Simulation of the FCC-hh collimation system

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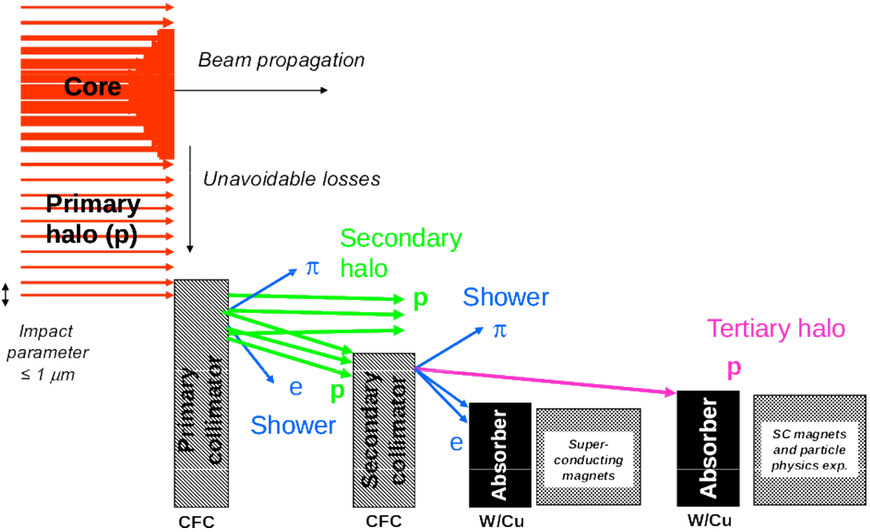
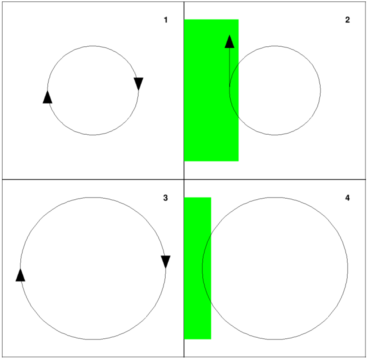
General collimation system operation



Collimation in normalised phase space



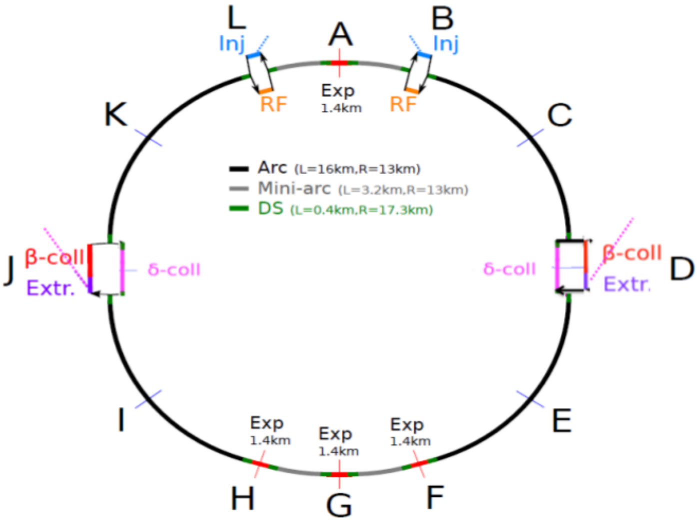
1. Particle circulates in phase space
2. Particle encounters a collimator jaw (green). Particle is scattered and has an increase in transverse momentum.
3. Particle circulates at a larger amplitude in phase space.
4. Particle encounters a secondary collimator at a larger phase space amplitude.

FCC parameters

Parameter	LHC (V6.503)	HL-LHC	FCC (V6)	Scale (LHC)
Length (m)	26658	26658	100171	$\times$3.76
Top beam energy (GeV)	7000	7000	50000	$\times$7.14
Bunch count (25ns)	2808	2808	10600	$\times$3.77
Bunch particle count (10^{11})	1.15	2.2	1	$\times$0.87
Stored beam energy (GJ)	0.362	0.693	8.4	$\times$23.2
Normalised emittance ($\mu mrad$)	3.75	2.5	2.2	$\times$0.59
Luminosity ($10^{34}\mathrm{cm}^2\mathrm{s}^{-1}$)	1	5	5	$\times$5
Beam-collimator interaction $\sqrt{s}$ (GeV)	114.619	114.619	306.315	$\times$2.67

- Remember: $E_{\text{fixed target}} = \sqrt{2m_p E_{\text{beam}} + 2m_p^2}$
- Note the 23x increase in stored beam energy
- The collimation system cleaning efficiency must be higher than the LHC!

