Beam Loss Modeling and Collimation in the LHC

B. Lindström with inputs from A. Abramov, R. Bruce, P. Hermes, S. Redaelli, F. Van Der Veken

Many thanks to the FLUKA and Vacuum teams!

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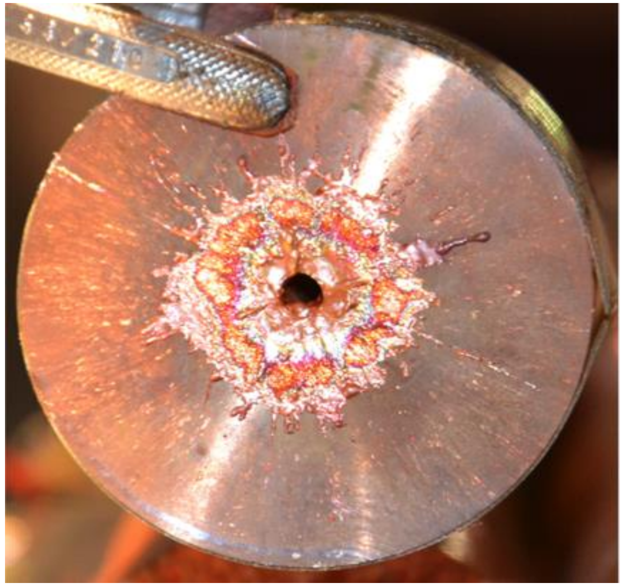
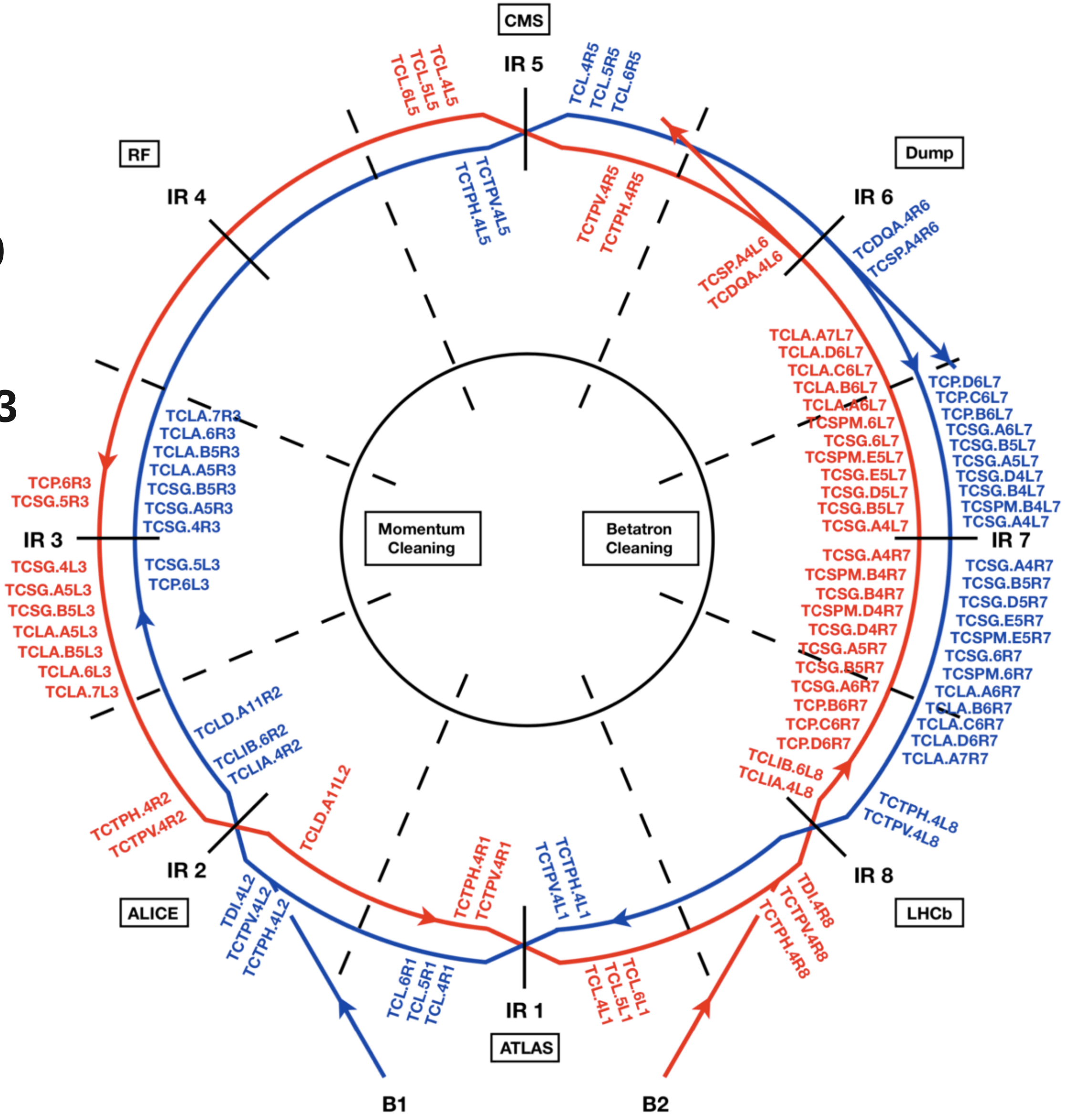
LHC collimation system

- **362 MJ stored beam energy**
- **Design criteria: handle 500 kW beam losses over min. 10 seconds**
- **Superconducting magnet quench limits ~10-20 mW/cm^3**



1.52 MJ deposited energy

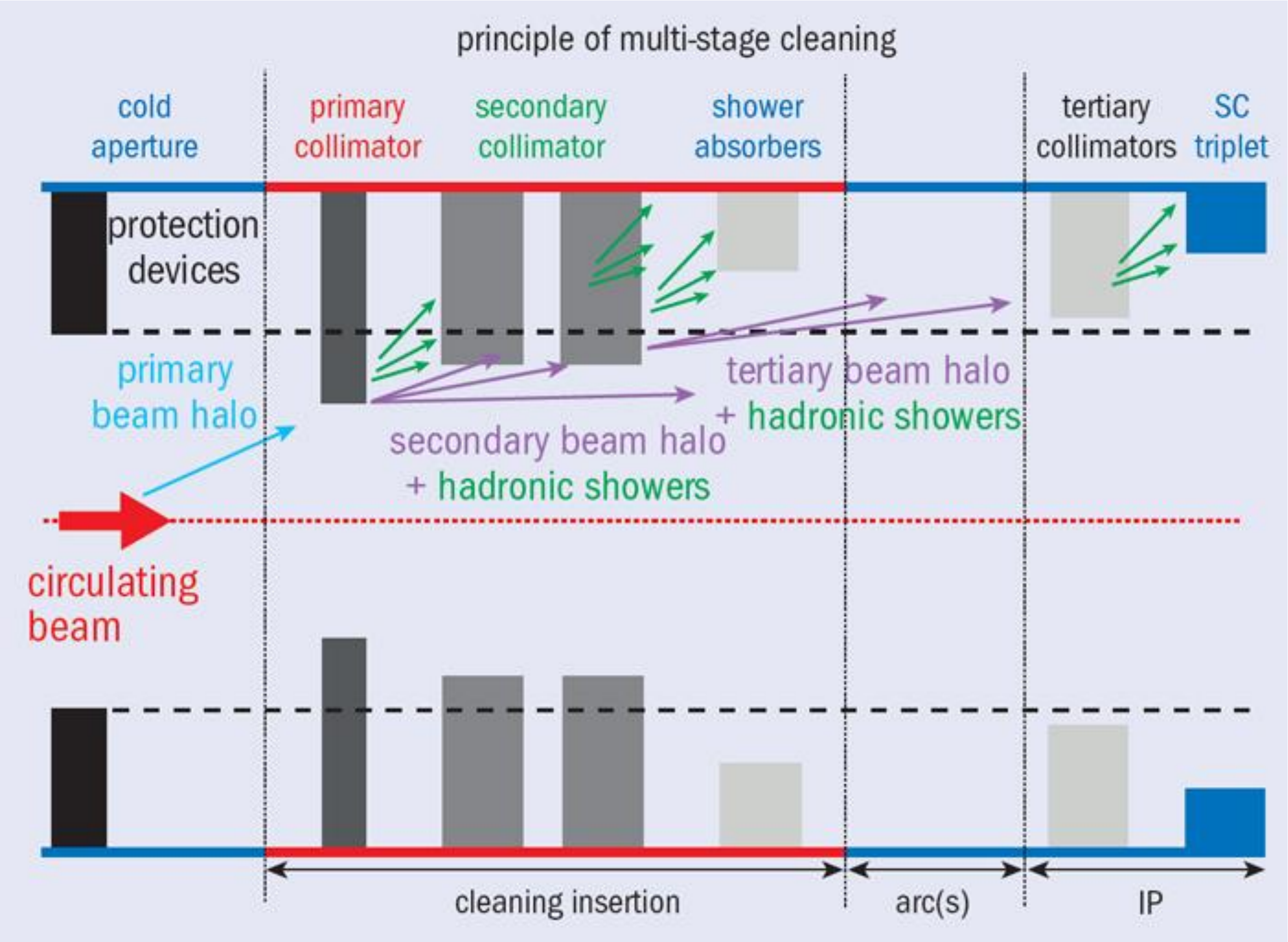
Courtesy of F. Burkart



- **LHC needs a highly performant collimation system to protect the machine (~ 100 collimators installed)**

