CERN Accelerator School: Basics of Accelerator Science and Technology at CERN
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Chavannes de Bogis, Vaud, Switzerland

Beam collimation at the Large Hadron Collider

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Accelerator and Beam Physics group

Outline

- Introduction
- Beam losses and collimation roles
- Single- and multi-stage cleaning
- LHC collimation layouts and design
- Achieved cleaning performance
- Conclusions

The LHC collimator

What is beam collimation and why we need it?

How many LHC collimators we need?

Where are they located in the ring?

How are they built, with which materials?

Beam collimation - definitions

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

Beam collimation - definitions

Beam halo collimation

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

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Gaussian beams: typically, particles above 3 RMS beam sizes.

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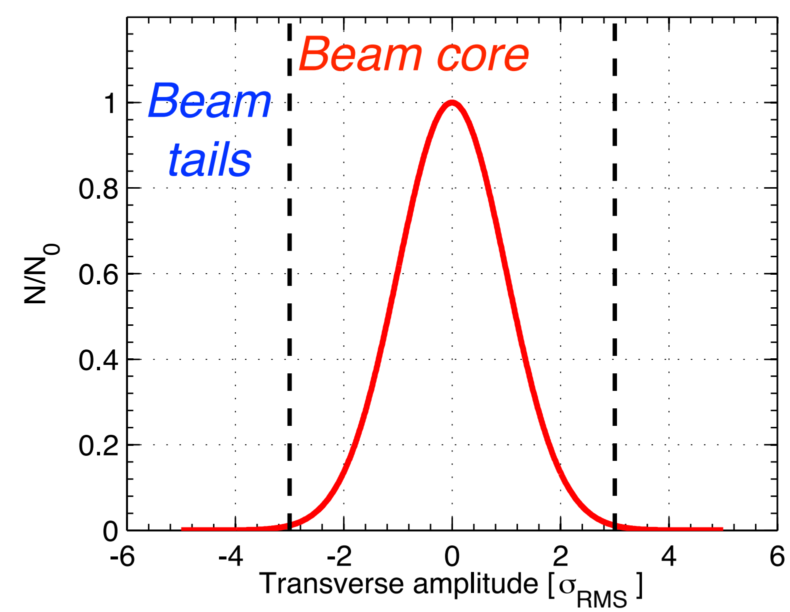

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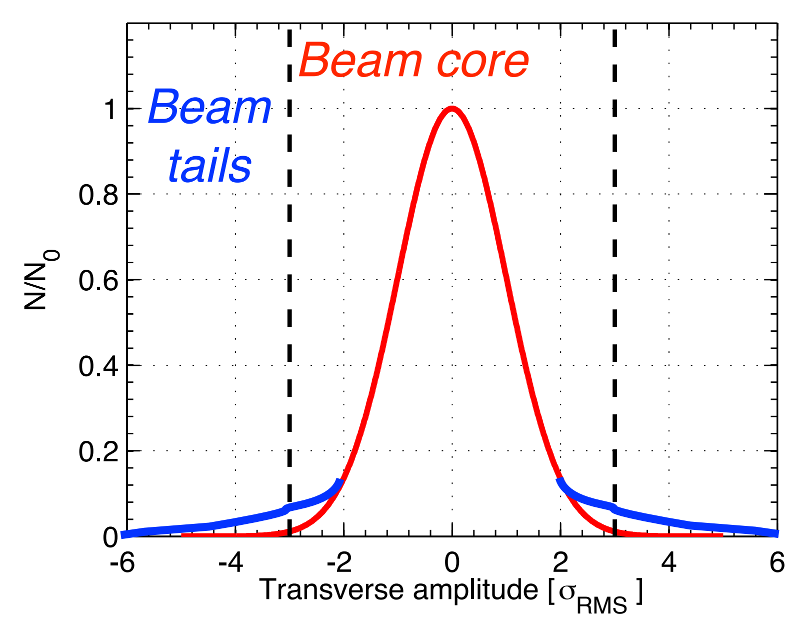

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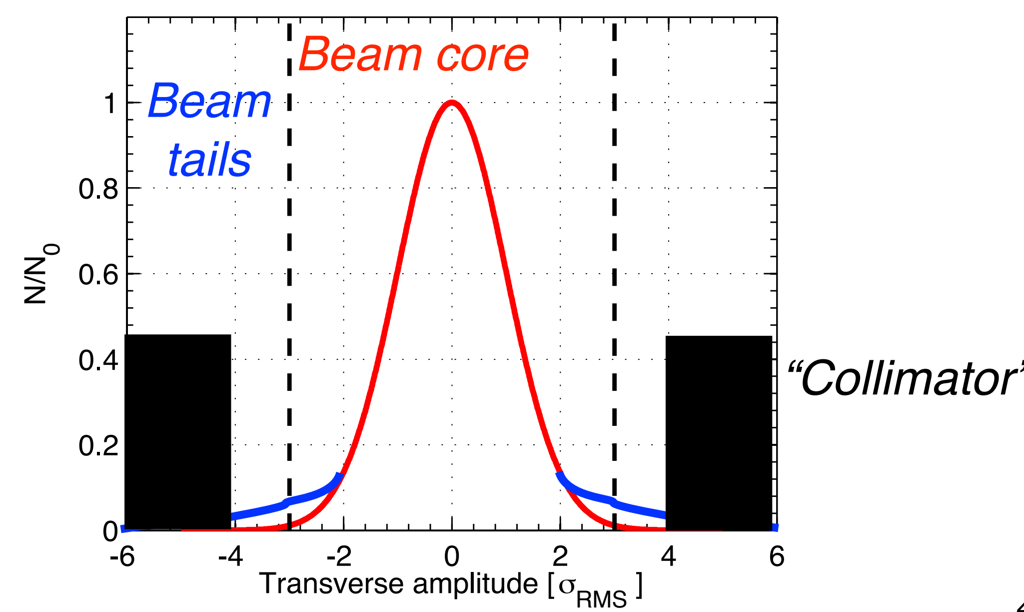

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Main design goal for the **collimation system** at the **LHC**

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

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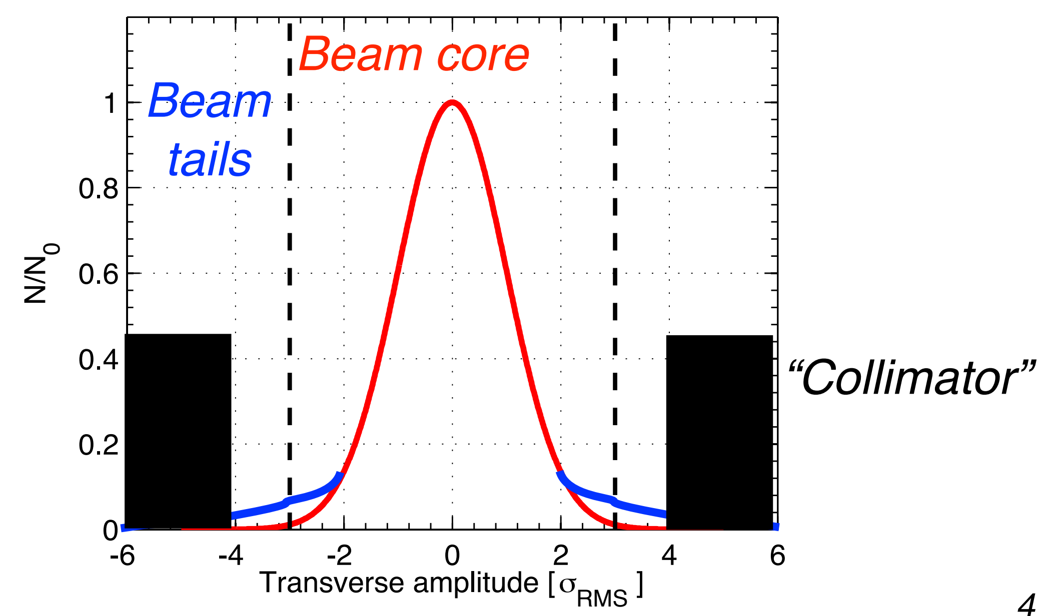
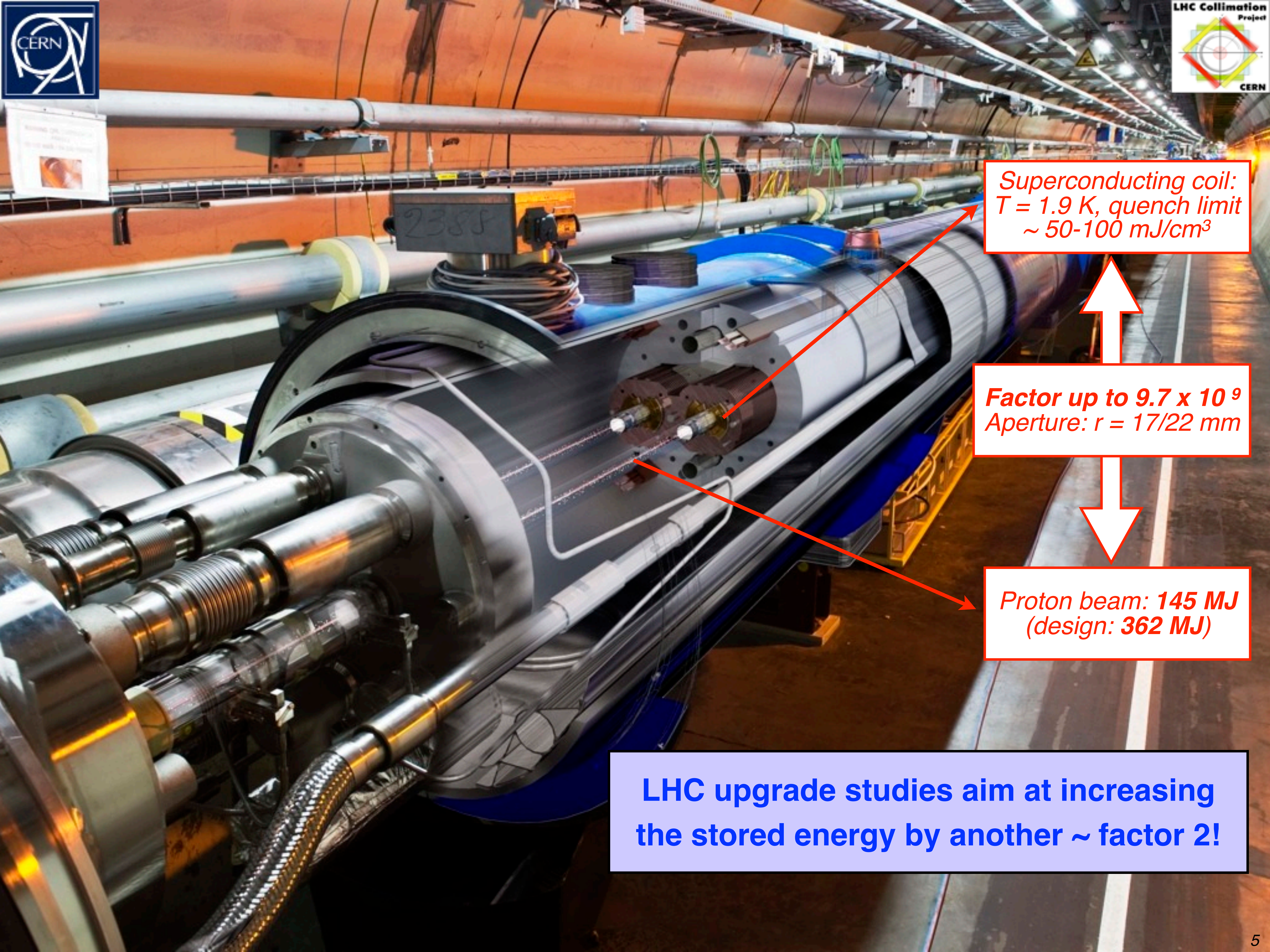
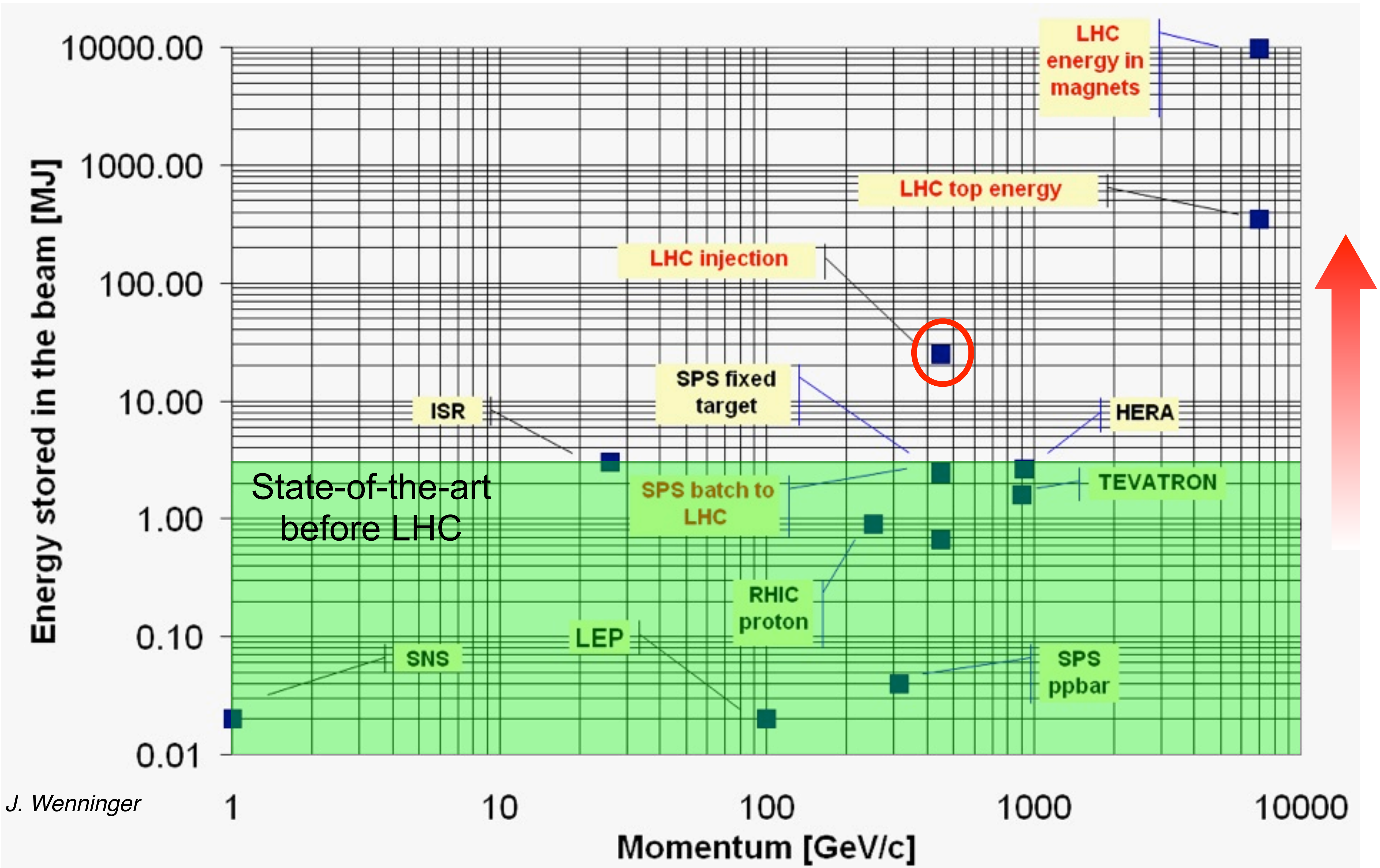



Superconducting coil:
T = 1.9 K, quench limit
~ 50-100 mJ/cm^3
Factor up to 9.7 x 10 ^{9}
Aperture: r = 17/22 mm
Proton beam: **145 MJ**
(design: **362 MJ**)
LHC upgrade studies aim at increasing the stored energy by another ~ factor 2!

The LHC stored energy challenge



J. Wenninger

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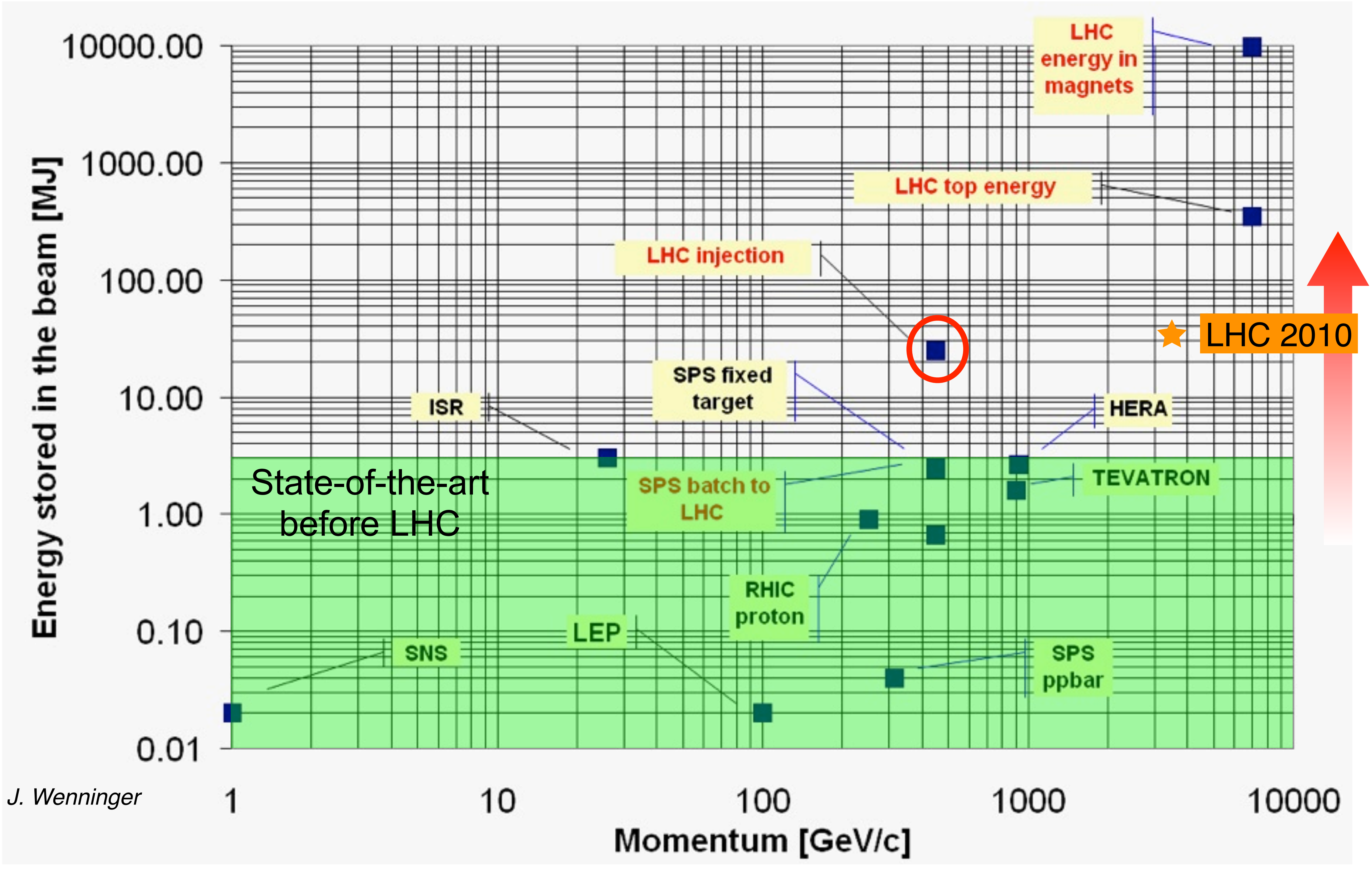

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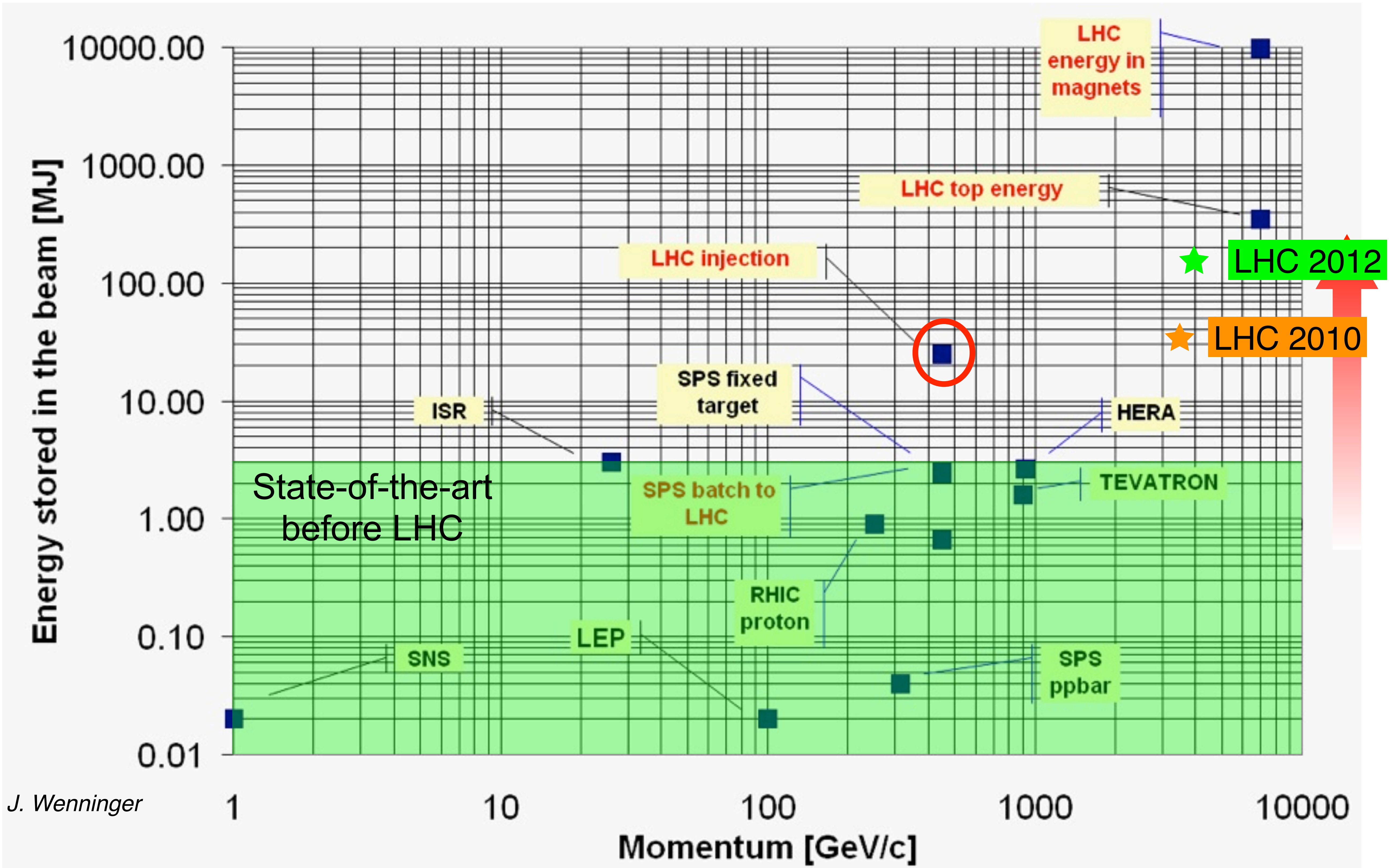

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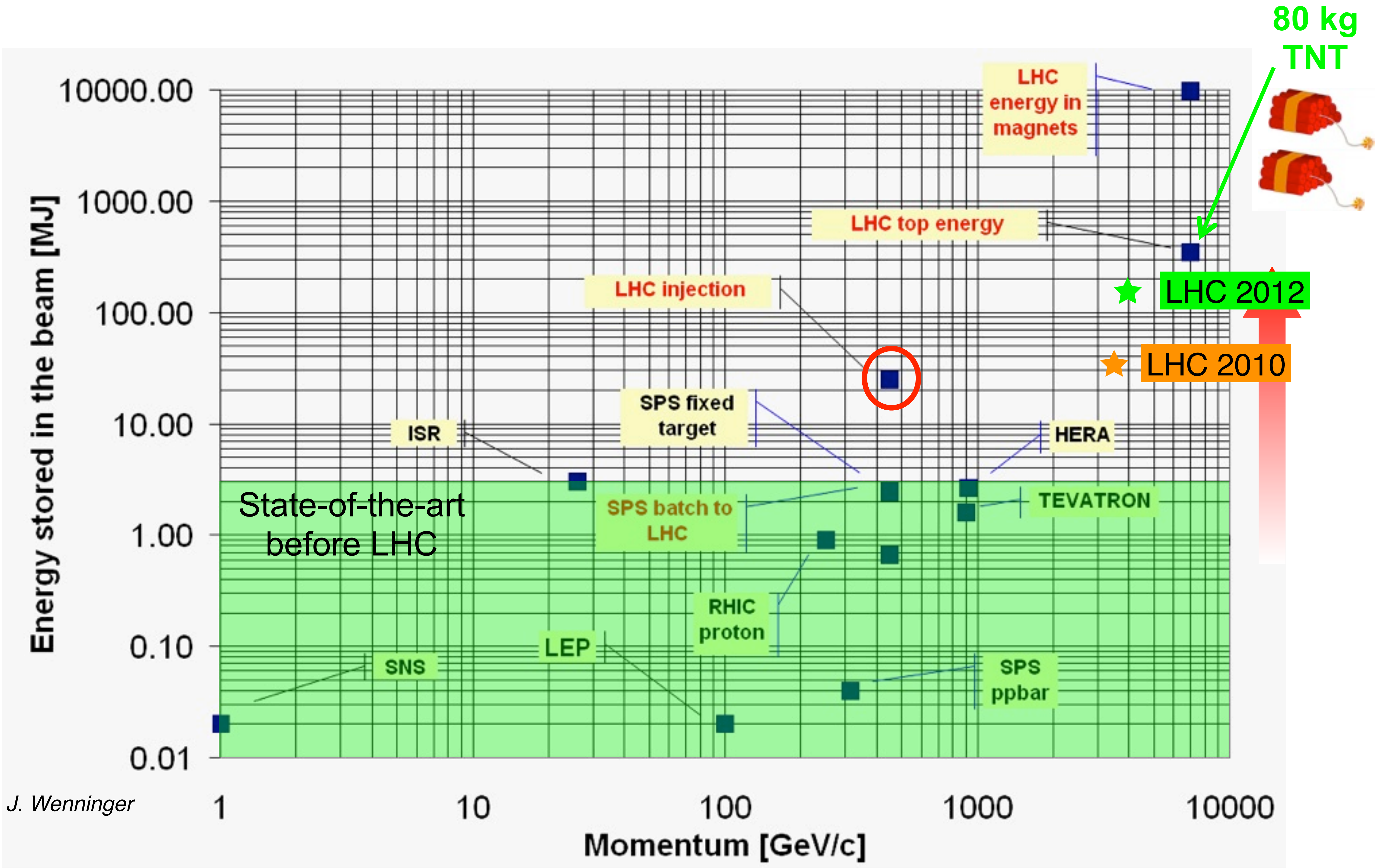

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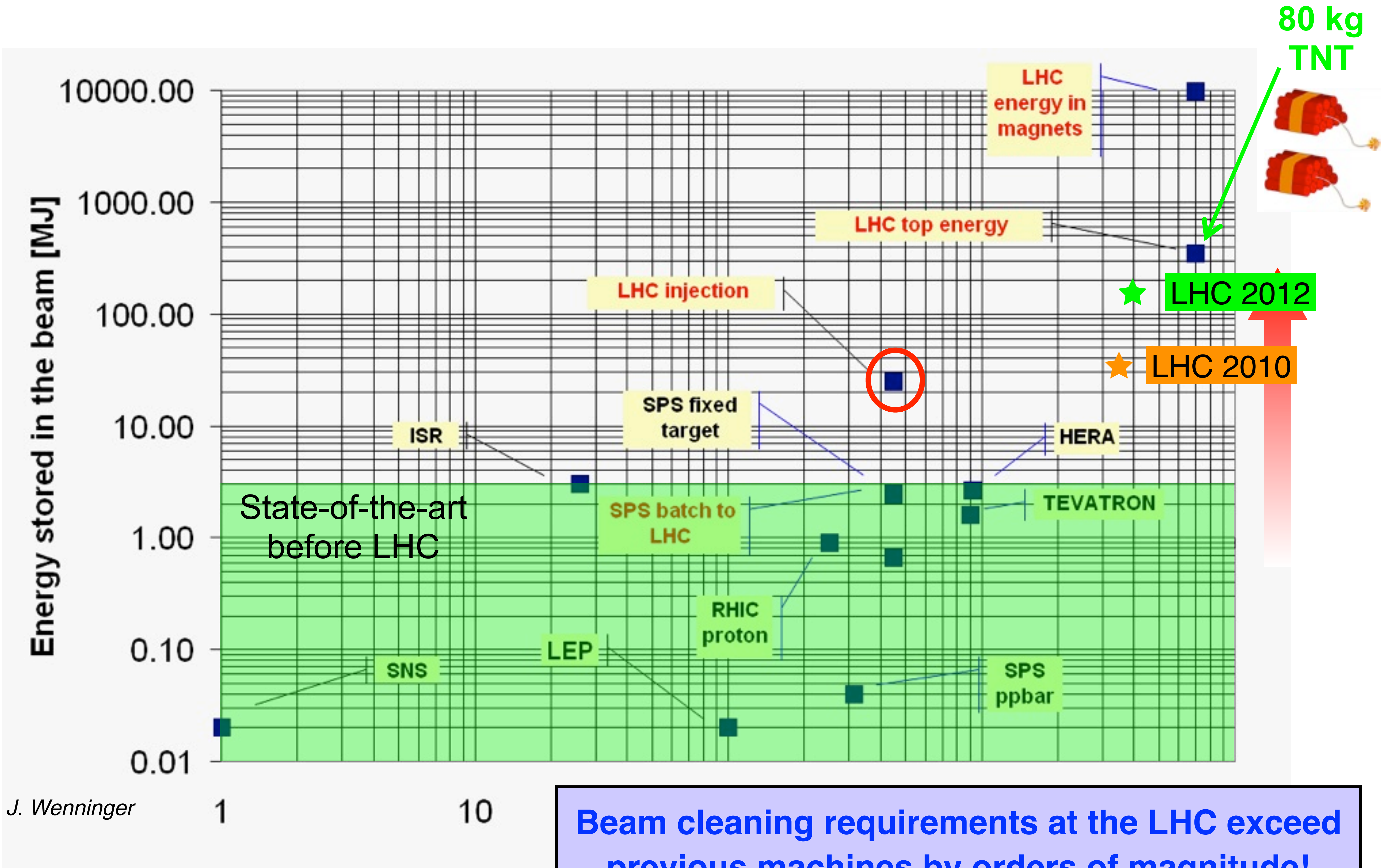

Beam cleaning requirements at the LHC exceed previous machines by orders of magnitude!

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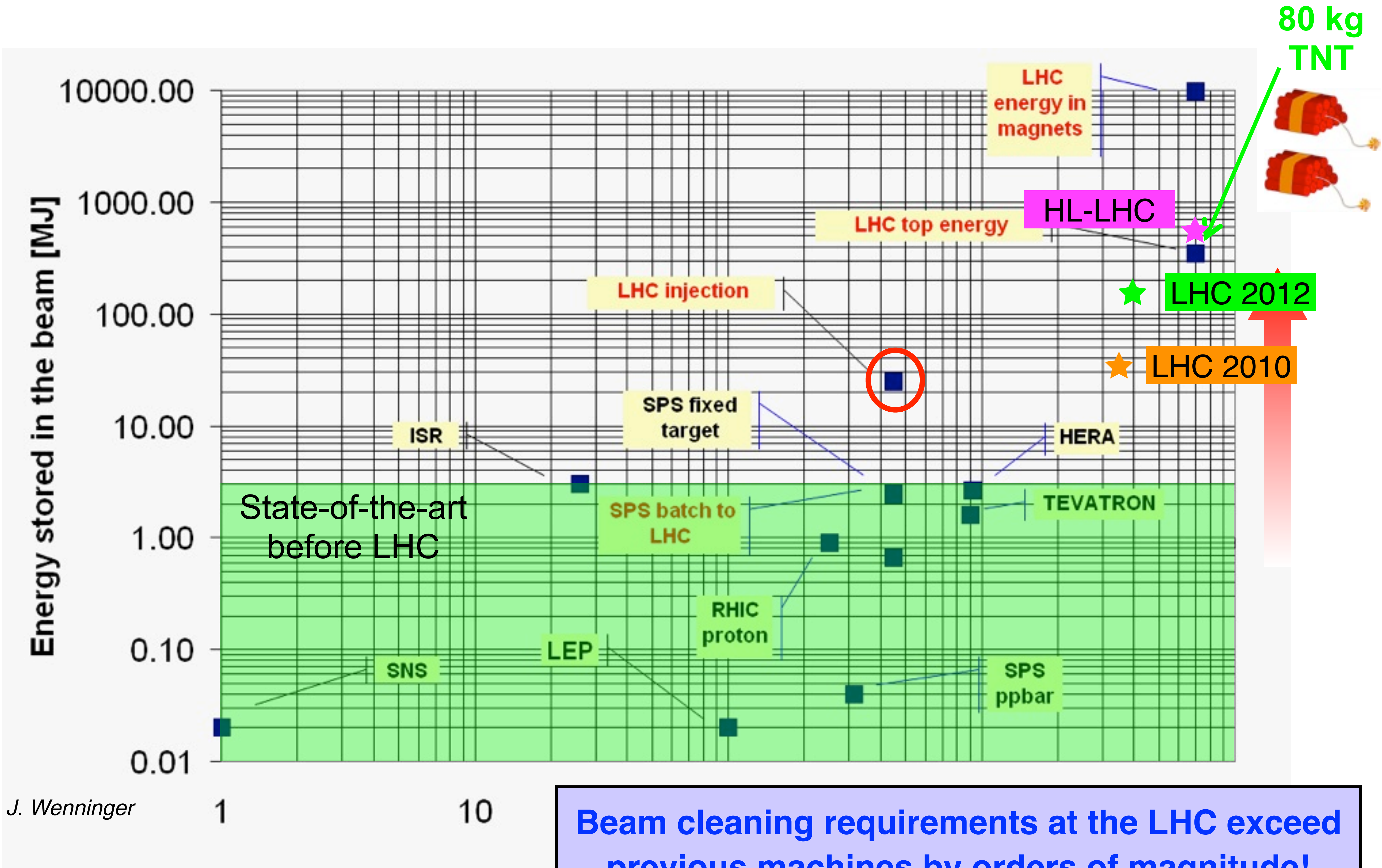

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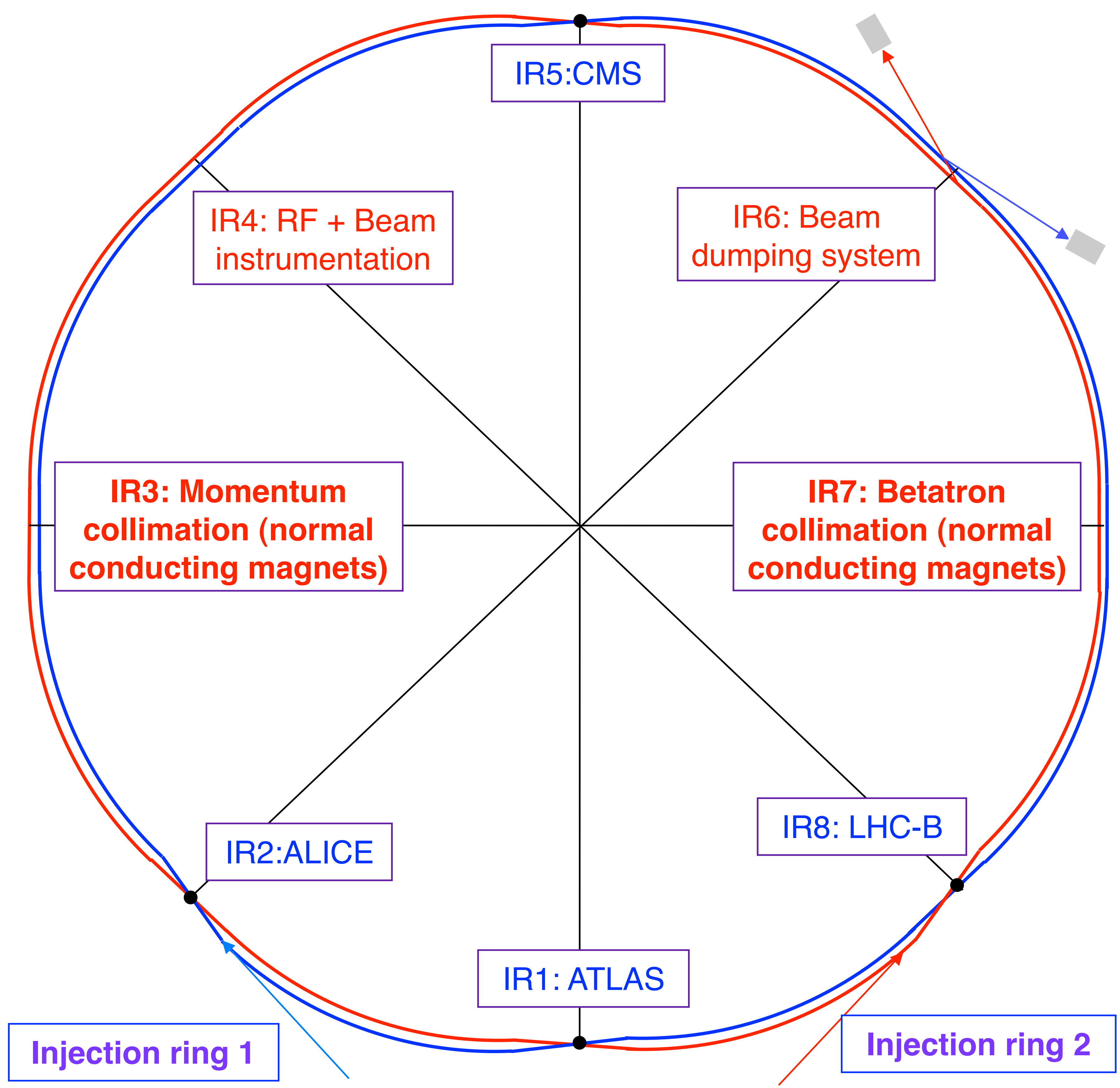
  Control and probe

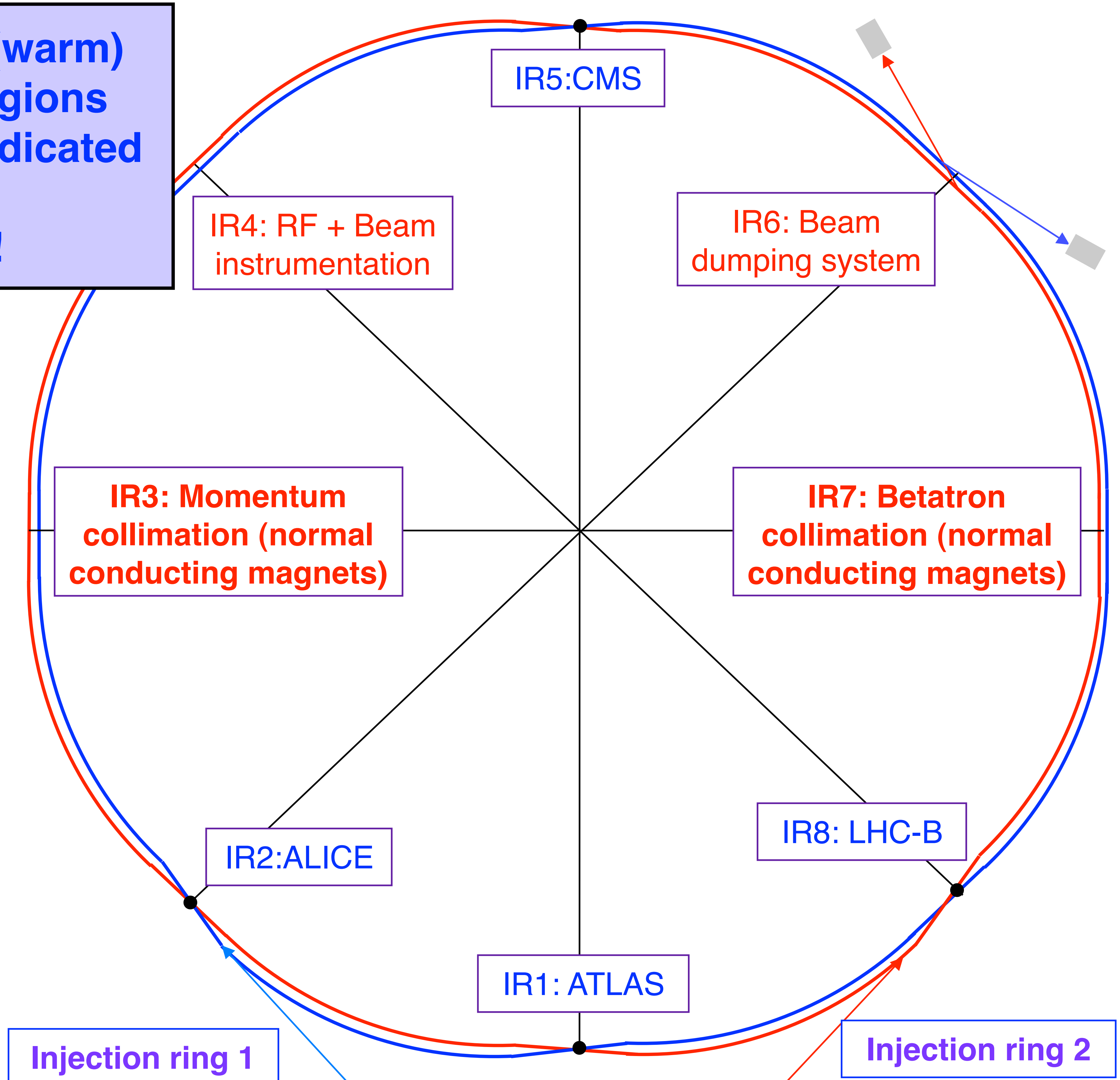
This lecture: focus on LHC, the only CERN machine with a collimation system that addresses all this requirements!

LHC ring layout



LHC ring layout

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



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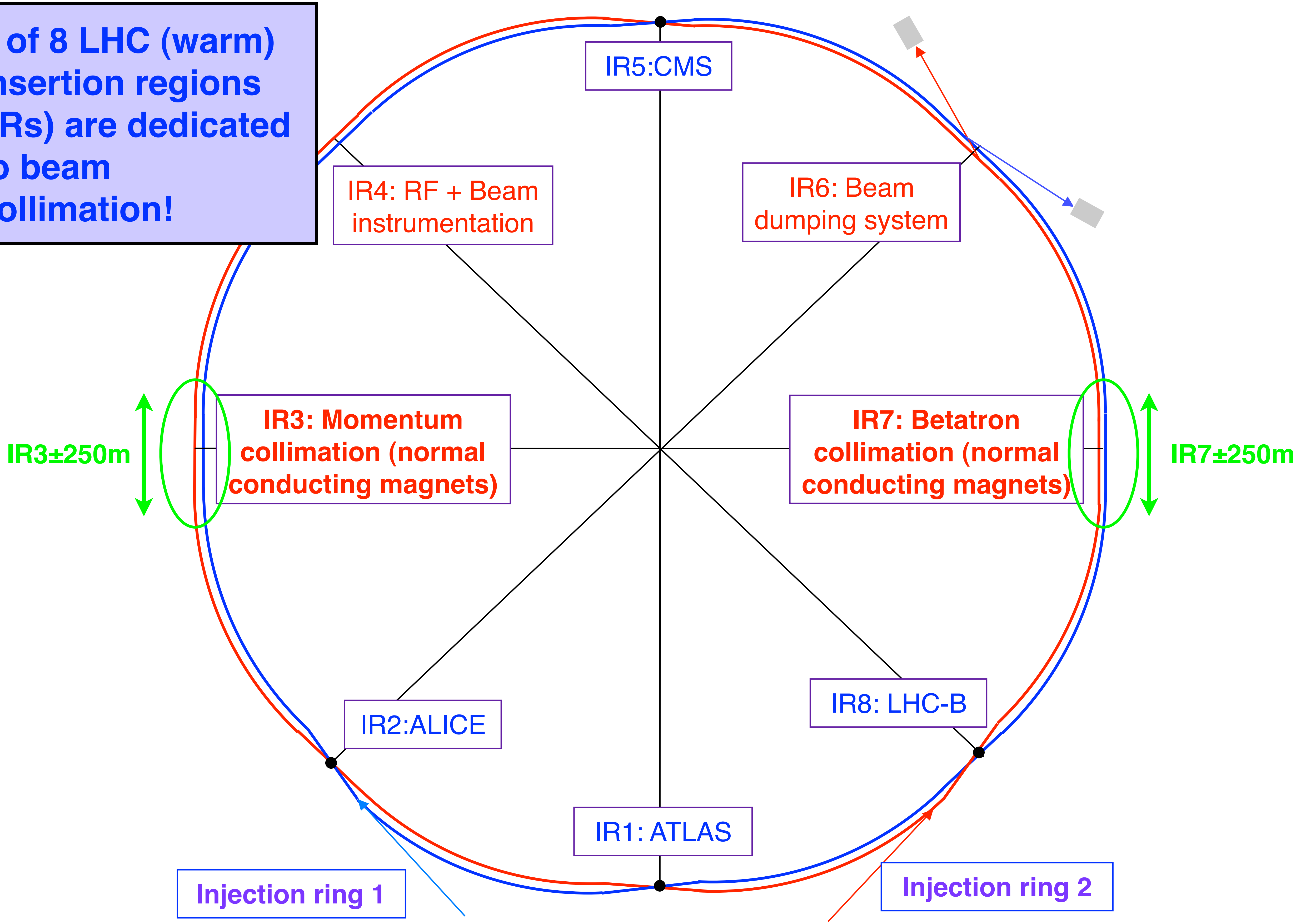

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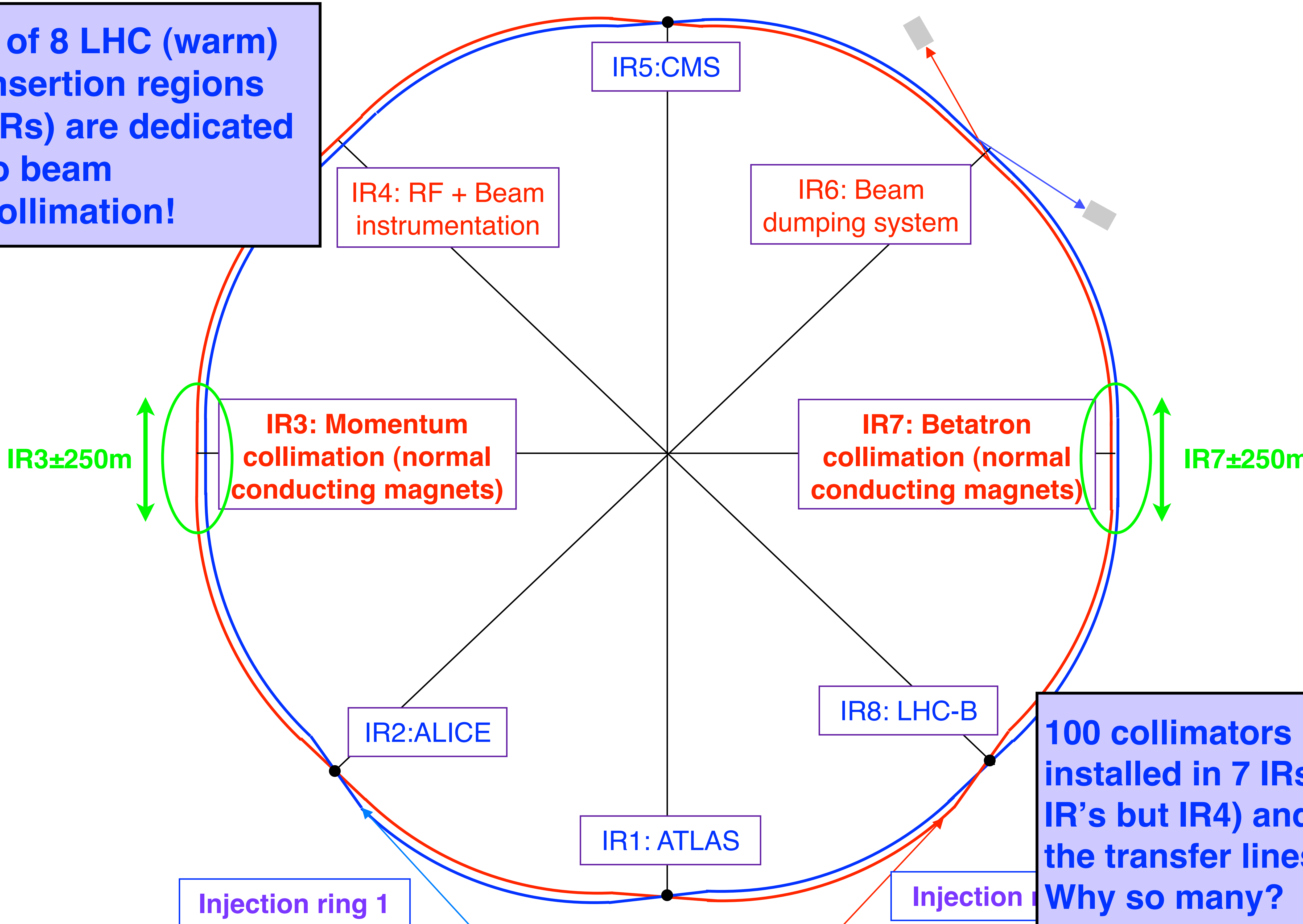
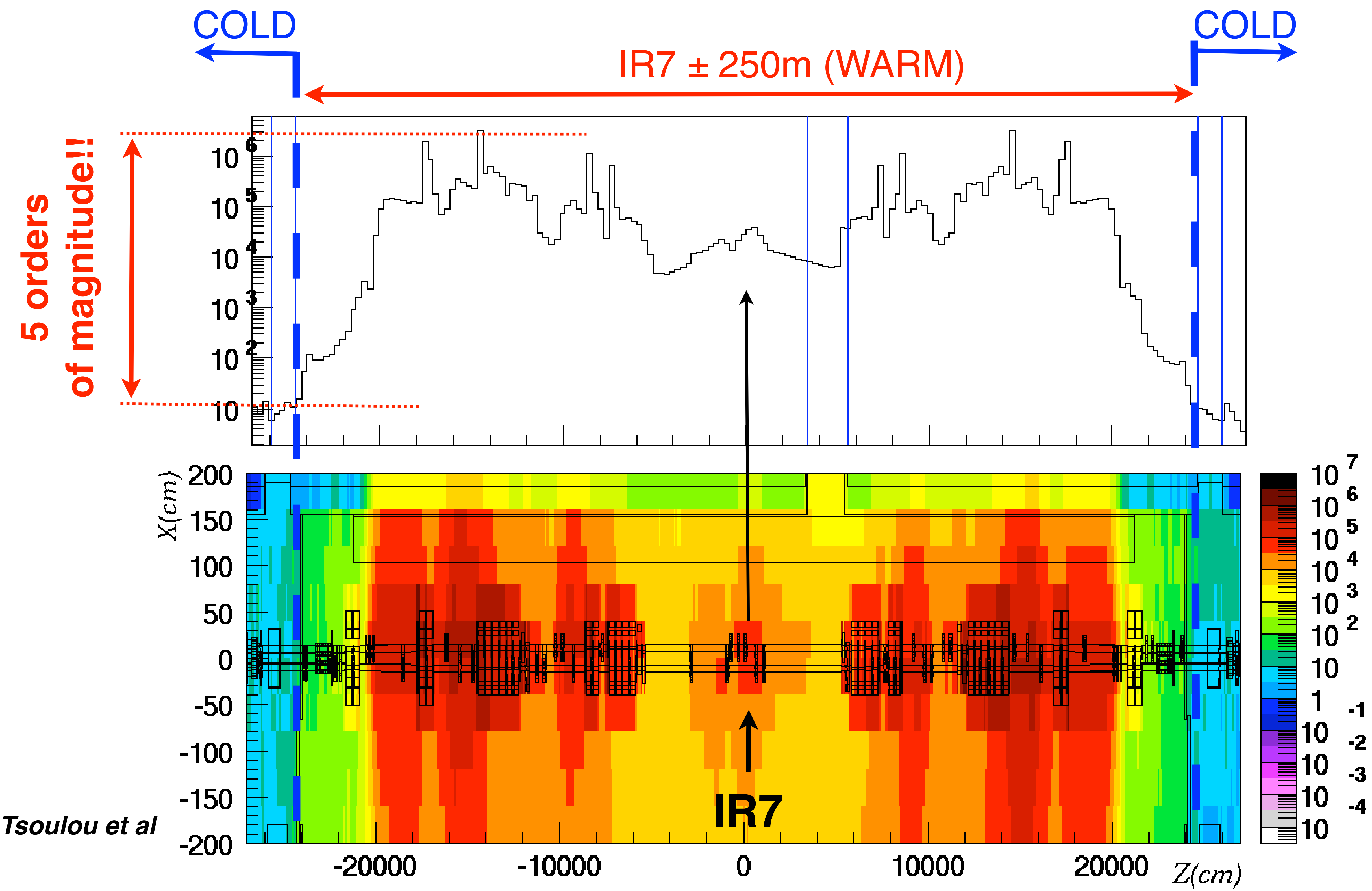


100 collimators installed in 7 IRs (all IR's but IR4) and in the transfer lines! Why so many?

Radiation doses in collimation region



K. Tsoulou et al

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

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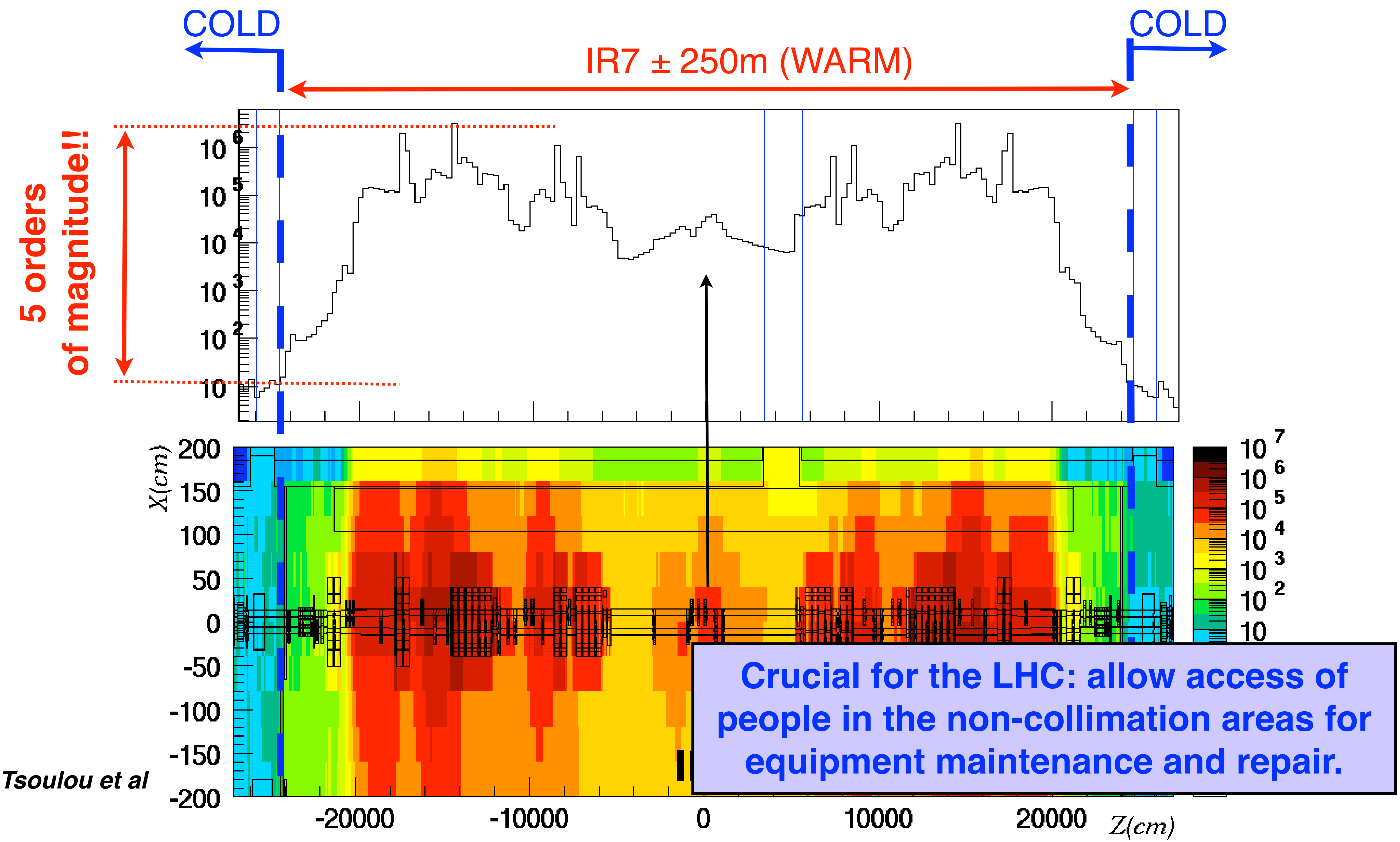

Crucial for the LHC: allow access of people in the non-collimation areas for equipment maintenance and repair.

K. Tsoulou et al

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

Why do we have beam losses?

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

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

No need for a collimation system!

