Optics Options for the HE-LHC

Acknowledgements to Michael Benedikt, Michael Hofer, Rogelio Tomás, Léon v. Riesen-Haupt, Thys Risselada, Demin Zhou, Frank Zimmermann

EuroCirCol Meeting
17. – 18. October 2018
KIT Karlsruhe, Germany
Outline

• Requirements of the HE-LHC

• Lattice Generation and Geometry Fitting

• Baseline Options

• Effect of Quadrupole Errors in the Main Dipoles

• Integrated Insertion Region Optics

• Conclusion and Outlook
Outline

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HE-LHC Requirements

- Same tunnel as the LHC
- Injection energy: 450 GeV, 900 GeV or 1.3 TeV
- Similar Design
  - Two counter rotating proton beams
  - Eight arcs, IRs
  - Four beam crossings
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- Centre of mass energy: 27 TeV
- Small geometry offset to the LHC (< 3 cm³)
- Beam Stay Clear > 10 σ

1 V. Mertens. Private communication.
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→ Generate and test different arc cell and dispersion suppressor options

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→ Tool: ALGEA (Automatic Lattice GEneration Application)

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ALGEA

- Based on a few input parameters flexible generation of
  - Sequence
  - Powering
  - Naming convention
  - Arcs and Dispersion Suppressors
  - Beam 1 and beam 2

- Constraints
  - Similar FODO cell layout as in LHC
  - Tunnel length
  - IP positions

OPTICS OPTIONS FOR THE HE-LHC
Geometry Optimisation in ALGEA
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- Lattice generation still challenging
  - new machine has to fit in the tunnel
  - DS and arcs have to be optimised for lattice
Geometry Optimisation in ALGEA

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  - DS and arcs have to be optimised for lattice

- Automatic survey fitting by varying parameters
  - Drift spaces in DS
  - Cell length
  - Dipole length

If varying the drift spaces is not enough:

Cell length; MB length

Extra drift between MB and MQ in the DS
(LHC: + 1.0m (IP3, IP7); + 0.8m (other IPs), compared to an arc cell)
Example of Geometry Fitting
Example of Geometry Fitting

• Before
  • Maximal offset up to 35 cm
  • Offset distributed irregularly over arc
Example of Geometry Fitting

• Before
  • Maximal offset up to 35 cm
  • Offset distributed irregularly over arc

• After
  • Maximal offset decreased by factor 4
  • Offset distributed symmetrically over arc
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Baseline Options
Baseline Options

- Studying various arc cell options lead to conclude on two baseline options
  - 18x90: 18 cells per arc, 90° phase advance per cell
  - 23x90: 23 cells per arc, 90° phase advance per cell

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>18x90</th>
<th>23x90</th>
</tr>
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<tbody>
<tr>
<td>Phase Advance per Cell</td>
<td>°</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Cell Length</td>
<td>m</td>
<td>137.33</td>
<td>106.9</td>
</tr>
<tr>
<td>Dipoles per Cell</td>
<td>-</td>
<td>8</td>
<td>6</td>
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<tr>
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<td>13.94</td>
<td>13.83</td>
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<td>Bending Angle per Dipole</td>
<td>°</td>
<td>0.28</td>
<td>0.29</td>
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<tr>
<td>Filling Factor</td>
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<td>0.81</td>
<td>0.78</td>
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<td>m</td>
<td>2.8</td>
<td>3.5</td>
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- Do they fulfil all HE-LHC requirements?

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- Centre of mass energy: 27 TeV
  - 18x90: 27 TeV
  - 23x90: 26 TeV

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### Baseline Options

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Geometry

- Small geometry offset to the LHC (< 3 cm)
Geometry

• Small geometry offset to the LHC (< 3 cm)
  • 18x90: ≈ 9 cm
  • 23x90: ≈ 1 cm

• Located in the first regular arc cell
  (part of dispersion suppressor)

• Result of different number
  and lengths of dipoles
Beam Stay Clear
Beam Stay Clear

- Beam Stay Clear > 10 sigma

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<th>MAD-X Input</th>
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<th>Value</th>
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<tr>
<td>APERTOL</td>
<td>Aperture Tolerances</td>
<td>mm</td>
<td>1, 1, 1</td>
</tr>
<tr>
<td>HALO</td>
<td>Halo Parameters</td>
<td>σ</td>
<td>6, 6, 6</td>
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<tr>
<td>BBEAT</td>
<td>Beam Size Beating</td>
<td>-</td>
<td>1.05</td>
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<td>DPARX</td>
<td>Frac. Hor. Paras. Disp.</td>
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<td>Frac. Ver. Paras. Disp.</td>
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<td>COR</td>
<td>Closed Orbit Uncertainty</td>
<td>m</td>
<td>0.002</td>
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<tr>
<td>DP</td>
<td>Rel. Momentum Offset</td>
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<td>0.0086</td>
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Note: Values in mm
R. Kersevan, FCC-hh design meeting Mar. 2018
Beam Stay Clear

