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Beam collimation at the Large Hadron Collider

Stefano Redaelli
Beams Department
Accelerator and Beam Physics group

Outline

- ☑ Introduction
- ☑ Beam losses and collimation
- ☑ Single- and multi-stage cleaning
- ☑ LHC collimation layouts
- ☑ Collimation cleaning
- ☑ Conclusions

The LHC collimator

What is beam collimation and why we need it?

How do we design a collimation system?

How many collimators are used at the LHC?

Where are they located in the ring?

How are they built, with which materials?

Beam collimation - definitions

Beam halo collimation

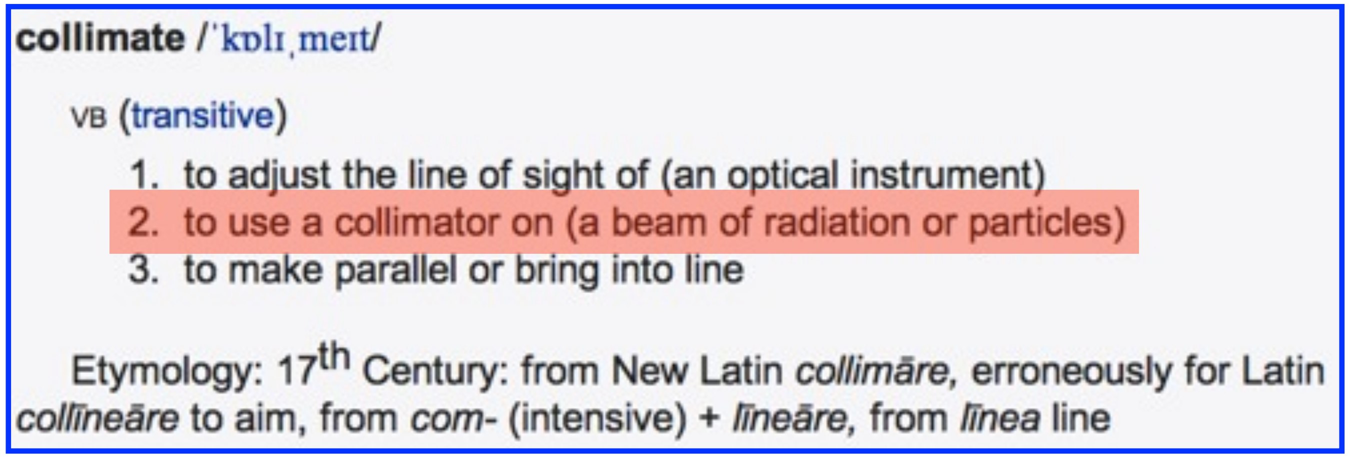
Controlled and safe disposal of beam halo particles produced by unavoidable beam losses.
Achieved by reducing the transverse cross section of the beam.

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.

Main design goal for the **collimation system** at the **LHC**

Ensure that beam losses in superconducting magnets remain below quench limits in all operational phases.

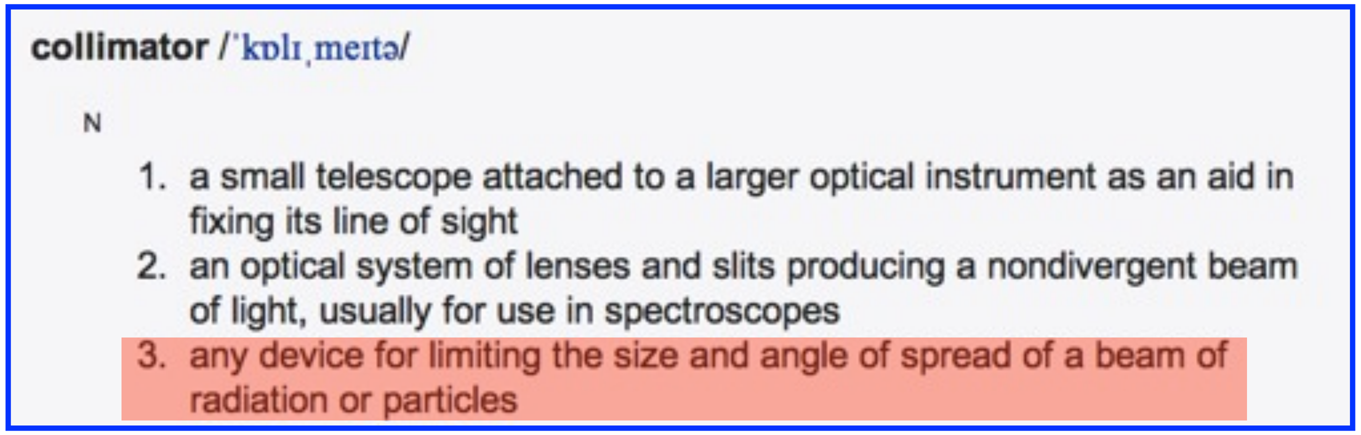


collimate /ˈkɒlɪˌmeɪt/

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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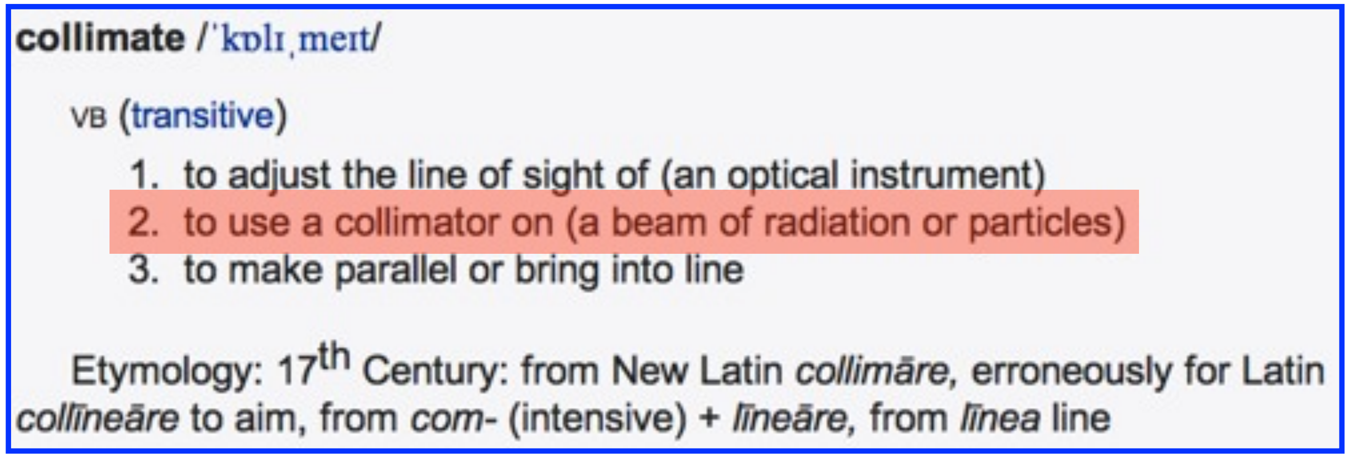

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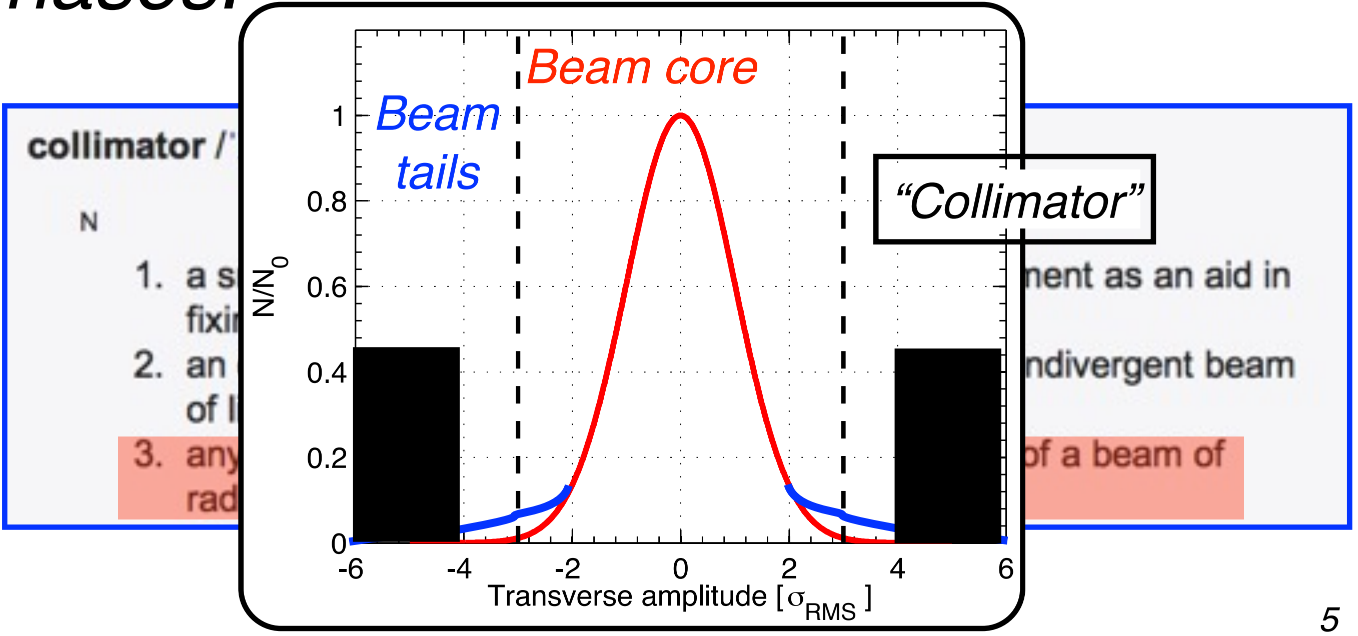
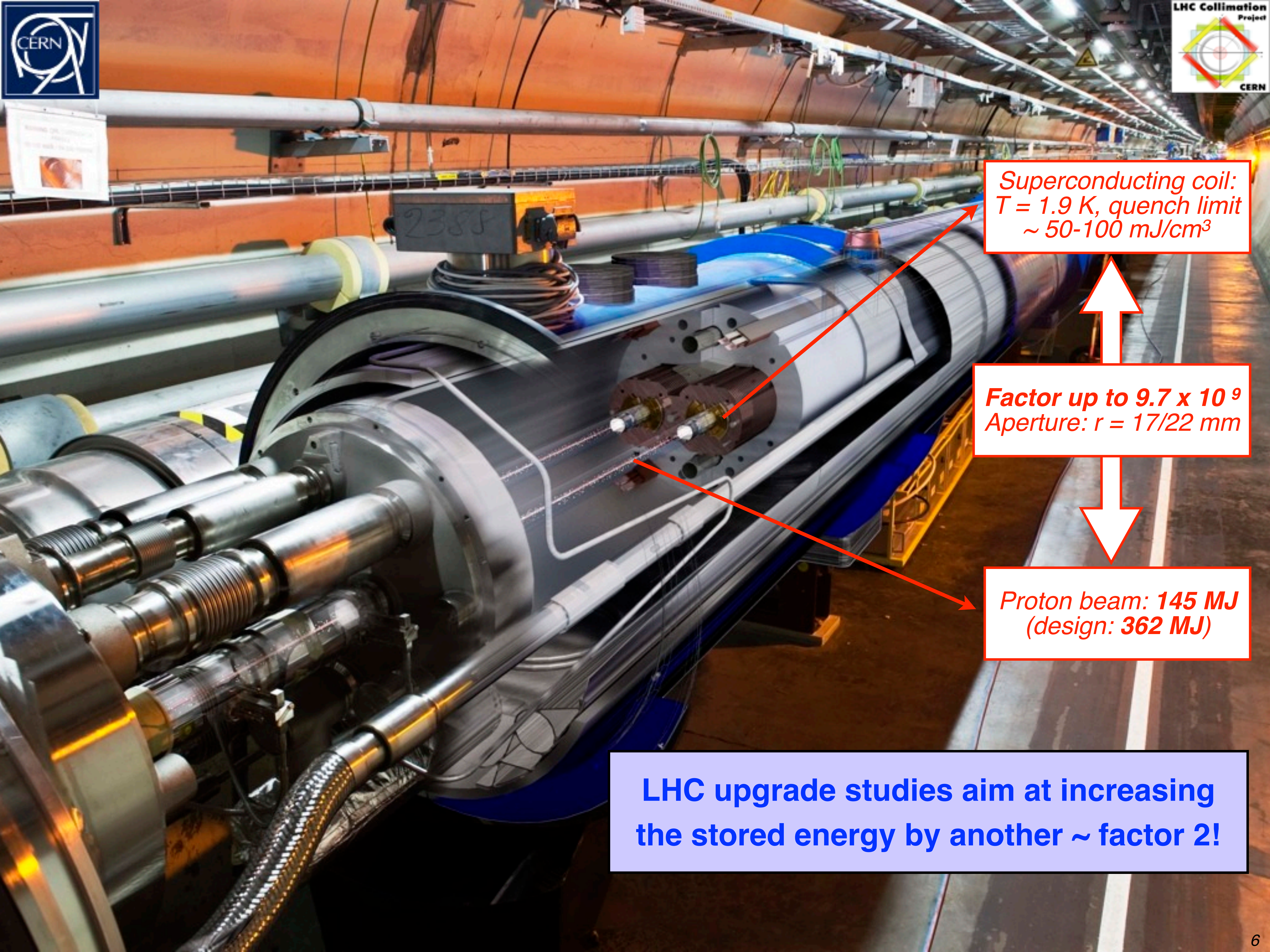


collimator /ˈ

N

1. a s … ment as an aid in
fixi
2. an … ndivergent beam
of l
3. any … of a beam of
rad



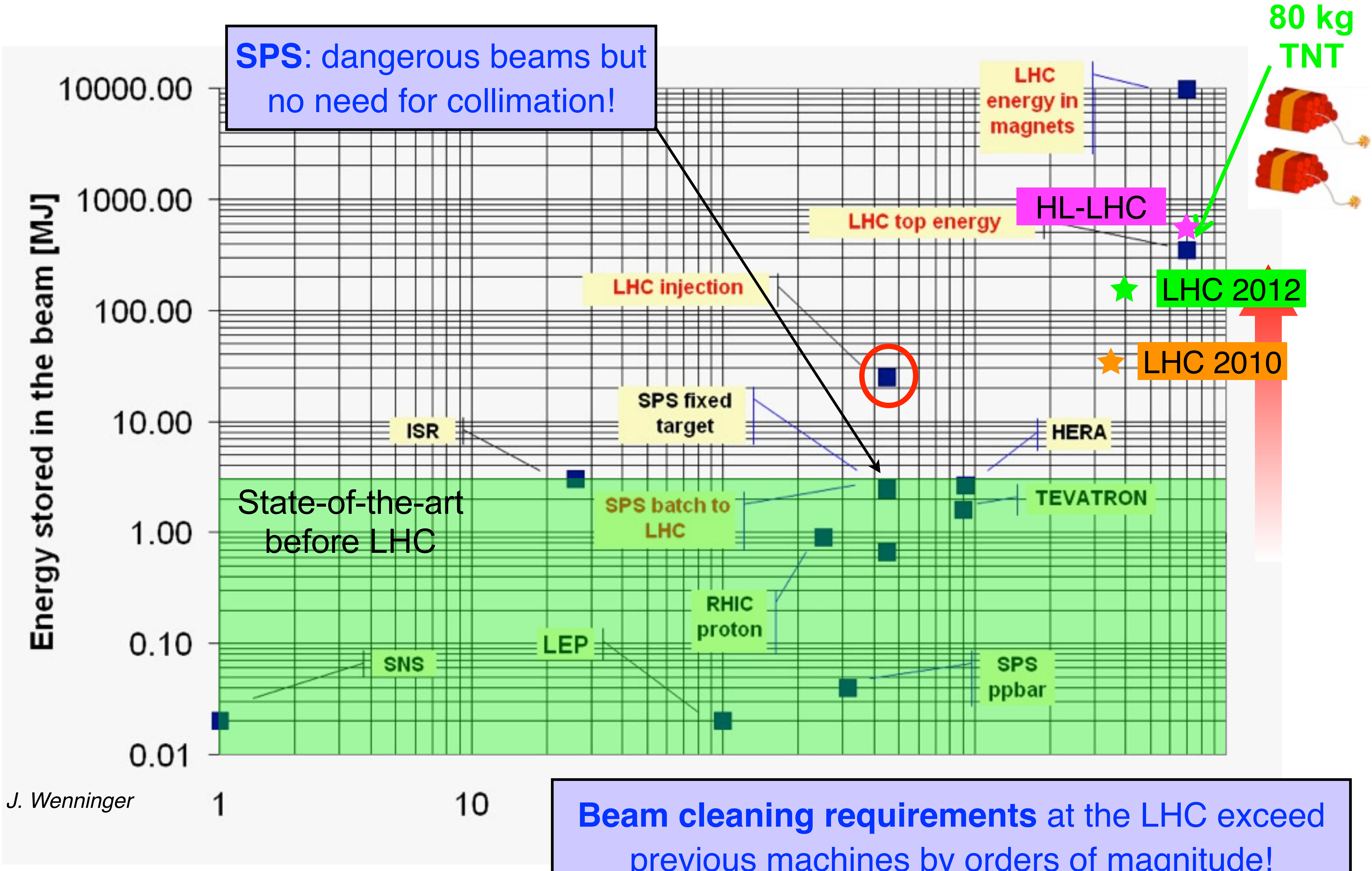
Superconducting coil:
T = 1.9 K, quench limit
$\sim$ 50-100 mJ/cm^3

Factor up to 9.7×10^{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!

The LHC stored energy challenge



SPS: dangerous beams but no need for collimation!

80 kg TNT

HL-LHC

LHC 2012

LHC 2010

State-of-the-art before LHC

J. Wenninger

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

Important roles of collimation

- **Halo cleaning** versus quench limits
- Passive **machine protection**

  First line of defense in case of accidental failures.

➛ See talk by J. Wenninger

- **Concentration of losses/activation** in controlled areas

  Avoid many hot locations around the 27km-long tunnel
- **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** (collision products)

  Avoid SC magnet quenches close to the high-luminosity experiments
- Optimize **background** in the experiments

  Minimize the impact of halo losses on
  (no big issue for the LHC)

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

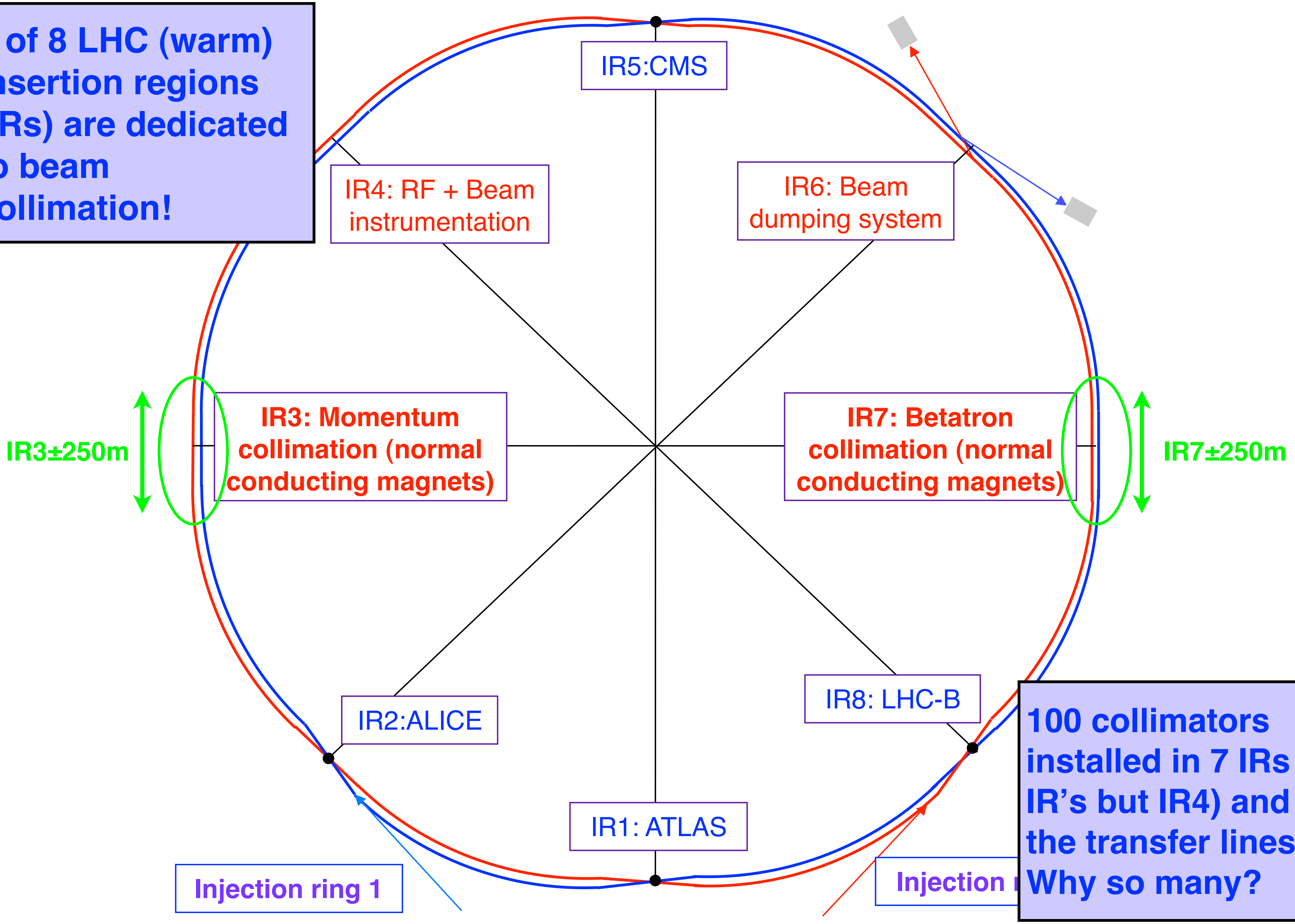
- Beam tail/halo **scraping**, **halo diagnostics**

  Control and probe

This lecture: focus on LHC, the only CERN machine with a collimation system that addresses all this requirements!