LHC collimation hierarchy

- **Primary collimators:**
  - Carbon-based (MoGr, CFC)
  - Diffuse particles without absorbing too much
  - Robust against beam impacts
- **Secondary collimators:**
  - Carbon-based (MoGr, CFC)
  - Diffuse particles further
- **Tertiary collimators / shower absorbers**
  - Tungsten-based (Inermet180)
  - Absorb energy and protect superconducting magnets
  - Can easily be damaged by beam



Modeling and tracking

- **Generic workflow used for many types of beam loss processes:**
  - 1: Generate a distribution of particles (depends on beam loss scenario)
  - 2: Track particles until they hit a collimator or the aperture (SixTrack, Xtrack, ...)
  - 3a: If particles hit a collimator, send them to a particle-matter interaction code (K2, FLUKA, Geant4, ...)
    3b: If particles hit the aperture, assume that they are lost
  - 4: Record lost particles/energy and continue tracking what comes out of the scattering module

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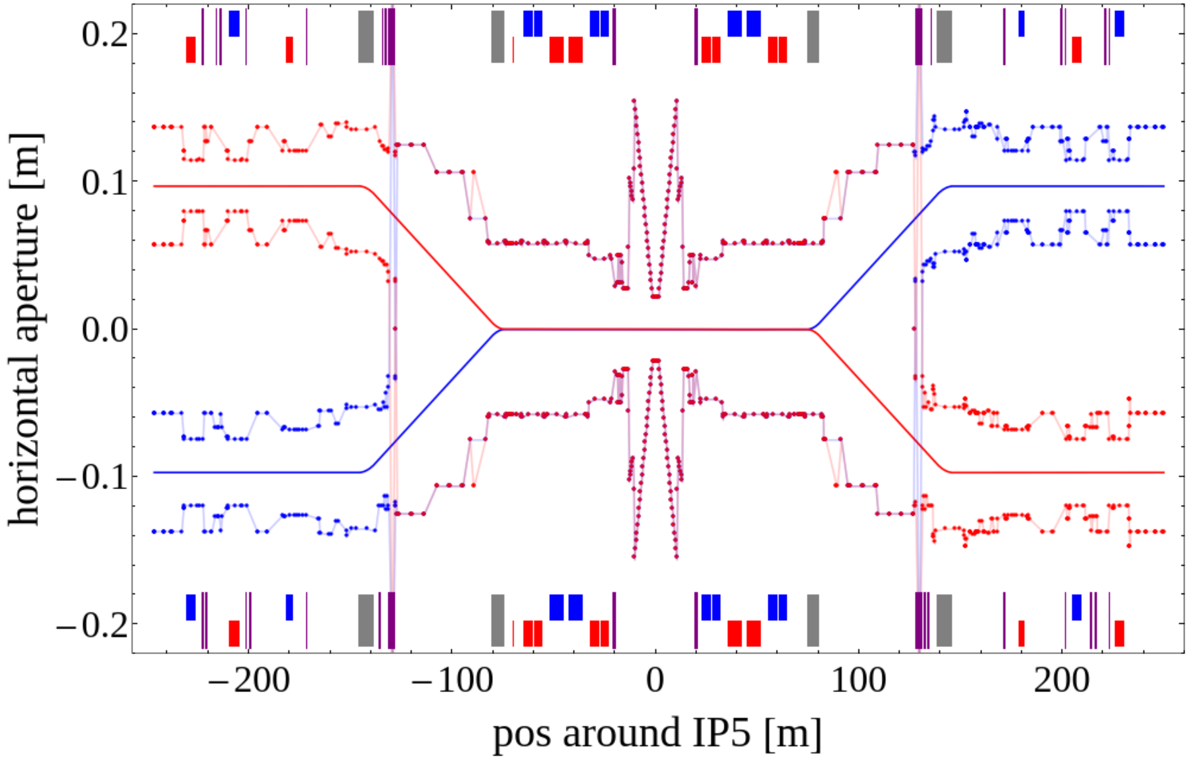
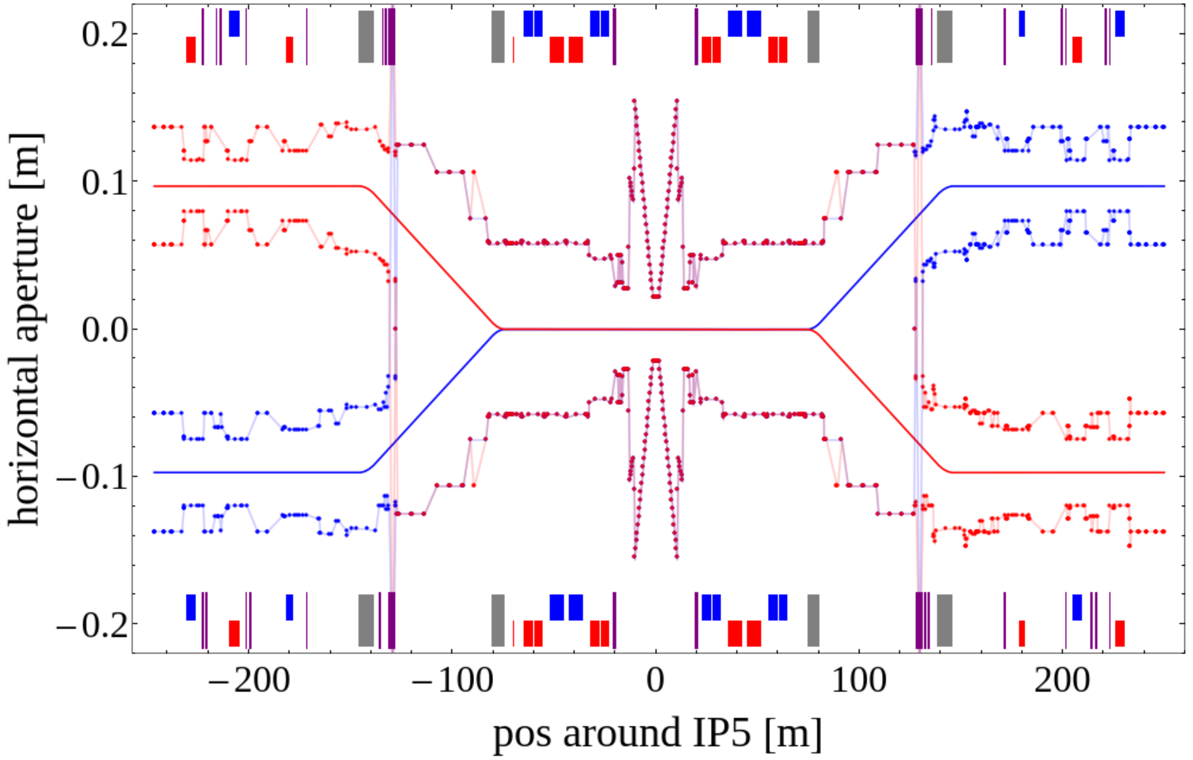


- **Required inputs:**
  - Machine model: Optics, lattice and detailed aperture model to determine loss locations
  - Detailed collimator model to scatter particles

Modeling and tracking



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- **Required inputs:**
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- **Post-processing:**
  - Summarize distribution of losses throughout the accelerator
  - Impact distribution of losses -> input for more detailed FLUKA simulations (in some cases, see following slides...)

