COLLIMATION IN FCC-HH

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CDR studies:
Outline

• Introduction: Challenges with FCC-hh collimation
• Recap: CDR, and status at last year’s FCC week
• Collimation system performance with updated layout
• New optics developments: high-beta optics for collimation
• Conclusions and outlook
Why do we need collimation?

**LHC**: 362 MJ stored beam energy = kinetic energy of TGV train at 155 km/h

**FCC-hh**: 8.3 GJ stored beam energy = kinetic energy of Airbus A380 (empty) at 880 km/h

FCC-hh beams are highly destructive!!
Collimation challenge: LHC vs FCC-hh

Loss of even a very small fraction of the beam could cause
- Damage to impacted elements
- Heating of superconducting magnets, leading to a quench

\[\text{LHC}\]
- Cold aperture, superconductors
- Loss power up to \(~0.5\text{ MW}\)
- Quench limit \(~30\text{ W/m}\)
- Beam: 362 MJ

\[\text{FCC-hh}\]
- Cold aperture, superconductors
- Loss power up to \(11.6\text{ MW}\)
- Quench limit \(~30-100\text{ W/m}\)
- Beam: 8.3 GJ

\[\text{Needed loss attenuation: factor } \sim 2 \times 10^4\]
\[\text{Needed loss attenuation: factor } > 10^5\]

Higher energy \(\Rightarrow\) smaller collimator gaps

\[\text{Need collimation!}\]
Collimation system design for FCC-hh

- Need collimation system to clean unavoidable regular losses, passive machine protection, optimize background and radiation dose
  - At the same time, keep the impedance within limits

- Main design loss scenarios
  - Unavoidable off-momentum losses of unbunched beam at start of ramp: 1% loss over 10 s
  - Extraction and injection kicker pre-fire, other possible failures
  - Betatron cleaning 0.2 h beam lifetime during 10 s or “steady-state” 1 h beam lifetime
  - 0.2 h lifetime and 8.3 GJ stored energy => 11.6 MW beam loss power
FCC-hh multi-stage collimation system

- As in the LHC, using a multi-stage system with primary and secondary collimators, shower absorbers, dispersion suppressor (DS) collimators
  - DS collimators are placed in the cold region, in between dipoles where dispersion has risen

- Similar layout as the LHC, but some modifications: DS collimators in many insertions, extra shower absorbers in extraction insertion, removal of skew primary
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FCC-hh collimation layout: CDR version

- Detailed previous studies done for the CDR, references:
  - R Bruce et al 2019 *J. Phys.: Conf. Ser.* **1350** 012009
  - Previous FCC week talks, FCC collimation meetings
  - Long CDR (not yet published)

- Betatron cleaning in PJ (2.8 km)
- Momentum cleaning in PF (1.4 km)

- The FCC-hh collimation system is a scaled up version of the HL-LHC/LHC system
  *NIM, A 894 (2018) 96-106*
  - Assuming also LHC-type collimators in CFC, MoGr, Inermet180
Design studies for the CDR (1)

- **Tracking studies**
  - Cleaning performance for betatron and off-momentum losses
  - Accidental scenarios (asynchronous beam dump)
  - Conclusion: collimation system provides excellent protection of cold aperture; dispersion suppressor collimators are critical

- **Tracking + energy deposition studies** on most exposed cold magnets
  - Peak power density of up to about 30 mW/cm³ – factor ~2 below estimated quench limit
Design studies for the CDR (2)

- Tracking + Energy deposition + thermomechanical studies of most exposed collimators

- Conclusions:
  - 92 kW on most loaded secondary collimator – should be OK, no permanent damage
  - 50 kW/cm³ peak power density at surface of primary collimator; 660° peak temperature – similar conditions achieved at HiRadMat without damage
  - Challenges: high temperature leading to potential outgassing, high deflection, load on cooling pipes
Updates since CDR

- Tunnel layout updated – need to revisit optics and layout of the whole ring
- Symmetric 8-point layout, ring circumference decreased from 97.7 km to 91.1 km
- Betatron collimation moved to shorter insertion: 2.1 km instead of 2.8 km
- Momentum collimation in longer insertion: 2.1 km instead of 1.4 km
- Same optics in all four experimental insertions
2022 FCC-week results

- First iteration of studies with 2022 layout shown at FCC week 2022
- CDR collimation system scaled to fit in shorter insertion
- Cleaning performance not good enough