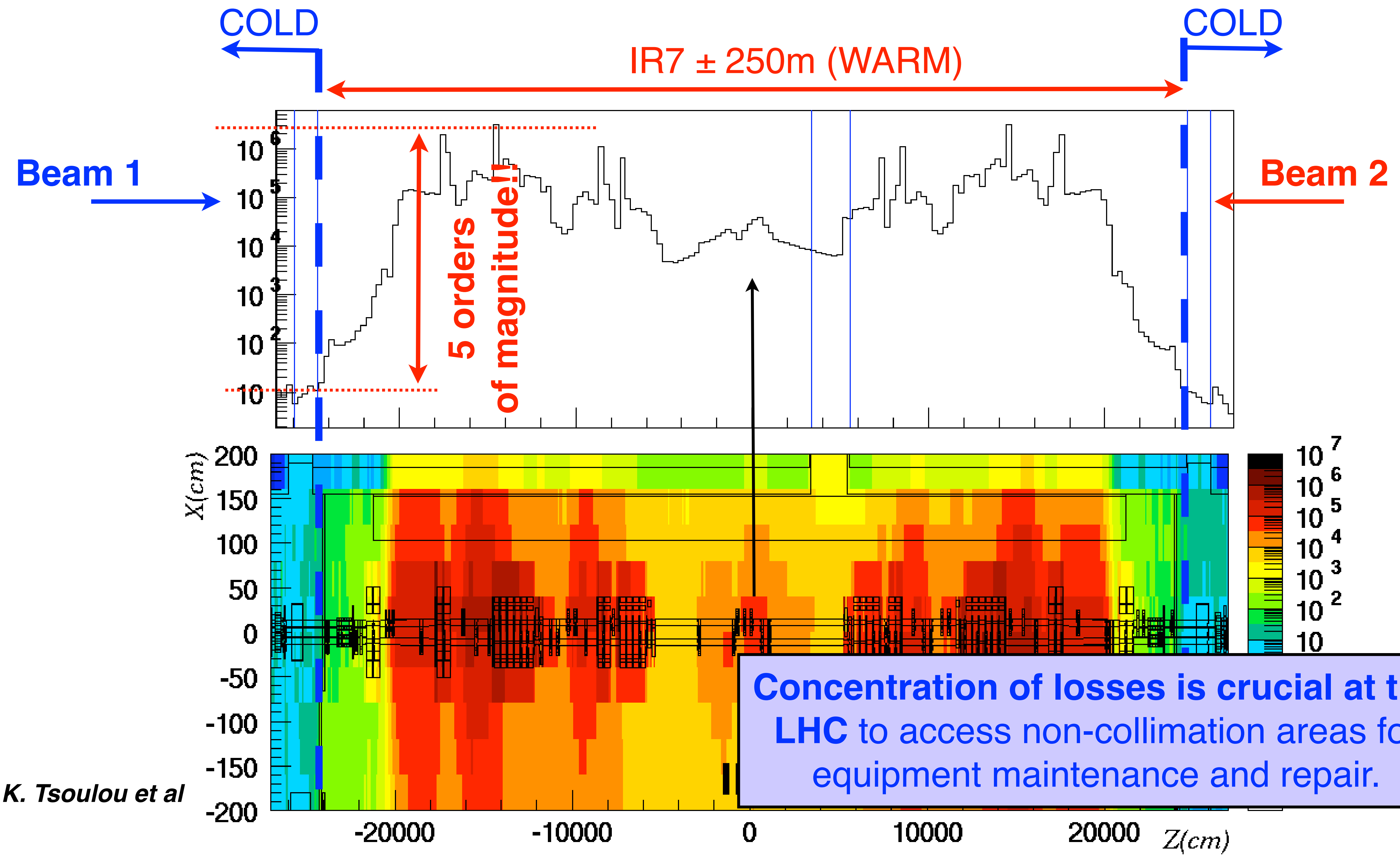
LHC ring layout

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



100 collimators installed in 7 IRs (all IR's but IR4) and in the transfer lines! Why so many?

Radiation doses in collimation region



K. Tsoulou et al

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!

Why do we have beam losses?

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

LHC: injection, ramp, squeeze, collisions, beam dump.

No need for a collimation system!

In reality, several effects can 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****"*
- *Beam* ***resonances****.*
- *Capture losses at beginning of the ramp.*
- *Injection and dump losses.*

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

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

Beam lifetime

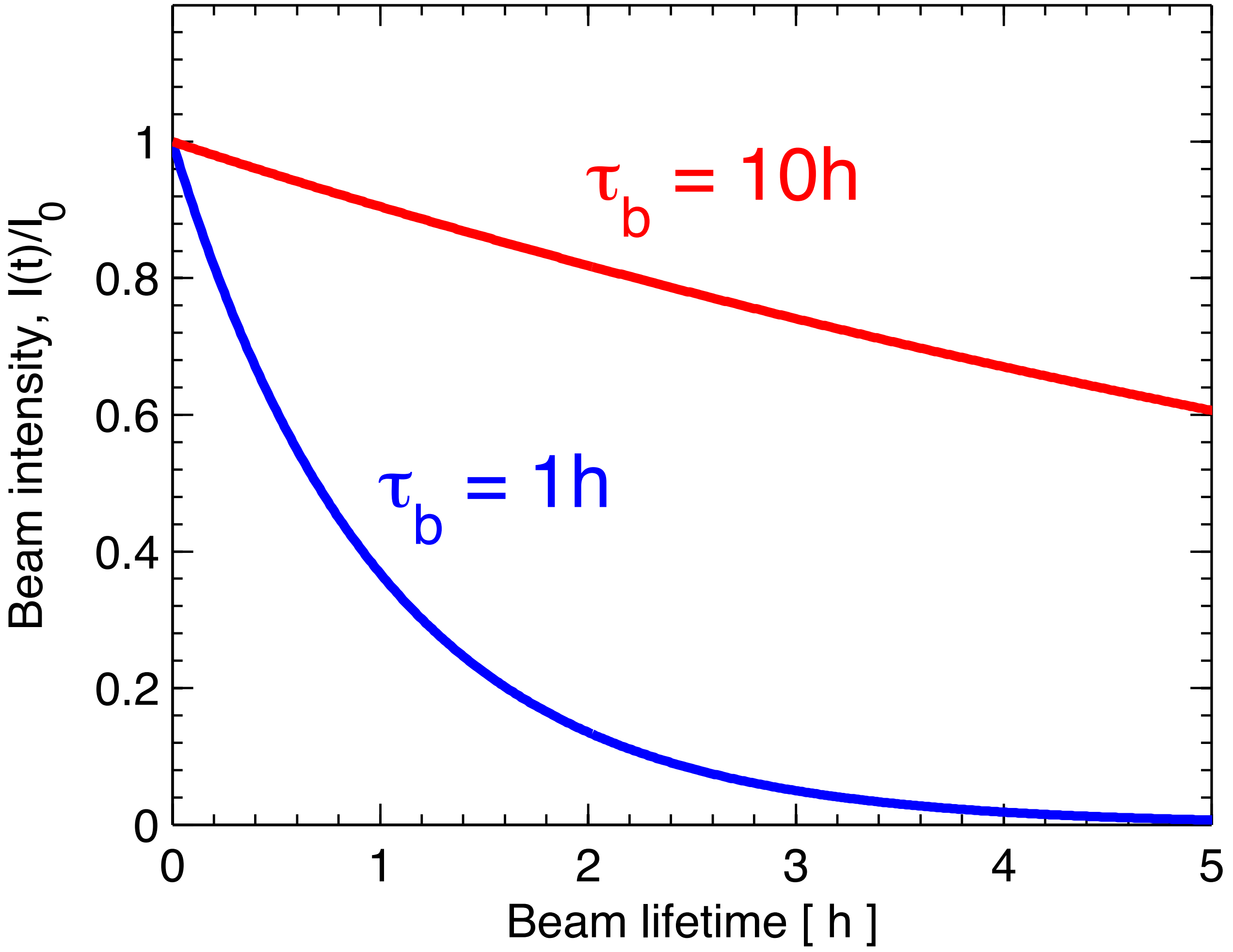
Beam loss mechanisms are modelled by assuming a non-infinite **beam lifetime,** τ_b

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

: Beam intensity versus time

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

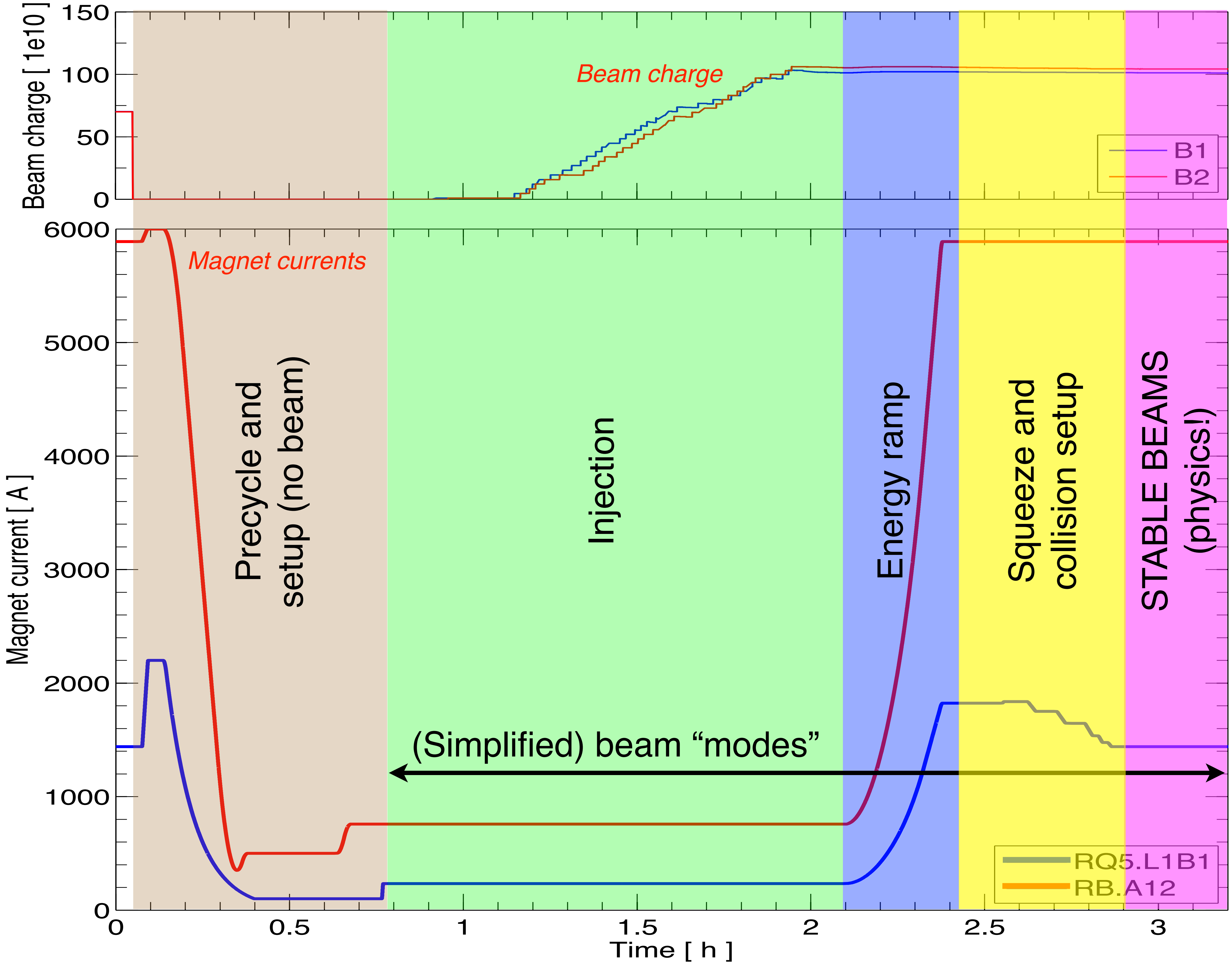
: Proton loss rate



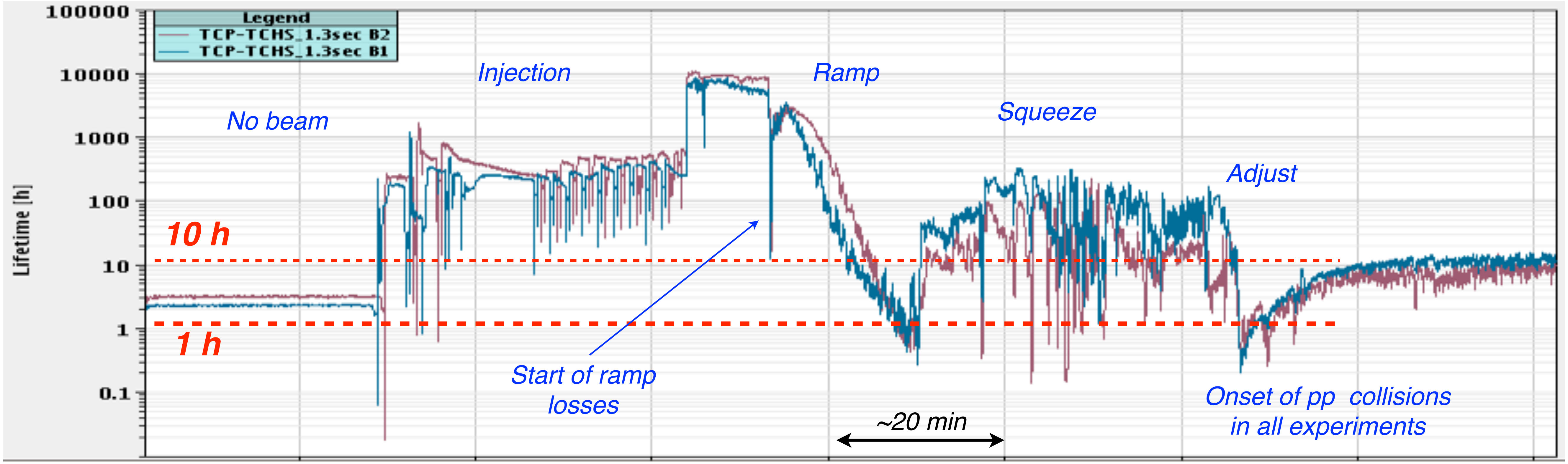
We will characterize beam losses by considering the time-dependent beam lifetime along the operational cycle.

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

LHC operational cycle



LHC lifetime in a physics fill



Example of a typical physics fill in 2012.

The **losses** from the beam core **must be caught** before they reach sensitive accelerator components!

In particular, the **peak power** deposited into the cold magnets must remain below quench limits of superconducting magnets

- ➛ *this is what the collimation system is designed for!*

LHC cleaning challenge: need an “inefficiency” ~20-100mJ/100kJ !

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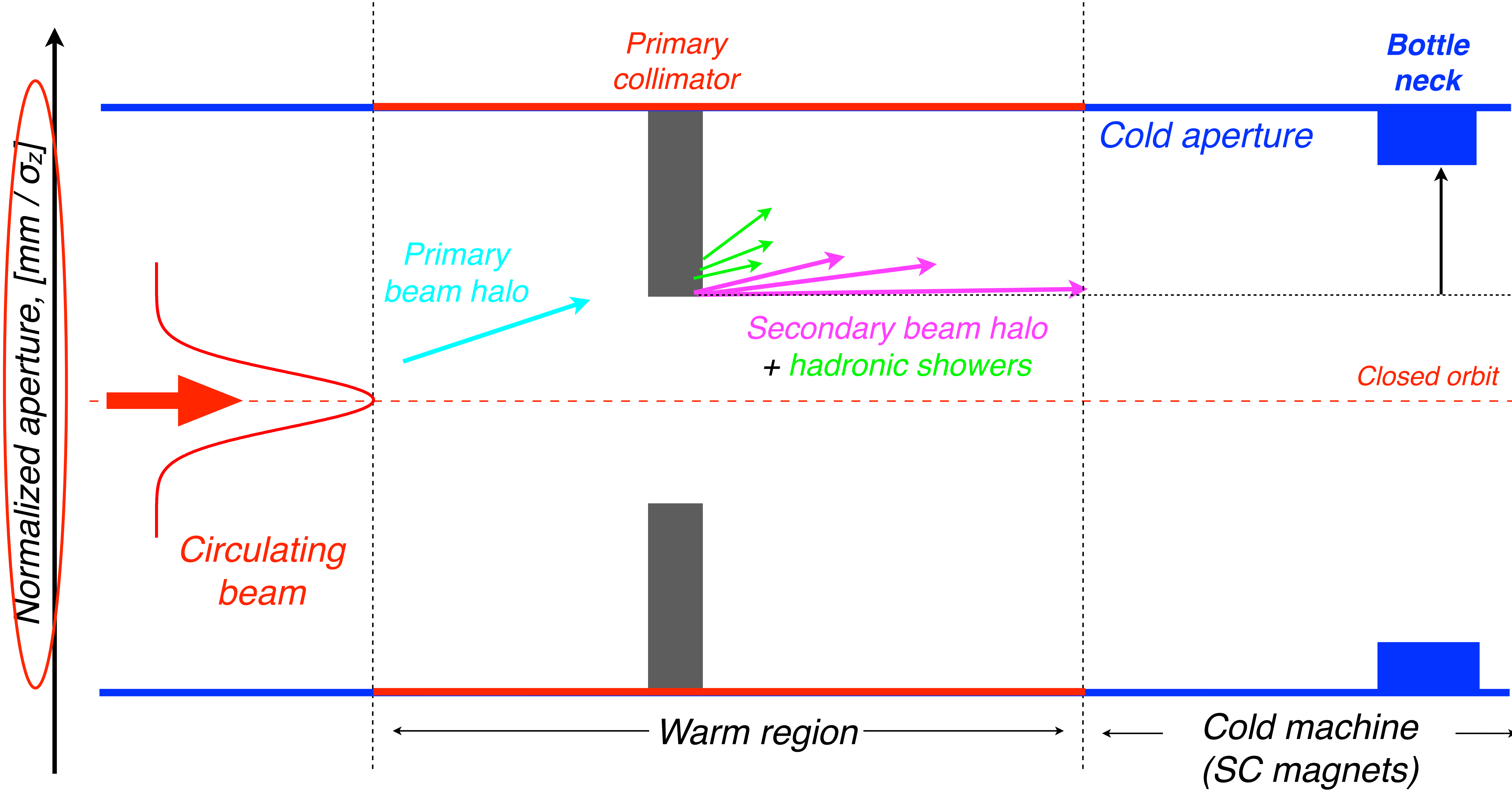
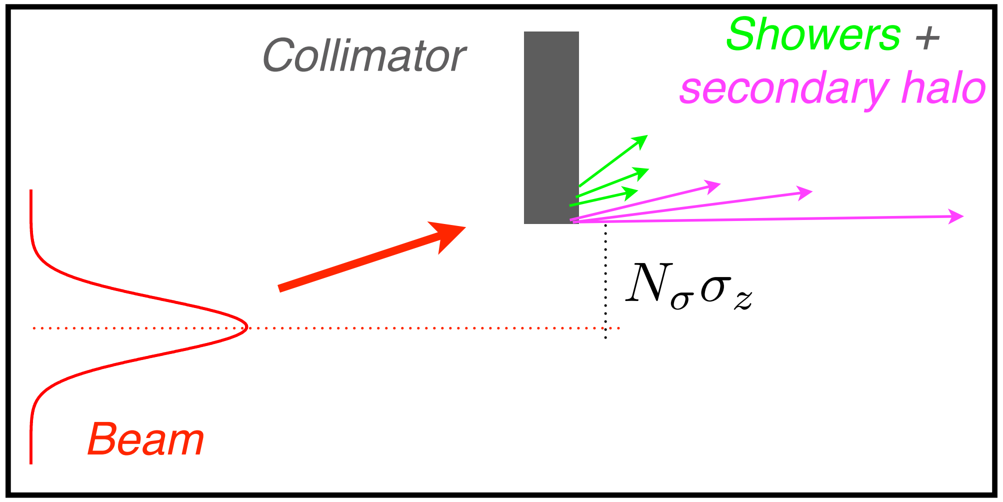
Aperture and single-stage cleaning



Particle lost from the beam core drift transversally, populate beam tails ultimately reach the machine *aperture bottleneck*.

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

Particle interaction with collimator

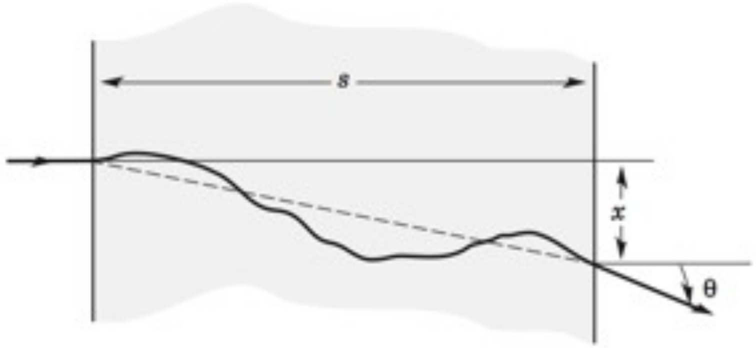


If the “primary” collimator were a black absorber, it would be sufficient to shield the aperture by choosing a gap $N_\sigma \sigma_z$ smaller that the aperture bottleneck !

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

See also Jörg W.’s talk.

Here: what matters in the energy leakage!