Source of Beam Losses

- **Different sources of betatron amplitude increase**
  - Diffusion
  - Instabilities
  - Dynamic aperture
  - Imperfections in feedback systems/power supplies
- **Collision debris from experiments**
- **Beam-gas/dust interactions**
- **Beam instrumentation (wire scanners, beam-gas curtain, ...)**
- **Failures**
  - Asynchronous beam dumps / dump kicker misfires
  - Injection kicker misfires / non-triggering
  - Any other failure that causes beam particles to hit the collimators / aperture

Initial particle distribution

- **Depends on what one is simulating**
  - Large number of particles necessary for good statistics (typically ~O(1e7) for LHC studies of beam-induced quenches)
  - Efficiency is thus critical and only ”relevant” particles should be generated

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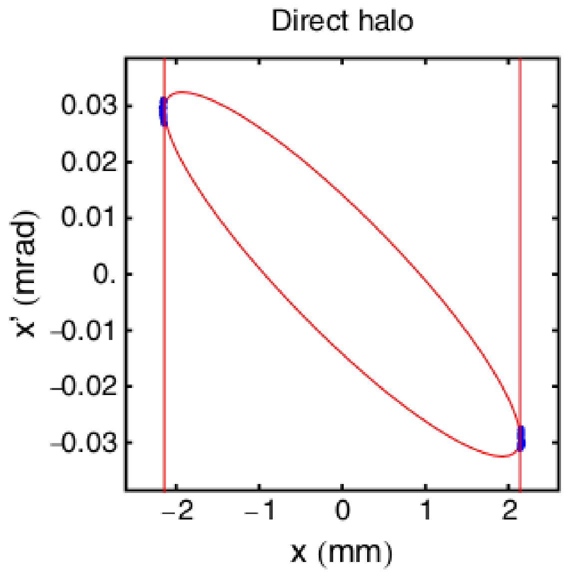

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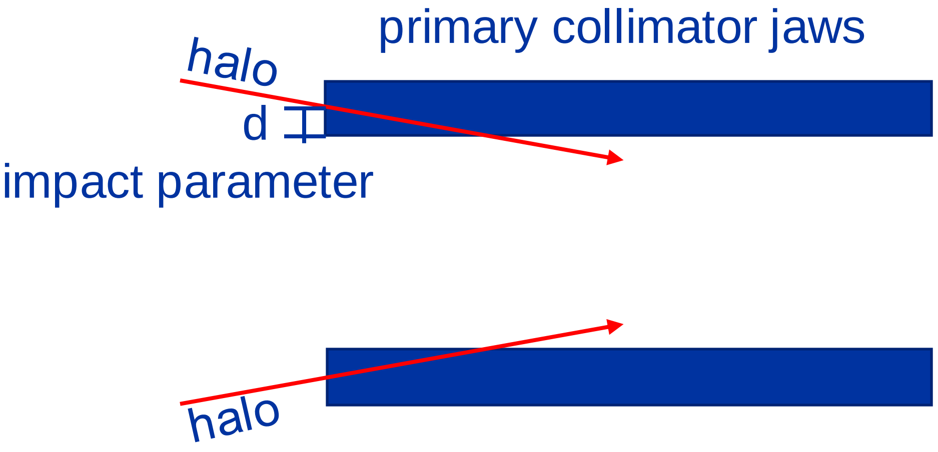

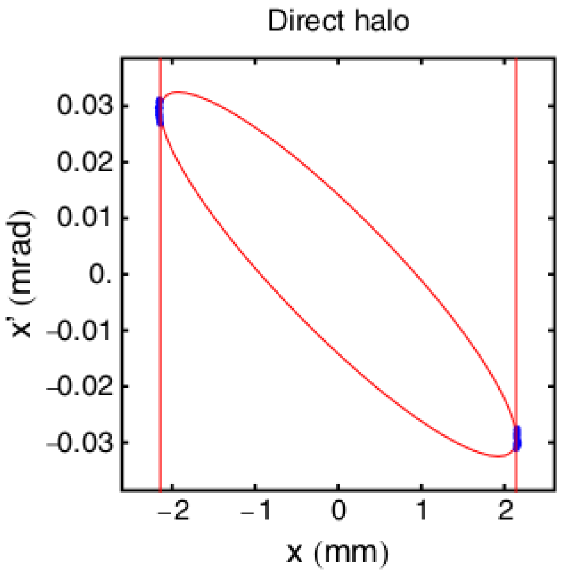

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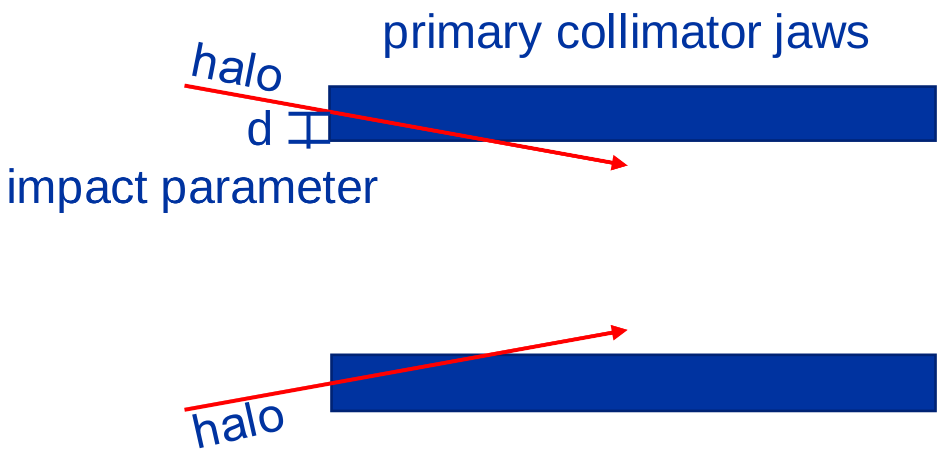

