Simulations and measurements of betatron and off-momentum cleaning performance in the energy ramp at the LHC

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Contribution WEC3C3

Outline

- Introduction
- Simulation tools
- Selected results
- Conclusions and future steps

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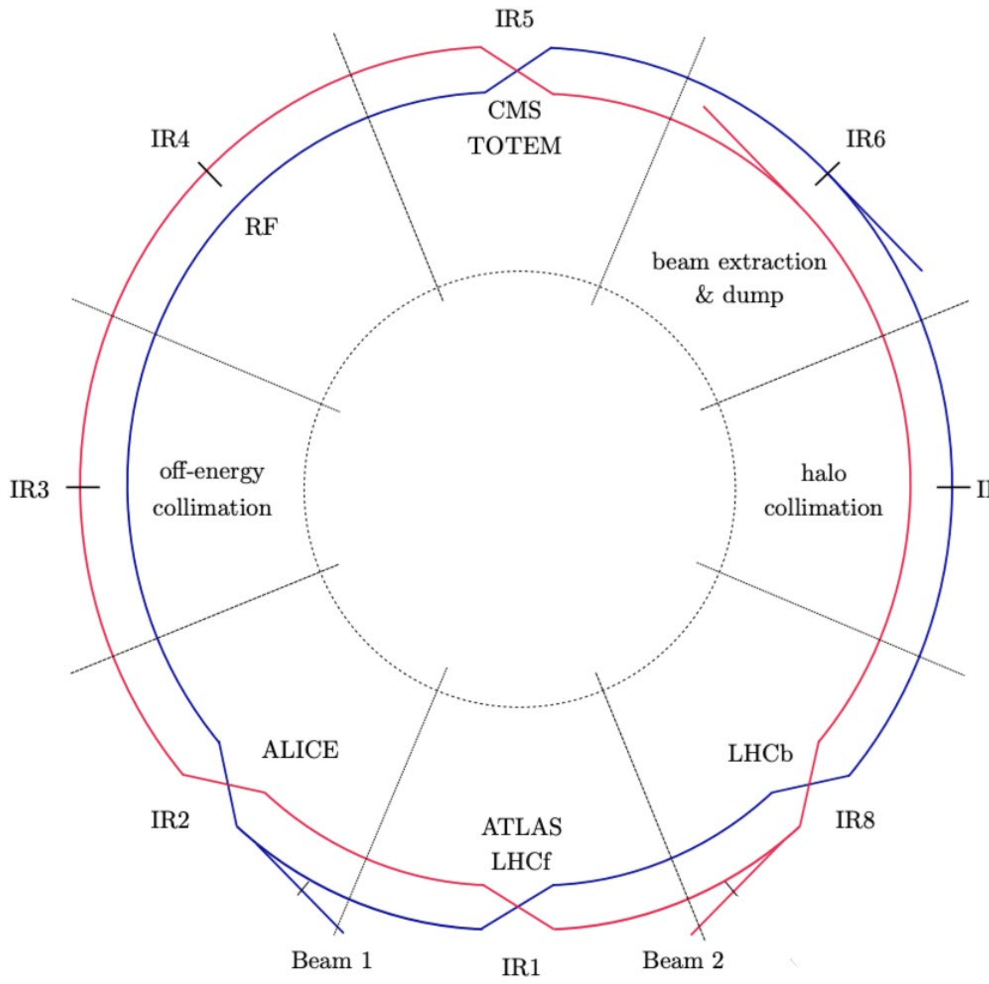
- **Introduction**
- **Simulation tools**
- **Selected results**
- **Conclusions and future steps**

Large Hadron Collider

- 27 km ring
- Two counter-rotating beams, 450 to 6800 GeV
- Four collision points
- In 2023 over 400 MJ beam energies stored in the machine
- Protection of machine hardware against beam losses
  → **Collimation system**