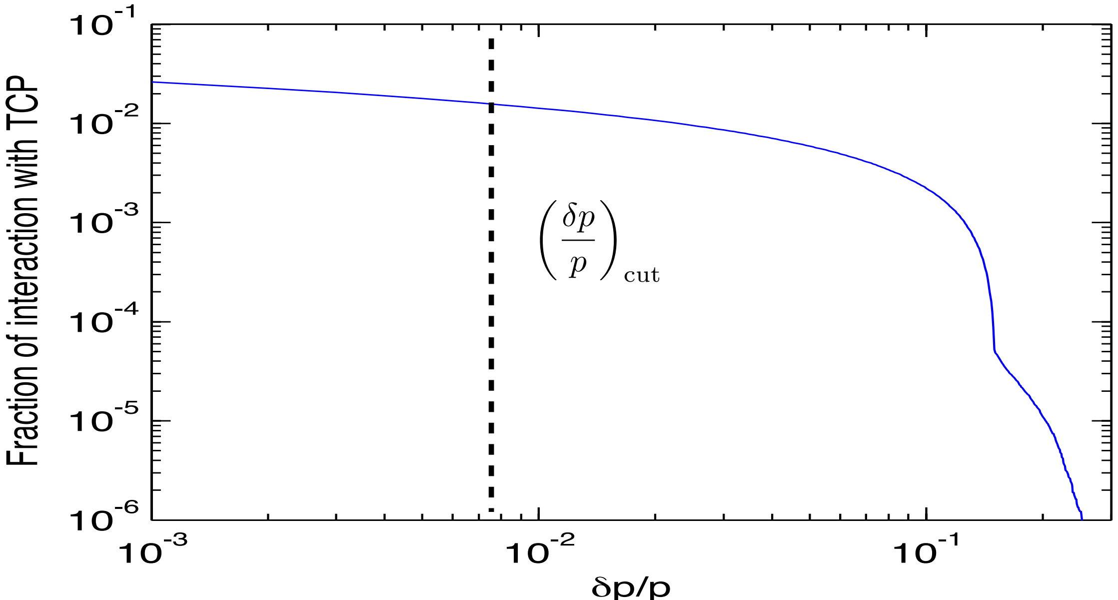


$$\sqrt{\langle\theta_p^2\rangle} = \frac{13.6}{cp[\mathrm{MeV}]}\sqrt{\frac{s}{\chi_0}}\left(1+0.038\cdot\left(\frac{s}{\chi_0}\right)\right)$$

χ_0 : radiation length

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

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



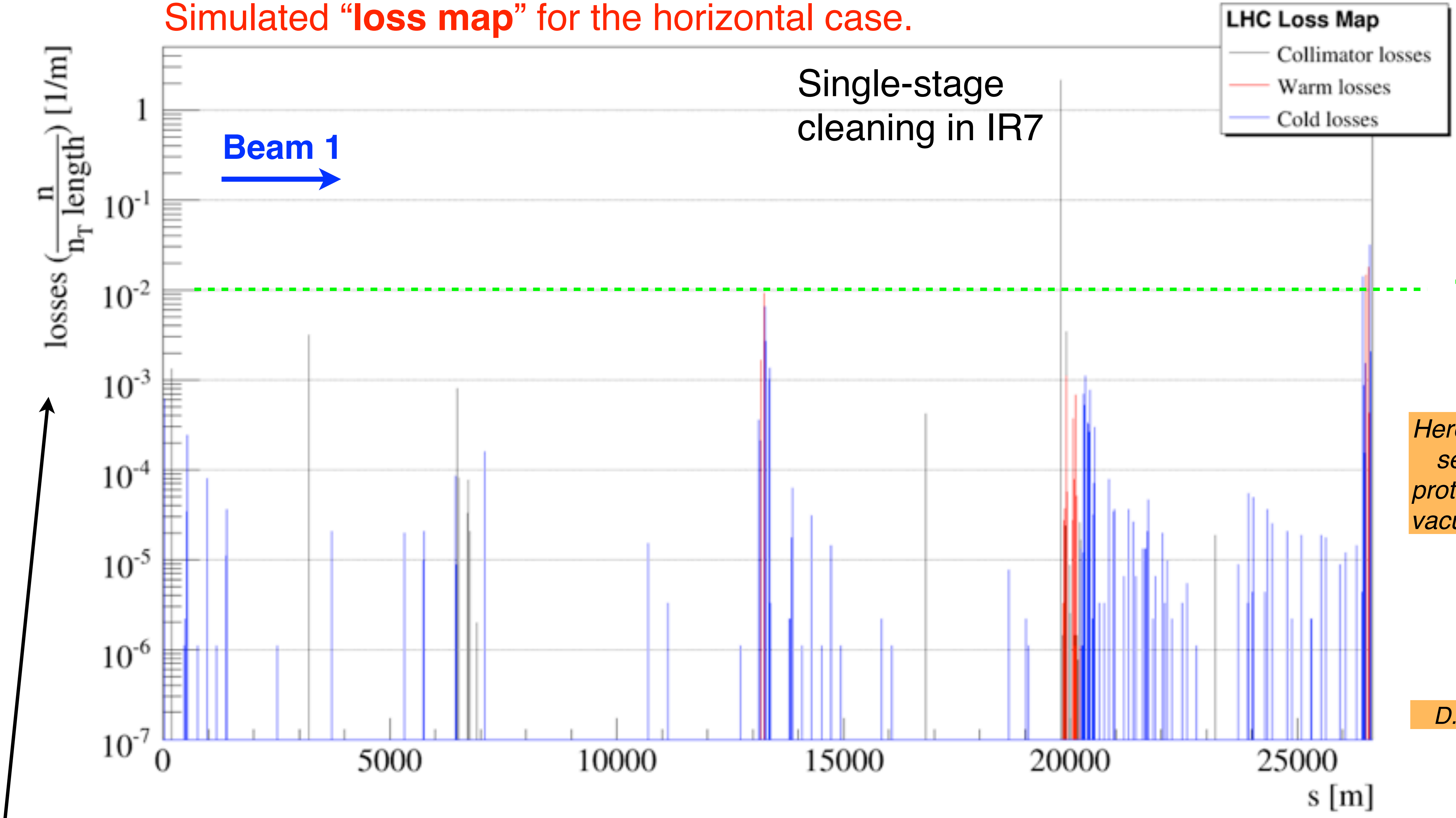
The interaction with collimator jaw materials is itself a source of betatron and off-momentum halo (secondary halo).

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

Simulated “**loss map**” for the horizontal case.



1 %

Here: looking at the secondary halo protons lost into the vacuum beam-pipe.

D. Mirarchi

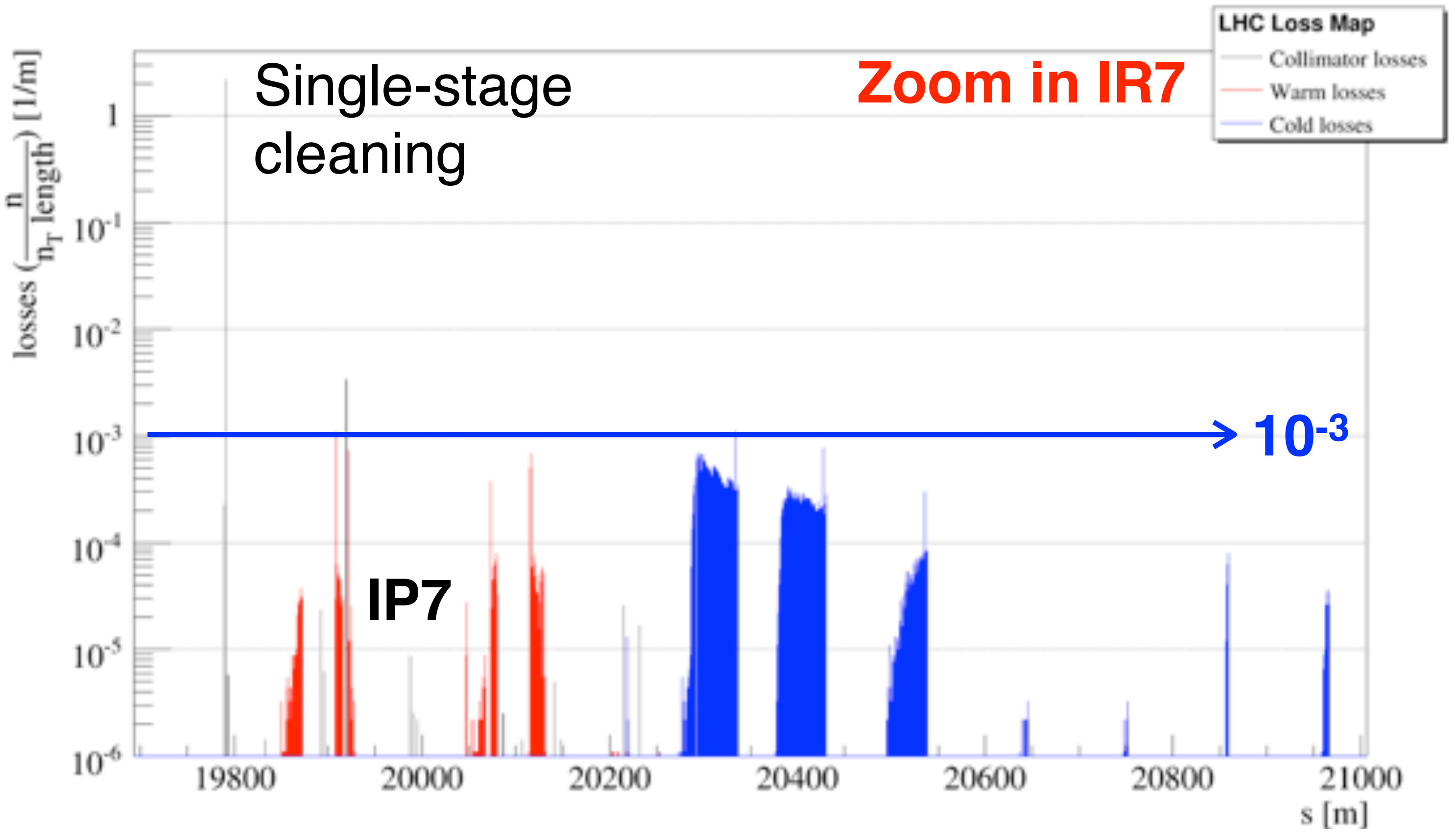
Local cleaning inefficiency

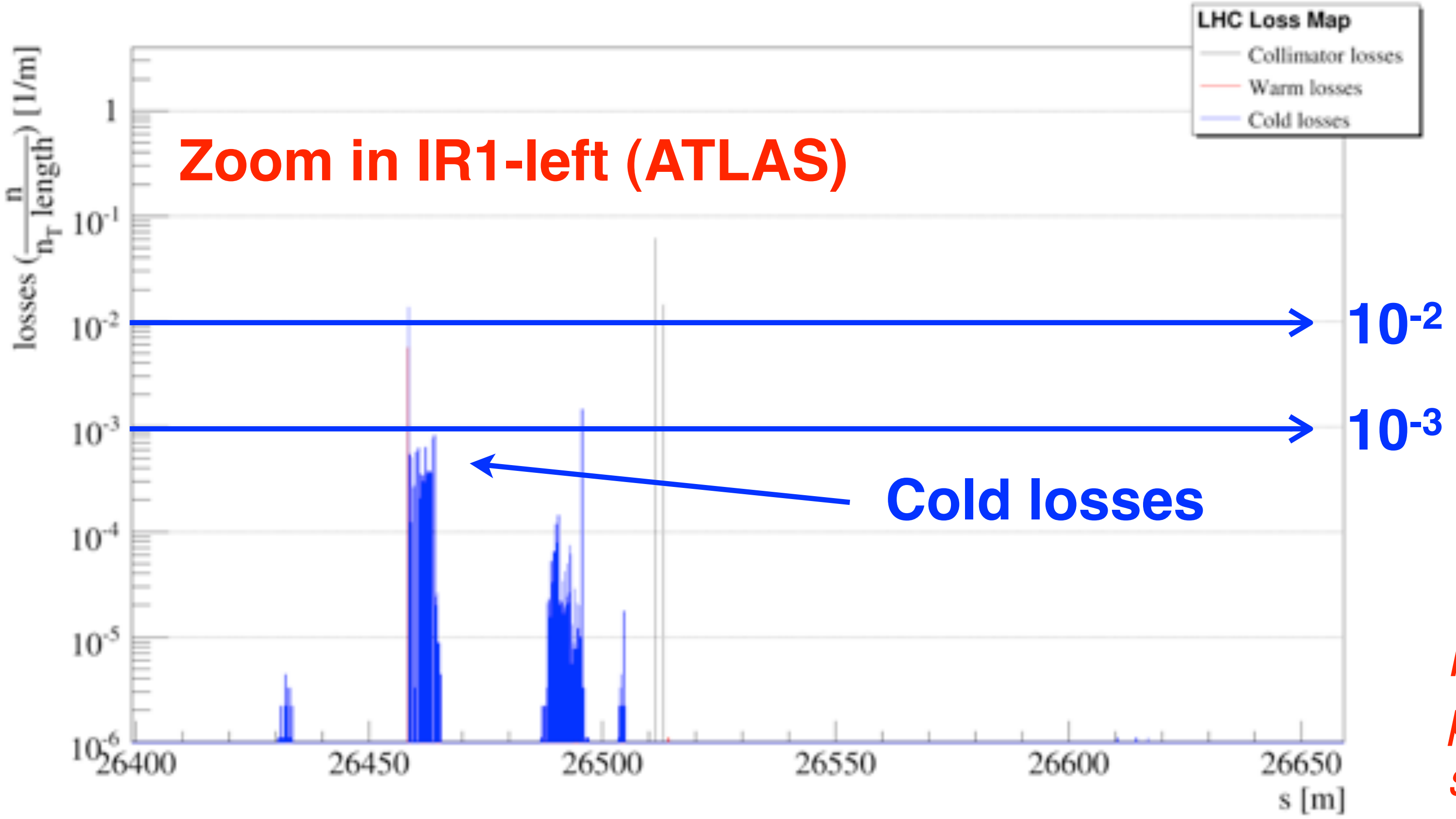
$$\tilde{\eta}_c(s) = \frac{1}{\Delta s} \frac{N_{\text{loss}}(s \rightarrow s + \Delta s)}{N_{\text{abs}}}$$

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:

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

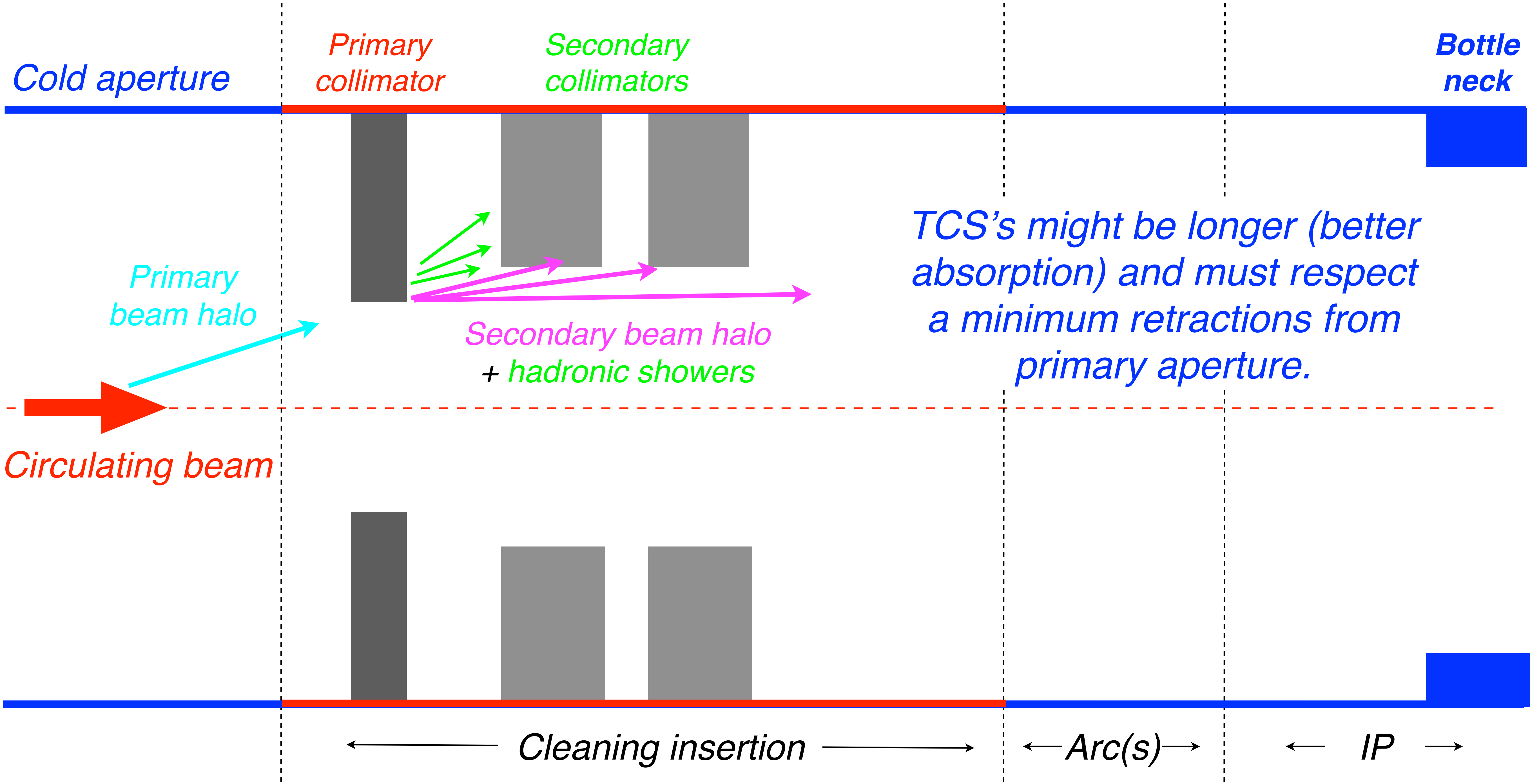
With the single-stage cleaning predicted by this model, losses are up to:

$\tau_b = 1\text{h} \rightarrow 90 \times 10^7$ p/m/s (**30 x R_q**)
$\tau_b = 0.1\text{h} \rightarrow 450 \times 10^7$ 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!*

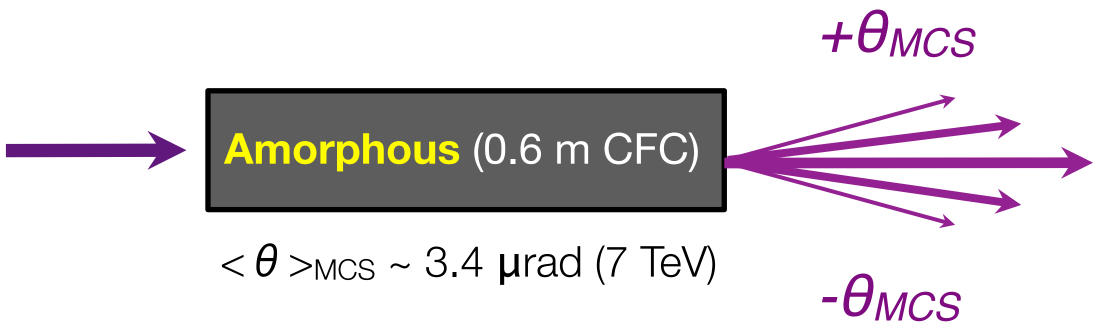
Two-stage collimation



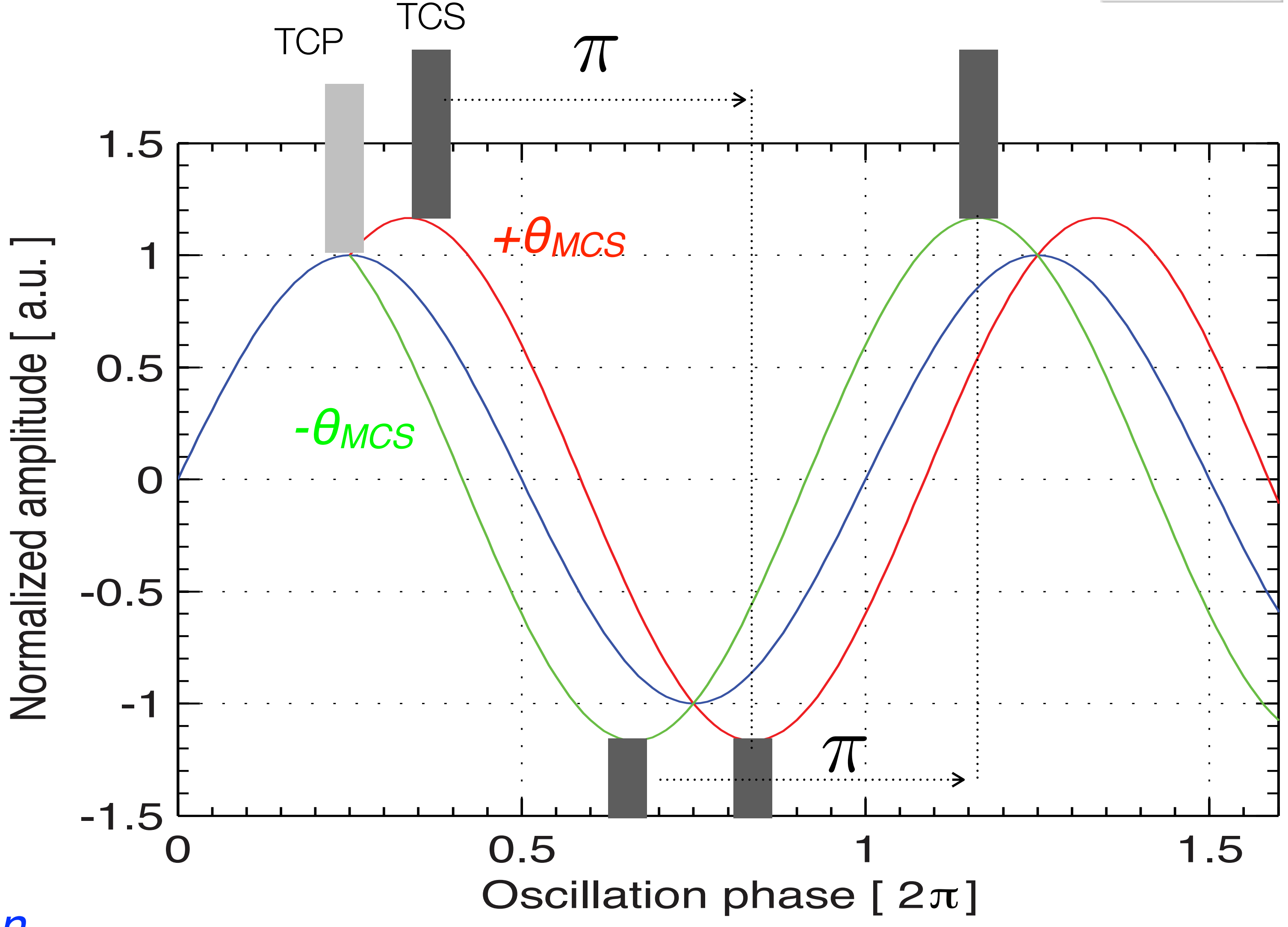
TCS's might be longer (better absorption) and must respect a minimum retractions from primary aperture.

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

Where do we put secondary collimators?



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.



