FUTURE
CIRCULAR
COLLIDER

Design and optimisation of the FCC-ee and FCC-hh collimation systems

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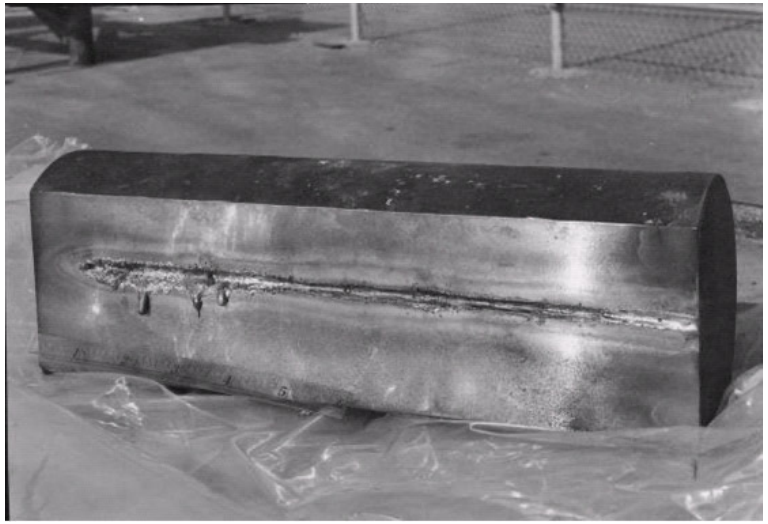
In this talk

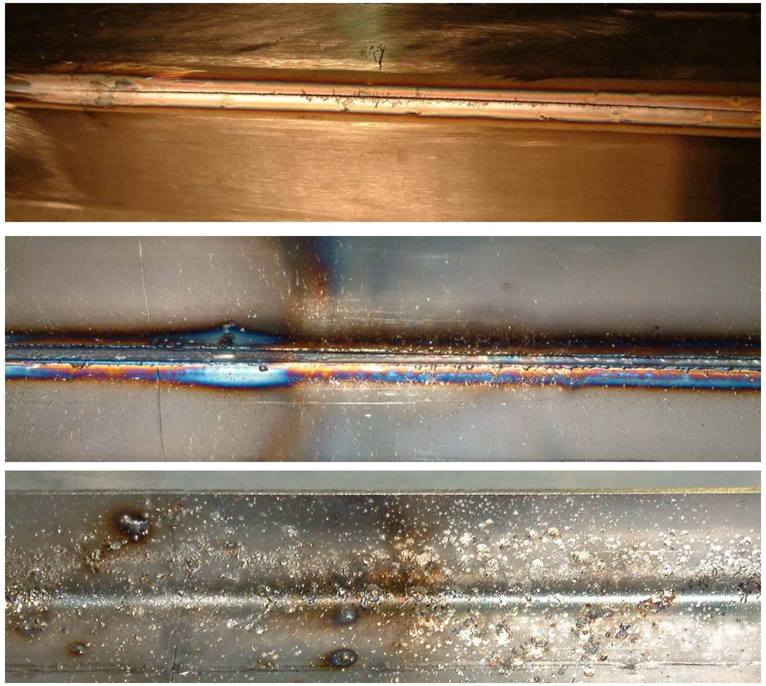
- **Introduction to beam losses and collimation systems**
  - LHC collimation system
- **FCC-hh collimation system design**
  - Challenges for collimation in the FCC-hh
  - Studies for the FCC conceptual design report (CDR)
  - Collimation system design for the new layout and optics baseline
- **FCC-ee collimation system design**
  - Challenges for collimation in the FCC-ee
  - Development of collimation simulation tools
  - Design of the collimation system for the latest FCC-ee baseline

High stored beam energy in accelerators

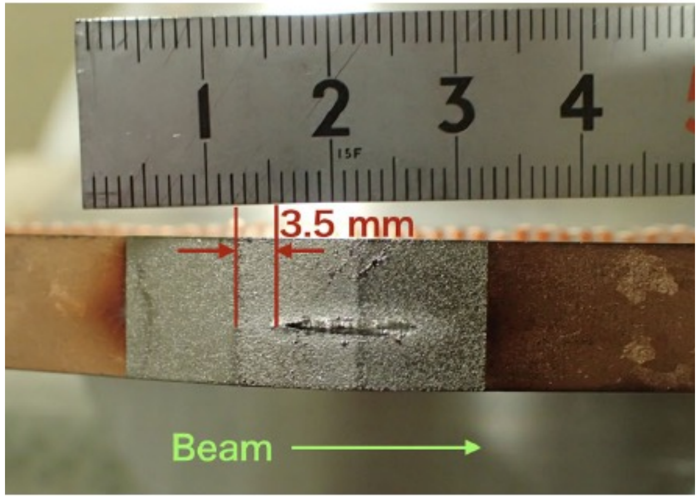
- **High-energy particle beams can be very destructive.**
- **Unintended beam losses can cause catastrophic damage to any equipment in its path.**
- **Beam losses should be carefully controlled in high stored beam energy accelerators**



Copper block
Beam – electron, 0.5 MJ @ 16 GeV,
dedicated test, SLAC



Steel vacuum chamber,
Beam - proton, 2.5 MJ @ 450 GeV,
SPS extraction failure, CERN



Collimator,
Beam - positron @ 4 GeV,
SuperKEKB loss event, KEK

Images:
https://today.slac.stanford.edu/feature/LARP.asp
https://cds.cern.ch/record/825806
https://doi.org/10.1103/PhysRevAccelBeams.23.053501

Collimation systems

- **The collimation system protects the accelerator from the beams**
  - Collimators are the closest devices to the beam in the accelerator
  - Primary beam particle losses should only occur on collimators

- **The general roles of the collimation system are:**
  - Protect against regular and accidental beam losses
  - Concentrate beam losses away from sensitive equipment
  - Reduce backgrounds to the physics experiment detectors
  - Provide local protection – injection, extraction, collision debris

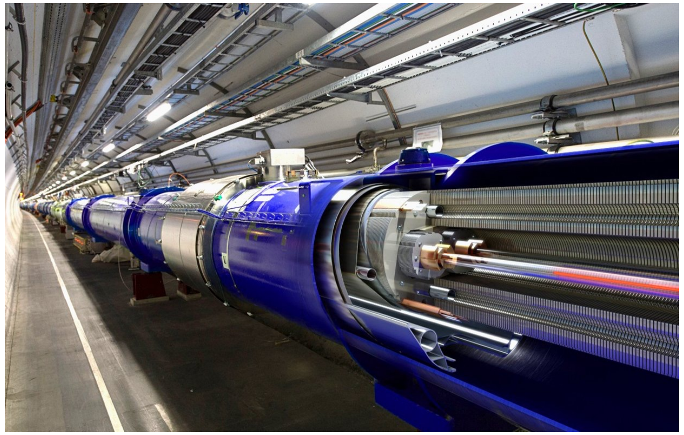
- **Design criteria**
  - Provide sufficient protection to avoid magnet quenches, damage, and intolerable backgrounds for defined beam loss scenarios
  - Protect the aperture bottlenecks with sufficient margin for static effects (e.g., imperfections, alignment) and dynamic effects (e.g., orbit fluctuation, β-beating)
  - Conform to specifications (e.g., beam impedance, collimator damage thresholds, cooling)

Example: The Large Hadron Collider (LHC) collimation

- The design stored energy per beam is 362 MJ
- The superconducting magnets in the LHC are very sensitive to beam losses.
- Coils are kept at 1.9 K and any heating can “quench” them.
- Losing a beam fraction 10^{-6} can cause permanent damage.
- Even unavoidable beam losses in normal operation can risk magnet quenches

Image: https://bonjourlafrance.com/carriers/trains-france/tgv/

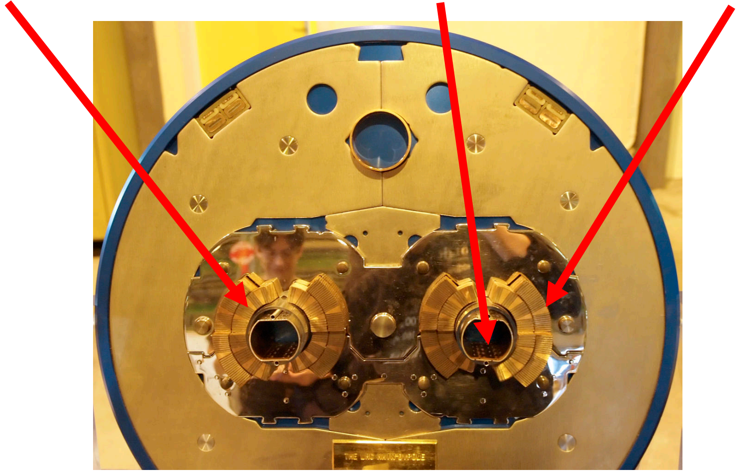
A single LHC beam’s energy is equivalent to that of a TGV train travelling at 150 km/h…



Coil quench limit:
~15 mJ cm^3

Beam:
362 MJ (design)
~100 μm avg. size

Beam pipe:
22 x 17 mm half-size



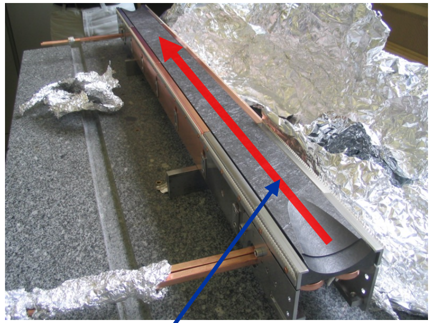
Images: https://cds.cern.ch/record/40524
https://twitter.com/cern/status/1014529578491097088

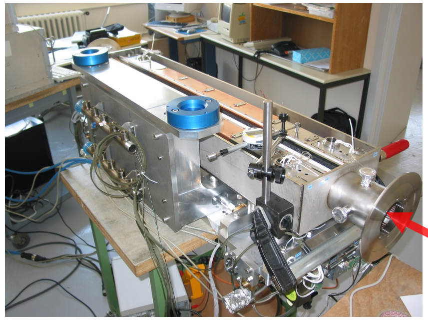
Protecting the machine

- **Unavoidable losses - beam halo**
  - Due to various processes (intra-beam scattering, beam-beam effects, residual gas interaction, etc.), beam particles continuously leave the beam core and populate “halo”
  - The beam halo contains only a fraction of the total power, but it is still dangerous to the magnets and other equipment
  - Backgrounds induced in the the detectors from beam losses must be controlled
- **Anomalous beam loss scenarios**
  - Injection kickers misfiring, asynchronous dump etc.
  - Can be very fast and lead to a loss of a significant fraction of the beam intensity
- **The collimation system has the tasks of protecting the machine, preventing experimental background and cleaning the beam halo.**
  - The LHC is fitted with a state-of-the-art multi-stage collimation system to clean the beam halo and protect the machine from other losses
  - The collimation performance is crucial for safe operation

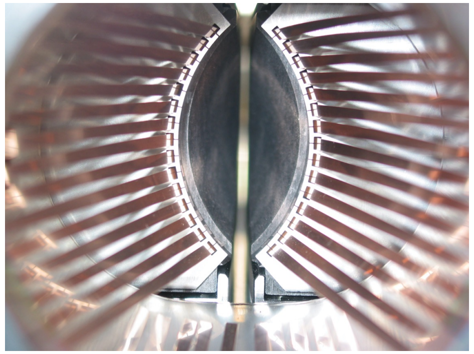
The LHC collimation system

- The collimation system includes a number of collimators – devices with moveable solid material jaws that are brought close to the beam.
- More than 120 collimators in the LHC
- 2 dedicated collimation insertions