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

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Beam lifetime

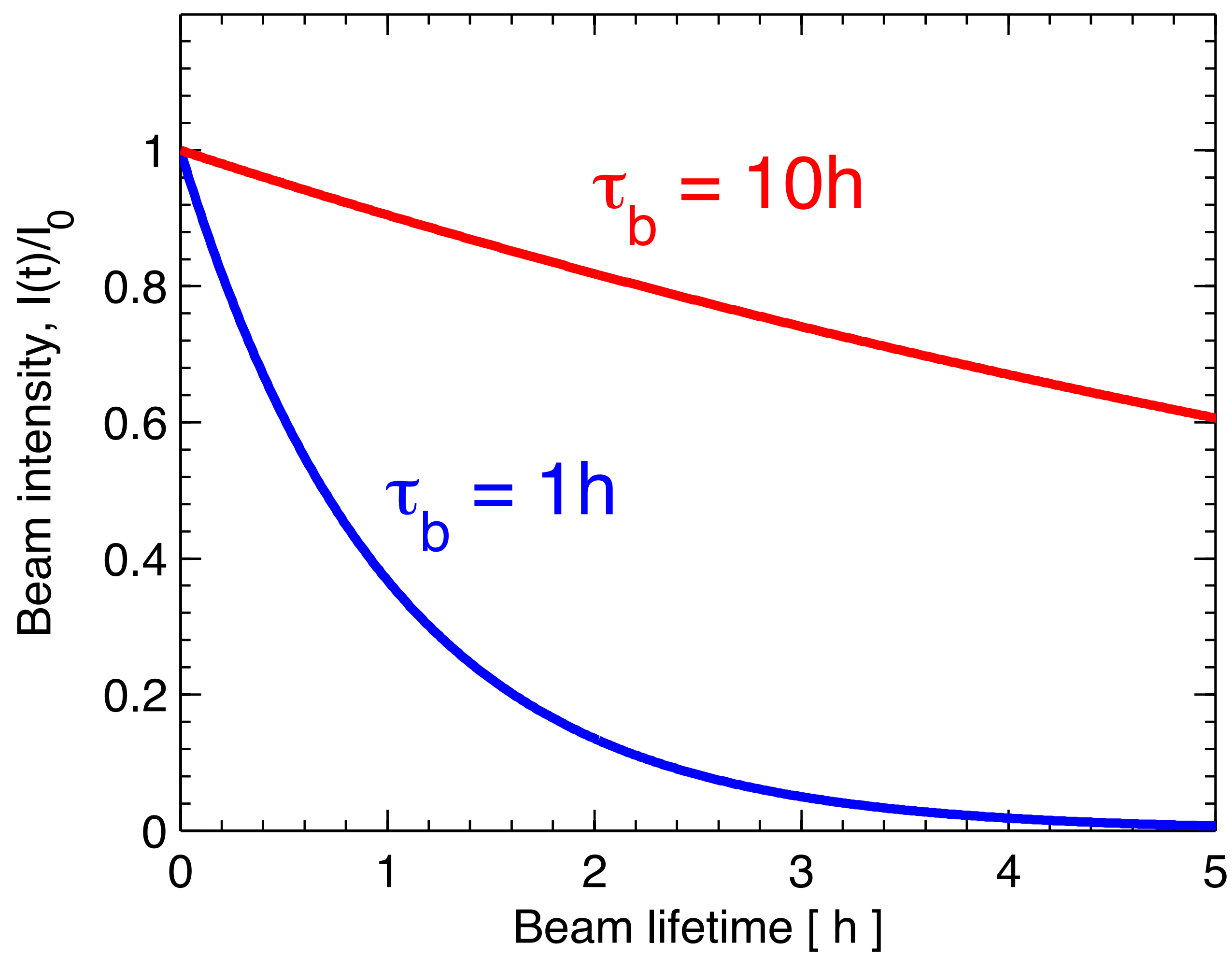
Beam loss mechanisms are modelled by assuming a non-infinite **beam lifetime,** τ_b

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

: Beam intensity versus time

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

: Loss rate



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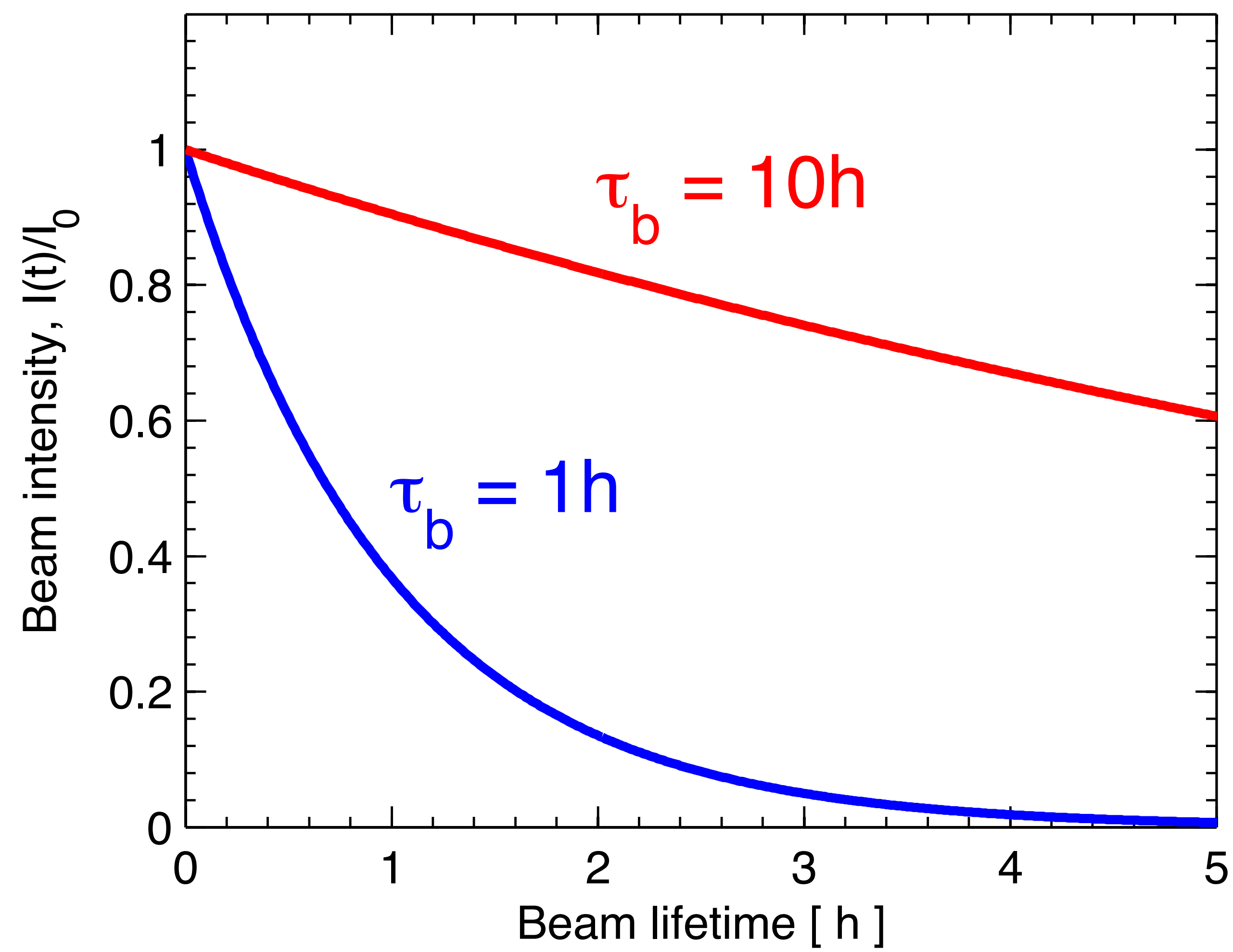

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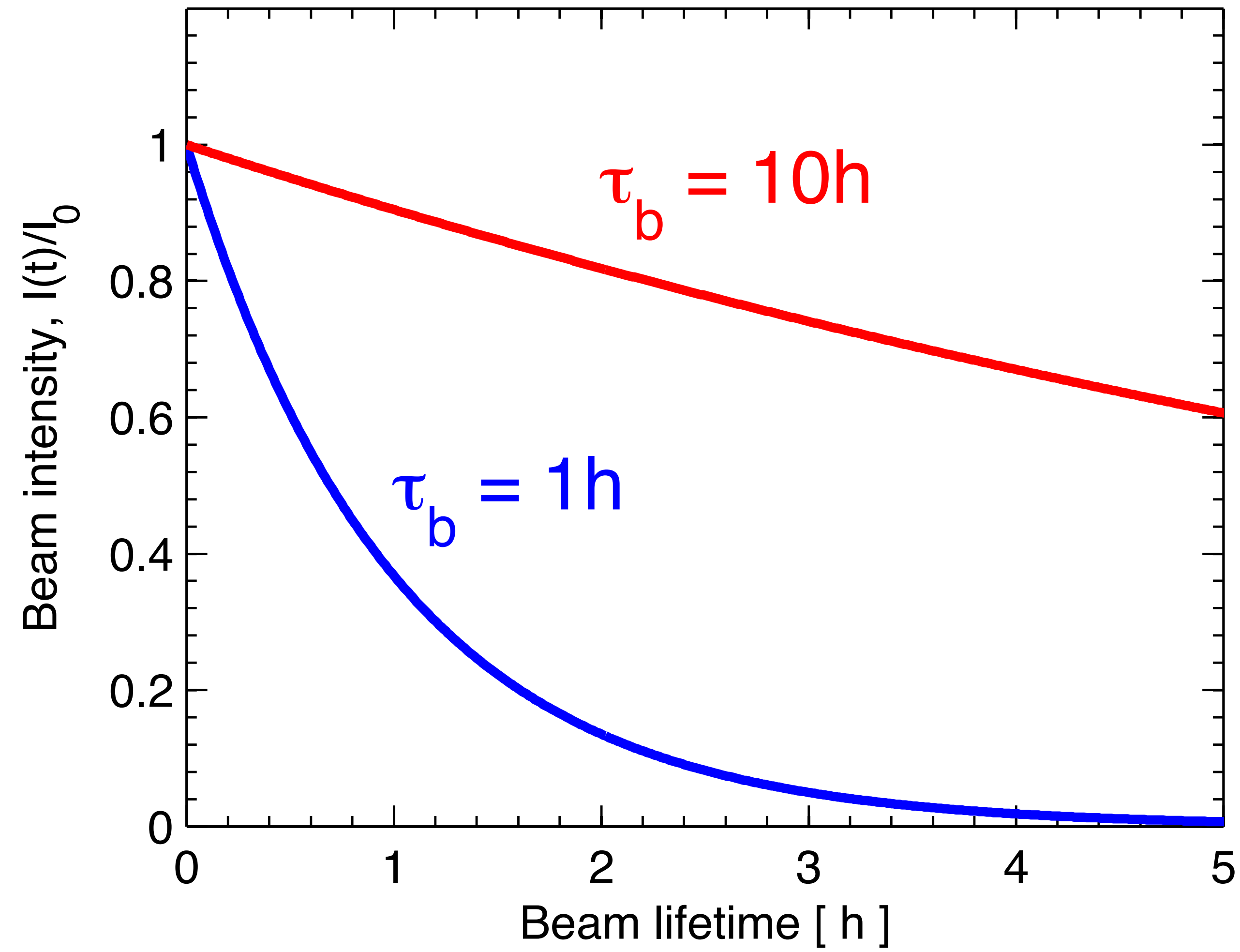

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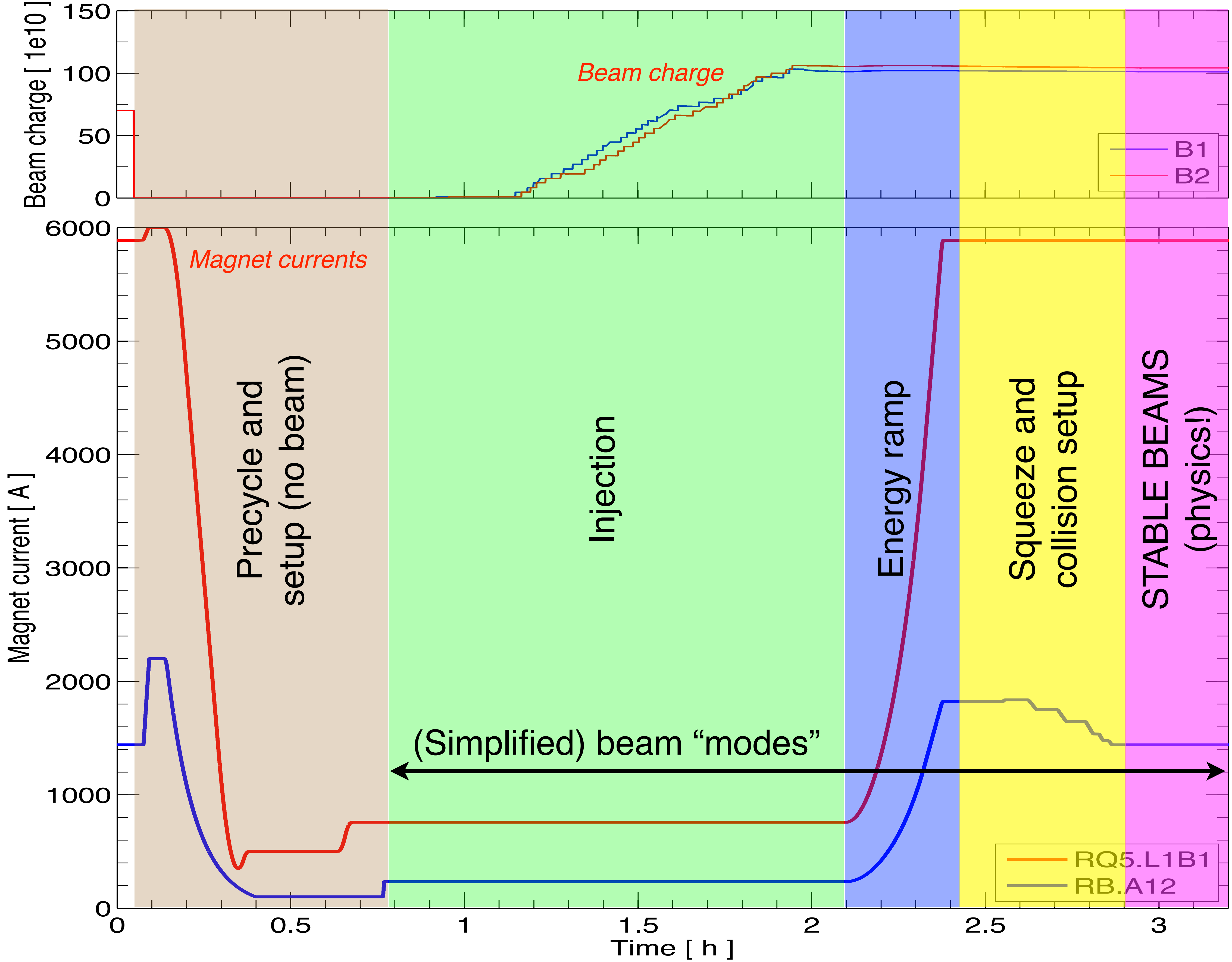
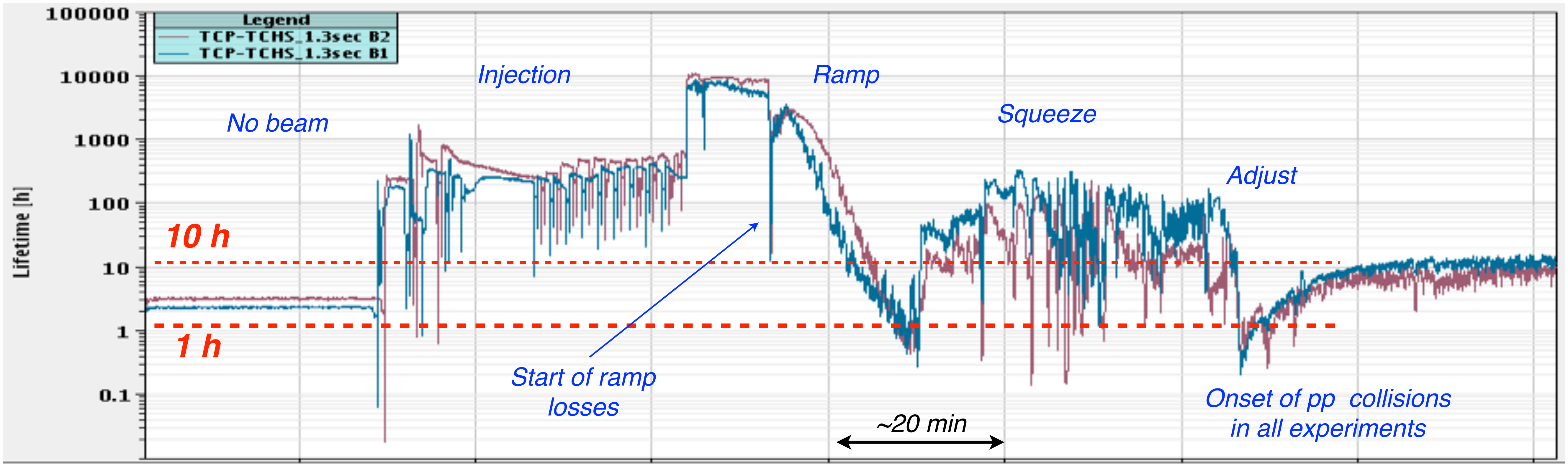
*LHC example at 7 TeV: **1h lifetime** at the full intensity of 3.2×10^{14} (320 hundred trillion) protons corresponds to a loss rate of about 90 billion proton per second, i.e. 0.1MJ/s = **100 KW**!*

Operational cycle (in 2010)



LHC lifetime in a physics fill



Example of a typical physics fill in 2012.

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

In particular, what "leaks" 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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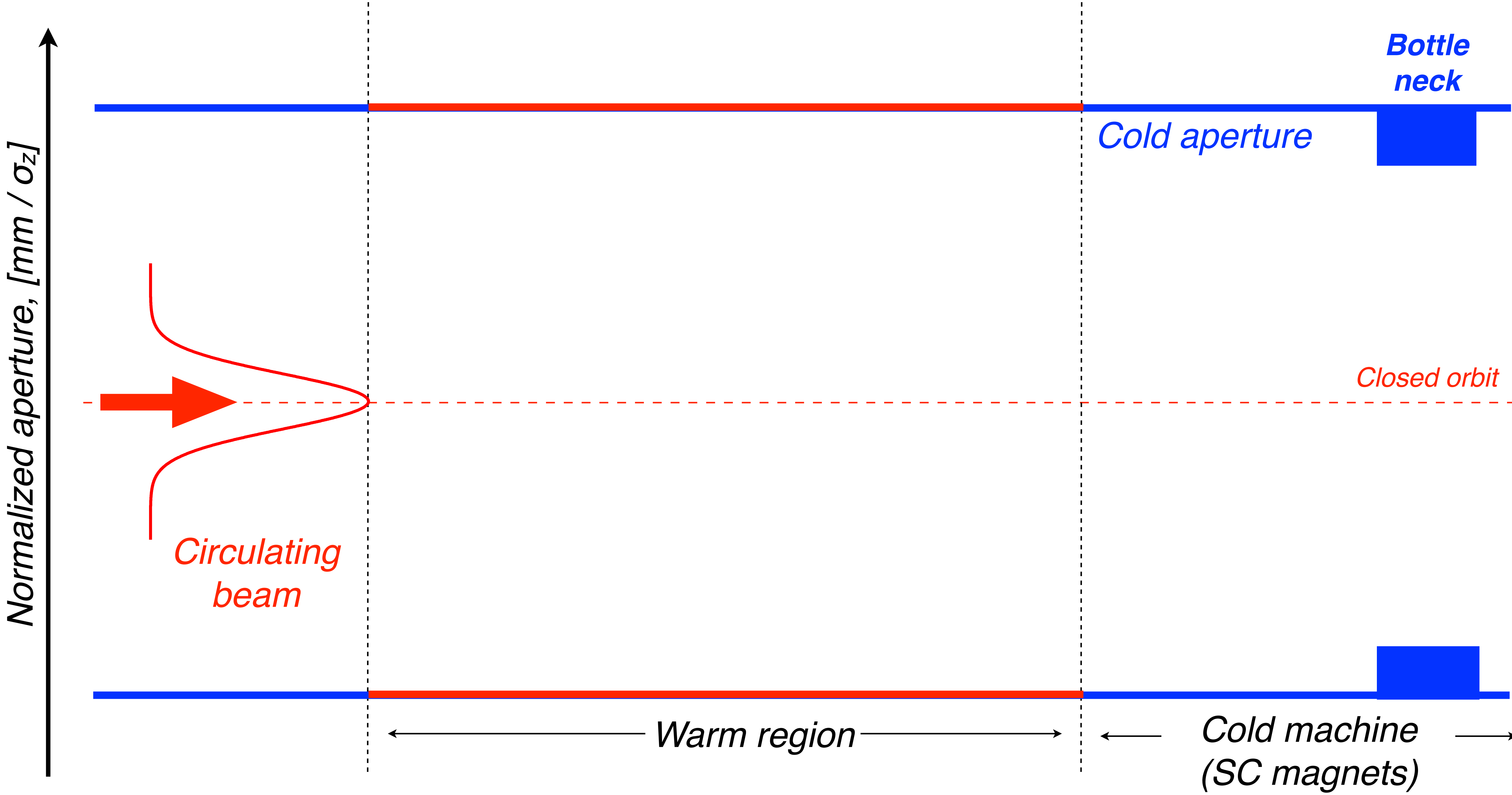
Aperture and single-stage cleaning



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

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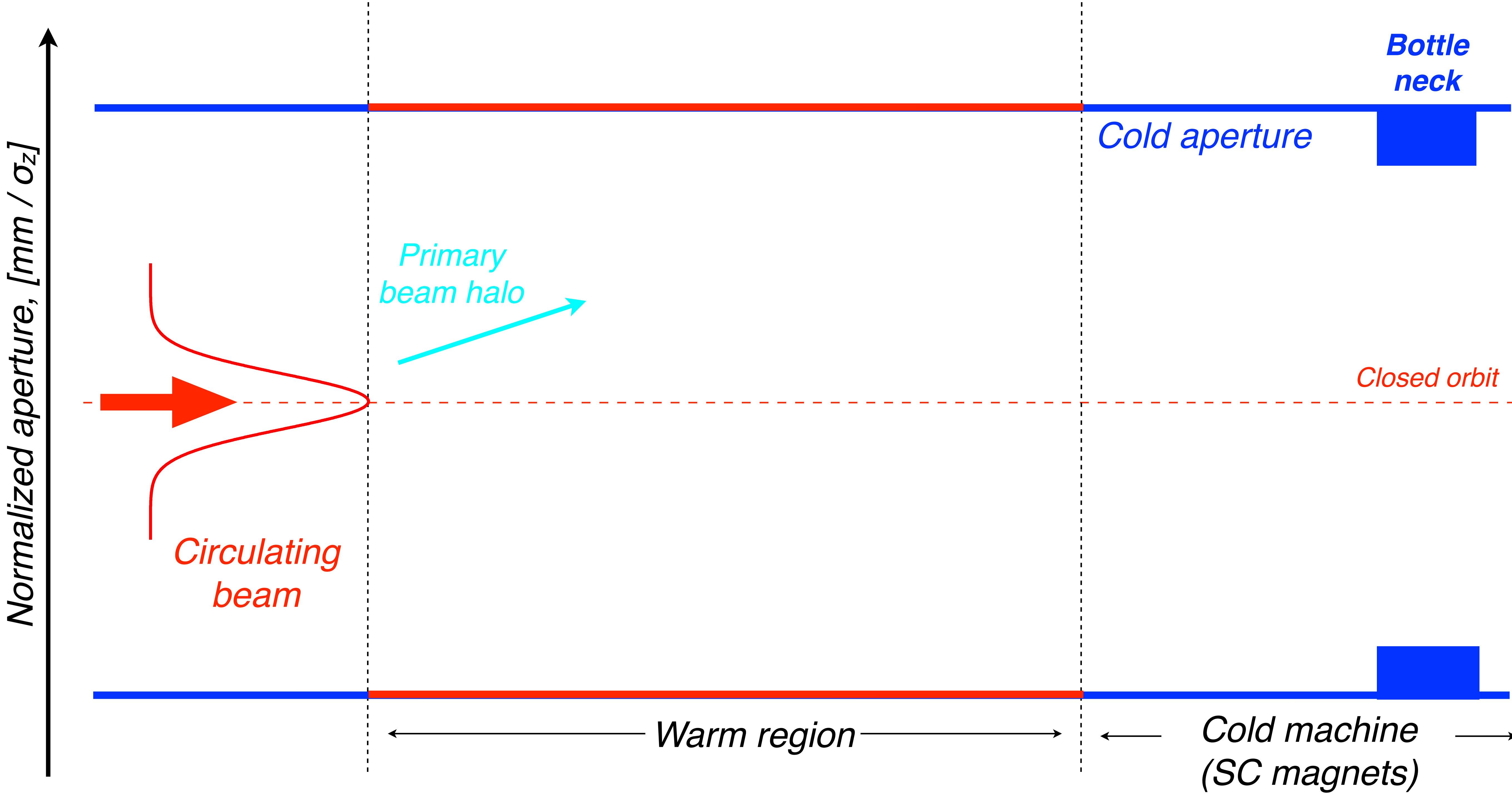

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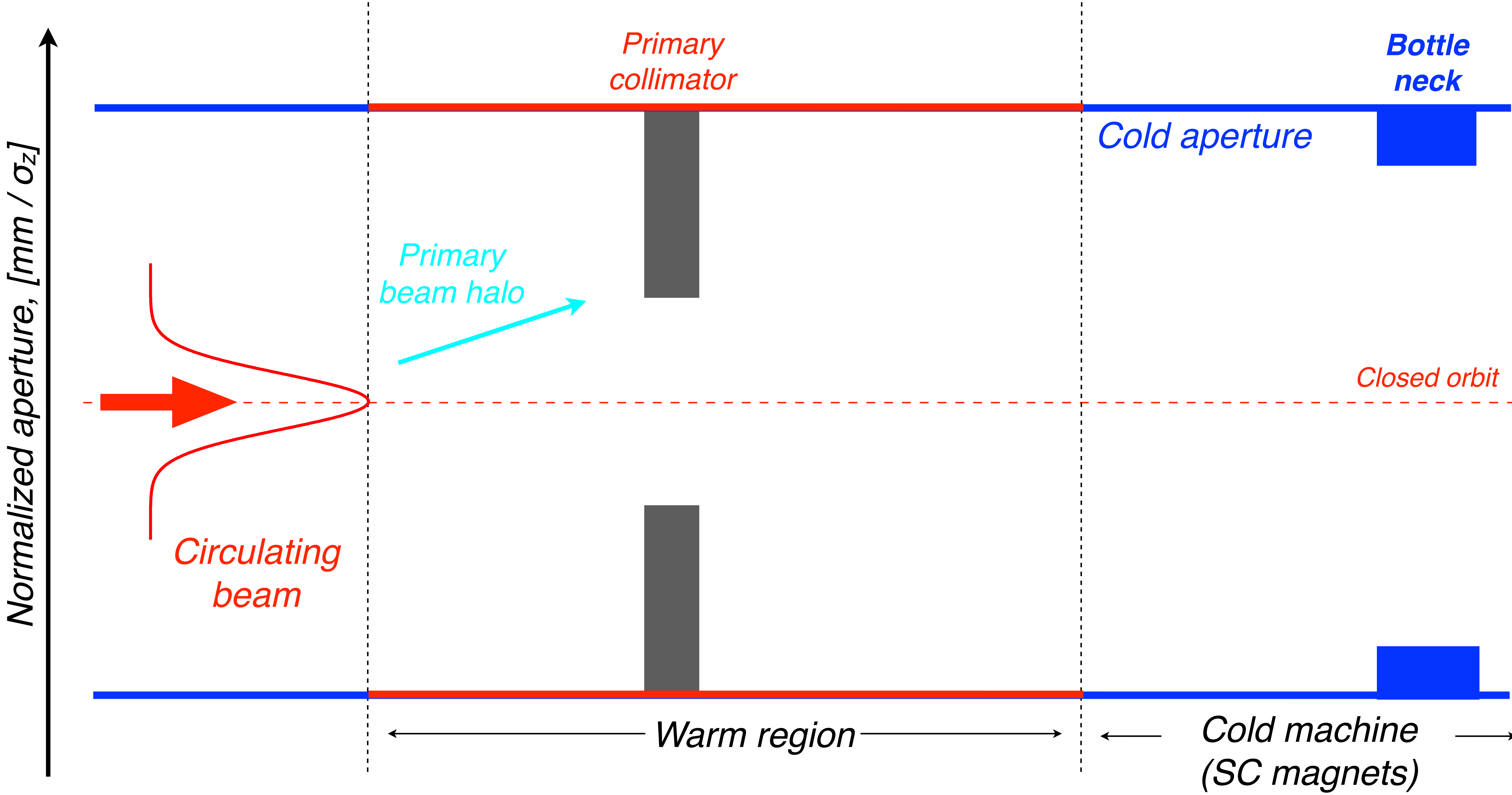

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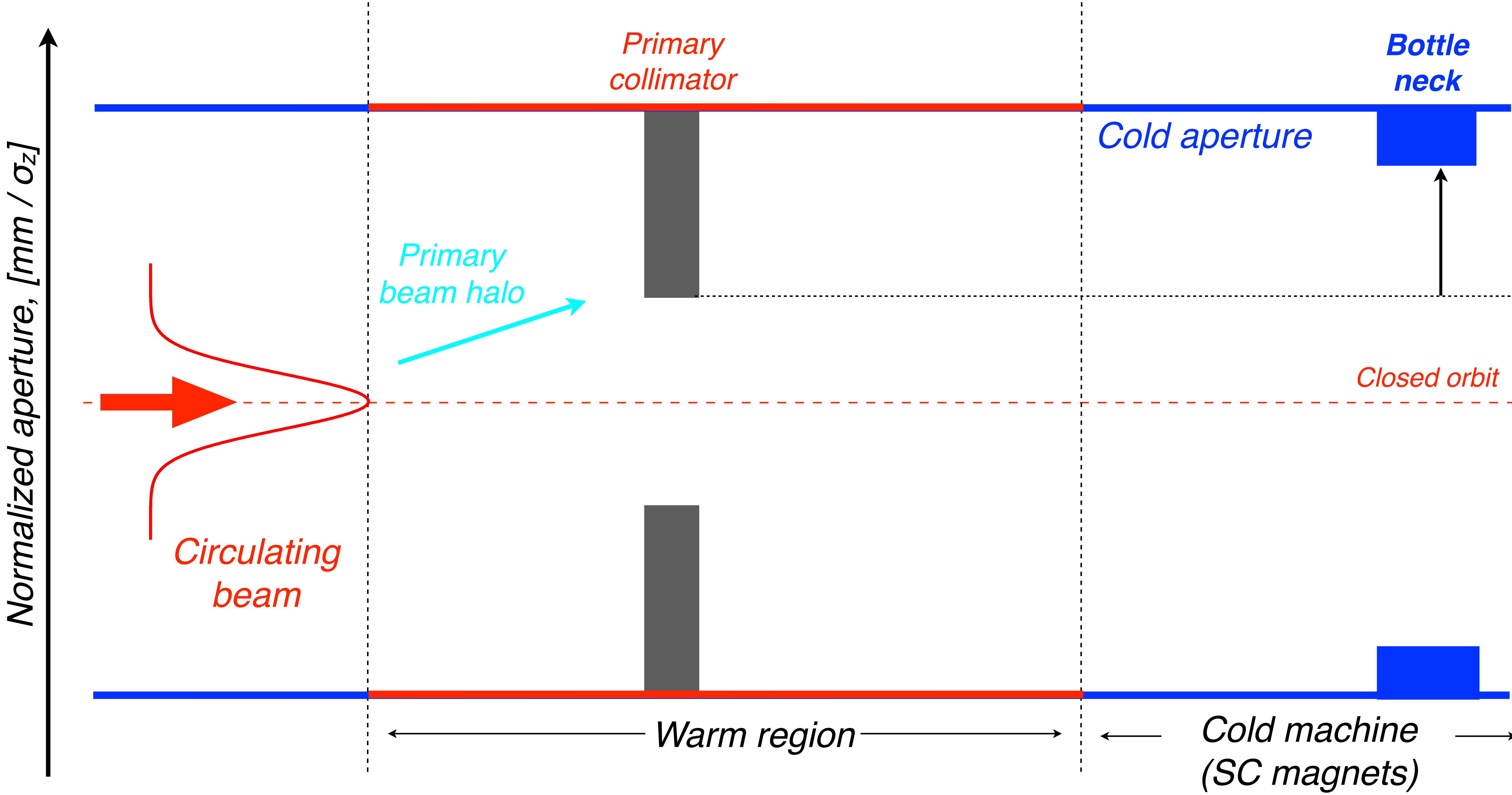

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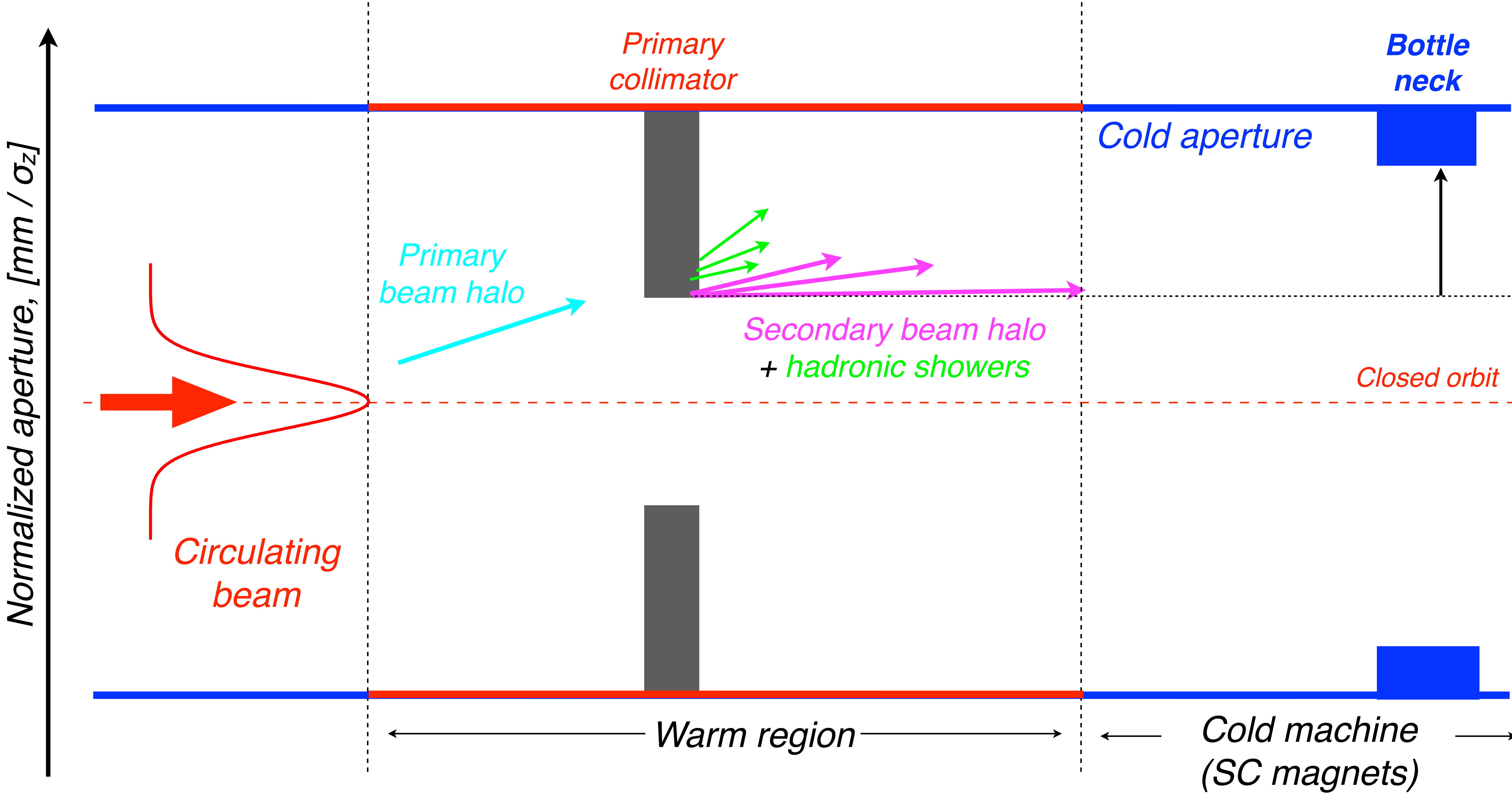

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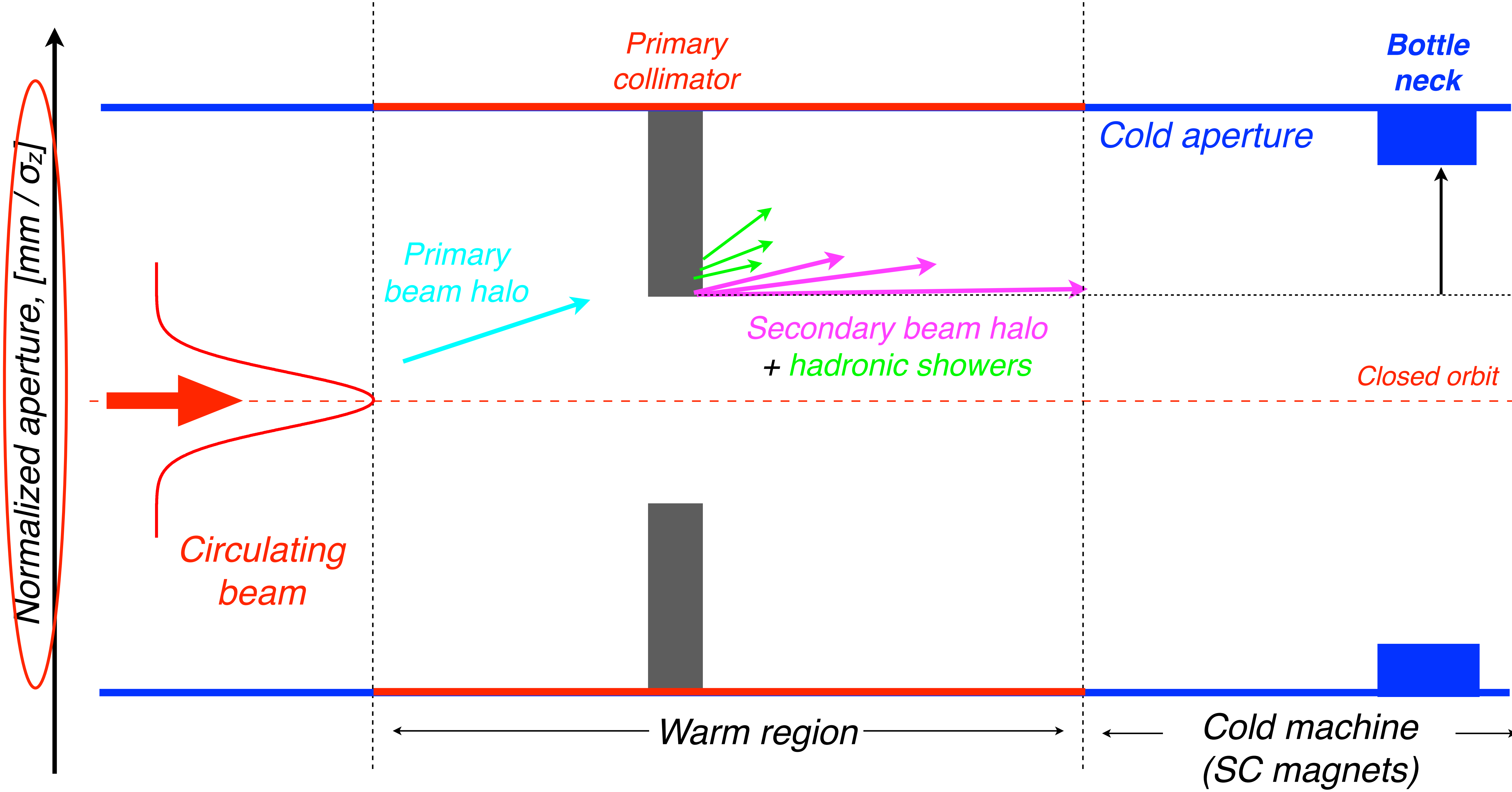

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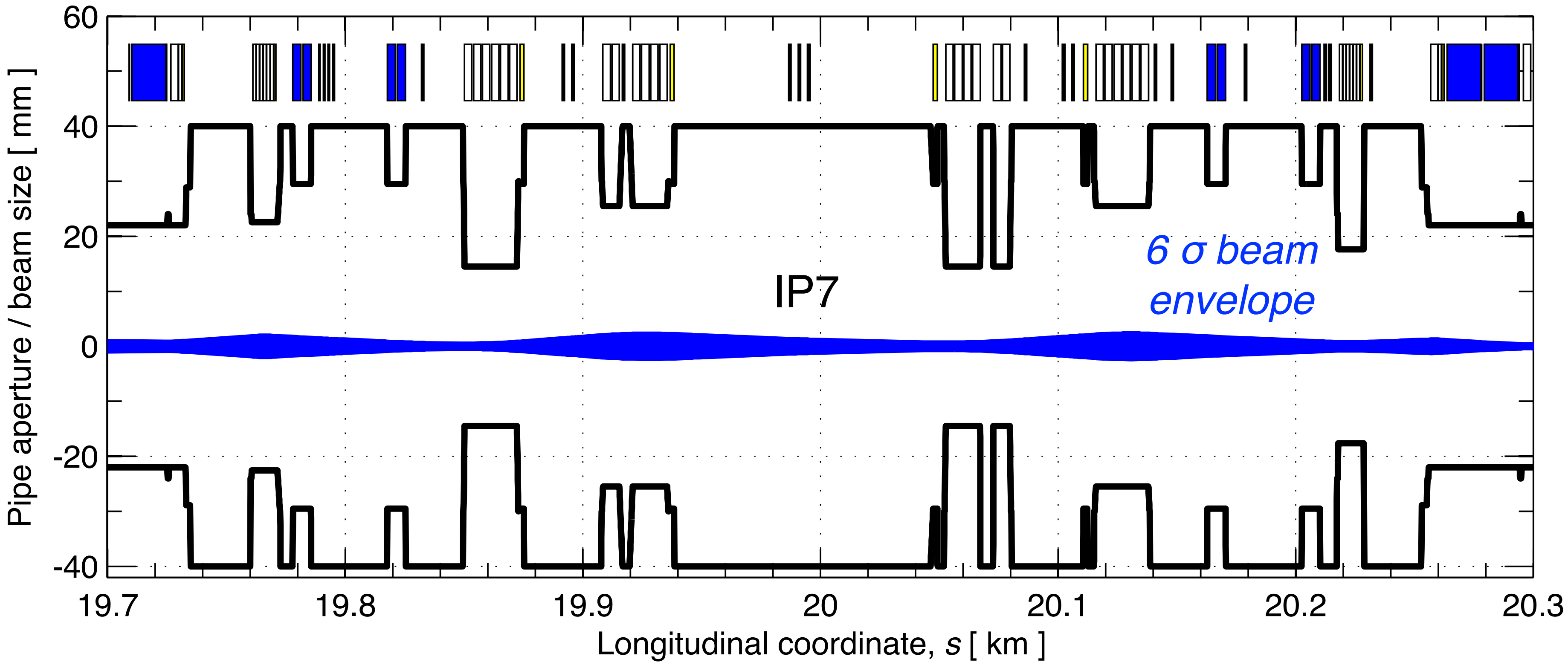
Setting/aperture notations



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

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

β_z : beta functions

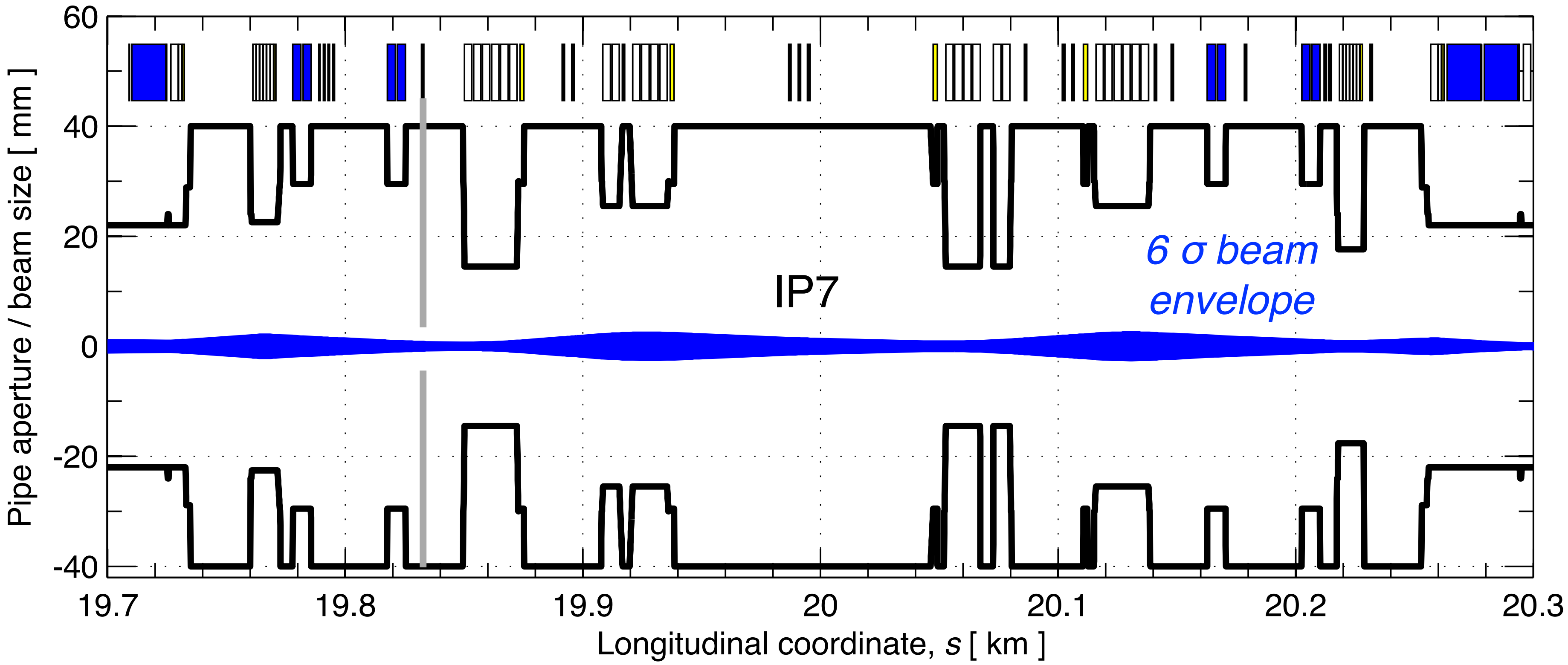
ϵ_z/γ : normalized emittance

D_z : dispersion function

$\delta p/p$: RMS energy spread

g : collimator gap in millimeters

Setting/aperture notations



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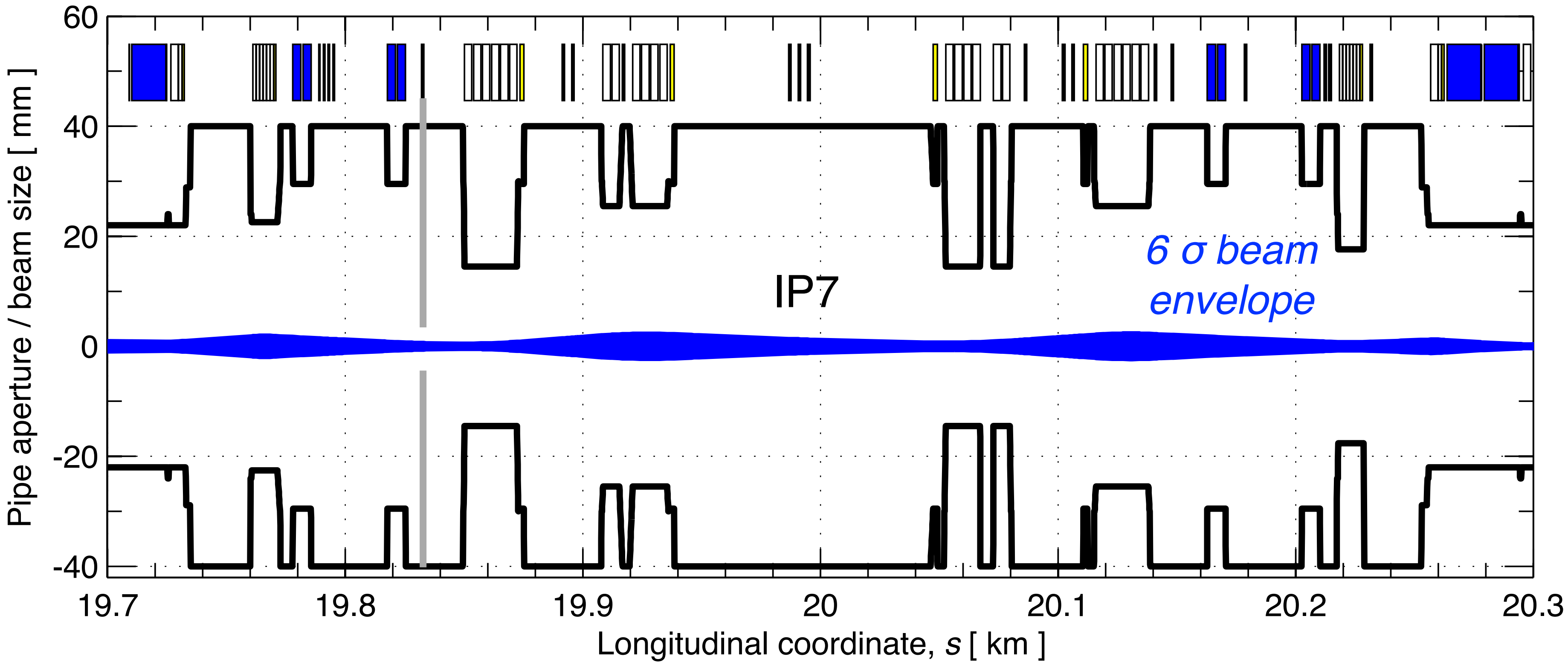

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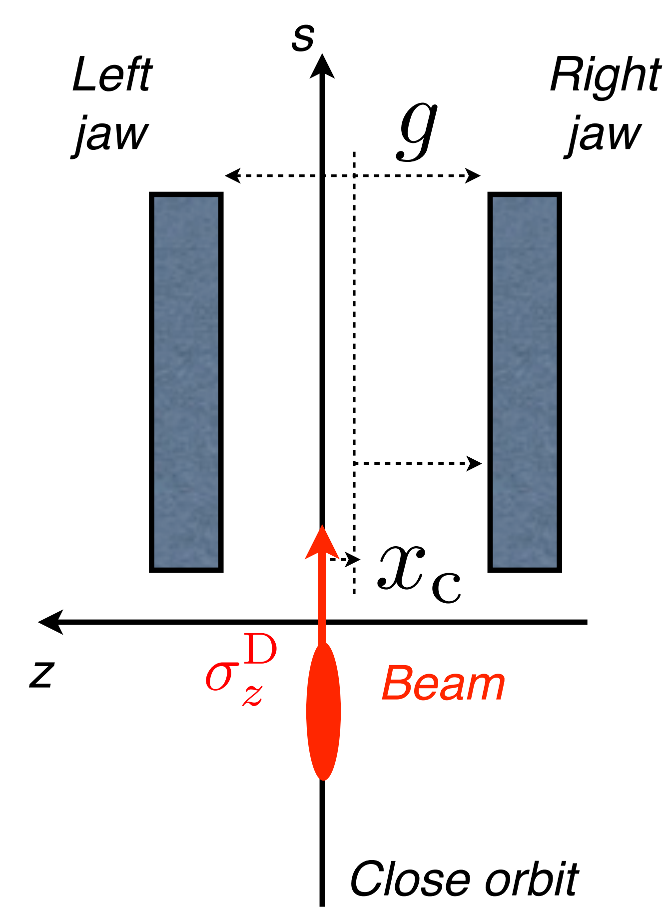
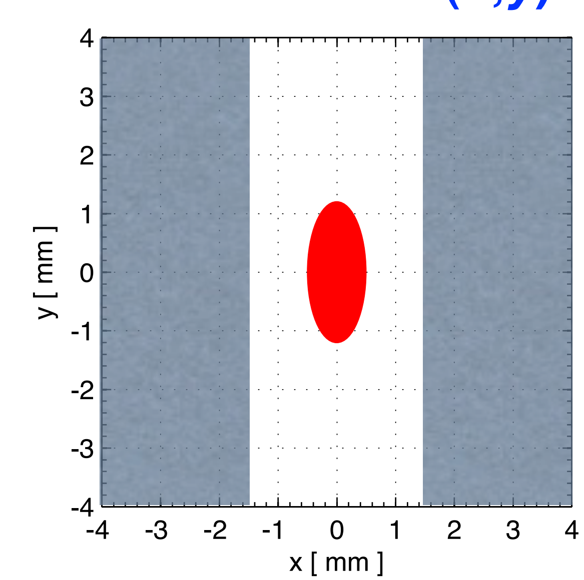
Top view (*x*,*s*)



Front view (*x*,*y*)



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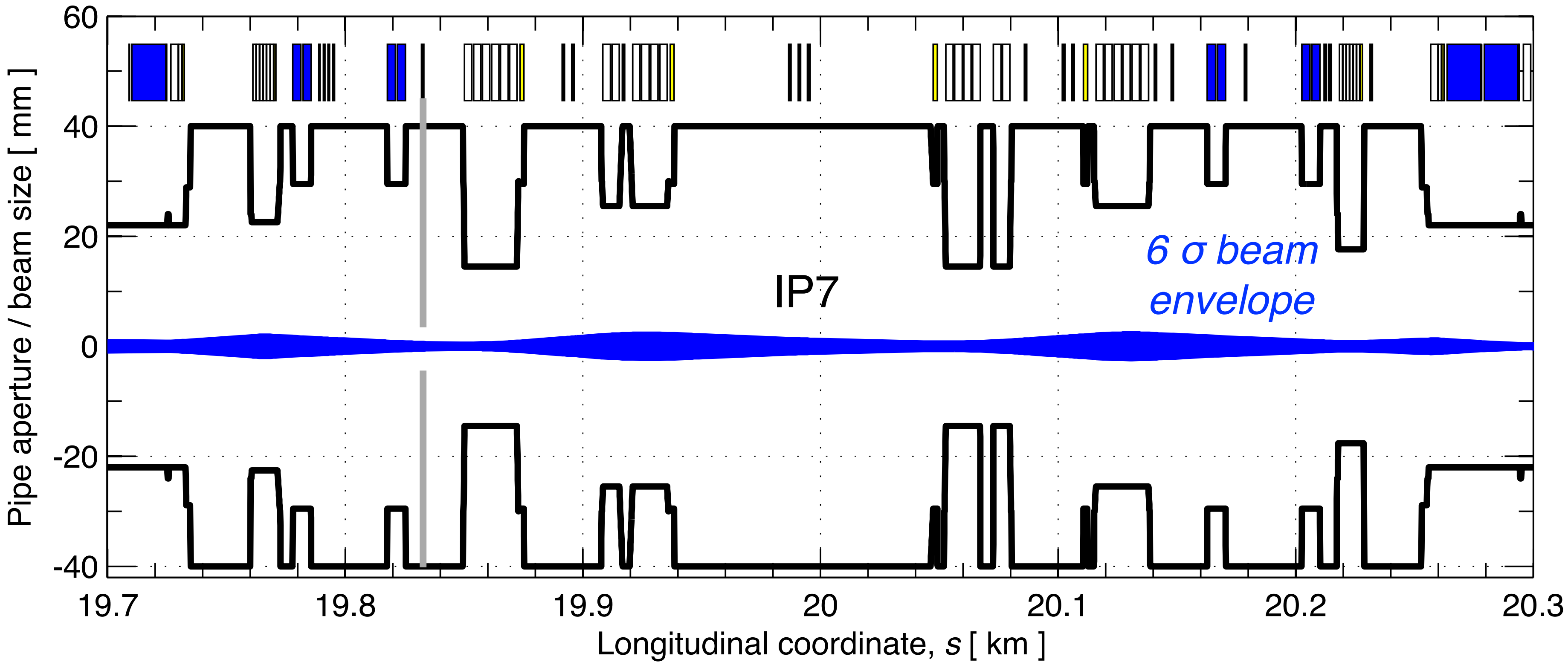

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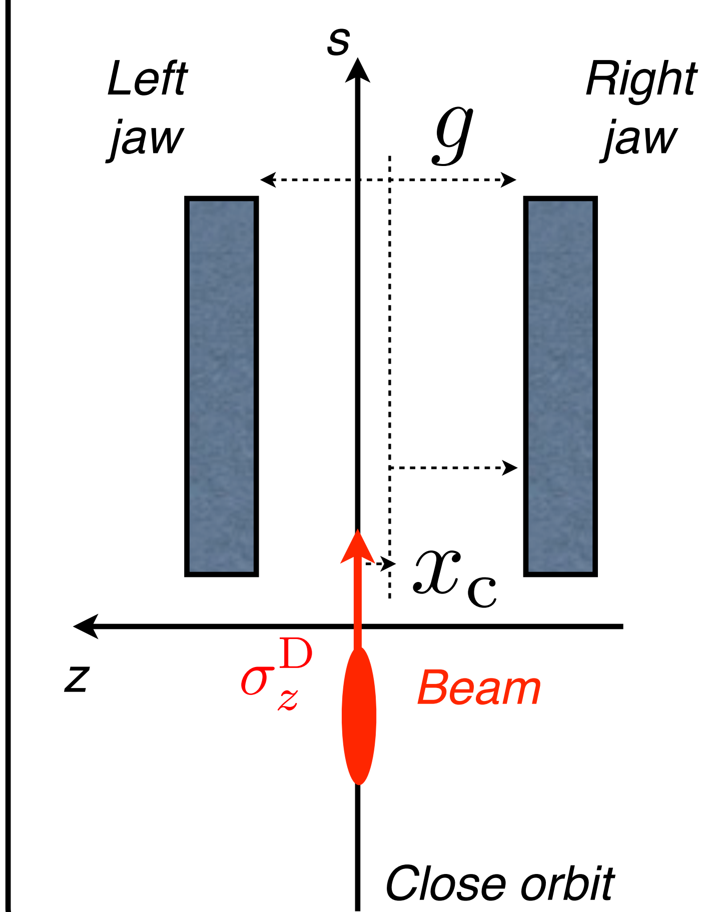

