COLLIMATION IN FCC-HH

R. Bruce, A. Abramov, M. Giovannozzi, G. Perez Seguarana, S. Redaelli, T. Risselada
CDR studies:
Y. Alexahin, W. Bartmann, A. Bertarelli, S. Arsenyev, I. Besana, F. Carra, F. Cerutti, A. Chance, B. Dalena, A. Faus-Golfe, M. Fiascaris, S. Gilardoni, E. Gianfelice-Wendt, G. Gobbi, J. Hunt, J. Jowett, A. Krainer, G. Lamanna, A. Langner, A. Lechner, R. Martin, A. Mereghetti, D. Mirarchi, N. Mokhov, J. Molson, A. Narayanan, L. Nevay, M. Pasquali, A. Perillo Marcone, E. Renner, M. Schaumann, D. Schulte, M. Serluca, E. Skordis, M.J. Syphers, I. Tropin, M. Varasteh, Y. Zou

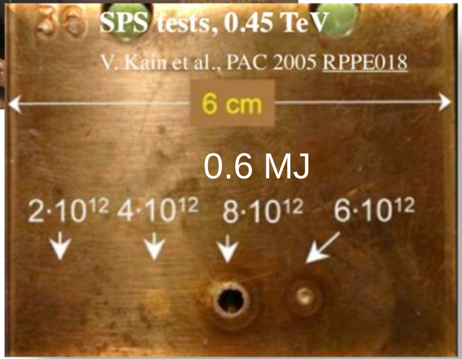
Outline

- 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



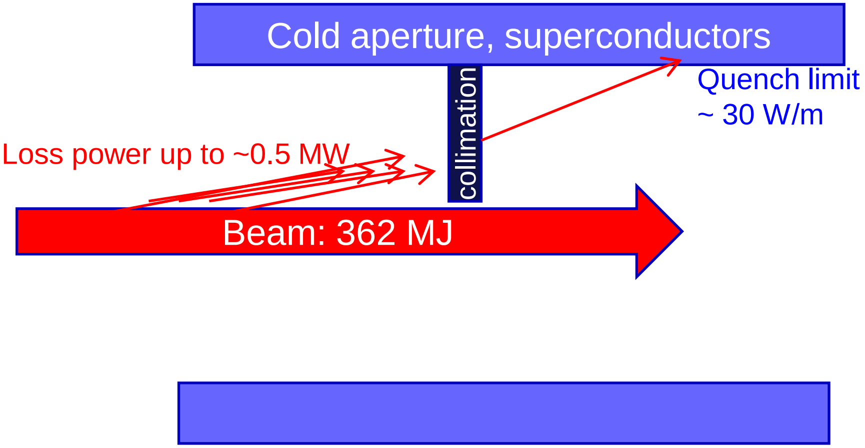
FCC-hh beams are highly destructive!!

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

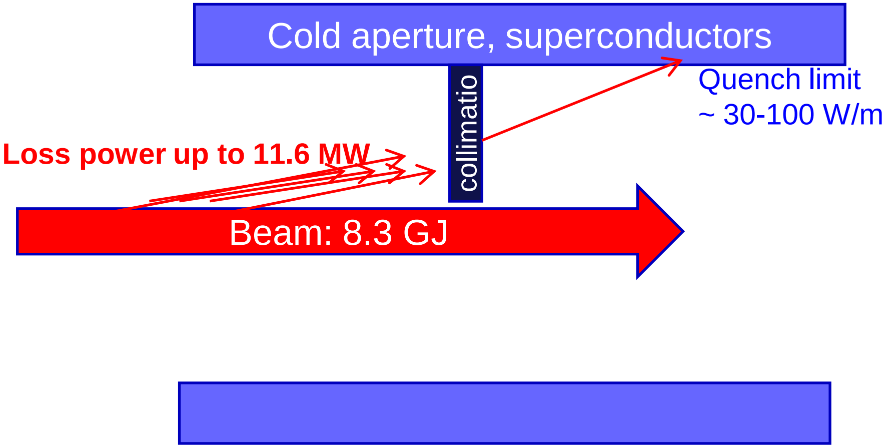
Need collimation!

LHC



Needed loss attenuation: factor ~2×10^4

FCC-hh



Needed loss attenuation: factor >10^5

Higher energy ➔ smaller collimator gaps

Collimation system design for FCC-hh

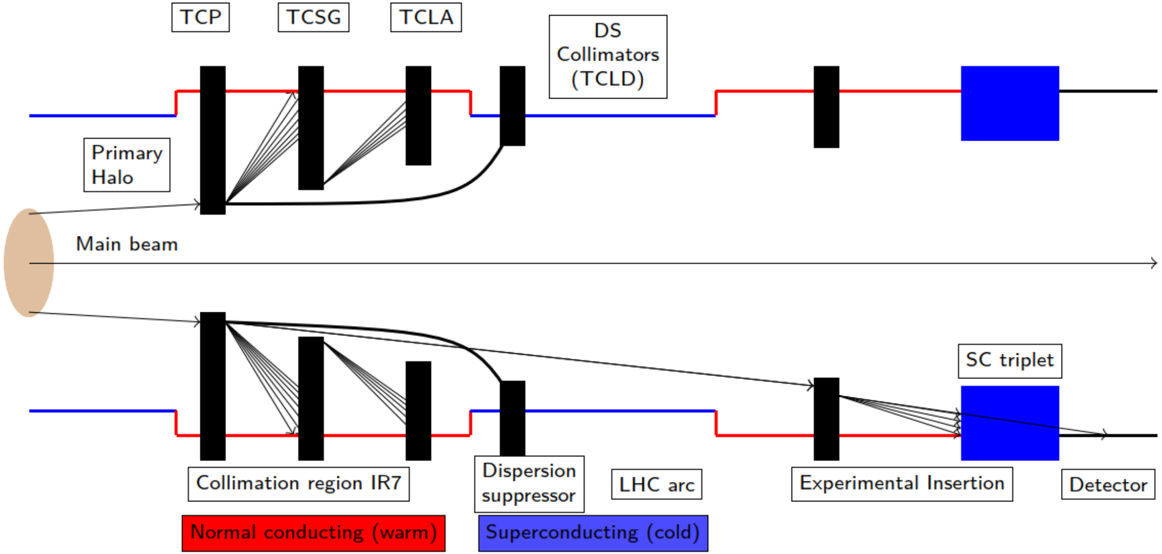
- **Need collimation system to clean unavoidable regular losses, passive machine protection, optimize background and radiation dose**
  - At the same time, keep the impedance within limits

- **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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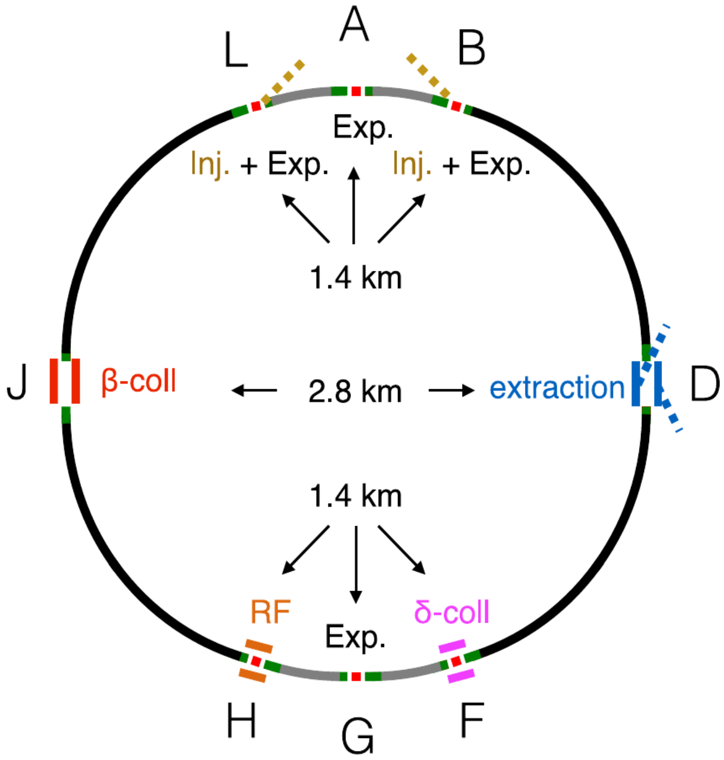
FCC-hh collimation layout: CDR version

