STATUS AND PLANS FOR FCC-HH COLLIMATION

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Challenges with beam losses in the FCC-hh

- Foreseen to have unprecedented 50 TeV beam energy in the FCC-hh, and much higher intensity than the LHC

- The loss of even a tiny fraction of the beam could cause a magnet quench or even damage

- Total stored energy beam
    - LHC design: 362 MJ
    - HL-LHC: 678 MJ
    - FCC: 8.3 GJ → more than factor 20 higher than LHC design!

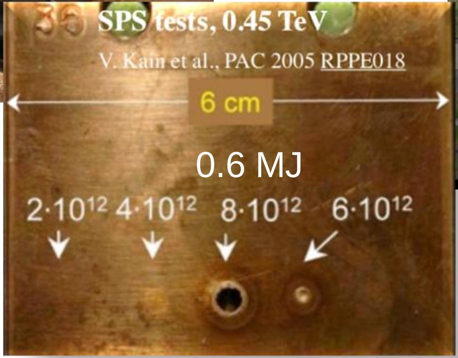
How much is 8.3 GJ?

LHC: 362 MJ - kinetic energy of

TGV train cruising at 155 km/h

FCC-hh: 8.3 GJ – kinetic energy of

Airbus A380 (empty) cruising at 880 km/h


SPS tests, 0.45 TeV

V. Kain et al., PAC 2005 RPPE018

Collimation in FCC-hh

- Crucial to safely handle beam losses in the FCC-hh

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

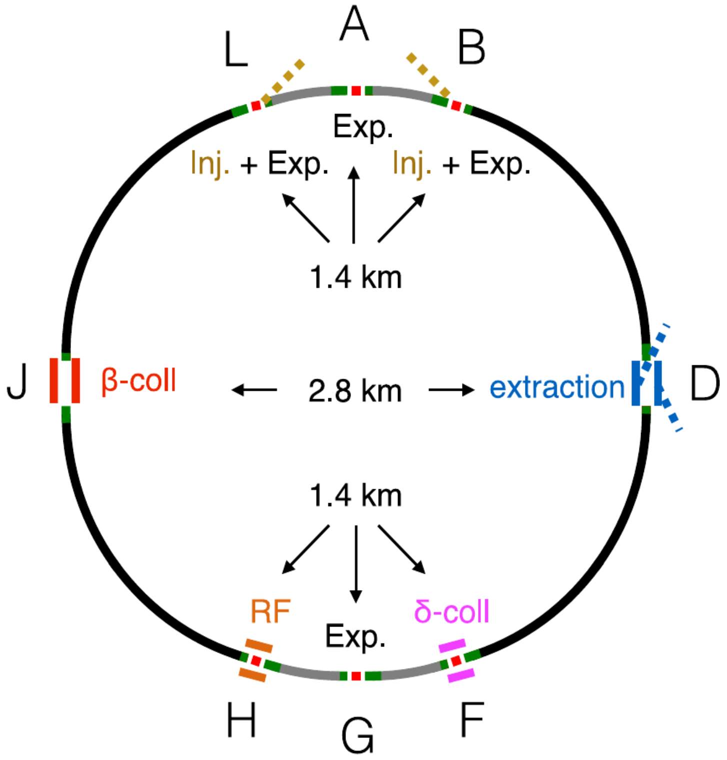
- Main design loss scenarios
    - Betatron cleaning 0.2 h beam lifetime during 10 s or “steady-state” 1 h beam lifetime
        - 0.2 h lifetime and 8.3 GJ stored energy => 11.6 MW beam loss power
    - Unavoidable off-momentum losses of unbunched beam at start of ramp: 1% loss over 10 s
    - Extraction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

- In addition: Special loss scenarios, e.g. collisional losses in heavy-ion operation

FCC-hh collimation layout

- The FCC-hh collimation system is a scaled up version of the HL-LHC/LHC system *(NIM, A 894 (2018) 96-106)*
  - Betatron collimation in IPJ
  - Momentum collimation in IPF

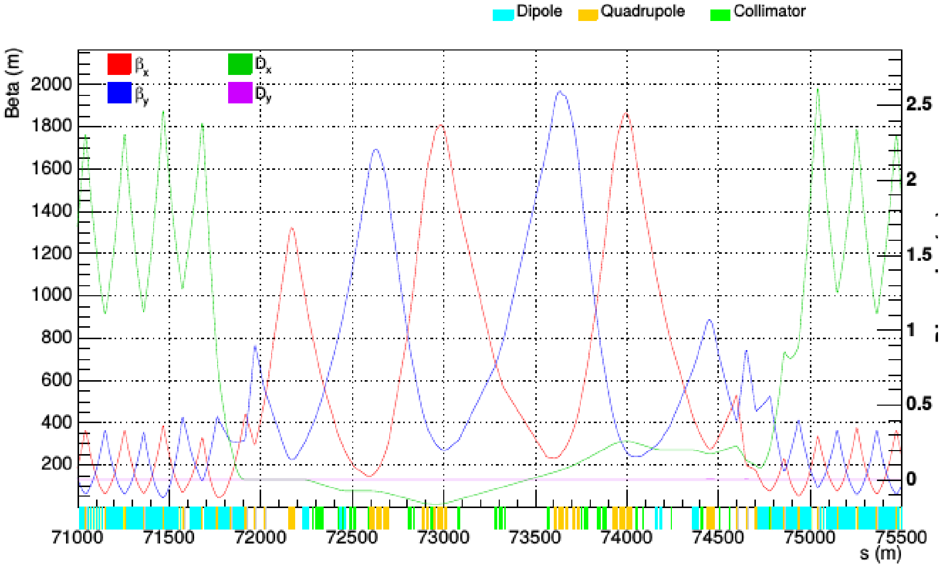
- Need much higher β-functions in FCC-hh than LHC to keep impedance under control and use mm gaps similar to the LHC