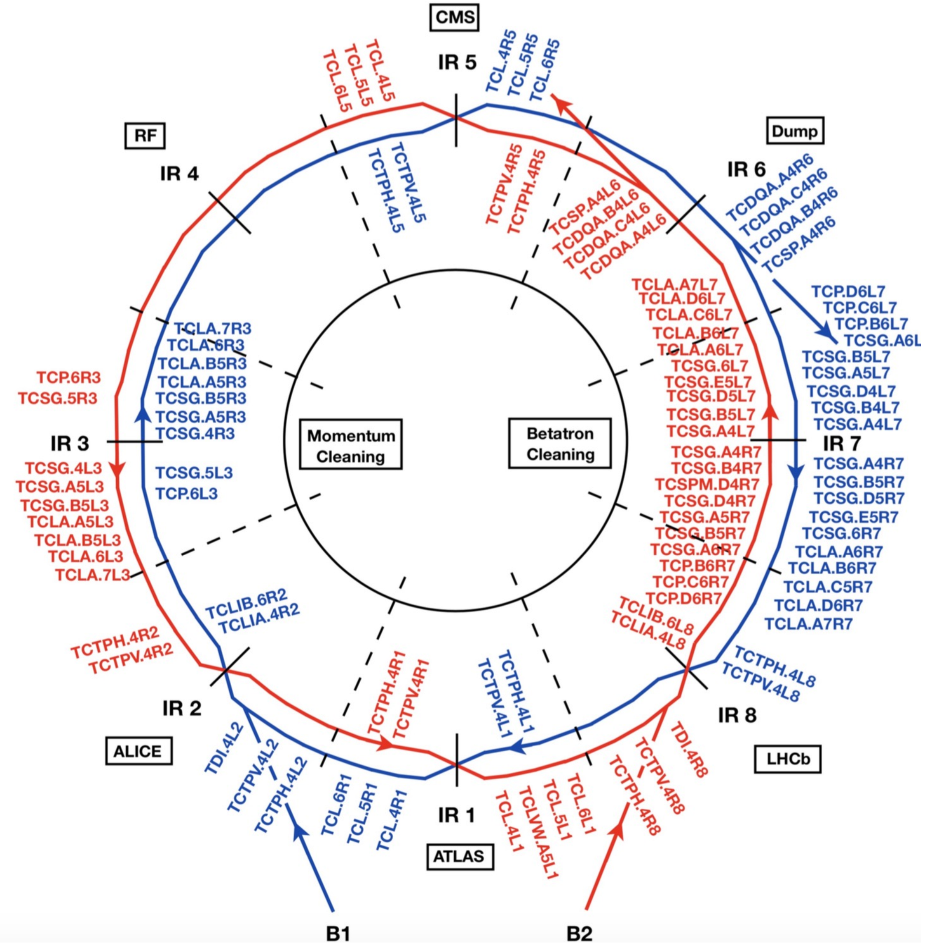
beam



LHC collimators

LHC Collimation
Project
CERN

Images: https://lhc-collimation-project.web.cern.ch/lhc-collimation-project/

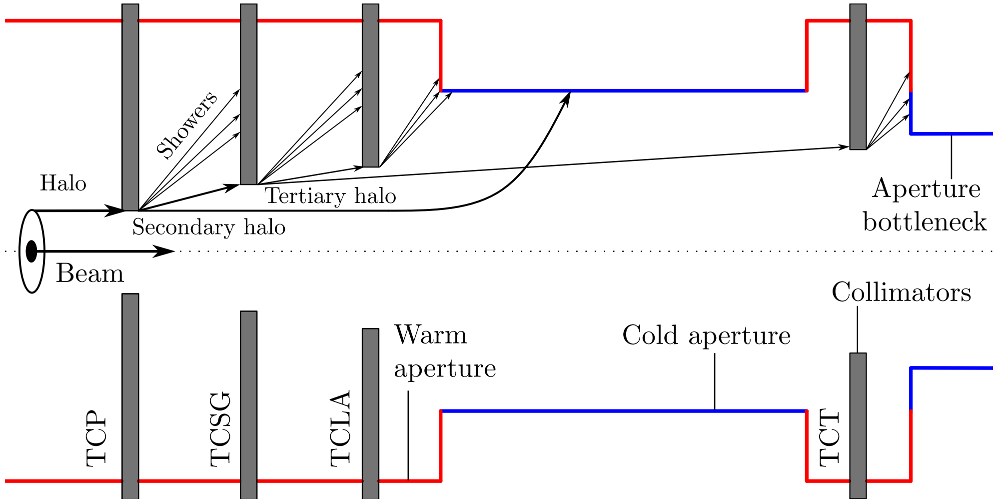


LHC Run 2 collimation layout

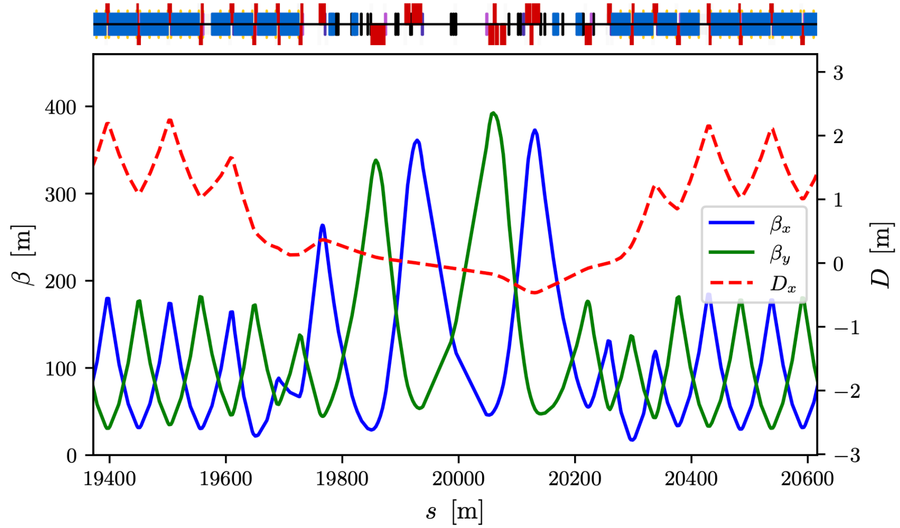
The LHC collimation system

- **Betatron and off-momentum multi-stage collimation systems**
  - Primary (TCP), secondary (TCSG) collimators.
    - The primary collimators scatter halo particles onto the secondary collimators where further scattering and interactions occur.
  - Shower absorbers (TCLA) intercept the shower products from the secondary collimators
  - Tertiary collimators (TCT) protect the aperture bottlenecks

- **Specialized insertion optics for collimation**



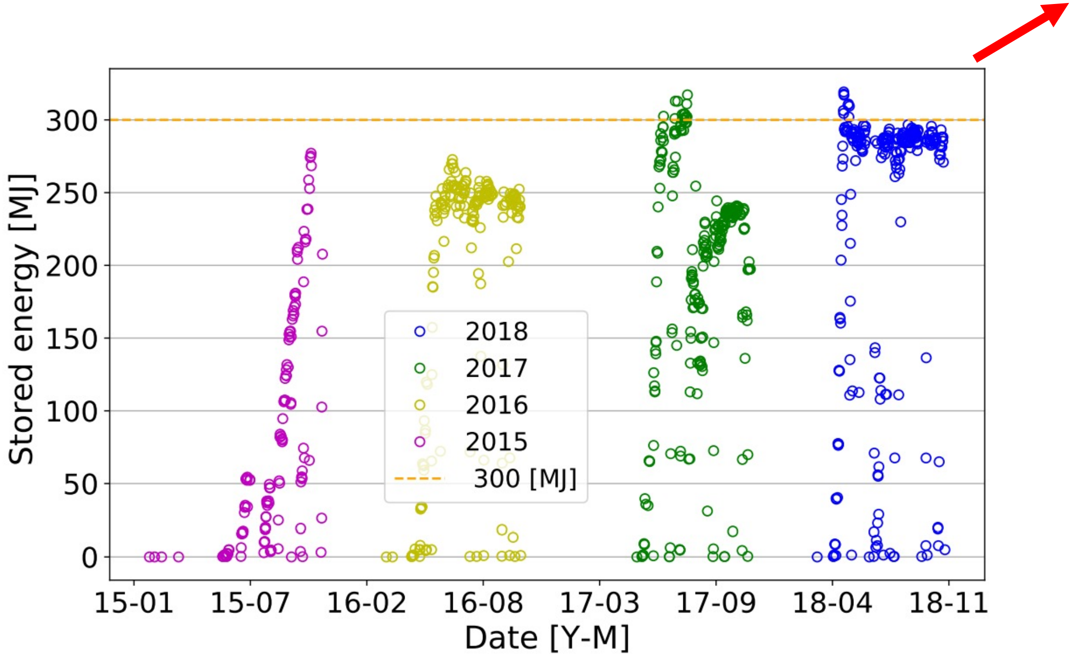
Betatron collimation hierarchy in the LHC



Specialized optics in the betatron collimation insertion

LHC operation

- **The collimation system has been crucial for the LHC performance**
  - Excellent protection demonstrated
  - In 2022, the LHC stored beam energy has reached up to 400 MJ, which is above the design value of 362 MJ
  - Optimized collimator settings helped reach β* values and peak luminosity beyond the design
- **It shows the benefits of careful collimation design and optimization**



Stored beam energy in the LHC in Run 2 (up to 2018)

Looking ahead: The Future Circular Collider (FCC)

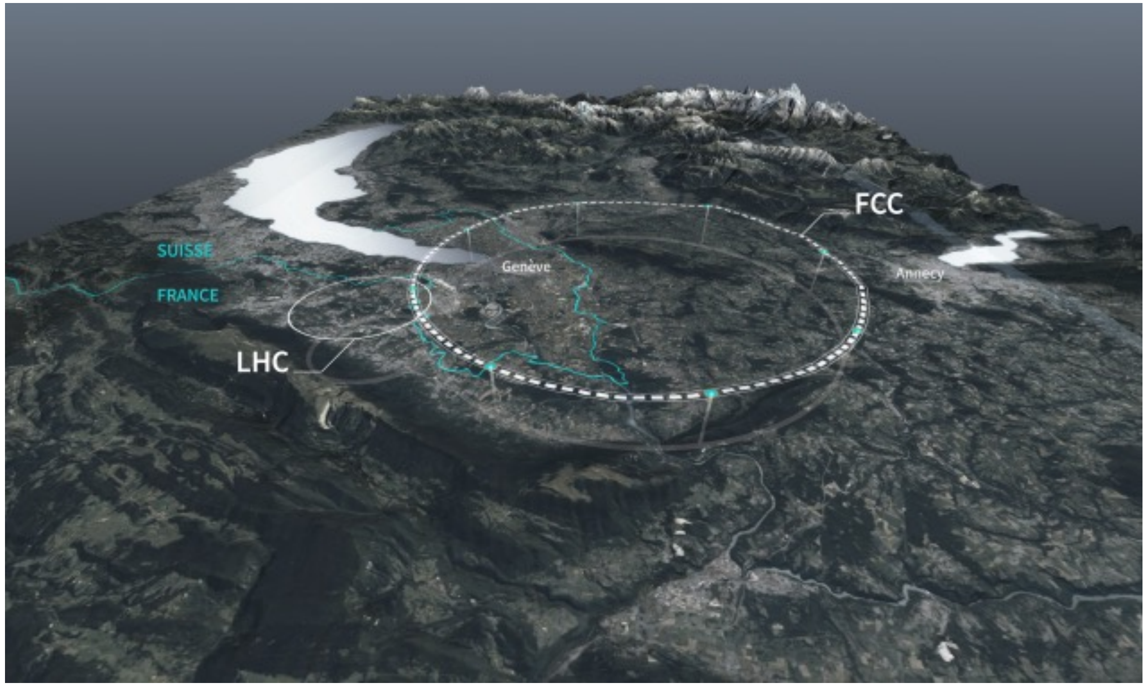
- **The FCC Feasibility Study is ongoing** (see previous talk)

- **Comprehensive long-term program maximizing physics opportunities**
  - Stage 1: e^+e^- collider FCC-ee as Higgs factory, EW & top factory, targeting unprecedented luminosities
  - Stage 2: proton collider FCC-hh pushing energy frontier with target c.o.m. energy of 100 TeV, with options for ion program or eh collisions

- **Common tunnel and technical infrastructure, building on existing CERN accelerator infrastructure**

- **FCC integrated program allows seamless transition of HEP after completion of the HL-LHC program**

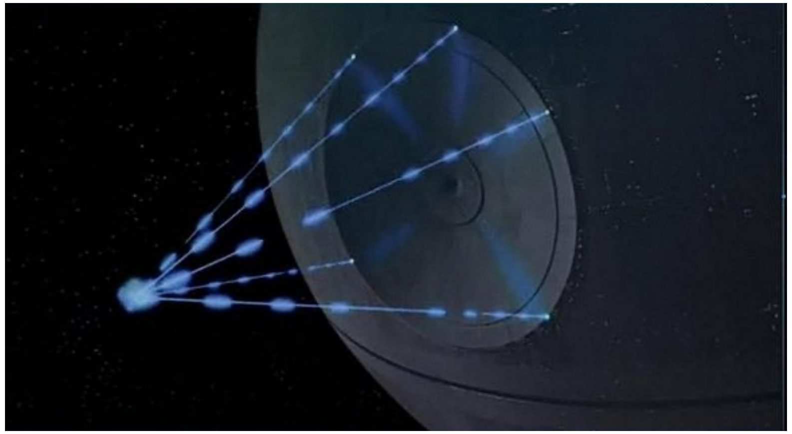
- **Collimation is one of many design challenges for both the FCC-ee and FCC-hh**



Collimation for the FCC-hh

- **Collimation system concept**
  - Studied for the **FCC Conceptual Design Report (CDR)**
  - Designed for **stored beam energy up to 8.3 GJ**
  - Stored beam energy a factor 23 higher than the LHC design
  - 50 TeV proton beam energy
  - Extremely challenging for the collimation system design
- **Main design loss scenarios**
  - “Steady-state” 1 h beam lifetime
  - Betatron cleaning 0.2 h beam lifetime during 10 s
  - 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 like collisional losses in heavy-ion operation

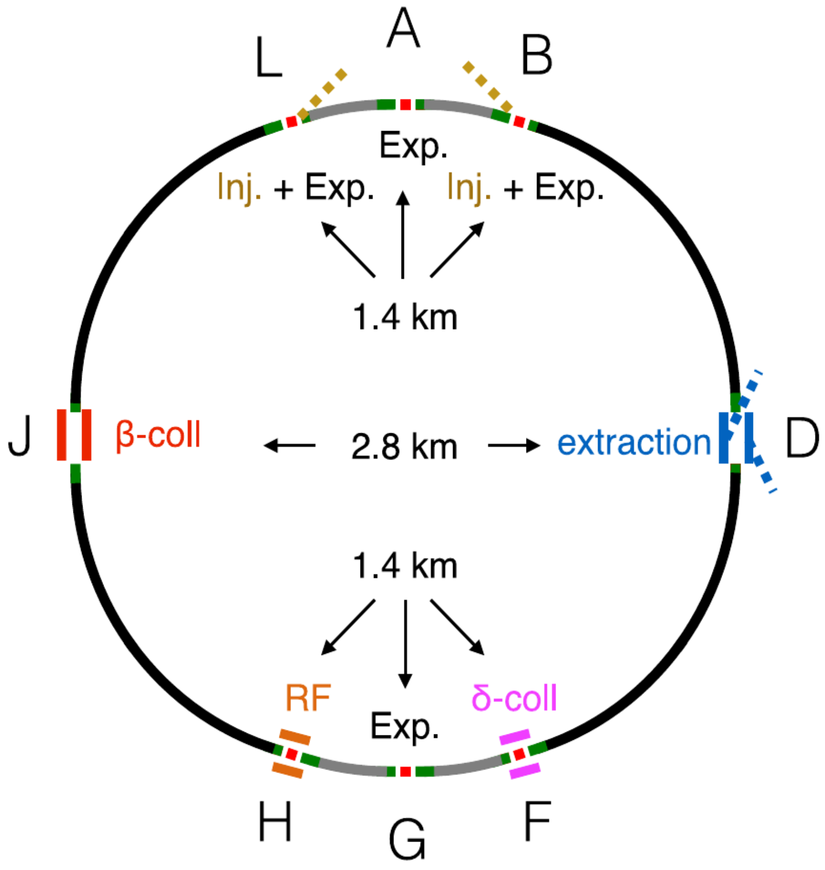
A single FCC-hh beam’s energy is equivalent to that of an Airbus A380 cruising at 880 km/h.