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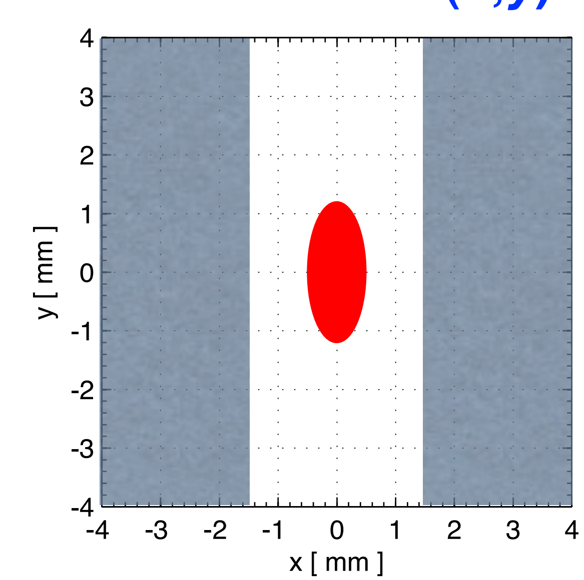

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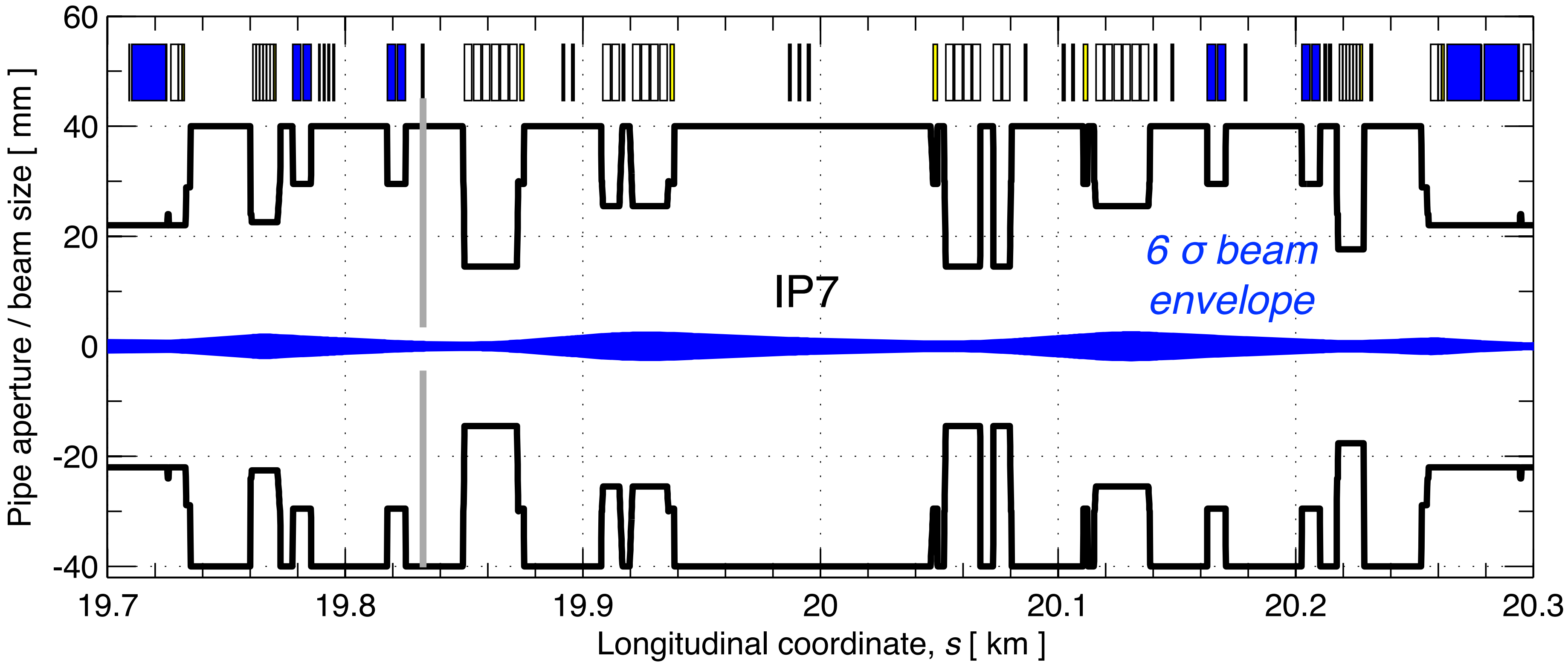

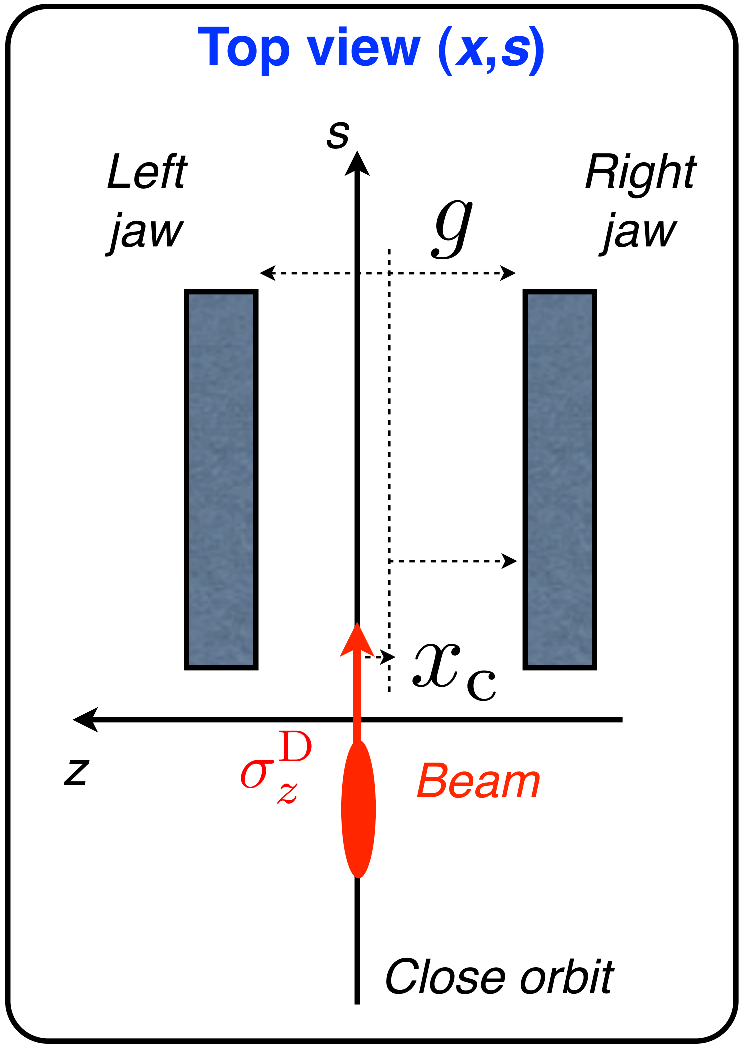

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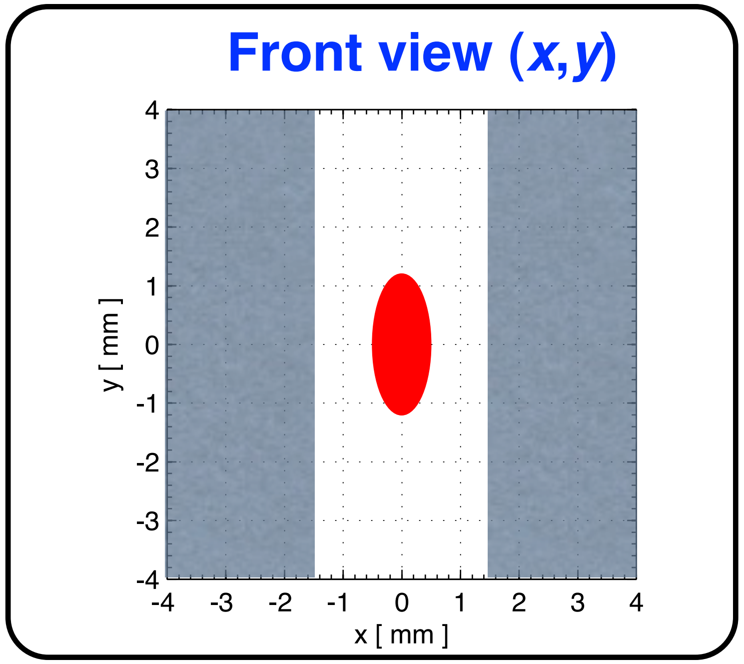
$$x_c \pm N_\sigma \cdot \sigma_z$$: **Collimator jaw positions**



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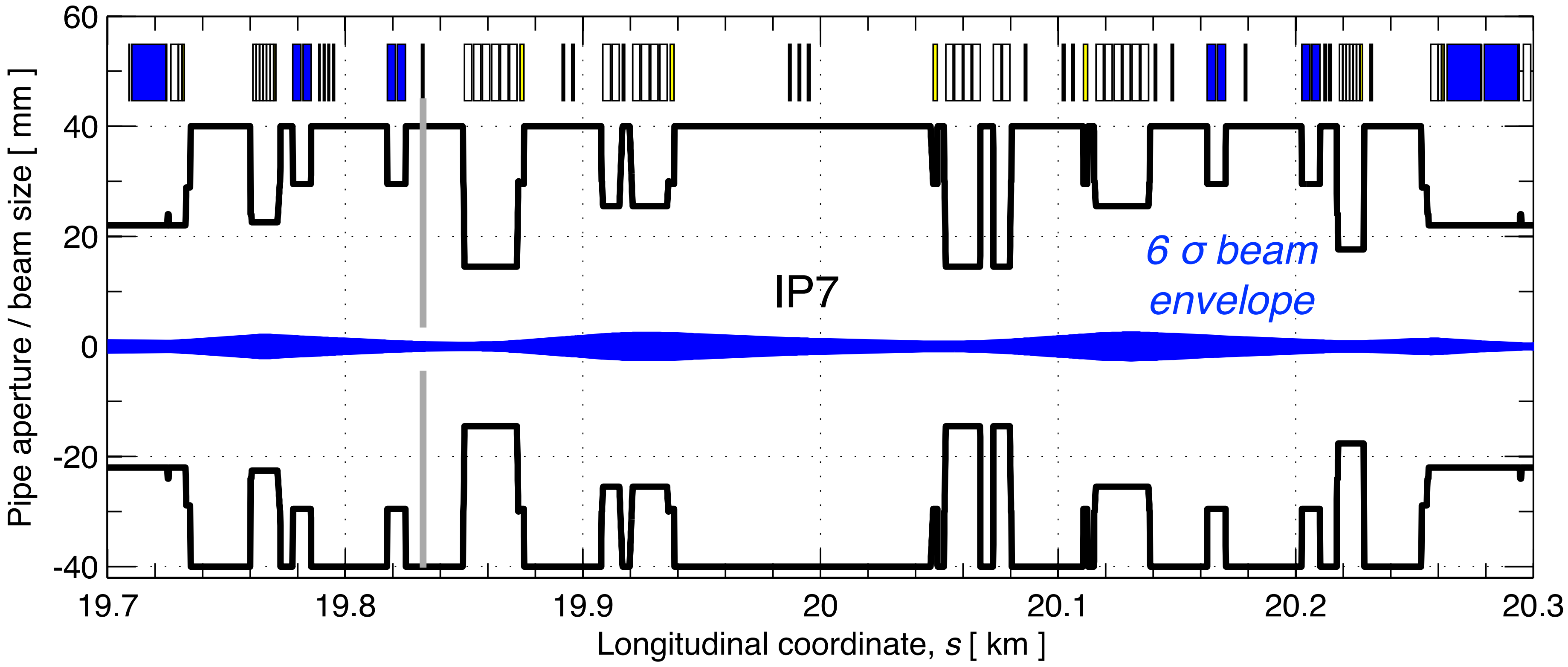

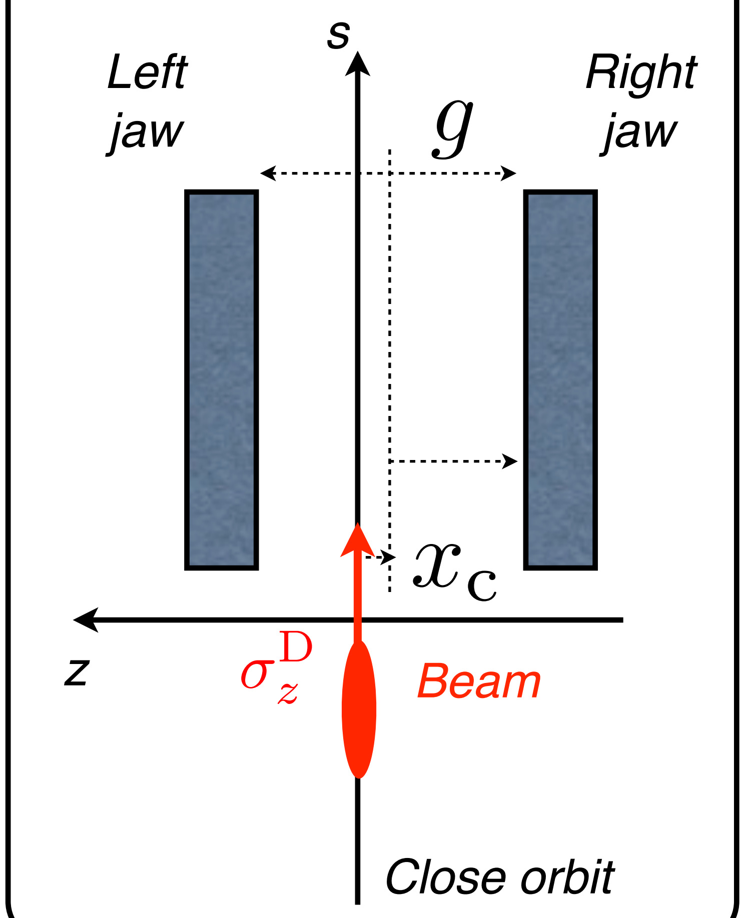

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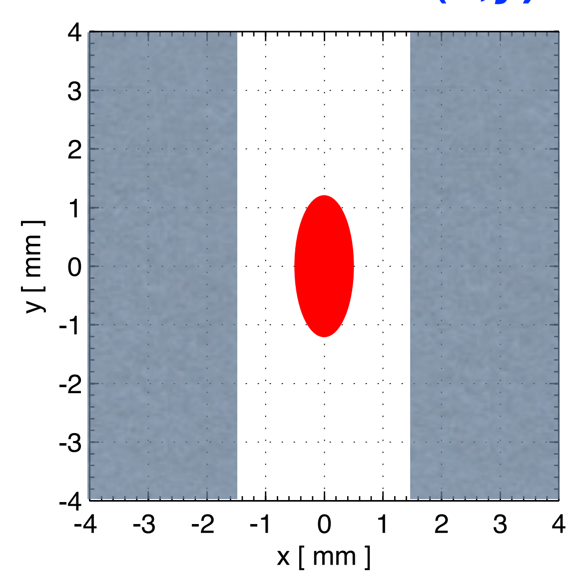

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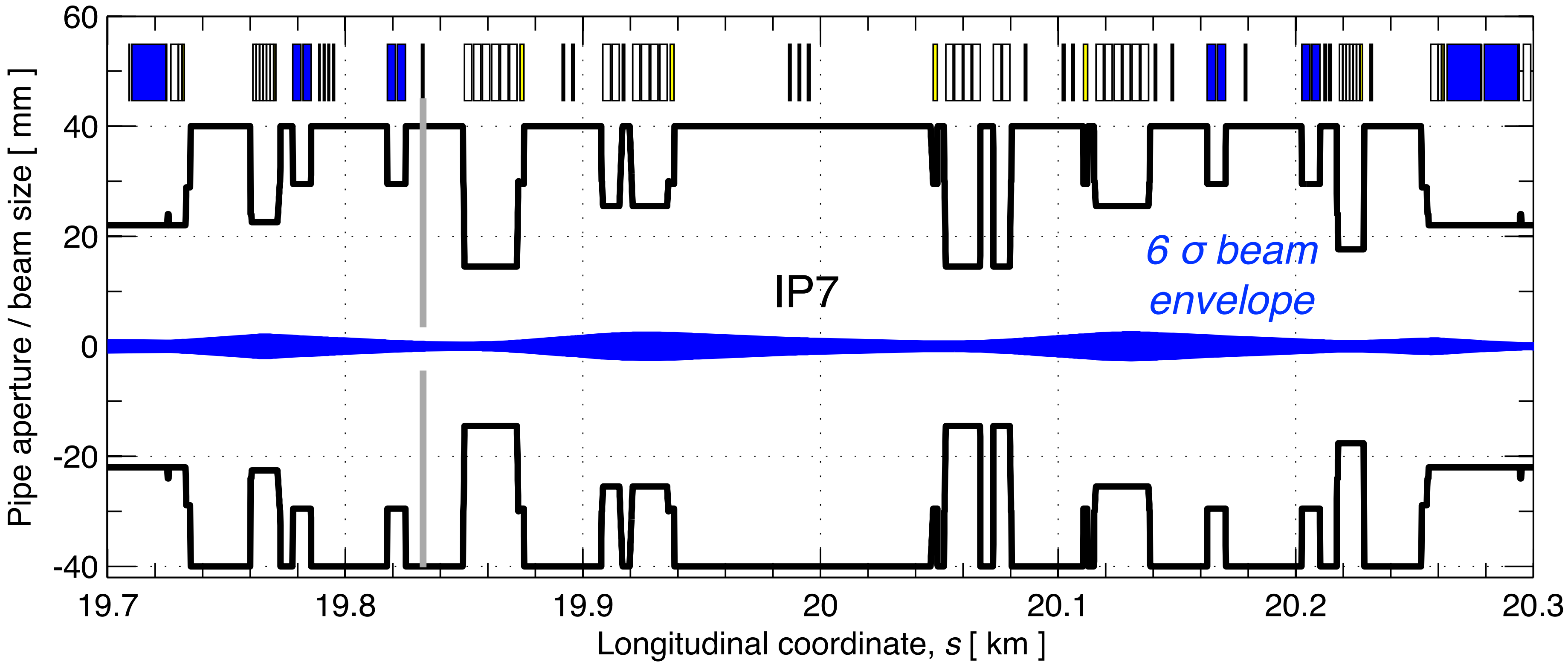

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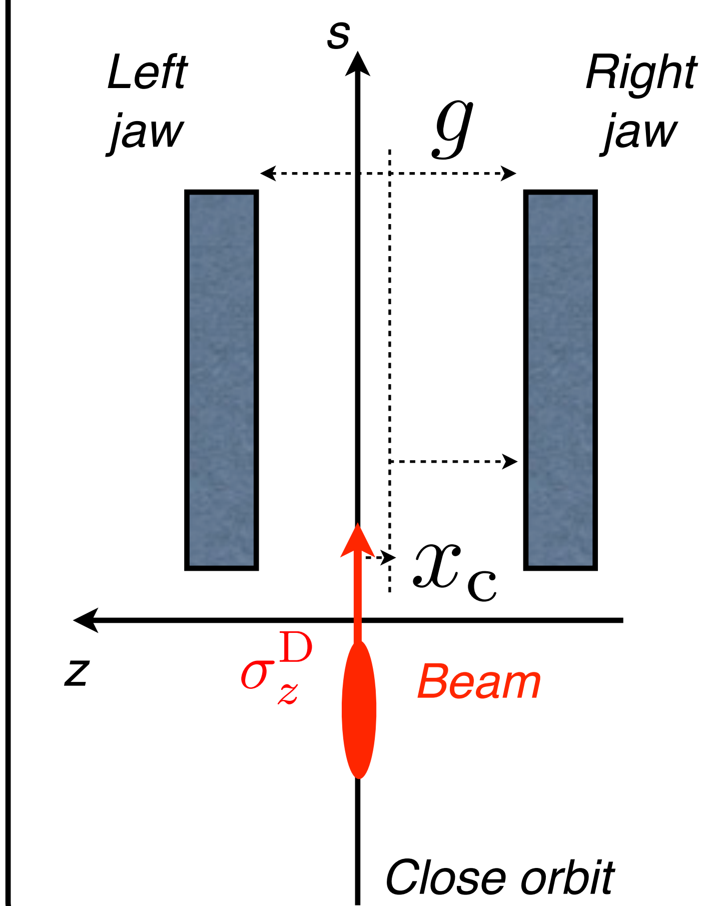
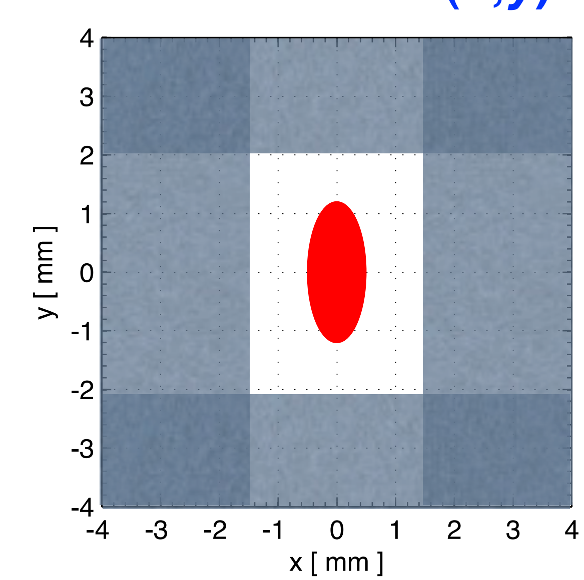


Front view (*x*,*y*)



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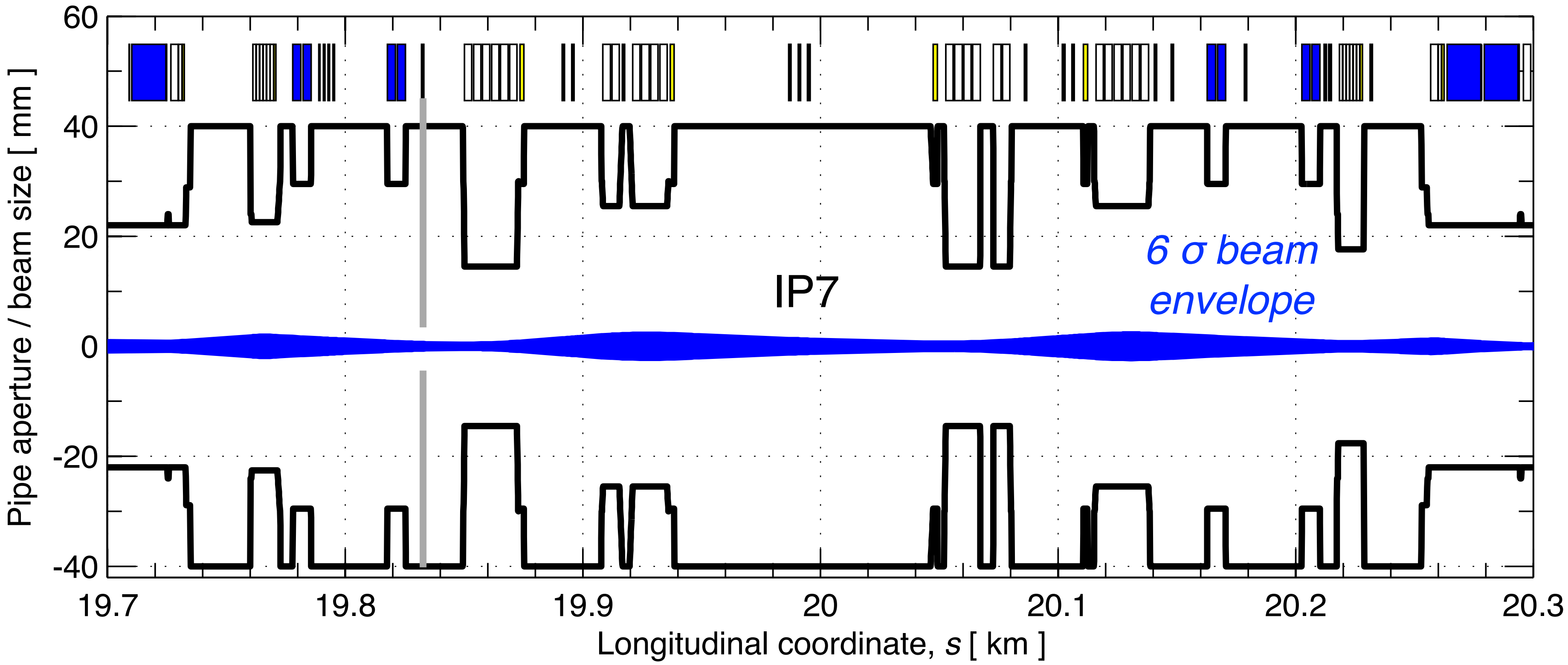

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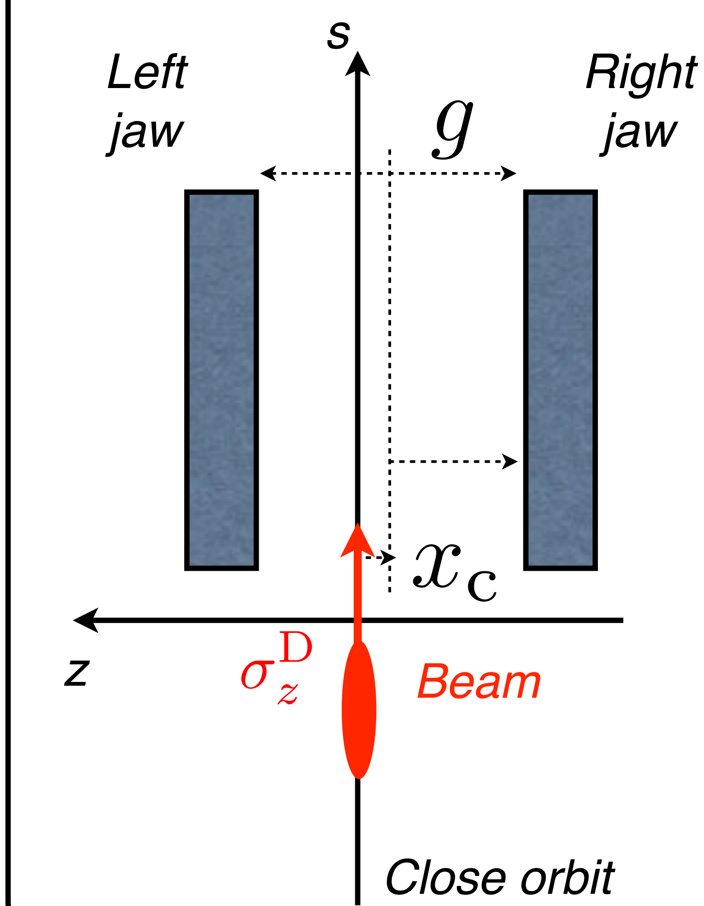

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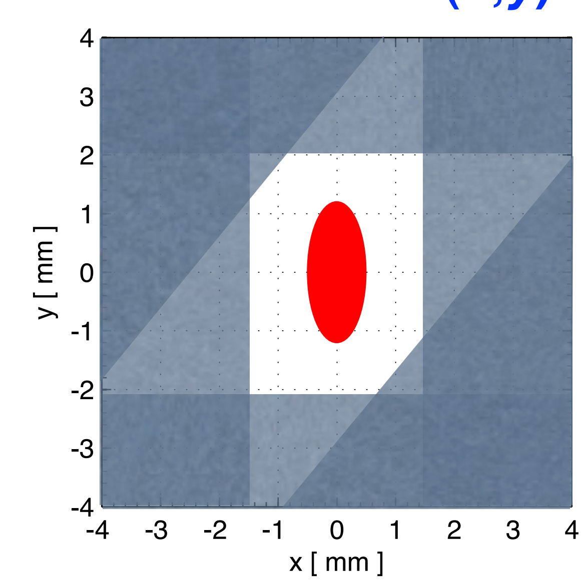

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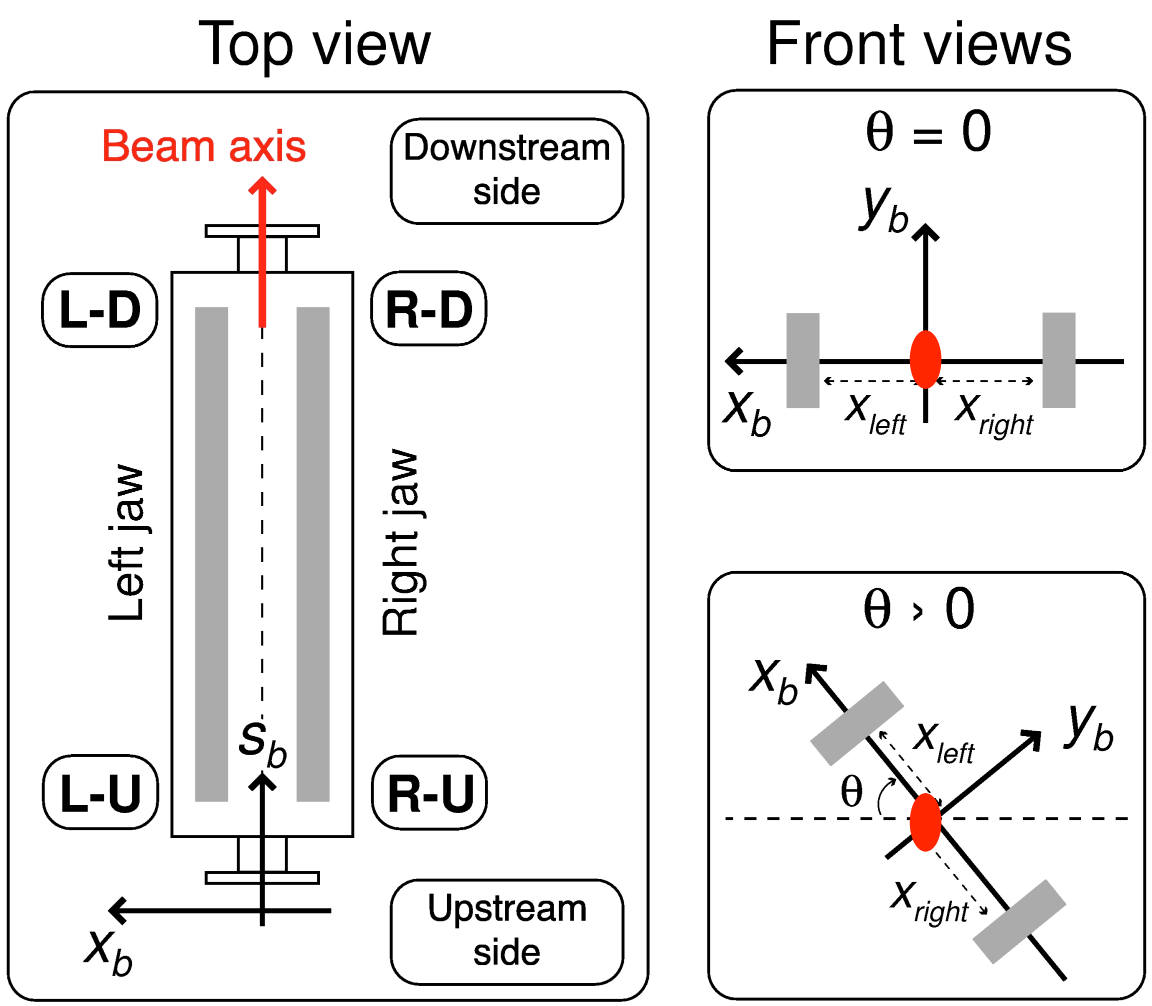
"Skew" collimators



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

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

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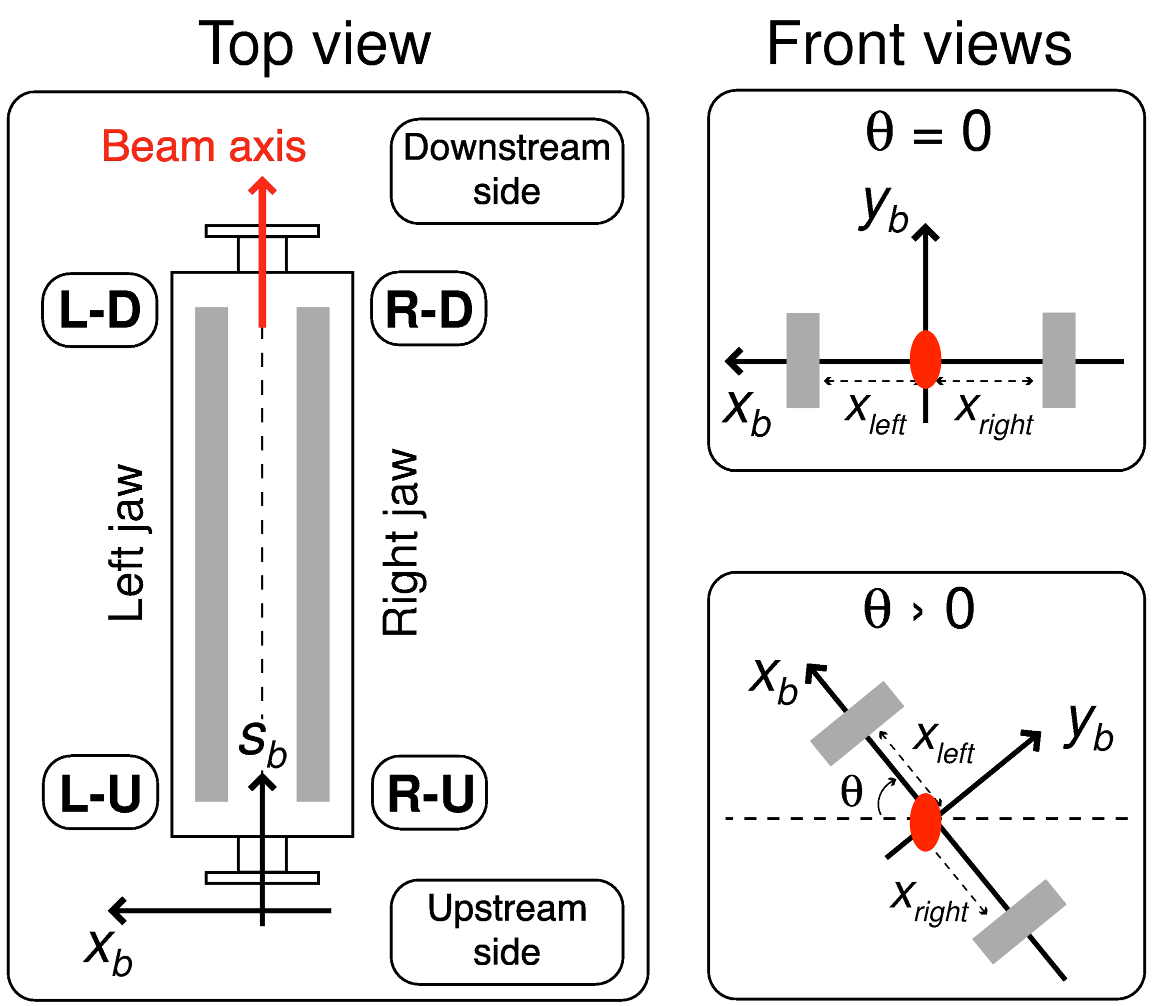

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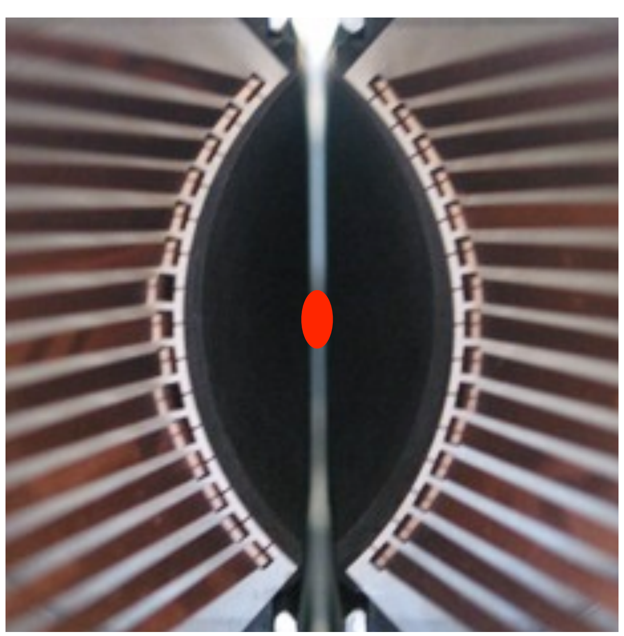
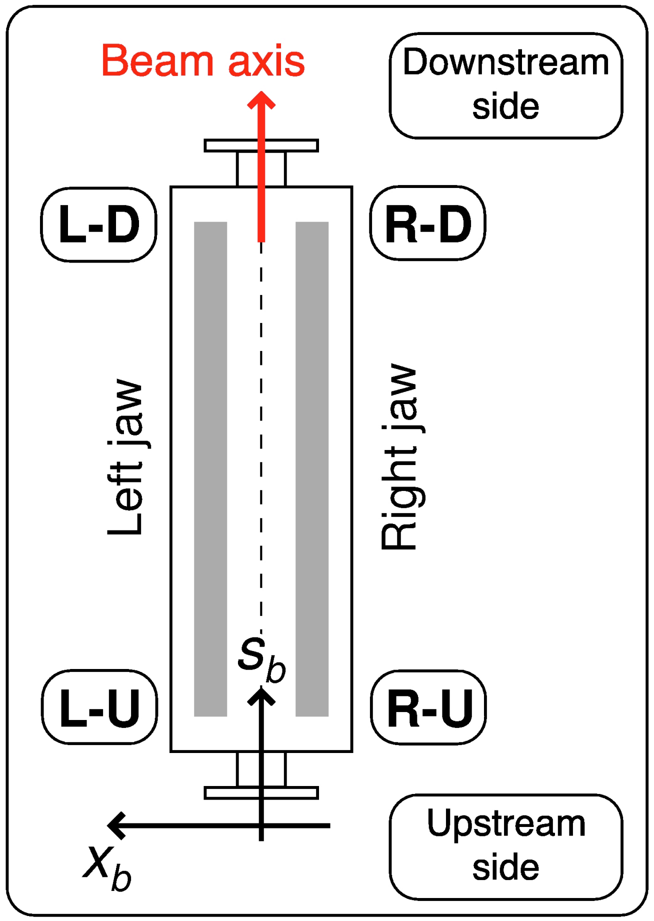
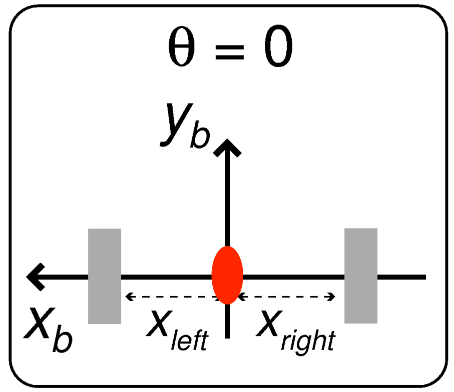


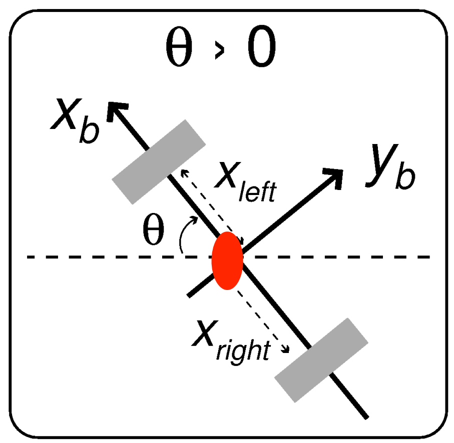
"Skew" collimators

Top view



Front views





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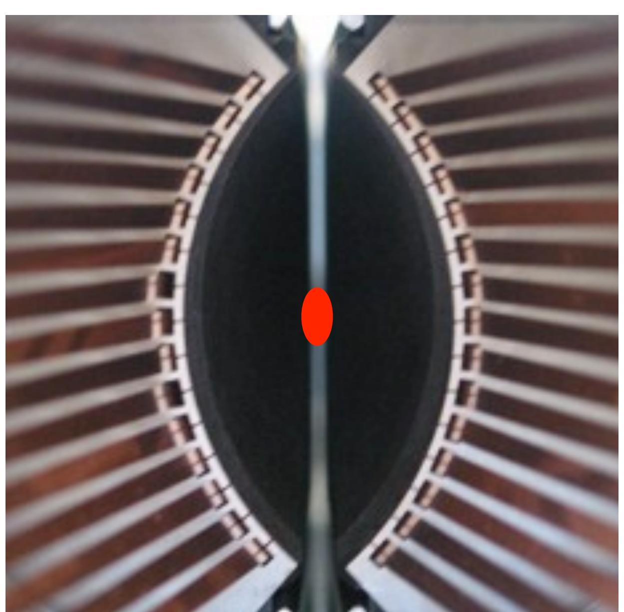
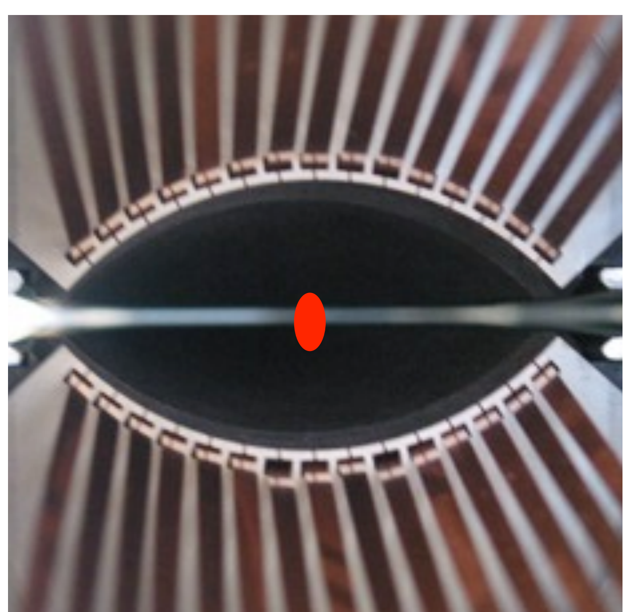


Vertical



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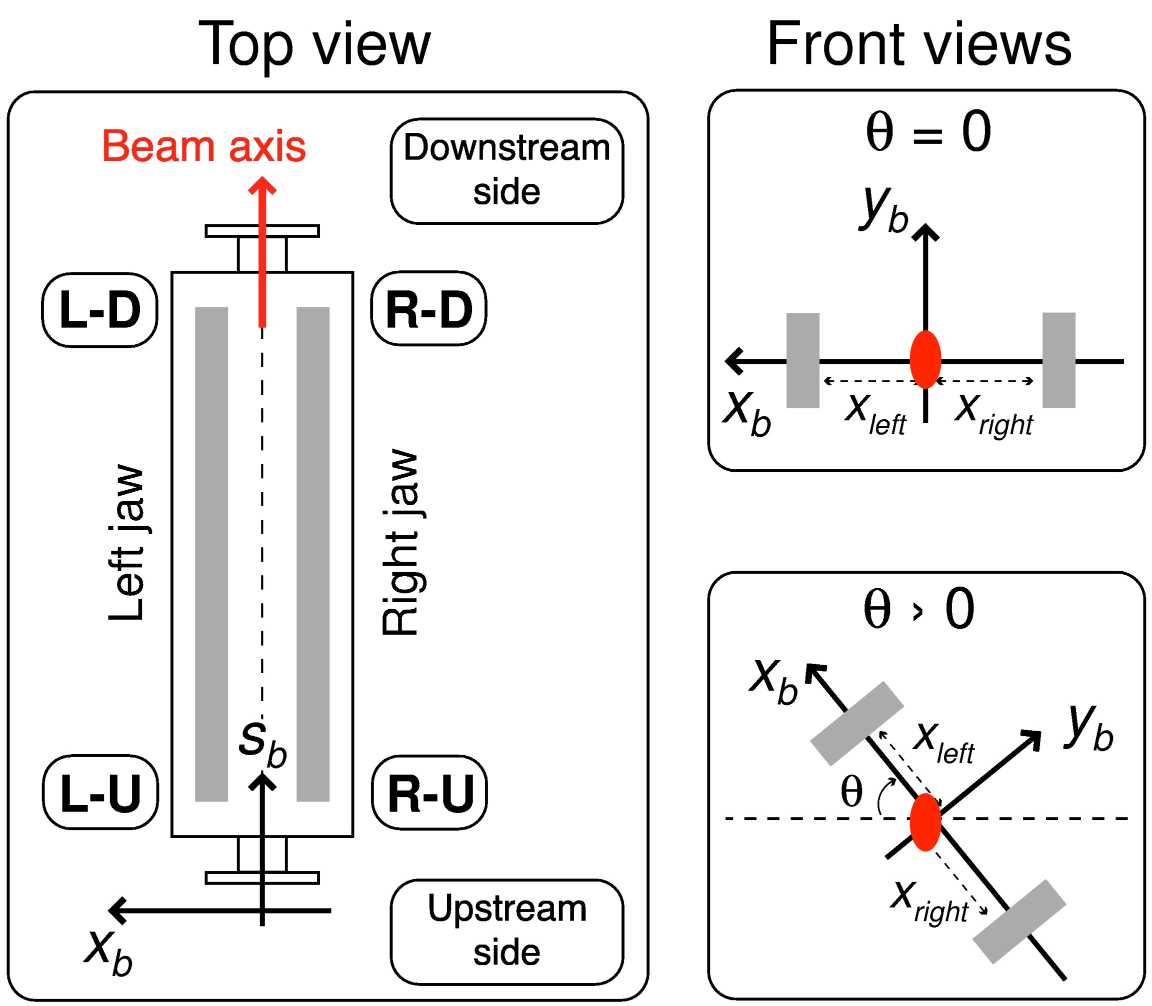

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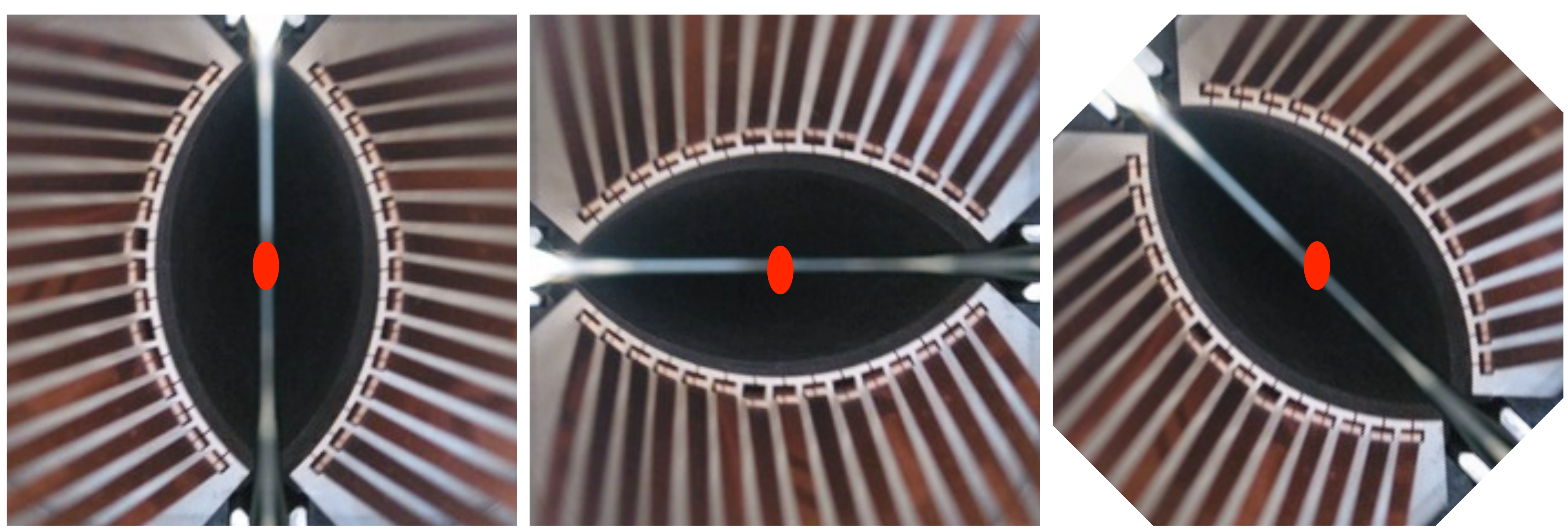
Horizontal **Vertical** **Skew**



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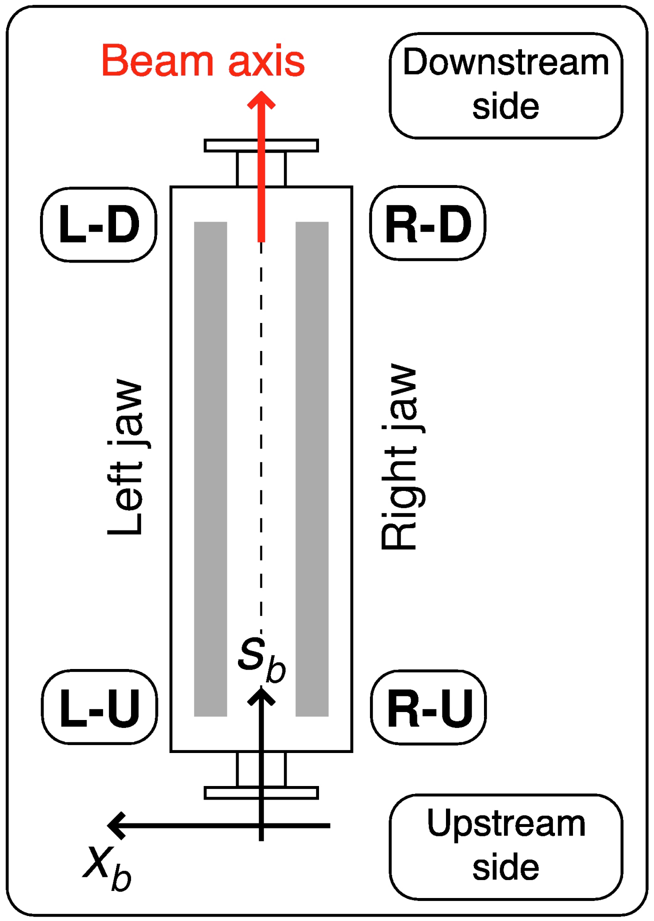

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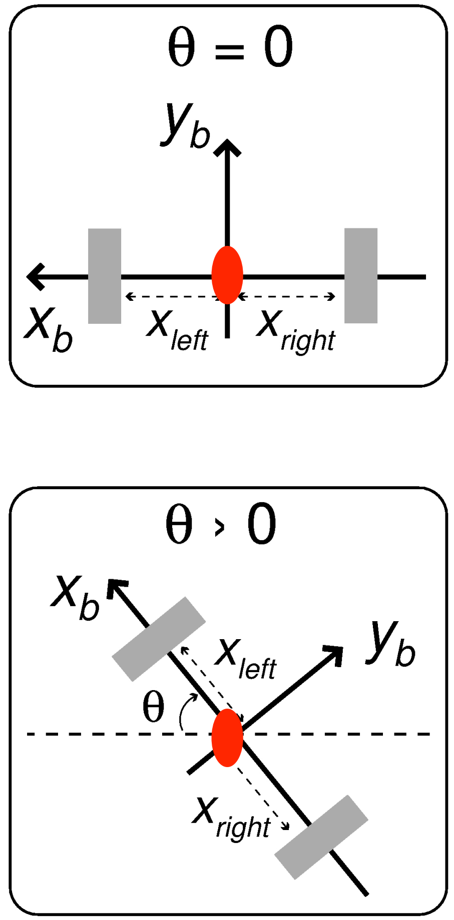

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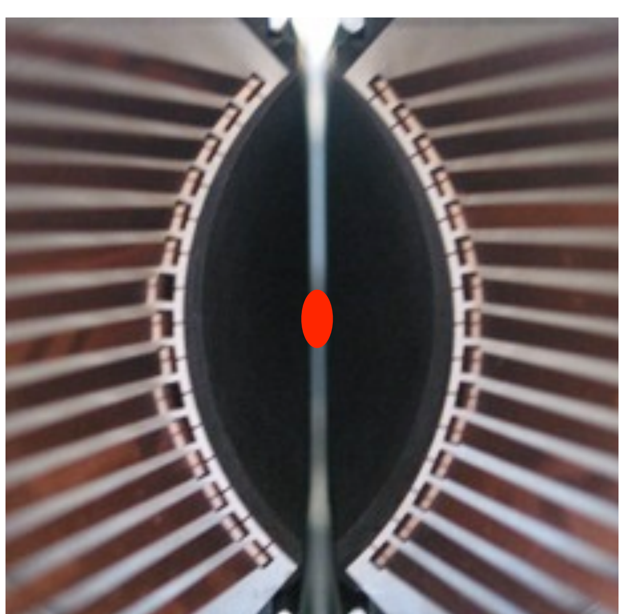
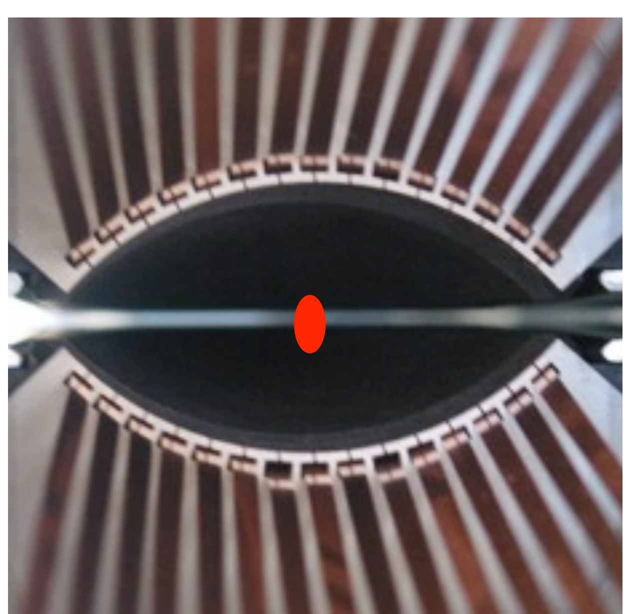


Vertical



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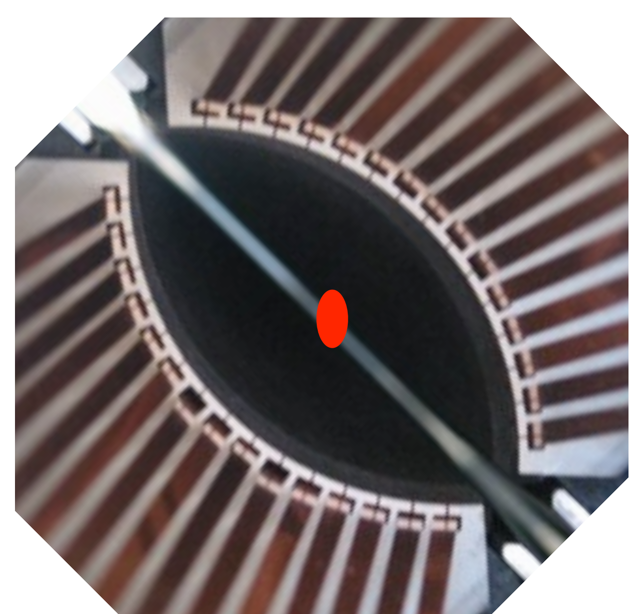
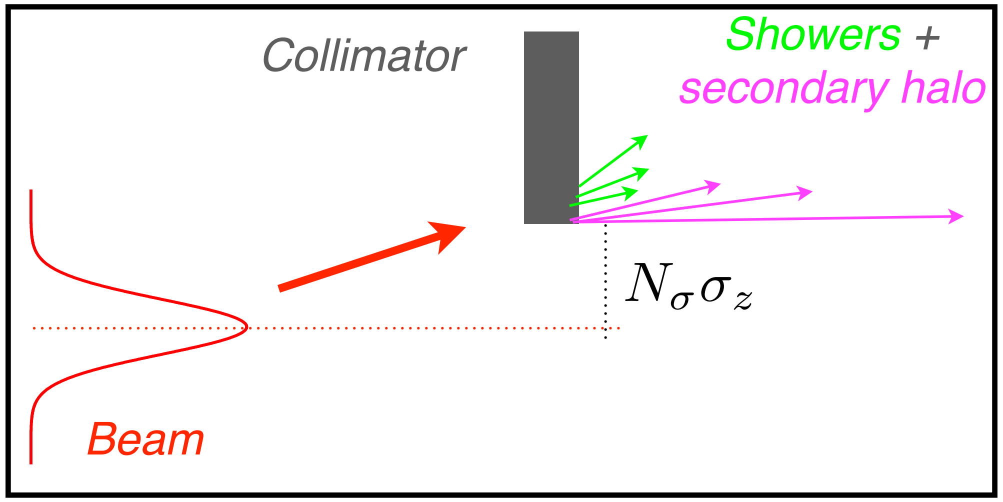


We need at least 3 **primary collimators** in order to protect the machine for all possible transverse betatron losses! Only horizontal collimation for momentum losses.

