Betatron collimation system insertion


European Organization for Nuclear Research (CERN)

FCC Week, 30.05.2017
Introduction

- Collimation system must protect the accelerator from harmful beam losses (Stored beam energy of 8.4 GJ, i.e. >20 times LHC)

- It must sustain high loss scenarios (beam lifetime drops to 12 min)

- Power load 11.8 MW —> very demanding for robustness of collimators

- Limit on losses in cold magnets $R_q$: $0.5 \cdot 10^6$ p/s/m —> avoid quenches

- Target cleaning inefficiency: $3 \cdot 10^{-7}$ p/m

\[
\frac{N_{tot}}{\tau_b} \cdot \tilde{\eta}_c < R_q
\]

- Desired beam intensity is related to cleaning inefficiency target
Multi-stage collimation system

Collimator settings depend on the aperture that needs to be protected

taken from M. Fiascaris, S. Redaelli - FCC week 2016
Multi-stage collimation system

Introduction

Cold aperture

Primary collimator

Secondary collimators

Cleaning insertion

Bottle neck

Circulating beam

Primary beam halo

Secondary beam halo + hadronic showers

Primary beam halo

Secondary beam halo + hadronic showers

Cleaning insertion

Arc(s)

IP

Collimator settings depend on the aperture that needs to be protected

taken from M. Fiascaris, S. Redaelli - FCC week 2016
Collimator settings depend on the aperture that needs to be protected.
Multi-stage collimation system

Collimator settings depend on the aperture that needs to be protected

taken from M. Fiascaris, S. Redaelli - FCC week 2016
Betatron collimation insertion

- Dedicated insertion (2.8km) for betatron collimation
- Scaled-up version of the LHC system
- Primary collimator half-gap ~0.9mm (0.84 times LHC gaps)
Betatron collimation insertion

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<table>
<thead>
<tr>
<th></th>
<th>HL-LHC $\epsilon = 2.5 , \mu m$</th>
<th>FCC-hh $\epsilon = 2.2 , \mu m$</th>
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<tbody>
<tr>
<td>Primaries</td>
<td>6.7</td>
<td>7.2</td>
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<tr>
<td>Secondaries</td>
<td>9.1</td>
<td>9.7</td>
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<tr>
<td>TCDQ</td>
<td>10.6</td>
<td>11.4</td>
</tr>
<tr>
<td>Tertiaries</td>
<td>12.9</td>
<td>13.7</td>
</tr>
<tr>
<td>min. aperture</td>
<td>14.5</td>
<td>15.5</td>
</tr>
</tbody>
</table>
Outline:

- Aperture
- Cleaning inefficiency
- Energy deposition
- Material & Impedance
• Aperture
• Cleaning inefficiency
• Energy deposition
• Material & Impedance
Assumptions for aperture calculations

- Collimation system protects a certain aperture
- No apertures in the ring allowed below in order to guarantee protection
- Use MAD-X aperture model to calculate local beam clearance around the ring

<table>
<thead>
<tr>
<th></th>
<th>Injection</th>
<th>Collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial closed orbit excursion</td>
<td>2 mm</td>
<td>2 mm</td>
</tr>
<tr>
<td>β-beating (%)</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Momentum offset</td>
<td>$6 \times 10^{-4}$</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>Relative parasitic dispersion</td>
<td>0.14</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Alignment tolerances from LHC Project Report 1007

- Horizontal, vertical and radial component
- Assumes worst case of linear addition
- Accounts for dynamic movements, survey errors, tunnel movements, cryostat assembly
- 1mm beam screen alignment tolerance

Figure 22.1: Definition of aperture tolerances

E.g.:
Main dipoles: $g=1.1\text{mm}$, $s=0\text{mm}$ and $r=1.65\text{mm}$
Main quadrupoles: $g=0.9\text{mm}$, $s=0\text{mm}$ and $r=1.14\text{mm}$

tolerances taken from HL-LHC, but dedicated study to refine them for FCC-hh planned
In general all apertures well above 15.5 $\sigma$

Only elements below specification are the recombination dipoles in IRA/G (not yet optimised)

Triplet magnets with shielding will become bottleneck
Most IRs meet or are close to the goal of $\sigma_{\text{min}} > 15.5$

By design the bottleneck is in the arc / dispersion suppressor

Bottleneck at dipoles where $\beta_x$ is large
Nb3Sn dipole magnets will be straight, i.e. not following the beam trajectory

Beam offset of up to 1.2mm (aperture loss of 2.5 $\sigma$)
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Exploring mitigations:

- Enlarge beam screen horizontally
- Aperture requirement at injection energy (different criteria at injection and top energy used at HL-LHC)
- Refine alignment tolerances
• Aperture
• **Cleaning inefficiency**
• Energy deposition
• Material & Impedance
DS collimators

Betatron Collimation Insertion (2.8km)

- Primary collimators
- Secondary collimators
- Shower absorbers
- Dispersion suppressor collimators

Scattered, off-momentum particles have different bending radii

Significant losses in dispersion suppressor region

courtesy of A. Krainer
Scattered, off-momentum particles have different bending radii.

