# 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**
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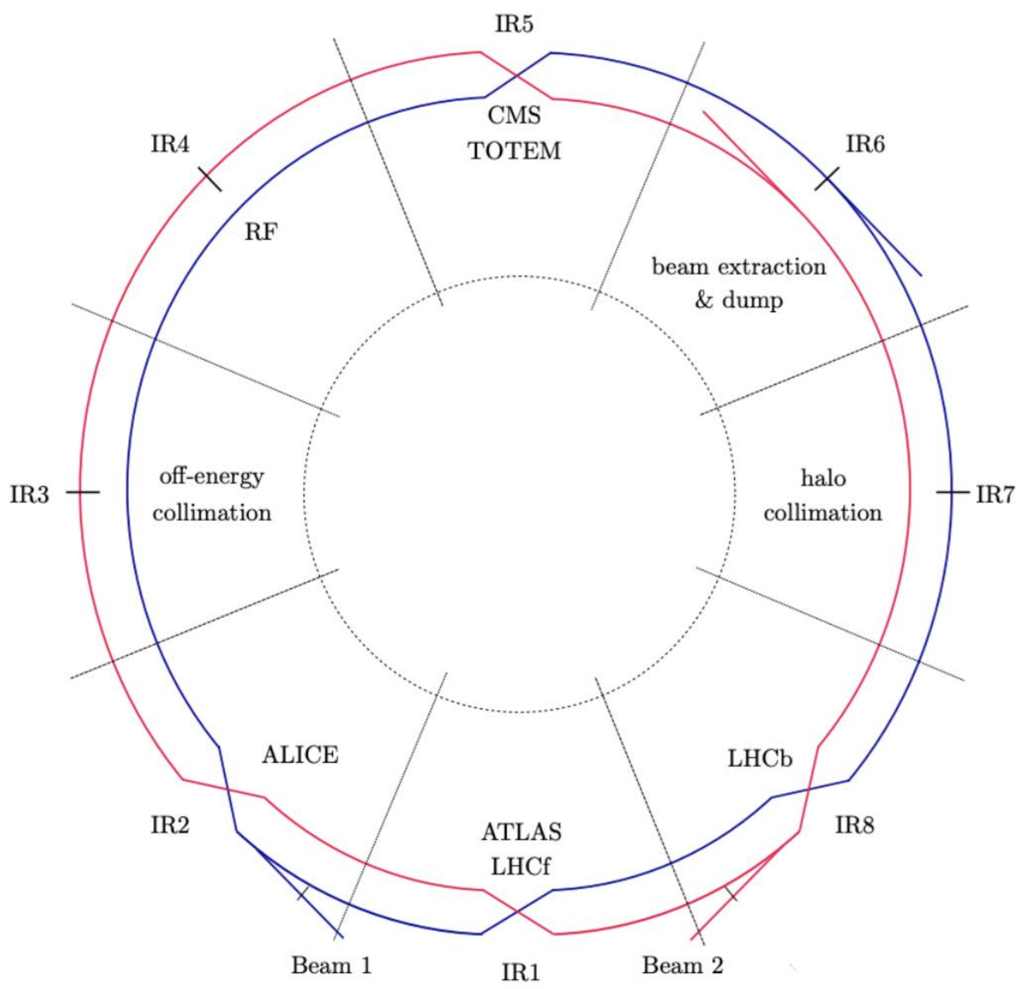
# Large Hadron Collider

- 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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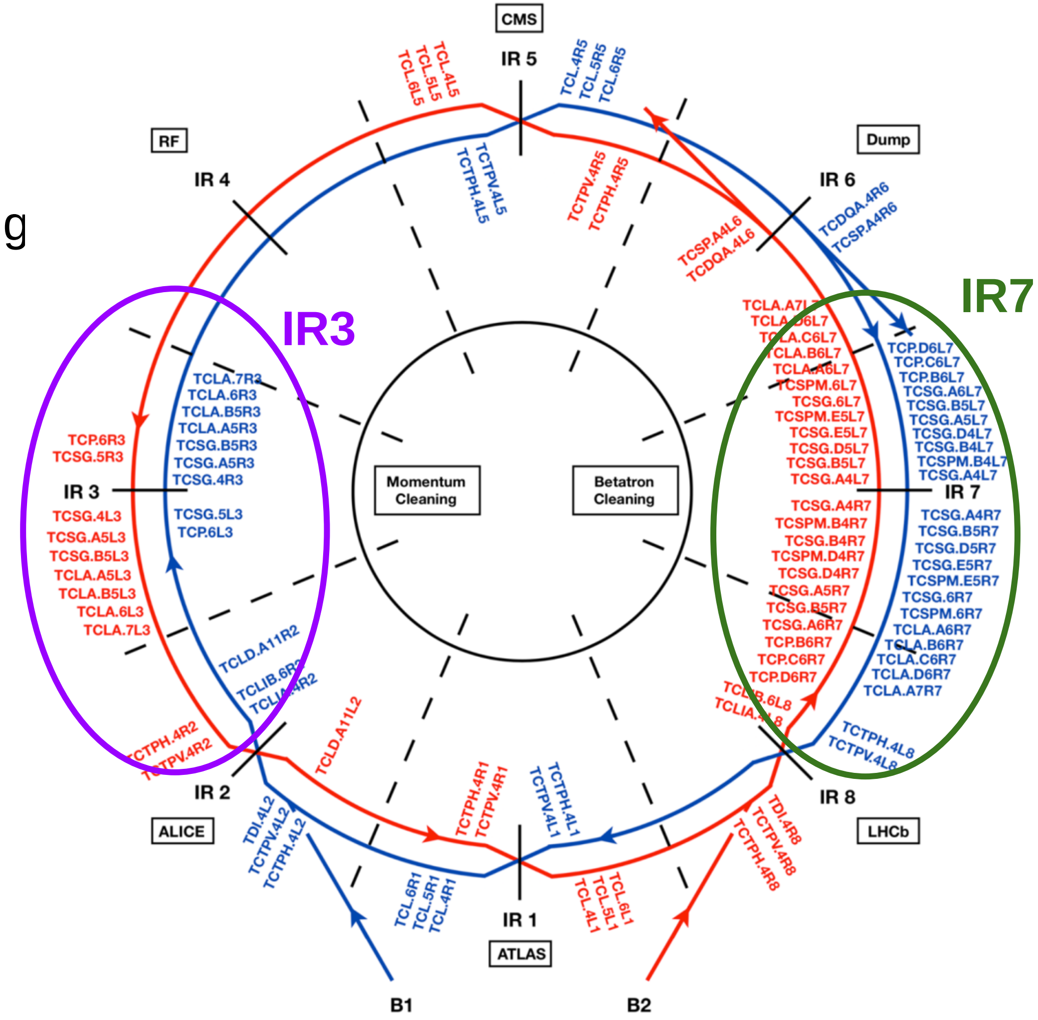
# LHC collimation system