FCC ring


L
A
B
Inj
Inj
Exp
1.4km
RF
RF
K
C
Arc (L=16km,R=13km)
Mini-arc (L=3.2km,R=13km)
DS (L=0.4km,R=17.3km)
J
β-coll
Extr.
δ-coll
δ-coll
β-coll
Extr.
D
I
E
Exp
1.4km
Exp
1.4km
Exp
1.4km
H
G
F

Collimation system simulation codes

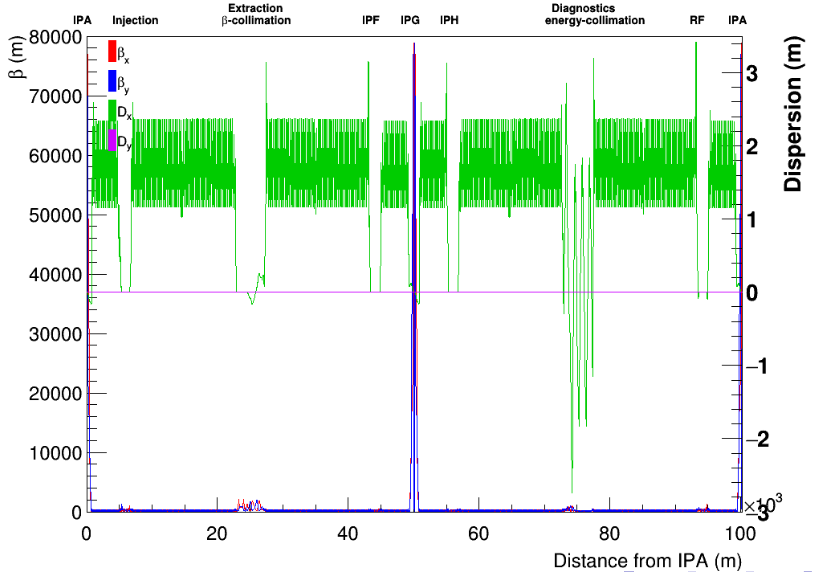
- Multiple computer codes are currently used for collimation simulations.
- Two methods currently exist: Only track beam protons (fast) or perform a full showering simulation (very slow).
- Only tracking beam protons is fast to simulate, but does not give the full energy deposition.
- Full showering calculations are very slow, and require a full description of the accelerator component geometry but is the most precise method.
- Sixtrack and Merlin use the first method (only track protons).
- FLUKA and BDSIM (Geant4) track full secondary particle showers.
- The development of collimation simulation tools follows on from previous EUCARD work for the LHC and HL-LHC.
- Without this previous work, the results for the FCC would not be possible yet!
- Multiple codes allow cross checking to take place (collaboration takes place with the LHC collimation teams).

Collimation system simulation codes

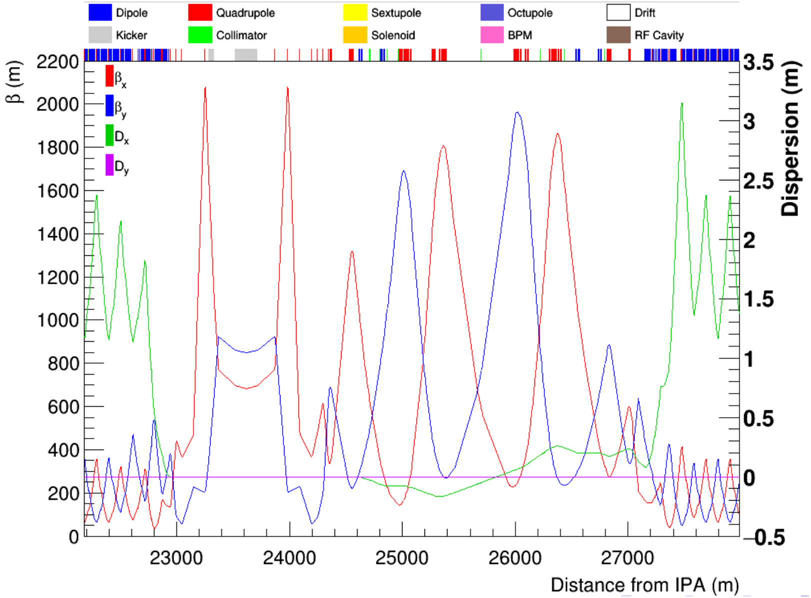
- The beam proton tracking method used in Sixtrack and Merlin simulates the passage of protons through collimator material only
- If a proton hits the beam pipe or interacts inelastically (to produce secondary particles), it is considered as lost and the location is recorded
- This can be used as an input to a detailed secondary particle generation and energy deposition calculation using FLUKA or Geant4
- Tracking only protons and their loss locations is what will be used for the initial simulation work
- See Maria's talk for sixtrack results.
- The following results use Merlin.

Collimation simulation requirements

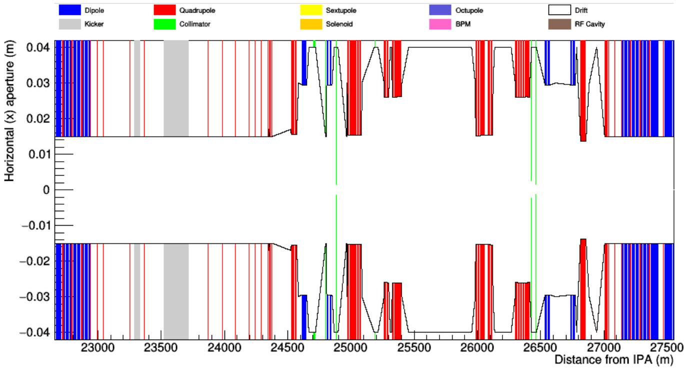
- In order to perform an accurate simulation the following items must be considered:
- Optics - magnet layouts and settings, magnet field and alignment errors, particle tracking/integration
- Aperture - including the collimator jaw settings and the beam pipe
- Physics - proton interactions with the collimator jaw materials
- Beam conditions - initial bunch distributions and matching bunches into the optics
- Changes in any of the above will give a different distribution in the output losses

