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Collimation Systems
Part 1

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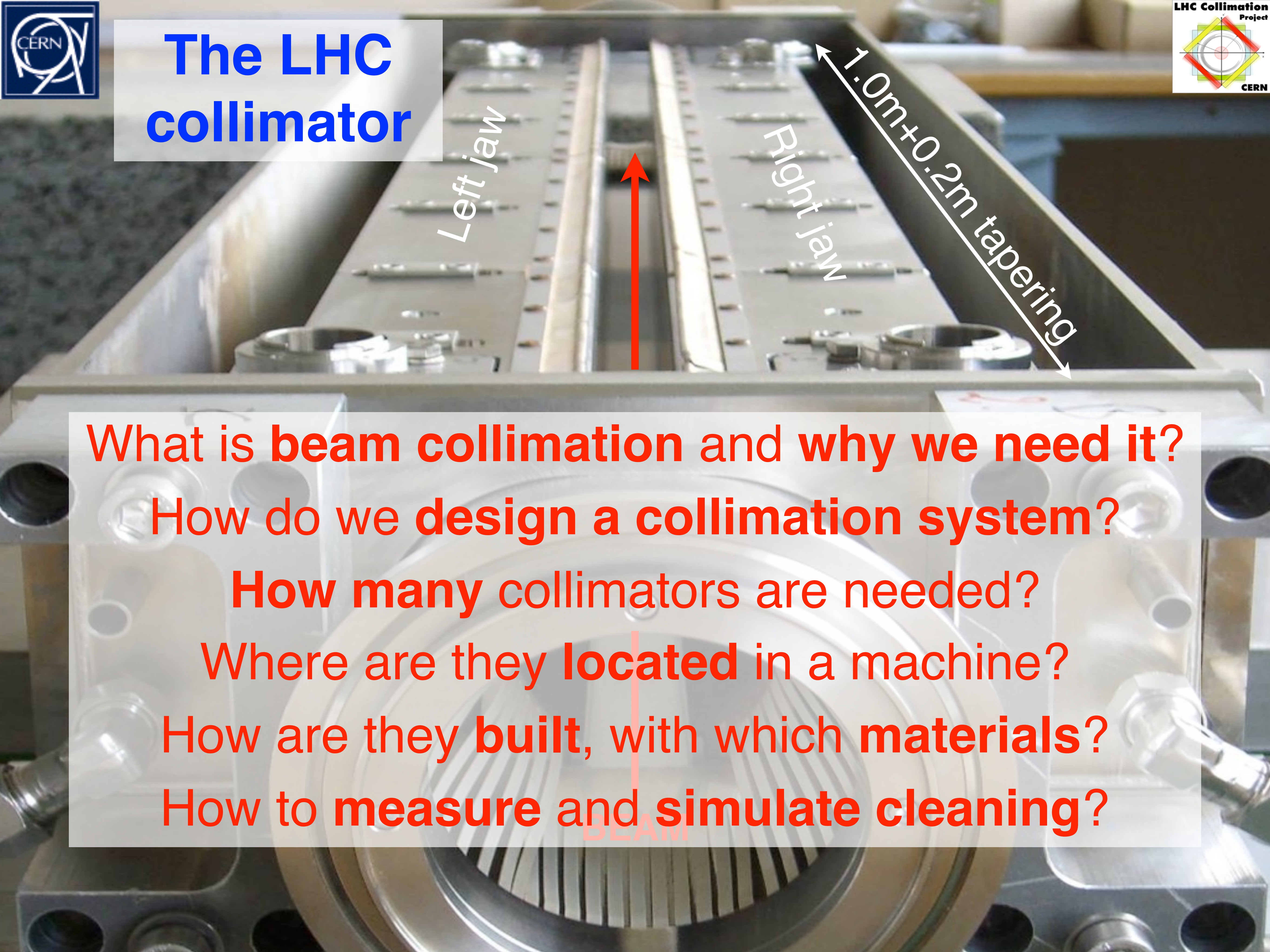
The LHC collimator



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 a machine?

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

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

Outline

- ☑ **Introduction**
- ☑ **Beam losses and collimation**
- ☑ **Multi-stage collimation**

Part 1

....

Part 2

- ☑ **LHC collimation design**
- ☑ **Beam cleaning performance**
- ☑ **Collimation simulations**

High-intensity circular hadron accelerators

Outline - Part 1/2

- ☑ Introduction
- ☑ Basic definitions and context
- ☑ Stored energy challenge
- ☑ Beam losses and collimation
- ☑ Design of a multi-stage collimation

Betatron and momentum

Beam collimation and halos

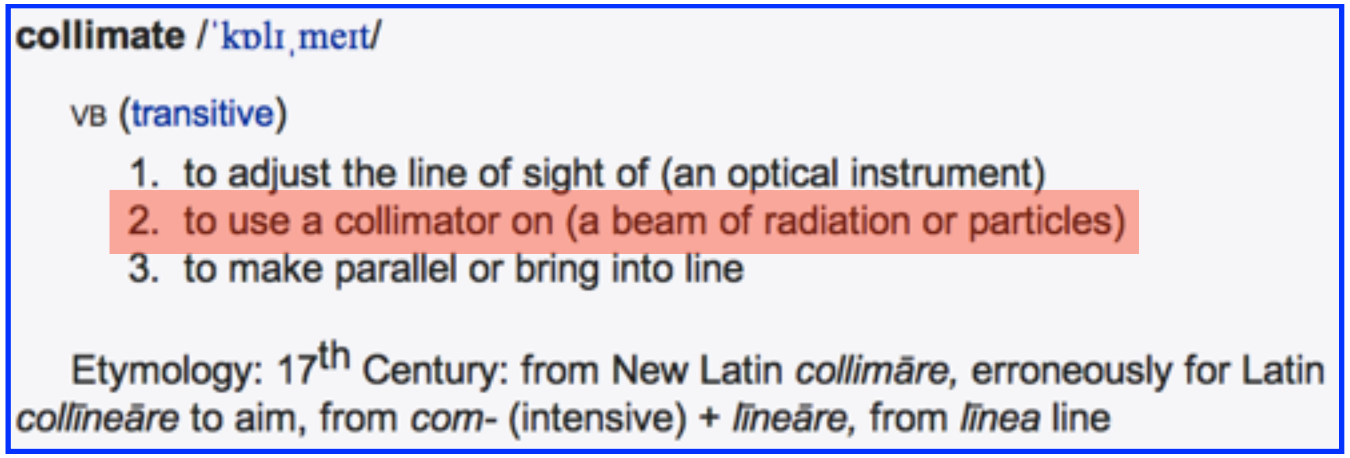
Beam collimation

Controlled and safe disposal of beam halo particles produced by unavoidable beam losses.
Achieved by limiting 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. "Negative" hidden meaning, nuance.
Colliders, Gaussian beams ↦ halo particles above 3 RMS beam sizes.

