COLLIMATION FOR FCC-hh AND FCC-ee

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Collimation in FCC-hh

- Crucial to safely handle beam losses in the FCC-hh:
  - Proton beam energy of 50 TeV
  - Stored beam energy is 8.3 GJ, a factor ~20 larger than the LHC design

- 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

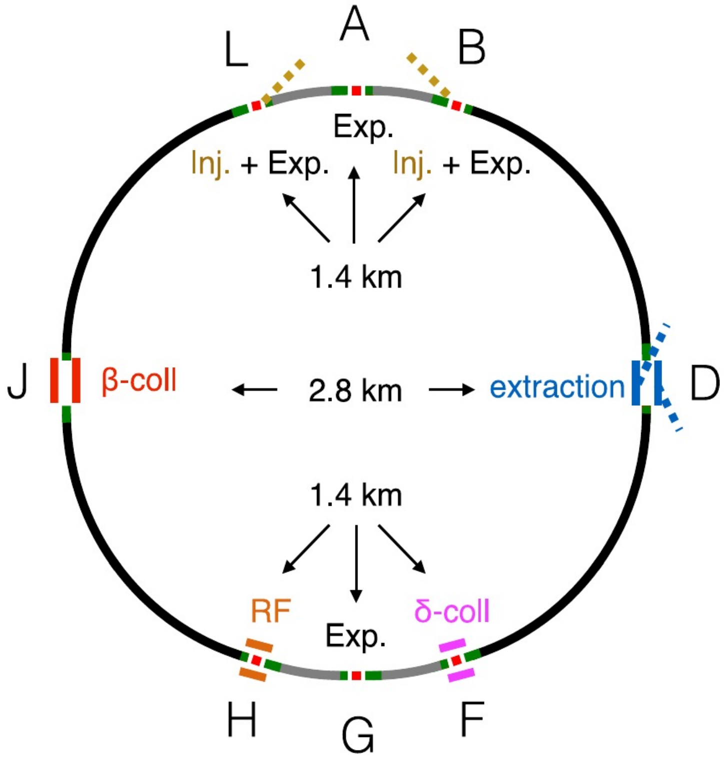
- Main design loss scenarios
  - Betatron cleaning 0.2 h beam lifetime during 10 s or “steady-state” 1 h beam lifetime
    - 0.2 h lifetime and 8.3 GJ stored energy => 11.6 MW beam loss power
  - Unavoidable off-momentum losses of unbunched beam at start of ramp: 1% loss over 10 s
  - Extraction and injection kicker pre-fire, other possible failures
  - 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,
  J. Phys.: Conf. Ser. 1350 012009 (2019))
  - Betatron collimation in IPJ
  - Momentum collimation in IPF
  - Present design based on CDR layout, other layouts not studied

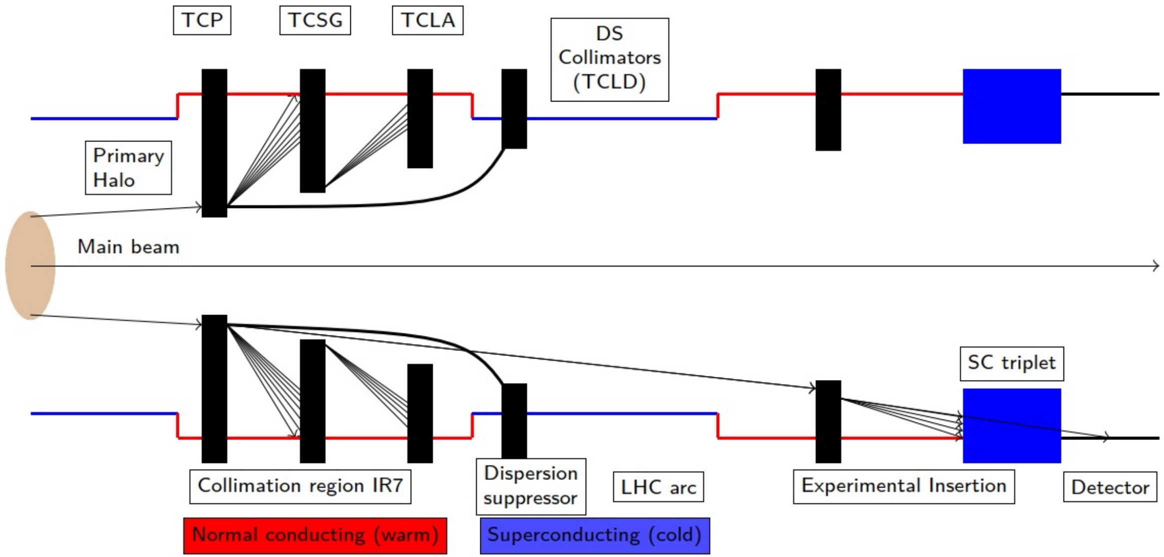
- Need much higher β-functions in FCC-hh than LHC to keep impedance under control and use mm gaps similar to the LHC

