The CERN Accelerator School

US-CERN-JAPAN-RUSSIA Joint International Accelerator School:
Beam Losses and Accelerator Protection
November 5th-14th, 2014, Newport Beach, California, USA

Beam Cleaning and Collimation Systems

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CERN

SEVENTH FRAMEWORK PROGRAMME

High Luminosity LHC

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

EuCARD²

LHC Collimation Project
CERN

Outline

- ☑ Introduction
- ☑ Beam losses and collimation
- ☑ Multi-stage collimation
- ☑ LHC collimation design
- ☑ Cleaning: operational performance
- ☑ Conclusions

High-intensity circular hadron accelerators

The LHC collimator

What is **beam collimation** and **why we need it**?

How do we **design a collimation system**?

How many collimators are needed?

Where are they **located** in the machine?

How are they **built**, with which **materials**?

How to **measure** and **simulate cleaning**?

Beam collimation - definitions

Beam halo collimation

Controlled and safe disposal of beam halo particles produced by unavoidable beam losses.
Achieved by reducing the transverse cross section of the beam.

Betatron (and off-momentum) **halo particles**

Particles with large betatron amplitudes (or energy deviations) with respect to the beam's reference particle.
Gaussian beams: typically, particles above 3 RMS beam sizes.

There are different goals of **collimation systems** depending on the machine.

collimate /ˈkɒlɪˌmeɪt/

VB (transitive)

1. to adjust the line of sight of (an optical instrument)
2. to use a collimator on (a beam of radiation or particles)
3. to make parallel or bring into line

Etymology: 17th Century: from New Latin *collimāre*, erroneously for Latin *collīneāre* to aim, from *com-* (intensive) + *līneāre*, from *līnea* line

collimator /ˈkɒlɪˌmeɪtə/

N

1. a small telescope attached to a larger optical instrument as an aid in fixing its line of sight
2. an optical system of lenses and slits producing a nondivergent beam of light, usually for use in spectroscopes
3. any device for limiting the size and angle of spread of a beam of radiation or particles

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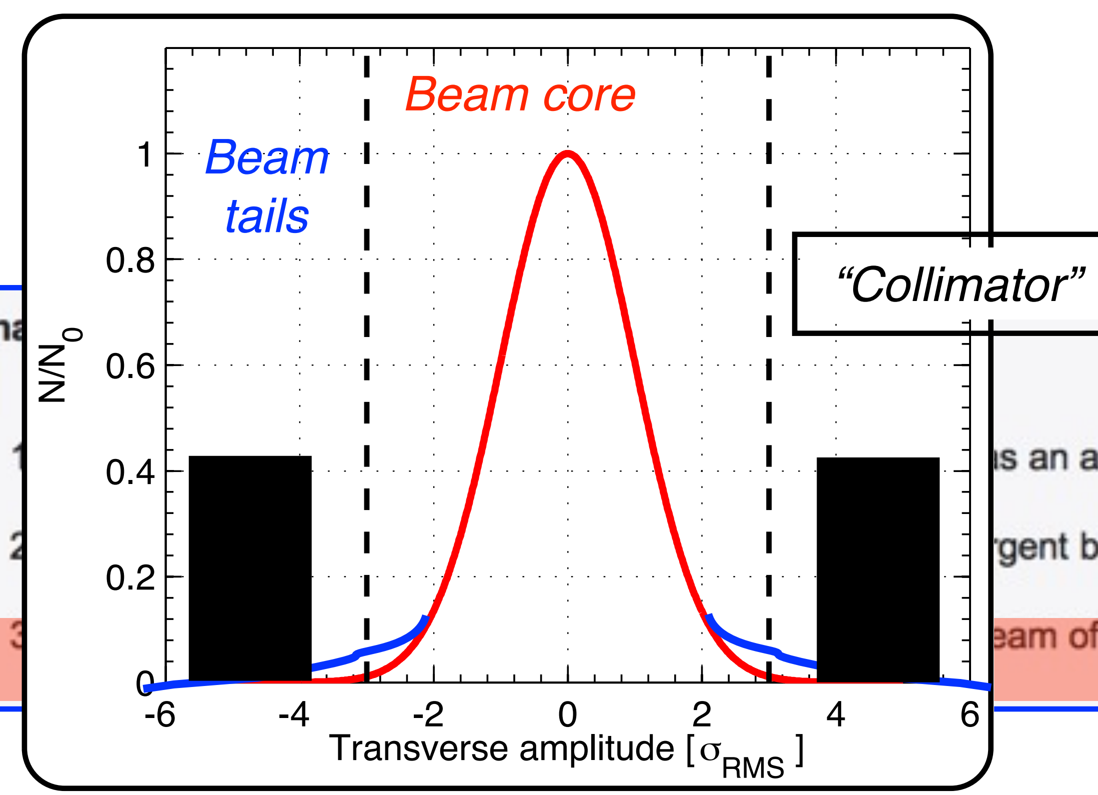

Roles of collimation systems

- **Halo cleaning** versus quench limits (super-conducting machines)
- Passive **machine protection**
    First line of defense in case of accidental failures.
- **Concentration of losses/activation** in controlled areas
    Ease maintenance by avoiding many distributed high-radiation areas.
- **Reduction total doses** on accelerator equipment
    Provide local protection to equipment exposed to high doses (like the warm magnets in cleaning insertions)
- **Cleaning of physics debris** (physics products, in colliders)
    Avoid magnet quenches close to the high-luminosity experiments
- Optimize **background** in the experiments
    Minimize the impact of halo losses on quality of experimental data
- Beam tail/halo **scraping**, **halo diagnostics**
    Control and probe the transverse or longitudinal shape of the beam

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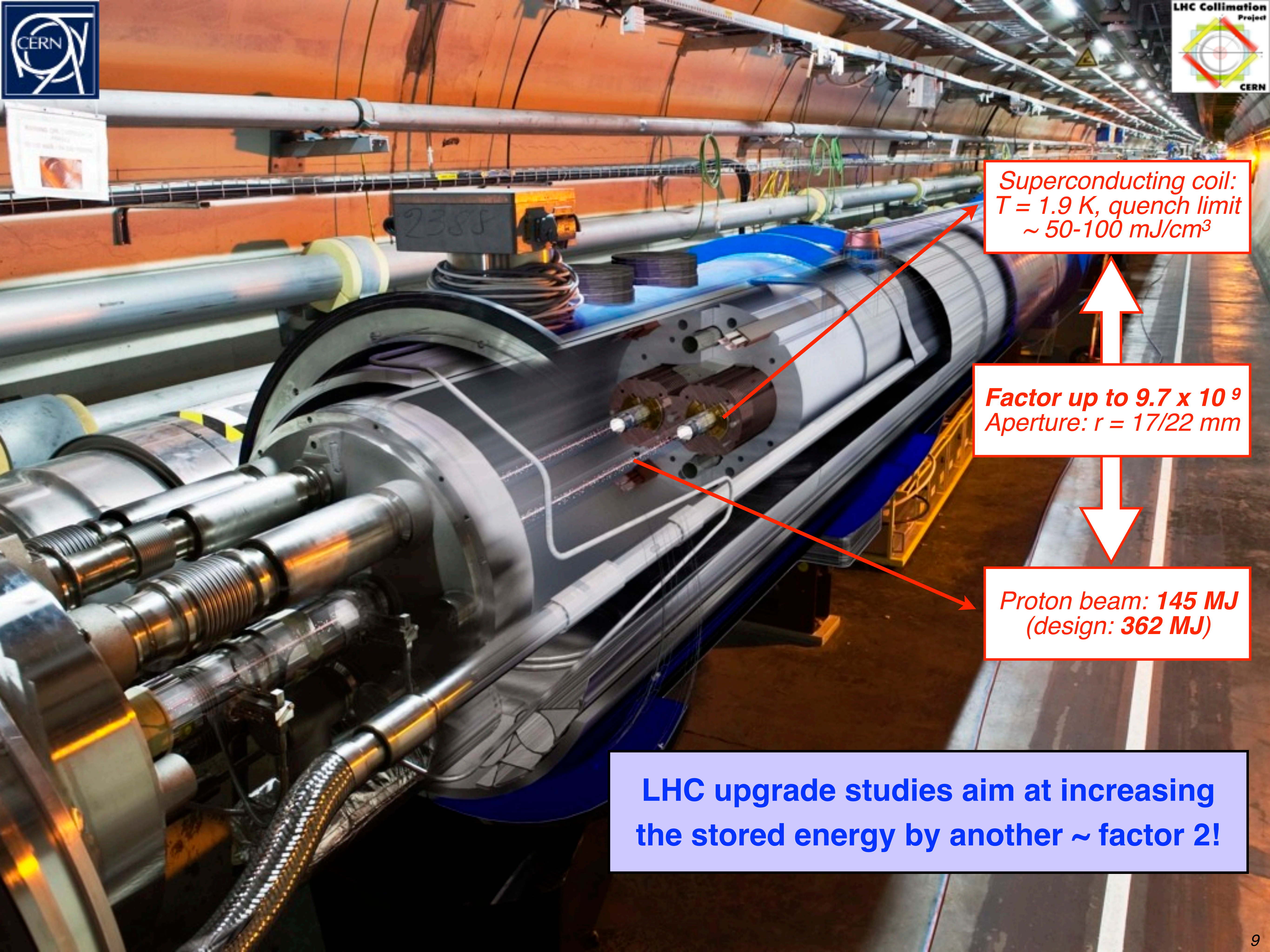
- Beam tail/halo **scraping**, **halo**

  Control and probe the transverse

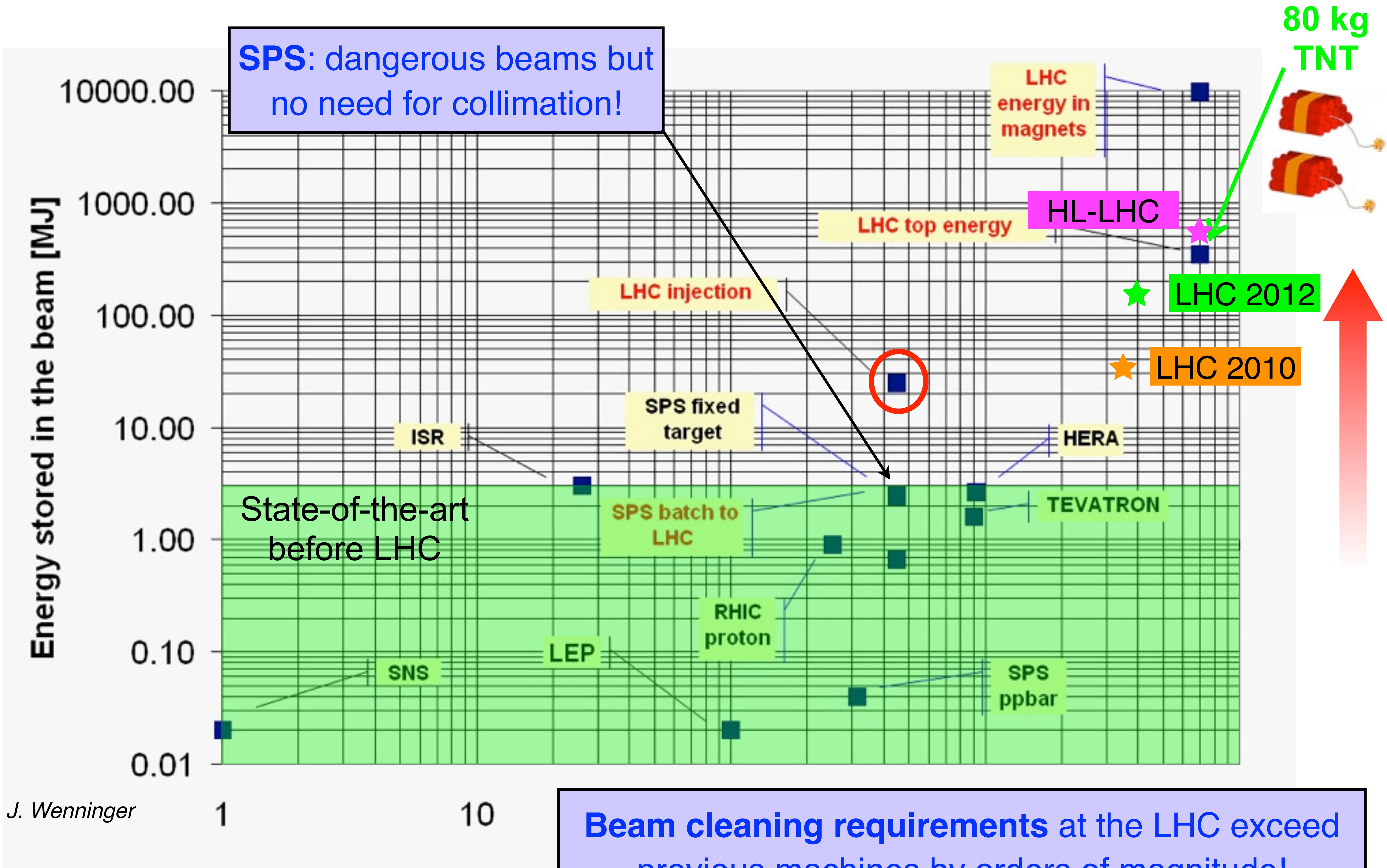
➛ Main role of collimation in previous hadron colliders (SppS, Tevatron, ...)

This lecture: focus **collimation cleaning** functionality. LHC examples as a case study because all these roles are addressed !

Why is the LHC so special for collimation matters?

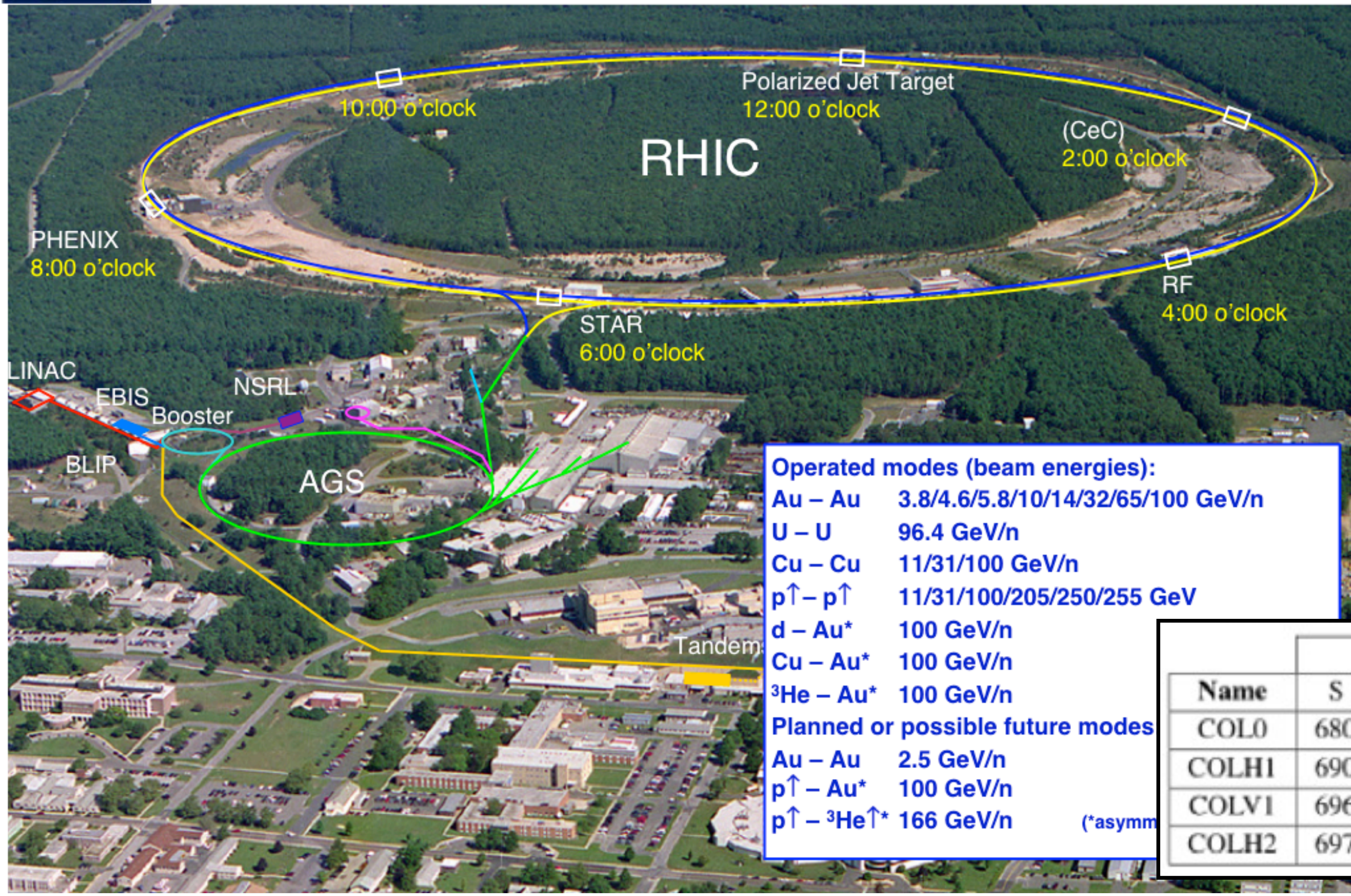

Superconducting coil:
T = 1.9 K, quench limit
~ 50-100 mJ/cm³
Factor up to 9.7 x 10 ⁹
Aperture: r = 17/22 mm
Proton beam: 145 MJ
(design: 362 MJ)
LHC upgrade studies aim at increasing
the stored energy by another ~ factor 2!
LHC Collimation Project
CERN

The stored energy challenge



Beam cleaning requirements at the LHC exceed previous machines by orders of magnitude!

RHIC collimation system



RHIC beam parameters [p]:

E_b = 250 GeV

N_{tot} = 110 x 10^{11}p

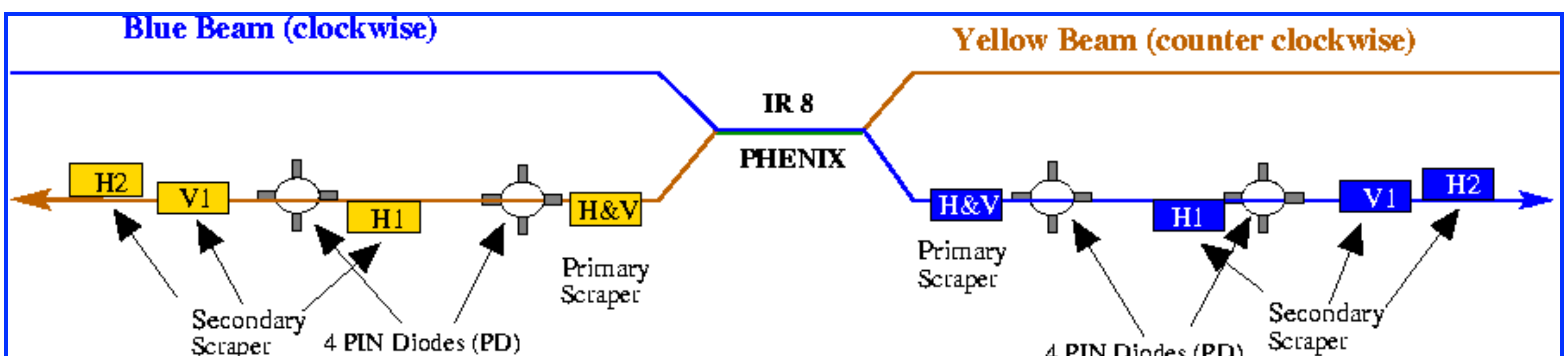
E_{stored} = ~ 440 kJ

Collimation system:

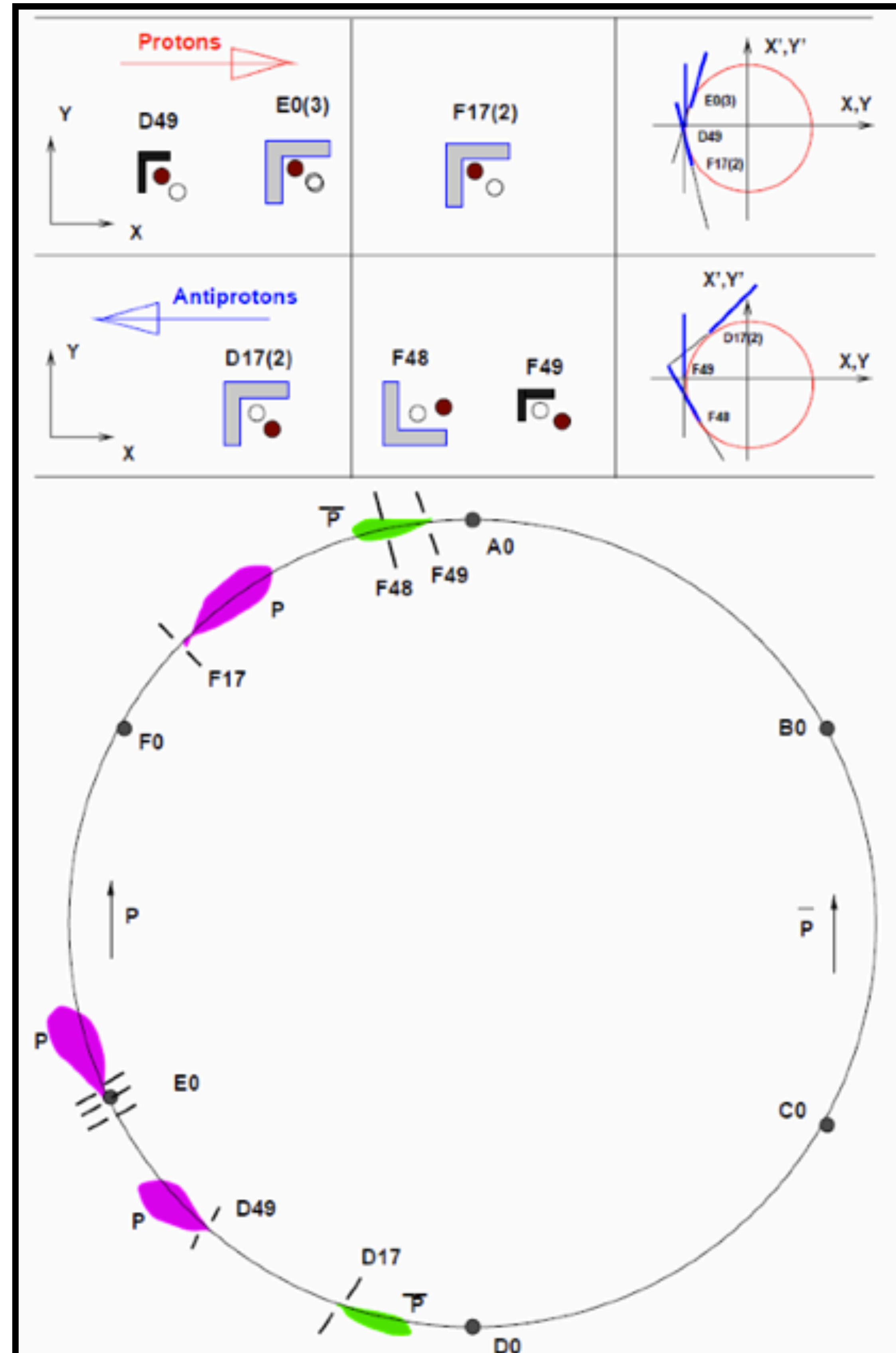
8 collimators

Some with L shape

	Blue		Yellow	
Name	S [m]	Plane	S [m]	Plane
COL0	680.752	Hor. + Vert.	3236.649	Hor. + Vert.
COLH1	690.533	Horizontal	3246.430	Horizontal
COLV1	696.706	Vertical	3252.603	Vertical
COLH2	697.728	Horizontal	3253.625	Horizontal



Tevatron Run II collimation system



Tevatron Run II parameters:

E_b = 1 TeV

E_{stored} = ~ 2 MJ

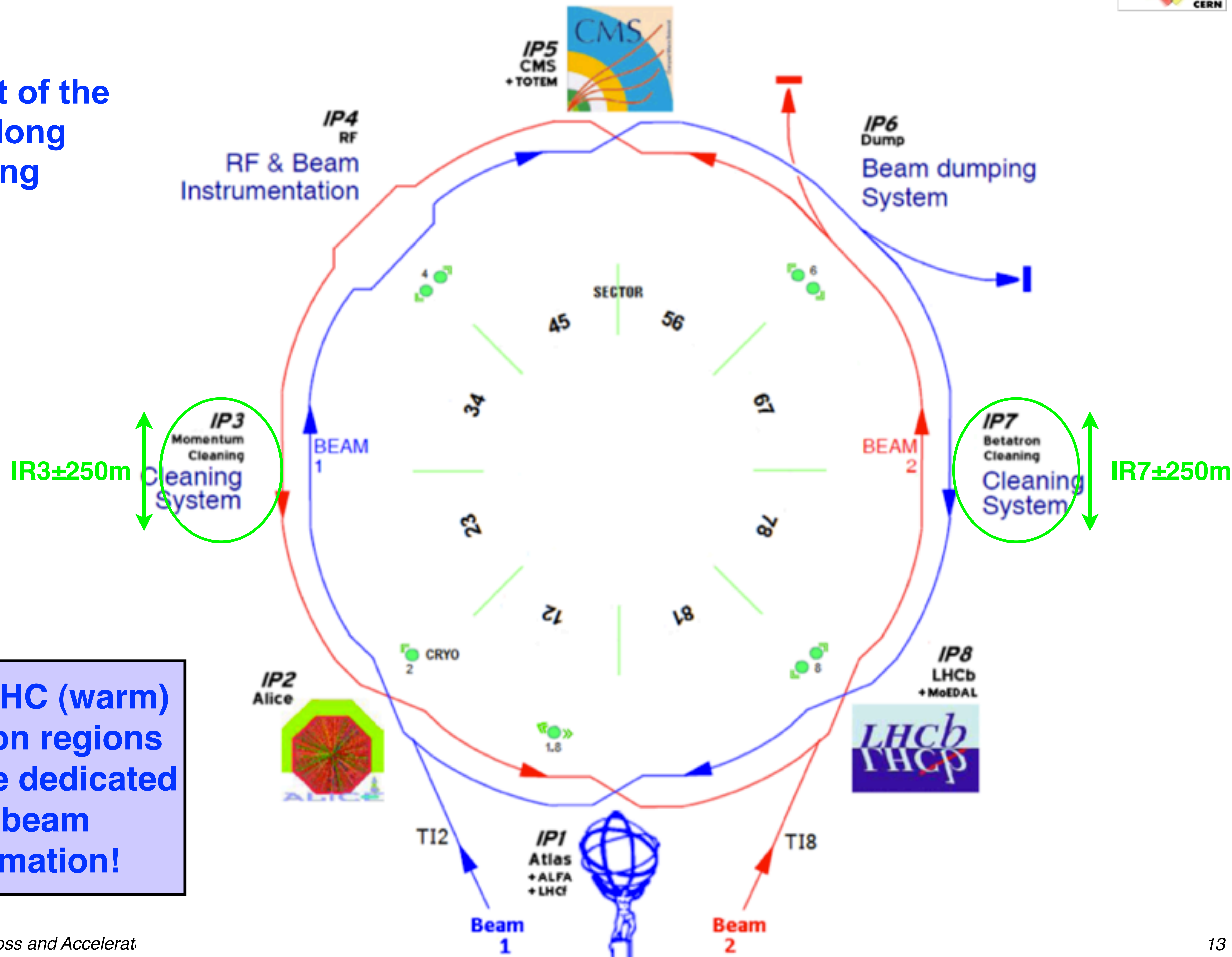
Collimation system:

13 collimators, L shape

26 positional degrees of freedom

LHC ring layout

Layout of the 27km-long LHC ring



2 of 8 LHC (warm) insertion regions (IRs) are dedicated to beam collimation!

LHC collimation layout

Collimation designed for nominal LHC design parameters:

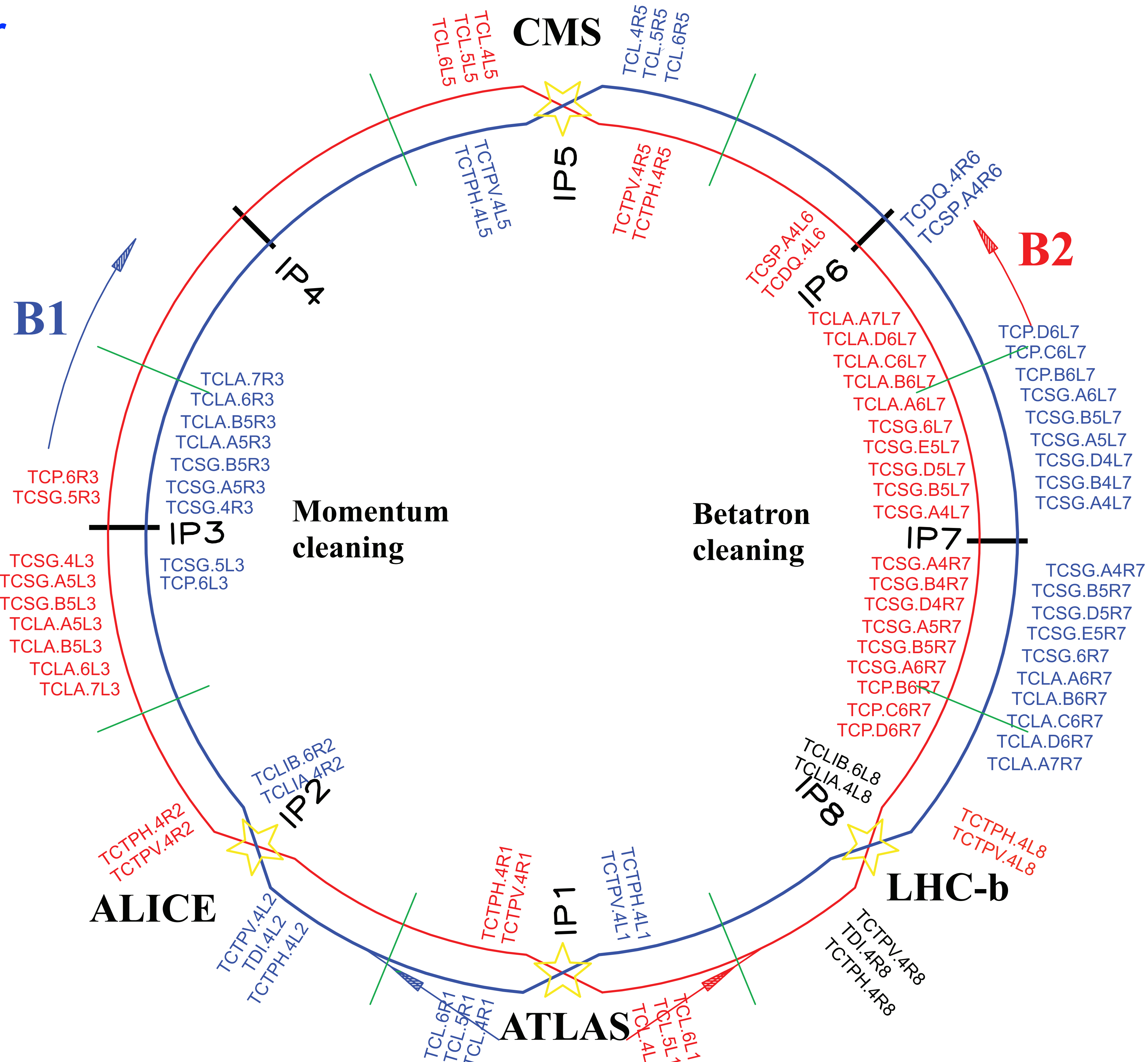
E_b = 7 TeV

I_{bunch} = 1.15 x 10^{11} p

I_{tot} = 3.2 x 10^{14} p

***E_{stored}* = 362 MJ**

Bunch spacing = 25ns



Total of 118 two-sided collimators
(108 are movable, 4 motors each).

Why so many collimators?

It is **difficult to "stop"** high-energy hadrons and the energy that they carry!

You have seen that in previous lectures...

There are **many different loss mechanisms** that impose the deployment of **different solutions** for beam collimation, machine protection, optics scenarios etc.

Betratron losses in horizontal, vertical and diagonal planes require full "phase-space" coverage.

Momentum losses occur in different locations than betatron's.

Different types of failures, slow and fast regimes, etc...

Collimators closest to the beams are made of **low-Z materials** (higher robustness at the expenses of absorption power).

Several collimators (respecting a well-defined hierarchy) are installed in ~500 m long warm insertions (LHC case).

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Extract from loss scenarios the key design parameters for a collimation system.

Beam losses vs. collimation

Ideal world (perfect machine): no beam losses throughout the operational cycle

Injection, energy ramp, betatron squeeze, collisions, beam dump.

No need for a collimation system!

In **real machines**, several effects cause **beam losses**:

- ***Collisions*** *in the interaction points (beam burn up)*
- *Interaction with* ***residual gas*** *and* ***intra-beam scattering***
- ***Beam instabilities*** *(single-bunch, collective, beam-beam)*
- *Dynamics changes during OP cycle (orbit drifts, optics changes, energy ramp, ...): "****operational losses****"*
- *Transverse* ***resonances****.*
- *Capture losses at beginning of the ramp.*
- *RF noise and out-of-bucket losses.*
- *Injection and dump losses.*

We do not need to study all that in detail to understand beam collimation!

These effects can increase the beam halo population and ultimately cause beam losses!

Beam losses through lifetime

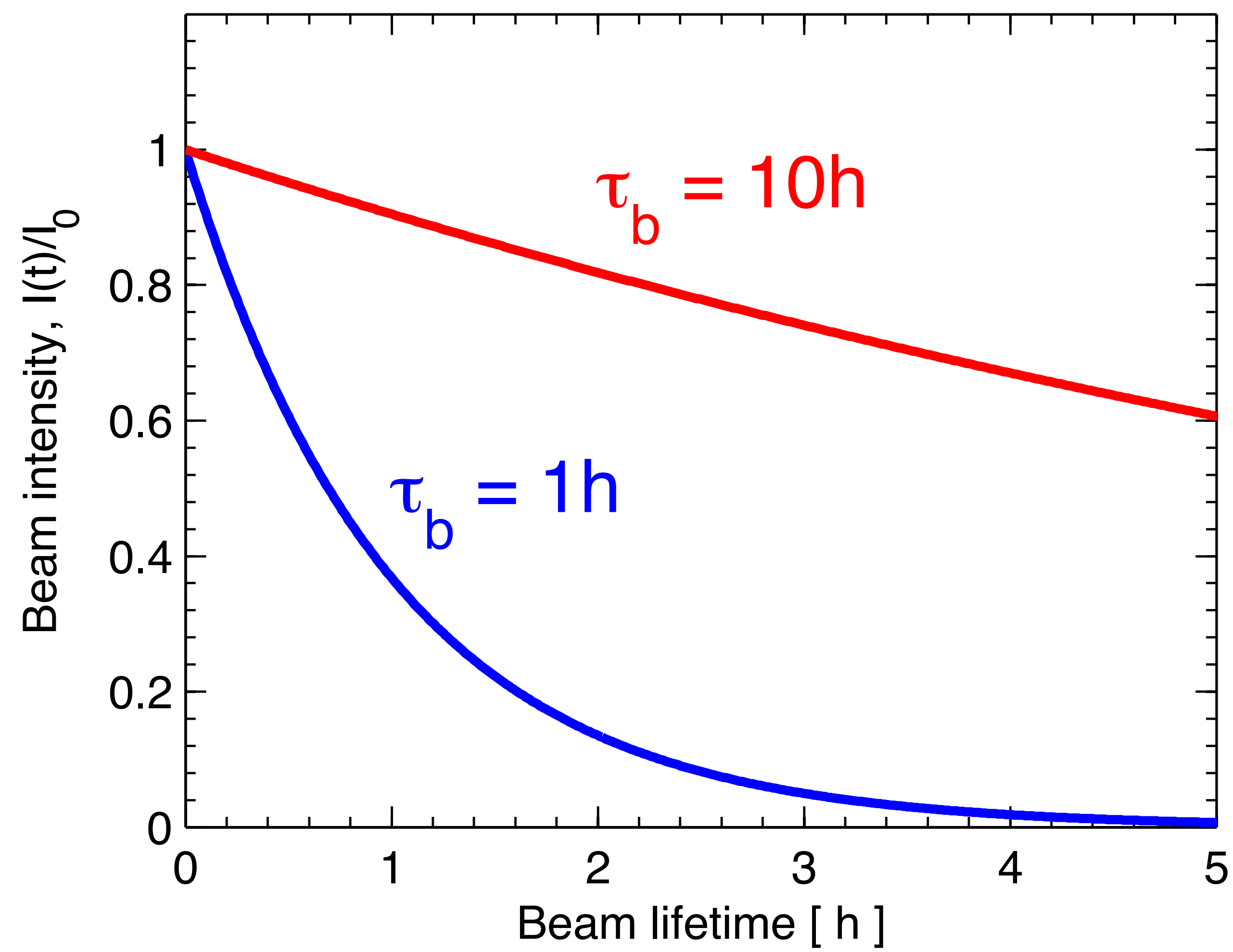
Beam loss mechanisms are modelled by assuming a non-infinite **beam lifetime,** τ_b

$$\boxed{I(t) = I_0 \cdot e^{-\frac{t}{\tau_b}}}$$

: Beam intensity versus time

$$\boxed{-\frac{1}{I_0}\frac{dI}{dt} = \frac{1}{\tau_b}}$$

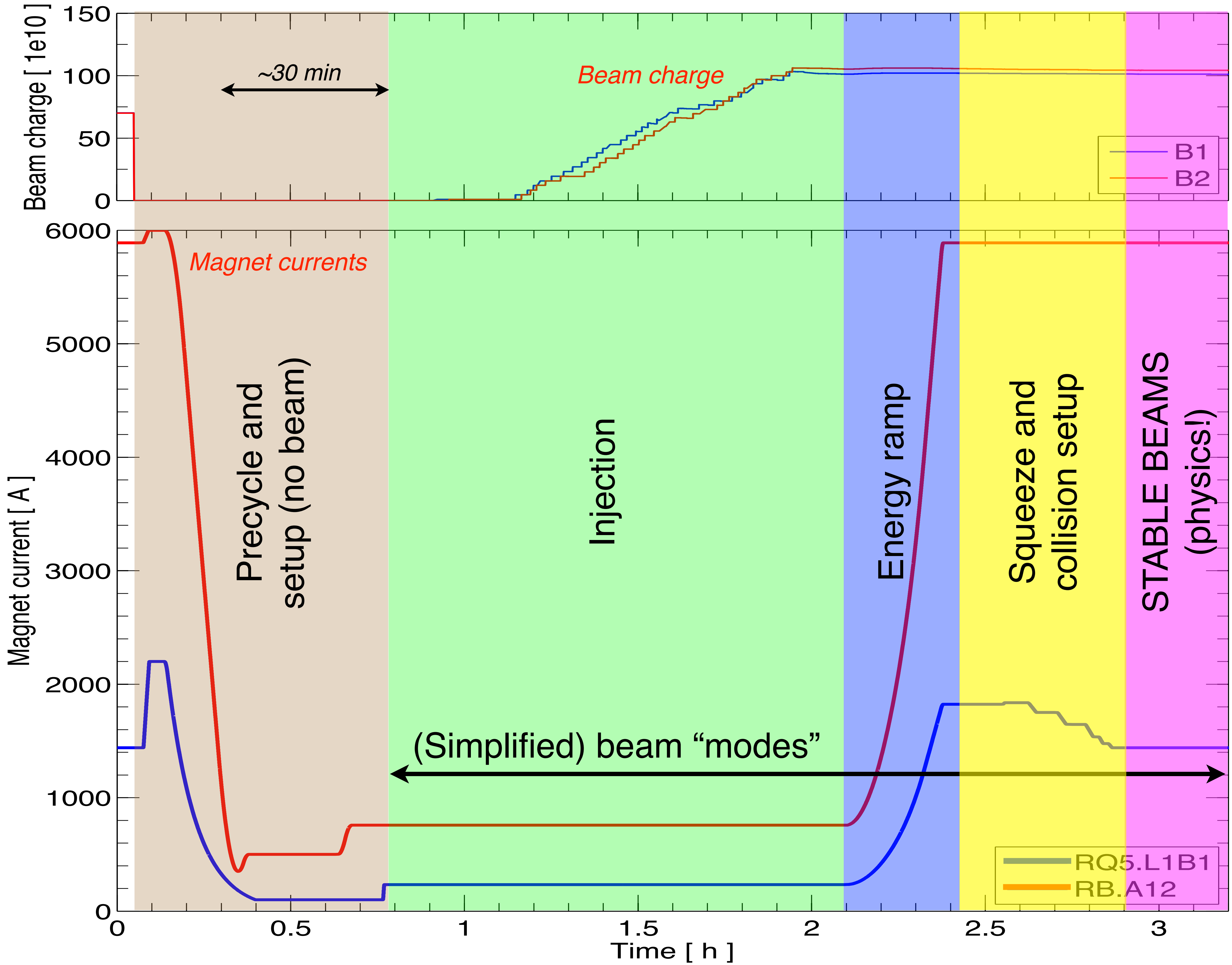
: Proton loss rate



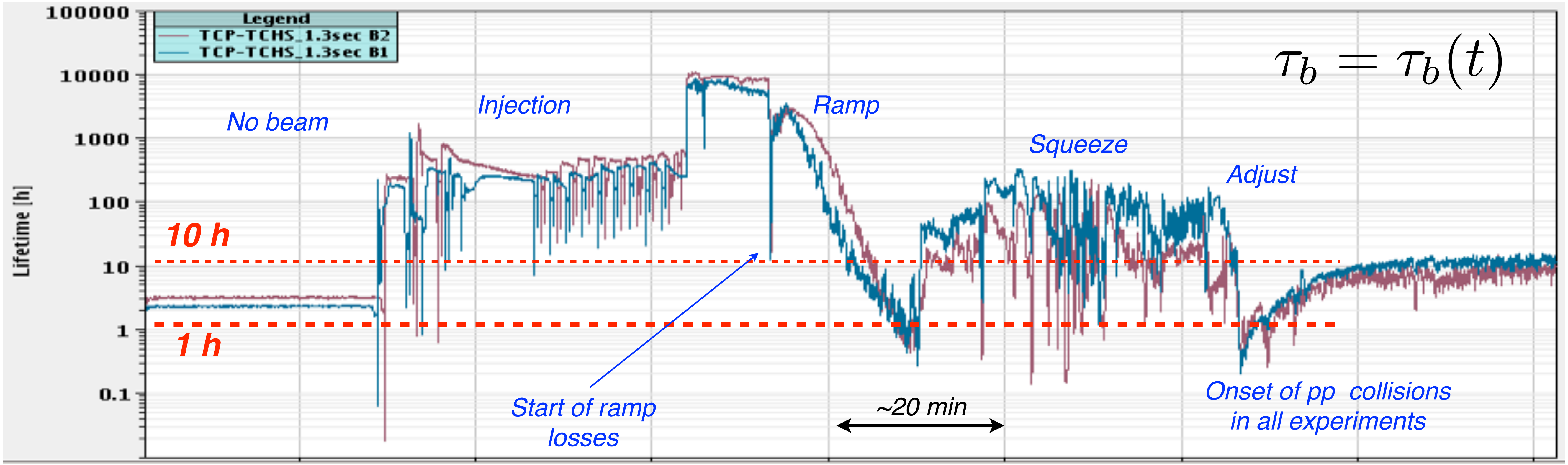
Beam losses mechanisms are characterized by a time-dependent beam lifetime during the machine cycle. This measures the **total beam losses** that a collimation system must handle.

*Example at 7 TeV: **1h lifetime** at the full intensity of $3.2\text{x}10^{14}$ protons (320 hundred trillion protons!) corresponds to a loss rate of about 90 billion proton per second, i.e. **0.1MJ/s = 100 kW**!*

Operational cycle of a collider



LHC lifetime in a physics fill in 2012



Example of a typical physics fill in 2012.

What matters is the minimum lifetime → see peaks below 1 h!

At 7 TeV, this corresponds to peak losses **larger than 100 kW** that would be lost in the cold aperture. They **must be caught** before!!

Goal of a collimation system: catch this and ensure that a controlled fraction of it reaches sensitive equipment.

Collimation "**inefficiency**" → measures the fraction of beam losses that goes into sensitive equipment out of the total lost from the beam.

Key collimation design parameters

In *real* machines affected by beam losses, we need a **collimation system** that intercepts the **primary beam losses** ("primary halo") and absorbs the energy that they carries.

Collimation designed to handle losses that otherwise would occur in <u>an uncontrolled</u> way around the machine.

Design loss rates are calculated from the **total beam intensity** and **beam energy** assuming a "**minimum allowed beam lifetime**" that can occur during operation.

A **collimation cleaning inefficiency** is defined to express the fraction of the total losses that goes into sensitive equipment.

Cold magnets, warm magnets, experiments (background), ...

Example: losses versus quench limits

N_{tot} : total beam populations [p]

$\dfrac{N_{\mathrm{tot}}}{\tau_b}$: proton loss rate [p/s]

R_q : quench limit [p/m/s]

Condition to operate the machine: losses in the magnets remain below their quench limit

$$\boxed{\frac{N_{\mathrm{tot}}}{\tau_b} \times \tilde{\eta}_c < R_q}$$

$\boxed{\tilde{\eta}_c}$: local cleaning inefficiency [1/m] → fraction of proton losses that is lost at a certain location.

$\tilde{\eta}_c = \tilde{\eta}_c(s)$: this is a function on the longitudinal coordinate (as seen later).

For the 1h lifetime case shown before, we get a loss rate at the LHC of 90×10^9 p/s. Assuming a quench limit of $R_q \sim 3.2 \times 10^7$ p/m/s at 7 TeV, one can calculate a **required inefficiency of a few 10-4**!!

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$\boxed{\tilde{\eta}_c}$: local cleaning ineffici

This is our **first specification** for the design of the collimation system. It can only be as good as the accuracy of "input" and "observable"...