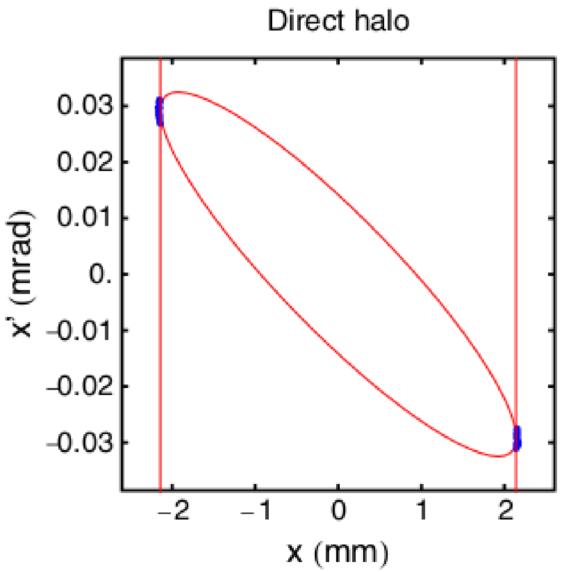

impact parameter depends on the machine

In LHC p+ simulations, typically 1~10 μm is used, giving similar results

For ions and leptons, impact parameter seems to play a bigger role

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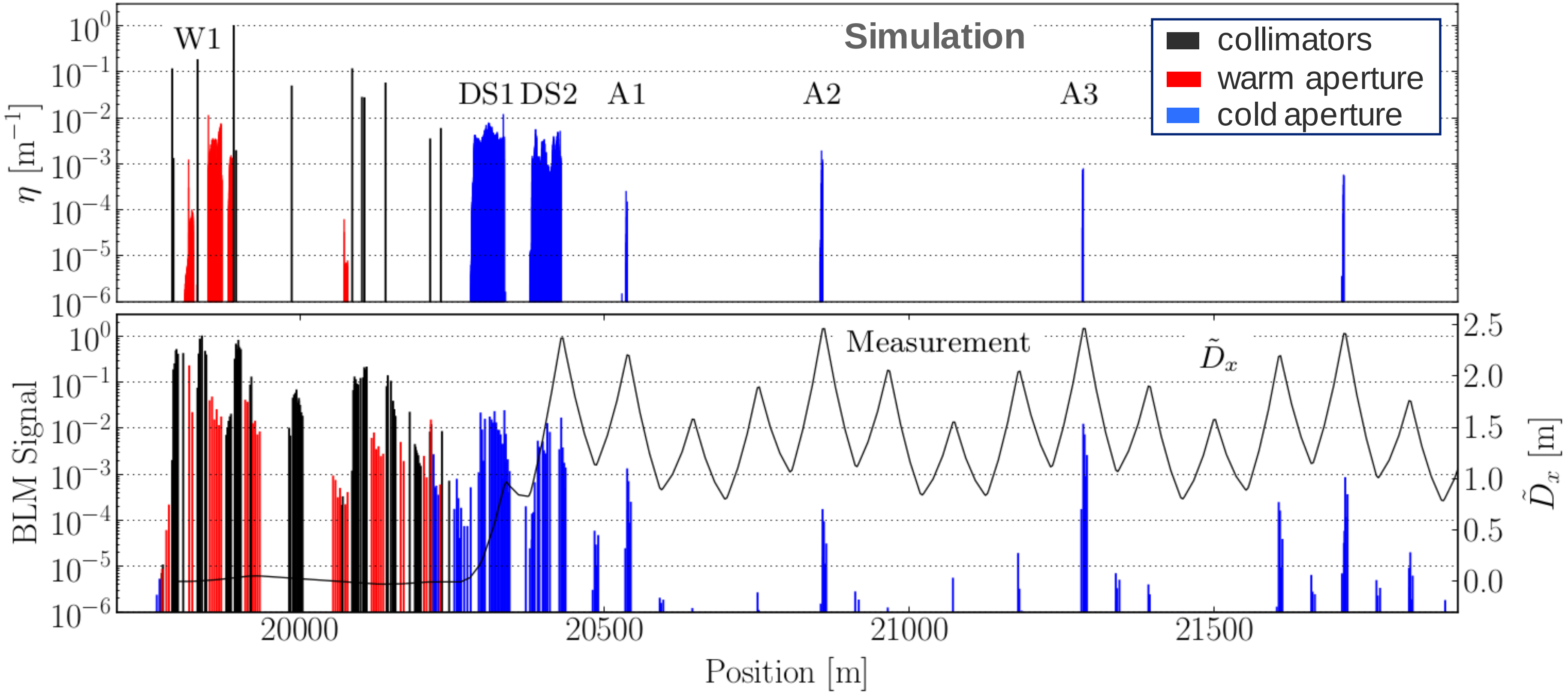
- **Failures:**
  - Generate a particle distribution that undergo the same dynamics as in the real failure
  - If ”small” fractions of the bunch is expected to be lost (e.g. crab cavity failures), a complete halo, without the bunch core, is generated
  - If the whole bunch is expected to be lost (e.g. dump kicker failures), a whole bunch, including core, is generated

Loss Maps – betatron cleaning insertion (IR7)

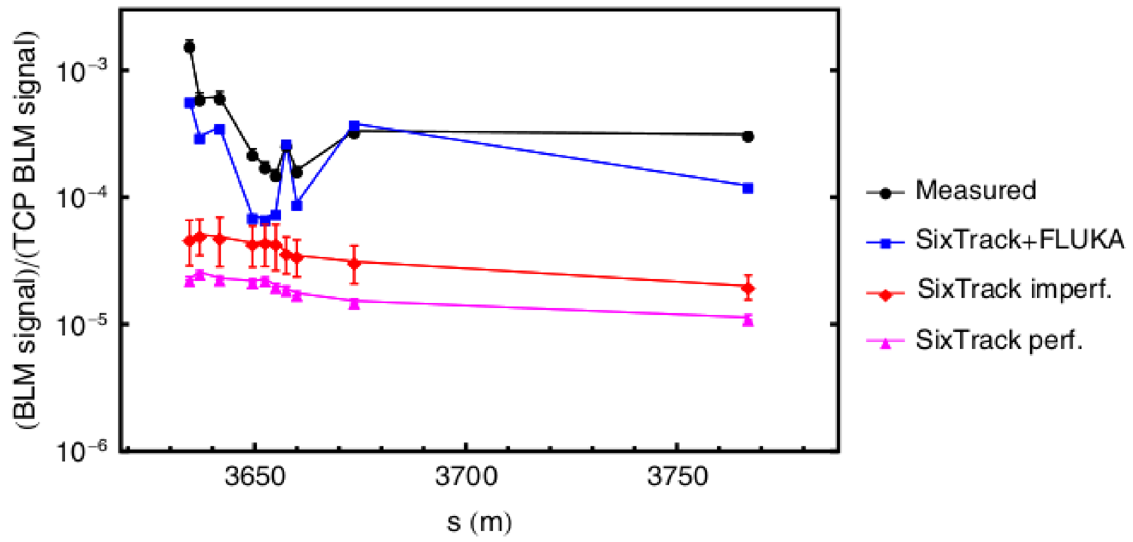
- **Particle losses around the ring are binned and normalized to maximum losses**
- **Good agreement between simulations (top) and measurements (bottom)**
- **Examples show Pb ion collimation results**

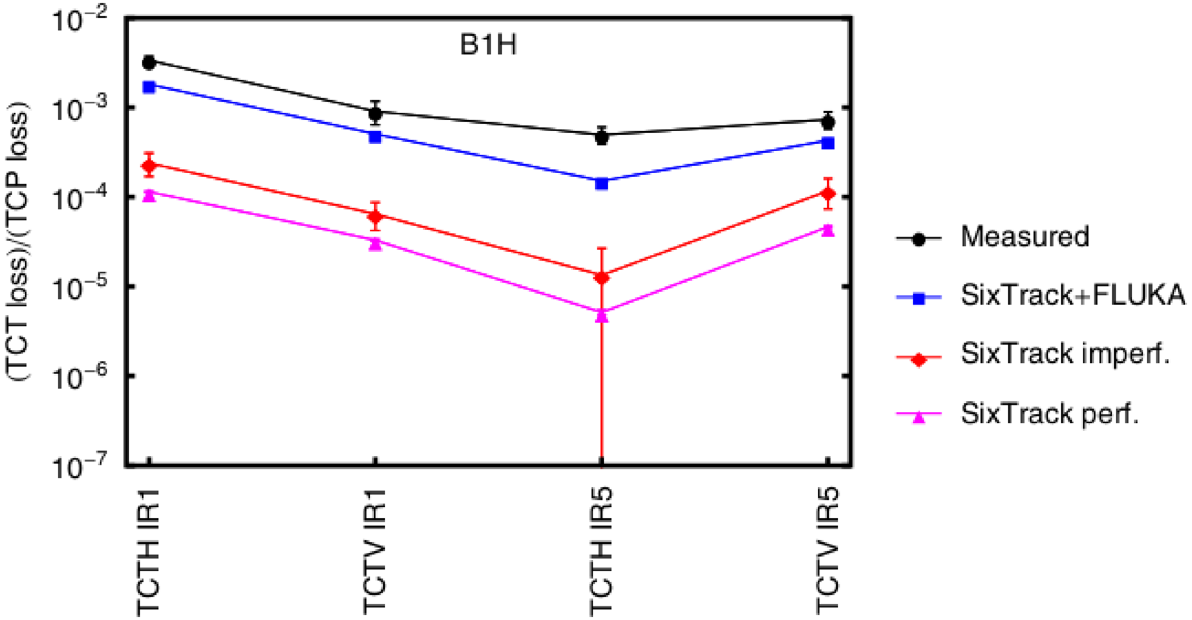


P. Hermes, PhD thesis – Heavy Ion Collimation at the Large Hadron Collider – Simulations and Measurements -

SixTrack limitations

- **SixTrack (with FLUKA coupling) can:**
  - Produce realistic loss distributions in aperture and collimators
  - Study a vast variety of machine states and beam loss mechanisms, over single or multiple turns
  - Can be used to compare different configurations (optics, collimator setups/locations/materials, ...) and find issues or possible improvements related to those
- **SixTrack cannot:**
  - Accurately quantify energy deposition in collimators or aperture / magnets
  - Simulate background signals in experiment detectors
  - Other tools necessary for this, e.g. standalone FLUKA or Geant4