- Optics design starting from a scaled version of the LHC collimation optics



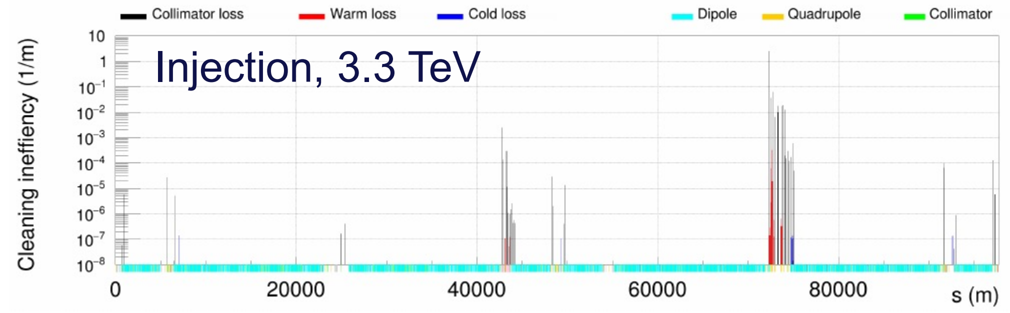
FCC-hh collimation hierarchy

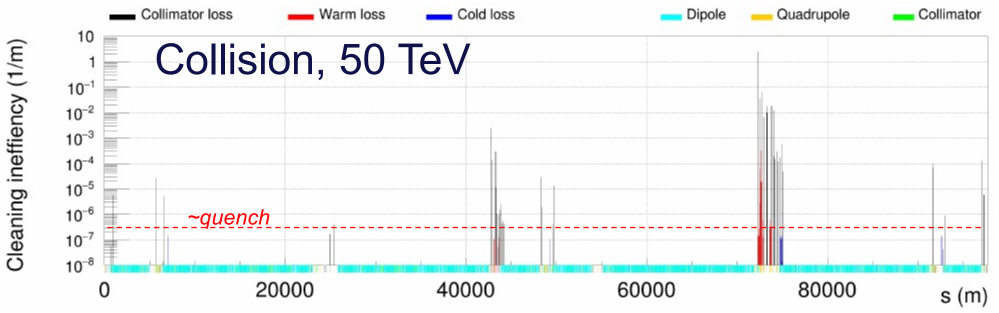
- As in the LHC, using a multi-stage system with primary and secondary collimators, shower absorbers, dispersion suppressor (DS) collimators
- Similar layout as the LHC, but some modifications: DS collimators in many insertions, extra shower absorbers in extraction insertion, removal of skew primary



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



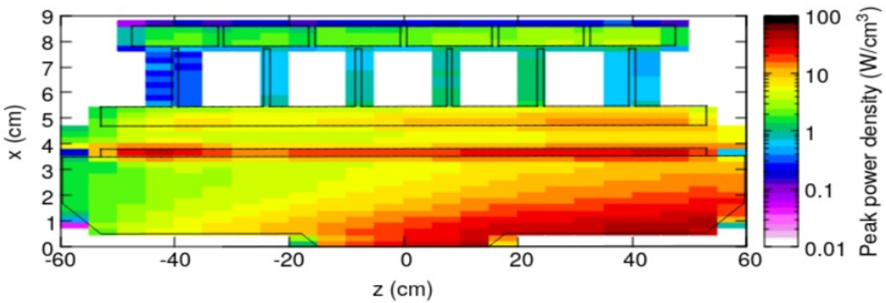


Energy deposition studies: warm section

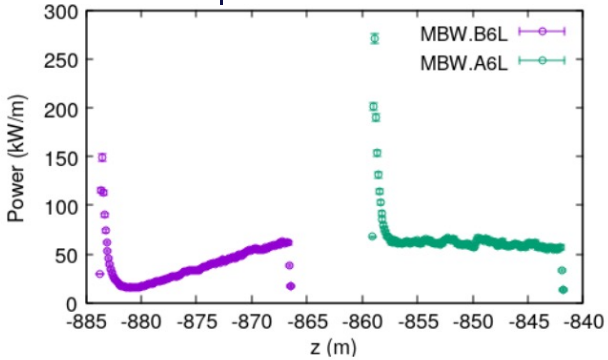
- Simulated power load in IRJ with FLUKA, for 12 minute beam lifetime at 50 TeV, with inputs from the SixTrack tracking studies