- Beam Stay Clear $> 10$ sigma
- Larger for higher energy
  - 18x90: 800 GeV sufficient
  - 23x90: 600 GeV sufficient

![Graph showing Beam Stay Clear vs. Energy]

**Minimum beam stay clear in FODO cell**

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Replacing half of the magnets with superconducting ones about 600 GeV reachable with the SPS

(already proposed 1972)

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Beam Stay Clear – Different Design
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Beam Stay Clear at 450 GeV [$\sigma$]

Cell Length [m]

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<th>70</th>
<th>90</th>
<th>110</th>
<th>130</th>
<th>150</th>
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<tbody>
<tr>
<td>Beam Stay Clear</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>7</td>
<td>6</td>
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</tbody>
</table>
Beam Stay Clear – Different Design

- Choose design with smaller cells $\rightarrow$ more cells per arc
Beam Stay Clear – Different Design

- Choose design with smaller cells → more cells per arc → 32 cells per arc lead to

Beam stay clear > 10 σ
Beam Stay Clear – Different Design

- Choose design with smaller cells → more cells per arc → 32 cells per arc lead to

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Centre of Mass Energy [TeV] < 25 TeV
Beam Stay Clear – Different Design

- Choose design with smaller cells → more cells per arc → 32 cells per arc lead to

Beam stay clear > 10 $\sigma$

$\sigma$ vs. Cell Length [m]

c.o.m. energy < 25 TeV

Centre of Mass Energy [TeV] vs. Cell Length [m]

Geometry offset >> 3 cm

Transverse Offset [cm] vs. S [km]
Beam Stay Clear – Combined Function Dipoles
## Beam Stay Clear – Combined Function Dipoles

- Combined function dipoles
- Every dipole provides an additional quadrupole field → $b_2$ component
- Assumption: different sign of $b_2$ in inner and outer aperture
Beam Stay Clear – Combined Function Dipoles

- Combined function dipoles

- Every dipole provides an additional quadrupole field \( \rightarrow b_2 \) component

- Assumption: different sign of \( b_2 \) in inner and outer aperture

- Best combination for both cells is shown here \( \rightarrow \) two different dipole types

<table>
<thead>
<tr>
<th></th>
<th>23x90</th>
<th>18x90</th>
</tr>
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<tbody>
<tr>
<td>Units of ( b_2 )</td>
<td>- - + - + + +</td>
<td>- - + - - + + +</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>9.89</td>
<td>9.62</td>
</tr>
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- 23x90:  
  - 450 units of \( b_2 \)
  - 9.89 \( \sigma \)

- 18x90:  
  - 500 units of \( b_2 \)
  - 9.62 \( \sigma \)
Beam Stay Clear – Beam Screen Dimension
Beam Stay Clear – Beam Screen Dimension

- Enlargement of the beam screen

Current beam screen design

Note: Values in mm
Beam Stay Clear – Beam Screen Dimension

- Enlargement of the beam screen

**Current beam screen design**

![Current beam screen design diagram](image1)

**23x90: 10% enlargement**

![23x90: 10% enlargement diagram](image2)

Note: Values in mm
Beam Stay Clear – Beam Screen Dimension

- Enlargement of the beam screen

**Current beam screen design**

**23x90: 10% enlargement**

**18x90: 22% enlargement**

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<th>Dimension</th>
<th>24.44</th>
<th>26.88</th>
<th>38.61</th>
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<tr>
<td>Height</td>
<td>16.6</td>
<td>18.26</td>
<td>20.25</td>
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Beam Stay Clear – Bottlenecks
Beam Stay Clear – Bottlenecks

- Optics functions have peaks in the IRs and DS
- Beam stay clear smaller than in a FODO cell
- Smallest beam stay clear at 450 GeV
  - 18x90: 5.5 σ in DS IR5
  - 23x90: 5.3 σ in DS IR4
Beam Stay Clear – Bottlenecks