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- **Multi-stage collimation**
  - **Betatron cleaning**
  - **Momentum cleaning**
  - **Local triplet protection**
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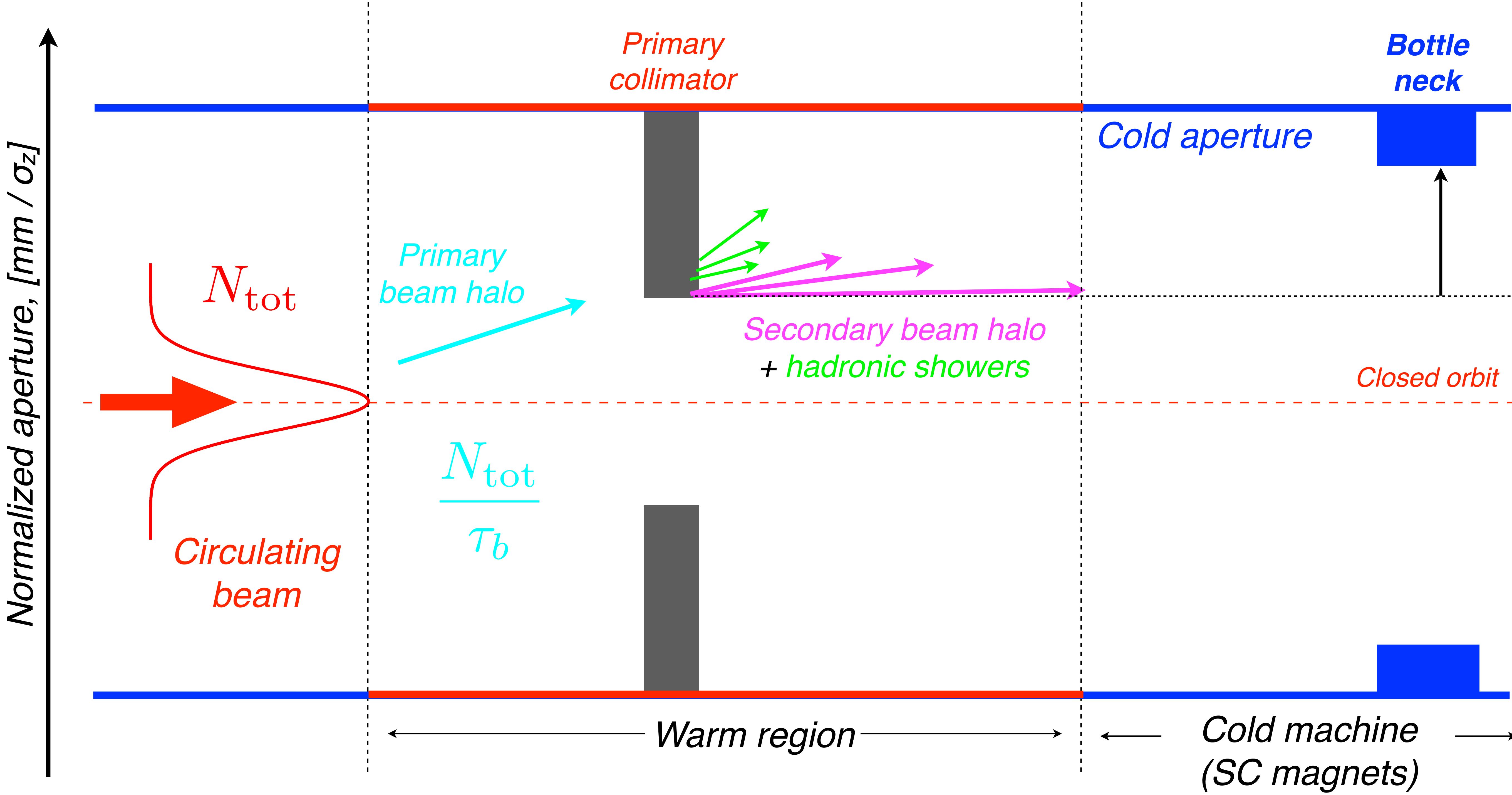
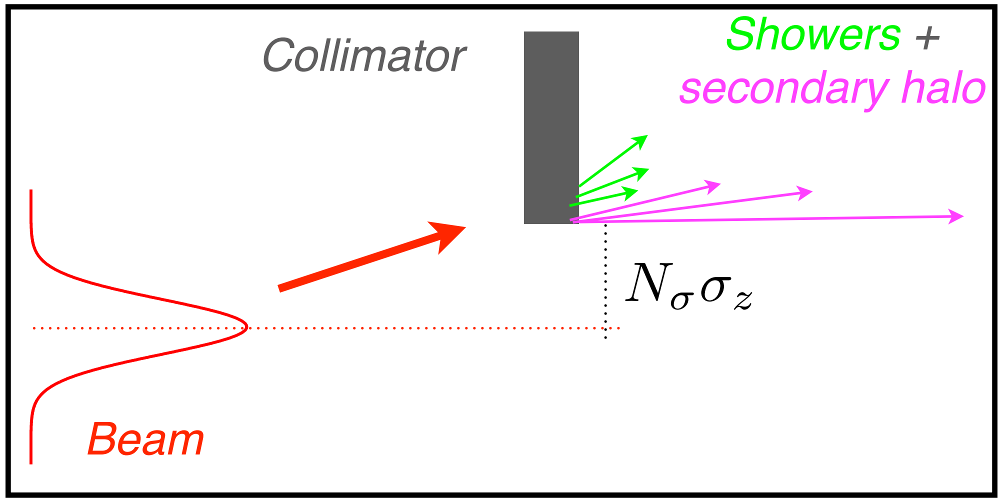
Aperture and single-stage cleaning



The particles lost from the beam core drift transversally and populate beam tails. Ultimately, they reach the machine *aperture bottleneck*.

Can we stop them with a single collimator that shields the cold aperture?

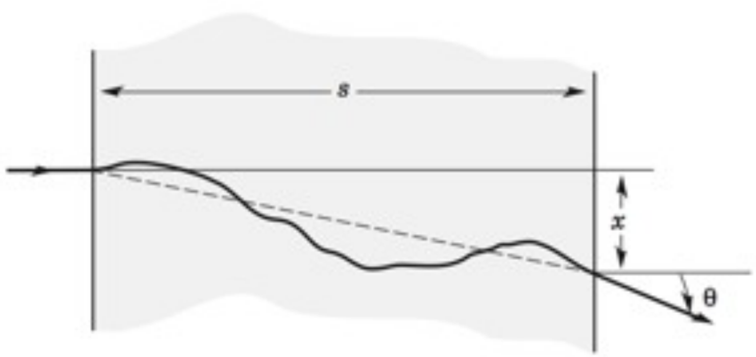
Particle interaction with collimators



If the "primary" collimator were a black absorber, it would be sufficient to shield the aperture by choosing a gap $N_\sigma\sigma_z$ smaller that the aperture bottleneck !

In reality, part of the beam energy and a fraction of the incident protons escape from the collimator!

For "cleaning" what matters is the energy leakage.

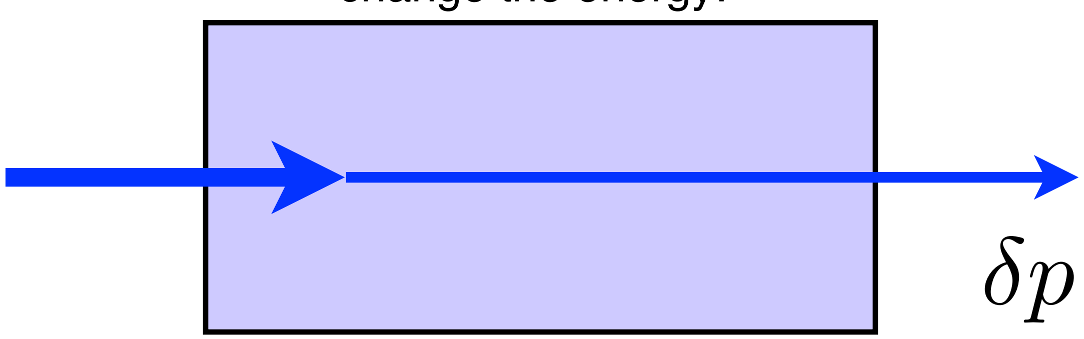


$$\sqrt{\langle\theta_p^2\rangle} = \frac{13.6}{cp[\mathrm{MeV}]}\sqrt{\frac{s}{\chi_0}}\left(1 + 0.038 \cdot \left(\frac{s}{\chi_0}\right)\right)$$

χ_0 : radiation length

Molière's multiple-scattering theory: scattered particles gain a **transverse RMS kick**.

Single-diffractive interactions change the energy!

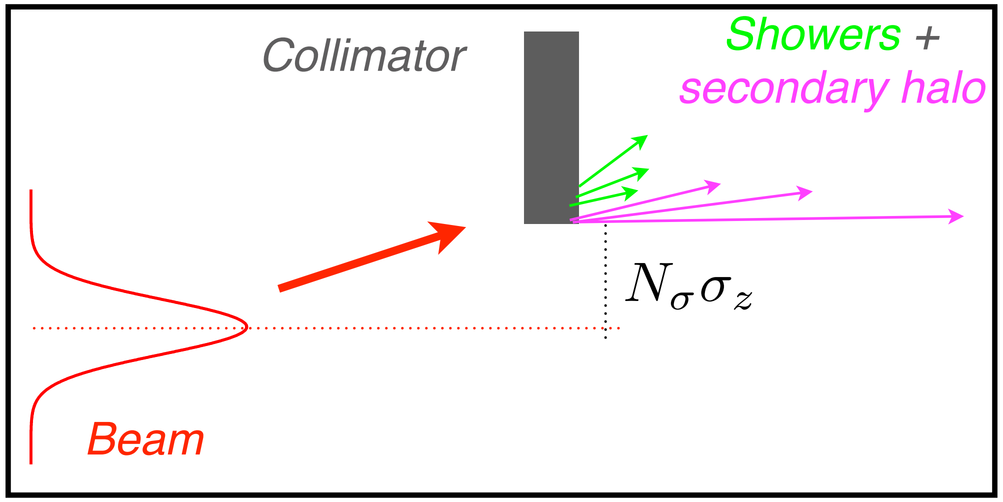


$$\frac{\delta p}{p}$$

Some protons escape from the collimator with a reduced "rigidity" after loosing energy through inelastic interactions.

Note: multi-turn interactions occur with sub-micron impact parameters → this has an important effect on the absorption efficiency.

Particle interaction with collimators



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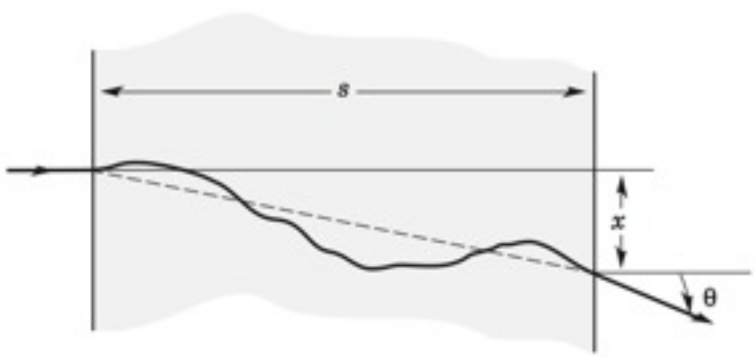

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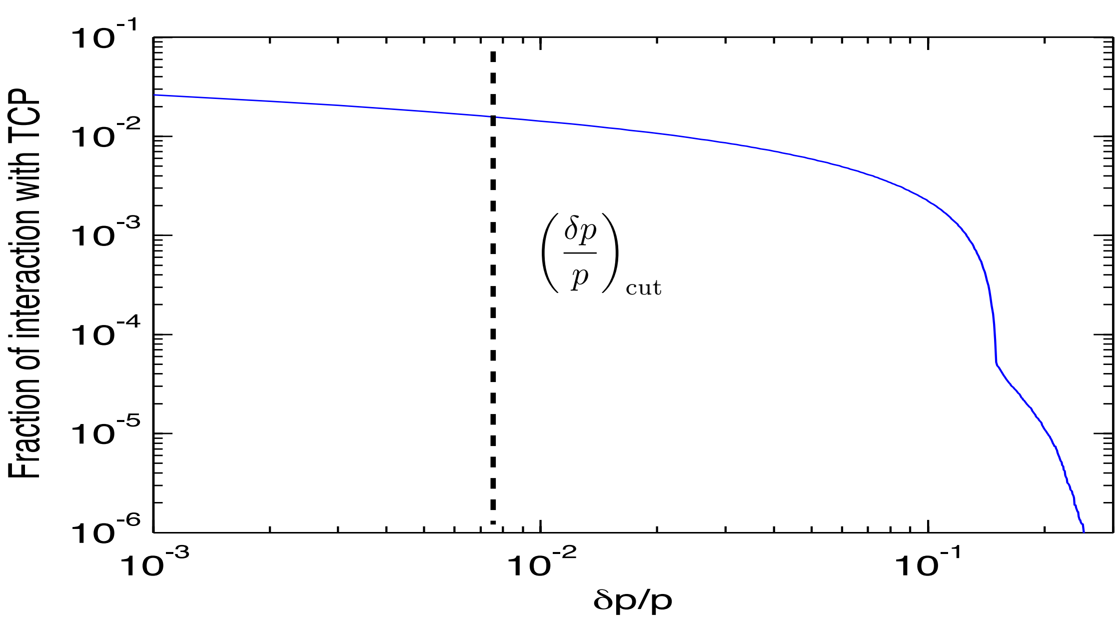
Distribution of energy lost after multi-turn interaction with 60cm TCP



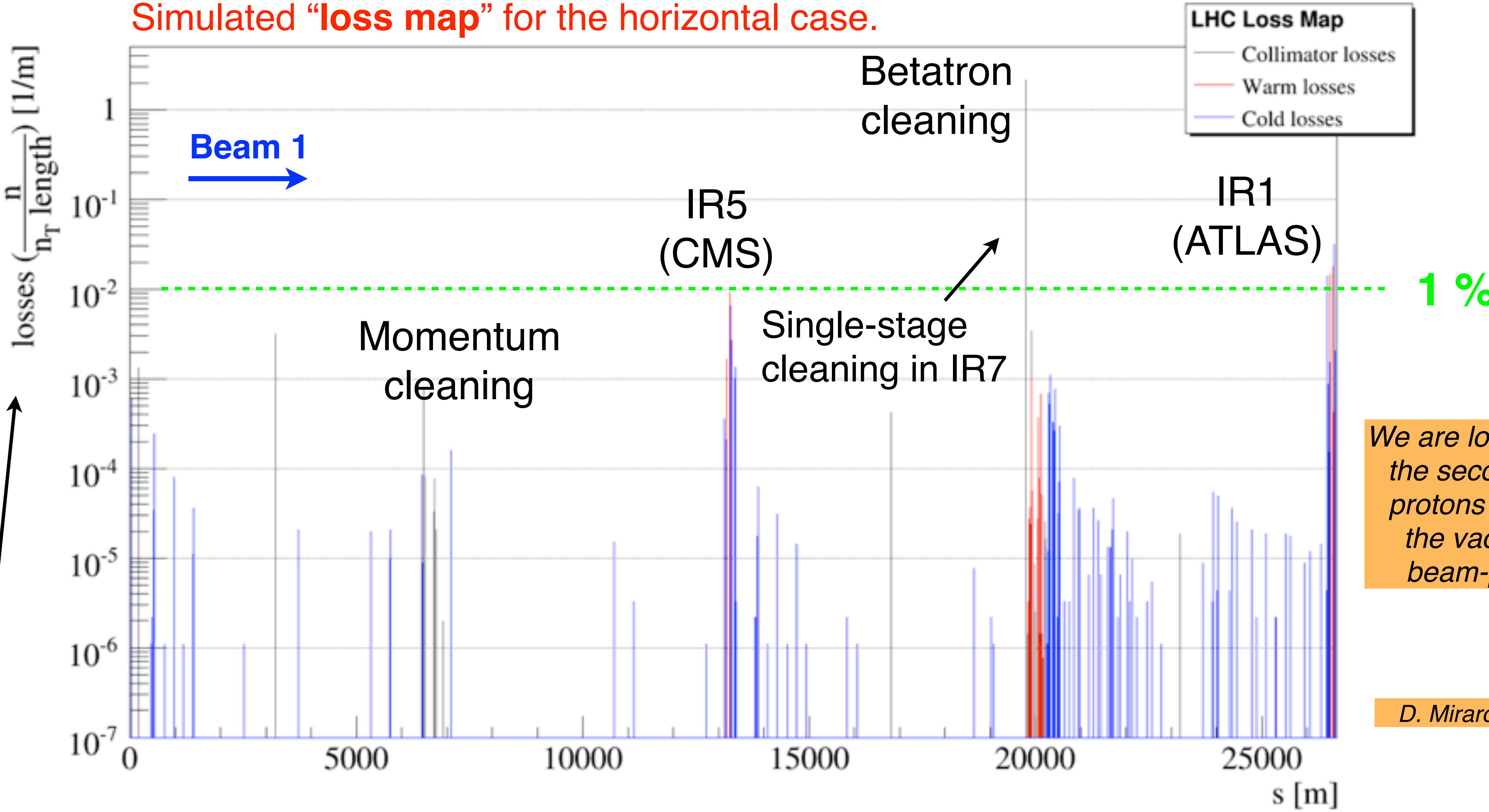
The interaction with collimator materials is itself a source of betatron and off-momentum halo (secondary halo).

Electro-magnetic and hadronic showers developed by the interaction carry an important fraction of the impacting beam energy that “escapes” from the collimator.

Note: multi-turn interactions occur with sub-micron impact parameters → this has an important effect on the absorption efficiency.

Single-stage cleaning - LHC at 7 TeV

Simulated "**loss map**" for the horizontal case.



We are looking at the secondary protons lost in the vacuum beam-pipe.

D. Mirarchi

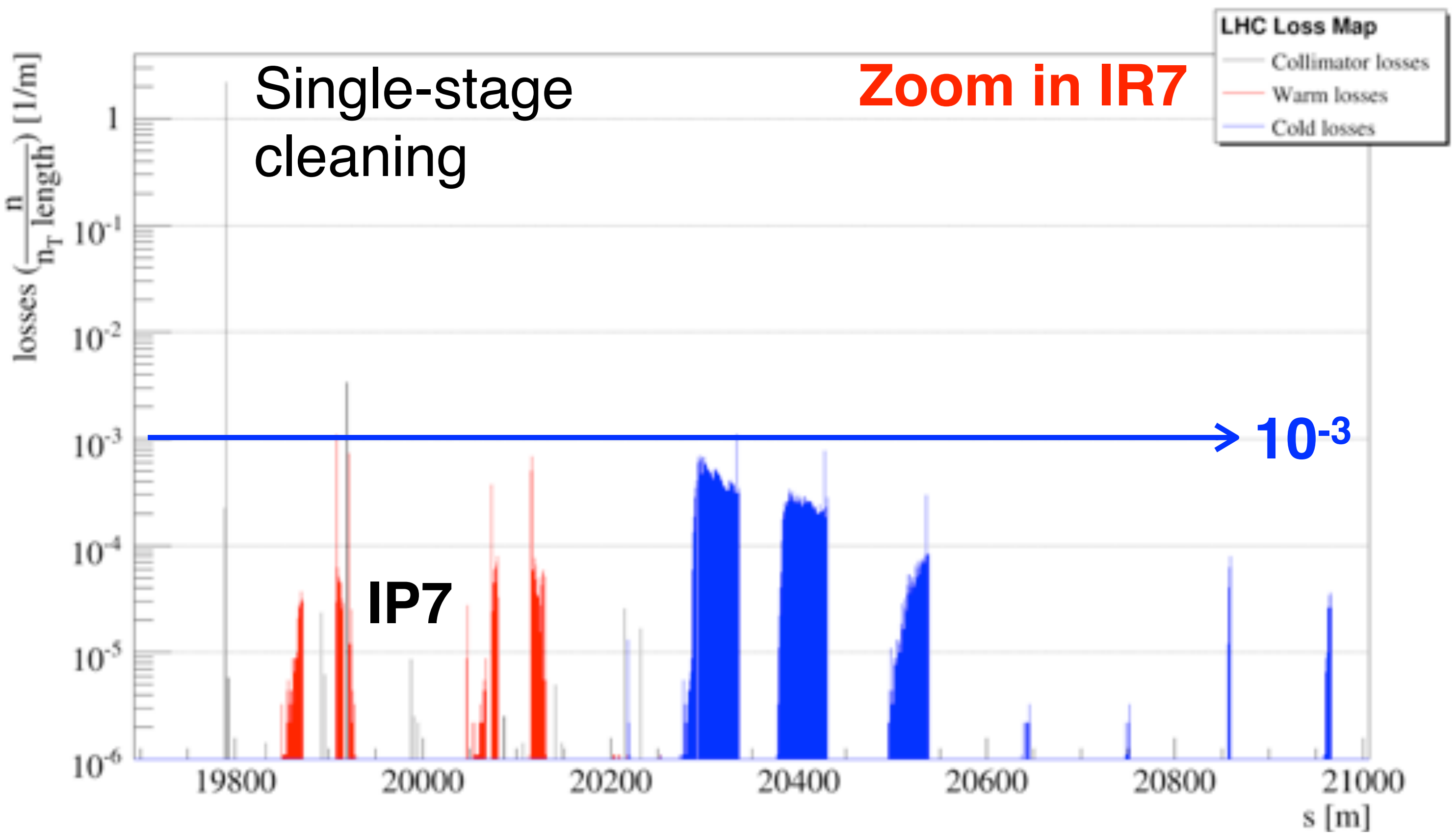
Local cleaning inefficiency

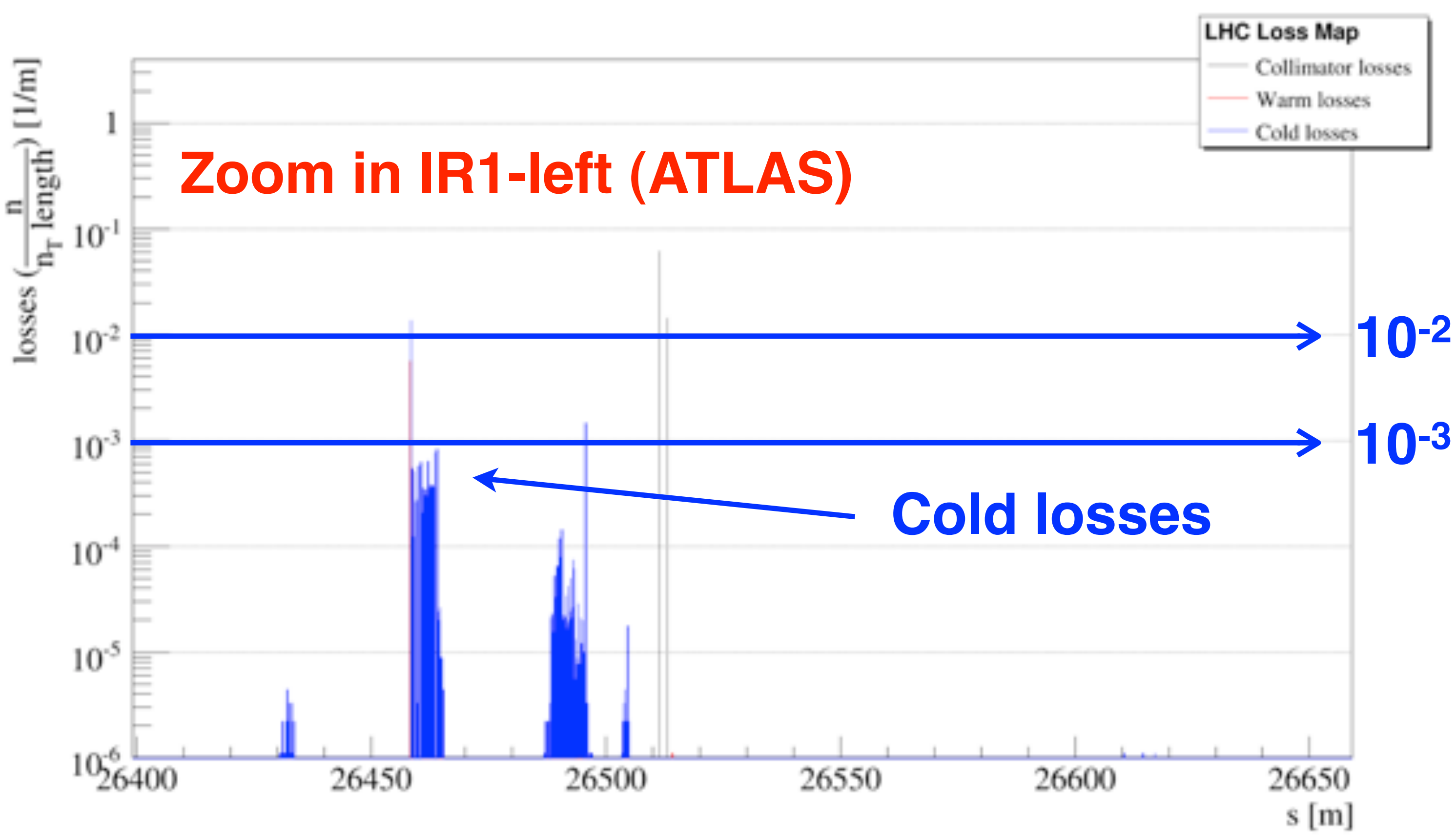
$$\tilde{\eta}_c(s) = \frac{1}{\Delta s}\frac{N_{\text{loss}}(s \to s + \Delta s)}{N_{\text{abs}}}$$

Fraction of proton lost per unit length.

Single-stage cleaning with one primary (H) collimator made 60 cm of Carbon: highest leakage in cold elements (blue spikes): **1-3 %**.

Comparison to quench limits





Typical assumed **quench limit** at 7 TeV for steady losses of ~second timescales:

$$R_q \text{ (7 TeV)} = 3.2 \times 10^7 \text{ p/m/s}$$

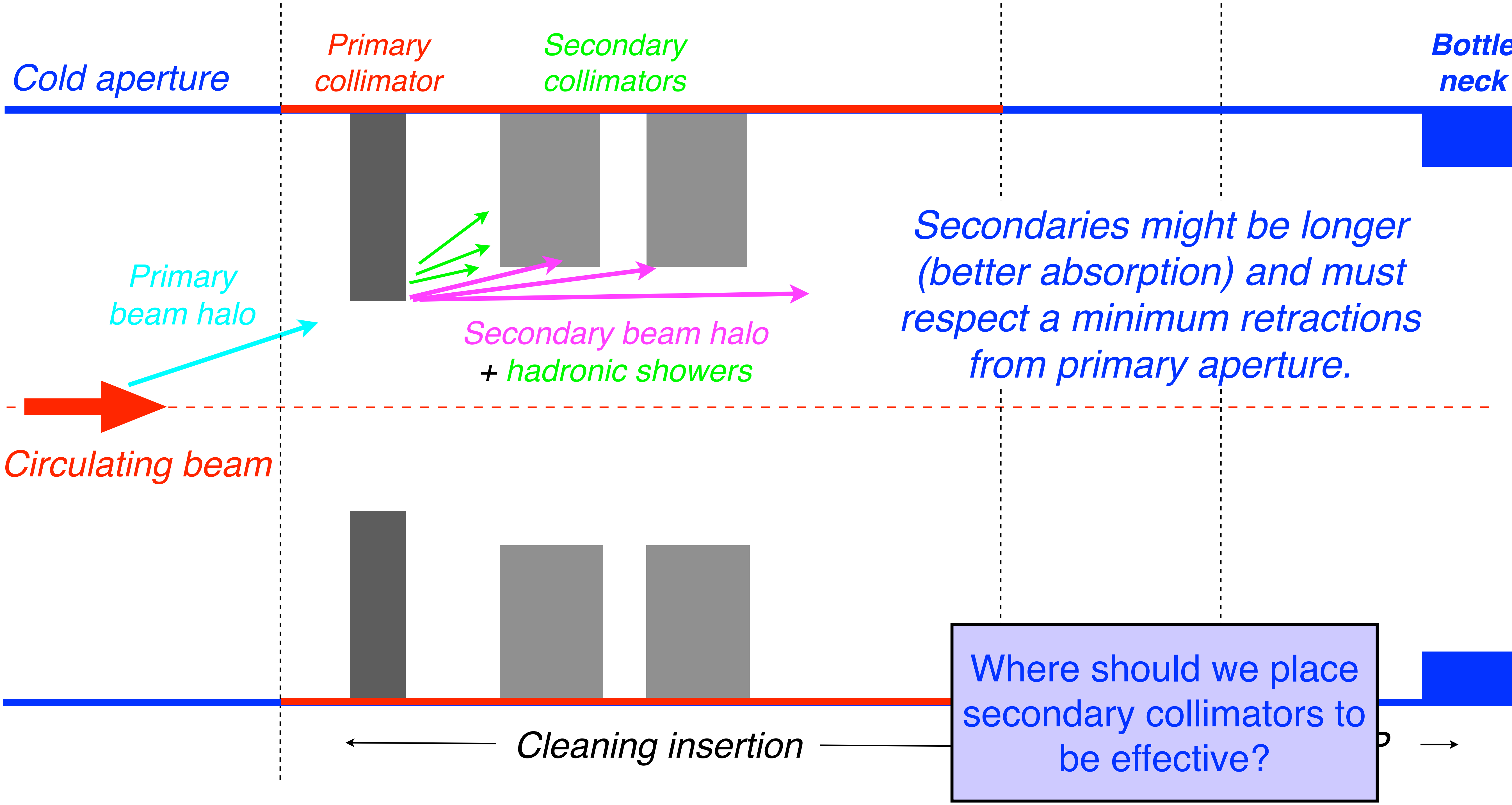
With the single-stage cleaning predicted by this model, losses are up to:

τ_b = 1h → 90 x 10^7 p/m/s (**30 x R_q**)
τ_b = 0.2h → 450 x 10^7 p/m/s (**150 x R_q**)

Single-stage cleaning is apparently not adequate for the LHC needs!

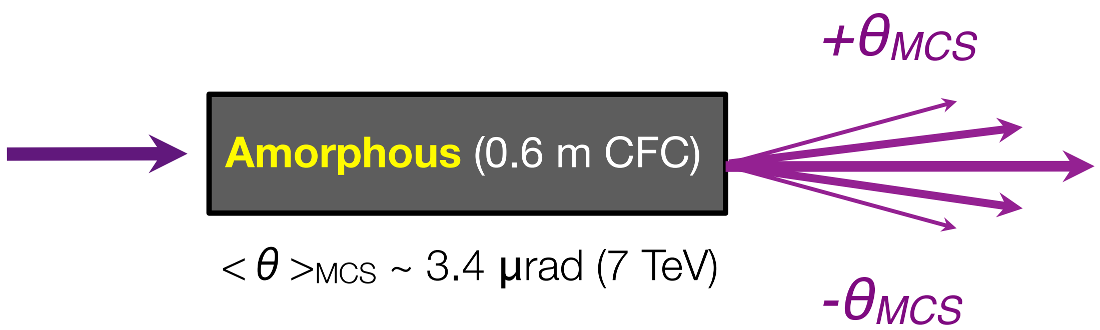
*Note: These are **approximated figures**! Detailed performance reach is estimated with more complex simulations including effects of showers!*

Two-stage collimation

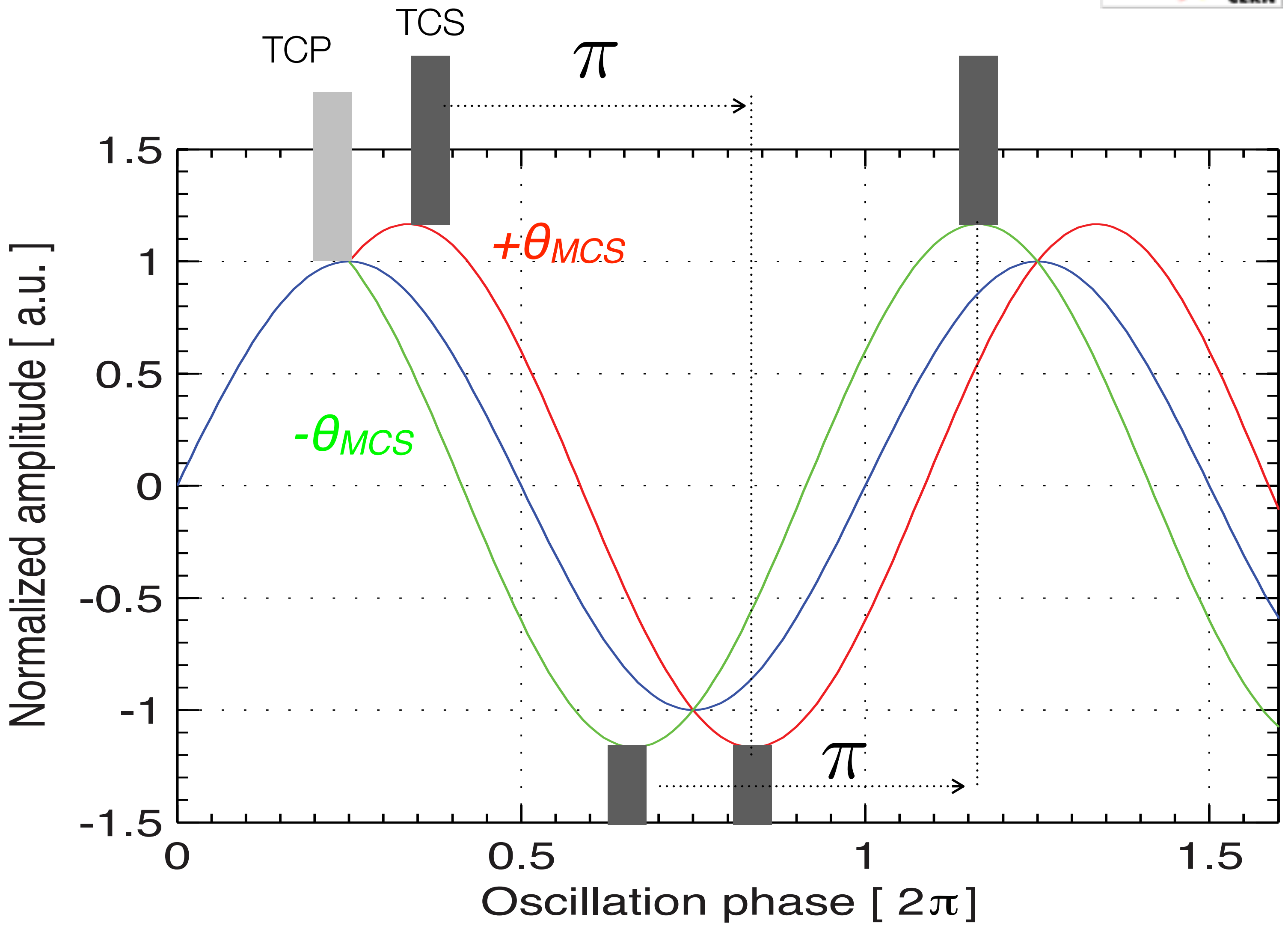


"Secondary" collimators (TCSs) can be added to intercept the secondary halo and the showers that leak out of the primary collimator.

Optimum secondary collimator locations



There are two optimum phase locations to catch the debris from the primary collimators (TCPs).
Minimum: set of 2 secondary collimators (TCSs) covering $+\theta_{MCS}$ and $-\theta_{MCS}$.
Optimum: 4 TCSs (per plane) providing redundant coverage.



Betatron motion in $z \equiv (x, y)$

$$\boxed{z_i(s) = \sqrt{\beta(s)\epsilon_i}\sin(\phi(s) + \phi_0)}$$

$\beta(s)$: betatron function versus s

Secondary collimators must be placed at **optimum phase** locations where kicks from the TCP scattering translates into the largest offset.

Reality is a bit more complicated...

Optimum phases depend on TCP/TCS retraction

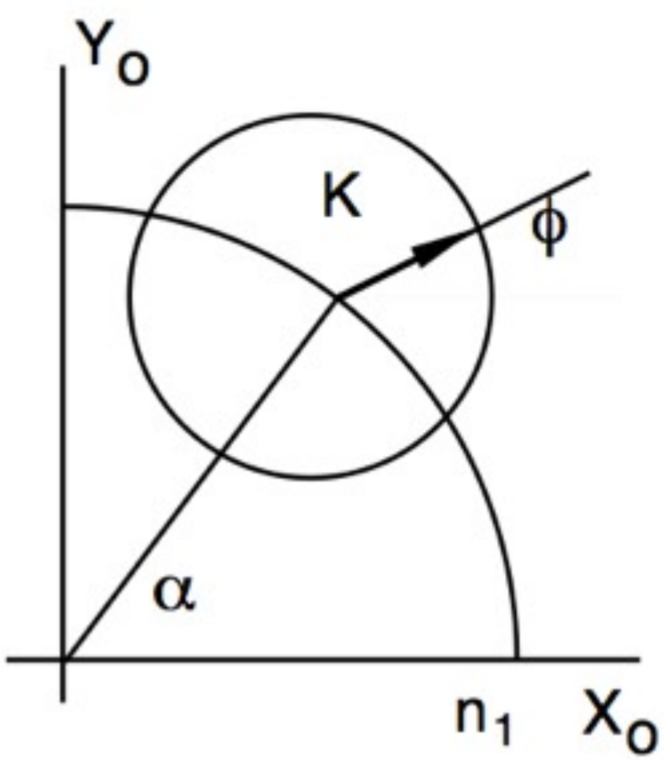
$$\tan \mu_x = \frac{\sqrt{n_{\mathrm{TCP}}^2 - n_{\mathrm{TCS}}^2}}{n_{\mathrm{TCP}}^2} \frac{\cos\phi}{\cos\alpha}$$

$n_{\mathrm{TCP}}, n_{\mathrm{TCS}}$: TCP and TCS half-gap

α, ϕ : collimator plane and scattering angle

$\cos\mu_0 = n_{\mathrm{TCP}}/n_{\mathrm{TCS}}$

Phys.Rev.ST Accel.Beams 1:081001,1998



Optics of a two-stage collimation system

J. B. Jeanneret

CERN, CH-1211 Geneva, Switzerland

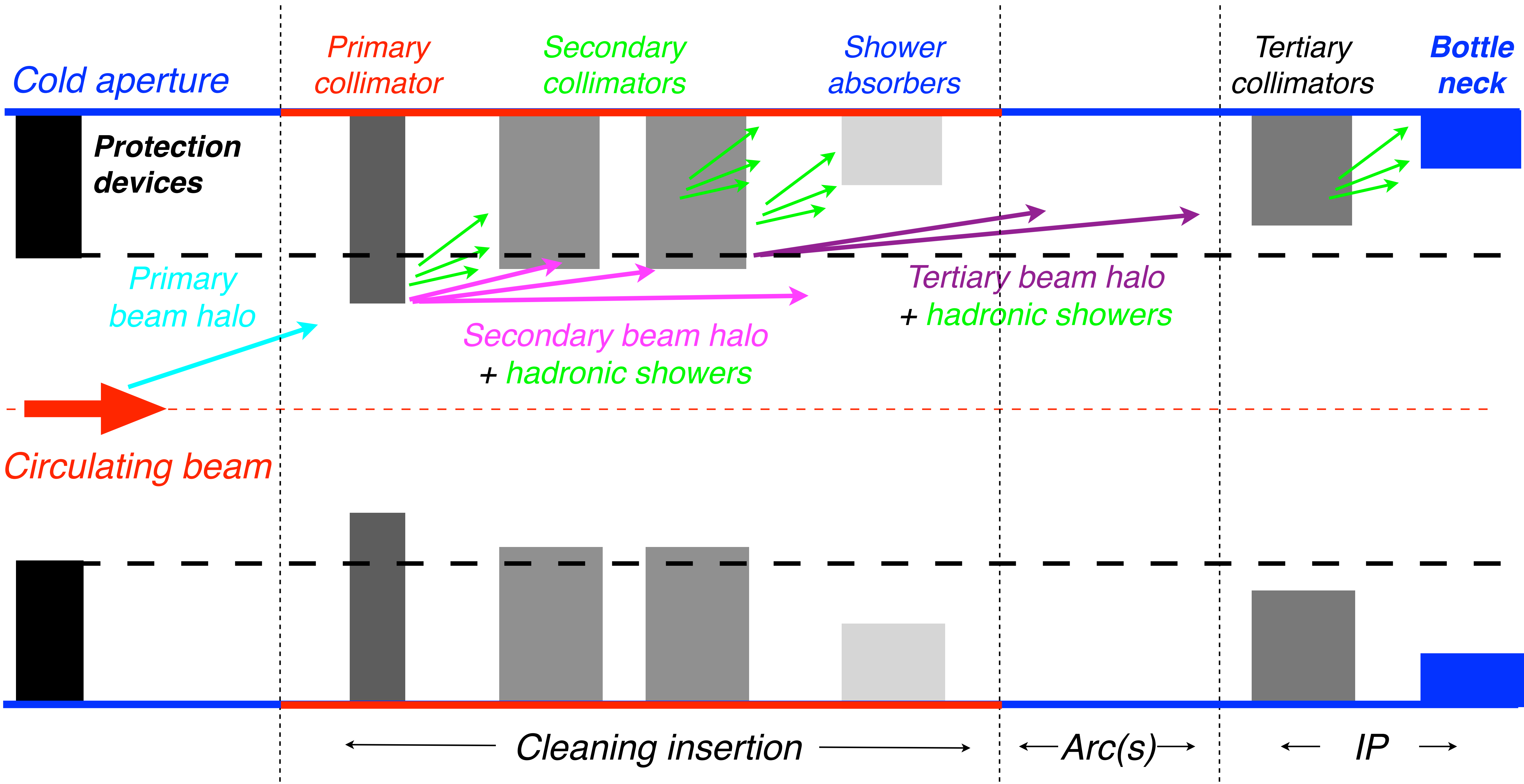
(Received 13 October 1998; published 21 December 1998)

A finite number of secondary collimators can be used to catch efficiently the halo with three primary collimator orientation.

Phase locations (μ_x, μ_y) and jaw orientation (α_J) to catch different scattering angle (ϕ) for horizontal (α=0), vertical (α=π/2) and skew (α=π/2) scattering source locations.

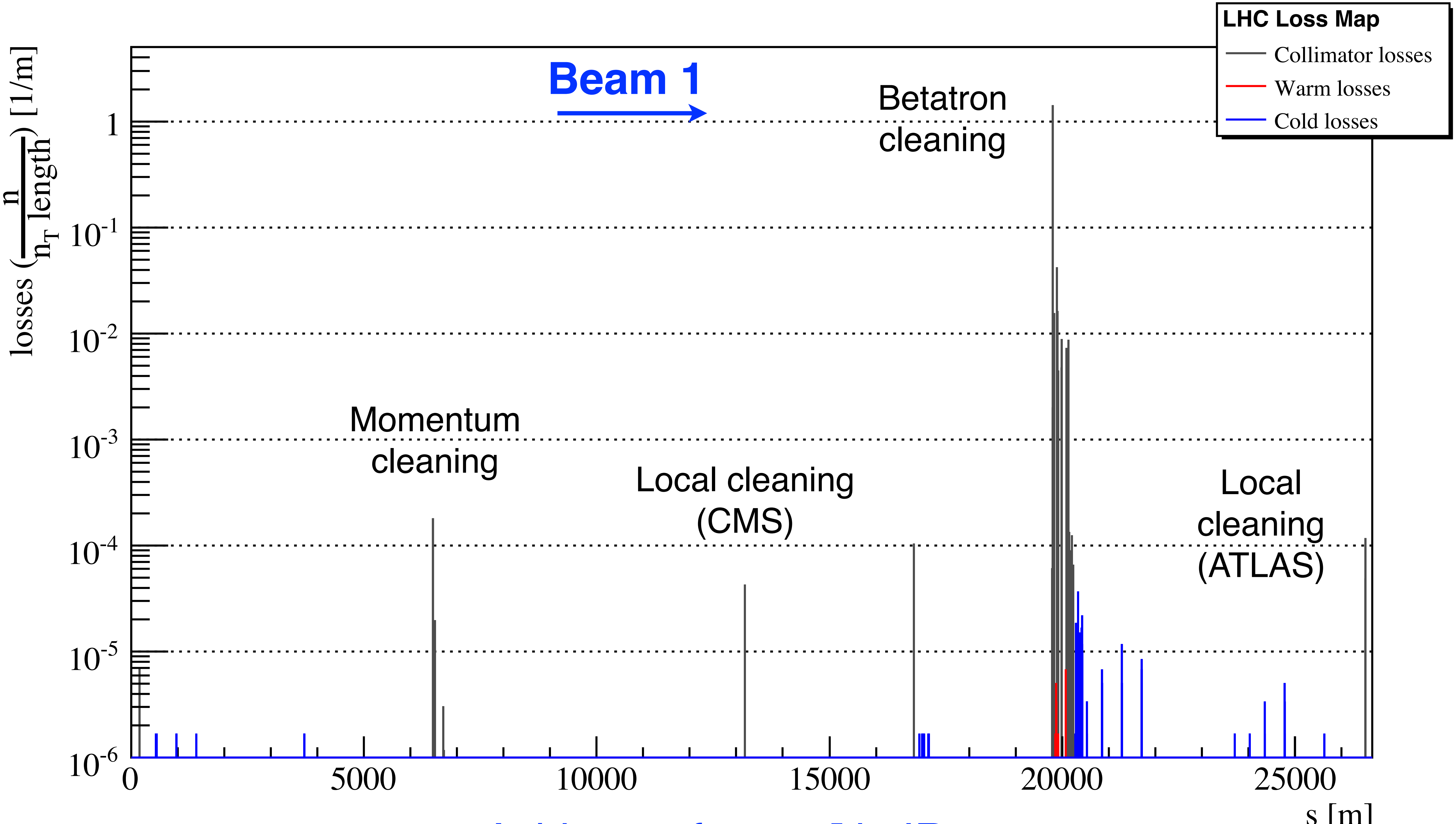
α	ϕ	μ_x	μ_y	α_J
0	0	μ_0	—	0
0	π	$\pi - \mu_0$	—	0
0	$\pi/2$	π	$3\pi/2$	μ_0
0	$-\pi/2$	π	$3\pi/2$	$-\mu_0$
$\pi/4$	$\pi/4$	μ_0	μ_0	$\pi/4$
$\pi/4$	$5\pi/4$	$\pi - \mu_0$	$\pi - \mu_0$	$\pi/4$
$\pi/4$	$3\pi/4$	$\pi - \mu_0$	$\pi + \mu_0$	$\pi/4$
$\pi/4$	$-\pi/4$	$\pi + \mu_0$	$\pi - \mu_0$	$\pi/4$
$\pi/2$	$\pi/2$	—	μ_0	$\pi/2$
$\pi/2$	$-\pi/2$	—	$\pi - \mu_0$	$\pi/2$
$\pi/2$	π	$\pi/2$	π	$\pi/2 - \mu_0$
$\pi/2$	0	$\pi/2$	π	$\pi/2 + \mu_0$

Multi-stage collimation at the LHC



Including protection devices, a **5-stage cleaning** in required!
The system performance relies on achieving the well-defined **hierarchy** between different **collimator families** and **machine aperture**.