LHC layout



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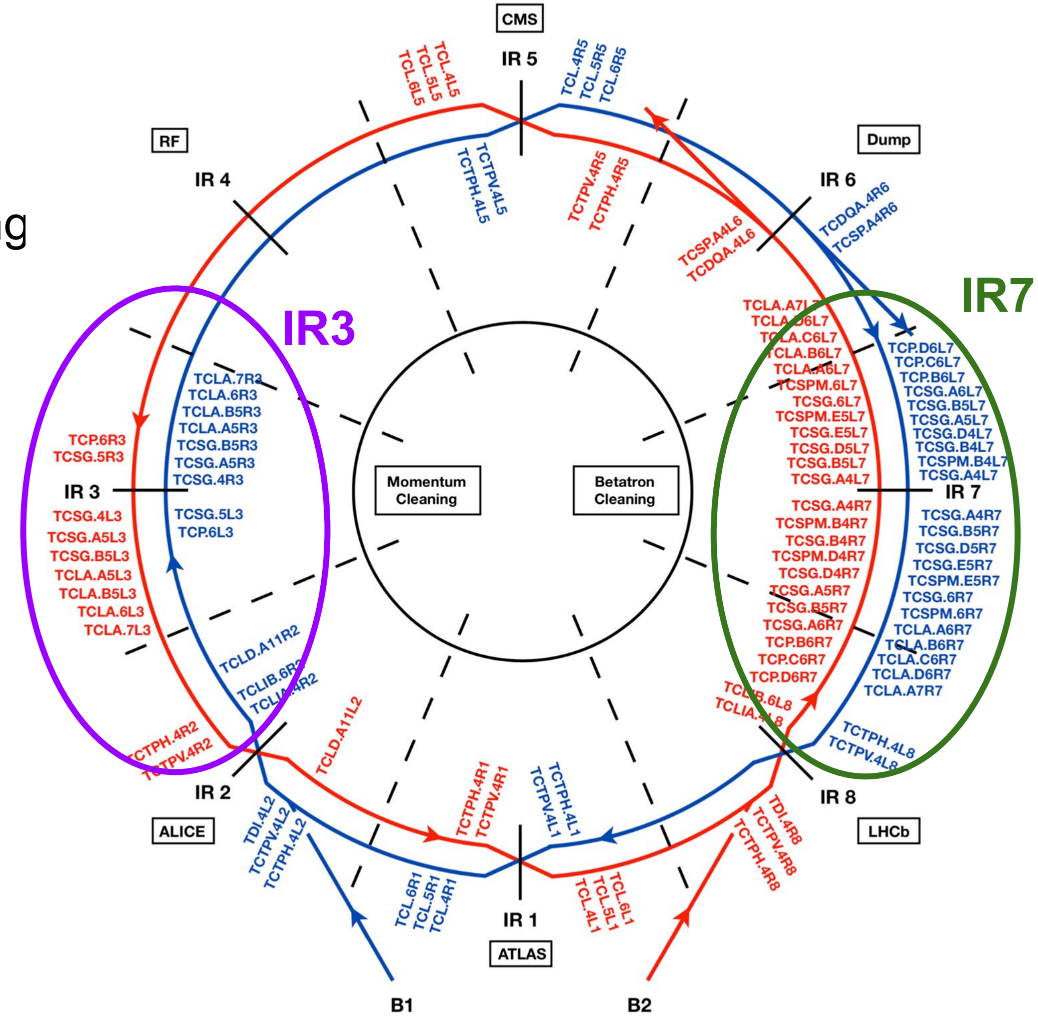
LHC collimation system

- Remove particles at large betatron / energy offsets from beam
- **Multistage** collimation system: > 100 collimators around the ring
- Most collimators in **IR3** / **IR7**: **momentum** / **betatron** cleaning
- **Cleaning inefficiency: particles** scattered out of collimators **lost outside of collimation system**
- Most critical: superconducting IR7 dispersion suppressor
  cleaning inefficiency < $10^{-4\,(*)}$ → **Excellent performance**
- Must protect at **all stages** of the **cycle**

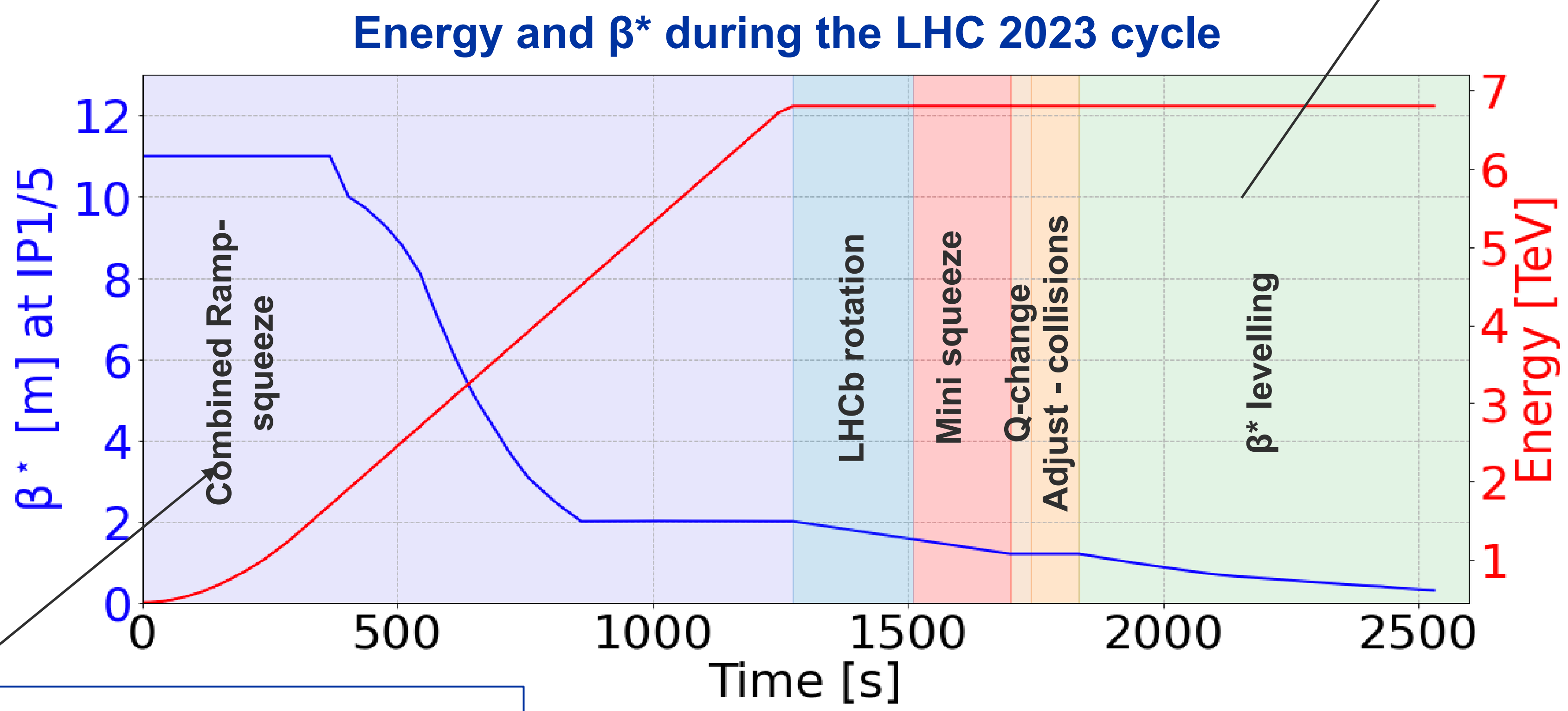
Collimator locations around LHC ring



(*) Normalised to the losses in the collimators.