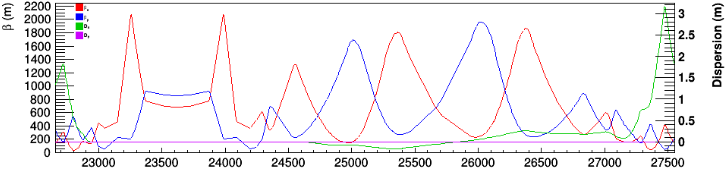

IPA
Injection
Extraction
β-collimation
IPF
IPG
IPH
Diagnostics
energy-collimation
RF
IPA
β (m)
80000
70000
60000
50000
40000
30000
20000
10000
0
βx
βy
Dx
Dy
Dispersion (m)
3
2
1
0
−1
−2
−3
×10³
0
20
40
60
80
100
Distance from IPA (m)

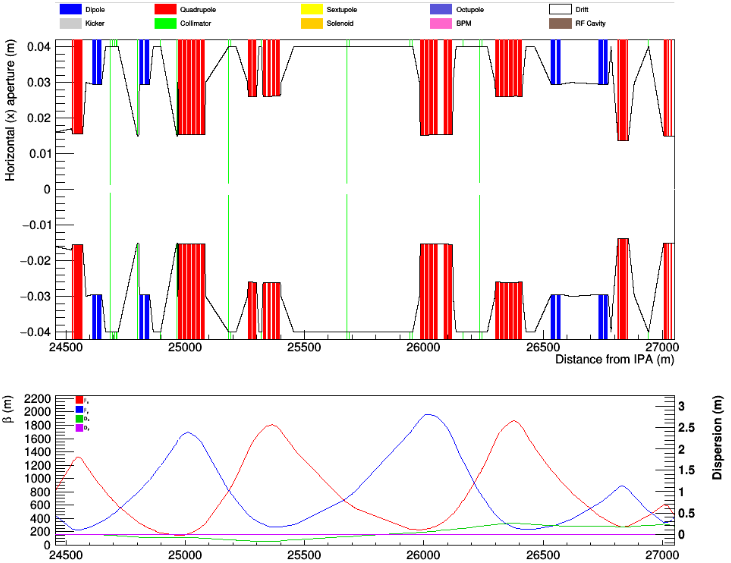
Optics - Betatron collimation system



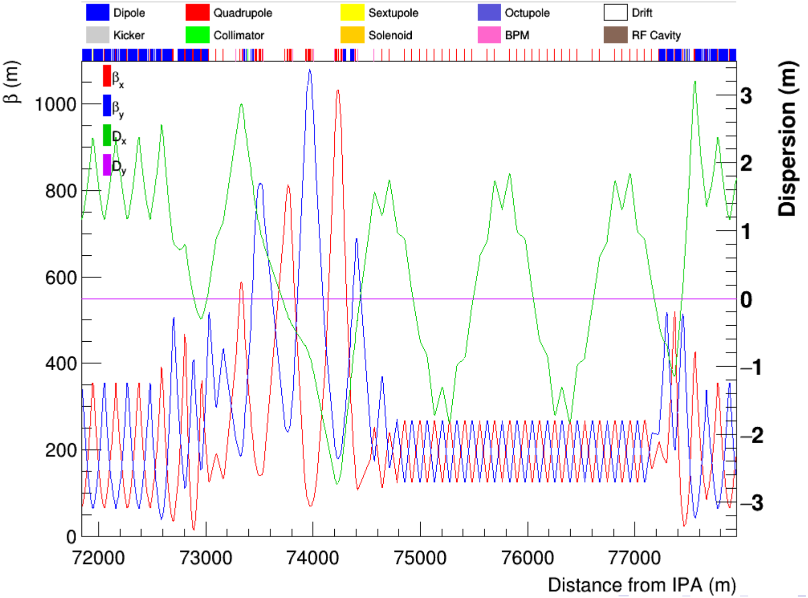
Aperture - Betatron collimation

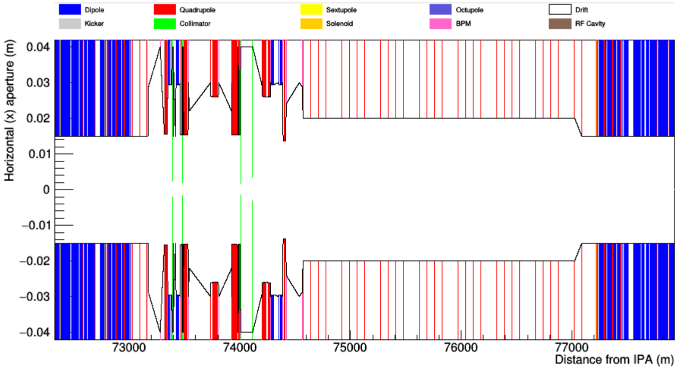




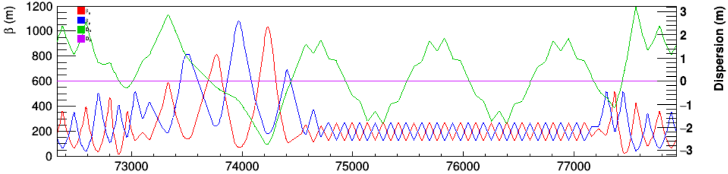

Dipole
Quadrupole
Sextupole
Octupole
Drift
Kicker
Collimator
Solenoid
BPM
RF Cavity
Horizontal (x) aperture (m)
Distance from IPA (m)
β (m)
Dispersion (m)