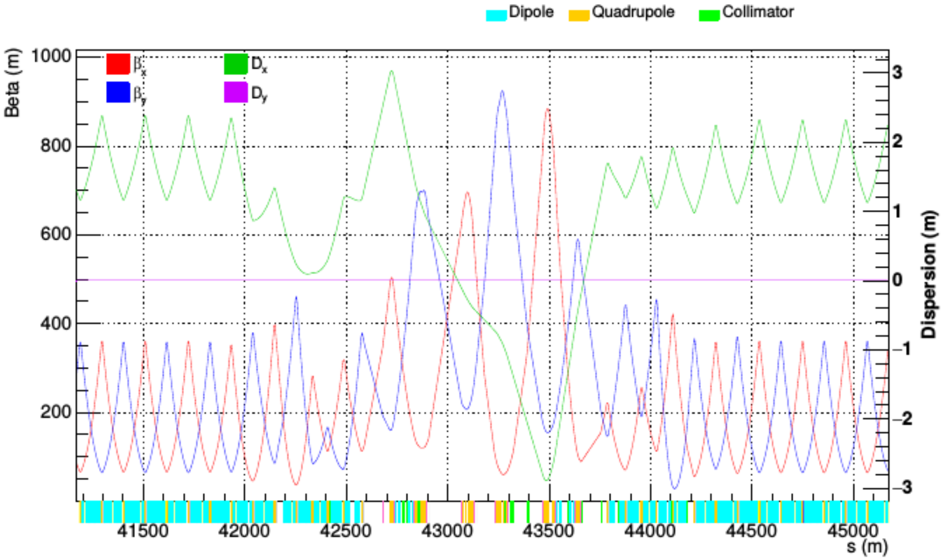
Optics of collimation insertions

- 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)

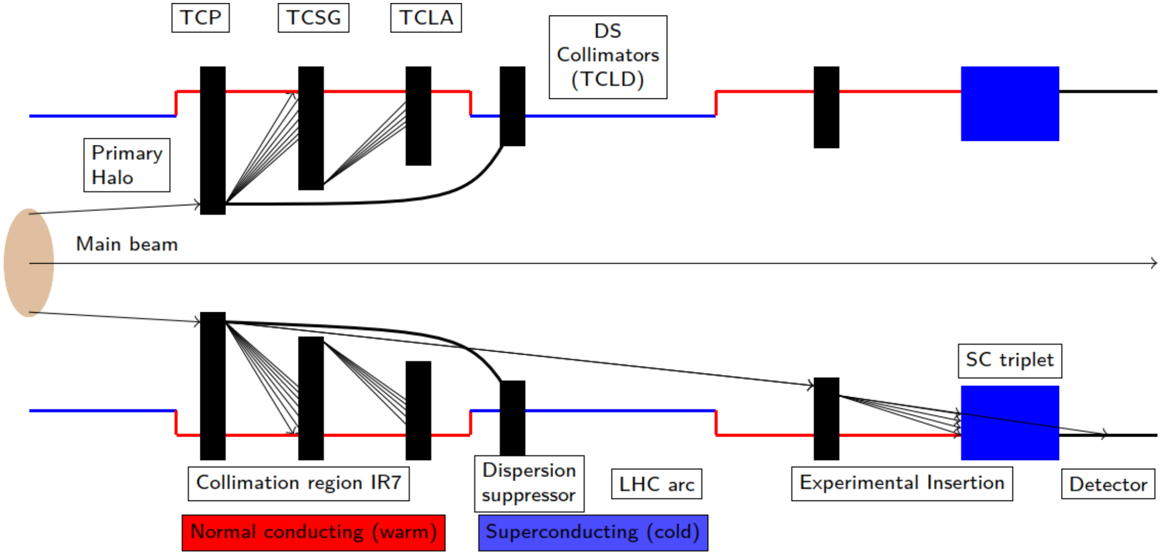


IRF (Momentum cleaning)



FCC-hh collimation hierarchy

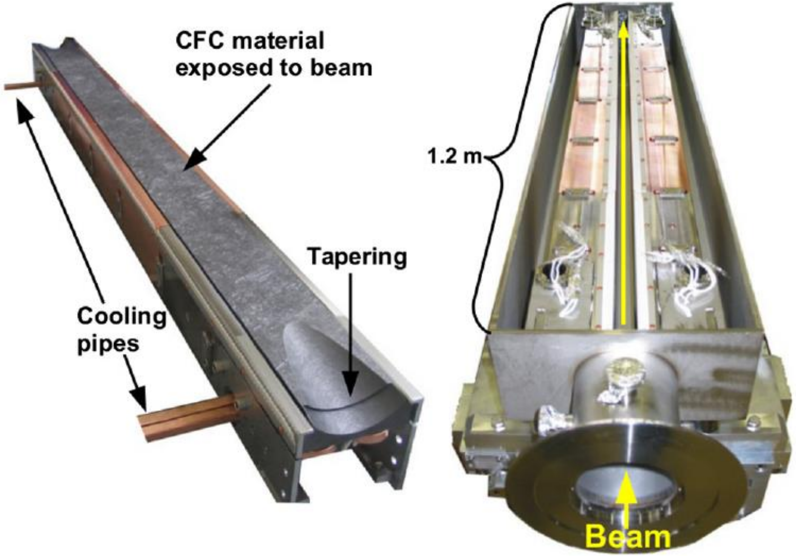
- As in the LHC, using a multi-stage system with primary and secondary collimators, shower absorbers, dispersion suppressor (DS) collimators
- Similar layout as the LHC, but some modifications: DS collimators in many insertions, extra shower absorbers in extraction insertion, removal of skew primary