Optimum phases depend on TCP/TCS retraction

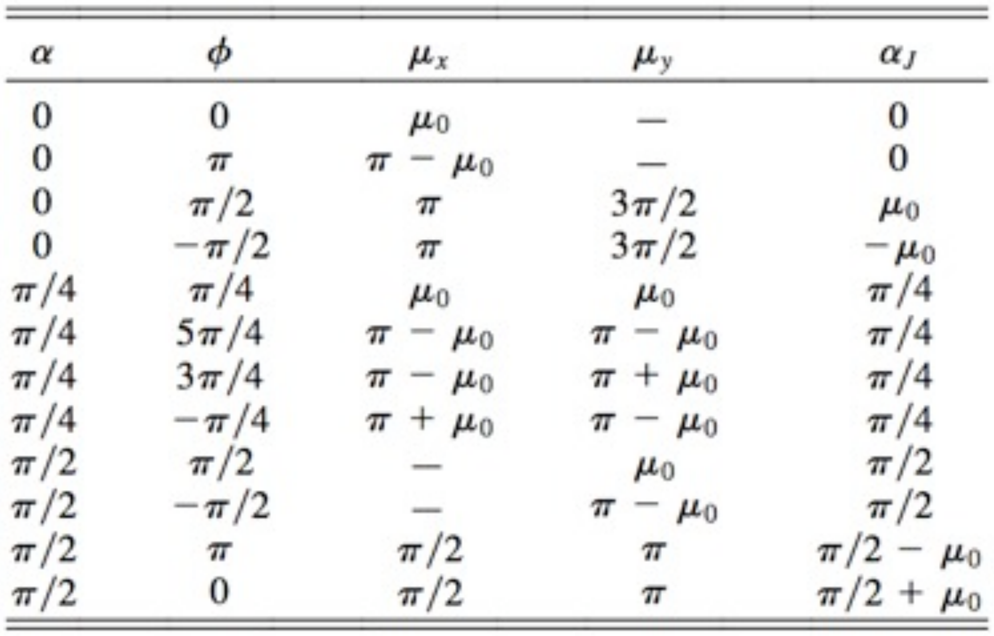
$$\tan \mu_x = \frac{\sqrt{n_{\mathrm{TCP}}^2 - n_{\mathrm{TCS}}^2}}{n_{\mathrm{TCP}}^2} \frac{\cos \phi}{\cos \alpha}$$

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

α, ϕ : collimator plane and scattering angle

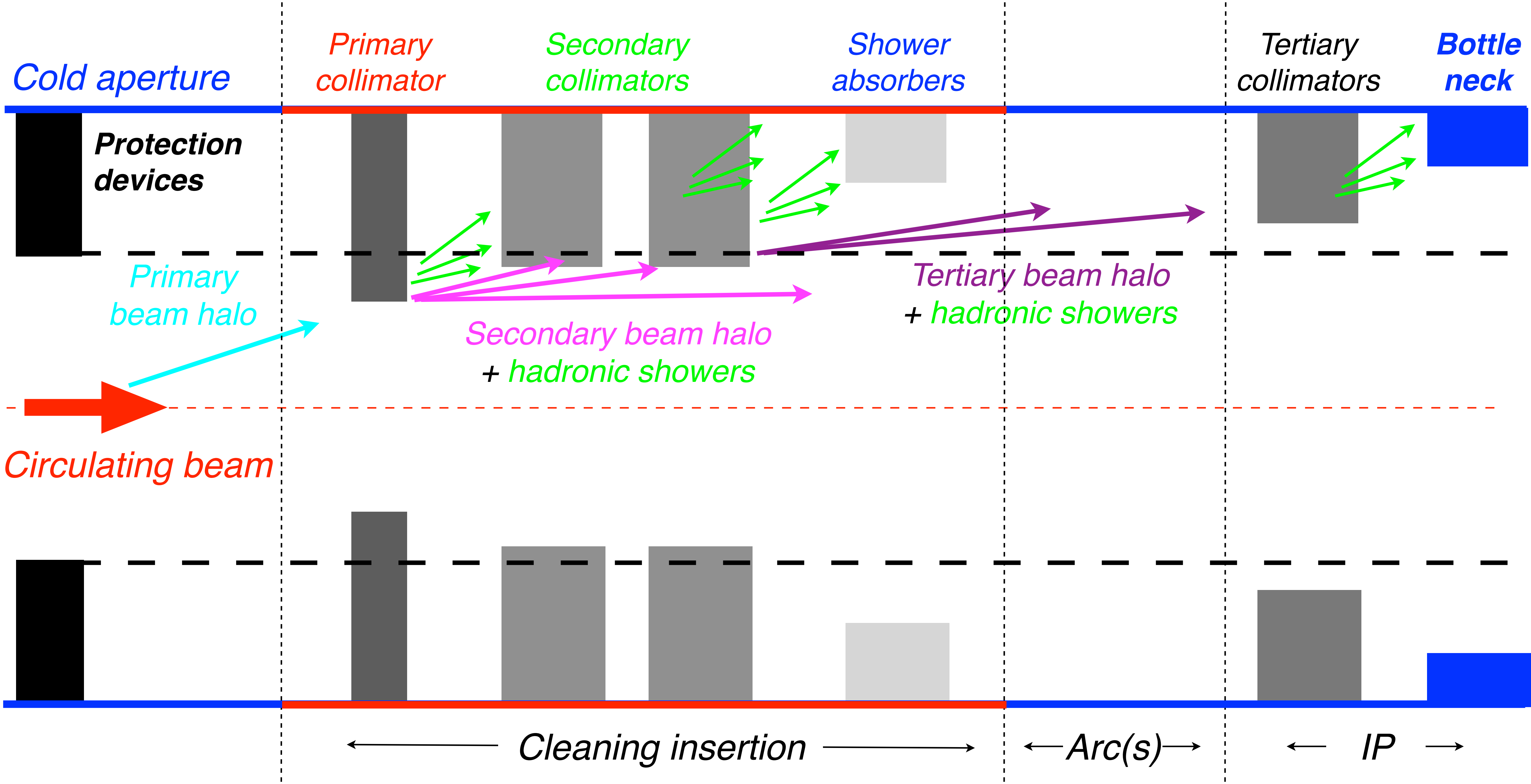
$$\cos \mu_0 = n_{\mathrm{TCP}} / n_{\mathrm{TCS}}$$

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



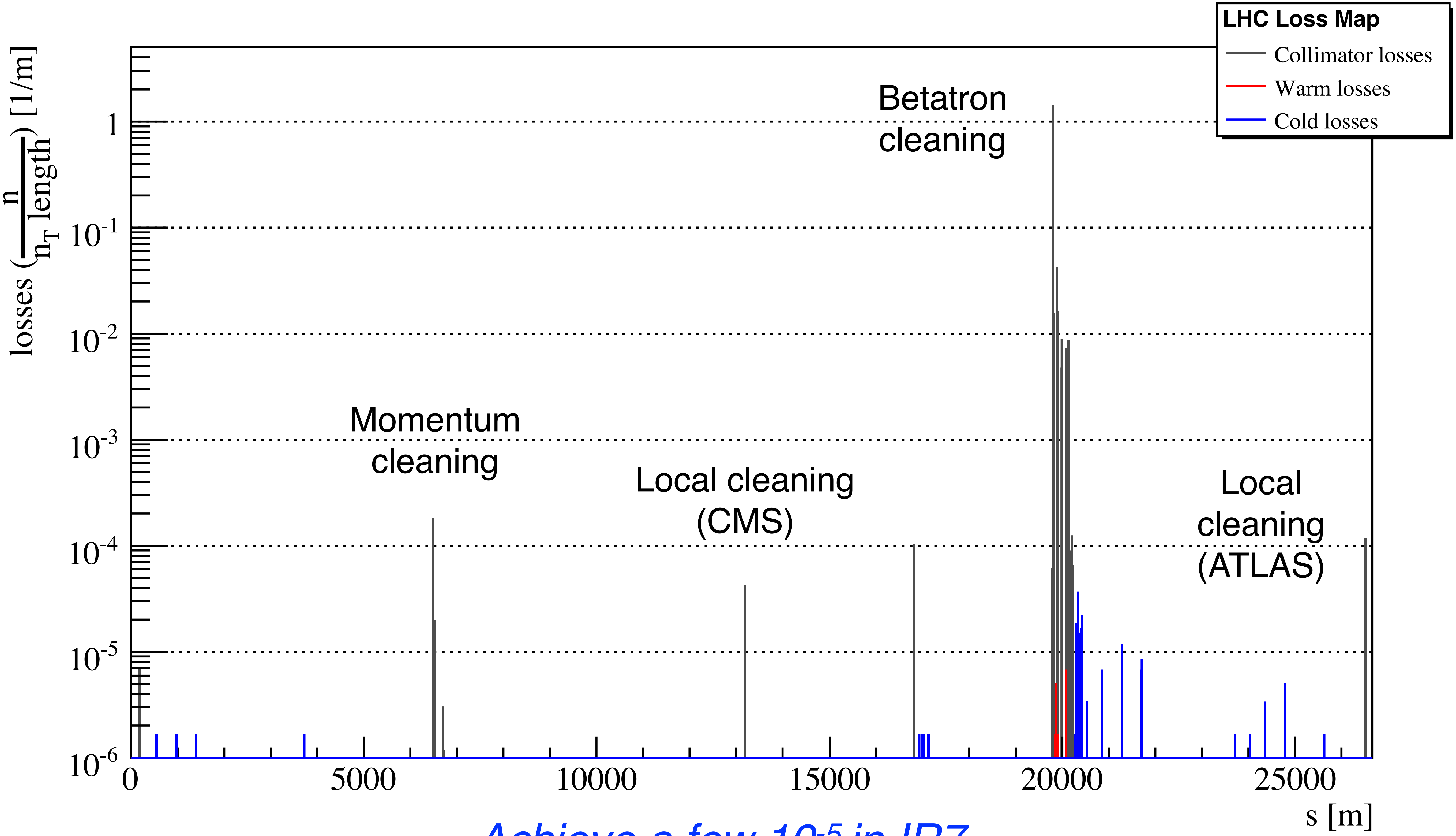
α	ϕ	μ_x	μ_y	α_J
0	0	μ_0	—	0
0	π	$\pi - \mu_0$	—	0
0	$\pi/2$	π	$3\pi/2$	μ_0
0	$-\pi/2$	π	$3\pi/2$	$-\mu_0$
$\pi/4$	$\pi/4$	μ_0	μ_0	$\pi/4$
$\pi/4$	$5\pi/4$	$\pi - \mu_0$	$\pi - \mu_0$	$\pi/4$
$\pi/4$	$3\pi/4$	$\pi - \mu_0$	$\pi + \mu_0$	$\pi/4$
$\pi/4$	$-\pi/4$	$\pi + \mu_0$	$\pi - \mu_0$	$\pi/4$
$\pi/2$	$\pi/2$	—	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 collimator families and machine aperture.

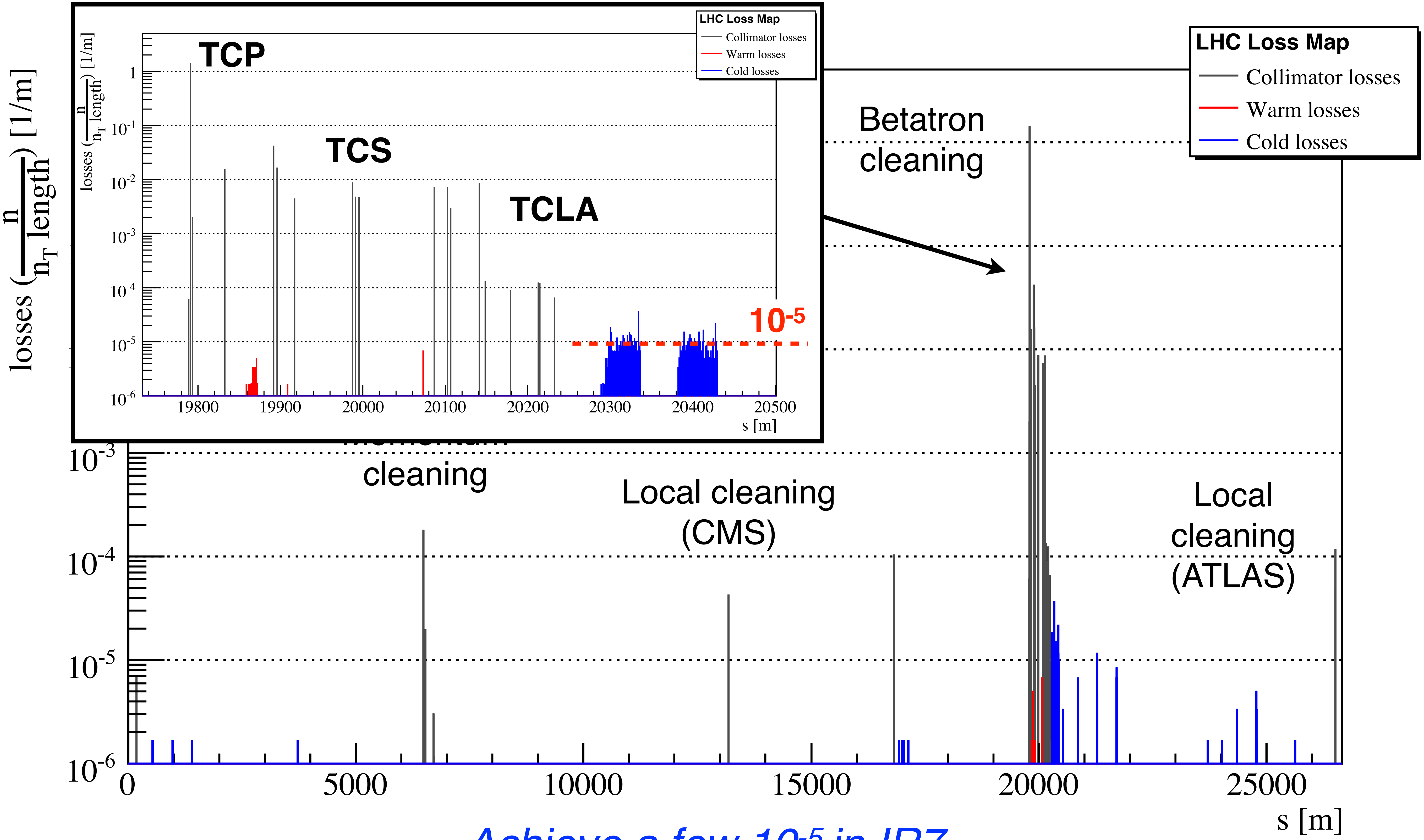
Simulated 7 TeV performance



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

Cold losses in experiments removed by local protection.

Simulated 7 TeV performance



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Main points to retain...

- **Beam collimation** is essential in modern high-power machines to safely dispose of unavoidable beam losses (*beam halo cleaning*).
  <u>LHC main concerns</u>: (1) minimize risk of quenches with 360 MJ stored energy, (2) passive machine protection in case of accidental failures. Many other important roles!
- 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.
- 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.
- **Multi-stage collimation** can provide the missing factors!
  Secondary collimators are placed at optimum locations to catch product of halo interactions with primaries (secondary halo+shower products).
- 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.*

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

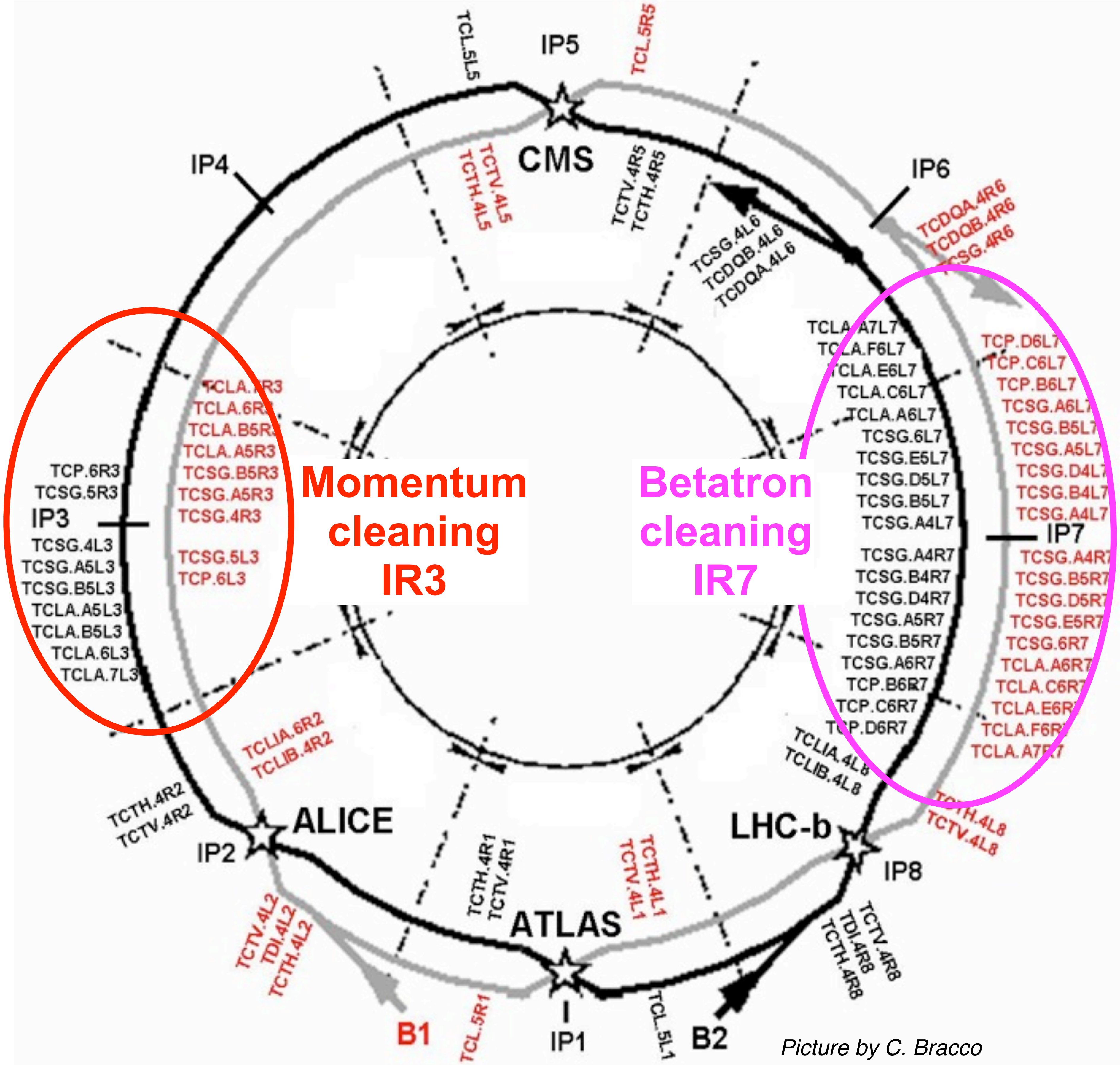
- **8 tertiary (2 per IP)**

Passive absorbers for warm magnets

Physics debris absorbers

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

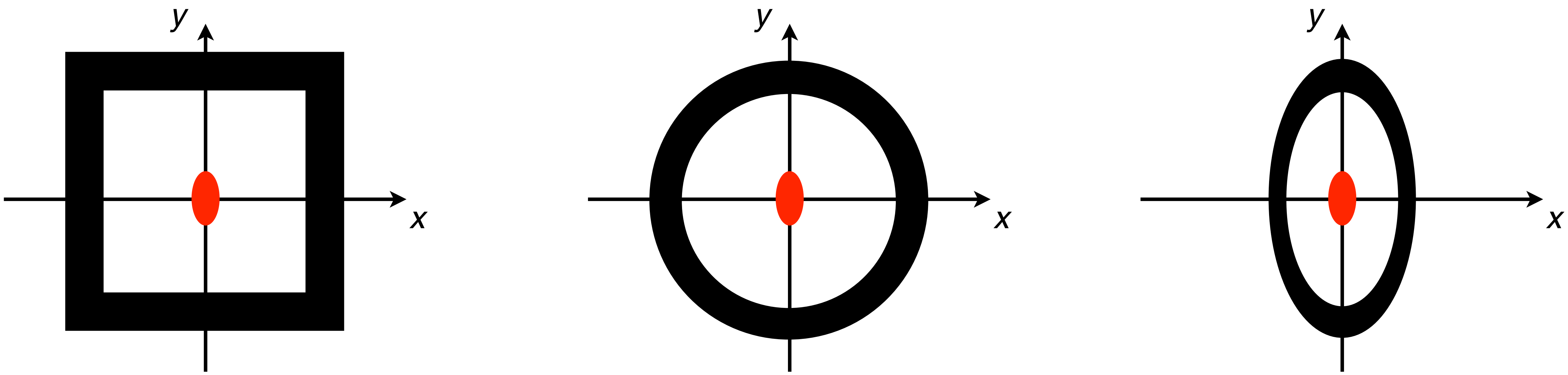
Total of 108 collimators (100 movable). Two jaws (4 motors) per collimator!



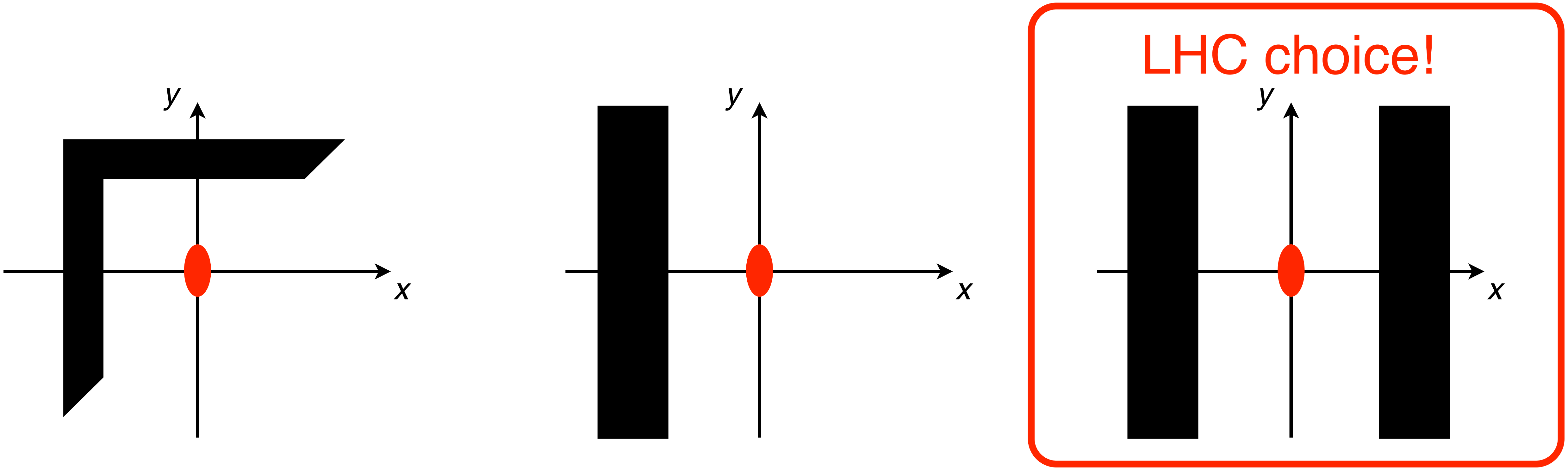
Picture by C. Bracco

Possible collimator designs

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

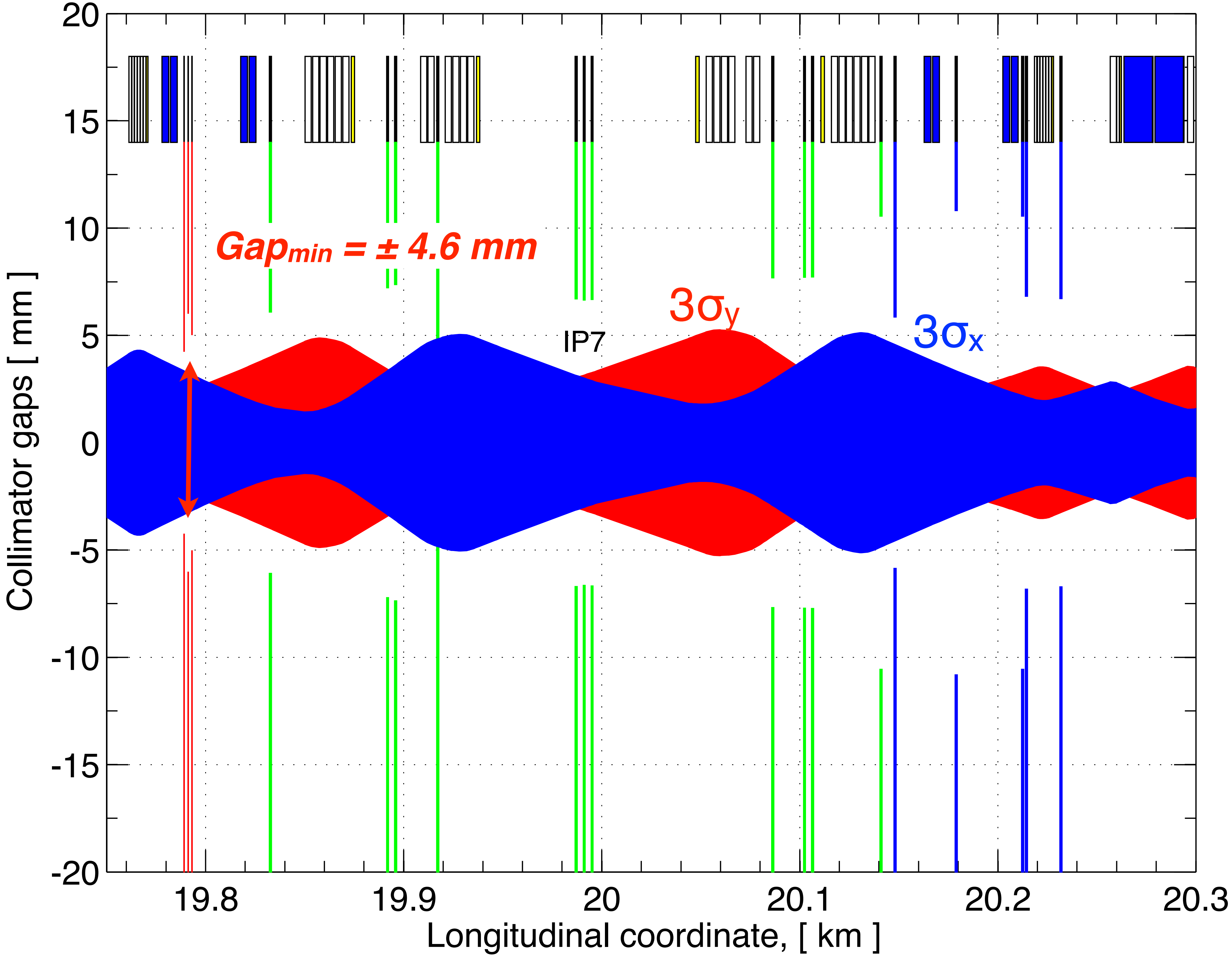


Movable collimators: L-shaped, one-sided, two-sided.