- Conclusions for warm section (see talk M. Varasteh):
  - Initially very worrying losses, triggered iterations
  - With modified collimator designs and skew TCP removed, all CFC/MoGr collimators remain 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



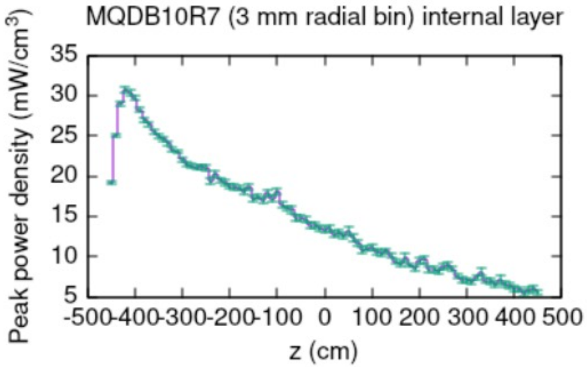
Warm dipoles

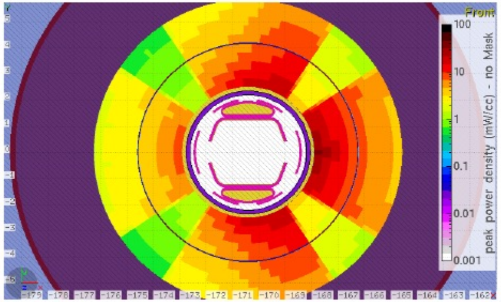


Energy deposition studies: cold section

- 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

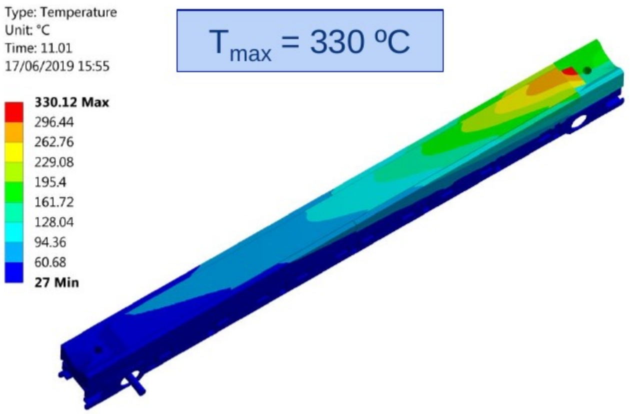


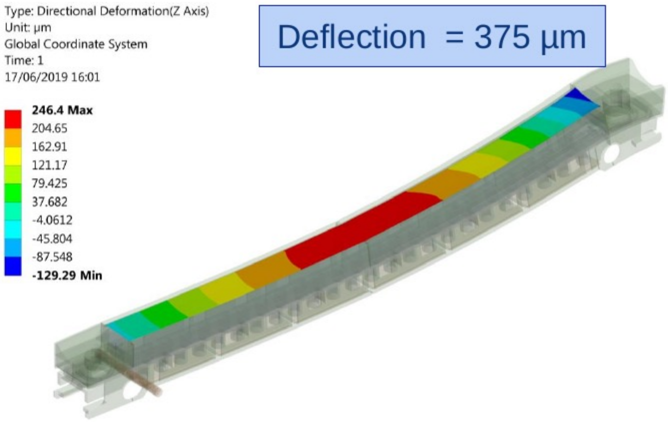


Thermo-mechanical studies

- 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)