Particle interaction with collimator



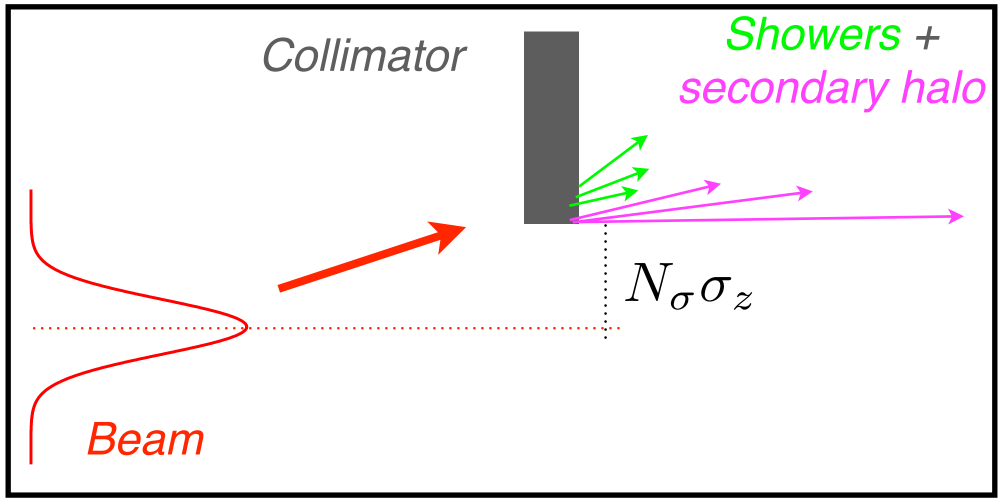
If the "primary" collimator were a black absorber, it would be sufficient to shield the aperture by choosing a gap $N_\sigma \sigma_z$ smaller that the aperture bottleneck !

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 leakage!

Particle interaction with collimator



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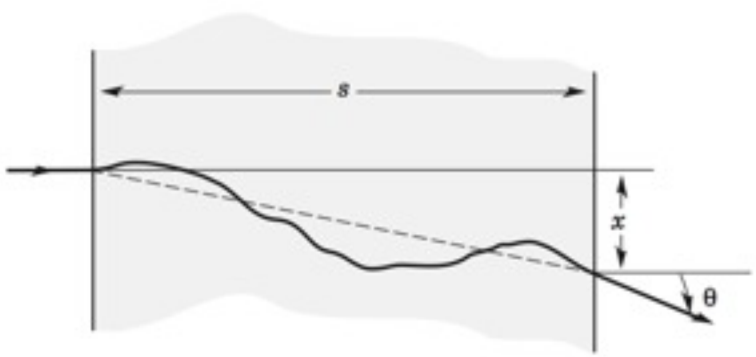

$$\sqrt{\langle \theta_p^2 \rangle} = \frac{13.6}{cp[\mathrm{MeV}]} \sqrt{\frac{s}{\chi_0}} \left(1 + 0.038 \cdot \left(\frac{s}{\chi_0}\right)\right)$$

χ_0 : radiation length

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

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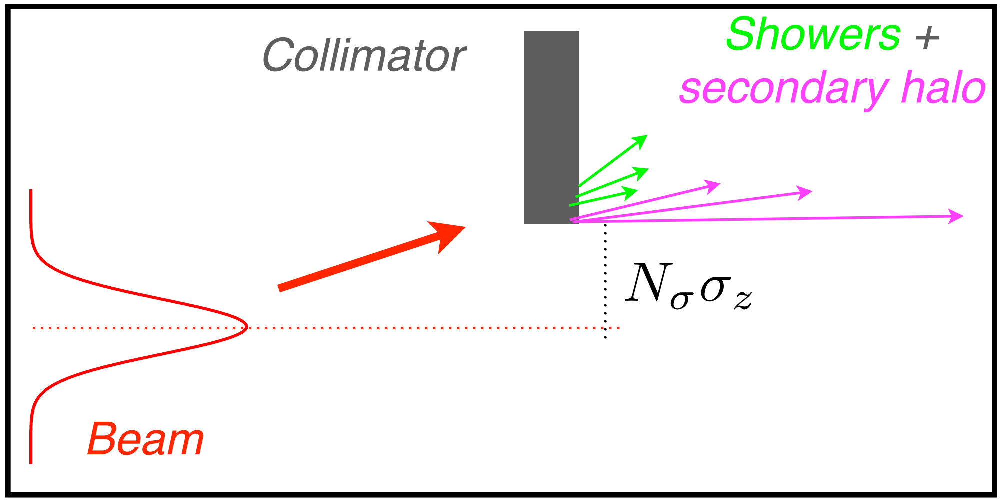

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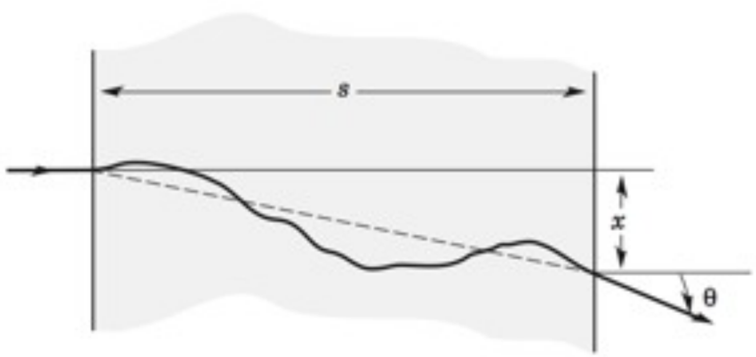

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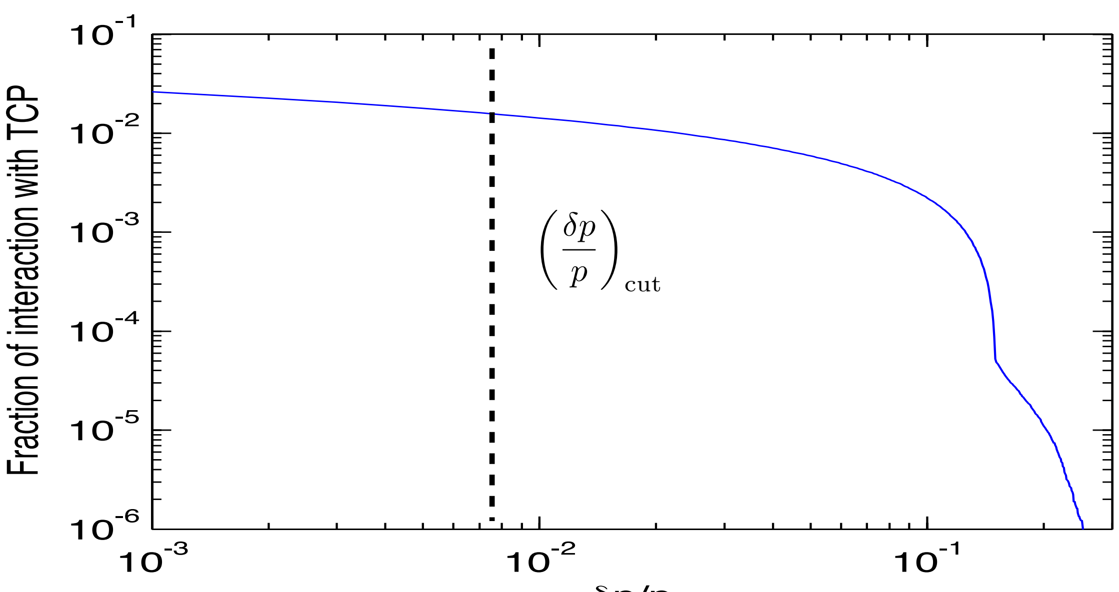
Distribution of energy lost after multi-turn interaction with 60cm TCP



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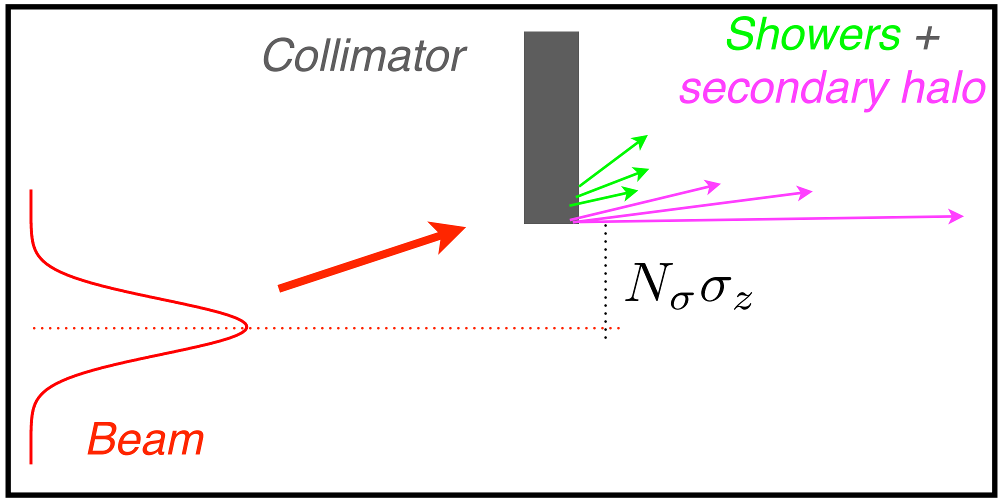

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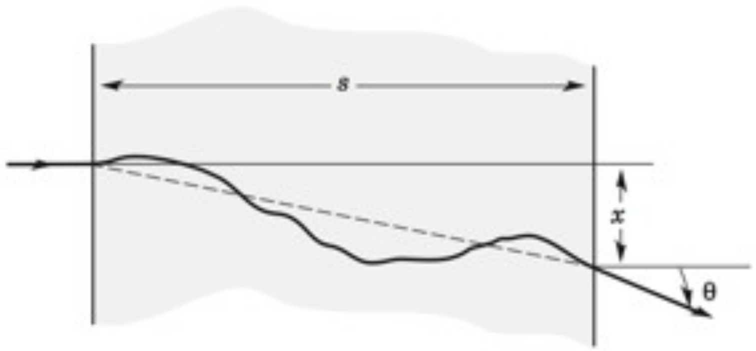

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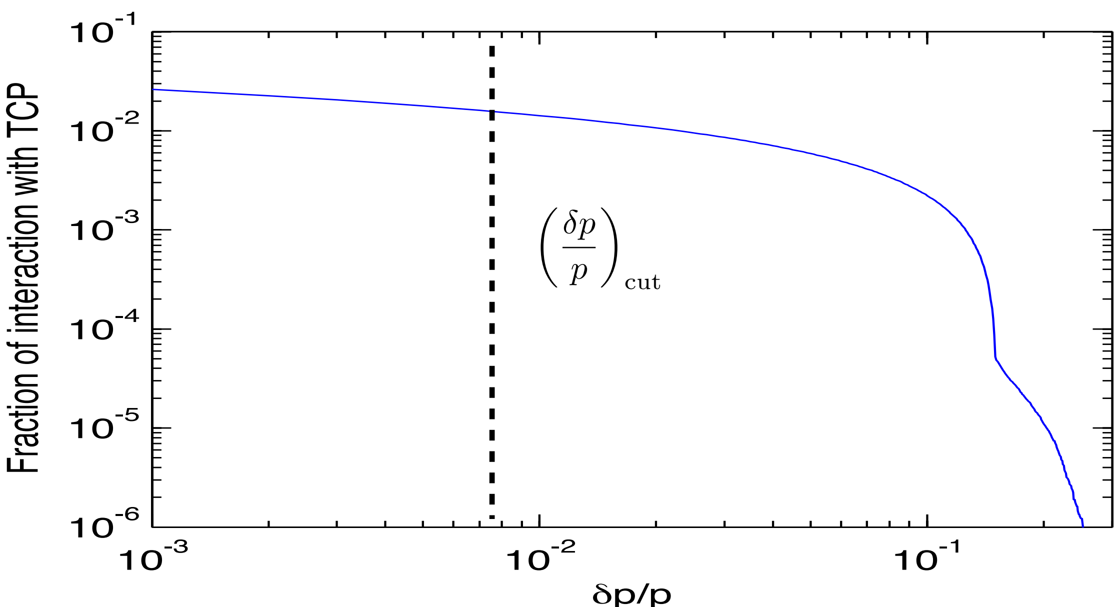
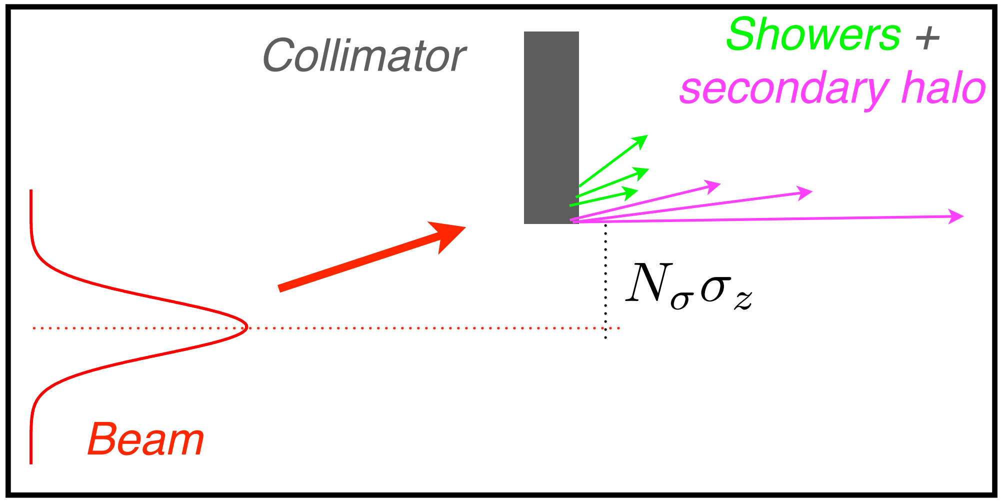


The interaction with collimator jaw materials is itself a source of betatron and off-momentum halo (secondary halo).

Particle interaction with collimator



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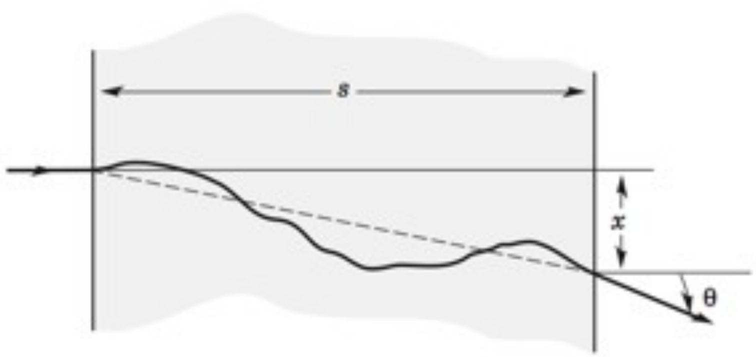

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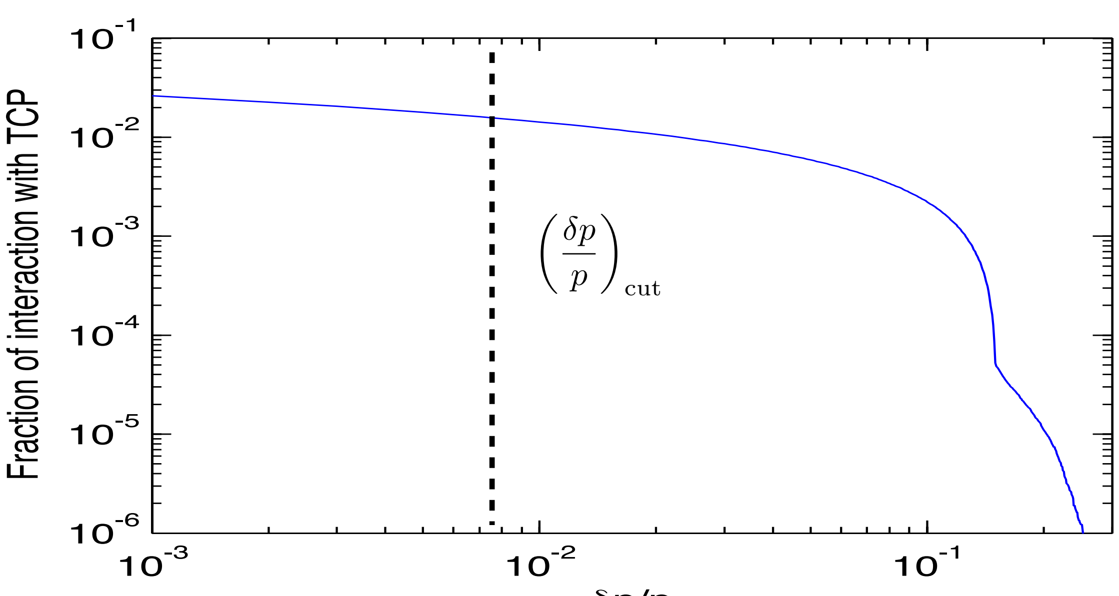
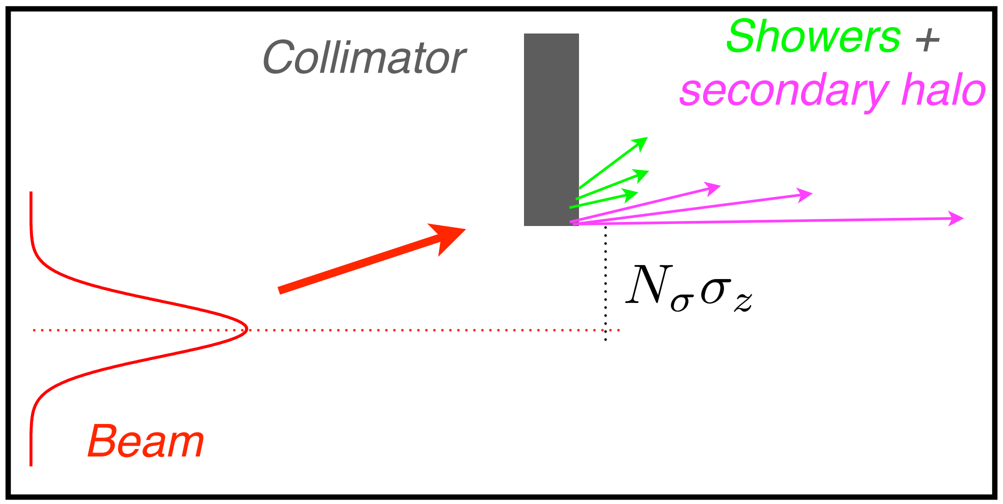


The interaction with collimator jaw materials is itself a source of betatron and off-momentum halo (secondary halo).

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

Particle interaction with collimator

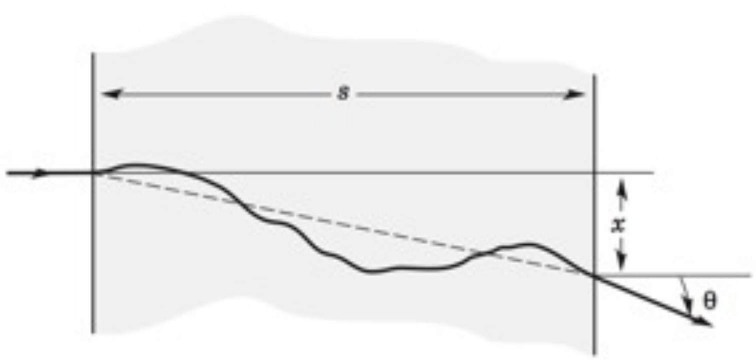


If the “primary” collimator were a black absorber, it would be sufficient to shield the aperture by choosing a gap $N_\sigma \sigma_z$ smaller that the aperture bottleneck !

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 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

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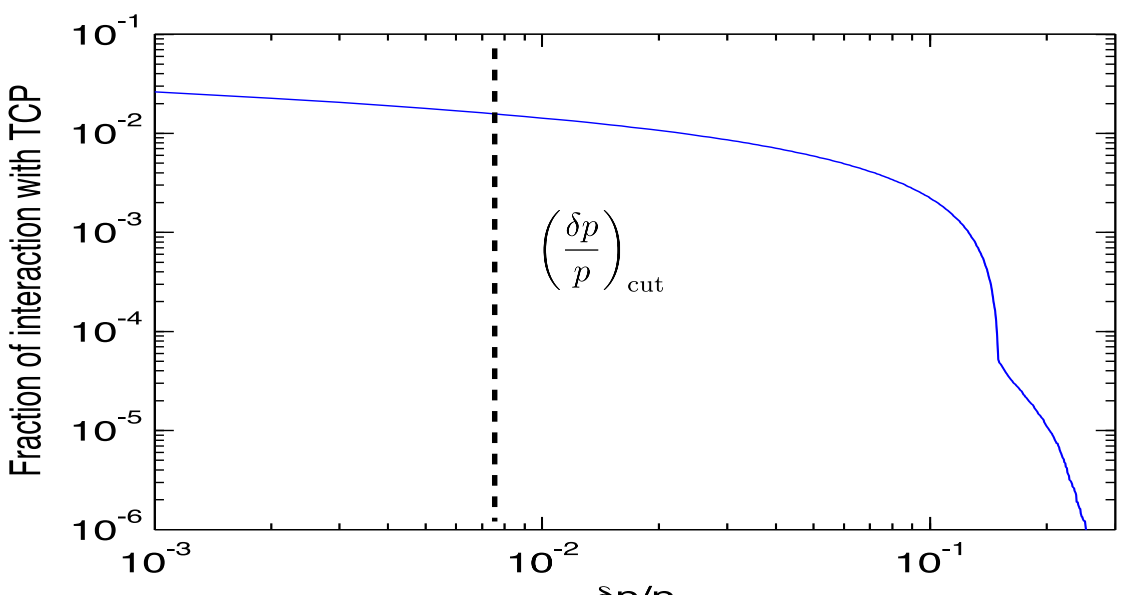

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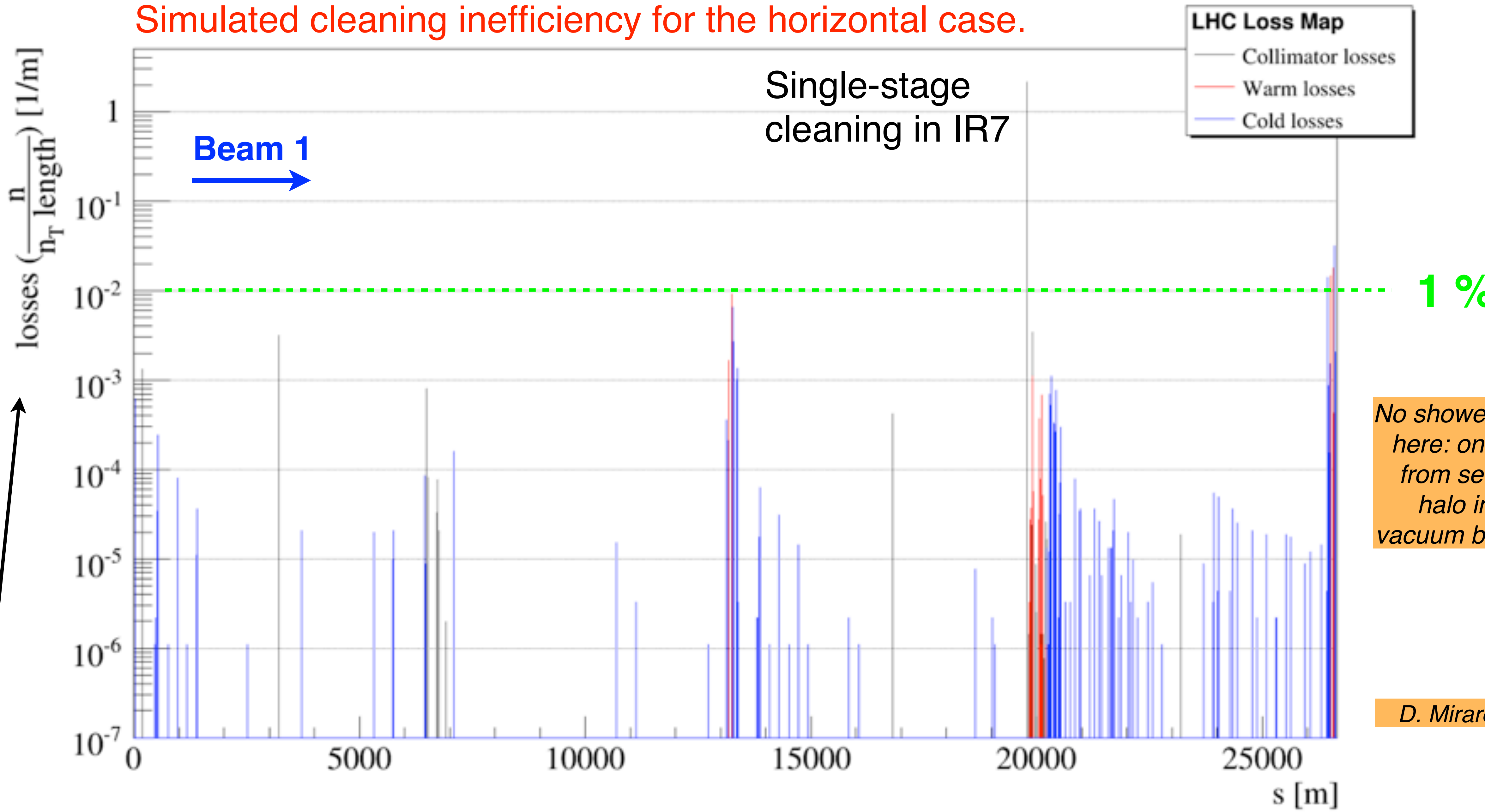
Note: multi-turn interactions occur with sub-micron impact parameters → this has an important effect on the absorption efficiency.

Single-stage cleaning

Simulated cleaning inefficiency for the horizontal case.



No shower products here: only losses from secondary halo into the vacuum beam-pipe.

D. Mirarchi

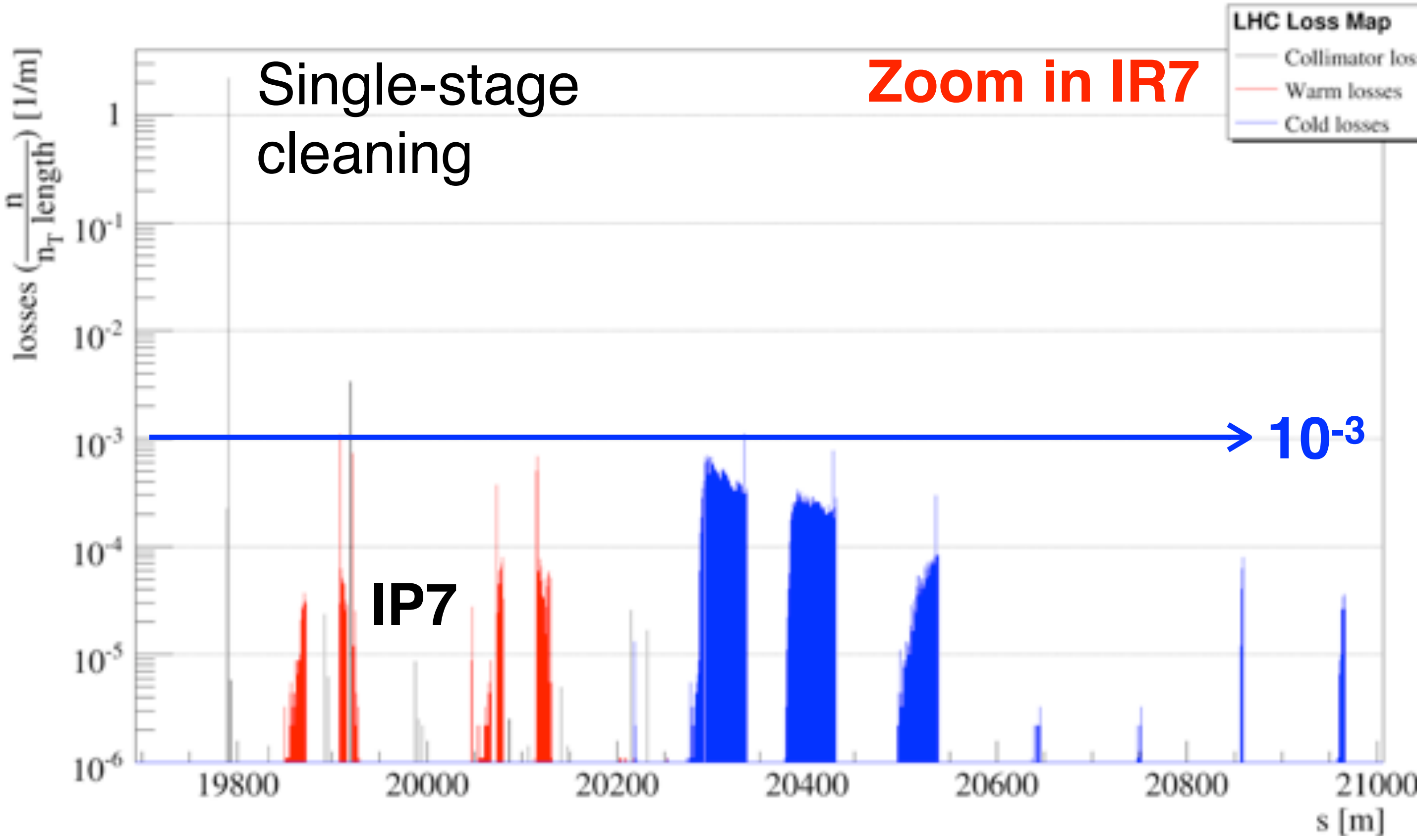
Local cleaning inefficiency

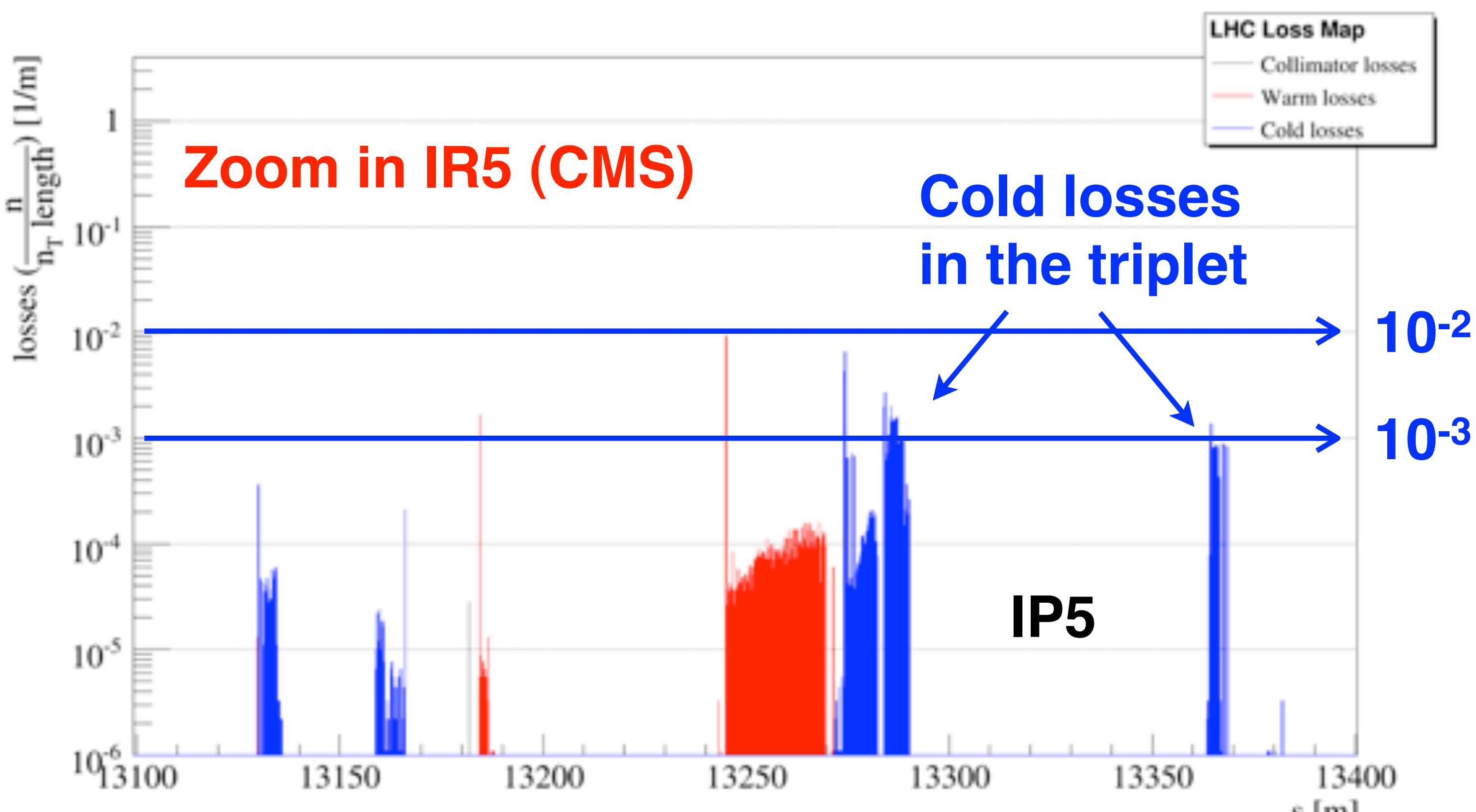
$$\tilde{\eta}_c(s) = \frac{1}{\Delta s} \frac{N_{\text{loss}}(s \rightarrow s + \Delta s)}{N_{\text{abs}}}$$

Fraction of proton lost per unit length.

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

Comparison to quench limits





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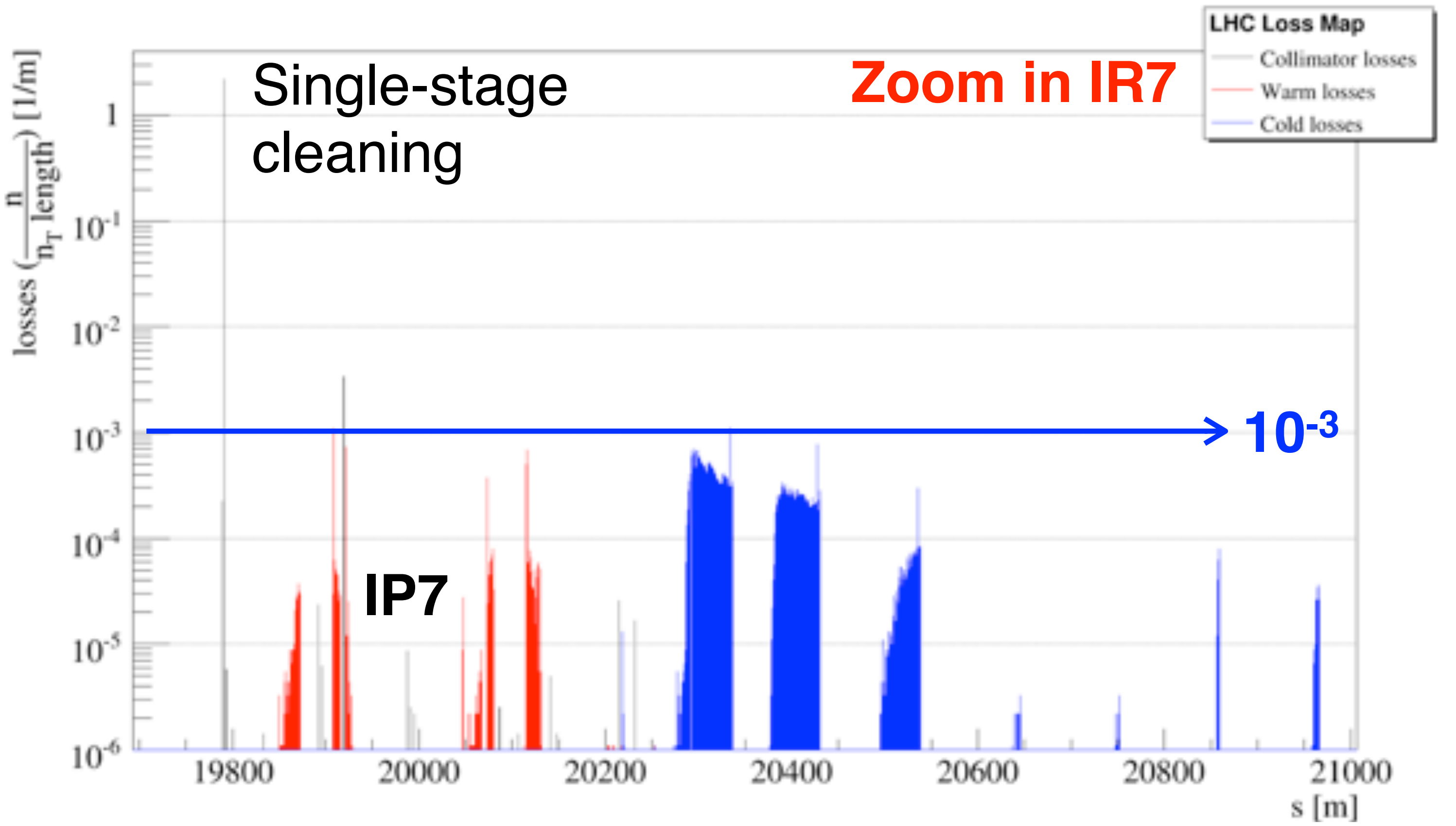

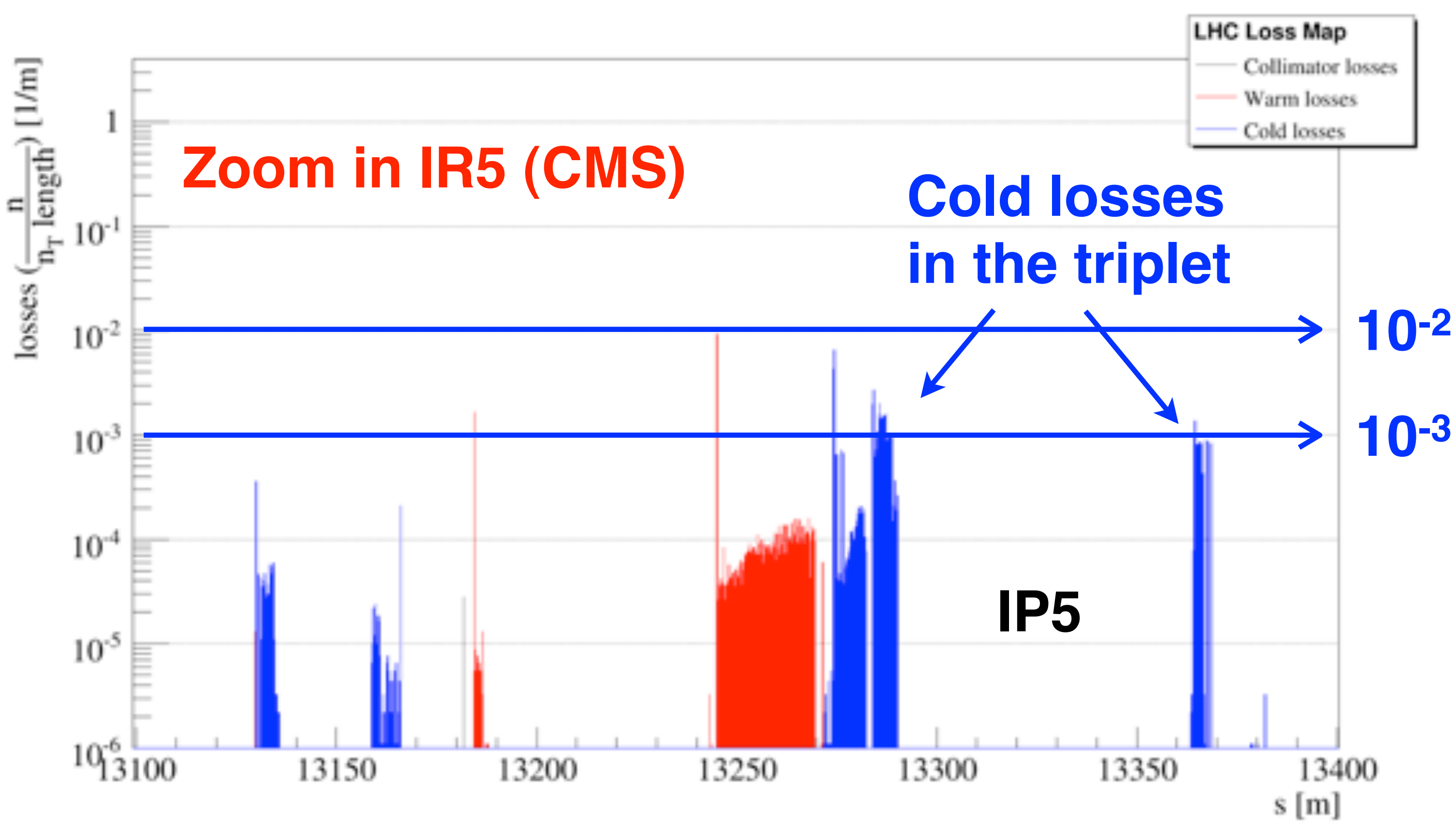

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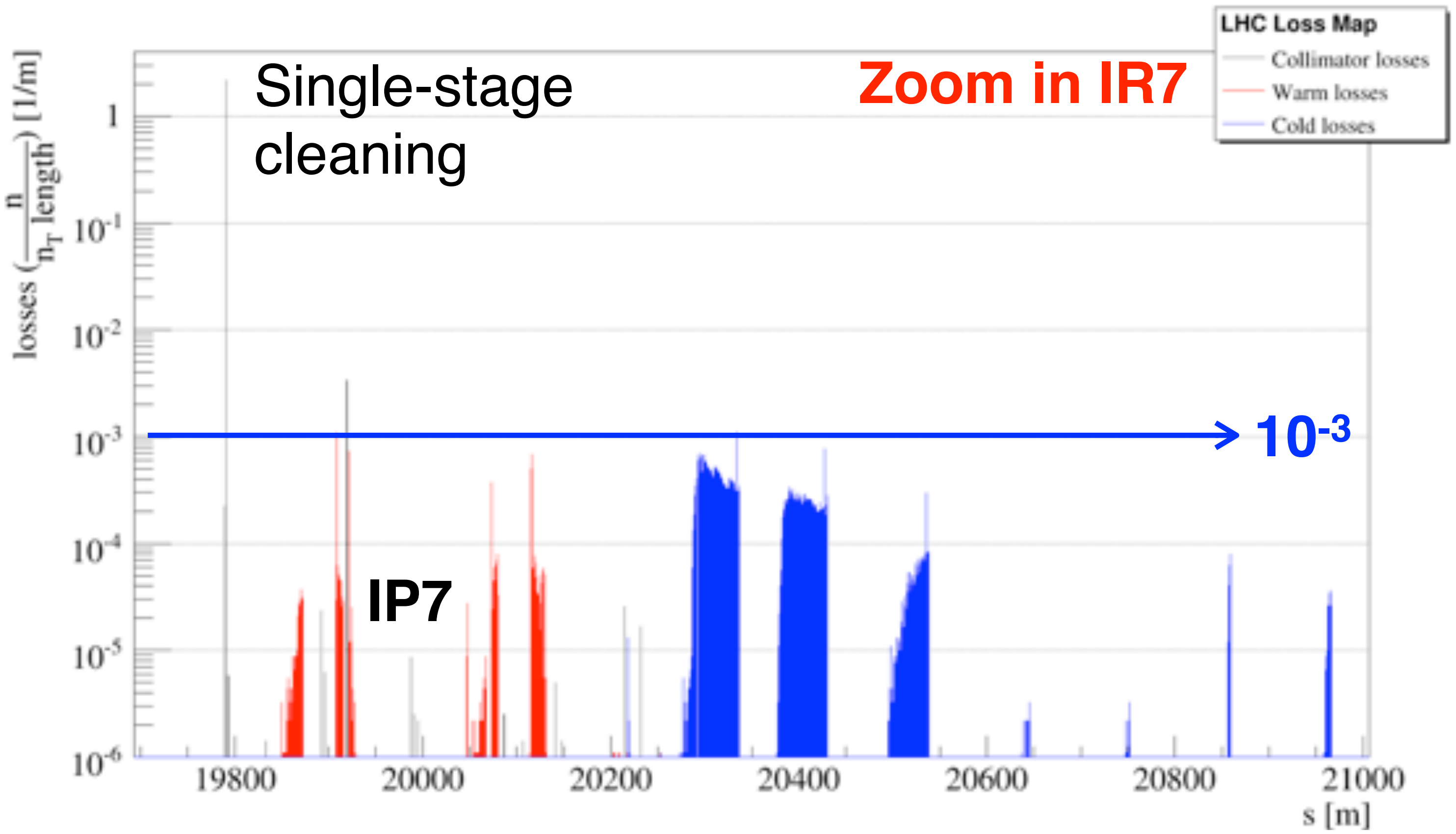

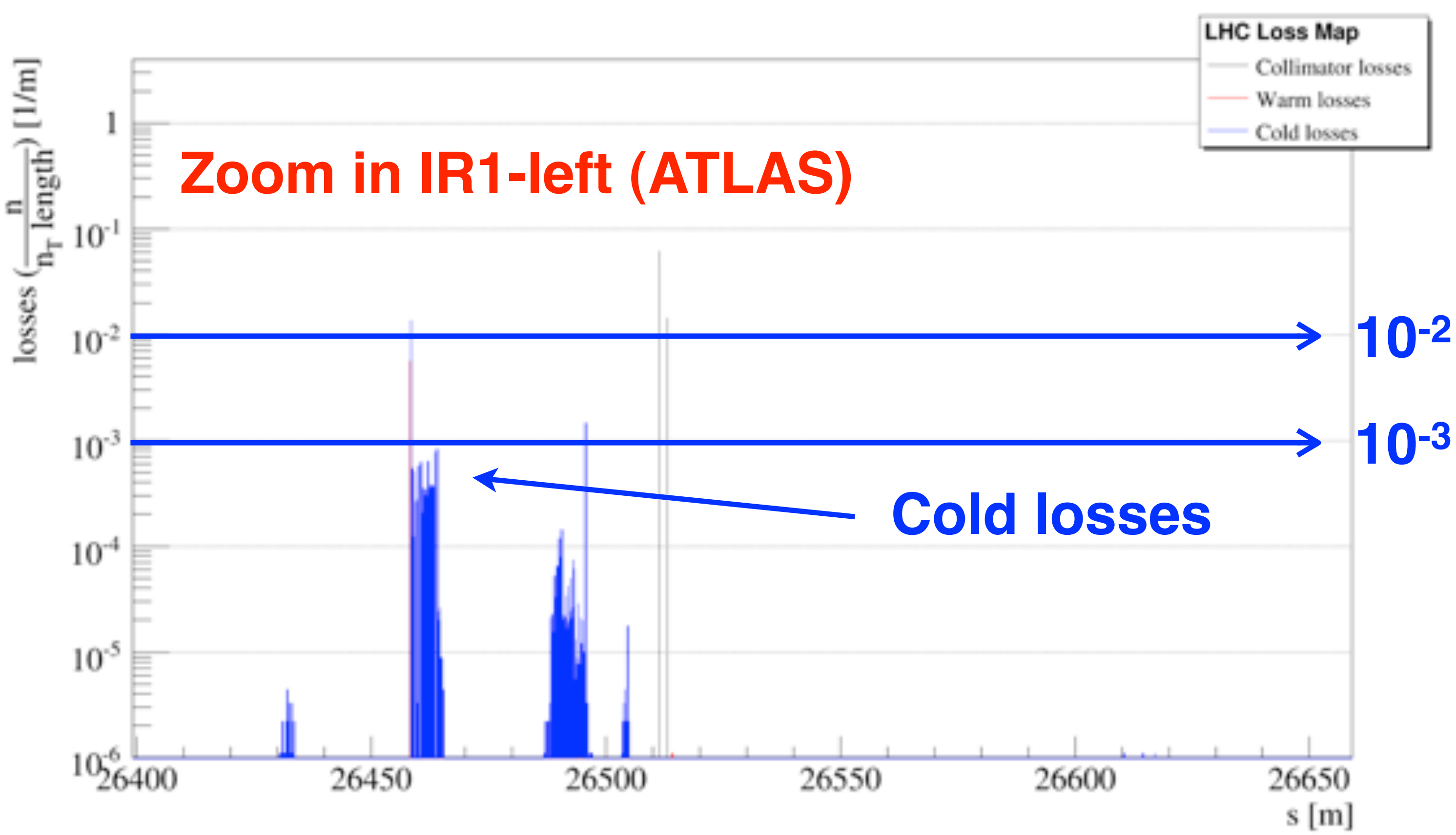

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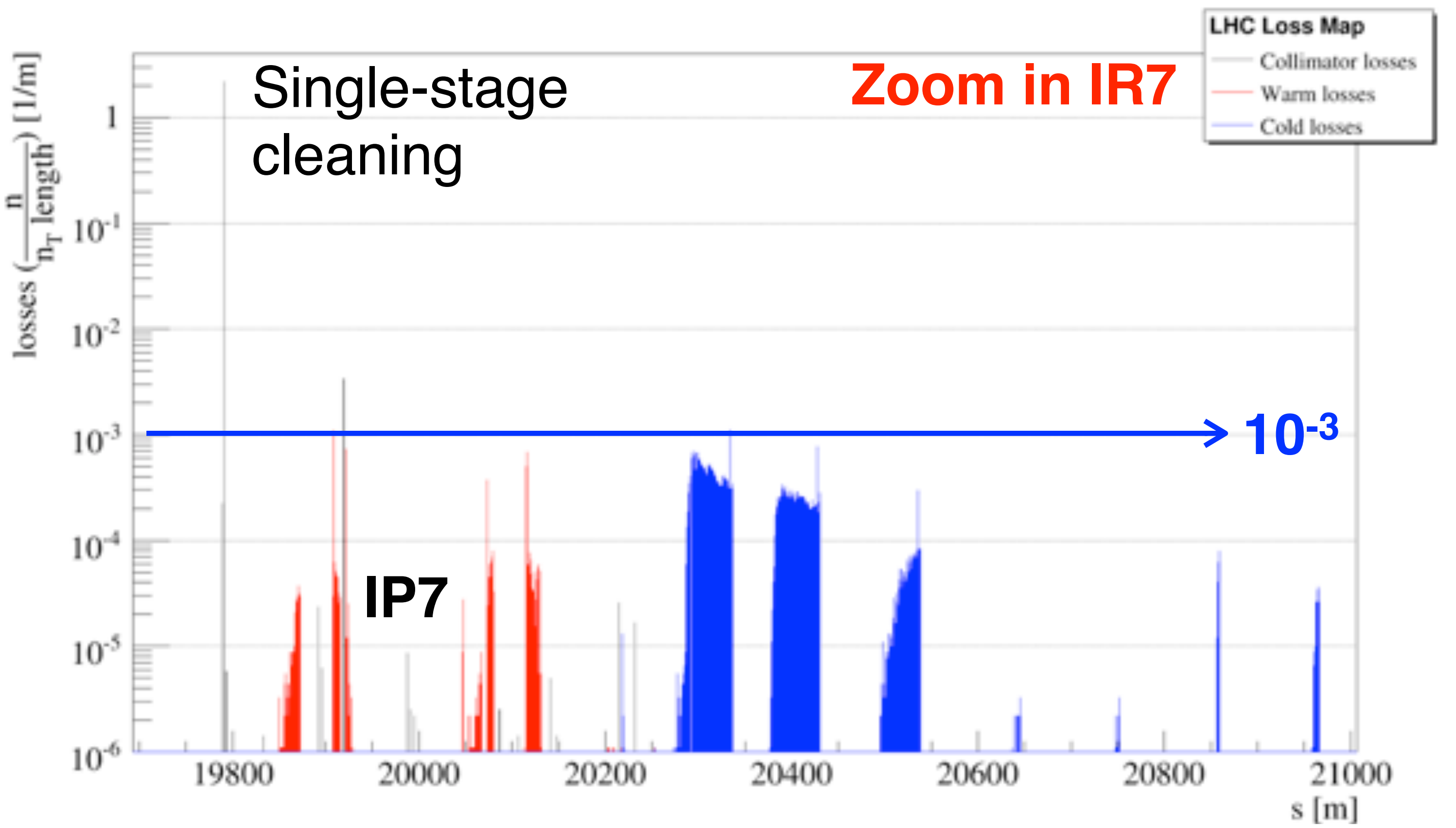

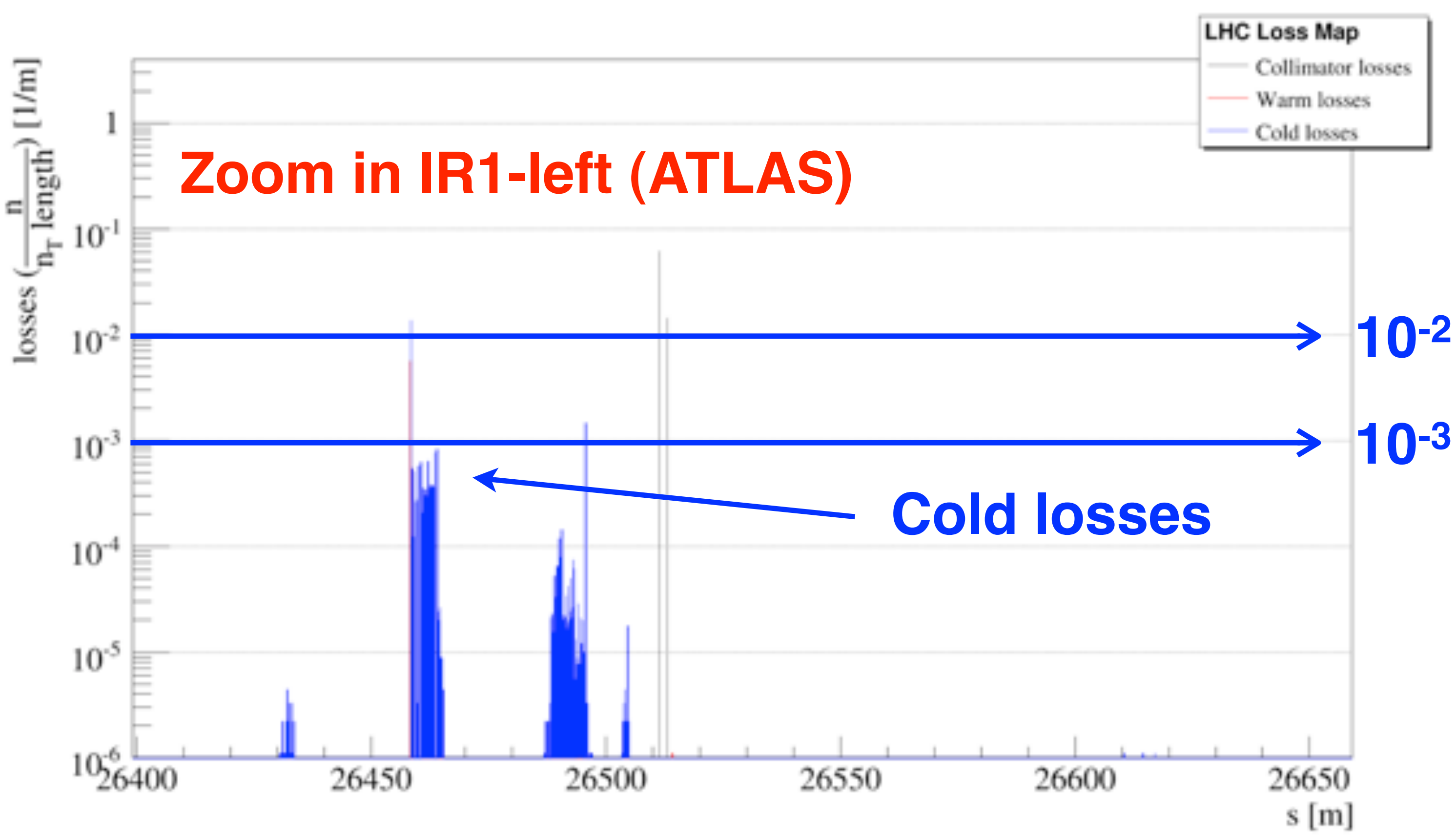

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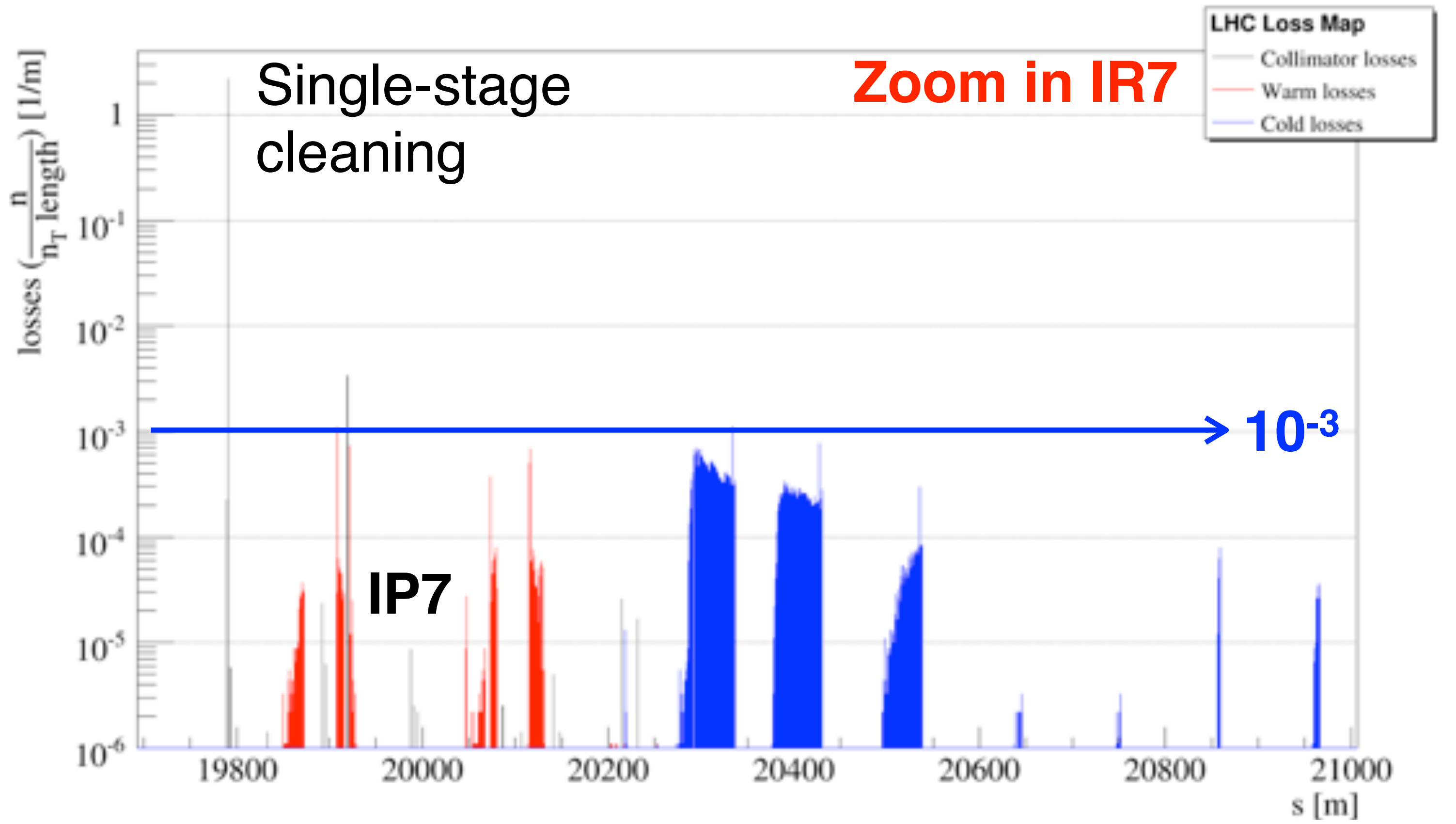