Collimation systems dispose of halo particles that can perturb the machine operation.

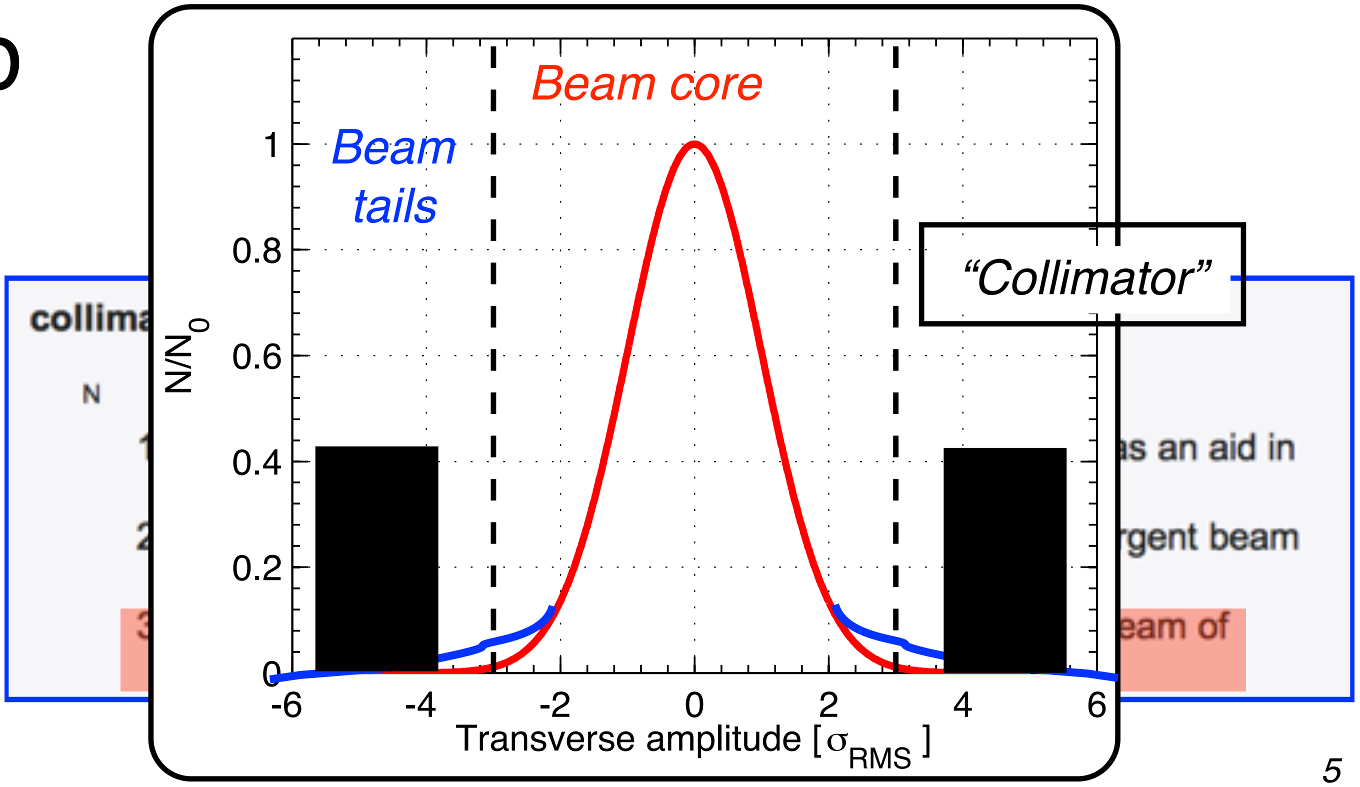


collimate /ˈkɒlɪˌmeɪt/

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 and halos

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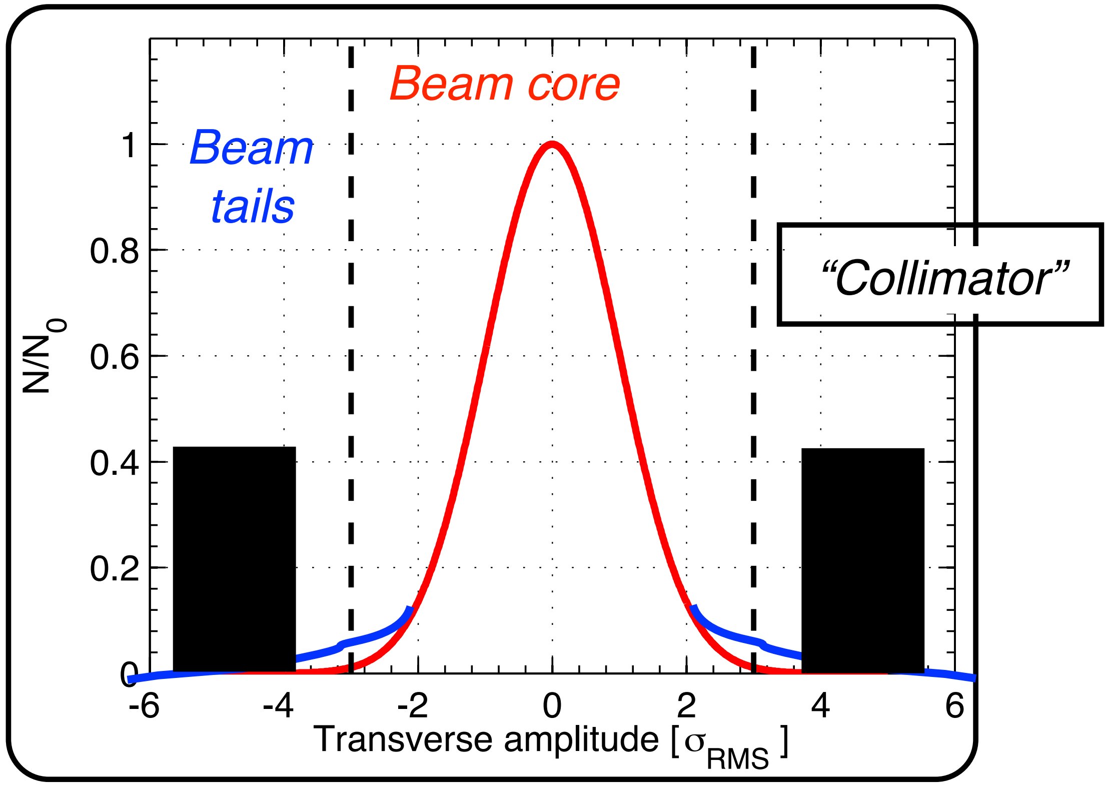
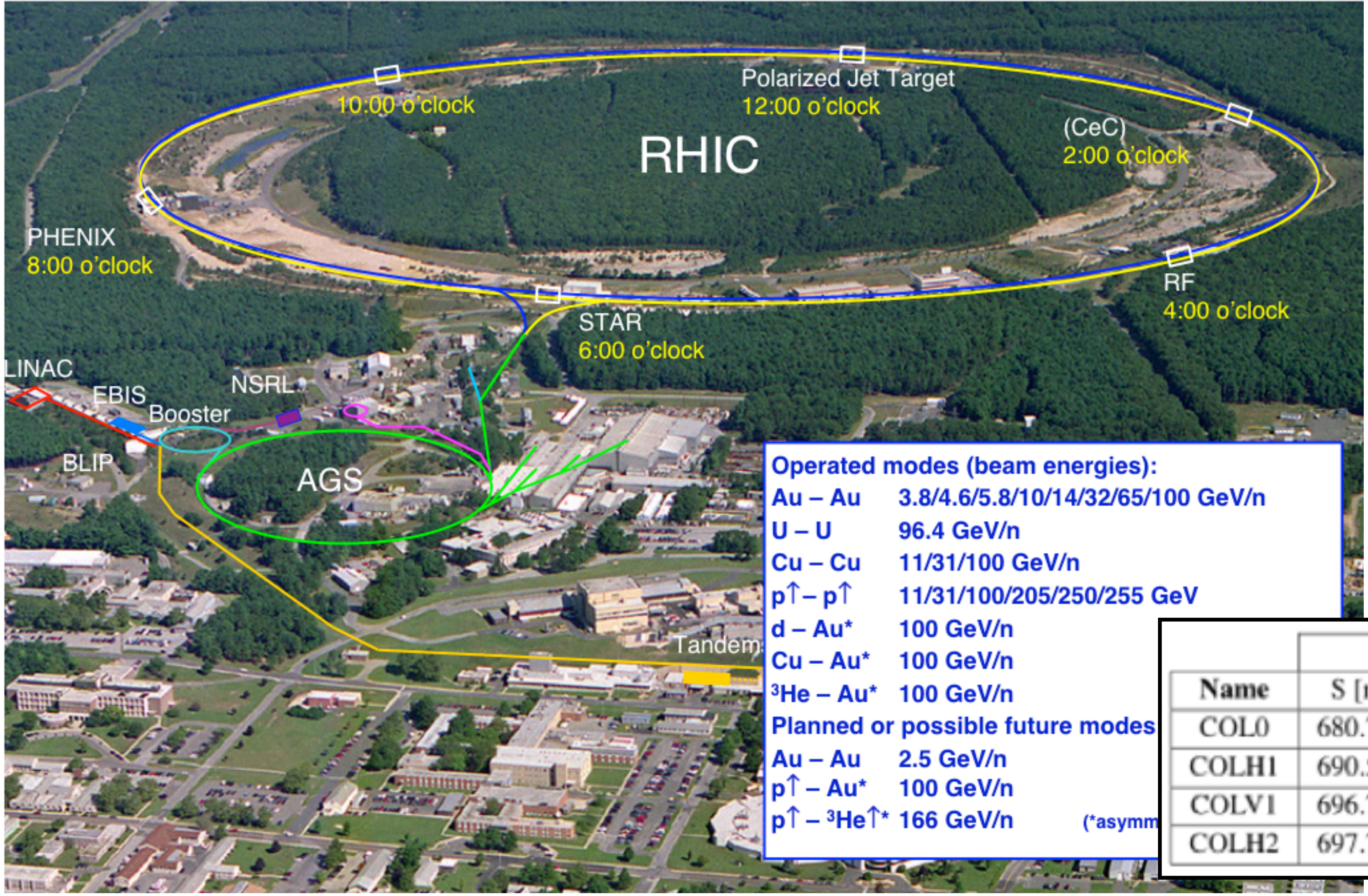


Modern accelerators —“super-colliders” — cannot work without adequate collimation systems…

Some examples…

RHIC collimation system



Operated modes (beam energies):

Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
U – U	96.4 GeV/n
Cu – Cu	11/31/100 GeV/n
p↑ – p↑	11/31/100/205/250/255 GeV
d – Au*	100 GeV/n
Cu – Au*	100 GeV/n
^{3}He – Au*	100 GeV/n

Planned or possible future modes

Au – Au	2.5 GeV/n
p↑ – Au*	100 GeV/n
p↑ – ^{3}He↑*	166 GeV/n

(*asymm

Relativistic Heavy Ion Collider: Parameters [p]:

E_b = 255 GeV

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

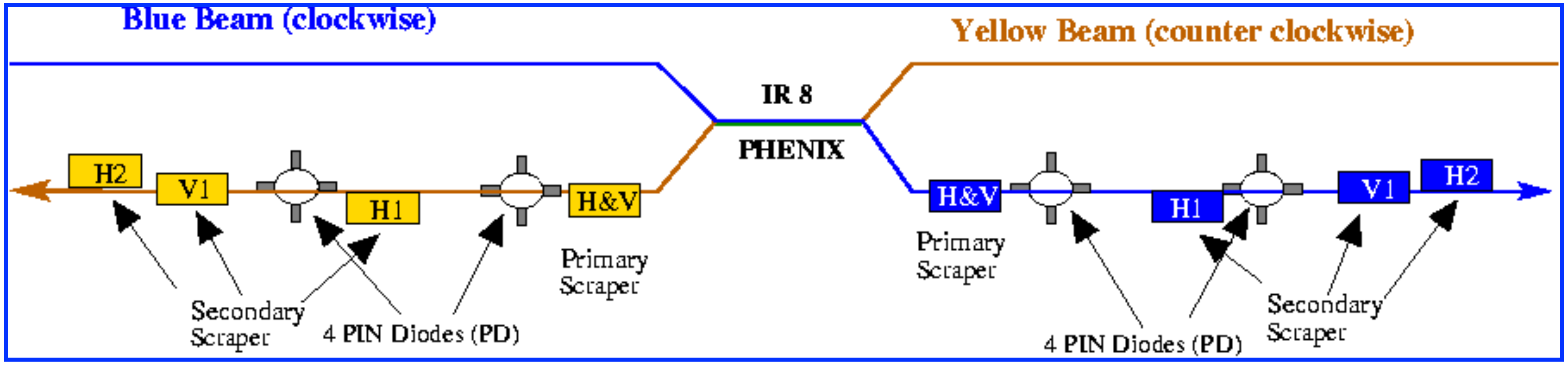
E_{stored} = ~ 440 kJ

Collimation system:

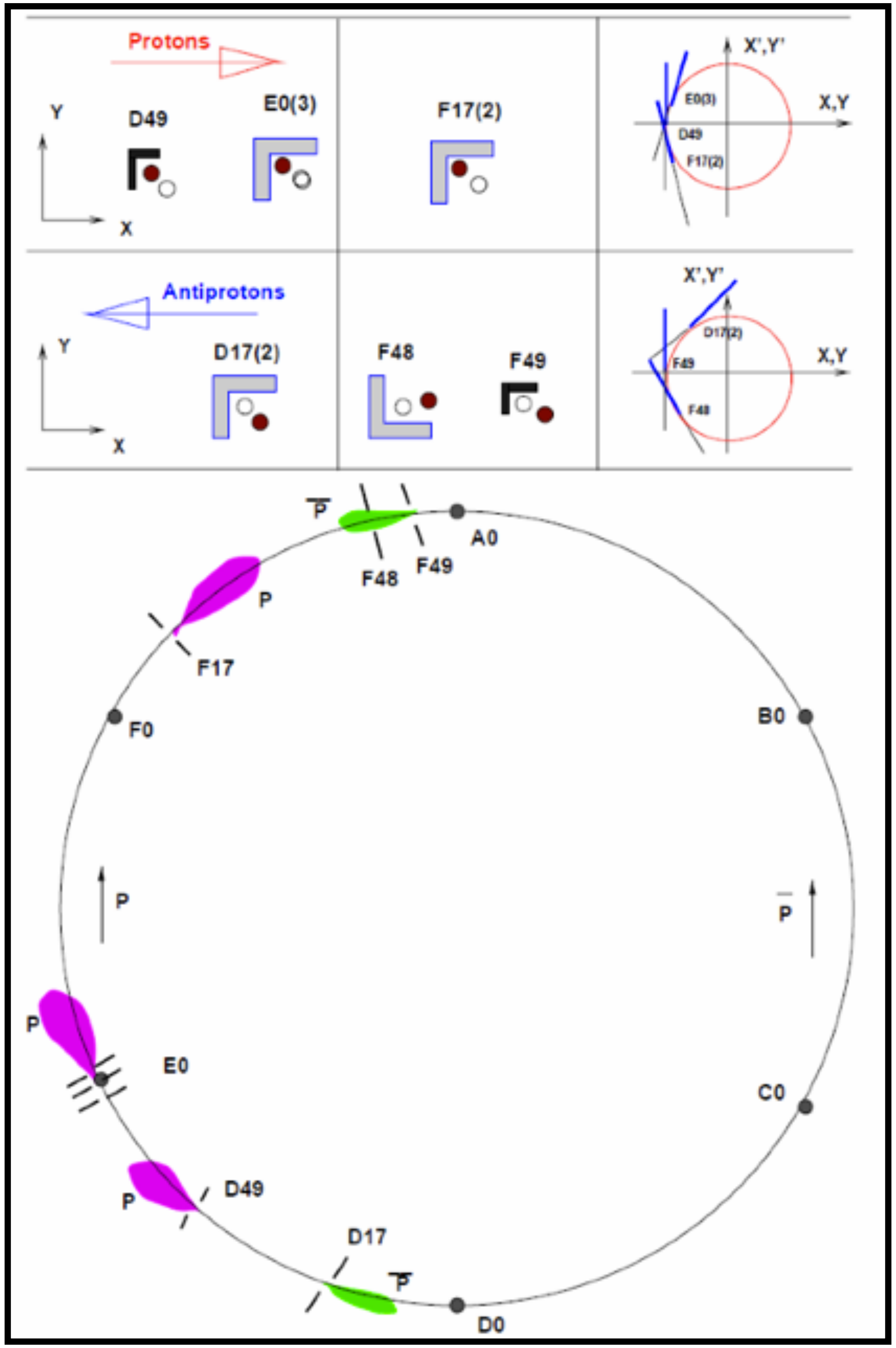
8 collimators

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

Large Hadron Collider — layout

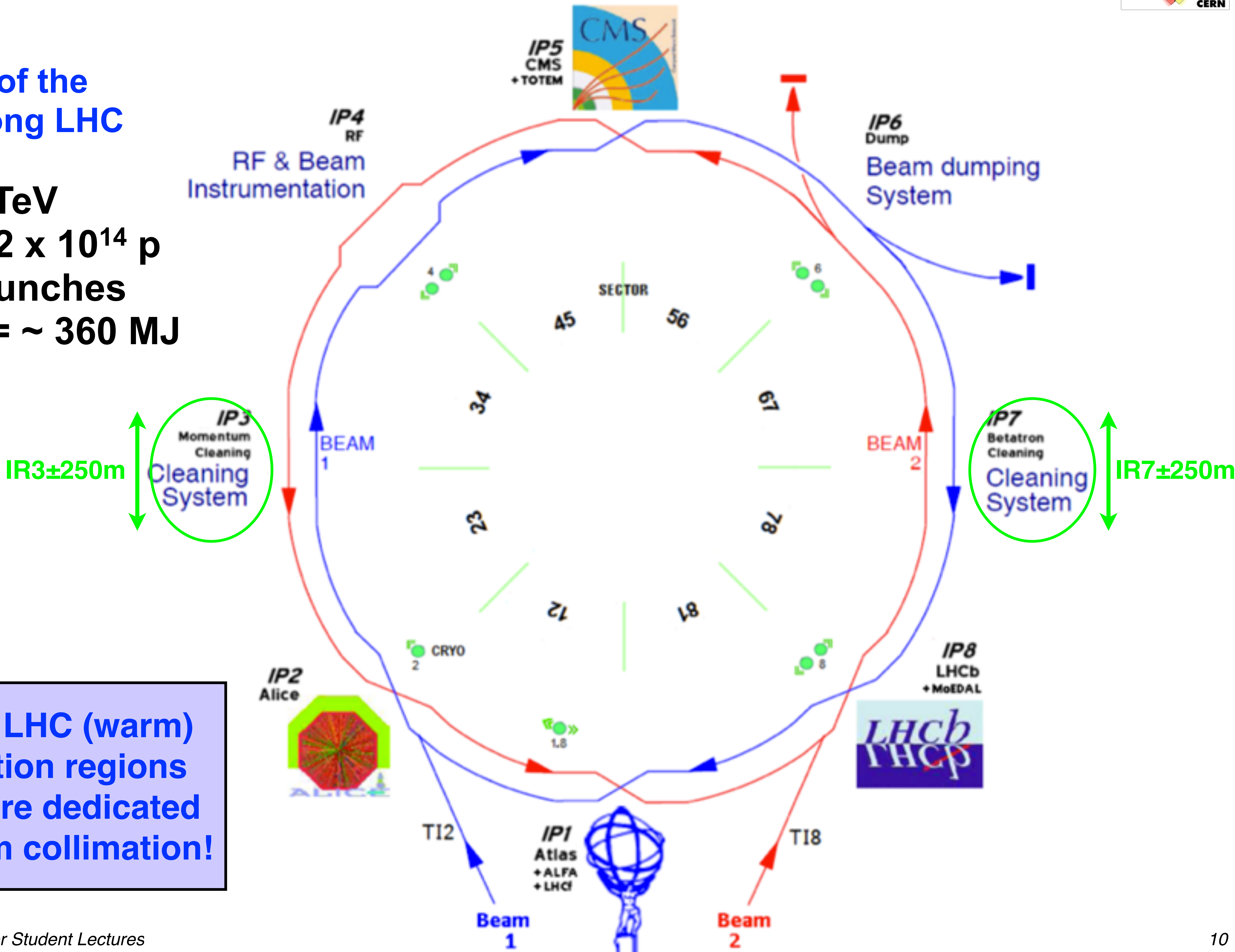
Layout of the 27km-long LHC ring

E_b = 7 TeV

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

2808 bunches

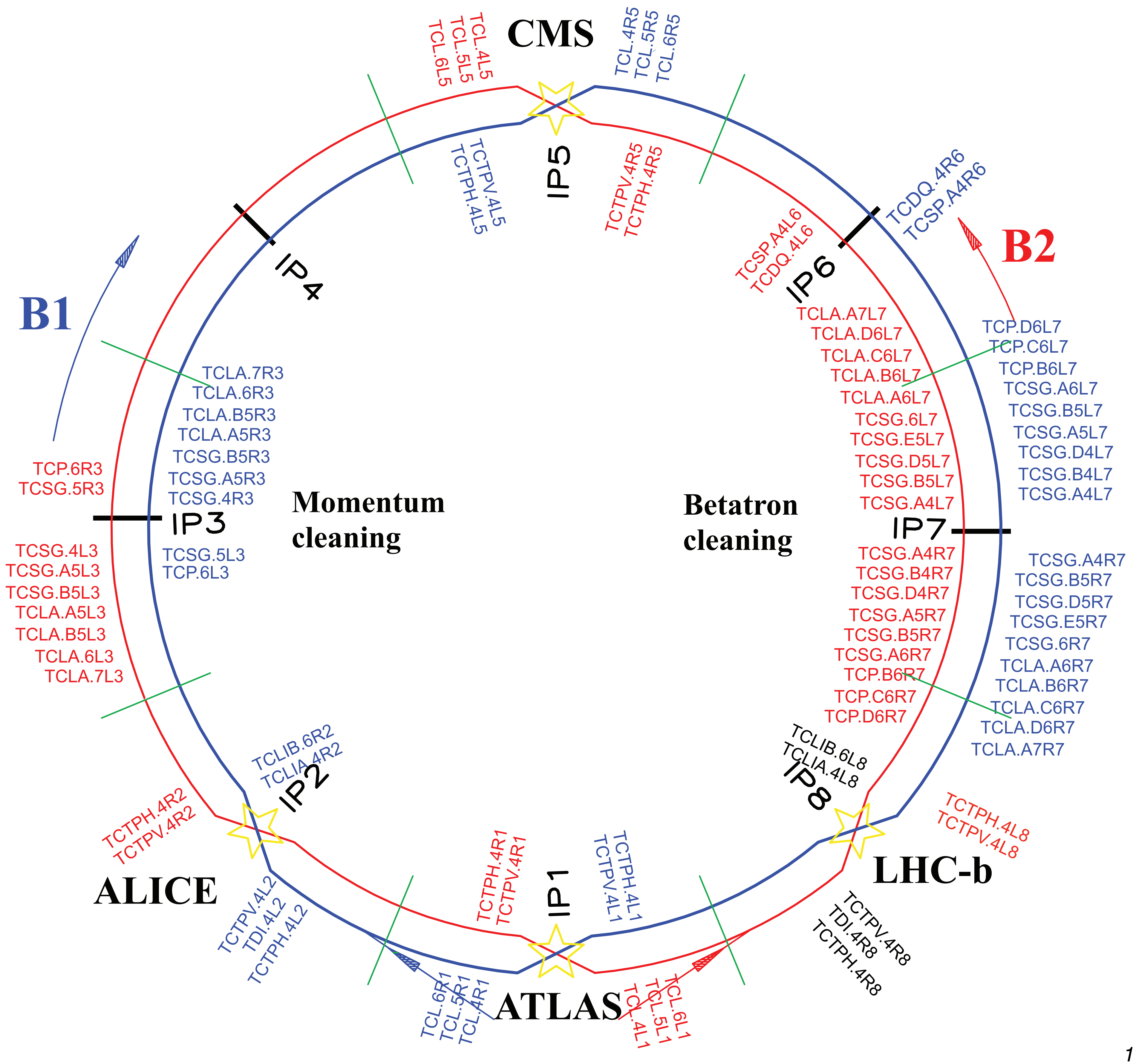
E_{stored} = ~ 360 MJ