FCC collimator hardware

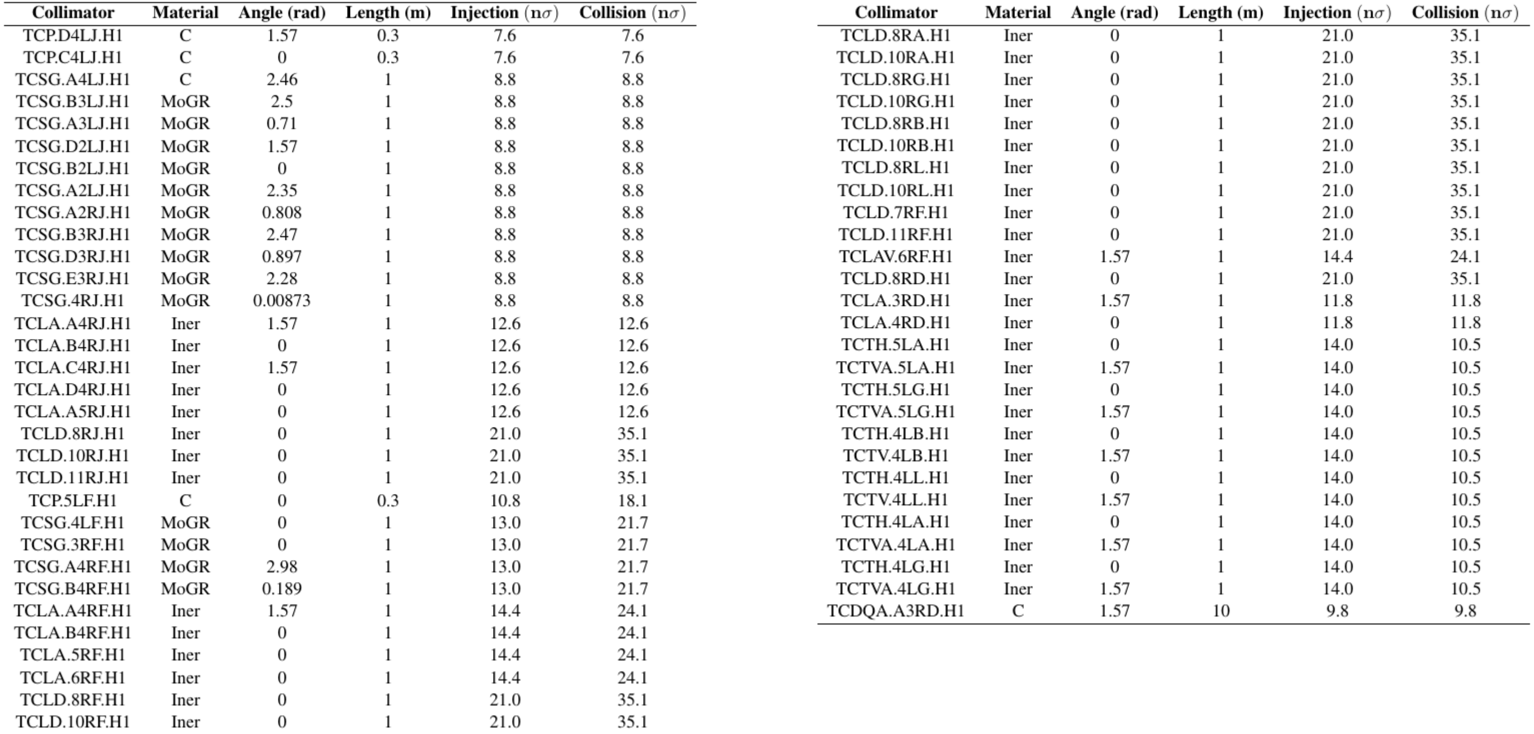
- Assuming LHC-type collimators, with some modifications, following iterative simulations of tracking, energy deposition and thermo-mechanical response
  - Shorter and thicker primary collimators (30 cm vs 60 cm length, 3.5 cm vs 2.5 cm thickness)
  - Thicker jaws of first secondary collimator (4.5 cm vs 2.5 cm)

- 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
  - High-density material Inermet180 in shower absorbers and tertiary collimators



All collimators – materials, settings, orientation

Table 9.6: The full list of FCC-hh movable collimators, including their materials, angles, active jaw lengths, and settings throughout the cycle. The settings are given for the reference value of the normalised emittance of 2.2 μm.