- 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**

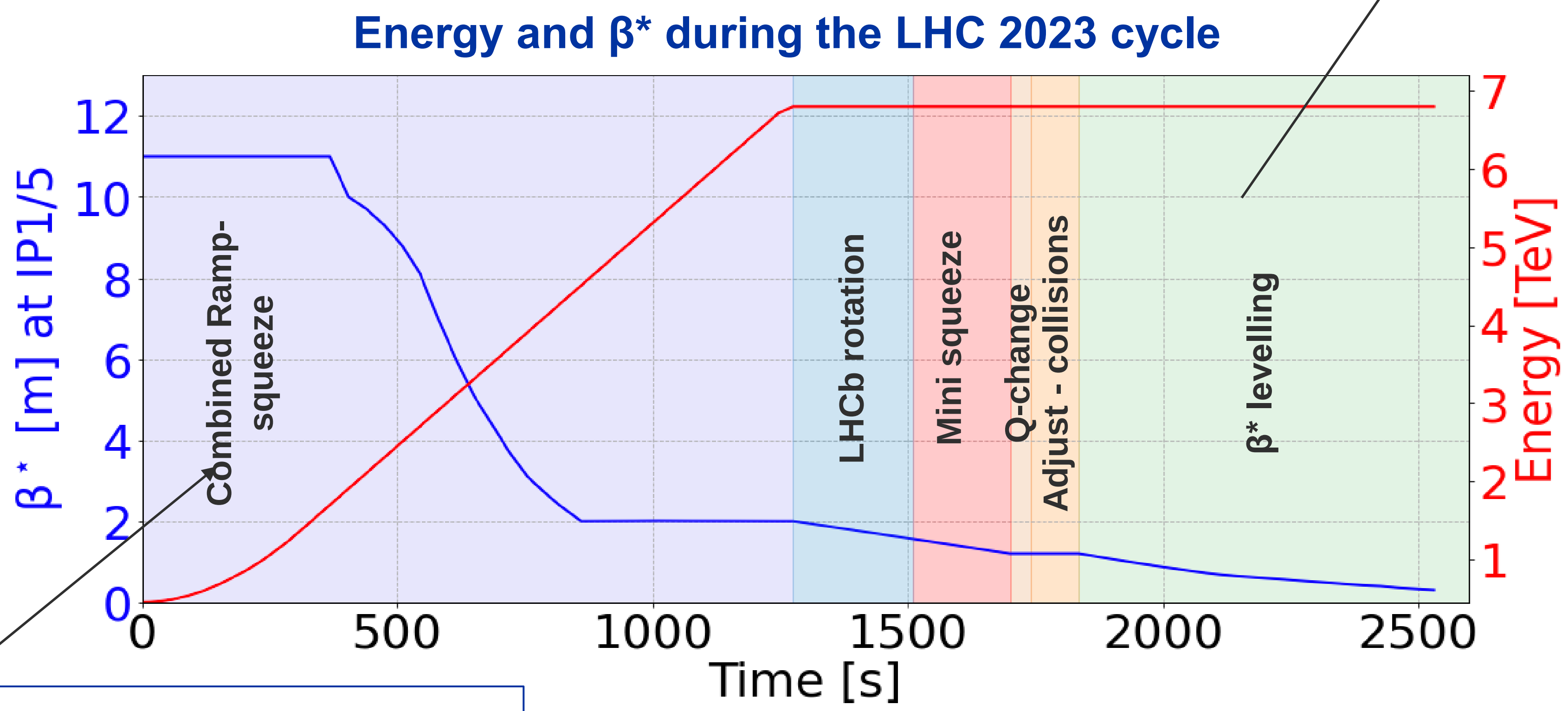
**Collimator locations around LHC ring**