- 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)

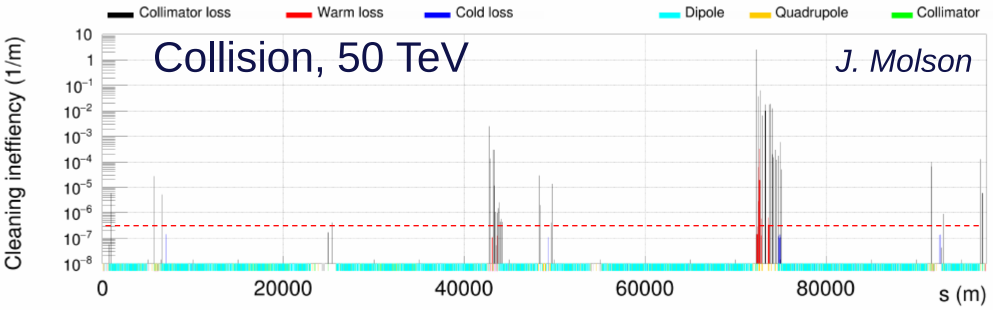
- The FCC-hh collimation system is a scaled up version of the HL-LHC/LHC system

  NIM, A 894 (2018) 96-106
  - Assuming also LHC-type collimators in CFC, MoGr, Inermet180

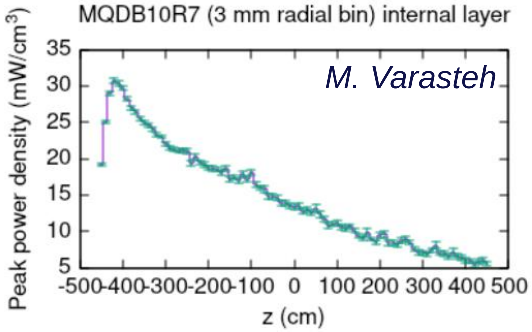


Design studies for the CDR (1)

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



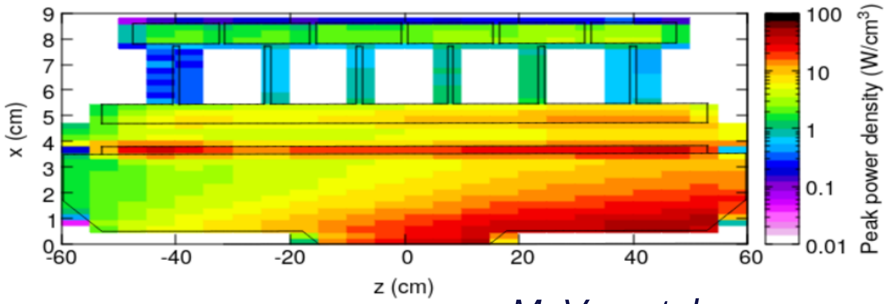
- **Tracking + energy deposition studies** on most exposed cold magnets
  - Peak power density of up to about 30 mW/cm3 – factor ~2 below estimated quench limit



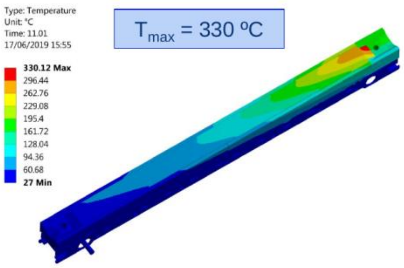
Design studies for the CDR (2)

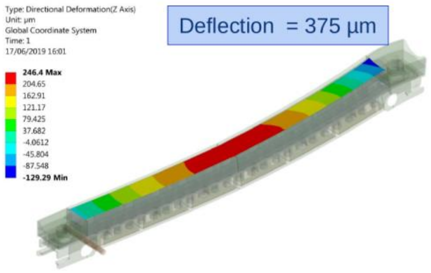
- **Tracking + Energy deposition + thermomechanical studies of most exposed collimators**

- Conclusions:
  - 92 kW on most loaded secondary collimator – should be OK, no permanent damage
  - 50 kW/cm^3 peak power density at surface of primary collimator; 660^o peak temperature – similar conditions achieved at HiRadMat without damage
  - Challenges: high temperature leading to potential outgassing, high deflection, load on cooling pipes