LHC operational cycle

Luminosity production



Combined ramp and squeeze: increasing beam energy and decreasing β* at the same time

This talk: challenges for collimation in this phase of cycle

Motivation

- **Combined ramp / squeeze: challenge for LHC collimation system**
- **Emittance shrinks** in **ramp** & **aperture** around collision points **shrinks** in **squeeze**: collimators must **track both**
- Requires excellent **control** & **understanding** of **collimation** system performance
  - Guarantee machine safety throughout the ramp
  - Maximize operational efficiency
- Qualification of cleaning performance in **measurements** is part of **machine commissioning**
- Simulations for performance optimization and issue mitigation: typical for other phases in cycle
- Initiated the **first simulation campaign** of the **cleaning performance** during the **ramp** (this talk):
  - Observable: distribution of losses around the machine, i.e. **loss maps**
  - Tools: **Xsuite** and its collimation package **Xcoll**

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Xsuite and Xcoll

- **Xsuite: Python** packages for particle simulations, combining functionalities of various tools used previously
- Two most relevant packages for our studies:
  - **Xtrack**: **Symplectic 6D particle tracking** through accelerator elements
    - Possibility to **include effects** such as synchrotron radiation, impedance, space charge etc
    - **Computes optics functions** and **generates matched** particle **distributions**
  - **Xcoll**: Simulates **particle-matter interaction** for **collimation** studies
    - **External engines: Geant4, FLUKA**
    - **Internal engine: K2 → Everest**
- **Improved versatility and simplified setup compared to previous tools**

G. Iadarola et al, TUA211

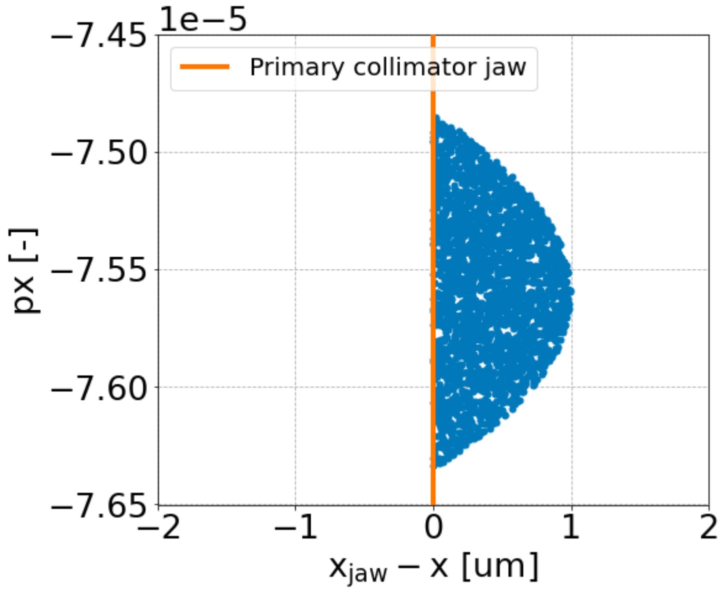
F. F. Van der Veken et al, THBP13

Simulating betatron cleaning with Xcoll

- **Qualification loss map measurements in operation**: blowing up emittance with transverse damper

- Simulation approach for a given energy
  - **Direct halo** sampled at jaw of primary collimator
    - \- Simplified beam dynamics, no diffusion considered
    - \+ Very efficient (200 turns)
  - **Count lost protons** in collimators and aperture
  - **Well benchmarked** against previous generation tools and measurements

Example initial particles distribution for betatron cleaning simulations in x-plane



Simulating off-momentum cleaning with Xcoll

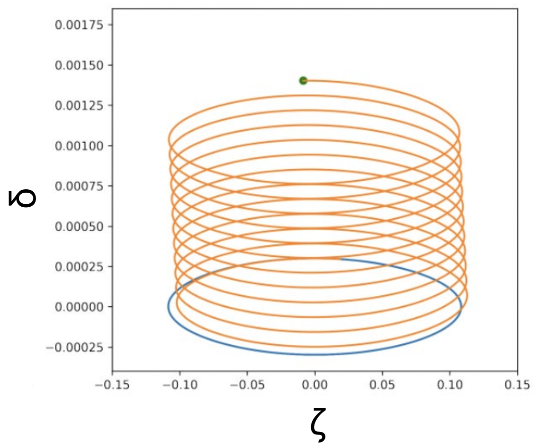
- Qualification in operation: shifting RF frequency by a few hundred Hz
- **Dynamic** simulation needed for RF sweep and complex beam dynamics
  - **Xcoll capable of mimicking RF sweep**
    - Shift applied adiabatically to all particles

$$\boxed{\Delta\zeta = L\frac{\Delta f_{\mathrm{RF}}}{f_{\mathrm{RF}} + \Delta f_{\mathrm{RF}}}}$$

where L is the ring circumference, Δf_{RF} is the shift in the RF frequency f_{RF}.