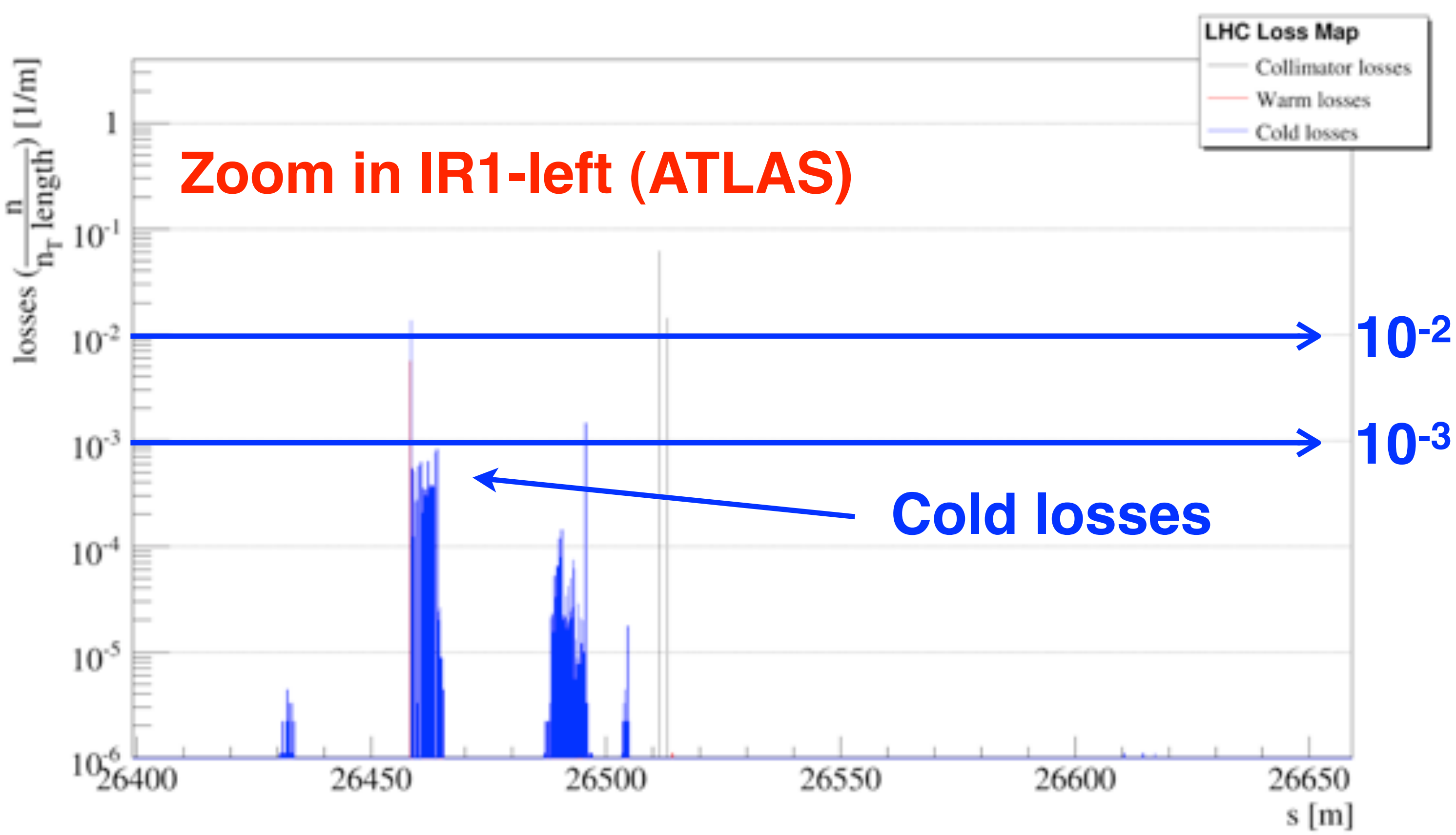

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With the single-stage cleaning predicted by this model, losses are up to:

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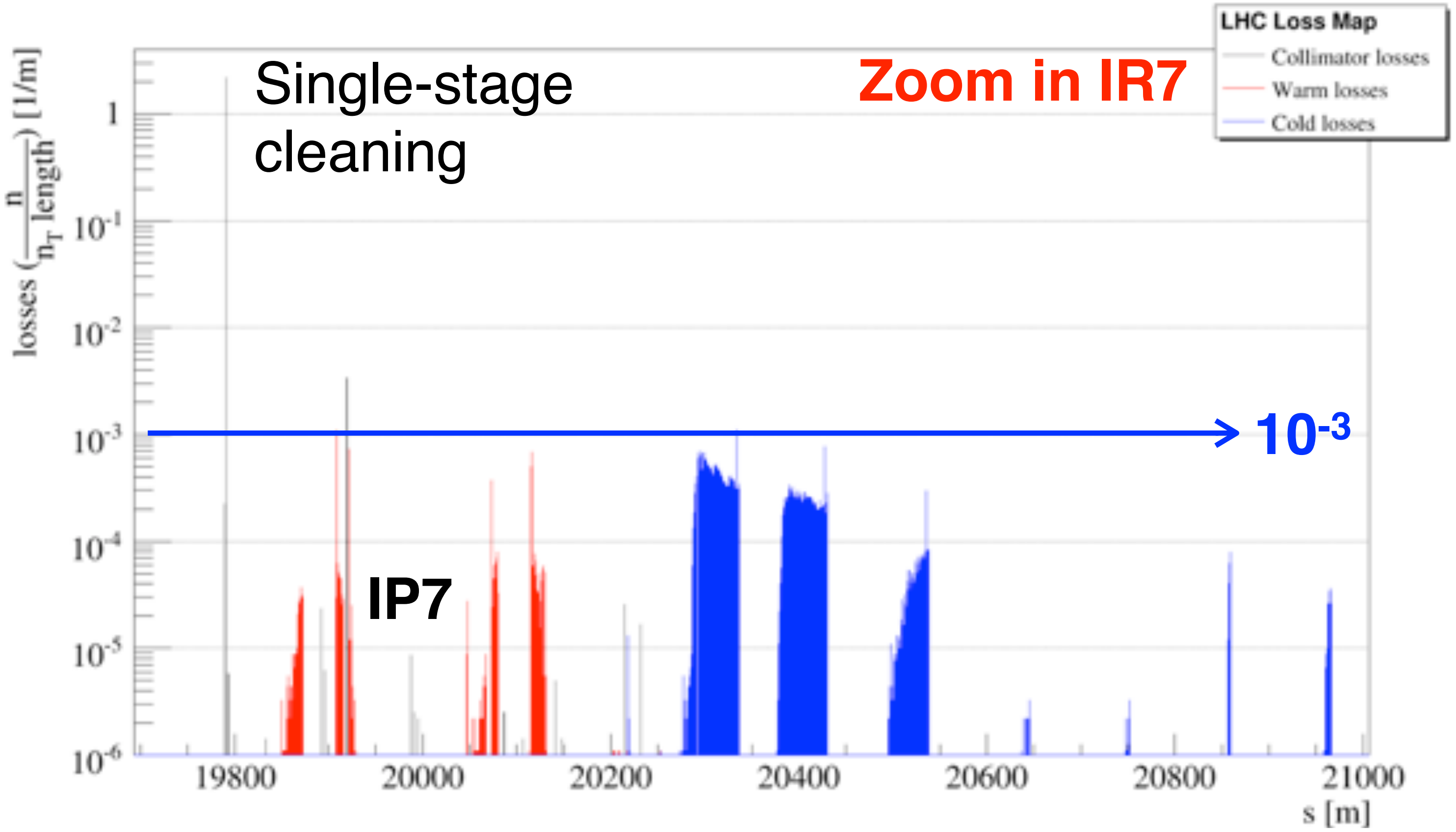

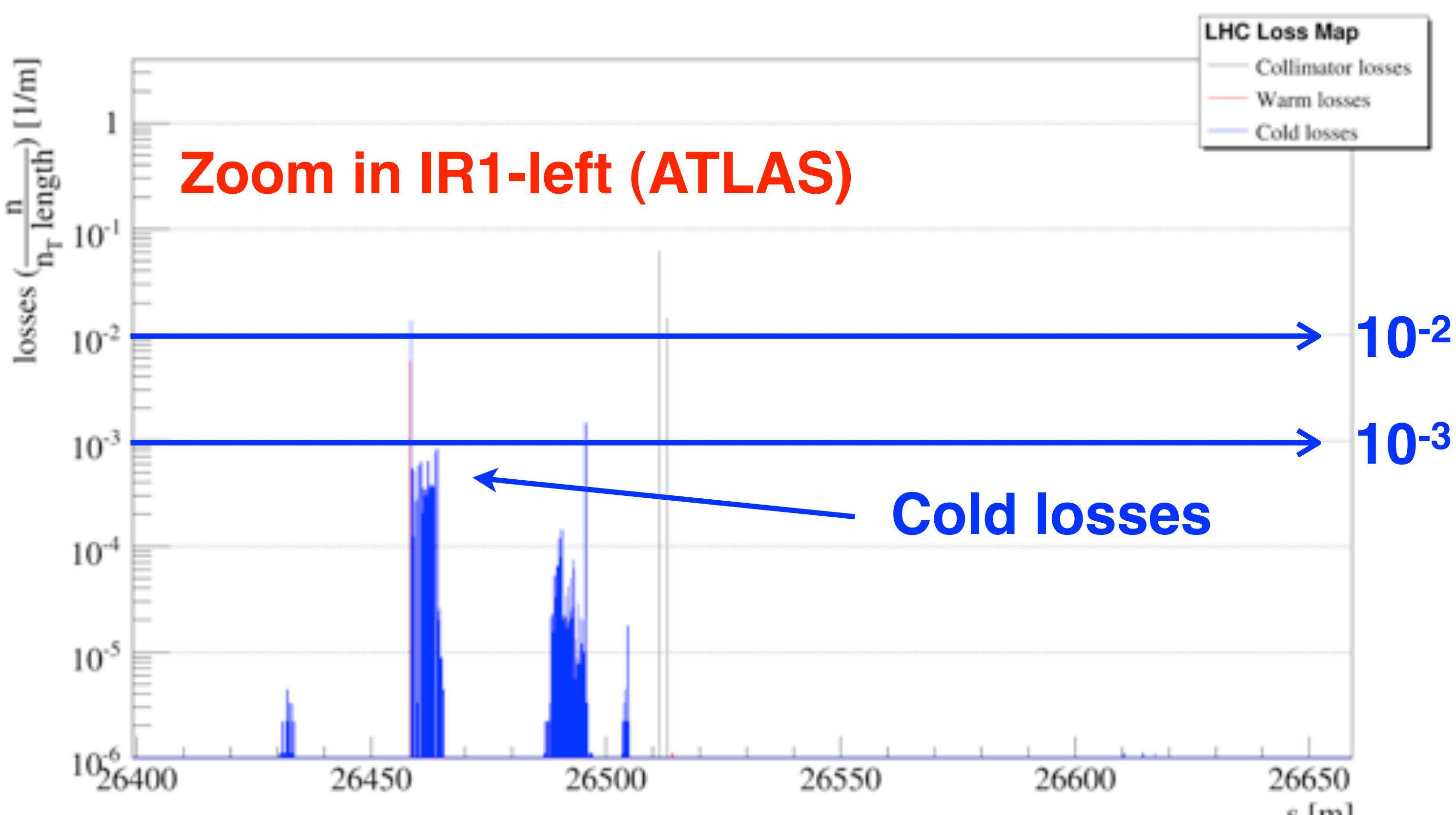

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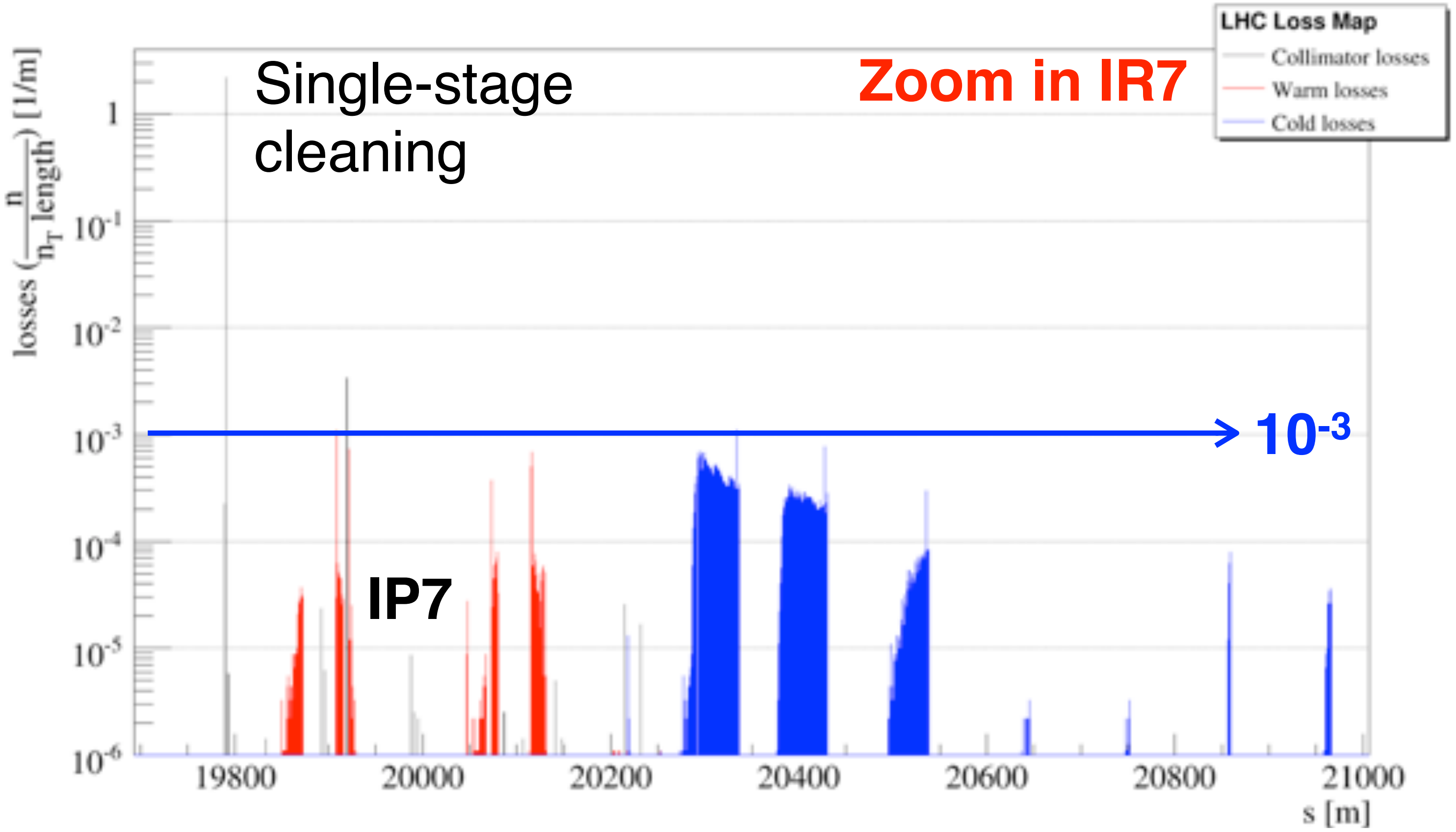

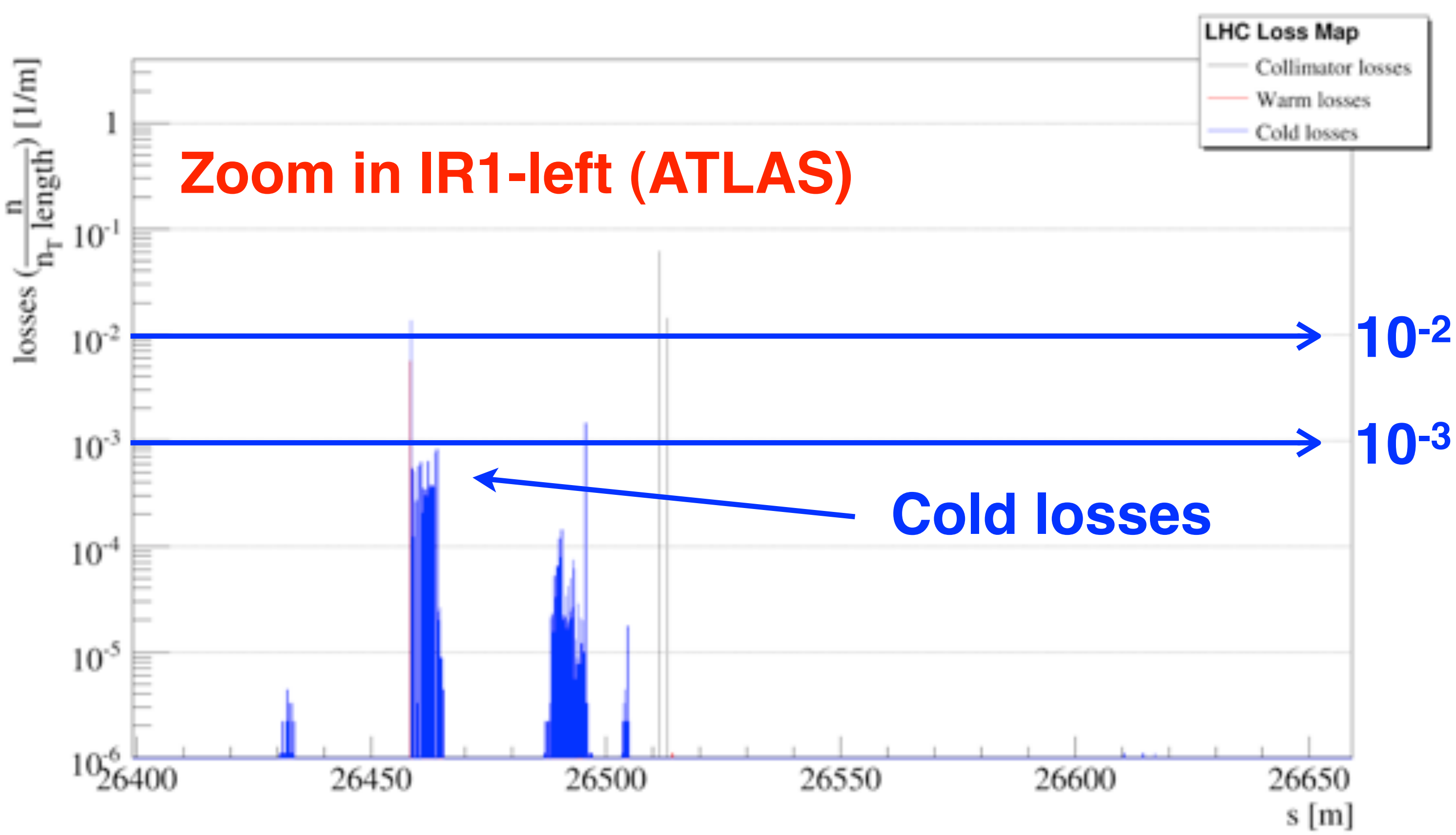

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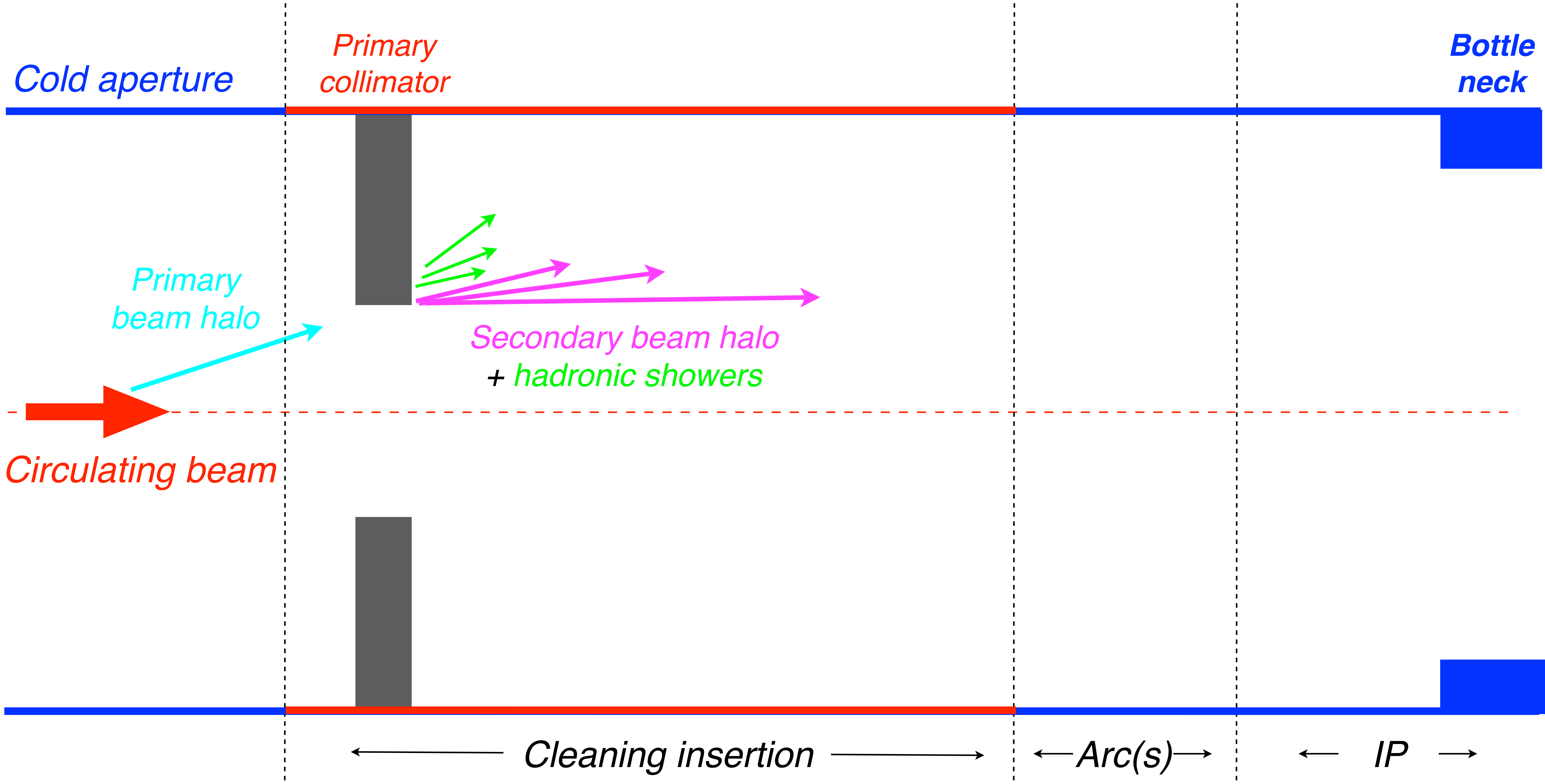
*Note: These are **approximated figures**! Detailed performance reach is estimated with more complex simulations including effects of showers!*

Two-stage collimation



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

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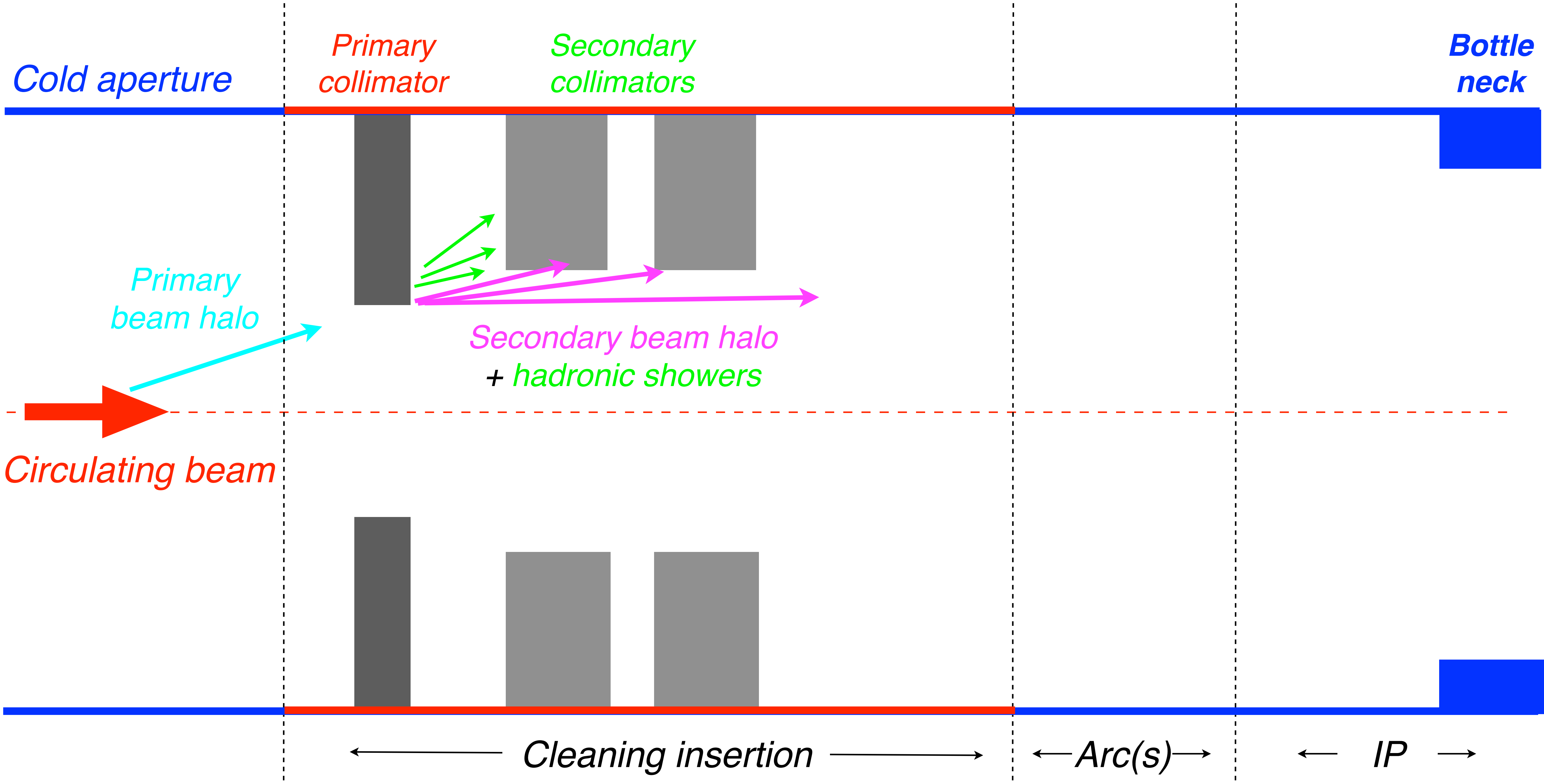

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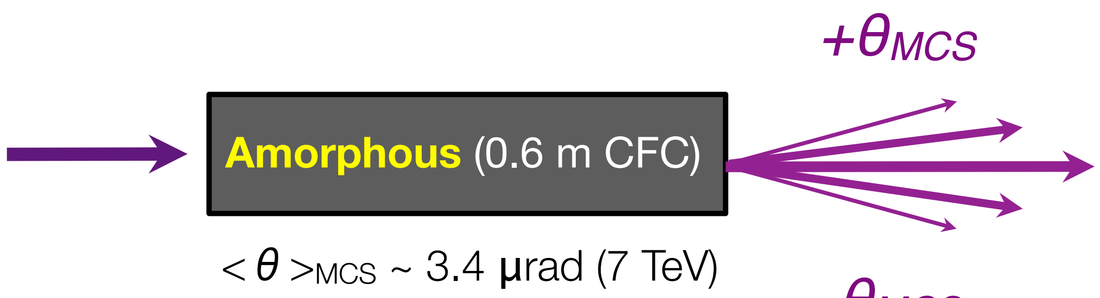
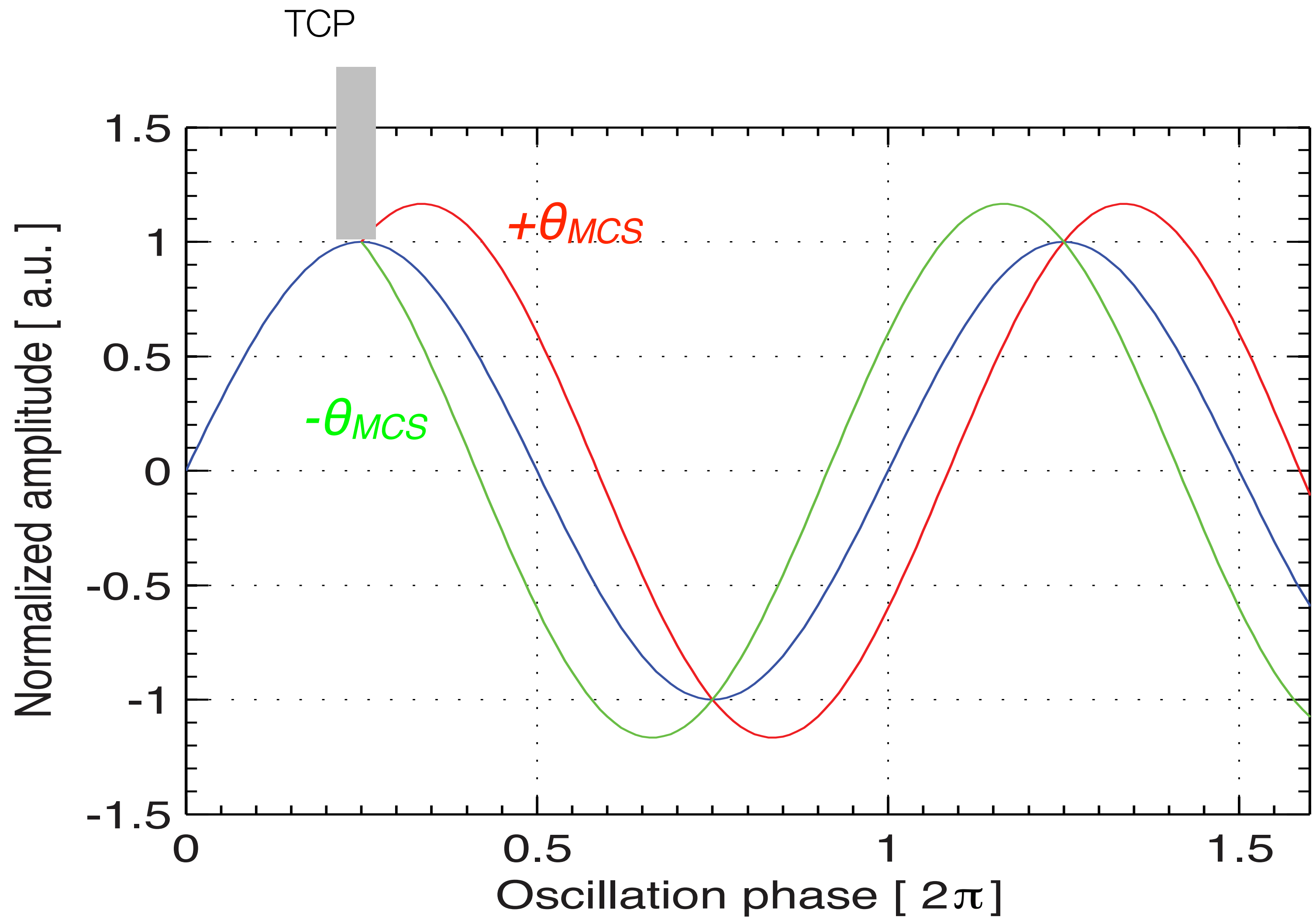


< θ >$_{MCS}$ ~ 3.4 µrad (7 TeV)

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.



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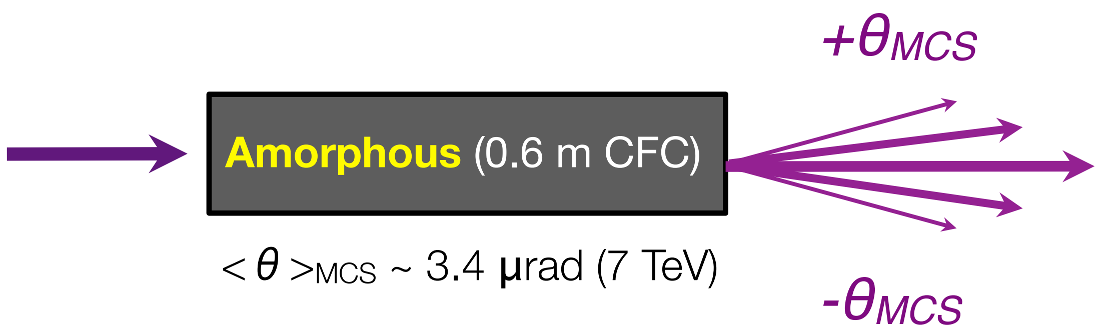

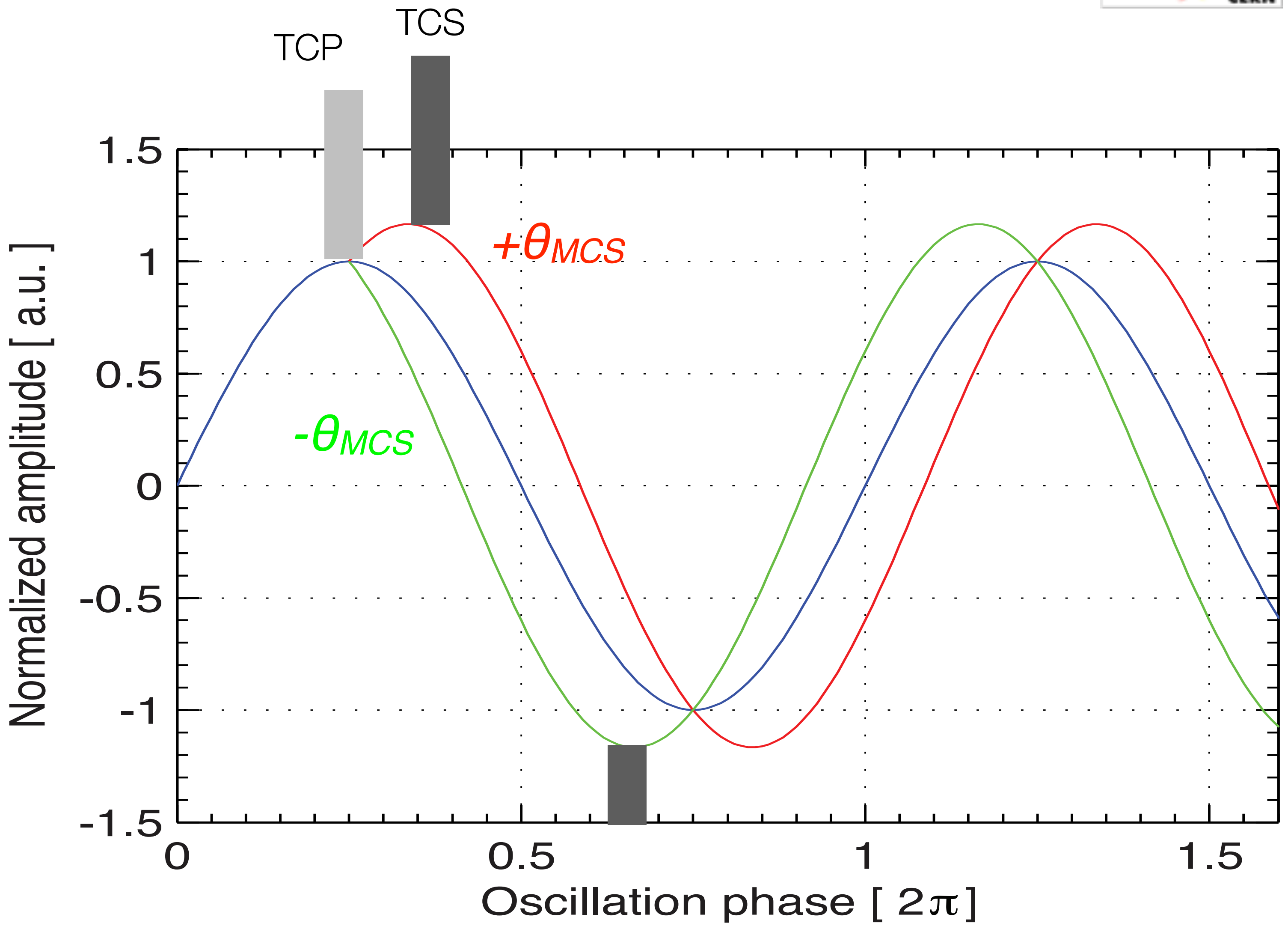

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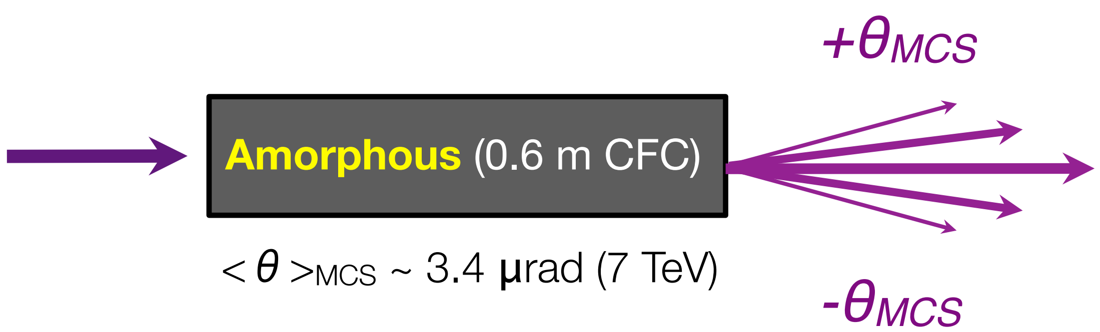

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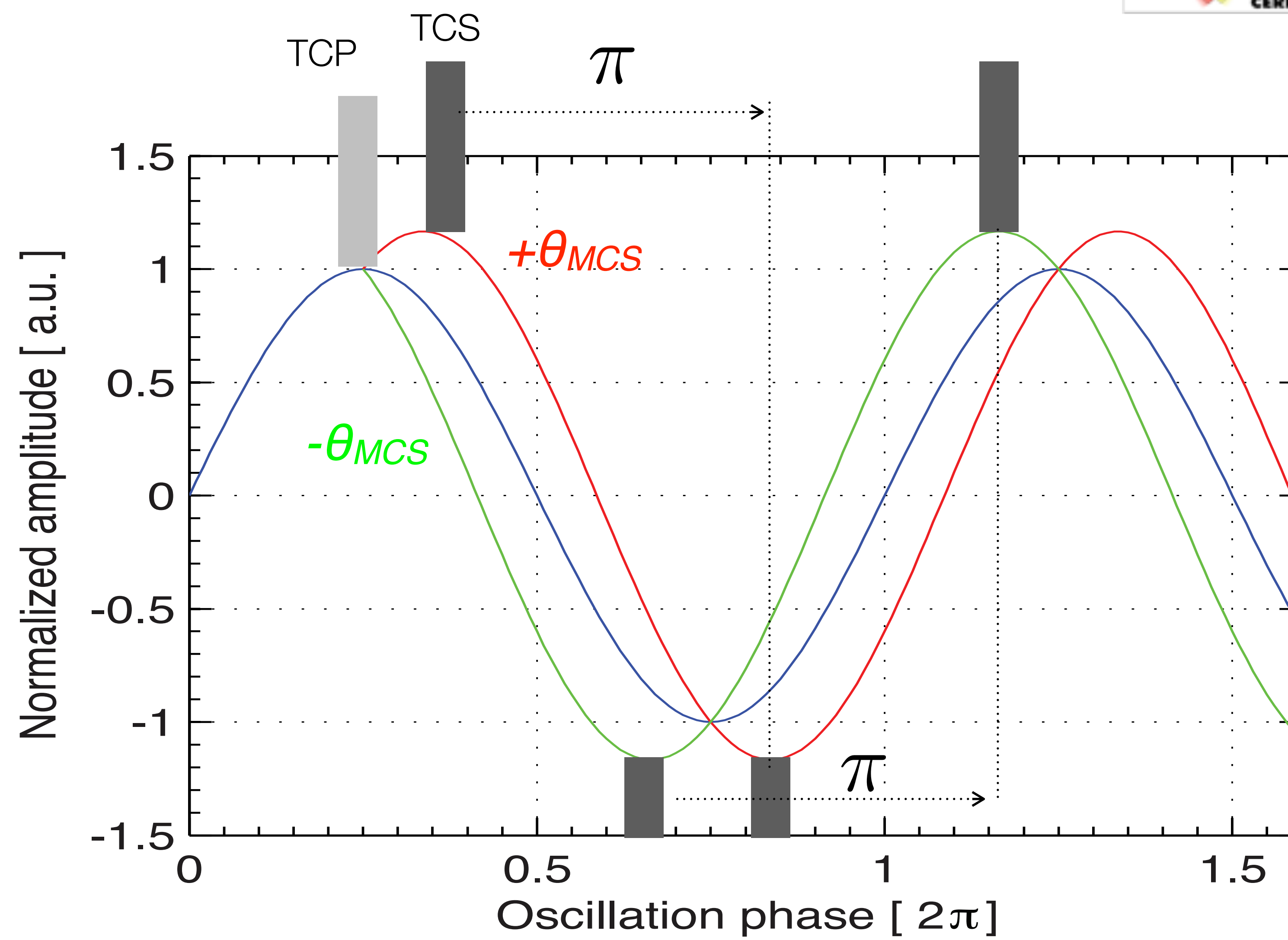

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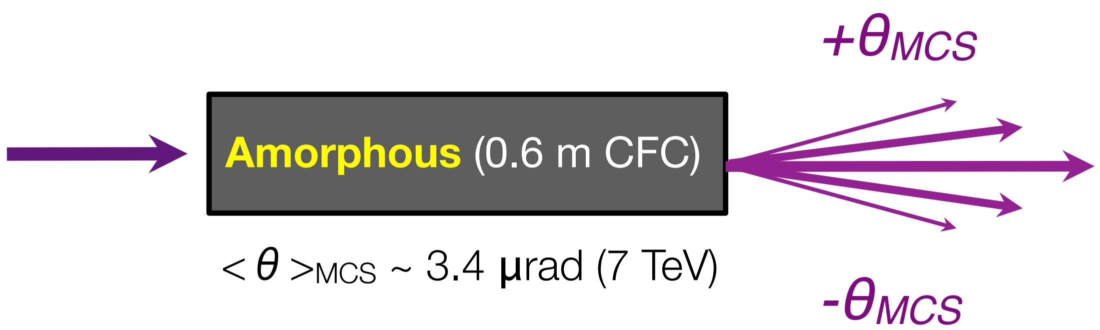

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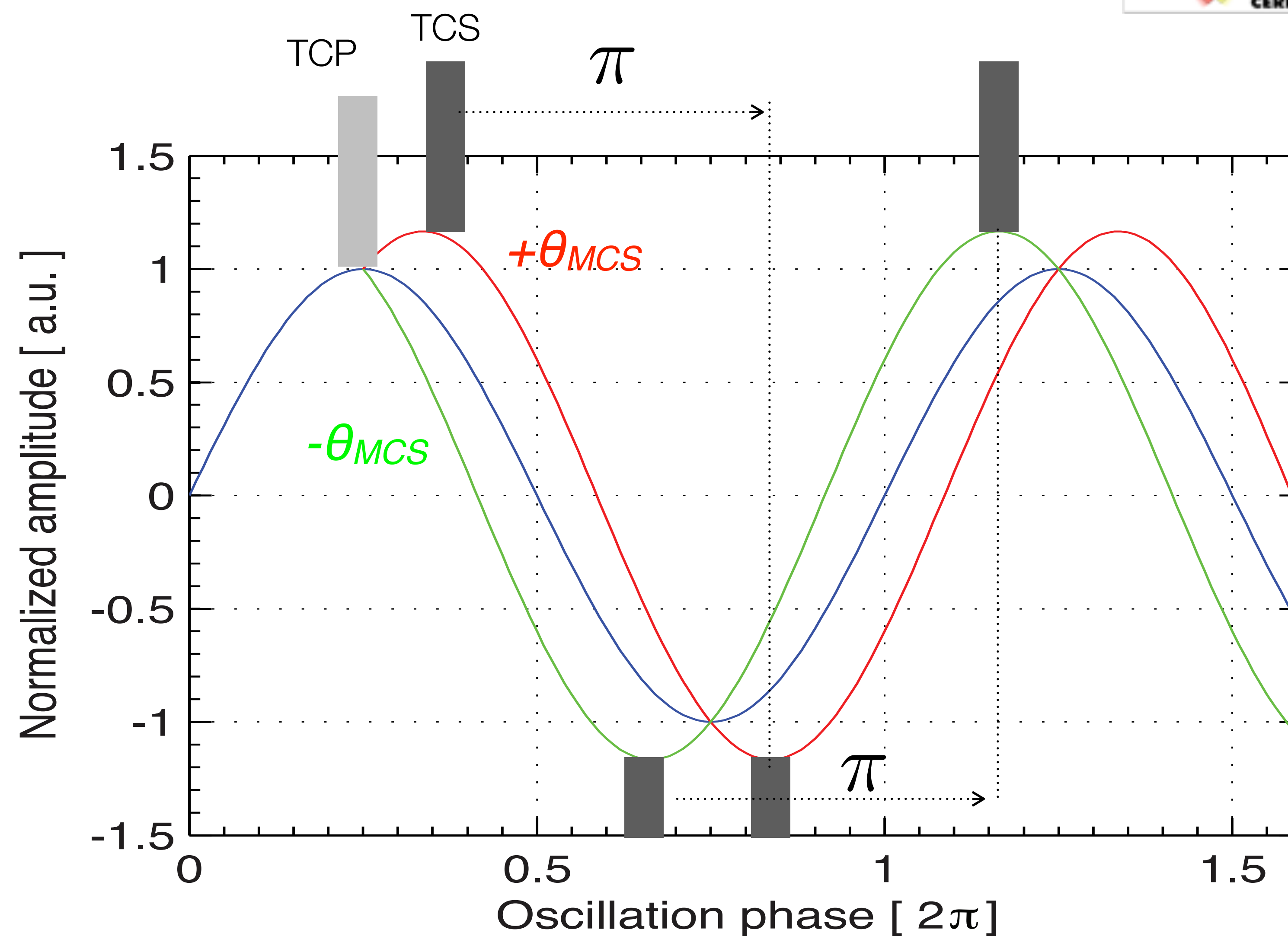

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(Received 13 October 1998; published 21 December 1998)

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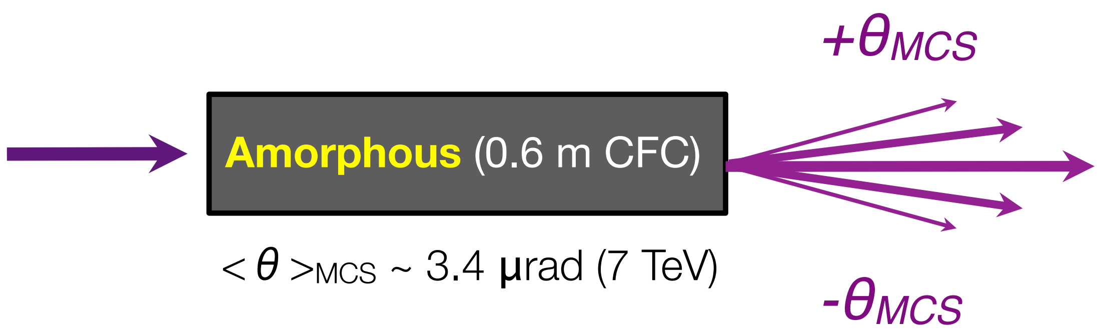

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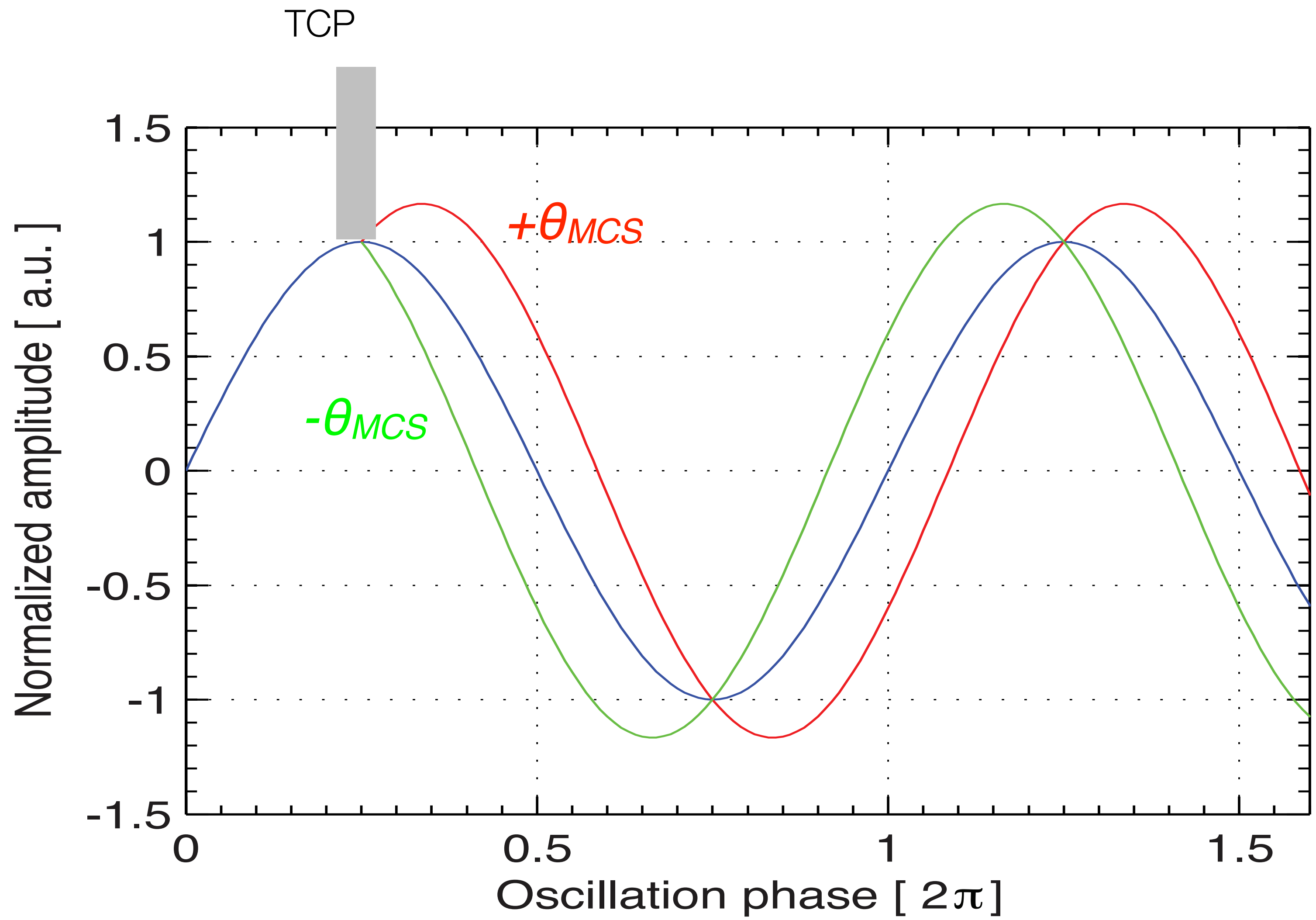

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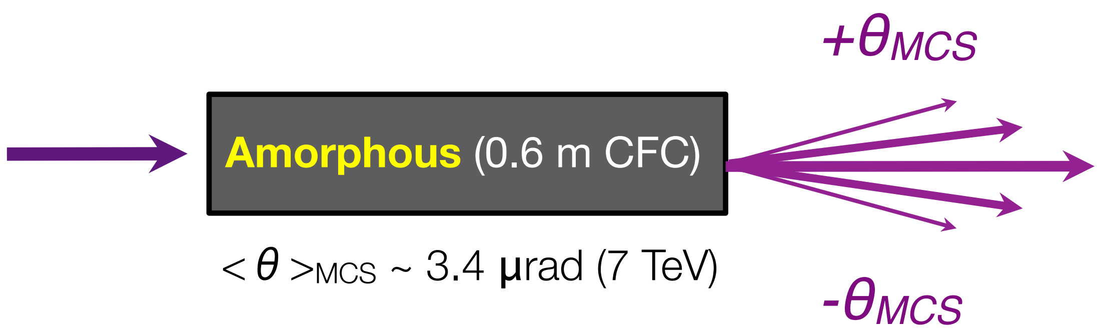

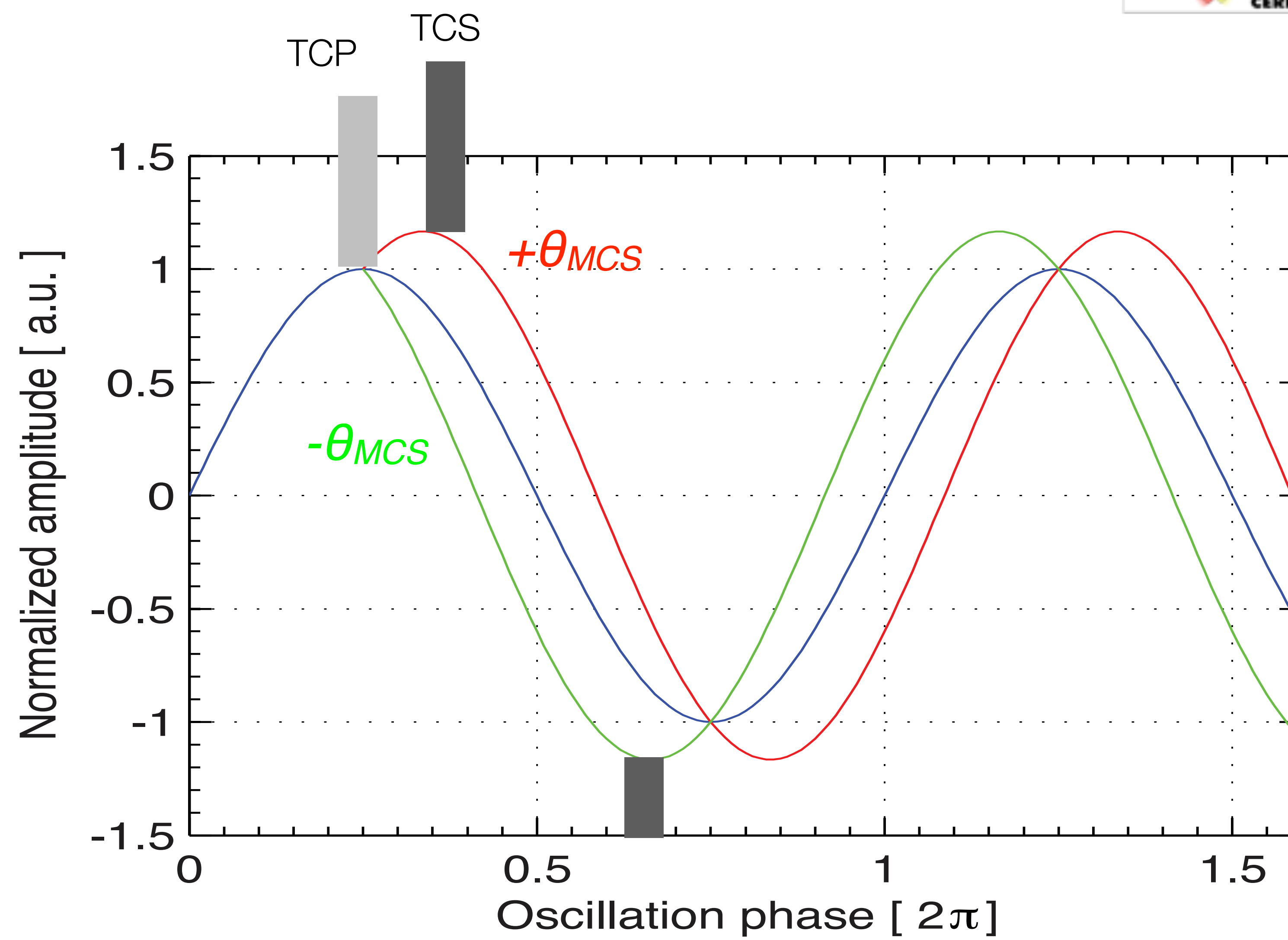

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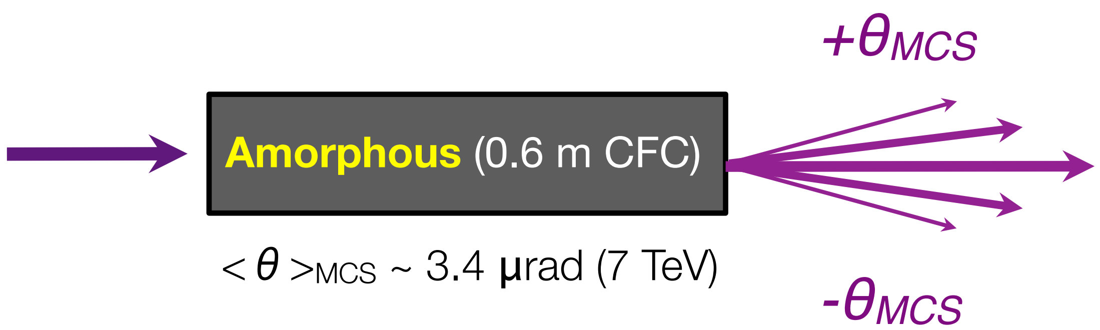