*Horizontal halo, beam 1, 50 TeV, Zoom in IRF, $\beta^*=55$ cm*
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Updates since FCC week 2022

- **Adaptation to the PA31 V1 layout (12 dipoles/arc cell)**
  - Several iterations performed on the collimation optics (T. Risselada) and collimation configuration
  - Other updates, e.g. decreased $\beta^*$, doglegs, injection/extraction optics

- **New optics with larger $\beta$-functions in the collimation insertion** - work in progress
  - Motivation: lower impedance, better cleaning performance, more spread-out power density on primary collimator
  - Based on studies for the LHC, using PA 31 V1

- **New lattice version with 16 dipoles per arc cell being set up** - see talks M. Giovannozzi, G. Perez Seguarana
  - Even shorter collimation insertion (2032 m instead of 2160 m)
  - Very fresh – not yet studied for collimation
Collimation optics: PA31 V1

• Optics adapted from LHC collimation insertions, with modifications
Aperture for PA31 V1

- Aperture model updated and adapted from the CDR – essential for tracking studies
- Significant aperture margins – bottleneck for beam-stay-clear above 25 σ

Aperture and collimators around the FCC-hh ring
FCC-hh collimation system

- Have now DS collimators in all insertion, extraction protection in PB, tertiary collimators in the experimental insertions

- Additional DS collimator in PF (four in total)

- Tighter secondary collimator settings in PF

- Impedance still to be verified

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</table>
Simulated cleaning performance (PA31 V1)

- The collimation performance was studied with SixTrack-FLUKA coupling
- **Good general performance of the collimation system**
  - excellent improvement since 2022 FCC week
  - In general only few losses on superconducting magnets
- **Caveats**
  - The performance is worse than in the CDR configuration
  - Higher TCT losses than in CDR
  - Even with a 4th DS collimator in PF, the losses there exceed the estimated quench limit by up to 55%

More info in *IPAC’23 paper*
Simulated cleaning performance (PA31 V1)

- Simulated DS losses above quench limit
- Cleaning target is possibly conservative
  - Calculated based on FLUKA studies assuming 12 min beam lifetime, and quench limit of $10 \times 10^{10} \text{mW/cm}^3$
  - Estimated quench limit could be higher – 70-100 mW/cm$^3$
    - exchange with L. Bottura and D. Tommasini
    - On the other hand, significant uncertainties, and imperfections could also bring up the losses
- New power deposition study would be needed to assess more accurately the risk of quenching
- This configuration could probably be further optimized, however, future efforts will be focused rather on the new 16-dipole lattice

More info in IPAC'23 paper
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High-β optics for collimation

- Small collimator gaps might lead to problematic impedance
  - Could be mitigated through an optics with larger β-functions

- Such an optics could also give significant gains in cleaning efficiency
  - Studied in simulation for LHC in IPAC’21 paper
  - Experimental tests in LHC started in 2022 – not conclusive yet, to be followed up in 2023

- Studies of high-β optics for FCC-hh
  - First design of high-beta collimation optics for the FCC-hh by T. Risselada
  - First try: introduce high β-functions and relax constraints on phases
  - Integrated in the PA31 V1 optics by G. Perez Segurana
FCC-hh collimation performance with high-β

- First studies of the collimation performance are ongoing

- Slight worsening of cleaning performance observed with high-β optics – unexpected result
  - Could be due to changes in phase advance and single-pass dispersion

- Work in progress - further optimization studies needed
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Conclusions

- The FCC-hh beam is highly destructive
  - 8.3 GJ stored beam energy, 11.6 MW beam loss power

- A highly performing collimation system is crucial to keep the FCC-hh safe, and to operate smoothly without quenches and premature beam dumps
  - Quite mature design presented in CDR

- System design and optics updated for PA31 V1 lattice
  - Shorter insertion length for betatron collimation
  - First studies of cleaning performance with new lattice ⇒ Generally good performance, but some bottlenecks need further study and performance improvements

- Alternative high-β optics under study
  - Goals: improved impedance and cleaning
  - First results do not show improved cleaning – work in progress

- Next steps: move to 16-dipole lattice; optimize system and repeat key studies done for the CDR
Thank you for your attention.
Next steps