Significant losses in dispersion suppressor region.

Additional collimators can successfully mitigate this issue (same idea as implemented for HL-LHC)
With DS collimators, the required cleaning inefficiency of $3 \cdot 10^{-7}$ could be achieved globally.

Few losses can still be seen in front of tertiary collimators and in the momentum collimation insertion.
• Aperture
• Cleaning inefficiency
• **Energy deposition**
• Material & Impedance
Previous plots show cleaning inefficiency in terms of simulated proton losses on the aperture.

For detailed assessment of performance, need to simulate energy deposition in all elements (collimators + magnets):

- Assess quenches and robustness of elements during high losses.
- Assess long-term radiation damage effects.

As for HL-LHC, using FLUKA,

- Starting conditions: output from the tracking studies (M. Fiascaris).
- Need to build detailed 3D geometry in FLUKA of the collimation insertion.
Warm magnets

- 8 dipole modules:
  - 17 m long warm dipoles
  - magnetic field 1.85 T
  - beam-beam separation: 250 mm and 400 mm in the dog-leg
  - beam-pipe aperture: 29.5 mm X 22 mm

- 24 quadrupoles:
  - 15.54 m long
  - very simplified design, LHC inspired, with 400 mm beam separation
  - beam-pipe aperture: 15.26 mm X 26.14 mm
Collimators

- Same collimators and absorbers as in LHC:
  - 3 TCP (primary collimator)
    - $7.6 \sigma$
    - 0.6 m long
    - carbon based collimators
  - 11 TCS (secondary collimator)
    - $8.8 \sigma$
    - 1 m long
    - carbon based collimators
  - Active absorbers
    - $12.6 \sigma$
    - 1 m long
    - tungsten based collimators
  - Passive absorbers put in front of the magnets:
    - 0.4m to 1.5m long

Courtesy of I. Besana
### FCC Power Sharing

FLUKA showering calculation taking as initial condition the touches distribution by the SixTrack+FLUKA coupling

<table>
<thead>
<tr>
<th>Power Fraction</th>
<th>FCC (50 TeV)</th>
<th>LHC (6.5 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Loss for 12 minutes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>beam life-time</td>
<td>11.8 MW</td>
<td>0.5 MW</td>
</tr>
<tr>
<td>Warm dipoles</td>
<td>16 %</td>
<td>8.5 %</td>
</tr>
<tr>
<td>Warm quadrupoles</td>
<td>4.6 %</td>
<td>9.5 %</td>
</tr>
<tr>
<td>TCP and TCS jaws</td>
<td>5.1 %</td>
<td>10.5 %</td>
</tr>
<tr>
<td>Passive absorbers (TCAP)</td>
<td>8.6 %</td>
<td>13.5 %</td>
</tr>
<tr>
<td>Beam pipe</td>
<td>14.2 %</td>
<td>8.6 %</td>
</tr>
<tr>
<td>Tunnel wall &amp; Other elements</td>
<td>47.5 %</td>
<td>42.3 %</td>
</tr>
<tr>
<td>Neutrinos/E —&gt; m</td>
<td>4 %</td>
<td>6.5 %</td>
</tr>
</tbody>
</table>

higher fraction at the FCC wrt to LHC —> FCC dipoles are 5 times longer & upstream collimators and absorbers are identical to LHC

the FCC longer quadrupoles are less impacted, thanks to the protection of upstream dipoles

courtesy of I. Besana
Power on Dipoles

- Two dipole modules downstream the TCPs take more than 90% of the total dose on dipoles.
Two dipole modules downstream the TCPs take more than 90% of the total dose on dipoles:

Effect of the absorber in front of MBW.B6L

At the peak: more than a factor of 3 reduction thanks to the passive absorber.

MBW.B6L: 0.8 MW

MBW.A6L: 1 MW
Different return coil design, to protect them from radiation (inspiration from A. Milanese’s design for the compensator dipole in the triplet)

Moving away from the beam pipe, a reduction of an order of magnitude is obtained for the dose of the return coil.
### Power on Collimator Jaws

#### Primaries

<table>
<thead>
<tr>
<th>Collimator</th>
<th>[kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPC_D6L</td>
<td>0.02</td>
</tr>
<tr>
<td>TPC_C6L</td>
<td>23.1</td>
</tr>
<tr>
<td>TPC_B6L</td>
<td>209.0</td>
</tr>
</tbody>
</table>