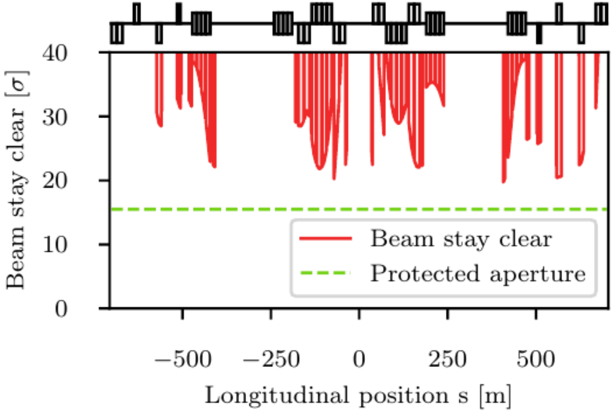
Collimator	Material	Angle (rad)	Length (m)	Injection $(n\sigma)$	Collision $(n\sigma)$
TCP.D4LJ.H1	C	1.57	0.3	7.6	7.6
TCP.C4LJ.H1	C	0	0.3	7.6	7.6
TCSG.A4LJ.H1	C	2.46	1	8.8	8.8
TCSG.B3LJ.H1	MoGR	2.5	1	8.8	8.8
TCSG.A3LJ.H1	MoGR	0.71	1	8.8	8.8
TCSG.D2LJ.H1	MoGR	1.57	1	8.8	8.8
TCSG.B2LJ.H1	MoGR	0	1	8.8	8.8
TCSG.A2LJ.H1	MoGR	2.35	1	8.8	8.8
TCSG.A2RJ.H1	MoGR	0.808	1	8.8	8.8
TCSG.B3RJ.H1	MoGR	2.47	1	8.8	8.8
TCSG.D3RJ.H1	MoGR	0.897	1	8.8	8.8
TCSG.E3RJ.H1	MoGR	2.28	1	8.8	8.8
TCSG.4RJ.H1	MoGR	0.00873	1	8.8	8.8
TCLA.A4RJ.H1	Iner	1.57	1	12.6	12.6
TCLA.B4RJ.H1	Iner	0	1	12.6	12.6
TCLA.C4RJ.H1	Iner	1.57	1	12.6	12.6
TCLA.D4RJ.H1	Iner	0	1	12.6	12.6
TCLA.A5RJ.H1	Iner	0	1	12.6	12.6
TCLD.8RJ.H1	Iner	0	1	21.0	35.1
TCLD.10RJ.H1	Iner	0	1	21.0	35.1
TCLD.11RJ.H1	Iner	0	1	21.0	35.1
TCP.5LF.H1	C	0	0.3	10.8	18.1
TCSG.4LF.H1	MoGR	0	1	13.0	21.7
TCSG.3RF.H1	MoGR	0	1	13.0	21.7
TCSG.A4RF.H1	MoGR	2.98	1	13.0	21.7
TCSG.B4RF.H1	MoGR	0.189	1	13.0	21.7
TCLA.A4RF.H1	Iner	1.57	1	14.4	24.1
TCLA.B4RF.H1	Iner	0	1	14.4	24.1
TCLA.5RF.H1	Iner	0	1	14.4	24.1
TCLA.6RF.H1	Iner	0	1	14.4	24.1
TCLD.8RF.H1	Iner	0	1	21.0	35.1
TCLD.10RF.H1	Iner	0	1	21.0	35.1
TCLD.8RA.H1	Iner	0	1	21.0	35.1
TCLD.10RA.H1	Iner	0	1	21.0	35.1
TCLD.8RG.H1	Iner	0	1	21.0	35.1
TCLD.10RG.H1	Iner	0	1	21.0	35.1
TCLD.8RB.H1	Iner	0	1	21.0	35.1
TCLD.10RB.H1	Iner	0	1	21.0	35.1
TCLD.8RL.H1	Iner	0	1	21.0	35.1
TCLD.10RL.H1	Iner	0	1	21.0	35.1
TCLD.7RF.H1	Iner	0	1	21.0	35.1
TCLD.11RF.H1	Iner	0	1	21.0	35.1
TCLAV.6RF.H1	Iner	1.57	1	14.4	24.1
TCLD.8RD.H1	Iner	0	1	21.0	35.1
TCLA.3RD.H1	Iner	1.57	1	11.8	11.8
TCLA.4RD.H1	Iner	0	1	11.8	11.8
TCTH.5LA.H1	Iner	0	1	14.0	10.5
TCTVA.5LA.H1	Iner	1.57	1	14.0	10.5
TCTH.5LG.H1	Iner	0	1	14.0	10.5
TCTVA.5LG.H1	Iner	1.57	1	14.0	10.5
TCTH.4LB.H1	Iner	0	1	14.0	10.5
TCTV.4LB.H1	Iner	1.57	1	14.0	10.5
TCTH.4LL.H1	Iner	0	1	14.0	10.5
TCTV.4LL.H1	Iner	1.57	1	14.0	10.5
TCTH.4LA.H1	Iner	0	1	14.0	10.5
TCTVA.4LA.H1	Iner	1.57	1	14.0	10.5
TCTH.4LG.H1	Iner	0	1	14.0	10.5
TCTVA.4LG.H1	Iner	1.57	1	14.0	10.5
TCDQA.A3RD.H1	C	1.57	10	9.8	9.8

Machine aperture

- Available normalized aperture, to be protected by collimators, studied with MAD-X, using HL-LHC-like tolerances
  - Future work: study correction of optics, orbit, alignment, etc, and possibly come up with a dedicated set of tolerances for the FCC-hh, as well as detailed studies of allowed aperture based on realistic beam losses

- At top energy and β*=30 cm : still some margin left - potential to squeeze to smaller β*

- At injection: most of the ring including arcs within tolerances. A few local DS bottlenecks slightly below allowed aperture