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

LHC collimation layout

Collimator distributed along the 27km LHC ring



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

Why does the LHC need such a powerful collimation system?

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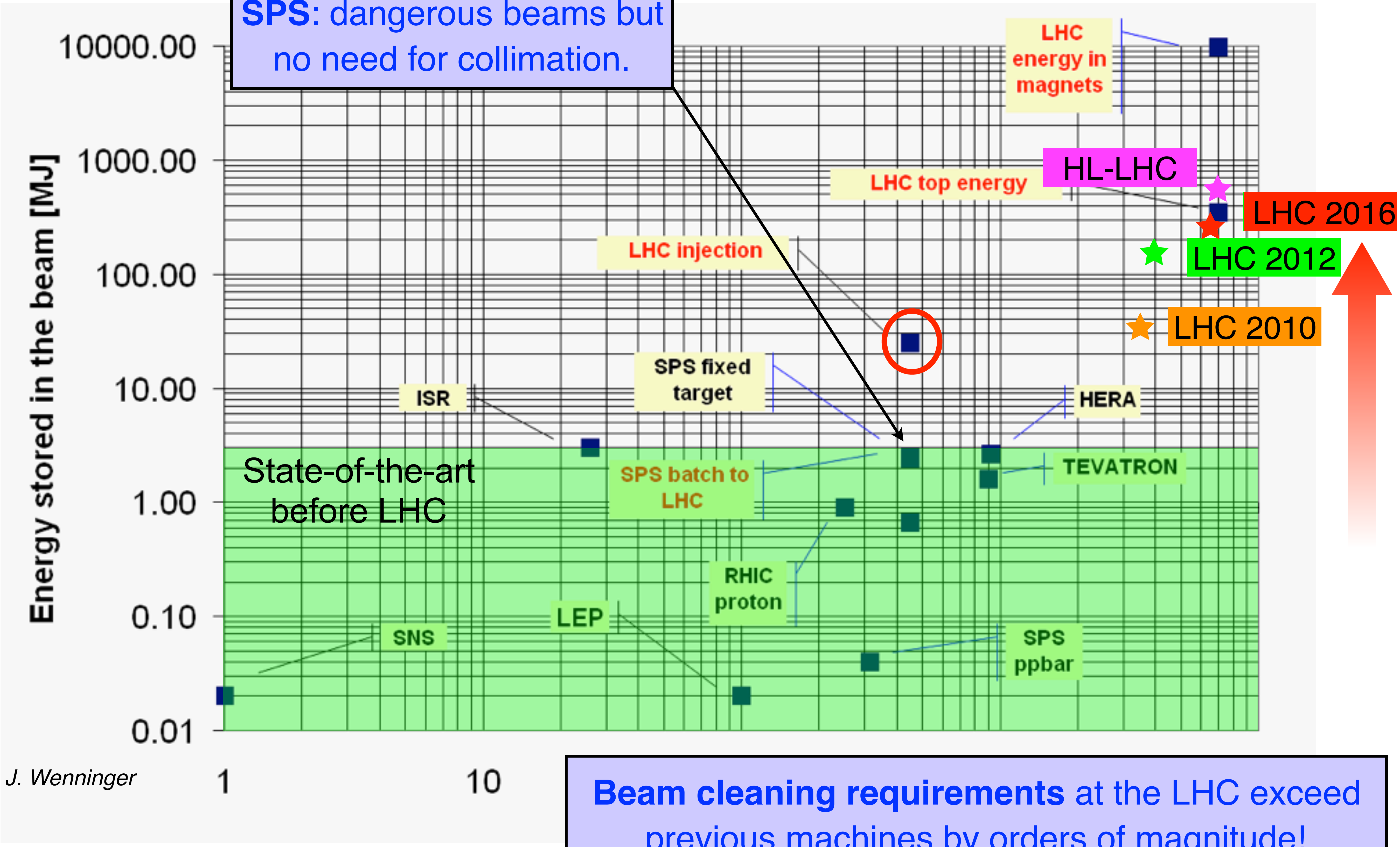
  Betatron and momentum

