Summary HE-LHC

Andrei A. Seryi (JAI)
On behalf of the HE-LHC design team
FCC meeting in Berlin
29 May – 2 June 2017
Plan

- Overview
- Baseline parameters
- Collider optics
- Interaction region optics
- Dynamic aperture
- Photon flux and e-cloud
- Conclusions and outlook
Overview

physics goals:
• 2x LHC collision energy with FCC-hh magnet technology
• c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T
• target luminosity ≥ 4 x HL-LHC (cross section $\propto 1/E^2$;

key technologies:
• FCC-hh magnets & FCC-hh vacuum system
• HL-LHC crab cavities & electron lenses

beam:
• HL-LHC/LIU parameters (25 ns baseline, also 5 ns option)
## Baseline parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FCC-hh</th>
<th>HE-LHC</th>
<th>HL-LHC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision energy cms [TeV]</td>
<td>100</td>
<td>27</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Dipole field [T]</td>
<td>16</td>
<td>16</td>
<td>8.33</td>
<td>8.33</td>
</tr>
<tr>
<td>Circumference [km]</td>
<td>97.75</td>
<td>26.7</td>
<td>26.7</td>
<td>26.7</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>0.5</td>
<td>1.12</td>
<td>1.12</td>
<td>0.58</td>
</tr>
<tr>
<td>Bunch intensity ([10^{11}])</td>
<td>1</td>
<td>1 (0.2)</td>
<td>2.2 (0.44)</td>
<td>2.2</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>25</td>
<td>25 (5)</td>
<td>25 (5)</td>
<td>25</td>
</tr>
<tr>
<td>Synch. rad. power / ring [kW]</td>
<td>2400</td>
<td>101</td>
<td>7.3</td>
<td>3.6</td>
</tr>
<tr>
<td>SR power / length [W/m/ap.]</td>
<td>28.4</td>
<td>4.6</td>
<td>0.33</td>
<td>0.17</td>
</tr>
<tr>
<td>Long. emit. damping time [h]</td>
<td>0.54</td>
<td>1.8</td>
<td>12.9</td>
<td>12.9</td>
</tr>
<tr>
<td>Beta* [m]</td>
<td>1.1</td>
<td>0.3</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>Normalized emittance [(\mu m)]</td>
<td>2.2 (0.4)</td>
<td>2.5 (0.5)</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>Peak luminosity ([10^{34} \text{ cm}^{-2}\text{s}^{-1}])</td>
<td>5</td>
<td>30</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>Events/bunch crossing</td>
<td>170</td>
<td>1k (200)</td>
<td>~800 (160)</td>
<td>135</td>
</tr>
<tr>
<td>Stored energy/beam [GJ]</td>
<td>8.4</td>
<td>1.3</td>
<td>0.7</td>
<td>0.36</td>
</tr>
</tbody>
</table>
Present working hypothesis for HE LHC design:
No major CE modification on machine tunnel and caverns

- Similar geometry and layout as LHC machine and experiments
- Due to 16 T dipole field and increased cryogenic load, magnet cryostat and cryo distribution line (QRL) larger than for LHC.
- Challenges for tunnel integration and QRL & 16 T cryostat design.
- **Maximum magnet cryostat external diameter compatible with LHC tunnel: 1200 - 1250 mm**
- Classical 16 T cryostat design based on LHC approach gives ~1500 mm diameter!

Slide from Michael Benedikt
16 T cryo-dipole approach

Design strategy: develop a single 16 T magnet, compatible with both HE LHC and FCC-hh requirements:

• Goal is reduction of external diameter to ~1200 mm
• Options und consideration:
  • Allow stray-field and/or cryostat as (partial) return-yoke
  • Active compensation with (simple) shielding coils
  • Optimization of inter-beam distance (compactness of coils)
  • *(QRL integrated in magnets, → negative impact on integral field because of longitudinal space required for service module (5%))*

→ Smaller diam. also relevant for FCC-hh cost optimization
→ Design optimization for specific project after decision