It is also the closest thing to the Death Star that we have designed so far…

CDR studies on FCC-hh collimation

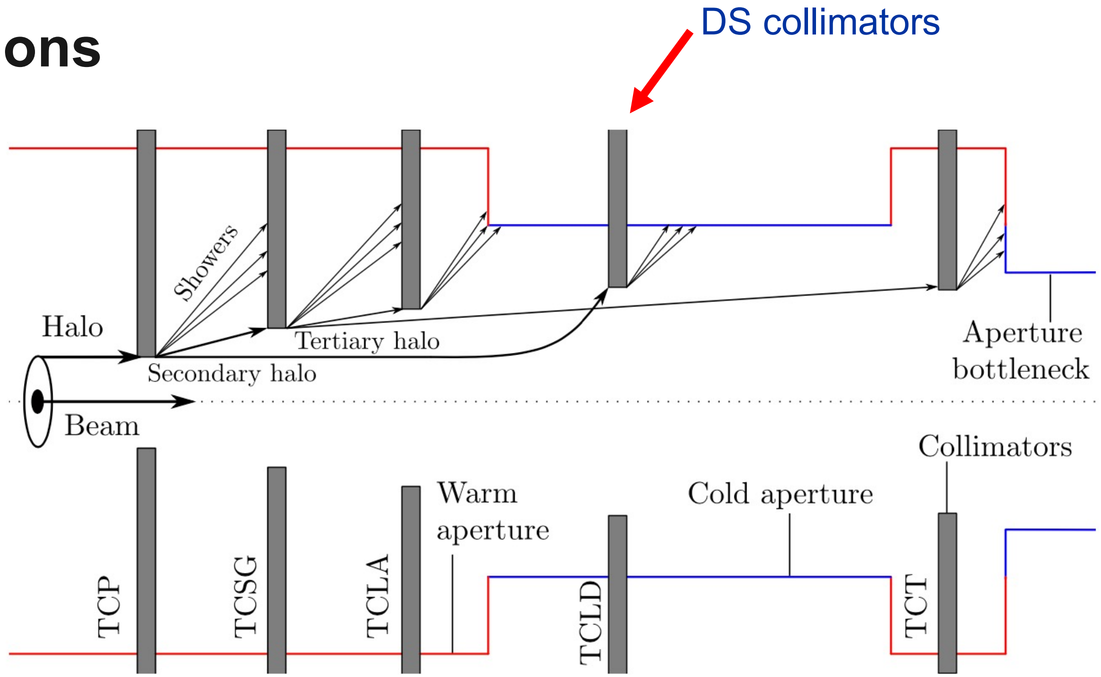
- **The FCC-hh collimation system is a scaled up version of the HL-LHC/LHC system**
  (NIM, A 894 (2018) 96-106, J. Phys.: Conf. Ser. 1350 012009 (2019))
  - Betatron collimation in IPJ
  - Momentum collimation in IPF
  - Design based on the 2-fold symmetry CDR layout
  - Need much higher β-functions 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 CDR 2-fold symmetry layout

FCC-hh CDR studies: collimation system

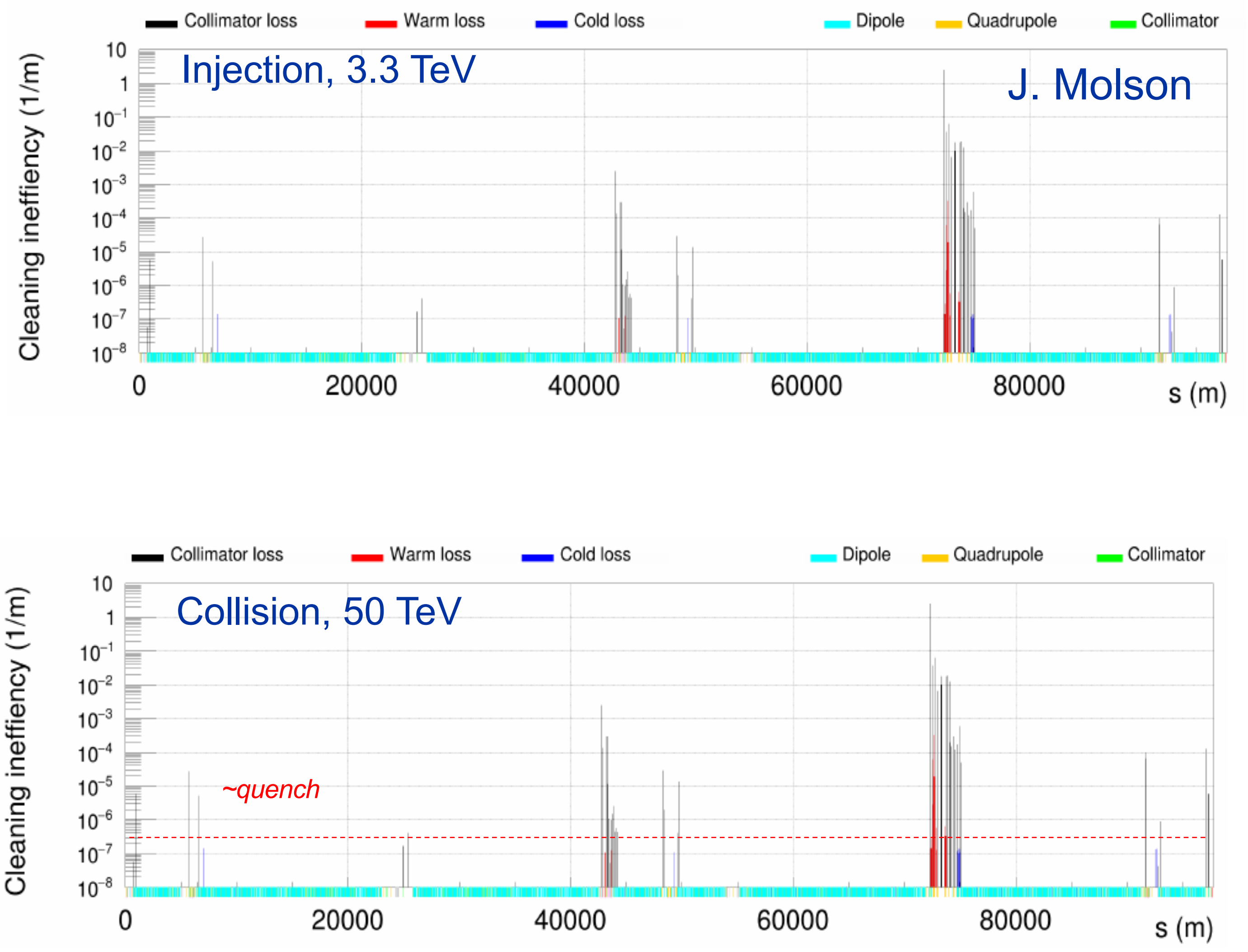
- **Using a multi-stage system as in the LHC**
  - Primary and secondary collimators, shower absorbers, tertiary collimators
- **Using dispersion suppressor (DS) collimators (TCLD)**
  - Like in the HL-LHC design
  - Necessary to intercept off-momentum particles with small transverse offsets
- **Similar layout as the LHC, but some modifications**
  - DS collimators in many insertions
  - Extra shower absorbers in extraction insertion
  - Removal of skew primary



FCC-hh collimation hierarchy

FCC-hh CDR studies: collimation peformance

- **Collimation performance checked with tracking studies using the SixTrack-FLUKA coupling**
- **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: $3\text{x}10^{-7}$ m^{-1} 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



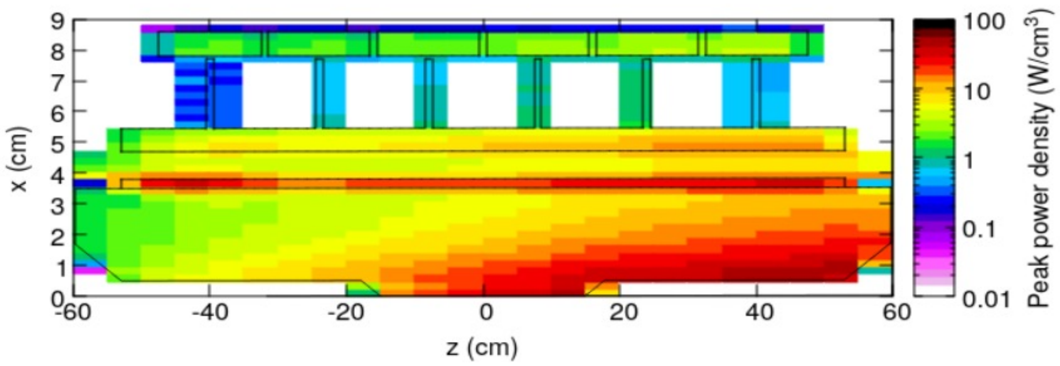
Loss maps for the FCC-hh CDR lattice

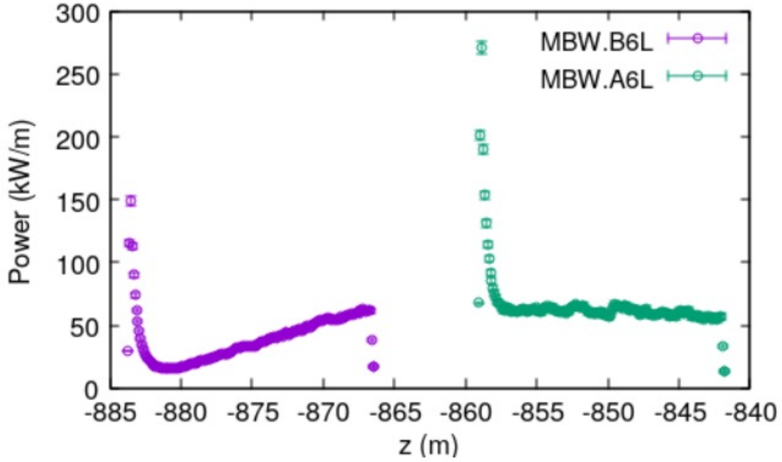
FCC-hh CDR studies: Energy deposition

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

- **For the warm section:**
  - Several iterations to bring the losses under control (M. Varasteh, talk):
  - 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

M. Varasteh

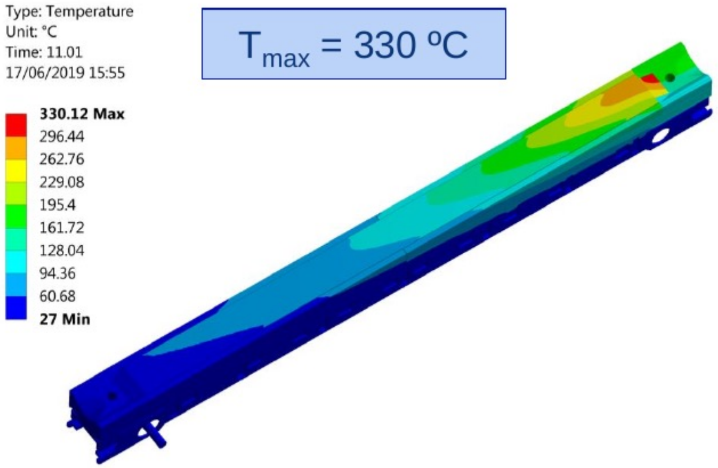

Horizontal primary collimator


Warm dipoles

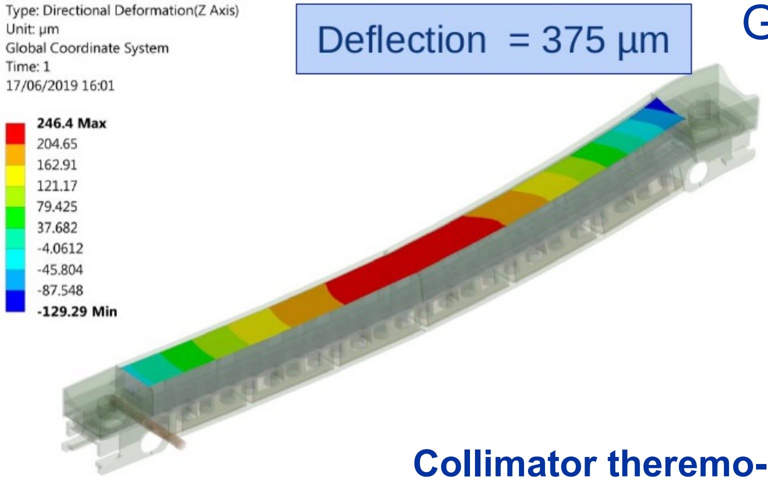
FCC-hh CDR studies: Thermo-mechanical studies

- **Based on FLUKA inputs, study thermo-mechanical response using Ansys**
  - Consider the most loaded collimators: vertical primary with highest peak power density 50kW/cm3, first secondary with highest total power load 92 kW (G. Gobbi, M. Pasquali, talk)

- **Conclusions:**
  - Collimators survive mainly without permanent damage in spite of extreme loss conditions, but significant non-permanent deflection and temperature increase
  - The only problem is possible damage to the cooling pipes, must investigate material change options
  - Outgassing could become an issue and must be studied further