Optics - Energy collimation system

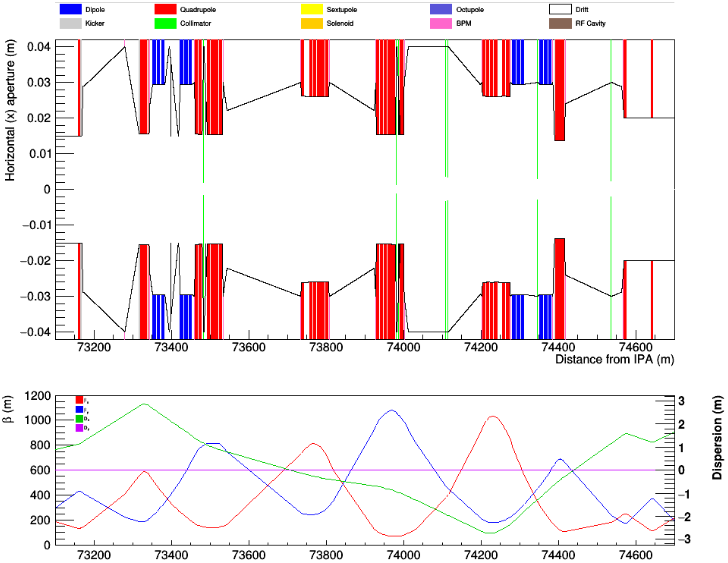




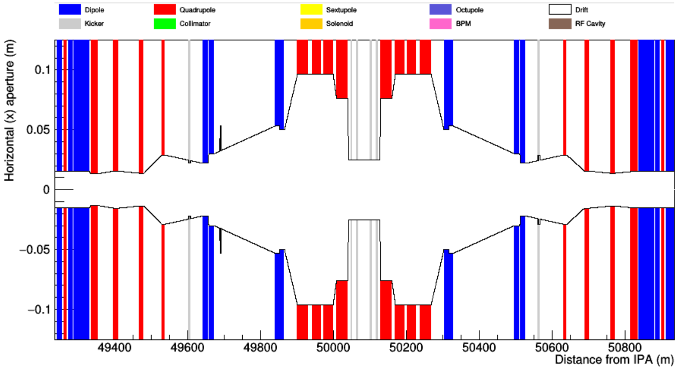
Dipole
Quadrupole
Sextupole
Octupole
Drift
Kicker
Collimator
Solenoid
BPM
RF Cavity
Horizontal (x) aperture (m)
0.04
0.03
0.02
0.01
0
−0.01
−0.02
−0.03
−0.04
73000
74000
75000
76000
77000
Distance from IPA (m)

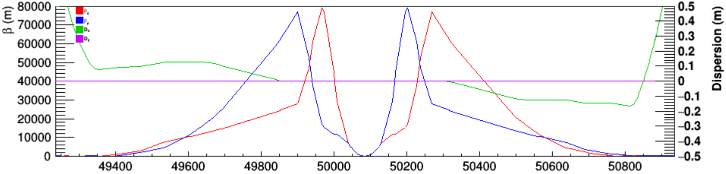


β (m)
1200
1000
800
600
400
200
0
73000
74000
75000
76000
77000
Dispersion (m)
3
2
1
0
−1
−2
−3


Dipole
Quadrupole
Sextupole
Octupole
Drift
Kicker
Collimator
Solenoid
BPM
RF Cavity
Horizontal (x) aperture (m)
Distance from IPA (m)
β (m)
Dispersion (m)