M. Varasteh



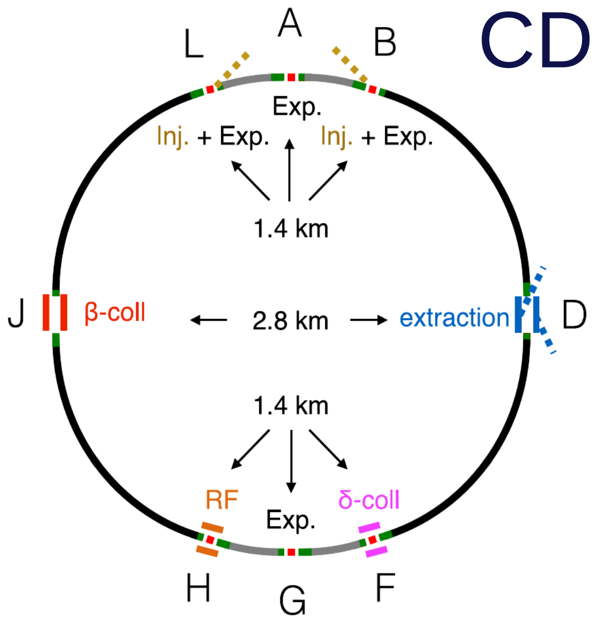


G. Gobbi, M. Pasquali

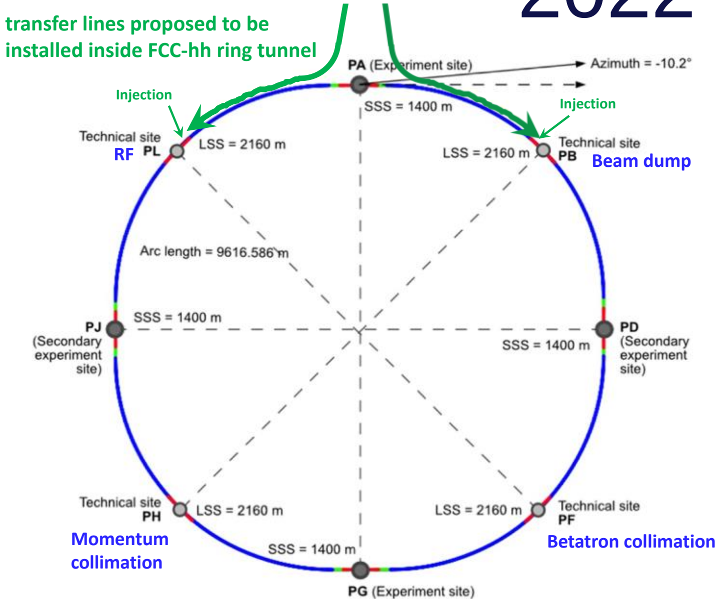
Updates since CDR

- 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

CDR



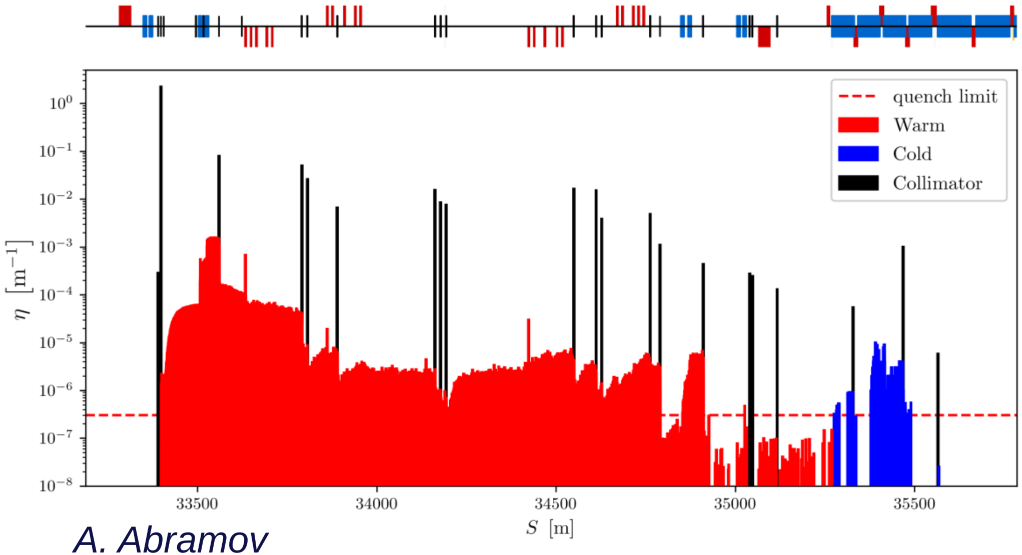
2022



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, β=55 cm*



A. Abramov

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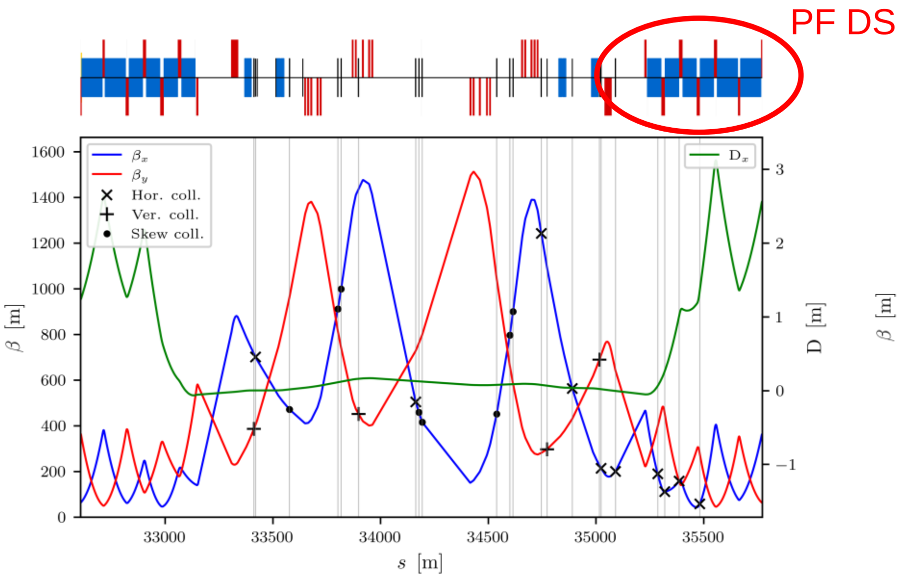
Updates since FCC week 2022

- **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 β*, doglegs, injection/extraction optics
- **New optics with larger β-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

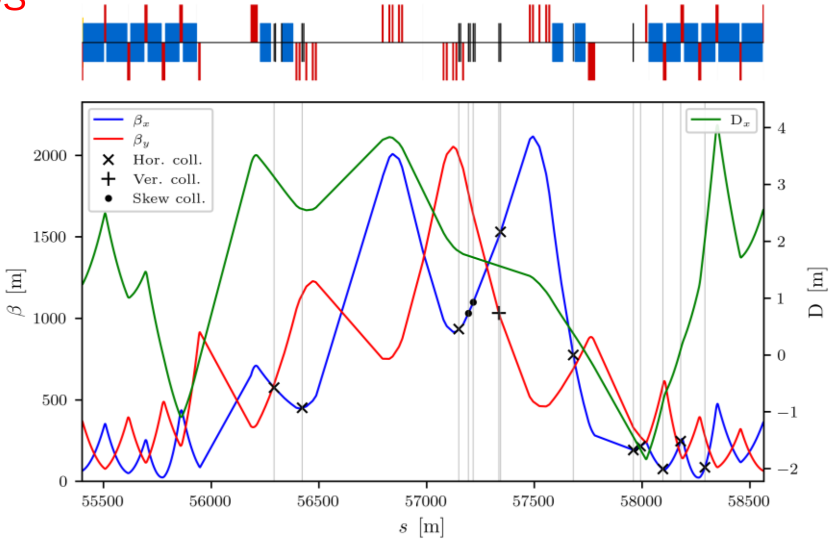
see following slides

Collimation optics: PA31 V1

- Optics adapted from LHC collimation insertions, with modifications



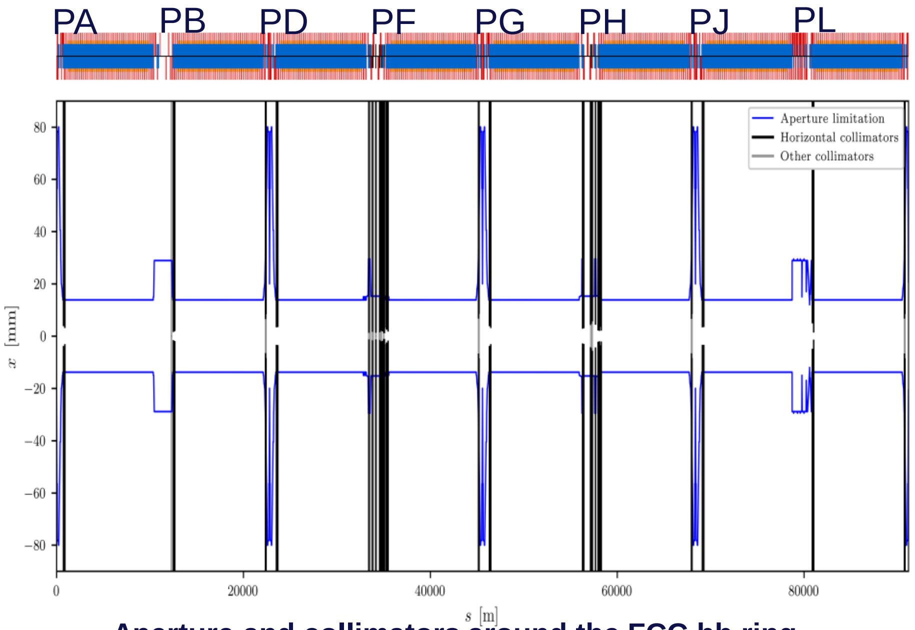
Betatron collimation insertion (PF)