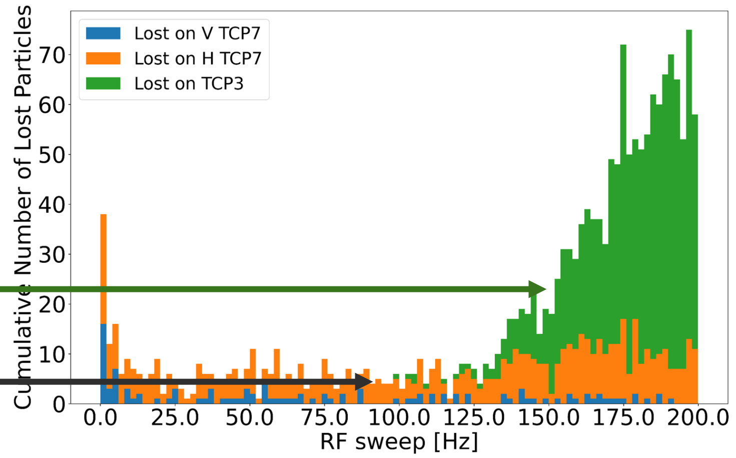
  - ~4000 turns needed, accounting for realistic initial particle distribution
  - **Time profile of losses agrees** with measurement:
    primary bottleneck moves IR7 → IR3 at ~160 Hz (at injection)

Evolution of a single particle during an RF sweep in LHC



F. F. Van der Veken

Time profile of losses during an RF sweep



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Machine configuration

- Studies conducted for **2023 proton configuration** during ramp
- Input: qualification loss maps from beam commissioning

Main settings

	Initial	Final
E_b	450 GeV	6.8 TeV
β*	11 m	2 m
V_{RF}	4 MV	12 MV
I_{KOF}	0 A	197 A
$Q'_{x,y}$	5 or 10	5 or 10

Collimator settings during the energy ramp for ϵ_{norm} = 3.5 μm

	Initial [σ]	Final [σ]
TCP7 / TCSG7 / TCLA7	5.7 / 6.7 / 10	5 / 6.5 / 10
TCP3 / TCSG3 / TCLA3	8 / 9.3 / 12	15 / 18 / 20
TCDQ / TCSP6	8 / 7.4	7.3 / 7.3
TCT1/5/8 / TCT2	13 / 13	18 / 37

Betatron cleaning

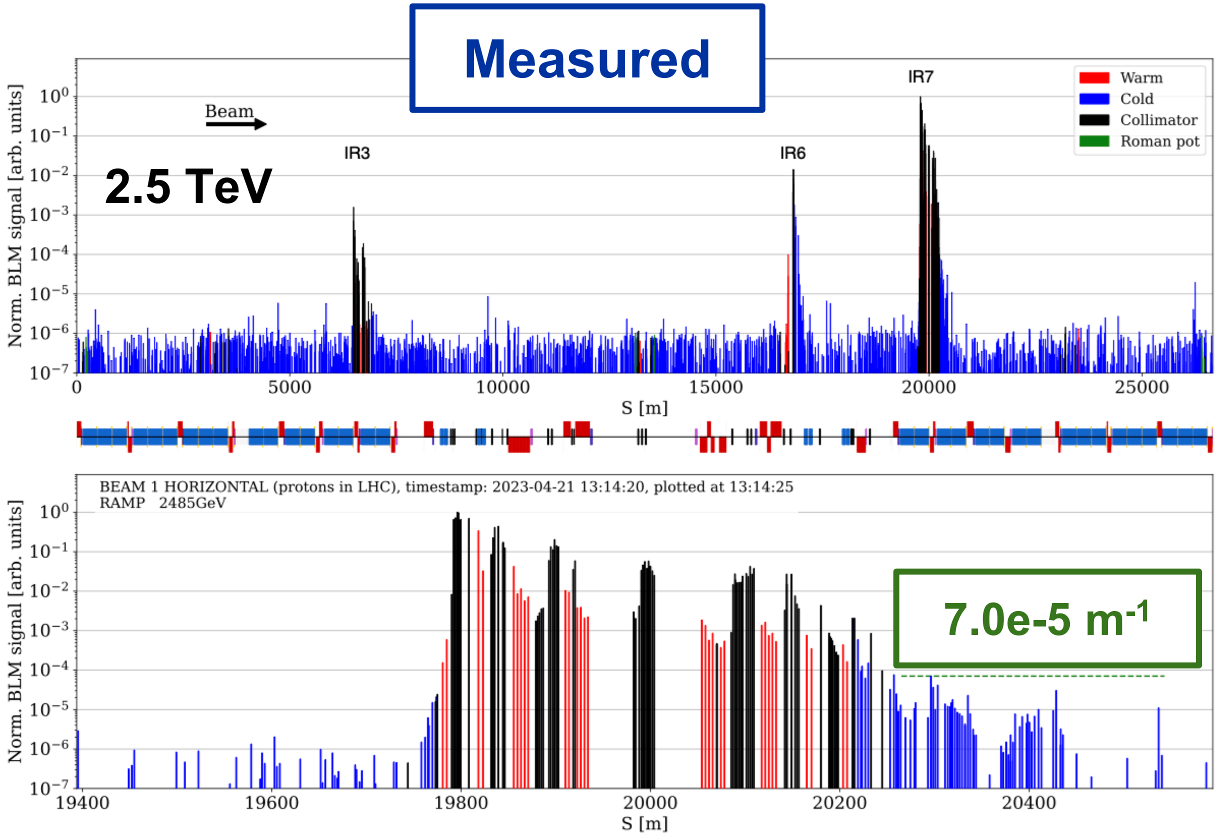
- **Good qualitative agreement** between measurements and simulations
  - Highest losses in **IR7**: similar **loss pattern**