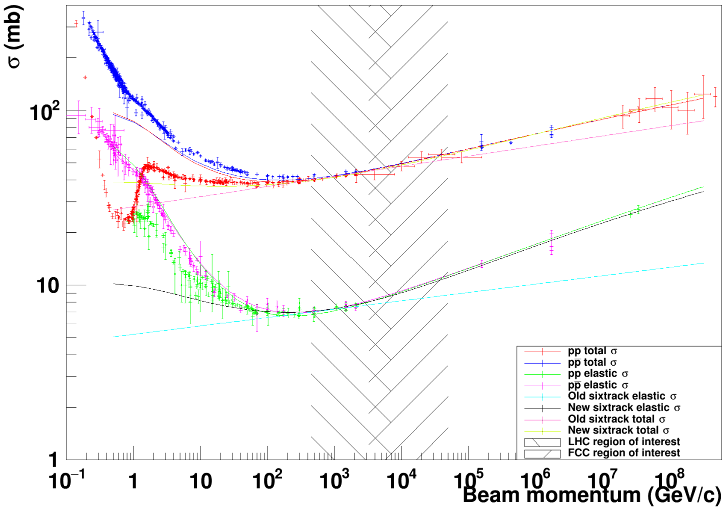
Aperture - Experimental IRs



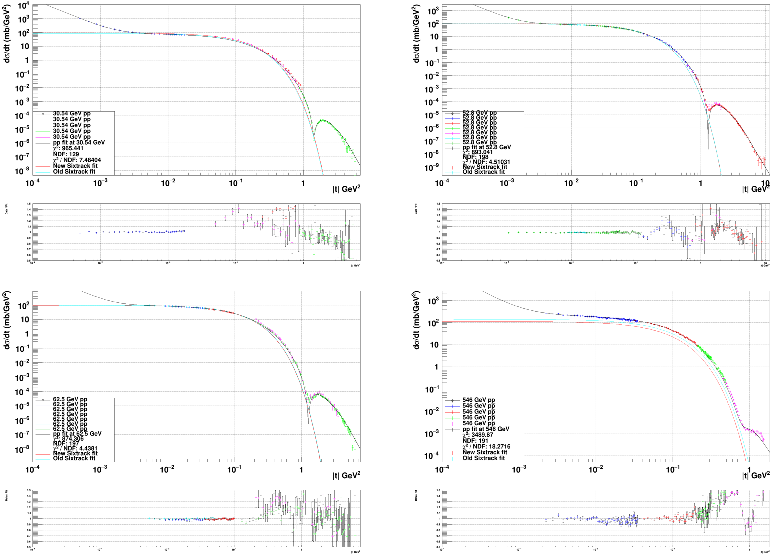


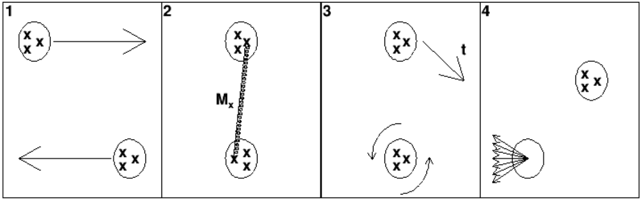
proton-collimator jaw interactions

- The passage of protons through collimator jaw materials must be modelled sufficiently accurately.
- Two main types of physics must be considered: interactions where the cross section is very large and can be modelled as a continuous process and rarer descrete processes where a proton interacts with a nucleon inside the collimator jaw directly.
- Examples of continuous process include multiple coulomb scattering and atomic ionization.
- Examples of proton-nucleon interactions include elastic and single diffractive scattering.
- The latter types require an accurate model for the total and differential cross sections up to $\sqrt{s} = 306 GeV$.
- Finally these models must be combined into a full proton-nucleus interaction model (still a work in progress).


σ (mb)
10^2
10
1
10^-1
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Beam momentum (GeV/c)
pp total σ
pp̄ total σ
pp elastic σ
pp̄ elastic σ
Old sixtrack elastic σ
New sixtrack elastic σ
Old sixtrack total σ
New sixtrack total σ
LHC region of interest
FCC region of interest

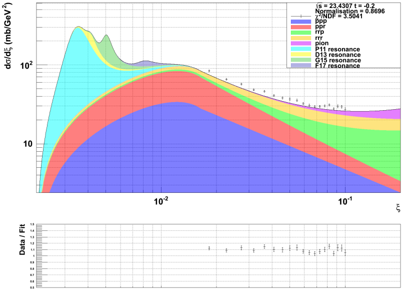
Physics - Elastic differential

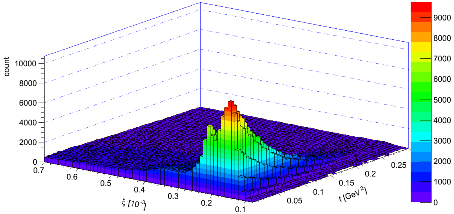




1. Two nucleons with quarks denoted as x approach each other.
2. A pomeron is exchanged between two quarks, with an energy transfer denoted M_x.
3. The lower proton is excited to a higher angular momentum state, and the upper proton acquires a momentum transfer t.
4. The lower proton de-excites and decays, whilst the upper proton survives with its trajectory and energy adjusted.

Physics - Single Diffraction





- Single diffraction generates an off-momentum beam halo due to the energy loss (M_x) of the incident proton.
- Shown is $\xi \approx \frac{M_x^2}{s}$
- Paper to be submitted on all of the above: R. Appleby, R. Barlow, J. Molson, M. Serluca, A. Toader - "The Practical Pomeron for High Energy Proton Collimation".

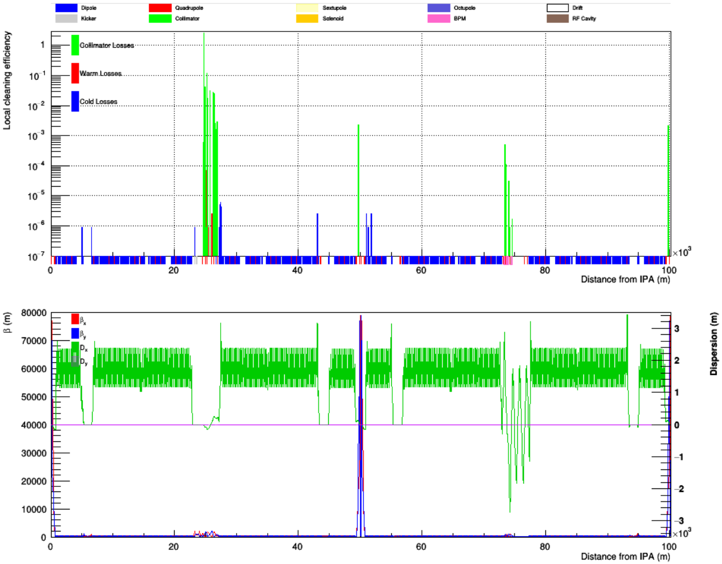
Simulation settings: Horizontal betatron

