Betatron collimation system insertions

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Configuration

- Using lattice V9 (with modifications).
- Many extra TCTs (tertiary collimator) around each experimental IR were required.
- Added the TCDQ (extraction protection) in the dump insertion and have split the extraction kicker into 300 modules.
- Multiple suggested collimator settings - scaled from the LHC or HL-LHC settings. This work uses a scaled LHC collimator configuration
- In each case the configuration is with 15cm β^* (beyond ultimate), 10600 bunches and 1×10^{11} particles per bunch.
- Usually simulate 100 million input protons for 250 turns.

Collimator settings

All simulations have used the following collimator configuration (scaled from the LHC with $2.2\mu m$ emittance):

Collimator	**Opening** σ
TCP β	7.6
TCSG β	8.8
TCLA β	12.6
TCP δ	18.1
TCSG δ	21.7
TCLA δ	24.1
TCT	10.5
TCDQ	9.8
TCLD	35.1

Current status

Have looked at:

- betatron losses at collision: Horizontal and vertical halos.
- betatron losses at injection: Horizontal and vertical halos.
- Extraction kicker failures.
- Extraction kicker failures with TCDQ errors.
- Heavy ion losses.

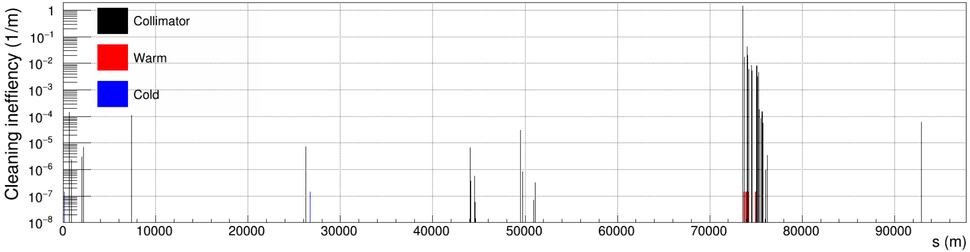
And many more!

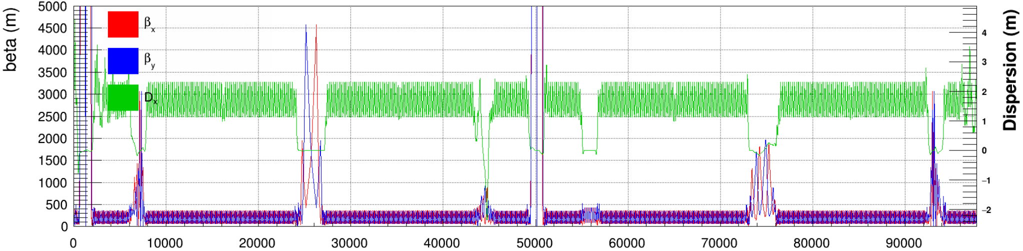
Simulation method

- Using SixTrack, a simulated beam is fired around the FCC-hh such that it just touches the required primary collimator in amplitude.
- Any particles that interact inelastically (excluding single diffraction) in the collimator are considered lost and are killed.
- Any particle that touches the mechanical beam pipe is considered lost and is killed.
- For full showering and energy deposition simulations, see the following talk.
- The following plots show loss maps with the cleaning inefficiency:

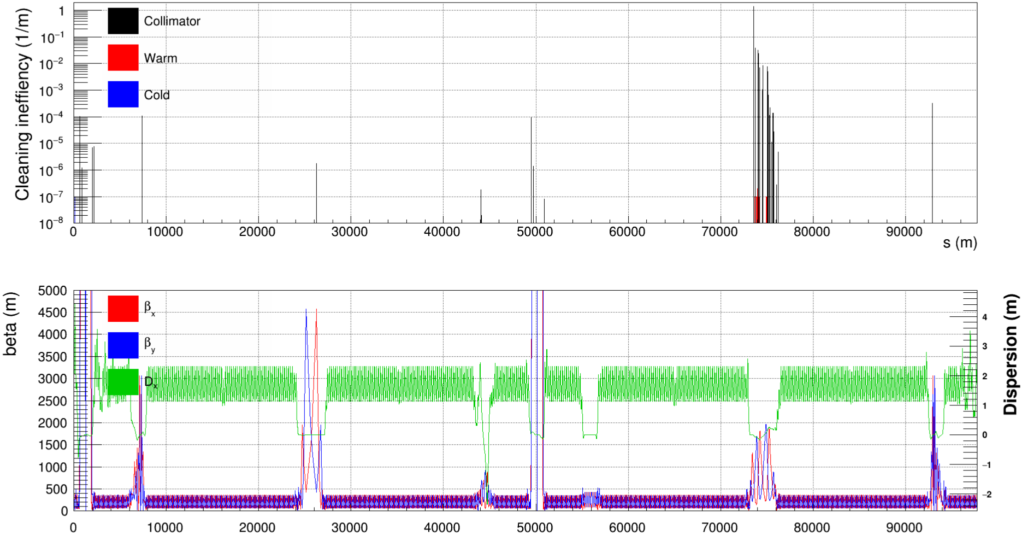
$$\eta(s) = \frac{n_{lost}(s)}{n_{total}\Delta s}$$

Betatron - collision - horizontal - full ring

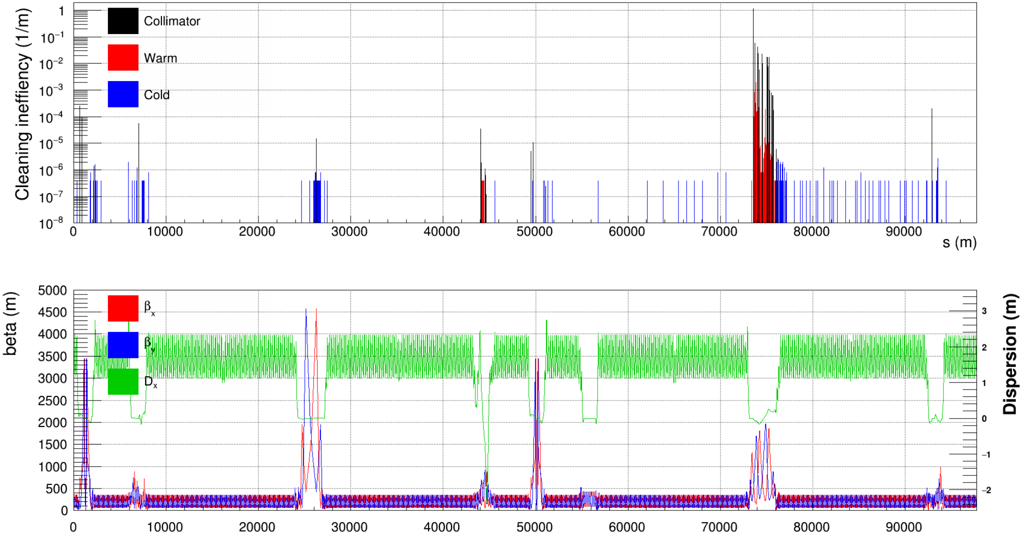




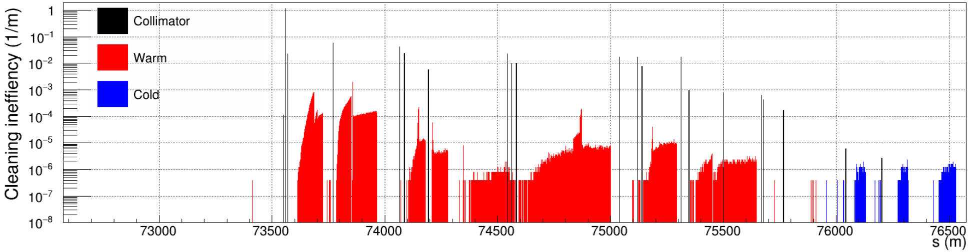
Betatron - collision - vertical - full ring