*(*) 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***

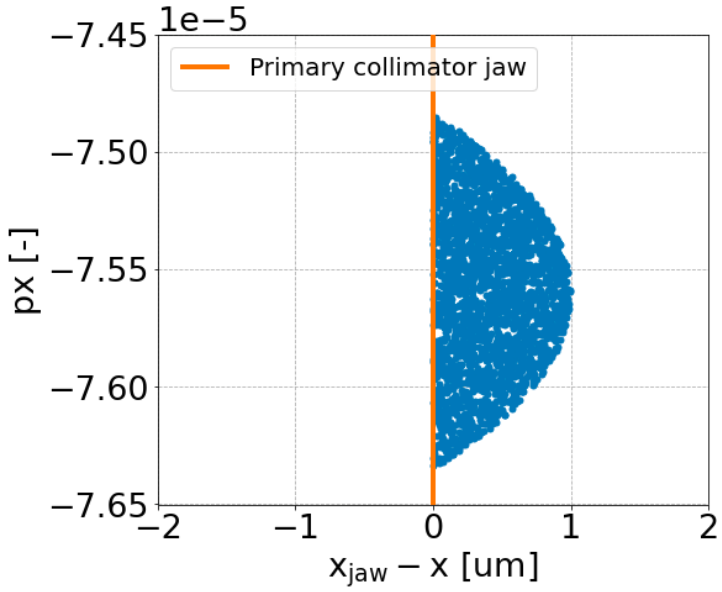
***F. F. Van der Veken et al, THBP13***

# 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

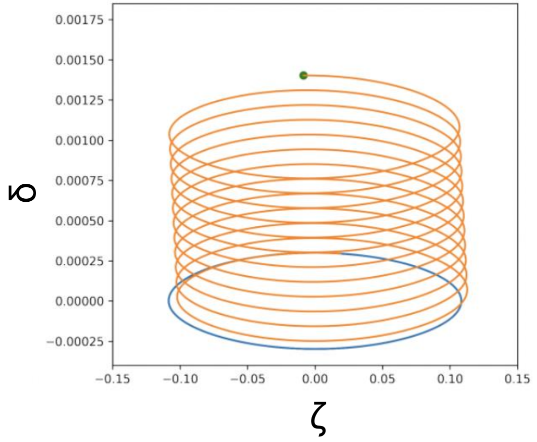
- Qualification in operation: shifting RF frequency by a few hundred Hz
- **Dynamic** simulation needed for RF sweep and complex beam dynamics
  - **Xcoll capable of mimicking RF sweep**
    - Shift applied adiabatically to all particles

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

*where L is the ring circumference, $\Delta f_{RF}$ is the shift in the RF frequency $f_{RF}$.*

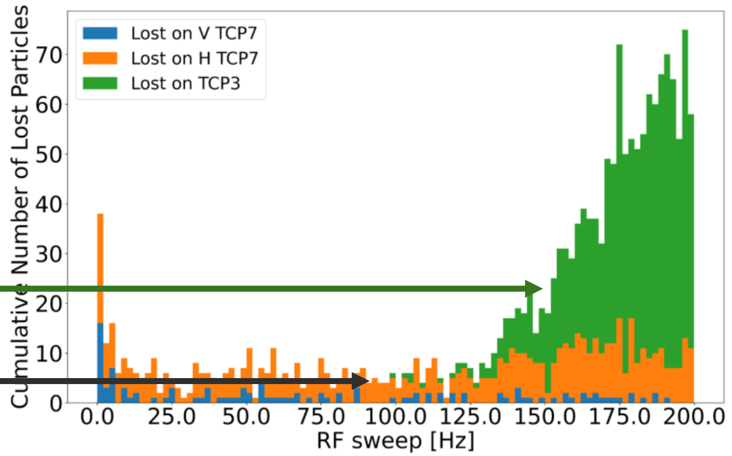
  - ~4000 turns needed, accounting for realistic initial particle distribution
  - **Time profile of losses agrees** with measurement: **primary bottleneck moves IR7 → IR3 at ~160 Hz** (at injection)

**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 |
| $\beta^*$ | 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 $\epsilon_{norm}$ = 3.5 $\mu$m**