- 50 TeV beam energy
- Lattice version 6
- Collimator settings - similar physical gaps as the LHC and layout
- Betatron: Primary 7.57σ, Secondary 8.83σ, Tertiary 12.61σ
- Energy: Primary 18.06σ, Secondary 21.67σ, Tertiary 24.08σ
- IR protection 10.47σ.
- 2.2μm rad emittance
- Horizontal beam halo - ring in x,x' point-like in y,y'
- No beam energy spread
- Start tracking on the primary horizontal betatron collimator jaw face
- $1\mu m$ impact factor on the horizontal primary collimator
- Particles are only generated on the jaw face
- 6.4M particles

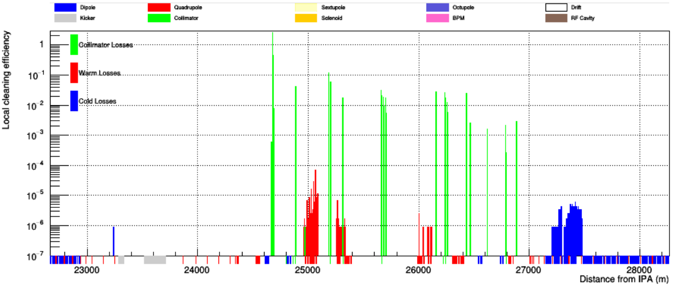
Simulation output

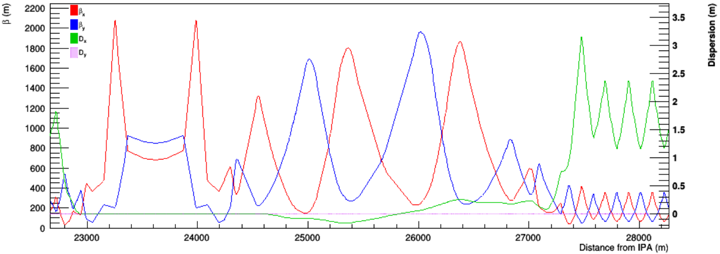
- Track particles and record the locations where they impact the beam pipe or are destroyed within a collimator.
- Use the loss locations to define the cleaning efficiency:
- $\eta_c = \frac{n_i}{n_{total} \Delta s}$
- n_i is the number of particles lost in a bin of size Δs.
- n_{total} is the total number of lost particles.
- A longitudinal bin size of 10cm is used (can be adjusted).
- Usually plotted around the ring as a log plot.
- Ideally all losses will be in the collimators (good).
- protons can escape the collimation system and impact with the cold magnets (bad).