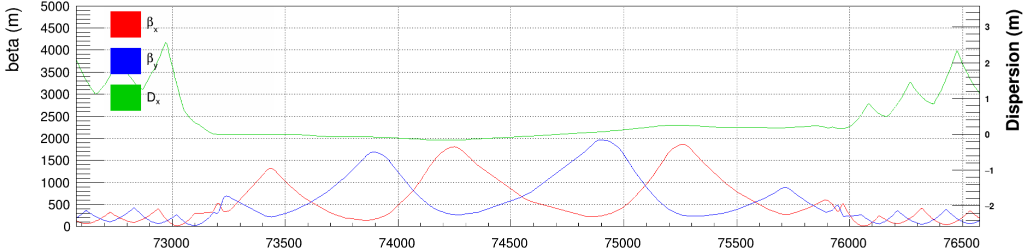


Betatron - injection - horizontal - full ring

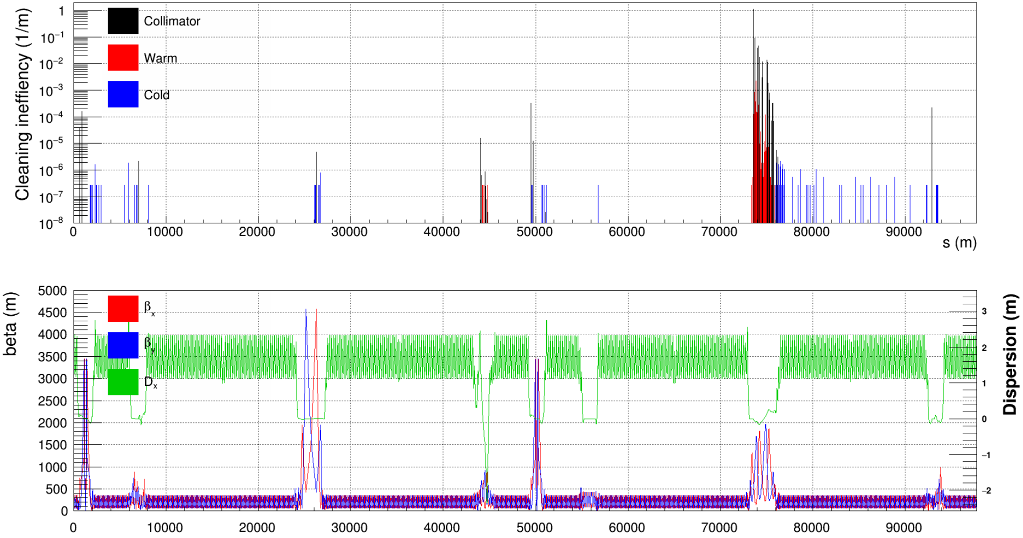


Betatron - injection - horizontal - betatron collimation

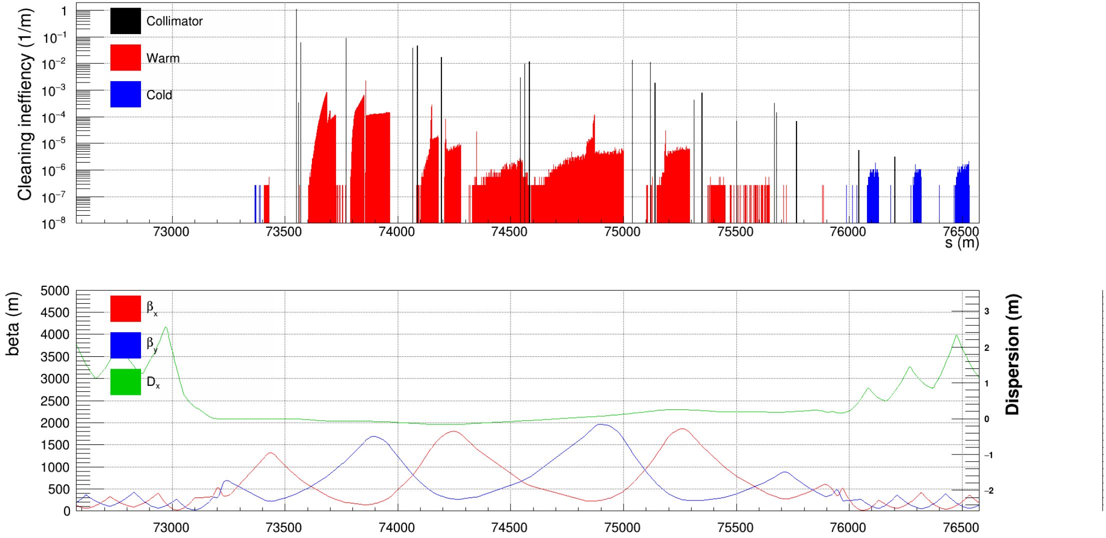




Betatron - injection - vertical - full ring



Betatron - injection - vertical - betatron collimation



Betatron collimation summary

- Cleaning at top energy is mostly good for both the horizontal and vertical case.
- At injection due to the larger emittance and wider scattering angles the situation is not as good...
- The beam energy is lower, so there will be less energy deposited per proton. All depends on the injection quench limits.
- Protons are lost into potentially sensitive areas at injection. e.g. the injection and extraction kickers.
- More work needs to be done in looking at IR protection with the latest lattice - more than 1 set of TCTs is required (currently not in the baseline lattice).

Extraction kicker pre-fires - asynchronous dump

