• Introduction
• FCC challenges for collimation
• The LHC collimation system
• First FCC collimation system design: status of simulations
• Outlook and Conclusions
Introduction: roles of collimation systems

- **Halo cleaning** versus quench limits (for SC machines)
- **Passive machine protection**
  First line of defense in case of accidental failures
- **Reduction of total doses** on accelerator equipment
  Provide local protection to equipment exposed to high doses
- **Cleaning of physics debris** (collision products)
  Avoid SC magnet quenches close to the high-luminosity experiments
- **Concentration of losses/activation** in controlled areas
  Avoid many loss locations around the 27-km tunnel
- **Optimize background** in the experiments
  Minimize impact of halo losses on quality of experimental data
Introduction: roles of collimation systems

- **Halo cleaning** versus quench limits (for SC machines)
- **Passive machine protection**
  First line of defense in case of accidental failures
- **Reduction of total doses** on accelerator equipment
  Provide local protection to equipment exposed to high doses
- **Cleaning of physics debris** (collision products)
  Avoid SC magnet quenches close to the high-luminosity experiments
- **Concentration of losses/activation** in controlled areas
  Avoid many loss locations around the 27-km tunnel
- **Optimize background** in the experiments
  Minimize impact of halo losses on quality of experimental data
Introduction: roles of collimation systems

- **Halo cleaning** versus quench limits (for SC machines)
- Passive **machine protection**
  
  First line of defense in case of accidental failures
- **Reduction of total doses** on accelerator equipment
  
  Provide local protection to equipment exposed to high doses
- **Cleaning of physics debris** (collision products)
  
  Avoid SC magnet quenches close to the high-luminosity experiments
- **Concentration of losses/activation** in controlled areas
  
  Avoid many loss locations around the 27-km tunnel
- **Optimize background** in the experiments
  
  Minimize impact of halo losses on quality of experimental data

Main role of collimation in hadron colliders before the LHC

Driving constraint for LHC and FCC-hh!
Outline

• Introduction

 → FCC challenges for collimation

• The LHC collimation system

• First FCC collimation system design: status of simulations

• Outlook and Conclusions
Collimation at the LHC

The **LHC collimation system** is the **current state-of-the-art** for particle accelerators.

**LHC beam highly destructive**

**Beam cleaning requirements** exceed previous machines by order of magnitudes!
## FCC vs LHC

<table>
<thead>
<tr>
<th></th>
<th>LHC (Design)</th>
<th>HL-LHC</th>
<th>FCC-hh (Baseline)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam energy</strong></td>
<td>7 TeV</td>
<td>7 TeV</td>
<td>50 TeV</td>
</tr>
<tr>
<td><strong>Beam intensity</strong></td>
<td>$3 \times 10^{14}$</td>
<td>$6 \times 10^{14}$</td>
<td>$10 \times 10^{14}$</td>
</tr>
<tr>
<td><strong>Stored energy</strong></td>
<td>360 MJ</td>
<td>690 MJ</td>
<td>8500 MJ</td>
</tr>
<tr>
<td><strong>Power load (τ=0.2h)</strong></td>
<td>~500 kW</td>
<td>~960 kW</td>
<td>~11800 kW</td>
</tr>
<tr>
<td><strong>Energy density</strong></td>
<td>~1 GJ/mm$^2$</td>
<td>~1.5 GJ/mm$^2$</td>
<td>~200 GJ/mm$^2$</td>
</tr>
</tbody>
</table>
## FCC vs LHC

<table>
<thead>
<tr>
<th></th>
<th>LHC (Design)</th>
<th>HL-LHC</th>
<th>FCC-hh (Baseline)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam energy</strong></td>
<td>7 TeV</td>
<td>7 TeV</td>
<td>50 TeV</td>
</tr>
<tr>
<td><strong>Beam intensity</strong></td>
<td>$3 \times 10^{14}$</td>
<td>$6 \times 10^{14}$</td>
<td>$10 \times 10^{14}$</td>
</tr>
<tr>
<td><strong>Stored energy</strong></td>
<td>360 MJ</td>
<td>690 MJ</td>
<td>8500 MJ</td>
</tr>
<tr>
<td><strong>Power load ($\tau=0.2h$)</strong></td>
<td>~500 kW</td>
<td>~960 kW</td>
<td>~11800 kW</td>
</tr>
<tr>
<td><strong>Energy density</strong></td>
<td>~1 GJ/mm$^2$</td>
<td>~1.5 GJ/mm$^2$</td>
<td>~200 GJ/mm$^2$</td>
</tr>
</tbody>
</table>

