Towards an optics baseline for HE-LHC

Demin Zhou

Acknowledgements:

19th HE-LHC design meeting, CERN, Sep. 22, 2017
Outline

➤ Overview of the lattices and tools developed by Thys
  ● Lattices with different arc schemes
  ● Tools for optics tuning

➤ Comparison of various lattices
  ● Survey
  ● Magnet parameters in arcs
  ● Ring optics
  ● n1 in arcs

➤ Summary and Future plan
1. Overview of the lattices and tools developed by Thys

➢ Recent updates of HE-LHC lattices by Thys

- Source files: `/afs/cern.ch/eng/lhc/optics/HELHC/
- Use IRs of SLHCV3.1a for all of the lattices
- **HE-LHC.17x90**
  - `-rw-r--r--. 1 riss si 292071 Sep 13 19:14 merged_HE-LHC.17x90_tr.seq`
  - `-rw-r--r--. 1 riss si 10436 Sep 15 11:27 merged_HE-LHC.17x90_tr.str`
- **HE-LHC.18x60 and HE-LHC.18x90**
  - `-rw-r--r--. 1 riss si 274907 Jul 9 16:44 merged_HE-LHC.18x60_tr.seq`
  - `-rw-r--r--. 1 riss si 10276 Sep 14 11:55 merged_HE-LHC.18x60_tr.str`
  - `-rw-r--r--. 1 riss si 295719 Sep 13 11:07 merged_HE-LHC.18x60_v102.seq`
  - `-rw-r--r--. 1 riss si 10278 Sep 14 11:55 merged_HE-LHC.18x60_v102.str`
  - `-rw-r--r--. 1 riss si 10462 Sep 13 19:18 merged_HE-LHC.18x90_v102.str`
- **HE-LHC.20x90**
  - `-rw-r--r--. 1 riss si 303240 Sep 13 19:12 merged_HE-LHC.20x90_v201.seq`
  - `-rw-r--r--. 1 riss si 10514 Sep 14 19:28 merged_HE-LHC.20x90_v201.str`
- **HE-LHC.24x60**
  - `-rw-r--r--. 1 riss si 377338 Sep 10 17:04 merged_HE-LHC.seq`
  - `-rw-r--r--. 1 riss si 9674 Sep 10 17:02 merged_HE-LHC.str`
1. Overview of the lattices and tools developed by Thys

Some features of the above lattices

● See Massimo’s talk: HE-LHC design meeting 14, May 23, 2017

● Ring separation in arcs: defined by a variable
  \[ \text{bsep} := 0.204; \quad \text{[current baseline]} \]

● Use one type of dipoles for both arcs and dispersion suppressors

● Full IRs of SLHCV3.1a integrated: Crossing angle and related parameters defined as variables

● Tune (\(\ast .28, \ast .31\)) and chromaticity (+1, +1) matched to proper values [except 18x60 and 24x60]

● \(\beta^*\) at IPs in experimental IRs matched to (10, 10) m: Injection optics
1. Overview of the lattices and tools developed by Thys

➤ Tools for optics tuning

- **Source files:** /afs/cern.ch/eng/lhc/optics/HELHC/toolkit/
- **Script for chromaticity correction:** chroma.madx
- **Script for Twiss parameters at arc cells:** GetArcPars.madx
- **Matching conditions in IRs:** rematch.ip*.madx
- **Script for changing phase advance in arc cells:** TuneCell.madx
2. Comparison of various lattices

➤ Ring survey

- Refer to Massimo’s talk: HE-LHC design meeting 14, May 23, 2017
- Likely two lattices do not close in survey?
  merged_HE-LHC.18x60_tr.seq and merged_HE-LHC.20x90_v201.seq
- 17x90 and 24x60: well optimized
- 18x60 and 20x90: Further optimizations (similar to 17x90) possible?
2. Comparison of various lattices