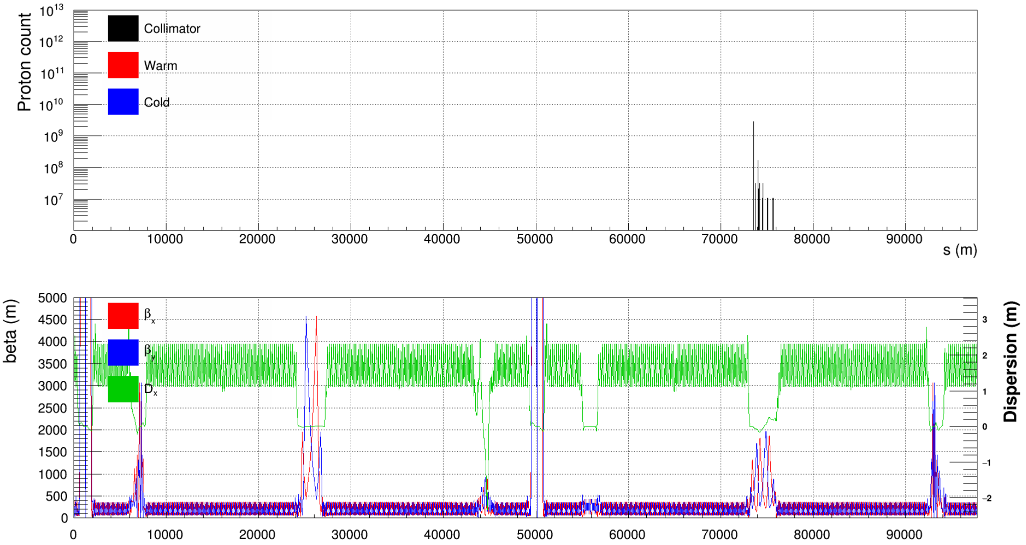
- One potential machine protection issue is the asynchronous dump.
- This is where the extraction kicker system either partially fires or fires at the incorrect time.
- This potentially could lead to the beam impacting with the machine aperture and collimation system instead of being extracted out of the ring to the dump.
- The current extraction system consists of 300 segmented extraction kickers.
- We simulate tracking for 3 turns, firing n kickers (each with a kick of 0.9σ), then extracting the beam the following turn.
- This simulates a failure, one turn where the beam circulates with an oscillation, and then a re-triggering of the system the following turn for a synchronous extraction in the next abort gap.
- Results do not show the cleaning inefficiency, but the total number of lost protons assuming a full nominal beam of 10600 bunches is kicked at exactly the worst time.
- Set a safe limit of 2 nominal bunches impacting a collimator.