| | 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 |

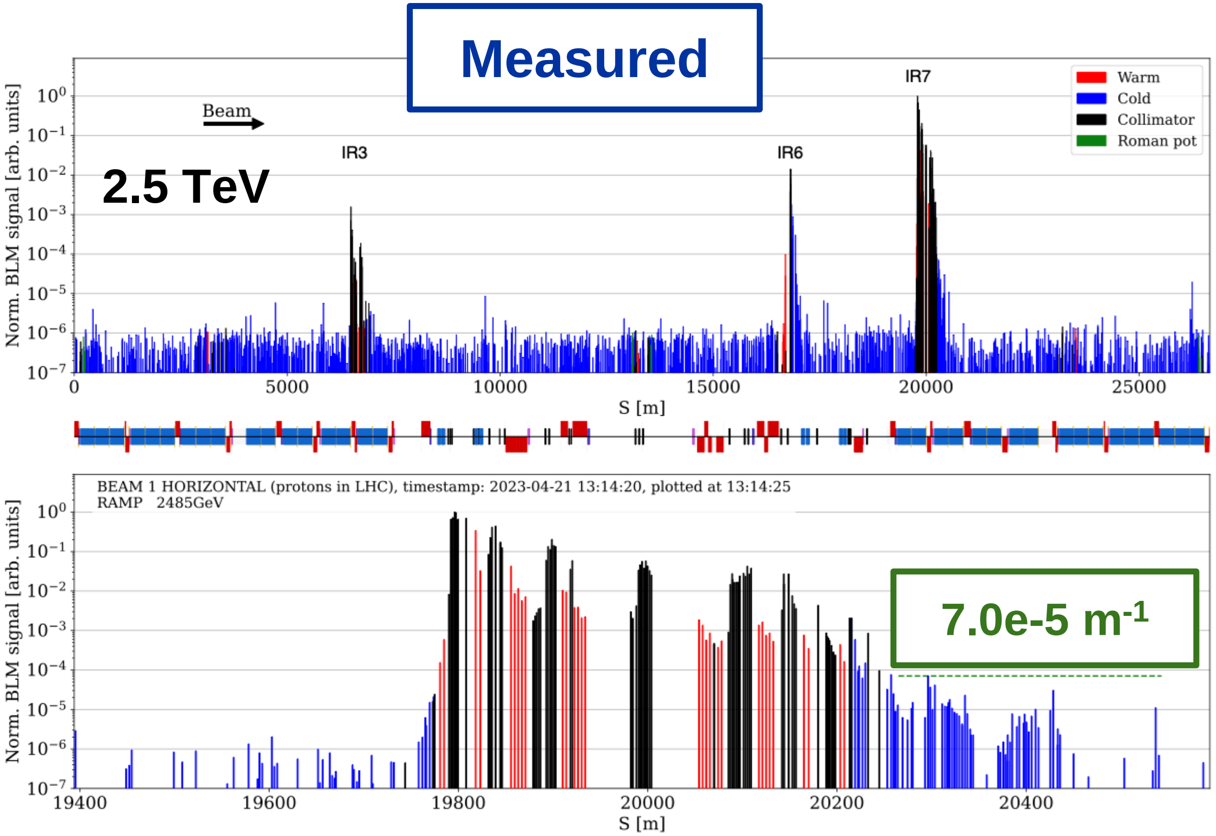
# Betatron cleaning

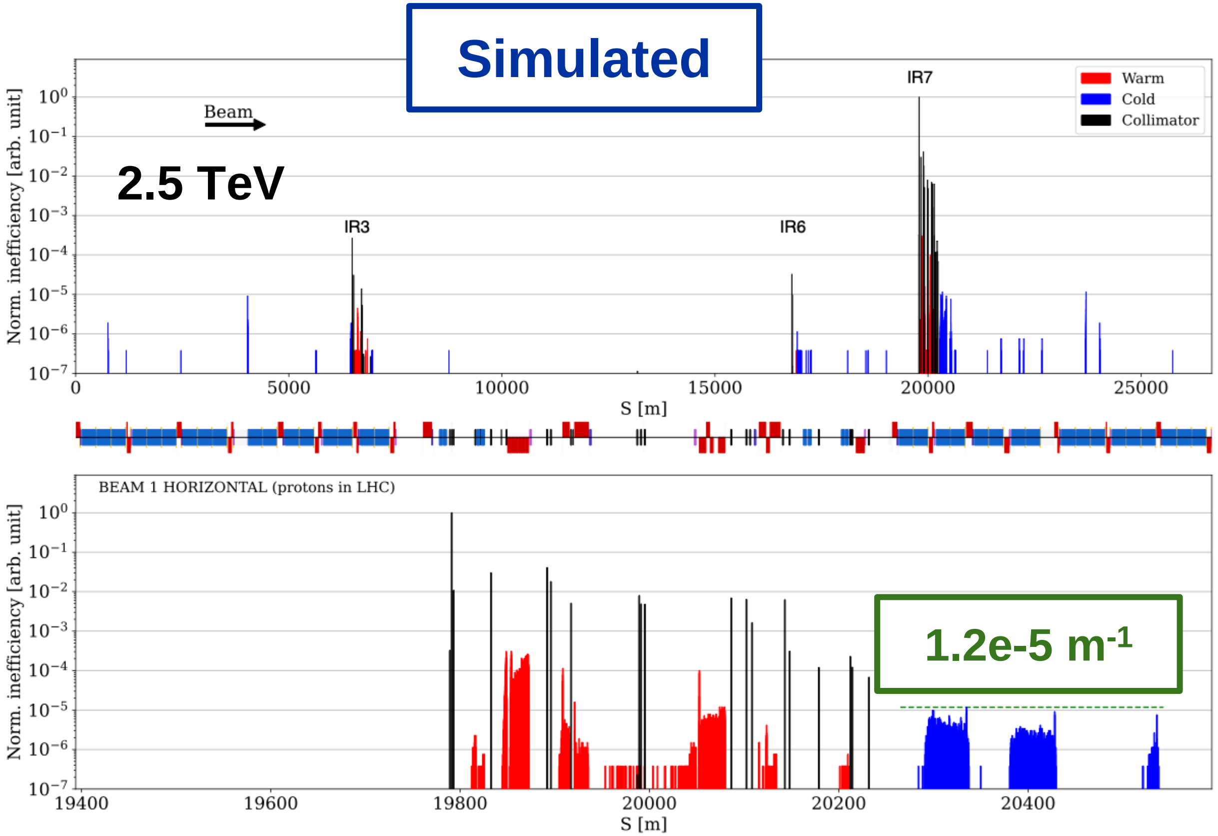
**Cleaning inefficiency simulations**

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

where $N_{loc}$ the local losses over distance $\Delta s$ and $N_{tot}$ is the total number of losses in the collimation system