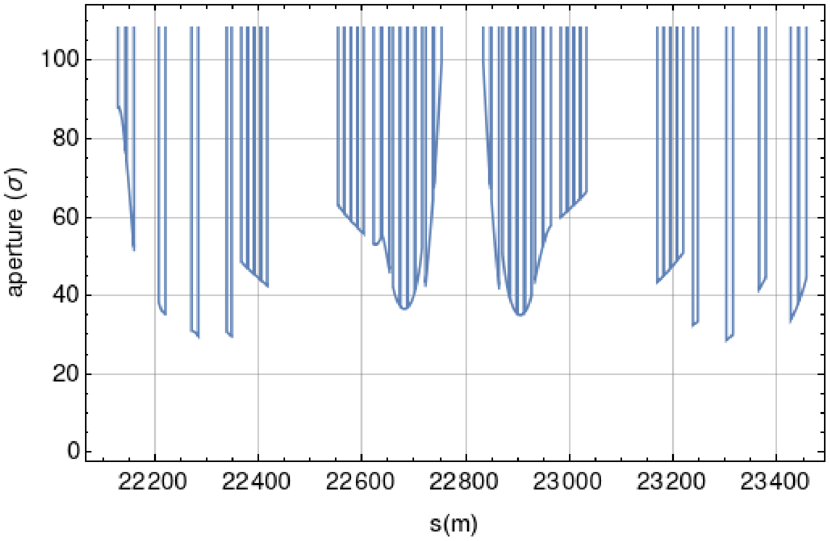
Off-momentum collimation insertion (PH)

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

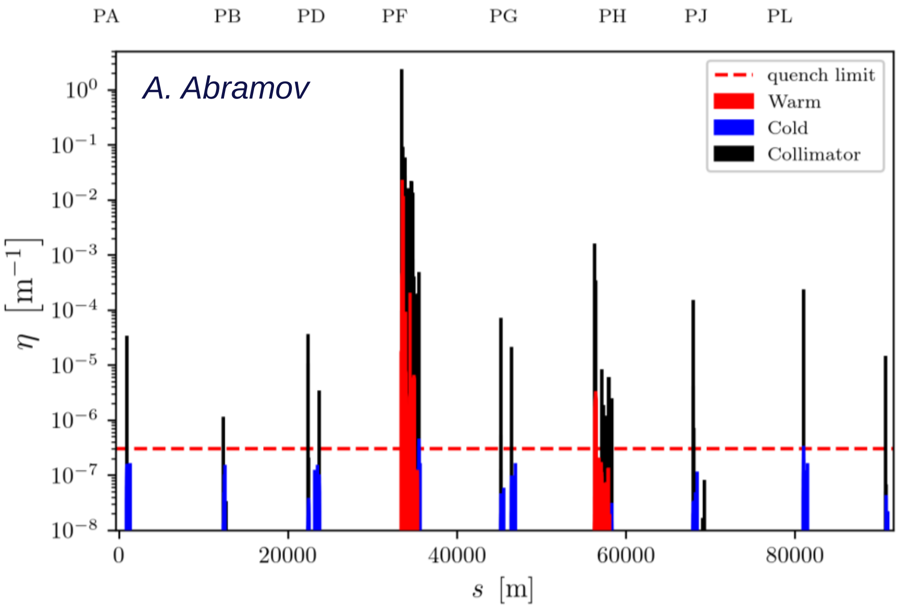
Collimator parameters and settings for the 2.2 μm normalized emittance

Type	Material	Length [m]	Gap [σ]
TCP PF	CFC	0.3	7.6
TCSG PF	MoGr, CFC	1.0	8.6
TCLA PF	Inermet180	1.0	12.0
TCLD PF	Inermet180	1.0	35.1
TCP PH	CFC	0.3	18.1
TCSG PH	MoGr	1.0	21.7
TCLA PH	Inermet180	1.0	24.1
TCLD PH	Inermet180	1.0	35.1
TCT PA,D,G,J	Inermet180	1.0	12.1
TCLD PA,D,G,J	Inermet180	1.0	35.1
TCDQ PB	CFC	10.0	9.8
TCLD PB, PL	Inermet180	1.0	35.1

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%



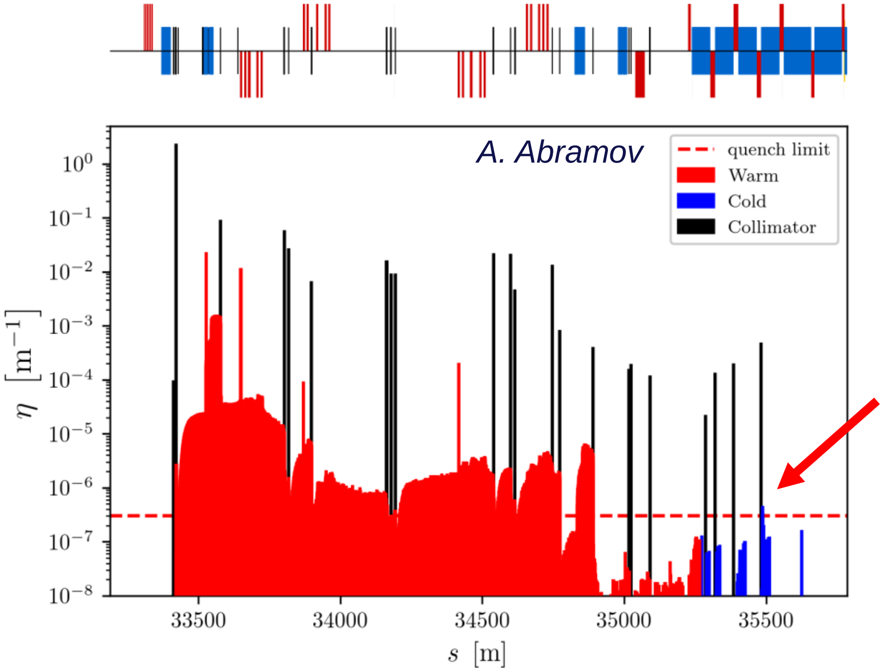
More info in IPAC'23 paper

B1H, 50 TeV, β*=30 cm
1 µm impact parameter

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 10 mW/cm³
  - Estimated quench limit could be higher – 70-100 mW/cm³
    - 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**



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B1H, 50 TeV, β*=30 cm
1 µm impact parameter
Zoom in PF

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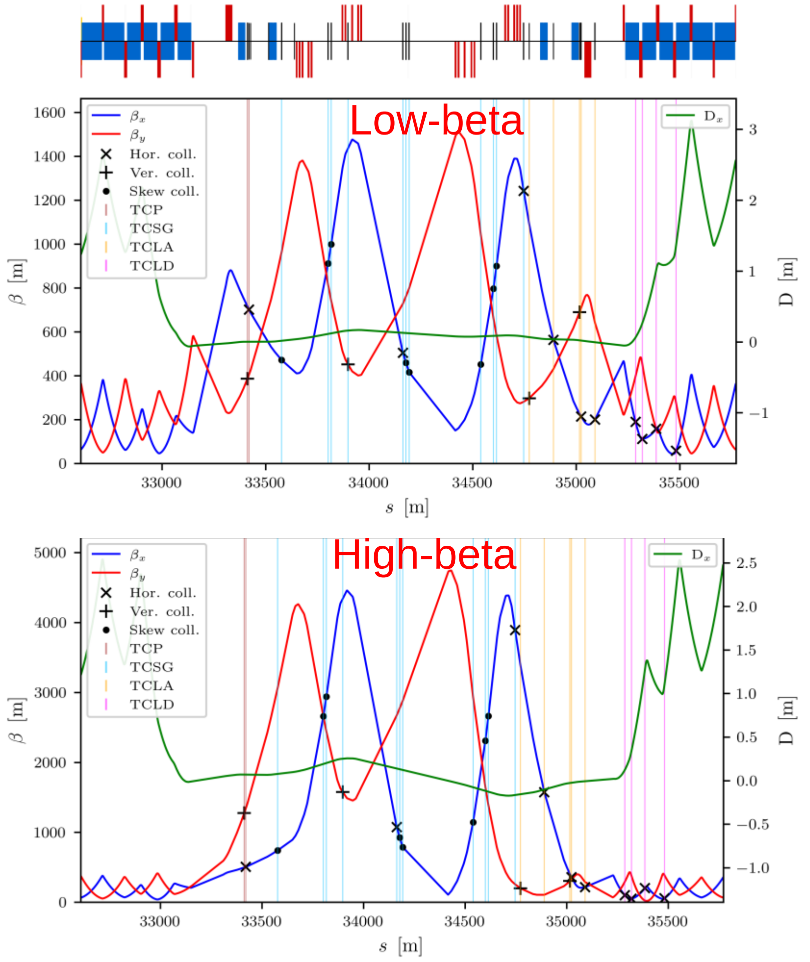
High-β optics for collimation