Full ring lossmap

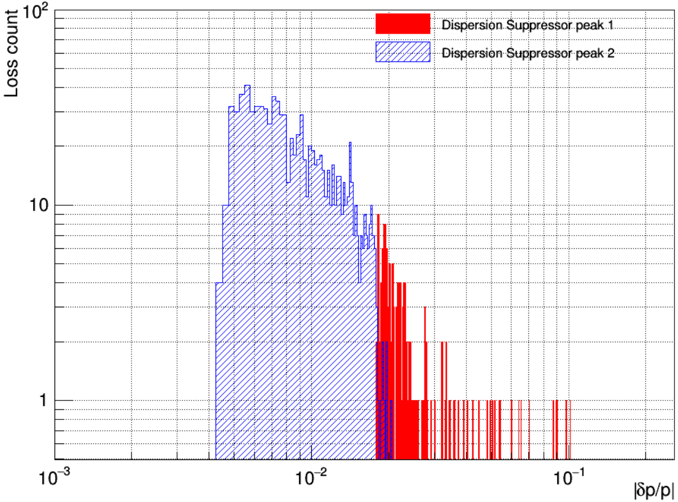


Betatron collimation region

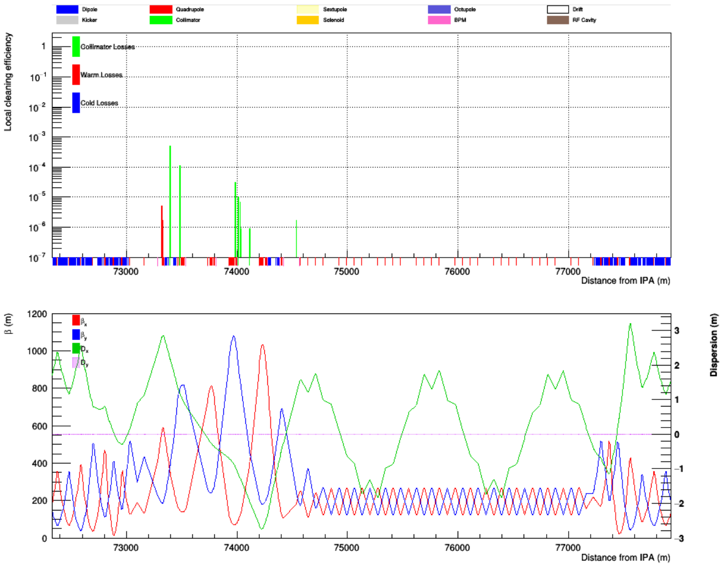




Dispersion suppressor losses



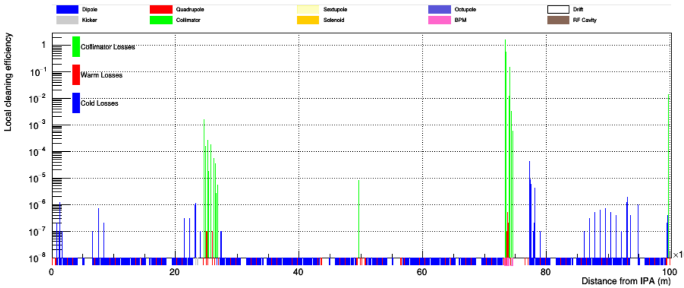
Energy collimation region

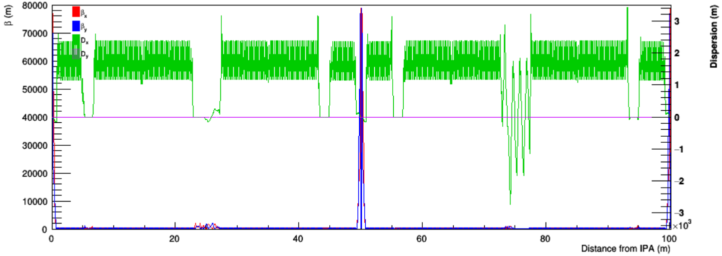


Simulation settings: energy collimation

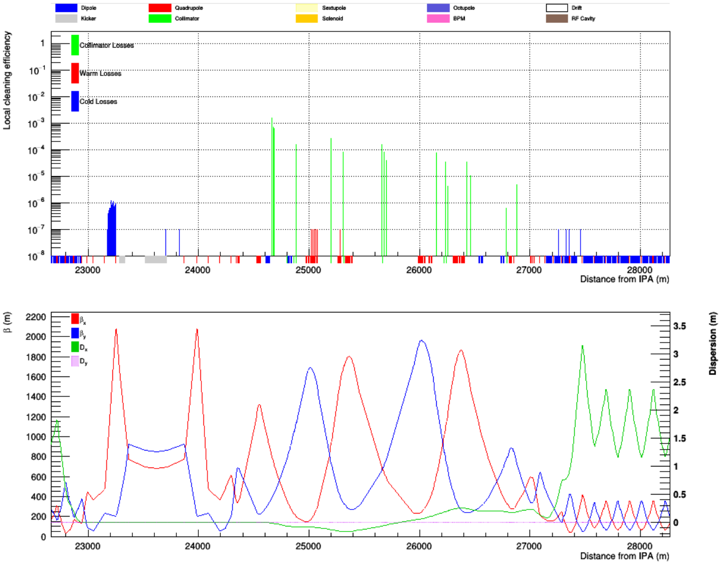
- 50 TeV beam energy.
- Lattice version 6.
- Collimator settings - set to cut at 1×10^{-3} - same as betatron simulation.
- 2.2μm rad emittance.
- Normal distribution in x, x' - Point like in y,y'.
- Start tracking on the primary energy collimator jaw face.
- Particles are only generated on the jaw face with a maximum impact parameter of $1\mu m$.
- 50M particles.