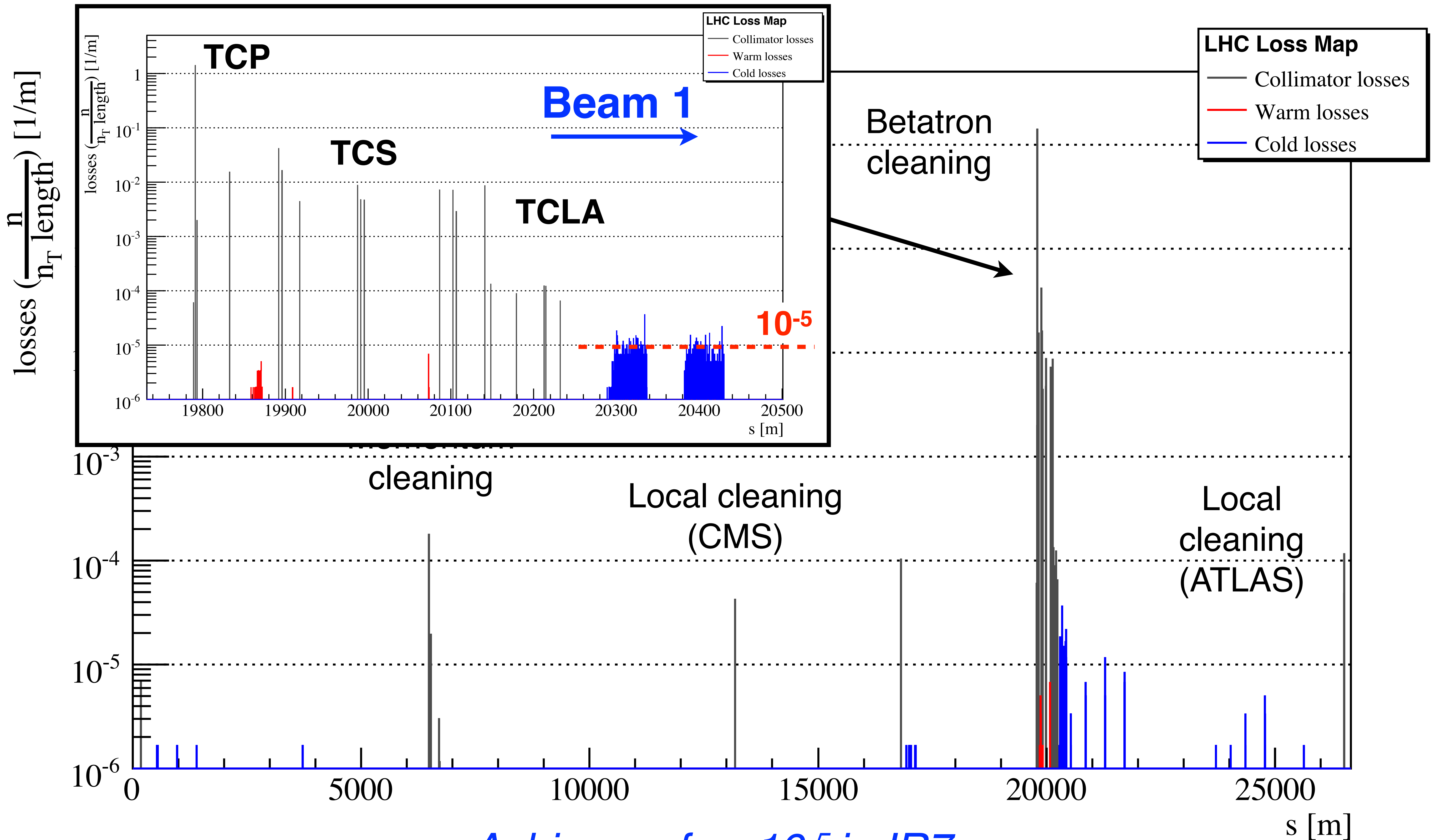
Simulated 7 TeV performance



Achieve a few 10^{-5} in IR7.

Cold losses in experiments removed by local protection.

Simulated 7 TeV performance

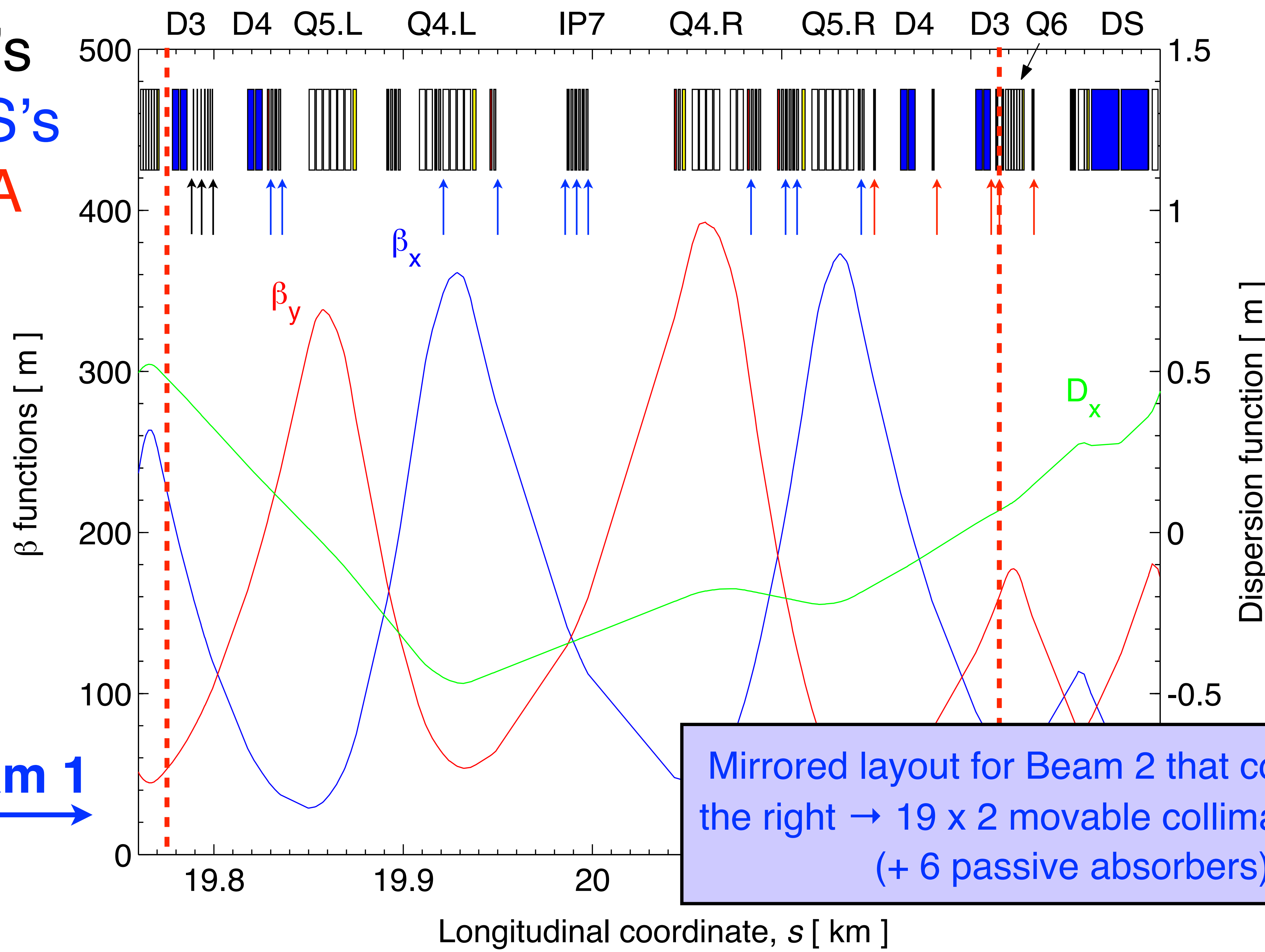


Achieve a few 10^{-5} in IR7.

Cold losses in experiments removed by local protection.

Betatron cleaning insertion

3 TCP's
11 TCS's
5 TCLA



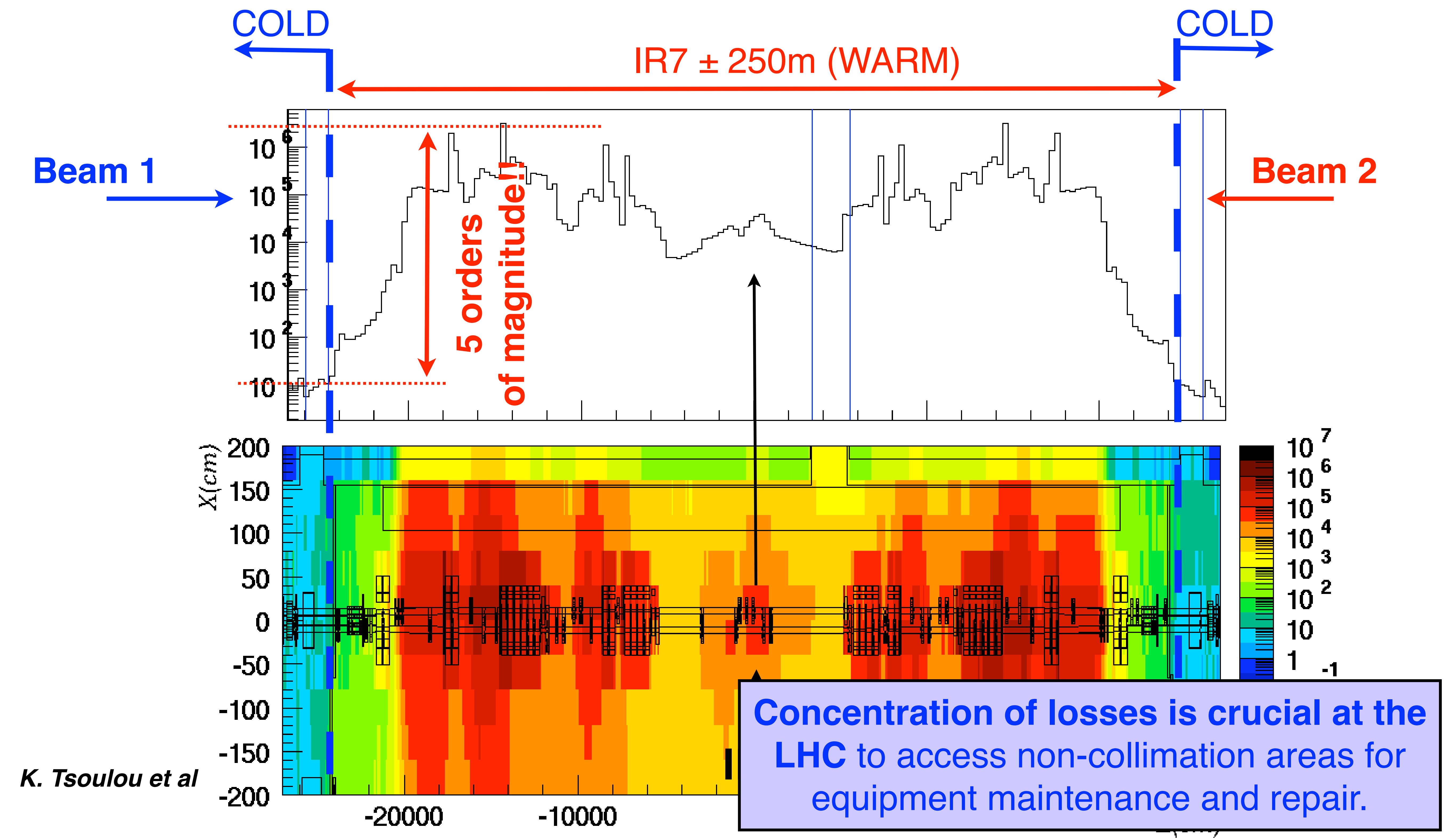
Beam 1 →

Mirrored layout for Beam 2 that comes from the right → 19 x 2 movable collimator in total (+ 6 passive absorbers)

$$z_i(s) = \sqrt{\beta(s)\epsilon_i}\sin(\phi(s)+\phi_0) + \left(\frac{\delta p}{p}\right)_i D_z(s)$$

One full oscillation of the betatron motion to meet in the warm part the optimum phase conditions.

Radiation doses in collimation region



Concentration of losses is crucial at the LHC to access non-collimation areas for equipment maintenance and repair.

Activation from halo losses is basically confined within the warm insertions!

Outline

- Introduction
- Beam losses and collimation
- **Multi-stage collimation**
  - Betatron cleaning
  - **Momentum cleaning**
  - **Local triplet protection**
- LHC collimation design
- Cleaning: operational performance
- Conclusions

Off-momentum cleaning systems

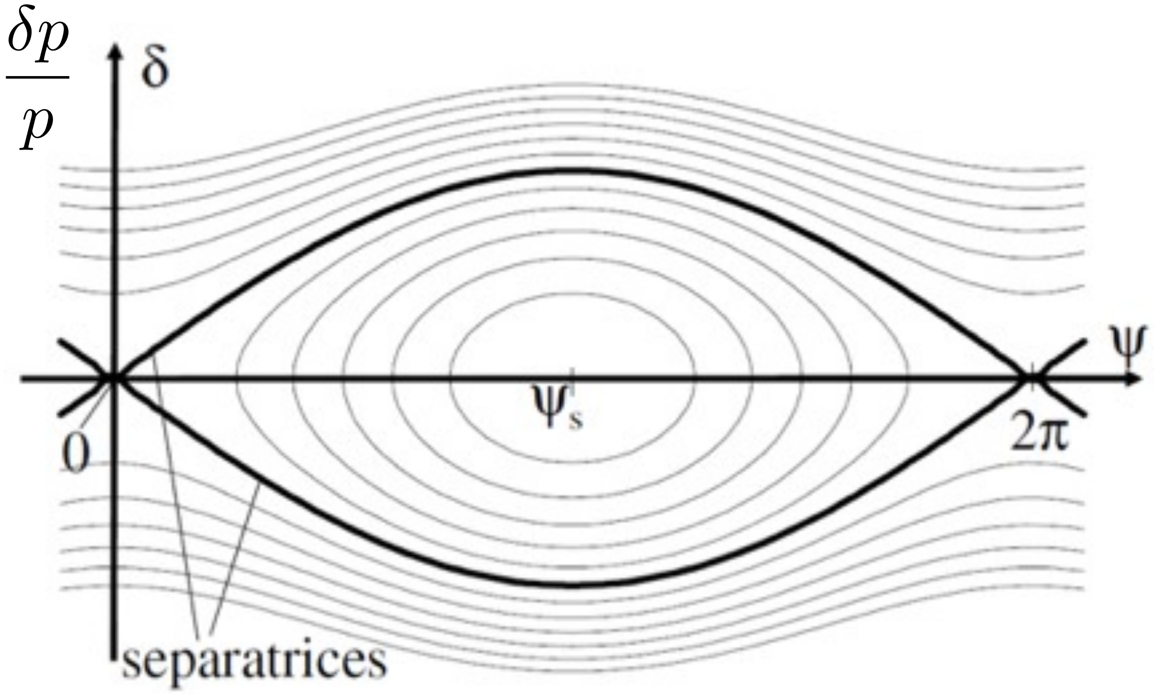
"**Off-momentum losses**" = losses occurring when beam particles lose the energy matching compared to the reference particle.

$$z_i(s) = \sqrt{\beta(s)\epsilon_i}\,\sin(\phi(s)+\phi_0) + \boxed{\left(\frac{\delta p}{p}\right)_i D_z(s)}$$

Examples: trips or setting errors of RF system, capture losses at the start of ramp, synchrotron radiation losses of particle outside RF buckets, collision with other beams or with collimator materials.

How do we collimate these particles?

$$\delta \equiv \frac{\delta p}{p}$$

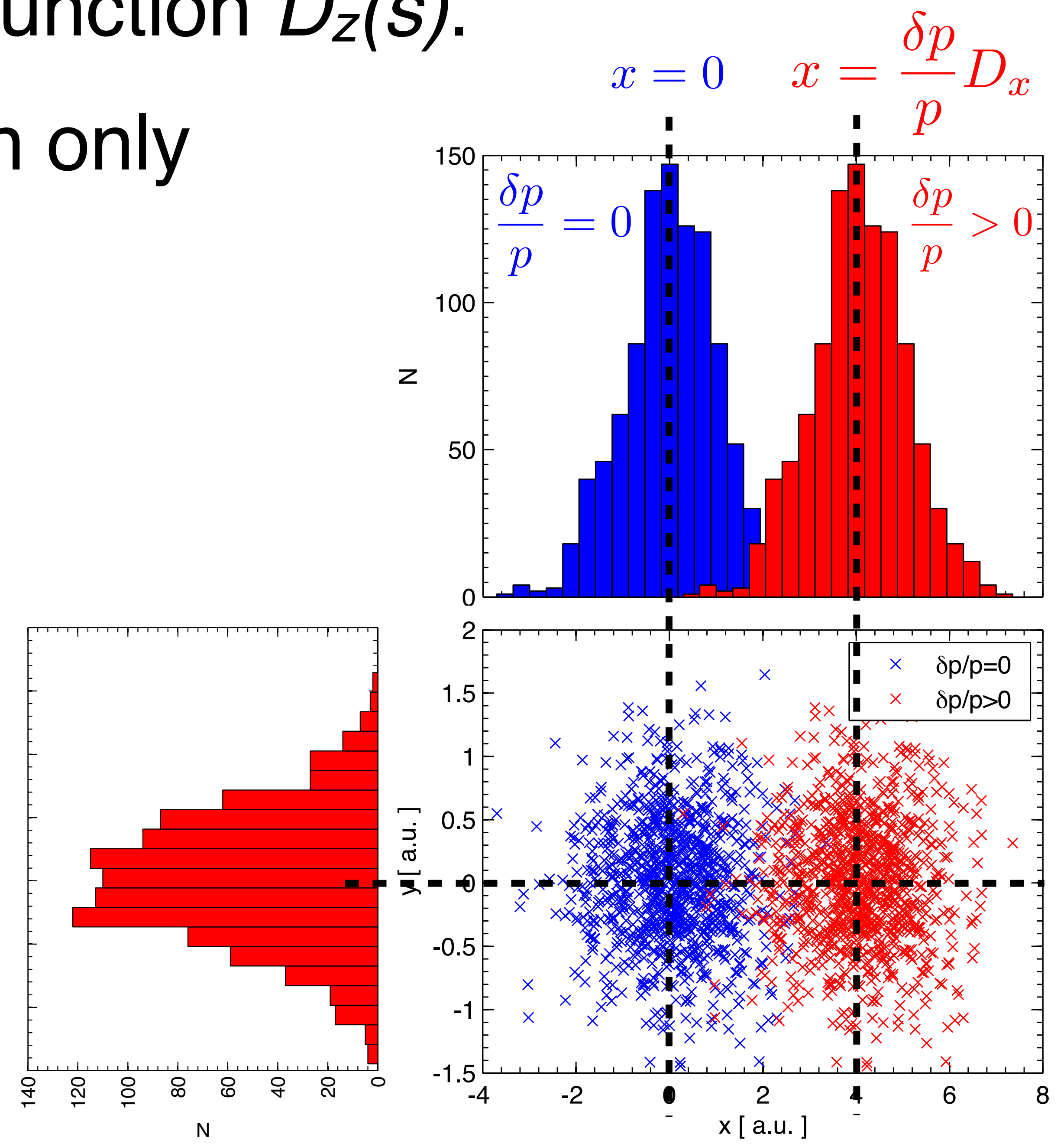


Catching off-momentum particles

For all off-momentum loss cases, individual halo particles or the entire beam maintain their initial betatron amplitude.

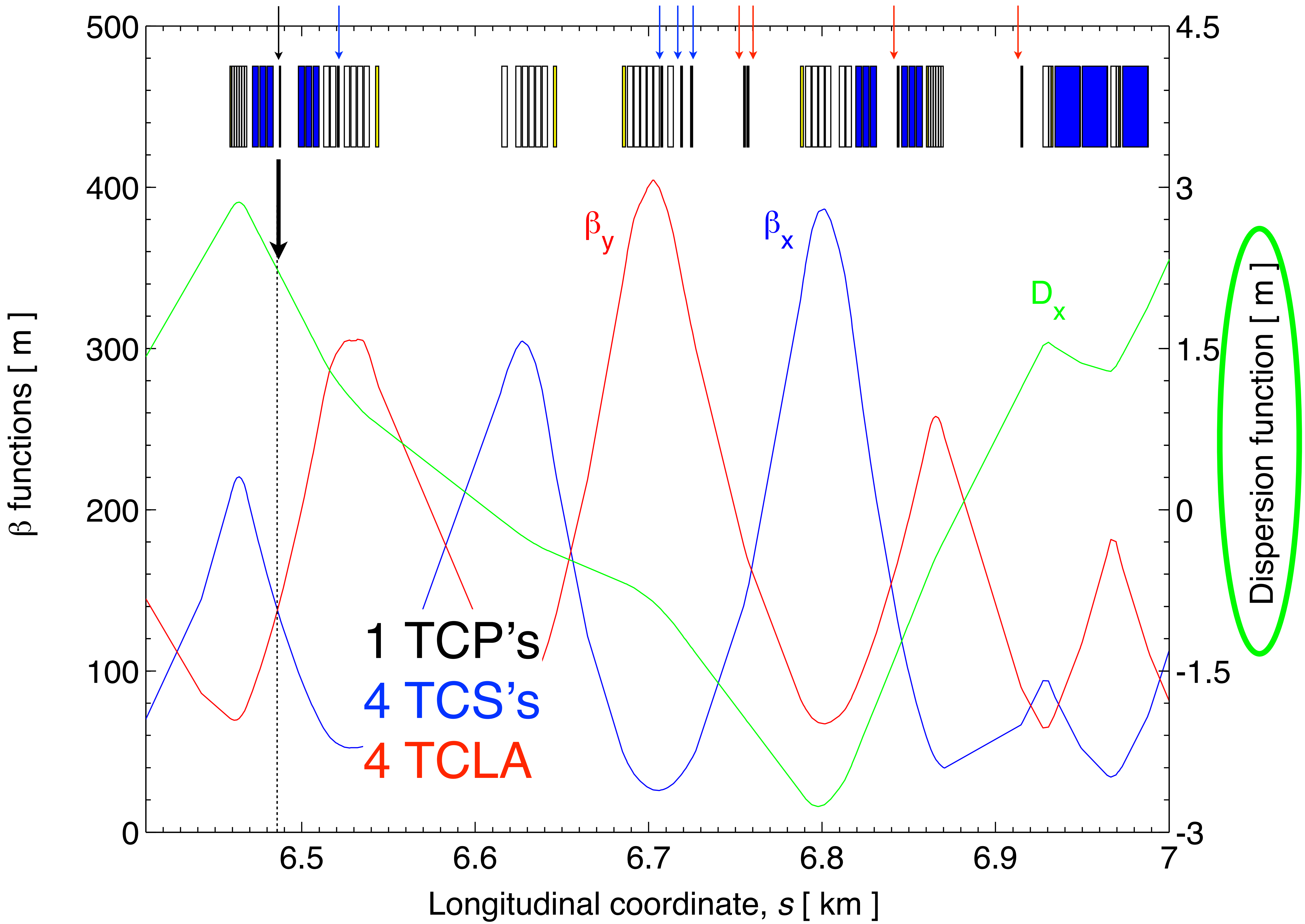
The **mismatch in energy** translates into a **shift of position** that follows the periodic dispersion function *$D_z(s)$*.

Circular accelerators have by design only horizontal dispersion
⇒ **only H momentum collimation**!

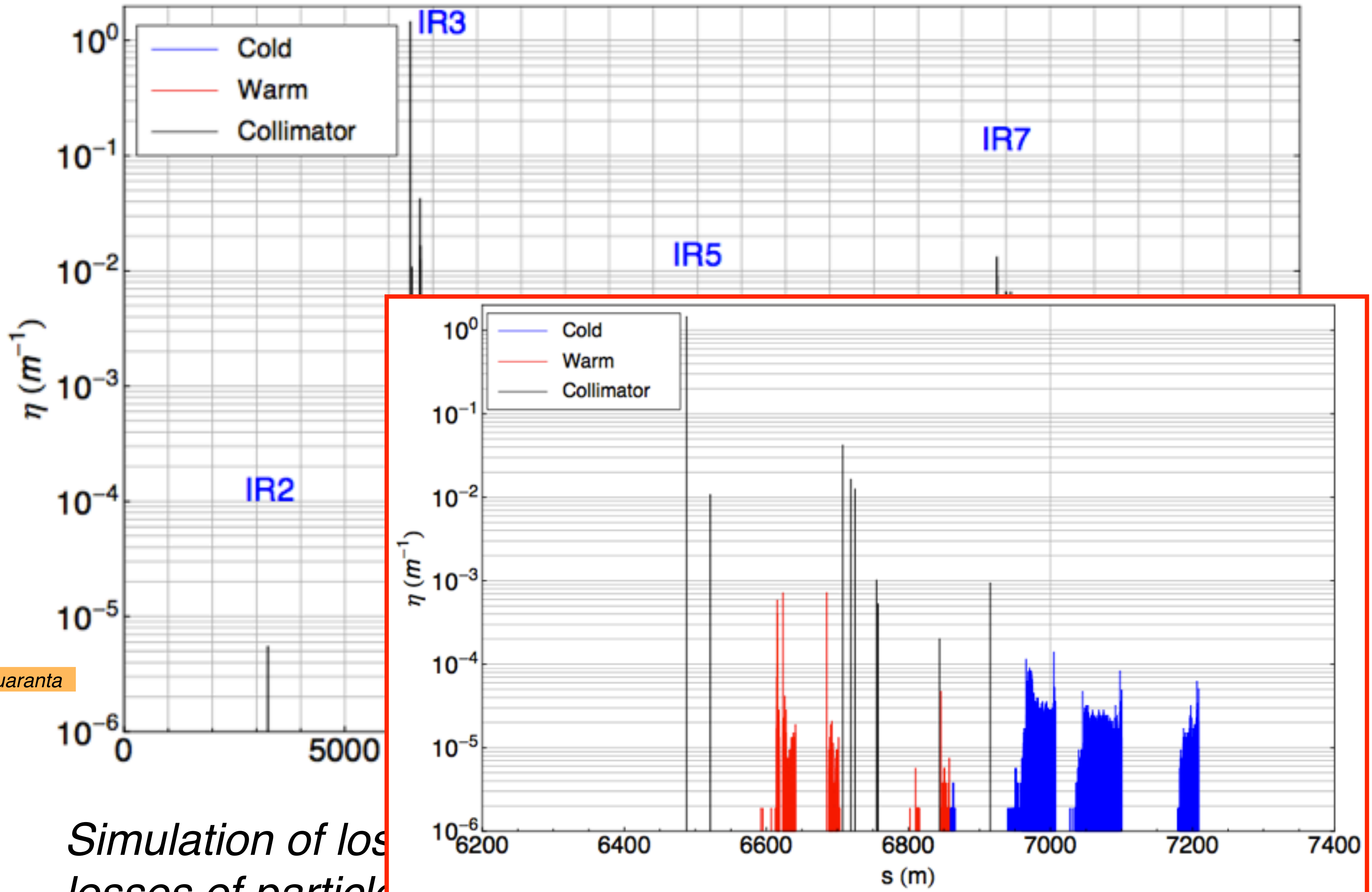


***Special optics conditions** in the momentum cleaning insertions ensure that the primary collimators are the "off-momentum bottleneck". Otherwise, a **similar multi-stage** approach is used for cleaning.*

Momentum cleaning optics



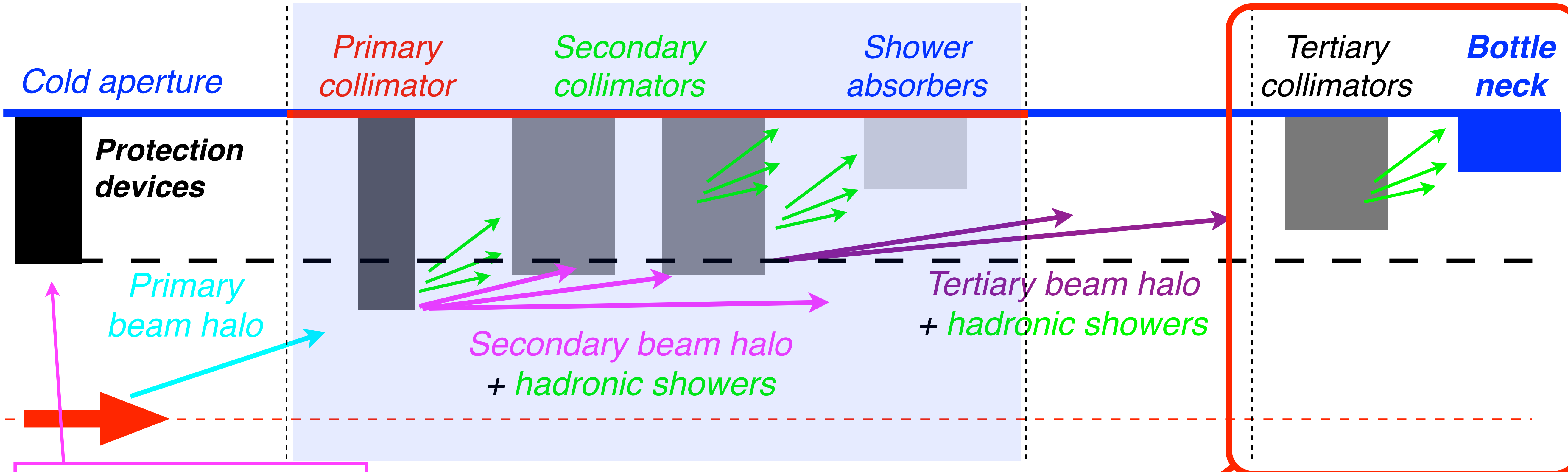
IR3 loss maps: synch. radiation losses



E. Quaranta

Simulation of los
losses of particle

Local cleaning and protection



Protection devices covered in another lecture.

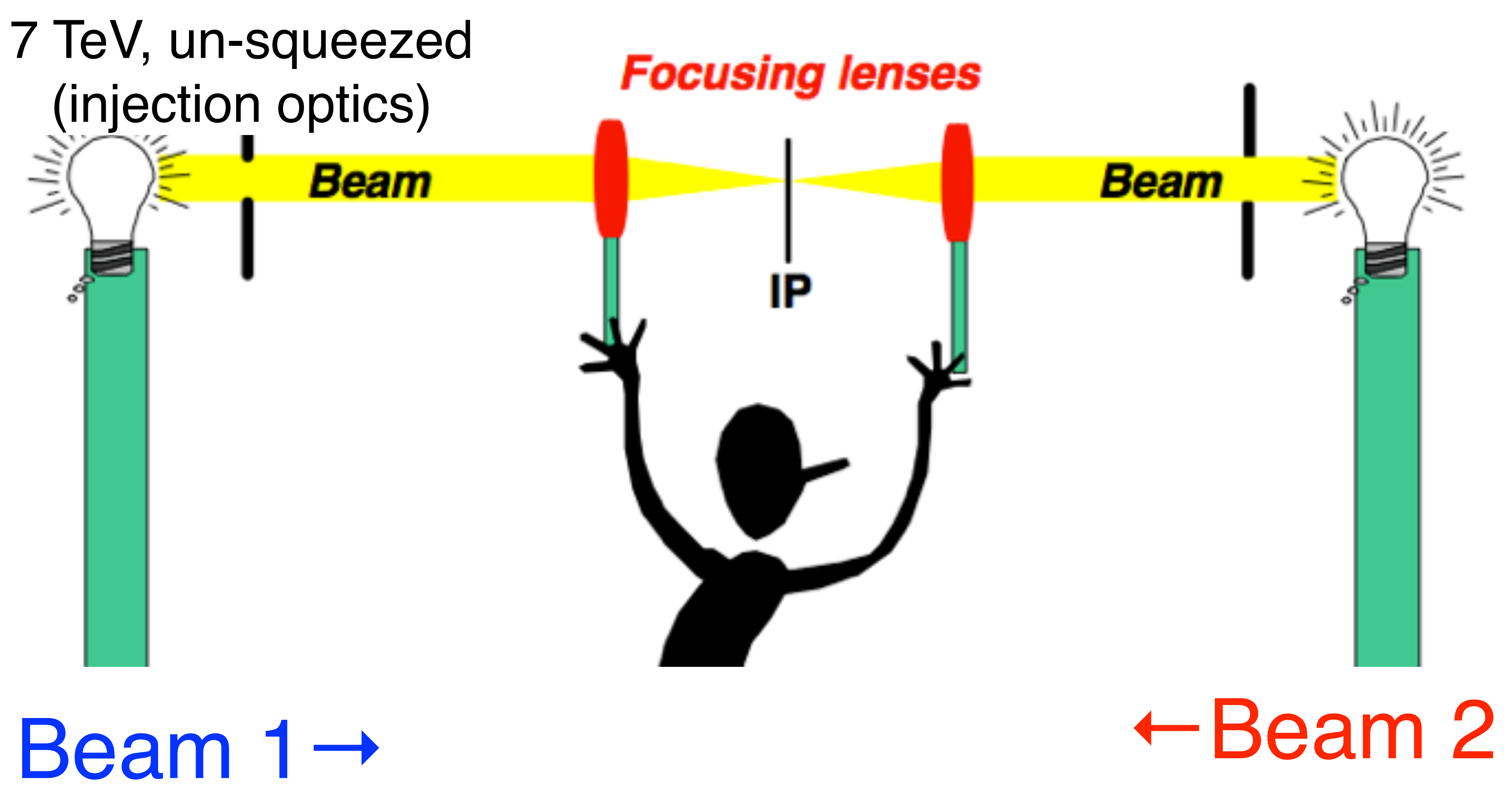
Note: all modern colliders had concerns with losses in the "low-β* insertions".

When do we need local protection?

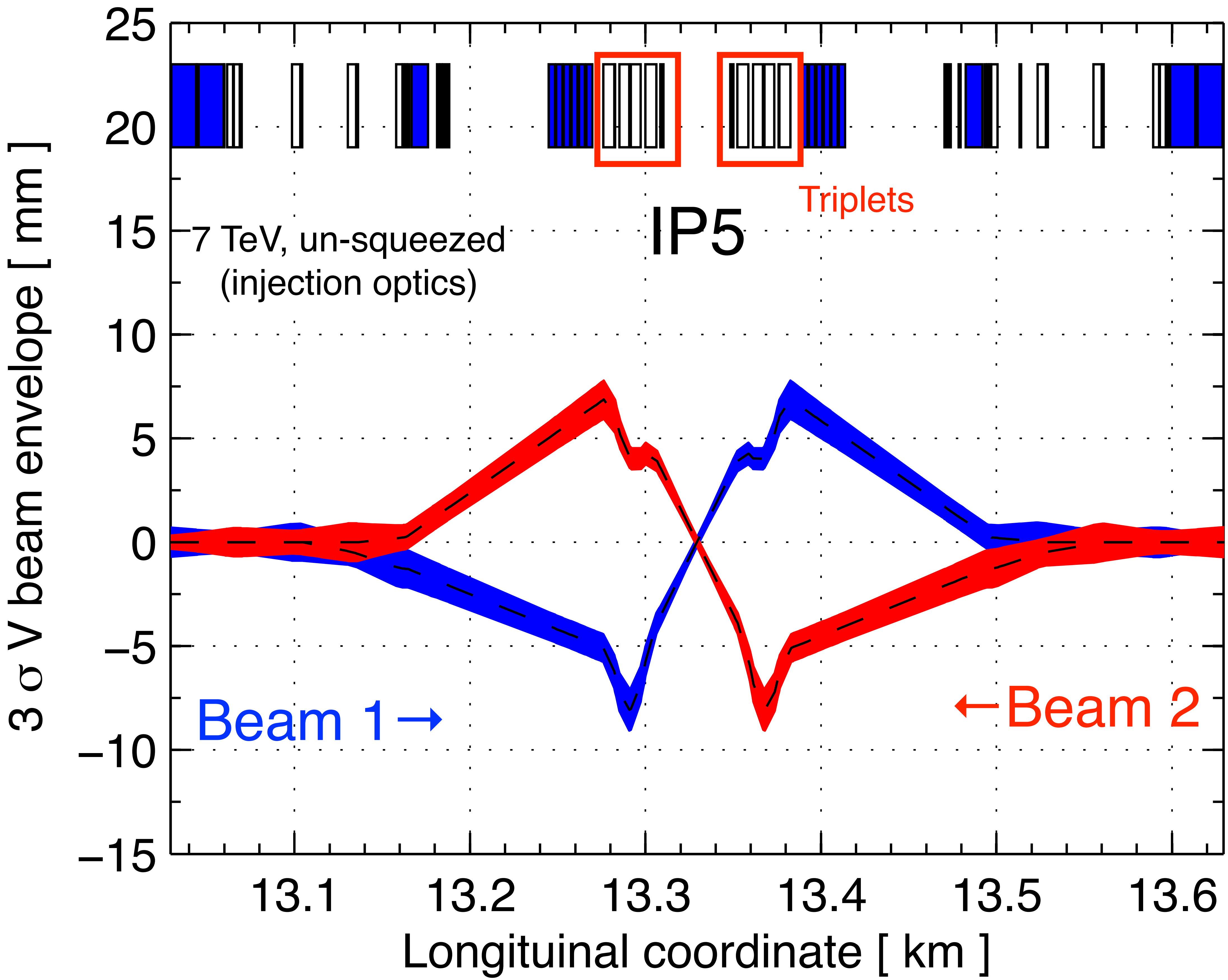
How is the collimator position chosen in these cases?

→ *Briefly look at the **tertiary collimators** that protect the **inner triplet** in all experimental regions.*

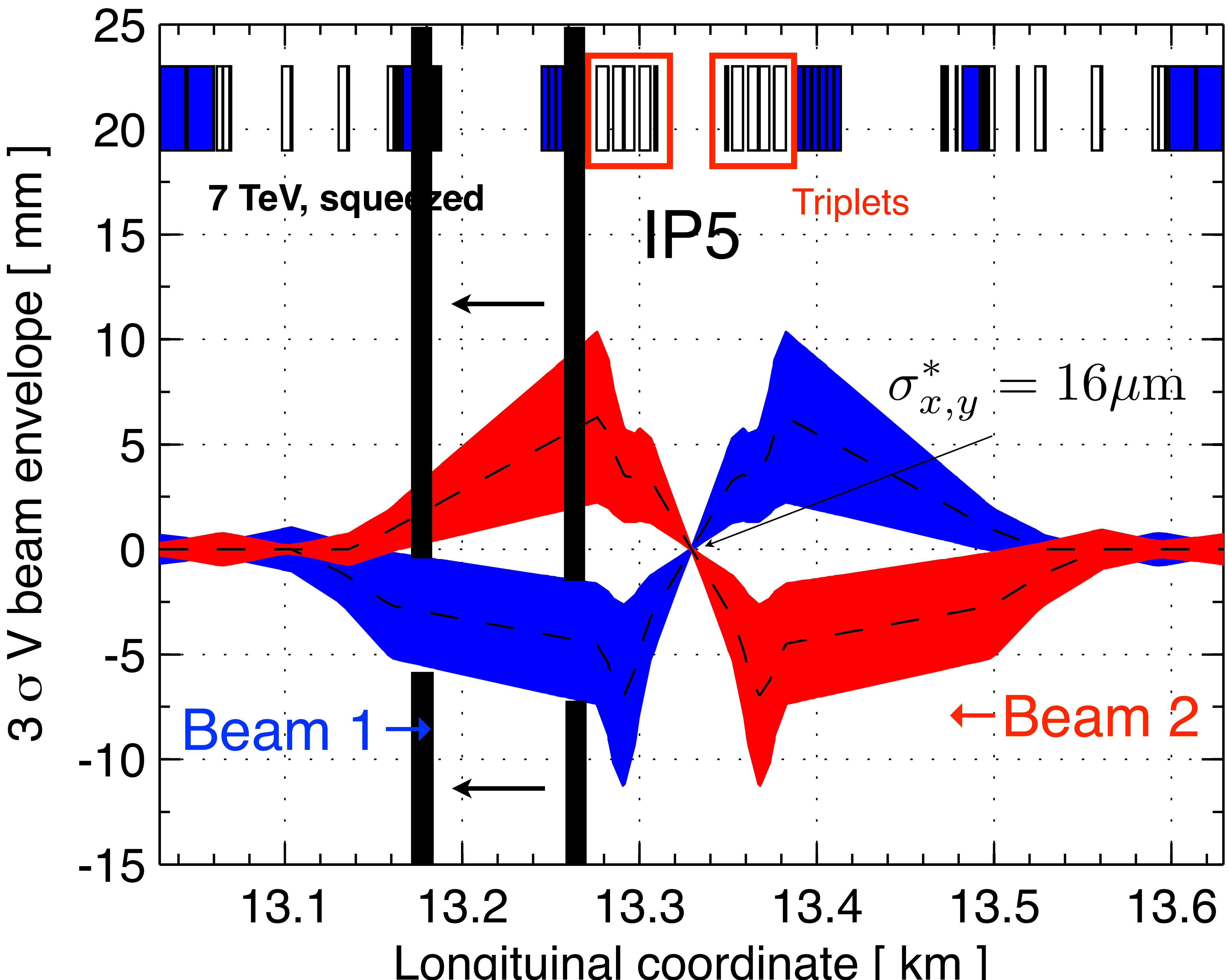
Optics in high-luminosity points



Optics in high-luminosity points



Optics in high-luminosity points



Role of LHC tertiary collimators

Tertiary collimators (TCT's) are part of the betatron collimation hierarchy and are used to protect the inner triplets of the low-β^* experiments

Clean the tertiary halo that leaks out of the cleaning insertions.
Protect the magnets in case of abnormal losses.
Tertiary collimators might be used to tune experiment backgrounds.

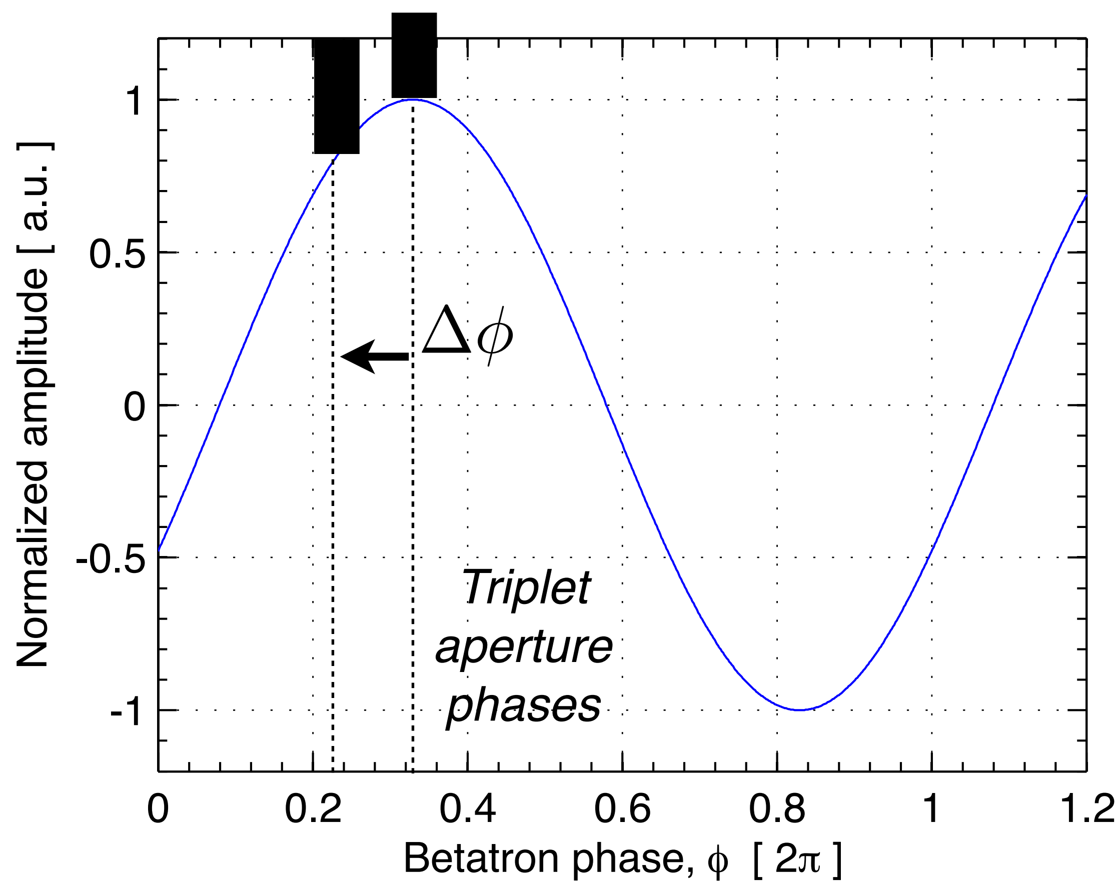
Triplet protection with "squeezed" beams is maximized by

Minimizing the "betatron phase difference" to the TCT
Use high-Z material to maximize absorption → in case of catastrophic failures, better destroy the collimator than a magnet!

TCT's are located typically in cold regions → settings must guarantee that they are not exposed to large beam loads.

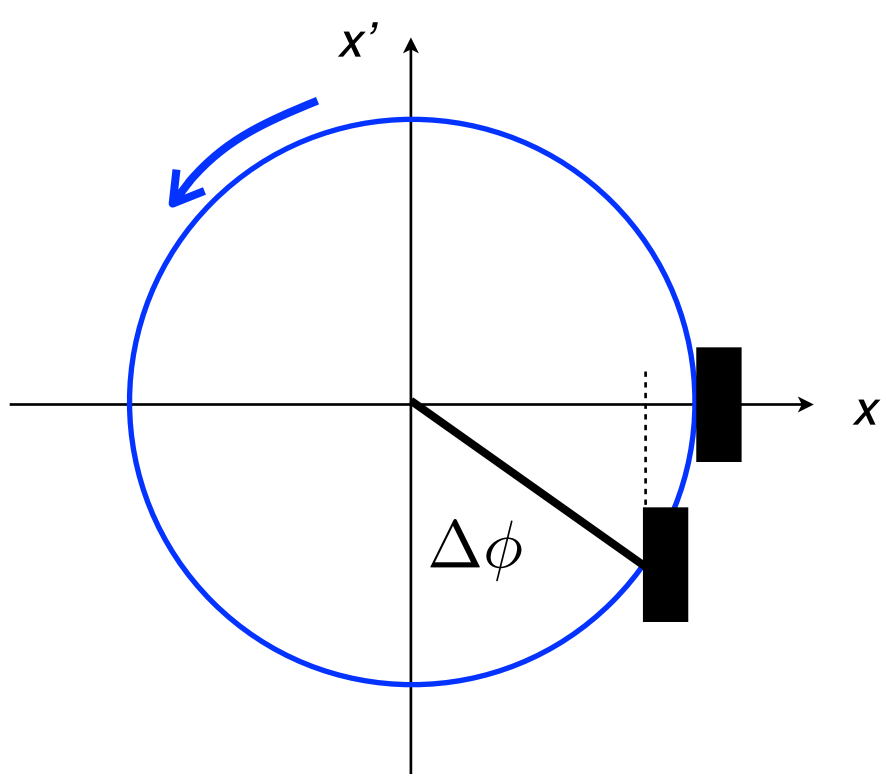
What if we cannot place TCT's at same phase of the triplet?

TCT settings versus aperture



*If one cannot install the TCT at the same phase at the aperture bottleneck, equivalent protection levels can only be achieved **closing the collimator to smaller gaps**.*

<u>Exercise</u>: calculate the required TCT settings changes versus the phase difference.



*Who is more familiar with the beam dynamics, can also see the solution in the **normalized phase-space diagram.***

Change is small: with squeezed optics, $\Delta\phi \cong 0$ at the TCT location available!

Main points to retain (i)

- **Beam collimation** is essential in modern high-power machines to safely dispose of unavoidable beam losses (*beam halo cleaning*).
  LHC main concerns:
  (1) minimize risk of quenches with 360 MJ stored energy,
  (2) passive machine protection in case of accidental failures.
  Many other important roles (warm vs cold machine, activation, backgrounds, etc...)!
- Collimation is achieved by constraining the transverse amplitudes of halo particles: collimator jaws are set close to the beam to shield the aperture.
- Many sources of beam losses (collisions, gas or beam scattering, operational losses,...) are modelled by looking at the time-dependent **beam lifetime**.
  Required cleaning depends on minimum allowed beam lifetime for given quench limit.
- We have see the key parameters involved in the specification of collimation systems (beam intensity and energy, assumed lifetime, ...)
- Single-stage collimation: efficiencies up to ~97-99%. This is not enough: the leakage must be reduced by another factor 100-1000 to avoid quenches.
  Many collimators are needed to catch efficiently high-energy halo particles.

Main points to retain (ii)

- A **multi-stage collimation** can provide the missing factors and fulfill the cleaning challenge!