T_{max} = 330 °C



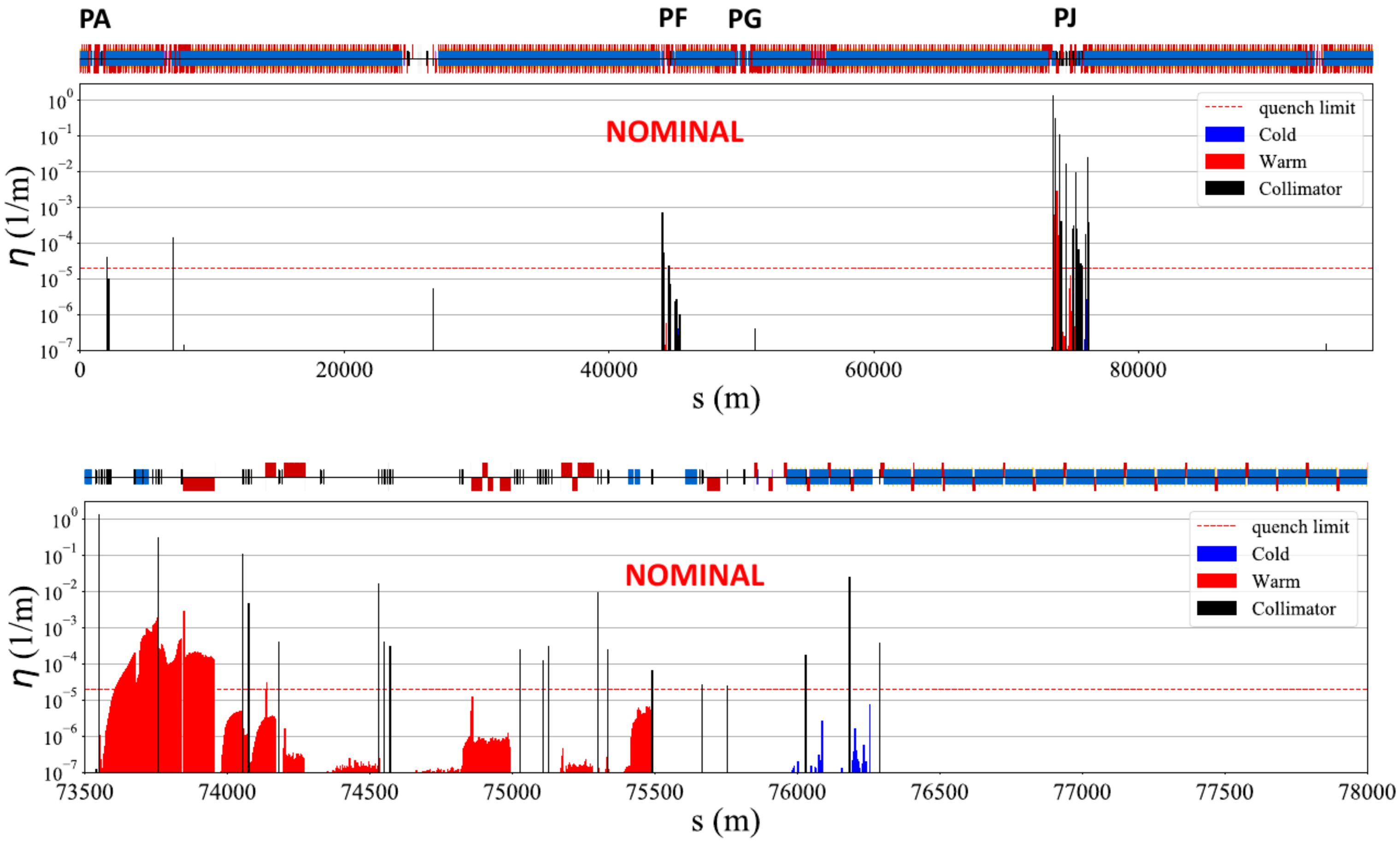
Deflection = 375 µm

G. Gobbi, M. Pasquali

Collimator theremo-mechanical studies

FCC-hh CDR studies: Heavy-ion collimation

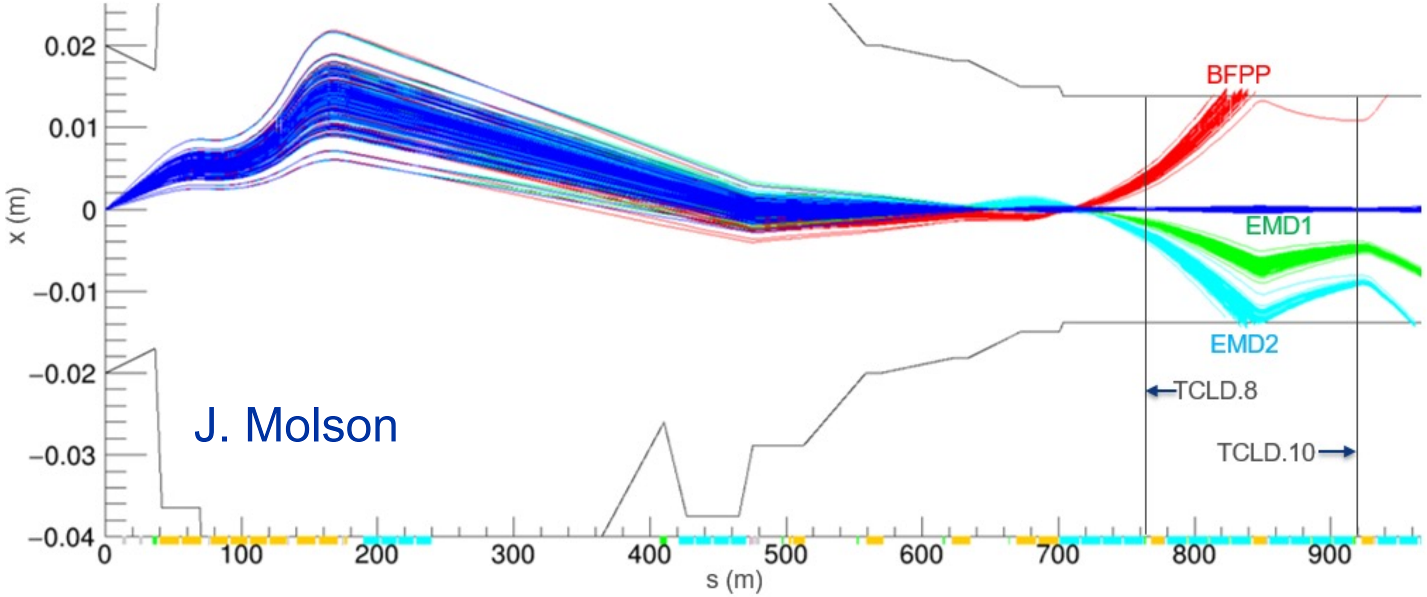
- **FCC-hh is also foreseen to operate with heavy ions**
  - Tentatively assuming Pb ions
- **Studied collimation efficiency using the SixTrack FLUKA coupling**
  - The collimation system performs well, and cold losses are kept below the assumed quench limit (A.Abramov, PhD thesis)
  - The DS collimators are essential for heavy-ion operation
  - Energy deposition studies needed for full assessment



Loss maps for Pb ions at top energy in the FCC-hh

FCC-hh CDR studies: Secondary ion beams

- **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 – can be intercepted by DS collimators** (J. Molson, talk)

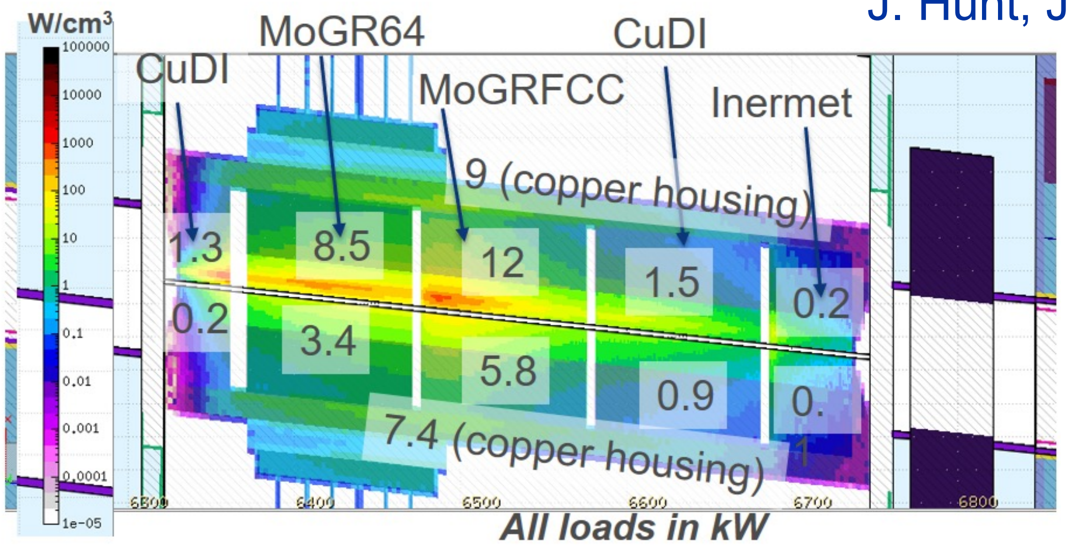


Tracks for secondary ion beams from the interaction points

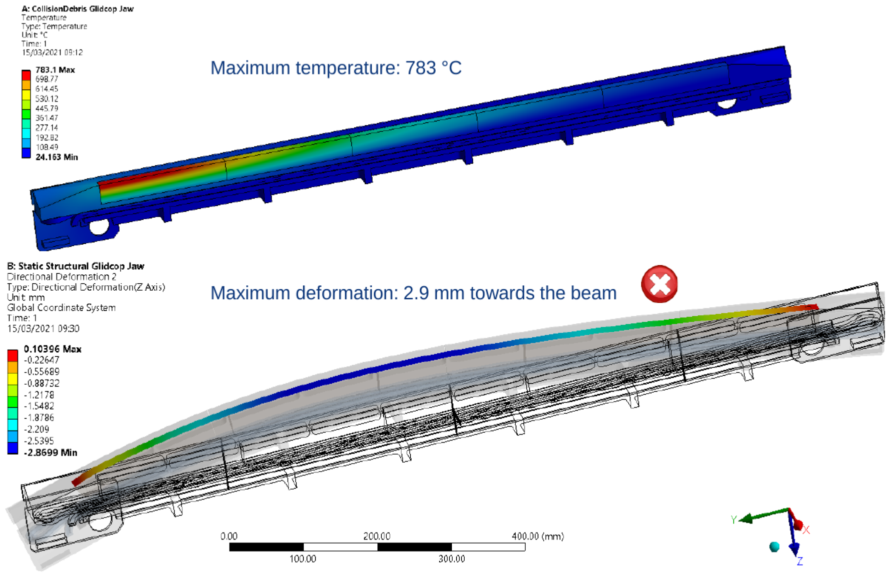
FCC-hh CDR studies: Secondary ion beams

- **Energy deposition and thermo-mechanical studies carried out to quantify impact of showers from DS collimators** (see J. Hunt IPAC21 paper, J. Guardia talk)
  - 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

J. Hunt, J. Guardia



Specialized absorber design



Thermo-mechanical studies before mitigation

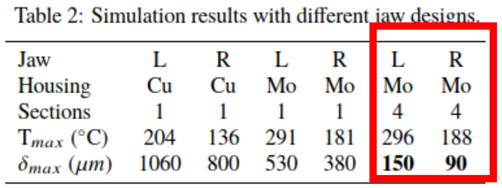


Table 2: Simulation results with different jaw designs.

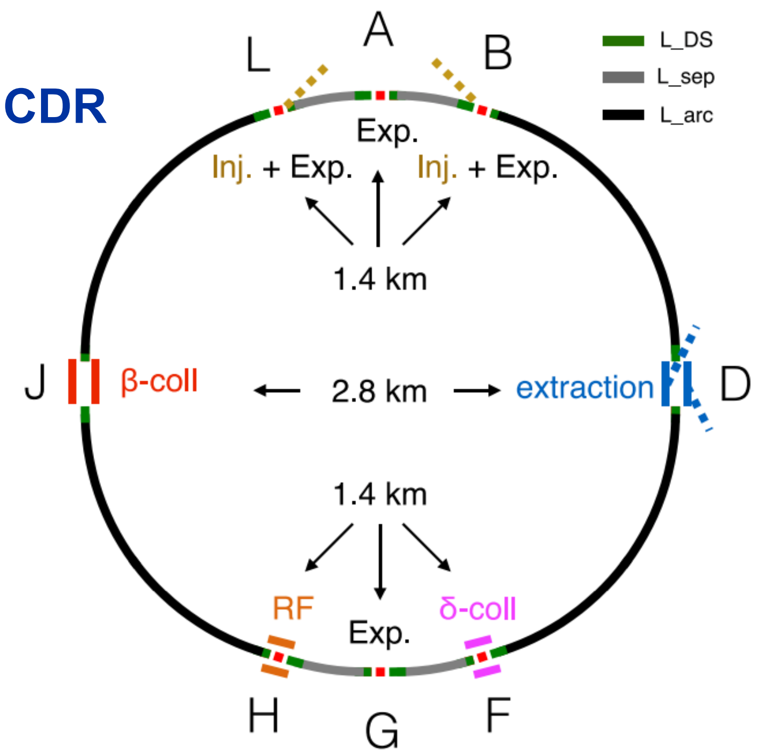
Jaw	L	R	L	R	L	R
Housing	Cu	Cu	Mo	Mo	Mo	Mo
Sections	1	1	1	1	4	4
T_{max} (°C)	204	136	291	181	296	188
δ_{max} (μm)	1060	800	530	380	**150**	**90**

After mitigations

FCC-hh new baseline

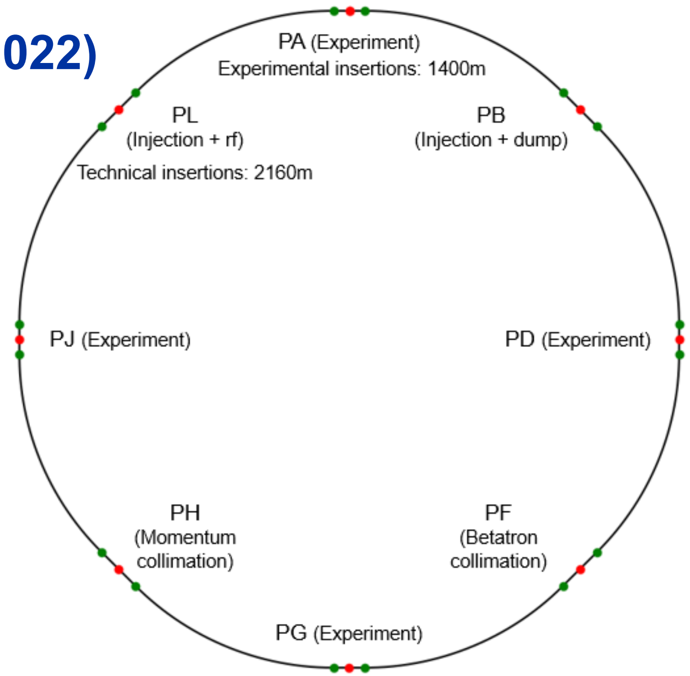
- **The latest studies have introduced significant changes to the layout and optics**
  - New shorter tunnel layout (97.7 -> 91.1km), 4-fold symmetry with 8 access points
  - Betatron collimation insertion 2.8 -> 2.1 km, Off-momentum collimation insertion 1.4 -> 2.1 km
  - Reworked optics for the collimation insertions, new dogleg geometry and beam separation
  - New optics for the injection / extraction insertions, and RF insertion

CDR



M. Giovanozzi
G. Perez Segurana
T. Risselada

PA31 (2022)