### Factor 20 x LHC:

stringent requirements on **cleaning inefficiency** to avoid quenches

- optimization of collimation cleaning
- addition of collimators in most critical loss location
**FCC vs LHC**

**Factor 20 x LHC:**
stringent requirements on **cleaning inefficiency** to avoid quenches

- optimization of collimation cleaning
- addition of collimators in most critical loss location

---

Maria Fiascaris

FCC week 24/03/2015
## FCC vs LHC

<table>
<thead>
<tr>
<th></th>
<th>LHC (Design)</th>
<th>HL-LHC</th>
<th>FCC-hh (Baseline)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam energy</strong></td>
<td>7 TeV</td>
<td>7 TeV</td>
<td>50 TeV</td>
</tr>
<tr>
<td><strong>Beam intensity</strong></td>
<td>3 x 10(^{14})</td>
<td>6 x 10(^{14})</td>
<td>10 x 10(^{14})</td>
</tr>
<tr>
<td><strong>Stored energy</strong></td>
<td>360 MJ</td>
<td>690 MJ</td>
<td>8500 MJ</td>
</tr>
<tr>
<td><strong>Power load ((\tau=0.2h))</strong></td>
<td>~500 kW</td>
<td>~960 kW</td>
<td>~11800 kW</td>
</tr>
<tr>
<td><strong>Energy density</strong></td>
<td>~1 GJ/mm(^2)</td>
<td>~1.5 GJ/mm(^2)</td>
<td>~200 GJ/mm(^2)</td>
</tr>
</tbody>
</table>
## FCC vs LHC

<table>
<thead>
<tr>
<th></th>
<th>LHC (Design)</th>
<th>HL-LHC</th>
<th>FCC-hh (Baseline)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam energy</strong></td>
<td>7 TeV</td>
<td>7 TeV</td>
<td>50 TeV</td>
</tr>
<tr>
<td><strong>Beam intensity</strong></td>
<td>$3 \times 10^{14}$</td>
<td>$6 \times 10^{14}$</td>
<td>$10 \times 10^{14}$</td>
</tr>
<tr>
<td><strong>Stored energy</strong></td>
<td>360 MJ</td>
<td>690 MJ</td>
<td>8500 MJ</td>
</tr>
<tr>
<td><strong>Power load ($\tau=0.2h$)</strong></td>
<td>~$500$ kW</td>
<td>~$960$ kW</td>
<td>~$11800$ kW</td>
</tr>
<tr>
<td><strong>Energy density</strong></td>
<td>~$1$ GJ/mm$^2$</td>
<td>~$1.5$ GJ/mm$^2$</td>
<td>~$200$ GJ/mm$^2$</td>
</tr>
</tbody>
</table>

2 order of magnitudes above the LHC:

outstanding challenges for collimator materials and mechanical position with 50 TeV beam
Outline

• Introduction
• FCC challenges for collimation
  ➡ The LHC collimation system
• First FCC collimation system design: status of simulations
• Outlook and Conclusions
IR3: Momentum cleaning
1 primary (H)
4 secondary (H)
4 shower absorber (H,V)

IR7: Betatron cleaning
3 primary (H,V,S)
11 secondary (H,V,S)
5 shower absorber (H,V)

Local cleaning at triplets
8 tertiary (2 per IP)

Passive absorbers for warm magnets
Physics debris absorbers
Transfer lines
Injection and dump protection

> 100 movable collimators

Two jaws (4 motors) per collimator
LHC collimation cleaning at 4 TeV

• No quenches up to 150 MJ of stored energy!
• Validation of simulations tools over 7 orders of magnitude
Very good performance of the collimation system so far

- Compatible with HL-LHC parameters at 7 TeV - pending verification with operational experience in 2015

Validation of simulation tools over 7 orders of magnitude
✓ **Very good performance** of the collimation system so far
  - Compatible with HL-LHC parameters at 7 TeV - pending verification with operational experience in 2015

✓ **Validation of simulation** tools over 7 orders of magnitude

➡ **Main cleaning limitation:** critical losses in the dispersion suppressor after the betatron cleaning

➡ The $\beta^*$ **reach** is determined by **collimation constraints:** respect collimator hierarchy - retraction between the dump and horizontal tertiary collimators which are not robust

➡ Collimators determine the **LHC impedance:** research of new materials

➡ Collimator handling in **radiation environment** is challenging
Outline

• Introduction
• FCC challenges for collimation
• The LHC collimation system
  ➡ First FCC collimation system design: status of simulations
• Outlook and Conclusions
FCC collimation: our initial approach

- Very good performance of the collimation system so far: solid solution to start with!