LHC choice!

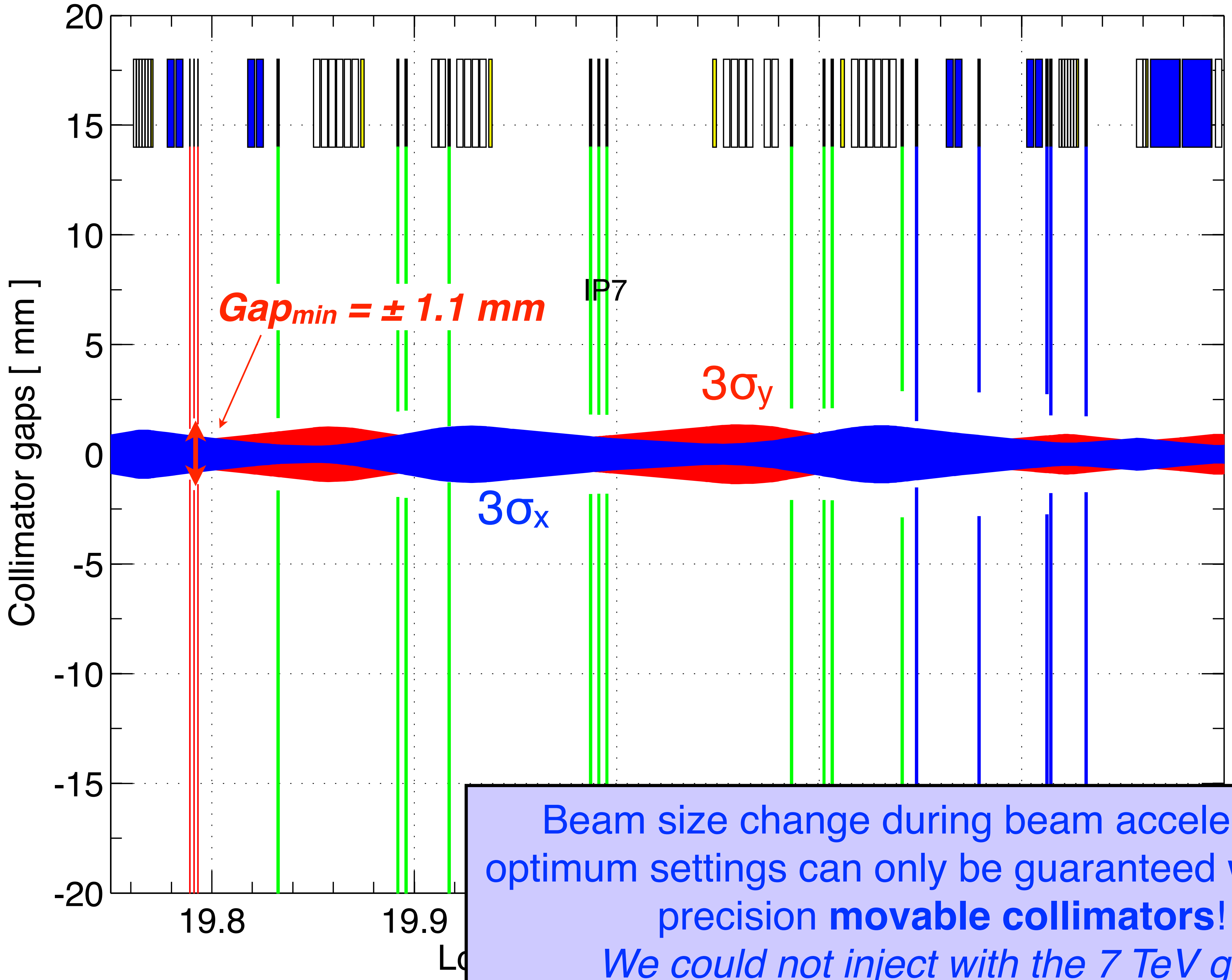
IR7 collimator settings at 450 GeV

$A_{TCP} = 5.7\ \sigma$ $A_{TCS} = 6.7\ \sigma$ $A_{TCLA} = 10\ \sigma$



IR7 collimator settings at 7 TeV

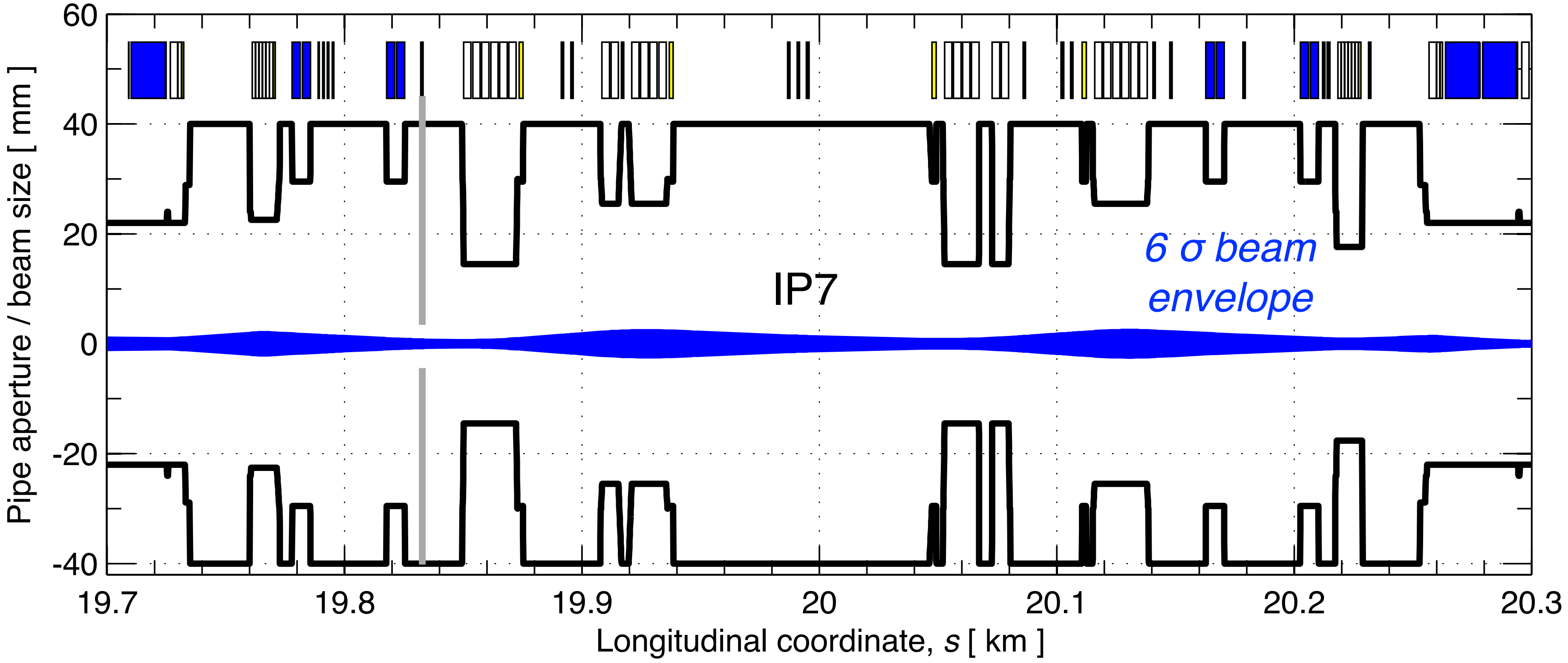
$A_{TCP} = 6\ \sigma$ **$A_{TCS} = 7\ \sigma$** **$A_{TCLA} = 10\ \sigma$**



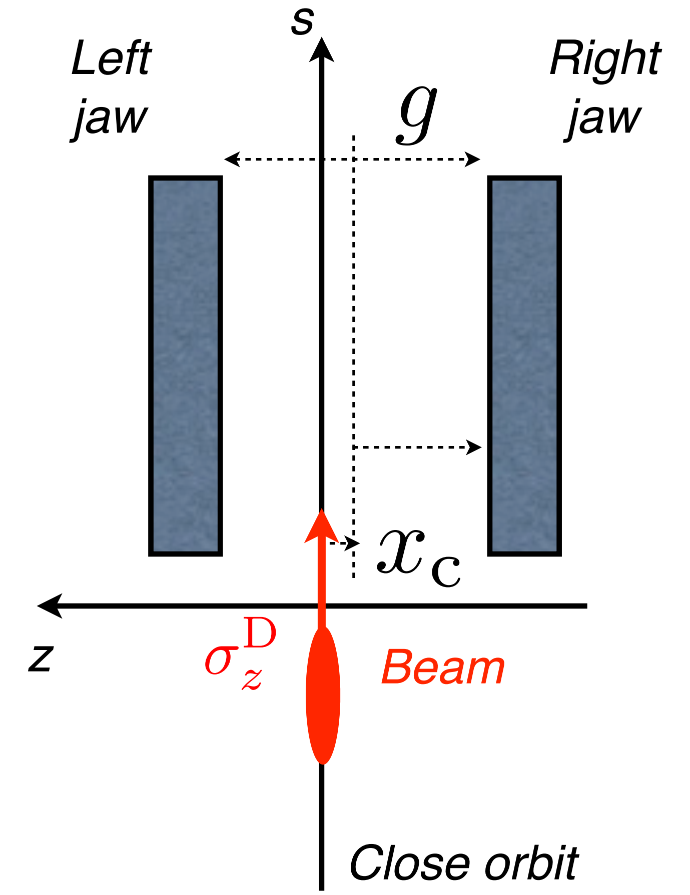
Beam size change during beam acceleration: optimum settings can only be guaranteed with high-precision **movable collimators**!

We could not inject with the 7 TeV gap!

Setting/aperture notations



Top view (*x*,*s*)



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

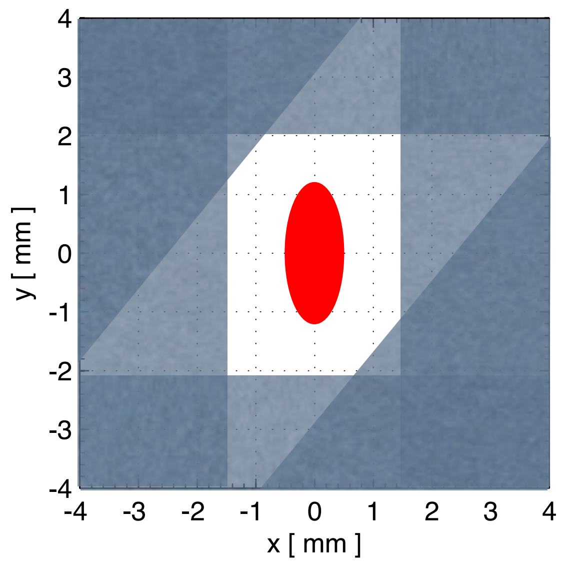
$$\boxed{N_\sigma = \frac{g}{2} \frac{1}{\sigma_z}}$$

: Normalized gap (beam size units)

$$\boxed{x_{\mathrm{c}} \pm N_\sigma \cdot \sigma_z}$$

: Collimator jaw positions

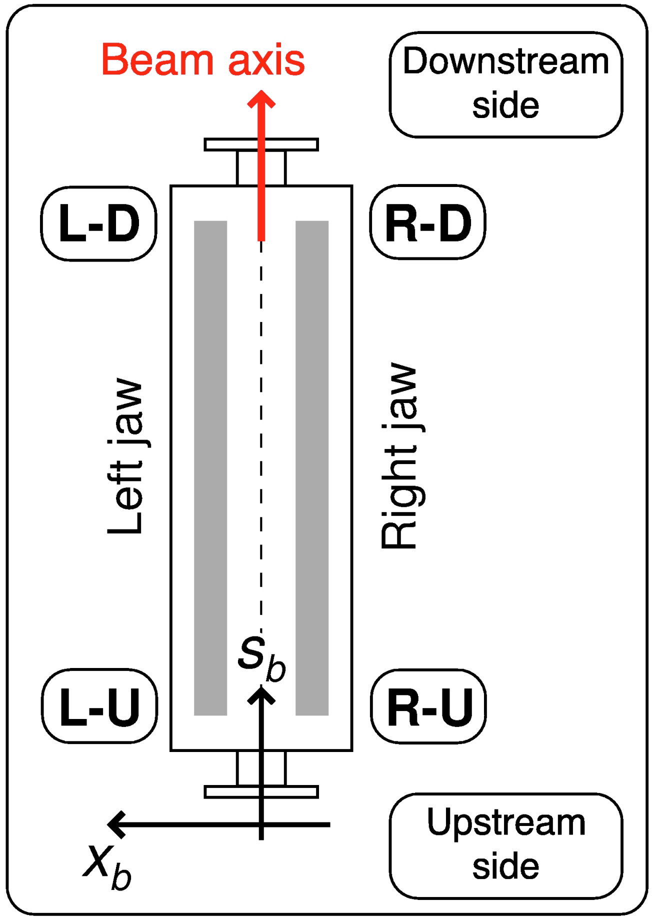
Front view (*x*,*y*)



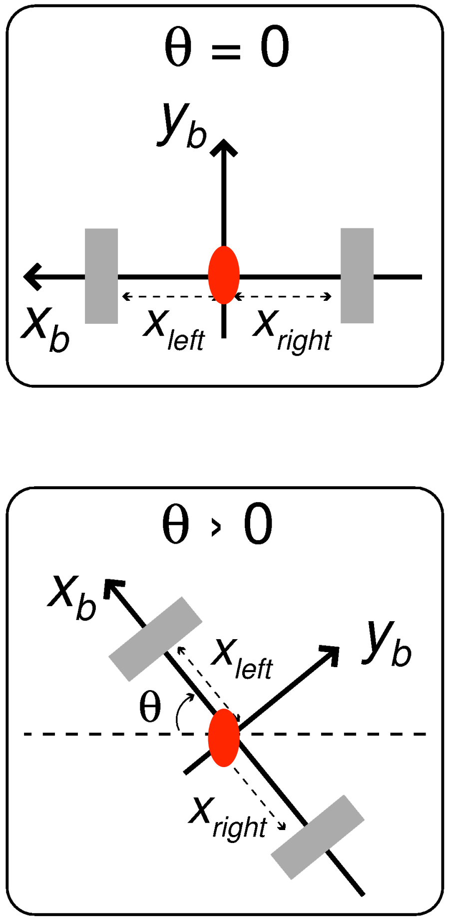
Collimator settings and aperture are expressed in normalized units, using the of local betatron beam size → enable to define the **setting "hierarchy"**!

“Skew” collimators

Top view



Front views



In the LHC, we also have “rotated” collimators that provide collimation in the ***skew plane.***

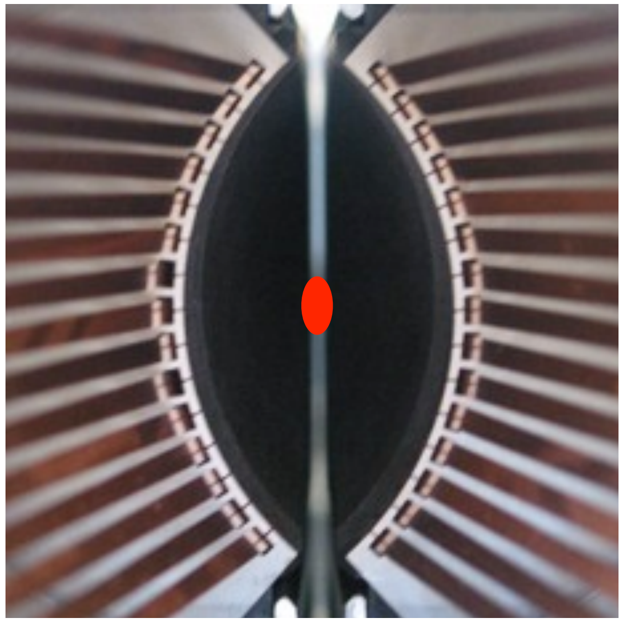
The collimator jaw movement occurs along the skew axis (still 1D movement). Normalized settings are defined for an appropriate effective beam size.

Same collimator design for all cases: rotate vacuum tank.

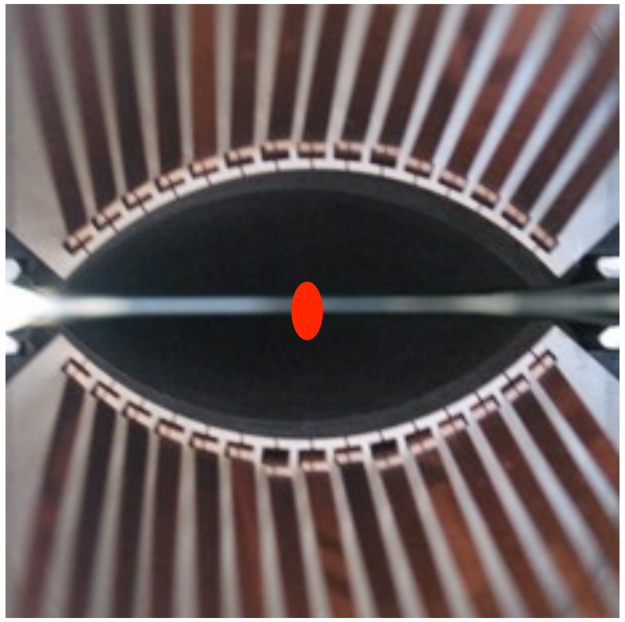
RMS *betatron* beam size in the collimator plane

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

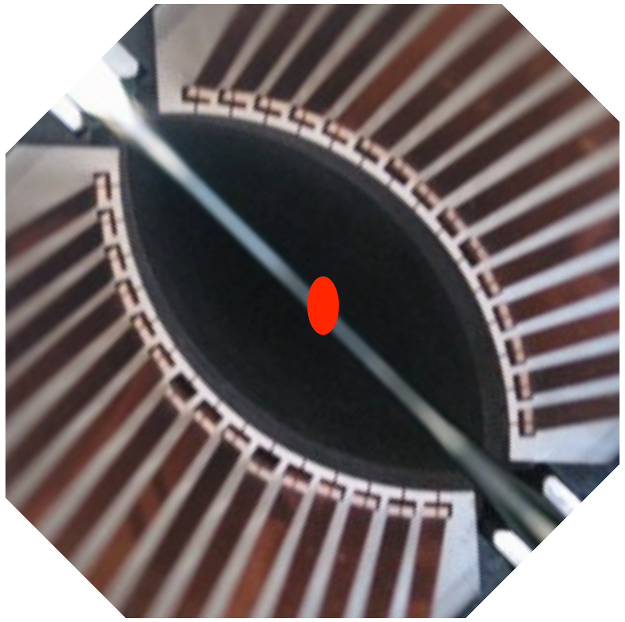
Horizontal



Vertical



Skew



We need at least 3 **primary collimators** in order to protect the machine for all possible transverse betatron losses! Only horizontal collimation for momentum losses.