(a) IRA at collision energy

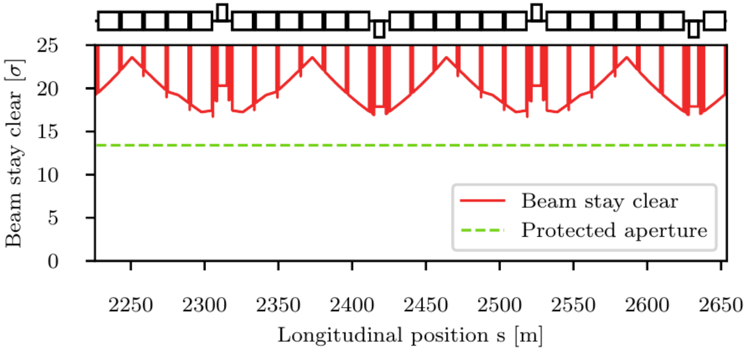
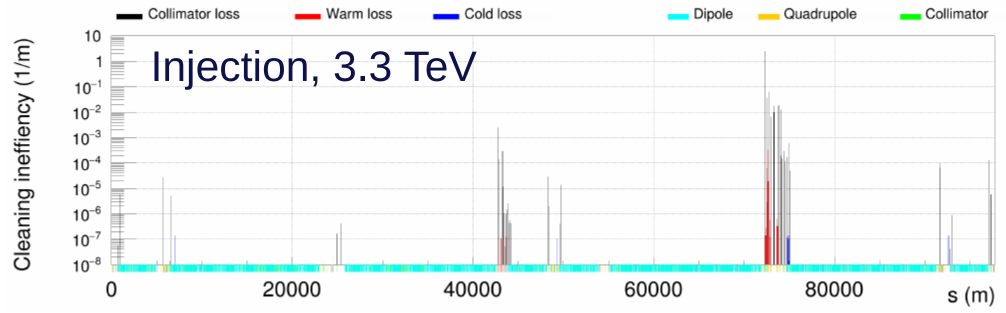
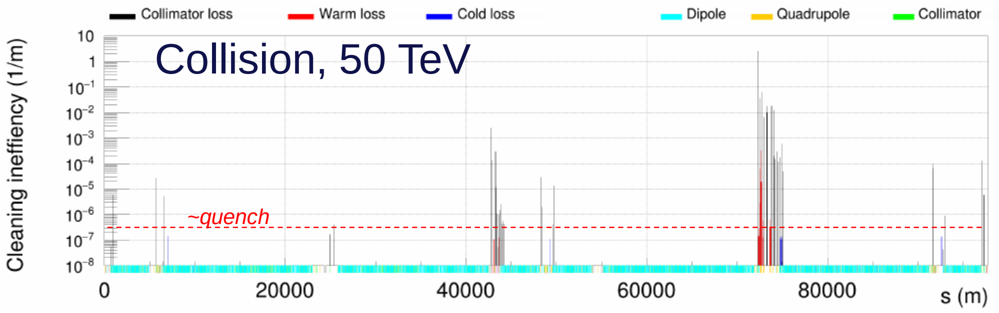


Figure 7: The calculated aperture at injection energy, as a function of distance s over two arc cells, shown together with the criterion for the minimum aperture.

Collimation performance – FCC-hh protons

- Collimation performance checked with tracking studies using the SixTrack-FLUKA coupling – see talk J. Molson
- Collimation system is extremely efficient at absorbing horizontal and vertical losses – almost no losses on cold machine aperture
- Rough quench limit at 50 TeV from energy deposition studies: 3E-7 /m for 12 minute lifetime
  - No simulated cold losses above quench limit for ideal machine
  - Imperfections may bring them close to the quench limit
  - Skew halo might need different lifetime limit. No large skew losses seen at LHC



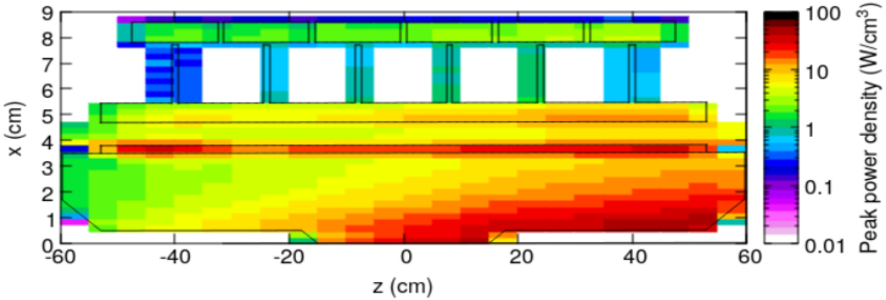


Energy deposition studies: warm section

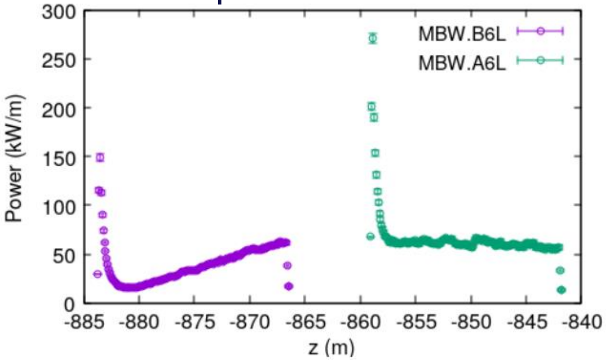
- Simulated power load in IRJ with FLUKA, for 12 minute beam lifetime at 50 TeV, with inputs from the SixTrack tracking studies

- Conclusions for warm section (see talk M. Varasteh):
  - Initially very worrying losses, triggered iterations
  - With modified collimator designs, all CFC/MoGr collimators below 100 kW – deemed acceptable
  - Passive absorbers and warm magnets receive impressive power loads (hundreds of kW) – need special attention to the design of the cooling system, but probably not a showstopper