#### Secondaries

<table>
<thead>
<tr>
<th>Collimator Jaws</th>
<th>[kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCSG_A6L</td>
<td>233.6</td>
</tr>
<tr>
<td>TCSG_B5L</td>
<td>8.2</td>
</tr>
<tr>
<td>TCSG_A5L</td>
<td>35.7</td>
</tr>
<tr>
<td>TCSG_D4L</td>
<td>27.6</td>
</tr>
<tr>
<td>TCSG_B4L</td>
<td>7.1</td>
</tr>
<tr>
<td>TCSG_A4L</td>
<td>15.1</td>
</tr>
<tr>
<td>TCSG_A4R</td>
<td>15.9</td>
</tr>
<tr>
<td>TCSG_B5R</td>
<td>4.9</td>
</tr>
<tr>
<td>TCSG_D5R</td>
<td>9.0</td>
</tr>
<tr>
<td>TCSG_E5R</td>
<td>15.7</td>
</tr>
<tr>
<td>TCSG_6R</td>
<td>3.5</td>
</tr>
</tbody>
</table>

About a factor 15 higher wrt to LHC (6.5 TeV, 500 kW power losses)

#### Active absorbers

<table>
<thead>
<tr>
<th>Collimator</th>
<th>[kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCLA_A6R</td>
<td>74.5</td>
</tr>
<tr>
<td>TCLA_B6R</td>
<td>13.5</td>
</tr>
<tr>
<td>TCLA_C6R</td>
<td>2.0</td>
</tr>
<tr>
<td>TCLA_D6R</td>
<td>2.6</td>
</tr>
</tbody>
</table>

A factor of 2-2.5 higher than LHC

#### Passive absorbers

<table>
<thead>
<tr>
<th>Collimator</th>
<th>[kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCAPA.6L</td>
<td>560.7</td>
</tr>
<tr>
<td>TCAPB.6L</td>
<td>93.4</td>
</tr>
<tr>
<td>TCAPC.6L</td>
<td>359.9</td>
</tr>
</tbody>
</table>

A factor of 35 higher than LHC

courtesy of I. Besana
FCC:
\(~1000 \text{ W cm}^{-3}\) on TCSG_A6L
70 W cm\(^{-3}\) on TCSG_A6L
25 W cm\(^{-3}\) on TCSG_D4L

LHC: 10 W cm\(^{-3}\)

Mitigations under study, in particular thicker jaws
• Aperture
• Cleaning inefficiency
• Energy deposition
• Material & Impedance
### Impedance and materials

<table>
<thead>
<tr>
<th>Element</th>
<th>([ReZ_{x,y}]_{TCBI}^{\text{eff}}) MOhm/m</th>
<th>([ImZ_{x,y}]_{TMCI}^{\text{eff}}) MOhm/m</th>
<th>([ImZ_{/n}]_{\text{Landau}}^{\text{eff}}) mOhm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Res. wall of collimators (including TDI)</td>
<td>baseline (CFC)</td>
<td>Inj: -13.5 (x)/-11.8 (y) Top E: -197.6(x)/-346.3(y)</td>
<td>Inj: 2.26 (x)/3.53 (y) Top E: 132.2 (x)/128.8 (y)</td>
</tr>
<tr>
<td>alternative 1 (MoC, no coatings)</td>
<td>Inj: -23.1 (x)/-22.5 (y) Top E: -237.1 (x)/-382.1 (y)</td>
<td>Inj: 0.98 (x)/1.45 (y) Top E: 75.2 (x)/77.3 (y)</td>
<td>Inj: 0.21 Top E: 1.35</td>
</tr>
<tr>
<td>alternative 2 (MoC, TCSG are coated)</td>
<td>Inj: -23.1 (x)/-22.5 (y) Top E: -237.1 (x)/-382.1 (y)</td>
<td>Inj: 0.85 (x)/0.69 (y) Top E: 40.2 (x)/54.5 (y)</td>
<td>Inj: 0.14 Top E: 1.11</td>
</tr>
<tr>
<td>Allowed total budget</td>
<td>Injection: 2700 Top energy: 40000 Assuming 30 turns feedback and (N_b = 10^{11})</td>
<td>Injection: 35 Top energy: 220 assuming (N_b = 10^{11}) and (N_b = 0.65N_b^{\text{Sach}}), and 32 MV of stabilizing RF</td>
<td>200, according to Elena</td>
</tr>
</tbody>
</table>

- CFC based collimators consume significant portion of the impedance budget
- Investigate alternative materials, e.g. Molybdenum Graphite (MoGr) which is foreseen for HL-LHC
Minimum apertures are not far away from the target

Slight beam screen modifications / Refine alignment tolerances / Different aperture target for injection energy —> Considering injection & extraction failures (in collaboration with injection and dump team)

Dispersion suppressor collimators significantly reduced losses
—> Target cleaning inefficiency of $3 \cdot 10^{-7}$ could be achieved

Few losses around tertiary collimators and in momentum cleaning insertion might be mitigated by adjusting collimator positions

Identified few collimators which suffer from high radiation doses

Investigate easy solutions first —> e.g. thicker jaws / shorter primaries / L-shape collimators

Further iterate on the design including the use of MoGr to mitigate impedance situation (Consider a re-design which is not based on a scaled LHC collimation system)