  Secondary collimators are placed at optimum locations to catch product of halo interactions with primaries (secondary halo+shower products).
  *Other collimators are needed to achieve ~1e-5 → complex **multi-stage hierarchy**.*

- Dedicated **momentum cleaning** might be needed if energy losses are a concern.

  Special optics solutions to protect the off-momentum aperture bottleneck, otherwise using the same multi-stage approach as for betatron cleaning.

- Back-bone of collimation placed in dedicated **warm insertions**, but some collimators also used for **local protection** of sensitive magnets.

- LHC collimation: unprecedented complexity in particle accelerators!
  *A total of 44 collimators per beam, ordered in a pre-defined **collimation hierarchy**: two dedicated warm insertions (2-stage collimation+shower absorbers), local cleaning in experiments, physics debris cleaning and protection collimators.*

Outline

- ☑ Introduction
- ☑ Beam losses and collimation
- ☑ Multi-stage collimation
- ☑ **LHC collimation design**
- ☑ Cleaning: operational performance
- ☑ Conclusions

FCC collimation studies at CERN

We have started to work on the design a collimation system for the 50 TeV proton beams of **Future Circular Collider** (FCC)!

Initial goal is to scale up the LHC system (optics, collimation layouts) to see what we can achieve with the state-of-the-art.

Two insertions of more than 3 km with similar optics.
Design the system from basic designs principles.

Provide initial inputs to collimator design (tolerances, materials, impedance, magnets, ...) → understand potential limitations.

Define paths for improvements relying on new techniques.

A post-doc started working with me on this topics. Will be looking for a PhD student in ~6 months or so after having worked out the first setup of simulation tools (optics, layouts, aperture...)

LHC collimation system layout

Two warm cleaning insertions, 3 collimation planes

- **IR3: Momentum cleaning**
  - **1 primary (H)**
  - **4 secondary (H)**
  - **4 shower abs. (H,V)**
- **IR7: Betatron cleaning**
  - **3 primary (H,V,S)**
  - **11 secondary (H,V,S)**
  - **5 shower abs. (H,V)**

Local cleaning at triplets

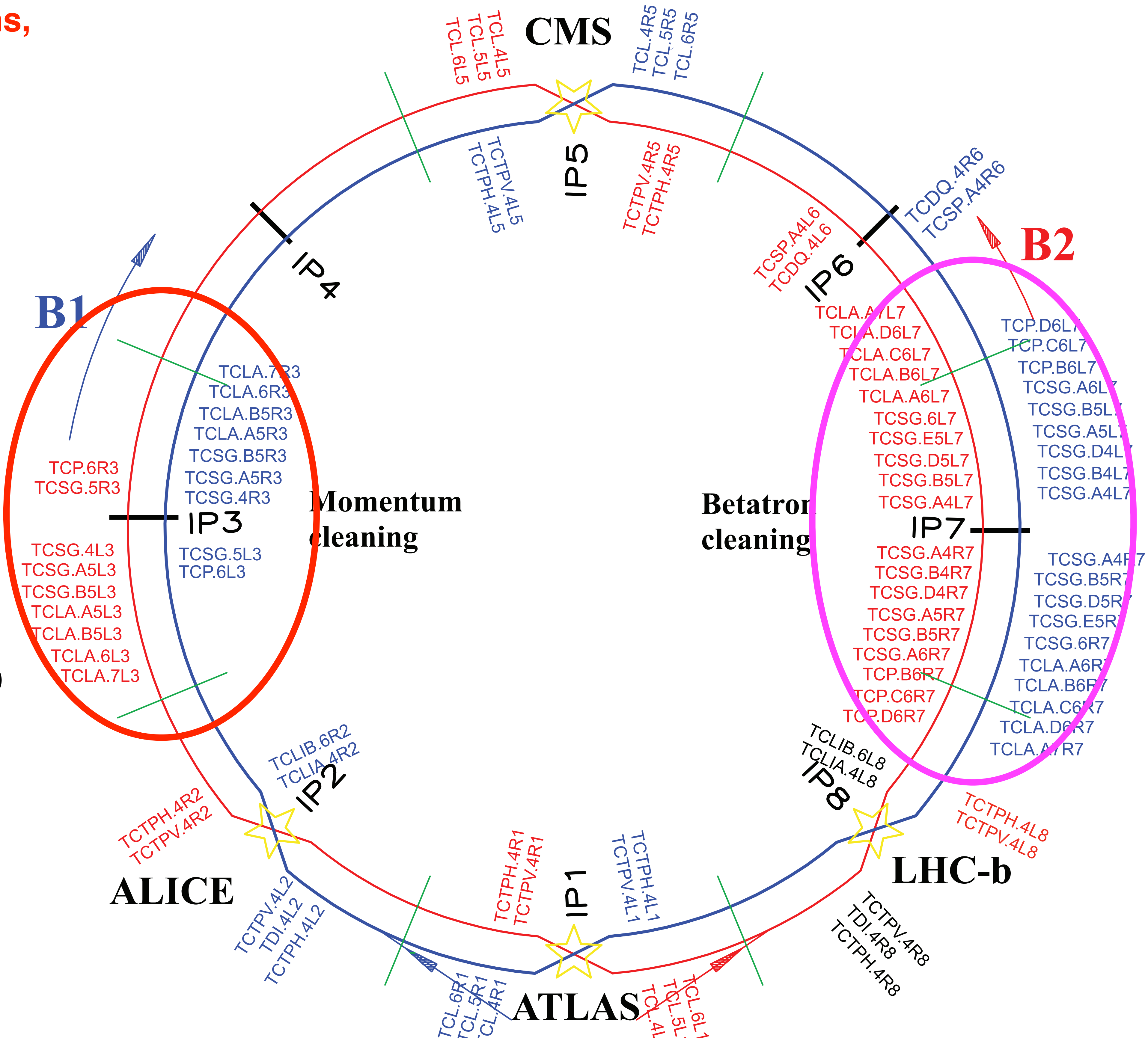
- **8 tertiary (2 per IP)**

Passive absorbers for warm magnets

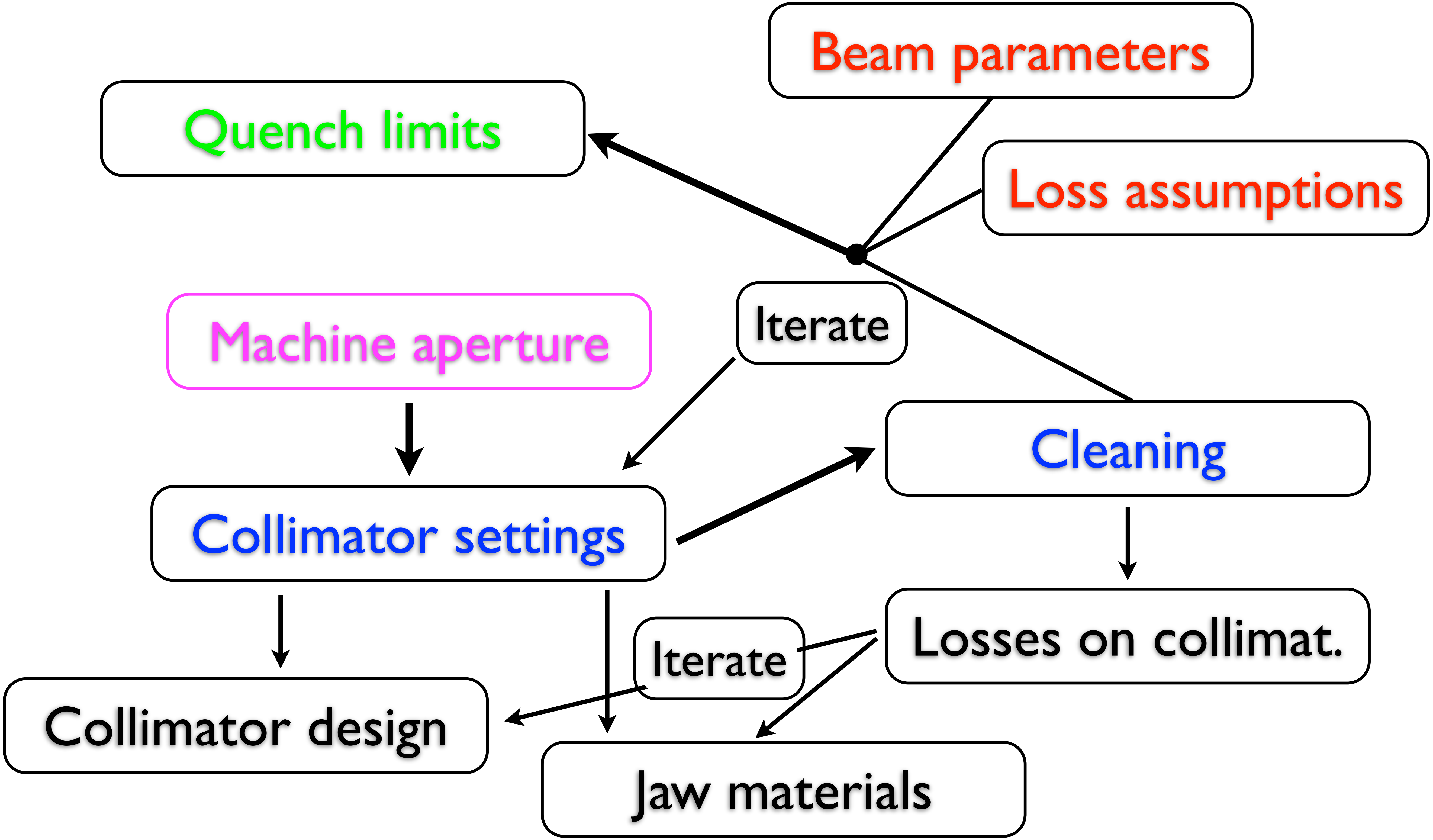
Physics debris absorbers

Transfer lines (13 collimators)
Injection and dump protection (10)

Total of 118 collimators (108 movable). Two jaws (4 motors) per collimator!



Workflow for collimation design



Similar might be drawn for different roles than cleaning

A multi-disciplinary topic...

The complete design chain rely on different key ingredients:

Tracking models

Collimation scattering models

Mokhov/Cerutti

Energy deposition simulations

Bertarelli

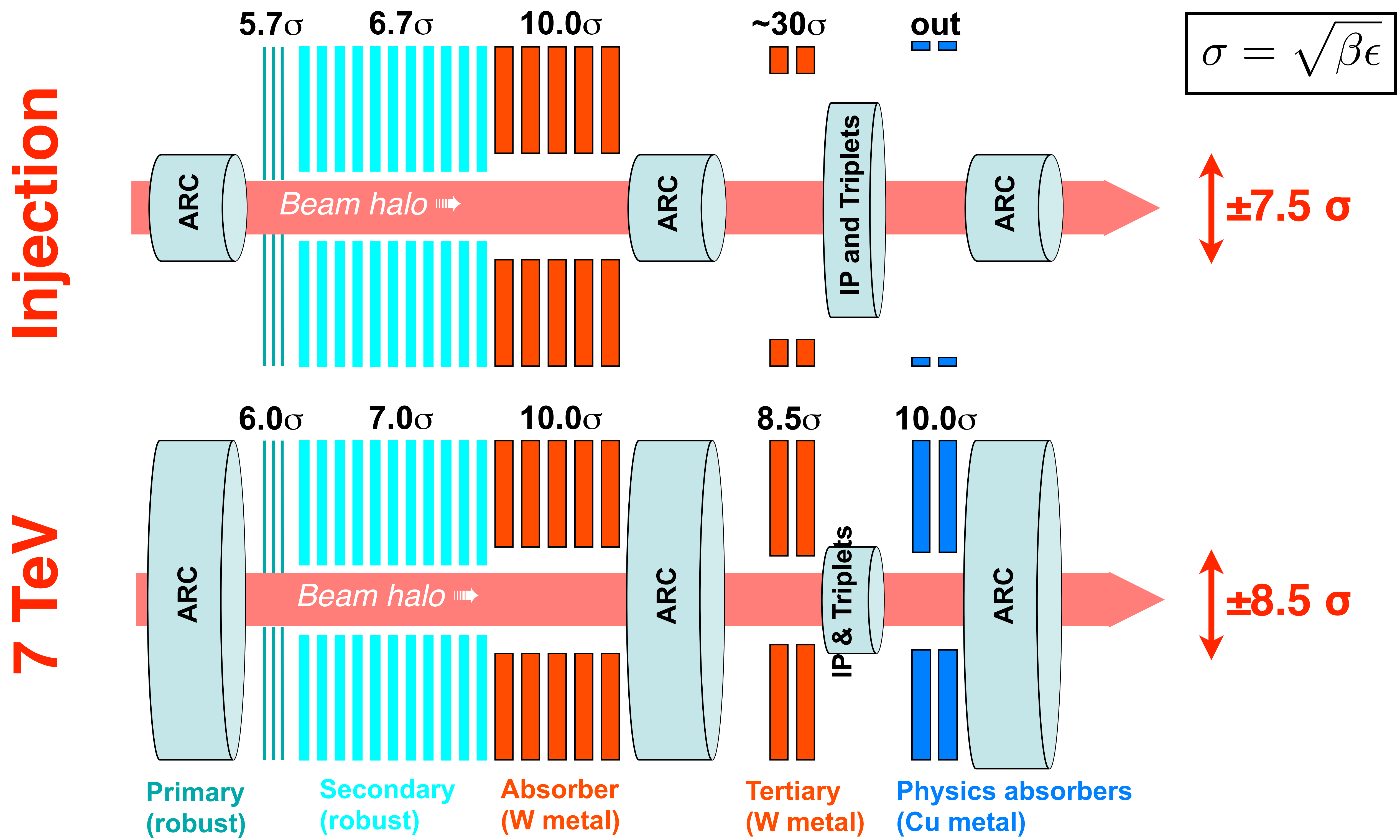
Thermo-mechanical analysis

Operational assumptions

Standard chain of tools developed and used at CERN:
(1) SixTrack with collimation
(2) FLUKA
(3) ANSIS / AutoDyn

Important effort worldwide to extend tools:
MARS, Geant4, Merlin, BDSIM, ...
Recent workshop within HiLumi-WP5:
https://indico.cern.ch/event/275446

Aperture design and collimator settings



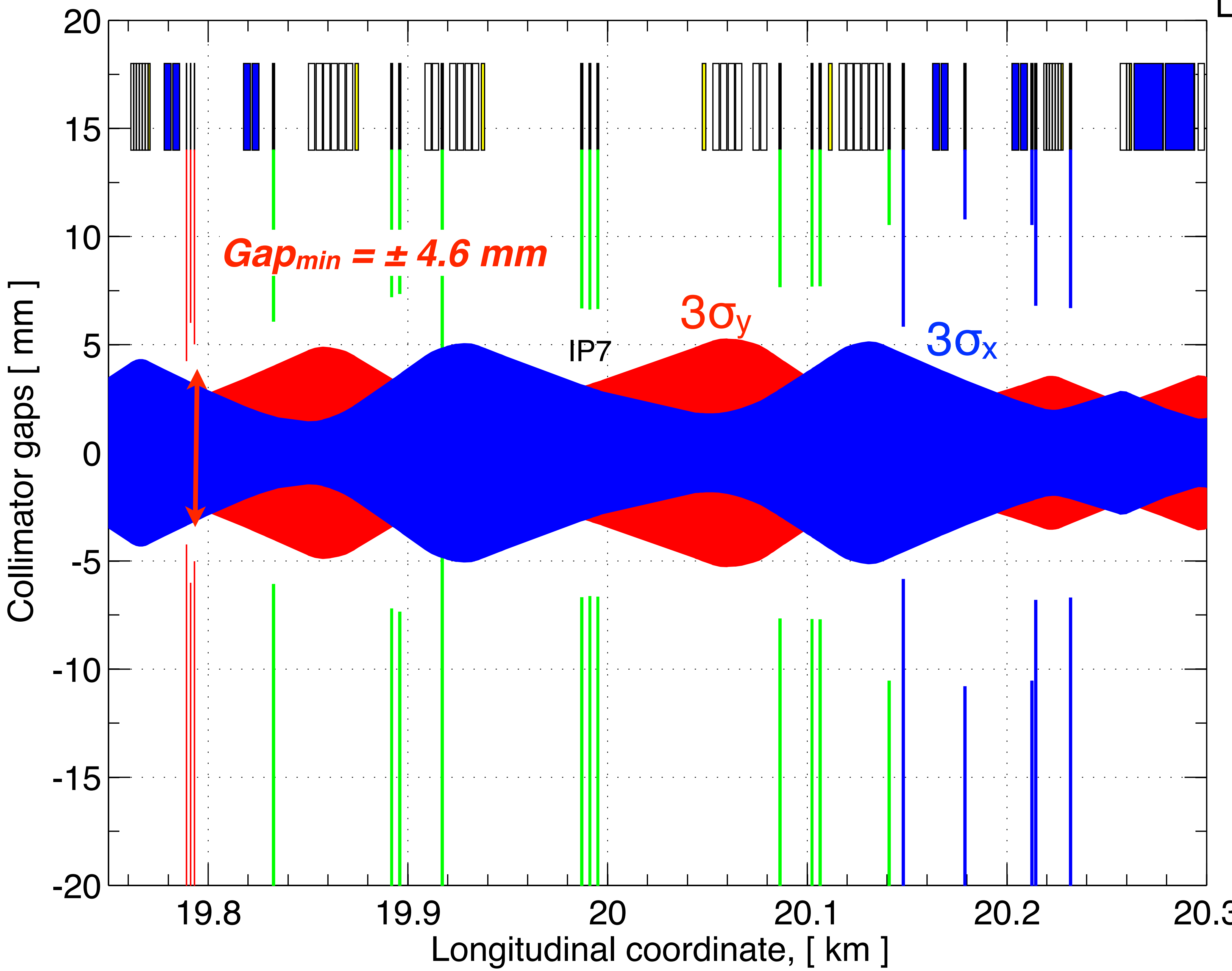
Ramp: beam sizes shrinks like sqrt(E).

Squeeze optics changes introduce bottlenecks triplet.

IR7 collimator settings at 450 GeV

A_{TCP} = 5.7 σ A_{TCS} = 6.7 σ A_{TCLA} = 10 σ

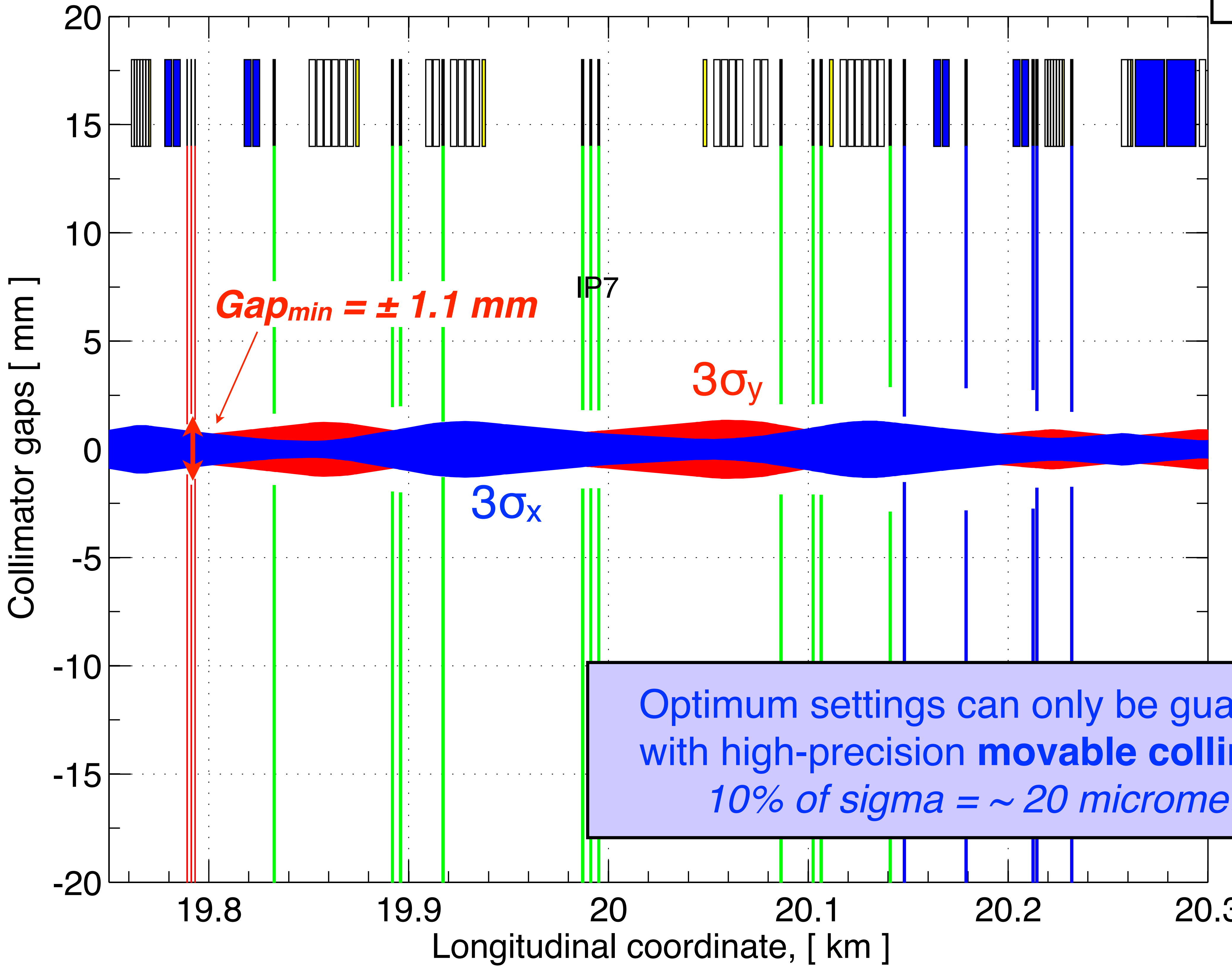
$$\sigma = \sqrt{\beta\epsilon}$$



IR7 collimator settings at 7 TeV

$A_{TCP} = 6\ \sigma$ $A_{TCS} = 7\ \sigma$ $A_{TCLA} = 10\ \sigma$

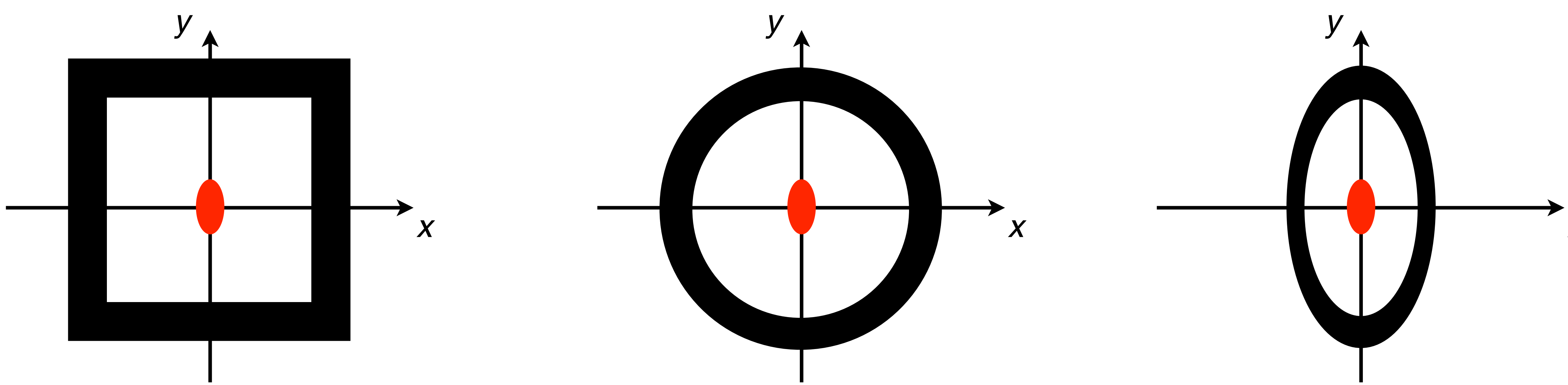
$$\sigma = \sqrt{\beta\epsilon}$$



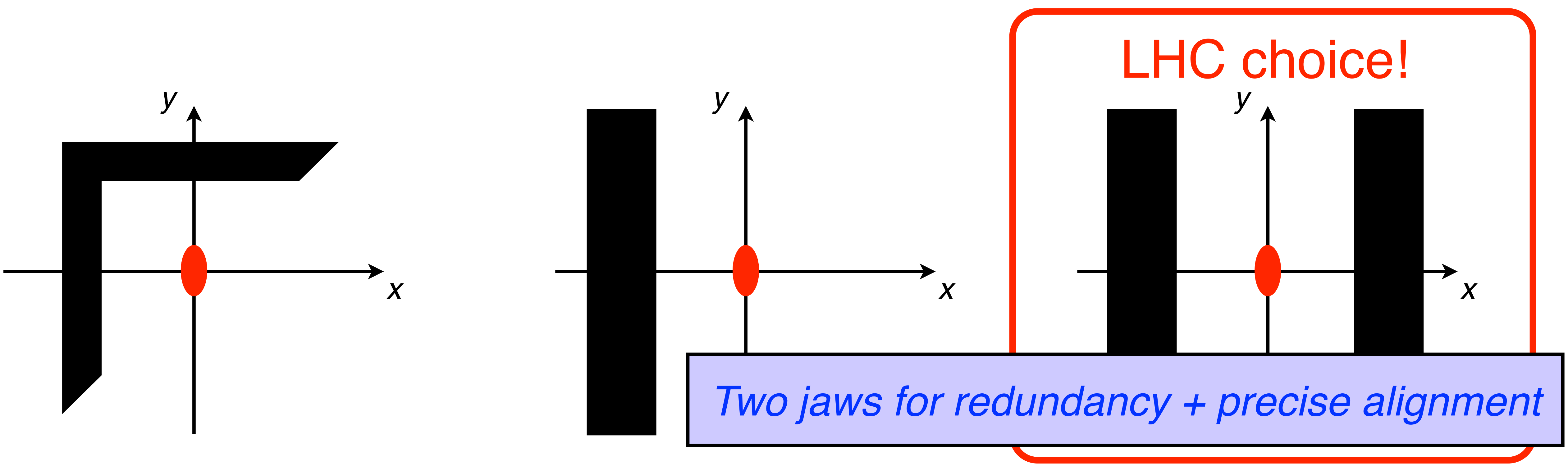
Optimum settings can only be guaranteed with high-precision **movable collimators**!
10% of sigma = ~ 20 micrometers!

Possible collimator designs

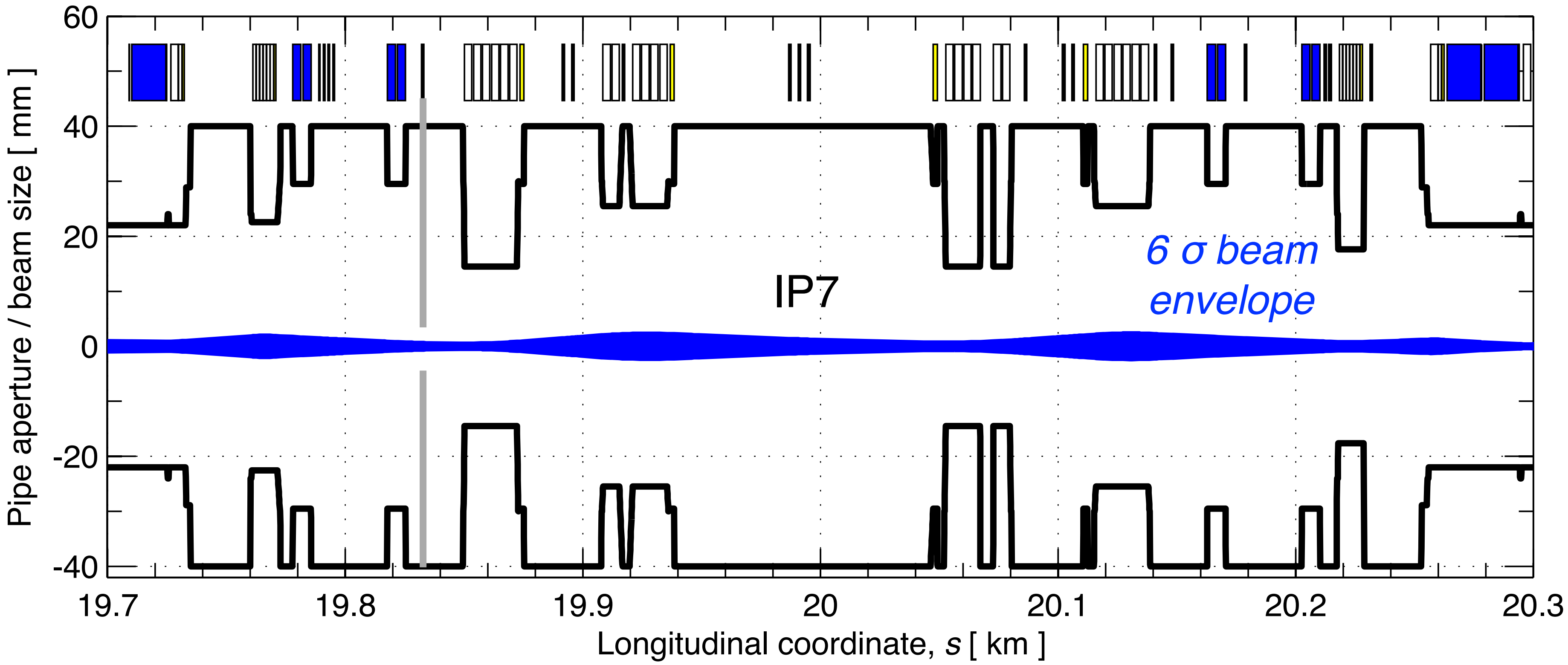
Fixed collimators (masks): square, circular, elliptical, ...



Movable collimators: L-shaped, one-sided, two-sided.



Setting/aperture notations



$$\sigma_z^{\mathrm{D}} = \sqrt{\beta_z \frac{\epsilon_z}{\gamma} + D_z \left(\frac{\delta p}{p}\right)^2}$$: RMS beam size

$z \equiv (x, y)$: Hor. and Ver. planes

β_z : beta functions

ϵ_z/γ : normalized emittance

D_z : dispersion function

$\delta p/p$: RMS energy spread

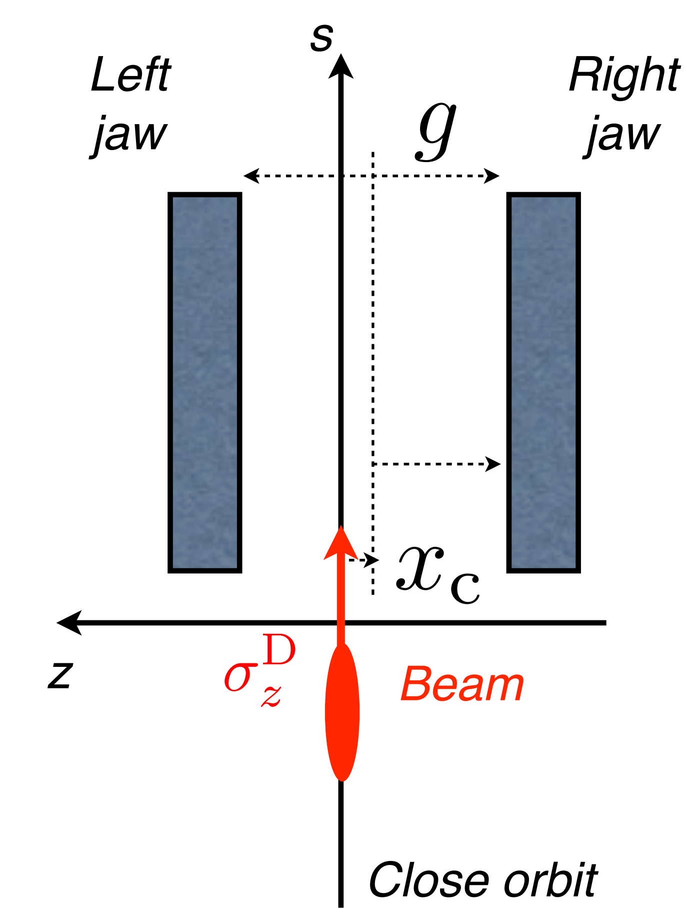
g : collimator gap in millimeters

$$\boxed{\sigma_z = \sqrt{\beta_z \frac{\epsilon_z}{\gamma}}}$$ **: RMS *betatron* beam size**

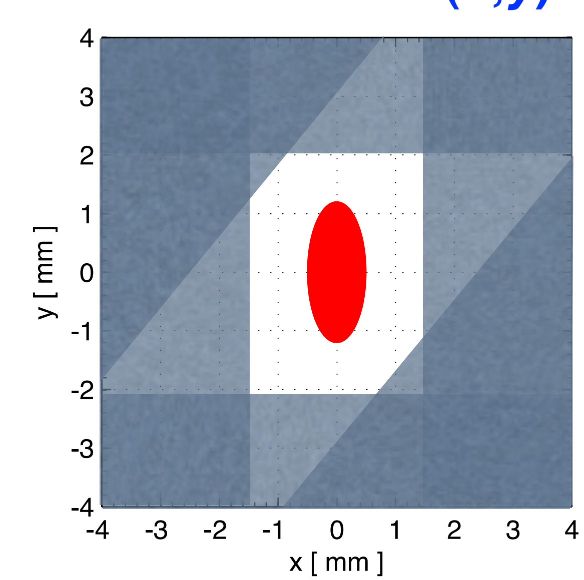
$$\boxed{N_\sigma = \frac{g}{2}\frac{1}{\sigma_z}}$$ **: Normalized gap (beam size units)**

$$\boxed{x_{\mathrm{c}} \pm N_\sigma \cdot \sigma_z}$$ **: Collimator jaw positions**

Top view (*x*,*s*)



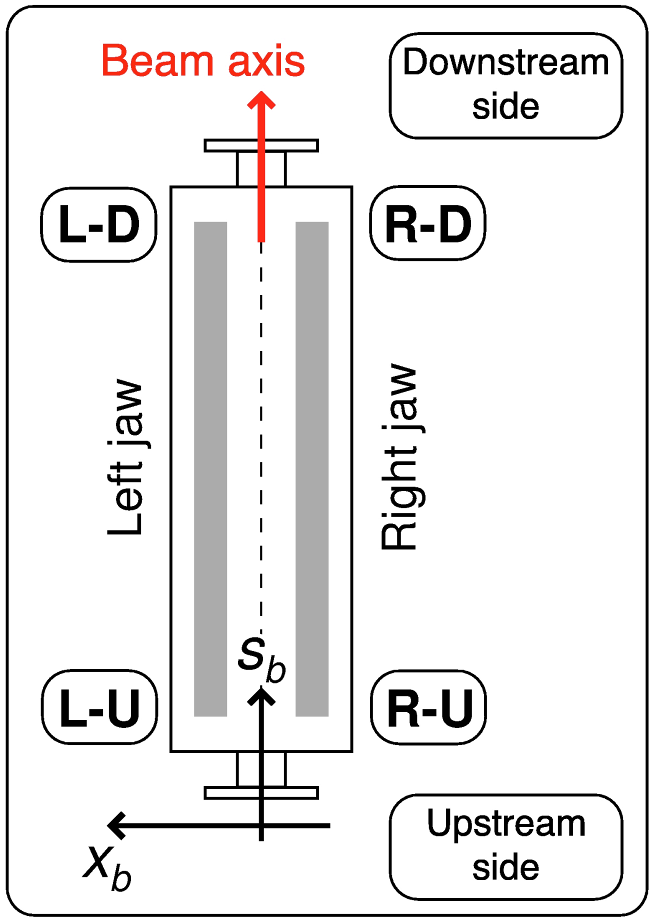
Front view (*x*,*y*)



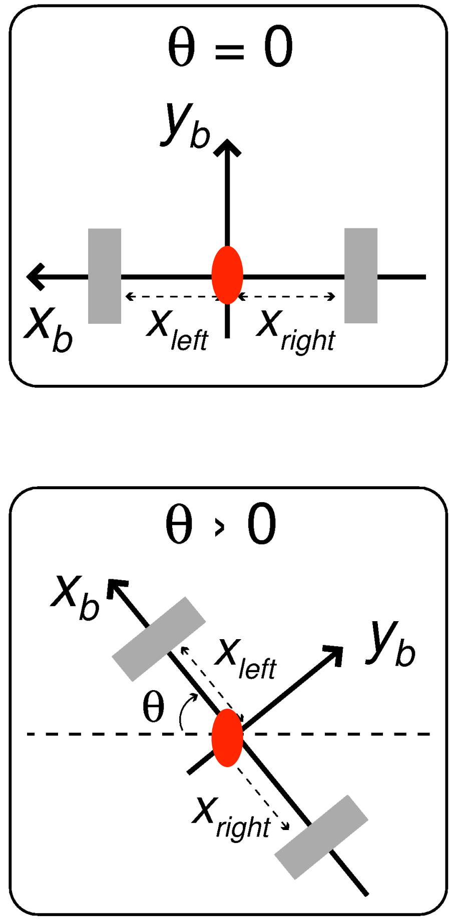
Collimator settings and aperture are expressed in normalized units, using the of local betatron beam size → enable to define the **setting "hierarchy"**!

“Skew” collimators

Top view



Front views

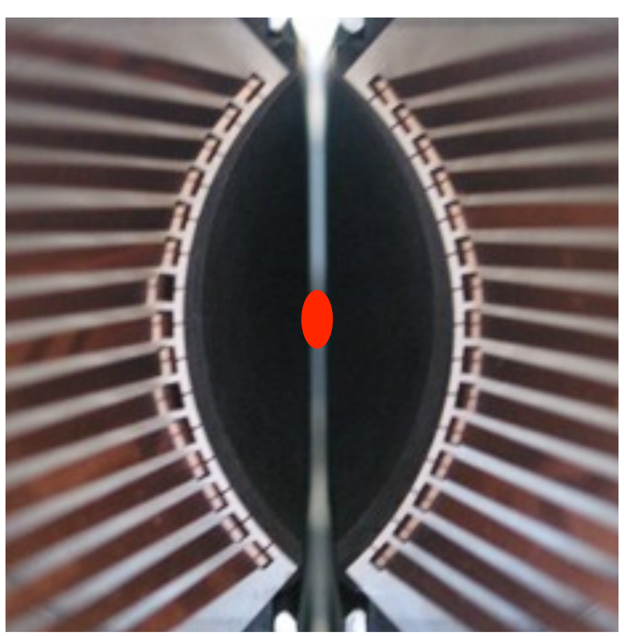


In the LHC, we also have “rotated” collimators that provide collimation in the ***skew plane.***
The collimator jaw movement occurs along the skew axis (still 1D movement). Normalized settings are defined for an appropriate effective beam size.
Same collimator design for all cases: rotate vacuum tank.

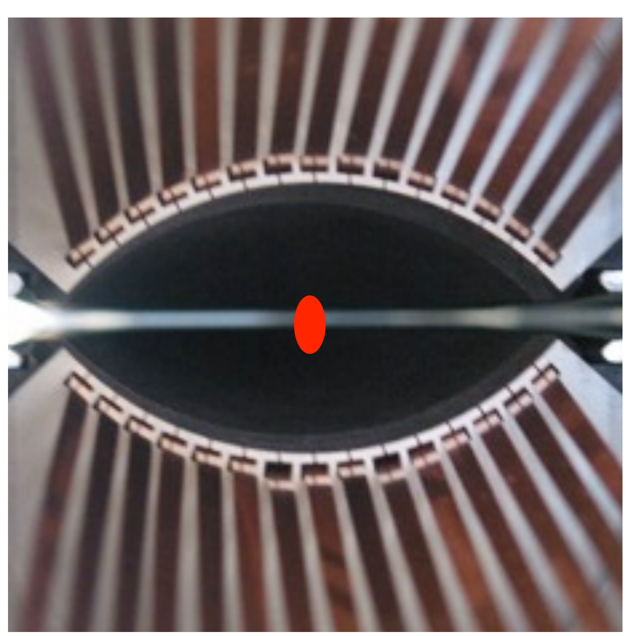
RMS *betatron* beam size in the collimator plane

$$\sigma_{\mathrm{coll}} = \sqrt{\cos^2(\theta_{\mathrm{coll}})\sigma_x^2 + \sin^2(\theta_{\mathrm{coll}})\sigma_x^2}$$

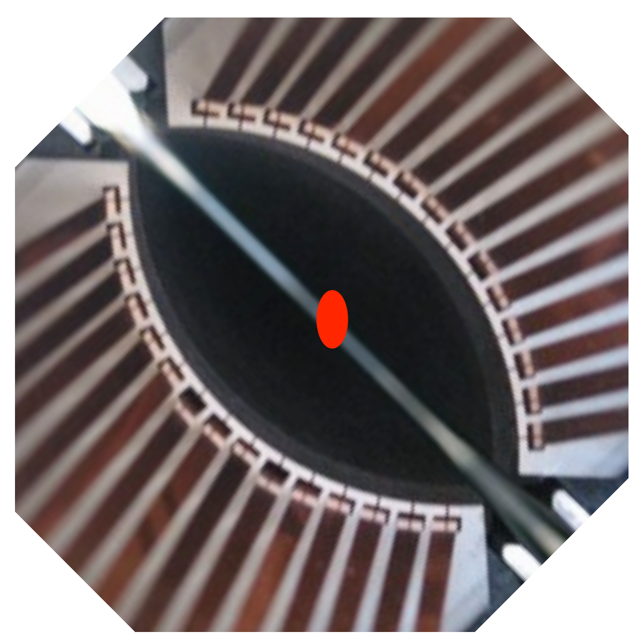
Horizontal



Vertical



Skew



3 **primary collimators** are needed to protect the machine against transverse betatron losses.
Only horizontal collimation for momentum losses.

Reference design goals

High stored beam energy (melt 500 kg Cu, required for 10^{34} cm^{-2} s^{-1} luminosity)	**~ 360 MJ/beam**
Large transverse energy density (beam is destructive, 3 orders beyond Tevatron/HERA)	**1 GJ/mm^2**
High required cleaning efficiency (clean lost protons to avoid SC magnet quenches)	**99.998 % (~10^{-5})**
Activation of collimation insertions (good reliability required, very restricted access)	**~ 1-15 mSv/h**
Small spot sizes at high energy (small 7 TeV emittance, no large beta in restricted space)	**~ 200 μm**
Collimation close to beam (available mechanical aperture is at ~10 σ)	**6-7 σ**
Small collimator gaps (impedance problem, tight tolerances: ~ 10 μm)	**~2.1 mm**
Big and distributed system (coupled with mach. protection / dump)	**~108 movable devices >430 motors**

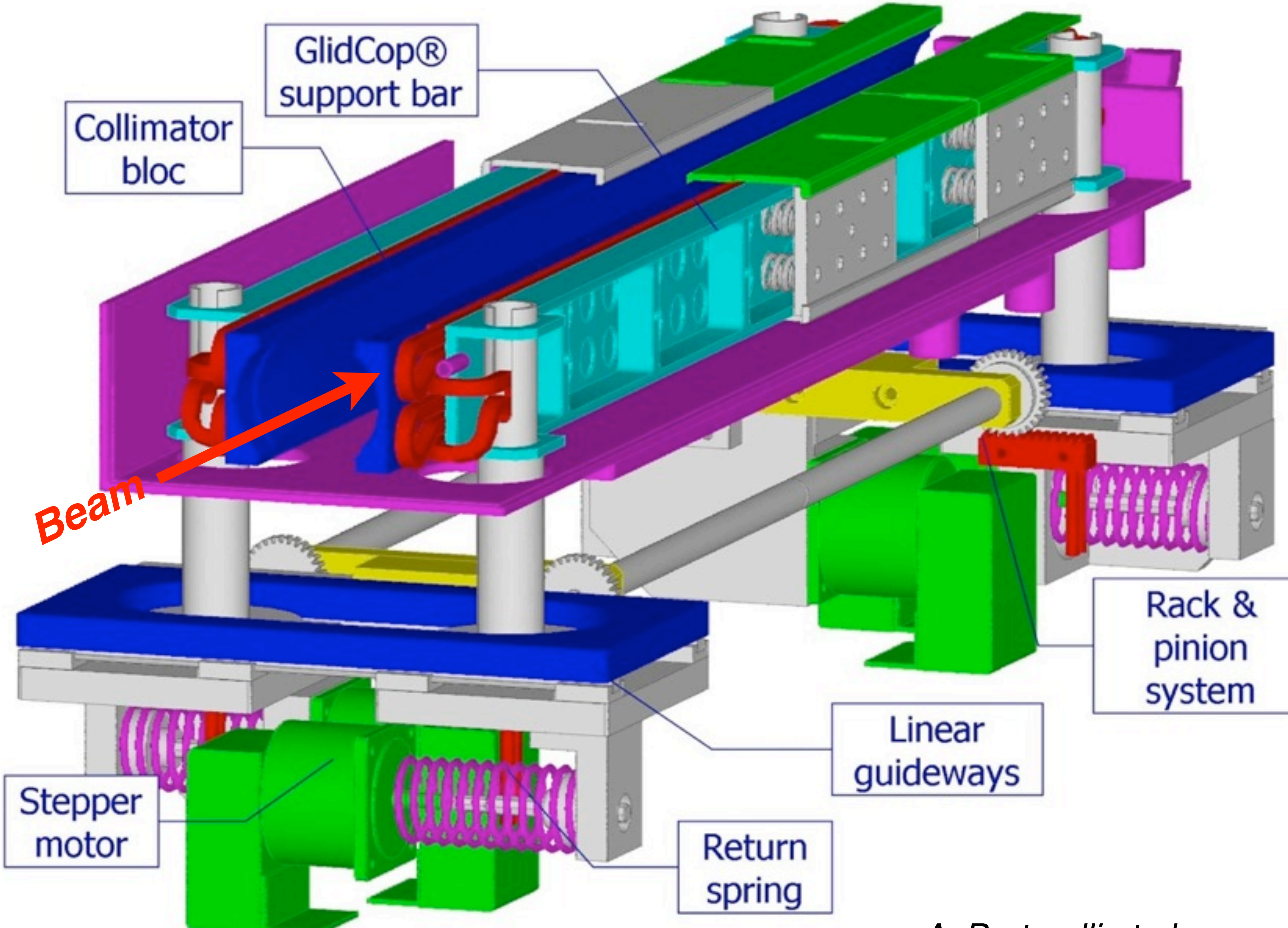
Quench
Damage
Heating
Activation
Stability
Impedance
Precision

All parameters derived meticulously following the "collimation design flow chart" introduced above...