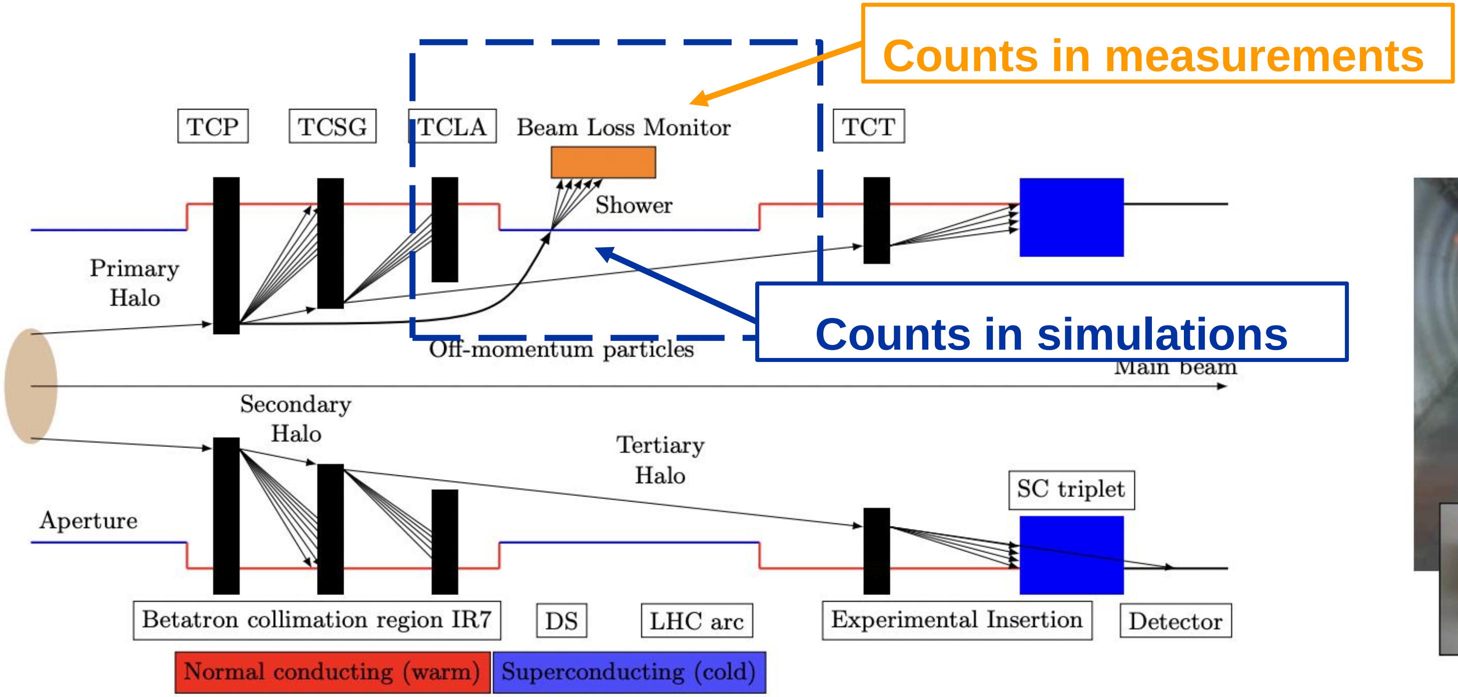
- **Good qualitative agreement** between measurements and simulations
  - Highest losses in **IR7**: similar **loss pattern**
- Measurements with BLMs and simulation in Xsuite not to be compared quantitatively (see next slide)