Example magnetic cryostat
coldmass 40t, total mass 62t

Slide from Michael Benedikt
### HE-LHC session

**Thursday, 1 June, afternoon**

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:30-17:00</td>
<td>HE-LHC design, chair Andrei Seryi, Oxford U./JAI</td>
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</tr>
<tr>
<td>15:30-15:45</td>
<td>Frank Zimmermann, CERN</td>
<td>HE-LHC Baseline Parameters</td>
</tr>
<tr>
<td>15:45-16:05</td>
<td>Yuri Nosochkov, SLAC</td>
<td>Optics Development for HE-LHC</td>
</tr>
<tr>
<td>16:05-16:25</td>
<td>Leon van Riesen-Haupt, JAI</td>
<td>HE-LHC Triplet</td>
</tr>
<tr>
<td>16:25-16:40</td>
<td>Demin Zhou, KEK</td>
<td>Nonlinear Analysis and Dynamic Aperture</td>
</tr>
<tr>
<td>16:40-17:00</td>
<td>Lotta Mether, EPFL</td>
<td>HE-LHC photon flux &amp; electron cloud</td>
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</tbody>
</table>
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HE-LHC Requires stronger magnets

- Present LHC magnets → 8.33 T dipole, 223 T/m arc quadrupole, 4430 T/m² sextupole, 56 mm aperture
- For HE-LHC → FCC technology: 16 T dipole, 400 T/m quad, 7800 T/m² sextupole, 50 mm aperture
- Dipole field must increase with energy to fit the ring → ~16 T
- Scaling LHC optics to 13.5 TeV: arc quadrupoles would slightly exceed 400 T/m; sextupoles at 7800 T/m² may be limiting collision β⁺ (M.P. Crouch)

Study lattices with reduced quadrupole and sextupole strengths

Field quality of dipoles for the HE-LHC energy range is not yet defined → assume pessimistic scenario with larger errors, particularly at injection energy → affects dynamic aperture, depends on injection energy (1.3 TeV proposed for HE-LHC)

Design lattice with reduced sensitivity to field errors

Yuri Nosochkov, Demin Zhou
Making ring optics – step 1

Reduce arc FODO cell phase advance $\mu$ 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>

Yuri Nosochkov, Demin Zhou
Making ring optics – step 2

Design arc lattice with reduced sensitivity to systematic non-linear field

- Choose cell phase advance and number of cells $N_c$ per arc such that $N_c \mu_c = 2\pi k$
  - $\mu_c = 60 \text{ deg} \rightarrow N_c = 24, 18, \ldots$; $\mu_c = 90 \text{ deg} \rightarrow N_c = 24, 20, \ldots$
  - Potential improvement of dynamic aperture