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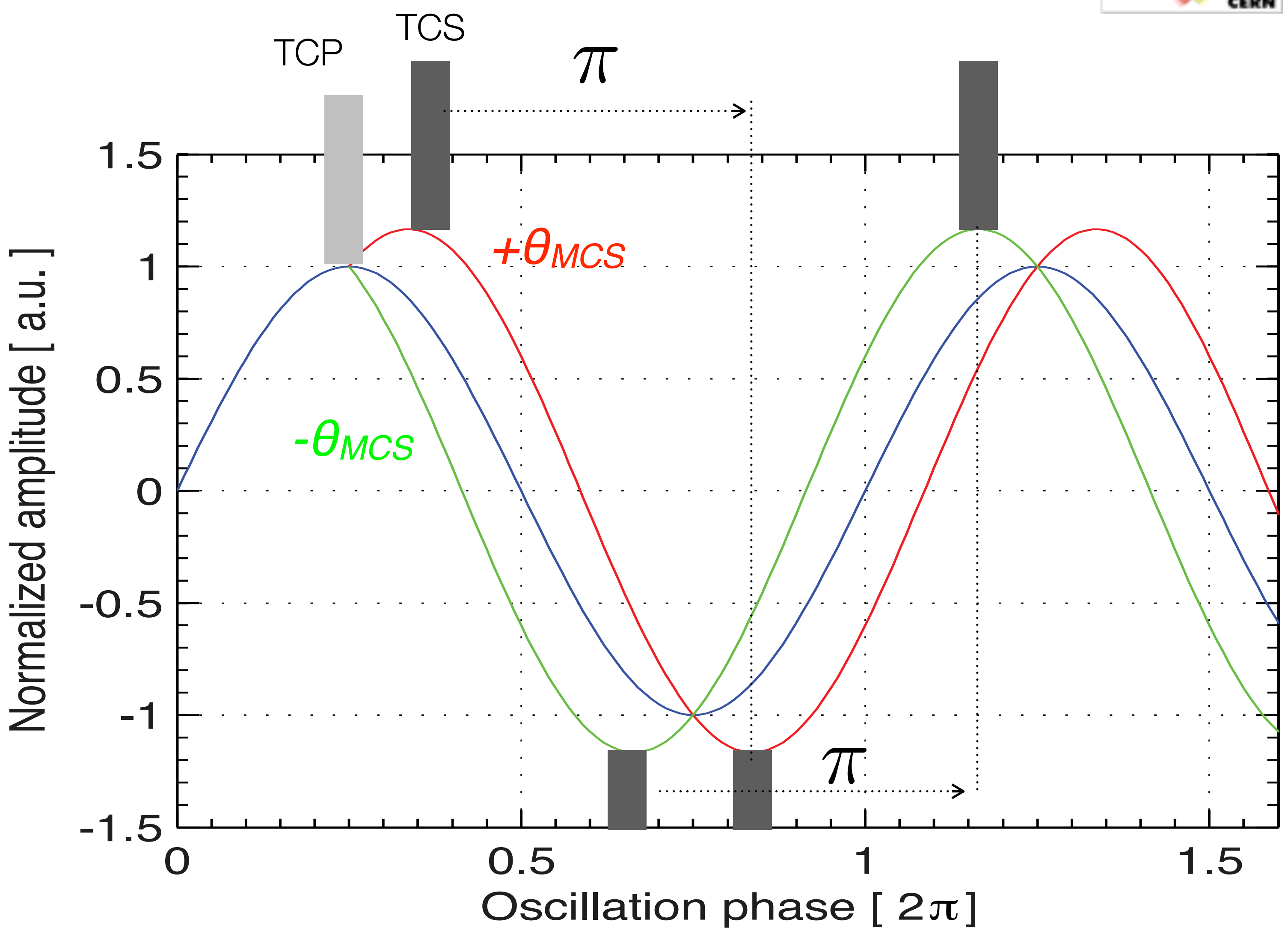

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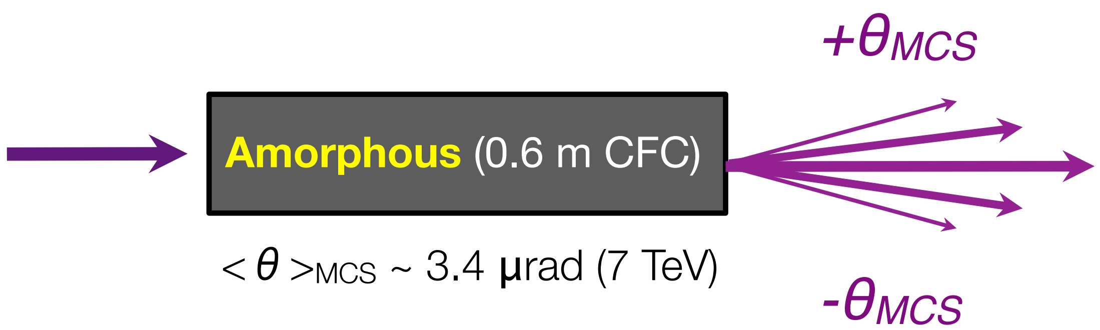

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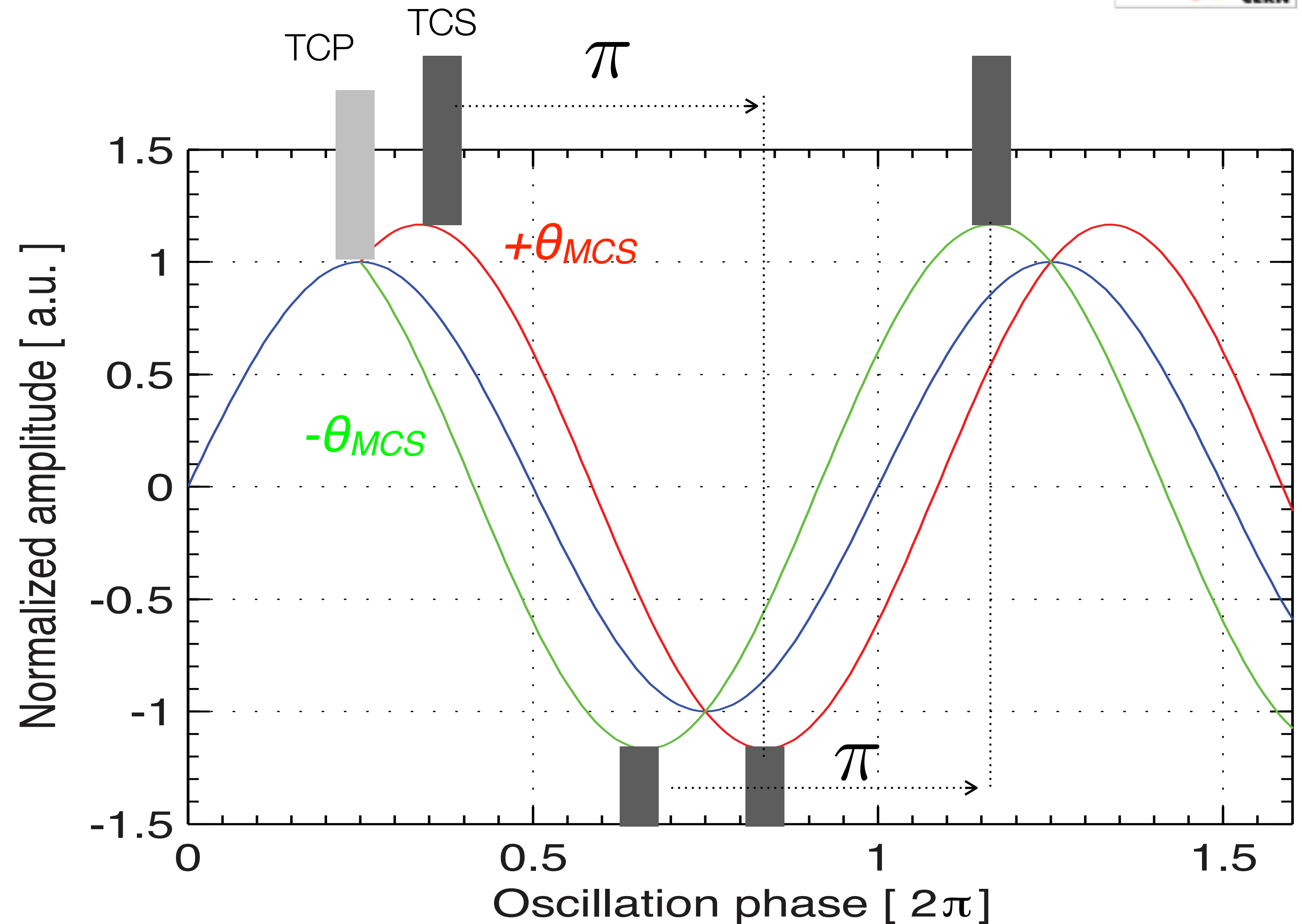

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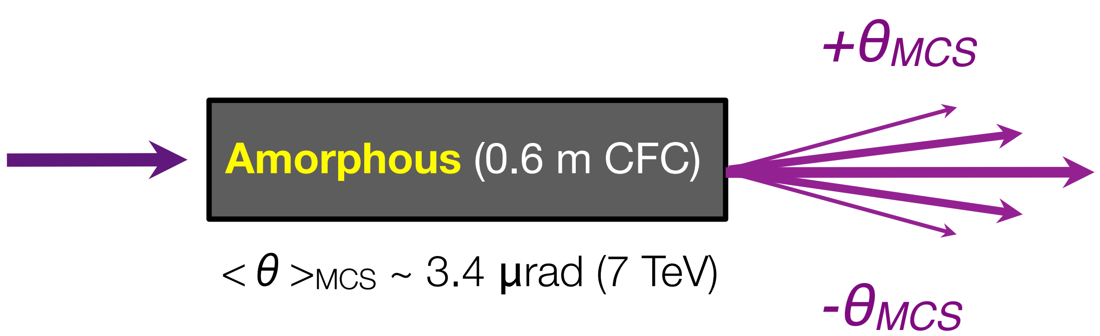

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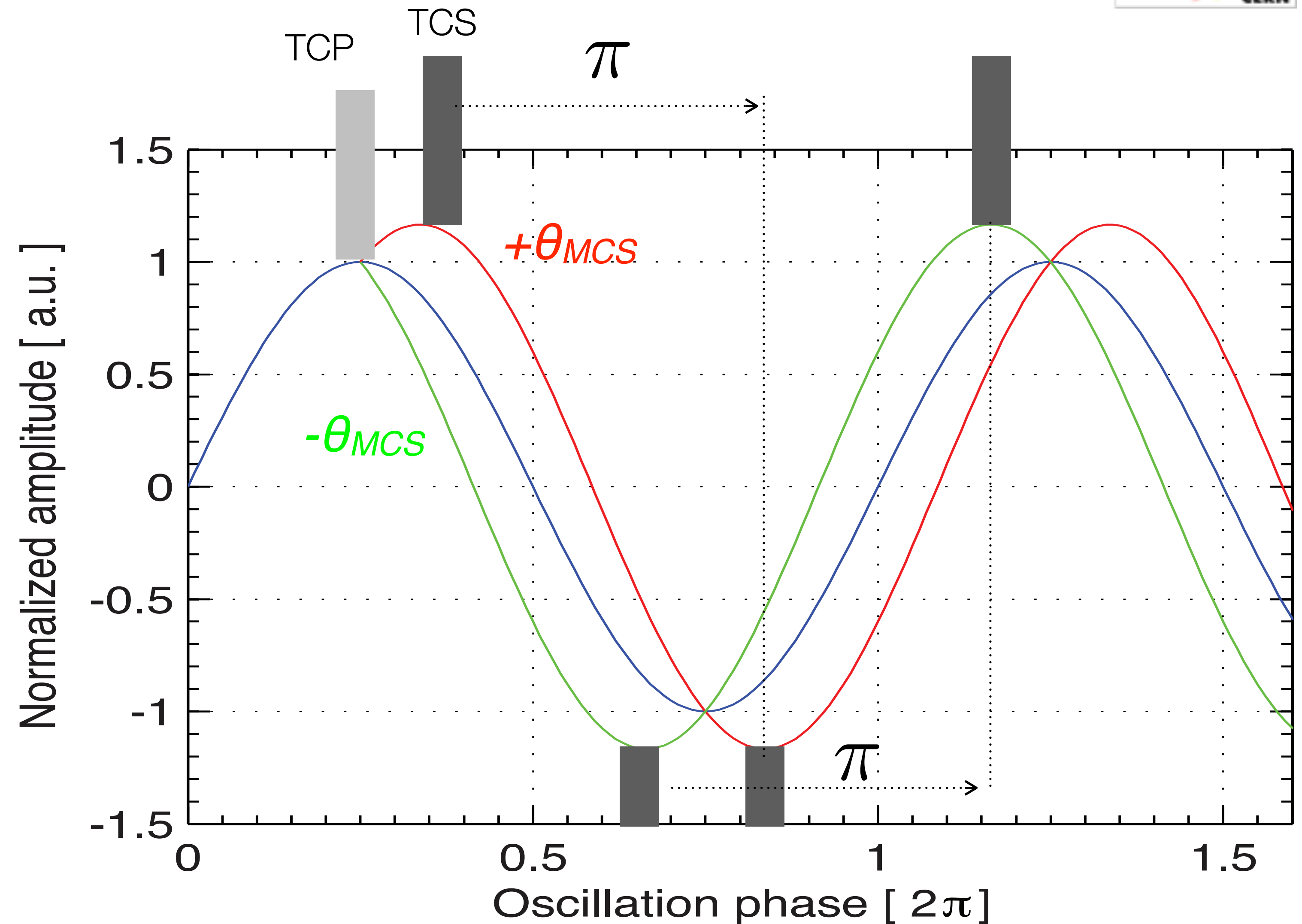

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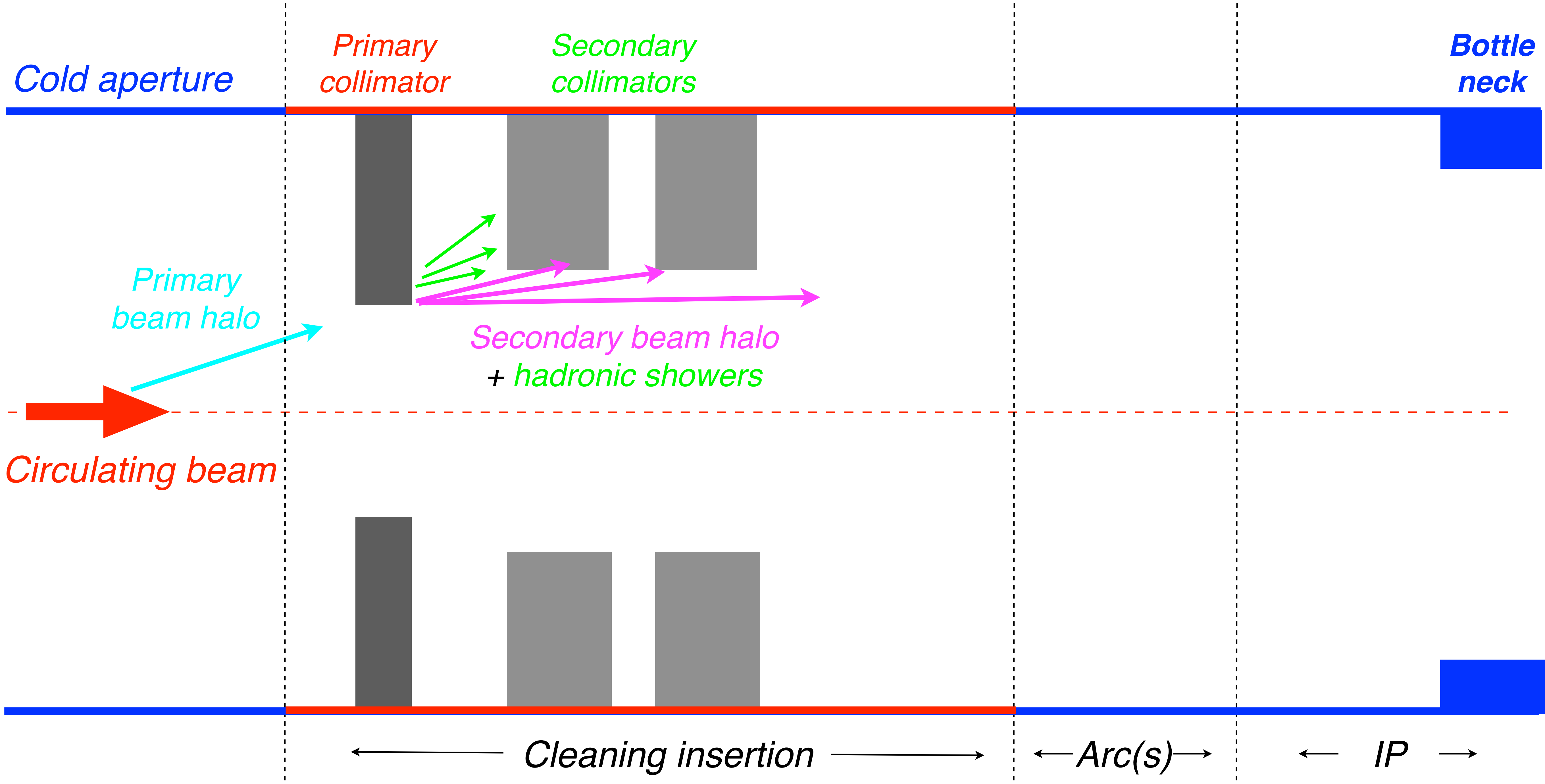
α	ϕ	μ_x	μ_y	α_J
0	0	μ_0	—	0
0	π	$\pi - \mu_0$	—	0
0	$\pi/2$	π	$3\pi/2$	μ_0
0	$-\pi/2$	π	$3\pi/2$	$-\mu_0$
$\pi/4$	$\pi/4$	μ_0	μ_0	$\pi/4$
$\pi/4$	$5\pi/4$	$\pi - \mu_0$	$\pi - \mu_0$	$\pi/4$
$\pi/4$	$3\pi/4$	$\pi - \mu_0$	$\pi + \mu_0$	$\pi/4$
$\pi/4$	$-\pi/4$	$\pi + \mu_0$	$\pi - \mu_0$	$\pi/4$
$\pi/2$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



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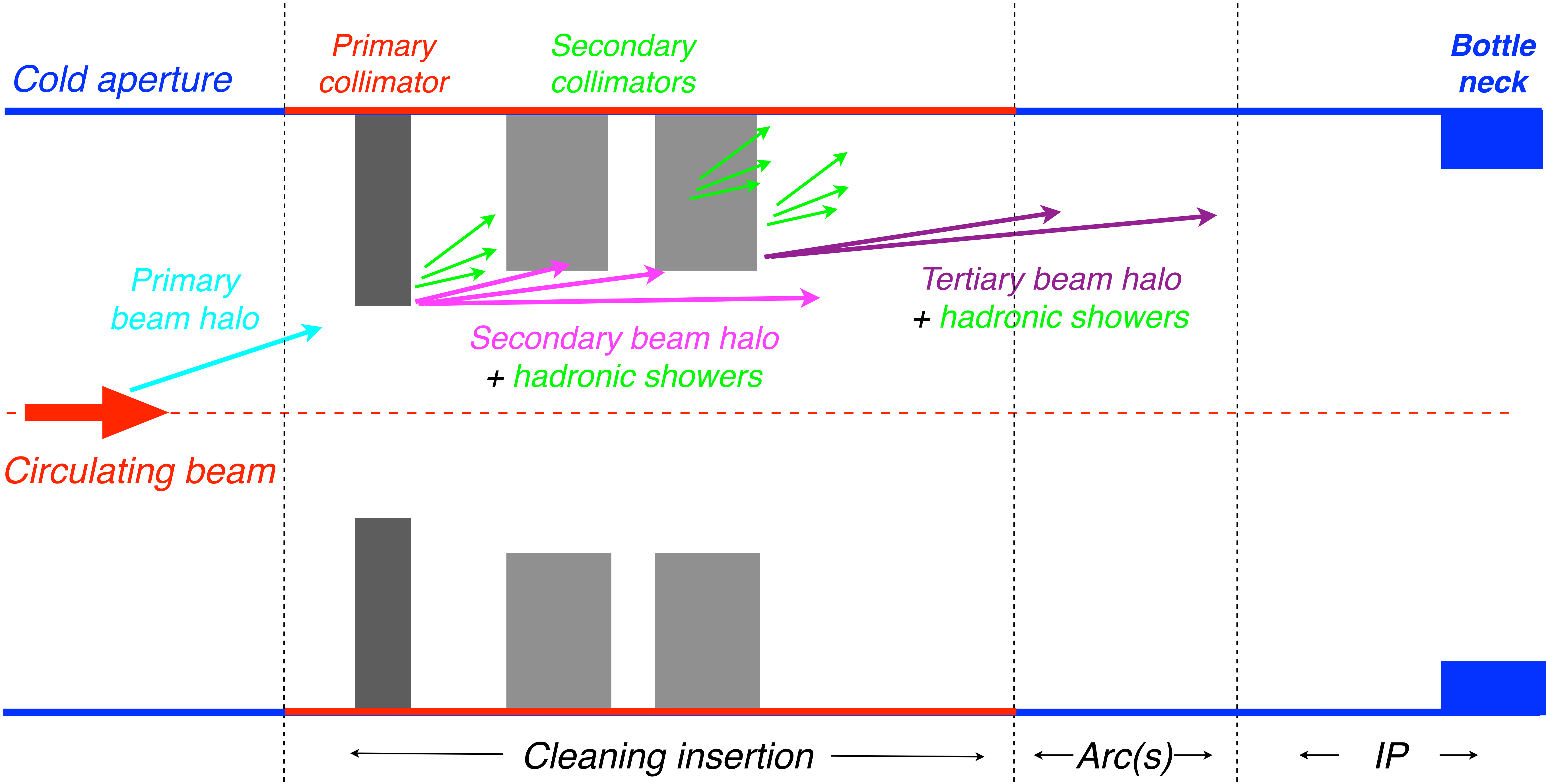

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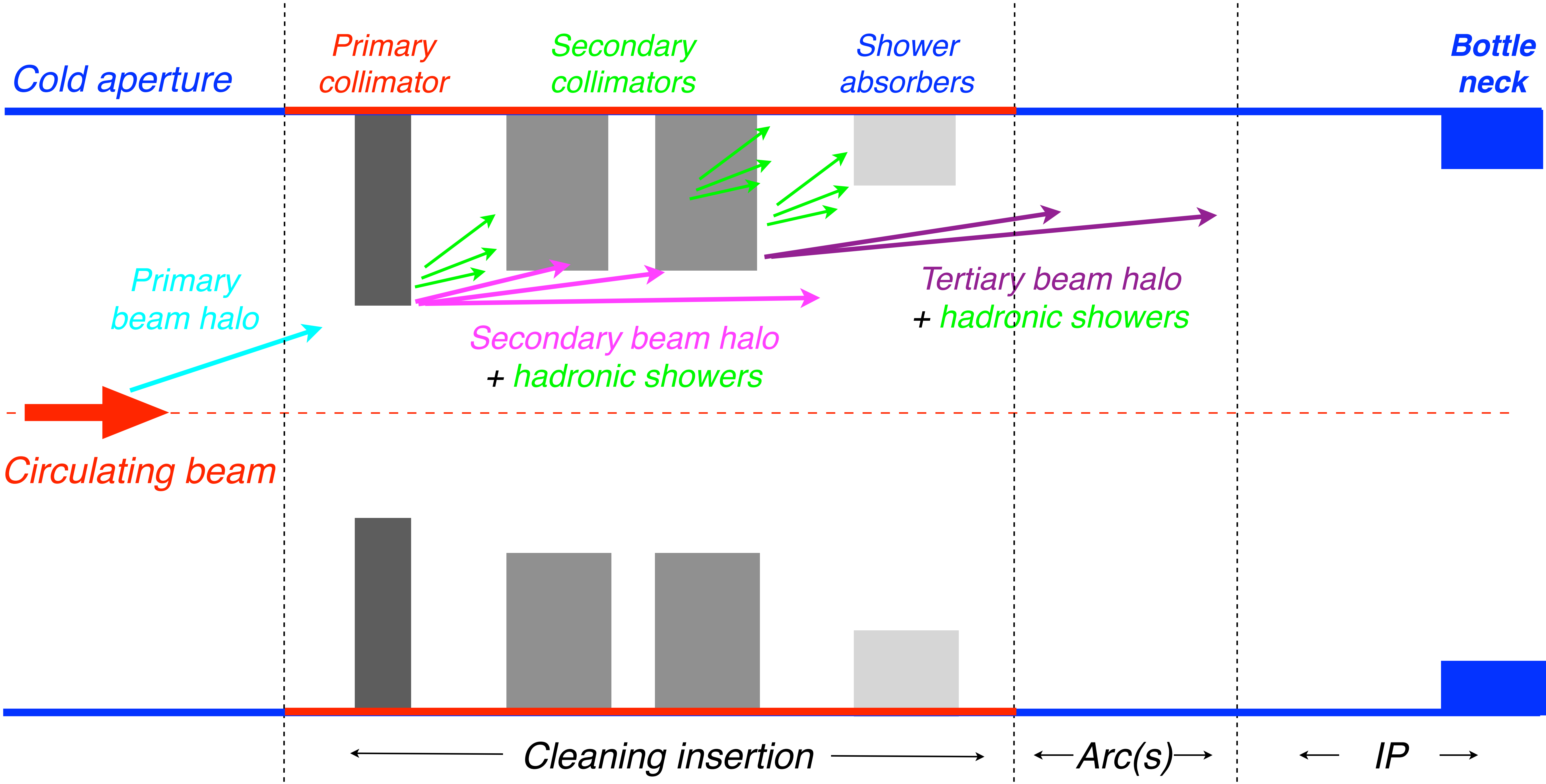

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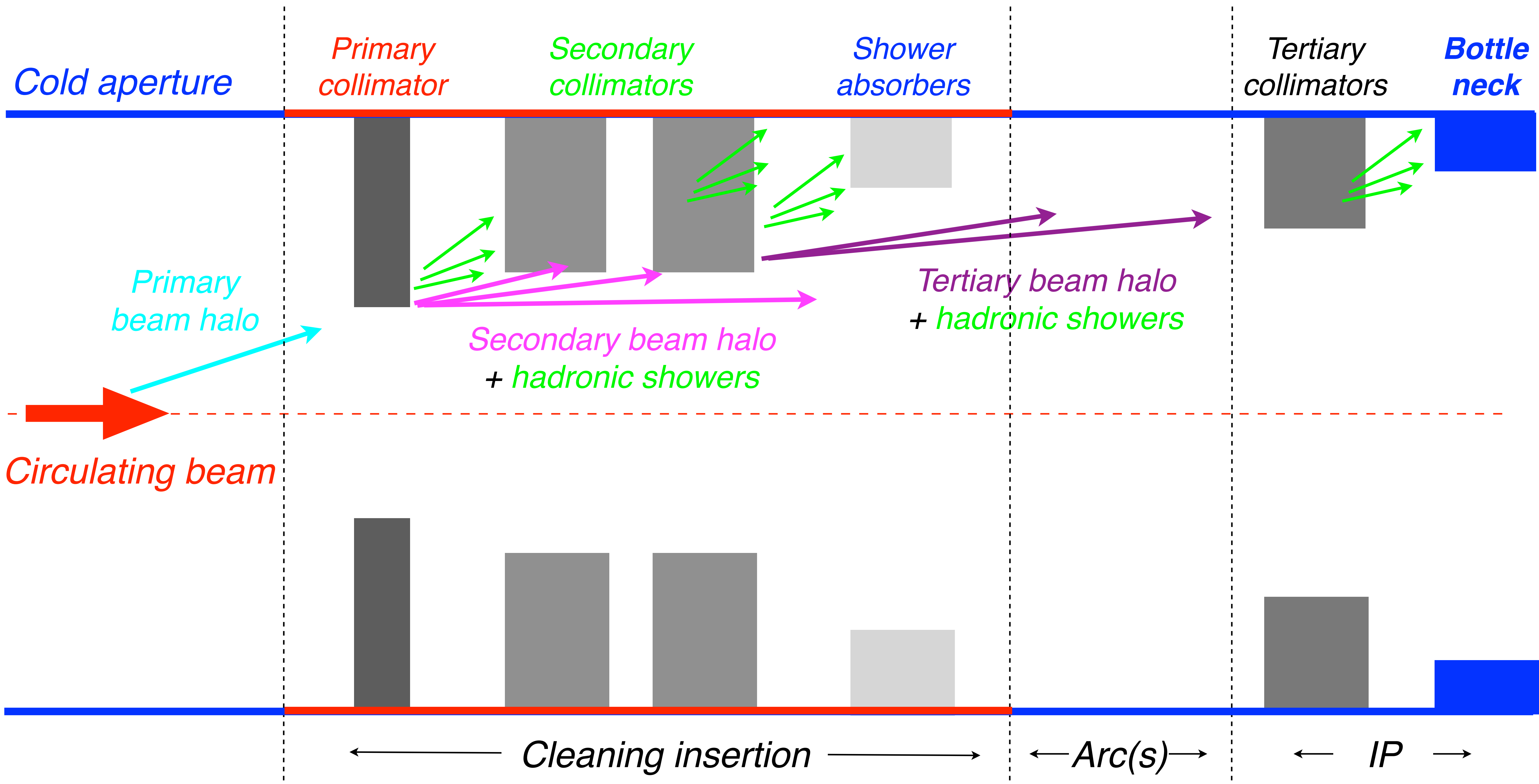

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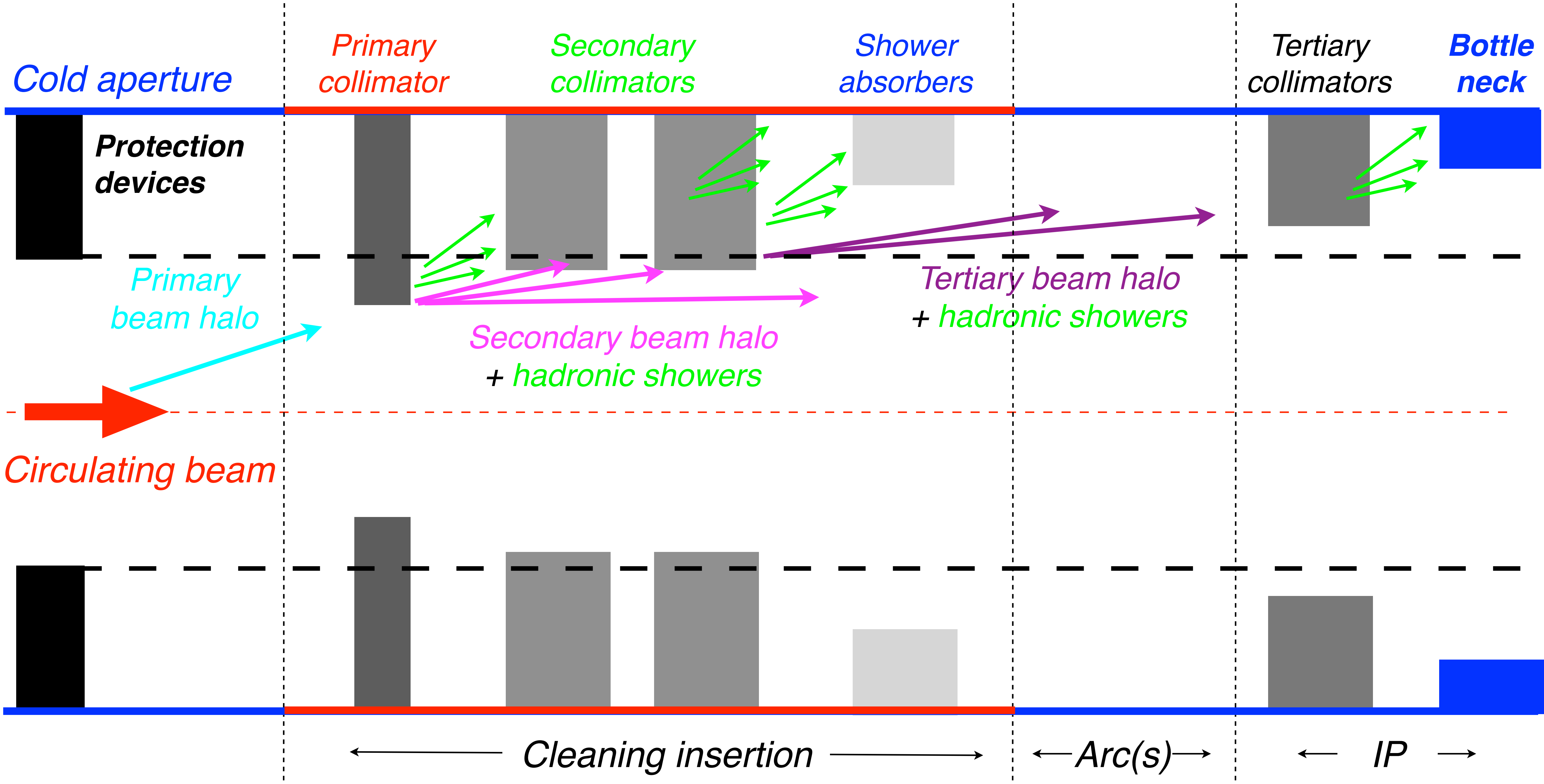

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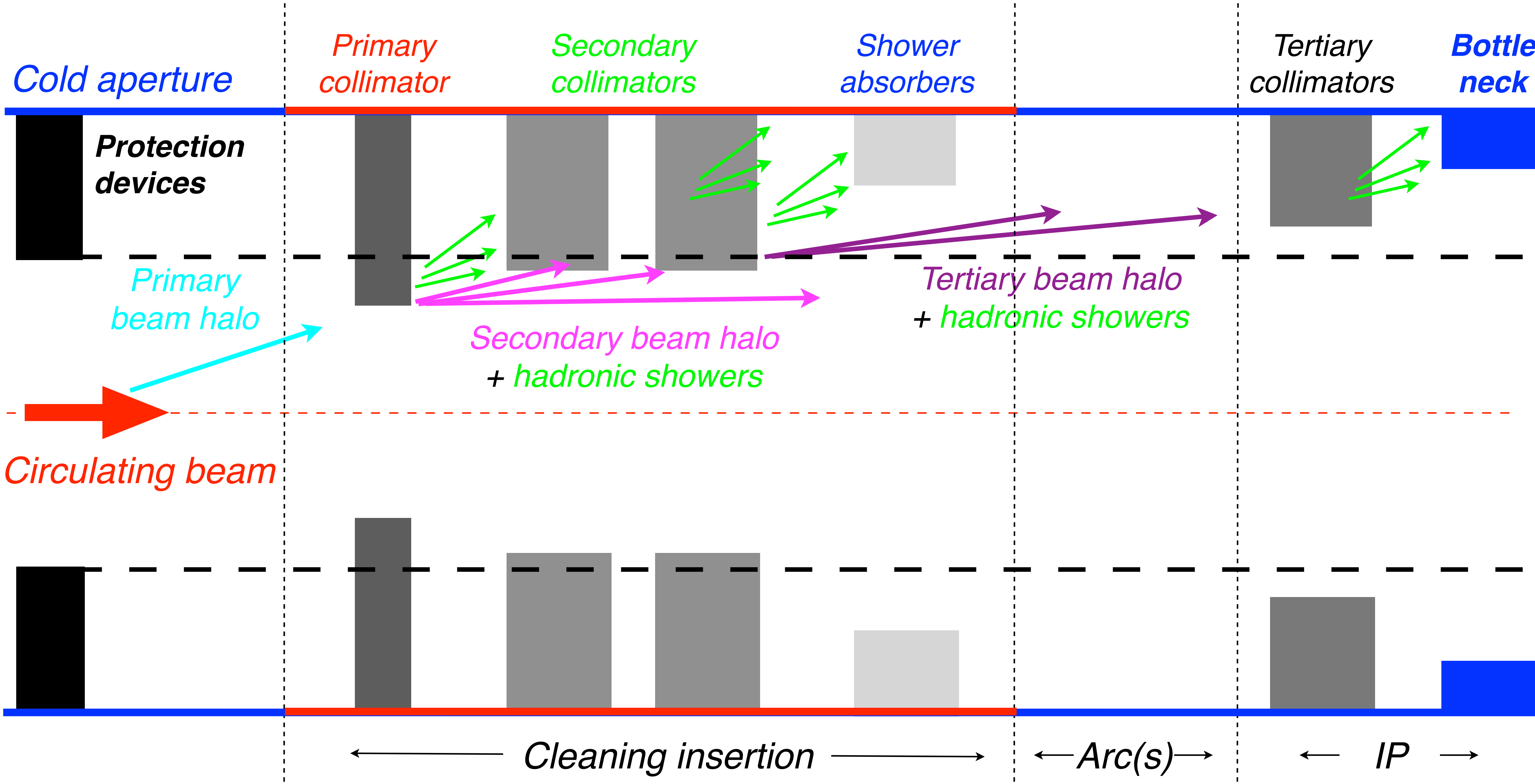
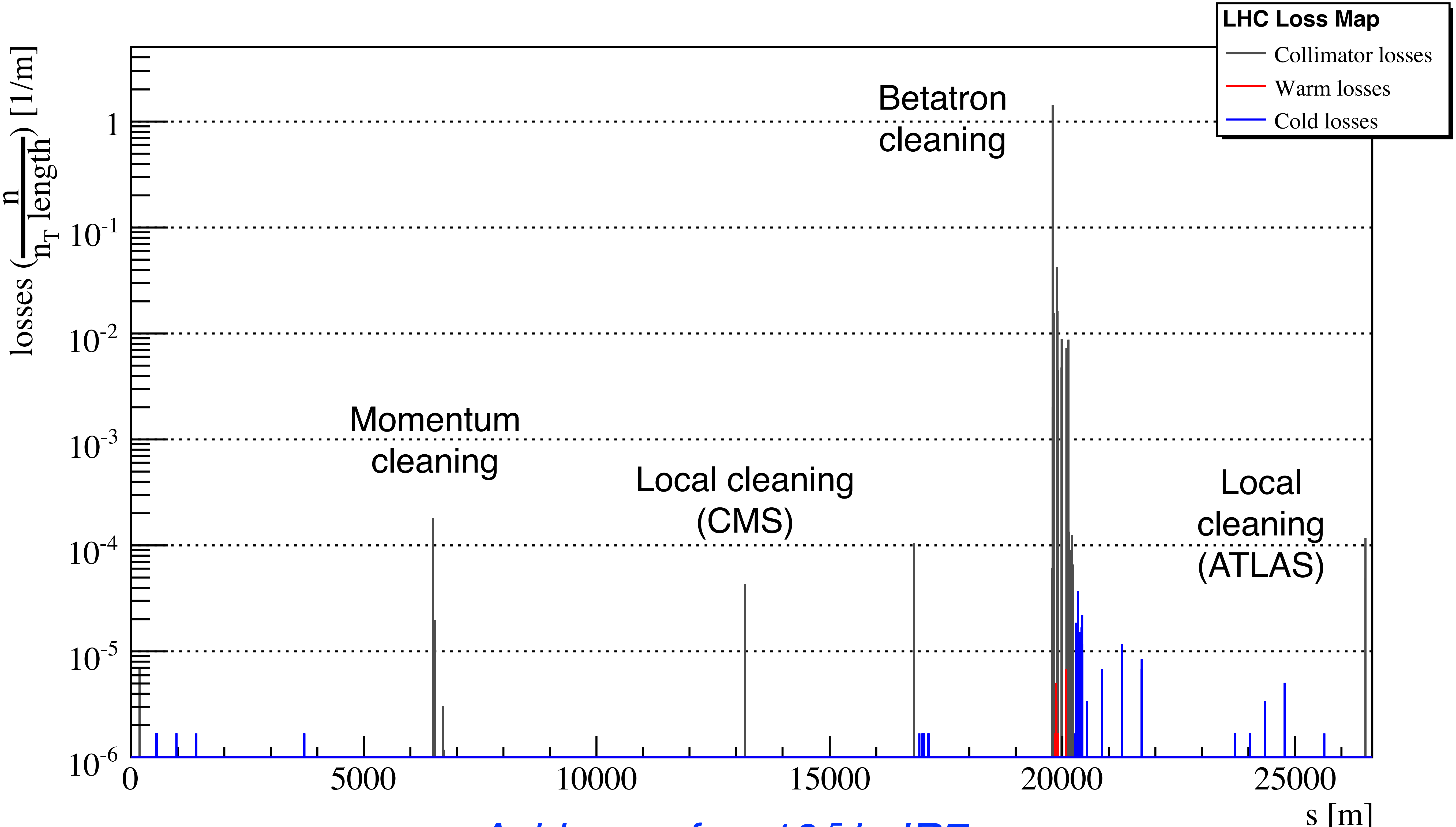


Including protection devices, a **5-stage cleaning** in required!
The system performance relies on achieving the well-defined **hierarchy** between collimator families and machine aperture.

Simulated 7 TeV performance



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Cold losses in experiments removed by local protection.

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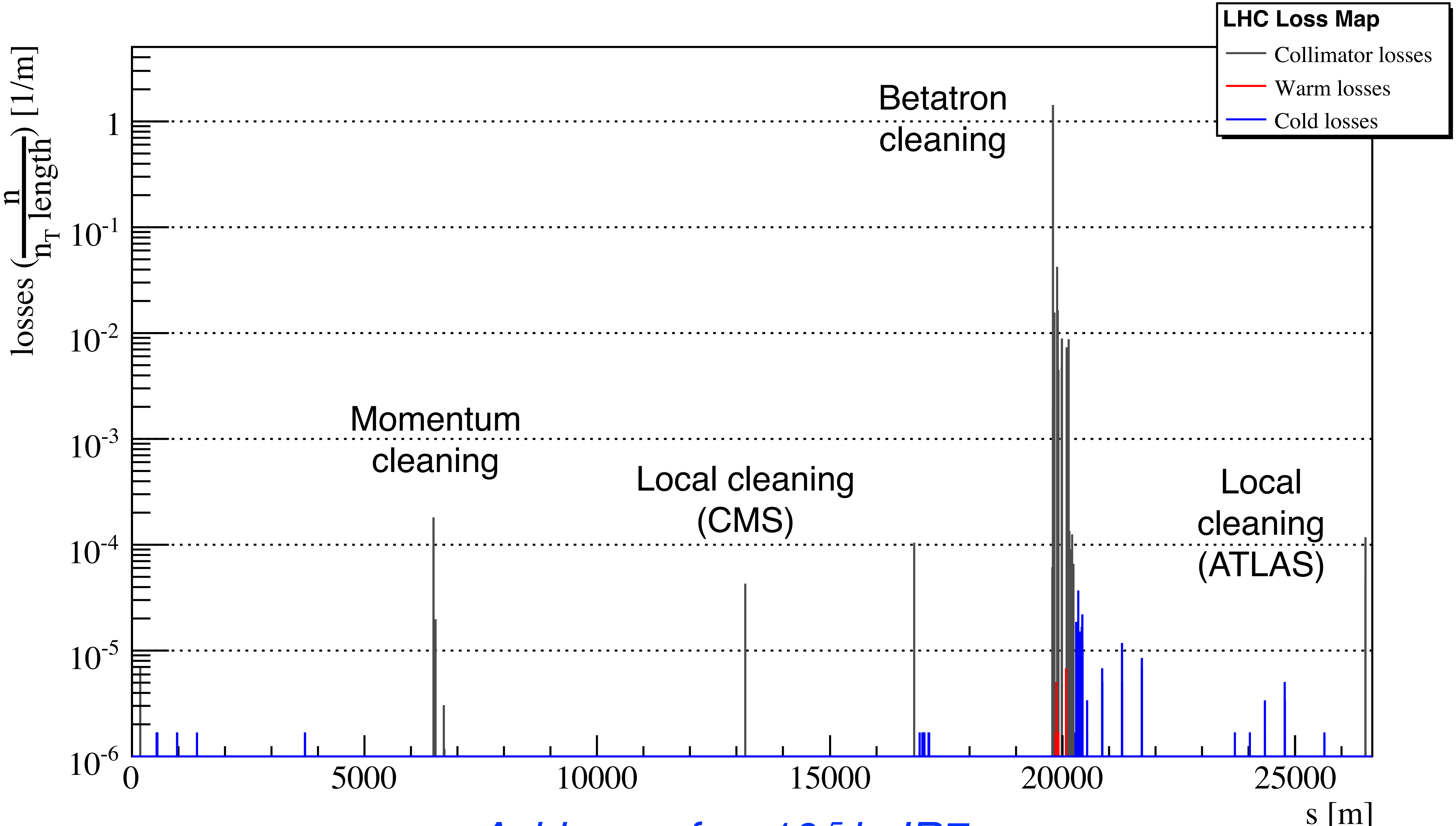

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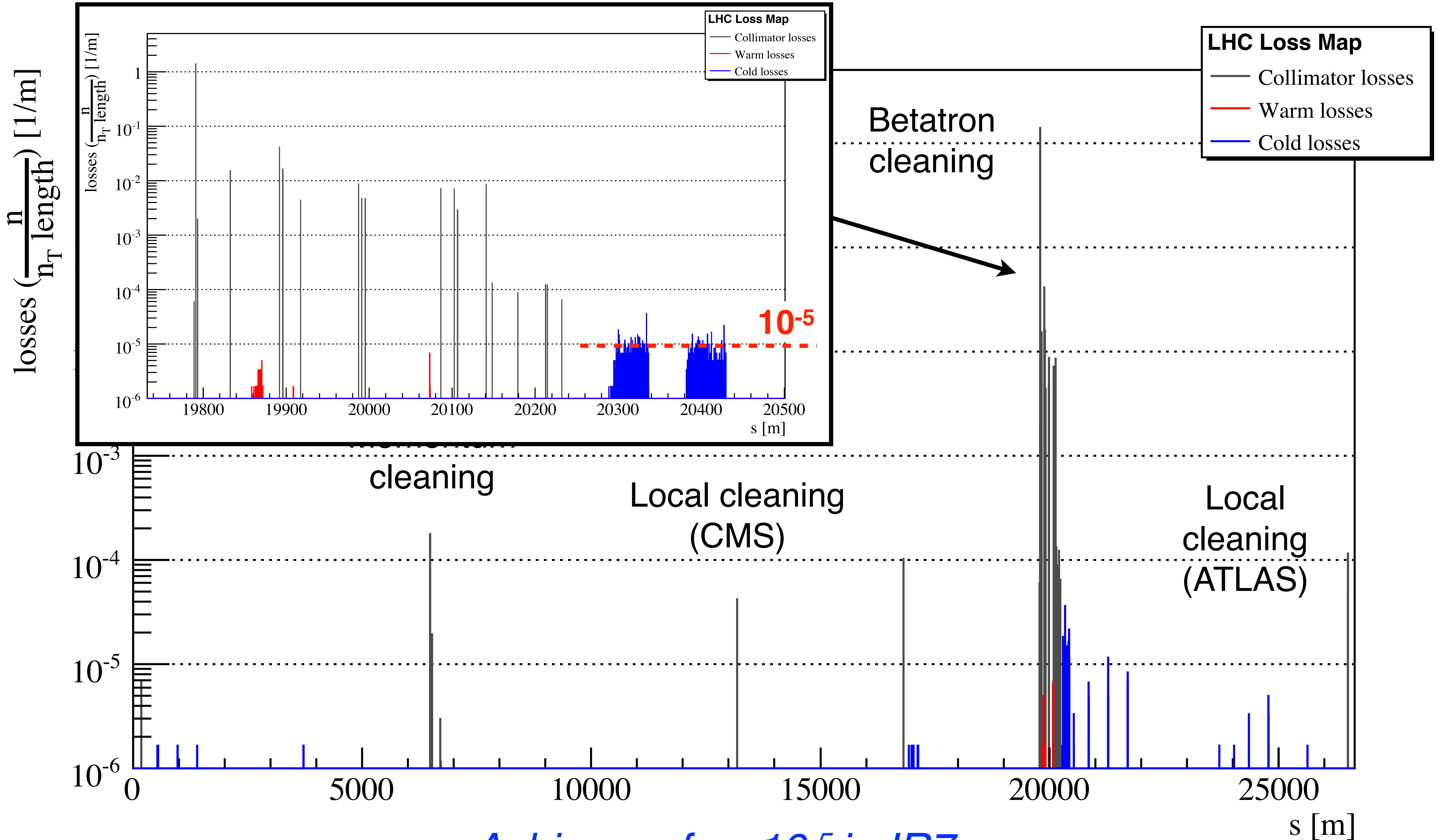

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  LHC main concerns: (1) minimize risk of quenches with 360 MJ stored energy, (2) passive machine protection in case of accidental failures. Many other important roles!
- Collimation is achieved by constraining the transverse amplitudes of halo particles: collimator jaws are set close to the beam to shield the aperture.

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  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!
- 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**.
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- 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 roles
- Single- and multi-stage cleaning
- **LHC collimation layouts and design**
- Achieved cleaning performance
- Conclusions

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

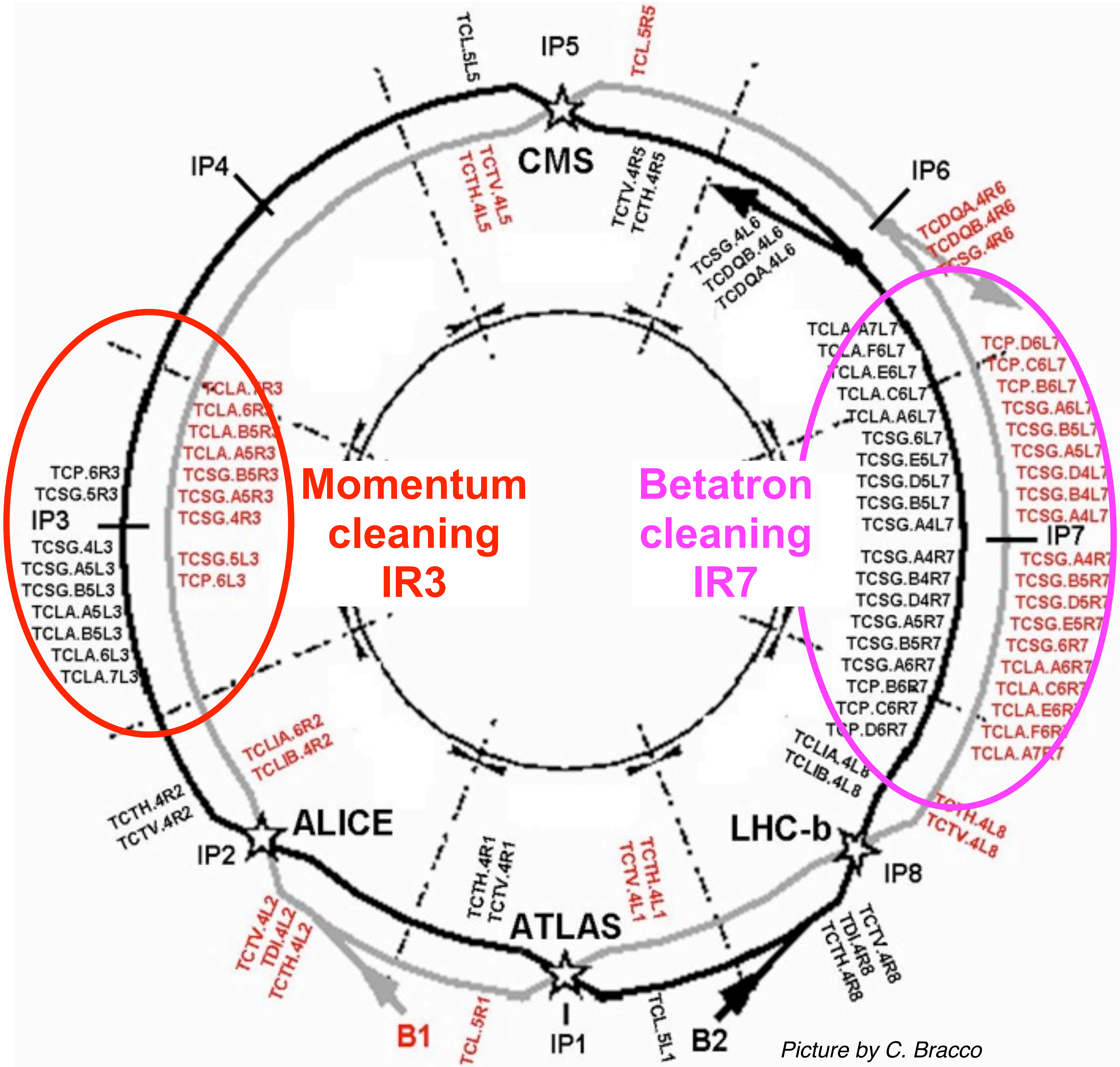
- **8 tertiary (2 per IP)**

Passive absorbers for warm magnets

Physics debris absorbers

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

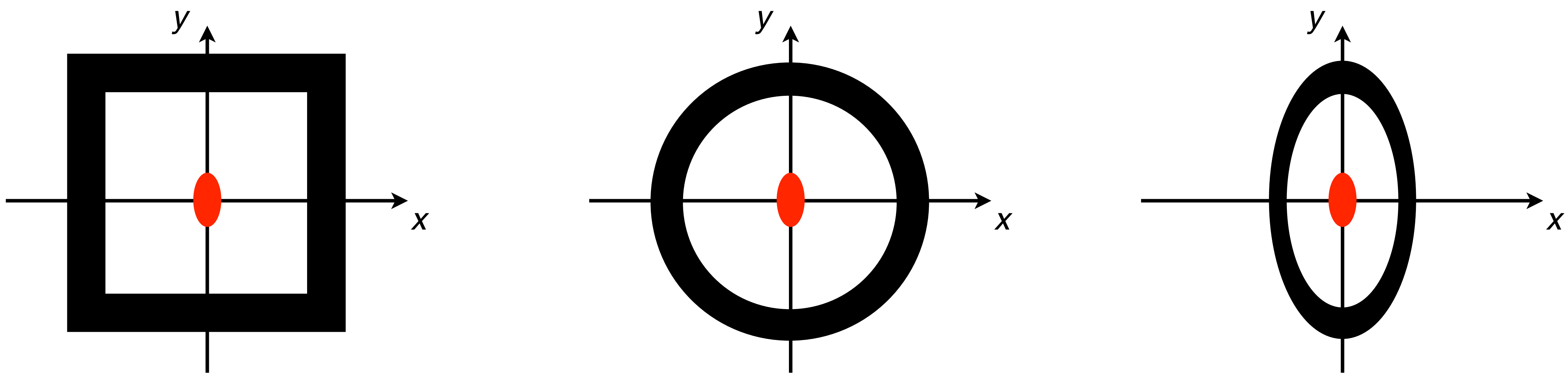
Total of 108 collimators (100 movable). Two jaws (4 motors) per collimator!