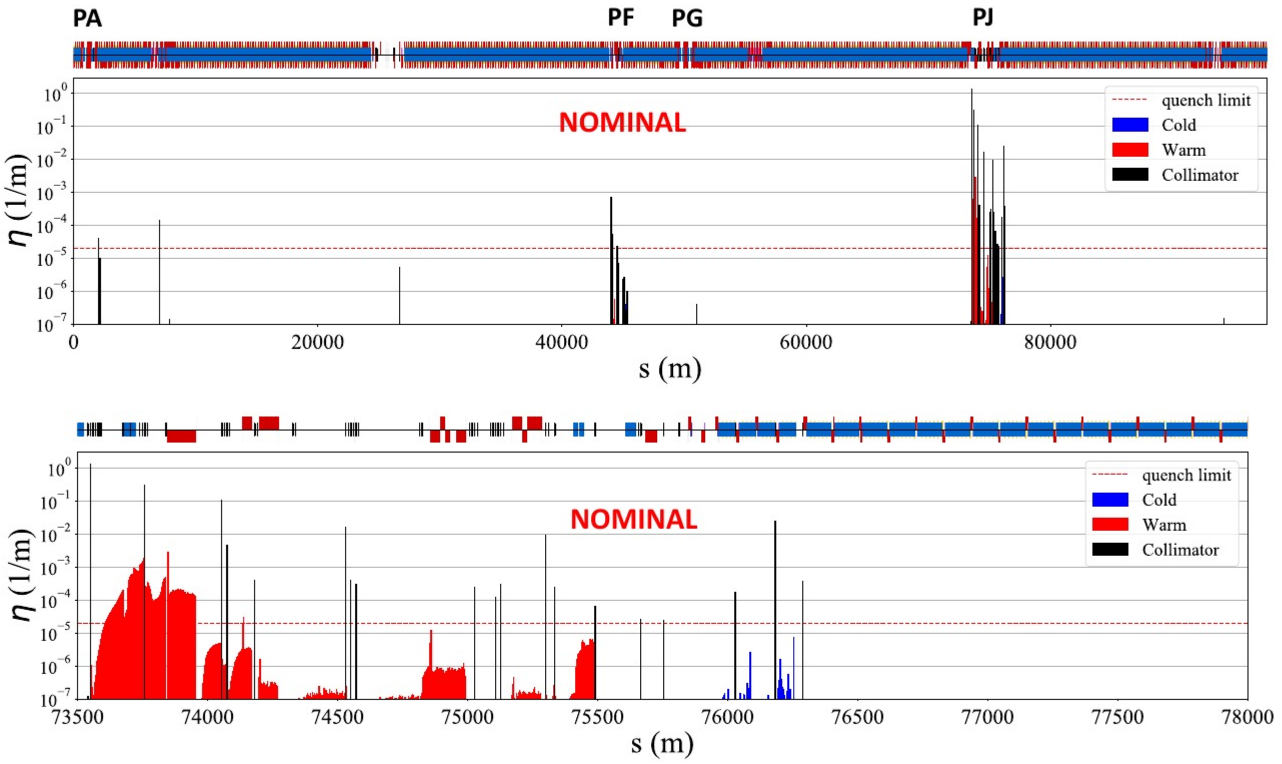
- Conclusions:
  - Collimators survive mainly without permanent damage in spite of extreme loss conditions, but significant deflection and temperature increase
    - Only exception: damage on cooling pipes - could probably be solved by material change
    - Outgassing could become an issue - to be investigated.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





Pb ion collimation

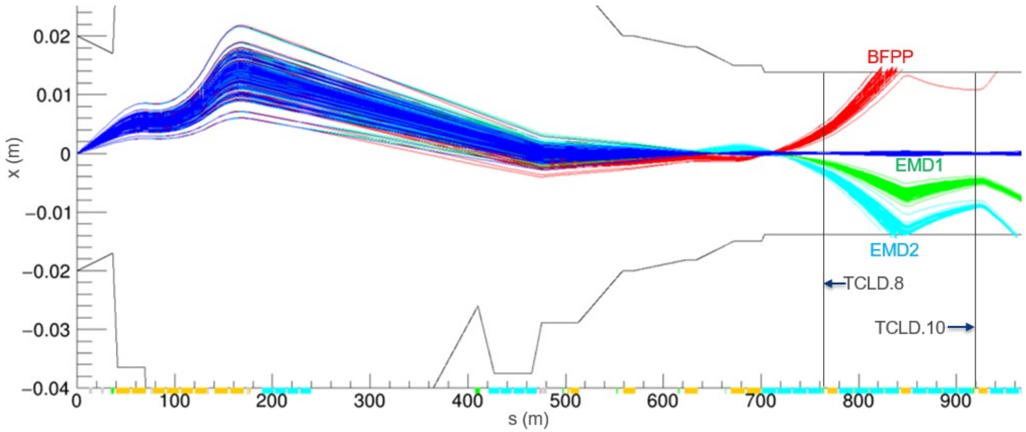
- FCC-hh also foreseen to operate with heavy ions, tentatively assuming Pb
- Studied collimation efficiency using the SixTrack FLUKA coupling (see PhD thesis)
- With DS collimators (essential!) cold losses are kept below the assumed quench limit
- Energy deposition studies needed for full assessment



Pb ion secondary beams (1)