LHC collimator design

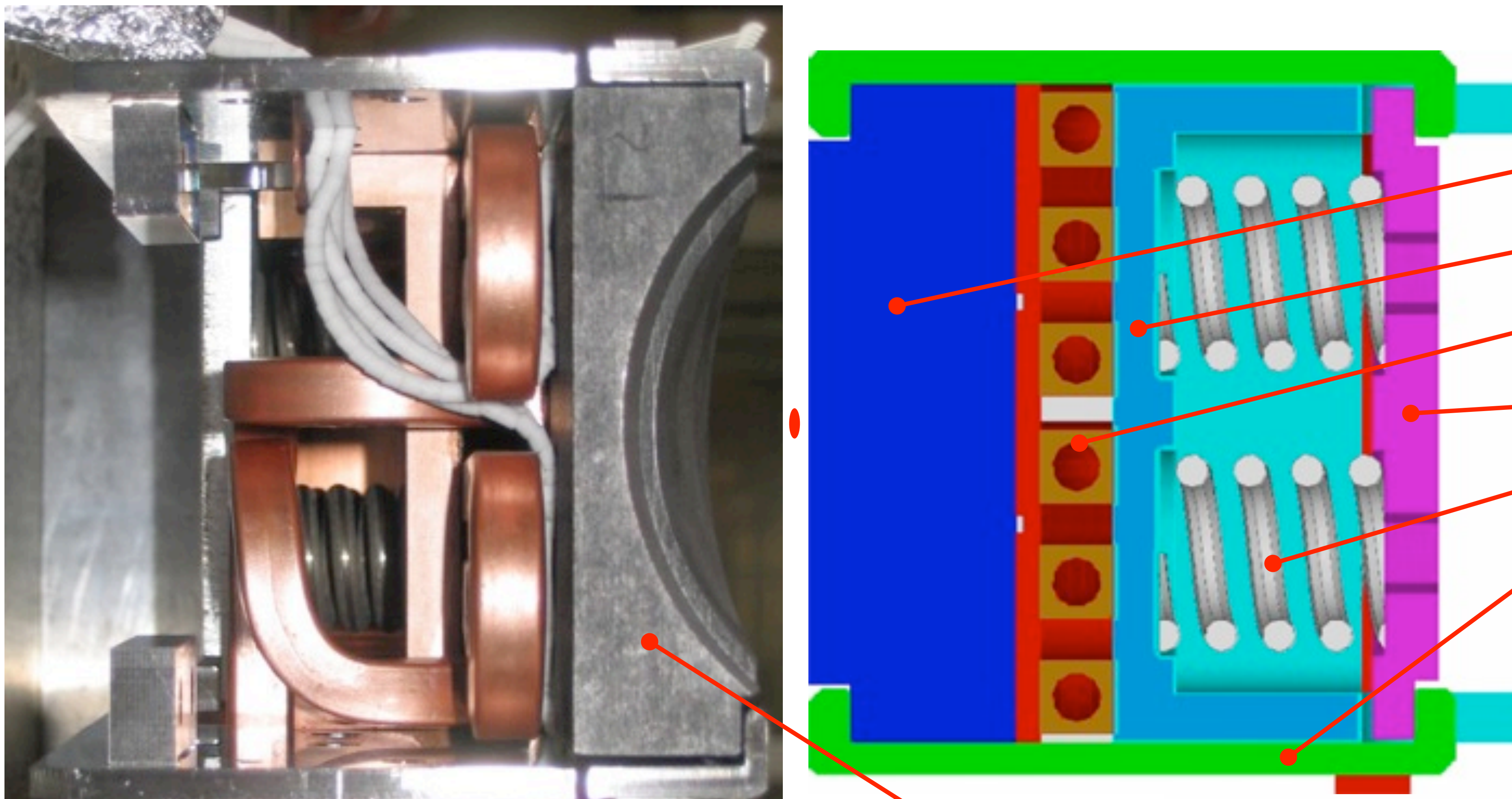
Main design features:

- Two jaws (position and angle)
- Concept of spare surface
- Different angles (H,V,S)
- External reference of jaw position
- Auto-retraction
- RF fingers
- Jaw cooling

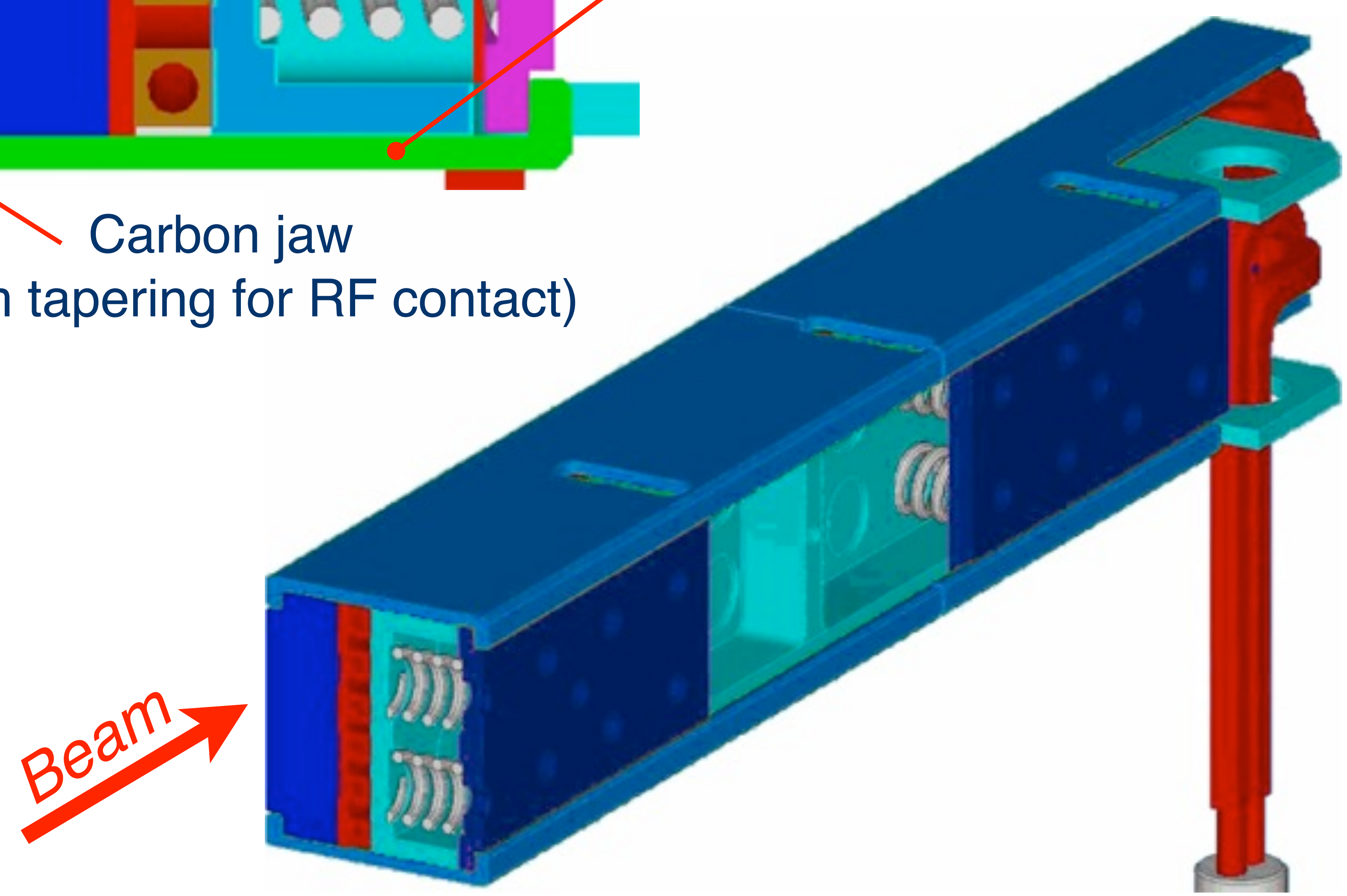


A. Bertarelli et al.

LHC collimator “jaw”

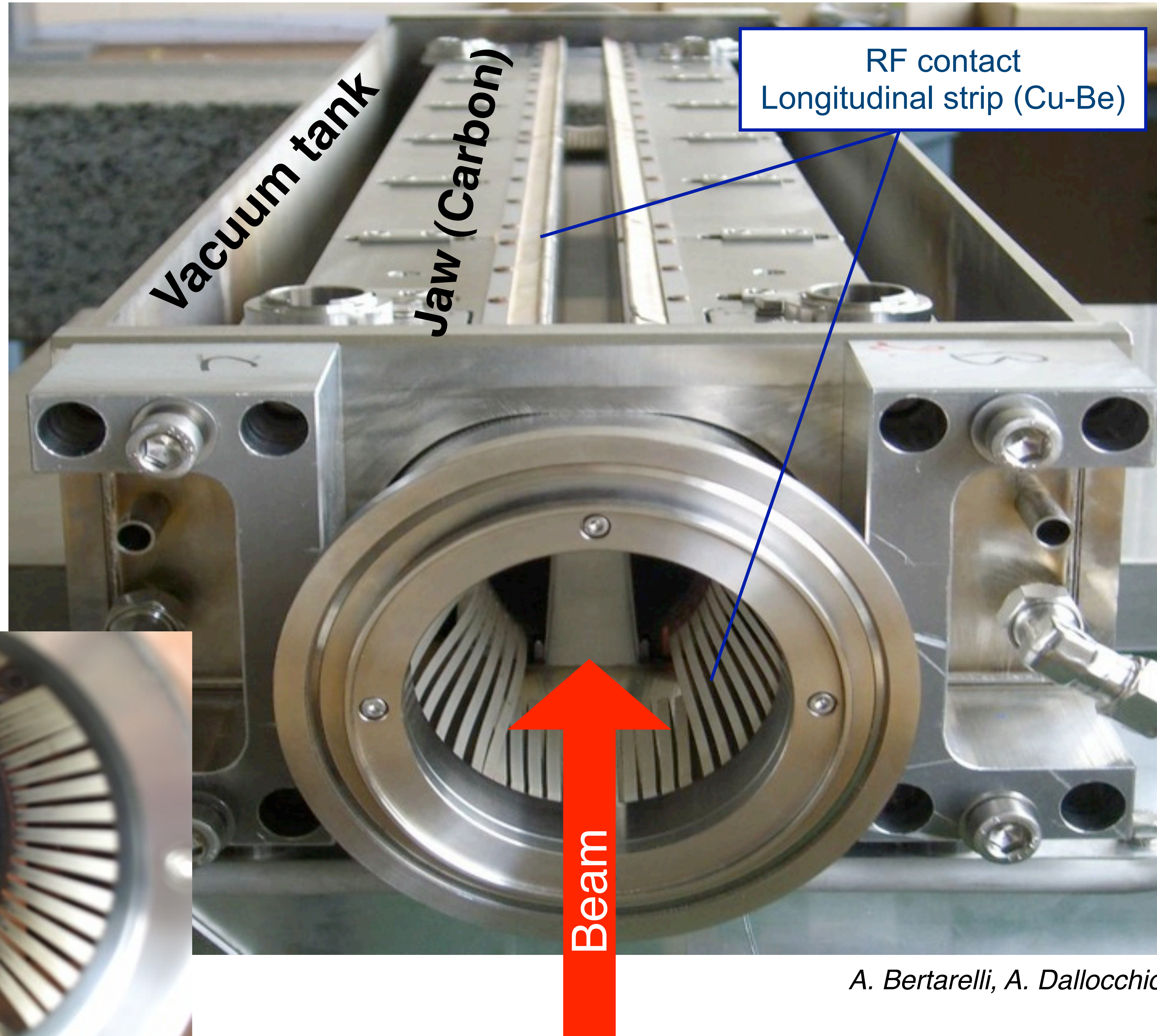


Special “sandwich” design to minimize the thermal deformations:
Steady (~5 kW) → < 30 μm
Transient (~30 kW) → ~ 110 μm
Materials: Graphite, Carbon fibre composites, Copper, Tungsten.



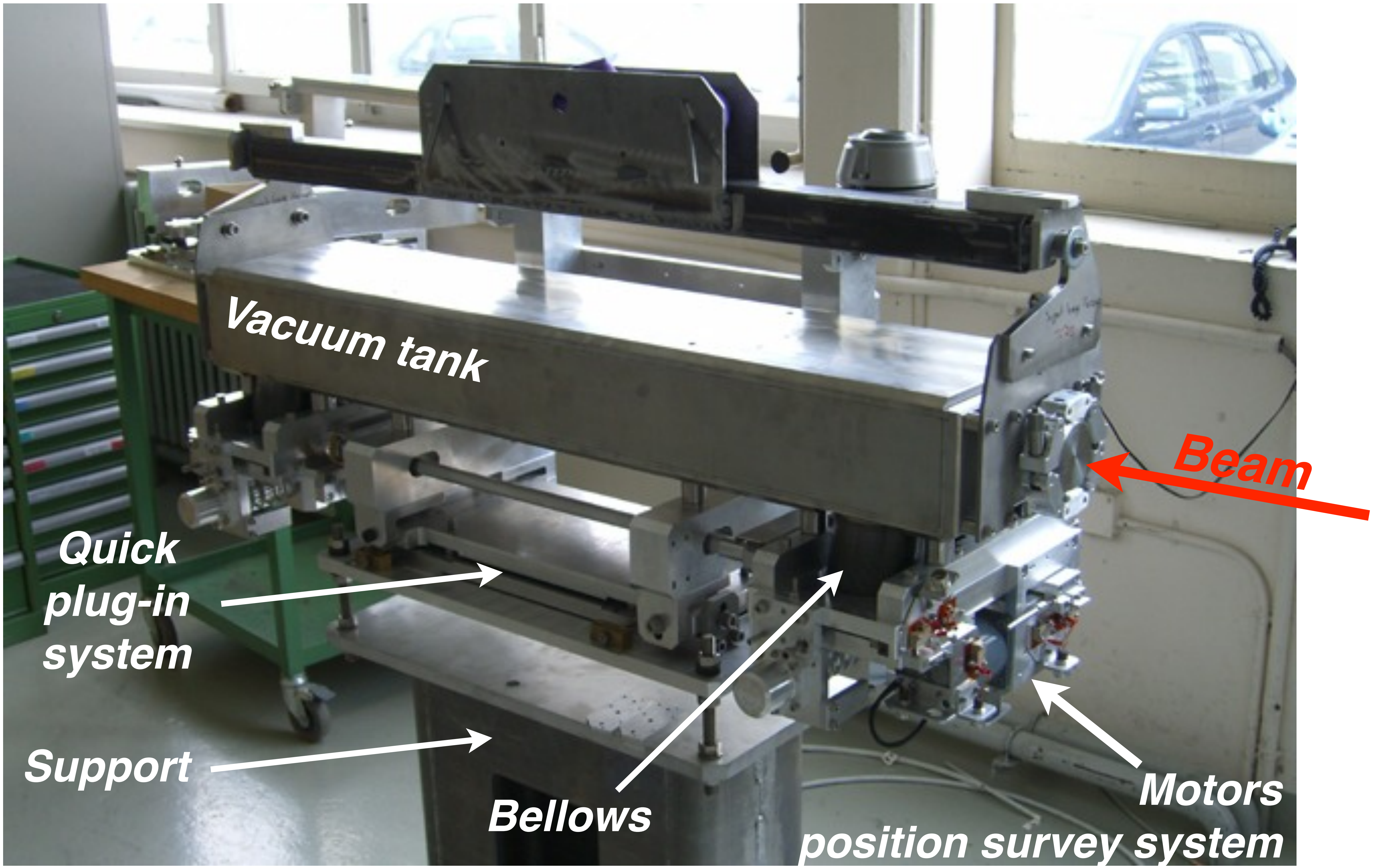
A look inside the vacuum tank

What the beam sees!

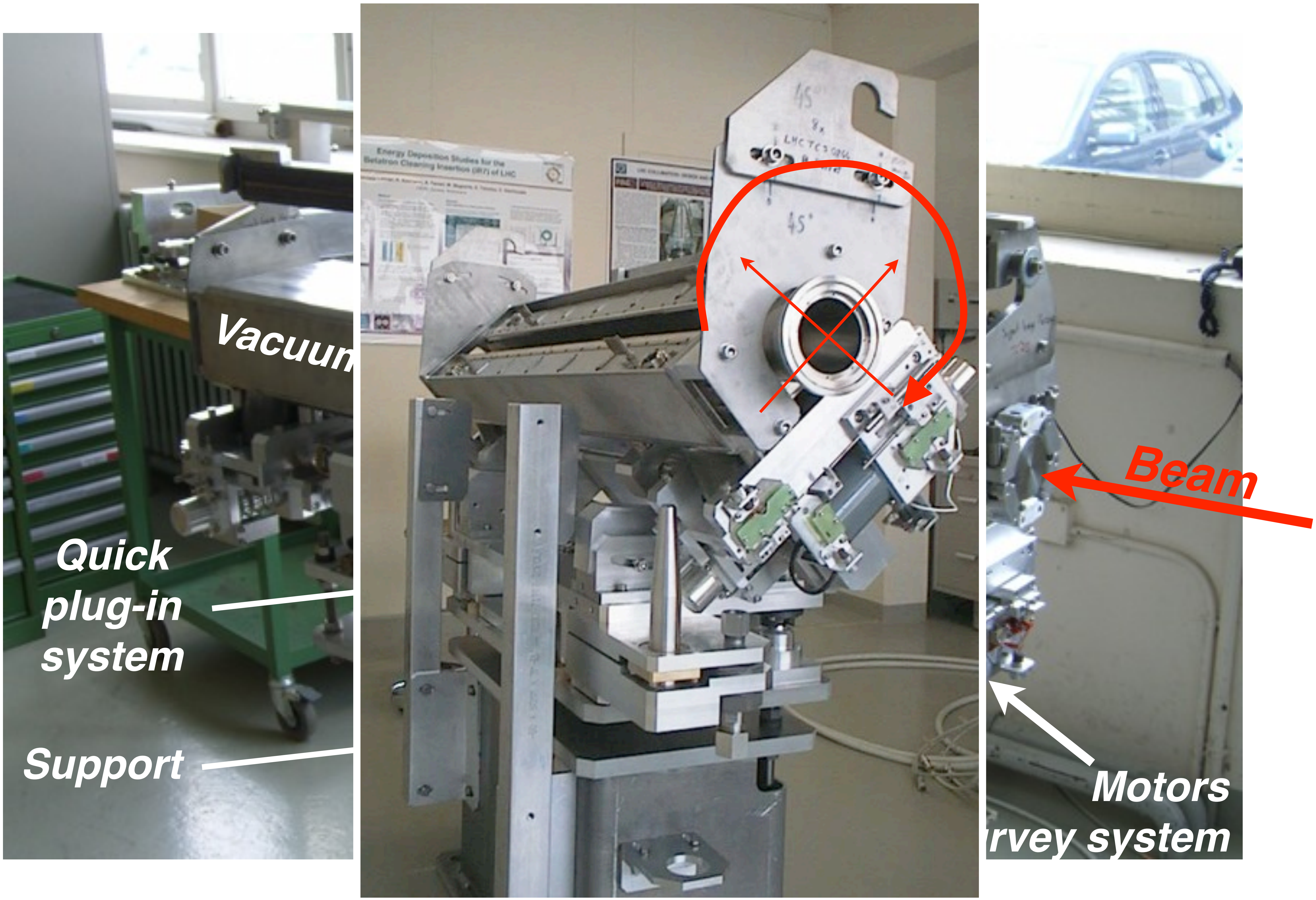


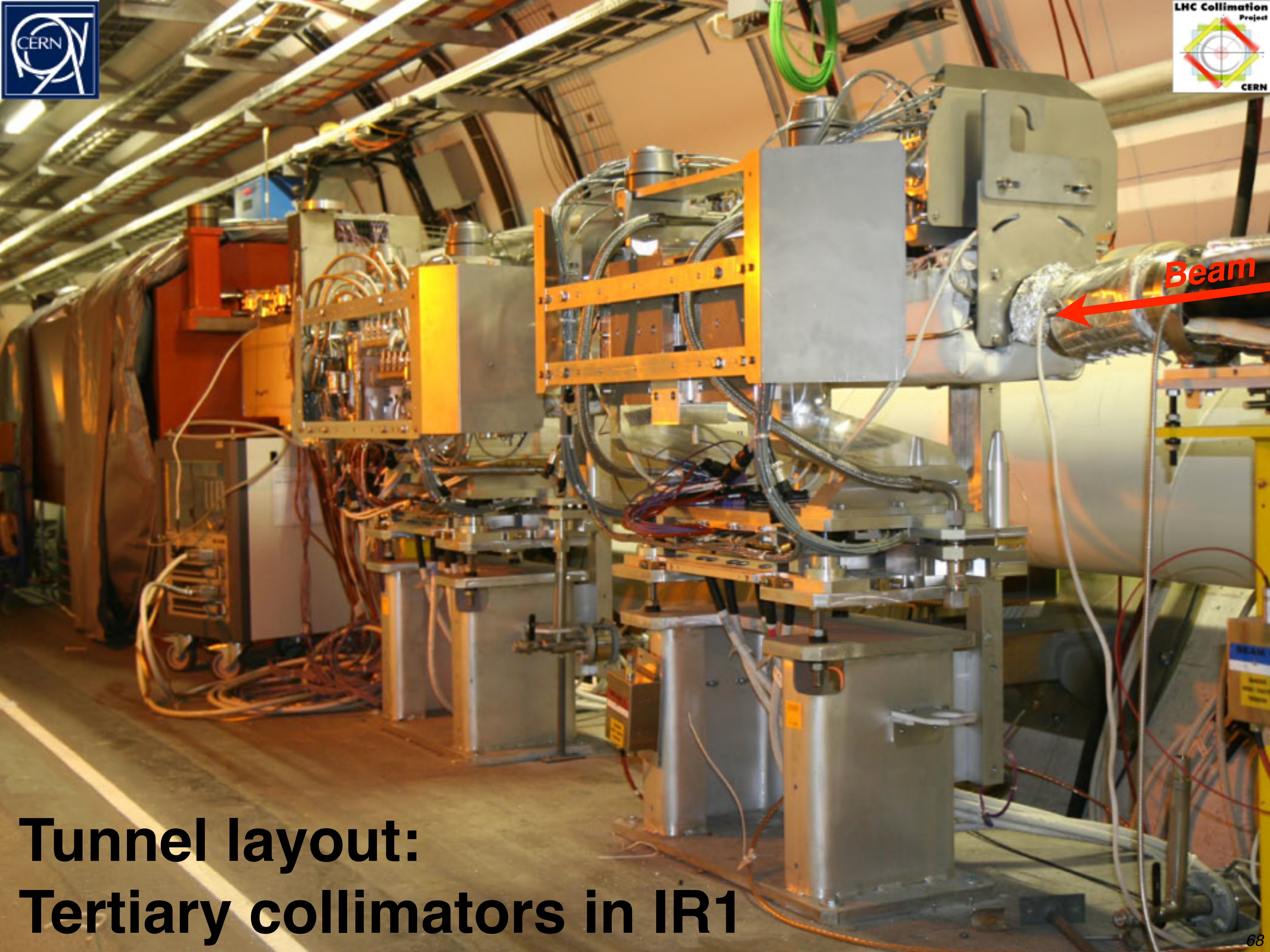
A. Bertarelli, A. Dallocchio

Complete collimator assembly



Complete collimator assembly





Tunnel layout:
Tertiary collimators in IR1

Outline

- Introduction
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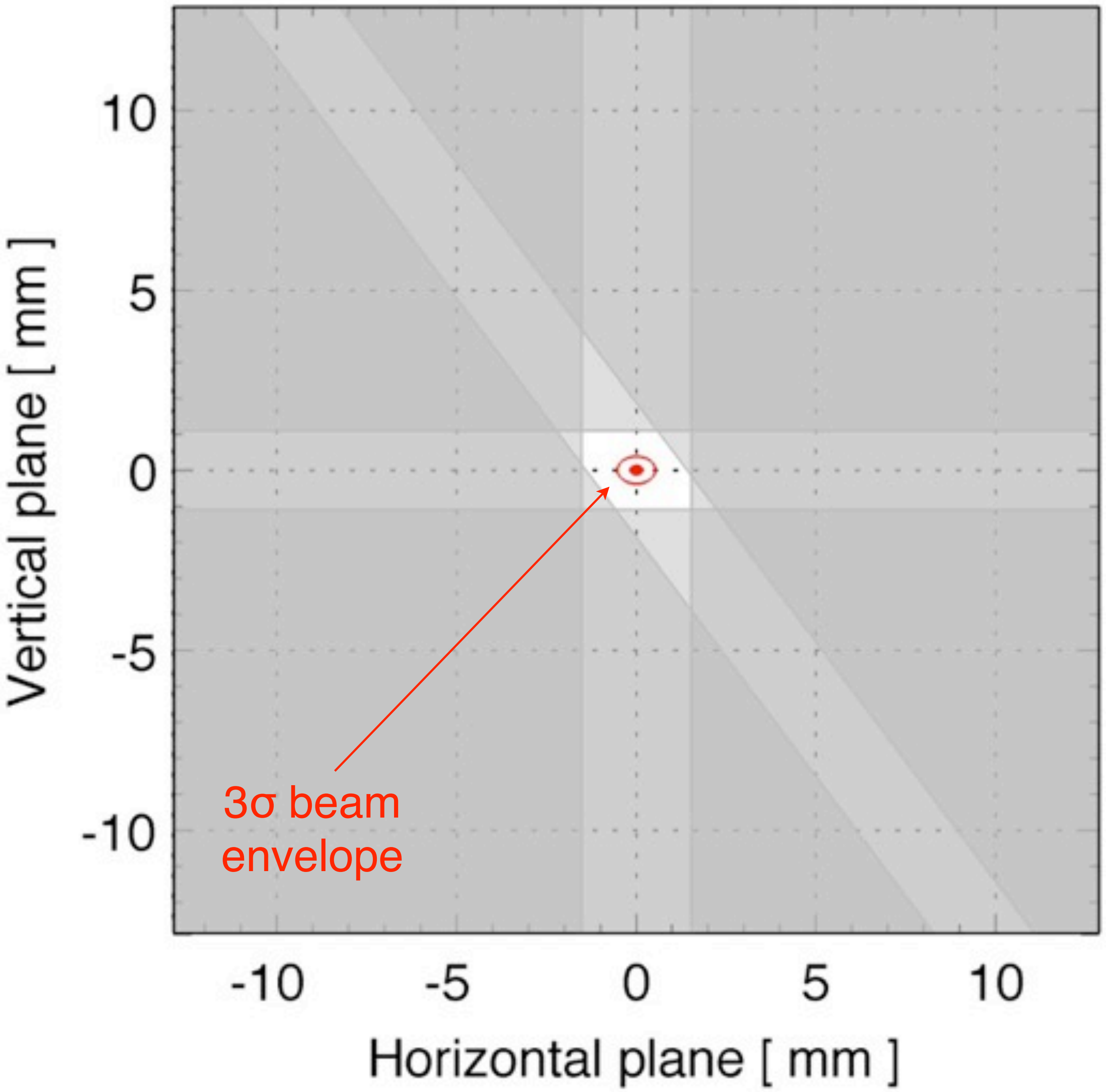
- LHC collimation design
- **Cleaning: operational performance**
  - **Measurements**
  - **Simulations**
- Conclusions

Collimation settings in 2012 at 4 TeV

Parameter	Unit	Plane	Type	Set 1	Set 2	Set 3	Set 4
				Injection	Top energy	Squeezed	Collision
Energy	[GeV]	n.a.	n.a.	450	4000	4000	4000
β^* in IR1/5	[m]	n.a.	n.a.	11.0	11.0	0.6	0.6
β^* in IR2	[m]	n.a.	n.a.	10.0	10.0	3.0	3.0
β^* in IR8	[m]	n.a.	n.a.	10.0	10.0	3.0	3.0
Crossing angle IR1/5	[μrad]	n.a.	n.a.	170	145	145	145
Crossing angle IR2	[μrad]	n.a.	n.a.	170	220 (H)	220 (H)	100 (V)
Crossing angle IR8	[μrad]	n.a.	n.a.	170	90	90	90
Beam separation	[mm]	n.a.	n.a.	2.0	0.65	0.65	0.0
Primary cut IR7	[σ]	H,V,S	TCP	5.7	4.3	4.3	4.3
Secondary cut IR7	[σ]	H,V,S	TCSG	6.7	6.3	6.3	6.3
Quartiary cut IR7	[σ]	H,V	TCLA	10.0	8.3	8.3	8.3
Primary cut IR3	[σ]	H	TCP	8.0	12.0	12.0	12.0
Secondary cut IR3	[σ]	H	TCSG	9.3	15.6	15.6	15.6
Quartiary cut IR3	[σ]	H,V	TCLA	10.0	17.6	17.6	17.6
Tertiary cut IR1/5	[σ]	H,V	TCT	13.0	26.0	9.0	9.0
Tertiary cut IR2/8	[σ]	H,V	TCT	13.0	26.0	12.0	12.0
Physics debris collimators	[σ]	H	TCL	out	out	out	10.0
Primary protection IR6	[σ]	H	TCSG	7.0	7.1	7.1	7.1
Secondary protection IR6	[σ]	H	TCDQ	8.0	7.6	7.6	7.6

Smallest collimator gaps in 2012

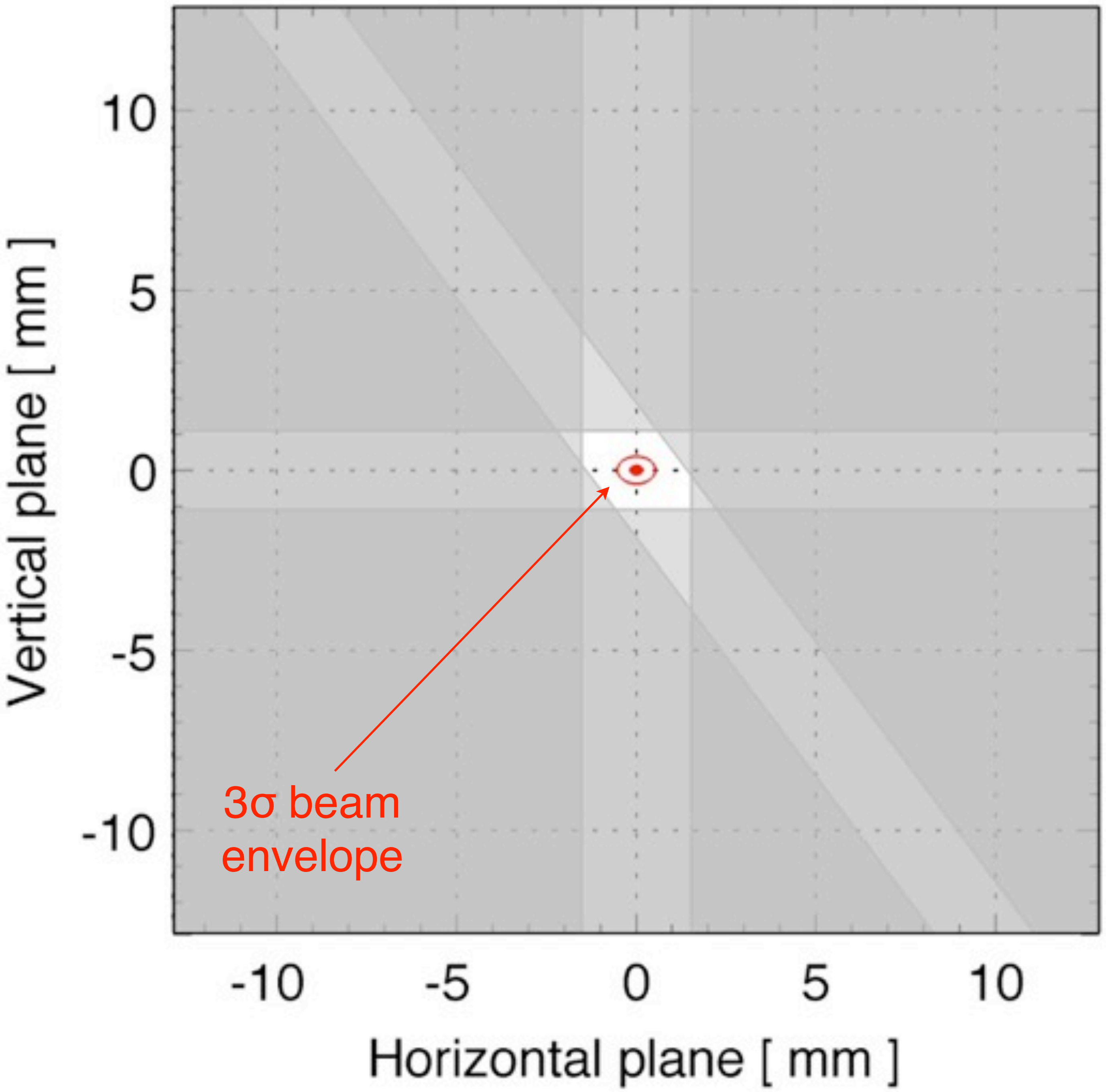
Transverse cuts from H, V and S primary collimators in IR7



2€ coin

Smallest collimator gaps in 2012

Transverse cuts from H, V and S primary collimators in IR7

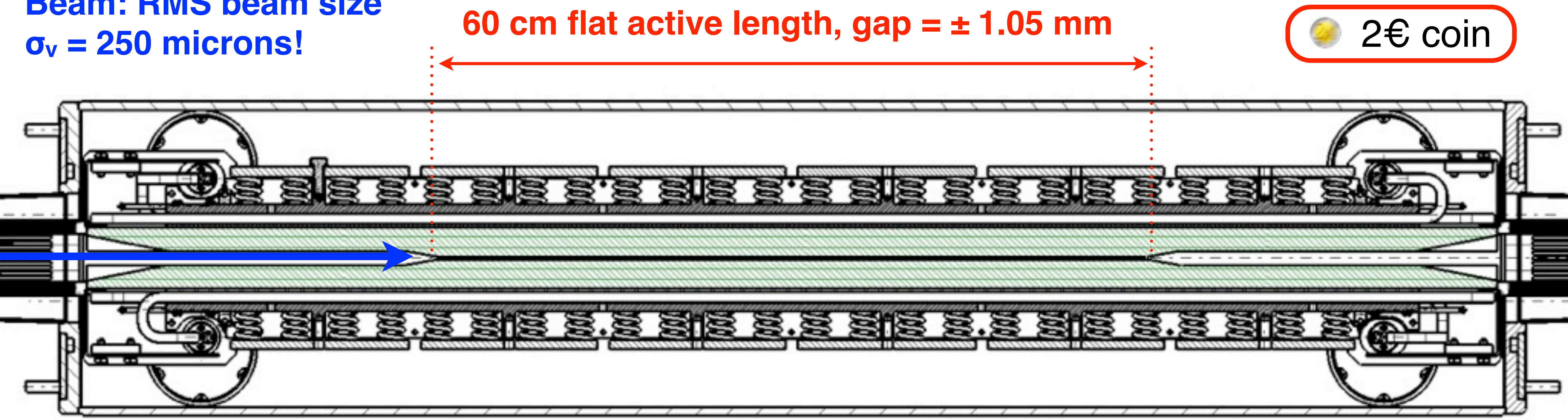


A quarter $ coin

A beam carrying up to 150MJ passes more than 11000 per second in such small collimator gaps!

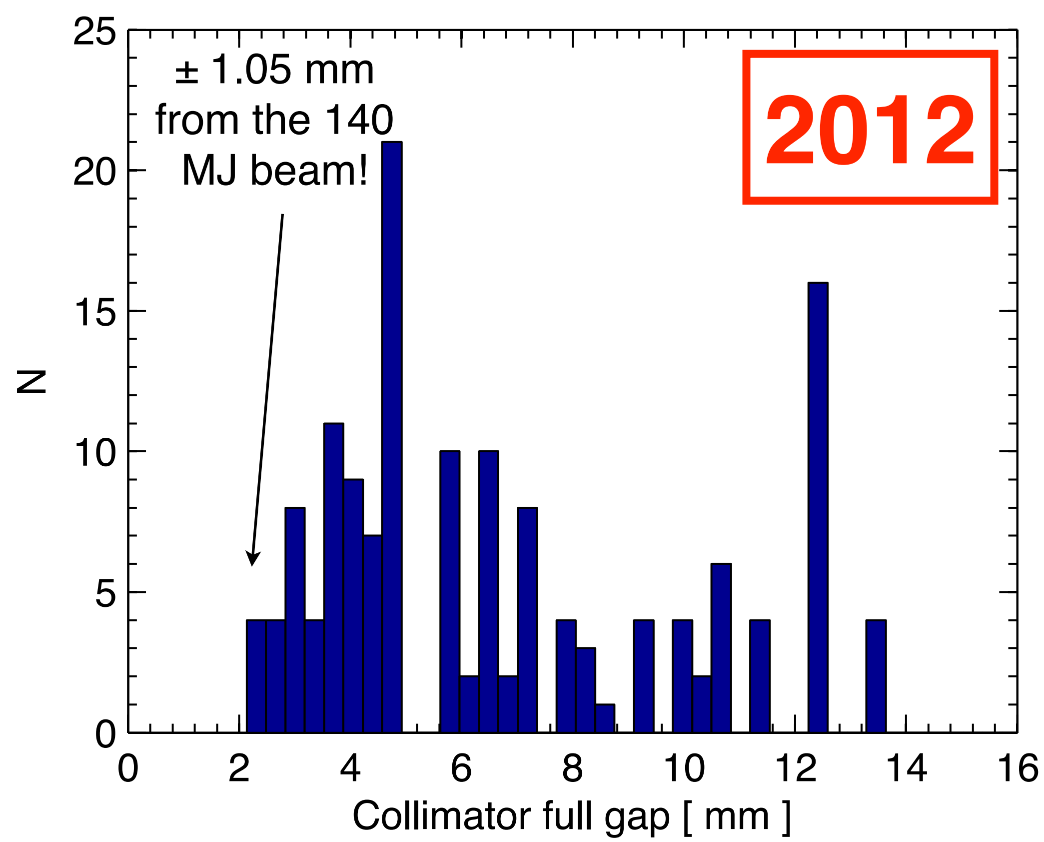
Side view of the vertical TCP

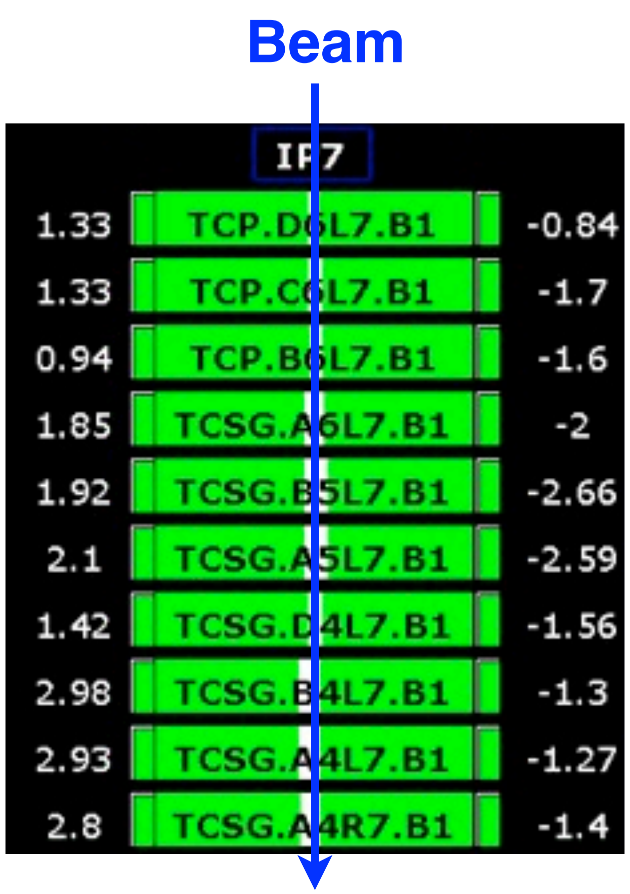
Beam: RMS beam size
σ_v = 250 microns!



L. Gentini

Distribution of collimator gaps in 2012





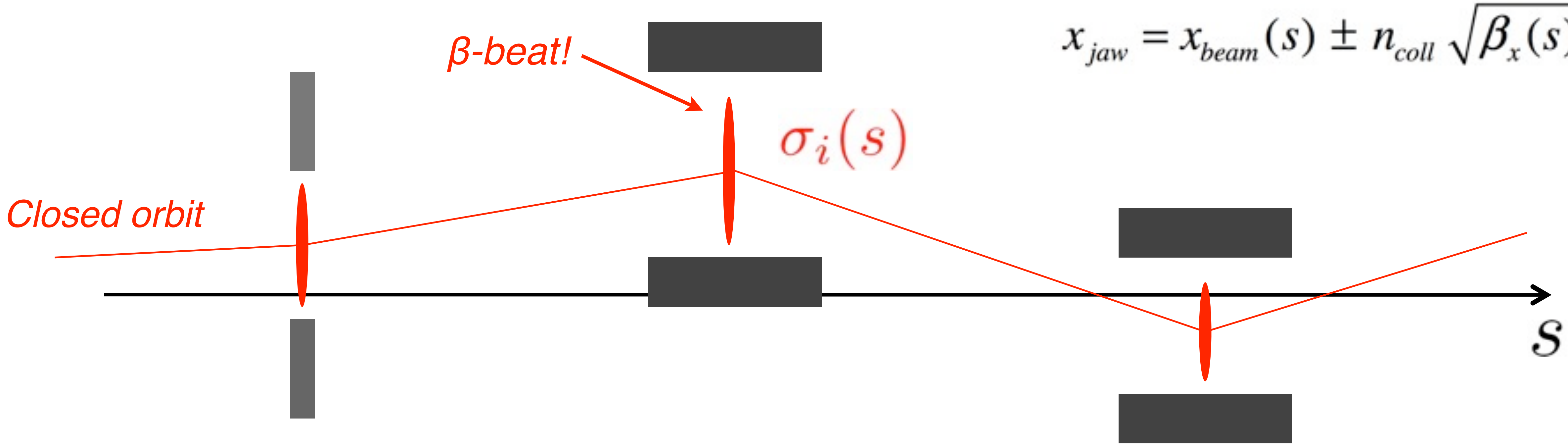
Demonstration of the feasibility of collimation with 40 micron flatness jaws!

Fixed display in the LHC control room showing the IR7 collimator gaps.

Collimator beam-based alignment

Normalized collimator settings must be converted to positions in [mm]:

- Center the two collimator jaws → Need the orbit!
- Adjust the gap to the correct setting → Need the beam size!

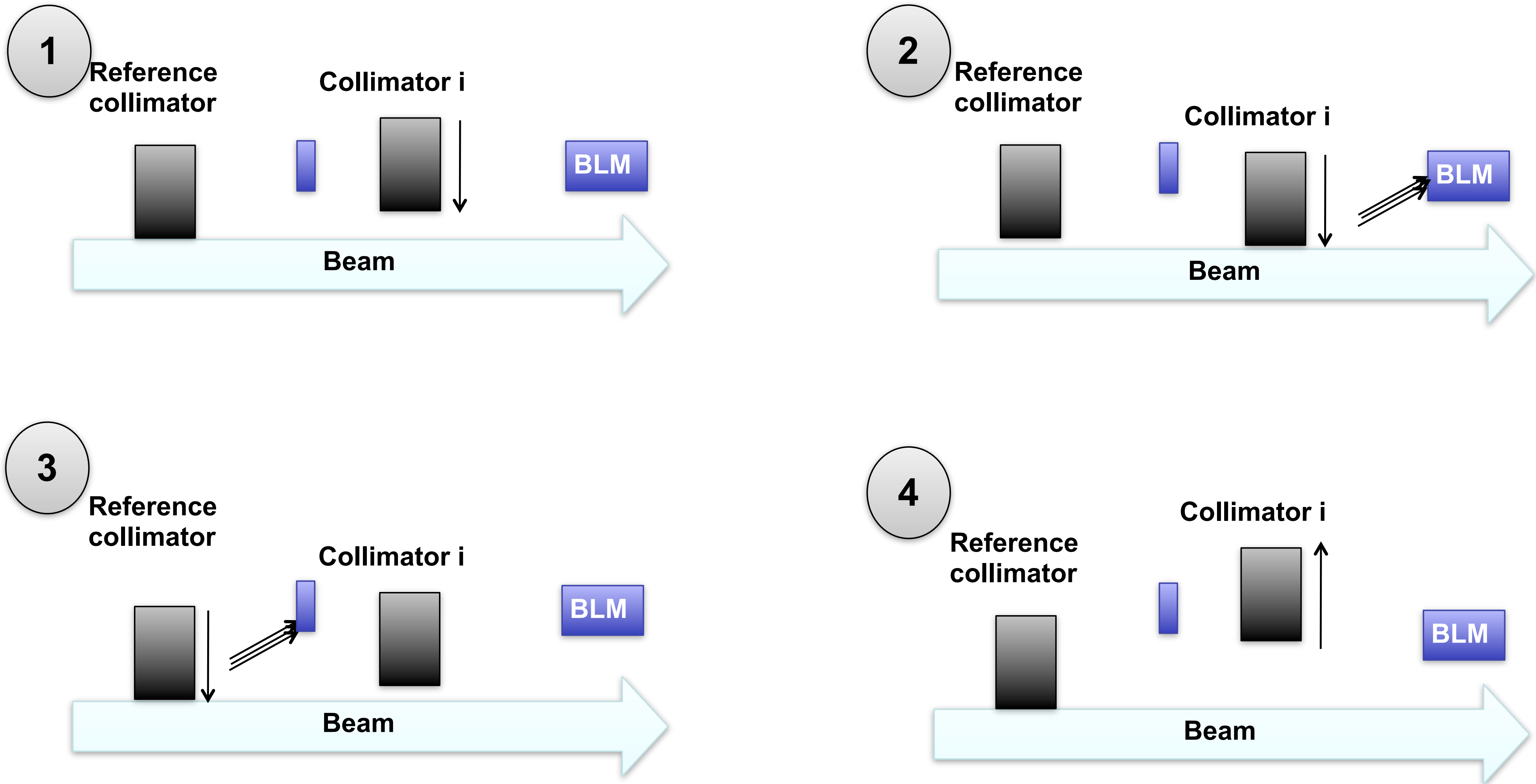


$$x_{jaw} = x_{beam}(s) \pm n_{coll} \sqrt{\beta_x(s)\ \varepsilon_x}$$

Due to the **very small gaps** involved, collimators <u>cannot</u> be set deterministically using nominal parameters: alignment errors, orbit imperfections and optics errors cause uncertainties large compared to gaps.

Beam orbit and beam size at each collimator is measured with **beam-based alignment techniques**.

LHC alignment technique



(1) Reference halo generated with primary collimators (TCPs) close to 3-5 sigmas.