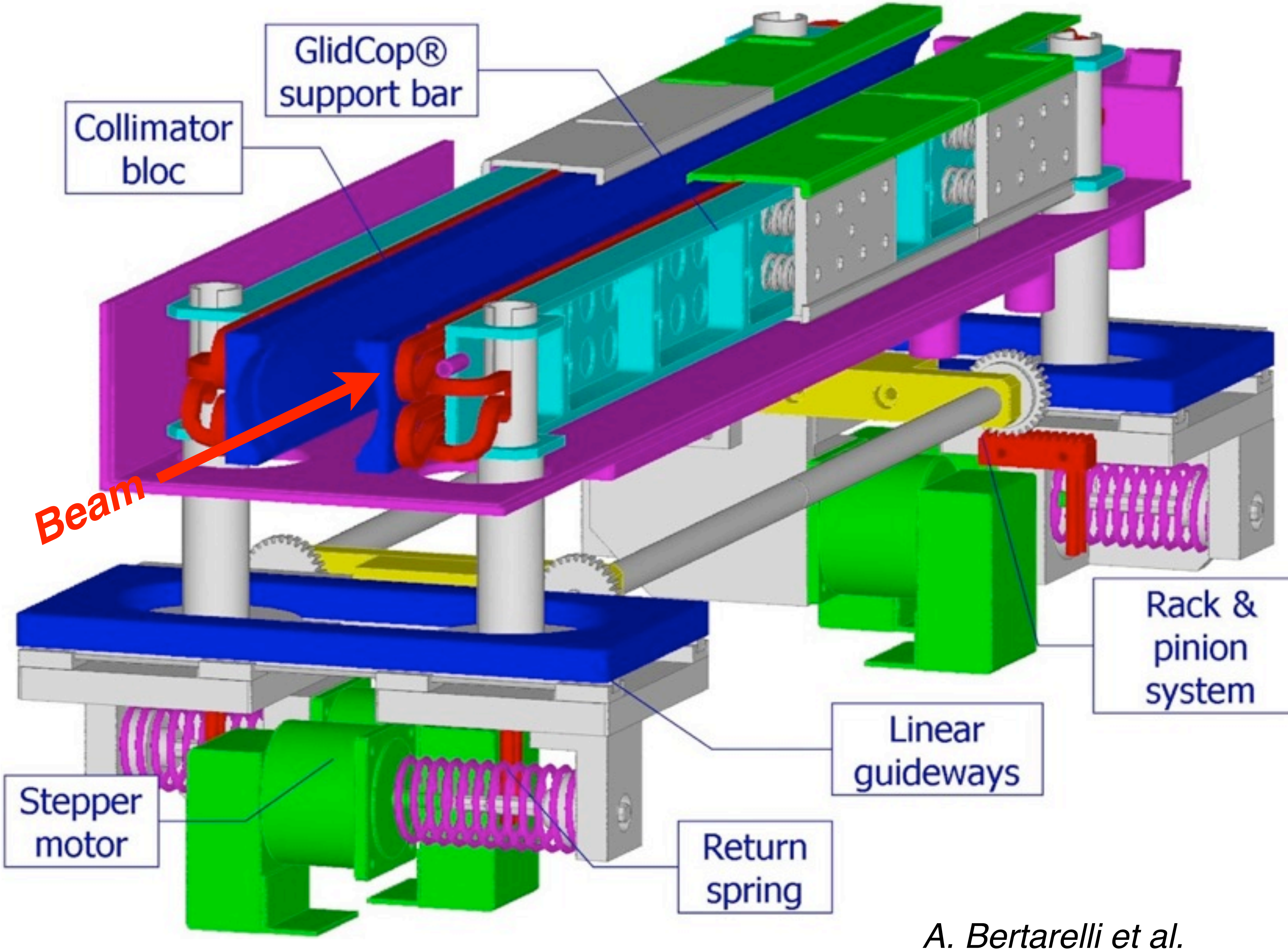
Reference design goals

High stored beam energy (melt 500 kg Cu, required for 10^{34} cm^{-2} s^{-1} luminosity)	**~ 360 MJ/beam**	Quench
Large transverse energy density (beam is destructive, 3 orders beyond Tevatron/HERA)	**1 GJ/mm^2**	Damage
High required cleaning efficiency (clean lost protons to avoid SC magnet quenches)	**99.998 % (~10^{-5})**	Heating
Activation of collimation insertions (good reliability required, very restricted access)	**~ 1-15 mSv/h**	Activation
Small spot sizes at high energy (small 7 TeV emittance, no large beta in restricted space)	**~ 200 μm**	Stability
Collimation close to beam (available mechanical aperture is at ~10 σ)	**6-7 σ**	Impedance
Small collimator gaps (impedance problem, tight tolerances: ~ 10 μm)	**~2.1 mm (at 7 TeV)**	Precision
Big and distributed system (coupled with mach. protection / dump)	**~100 devices** **~500 deg. of freedom**	

LHC collimator design

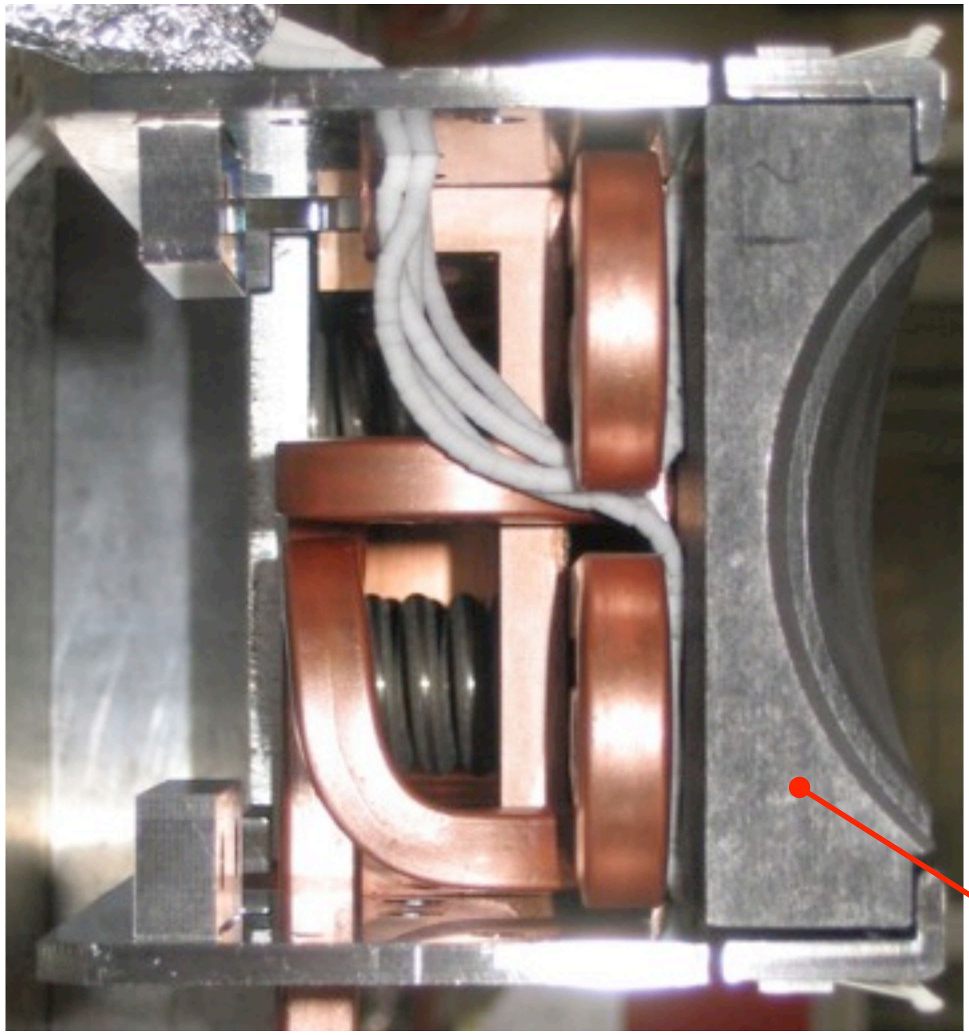
Main design features:

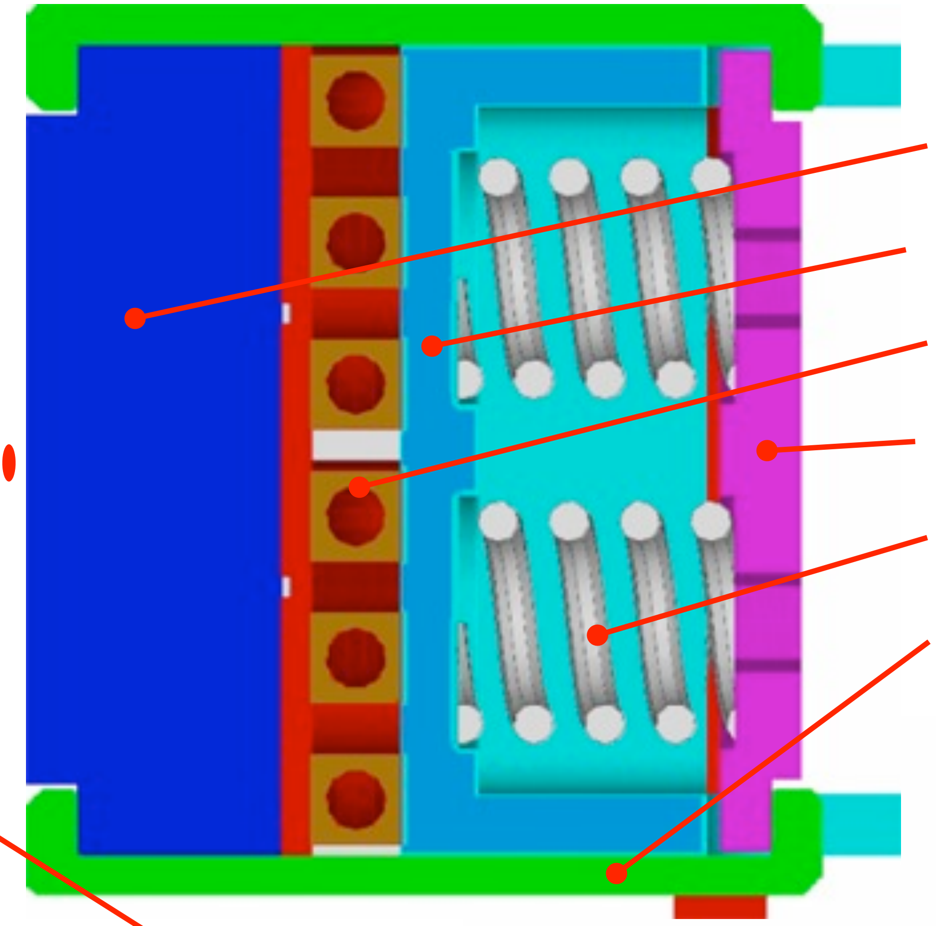
- Two jaws (position and angle)
- Concept of spare surface
- Different angles (H,V,S)
- External reference of jaw position
- Auto-retraction
- RF fingers
- Jaw cooling



A. Bertarelli et al.

LHC collimator “jaw”





Collimating Jaw (C/C composite)

Main support beam (Glidcop)

Cooling-circuit (Cu-Ni pipes)

Counter-plates (Stainless steel)

Preloaded springs (Stainless steel)

Clamping plates (Glidcop)

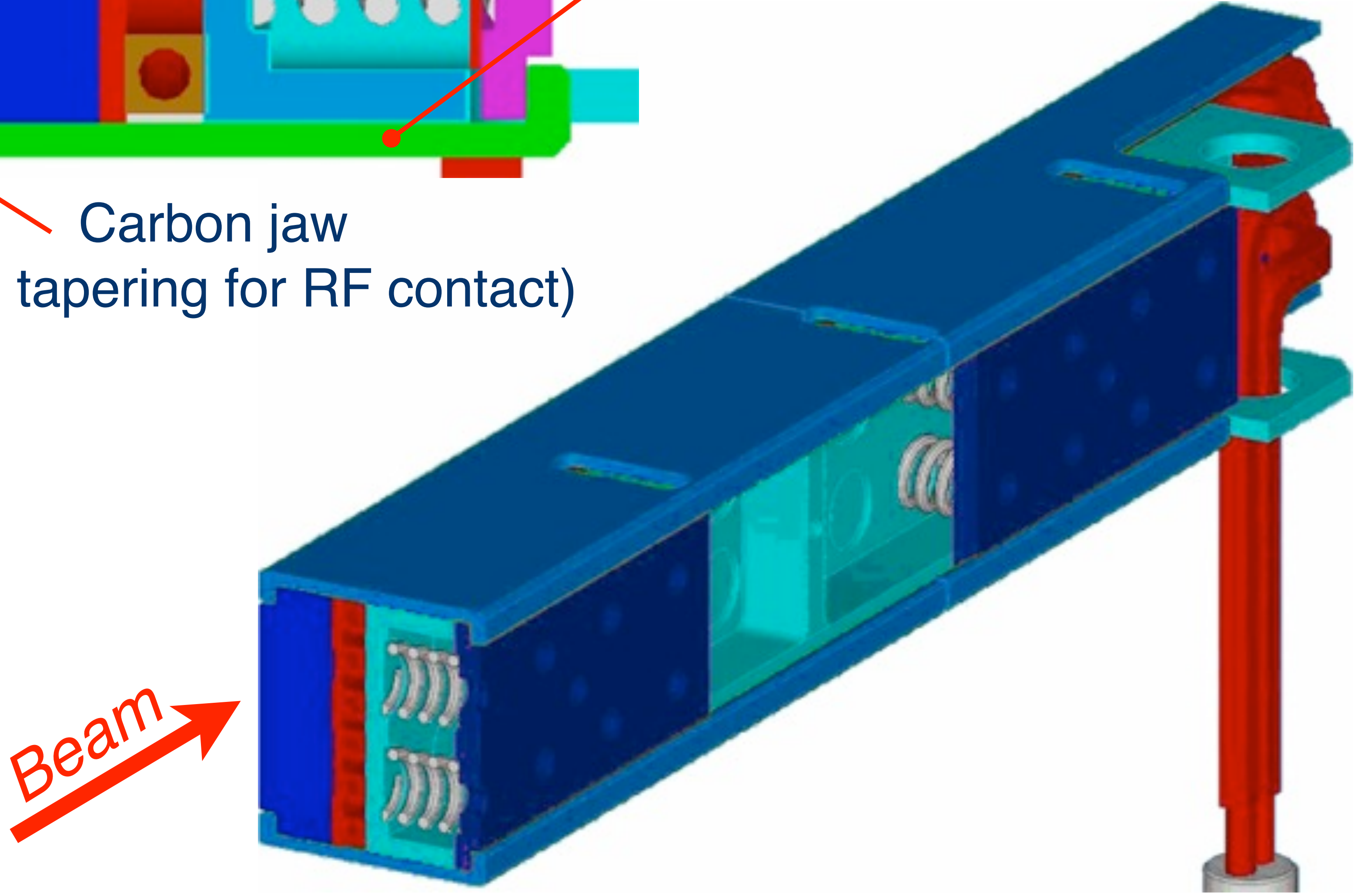
Carbon jaw
(10cm tapering for RF contact)

Special “sandwich” design to minimize the thermal deformations:

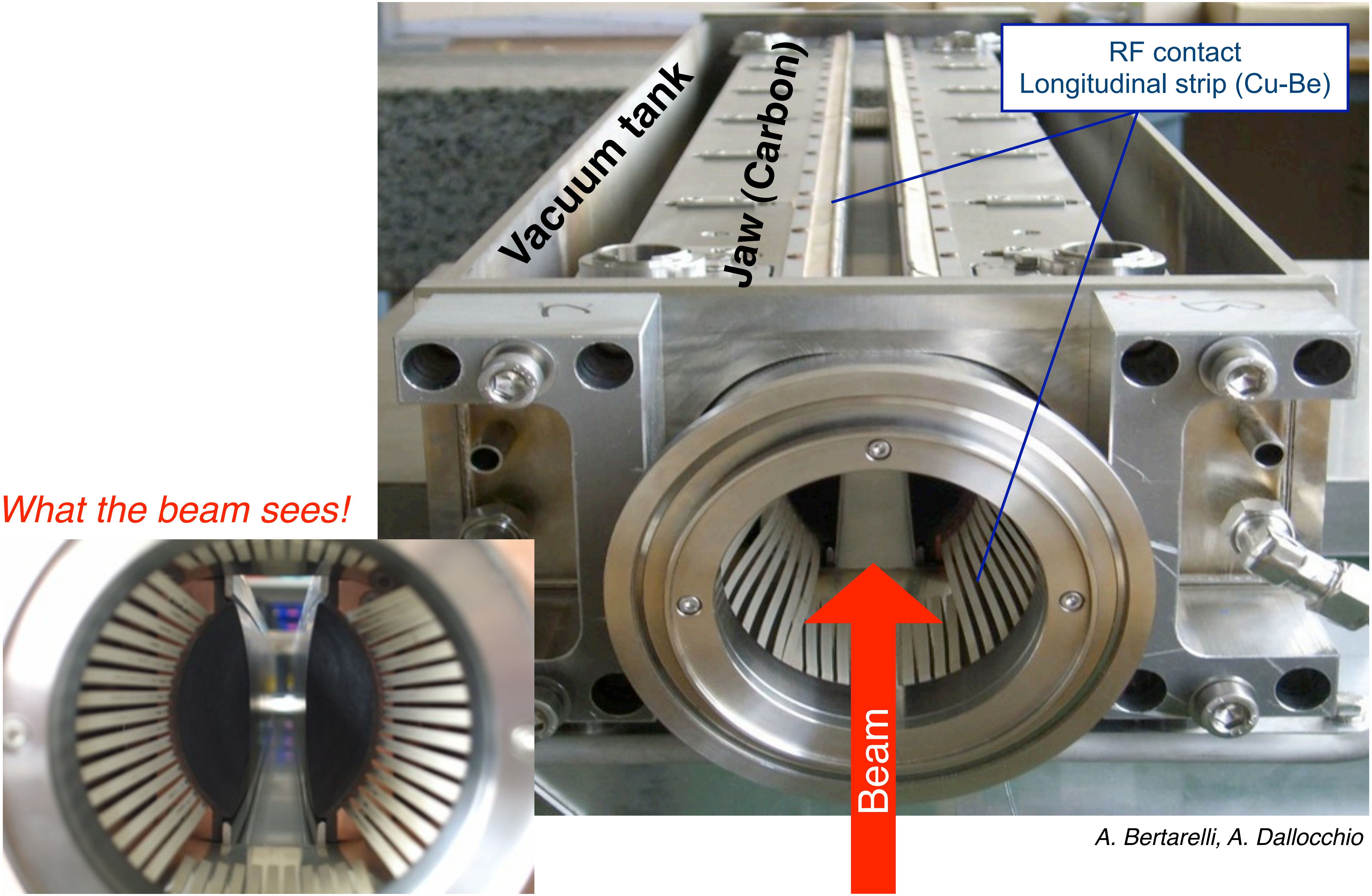
Steady (~5 kW) → < 30 µm

Transient (~30 kW) → ~ 110 µm

Materials: Graphite, Carbon fibre composites, Copper, Tungsten.



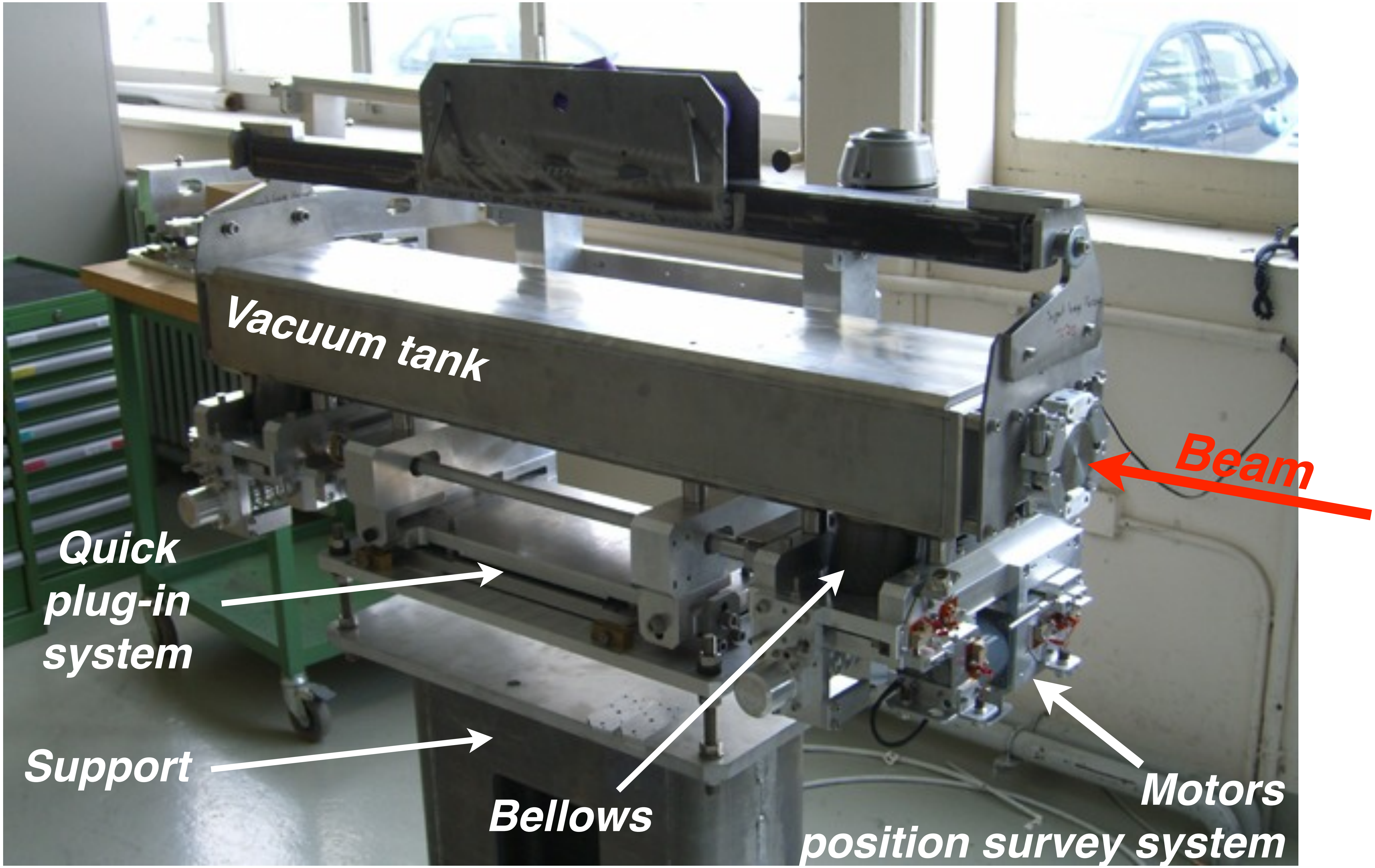
A look inside the vacuum tank



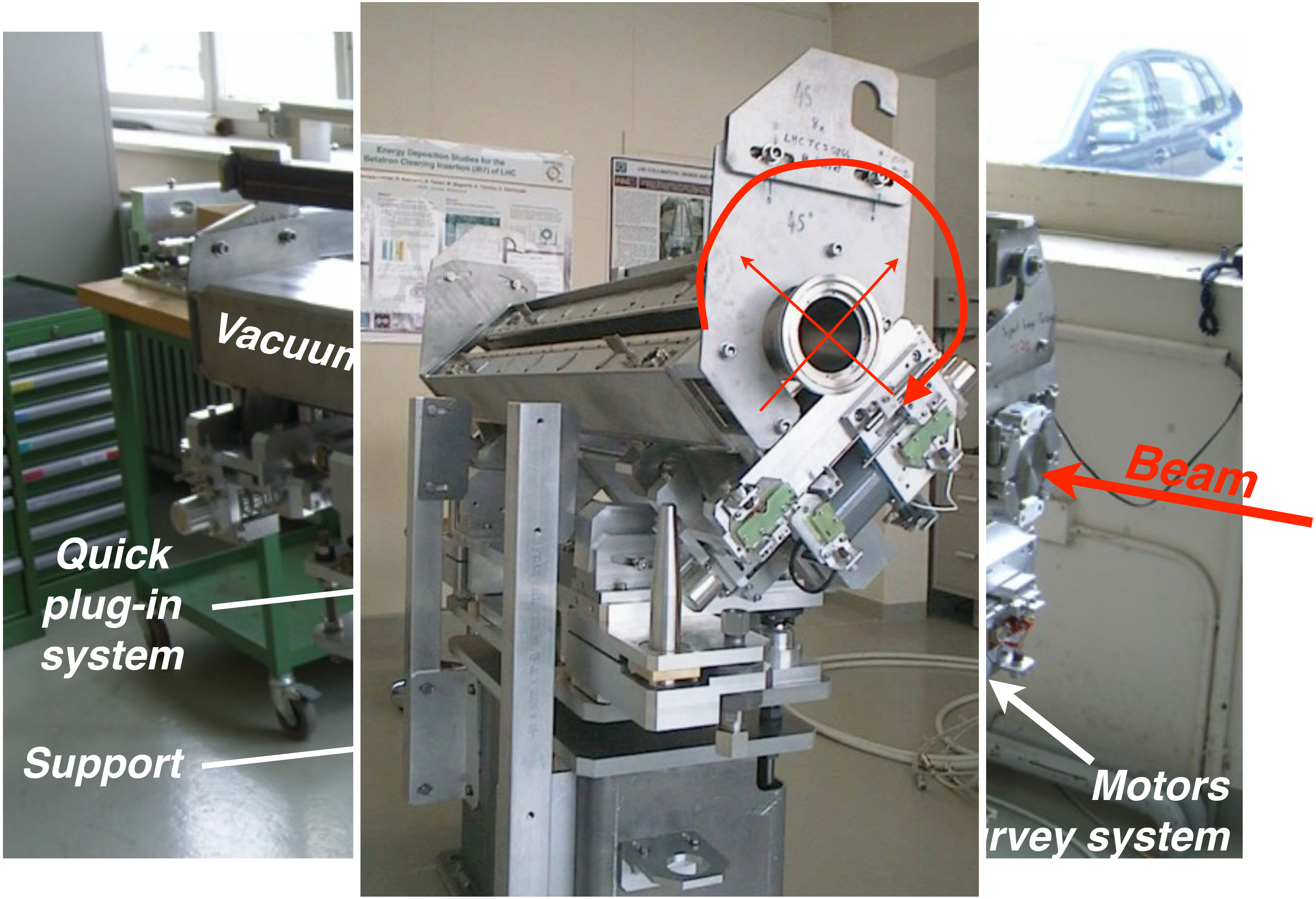
What the beam sees!