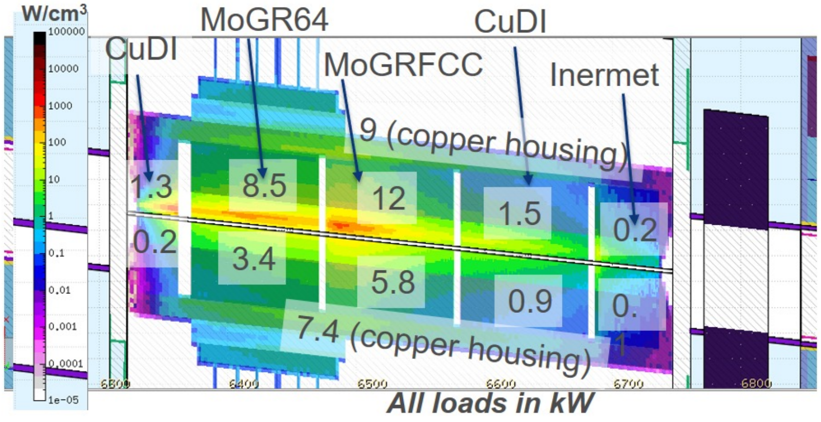
- In Pb ion operation, secondary beams from the collisions at the IPs may quench magnets
  - Ions with changed rigidity (acquiring electrons – BFPP – loss of one or several nucleons) wrongly bent by magnetic fields
  - HL-LHC: power load of up to ~170 W for BFPP
  - FCC-hh: power load of up to ~56 kW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

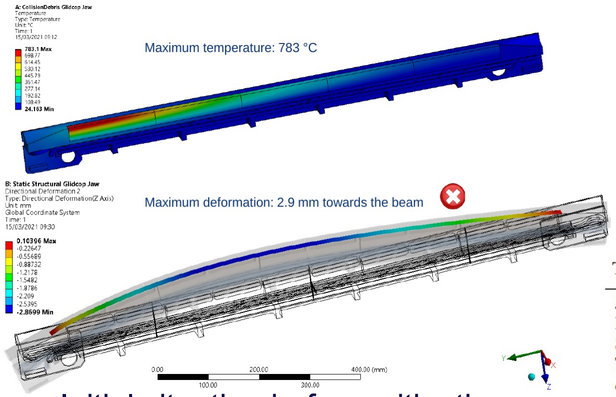
- Losses tracked in SixTrack (see talk J. Molson) – can be intercepted by DS collimators



Pb ion secondary beams (2)

- Energy deposition and thermo-mechanical studies carried out to quantify impact of showers from DS collimators (see talk and IPAC21 paper by J. Hunt, talk by J. Guardia)
  - 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 (~3.8 m total length), composed of blocks of different materials





Initial situation before mitigation

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**

FCC-hh summary

- 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
  - Present design based on CDR ring layout, other layouts to be studied

- 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, summarized later

FCC-hh collimation : future work and open points

Future work on present system design (based on the CDR):

- Refine tolerances for aperture calculations
- Further error studies, including also alignment and magnetic field errors
- Some studies of failure scenarios done (not shown here) – some more might be needed
- Study outgassing and cooling of the most impacted elements in collimation insertion
- Study different materials in cooling pipes to avoid damage
- Consider HiRadMat tests of collimator materials with FCC-equivalent beam impacts if available
- Impedance is on the limit – we might want to improve it
- 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
- Studies of an optimized dog-leg geometry are ongoing
- Consider novel collimation scenarios – crystal collimation, combining betatron and off-momentum collimation
- Study alternative collimator / jaw designs, which are not based on the LHC design