Fractional phase advances from the first extraction kicker (degrees)

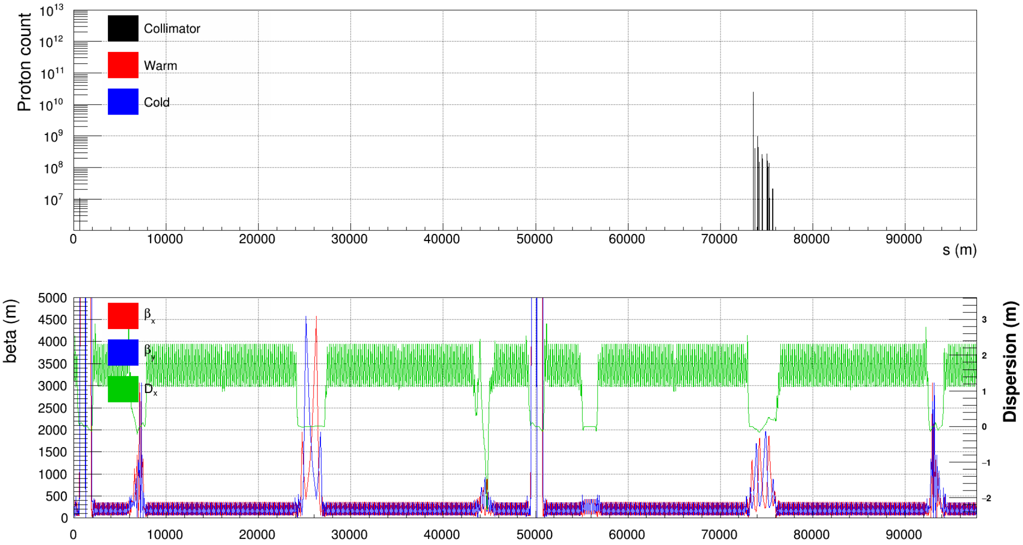
Name	μ_x	μ_y
TCP.6L3.B1	316.1	323.9
TCP.D6L2.B1	269.1	233.0
TCP.C6L2.B1	269.8	234.4
TCP.B6L2.B1	270.6	235.8
TCTH.4LA.H1	220.3	313.9
TCTVA.4LA.H1	220.3	313.9
TCTH.4LG.H1	57.4	351.8
TCTVA.4LG.H1	57.4	351.8

Note: Changing the phase advances between each experimental IP will change these values! Simulations will need to be re-run.