➤ Ring survey

- Ring separation in arcs set to zero as suggested by This

real const aip1 = 0;
real const aip2 = 0;
real const aip3 = 0;
real const aip4 = 0;
real const aip5 = 0;
real const aip7 = 0;
real const aip8 = 0;
### 2. Comparison of various lattices

#### Parameters for arc cells

- **LQ=3.1 m, LS=0.369 m**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC</th>
<th>17x90</th>
<th>18x60</th>
<th>18x90</th>
<th>20x90</th>
<th>24x60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc cell phase</td>
<td>~90/90</td>
<td>90/90</td>
<td>60/60</td>
<td>90/90</td>
<td>90/90</td>
<td>60/60</td>
</tr>
<tr>
<td>Arc cell length [m]</td>
<td>107</td>
<td>144.4</td>
<td>137.2</td>
<td>124.8</td>
<td>102.9</td>
<td></td>
</tr>
<tr>
<td>K1 [m$^{-2}$]</td>
<td>0.009</td>
<td>0.0064</td>
<td>0.0048</td>
<td>0.0068</td>
<td>0.0076</td>
<td>0.0064</td>
</tr>
<tr>
<td>$\beta_{\text{max/min}}$ [m]</td>
<td>181/32</td>
<td>241/43</td>
<td>234/80</td>
<td>229/41</td>
<td>208/37</td>
<td>175/61</td>
</tr>
<tr>
<td>$\eta_{\text{max/min}}$ [m]</td>
<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>
</tr>
<tr>
<td>Dipole field [T] @13.5TeV</td>
<td>16.06</td>
<td>15.94</td>
<td>15.59</td>
<td>15.92</td>
<td>16.3</td>
<td></td>
</tr>
<tr>
<td>Quad. grad. [T/m] @13.5TeV</td>
<td>405</td>
<td>289</td>
<td>215</td>
<td>304</td>
<td>340</td>
<td>288</td>
</tr>
<tr>
<td>Sext. grad. [T/m$^2$] @13.5TeV</td>
<td>4826</td>
<td>2035</td>
<td>~870</td>
<td>2470</td>
<td>2943</td>
<td>1997</td>
</tr>
<tr>
<td>Filling factor</td>
<td>0.802</td>
<td>0.809</td>
<td>0.827</td>
<td>0.809</td>
<td>0.791</td>
<td></td>
</tr>
</tbody>
</table>
2. Comparison of various lattices

- Global parameters for injection optics
  - Circumference = 26658.8832 m
  - Matching 18x60 and 24x60 lattice not successful

<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>37.23/36.06</td>
<td>50.28/49.31</td>
<td>54.28/53.31</td>
<td>46.45.8</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>1.5/9.4</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>β* (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>194</td>
</tr>
</tbody>
</table>
2. Comparison of various lattices

➤ Ring optics: LHC V6.503

![Graph showing various lattices comparison]
2. Comparison of various lattices

➤ Ring optics: HE-LHC 17x90
2. Comparison of various lattices

➤ Ring optics: HE-LHC 18x60

![Graph of HE-LHC 18x60 with insertions of SLHCv3](image)
2. Comparison of various lattices

➤ Ring optics: HE-LHC 18x90
2. Comparison of various lattices

➤ Ring optics: HE-LHC 20x90
2. Comparison of various lattices

➤ Ring optics: HE-LHC 24x60
2. Comparison of various lattices

➤ Check n1

- “1-D” aperture [Ref. J.B. Jeanneret and T. Risselada, LHC Project Note 66, 1996]
- Parameters [Ref. F. Zimmermann, 12th HE-LHC meeting, Apr.16, 2017]:
  \[ t_x = (2+1) \text{ mm}, \; f_{\text{arc}} = 0.14, \; \delta_p = 8.6 \times 10^{-4}, \; \varepsilon_x = 2.5 \text{ µm}, \; k_\beta = 1.05 \]
- See my talk in 18th HE-LHC design meeting for the analytic theory, Aug. 22, 2017