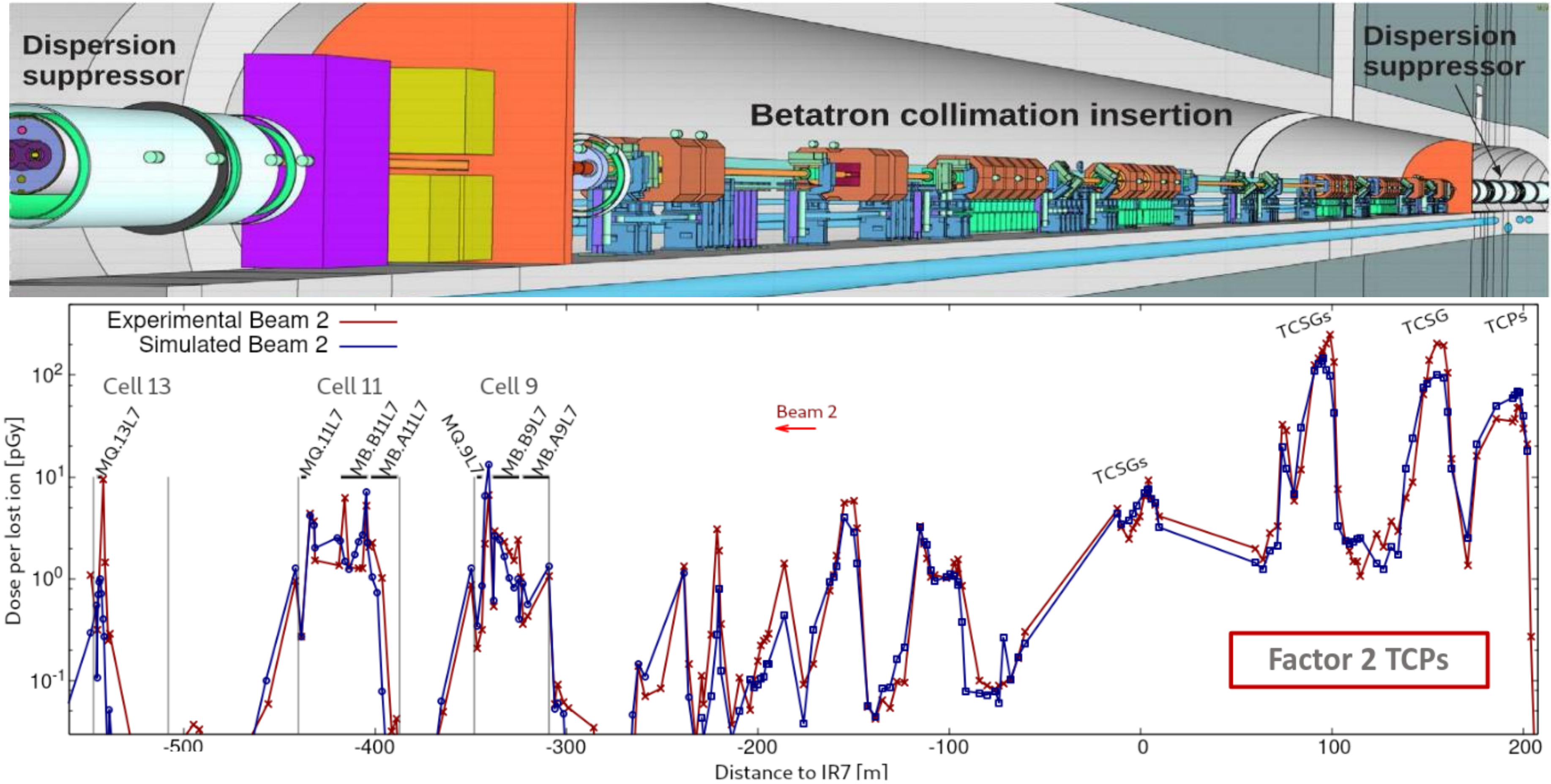




R. Bruce, Simulations and measurements of beam loss patterns at the CERN Large Hadron Collider, Phys. Rev. Spec. Top. Accel. Beams 17 (2014) 081004

Benchmarking of BLMs

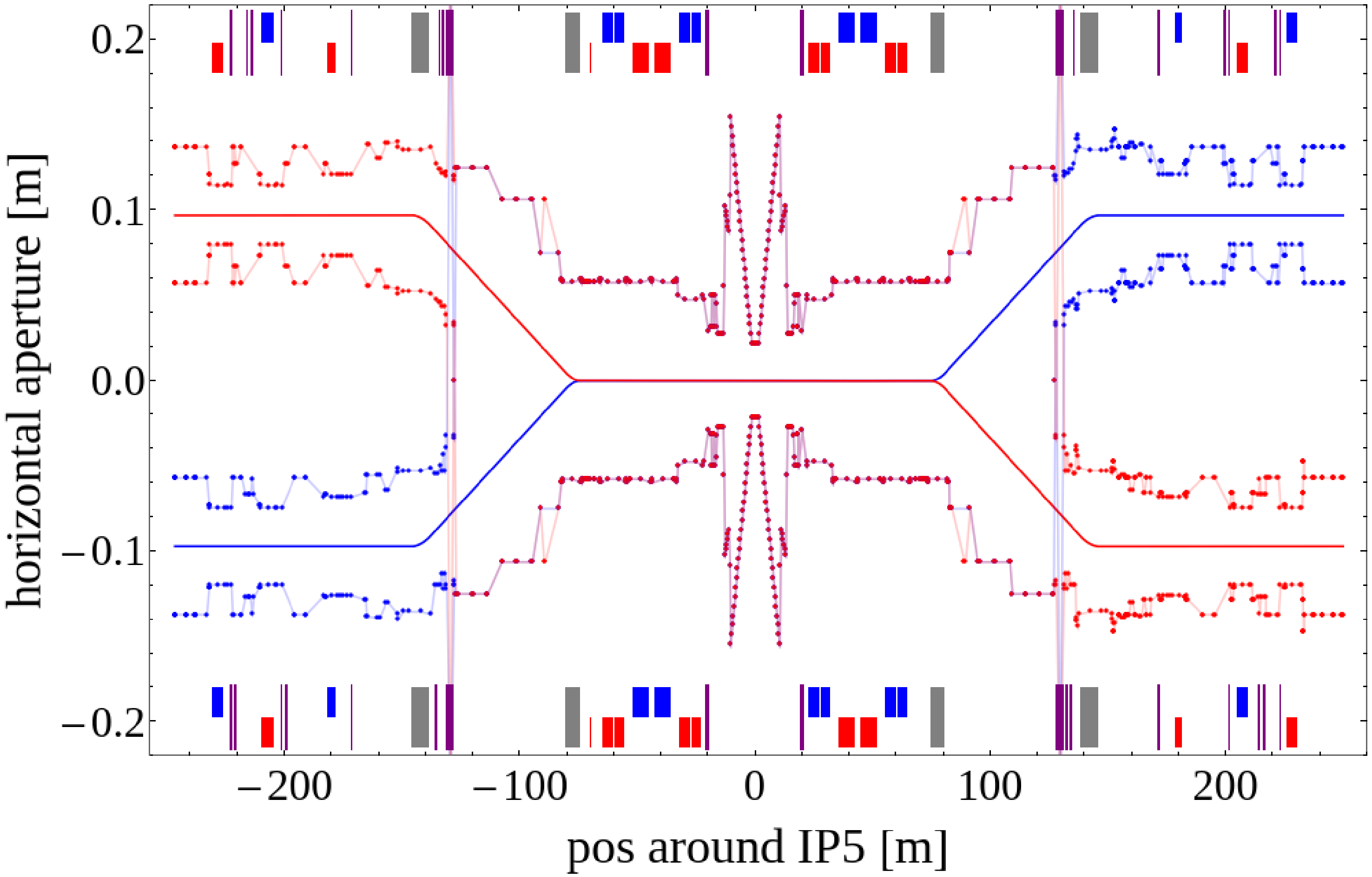
- **Multiturn cleaning is simulated with SixTrack**
- **Proton impacts on collimators / aperture are sent to FLUKA team for a second round of pure simulations**
- **FLUKA simulates shower propagation and energy depositions**
- **BLM signals are benchmarked**
- **Used to simulate energy deposition in magnets and evaluate quench risk**



J-B. Potoine, "Latest results of power deposition studies for crystal-assisted Pb collimation", 155th CollUSM, https://indico.cern.ch/event/1212179/

Experiment Background

- **Generated by:**
  - Impacts on collimators (TCTs)