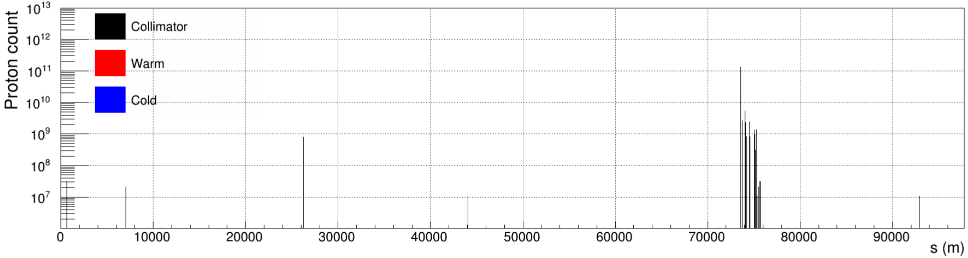
Asynchronous dump - 1 kicker

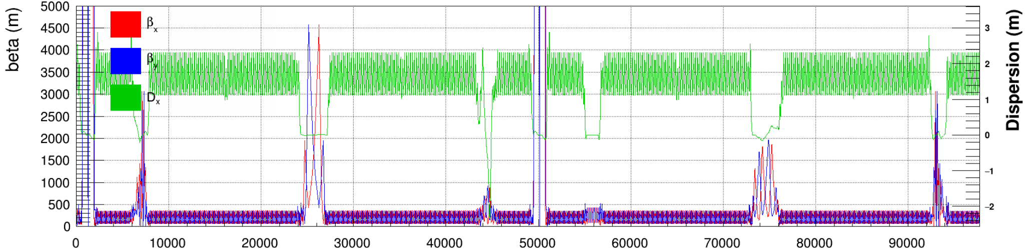


Asynchronous dump - 2 kickers

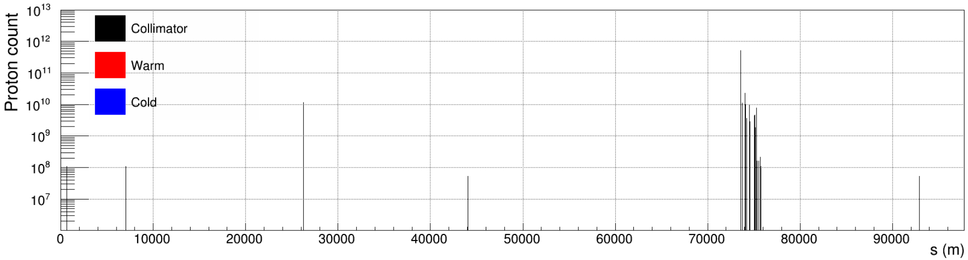


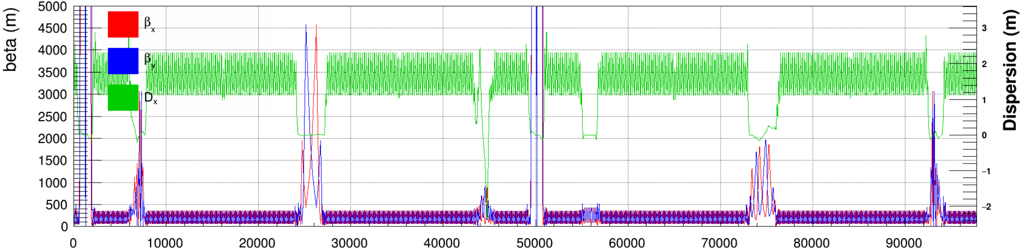
Asynchronous dump - 3 kickers



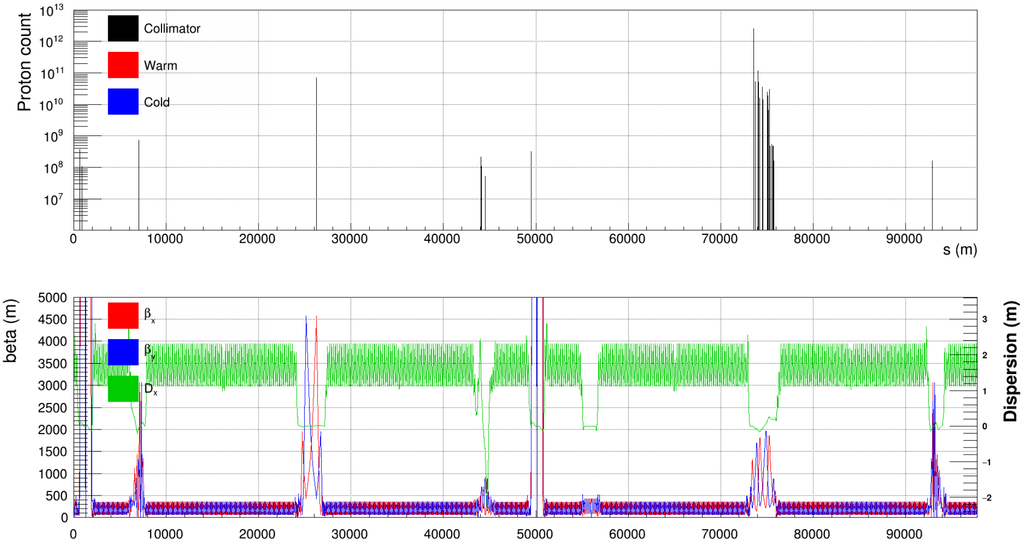


Asynchronous dump - 4 kickers





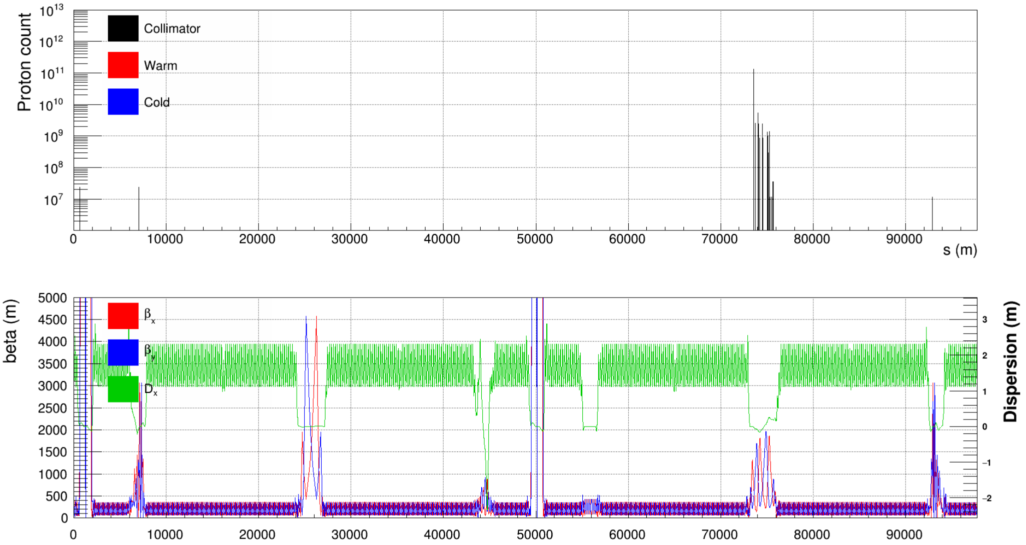
Asynchronous dump - 5 kickers