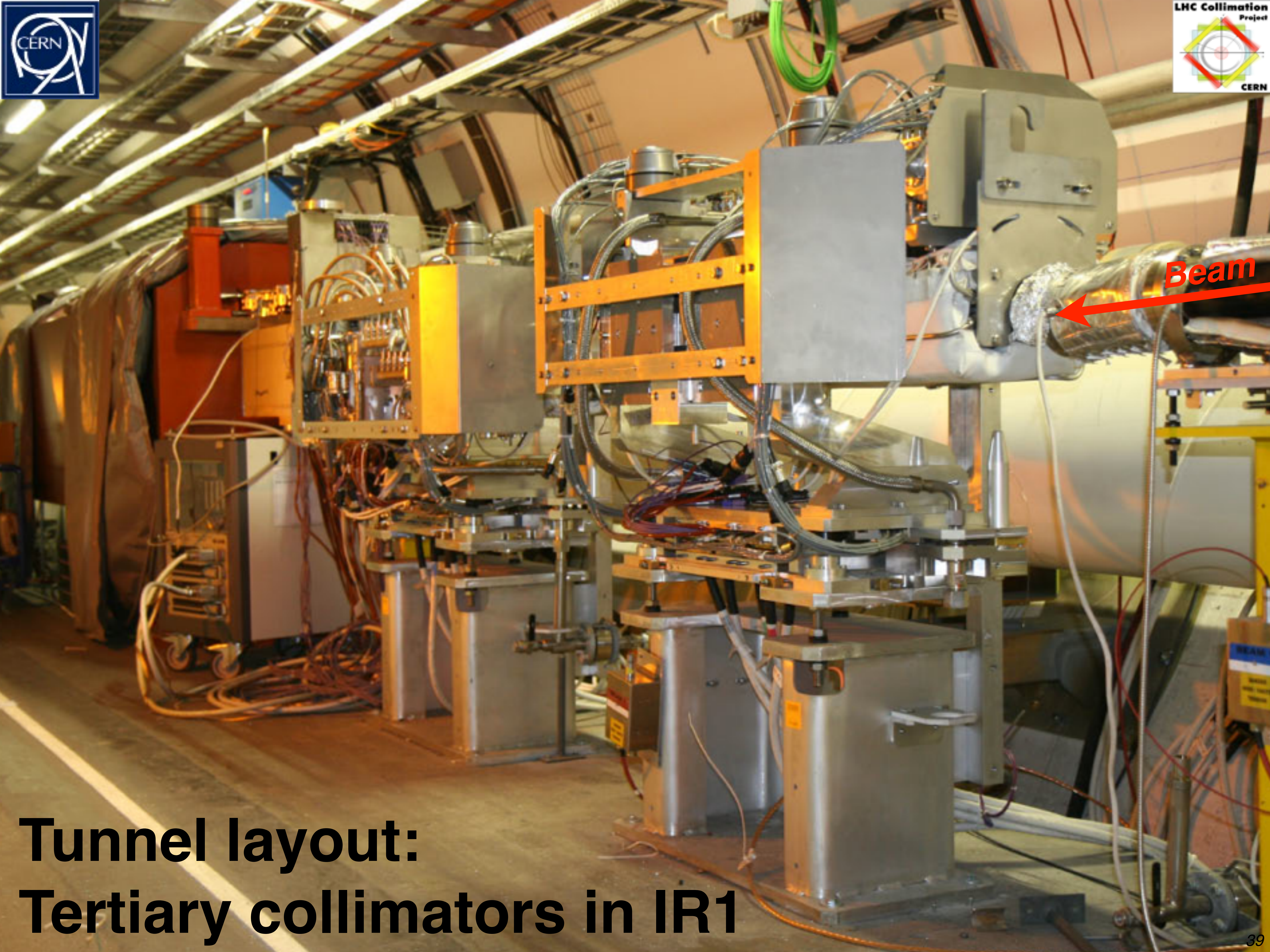
A. Bertarelli, A. Dallocchio

Complete collimator assembly



Complete collimator assembly



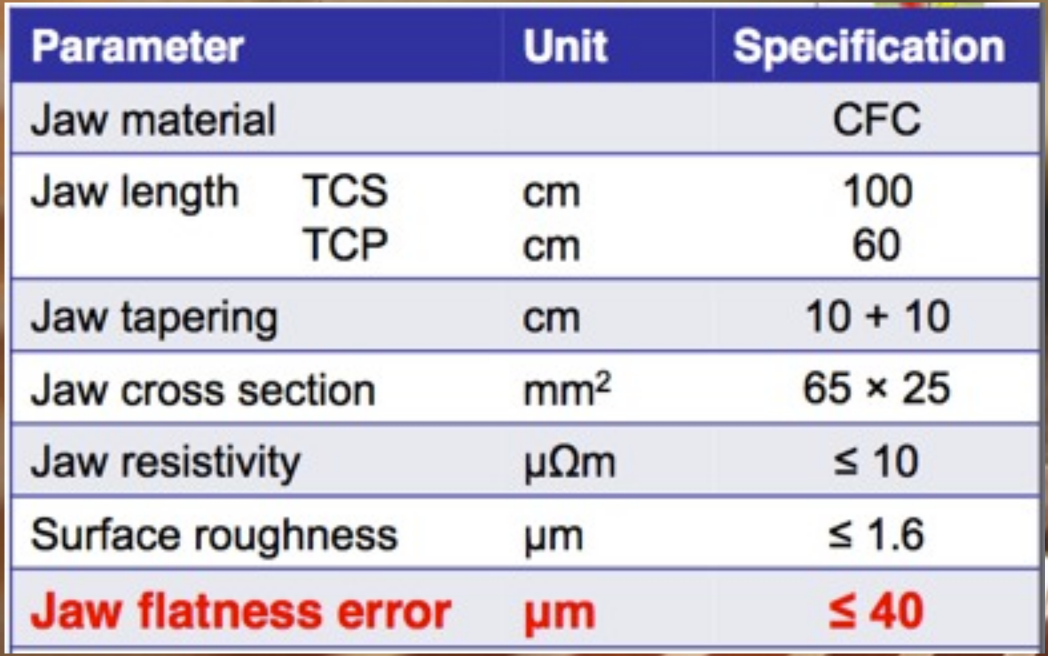


Tunnel layout:
Tertiary collimators in IR1

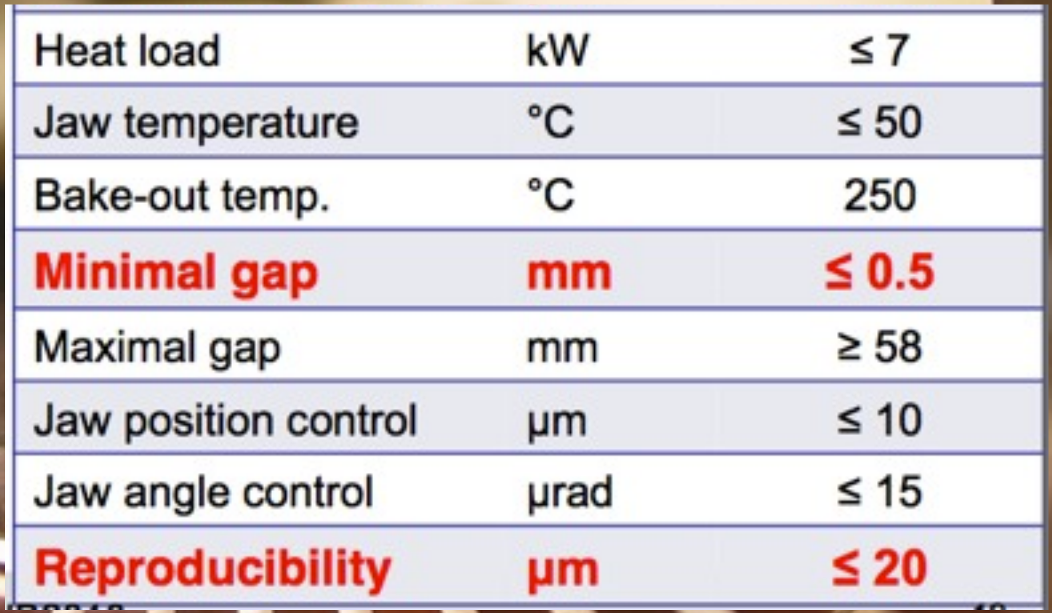
Recap. of design challenges for 360MJ

Main **collimation challenges**:

- **High stored energy**: Collimators needed in **all phases** *(inj., ramp, squeeze, physics);*
  Function-driven controls of jaw positions mandatory;
  Robustness and **cleaning efficiency**;
  Big and **distributed** system (100 collimators).
- **Small gaps**: Mechanical **precision**, **reproducibility** (< 20 microns);
  Constraints on orbit/optics **reproducibility**;
  Machine **impedance** and beam instabilities.
- **Collimator hierarchy**: Collimators determine the LHC **β^* reach.**
- **Machine protection**: Redundant **interlocks** of collimator jaw positions and gaps.
- **High-radiation environ.**: **Radiation**-hard components (HW + SW);
  Challenging remote **handling**, design for quick installation.



Parameter		Unit	Specification
Jaw material			CFC
Jaw length	TCS TCP	cm cm	100 60
Jaw tapering		cm	10 + 10
Jaw cross section		mm²	65 × 25
Jaw resistivity		µΩm	≤ 10
Surface roughness		µm	≤ 1.6
Jaw flatness error		**µm**	**≤ 40**



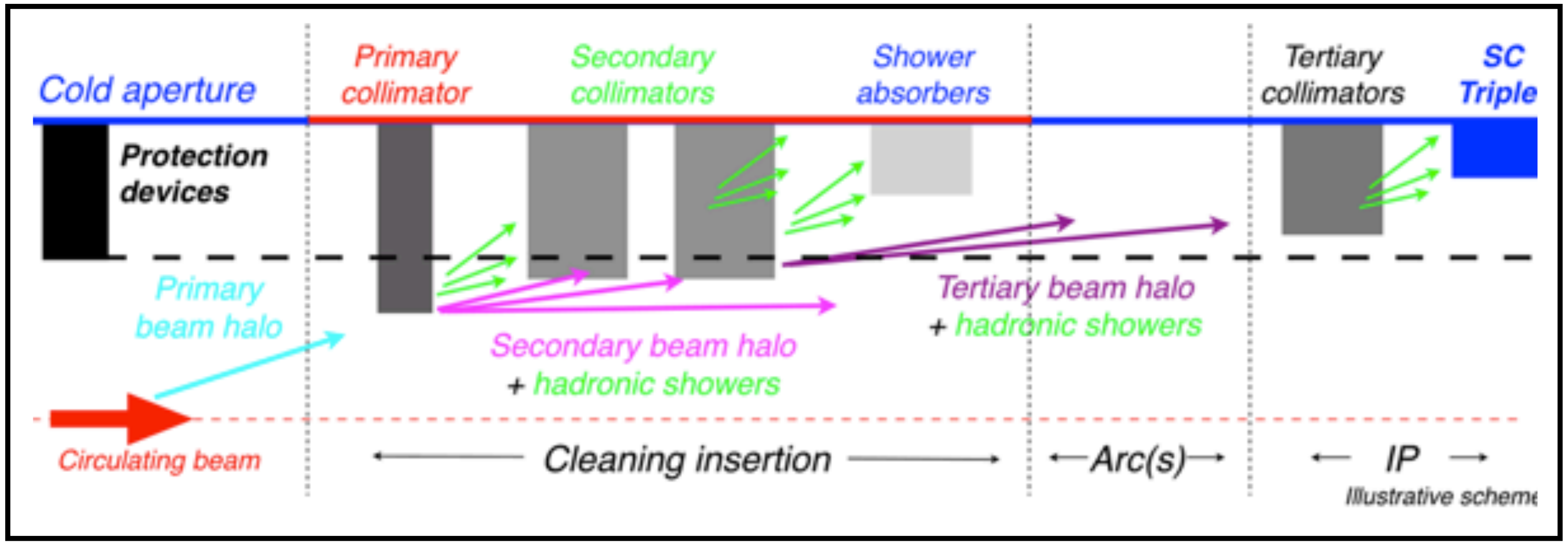
Heat load	kW	≤ 7
Jaw temperature	°C	≤ 50
Bake-out temp.	°C	250
Minimal gap	**mm**	**≤ 0.5**
Maximal gap	mm	≥ 58
Jaw position control	µm	≤ 10
Jaw angle control	µrad	≤ 15
Reproducibility	**µm**	**≤ 20**

R. Assmann et al. (2003)

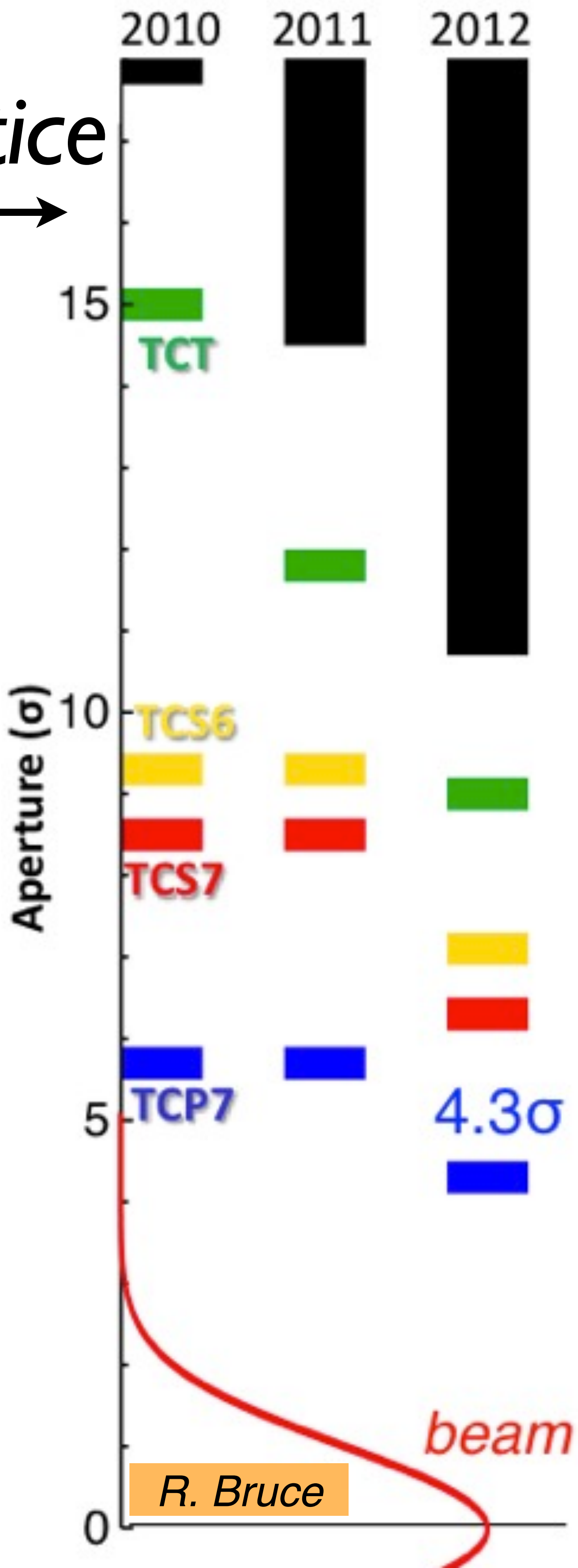
Outline

- ☑ Introduction
- ☑ Beam losses and collimation
- ☑ Single- and multi-stage cleaning
- ☑ LHC collimation layouts
- ☑ **Collimation cleaning**
- ☑ Conclusions

Configurations for LHC-run1 (2010-12)



In practice →

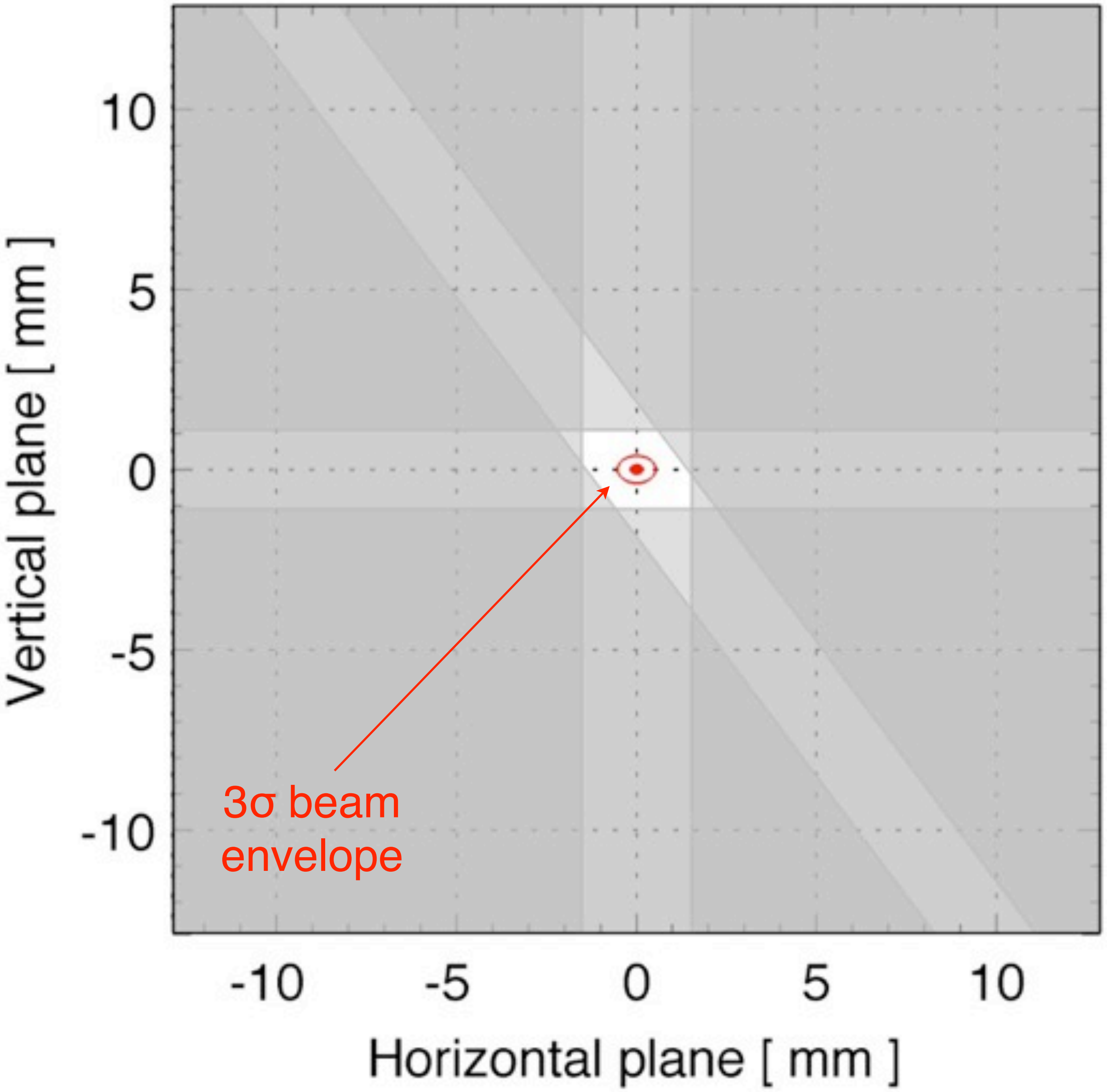


R. Bruce

- Setting hierarchy was tightened while gaining operational experience and confidence in the machine (optics/orbit stability, lifetime measurements, cleaning requirements, ...)
- Started with “relaxed” settings (easier commissioning, less challenging tolerance), then achieved “tight” settings at 4 TeV equivalent in mm to **design 7 TeV goal!**
- Smaller beta* in ATLAS and CMS (not subject of this lecture).
- Improve cleaning performance but reduce lifetime in 2012.