The stored energy challenge

SPS: dangerous beams but no need for collimation.



J. Wenninger

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

362 MJ stored energy

90 kg of TNT

8 litres of gasoline

15 kg of chocolate

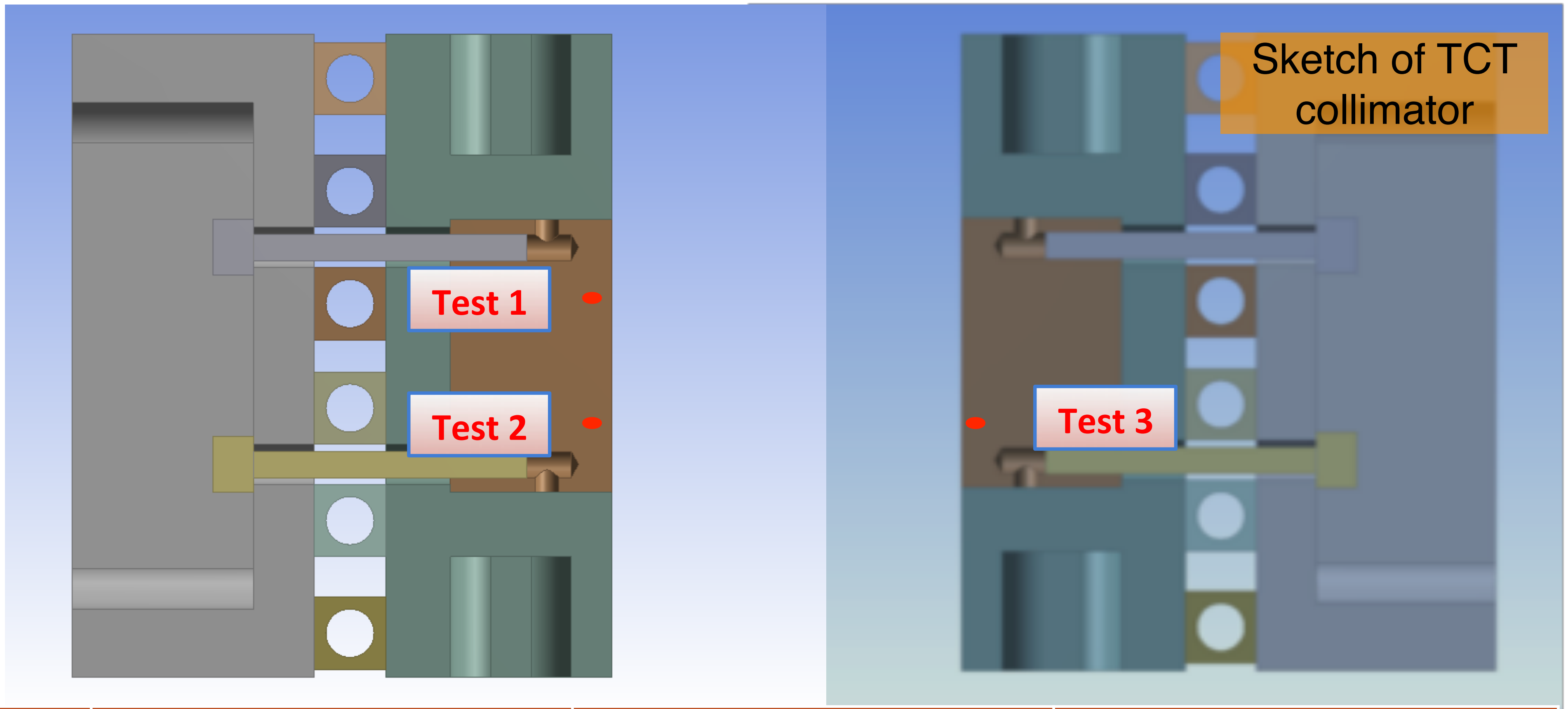
The kinetic energy of a 200 m long train at 155 km/hour

Key factor : how **fast** the energy is released ?!

The collimation system is designed to **handle safely** these energy for all relevant loss scenarios at the LHC.