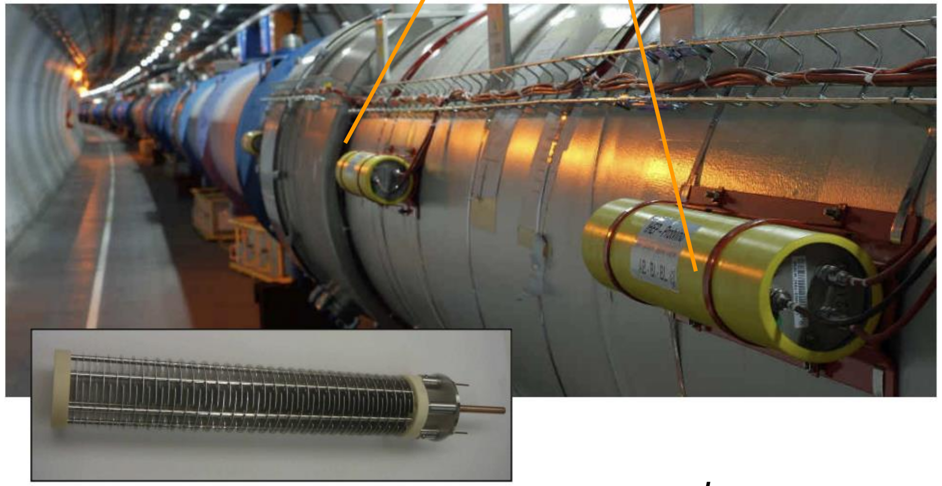



# Collimation measurements vs simulations

- **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

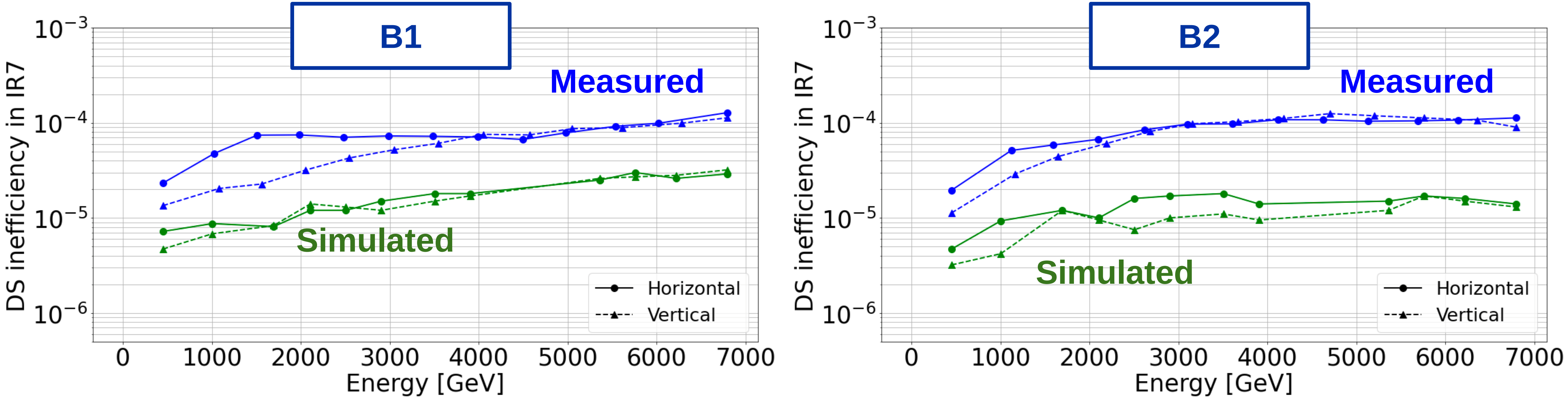


*Images source link*

# 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)

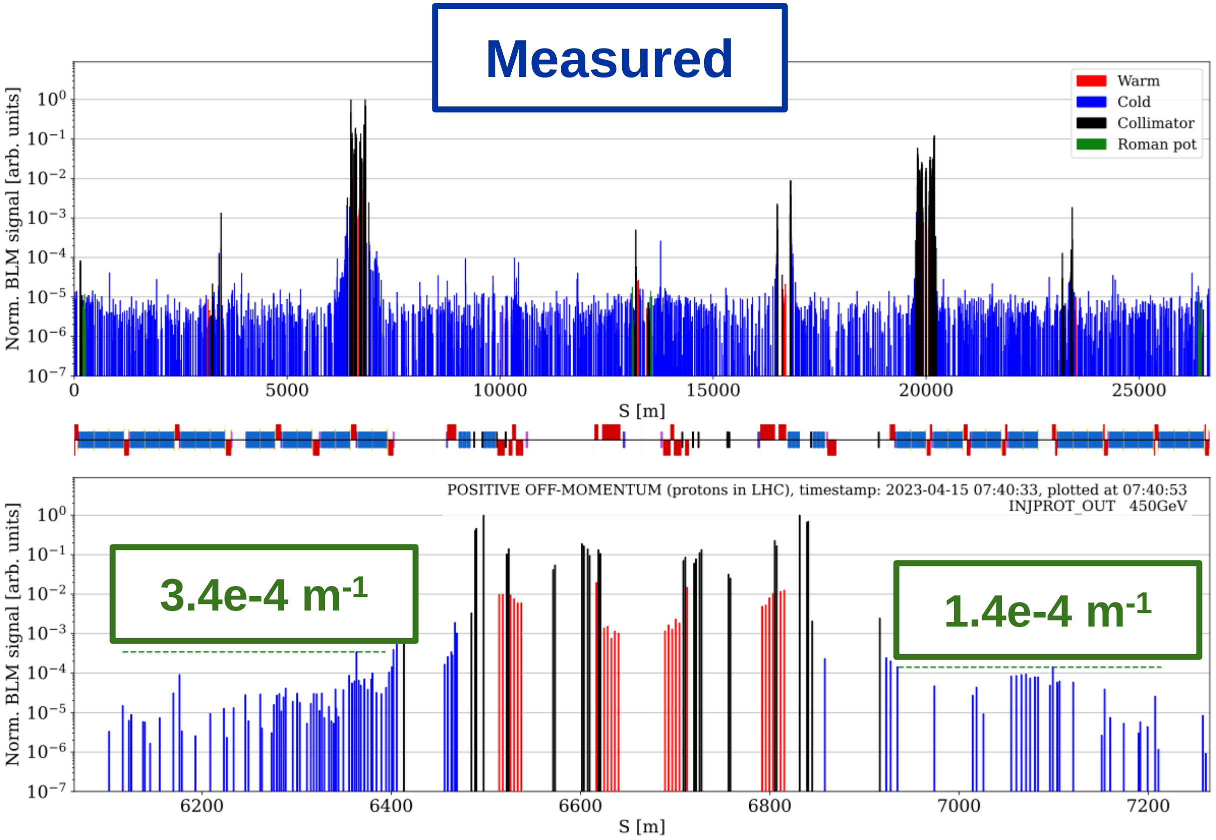