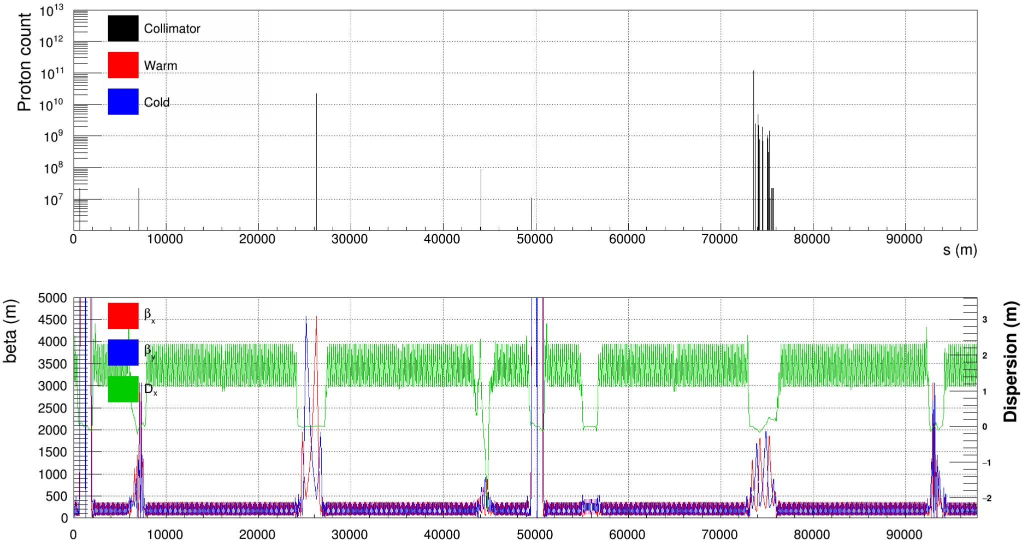
Asynchronous dump

- As can be seen, 4 or more kickers firing will push the beam past the "safe" limit of 2×10^{11}.
- Currently 3 kickers or fewer can be considered "safe", but this does assume a perfect lattice and collimation system.
- Had a look at adding a gap error to the TCDQ (with 3 kickers firing).
- Open by 0.5 and 1.0mm to give a gap of 10.99σ and 12.16σ.
- Close by 0.5mm to give a gap of 8.66σ.