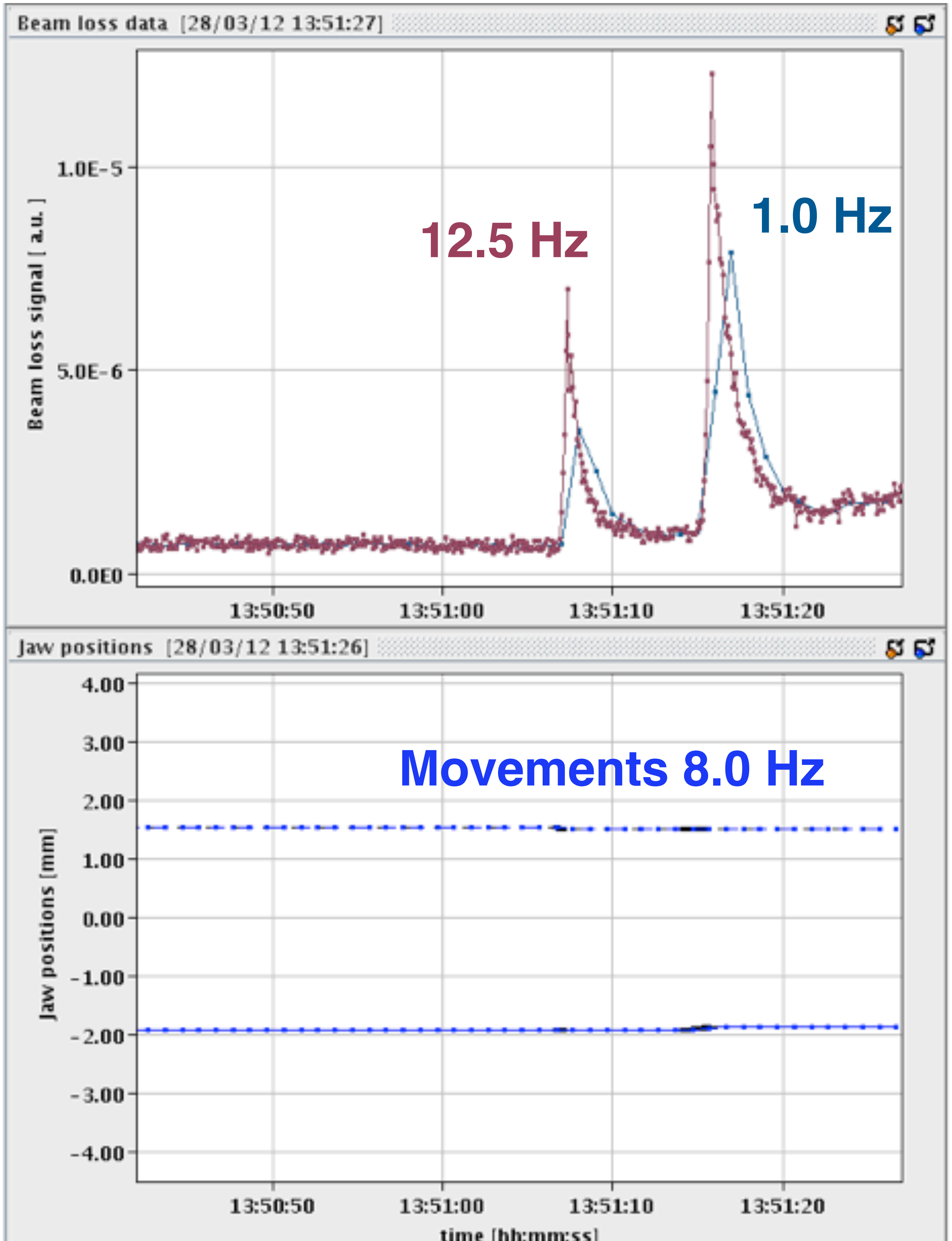
(2) “Touch” the halo with the other collimators around the ring (**both sides**) → <u>local beam position</u>.

(3) Re-iterate on the reference collimator to determine the relative aperture → <u>local beam size</u>.

(4) Retract the collimator to the correct settings.

Tedious procedure that is repeated for each machine configuration.

Can we make it faster?



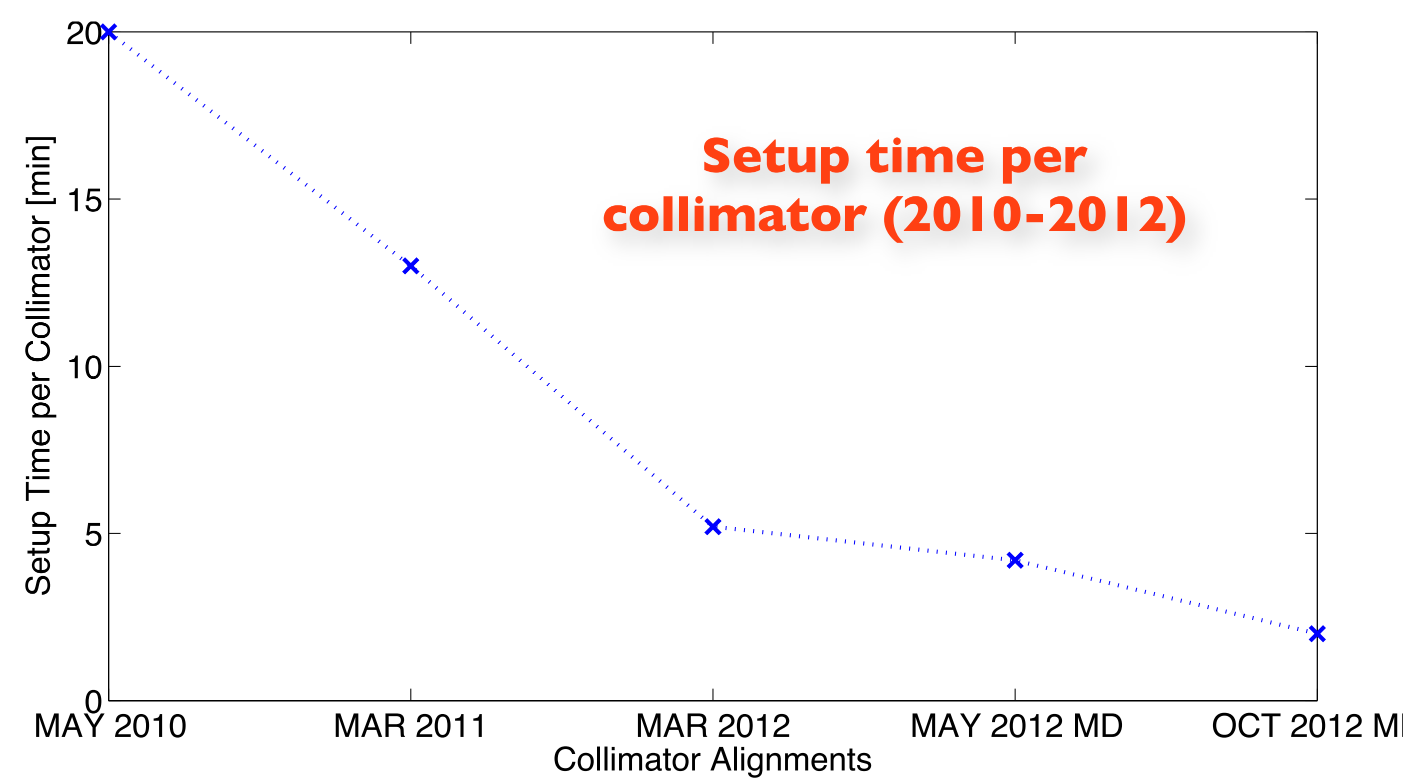
1) 2010: fully manual procedure > 15 min/device

Limitation of operational efficiency

2) 2011: automated procedure based on feedback loop between BLM and motors

3) 2012: further improved algorithms, faster rates of BLM acquisition and settings trims

Note: only done in low-intensity fills, then rely on the machine and setting reproducibility.



PhD thesis work G. Valentino

Can we make it even faster?

- **16 tungsten TCTs** in all IRs and the **2 Carbon TCSGs in IR6** will replaced in 2014 by new collimators with **integrated BPMs**.

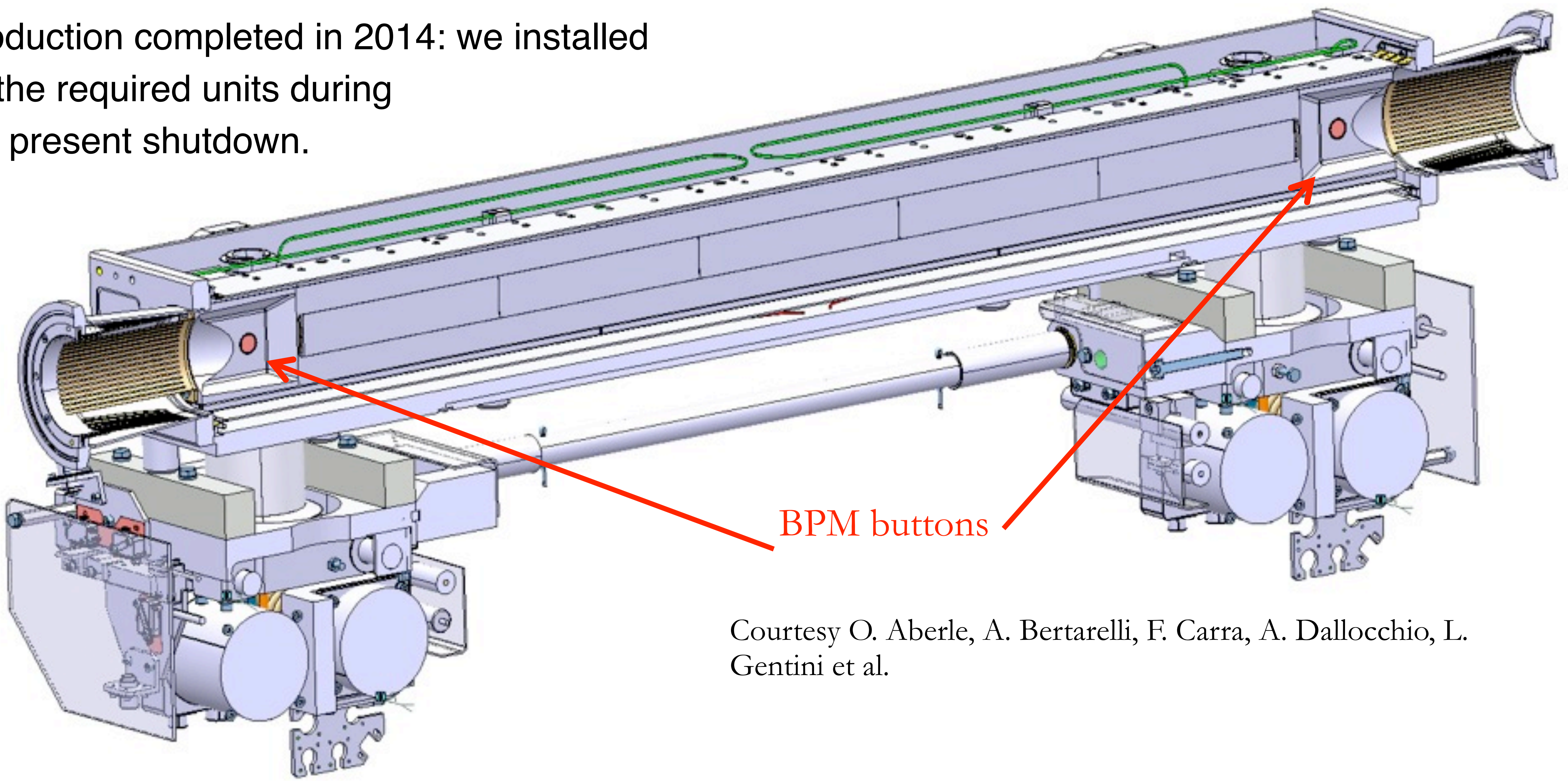
  Gain: can align the collimator jaw without “touching” the beam ➙ no dedicated low-intensity fills.

  ➙ *Drastically reduced setup time => more flexibility in IR configurations*

  ➙ *Reduced orbit margins in cleaning hierarchy*

  ➙ *Improved monitoring of local orbit and interlocking strategy*

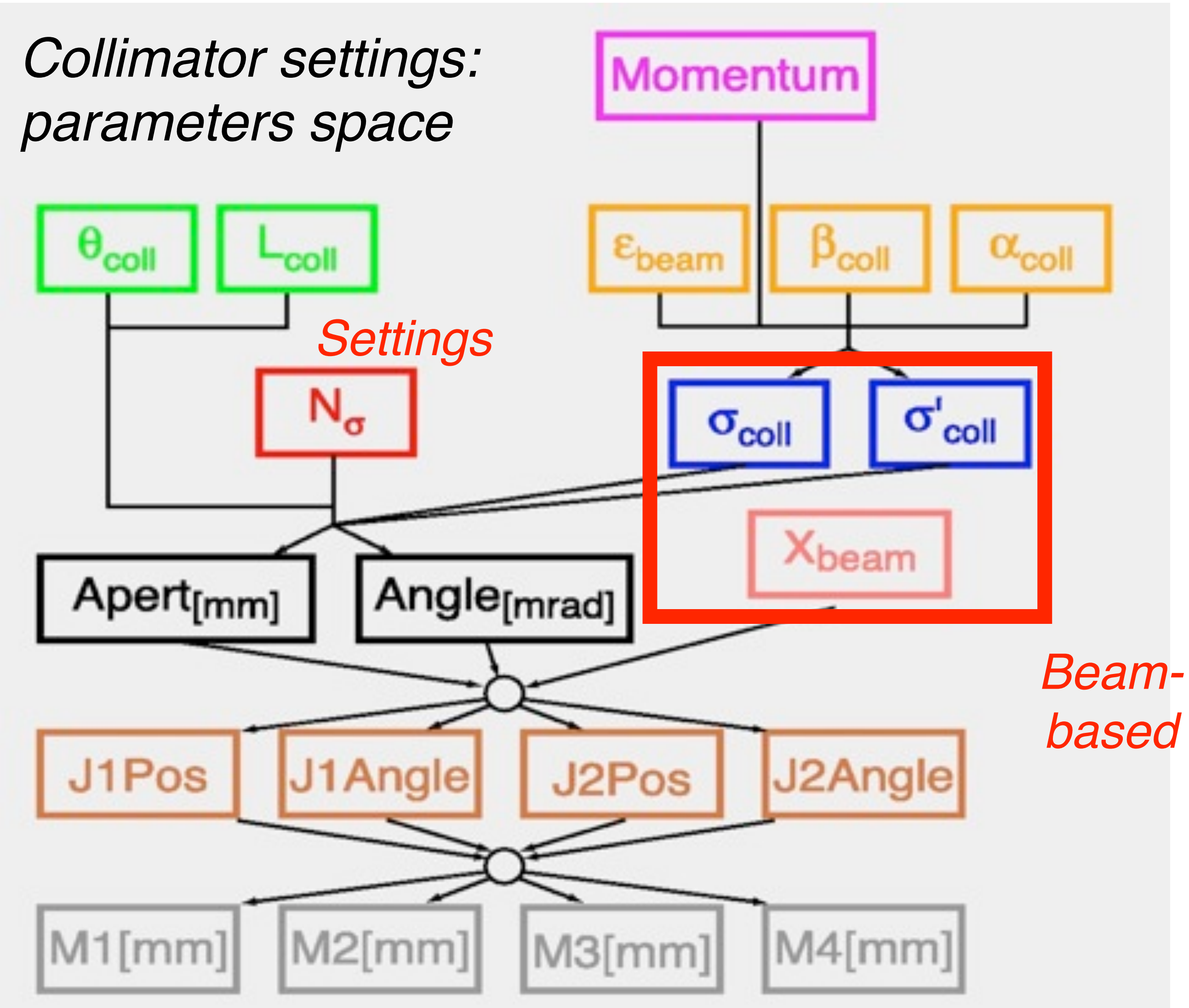
- Production completed in 2014: we installed all the required units during the present shutdown.



Courtesy O. Aberle, A. Bertarelli, F. Carra, A. Dallocchio, L. Gentini et al.

Setting generation

What do we do when we have **orbit** and **beam size** at every collimator during the cycle?



$$\text{jaw} = x_{\text{beam}} \pm n_0 \times \sigma_x$$

$\sigma_x = \sqrt{\frac{\epsilon_n}{\gamma}\beta_x}$ *: Beam size in coll. plane*

$n_0^{\text{tcp}} = 6$

$n_0^{\text{tcsg}} = 7$ *: Normalized settings*

__Energy ramp__: all parameters change as a function of gamma (BB sigma at 450GeV, nominal optics at flat-top)

__Betatron squeeze__: additional change of beam size for different optics

Scaling for ramp settings:

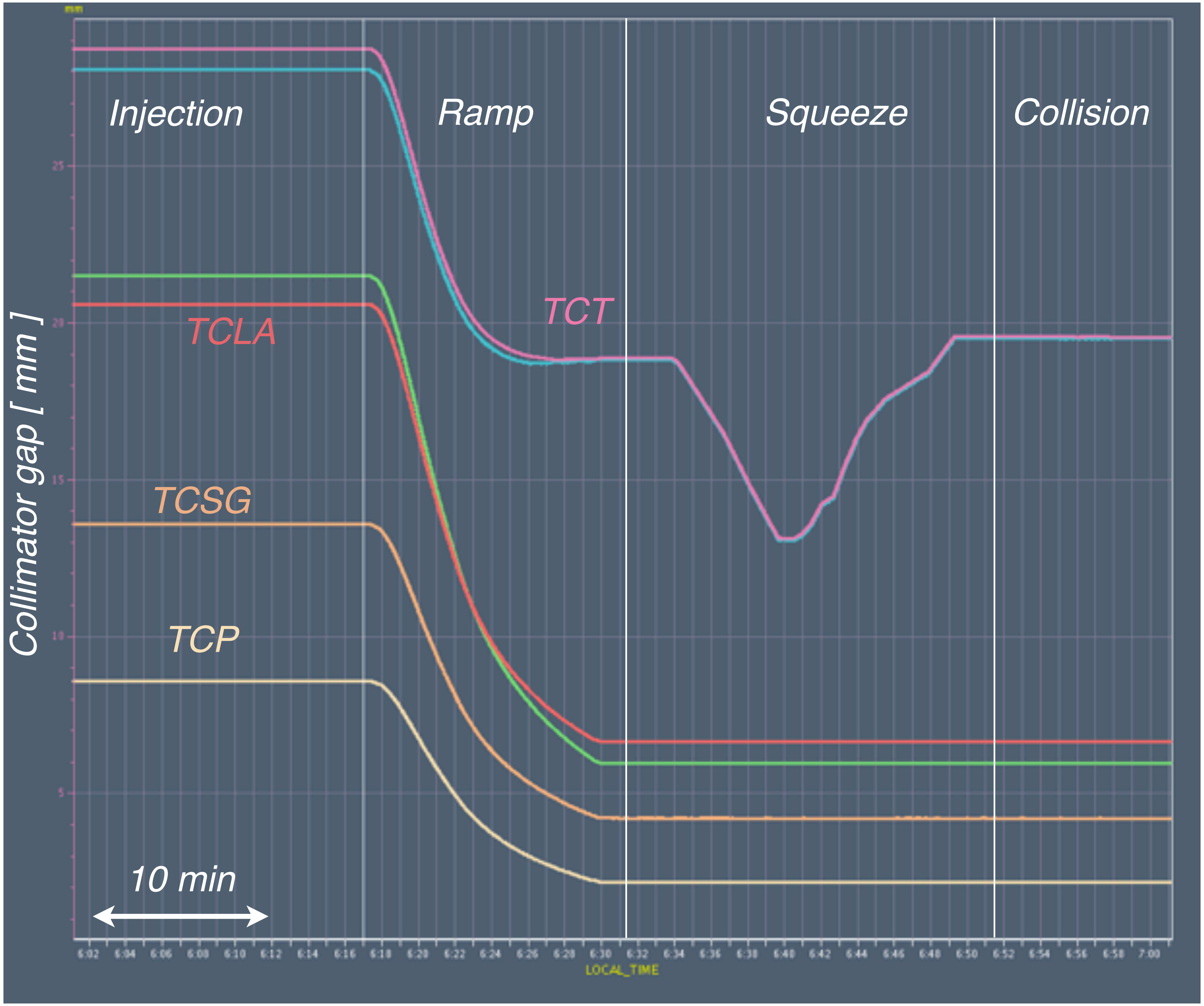
$n_0 = n_0(\gamma) \qquad \sigma_x = \sigma_x(\gamma) \qquad h(\gamma) = n_0(\gamma) \times \sigma_x(\gamma)$

$$h(\gamma) = \left[n_0 + \frac{n_1 - n_0}{\gamma_1 - \gamma_0}(\gamma - \gamma_0)\right] \times \frac{1}{\sqrt{\gamma}}\left[\frac{\sqrt{\epsilon_1\beta_1} - \sqrt{\epsilon_0\beta_0}}{\gamma_1 - \gamma_0}(\gamma - \gamma_0)\right]$$

$$\text{jaw}(\gamma) = \left[x_0 + \frac{x_1 - x_0}{\gamma_1 - \gamma_0}(\gamma - \gamma_0)\right] \pm h(\gamma)$$

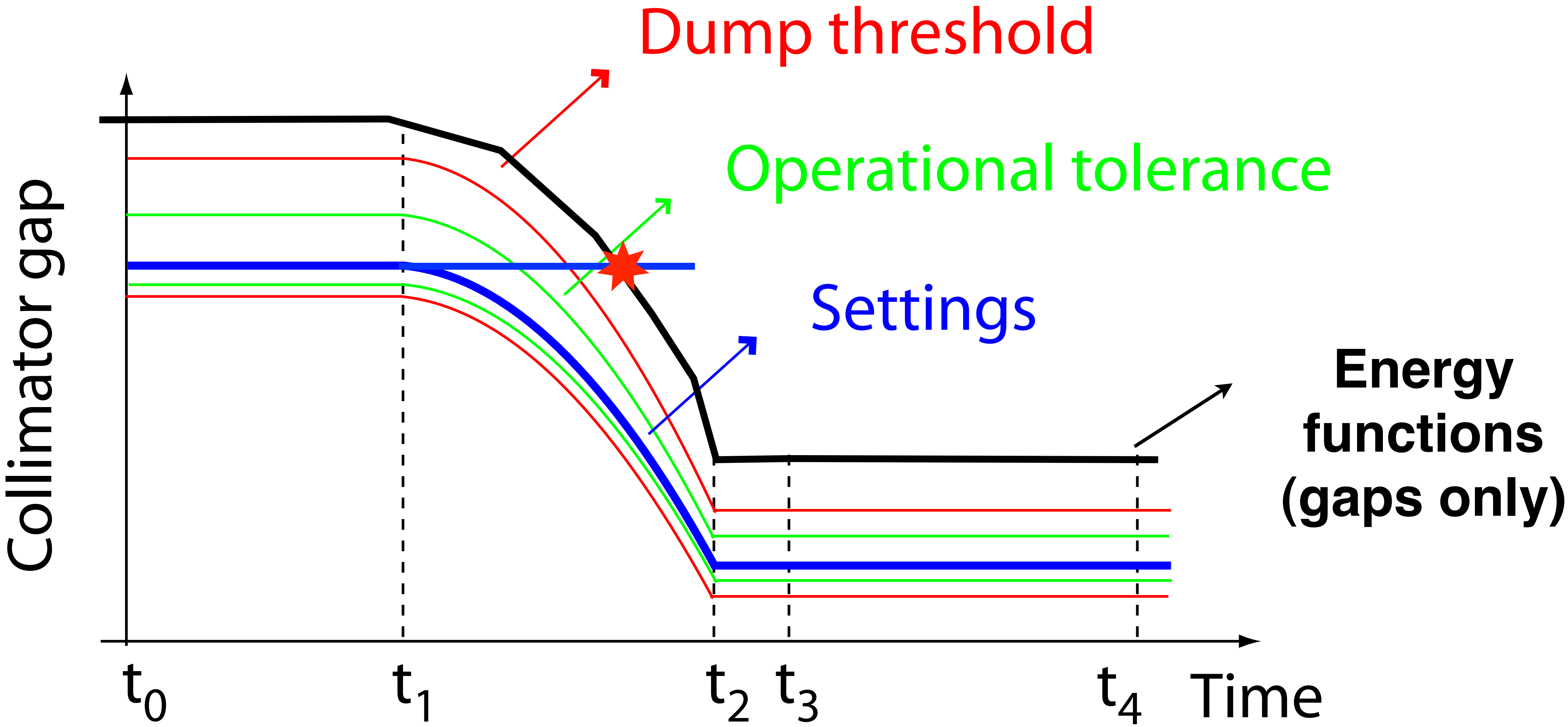
Collimation during cycle

Example from 2012



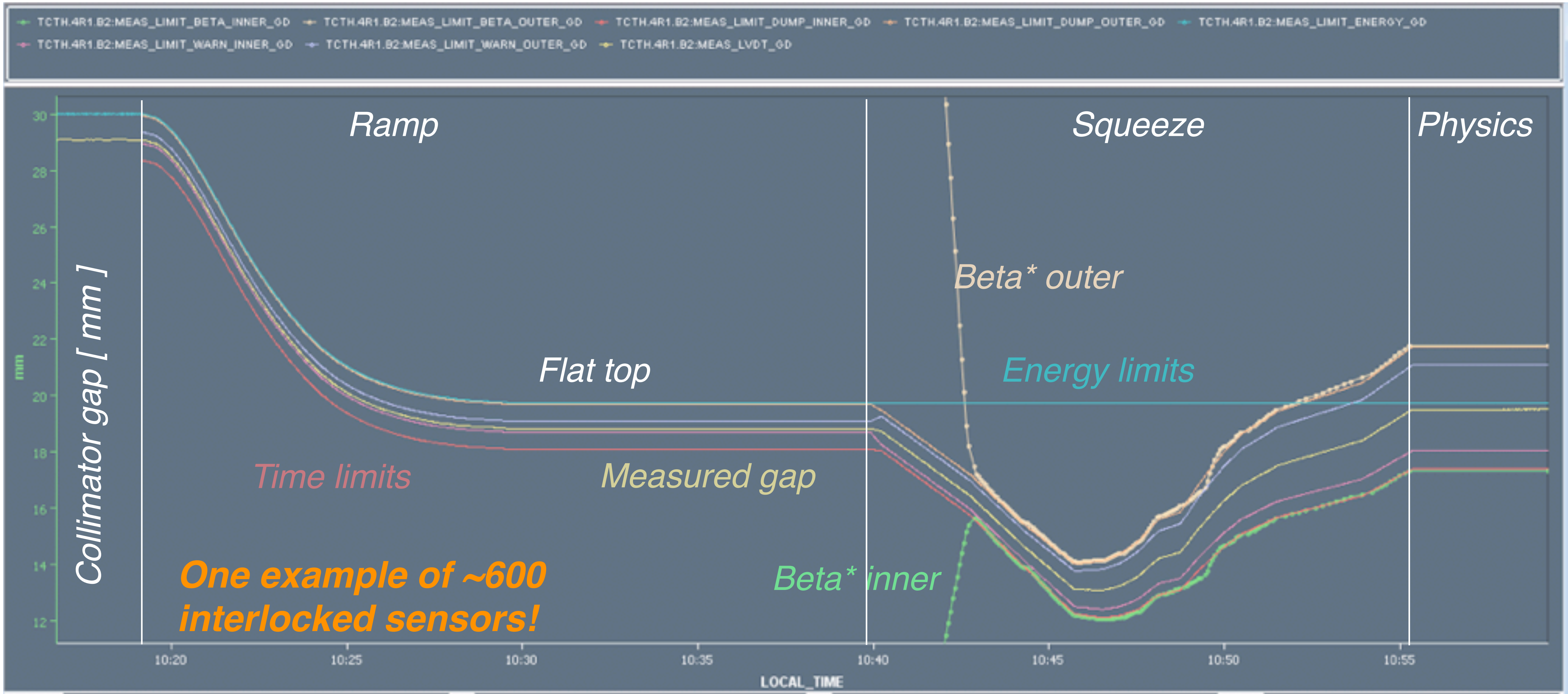
At the LHC, collimator are moved through setting functions versus time.

Gap and position interlocks



- **Inner** and **outer thresholds** as a function of **time** for each motor **axis** and **gap** (<u>24 functions per collimator</u>). Triggered by timing event (e.g. start of ramp).
  "Double protection" → beam interlock AND jaws stopped
- <u>Redundancy</u>: **maximum allowed gap versus energy** (2 per collimator: OUT)
  Beams dumped if a collimator does not start its ramp function.
- <u>Redundancy</u>: **max. and min. allowed gap versus beta*** (4 per collimator: IN/OUT)
  Beams dumped if a collimator does not start its squeeze function.

Interlock limits in practice...



Energy limits active already at injection:

- Prevent injection of unsafe beams if collimators are open!
- Test at every fill the interlock chain, when collimators go to parking.
- They dump the beams if a collimator does not start ramp functions.

Beta* limits became active for the TCTs at the first squeeze step to 9m.

Physics: 3 redundant limits (vs time, energy and beta*active at the same time!!

Collimator control challenge

Table 1: LHC collimators for the 2010-2013 run.

Functional type	Name	Plane	Num.	Material
Primary IR3	TCP	H	2	CFC
Secondary IR3	TCSG	H	8	CFC
Absorbers IR3	TCLA	H,V	8	W
Primary IR7	TCP	H,V,S	6	CFC
Secondary IR7	TCSG	H,V,S	22	CFC
Absorbers IR7	TCLA	H,V	10	W
Tertiary IR1/2/5/8	TCT	H,V	16	W/Cu
Physics absor. IR1/5	TCL	H	4	Cu
Dump protection IR6	TCSG	H	2	CFC
	TCDQ	H	2	C
Inj. prot. (lines)	TCDI	H,V	13	CFC
Inj. prot. IR2/8	TDI	V	2	C
	TCLI	V	4	CFC
	TCDD	V	1	CFC

Table 2: 2012 collimation parameters table.

Parameters	**Number**
Movable collimators in the ring	85
Transfer line collimators	13
Stepping motors	392
Resolvers	392
Position/gap measurements	584
Interlocked position sensors	584
Interlocked temperature sensors	584
Motor settings: functions / discrete	448/1180
Threshold settings versus time	9768
Threshold settings versus energy	196
Threshold settings versus β^*	384
Temperature thresholds	490

*The controls system of the LHC collimation reached an unprecedented complexity. This is necessary to redundantly ensure that collimators are at the good positions: a **beam dump** is requested if any **abnormal behaviour** is detected within the system.*

Are internal system checks enough to ensure that the performance is adequate?

Beam validation through “loss maps”

Internal system checks are crucial but not sufficient to validate the collimation cleaning performance. **Only beams tell the true!**

We also need a **direct measurement** of what the beams “will see” and of how the collimation system will behave in presence of high beam losses!

Can we exclude setting errors? Is the setting hierarchy respected?
Is the local cleaning in cold magnets as expected for a given hierarchy?
Does the system - and the machine - provide stable performance in time?

Each set of settings of the collimation system is validated through loss maps with low-intensity beams (few bunches)

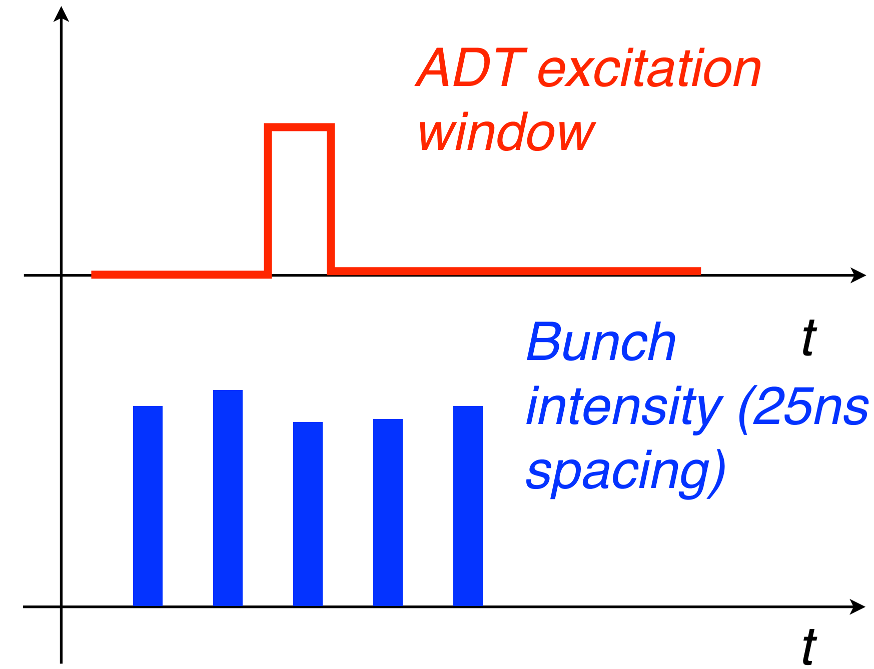
Beam loss rates are abnormally **increased in a controlled way** to simulated large beam losses that might occur during nominal high-intensity operation.

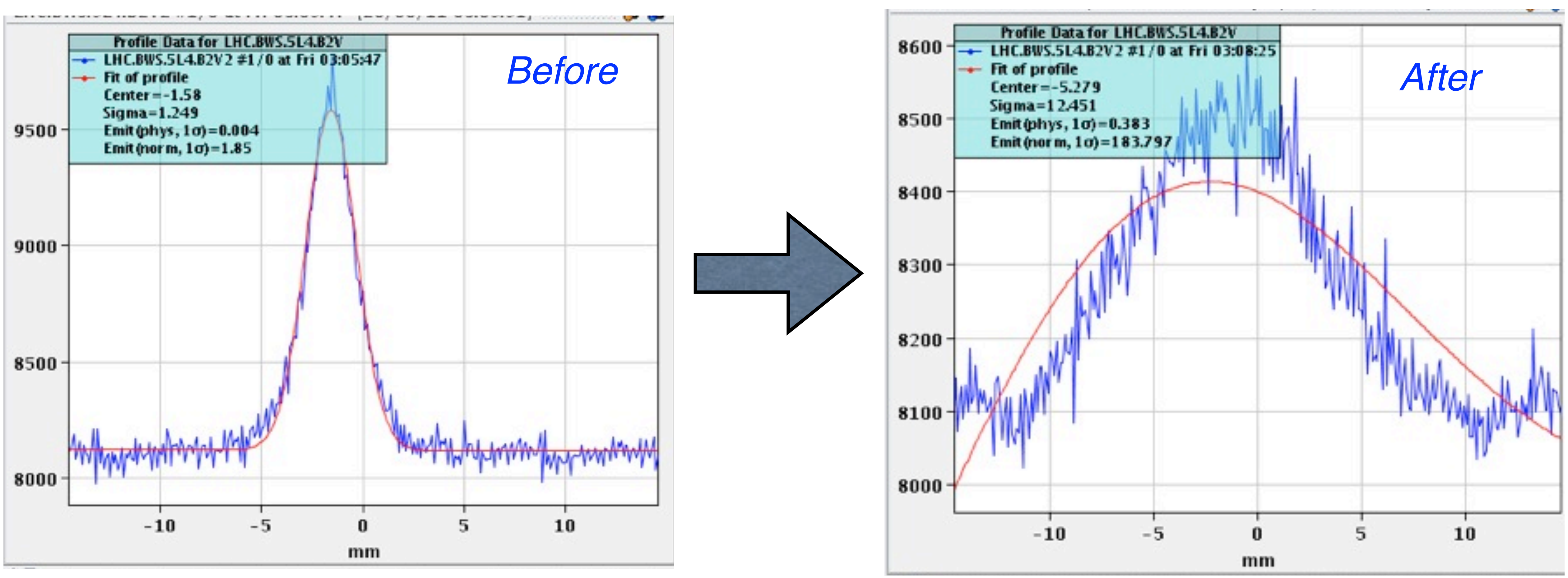
Excite beam resonances by changing the tunes;
*controlled blow-up with **transverse damper**.*

Excitation with transverse damper

The LHC transverse damper (“ADT”) uses fast kicker magnets to stabilize the beams.

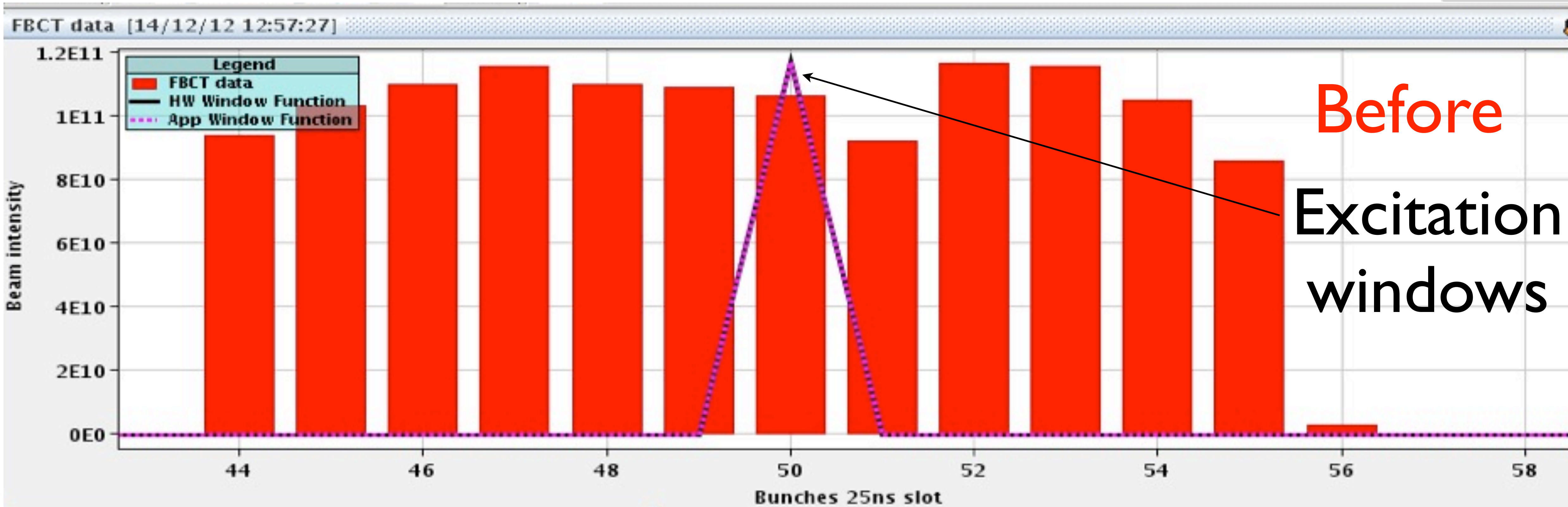
We also use it to “inject” noise into the beam, causing an emittance blow-up that leads to fast losses!

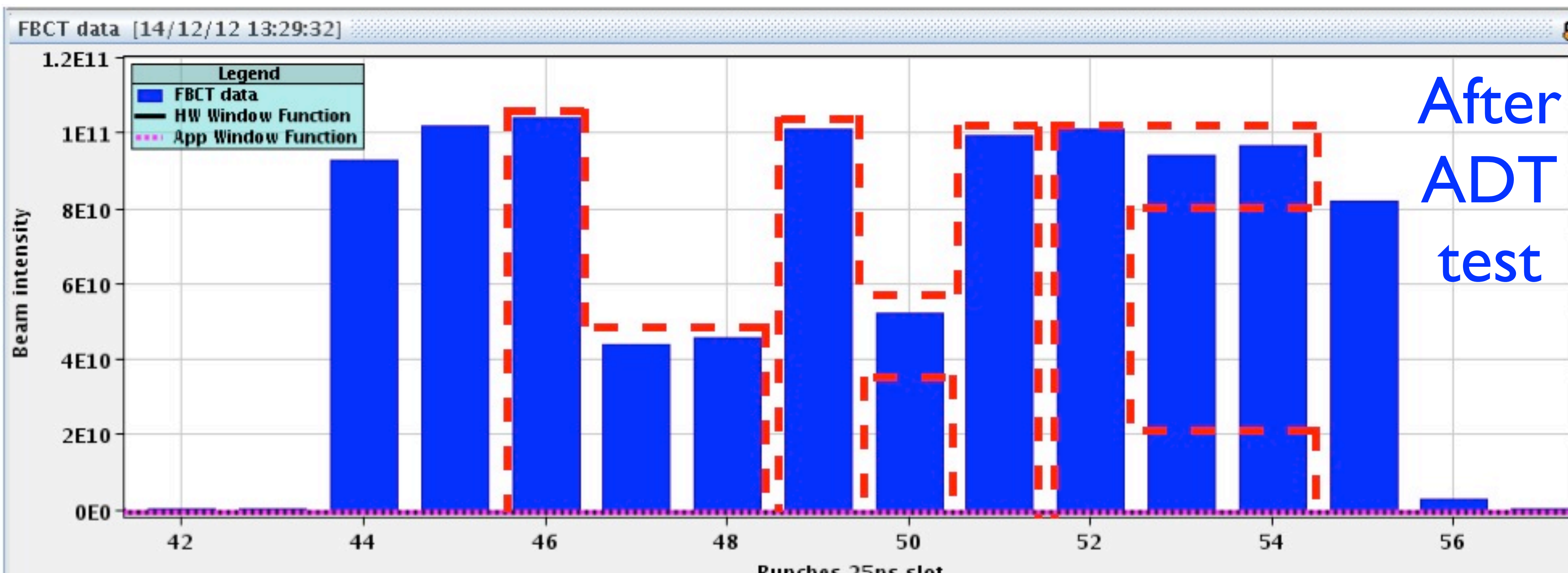




Emittance measurement through wire scanners of an individual bunch within a train.

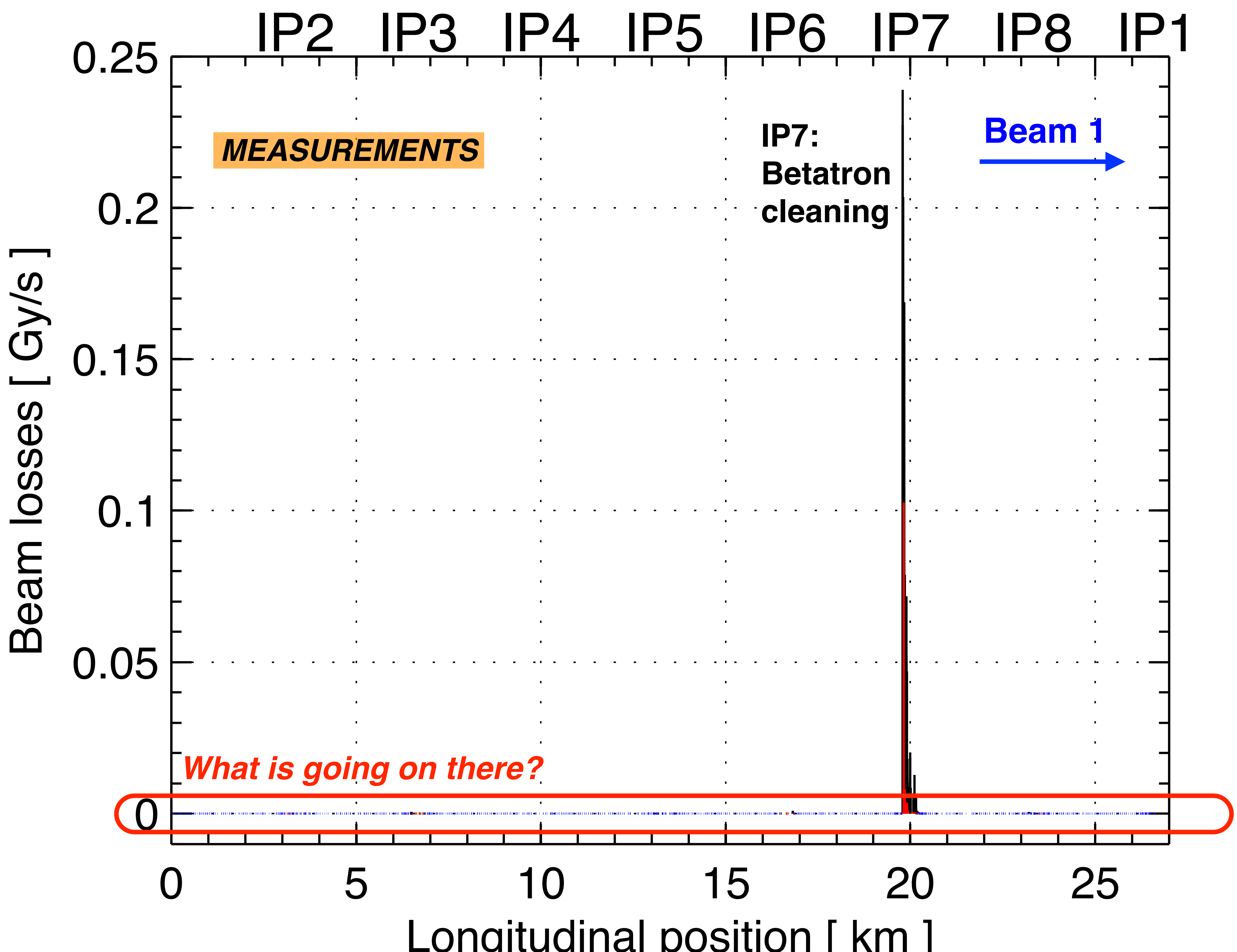
Acting on individual 25ns bunches



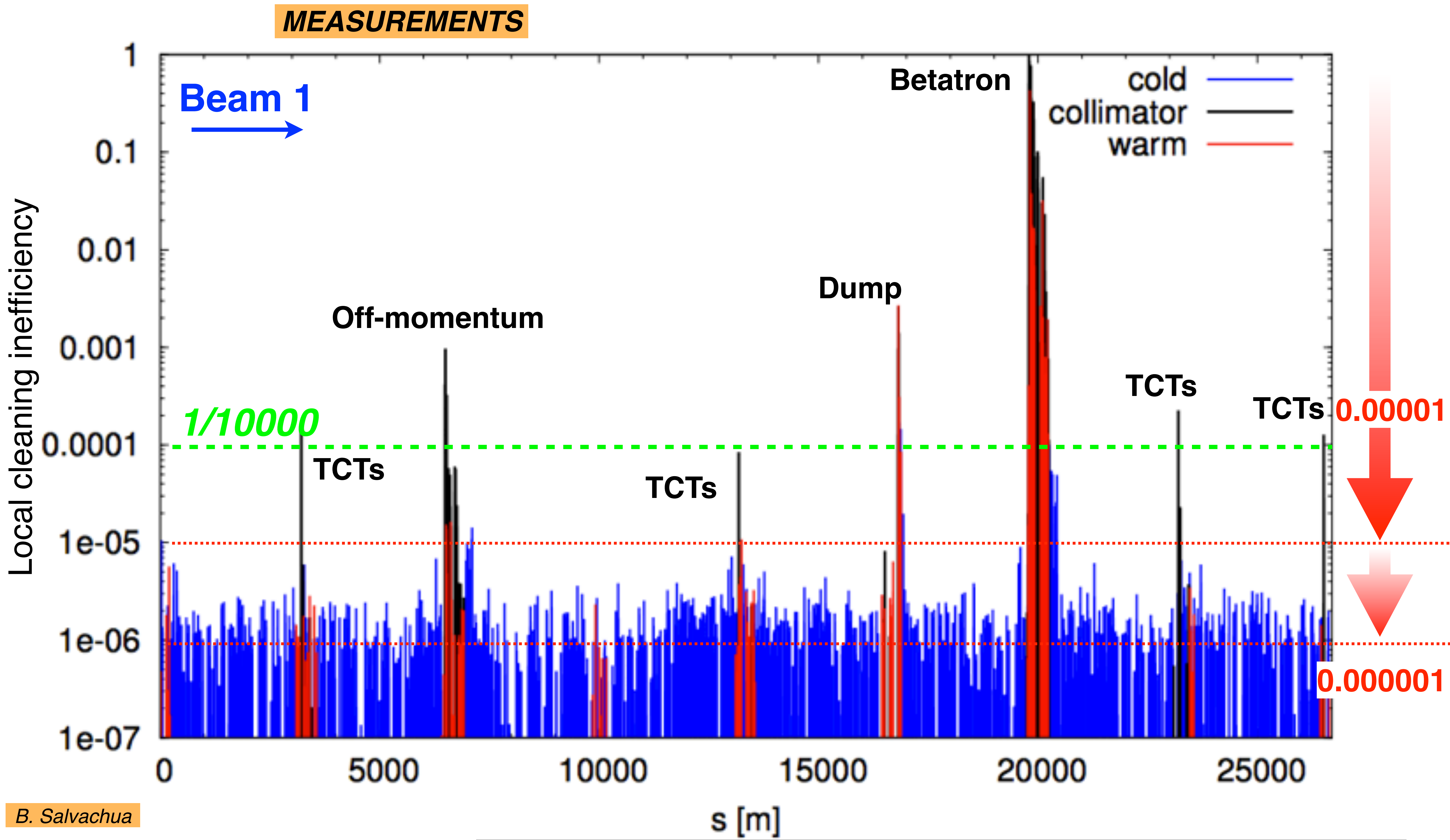


Collimation cleaning

3600 beam loss monitors (BLMs) along the 27 km during a loss map



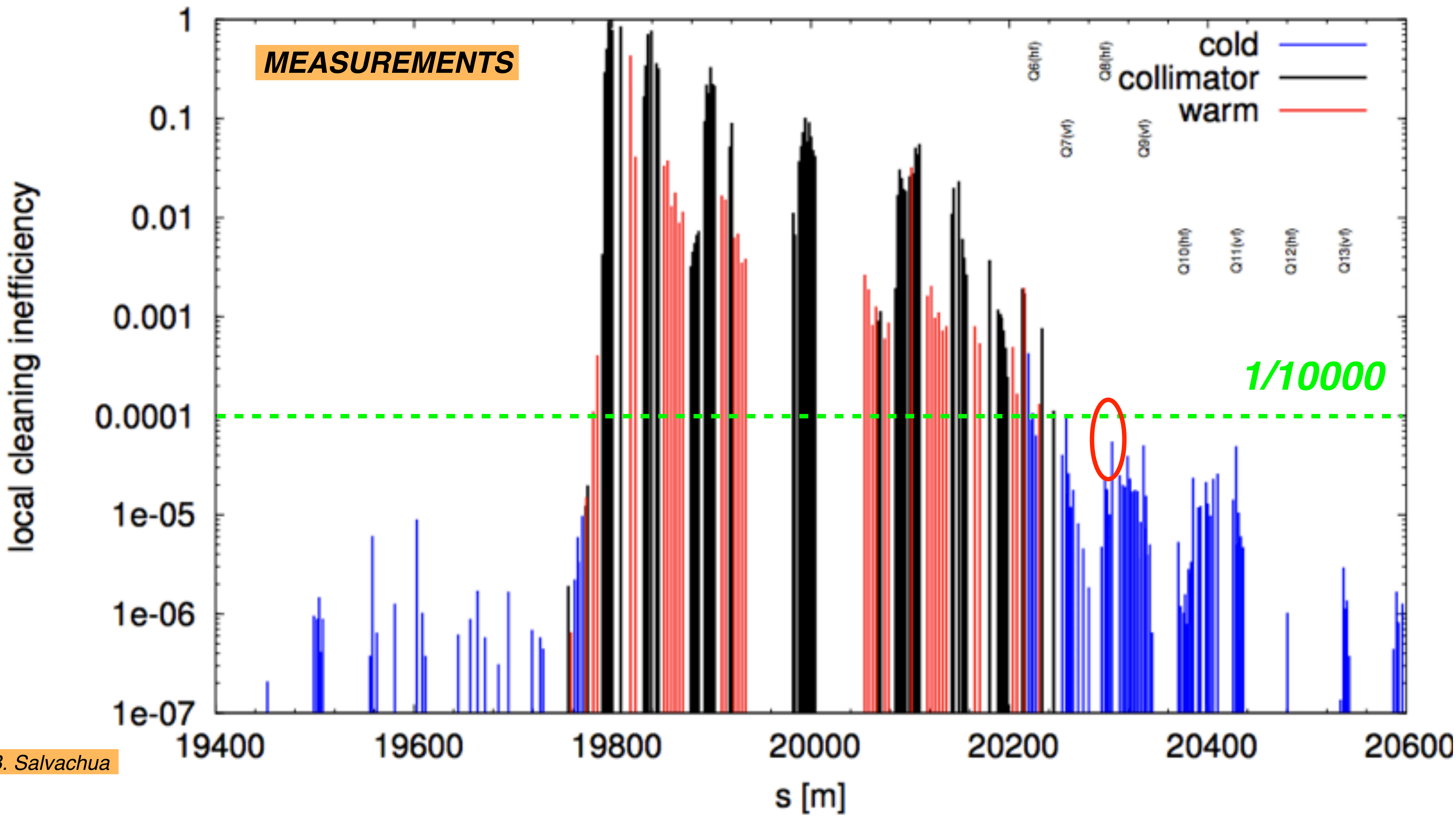
Collimation cleaning: 4.0 TeV, β^*=0.6 m