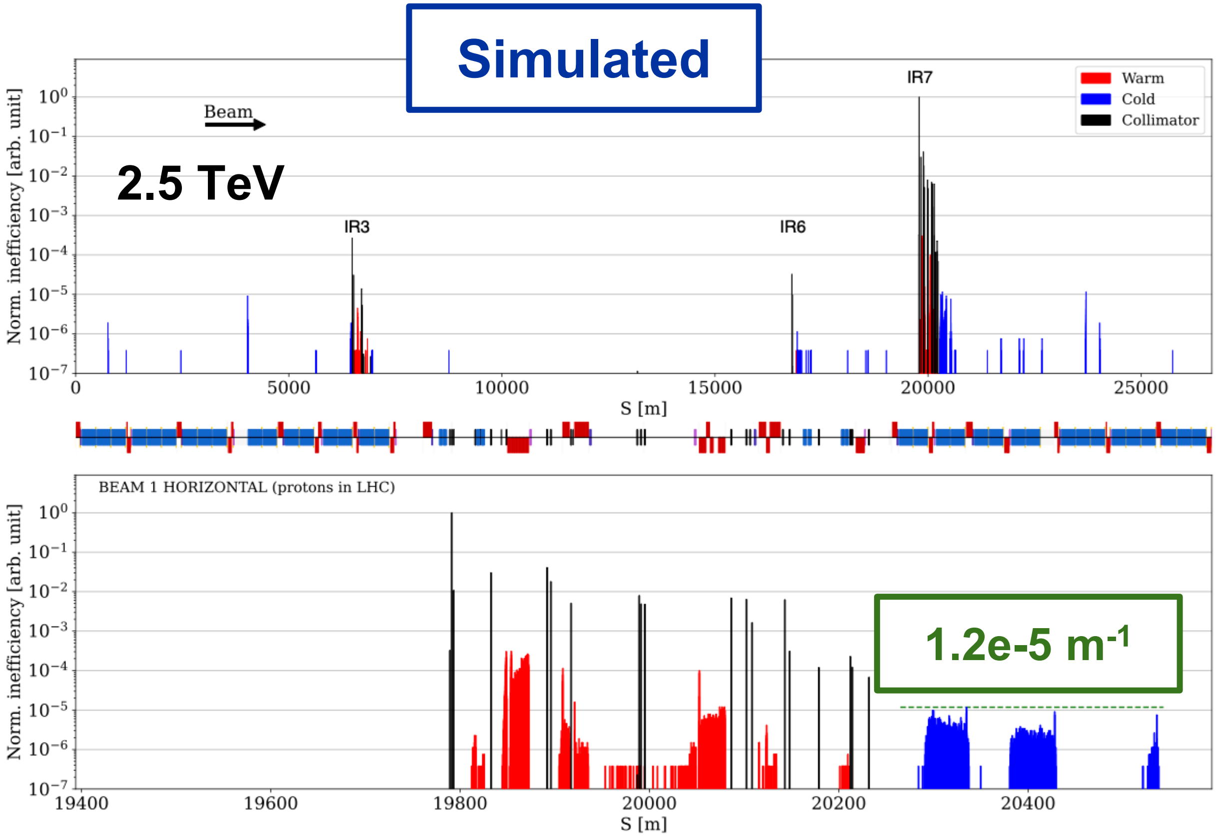
- Measurements with BLMs and simulation in Xsuite not to be compared quantitatively (see next slide)

Cleaning inefficiency simulations

$$\eta = \frac{N_{\mathrm{loc}}}{N_{\mathrm{tot}} \Delta s}$$

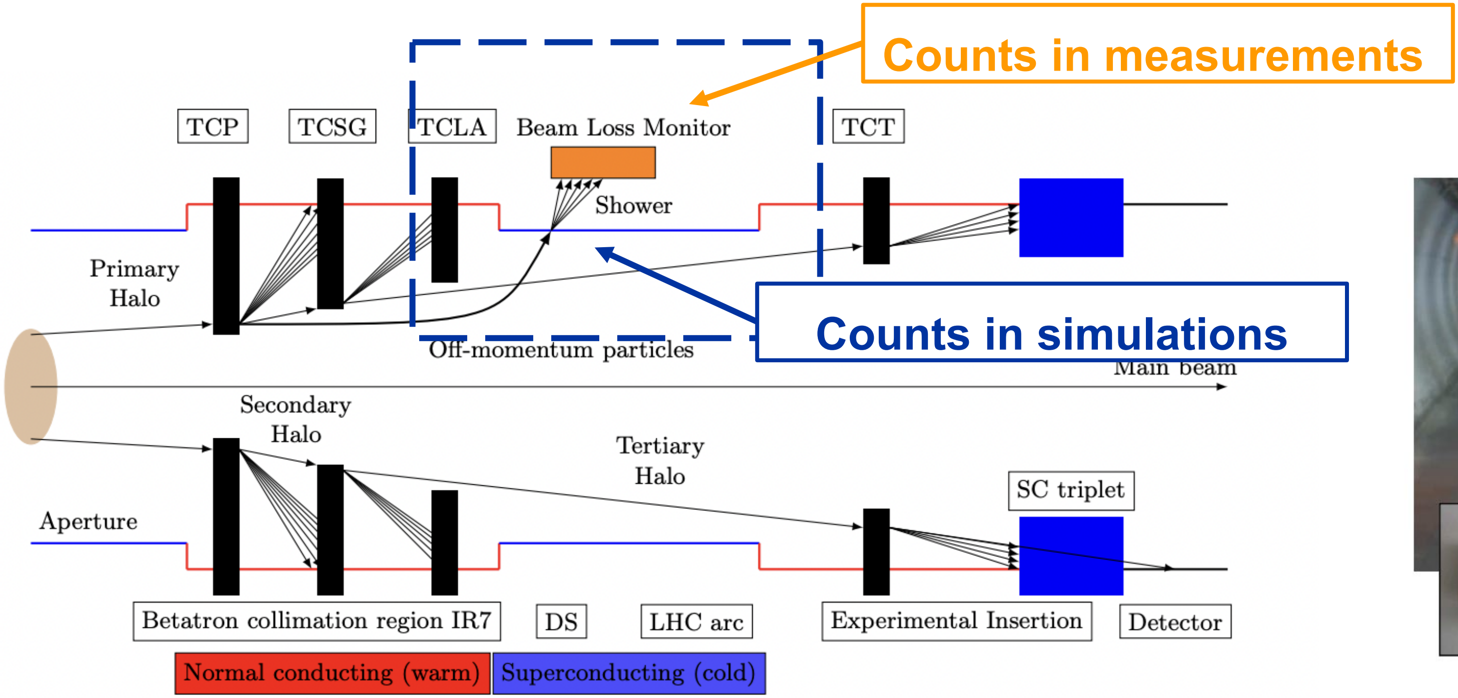
where N_{loc} the local losses over distance Δs and N_{tot} is the total number of losses in the collimation system