Horizontal primary



Warm dipoles

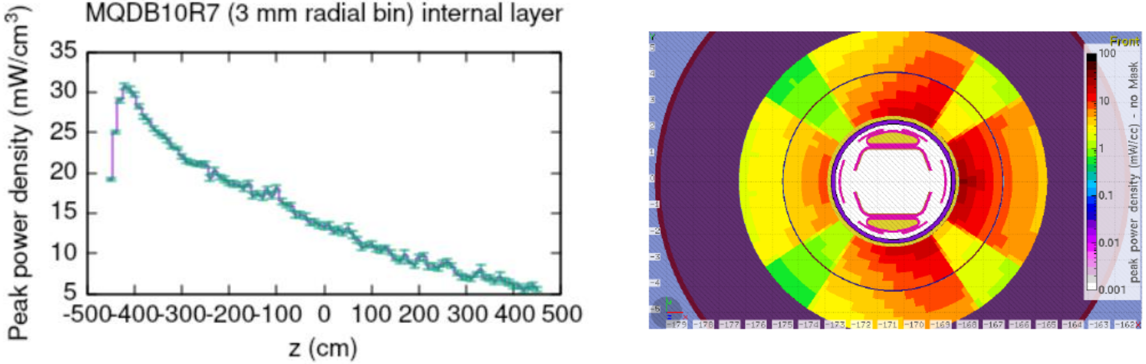


Energy deposition studies: cold section

- Simulated power load in IRJ for 12 minute beam lifetime at 50 TeV using FLUKA

- Conclusions for cold section (see talk M. Varasteh):
  - DS collimators are strictly needed – reduce power load by an order of magnitude
  - All magnets below estimated quench limit of 70 mW/cm3, but need additional mask on most exposed quadrupole
  - Most loaded DS collimator intercepts around 4 kW

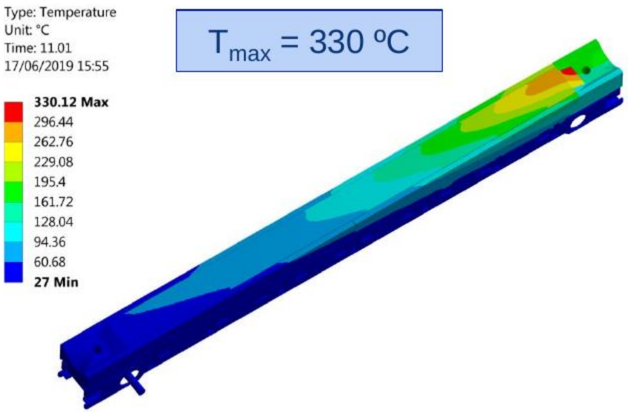
Most loaded cold magnet

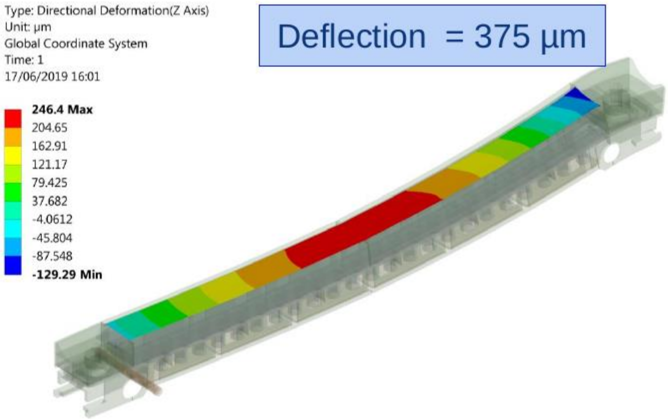


Thermo-mechanical studies

- Based on FLUKA inputs, studied thermo-mechanical response of the most loaded collimators (vertical primary with highest peak power density 50kW/cm^3, first secondary with highest total power load 92 kW) using Ansys (see talk G. Gobbi, M. Pasquali)

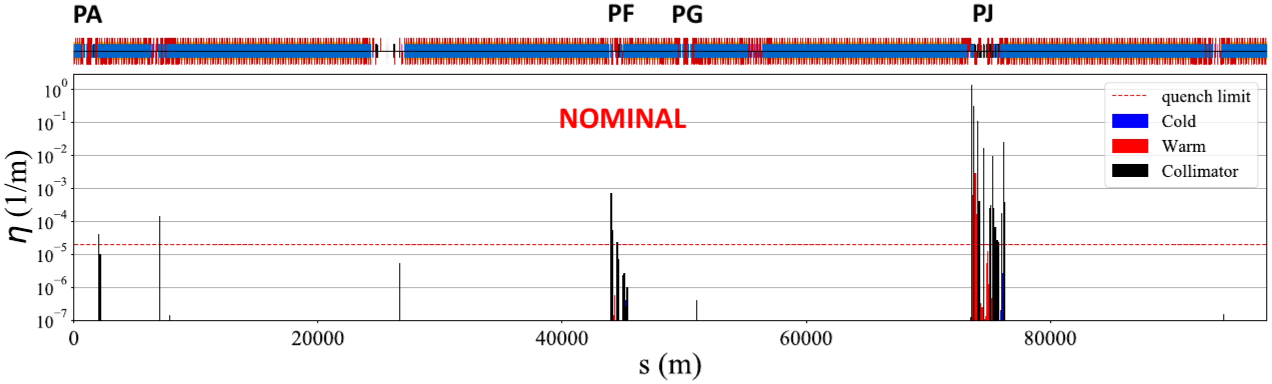
- Conclusions:
  - Collimators survive mainly without permanent damage in spite of extreme loss conditions, but significant deflection and temperature increase
    - Only exception: damage on cooling pipes - could probably be solved by material change
    - Outgassing could become an issue - to be investigated. Add local pumping?