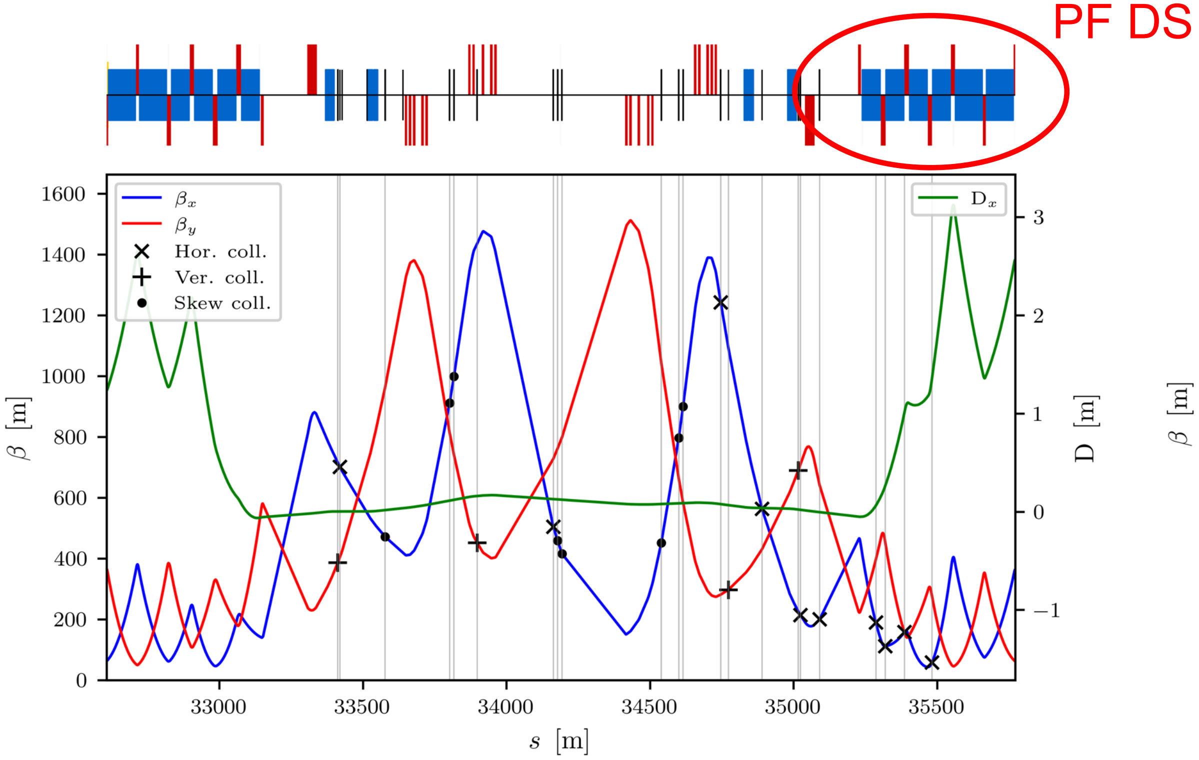


See M. Giovannozzi, IPAC’23

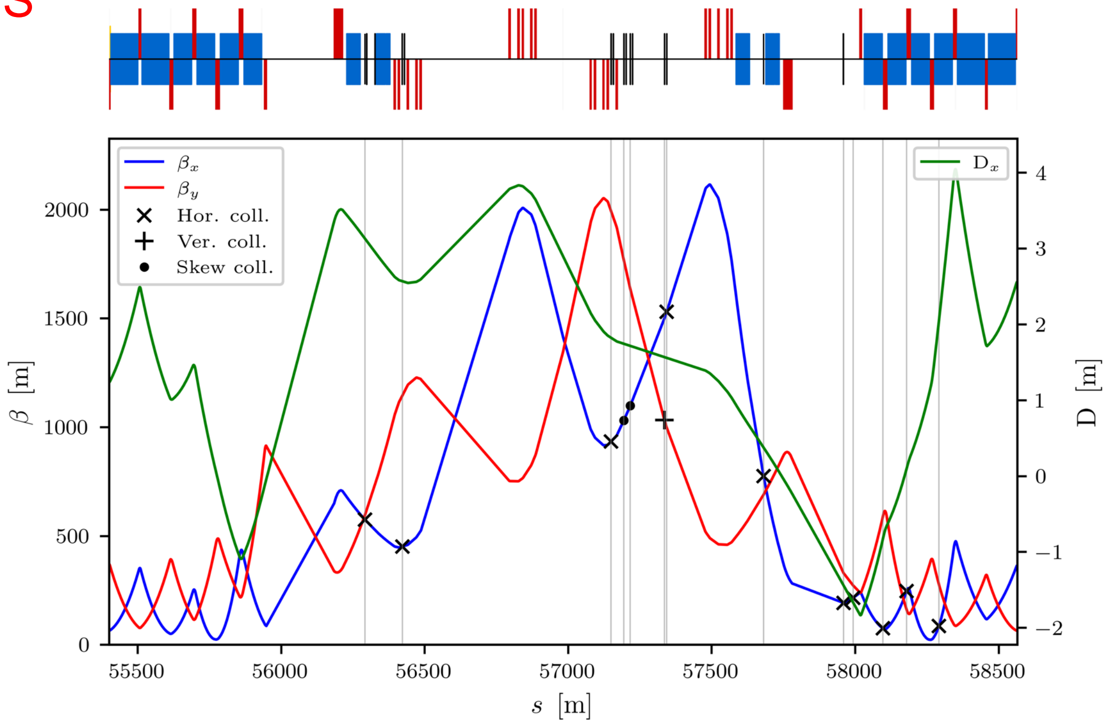
FCC-hh collimation system

- **The collimation system must be adapted to the new layout**
  - The length and optics change of the collimation insertions can have a significant effect on the performance
  - The design of the collimation system is based on a scaling from the CDR design
  - Changes were required – an additional DS collimator in PF, tighter secondary collimator settings in PF
  - Studies and optimization ongoing

See A. Abramov, IPAC'23



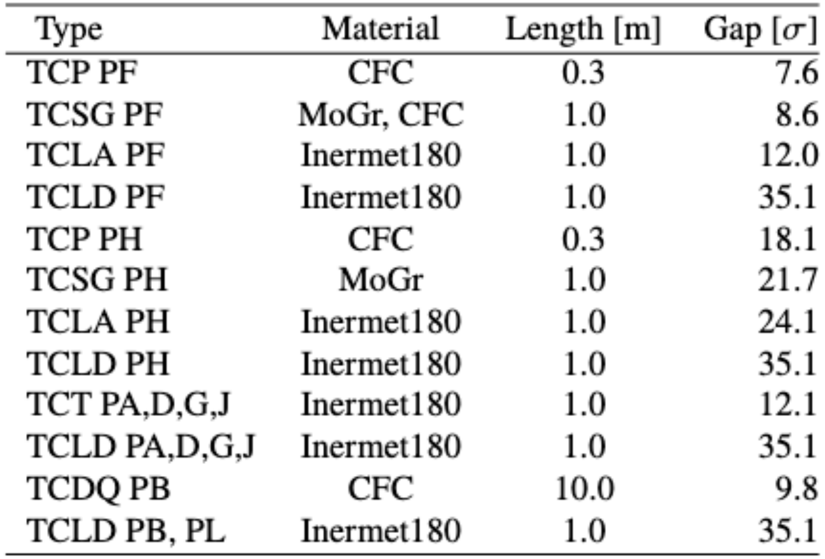
Betatron collimation insertion (PF)



Off-momentum collimation insertion (PH)

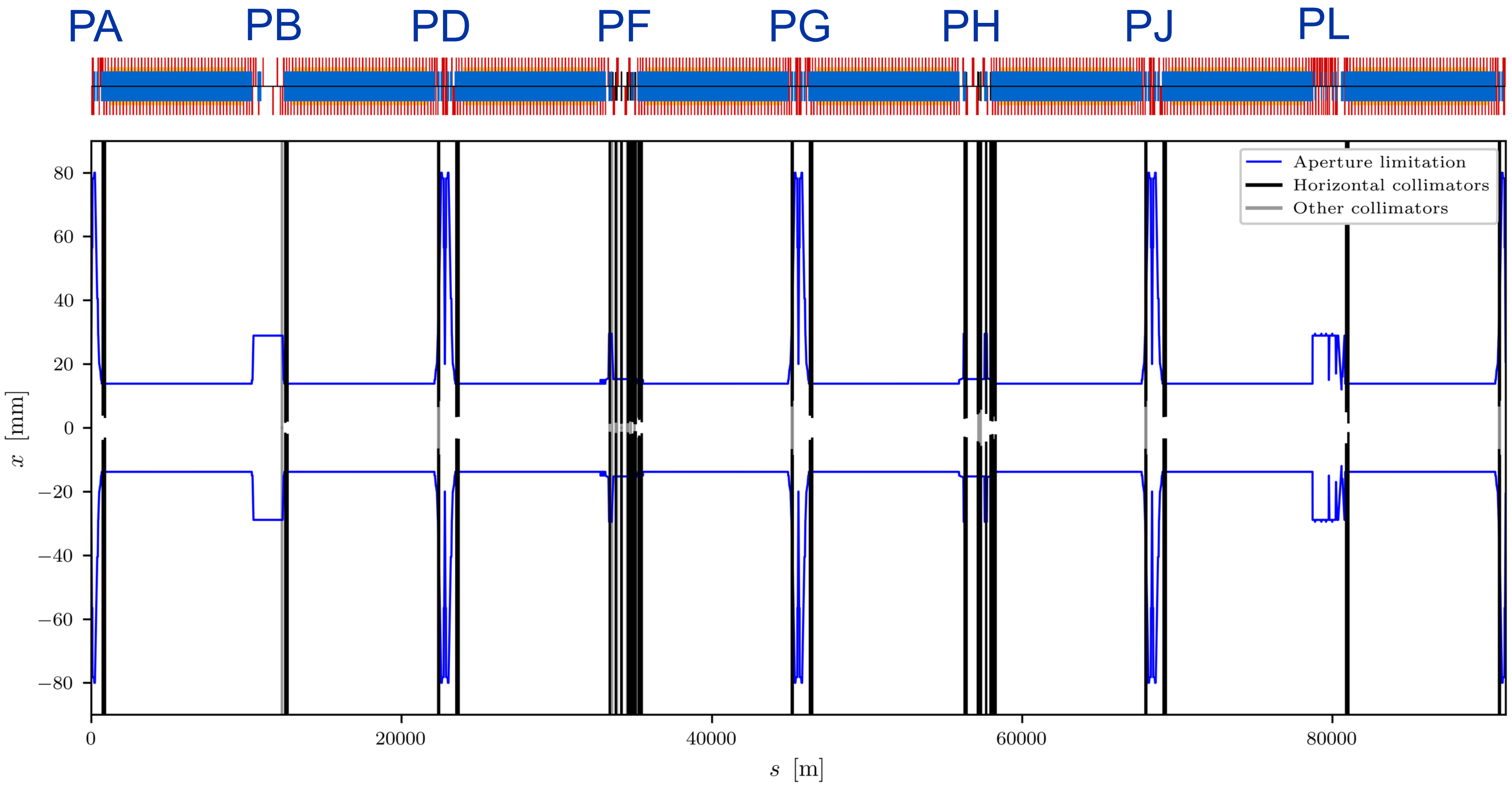
FCC-hh collimation system

- **Complete collimation system**
  - Aperture model adapted from the CDR
  - DS collimators in all insertion, extraction protection in PB, tertiary collimators in the experimental insertions



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

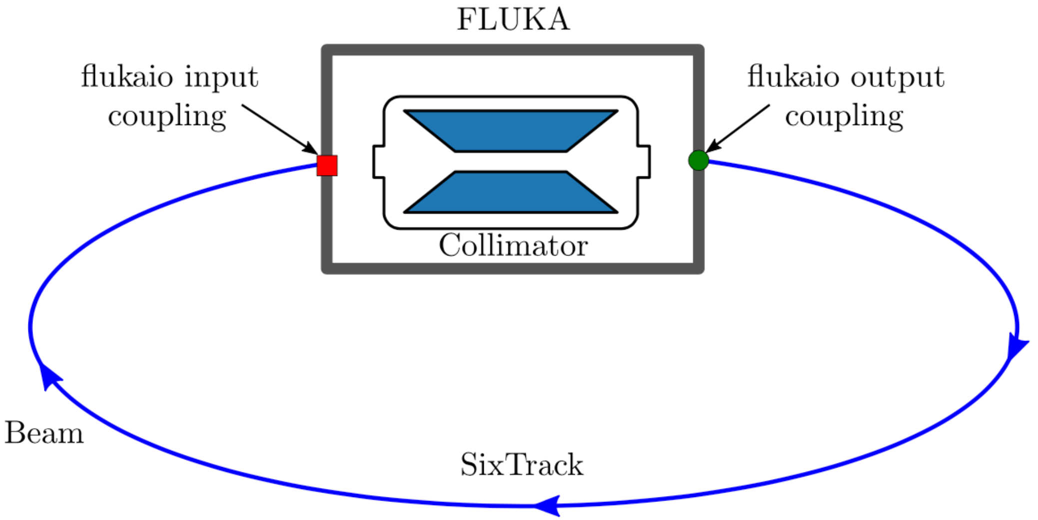
Collimator parameters and settings for the 2.2 µm normalized emittance



Aperture and collimators around the FCC-hh ring

FCC-hh collimation simulation studies

- **Currently investigating the FCC-hh collimation performance in simulations**
  - Using the SixTrack-FLUKA coupling
  - Focusing on one of the most challenging scenarios: 12 minute beam lifetime at the top energy of 50 TeV
  - 10^8 primary particles simulated, impacting the betatron primary collimator with a 1 µm impact parameter
  - Comparing with an approximate quench limit, corresponding to a cleaning inefficiency $\eta_c = 3 \times 10^{-7}\ \mathrm{m}^{-1}$

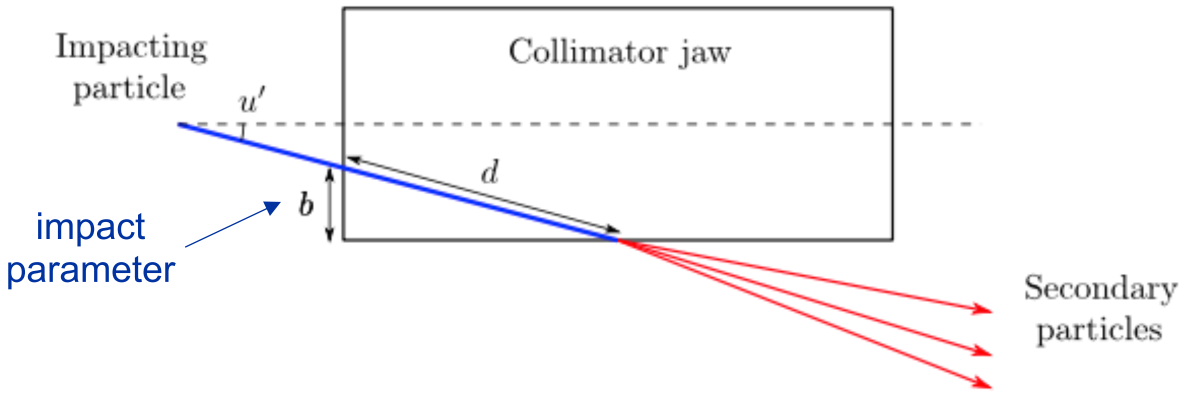


$$\eta(s) = \frac{E_{\mathrm{loc}}}{E_{\mathrm{max}}\Delta s} \quad [\mathrm{m}^{-1}]$$

$\eta(s)$ - **cleaning inefficiency**

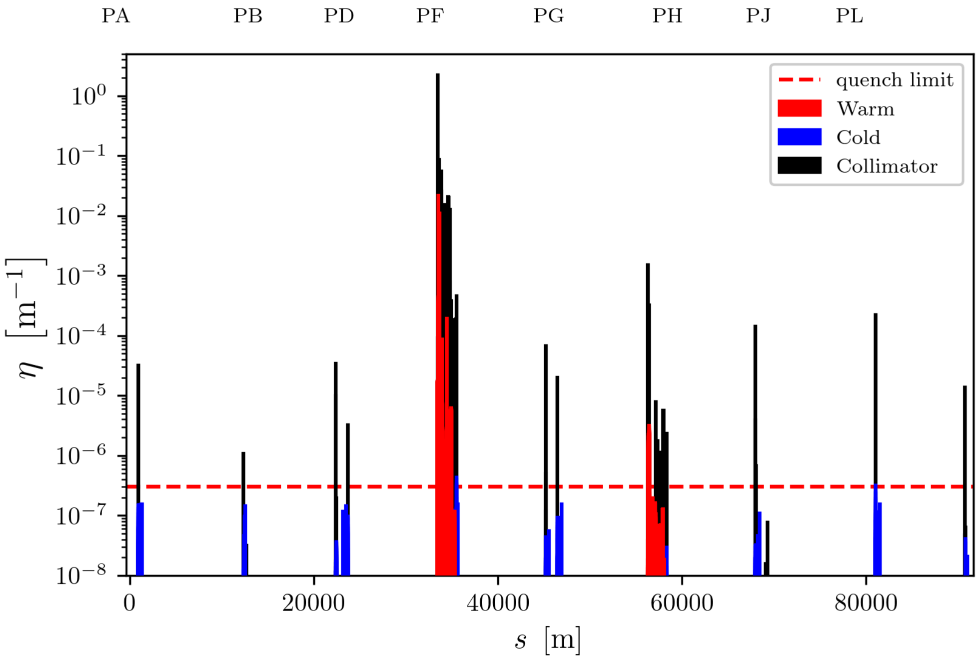
E_{loc} - energy lost in $[s, s+\Delta s]$