- First conceptual solution for the betatron collimation at the FCC: scaled-up system derived from the present one
FCC collimation: our initial approach

- Very good performance of the collimation system so far: **solid solution** to start with!

- First conceptual solution for the betatron collimation at the FCC: **scaled-up system** derived from the present one
  - Standard optics for multi-stage cleaning
  - Beta functions scaled to have similar collimator gaps as in the LHC → push until later technological developments beyond present state-of-the-art
  - Initially, keep current collimation system layout (same number of collimators, positioned at same phase advance, based on C-reinforced-C material for primary and secondary stages) → to be optimized later (more collimators for secondary and tertiary stages, new materials...)

Secondary collimators must be placed at optimum phase locations to catch secondary halo


- Dedicated insertion for off-momentum cleaning
FCC collimation: our initial approach

- Very good performance of the collimation system so far: **solid solution** to start with!
- First conceptual solution for the betatron collimation at the FCC: **scaled-up system** derived from the present one
FCC collimation: our initial approach

- Very good performance of the collimation system so far: **solid solution** to start with!

- First conceptual solution for the betatron collimation at the FCC: **scaled-up system** derived from the present one

LHC IR7 - betatron cleaning

FCC IR2 - betatron cleaning

**Optics and insertion lengths scaled up by a factor 5**

- insertion length ~ **2.7 km**
- collimator gaps (in mm): **0.84 x LHC gaps**
Tracking simulations using a lattice with:

- 2 low-beta insertions
- 2 cleaning insertions

- Implemented a three-stage betatron cleaning with 19 collimators

**Collimator Settings**

<table>
<thead>
<tr>
<th>Type</th>
<th>Setting</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 primaries</td>
<td>TCP</td>
<td>7.6</td>
</tr>
<tr>
<td>11 secondaries</td>
<td>TCSG</td>
<td>8.8</td>
</tr>
<tr>
<td>5 absorbers</td>
<td>TCLA</td>
<td>12.6</td>
</tr>
</tbody>
</table>

* same settings as for LHC nominal (6/7/10 σ) expressed in σ units for the FCC-hh emittance of 2.2 µm

- No momentum cleaning, nor collimation in experimental IRs or dump
- No aperture model available yet
Tracking simulation results

Annular halo setup with predefined impact on primary collimators

Horizontal halo at $7.6 \sigma$

Gaussian distribution in $y$-plane

Impact parameter on TCP

10 $\mu$m

Distribution of inelastic impacts on the primary collimators

Vertical

Skew

Horizontal
Cleaning inefficiency

Performance of the system characterized by a global cleaning inefficiency

- depends on collimator settings
- no need for machine aperture model

Cleaning inefficiency vs. radial amplitude

$$\eta_c(A_i) = \frac{N_p(A > A_i)}{N_{abs}}$$

- number of particles above amplitude $A_i$
- number of particles absorbed in coll. system

Cleaning inefficiency vs. $\Delta p / p$

(off-momentum halo population)

$\Delta p / p$: relative momentum loss of protons after interaction in the collimators
Cleaning inefficiency

Performance of the system characterized by a global cleaning inefficiency

- depends on collimator settings
- no need for machine aperture model

Cleaning inefficiency vs. radial amplitude

\[ \eta_c(A_i) = \frac{N_p(A > A_i)}{N_{abs}} \]

- number of particles above amplitude \( A_i \)
- number of particles absorbed in coll. system

At LHC \( \eta < \sim 10^{-3} \) for \( A = 10 \sigma \)

- (minimum mechanical aperture)
- \( \eta \sim 7 \cdot 10^{-4} \)
- power load \( \sim 8 \text{ kW} \)

Assumed

- triplet aperture

Cleaning inefficiency vs. \( \Delta p / p \)

- (off-momentum halo population)
- \( \Delta p / p \): relative momentum loss of protons after interaction in the collimators

- \( \eta \sim 1.2 \cdot 10^{-4} \)
- power load \( \sim 1.4 \text{ kW} \)

Arc acceptance

- if beam screen \( w = 13 \text{ mm} \)
- and peak \( D_x = 2 \text{ m} \)

Power loads on cold elements will depend on longitudinal distribution of losses

Maria Fiascaris

FCC week 24/03/2015
Cleaning inefficiency vs. settings

Performed a scan of simulation varying the retraction between primary and secondary collimators

→ will re-optimize phases and optics if needed, once aperture well defined
Outline

- Introduction
- FCC challenges for collimation
- The LHC collimation system
- First FCC collimation system design: status of simulations

➡ Outlook and Conclusions
Outlook: where we are

• Tools we have in hand already allow us to improve the system performance by optimizing the cleaning inefficiency curves $\eta (A), \eta (\Delta p/p)$.