- Optics functions have peaks in the IRs and DS
- Beam stay clear smaller than in a FODO cell
- Smallest beam stay clear at 450 GeV
  - 18x90: 5.5 $\sigma$ in DS IR5
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- Local Problem
  - Small changes in dispersion suppressor
  - Improving optics
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Quadrupole Errors at Collision Energy
Quadrupole Errors at Collision Energy

- Magnetic field of e.g. dipoles includes higher magnetic orders
- $b_2$ – component = quadrupole error

---

$E_\text{max} = 360 \text{T/m}$

18x90 13.5 TeV

23x90 13 TeV

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1. S. Izquierdo Bermudez, private communication, Jan 2018
2. S. Izquierdo Bermudez, private communication, Oct 2018
Quadrupole Errors at Collision Energy

- Magnetic field of e.g. dipoles includes higher magnetic orders
- $b_2$ – component = quadrupole error
- Jan 2018: at collision energy $b_2 = 46.840$ units\(^1\)
  - Quadrupole exceeds limit of 360 T/m
  - Longer quadrupoles for correction
- 23x90: Shorter dipoles, reduced c.o.m energy of 25.9 TeV
- 18x90: no effect due to extra drift space in lattice

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  - Longer quadrupoles for correction
  - 23x90: Shorter dipoles, reduced c.o.m energy of 25.9 TeV
  - 18x90: no effect due to extra drift space in lattice

- Oct 2018: at collision energy $b_2 = 0.025$ units$^2$
  - No effect on lattice

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Experimental Insertion - Injection

- IR 1/5 by Léon van Riesen-Haupt is integrated
- Injection: $\beta^* = 11$ m
Experimental Insertion - Collision

- IR 1/5 by Léon van Riesen-Haupt is integrated
- Collision: $\beta^* = 0.45 \, \text{m}$
- Half crossing angle: 165 mrad
Radio Frequency

- IR4 by Pablo Mirave and Léon van Riesen-Haupt is integrated
- Contains additional quadrupoles compared to LHC IR4 helps tuning the ring
Injection Beam 1 and Experiment

- Beam 1 is injected in IR2
- Taken from LHC
Injection Beam 2 and Experiment

- Beam 2 is injected in IR8
- Taken from LHC
Extraction

• IR6 design from Wolfgang Bartmann and Brennan Goddard

![Graph of Beam 1 and Beam 2 showing parameters βₓ, βᵧ, and D vs. S [km]]
Momentum Collimation

• IR3 from LHC is integrated
• Thys Risselada has already released a new IR
  → integration in the next version
• IR7 from LHC is integrated

• Matthew Crouch and Thys Risselada have already released a new IR → integration in the next version
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Conclusion and Outlook

- Two baseline designs
  - 23x90: Offset 1 cm, 26 TeV c.o.m. energy
  - 18x90: Offset 9 cm, 27 TeV c.o.m. energy

- Sufficient beam stay clear reached if
  - Injection energy of 800 GeV/600 GeV for the 18x90/23x90 design
  - Choosing a different design with 32 cells per arc → below 25 TeV c.o.m. energy, bad geometry
  - Using combined function dipoles with at least 500 units/450 units for the 18x90/23x90 design
  - Scaling the beam screen by 22%/10% for the 18x90/23x90 design

- Current $b_2$ errors negligible → no effect on designs

- V0.5 optics ready to release
  - 18x90 and 23x90 designs
  - Injection and collision
  - Beam 1 and beam 2
  - Thick and thin

- Mitigate geometry offset of 18x90
- V0.6 including new IR3 and IR7 designs ongoing
BACKUP SLIDES
Different Beam Screens (BS) taken from FCC-hh

APERTURE = {0.015, 0.0132, 0.015, 0.015}

2016

29.6
26.4
7.5
2.9
0.47
0.44

2017

31.55
26.4
16.6
27.55
7.5

2018

31.65
24.44
16.6
27.65

Note: values in mm

C. Garion, FCC Week Apr. 2016

J. Bellafont, EuroCirCol meeting Oct. 2017

R. Kersevan, FCC-hh design meeting Mar. 2018
For small gain in beam stay clear (n1) it is enough to increase only the horizontal aperture; however at some point the vertical aperture needs to be enlarged as well to improve n1 further.

→ It is not enough to increase only the horizontal dimensions of the beam pipe.
Beam Stay Clear Values at Injection Energies

- Energy [GeV] | Beam Stay Clear [$\sigma$]
  - 18x90 | 23x90
  - 450 | 7.51 | 8.78
  - 900 | 10.62 | 12.42
  - 1300 | 12.77 | 14.93