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

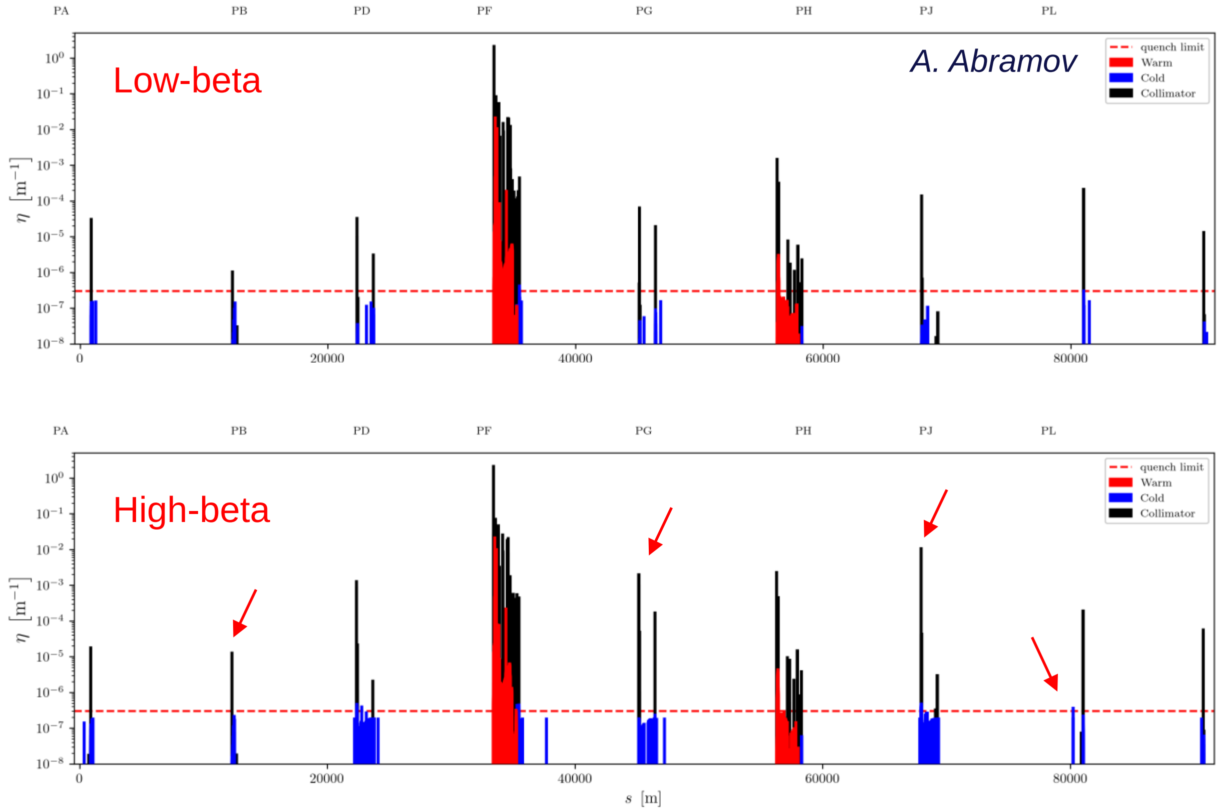
- **Such an optics could also give significant gains in cleaning efficiency**
  - Studied in simulation for LHC in IPAC’21 paper
  - Experimental tests in LHC started in 2022 – not conclusive yet, to be followed up in 2023

- **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.

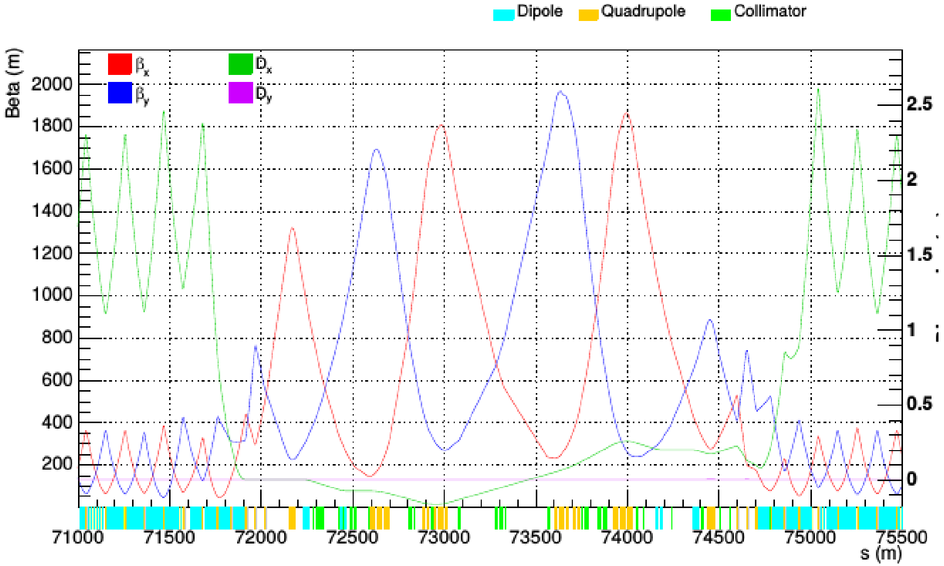
Next steps

- 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?

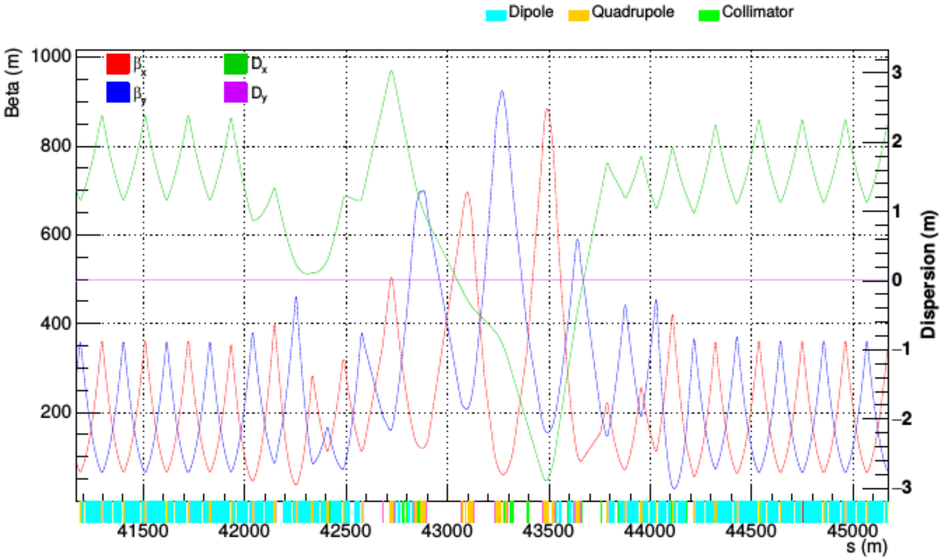
Optics of collimation insertions: CDR version

- Scaled β-functions and insertion length by factor 5 from the LHC → 2.8 km insertion length
- Increased dispersion in momentum cleaning insertion

IRJ (Betatron cleaning)