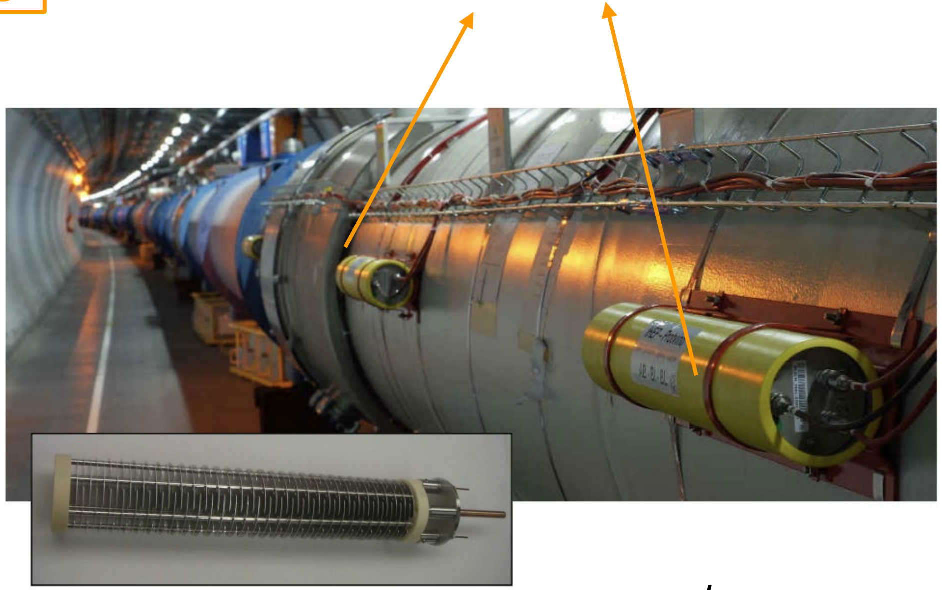


Collimation measurements vs simulations

- **Beam Loss Monitors** measure **secondary particle showers** outside of the magnet cryostat
- **Simulations** count **protons** lost in the **aperture**
- Measured and simulated loss maps **cannot** be **compared quantitatively**