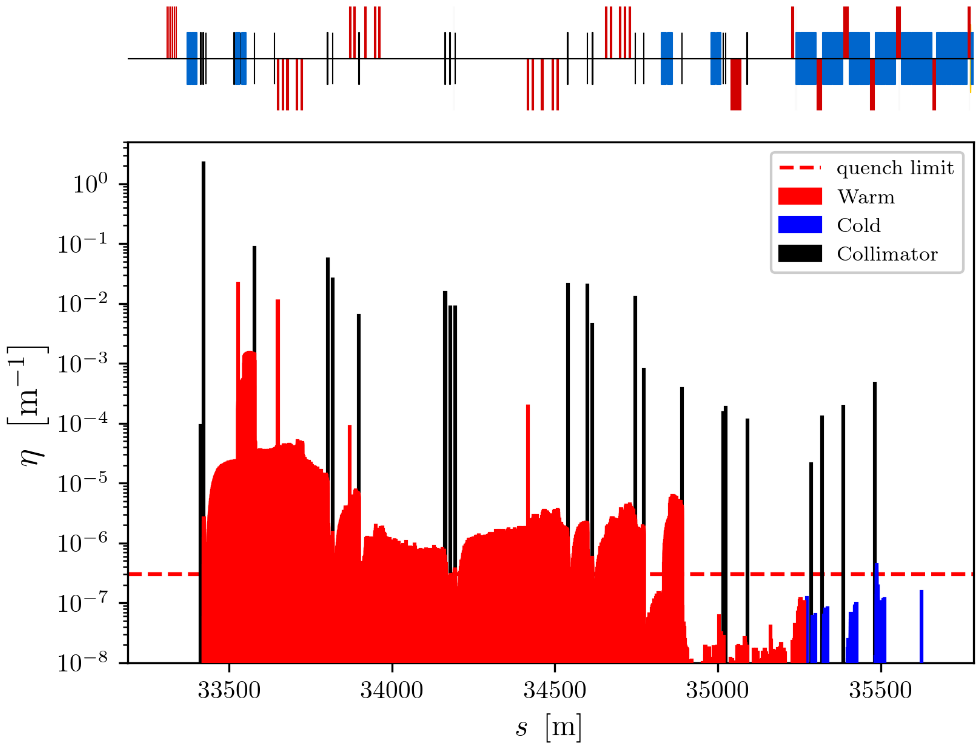
E_{max} - peak energy lost



FCC-hh collimation simulation studies

- **Good general performance of the collimation system observed, with some caveats**
  - Few cold losses observed on superconducting elements, despite the extreme 12 minute lifetime scenario
  - The performance is worse than in the CDR configuration
  - Even with of a 4th DS collimator in PF, the losses there exceed the estimated quench limit by up to 55%
  - This is a preliminary configuration; future iterations will focus on optimizing the performance





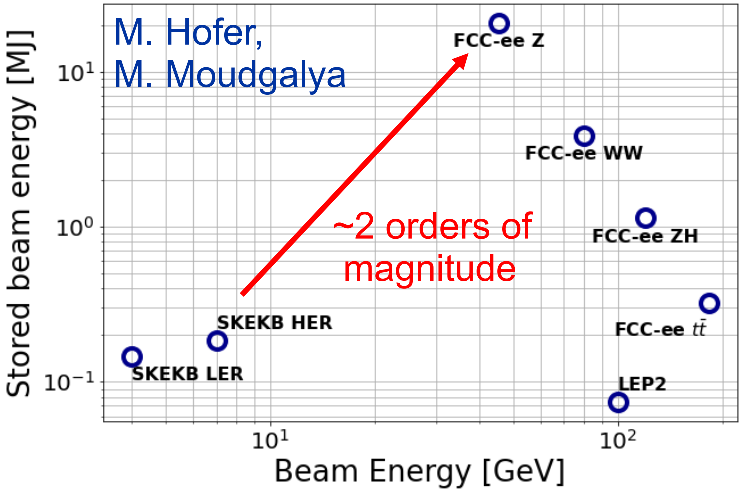
FCC-hh collimation and future work

- **Optimize the collimation system design for the new FCC-hh baseline**
  - In the CDR configuration, the FCC-hh collimation system was found adequte to protect the machine from quenches during lifetime drops to 12 minutes with 11.6 MW of loss power.
  - The goal is to recover and improve on the CDR performance, while staying within the requirements
  - Iterations on the collimation optics and the collimation system parameters are ongoing
  - The impact on the collimators and magnets should be checked with energy deposition studies
  - The impedance must also be checked in the new configuration
  - Repeat FLUKA energy deposition studies and thermo-mechanical studies with the latest lattice

- **Need to study all relevant beam loss scenarios**
  - Off-momentum collimation
  - Failure modes like asynchronous dump
  - Pb ion beam collimation

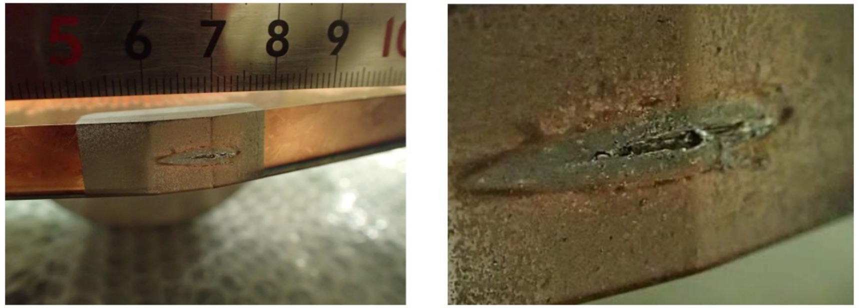
Collimation for the FCC-ee

- **The FCC-ee is the FCC first stage e+e- collider**
  - 91 km circumference, tunnel compatible with the FCC-hh
  - 4 beam operation modes, optimized for production of different particles: ***Z*** (45.6 GeV), ***W*** (80 GeV), ***H*** (120 GeV), $t\bar{t}$ (182.5 GeV)



Comparison of lepton colliders

- **The FCC-ee presents unique challenges**
  - The stored beam energy reaches **17.8 MJ** for the **45.6 GeV (*Z*)** mode, which is comparable to heavy-ion operation at the LHC
  - Such beams are highly destructive: a collimation system is required
  - The main roles of the collimation system are:
    - Reduce the backgrounds in the experiments
      - Main goal of existing and previous e+e- colliders, but for the FCC-ee the beams are very dangerous for the machine itself
    - Protect the equipment from unavoidable losses
  - Two types of collimation foreseen for the FCC-ee:
    - The beam halo (global) collimation
    - Synchrotron Radiation (SR) collimation – near the IPs

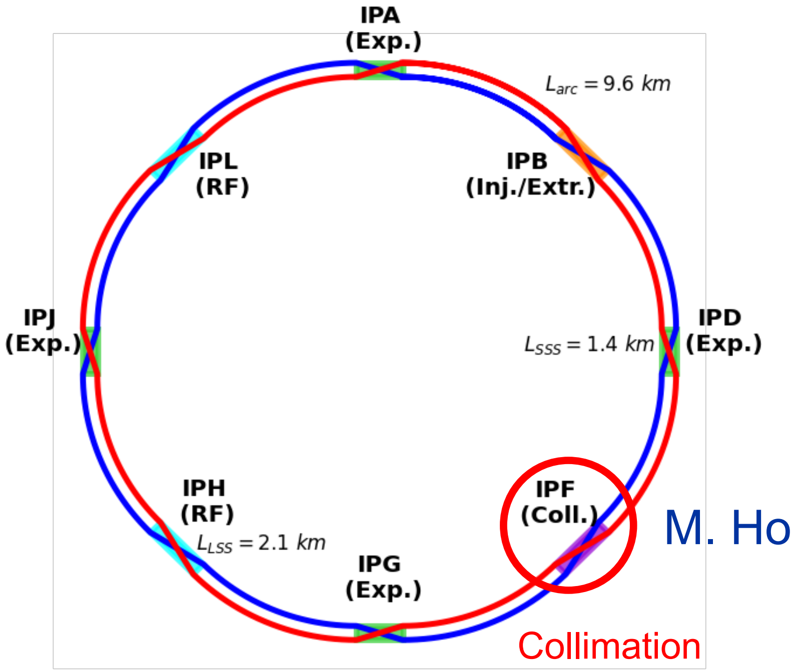


Damage to coated collimator jaw due to accidental beam loss in the SuperKEKB – T. Ishibashi (talk)

FCC-ee collimation system

- **Dedicated halo collimation system in PF**
  - Two-stage betatron and off-momentum collimation in one insertion
  - Defines the global aperture bottleneck
  - Dedicated collimation optics (M. Hofer)
  - First collimator design for beam cleaning performance (G. Broggi)

- **Synchrotron radiation collimators around the IPs**
  - 6 collimators and 2 masks upstream of the IPs (K. André, talk)
  - Designed to reduce detector backgrounds and power loads in the inner beampipe due to photon losses

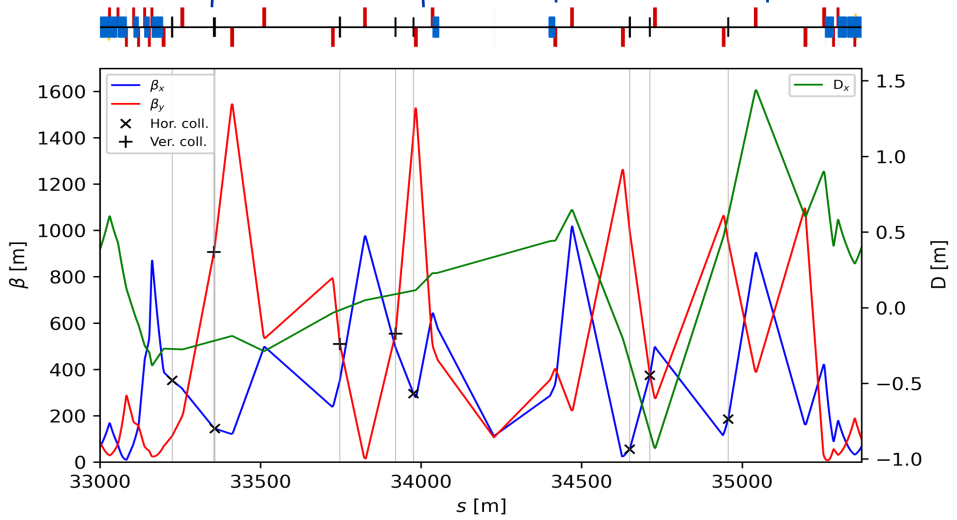


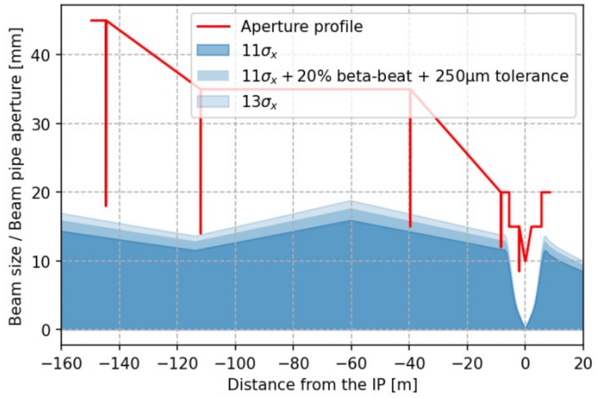
M. Hofer

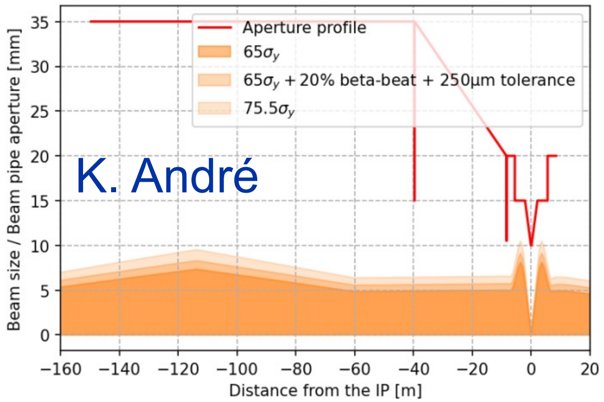
Collimation insertion

betatron

off-momentum



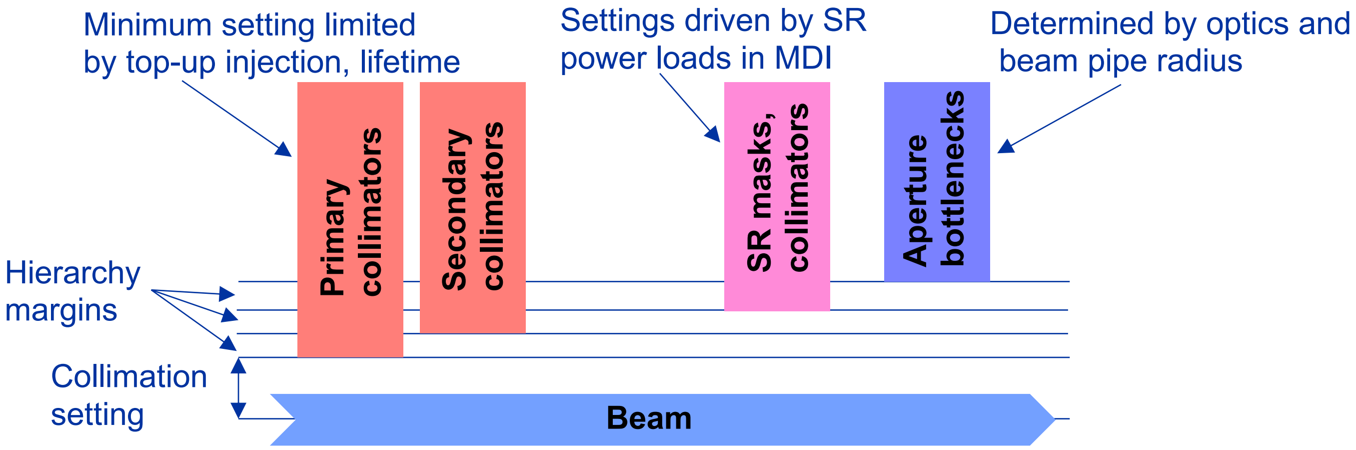




K. André

FCC-ee aperture

- **The aperture bottlenecks are in the experimental interaction regions (IRs)**
- **The bottlenecks must be protected**
  - The final focus quadrupoles are superconducting and there is a risk of quenches
  - The detector is sensitive to backgrounds from beam losses
  - The SR collimators and masks are not robust to large direct beam impacts, can also produce backgrounds
  - The collimation tolerances are tight (M. Hofer, talk)