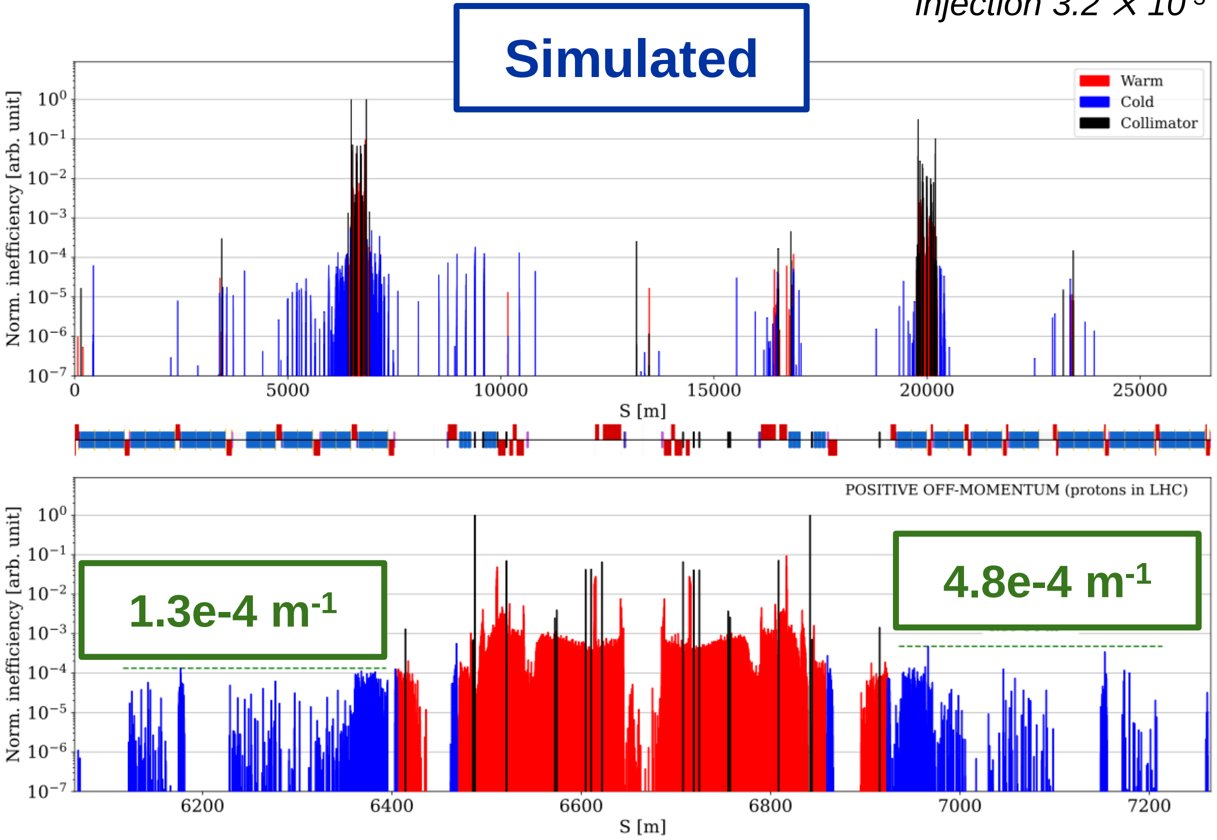
# Off-momentum cleaning

- 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**

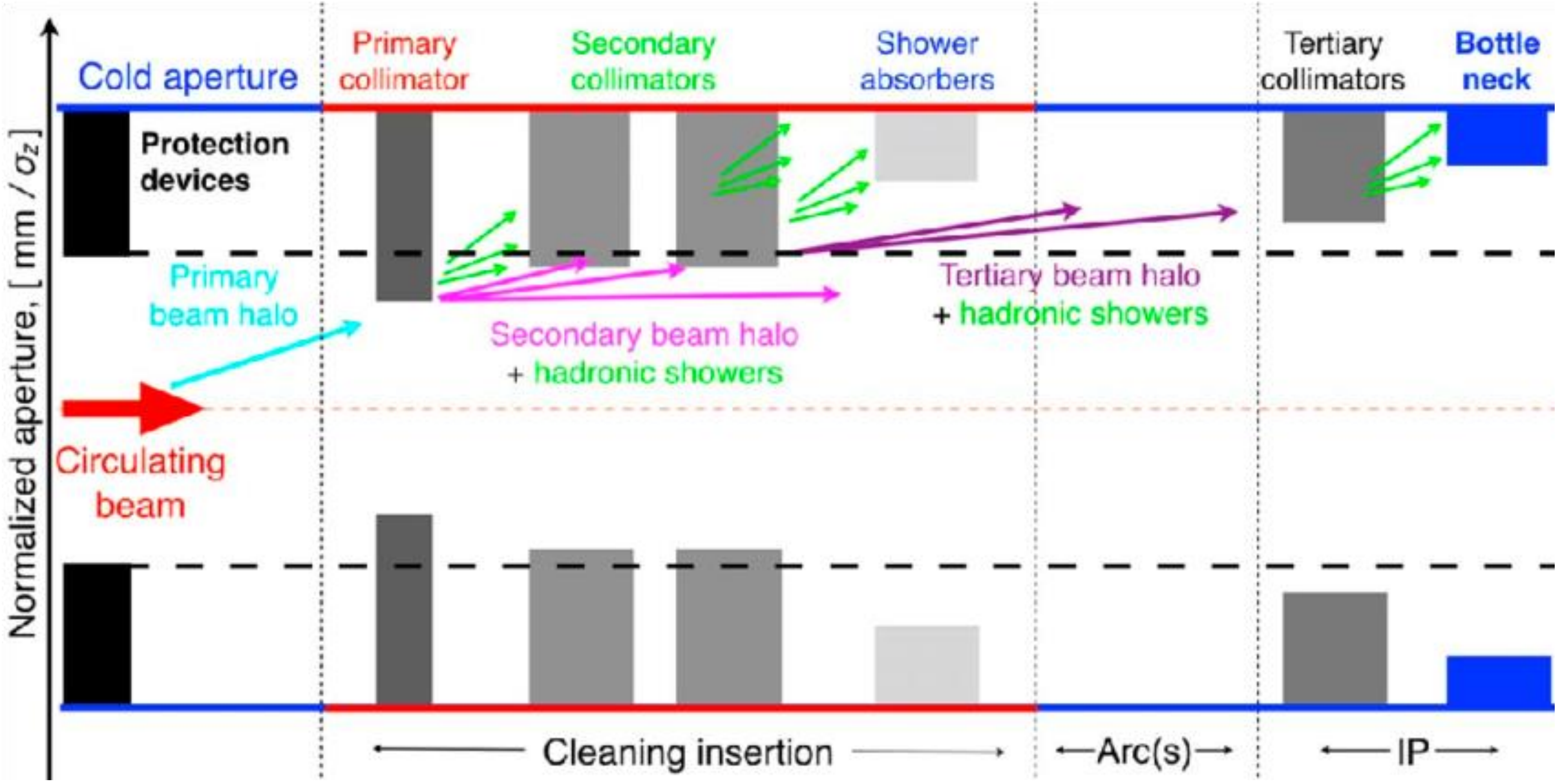
- Study possible impact of machine imperfections and collimator misalignments