Collimation in FCC-ee

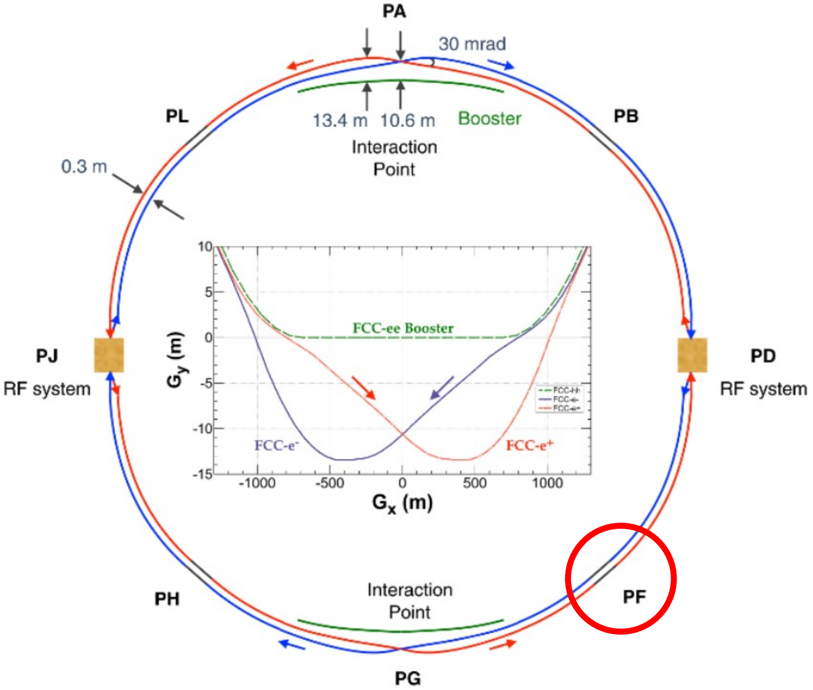
- Crucial to safely handle beam losses in the FCC-ee:
  - Electron and positron beams with energy in the range 45.6 – 182.5 GeV
  - Stored beam energy up to 20 MJ for the Z-pole mode, two orders of magnitude higher than existing lepton colliders.
  - Nominal beam lifetime down to 18 min for the ttbar mode.

- Roles of collimation system: reduce detector backgrounds from synchrotron radiation and beam losses, clean the beam halo, protect sensitive equipment
  - Must also keep the impedance within the limits and not impact the luminosity.

- Beam loss scenarios (reference losses not defined yet!)
  - Beam halo from a variety of processes (beam-gas scattering, Touscheck scattering)
  - Spent beam from beam-beam interactions at the IP (Beamstrahlung, Bhabba scattering)
  - Top-up injection losses
  - Failure scenarios, instabilities

Collimation system

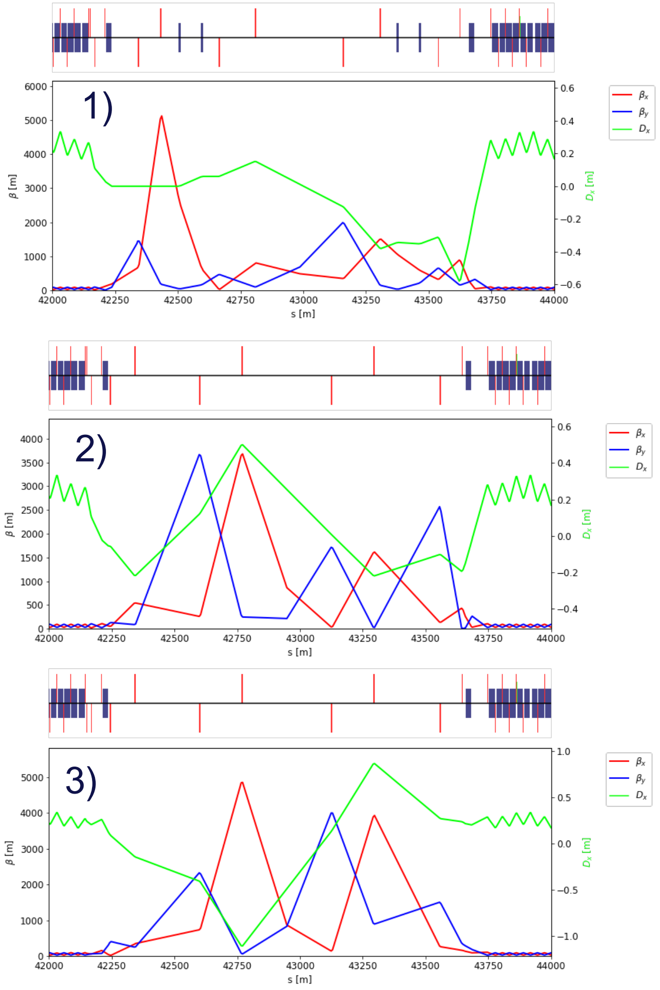
- Collimation system design
  - Collimators around IPs to intercept SR and off-momentum electrons
  - 2-stage halo collimation system in a dedicated insertion
- IRF is the preliminary choice of a collimation insertion
  - Based on the CDR layout and 2 IPs
  - A second collimation insertion is considered (separate betatron and off-momentum cleaning)
- The new layout and the 4 IP options must be studied



Collimation optics

- Based on the LHC collimation optics as a starting point (see the FCC week talk).
- Three separate options considered:
  1) Optics with space for polarimeter (FCC week)
  2) No polarimeter, low dispersion (betatron)
  3) No polarimeter, high dispersion (combined)
- Integrated with the CDR optics version
- The new layout and optics are under study now