Asynchronous dump - open TCDQ 0.5mm



Asynchronous dump - close TCDQ 0.5mm



Asynchronous dump - Summary table

Kickers	Peak proton loss
1	2.87×10^{9}
2	2.47×10^{10}
3	1.31×10^{11}
4	5.13×10^{11}
5	2.54×10^{12}
3 + close TCDQ 0.5mm	1.15×10^{11}
3 + open TCDQ 0.5mm	1.32×10^{11}

Asynchronous dump - Summary

- In summary, the system can be expected to survive 3 kickers pre-firing with a 2×10^{11} proton limit on a single collimator jaw.
- The addition of errors to the system (alignment, field, orbit, etc) could potentially cause this to decrease to 2, which will be investigated.
- With an increase gap size for the TCDQ, the beam safely hits the collimation system and does not impact the TCDQ (with 3 kickers firing).
- With a gap close of 0.5mm, the system is still safe, but the TCDQ becomes a secondary collimator, and this should be avoided.
- Currently with 3 kickers firing 1.51×10^{11} protons impact on the collimation system before the beam is extracted (with a peak of 1.31×10^{11}).
- Since these simulations have taken place, a new extraction system now exists, but the design is yet to be integrated into the main lattice. When this is done, new simulations will be performed.

Heavy ion loss maps

- Heavy ion loss maps are now being simulated for the FCC-hh.
- Early results have been performed with the STIER approach - only track secondary particles and fragmentations from the primary collimator.
- See poster “Betatron-collimation studies for heavy ions in FCC-hh” - E. Agaliotis.
- For full showering simulations, the code and simulation input configurations are now ready, and simulations are in progress.
- Unfortunately not finished in time for this week, but will be available shortly!

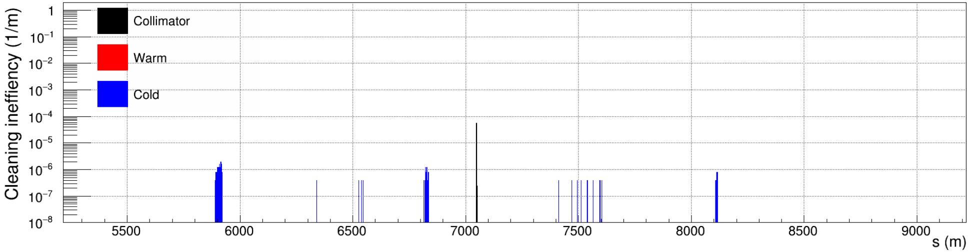
Conclusion and future

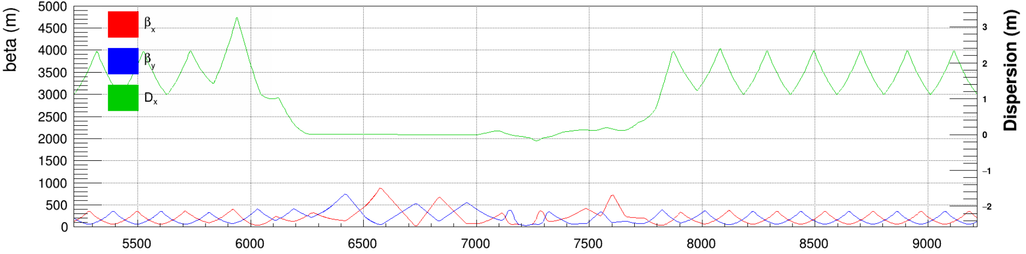
- We have simulated the FCC-hh betatron collimation system at collision and injection energies. The system looks good at collision, but some aperture restrictions could exist at injection.
- Studies of the asynchronous dump failure have taken place with the conclusion being a failure of up to 3 kickers could take place with the current layout.
- The framework developed for this study can also be used for other failures, such as warm magnets or crab cavity failures.

Many future enhancements can take place:

- Use the latest lattice layout.
- Create a better beam pipe description, including the dipole shape.
- Use new collimation layouts - shorter primaries, new material secondaries, no skew TCP, and adjust some collimator gap sizes, e.g. use the scaled HL-LHC collimator gap sizes.
- Re-visit the energy collimation system.
- Produce ion loss maps.

Betatron - injection - horizontal - injection insertion





Betatron - injection - horizontal - extraction insertion