• Need to move to new 16-dipole lattice and repeat basic performance studies
• Explore optimizations of optics and collimator settings
• Study performance of momentum cleaning
• Study impedance
• Energy deposition studies to quantify risk of quench for design losses
• Maybe new thermo-mechanical studies of most loaded collimators
• Study outgassing and cooling of the most impacted elements in collimation insertion
• Study failure scenarios
• Collimation for Pb ion operation
  • Energy deposition studies of collimation insertion and dispersion suppressor, possibly including imperfections
  • Further studies of secondary beams from collision points
• Imperfection studies?
Optics of collimation insertions: CDR version

- Scaled $\beta$-functions and insertion length by factor 5 from the LHC $\rightarrow$ 2.8 km insertion length
- Increased dispersion in momentum cleaning insertion

**IRJ (Betatron cleaning)**

**IRF (Momentum cleaning)**
Collimation performance – FCC-hh protons

- Collimation performance checked with tracking studies using the SixTrack-FLUKA coupling and dedicated FLUKA simulations of exposed magnets.

- Collimation system is extremely efficient at absorbing horizontal and vertical losses – almost no losses on cold machine aperture, thanks to dispersion suppressor collimators.

Collision, 50 TeV

Most loaded cold magnet
FCC collimator design

- Assuming LHC-type collimators, with some design modifications, following iterative simulations of tracking, energy deposition and thermo-mechanical response

- Materials
  - Primary collimators, and most loaded secondary collimator made of carbon-fiber-composite (CFC) for maximum robustness
  - Remaining secondary collimators in MoGr with 5 μm Mo coating for a good compromise between impedance and robustness

- Collimators would survive design losses in simulations, but some challenges remain: high temperature leading to potential outgassing, high deflection, load on cooling pipes
Updates to betatron collimation layout

- Scaling the original LHC collimation optics to new insertion lengths (T. Risselada)
- Similar collimator layout as LHC, but including 3 dispersion suppressor collimators as CDR-version of FCC-hh
- Insertion length and beta functions scaled by a factor ~4 compared to the LHC
- Smallest collimator half gap (vertical primary) around 0.8 mm
  - Compare: ~1mm in LHC
Momentum collimation

- For momentum collimation, LHC scaling used as starting point
- First implementation of optics and layout available
- Features high dispersion at primary collimator to give flexibility and independence between betatron and momentum cuts
- DS collimators added
Optimization of doglegs

- Dogleg changes the distance between the beams in collimation insertion
  - Separate primary beam from neutrals.
  - Minimise flux of neutrals on the first superconducting magnet on right side of IP
  - Needed separation depends on geometry of insertion

- CDR layout: dogleg scaled from the LHC

- New version: dogleg geometry worked out based on actual geometry in IRH
  - 290 mm separation proposed (compare 250 mm in the arc)
  - To be confirmed with energy deposition studies
Collimation in experimental insertions

- Two pairs (horizontal-vertical) tertiary collimators on incoming beam
- Two dispersion suppressor collimators on outgoing beam
- Physics debris collimators still to be implemented
Updates to aperture model

- A detailed aperture model around the ring is crucial for collimation studies
- First implementation of new aperture model, based on mapping from CDR lattice (A. Abramov)
  - Including main magnets and collimators in insertion regions and arcs
- To be refined in future iterations
Aperture model in insertions

- Apertures mapped from similar elements in CDR lattice – to be refined in future iterations

Preliminary result

IRH (momentum collimation)

IRF (betatron collimation)

A. Abramov
Simulations of collimation performance

- Collimation performance simulated for latest version of FCC-hh using the SixTrack-FLUKA coupling
  - Magnetic tracking using SixTrack, particle-matter interactions in FLUKA

- Simulation assumptions
  - 1 μm impact parameter of generic halo on primary collimator – not simulating diffusion bringing halo onto collimators
  - Same collimator settings in σ and materials as in CDR
Simulated performance

- Generally very good protection of the ring, losses localized on betatron collimation system
- Rather high losses on tertiary collimators, with downstream leakage to cold magnets
  - Potentially problematic, to be followed up in future iterations

*Horizontal halo, beam 1, 50 TeV*

A. Abramov

Preliminary result
Simulated performance - IRF

- Dispersion suppressor collimators essential for protecting the ring and the DS

- Nevertheless losses in between them are well above the assumed quench limit
  - Further iterations are needed to optimize collimation performance

- Energy deposition should be evaluated with dedicated studies at critical locations – future work
  - Compare power load in magnet coils with quench limit
  - Note: Particle showers not seen in the loss map plots, which show only proton losses