B. Salvachua

Highest COLD loss location: efficiency of > 99.99% !
Most of the ring actually > 99.999%

Zoom in IR7



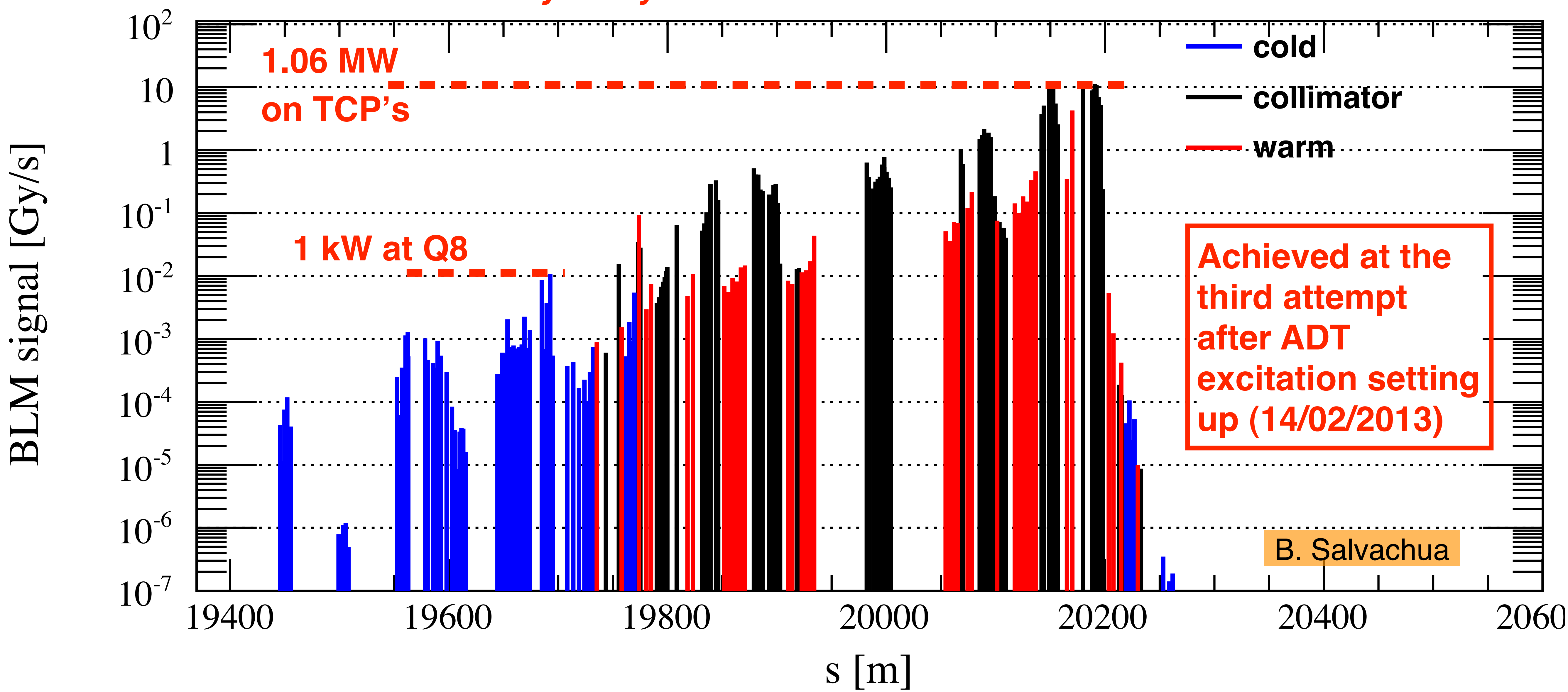
B. Salvachua

<u>Critical location</u> (both beams): losses in the "dispersion suppressor".

With "squeezed" beams: tertiary collimators (TCTs) protect locally the triplets.

One extreme example: quench test

Preliminary analysis of beam tests done on 14/02/2013



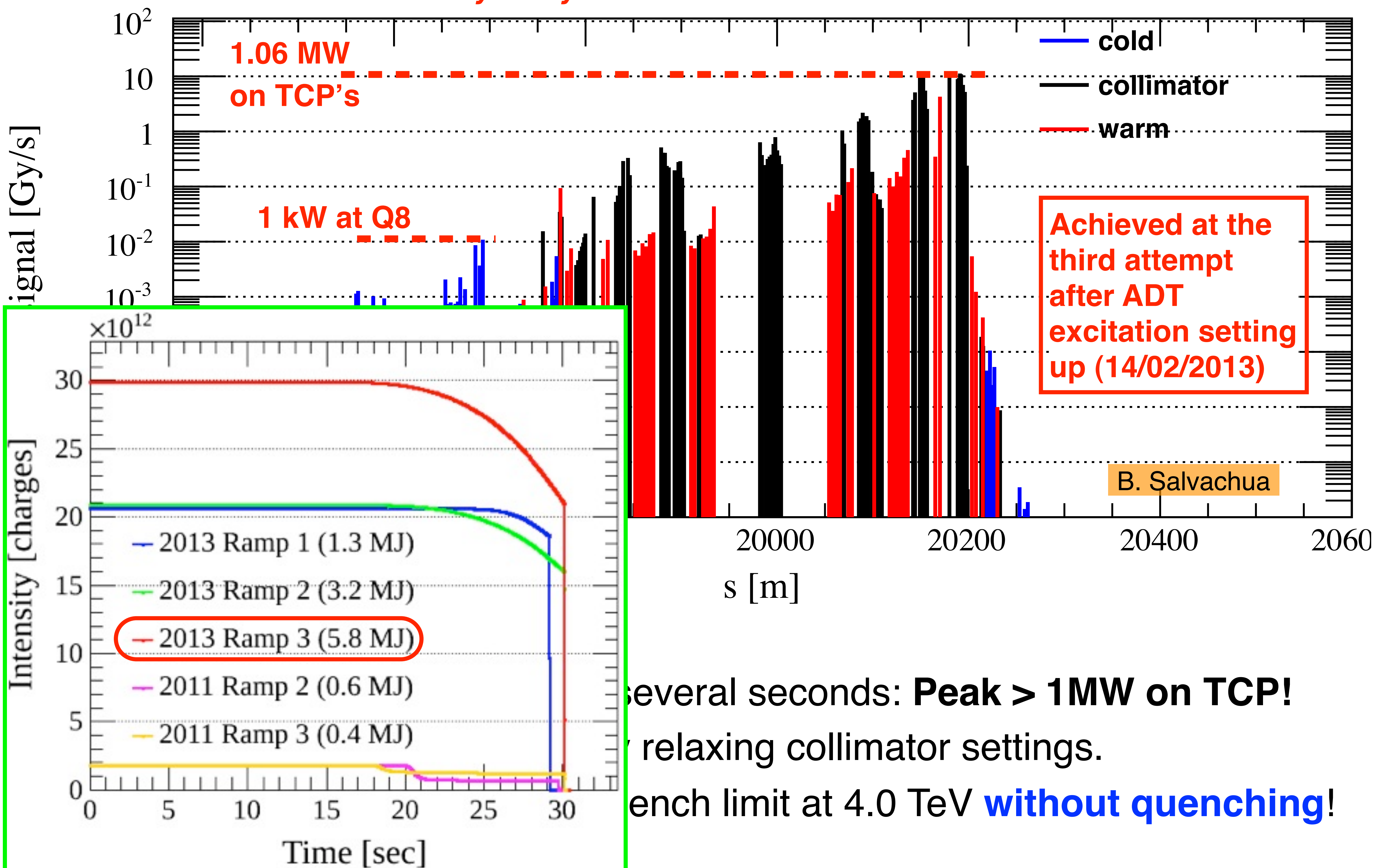
Controlled beam excitation over several seconds: **Peak > 1MW on TCP!**

Worsened cleaning by relaxing collimator settings.

Achieved 3.4 times the assumed quench limit at 4.0 TeV **without quenching**!

One extreme example: quench test

Preliminary analysis of beam tests done on 14/02/2013

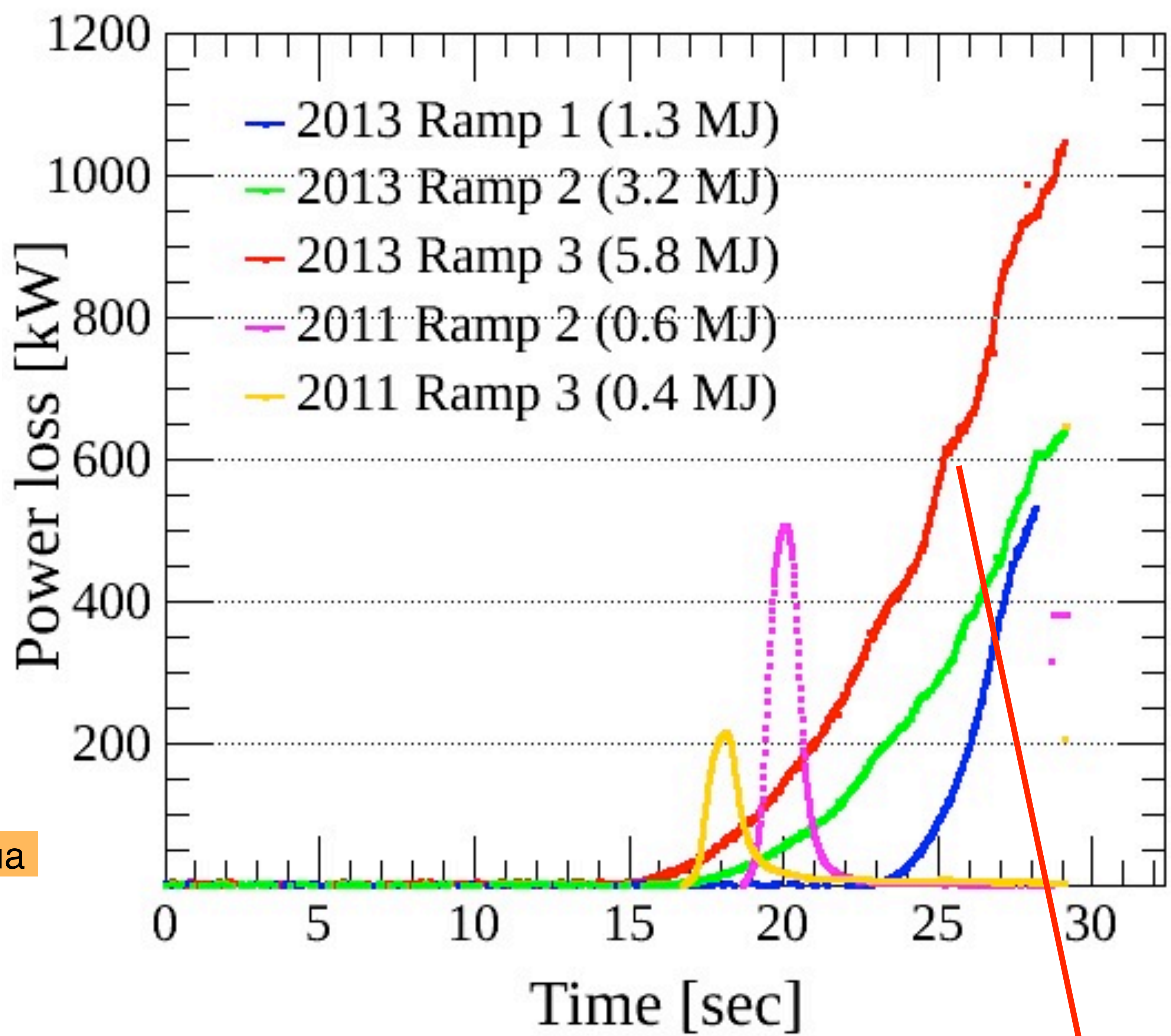


several seconds: **Peak > 1MW on TCP!**

relaxing collimator settings.

ench limit at 4.0 TeV **without quenching**!

Handling 1 MW losses



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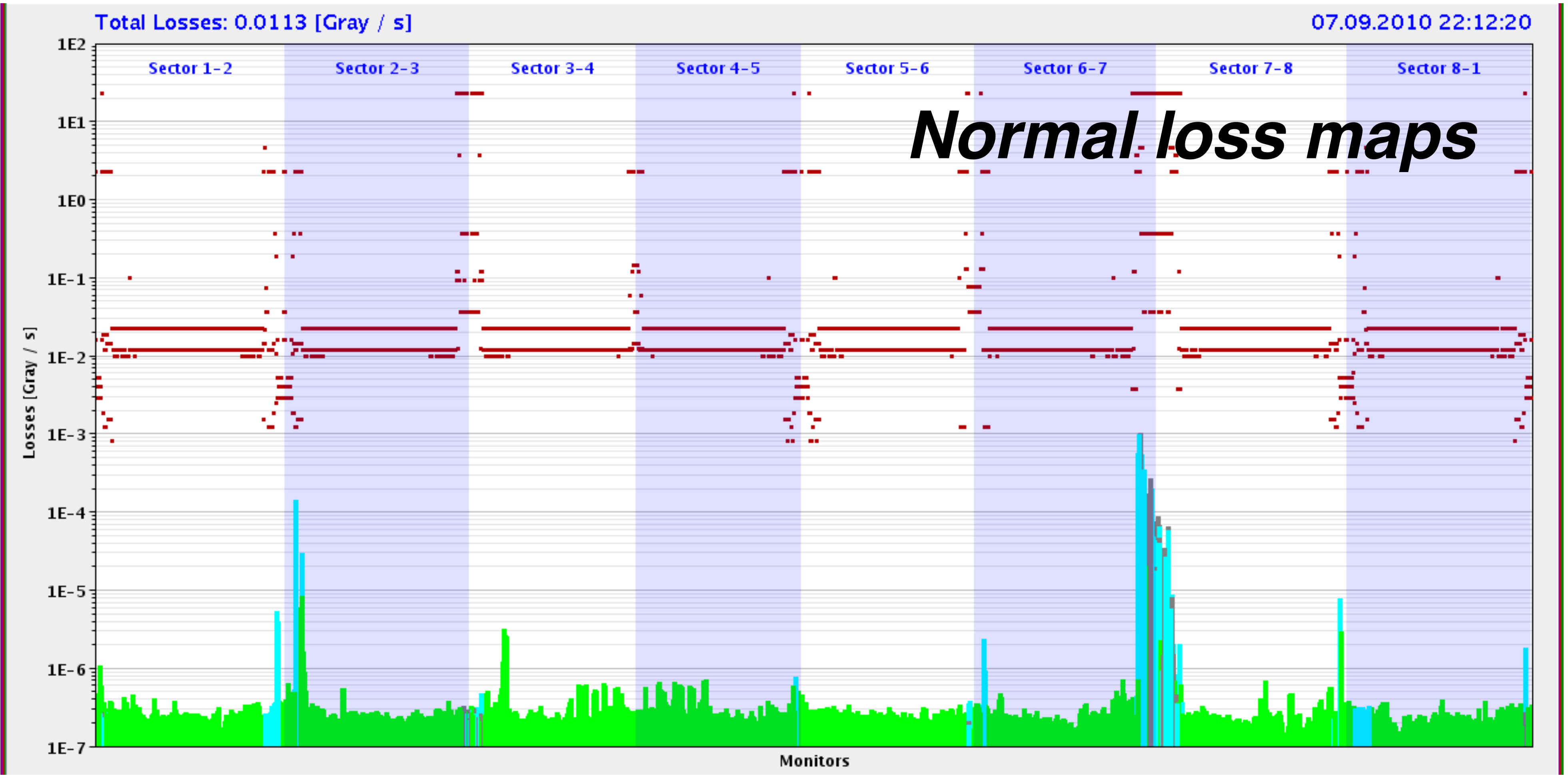
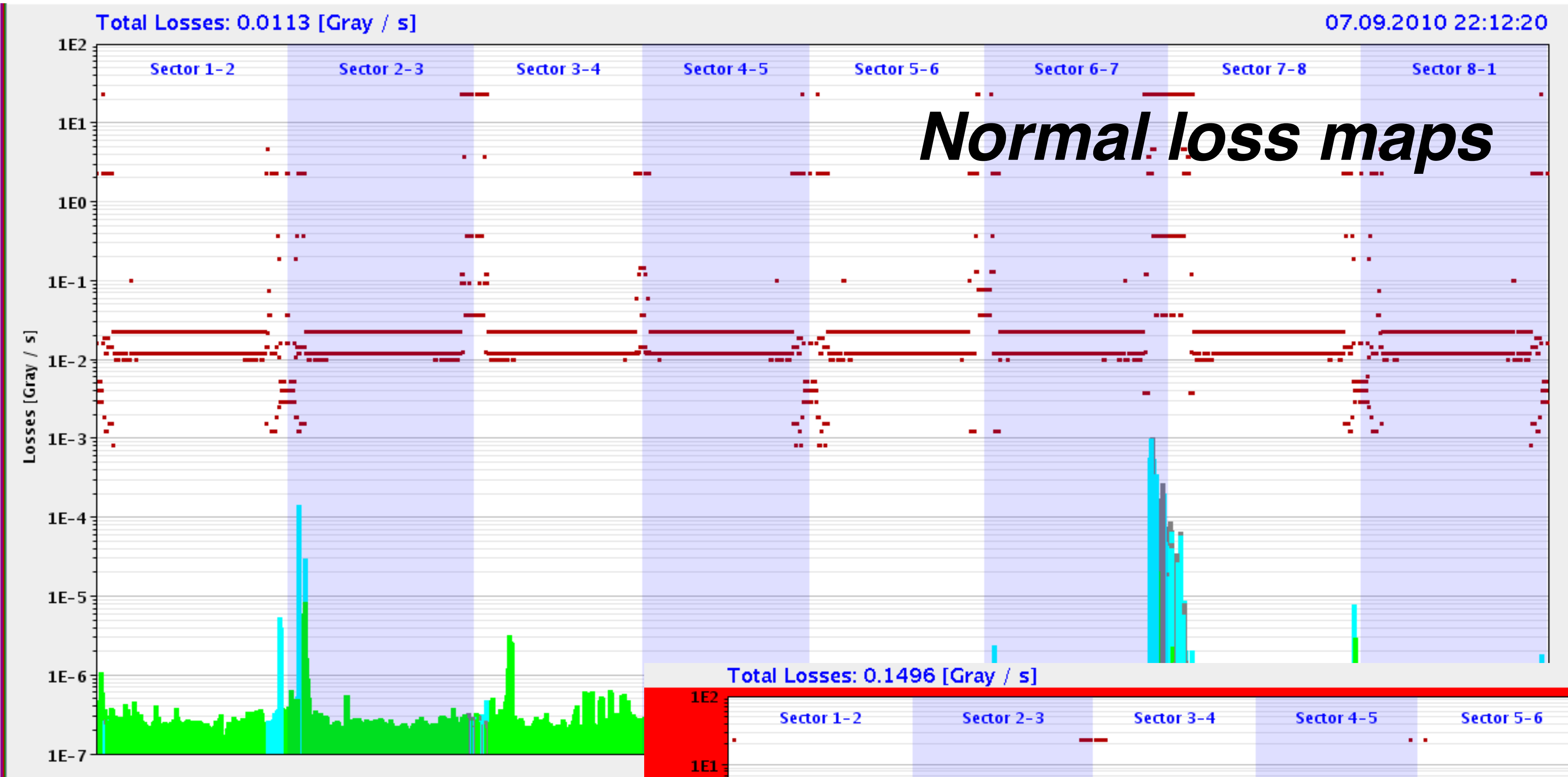
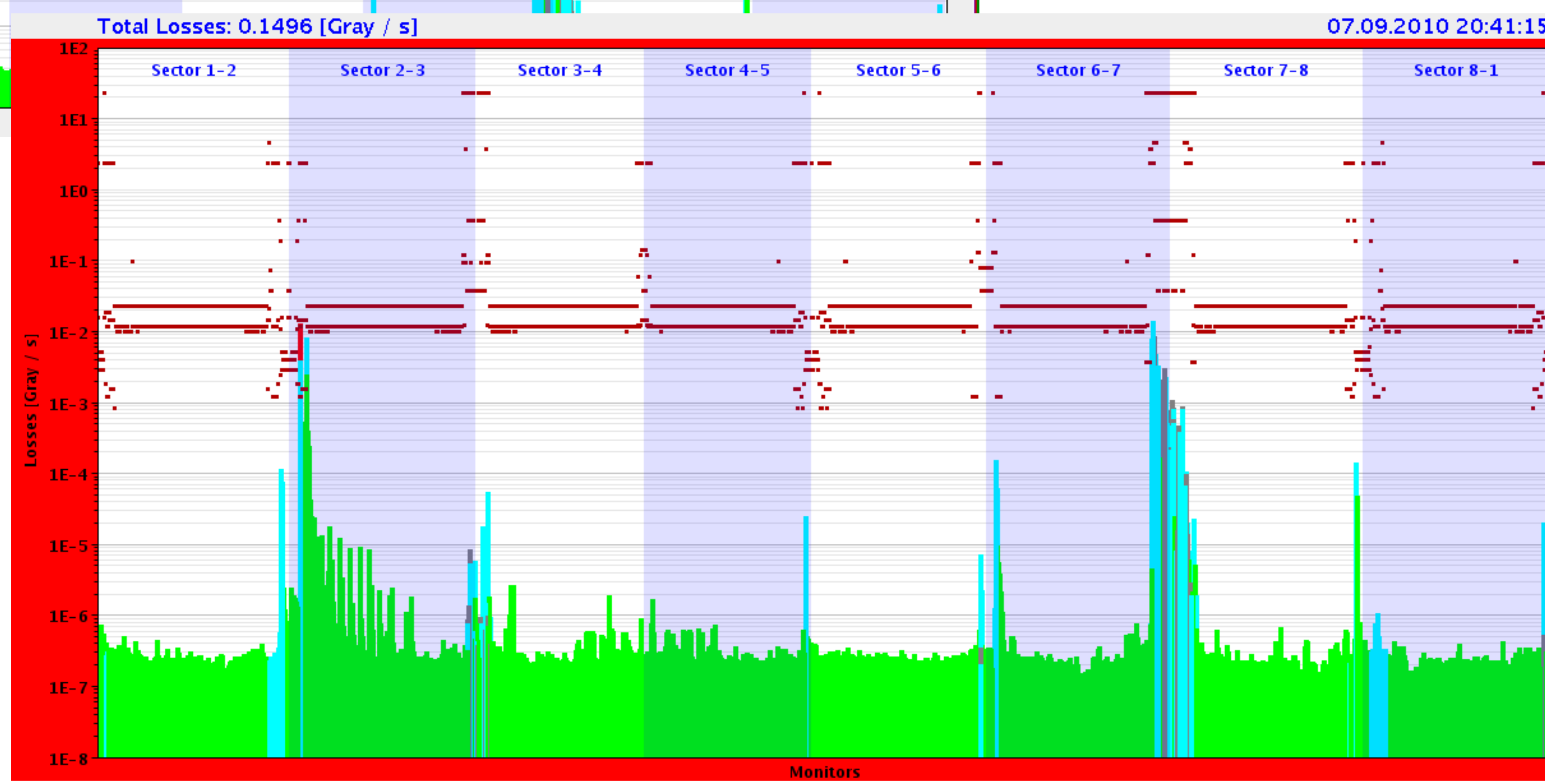
Primary beam losses equivalent to the stored energy of > 3 Tevatron beams (but energy 4 times larger!) lost without quenching!

Can something go wrong?



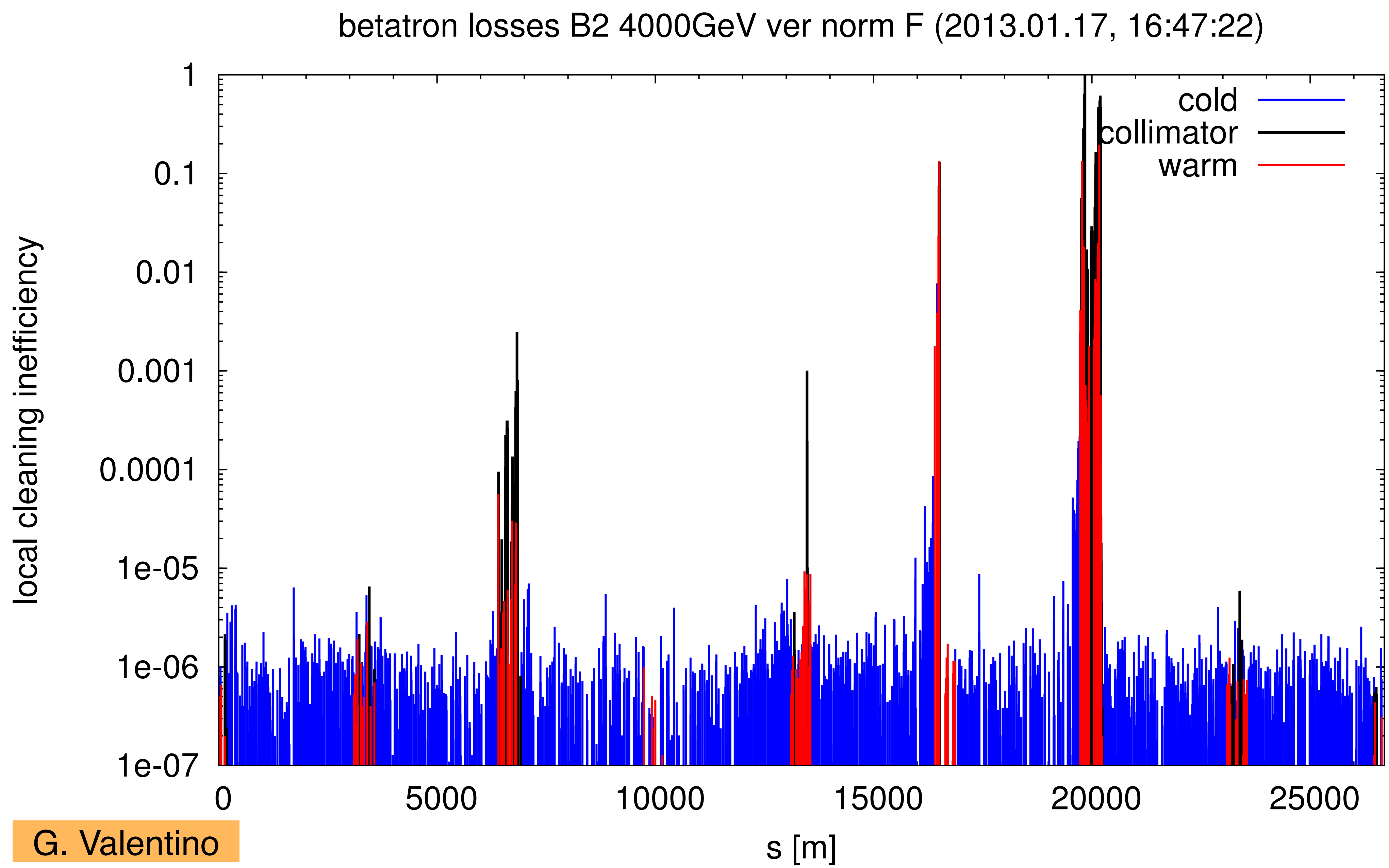
Can something go wrong?





One injection protection collimator in IR2 forgot in...

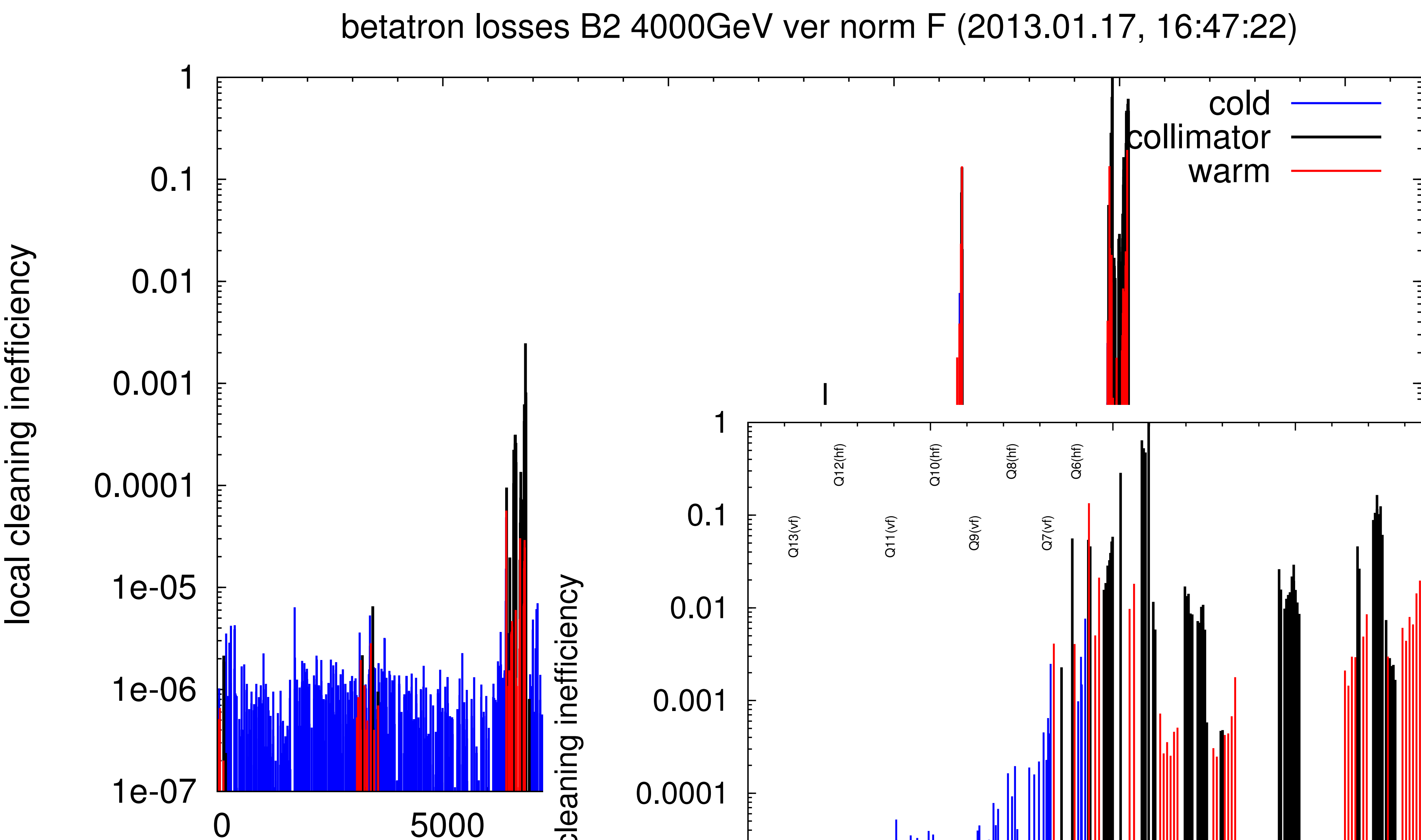
Catching setting errors

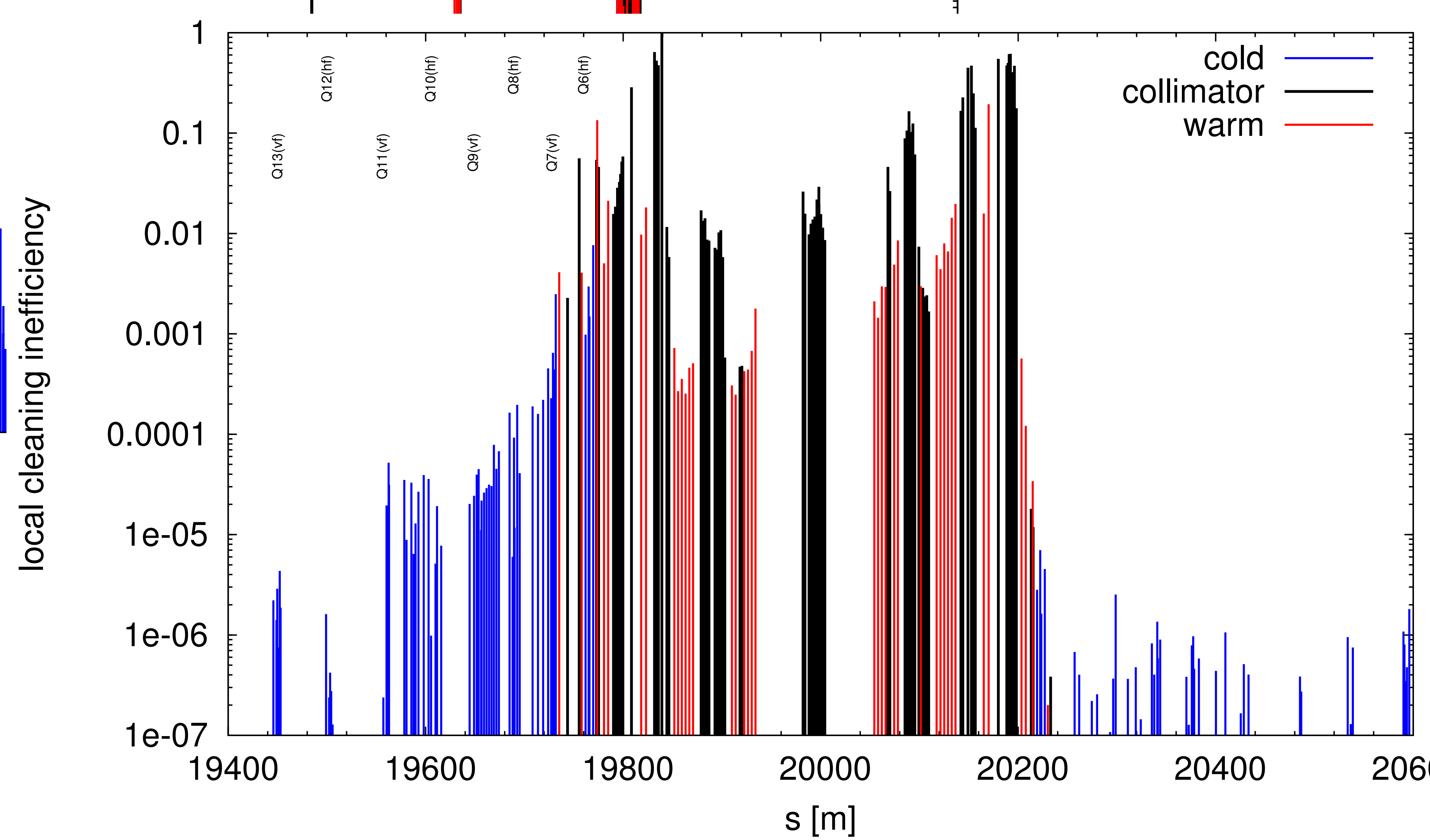


G. Valentino

Alignment error of one TCLA collimators

Catching setting errors



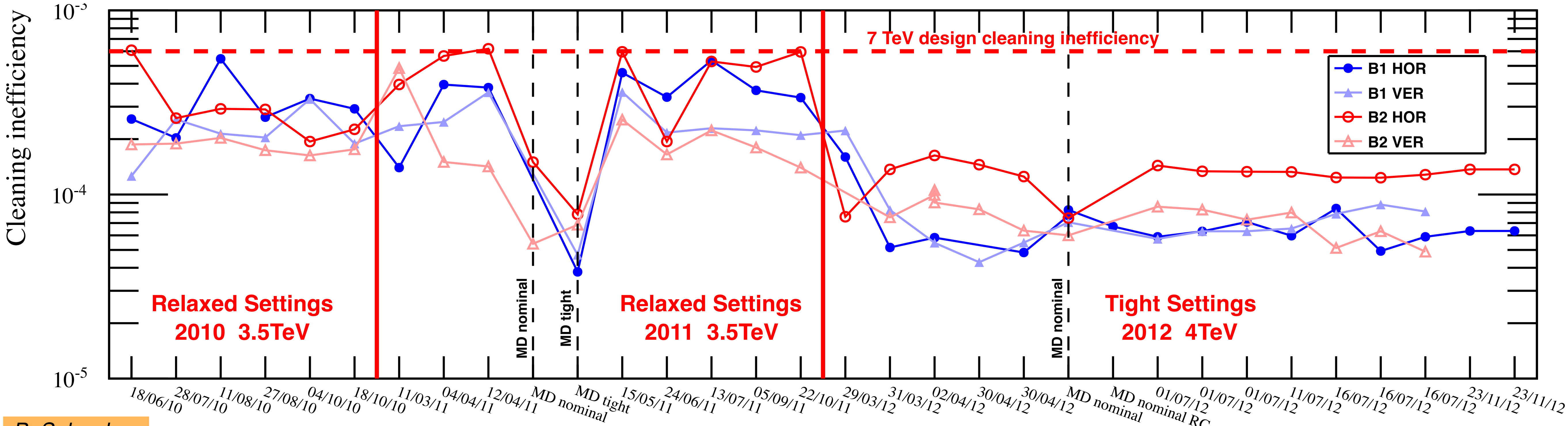


Alignment error of one TCLA collimators

G. Valentino

Can catch small settings errors. Student working on detailed analysis

Continuous performance monitoring



B. Salvachua

- The loss maps are regularly performed to **validate the system functionality**.
  Shown here: cleaning at the highest COLD loss location of the ring (DS in IR7)
- We can monitor the performance stability within a few 1e-4.
- **Excellent stability** of cleaning performance observed!
  Steps in the graph determined by changes of collimator settings.
- Collimators (and protection devices) must be re-aligned in case of abnormal issues with the cleaning performance.
  *So far, **1 alignment per year** proved to be sufficient thanks to the excellent stability of the machine and of the collimator settings.*

Outline

- Introduction
- Beam losses and collimation
- Multi-stage collimation
- LHC collimation design
- Cleaning: operational performance
    - Measurements
    - **Simulations**
- Conclusions

Do we understand the observed collimation losses?

LHC collimation: simulation challenges

- Model precisely the **complex** and **distributed collimation** system
  - → *44 collimator per beam along 27 km; **multi-stage cleaning**;*
  - → *2 jaw design for **3 collimation planes**: horizontal, vertical and skew;*
  - → *impact parameters in the sub-micron range;*
  - → *beam proton **scattering** with different collimator materials.*
- **Collimation** is designed to provide cleaning efficiencies > 99.99%
  - → *need **good statistical accuracy** at limiting loss locations;*
  - → *simulate only halo particles that interact with collimators, not the core.*
- Detailed description of the **LHC aperture** all along the 27 km
  - → *10 cm binning, i.e. 270000 check points.*
- Accurate tracking of particles with large **orbit** and **energy deviations**
  - → *need state-of-the-art tools for multi-turn tracking.*
- At the scale of 7 TeV beam sizes (~200 microns), small errors matter!

  Need to **model the relevant imperfections**
  - → *Jaw flatness of the order of 40 microns;*
  - → *Jaw positioning (gap/angles);*
  - → *Machine optics and orbit errors.*

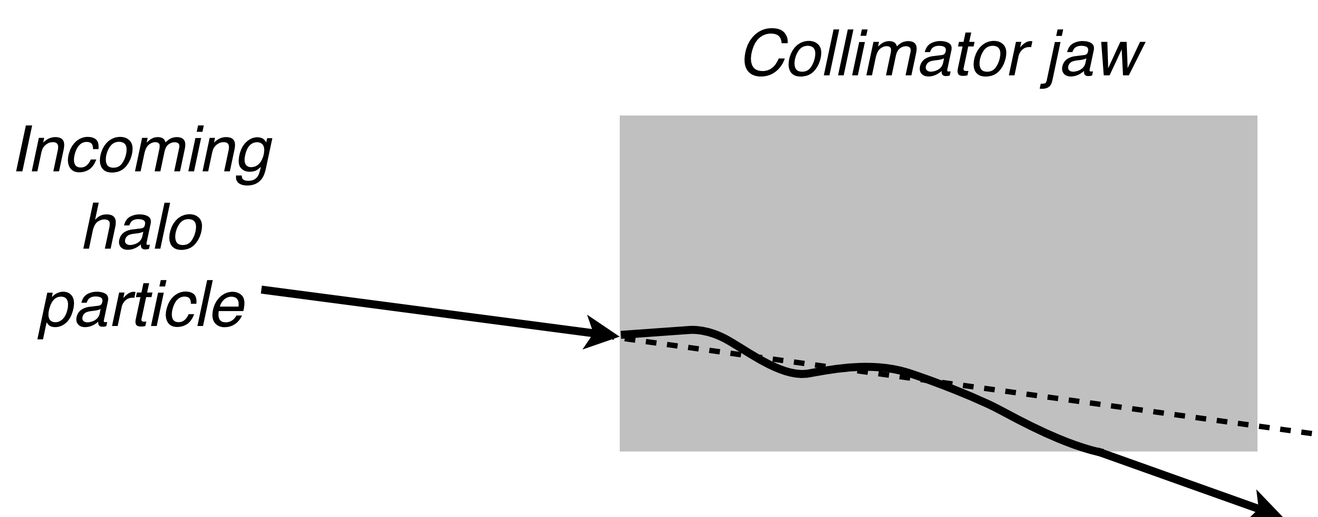
Simulation goal: determine energy lost in (cold) magnets for given beam intensity impinging on collimators.