Minimum setting limited by top-up injection, lifetime

Settings driven by SR power loads in MDI

Determined by optics and beam pipe radius

Primary collimators

Secondary collimators

SR masks, collimators

Aperture bottlenecks

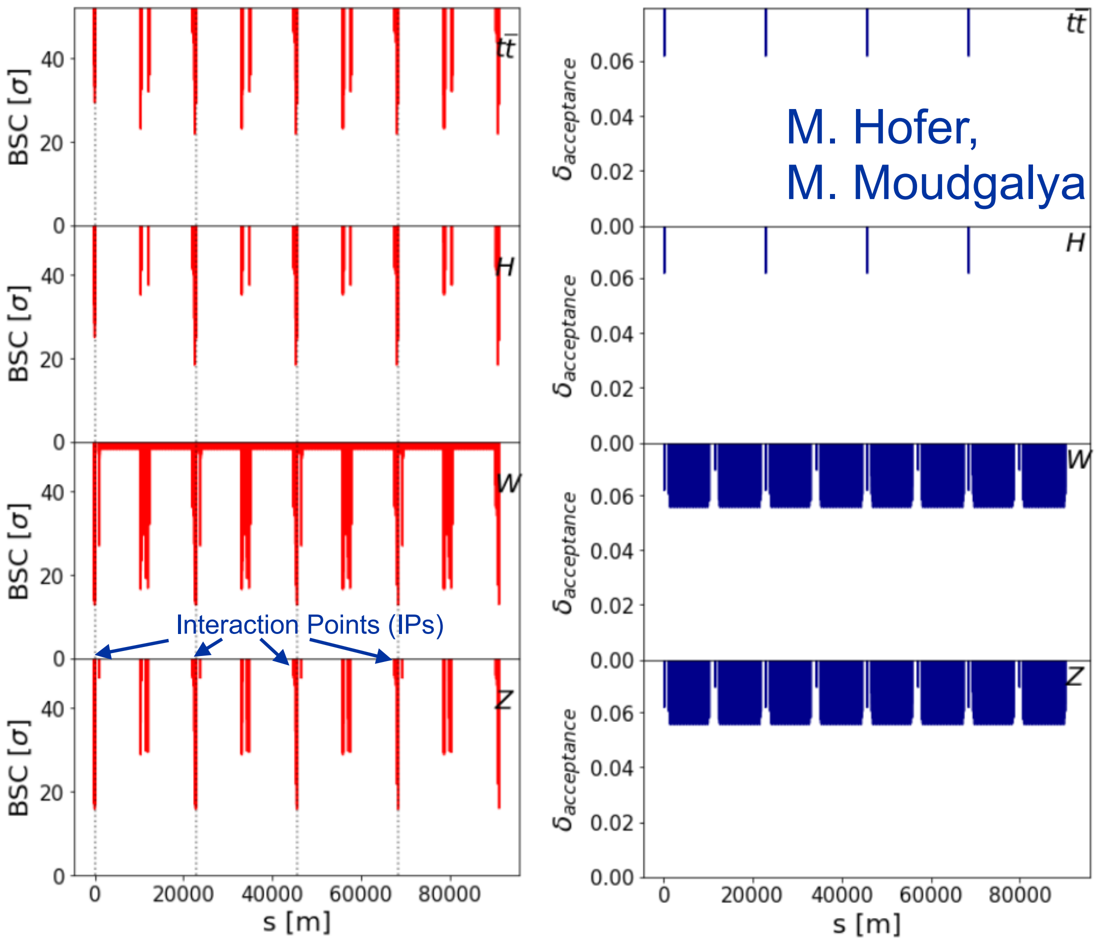
Hierarchy margins

Collimation setting

Beam

Beam stay-clear (**BSC**) is the distance from the beam to the aperture in units of beam size

The momentum acceptance is the $\delta = A / D$, where **A** is mechanical aperture and **D** is dispersion



M. Hofer, M. Moudgalya

Aperture bottlenecks for the different operating modes

FCC-ee beam losses

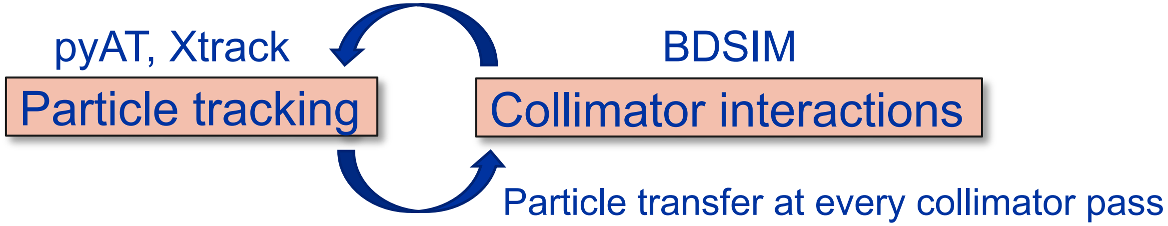
- **The FCC-ee will operate in a unique regime**
  - Electron / positron beam dynamics and beam-matter interactions
  - Stored beam energy exceeding material damage limits
  - Superconducting final focus quadrupoles, crab sextupoles, and RF cavities
  - Must study the beam loss processes and define the ones to protect against (H. Burkhardt, talk)
  - Must study the equipment loss tolerances, for both regular and accidental losses

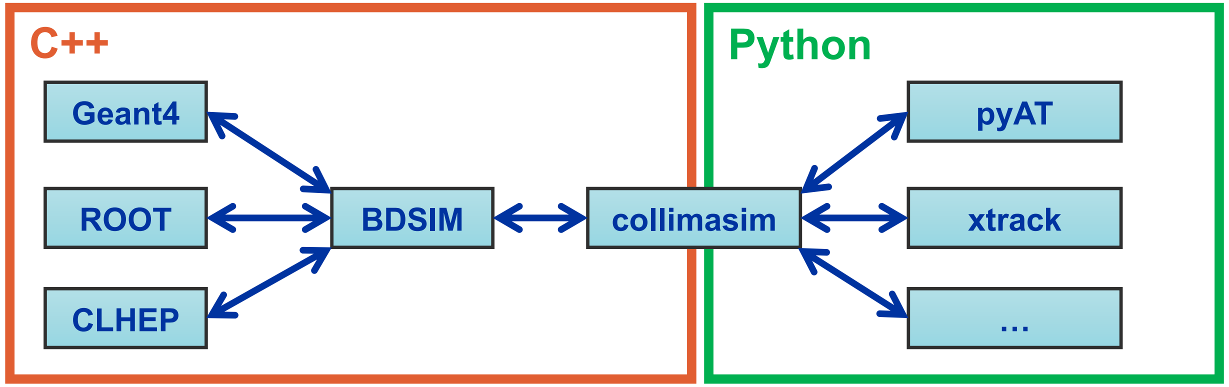
- **Loss scenarios selected for particle tracking studies:**
  - Beam halo
  - Top-up injection
  - Spent beam due to collision processes (Beamstrahlung, Bhabha scattering)
  - Failure modes (injection failures, asynchronous dump, others)
  - Beam tails from Touschek scattering and beam-gas interactions

FCC-ee collimation simulation setup

- **The FCC-ee presents unique challenges for collimation simulations:**
  - Synchrotron radiation and magnet strength (optics) tapering to compensate it
  - Complex beam dynamics – strong sextupoles in lattice, strong beam-beam effects (Beamstrahlung)
  - Electron/positron beam particle-matter interactions
  - Large accelerator – 91 km beamline, efficiency is crucial

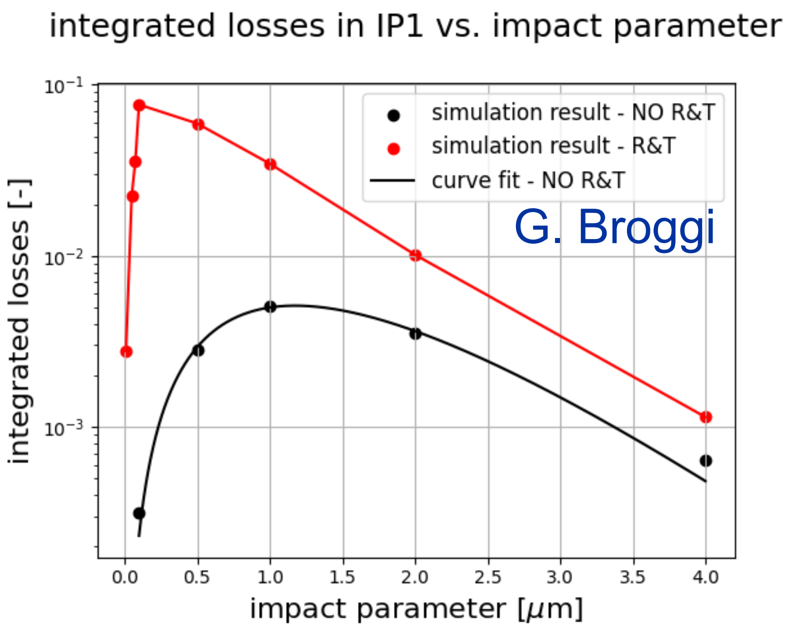
- **Xsuite + BDSIM (Geant4)**
  - Benchmarked against other codes for FCC-ee – MAD-X, pyAT, SixTrack-FLUKA coupling (IPAC’22 paper)
  - Used for for the latest FCC-ee collimation studies
  - Tests / benchmarks in other machines:
    - LHC (FCC-ee optics meeting talk) – G. Broggi
    - PS (NDC section meeting talk) – T. Pugnat





Current study: beam halo losses

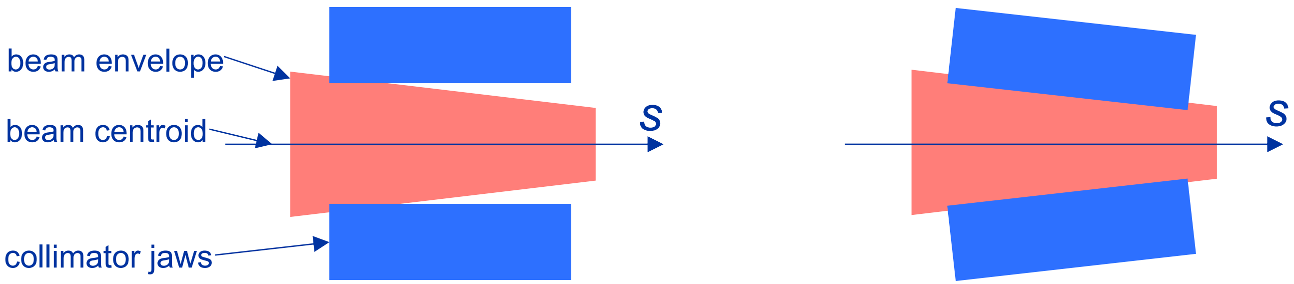
- **"Generic beam halo" beam loss scenario:**
  - Assume a slow diffusion process – halo particles intercepted by the primary collimators
  - The diffusion is not simulated, all particles start impacting a collimator
  - The particles have the "worst" impact parameter
    - Determined with an impact parameter scan
    - Provides a conservative performance estimate
  - Study horizontal and vertical betatron halo, and off-momentum halo impacts
  - Track the particles scattered out from the collimator and record losses on the aperture
  - Specify a beam lifetime that must be sustained
    - Currently assuming a **5 minute** lifetime



Impact parameter scan for 2 IP CDR lattice with MoGr primary collimator, with and without radiation and tapering (R&T)

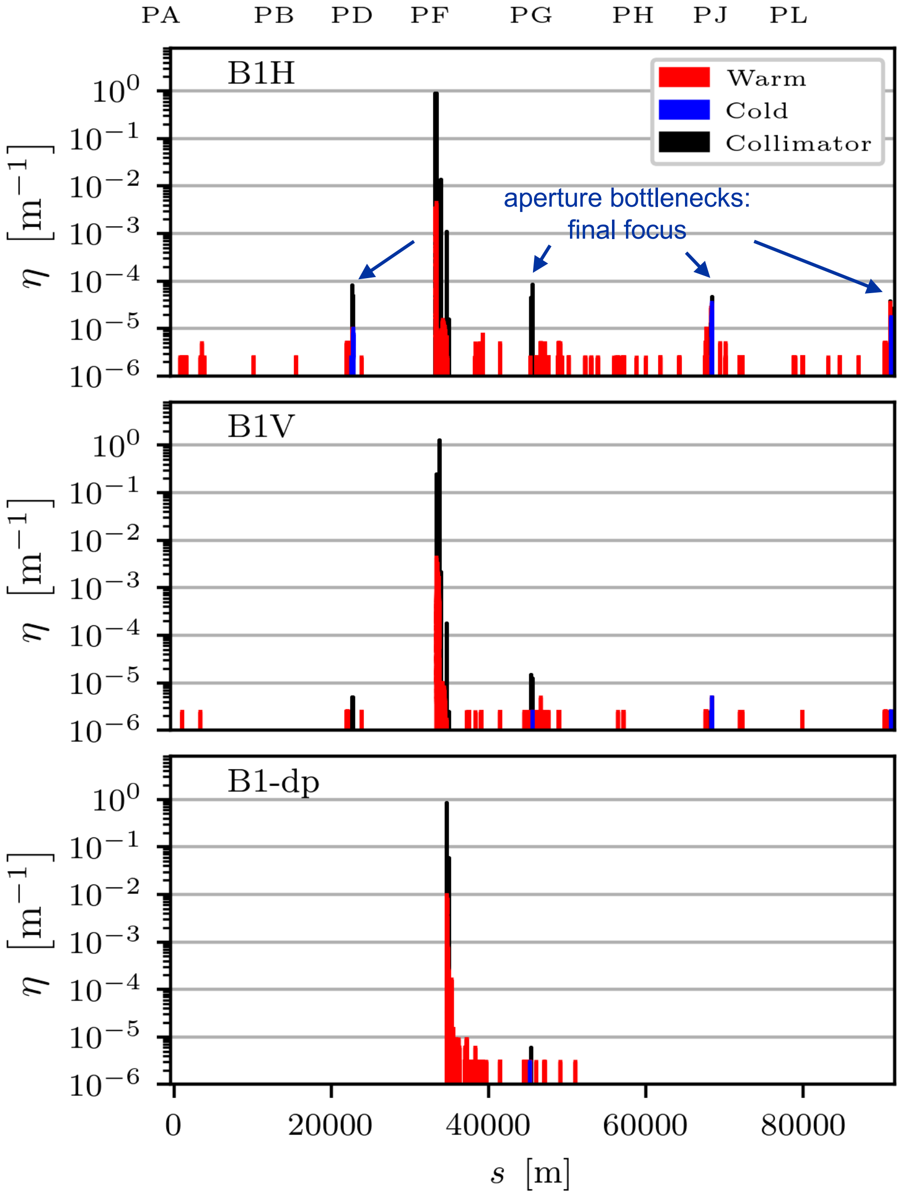
Beam halo losses for the *Z* mode

- The *Z* mode is the current focus (Beam 1, 45.6 GeV positrons), **17.8 MJ** stored beam energy
- Particles simulated directly impacting the primary collimators
- Radiation and tapering included, **1 μm** impact parameter
- **5 min** beam lifetime assumed, total loss power **59.2 kW**
- Studied 3 cases:
  - **Horizontal betatron losses (B1H)**
  - **Vertical betatron losses (B1V)**
  - **Off-momentum losses $\delta < 0$ (B1-dp)**
- For the off-momentum case, using a tilted collimator, aligned to the beam divergence



Parallel jaw and tilted collimator schematic (See G. Broggi, IPAC'23)