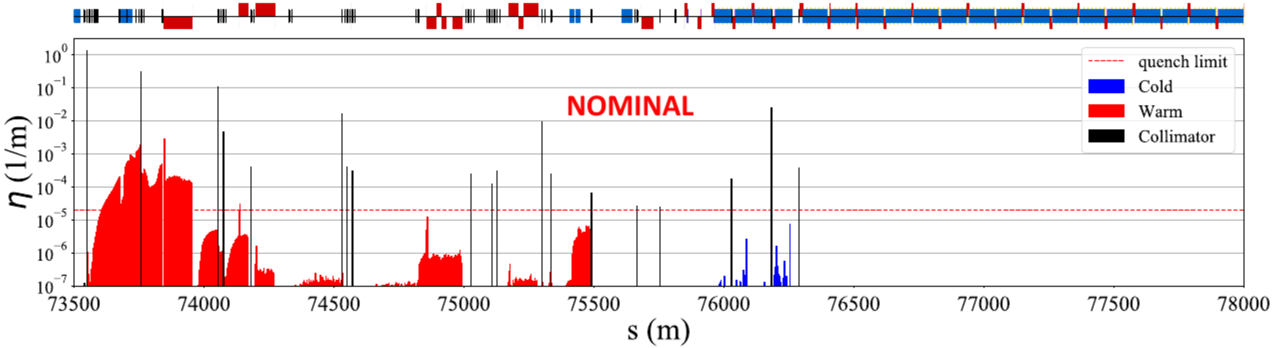

T_{max} = 330 ºC


Deflection = 375 µm

Pb ion collimation

- FCC-hh also foreseen to operate with heavy ions, tentatively assuming Pb
- Studied collimation efficiency using the SixTrack FLUKA coupling (see PhD thesis)
- With DS collimators (essential!) cold losses are kept below the assumed quench limit
- Energy deposition studies needed for full assessment

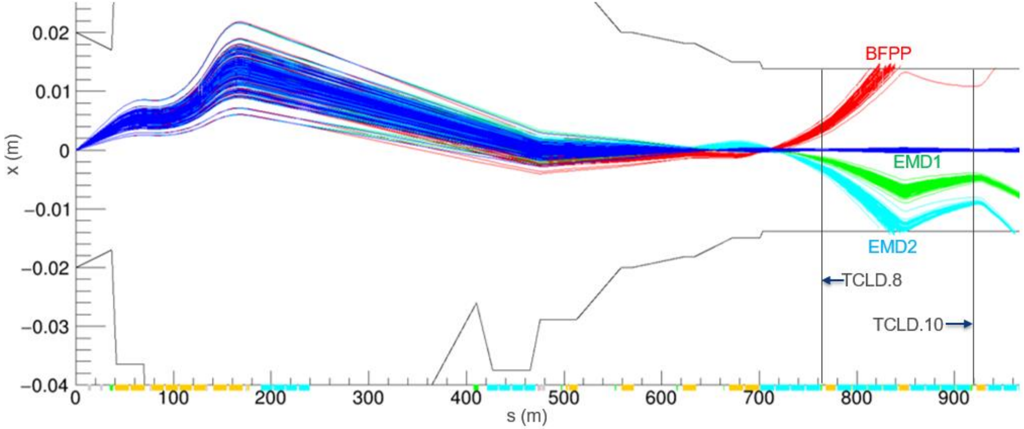




Pb ion secondary beams (1)

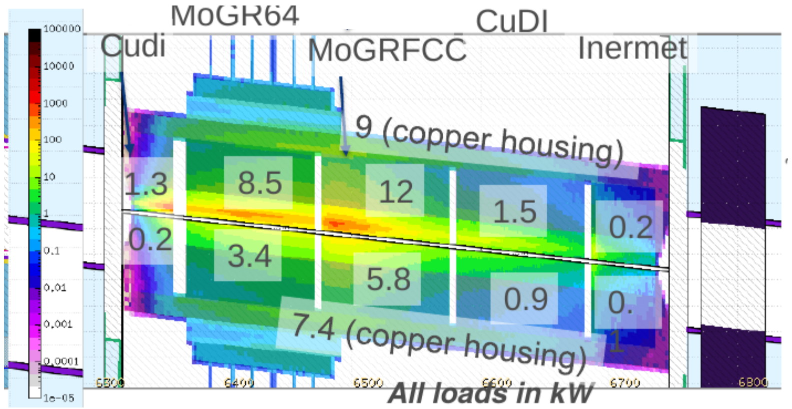
- In Pb ion operation, secondary beams from the collisions at the IPs may quench magnets
  - Ions with changed rigidity (acquiring electrons – BFPP – loss of one or several nucleons) wrongly bent by magnetic fields
  - HL-LHC: power load of up to ~170 W for BFPP
  - FCC-hh: power load of up to ~56 kW for BFPP (more than 100 kW for the most common beams)