3rd and 4th order RDT from sextupoles in 60° arcs

Yuri Nosochkov, Demin Zhou
Optics: LHC & 3 models

LHC V6.503, 23 x 90° arc, Q = 64.28, 59.31

Model, 20 x 90° arc, Q = 56.28, 57.31

Model, 24 x 60° arc, Q = 49.28, 47.31

Model, 18 x 60° arc, Q = 37.28, 39.31
## Optics parameters

<table>
<thead>
<tr>
<th></th>
<th>LHC V6.503 23 x 90 deg</th>
<th>Model 24 x 60 deg</th>
<th>Model 18 x 60 deg</th>
<th>Model 20 x 90 deg</th>
<th>SLHCV3.1a 24 x 60 deg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cell length, m</strong></td>
<td>106.90</td>
<td>102.45</td>
<td>136.59</td>
<td>122.94</td>
<td>102.89</td>
</tr>
<tr>
<td><strong>Dipole length, m</strong></td>
<td>14.3</td>
<td>13.56 (1)</td>
<td>14.1 (1)</td>
<td>12.39 (1)</td>
<td>13.56</td>
</tr>
<tr>
<td><strong>Number of dipoles</strong></td>
<td>1232</td>
<td>1280</td>
<td>1280</td>
<td>1424 (2)</td>
<td>1280</td>
</tr>
<tr>
<td><strong>Dipole B, T</strong></td>
<td>16.06</td>
<td>16.30 (1)</td>
<td>15.68 (1)</td>
<td>16.04 (1)</td>
<td>16.30</td>
</tr>
<tr>
<td><strong>Cell quad B’, T/m</strong></td>
<td>404.8</td>
<td>289.5</td>
<td>215.9</td>
<td>340.0</td>
<td>288.2</td>
</tr>
<tr>
<td><strong>Sextupole B”, T/m² (3)</strong></td>
<td>4883</td>
<td>2057</td>
<td>1103</td>
<td>3366</td>
<td>1891</td>
</tr>
<tr>
<td>Max/Min arc β, m</td>
<td>184 / 29</td>
<td>177 / 60</td>
<td>236 / 79</td>
<td>209 / 36</td>
<td>178 / 60</td>
</tr>
<tr>
<td>Max/Min arc η, m</td>
<td>2.03 / 0.96</td>
<td>3.75 / 2.26</td>
<td>6.67 / 4.02</td>
<td>2.92 / 1.41</td>
<td>3.78 / 2.28</td>
</tr>
<tr>
<td>Tune, x/y</td>
<td>64.28 / 59.31</td>
<td>49.28 / 47.31</td>
<td>37.28 / 39.31</td>
<td>56.28 / 57.31</td>
<td>46.28 / 45.31</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>3.22 10⁻⁴</td>
<td>6.41 10⁻⁴</td>
<td>1.13 10⁻³</td>
<td>4.57 10⁻⁴</td>
<td>6.50 10⁻⁴</td>
</tr>
</tbody>
</table>
Overview
Baseline parameters
Collider optics
Interaction region optics
Dynamic aperture
Photon flux and e-cloud
Conclusions and outlook
• High Luminosity LHC triplet would not have enough acceptance
• Ran first iteration of triplet optimization
  – Same tools as FCC
  – Triplet code to find optimum triplet
  – Initial 10 mm shielding

Leon Van Riesen-Haupt, Jose Abelleira-Fernandez
Interaction region optics

- New HE-LHC triplet integrated into EIR optics

Leon Van Riesen-Haupt, Jose Abelleira-Fernandez
Interaction region optics

- Performed energy deposition studies
  - Dose too high
  - Further iterations of optimisation needed
  - Need more shielding
  - Further design iterations will be done

Leon Van Riesen-Haupt,
Jose Abelleira-Fernandez
Plan

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• Baseline parameters
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• Conclusions and outlook
• Huge DA of model lattices due to built-in arc non-linear compensation (cancellation of sextupole effects), but also due to 4-fold periodicity
• Larger DA of realistic SLHCV3.1a model compared to LHC V6.503, due to 60 deg arcs with weaker sextupoles
Dynamic aperture

- Short-term DA for injection lattice w/o errors

24x 60-deg+Basic IRs  18x 60-deg+Basic IRs  20x 90-deg+Basic IRs  LHC injection optics V6.503

24x 60-deg arcs & IRs of SLHCV3.1a
By T. Risselada

Demin Zhou, Yuri Nosochkov
Dynamic aperture

- DA for injection lattice with errors – started studies
  - Example:
    - DA for $b3s = +6$ and $b5s = -1$ in dipoles
  - Promising results
  - Systematic studies of DA with errors – to be continued

Yuri Nosochkov
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Beam screen options for HE-LHC

- Scaled LHC beam screen
  - Pumping slots in main chamber
  - Saw-tooth structure at impact of synchrotron radiation fan

- FCC beam screen
  - Shielded pumping slots
  - Minimized photon absorption in main chamber

Lotta Mether
Photon flux & e-cloud

Heat load of SR ~ 4.6 W/m/beam

- Multipacting threshold around SEY ~ 1.45
  - Higher heat load for scaled LHC chamber (more photoelectrons)

- Multipacting threshold around SEY ~ 1
  - Similar heat load for both chambers
  - Very high heat load

Lotta Mether
Threshold electron density for single bunch instability

- Central density below threshold for 25 ns beam
- For 5 ns density below threshold for SEY < 1.1
Plan

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Conclusions

• HE-LHC ring optics
  – Developed models that fit to FCC magnet technology
  – Due to selected design approach dynamic aperture considerably increased

• Experimental Interaction Region
  – First optics created and integrated

• Electron cloud studies performed
  – 5 ns case require attention

• Great progress, a lot of studies to be done further