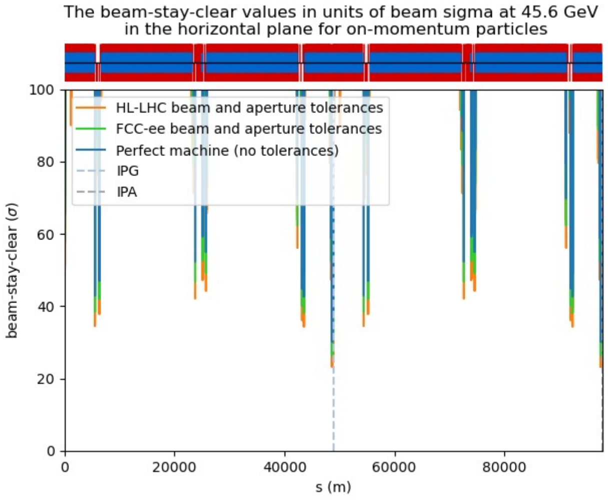
Z mode

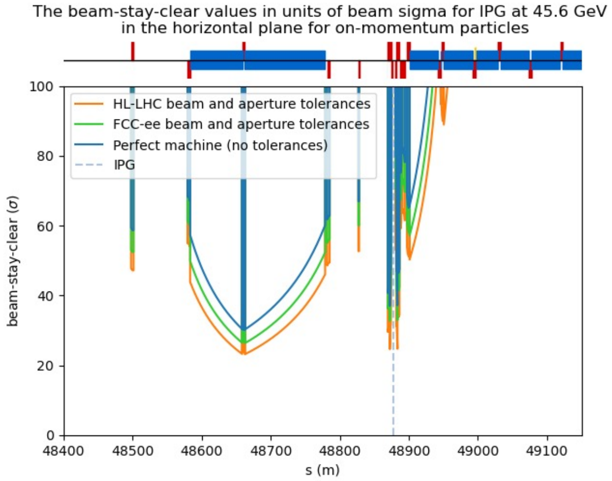


Machine aperture

- The first aperture study was performed (see FCC week talk)
    - The study is performed using MAD-X.
    - The mechanical aperture outside of IRA and IRG is a 35 mm radius circular aperture.
    - Includes a first guess of mechanical and beam tolerances.

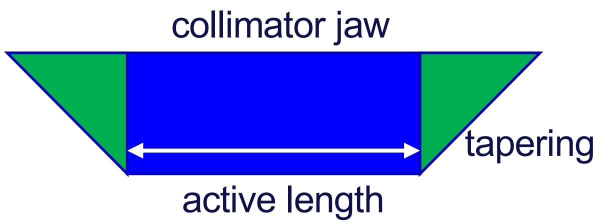
- The aperture bottlenecks in the EIRs for all beam modes
    - Beam stay clear in the range 13-23 σ
    - Momentum acceptance around 6%.
    - Off-momentum aperture not tolerable.
    - Further studies needed with local corrections and refined beam tolerances.





Z mode

Collimator design



- The material and the active length are important for collimation.
- Compromise between robustness and absorption.
  - Shallow impact parameters may require absorbent materials to ensure cleaning efficiency.
  - The halo primary collimators must be robust to losses.
  - Steady-state power loads from SR will contribute to heating of the collimators.
- Must optimize the collimator impedance.
  - The material, length, mechanical design and settings will affect the impedance.
- Start from the LHC, SuperKEK, and LEP collimator designs
- Some materials to consider are C, Al, Cu, W, MoGr, CuCD
  - Different materials may be needed for the different collimation stages

Simulation tools for collimation tracking studies

- Tracking studies are essential for designing a collimation system

- The requirements for collimation simulation tools are:
  - Tracking of beam electrons (and positrons) in the magnetic lattice
  - Particle-matter interactions inside the collimators
  - Aperture modelling
  - Accurate and efficient tracking over many turns
  - Radiation damping and optics tapering
  - Beam-beam effects

- No established frameworks currently available, development is ongoing (talk yesterday)

- Many other simulation tools, aside from tracking
  - Energy deposition, impedance, vacuum, thermo-mechanical, other aspects

FCC-ee summary

- The FCC-ee collimation studies are at an early stage.
- The first studies are in progress:
  - Optics and layout for a halo collimation insertion.
  - Machine aperture.
  - Simulation frameworks for tracking studies.
- Many open points remain (next slide).