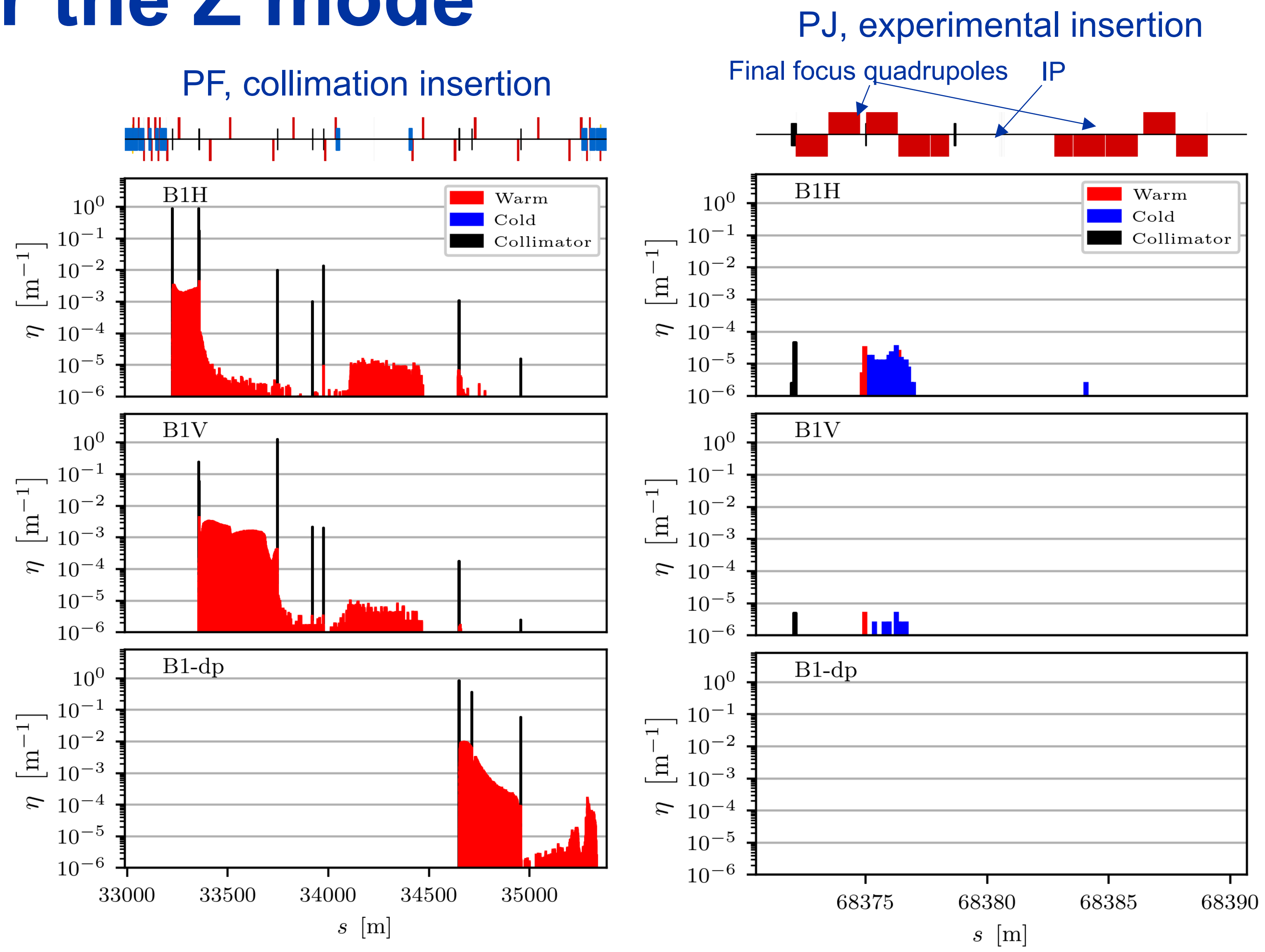
Total loss power: **59.2 kW**



Z-mode betatron halo loss maps

Beam halo losses for the Z mode

- The beam collimation system shows good performance
  - More than **99.96%** of losses contained within the collimation insertion PF
  - Only up to 1.7 W of losses reaching the experimental IRs
  - Tilted primary collimators are essential for the performance at the Z mode
  - Energy deposition studies are required for the collimators and most exposed magnets


PF, collimation insertion

PJ, experimental insertion

Final focus quadrupoles

IP

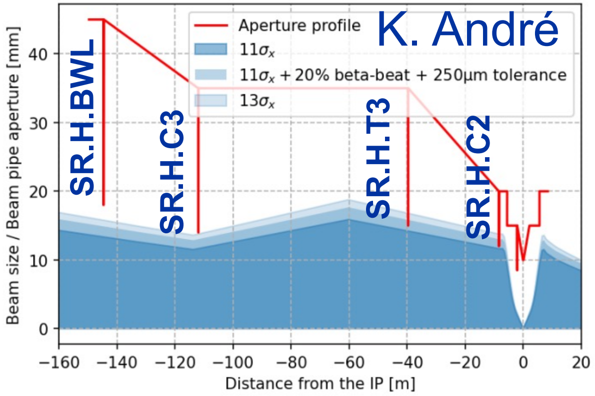
Z-mode betatron halo loss maps for selected regions

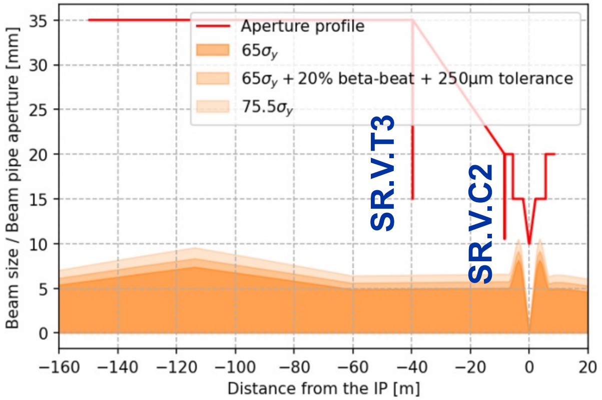
Z mode losses on SR collimators

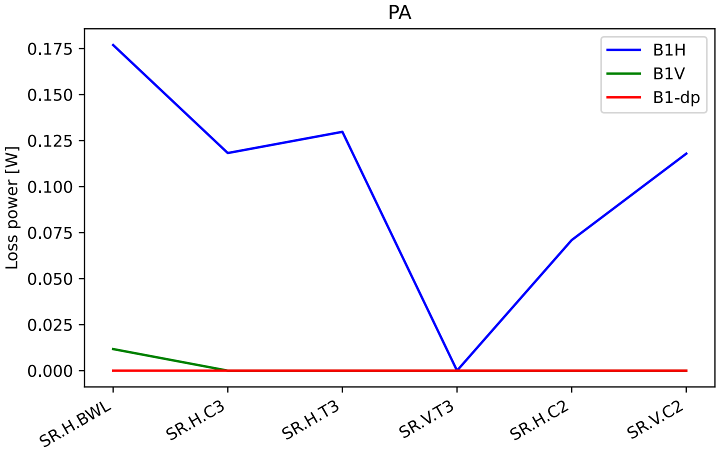
- **The SR collimators intercept losses for all cases**
  - Highest load on BWL and C3 horizontal collimators
  - Lowest load on the vertical T1 collimator

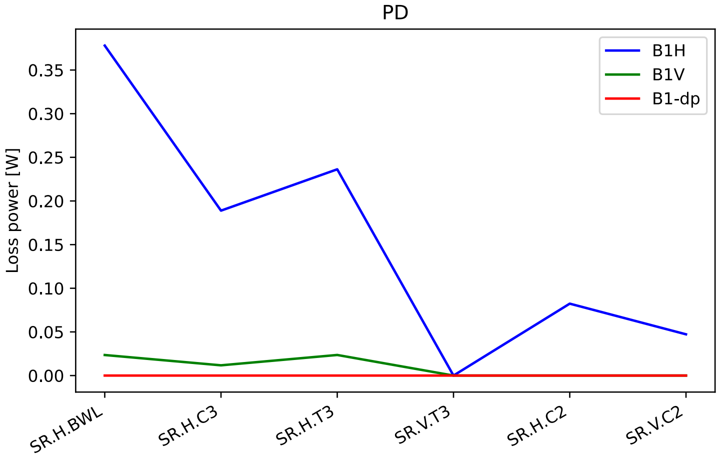
beam

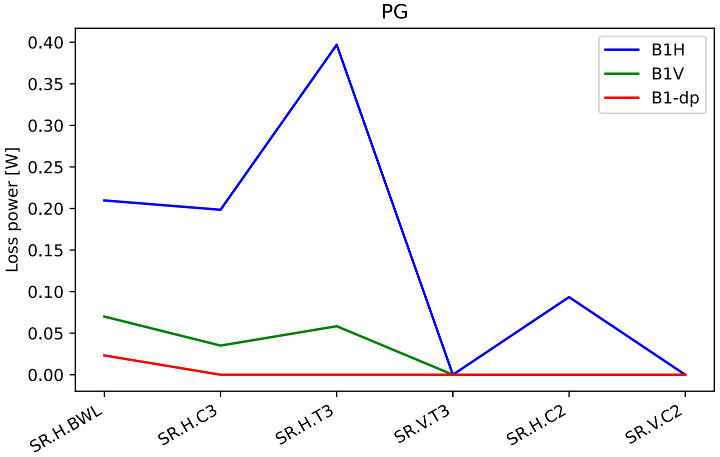
Total loss power: **59.2 kW**

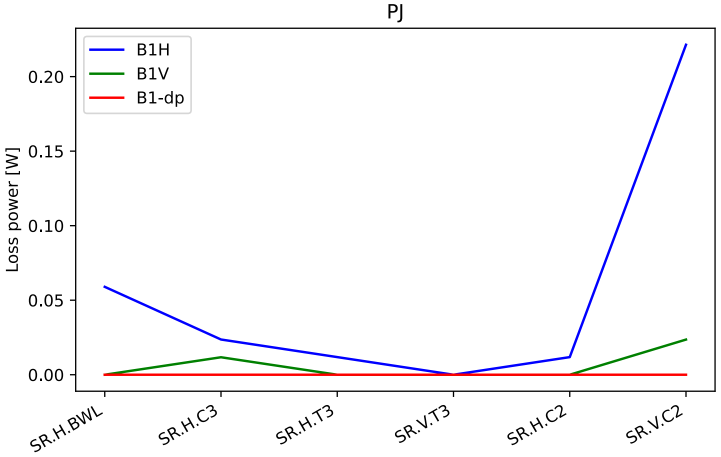






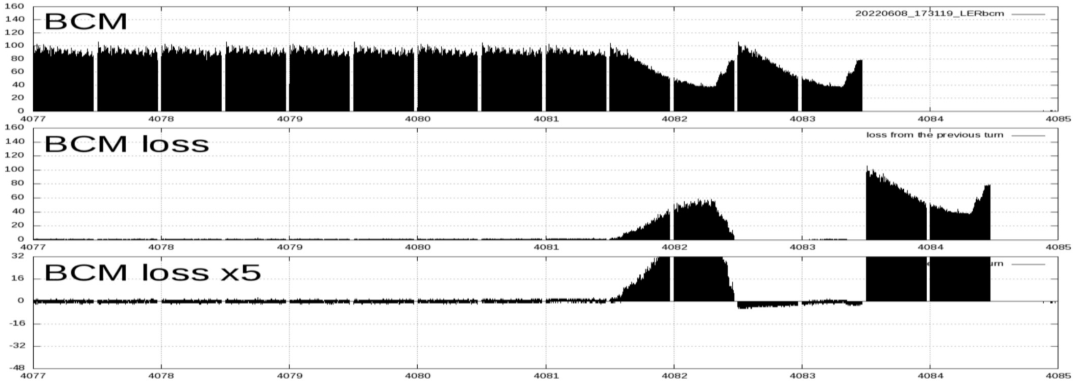






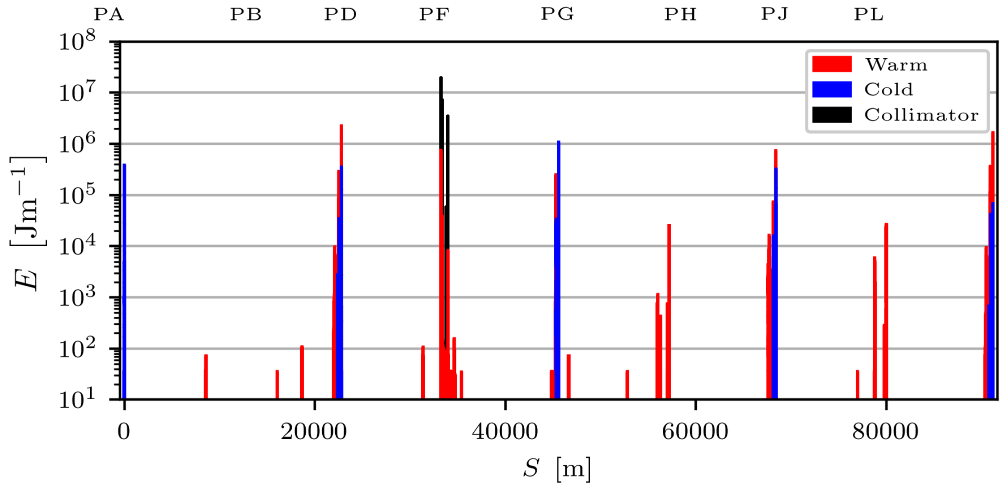
Fast beam losses for the FCC-ee

- **Fast beam losses due to failures are important to study**
  - SuperKEKB has experiences sudden beam loss, up to 80% intensity loss over 2 turns (T. Ishibashi, talk)
  - Such events have damaged collimators, and the cause is not well understood



Beam current during a sudden beam loss in the SuperKEKB – T. Ishibashi (talk)

- **Fast beam losses for the FCC-ee**
  - It is not clear if such a scenario could occur in the FCC-ee
    - Accidental beam loss scenarios and their likelihood should be studied in detail to devise a protection strategy
  - If protection against SuperKEKB-type losses is needed, it could drive significant changes in the collimation design
    - Preliminary studies show that a bespoke solution would be needed to handle such losses
    - As a worst-case, sacrificial collimators can be considered



Preliminary FCC-ee Z-mode fast beam loss with 80% intensity loss over 2 turns

FCC-ee collimation summary

- **Studies of beam losses and collimation for the FCC-ee**
  - First collimation system design available, including beam halo and SR collimators
  - Simulations of beam loss scenarios ongoing
    - Beam halo losses studied Z mode
    - No show-stoppers identified so far
    - Input on equipment loss tolerances needed to optimize performance
  - First consideration of fast beam losses due to failures
    - A better definition of the loss scenarios is needed, can not evaluate if the design is adequate

- **Next steps**
  - Study other beam loss scenarios
  - Obtain input for the equipment loss tolerances – superconducting magnets, collimators, other
    - **Energy deposition studies required for magnets, collimators, and masks**
    - **Detailed evaluation of detector backgrounds required – shielding, muon backgrounds**
  - Study all beam modes

Thank you!