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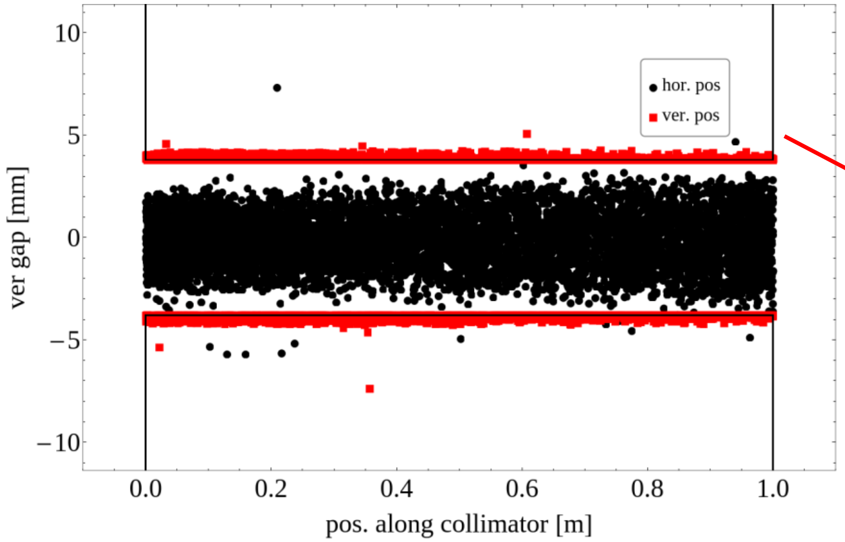
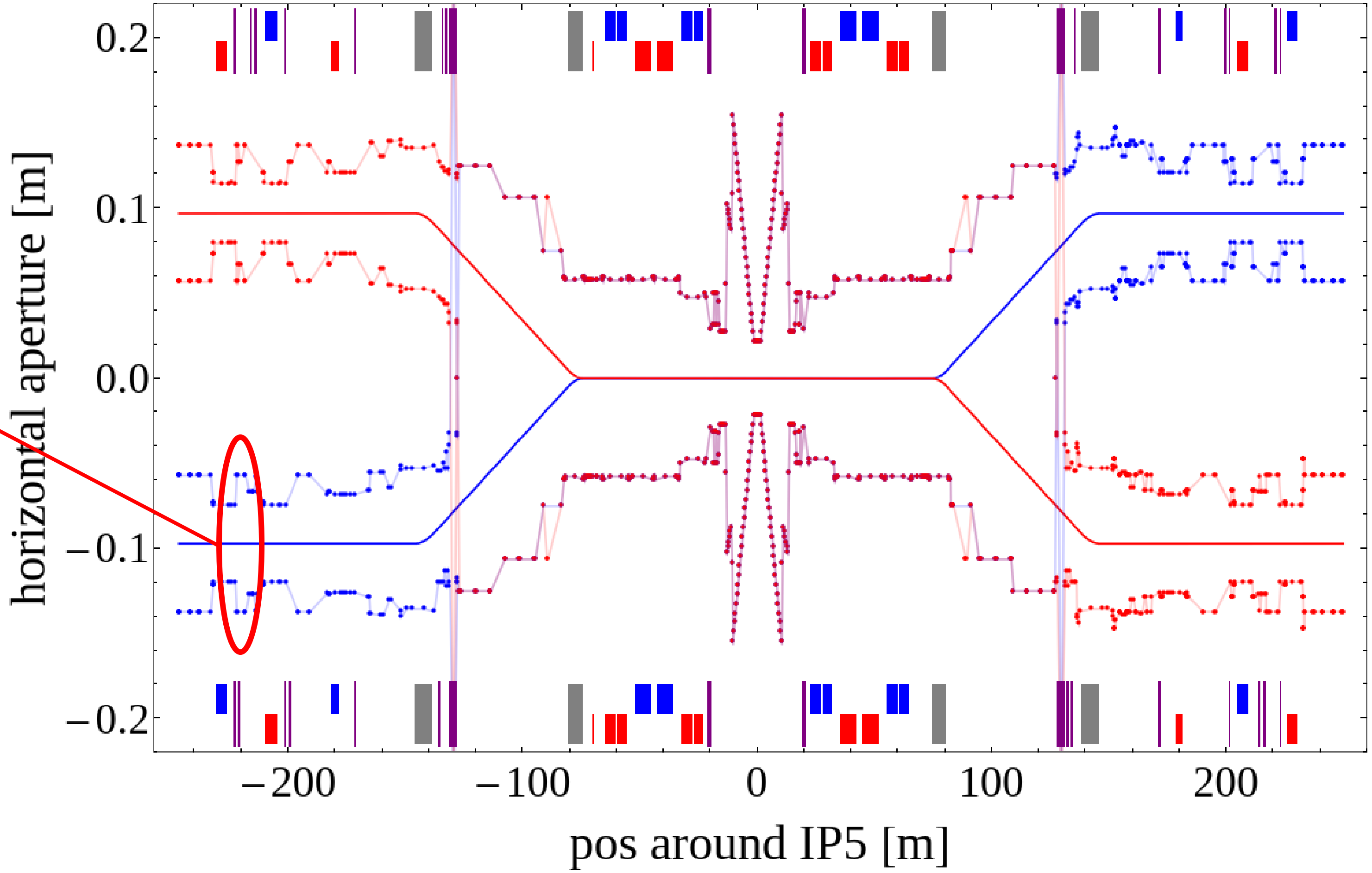
TCT – impacts simulated with SixTrack





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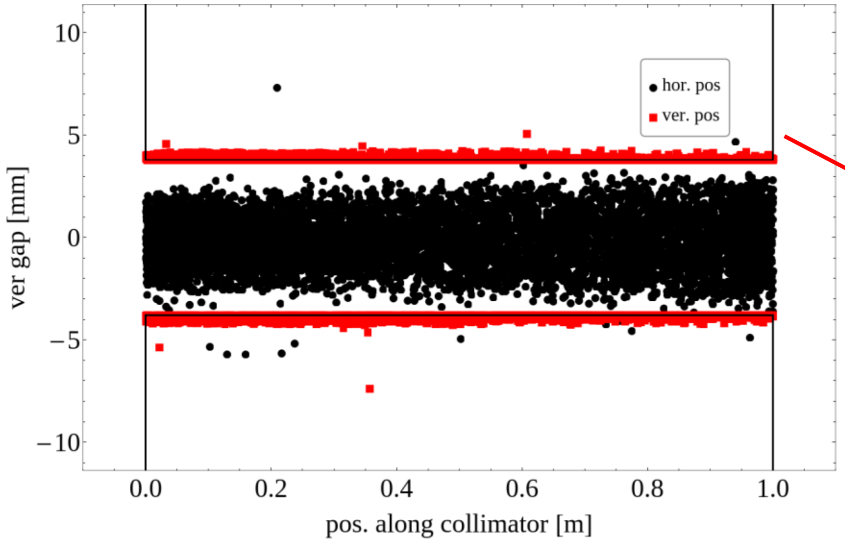
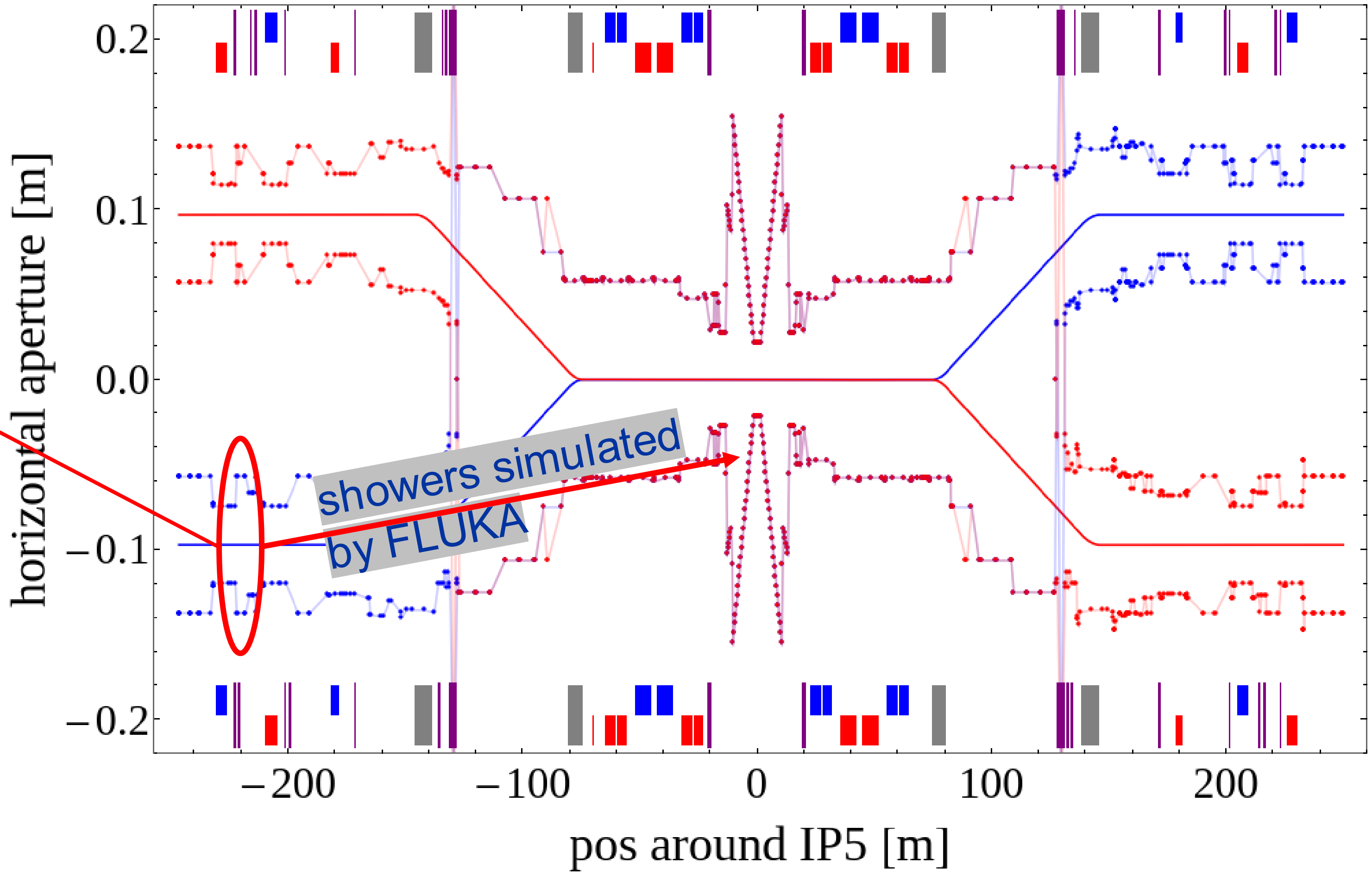
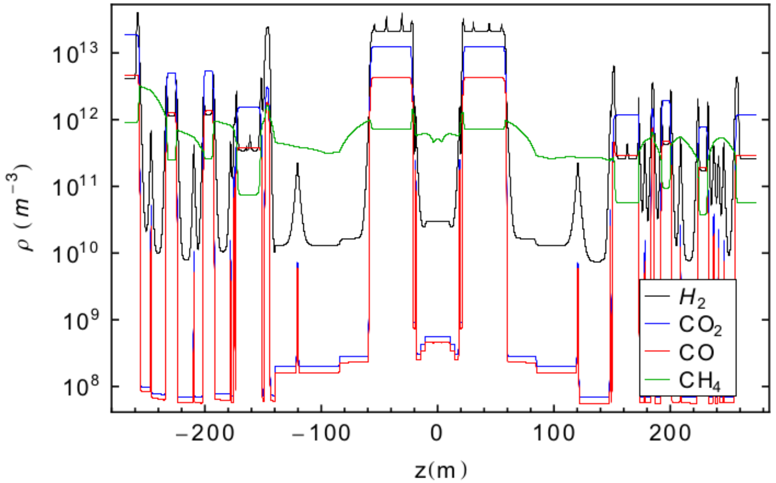