Simulation tools

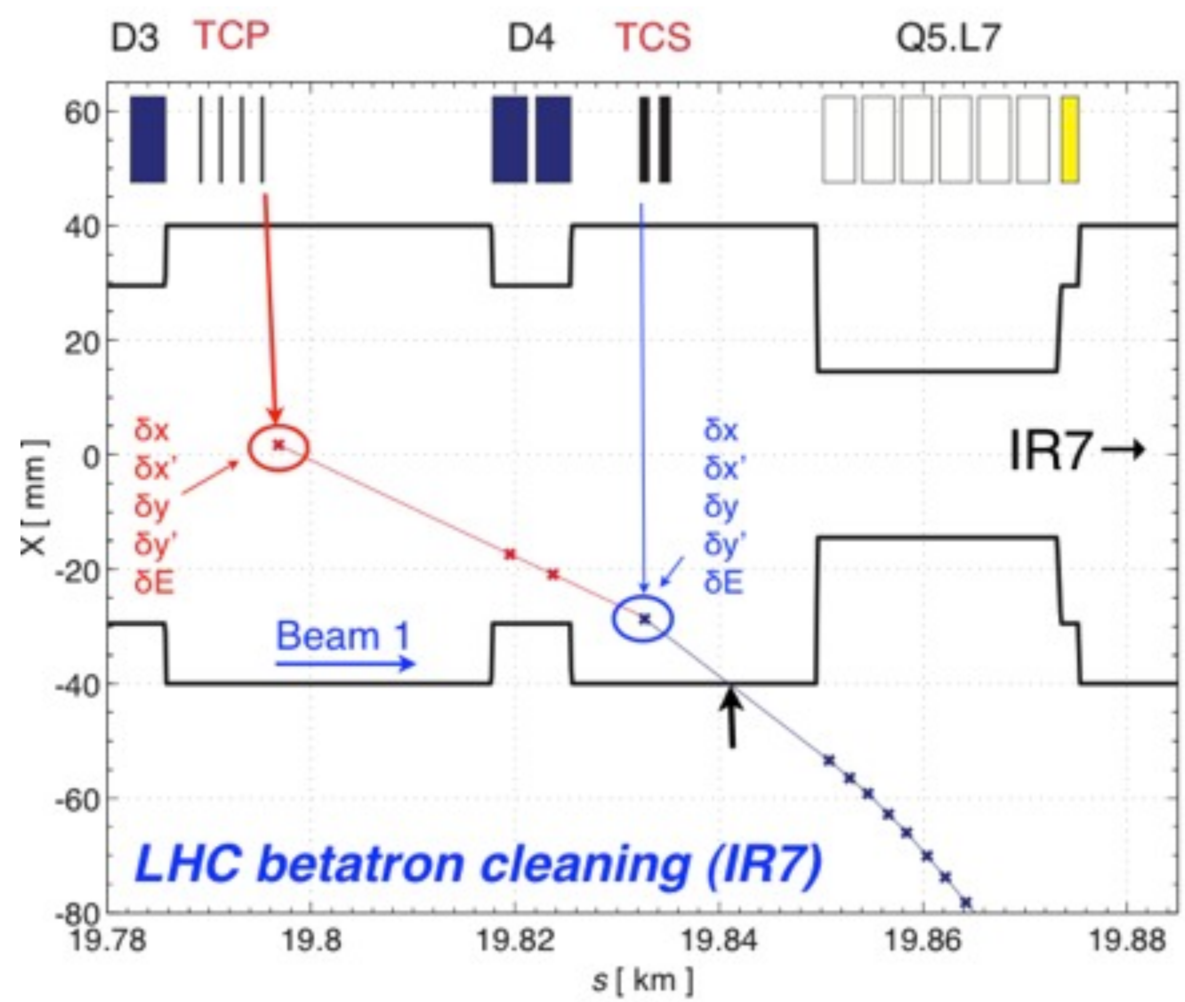
Accurate tracking of halo particles 6D dynamics, chromatic effects, δp/p, high order field errors, ...	**SixTrack**†
Detailed collimator geometry Implement all collimators and protection devices, treat any azimuthal angle, tilt/flatness errors	
Scattering routine Track protons inside collimator materials	**K2**
Detailed aperture model Precisely find the locations of losses	**BeamLossPattern**

All combined in a simulation package for collimation cleaning studies: G. Robert-Demolaize, R. Assmann, S. Redaelli, F. Schmidt, **A new version of SixTrack with collimation and aperture interface**, PAC2005

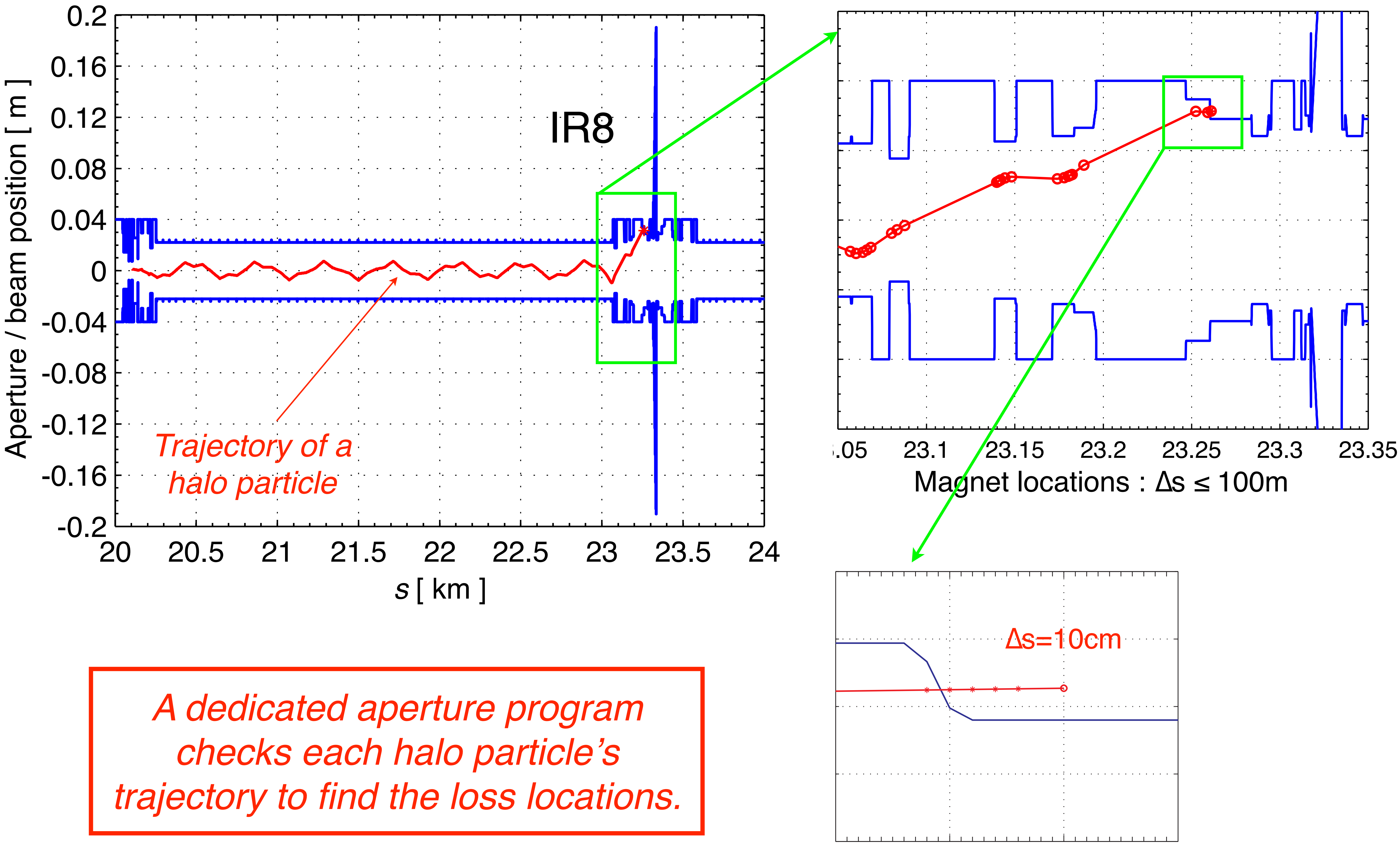
† See also talk by F. Schmidt .



An illustrative scheme



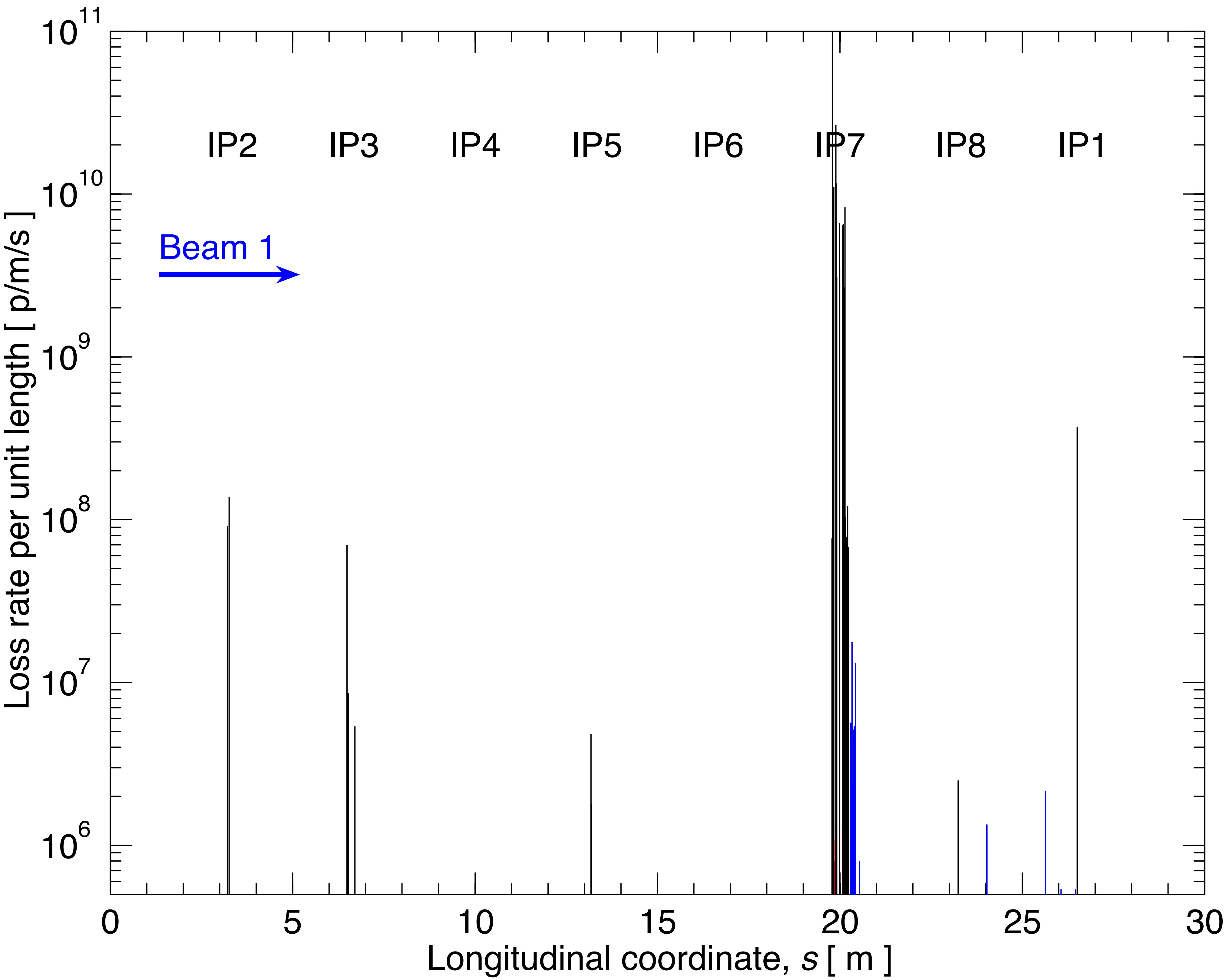
Example: trajectory of a halo particle



Interpolation: Δs=10cm
(270000 points!)

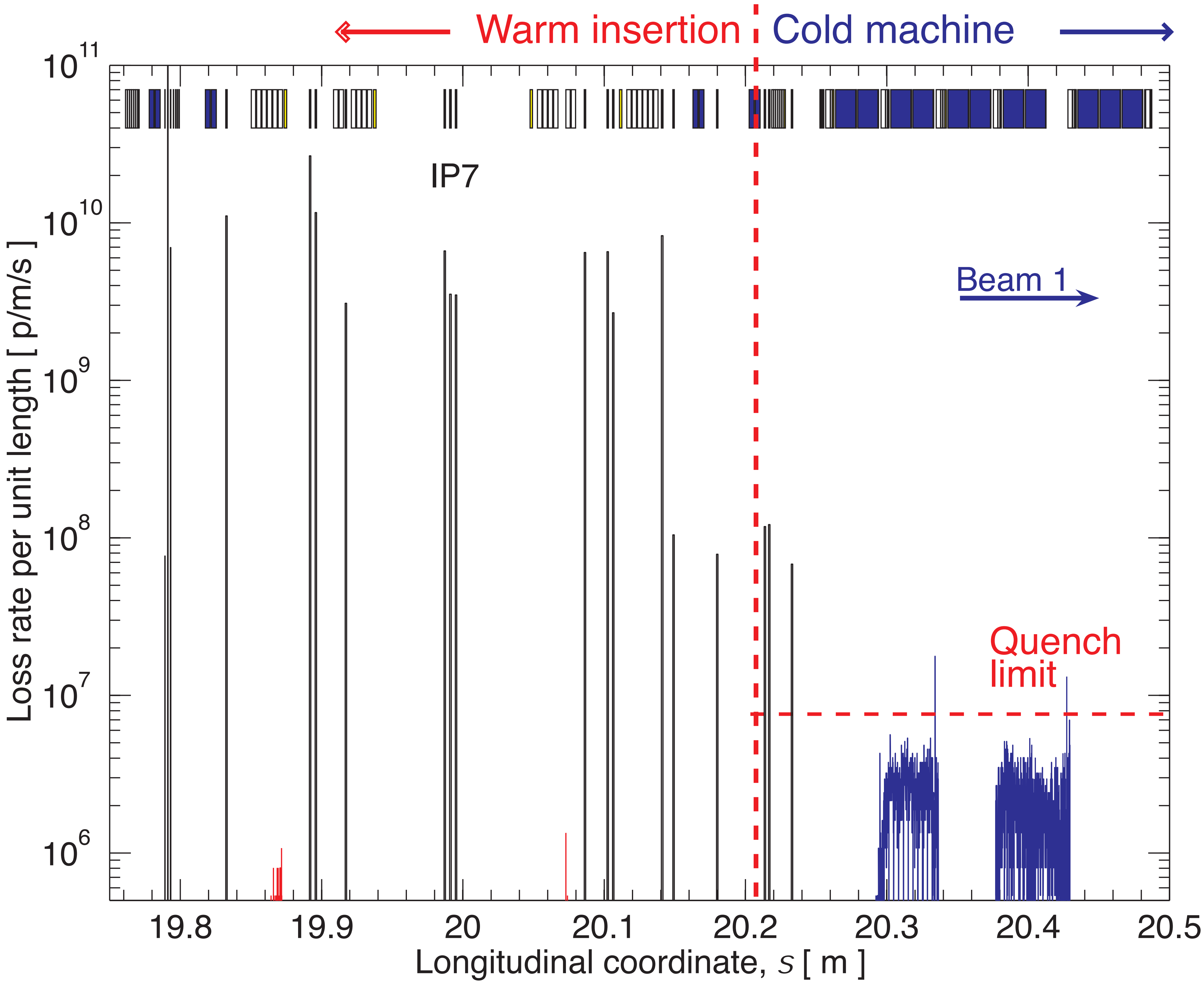
A dedicated aperture program checks each halo particle's trajectory to find the loss locations.

Example of simulated "loss map"



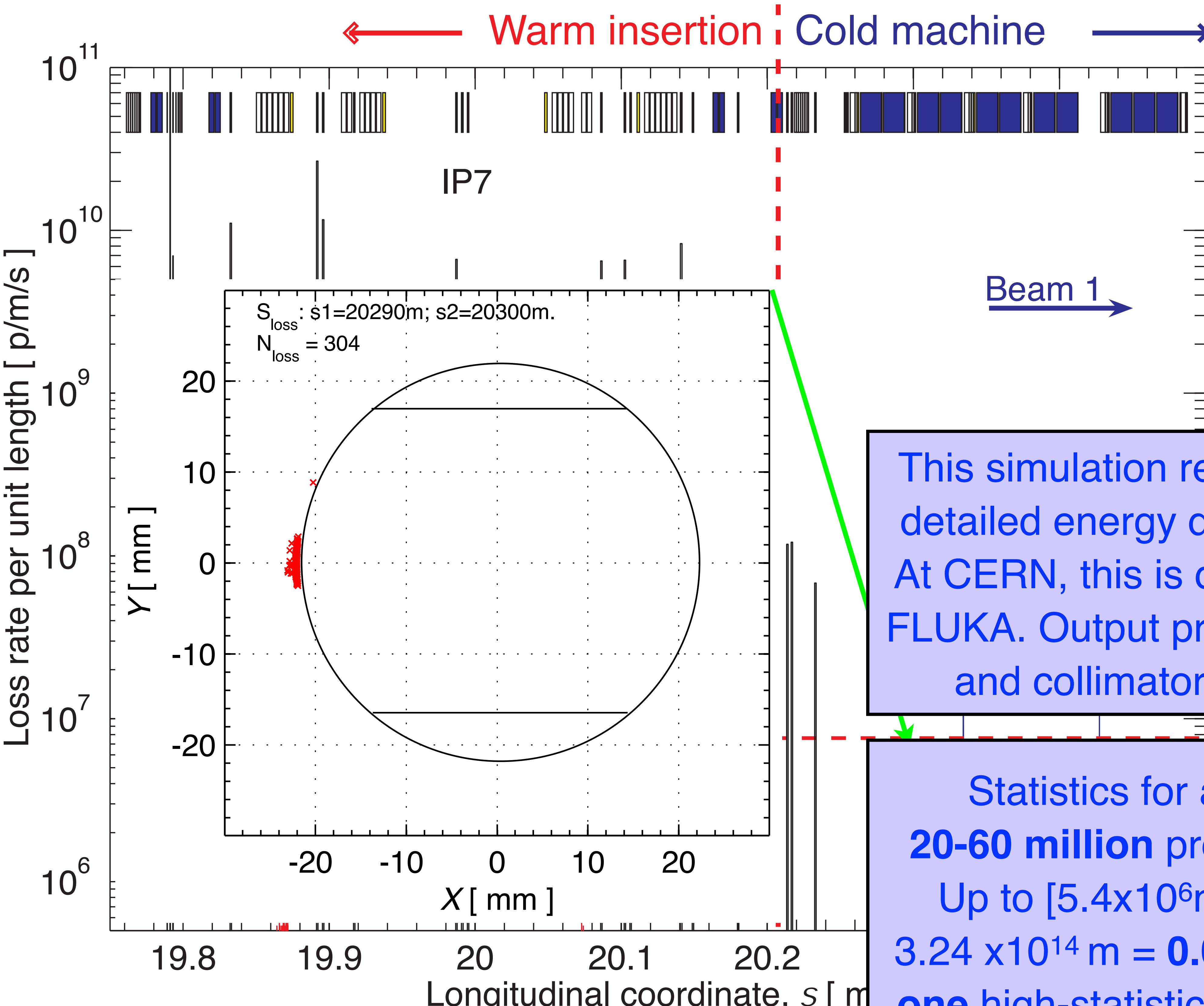
Nominal 7 TeV case, perfect machine

Example of simulated "loss map"



Nominal 7 TeV case, perfect machine

Example of simulated "loss map"



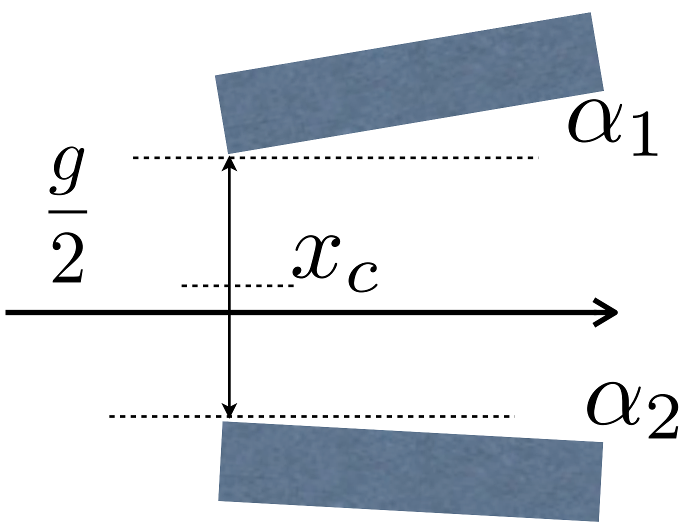
Nominal 7 TeV case, perfect machine

This simulation results are used for detailed energy deposition studies! At CERN, this is done with program FLUKA. Output provided to magnets and collimator design teams.

Statistics for a typical case:
20-60 million protons, **200 turns**.
Up to [5.4×10^6m] x [60×10^6p] = 3.24×10^{14} m = **0.034 lightyears** for **one** high-statistics simulation case!

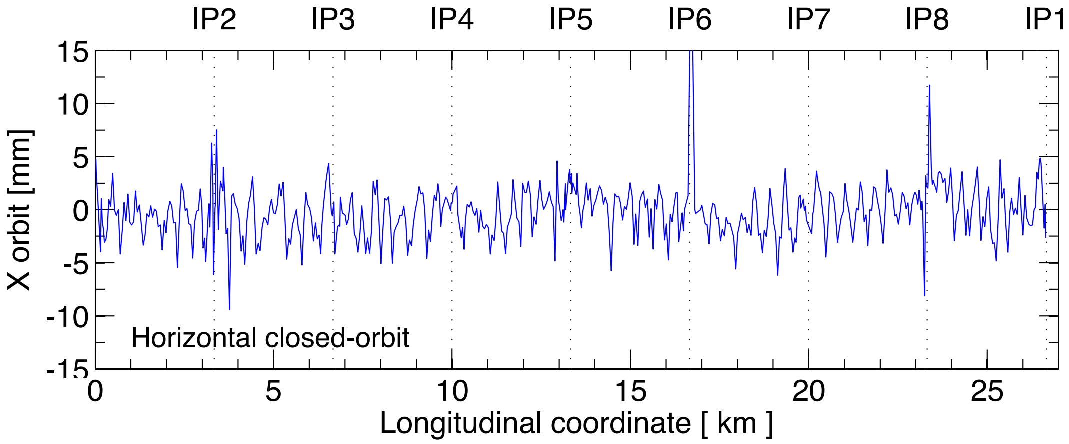
Importance of error models

Collimator positioning with respect to the beam



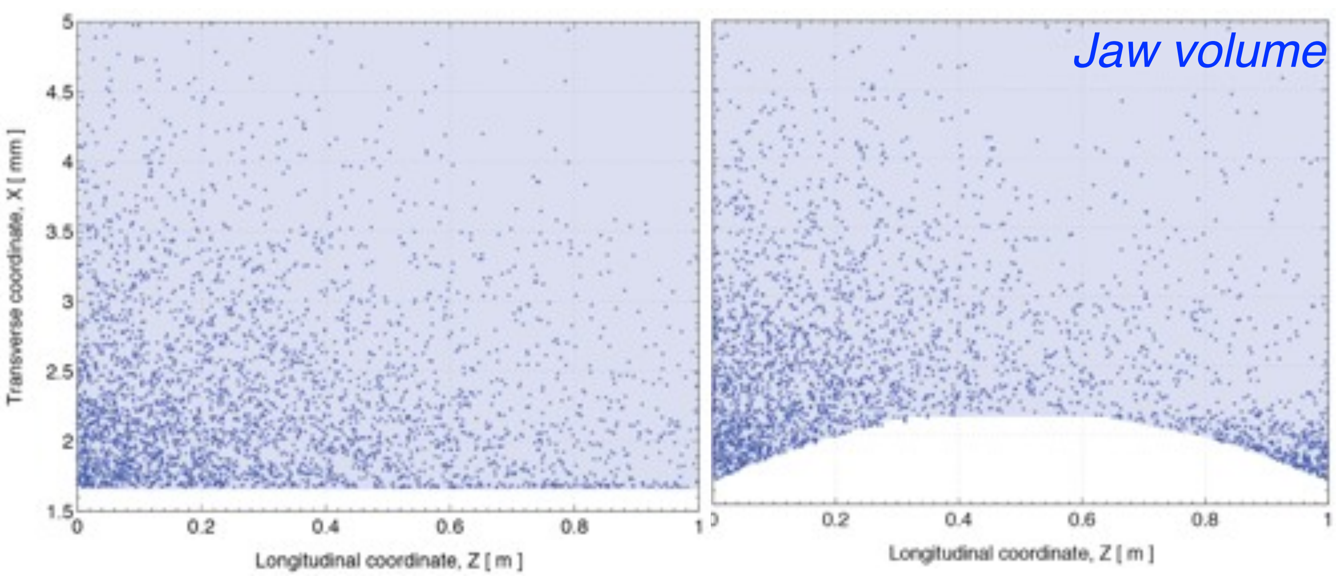
Can apply random errors to collimator geometry.
Typical RMS values:
Collimator centre = 50μm
Gap = 0.1 σ
Jaw tilt angle = 200 μrad

Closed-orbit errors around the ring



Design value: +/- 3-4mm peak-to-peak

Collimator jaw flatness



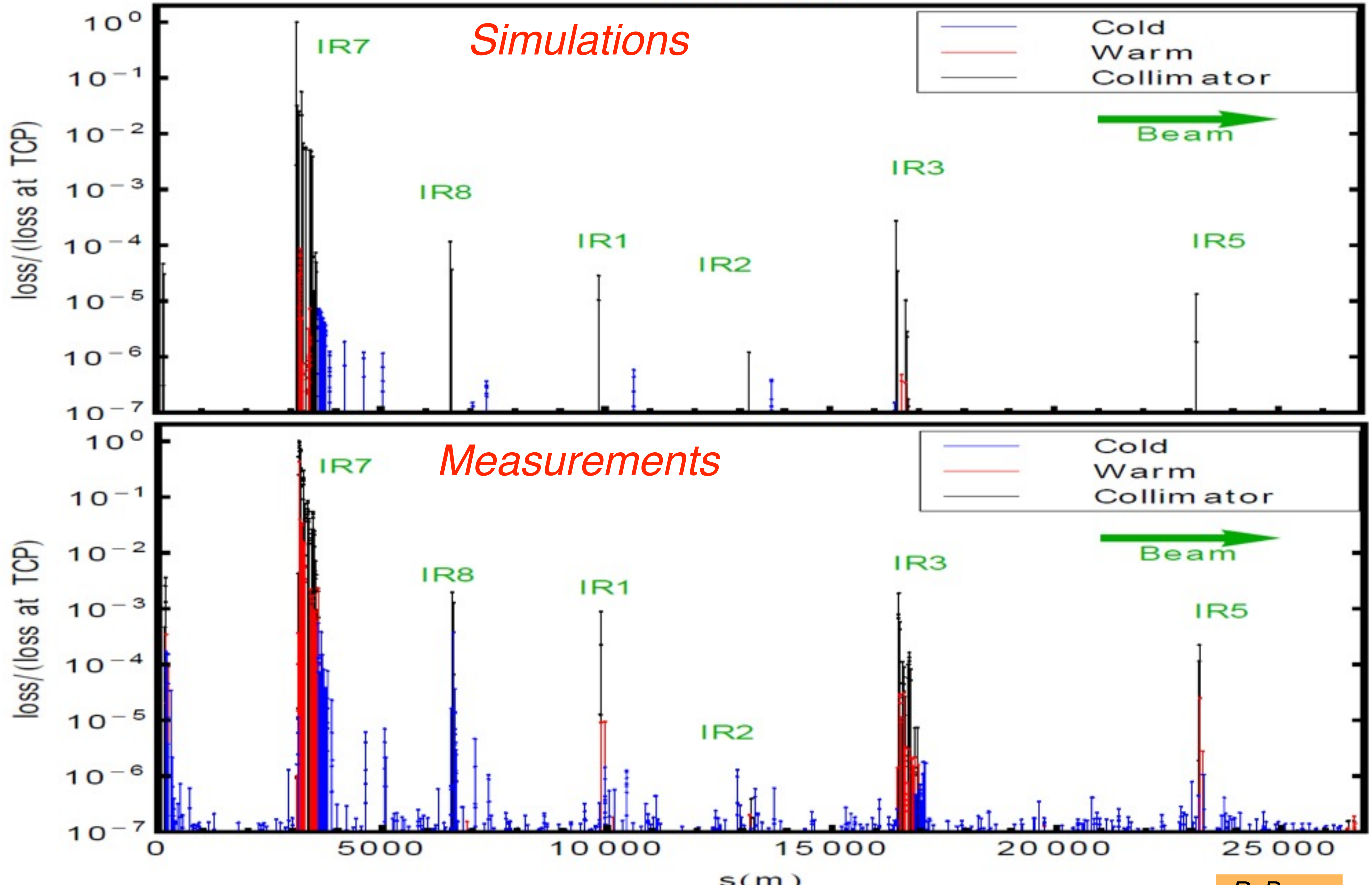
5th order polynomials to fit measured flatness of all Carbon collimators: ≥ 40 μm

Machine aperture misalignments

Element type	Description	Design		Measured	
		$\sigma_{\Delta x}$ [mm]	$\sigma_{\Delta y}$ [mm]	$\sigma_{\Delta x}$ [mm]	$\sigma_{\Delta y}$ [mm]
MB	main dipole	2.40	1.56	1.83	1.10
MQ	arc quadrupole	2.00	1.20	1.36	0.76
MQX	triplet quadrupole	1.00	1.00	1.53	1.53
MQWA	warm quadrupole	2.00	1.20	0.67	0.41
MQWB	warm quadrupole	2.00	1.20	0.67	0.41
MBW	warm dipole	1.50	1.50	1.96	1.49
BPM	beam position monitor	0.50	0.50	1.36	0.76

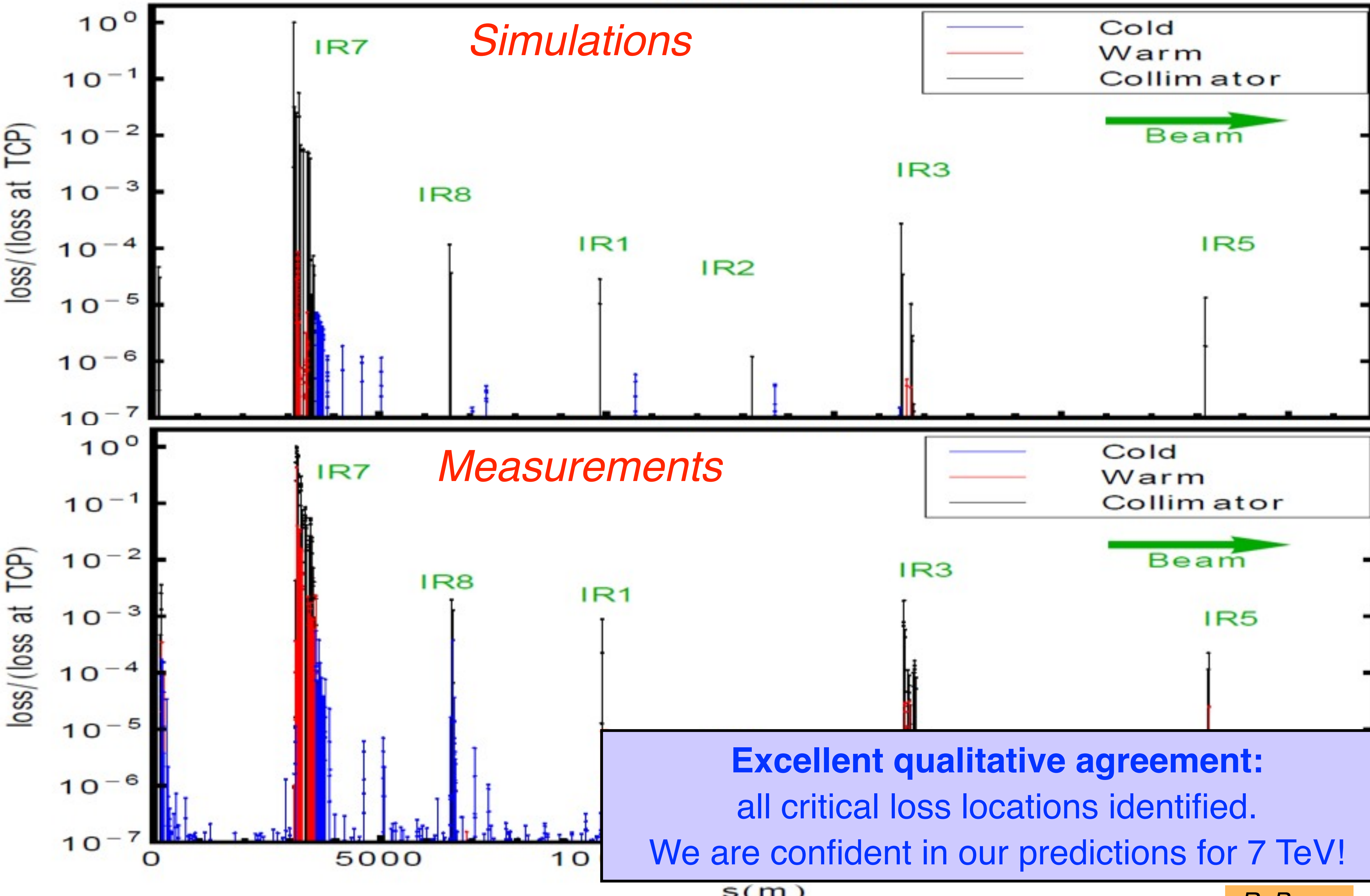
In addition, all optics and multipole errors well established for the standard MADX / sixtrack interface can be applied.

Comparison with measurements



R. Bruce

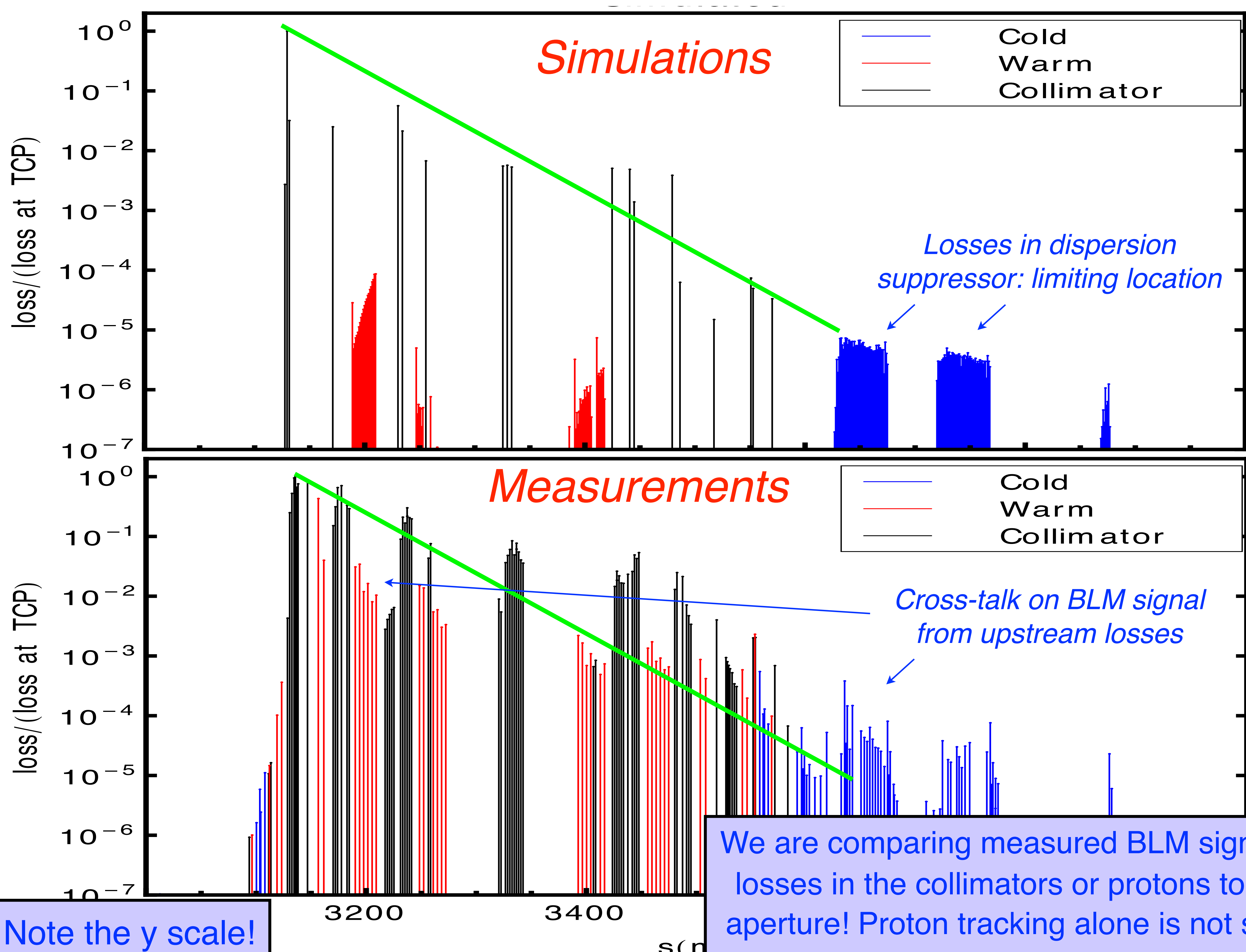
Comparison with measurements



Excellent qualitative agreement:
all critical loss locations identified.
We are confident in our predictions for 7 TeV!

R. Bruce

Comparison in the betatron cleaning

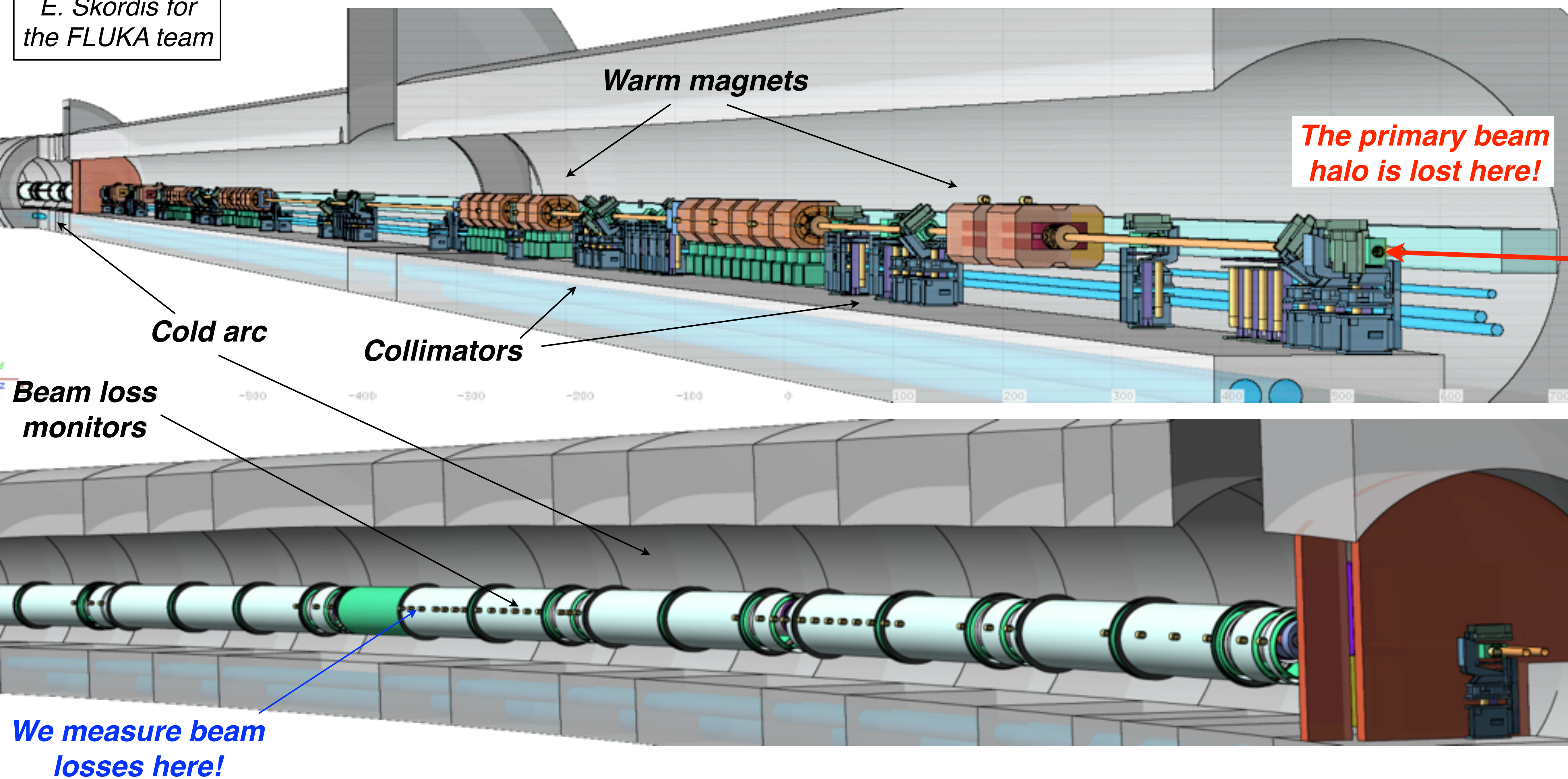


Note the y scale!

We are comparing measured BLM signals against losses in the collimators or protons touching the aperture! Proton tracking alone is not sufficient to reproduce the deposited energy profile!

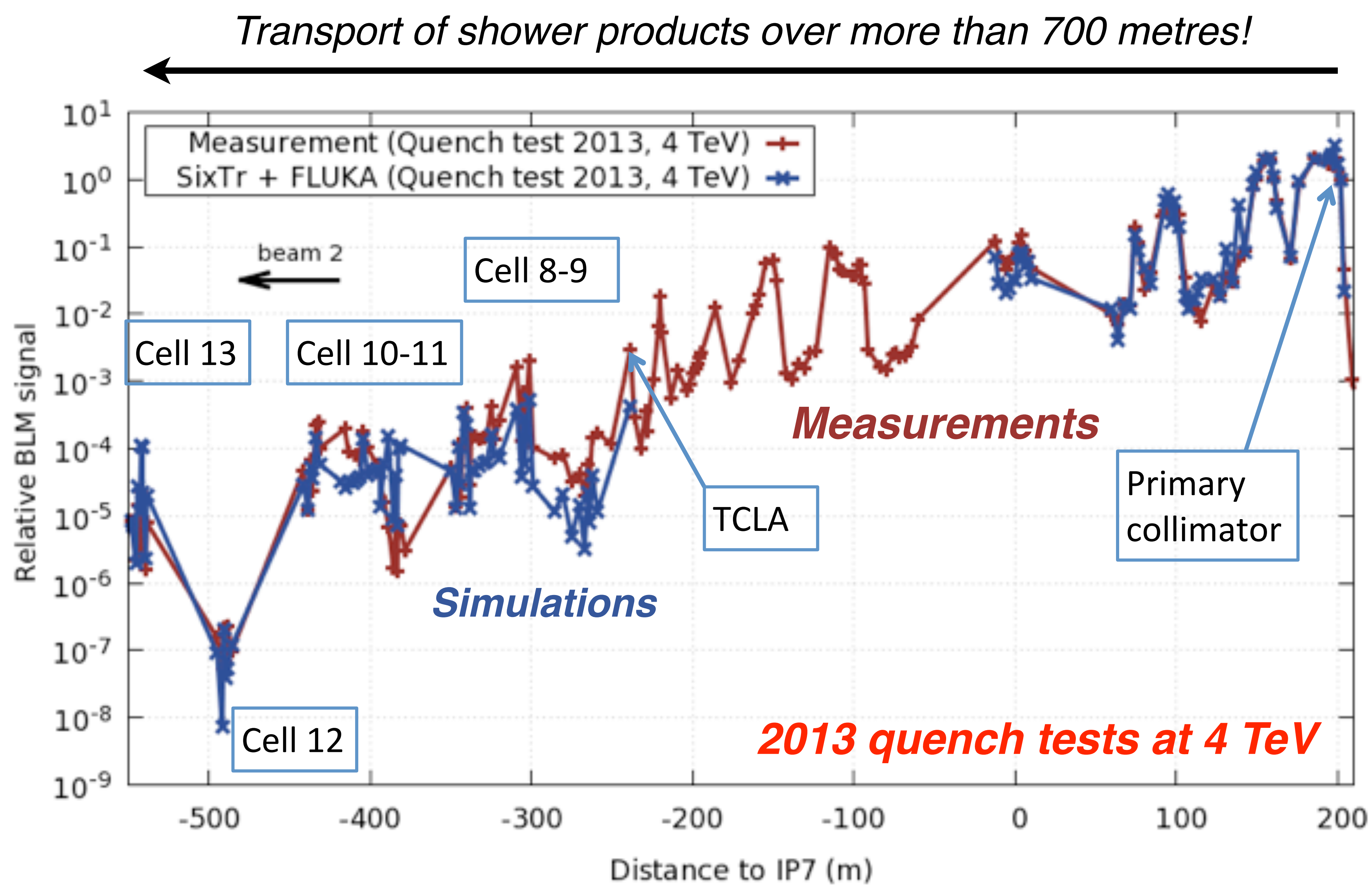
Integrated simulations

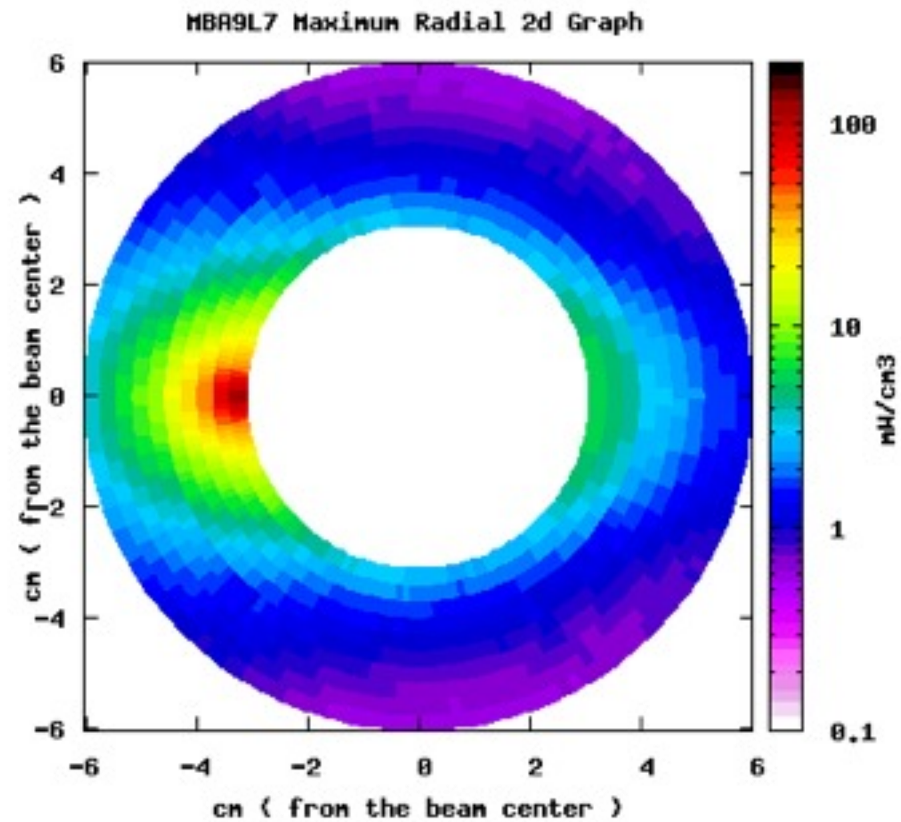
E. Skordis for the FLUKA team



- Impressive machine model for **energy deposition studies** for collimation! This is required to reproduce the details observed in the measurements...

Comparison against measurements





E. Skordis et al.

- Compared measured data from BLM's in IR7 against doses from shower cascades.
- **Impressive agreement** considering the complexity of the simulation behind!
- Working on improving further the agreement - some "factors" missing at specific locations (like TCLA collimators).
- Important **immediate outcome**: cross-calibration of loss measurements and peak deposited energy in the magnet coils for updated **quench limit** estimates.

Conclusions

- ☑ Beam cleaning and collimation becomes increasingly important for large circular accelerators.
- ☑ The basic design strategy for multi-stage collimation in high-energy hadron accelerators was presented.
  - *Key parameters relevant for collimation design reviewed.*
  - *Collimation settings worked out from aperture.*
  - *Seen how this defines the collimator design.*
- ☑ The present LHC collimation system was presented as a case study to illustrate various collimation “roles”.
- ☑ Detailed look at collimation settings and operation.
- ☑ Cleaning performance and simulations were discussed.

Paths to improve beam collimation

- We are happy with the present system performance but are actively working on **advanced collimation concepts** and designs for the challenges of future upgrades.
- Novel collimator materials: more robust and low impedance.
- Crystal collimation as a way to improve cleaning.
- Hollow electron lenses for active control of primary halo.
- New collimators in the cold regions will be used to overcome the cleaning limitations in the dispersion suppressors.
- Continue improving the system performance and alignment techniques for efficient operation (BPM collimators).
- Rotatable collimator concept in case of frequent damage.