  - Tolerance for dispersion distortion: $f_{\text{arc}}=0.14$
  - Momentum spread: $\delta_p=8.6*10^{-4}$
  - Normalized emittance: $\epsilon_x=2.5$ μm
  - Half beam screen width: $L_x=15$ mm(FCC-hh), 19 mm(scaled-LHC), 22 mm(LHC)

\[
n_{1x} = \frac{L_x - t_x - (1 + f_{\text{arc}})D_x\delta_p}{k_\beta \sigma_x}
\]

\[
\sigma_x = \sqrt{\beta_x \epsilon_x}
\]

\[
\sin(\Phi/2) = \frac{1}{4} K_1 L_{\text{cell}}
\]

\[
\beta_{\pm} = \frac{2(1 \pm K_1 L_{\text{cell}}/4)}{K_1 \sqrt{1 - (K_1 L_{\text{cell}}/4)^2}}
\]

\[
\eta_{\pm} = \frac{4}{\rho K_1^2} (1 \pm K_1 L_{\text{cell}}/8)
\]
4. Physical aperture

➤ n1 at QF for N-cell arcs at $E_{\text{inj}}=450$ GeV

- Phase advance per cell: 90 deg [Assume fixed arc length: 2460 m]
- $t_x=(2+1)$ mm, $f_{\text{arc}}=0.14$, $\delta_p=8.6 \times 10^{-4}$, $\varepsilon_x=2.5 \ \mu\text{m}$, $k_\beta=1.05$
4. Physical aperture

n1 at QF for N-cell arcs at $E_{\text{inj}}=450$ GeV

- Phase advance per cell: 60 deg [Assume fixed arc length: 2460 m]
- $t_x=(2+1)$ mm, $f_{\text{arc}}=0.14$, $\delta_p=8.6\times10^{-4}$, $\varepsilon_x=2.5$ μm, $k_\beta=1.05$
4. Physical aperture

➤ n1 for 18-cell arcs with LHC beam screen: \( L_x=22 \text{ mm} \)
- \( n1=13.3/18.9/22.7 @E_{inj}=0.45/0.9/1.3 \text{ TeV} @90 \text{ deg/cell} \)
- \( t_x=(2+1) \text{ mm}, f_{arc}=0.14, \delta_p=8.6*10^{-4}, \varepsilon_x=2.5 \mu\text{m}, k_\beta=1.05 \)
4. Physical aperture

➤ n1 for 18-cell arcs with scaled-LHC screen: \( L_x = 19 \) mm

- \( n_1 = 10.7/15.2/18.3 \) @\( E_{\text{inj}} = 0.45/0.9/1.3 \) TeV @90 deg/cell
- \( t_x = (2+1) \) mm, \( f_{\text{arc}} = 0.14, \delta_p = 8.6 \times 10^{-4}, \varepsilon_x = 2.5 \) μm, \( k_\beta = 1.05 \)

![Graph showing horizontal aperture (n1) vs. phase advance per cell]
4. Physical aperture

➤ n1 for 18-cell arcs with **FCC-hh beam screen**: $L_x=15$ mm

- $n_1=7.3/10.3/12.4$ @ $E_{\text{inj}}=0.45/0.9/1.3$ TeV @ 90 deg/cell
- $t_x=(2+1)$ mm, $f_{\text{arc}}=0.14$, $\delta_p=8.6 \times 10^{-4}$, $\varepsilon_x=2.5 \, \mu m$, $k_\beta=1.05$
5. Summary

➤ Arc optics
- Reduce dipole field by increasing filling factor
- Reduce quad and sext. strengths by increasing cell length and/or reduce phase advance per cell
- 18x90 arc scheme chosen as the baseline with respect to overall performance

➤ Ring geometry
- Geometry is not a limit in choosing arc scheme
- Further refinement can be done but should not change beam dynamics

➤ Physical aperture
- Can be a concern when reducing number of arc cells
- Increasing injection beam energy and/or reducing beam emittance is preferred in the current baseline design (18x90)