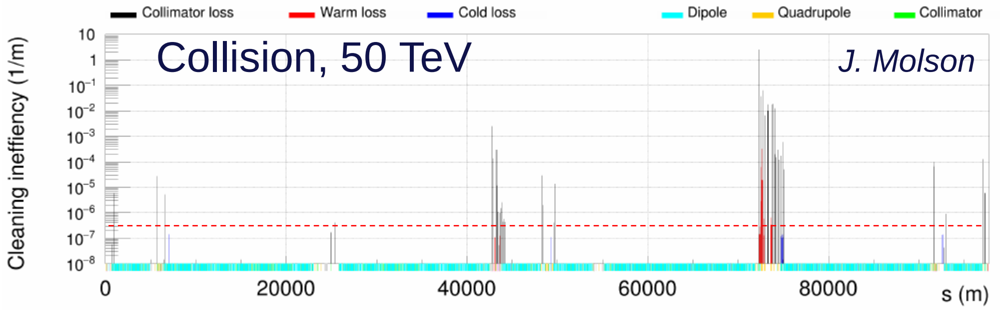
IRF (Momentum cleaning)



Collimation performance – FCC-hh protons

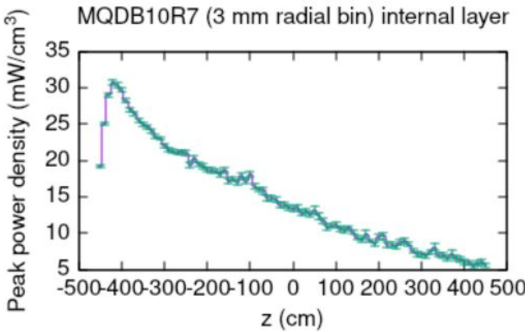
- Collimation performance checked with tracking studies using the SixTrack-FLUKA coupling and dedicated FLUKA simulations of exposed magnets

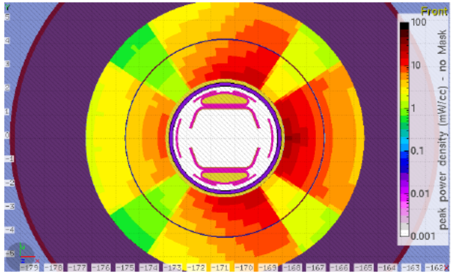
- Collimation system is extremely efficient at absorbing horizontal and vertical losses – almost no losses on cold machine aperture, thanks to dispersion suppressor collimators



Most loaded cold magnet

M. Varasteh





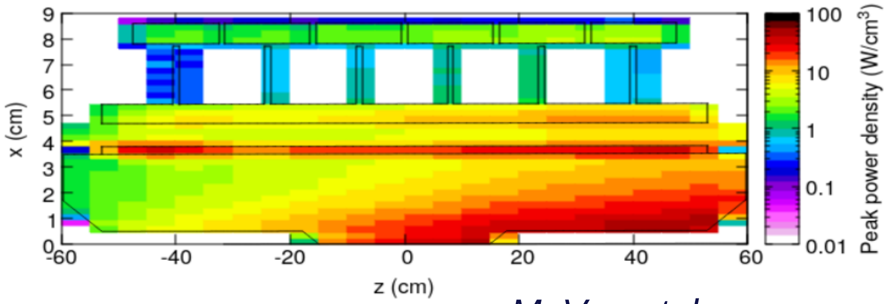
FCC collimator design

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

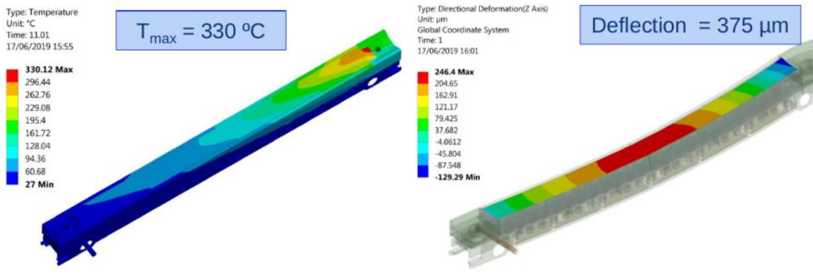
- Materials
  - Primary collimators, and most loaded secondary collimator made of carbon-fiber-composite (CFC) for maximum robustness
  - Remaining secondary collimators in MoGr with 5 μm Mo coating for a good compromise between impedance and robustness