Picture by C. Bracco

Possible collimator designs

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



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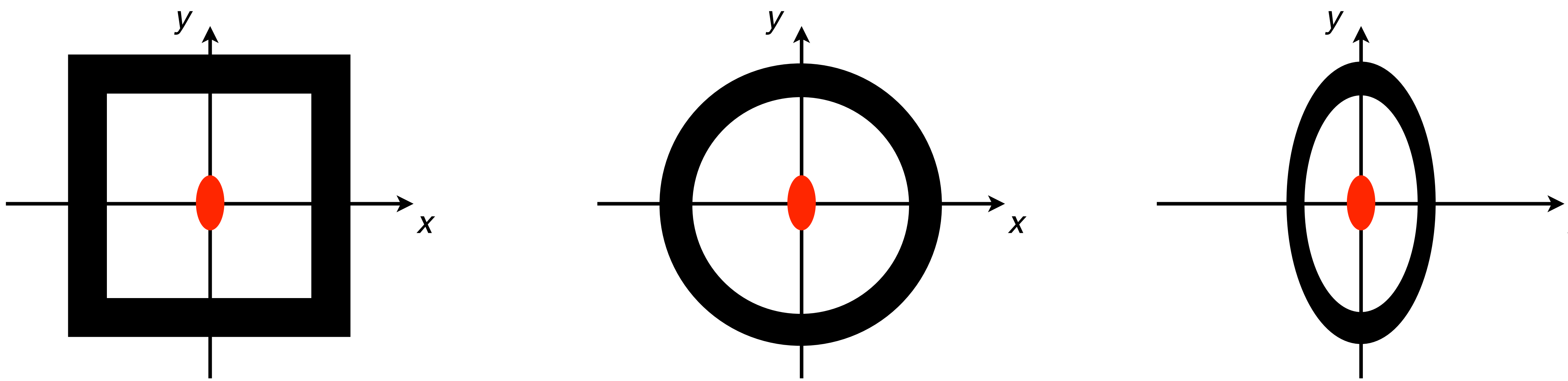
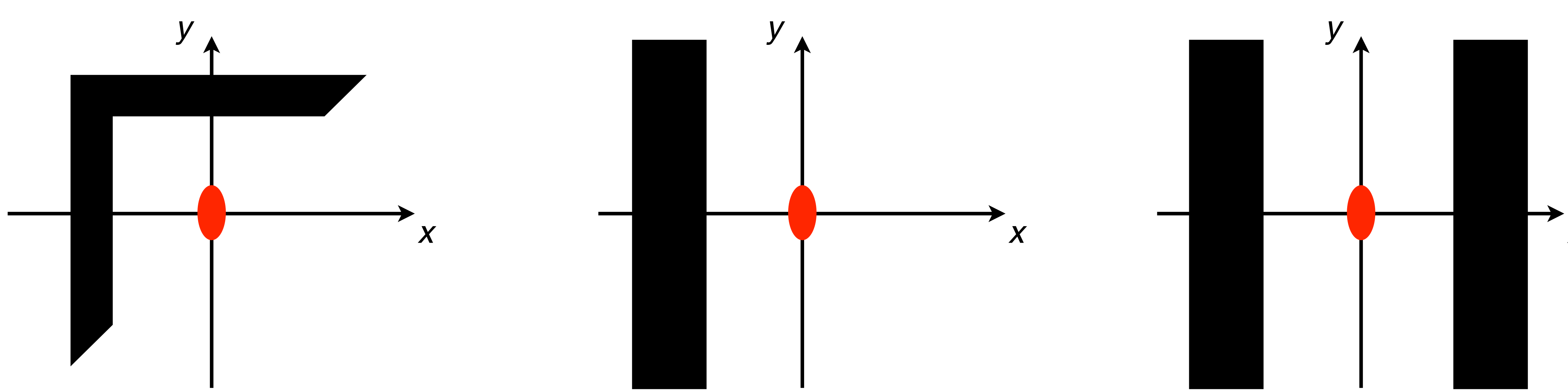


Movable collimators: L-shaped, one-sided, two-sided.



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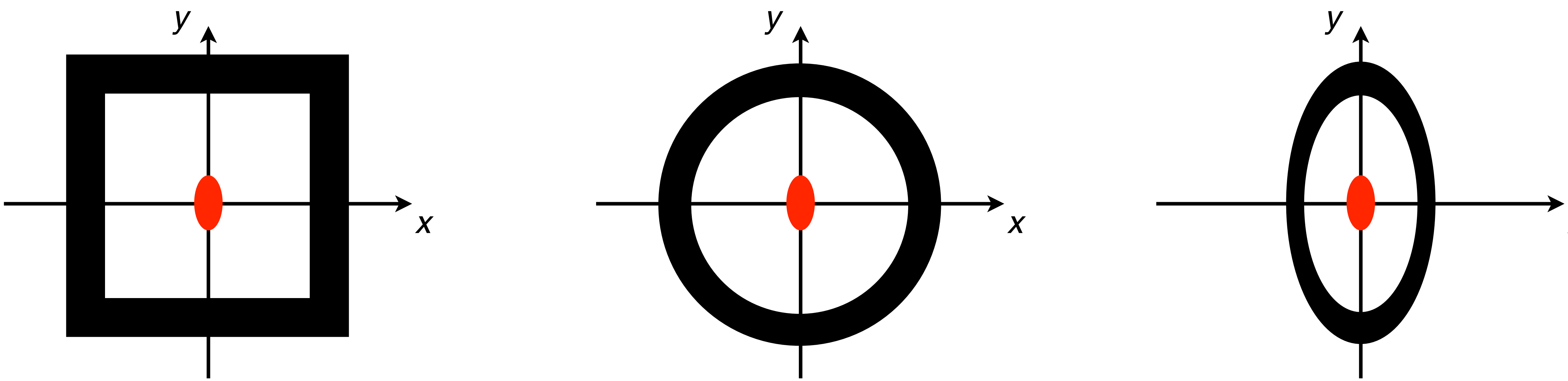

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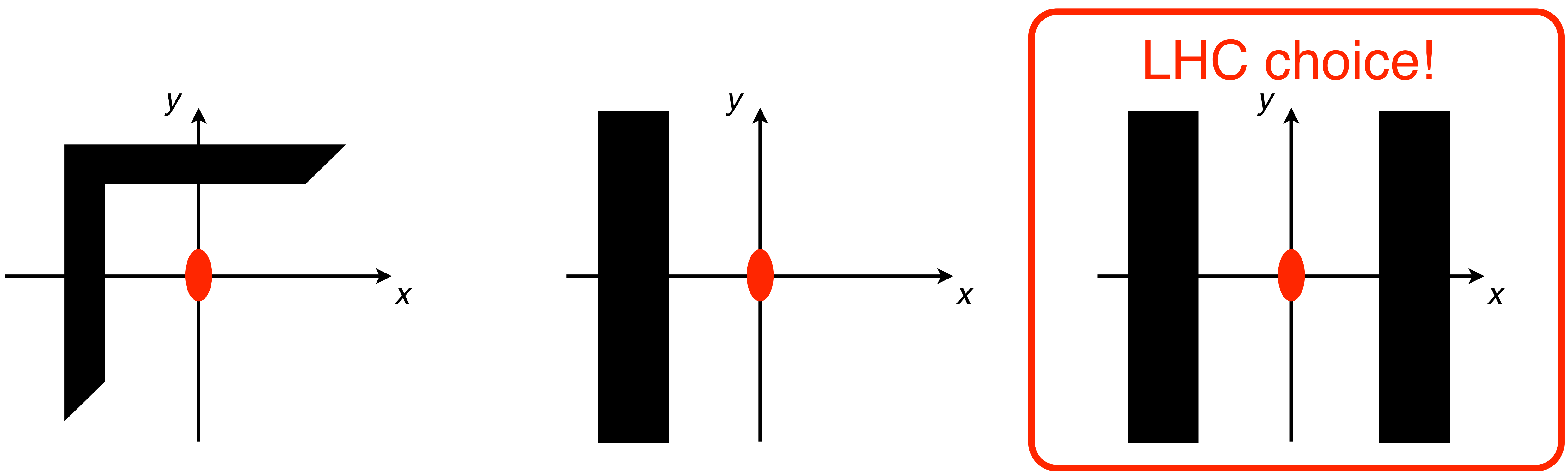
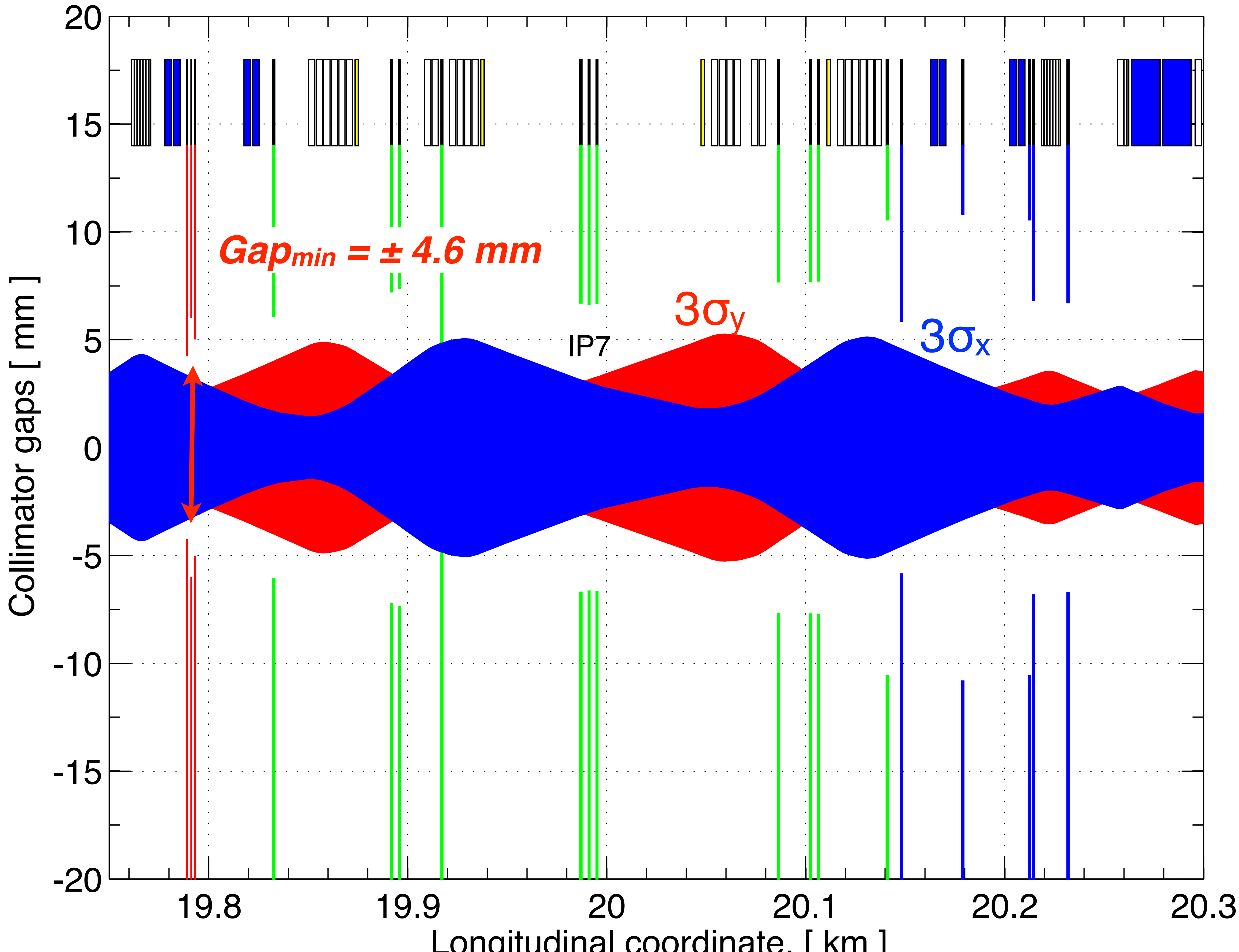


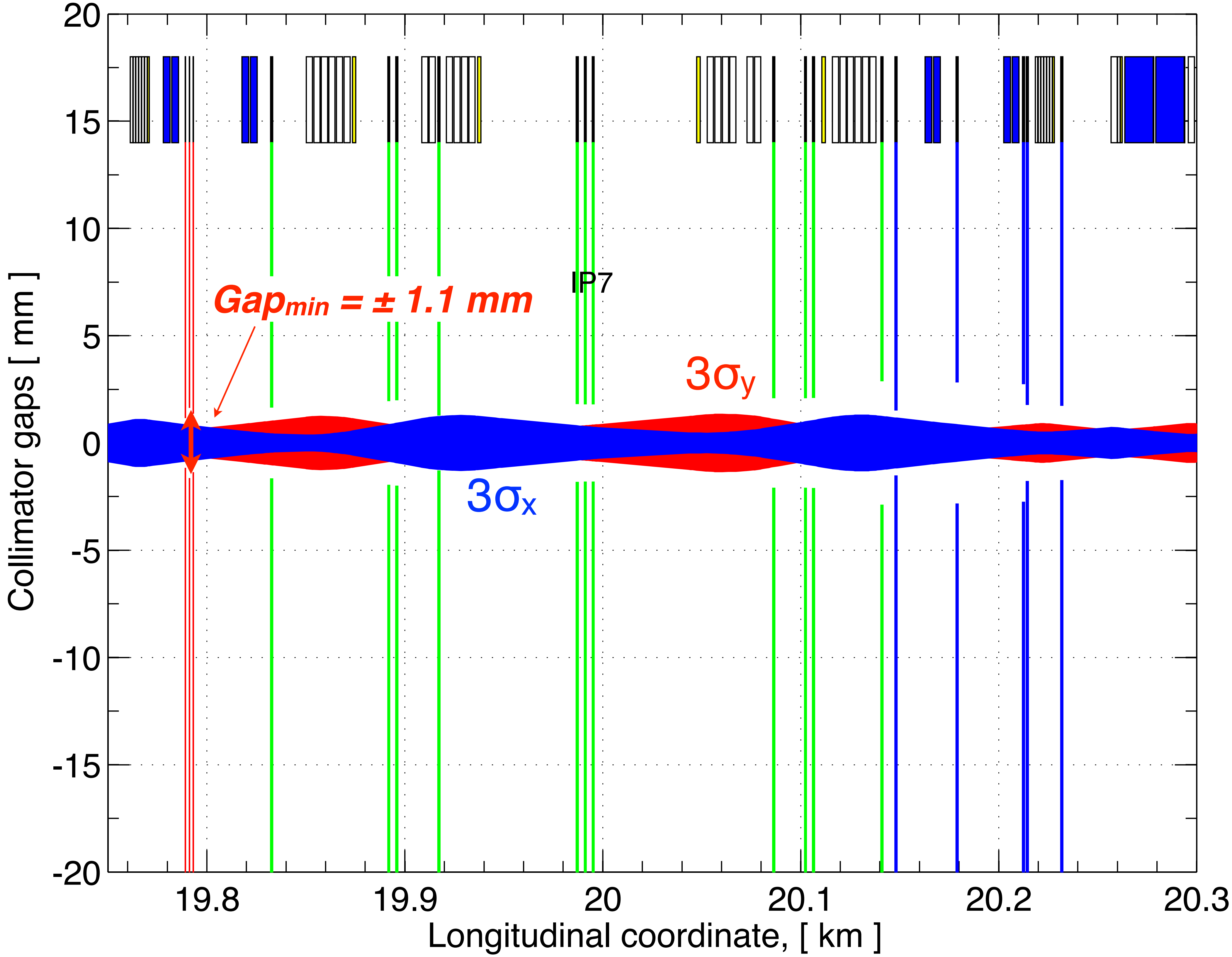
IR7 collimator settings at 450 GeV

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



IR7 collimator settings at 7 TeV

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



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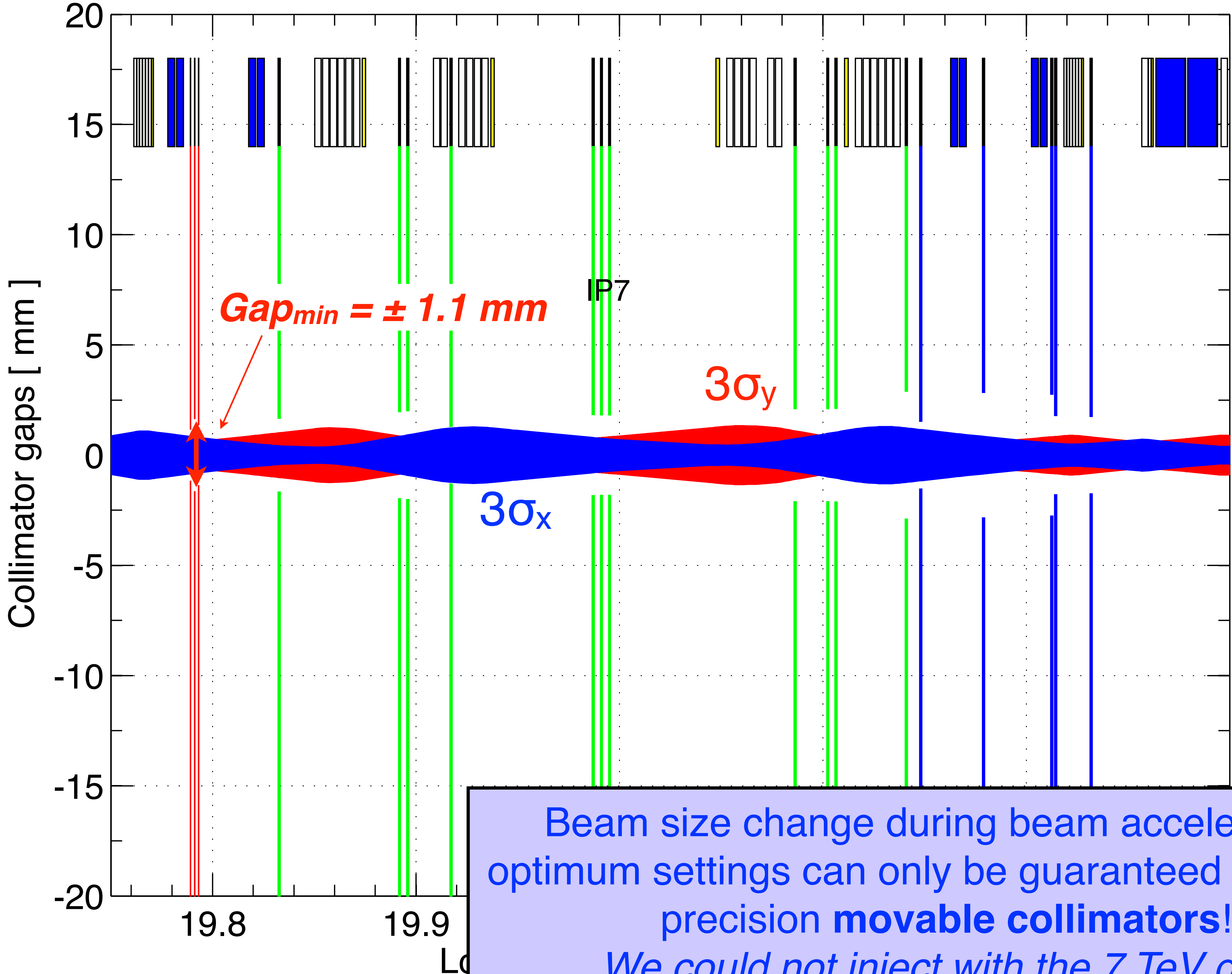


Beam size change during beam acceleration: optimum settings can only be guaranteed with high-precision **movable collimators**!
We could not inject with the 7 TeV gap!

Reference design goals

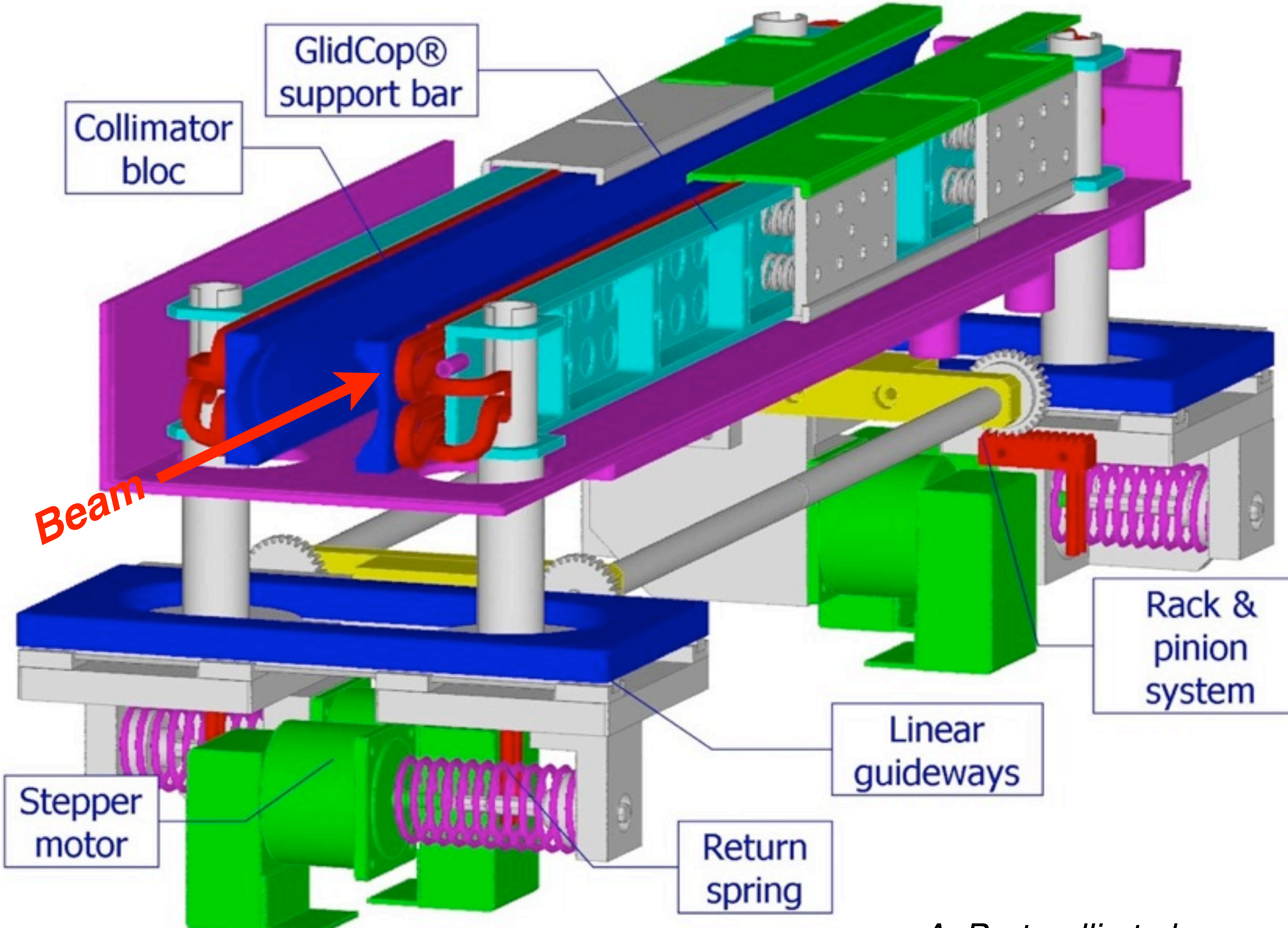
High stored beam energy (melt 500 kg Cu, required for 10^{34} cm^{-2} s^{-1} luminosity)	~ 360 MJ/beam
Large transverse energy density (beam is destructive, 3 orders beyond Tevatron/HERA)	1 GJ/mm^2
High required cleaning efficiency (clean lost protons to avoid SC magnet quenches)	99.998 % (~10^{-5}p/m)
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 (at 7 TeV)
Big and distributed system (coupled with mach. protection / dump)	~100 devices ~500 deg. of freedom

Quench
Damage
Heating
Activation
Stability
Impedance
Precision

Collimator design

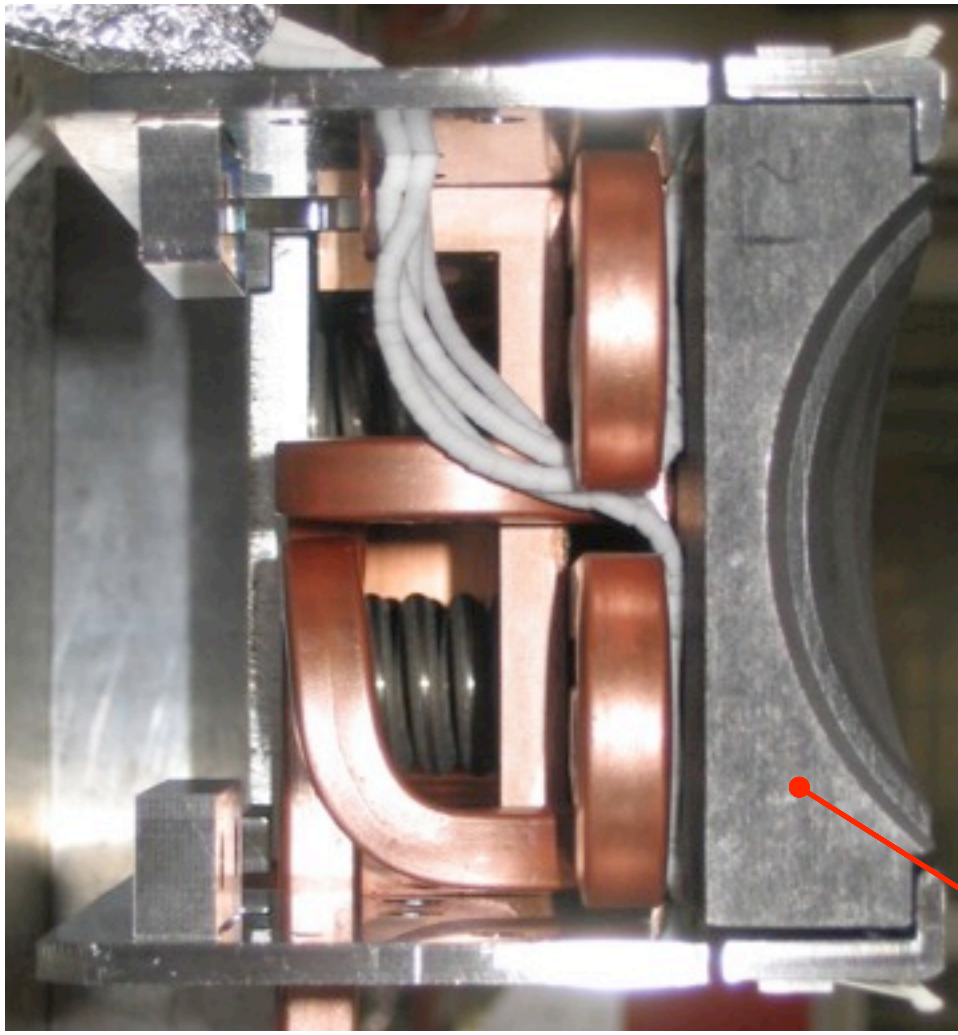
Main design features:

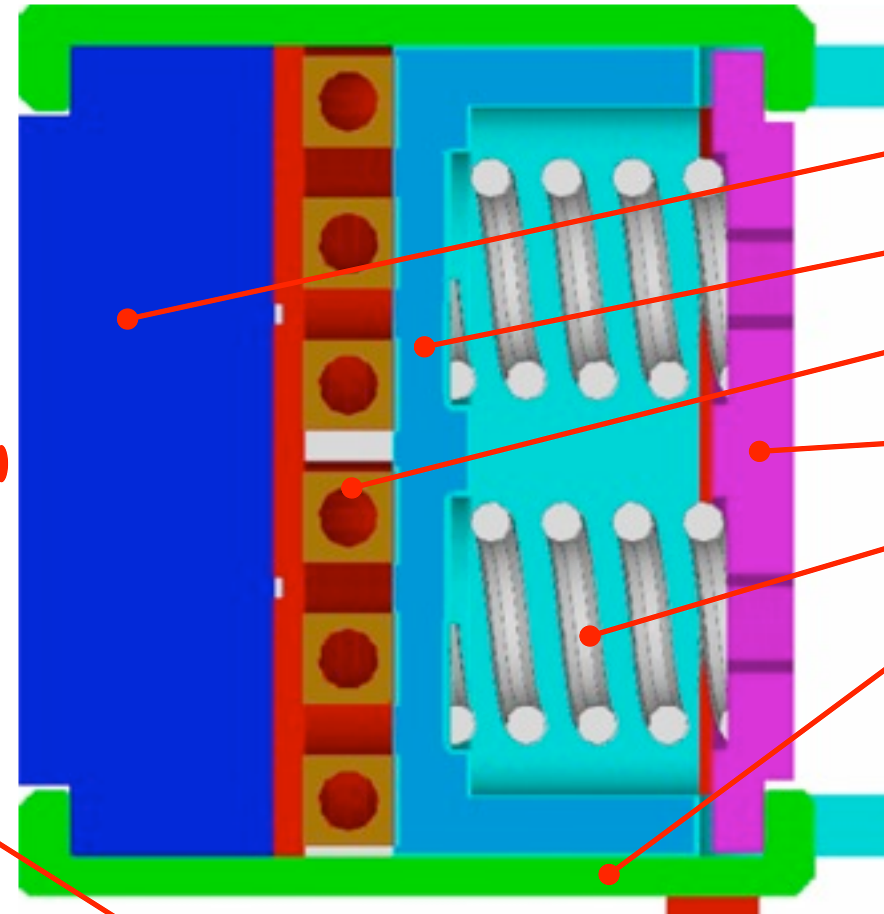
- Two jaws (position and angle)
- Concept of spare surface
- Different angles (H,V,S)
- External reference of jaw position
- Auto-retraction
- RF fingers
- Jaw cooling



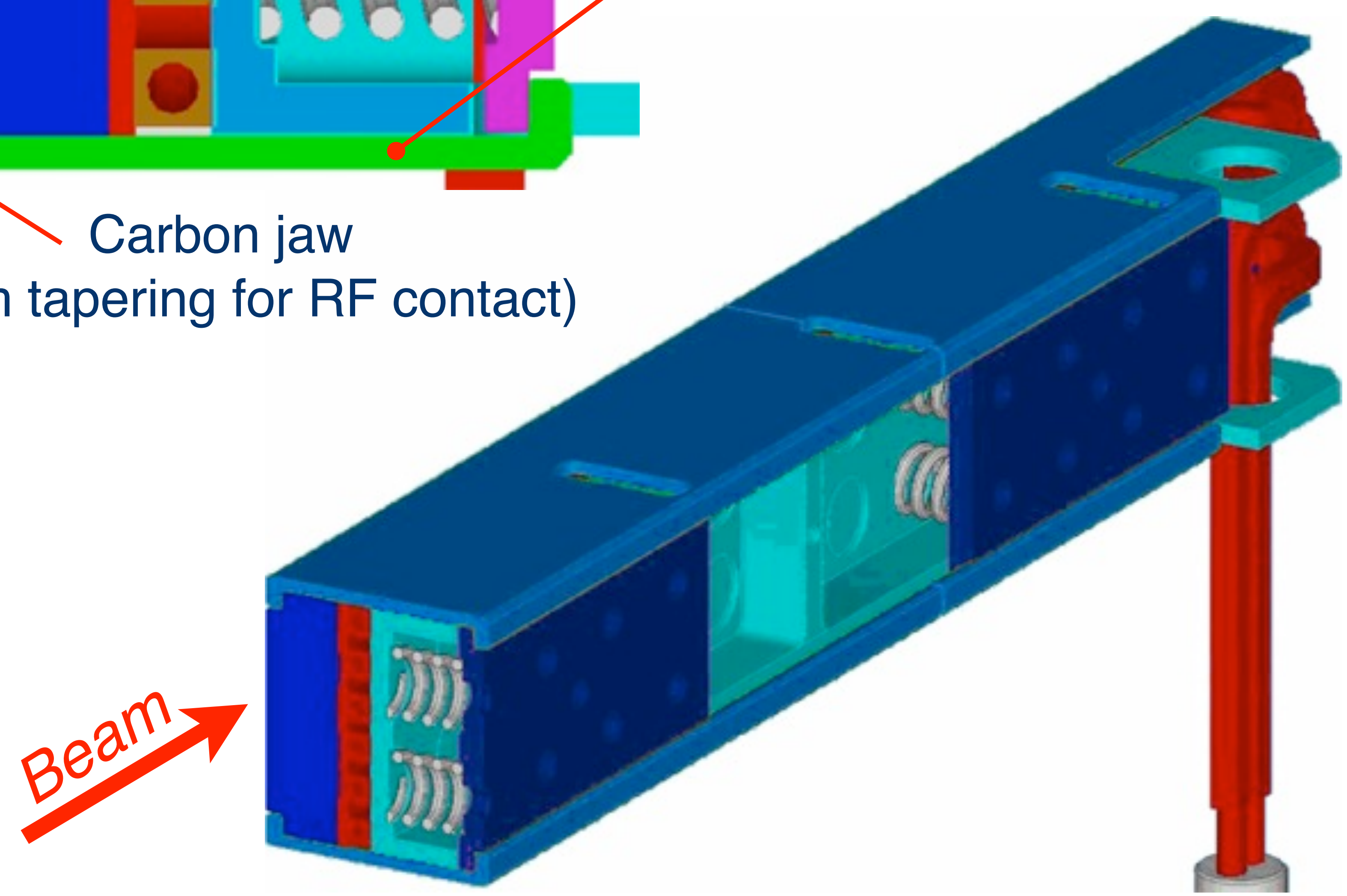
A. Bertarelli et al.

LHC collimator jaw design

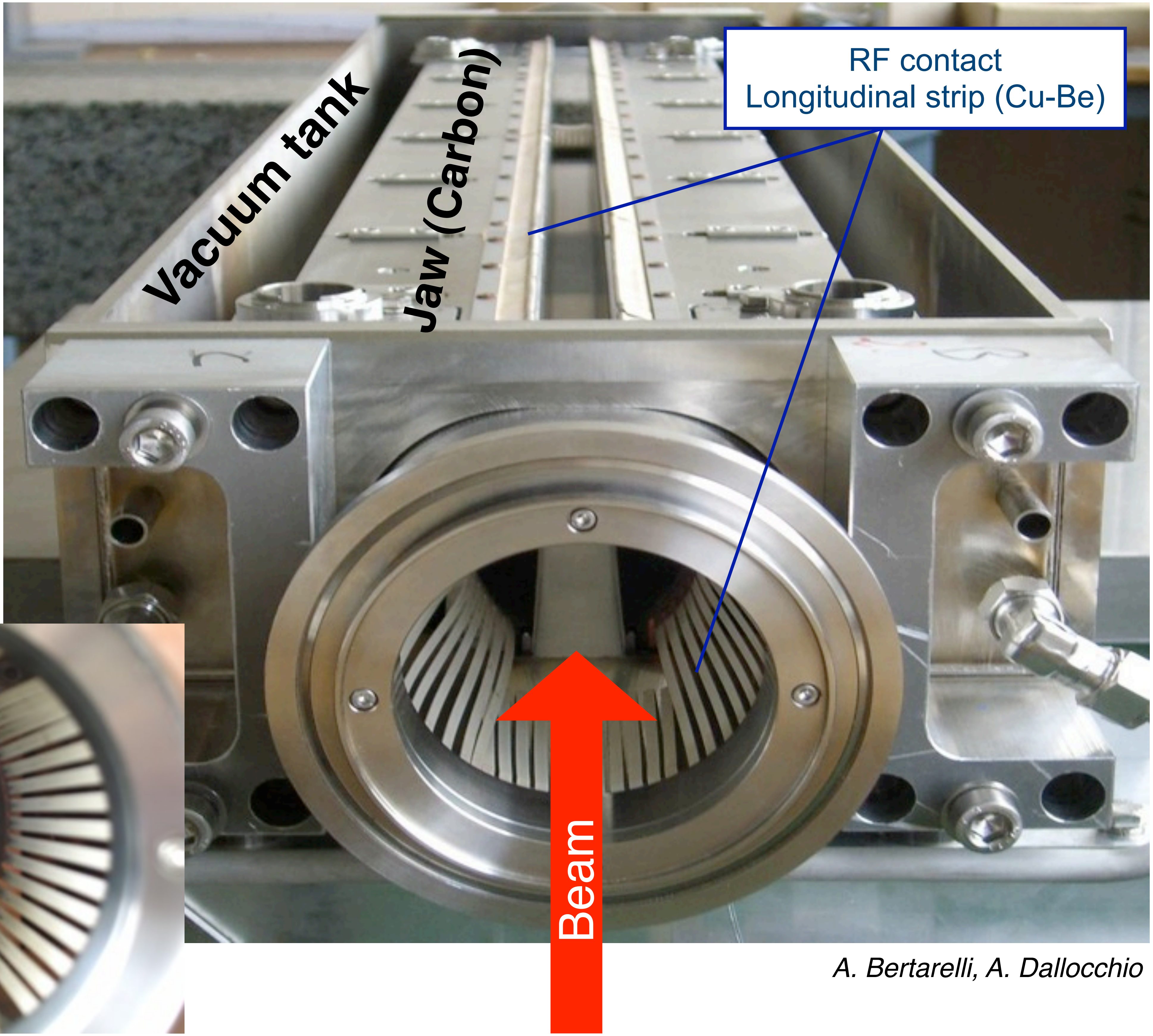




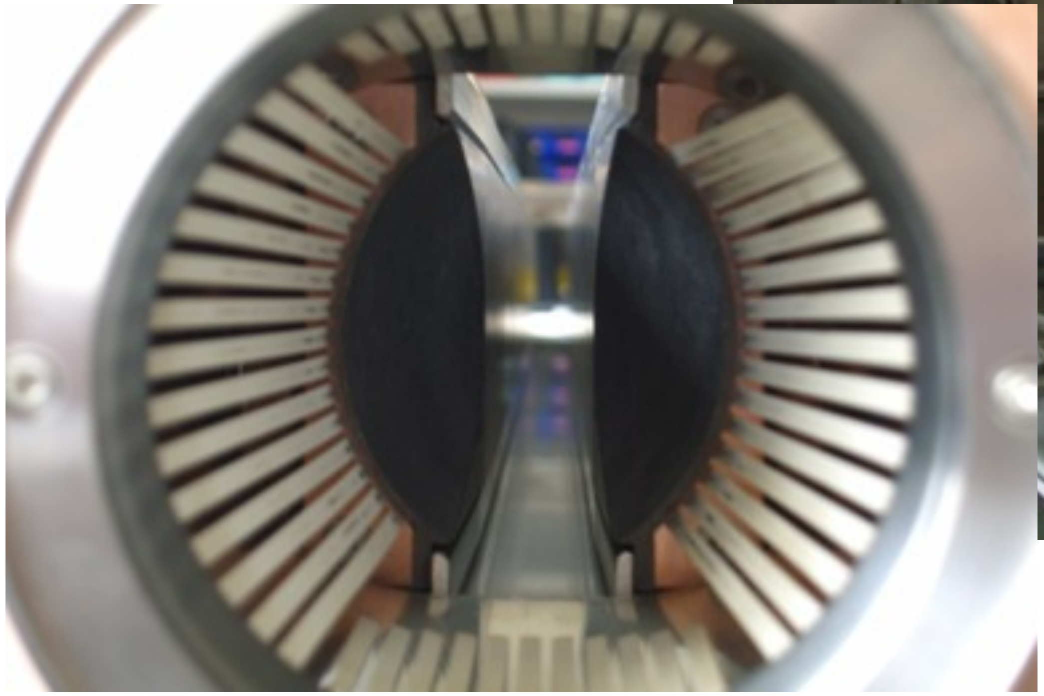
Special "sandwich" design to minimize the thermal deformations:
Steady (~5 kW) → < 30 μm
Transient (~30 kW) → ~ 110 μm
Materials: Graphite, Carbon fibre composites, Copper, Tungsten.



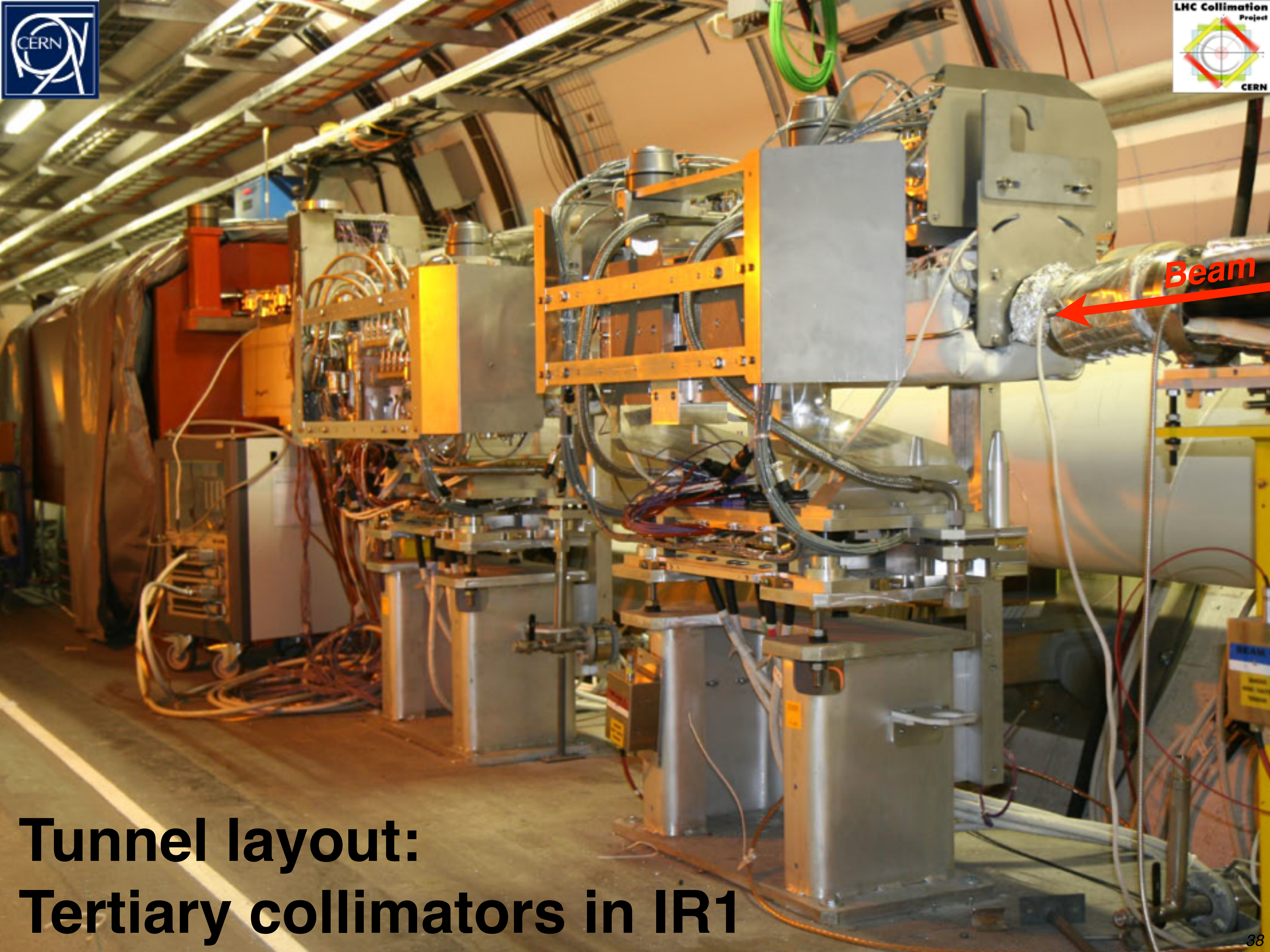
A look inside the vacuum tank



What the beam sees!



A. Bertarelli, A. Dallocchio



Tunnel layout: Tertiary collimators in IR1

Recap. of design challenges for 360MJ

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	cm	100
	TCP	cm	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**

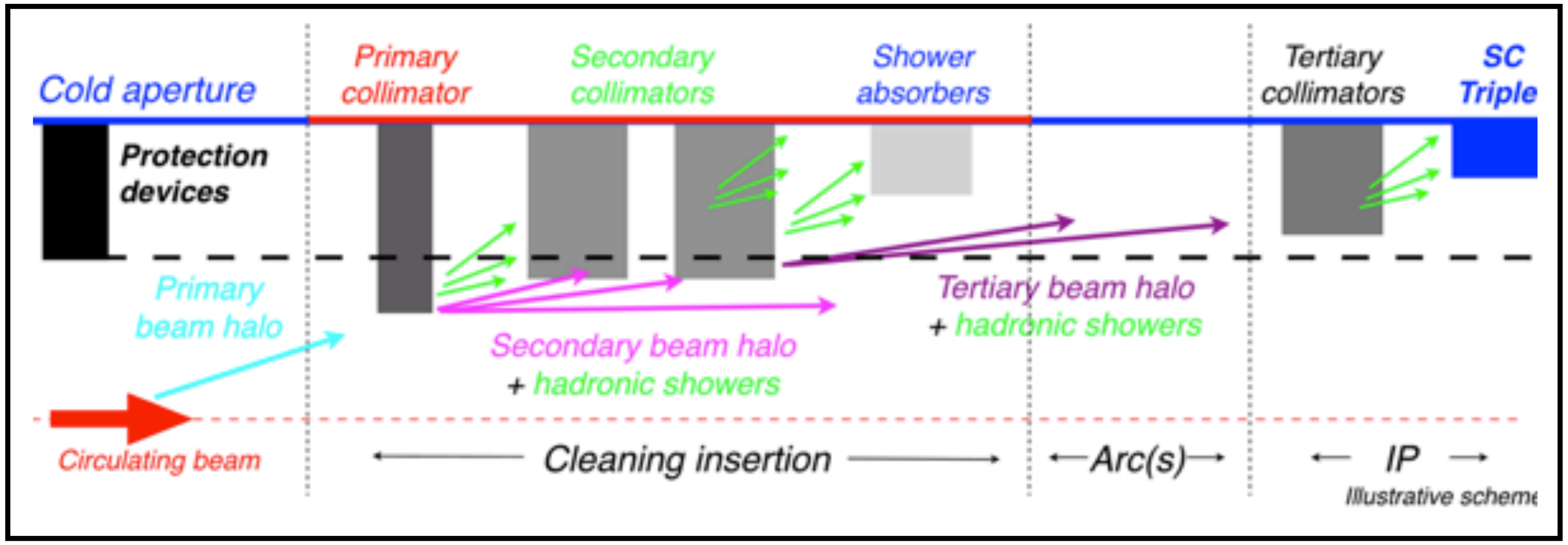
Heat load	kW	≤ 7
Jaw temperature	°C	≤ 50
Bake-out temp.	°C	250
Minimal gap	**mm**	**≤ 0.5**
Maximal gap	mm	≥ 58
Jaw position control	μm	≤ 10
Jaw angle control	μrad	≤ 15
Reproducibility	**μm**	**≤ 20**

R. Assmann et al. (2003)

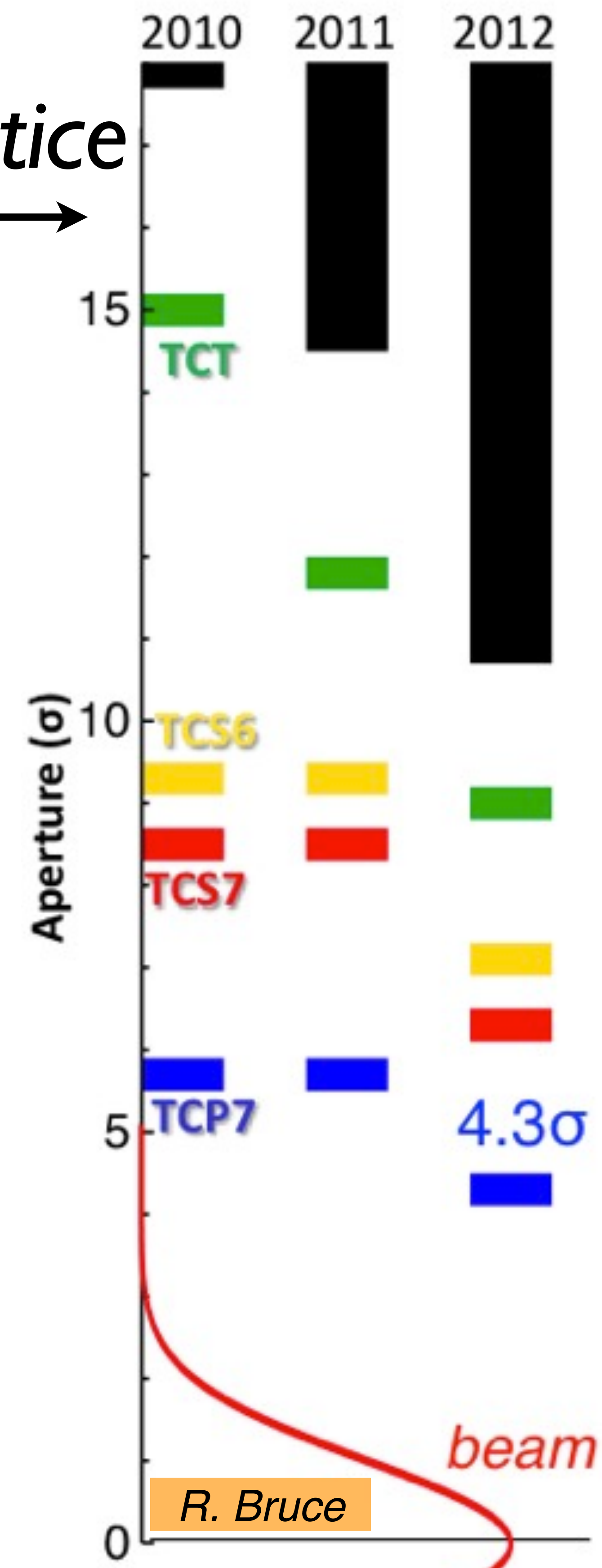
Outline

- ☑ Introduction
- ☑ Beam losses and collimation roles
- ☑ Single- and multi-stage cleaning
- ☑ LHC collimation layouts and design
- ☑ **Achieved cleaning performance**
- ☑ Conclusions

Configurations for LHC-run1 (2010-12)



In practice →

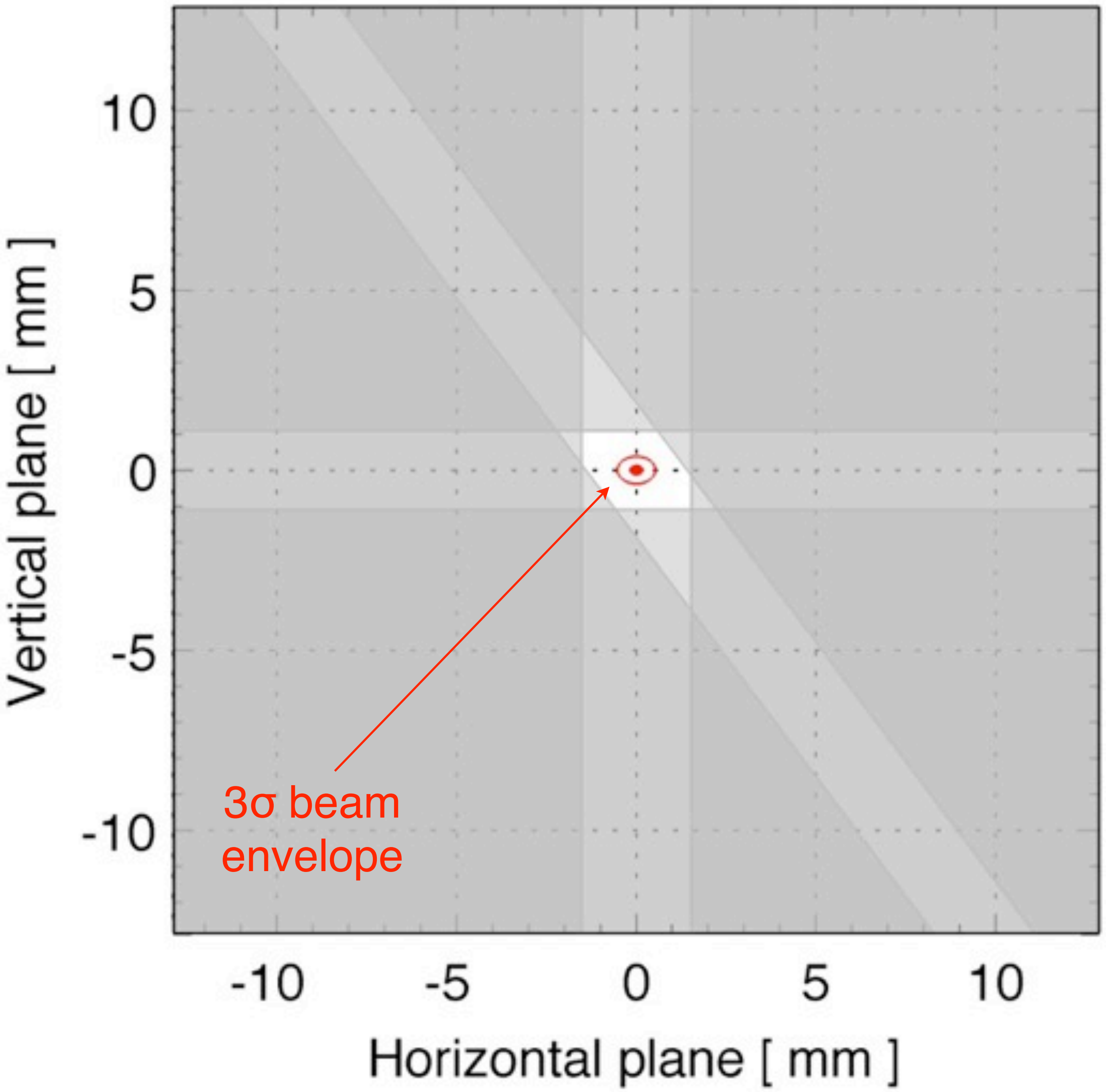


- Setting hierarchy was tightened while gaining operational experience and confidence in the machine (optics/orbit stability, lifetime measurements, cleaning requirements, ...)
- Started with "relaxed" settings (easier commissioning, less challenging tolerance), then achieved "tight" settings at 4 TeV 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

Smallest collimator gaps in 2012

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



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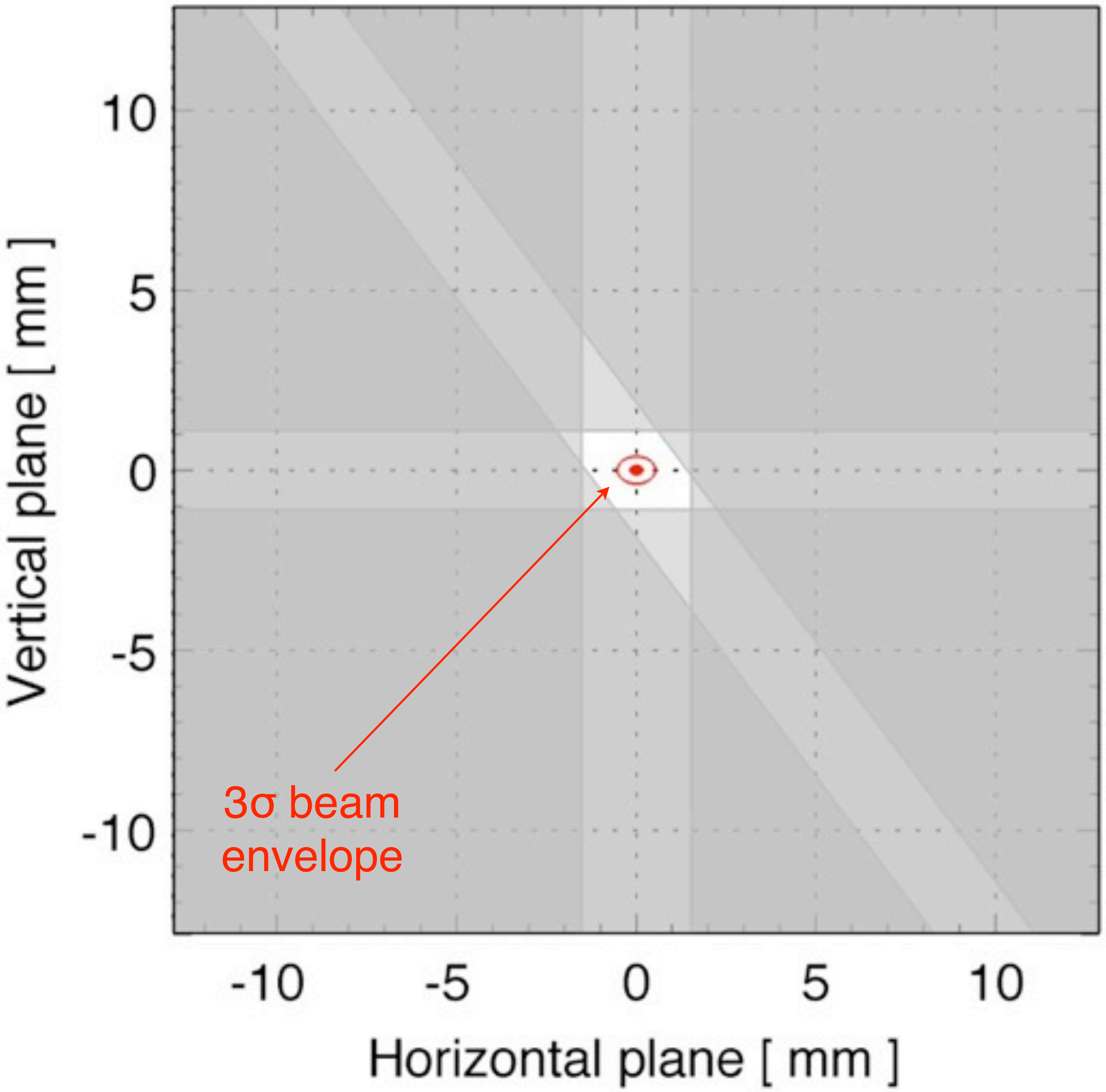
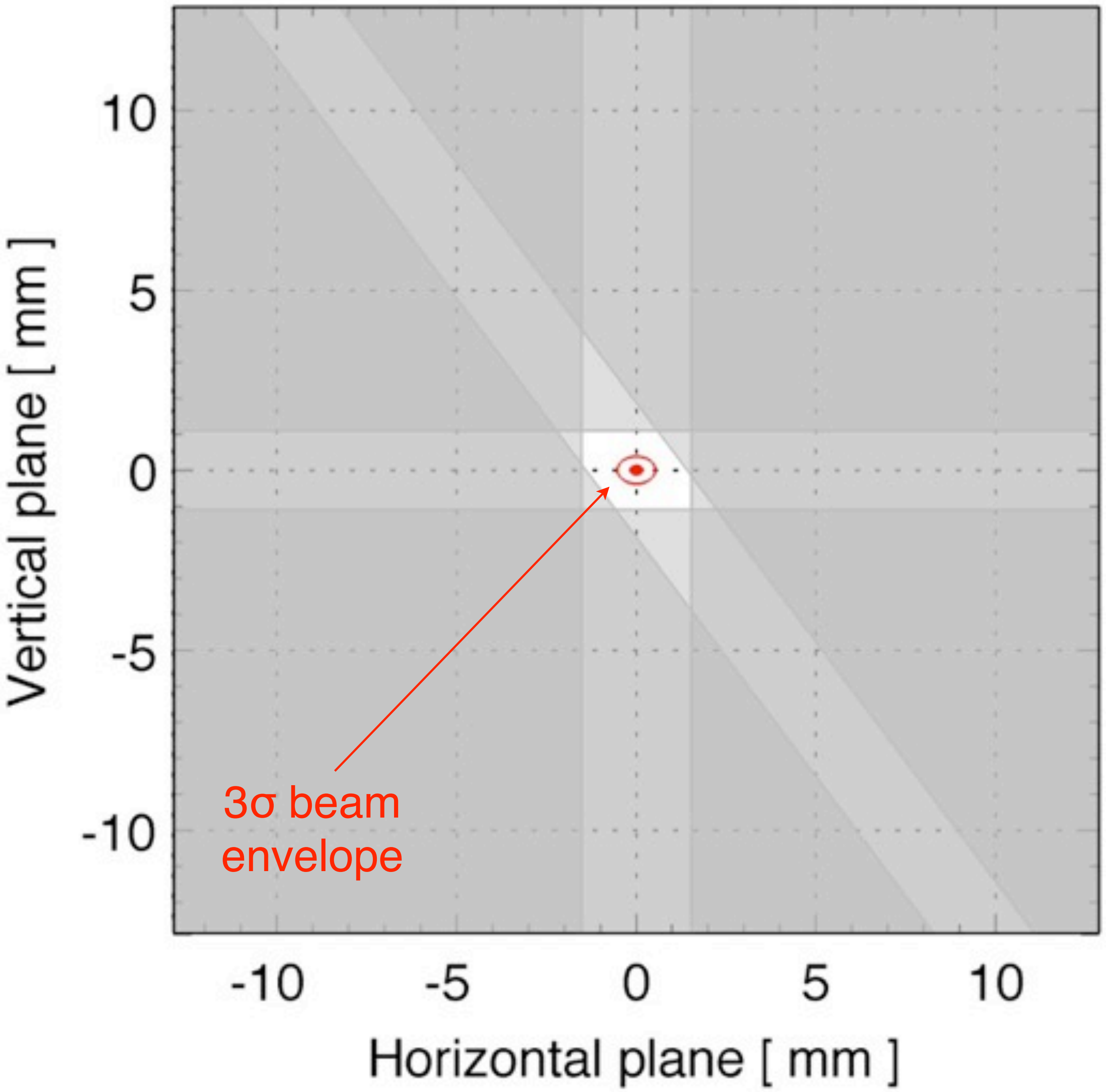


2€ coin

Smallest collimator gaps in 2012

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



2€ coin

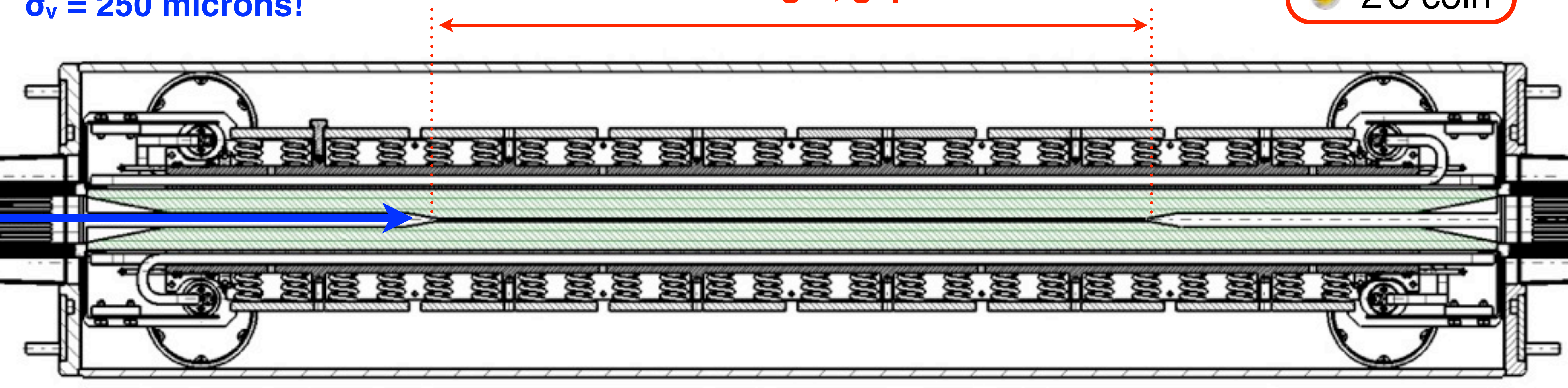
A beam carrying up to 150MJ passes more than 11000 per second in such small collimator gaps!