Controlled collimation material tests

- Beam energy: **440 GeV**
- Impact depth: **2mm**
- Jaws half-gap: **14 mm**



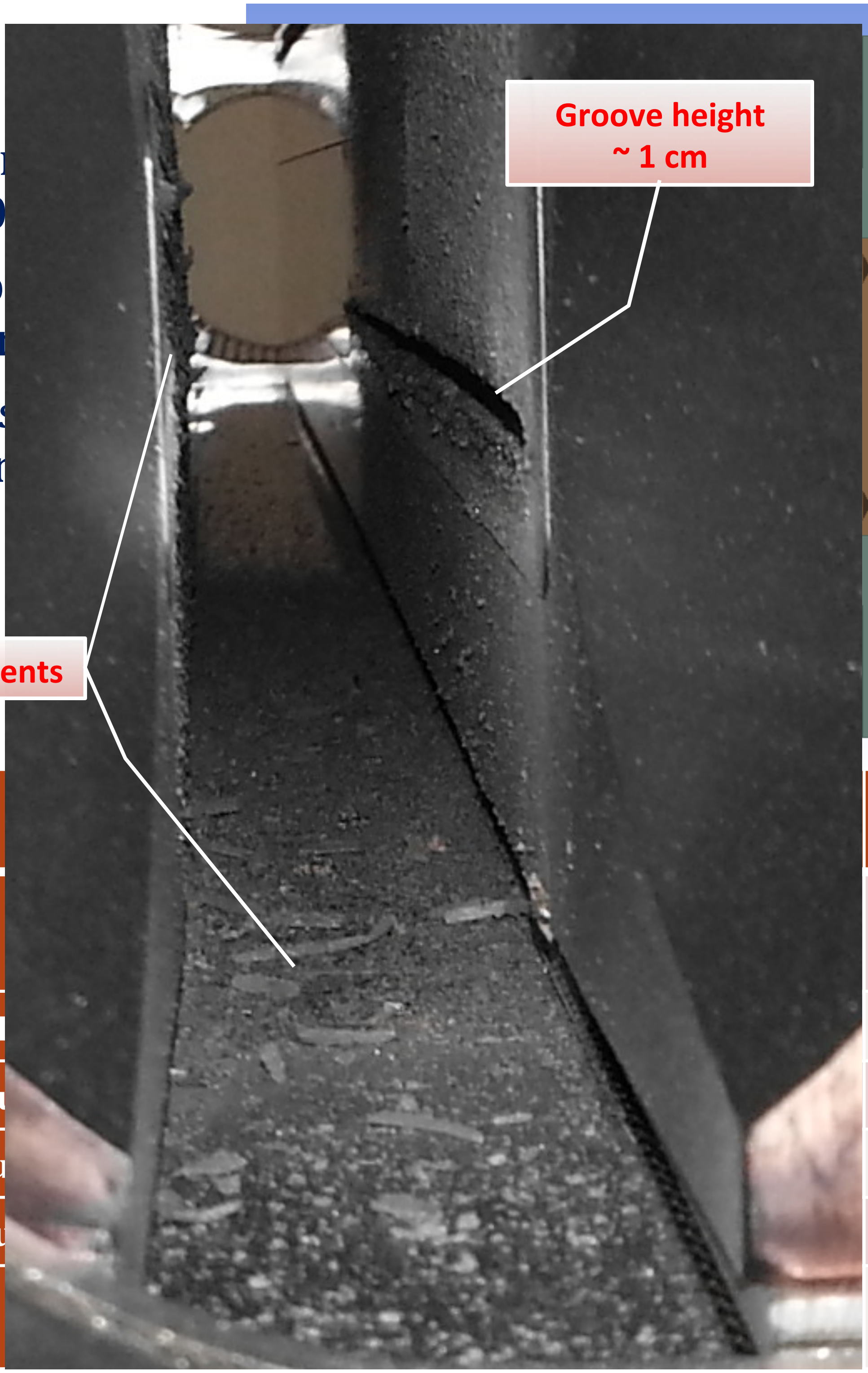
Sketch of TCT collimator

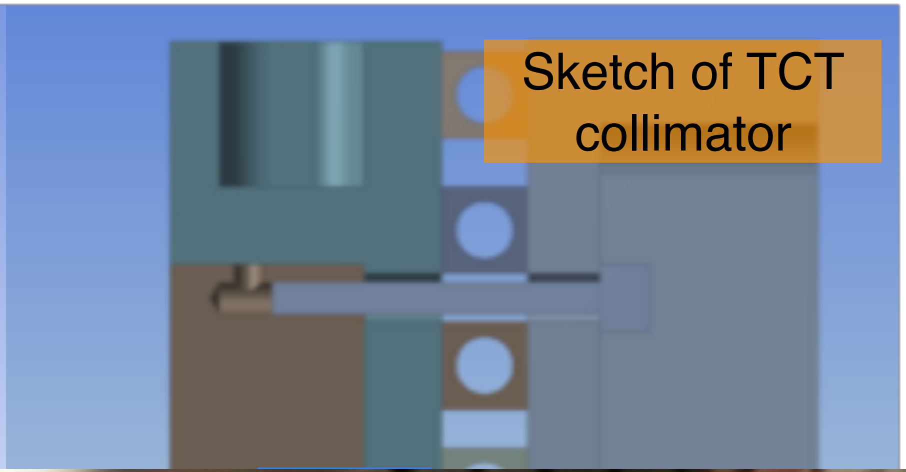
	Test 1	Test 2	Test 3
Goal	**Beam impact equivalent to 1 LHC bunch @ 7TeV**	**Identify onset of plastic damage**	**Induce severe damage on the collimator jaw**
Impact location	Left jaw, up (+10 mm)	Left jaw, down (-8.3 mm)	Right jaw, down (-8.3 mm)
Pulse intensity [p]	3.36 x 10^{12}	1.04 x 10^{12}	9.34 x 10^{12}
Number of bunches	24	6	72
Bunch spacing [ns]	50	50	50
Beam size [σ_x - σ_y mm]	0.53 x 0.36	0.53 x 0.36	0.53 x 0.36

HiRadMat test facility at CERN allows studying material behaviour under ***extreme beam impact conditions.***