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

Horizontal primary



M. Varasteh

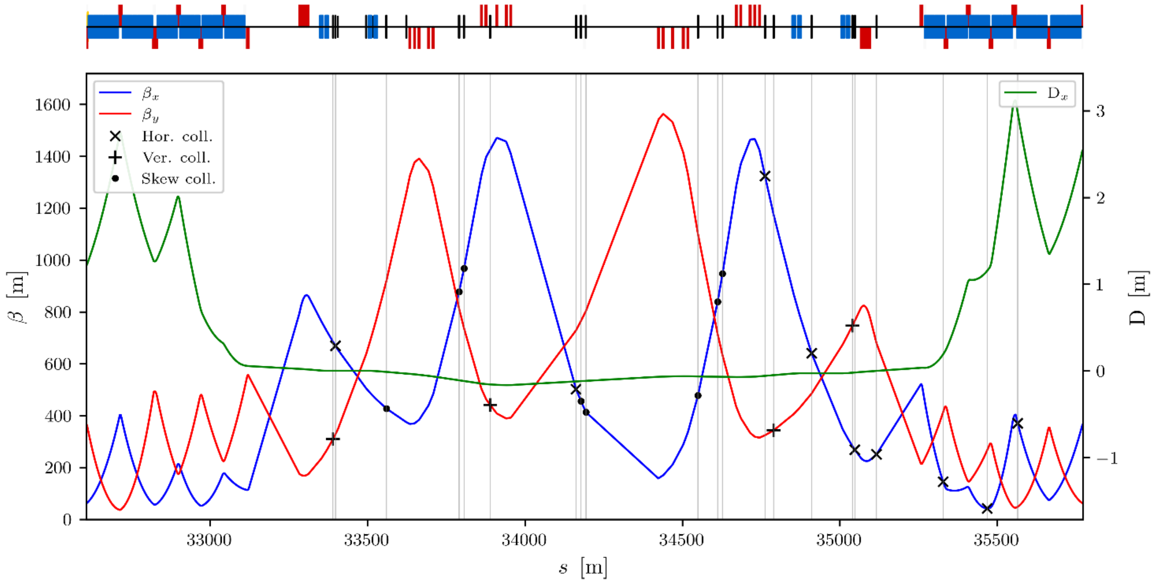


G. Gobbi, M. Pasquali

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

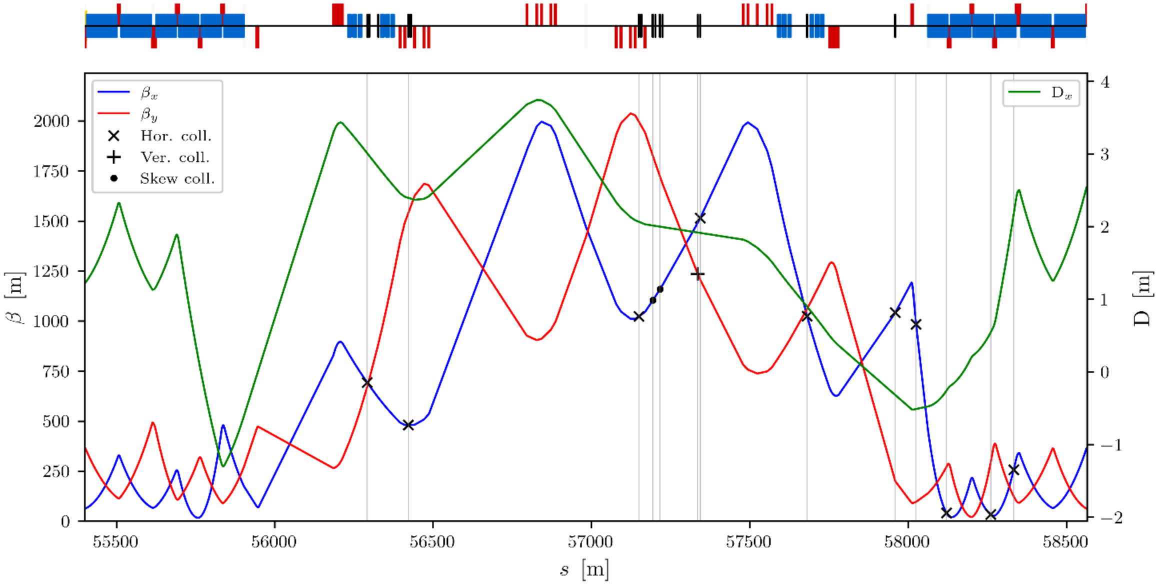
IRF



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

IRH



Optimization of doglegs

M. Giovannozzi

- 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

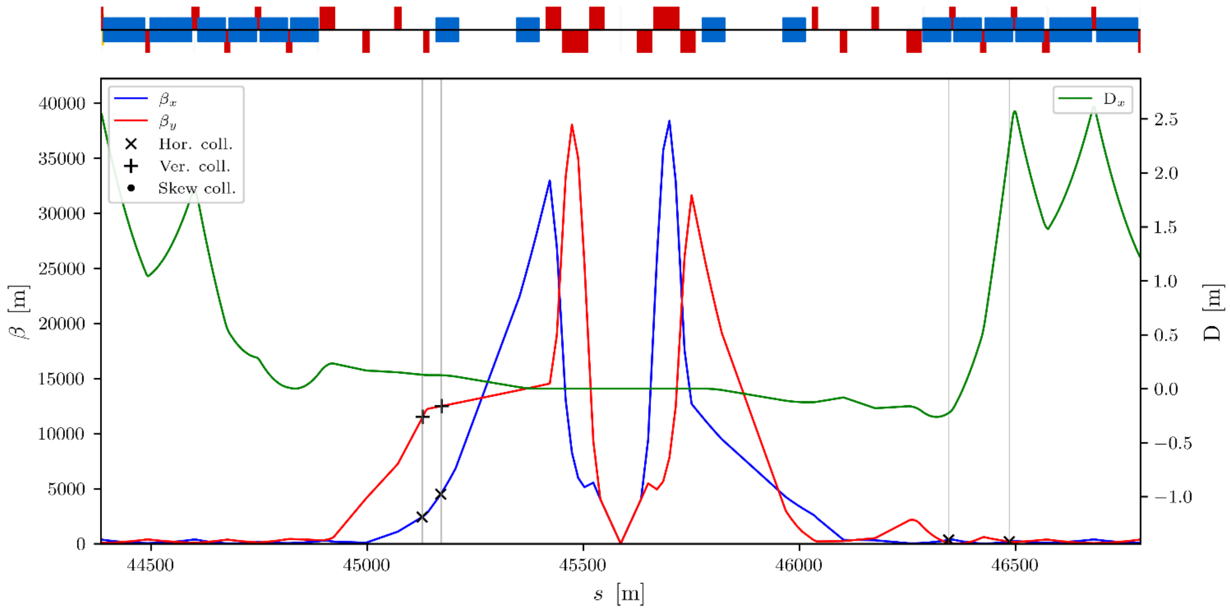
Collimation in experimental insertions

- Two pairs (horizontal-vertical) tertiary collimators on incoming beam

- Two dispersion suppressor collimators on outgoing beam

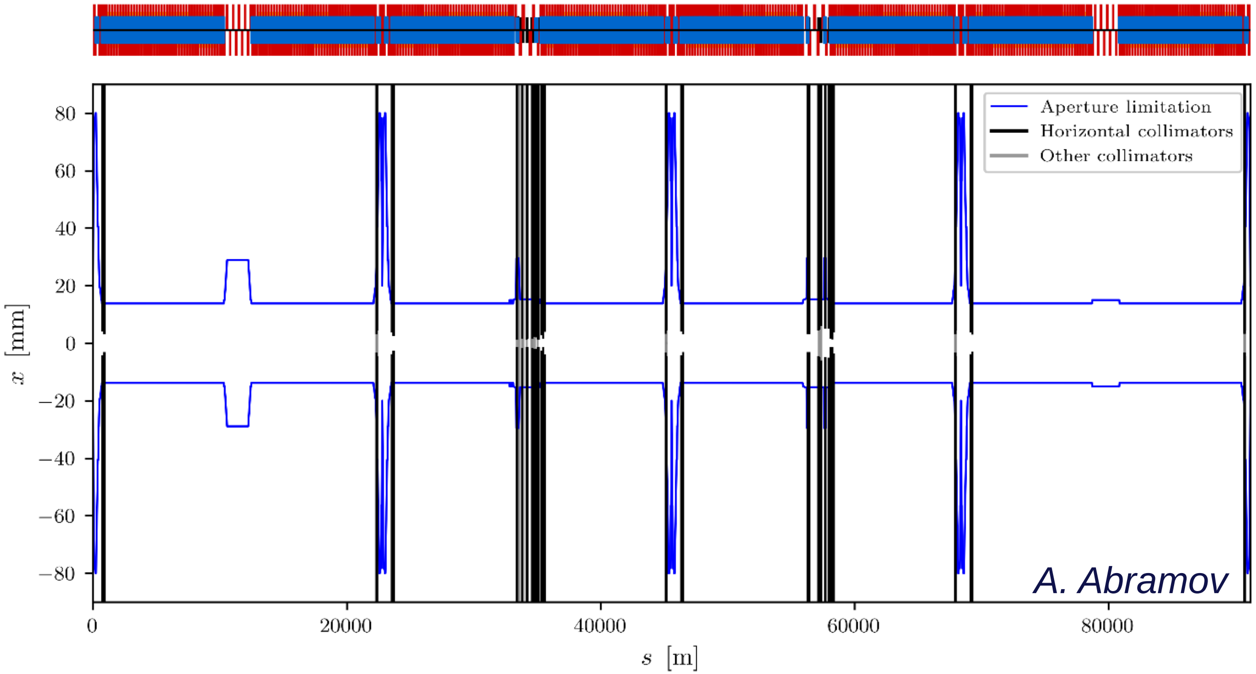
- Physics debris collimators still to be implemented

IRG



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

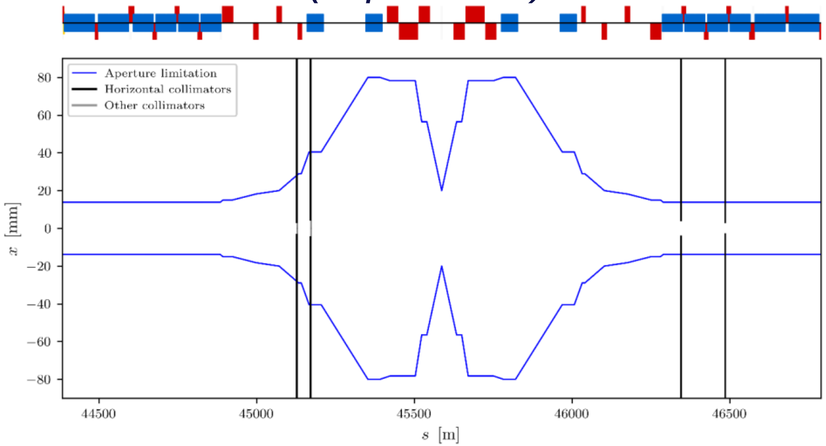


Aperture model in insertions

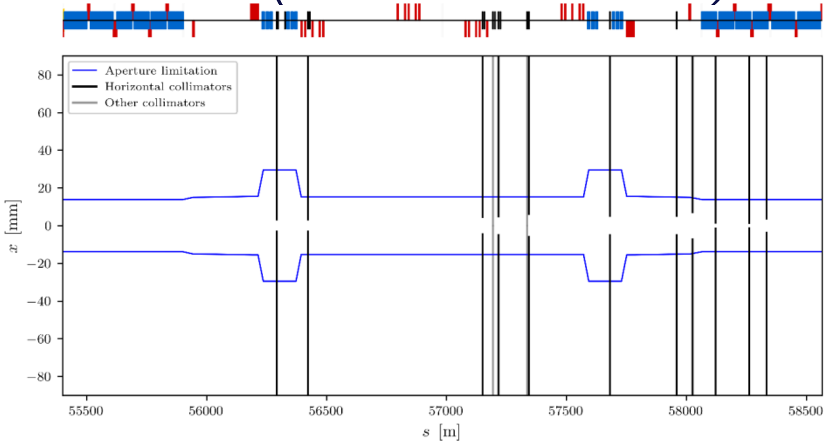
- Apertures mapped from similar elements in CDR lattice – to be refined in future iterations