Side view of the vertical TCP

Beam: RMS beam size
σ_v = 250 microns!

60 cm flat active length, gap = ± 1.05 mm

2€ coin



L. Gentini

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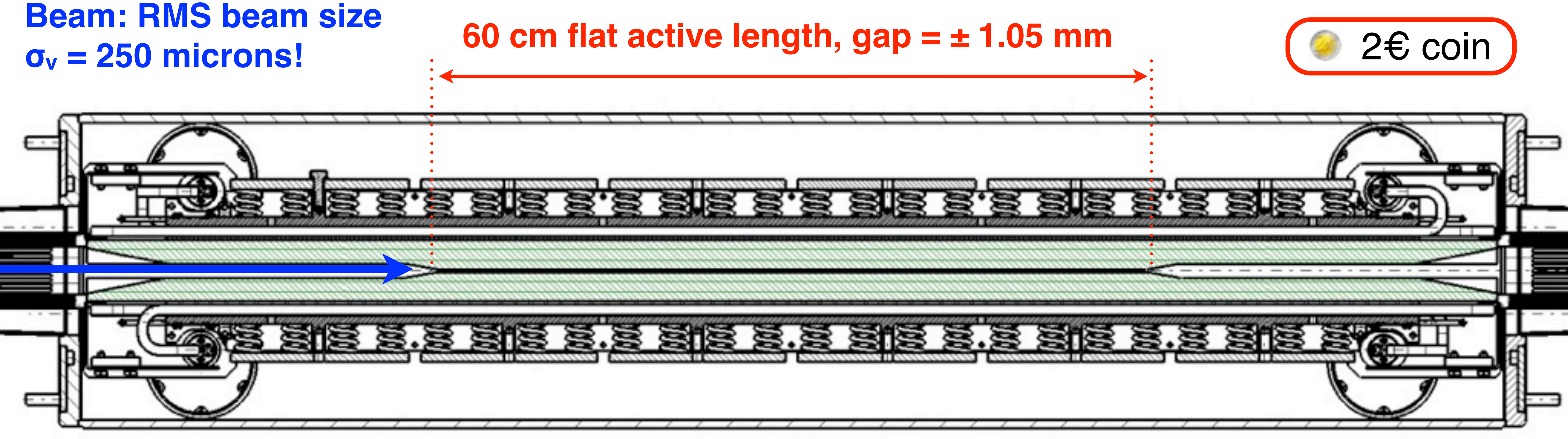
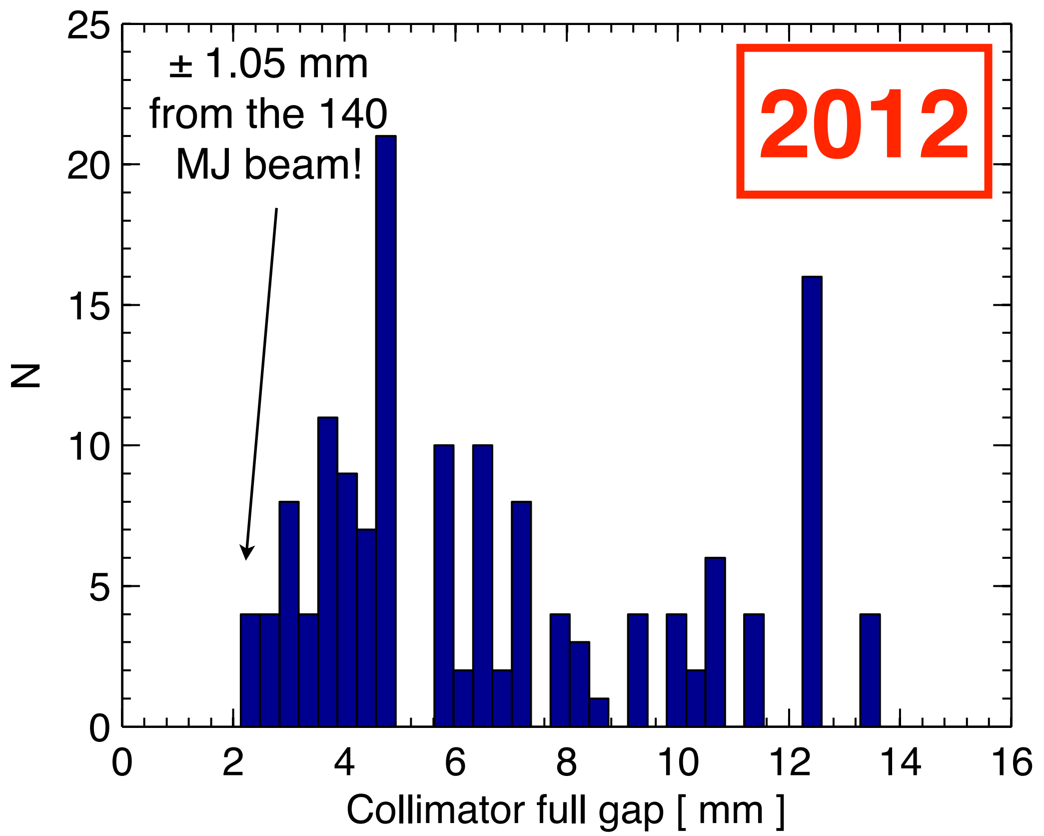


L. Gentini

Distribution of collimator gaps in 2012



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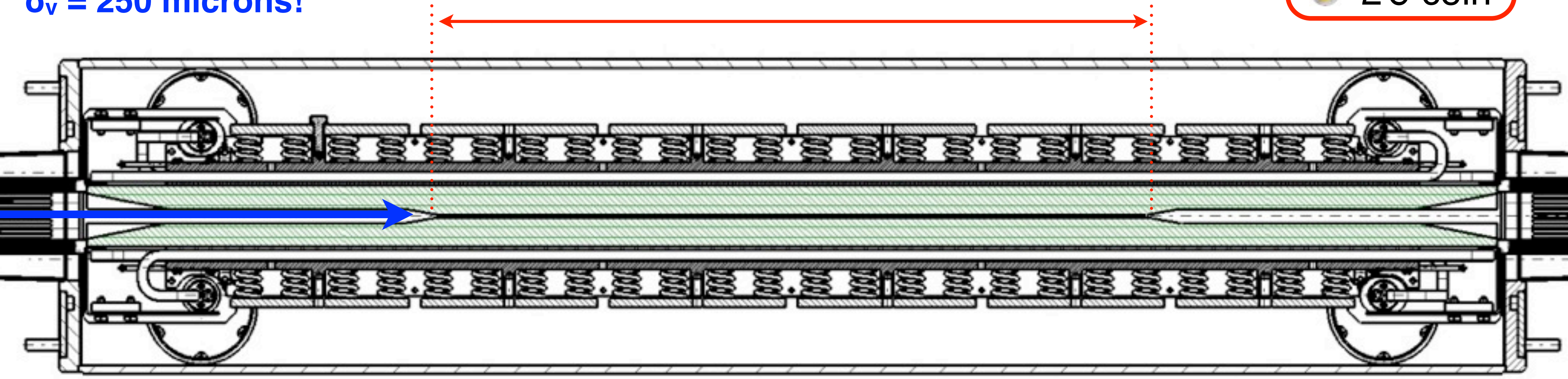

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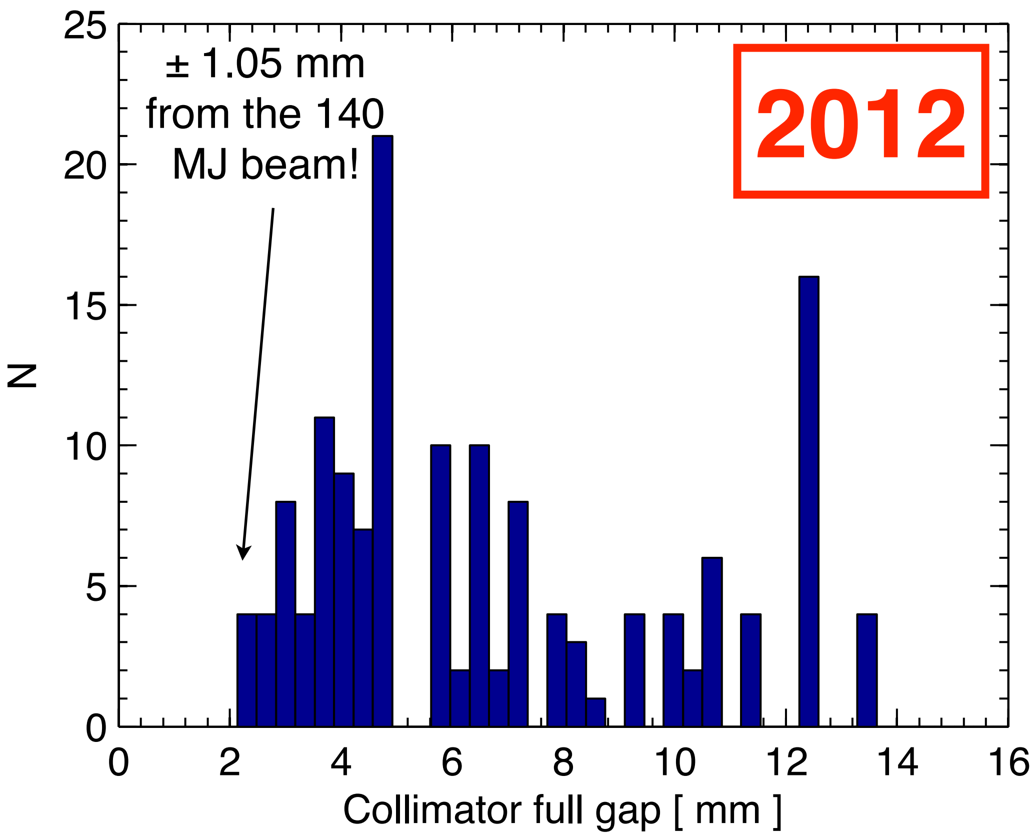

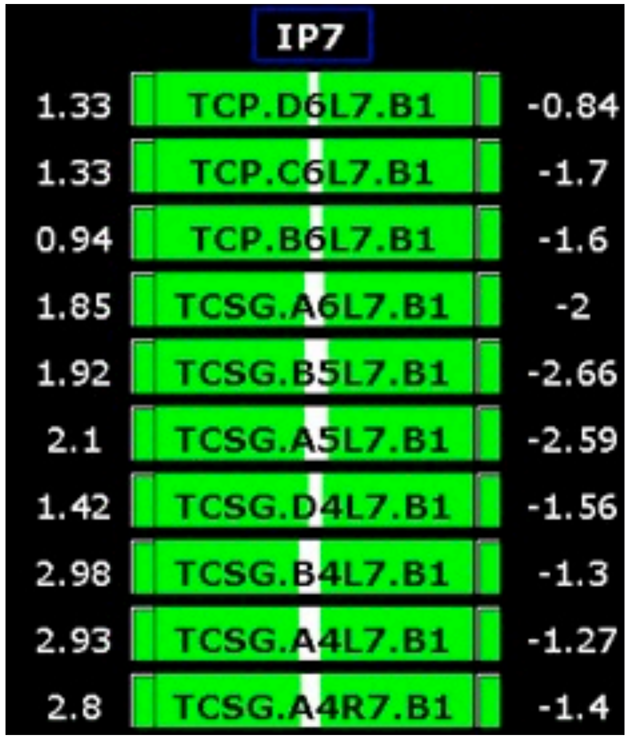

	IP7	
1.33	TCP.D6L7.B1	-0.84
1.33	TCP.C6L7.B1	-1.7
0.94	TCP.B6L7.B1	-1.6
1.85	TCSG.A6L7.B1	-2
1.92	TCSG.B5L7.B1	-2.66
2.1	TCSG.A5L7.B1	-2.59
1.42	TCSG.D4L7.B1	-1.56
2.98	TCSG.B4L7.B1	-1.3
2.93	TCSG.A4L7.B1	-1.27
2.8	TCSG.A4R7.B1	-1.4

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

Side view of the vertical TCP

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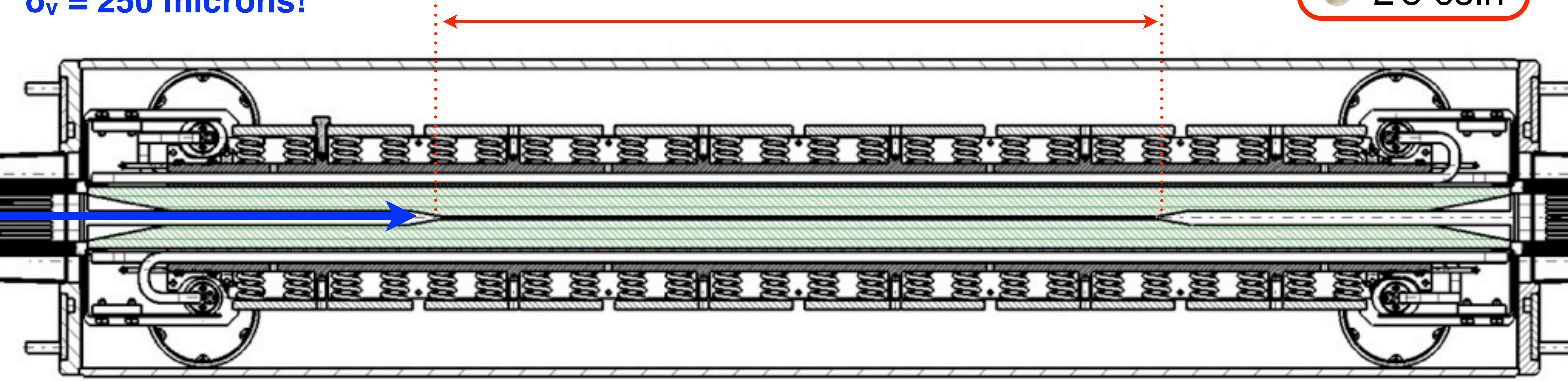
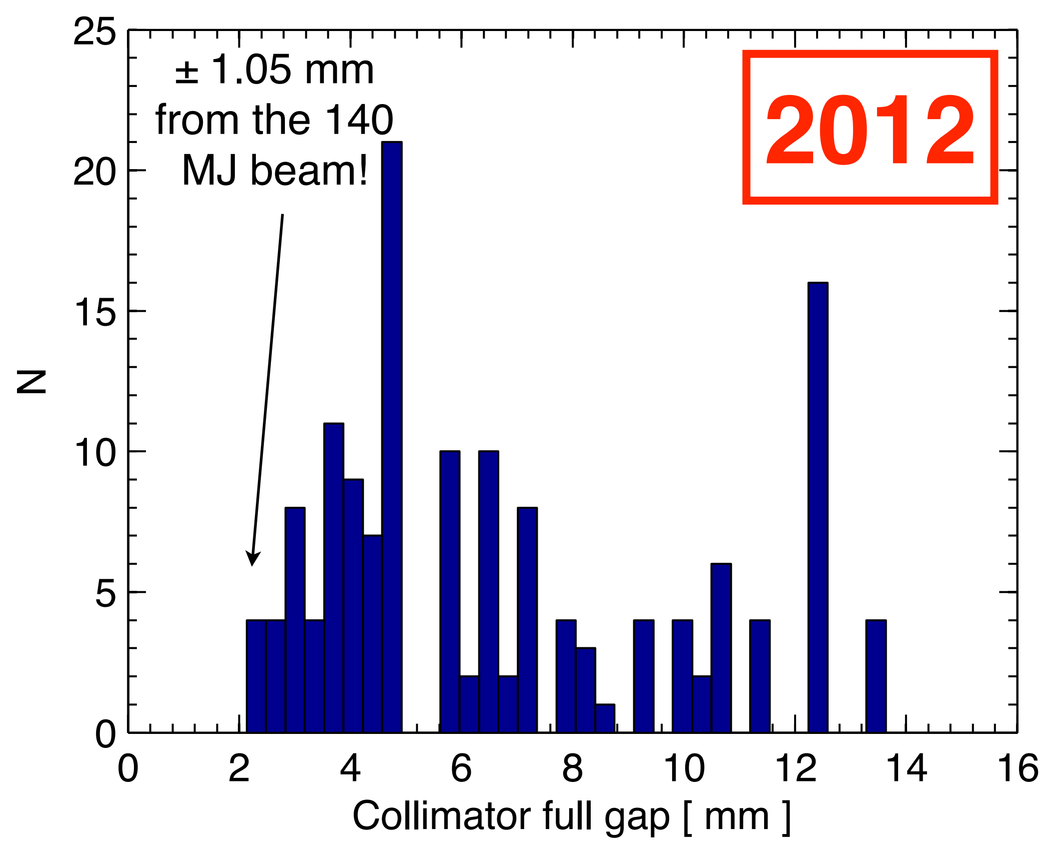
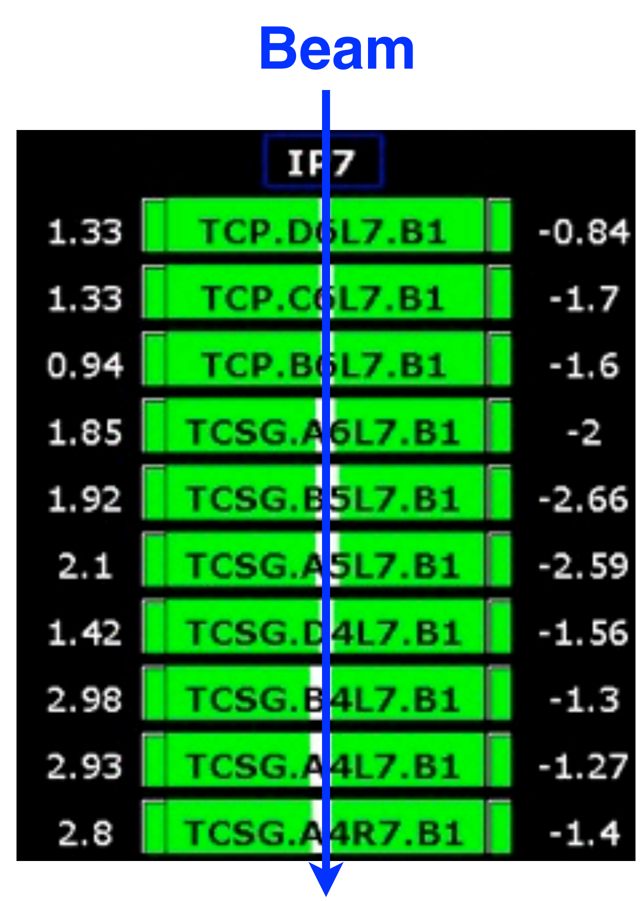


L. Gentini

Distribution of collimator gaps in 2012





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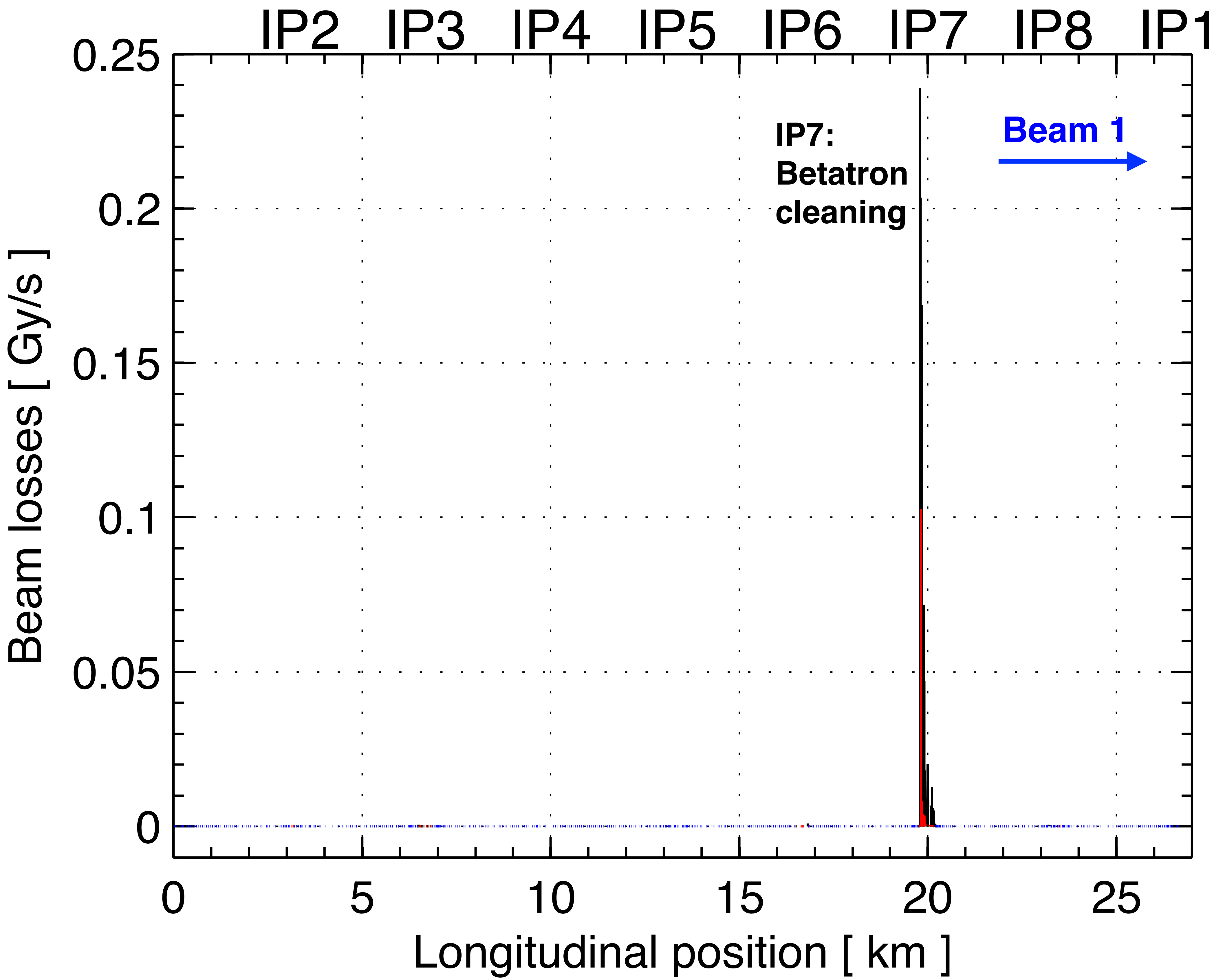
Collimation cleaning

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



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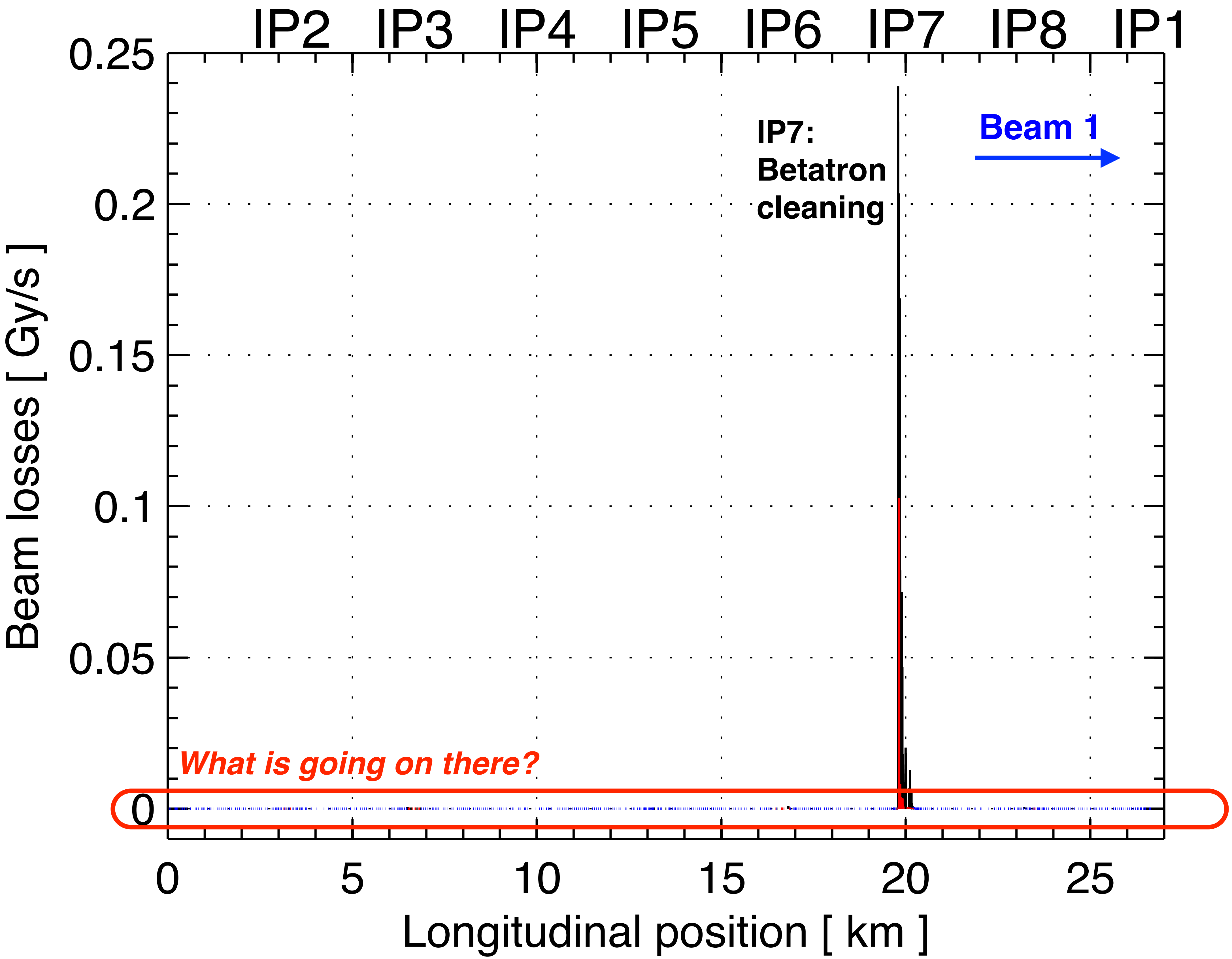
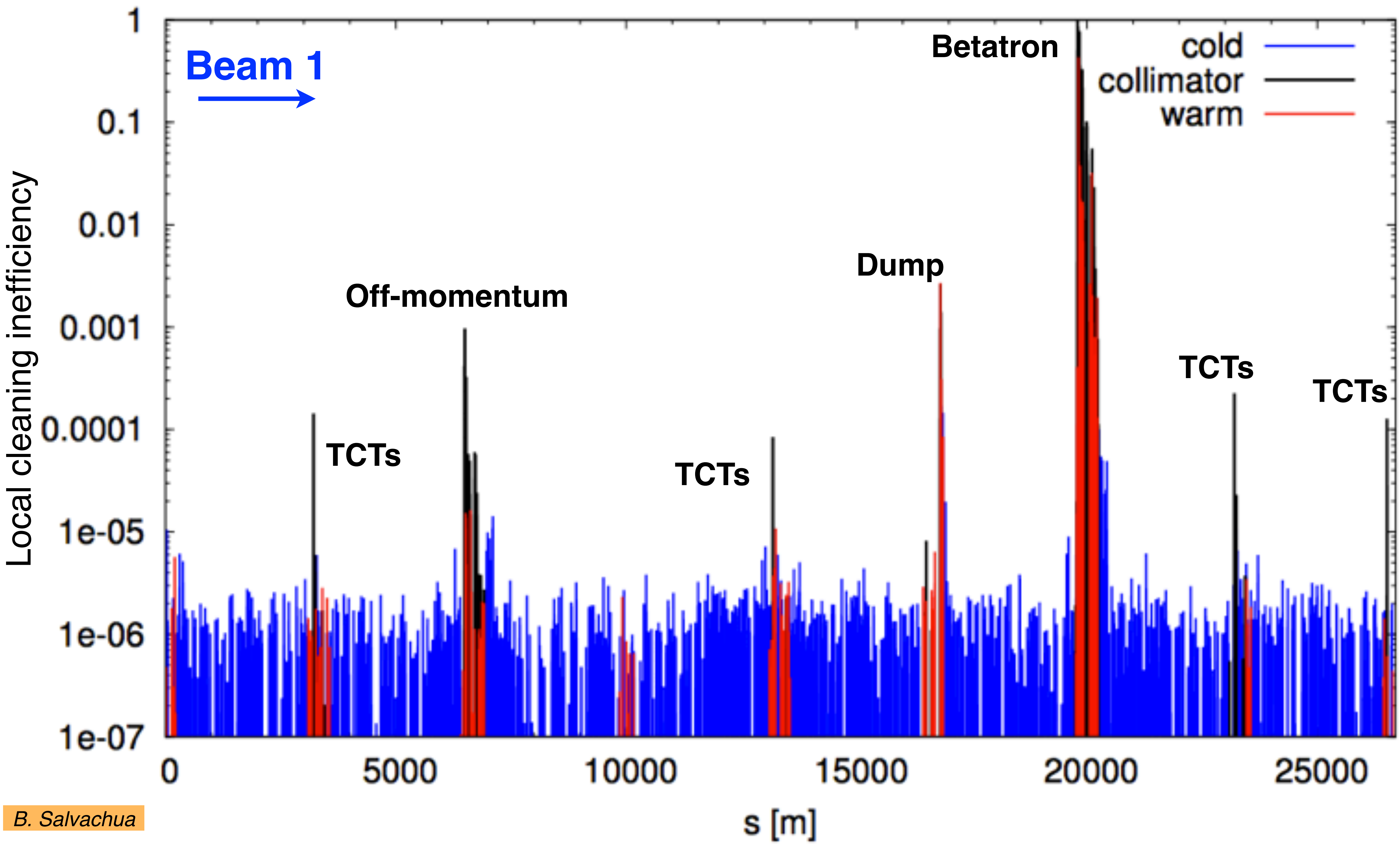
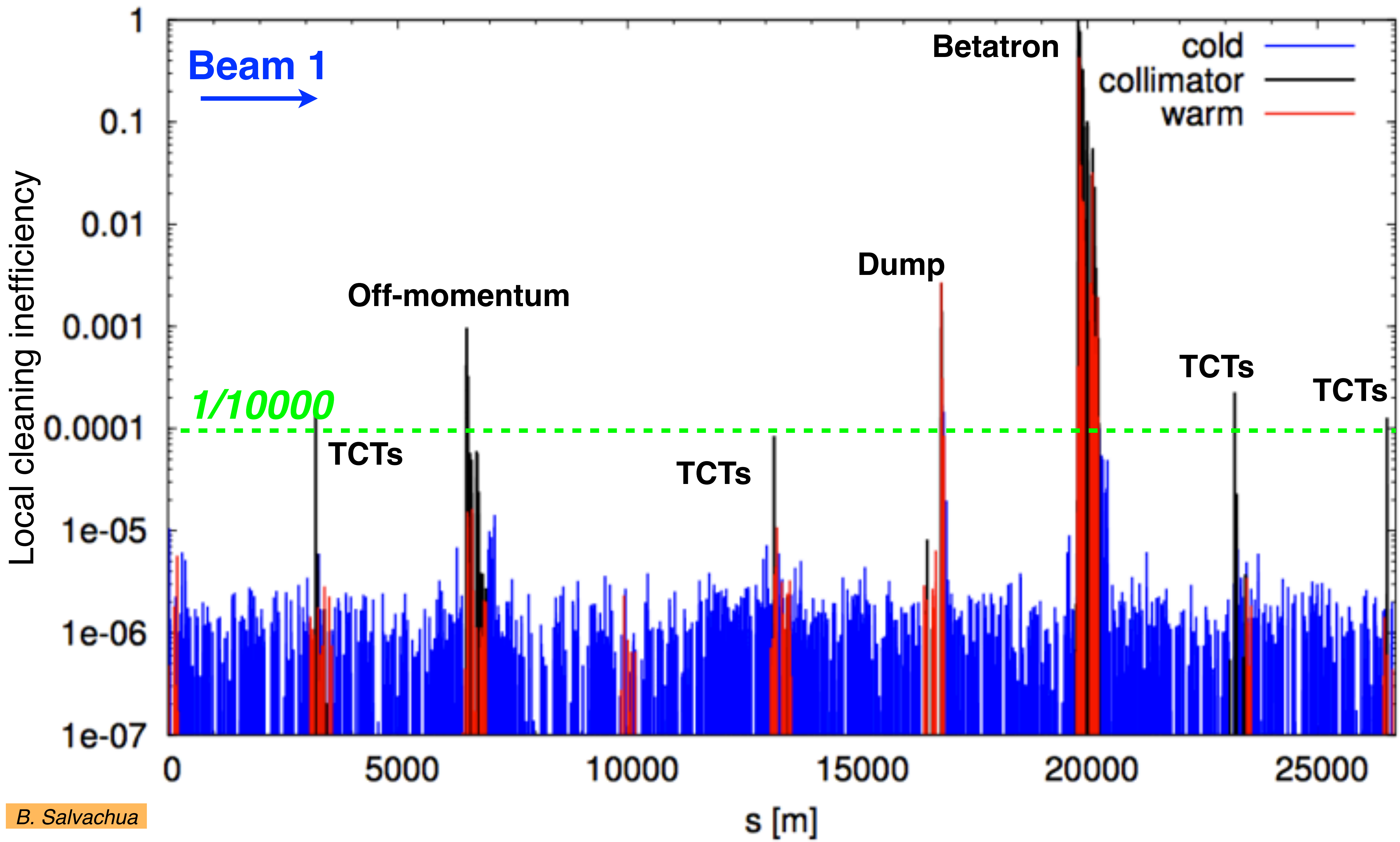


Collimation cleaning: 4.0 TeV, β^*=0.6 m



B. Salvachua

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



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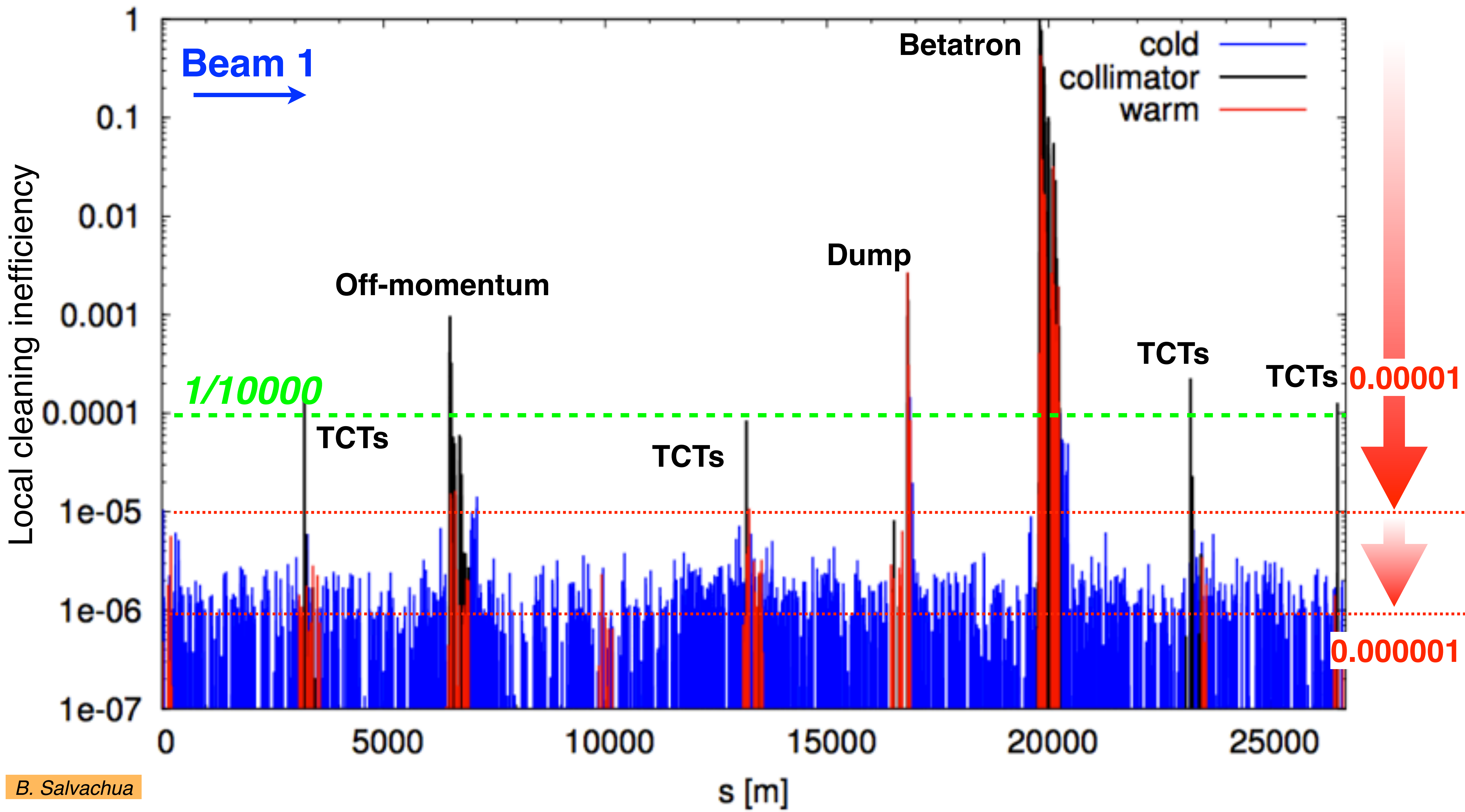

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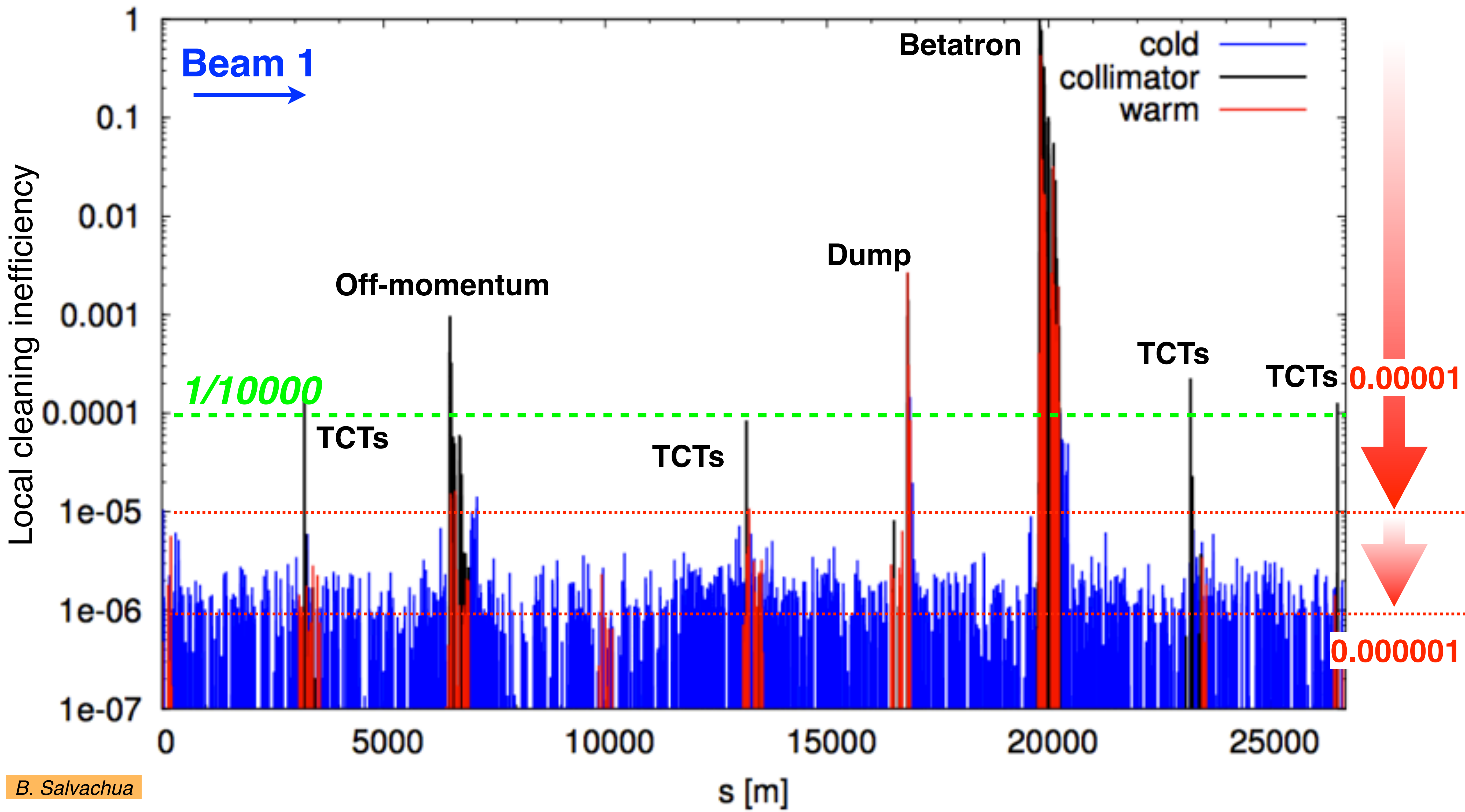
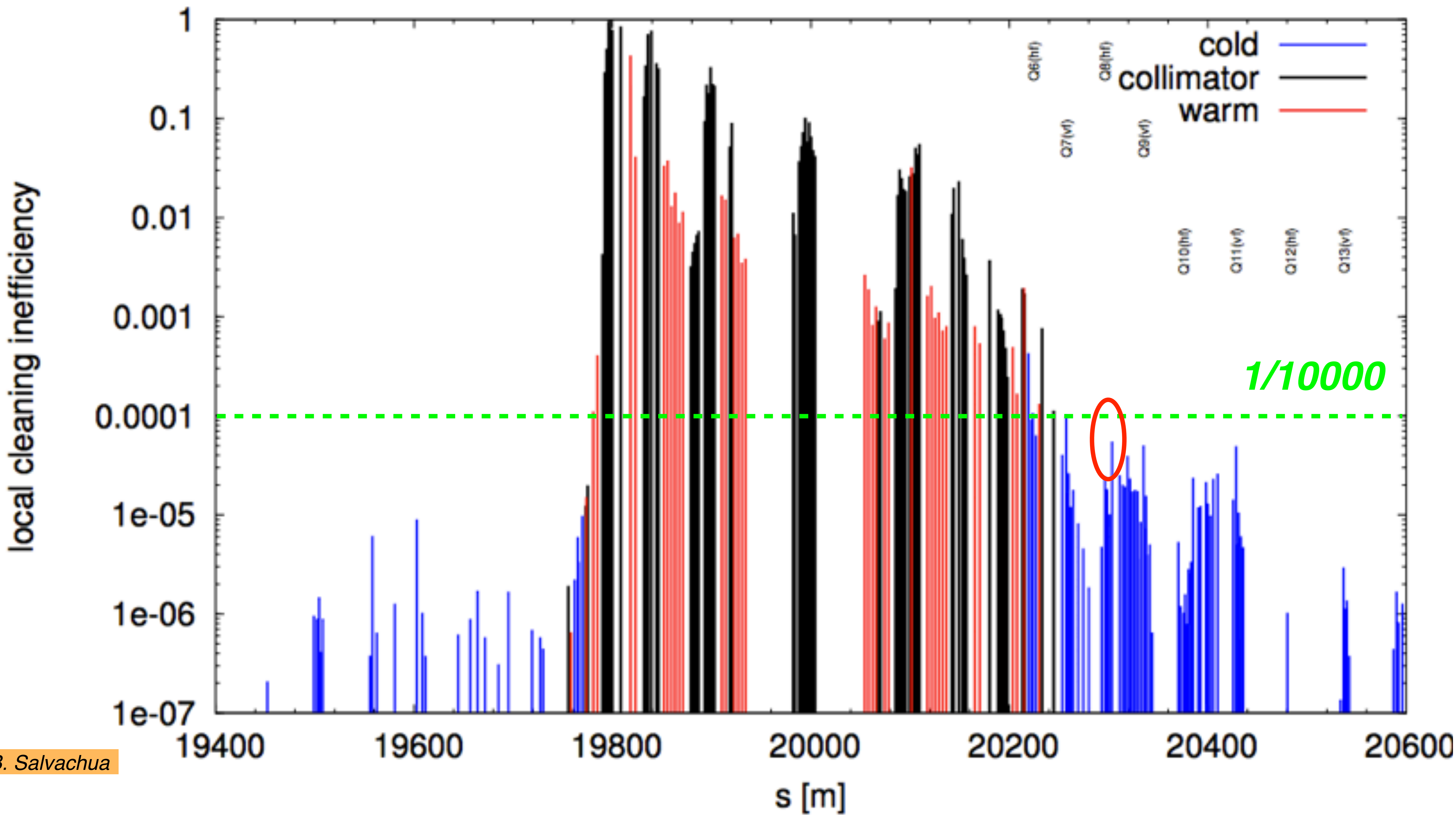


B. Salvachua

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

Zoom in IR7

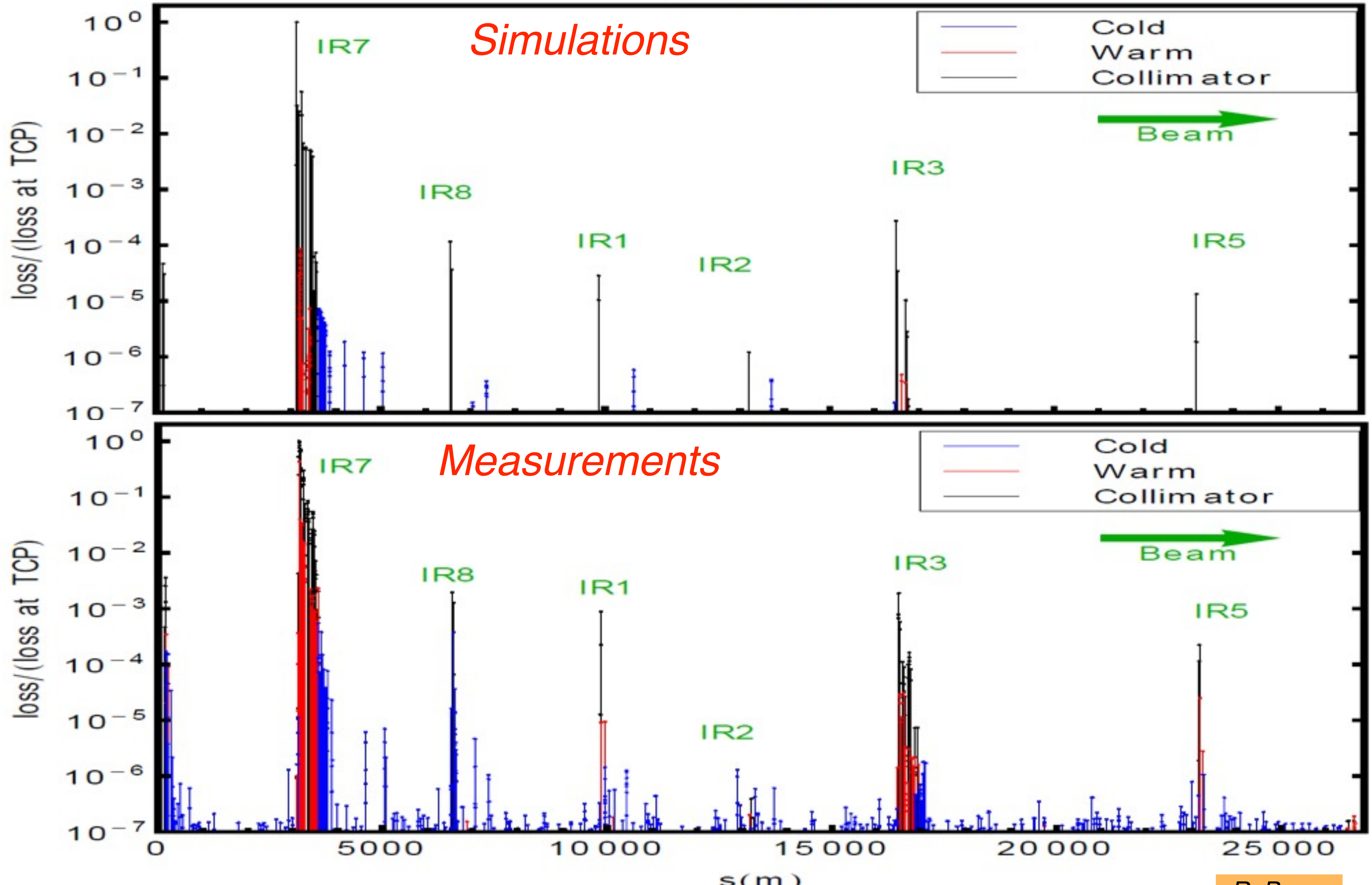


B. Salvachua

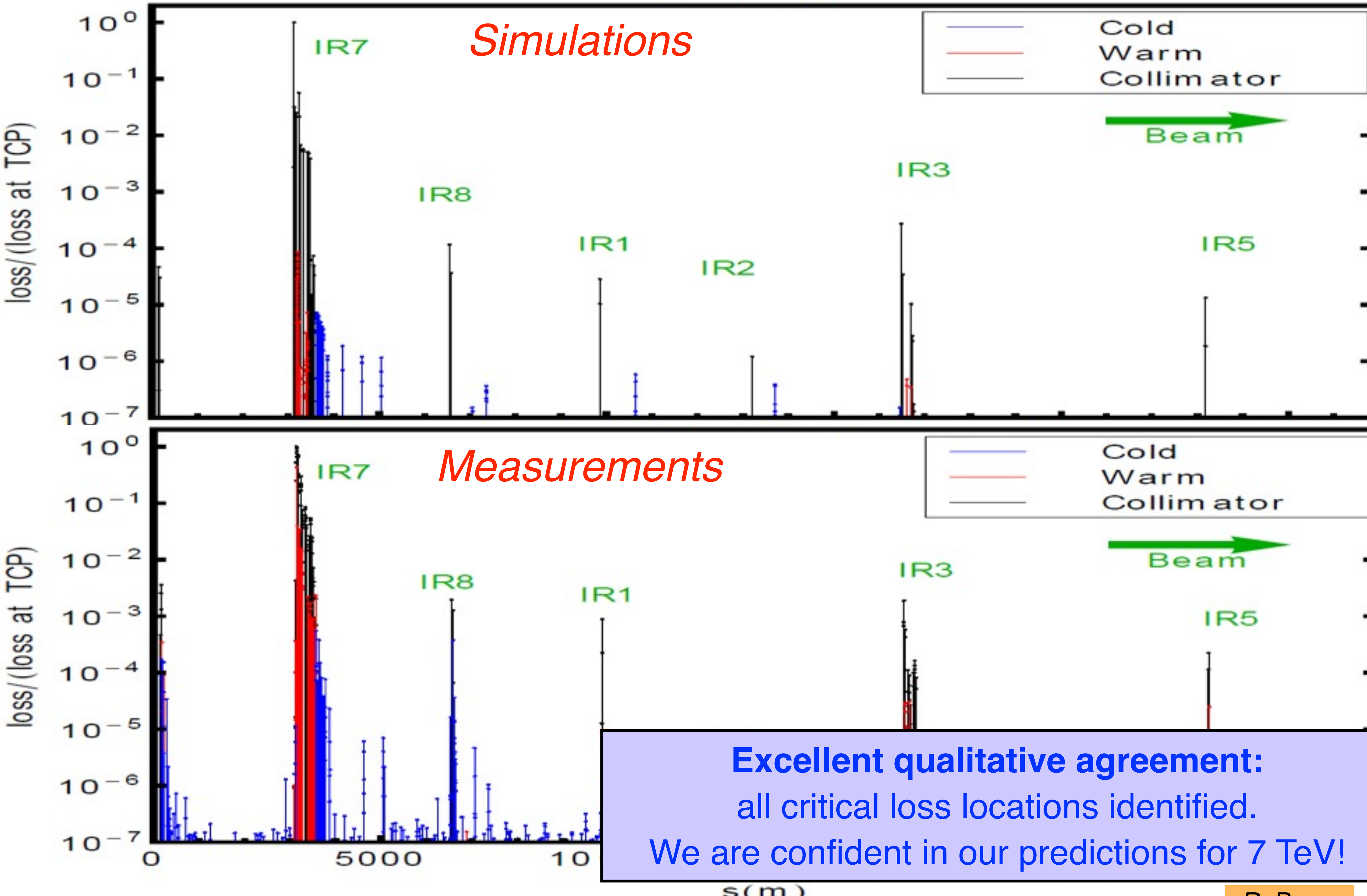
<u>Critical location</u> (both beams): losses in the "dispersion suppressor".

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

Comparison with measurements



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...