• More **inputs required** to assess if the performance of the collimation system is sufficient to run at the design parameters (maximum intensity, $\beta^*$ reach):
  
  eg. knowledge of the mechanical aperture, quench limits for superconducting magnets.

• Interactions with other teams:
  
  • **Collimator settings:** trade-off between **impedance** and efficiency of the system
    → iterations with impedance team, study of new materials (**talk by A. Bertarelli on Thursday**)
  
  • **Collimator design specifications:** to be defined once we have more detailed studies on **energy deposition** (**talk by A. Lechner on Thursday**)
  
  • **Performance optimization:** need iterations with **optics team** to add collimators in critical locations (like in the dispersion suppressor) and maximize their performance.
**Advanced collimation concepts**

### Hollow e-lens

- Hollow electron beam parallel to the p-beam:
  - Halo particles see field dependent on \((Ax,Ay)\) plane, while core is unaffected
  - Adjusting e-beam parameters can be used as halo scraper
  - Expect to be a key asset to control loss rates on collimators
  - Working on a design for implementation in LHC in LS2, if needed → also crucial for FCC

### Crystal collimation

- Bent crystal can be used for channeling and extracting the beam halo in a controlled way
  - Can improve cleaning efficiency
  - Reduce impedance: less secondary collimators, larger gaps
  - Low intensity beam tests at the LHC in 2015
  - Promising for the FCC, but large uncertainties on extrapolations to high energies and several operational challenges.
Conclusions

• **Large stored energy** of the FCC implies new challenges for the collimation system!

• Baseline available for a **0th order FCC betatron collimation layout**:
  • “conservative approach”: first conceptual design based on a scaled-up version of the present system
  • results should tell us how far we can go with current state-of the art

• Simulation tools are well set-up and we performed **first systematic studies of betatron cleaning**
  • however to assess if the performance is sufficiently good we need more inputs (quench limits, aperture model, etc.)

• Collimation **layout to be extended** soon to include momentum cleaning and collimation in the experimental insertions and dump

• **Further optimization** of the system and studies of advanced collimation concepts are foreseen.
EXTRAS
The LHC collimation system

Collimation cleaning requirement: one of the key parameters that determine the intensity reach in a collider

For given quench limit, trade-off between: inefficiency - maximum intensity - minimum allowable lifetime

Beam lifetime 0.2h

R. Assmann
Multi-stage collimation at the LHC

Cold aperture

Protection devices

Primary beam halo

Primary collimator

Secondary collimators

Secondary beam halo + hadronic showers

Cleaning insertion

Arc(s)

Tertiary collimators

Tertiary beam halo + hadronic showers

Circulating beam

Bottle neck

IP
**Critical location:** fundamental limitation of the current system are losses in the cold dispersion suppressor from single diffractive interactions with the primary collimators.

- **IR7**
- **HL-LHC loss maps**
- **TCLD collimator**

Need to catch losses close to the first dipoles where dispersion starts growing.

Present system: make space for a room temperature collimator replacing one 15m long dipole with two 5.5m long 11T dipoles.

Appropriate solutions must be foreseen early on into the FCC lattice design!
SixTrack used for detailed studies to predict the beam loss distribution around the LHC ring. Comparison between measurement and simulation show very good agreement: confidence in the reliability of simulation tools.
Inputs to cleaning studies

Key parameters that determine the intensity reach in a collider:

- **Collimation cleaning**
  
  Determined by **collimation system**: optics, collimation layouts, materials, settings,... Requires an understanding of the **machine aperture**!

- **Quench limits of superconducting magnets**
  
  Parameter that “evolved” in last years. Now relying on beam induced quench tests. What about magnets for 50 TeV machine?

- **Beam lifetime assumptions**
  
  This is a crucial parameter for the design, but difficult to “guess”
  → determines the total losses in cold magnets for given cleaning;
  → determines the power loads on the collimators, input to the mechanical design.

from S. Redaelli
Simplified cleaning analysis

- High level of accuracy in LHC loss maps is the result of years of experience and operations.
- In view of FCC studies we need to go one step backward, reviving the performance studies done at the time of the LHC system design.

Cleaning inefficiency

\[ \eta_c(A_i) = \frac{N_p(A > A_i)}{N_{abs}} \]

- depends on collimator settings
- no need for machine aperture model

→ Included new performance plots for momentum cleaning performance studies
FCC simulations

Distribution of inelastic interactions at collimators

Distribution of absorbed particles at collimators