Full ring lossmap

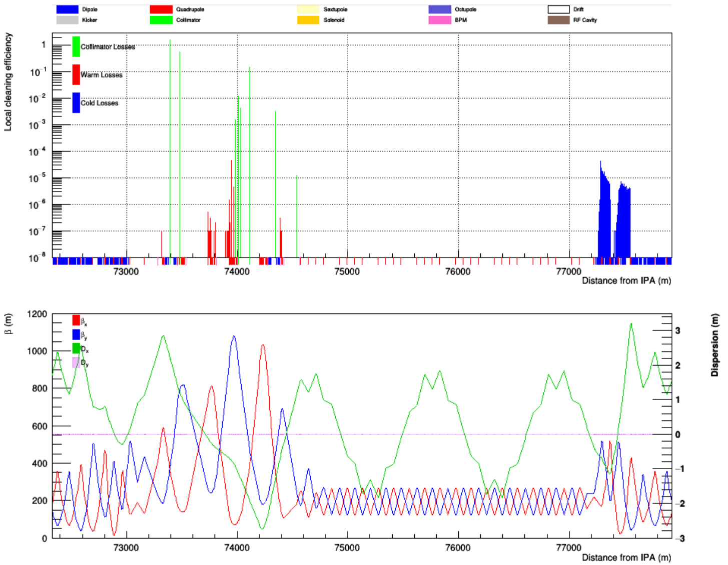


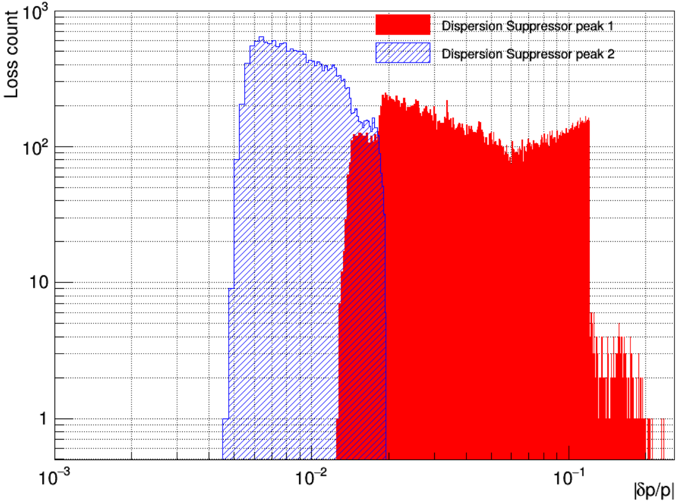


Betatron collimation region



Energy collimation region




Dispersion Suppressor peak 1
Dispersion Suppressor peak 2
Loss count
10^3
10^2
10
1
10^{-3}
10^{-2}
10^{-1}
|δp/p|

Conclusion

- We now have a baseline accelerator layout using an integrated scaled energy and betatron collimation system taken from the LHC.
- Can now produce loss maps for this baseline lattice, including the betatron, energy, and IR protection.
- Next steps are clear - optimise the mechanical beam pipe aperture for the machine and work on methods to reduce the cold magnet dispersion suppressor losses.
- Explore new optical designs and collimation concepts - a pure scaling of the LHC collimation system will not be sufficient for the FCC-hh.

LHC Collimator pictures

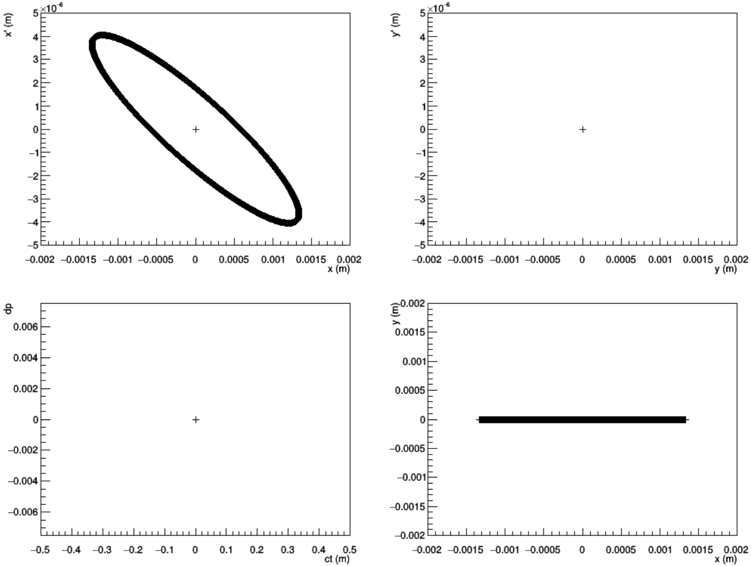
1. Images show a secondary 1m graphite collimator jaw with cooling pipes, and also the geometric jaw taper
2. A view down the collimator jaws as a particle would encounter. Typical jaw gap sizes are 2 to 5mm
3. The collimator jaws installed in the vacuum tank

- Old code commonly used at CERN for tracking - written in fortran 77.
- Currently the standard CERN collimation tool.
- A tracking code that had proton-collimator interactions added from a code called K2.
- Thin lens code with offline aperture checking.

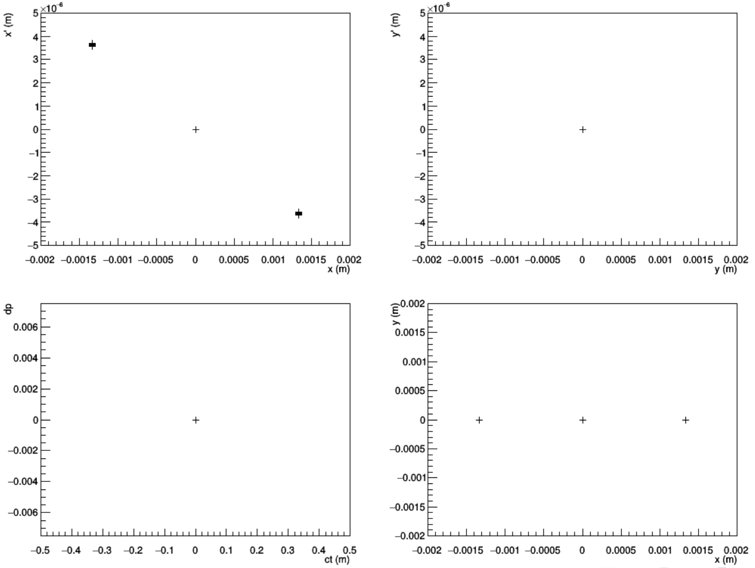
Merlin

- Merlin is a C++ accelerator physics library that was initially developed to simulate the ILC.
- Since it is a library of functions one must write their own simulation code - this allows more flexibility.
- Merlin has already been used to simulate the LHC and HL-LHC collimation system.
- Thick lens tracking with online aperture checking.
- It contains proton-collimator interaction enhancements that allow correct simulations to take place at FCC energies ($\sqrt{s} = 306.3\text{GeV}$) which are different to sixtrack.

Input bunch distribution (without cut)



Input bunch distribution (with cut)



E-col input bunch distribution