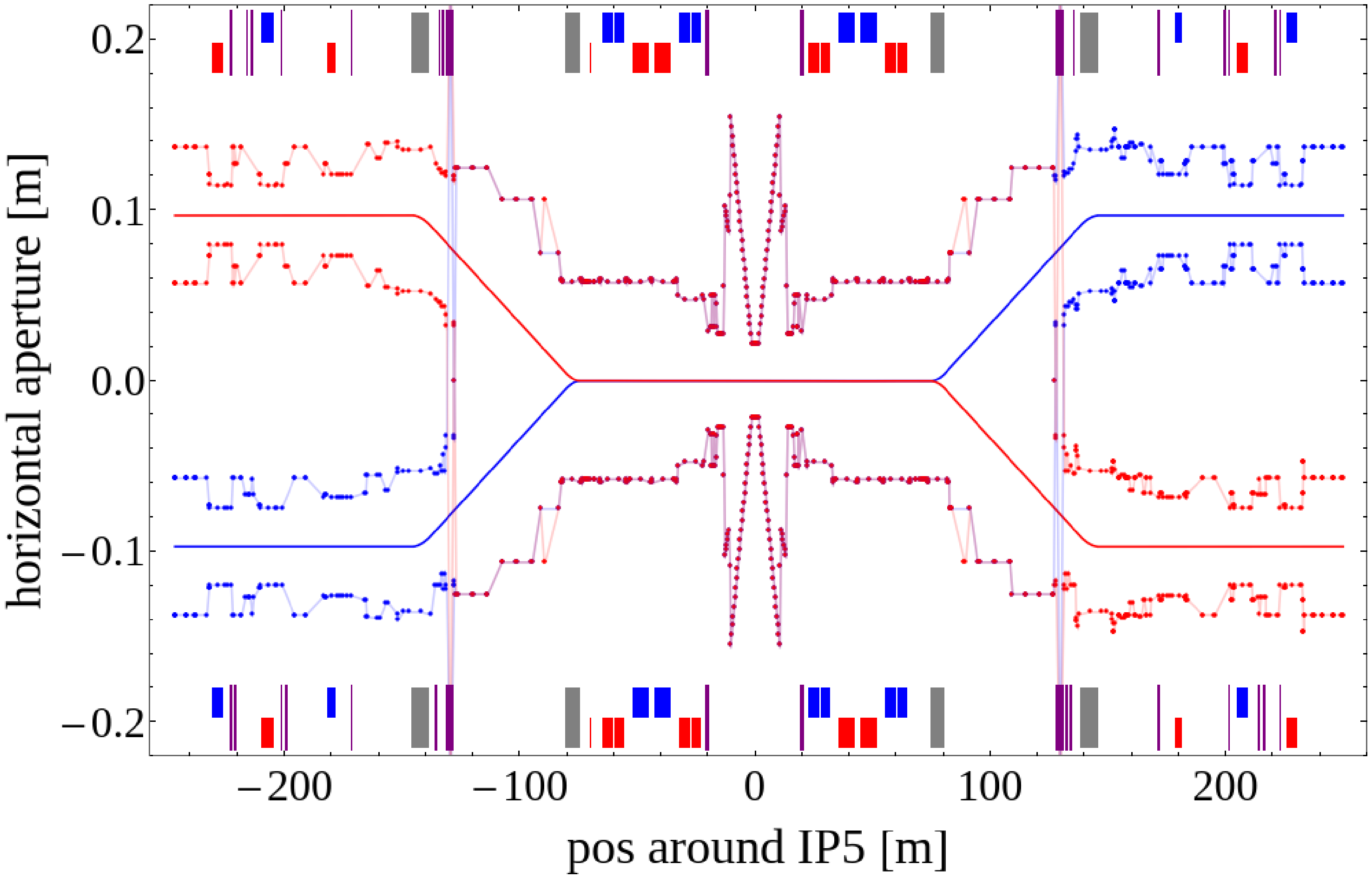


Experiment Background

- **Generated by:**
  - Impacts on collimators (TCTs)
  - Beam-gas interactions near IPs
    - Pure FLUKA simulation from forced inelastic interactions of p+ with gas
    - Realistic distribution of different gas species needed as input

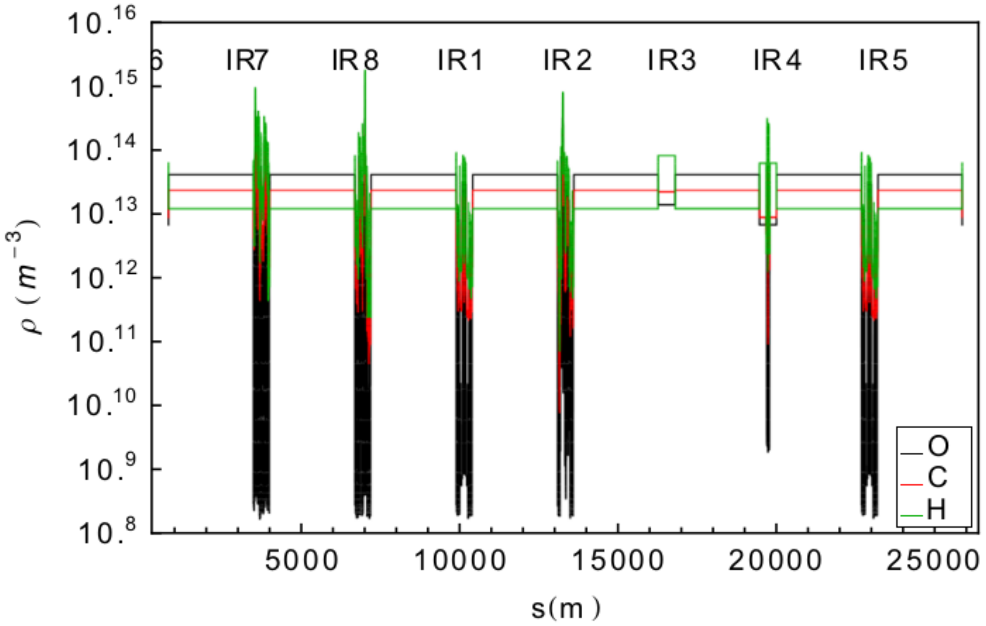
Gas denstiy simulated by vacuum team (VASCO, MolFlow, ...)