Smallest collimator gaps in 2012

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

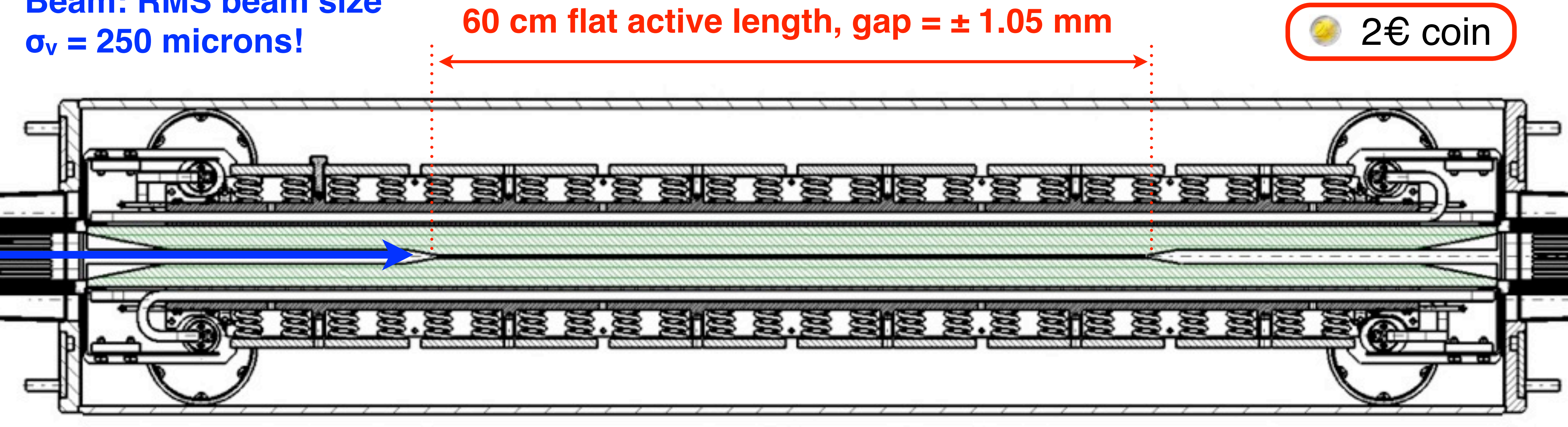


2€ coin

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

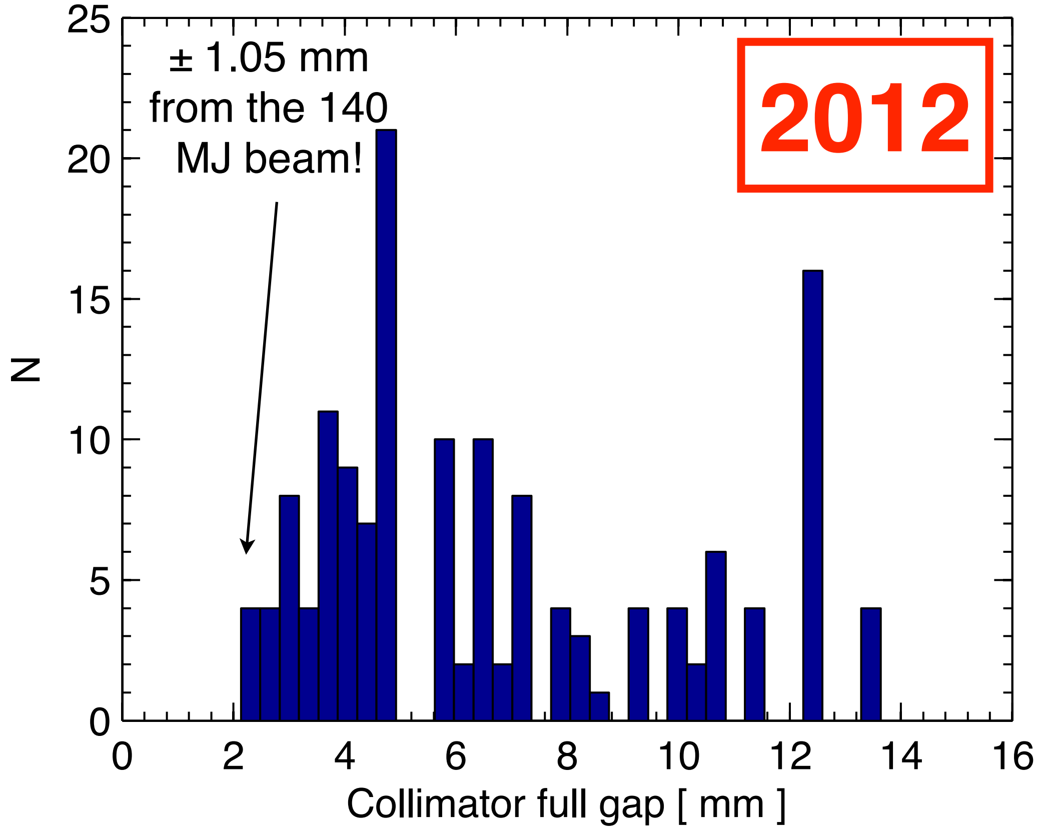
Side view of the vertical TCP

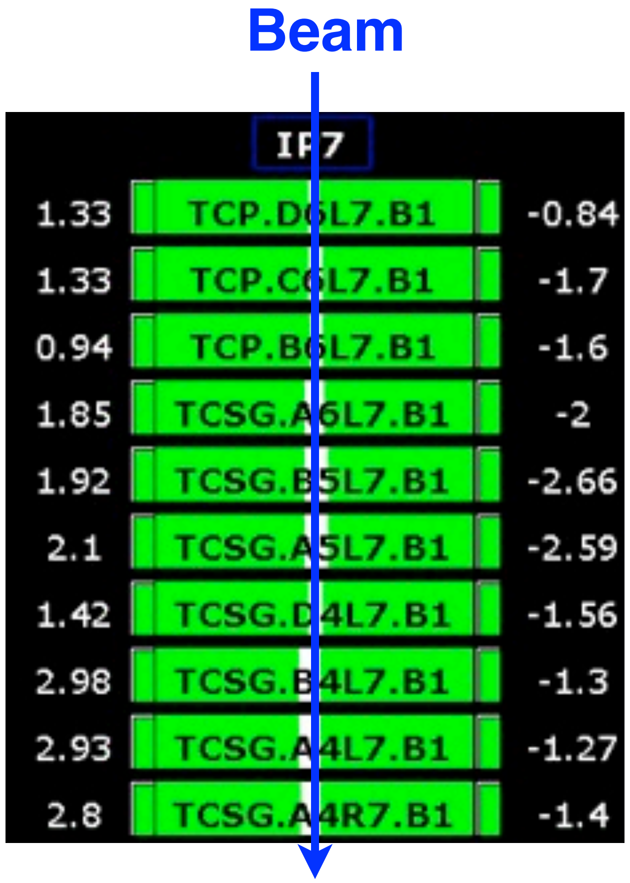
Beam: RMS beam size
σ_v = 250 microns!



L. Gentini

Distribution of collimator gaps in 2012



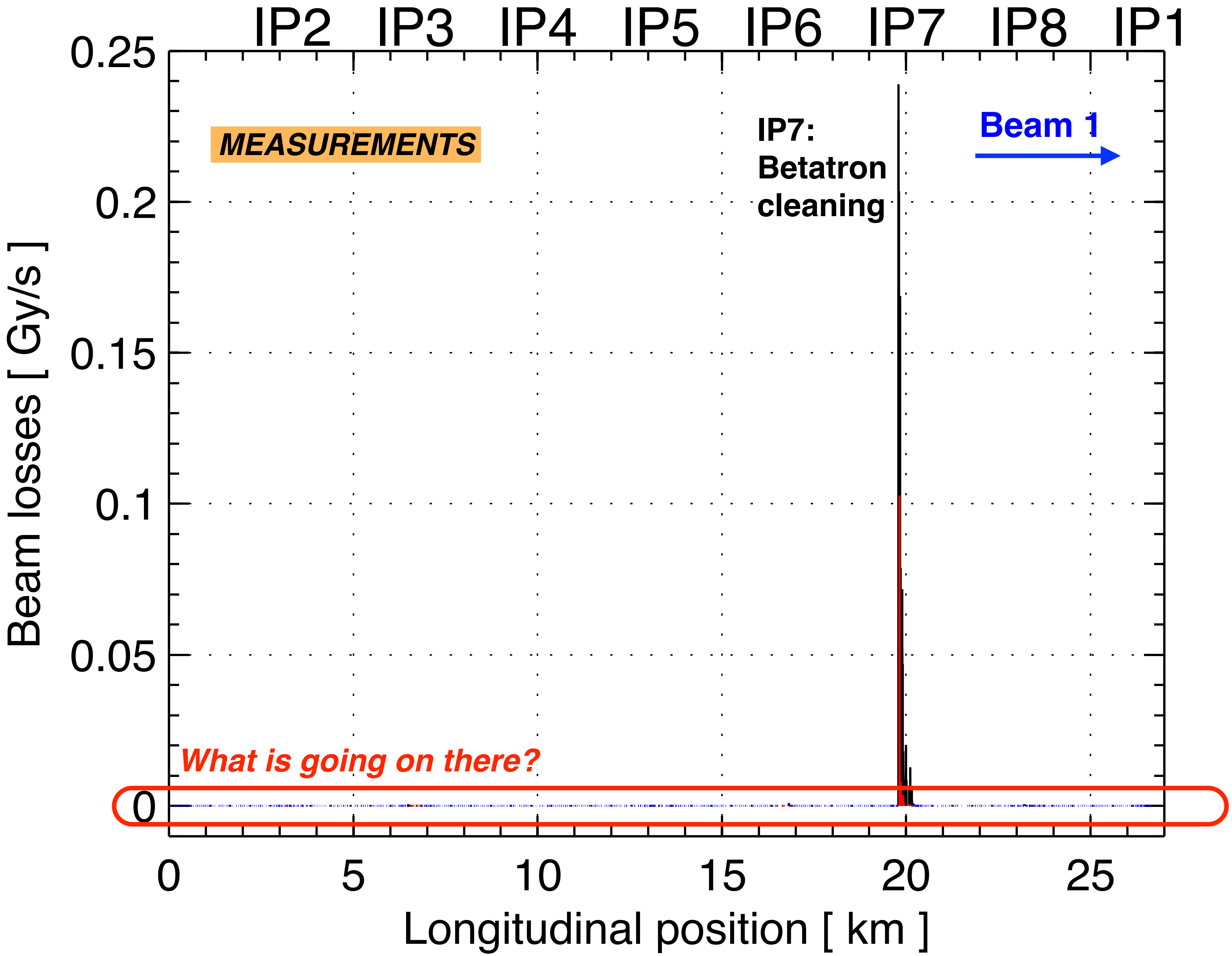


	IR7	
1.33	TCP.D6L7.B1	-0.84
1.33	TCP.C6L7.B1	-1.7
0.94	TCP.B6L7.B1	-1.6
1.85	TCSG.A6L7.B1	-2
1.92	TCSG.B5L7.B1	-2.66
2.1	TCSG.A5L7.B1	-2.59
1.42	TCSG.D4L7.B1	-1.56
2.98	TCSG.B4L7.B1	-1.3
2.93	TCSG.A4L7.B1	-1.27
2.8	TCSG.A4R7.B1	-1.4

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

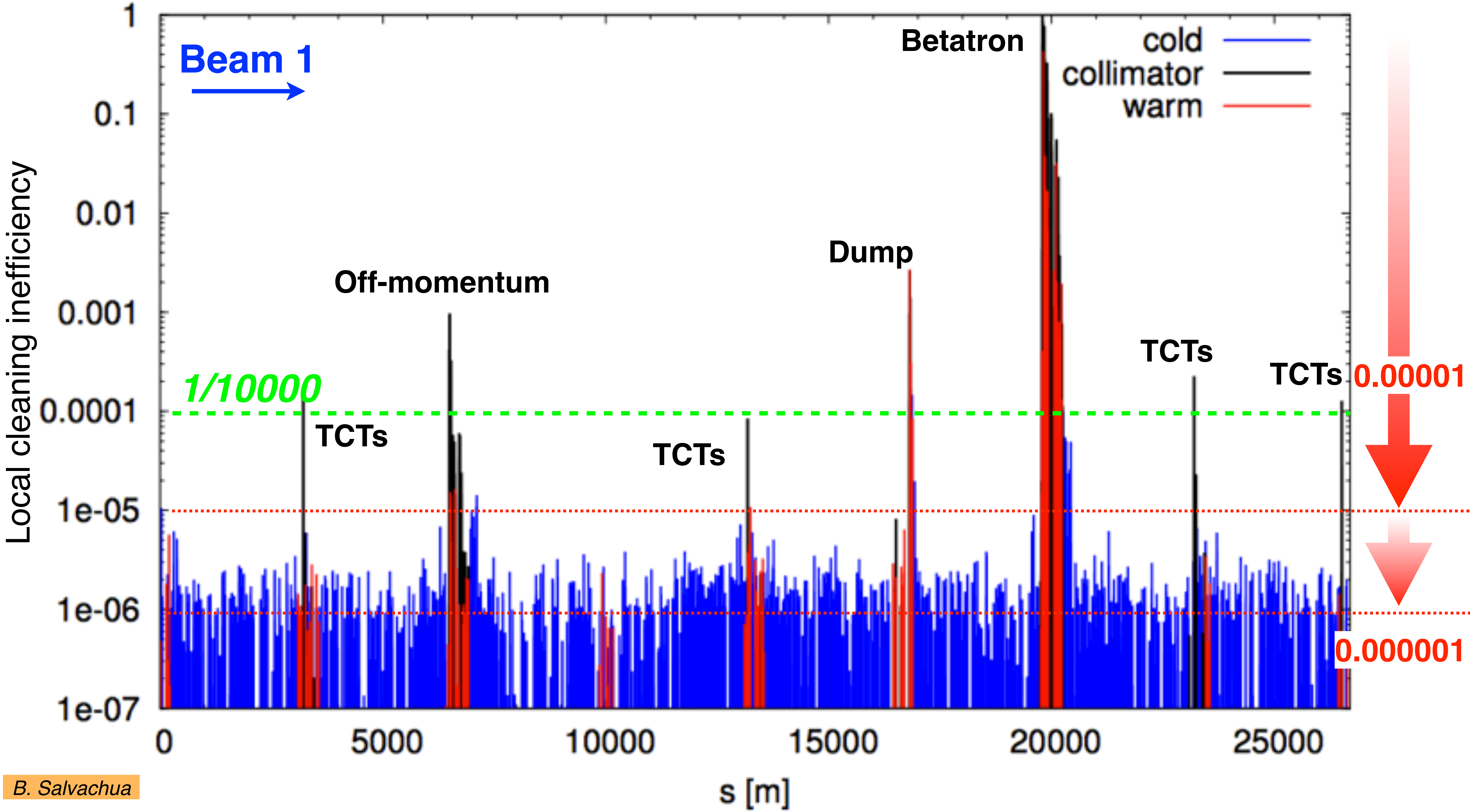
Collimation cleaning

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



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

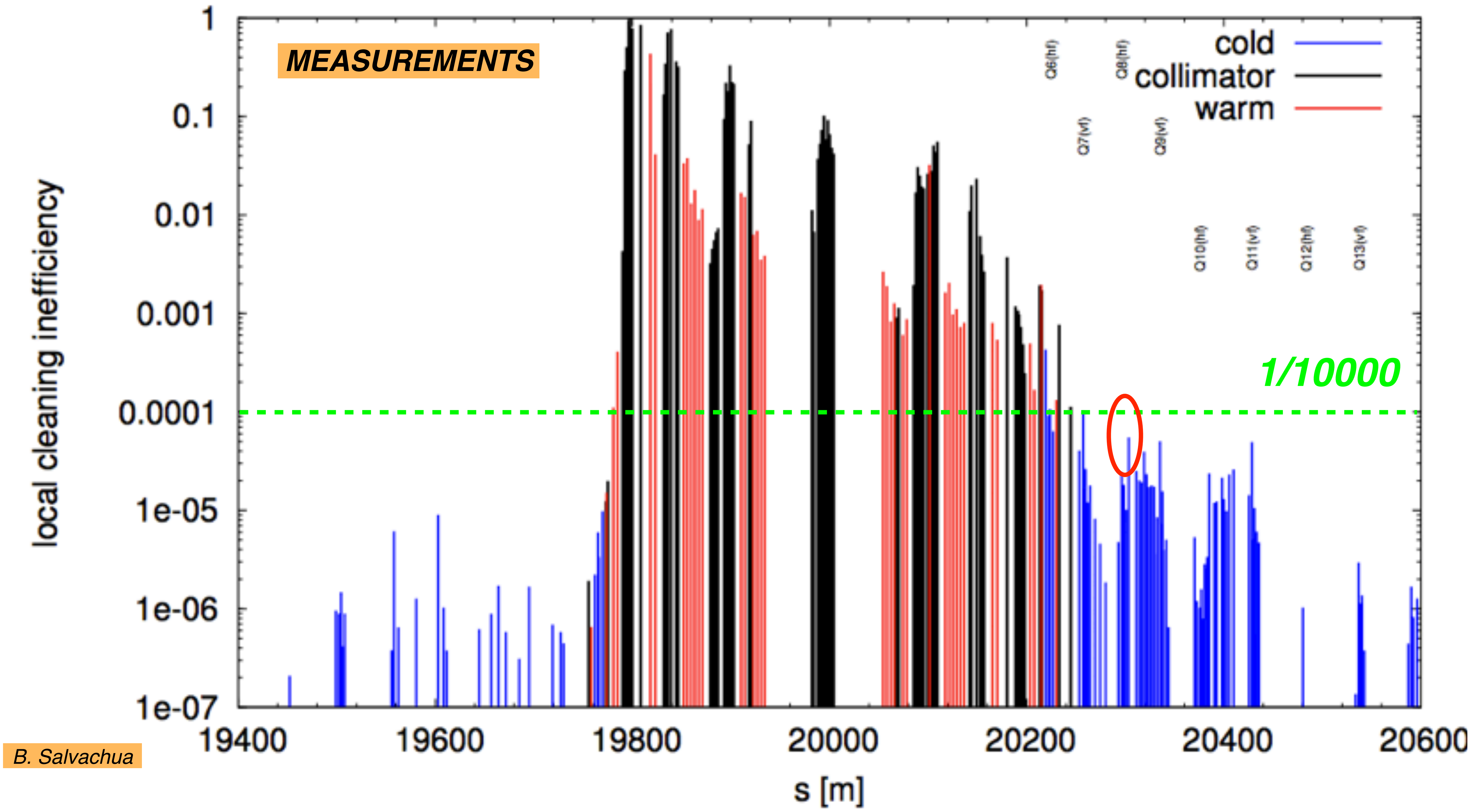
MEASUREMENTS



B. Salvachua

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

Zoom in IR7

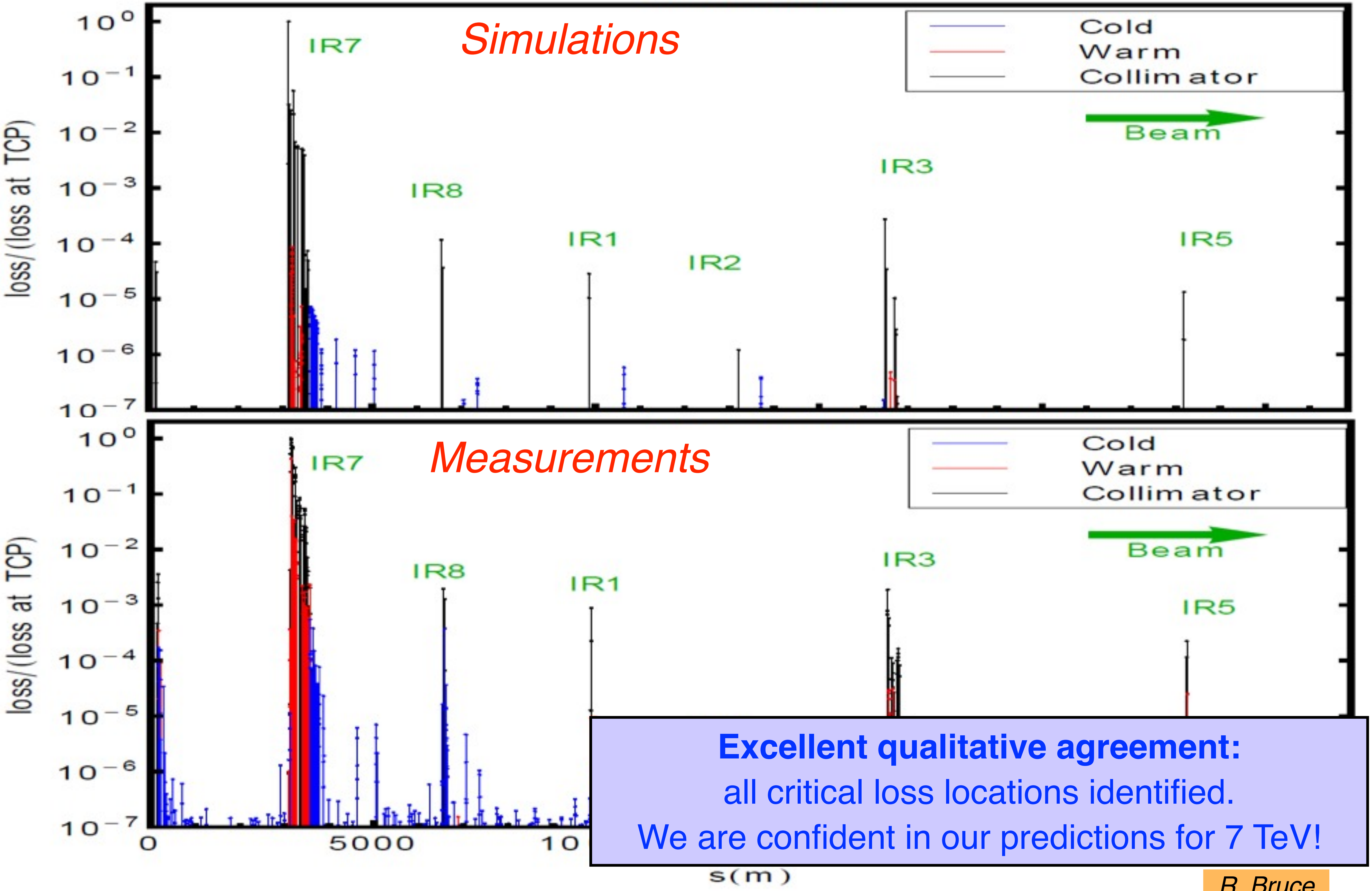


B. Salvachua

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

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

Comparison with measurements



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

R. Bruce

Conclusions

- ☑ The collimation challenges for the LHC were presented.
- ☑ The basic design strategy for collimation systems for high-energy hadron accelerators was reviewed.
- ☑ The present LHC collimation system was presented:
    - solutions to the key design constraints and challenges;
    - tunnel layouts for a complex multi-stage system;
    - collimator design main features.
- ☑ The main performance achievements during the LHC Run1 in 2010-12 were also discussed.
- ☑ We are looking forward to collimating the ~7 TeV LHC beams in 2015!

Collimation matters not covered here

- ☑ Collimation in other CERN machines
  - *LHC taken as case study because the complexity of its collimation system cover all the collimation design goals.*
- ☑ Role of energy deposition studies in collimation system design
- ☑ Material science related to collimators and advanced designs
  - *Robustness versus impedance*
  - *New material development to handle higher energy/brightness beams*
- ☑ Collimator technology and handling for high radiation environment.
  - *Optimized design and components to keep high performance with high doses.*
- ☑ Physics debris collimation and IR losses
- ☑ Collimation upgrade plans for the High Luminosity (HL) LHC era.
- ☑ Advanced collimation concepts:
  - *Collimator in cold regions, Hollow e-lenses as halo control devices, crystal collimation...*