FCC-ee collimation : future work and open points

Future work on the collimation system design:

- Define equipment loss tolerances – detectors, superconducting magnets
- Define reference loss scenarios
- Study the failure scenarios
- Refine the optics and the layout of the collimation system
- Adapt to the new layout and optics
- Improve the aperture model and the mechanical and beam tolerances
- Study the mechanical design of collimators the materials, and the impedance
- Develop and validate simulation frameworks for tracking studies
- Perform tracking studies to determine the collimation performance
- Perform energy deposition studies in collaboration with the FLUKA team

Additional future work

- Study collimation aspects for secondary photon beams from the IPs
- Determine if collimation in the Booster is required
- Perform tracking studies for top-up injection
- Planned work with EPFL to implement new tools on BOINC with GPUs, in the context of machine-learning applied to loss rate modelling for both the FCC-ee and FCC-hh

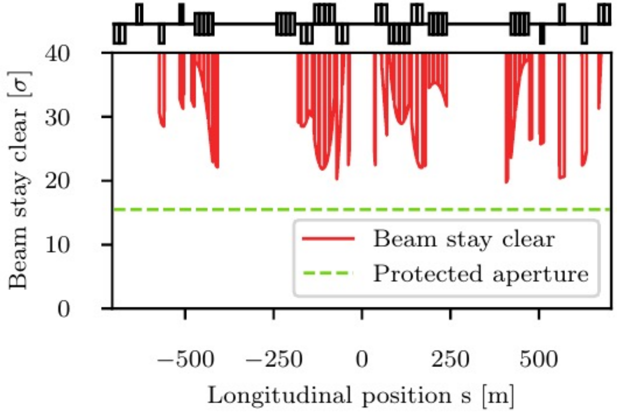
FCC

Thank you for your attention.

Backup slides

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

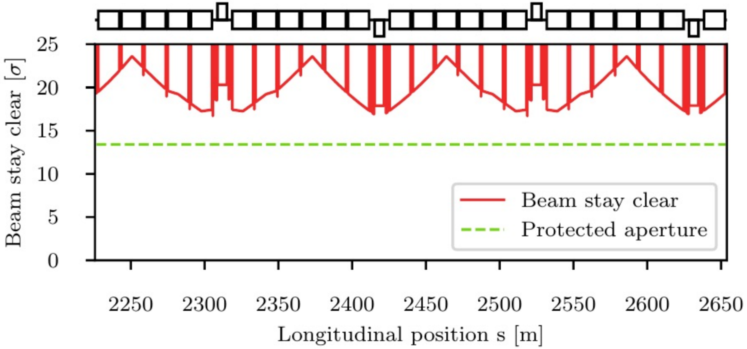
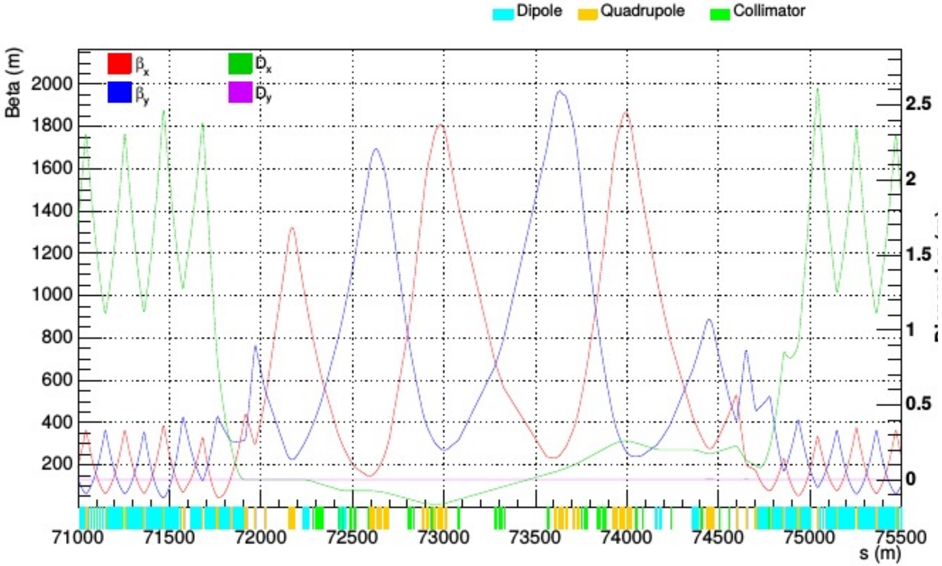


Figure 7: The calculated aperture at injection energy, as a function of distance s over two arc cells, shown together with the criterion for the minimum aperture.

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)