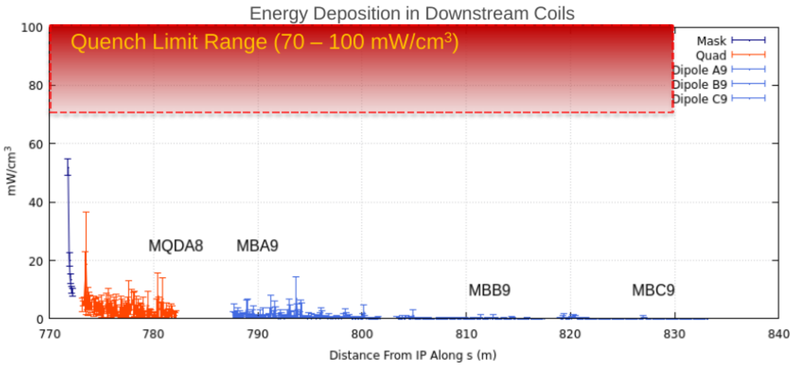
- Losses tracked in SixTrack (see talk J. Molson) – can be intercepted by DS collimators



Pb ion secondary beams (2)

- Energy deposition studies carried out to quantify impact of showers from DS collimators (see talk and IPAC21 paper by J. Hunt)
  - Safely disposing of >100 kW localized losses in steady state operation poses a great challenge!
- Initial studies showed very high loads on collimator, and power loads far above the quench limit on downstream magnets
- Iterating on various, designs, greatly improved solution found: intercept all secondary beams with one large absorber in cell 8, composed of blocks of different materials

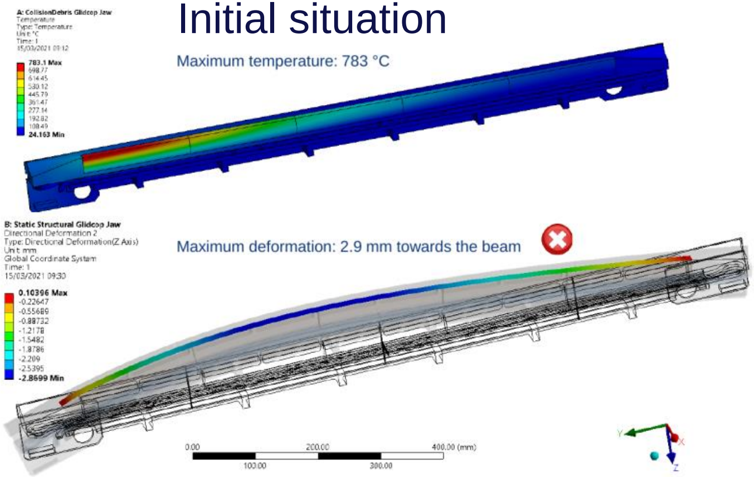




Pb ion secondary beams (3)

- Thermo-mechanical analysis using Ansys of the DS impacted collimator (see talk J. Guardia Valenzuela)
- Initially found unsustainable deformations and temperature increase
- Mitigations:
  - Changing orientation of the MoGr part of the absorber (denser MoGr than for secondary collimators)
  - Changing the housing material from Glidcop to Molybdenum
  - “Segmenting” the collimator in several shorter modules : ½ or ¼ of full length
- => Greatly improved situation, but more work needed to quantify acceptable deformation and the mechanical collimator design. Modify optics to increase β-functions? Outgassing?

Initial situation


Maximum temperature: 783 °C

Maximum deformation: 2.9 mm towards the beam

Final situation, after mitigations

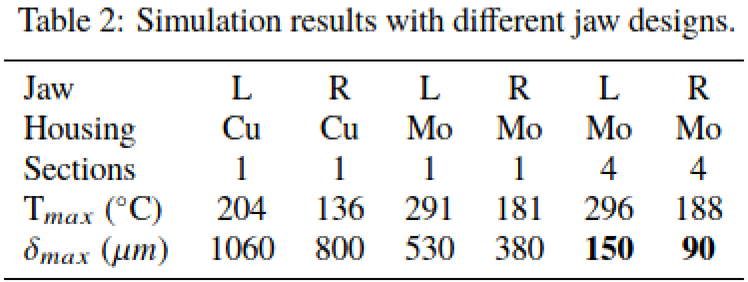


Table 2: Simulation results with different jaw designs.

Jaw	L	R	L	R	L	R
Housing	Cu	Cu	Mo	Mo	Mo	Mo
Sections	1	1	1	1	4	4
T_{max} (°C)	204	136	291	181	296	188
δ_{max} (μm)	1060	800	530	380	**150**	**90**

Summary (1)

- An excellent collimation performance is crucial to keep the FCC-hh safe, and to operate smoothly without quenches
  - 8.3 GJ stored beam energy, 11.6 MW beam loss power

- A collimation system has been designed, scaled up from the LHC system

- Performance has been studied through a simulation chain of tracking, energy deposition, thermo-mechanical analysis
  - During lifetime drops to 12 minutes, the present design can protect the machine from quenches without being damaged, for both protons and Pb ions
  - A few minor open points – see next slide

Summary (2) : future work and open points

Future work on present system design:

- Refine tolerances for aperture calculations
- Study outgassing and cooling of the most impacted elements in collimation insertion
- Study different materials in cooling pipes to avoid damage
- Some studies of failure scenarios done (not shown here) – some more might be needed
- Impedance is on the limit – we might want to improve it
- Further error studies, including also alignment and magnetic field errors
- Any tests for HiRadMat?
- Pb ion operation
  - Energy deposition studies of collimation insertion and dispersion suppressor, possibly including imperfections
  - Further studies of secondary beams from collision points

Alternative system designs

- Present FCC-hh IRJ has a 2.8km length – requests to shorten insertion to 2.1 km or less
  - Need to re-think the layout – could possibly re-use work for the LHC on a new betatron cleaning optics with higher β-functions, which would require a lower scaling factor of the insertion length
  - Would require redoing most of the studies presented today

Thank you for your attention.