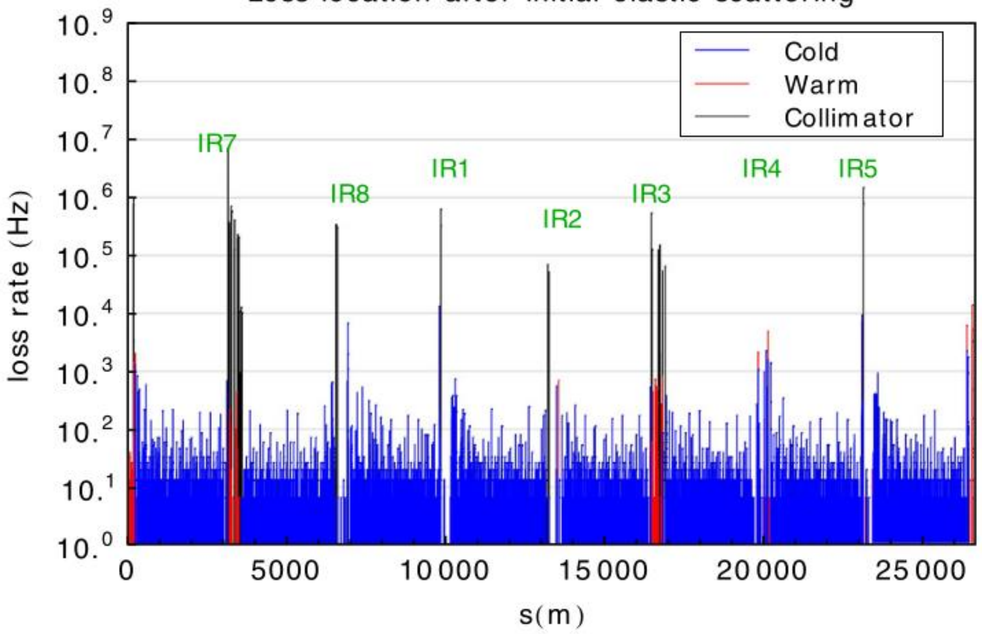


Global beam gas

- **Gas pressure throughout ring simulated by vacuum team (VASCO, MolFlow, ...)**
- **Non-local inelastic scattering does not contribute to detector background**
- **Elastically scattered protons can be lost close to the IPs and produce background**
- **Simulation workflow:**
  - Pressure profile is fed into SixTrack where a bunch is tracked – pressure profile provides probability of interaction
  - Lookup table from FLUKA is used to determine type of interaction and kick on proton
  - Surviving protons are tracked until lost (collimator or aperture)



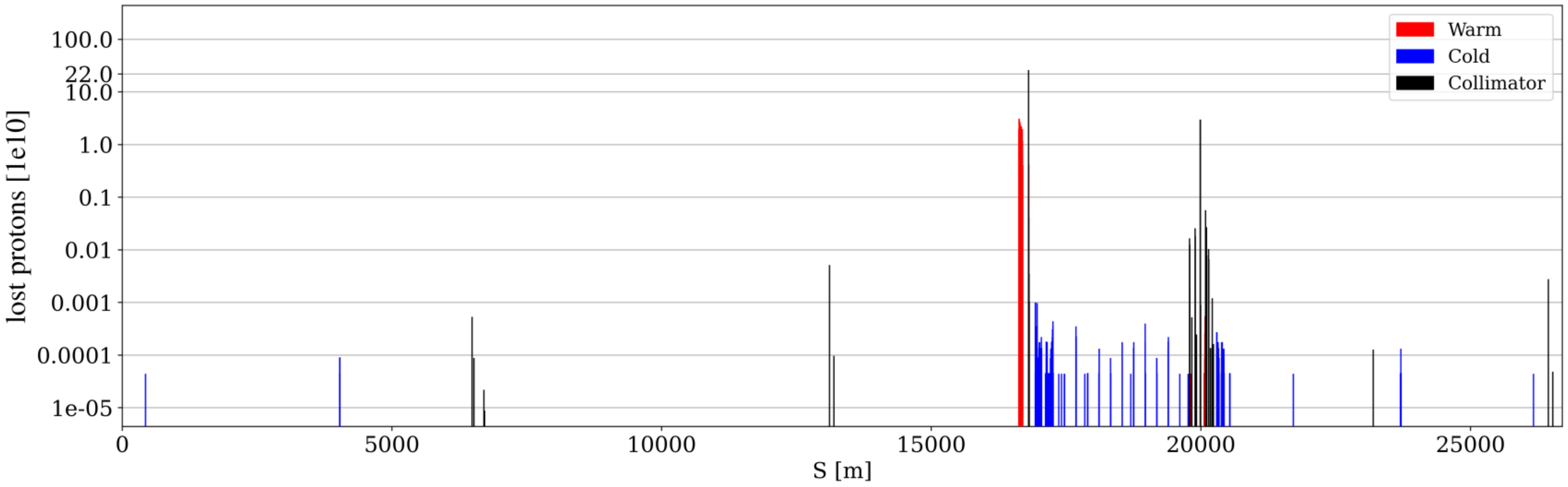
Loss location after initial elastic scattering

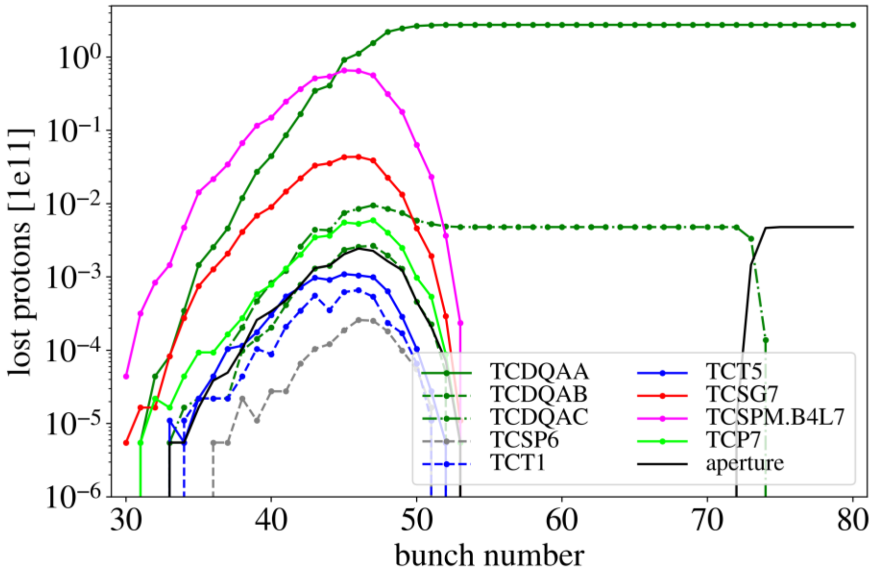


R. Bruce, Sources of machine-induced background in the ATLAS and CMS detectors at the CERN Large Hadron Collider, Nucl. Instrum. Methods Phys. Res., A 729 (2013) 825-840

Dump kicker magnet misfire

- One out of 15 dump kicker magnets fires accidentally
- A full bunch (gaussian) is tracked
- From second turn, the DYNK module in SixTrack applies a dynamic kick for extraction kickers
- Several consecutive bunches tracked, passing kicker at different times
  -> different kicks
- Results are summed over all bunches
- Injection kicker failures are essentially
  treated in the same way





Summary

- The stored energy in the LHC beams provides significant challenges
- A sophisticated collimation system is employed to protect the machine from damage as well as the superconducting magnets from quenches
- Simulation of beam losses is done in multiple stages using a combination of tracking (SixTrack), particle-matter interactions (FLUKA), as well as thermomechanical and vacuum codes
- Beam loss distribution, studies of mitigation methods, comparison of different machine configurations can be done using SixTrack (and Xtrack)
- For power deposition, quench evaluation, detector background simulations, SixTrack results are fed into FLUKA

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