Preliminary result

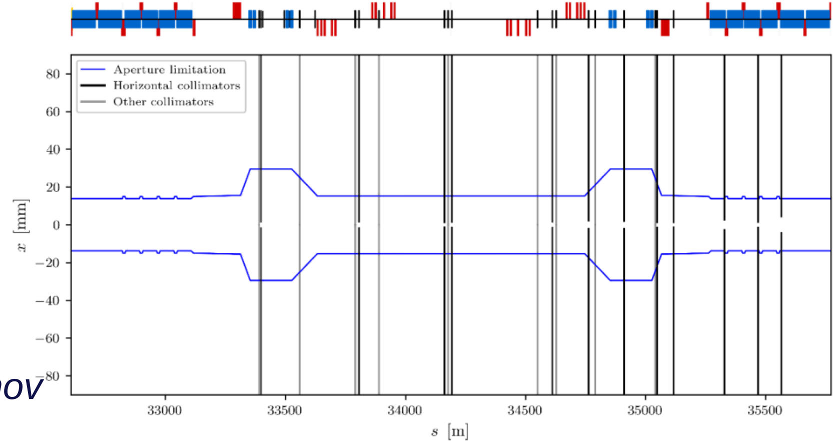
IRG (experiment)



IRH (momentum collimation)



IRF (betatron collimation)

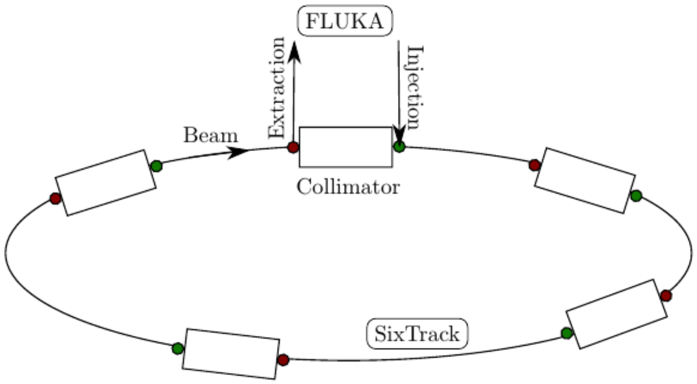


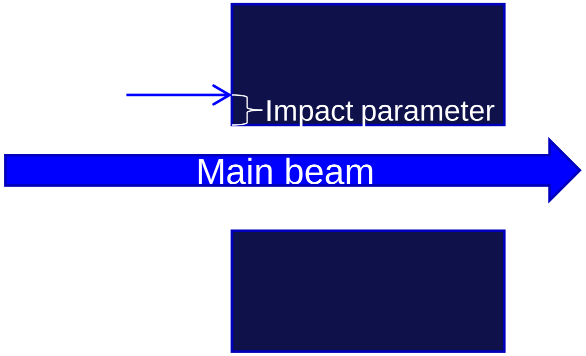
A. Abramov

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

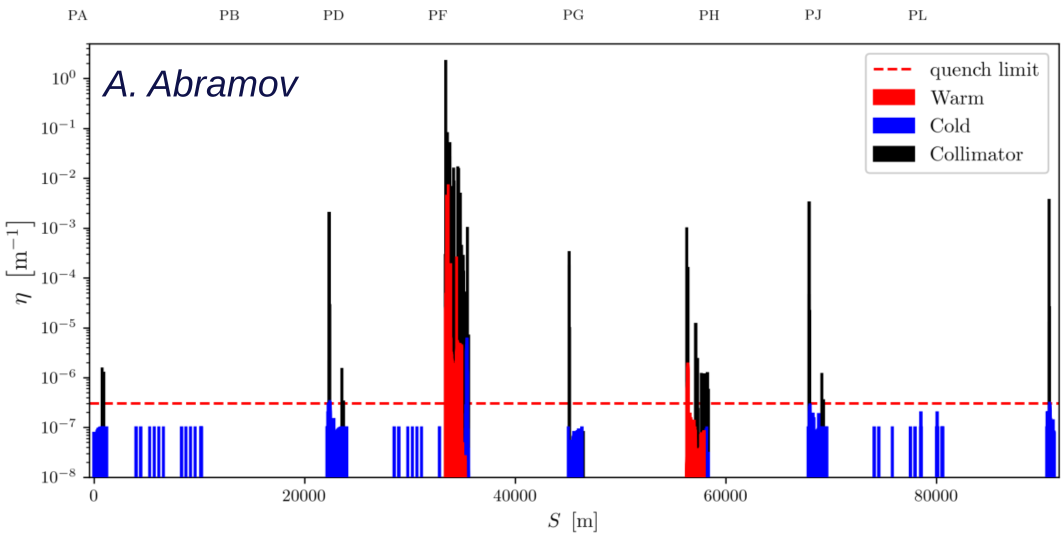




Simulated performance

- 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

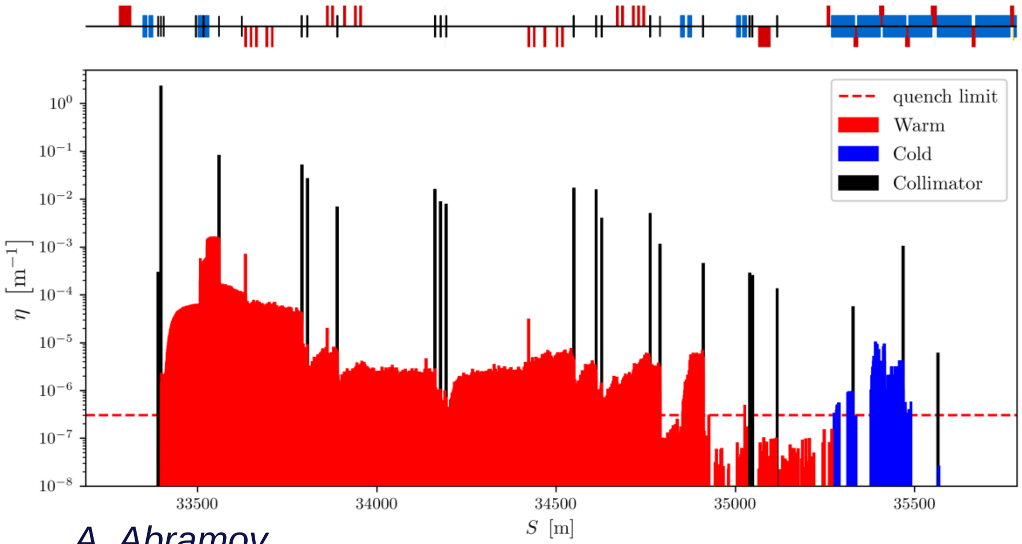


Preliminary result

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

Horizontal halo, beam 1, 50 TeV, Zoom in IRF



A. Abramov

Preliminary result