Beam Loss Monitor system mounted at an LHC magnet

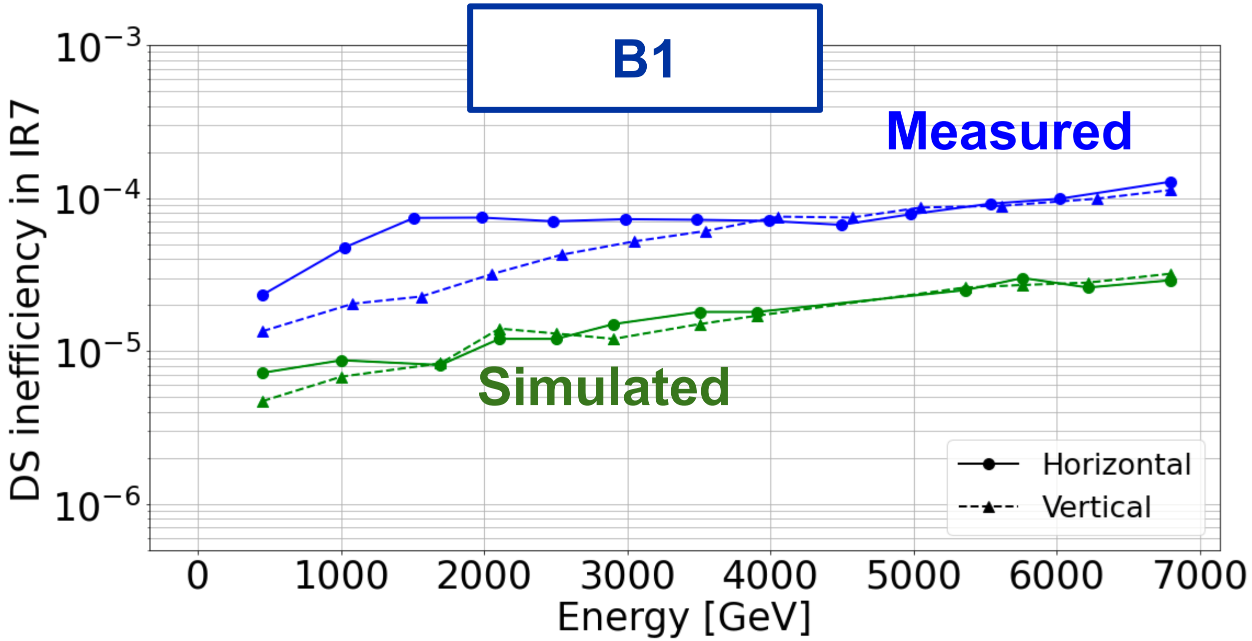


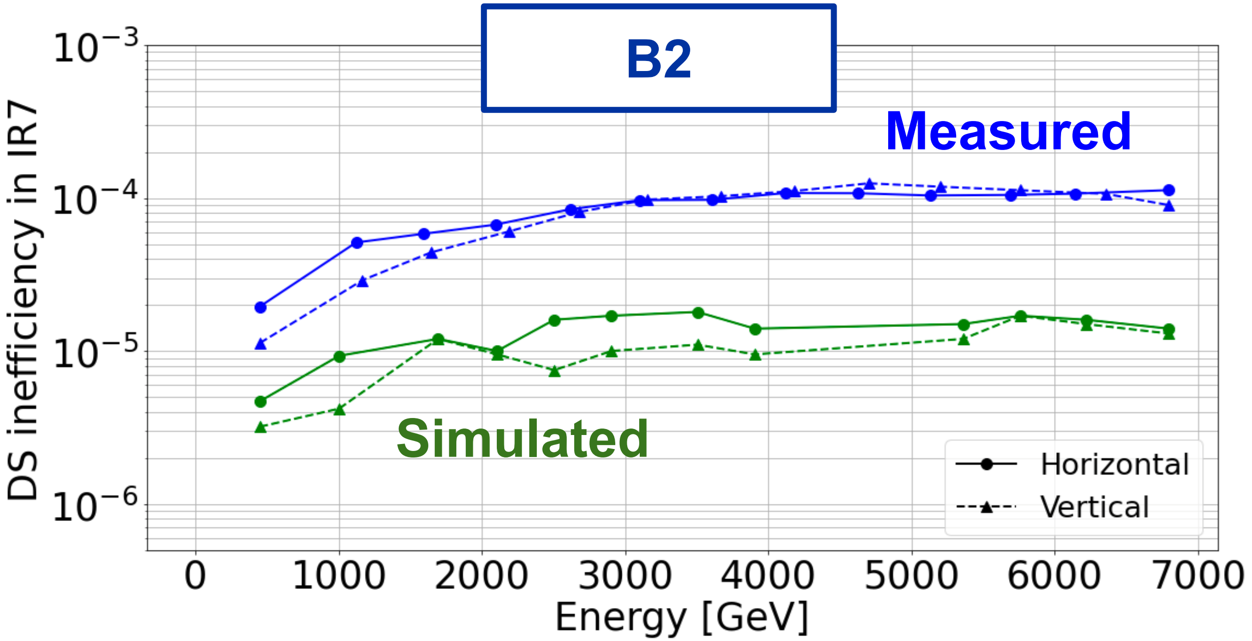
Images source link

Betatron cleaning during the energy ramp

- **Good qualitative agreement** between measurements and simulations
  - B1: Continuous increase of the inefficiency with the energy
  - B2: Increase until ~3 TeV after which it reaches a plateau
  - Apparent correlation of inefficiency vs energy between measurement and simulation

- **Quantitatively**: inefficiency differs by up to one order of magnitude (acceptable considering known limitations)