- 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

# Back up

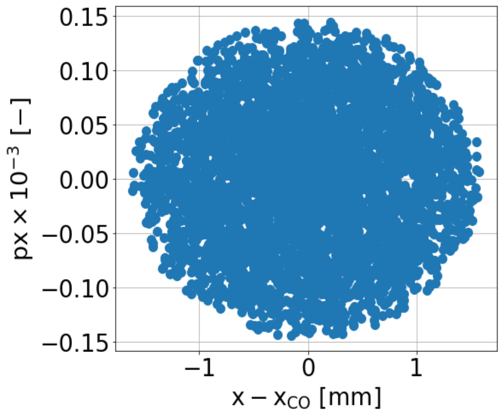
# LHC multistage collimation system



# RF sweep in Xcoll - details

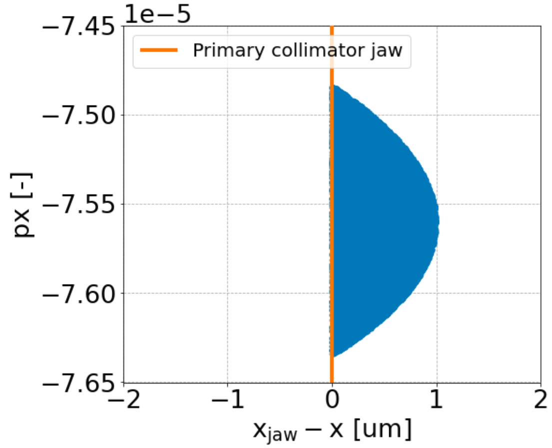
- It has to be applied **adiabatically**, slower than the synchrotron oscillation period
  - For LHC, 50 mHz/turn is adequate
- It can account for realistic transverse distribution:
  - Initialise uniform distribution at selected σ; phases in [0,π/2]
  - Weight losses in collimators/aperture from past halo scrapings data, based on starting amplitude
  - Flexibility in options based on the simulation scenario

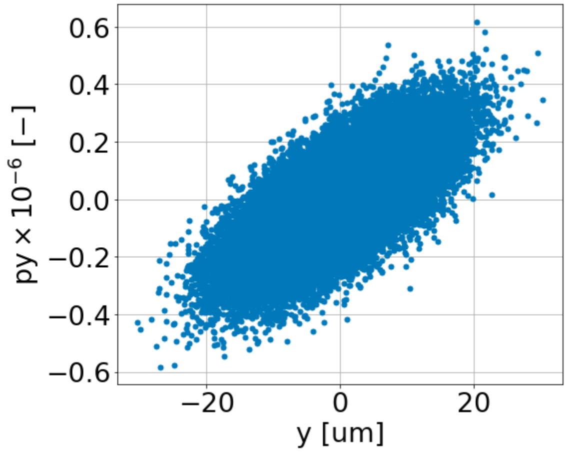
**Initial particles distribution for betatron cleaning simulations in x-plane**



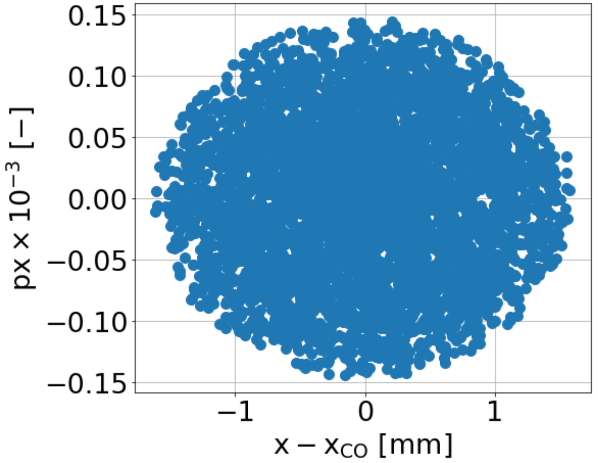
# Initial distributions used in Xcoll simulations

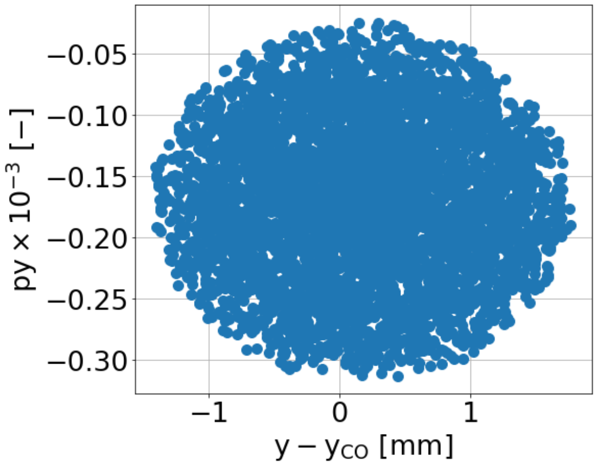
## Betatron loss maps

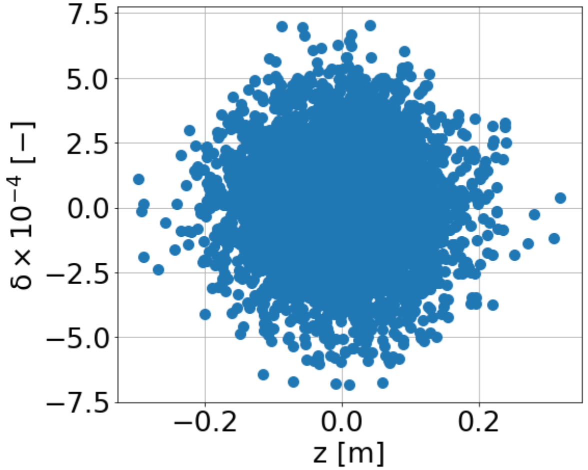



## Off momentum loss maps



# Refining loss location in Xtrack

- **Before tracking:** aperture markers are installed at locations of known aperture changes
- **During tracking:** Tracking stops for particles found to be outside of the aperture marker. Typically a few meters uncertainty in their actual loss location
- **After tracking:** Higher precision is required for collimation studies
  - Achieved by further post processing → **Backtracking in Xtrack**
  - Further aperture markers are installed every 10 cm and the particles are tracked backwards performing linear interpolation from its initial location till it hits the more refined aperture.

***More details: G. Iadarola et al, TUA211***