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

\[
\sigma_x = \sqrt{\beta_x \varepsilon_x}
\]
2. Comparison of various lattices

- General scaling laws
  - Assume ideal FODO cell [thin-lens, 100% filling factor]

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

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

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

\[
K_{2\pm} = \frac{K_1}{\eta_{\pm}}
\]

Note:
- Sextupole strength for chromaticity correction ONLY in arc cells.
- IRs and DSs require higher \(K_2\)
2. Comparison of various lattices

➤ Check n1 at QF for 18-cell arcs

- FCC-hh beam screen: \( L_x = 15 \text{ mm} \)
- \( t_x = (2+1) \text{ mm, } f_{\text{arc}} = 0.14, \delta_p = 8.6 \times 10^{-4}, \varepsilon_x = 2.5 \ \mu\text{m, } k_\beta = 1.05 \)
- \( n_1 = 4.6/6.8/7.3 @60/80/90 \text{ deg } @E_{\text{inj}} = 0.45 \text{ TeV} \)
2. Comparison of various lattices

➤ Check $n_1$ at QF for 18-cell arcs

- LHC beam screen: $L_x=22$ mm
- $t_x=(2+1)$ mm, $f_{\text{arc}}=0.14$, $\delta_p=8.6 \times 10^{-4}$, $\varepsilon_x=2.5$ μm, $k_\beta=1.05$
- $n_1=10.6/12.9/13.3$ @60/80/90 deg @$E_{\text{inj}}=0.45$ TeV

![Graph showing phase advance per cell for different energies]
2. Comparison of various lattices

➤ Check $n_1$ at QF for 18-cell arcs

- Scaled LHC beam screen: $L_x=19$ mm
- $t_x=(2+1)$ mm, $f_{arc}=0.14$, $\delta_p=8.6 \times 10^{-4}$, $\varepsilon_x=2.5 \, \mu$m, $k_\beta=1.05$
- $n_1=8.0/10.3/10.7$ @60/80/90 deg @$E_{inj}=0.45$ TeV
2. Comparison of various lattices

➤ Check n1 at QF for N-cell arcs

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

- **Check n1 at QF for N-cell arcs**
  - Phase advance per cell: 60 deg [Assume fixed arc length: 2460 m]
  - $t_x=(2+1)$ mm, $f_{arc}=0.14$, $\delta_p=8.6 \times 10^{-4}$, $\varepsilon_x=2.5$ μm, $k_\beta=1.05$
2. Comparison of various lattices

➤ Check n1 at QF in arcs

● Further gain could be achieved by:
  * controlling COD distortion and mechanical misalignment: 3 => 2 mm?
  * Reducing injection beam emittance: 2.5 => 1.5 μm?
  * Increasing injection beam energy: 0.45 => 1 TeV?
3. Summary and future plan

➤ Lattice files and tools for HE-LHC
  ● Thanks to Thys’ excellent work, full lattice files in madx format are available now
  ● Thanks to Thys and Michael Hofer, tuning tools are available now

➤ Toward an optics baseline for HE-LHC
  ● Upgrade of IRs: see Leon’s talk
  ● Installation of tuning magnets, collision optics, optics corrections with errors, etc.: see Michael’s talk
  ● 18x60 (poor n1 in arcs) and 24x60 (strong dipole field) rolled out?
  ● 18x90 lattice as the baseline?
    * Good DA: see Yuri’s talk for the first comparison
    * Good margins for magnet strengths in arcs
    * Good matching to IRs (?)
    * Ring geometry needs to be improved? Possible?
    * n1 in arcs is good enough?
3. Summary and future plan

➢ Toward an optics baseline for HE-LHC (cont’d)
  ● 17x90 and 20x90 as the optional choices?
    * 17x90 by Thys: Good fit to LHC geometry
    * 20x90: better n1 in arcs, but need improvement in geometry?

➢ Future plan
  ● Further optics tuning and announce optics versions periodically for collaborators
  ● Detailed DA simulations and optimizations with errors
  ● Request and feedback from collaborative groups