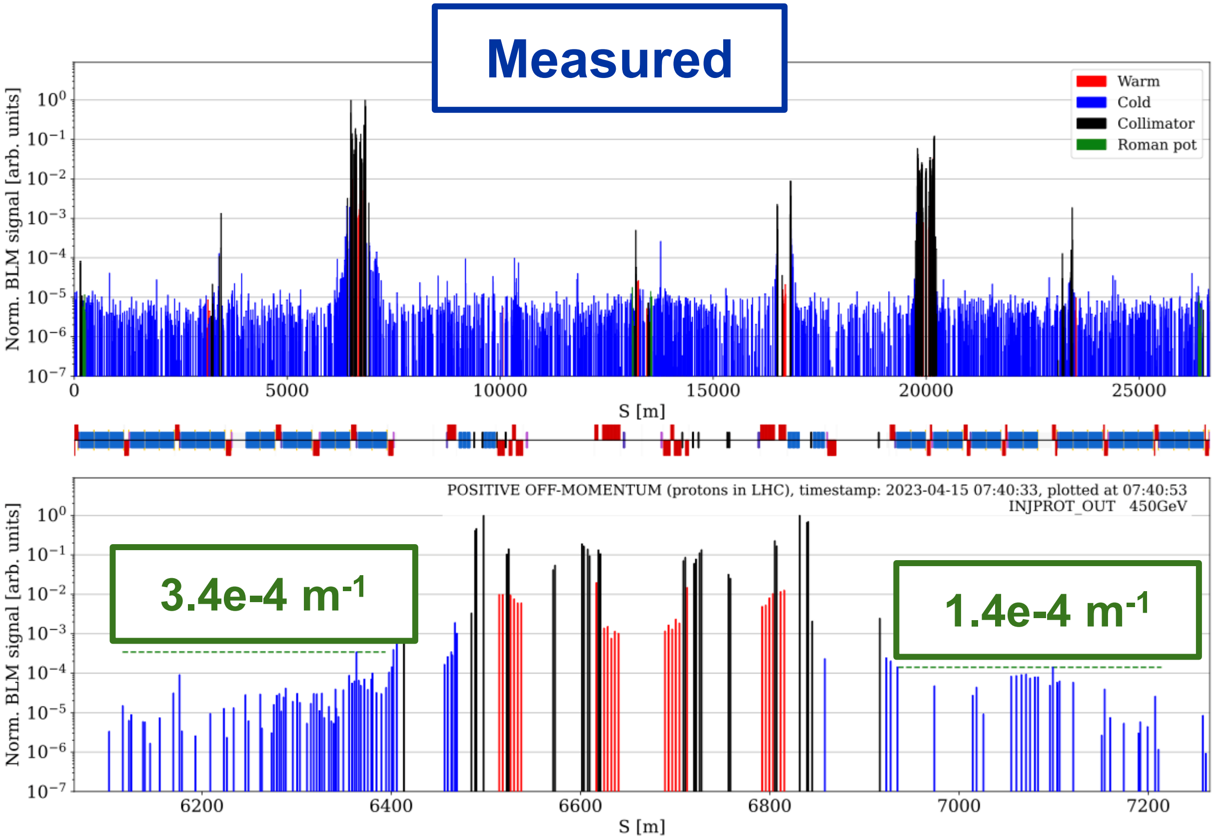


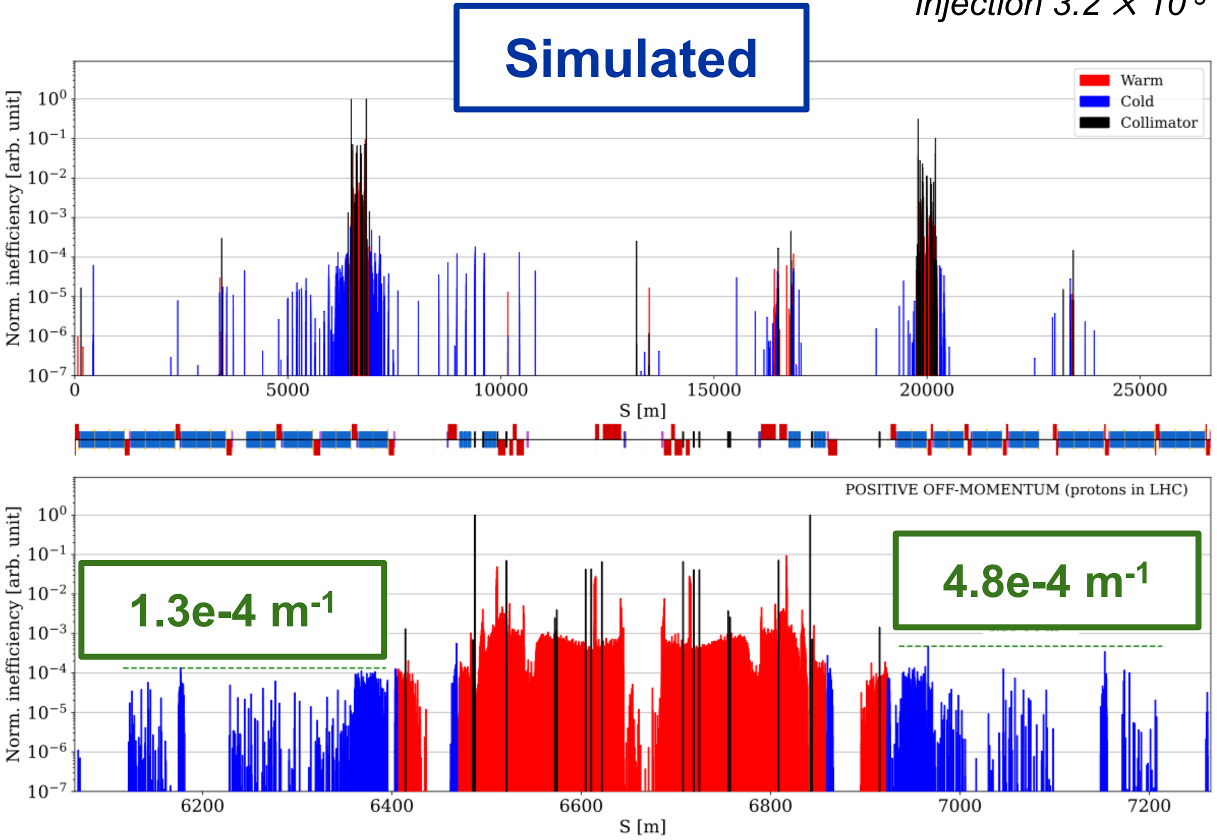
Off-momentum cleaning

- Example **positive off-momentum** loss maps at **injection** energy, **RF sweep -200 Hz**

- **Very good agreement** between measurement and simulation
  - Highest losses in **IR3**

Off-momentum cut at injection 3.2 × 10^{-3}





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Conclusions and future steps

- Review of LHC **collimation system performance** during **energy ramp** at commissioning 2023
- Use of **Xsuite** and **Xcoll** for collimation simulations: **very easy set up and implemented RF sweep module**
- **First simulation results** in the **energy ramp for the LHC** and use of the **dynamic RF sweep in Xtrack**
  - **Very good qualitative agreement** between measurements and simulations
  - Quantitative discrepancies observed but expected: BLM signals/simulations represent secondary showers/protons impacting the aperture

Next steps

- Study possible impact of machine imperfections and collimator misalignments
- Use of the RF sweep module to simulate the high losses observed at the start of the ramp, ~2s, in IR3

Thank you for your attention