Controlled collimation material tests

- Bear
  440
- Imp
  2m
- Jaws
  14 r





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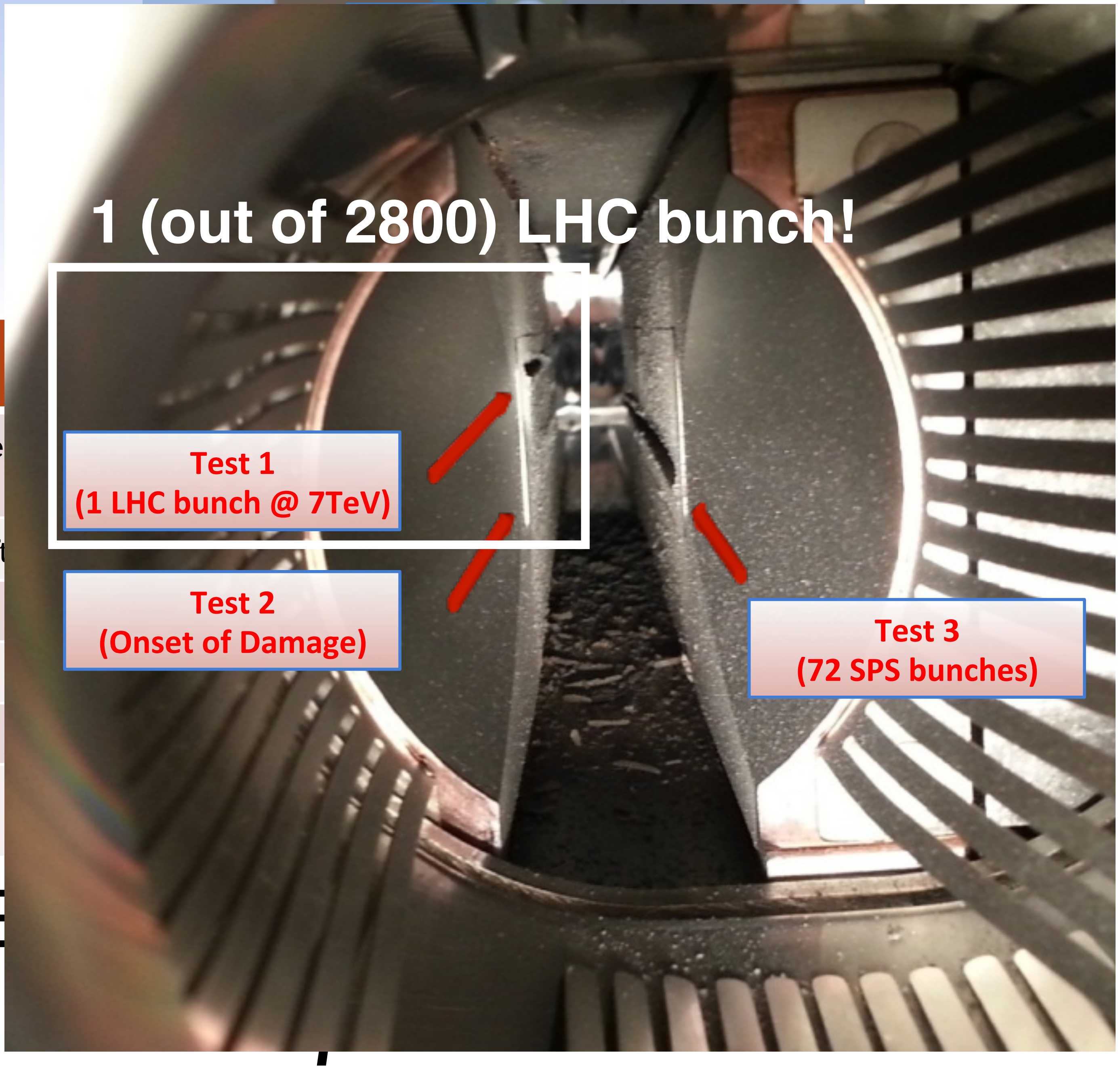
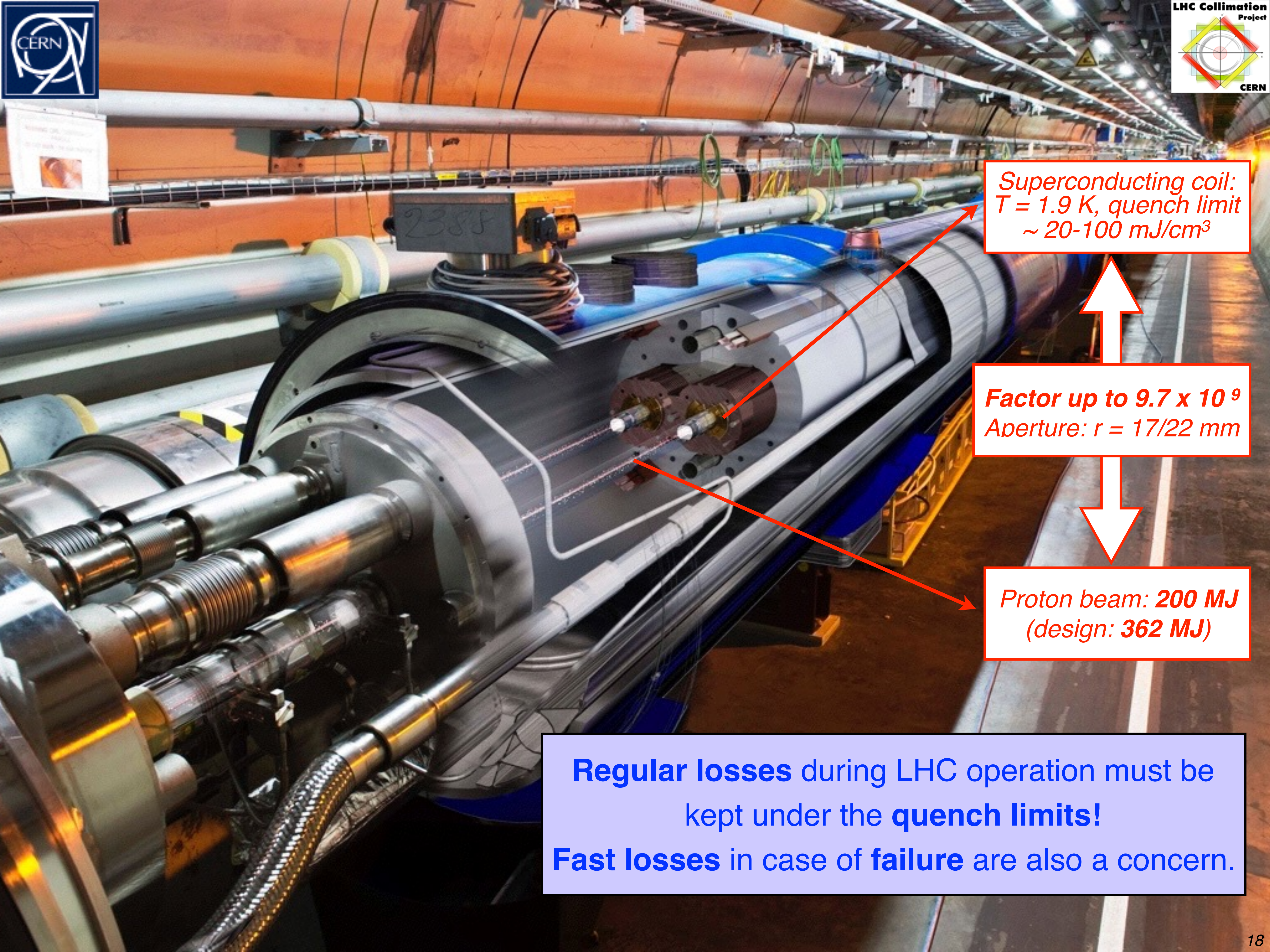


HiRadMat test facility[12] *at CE*
behaviour under ***extreme***



Superconducting coil: $T = 1.9$ K, quench limit ~ 20-100 mJ/cm^3

Factor up to 9.7 x 10 ^{9}

Aperture: r = 17/22 mm

Proton beam: ***200 MJ***
(design: ***362 MJ****)*

Regular losses during LHC operation must be kept under the **quench limits!**
Fast losses in case of **failure** are also a concern.

Roles of collimation systems

- **Halo cleaning** versus quench limits (super-conducting machines)
- Passive **machine protection**

  First line of defence 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**, **hal**

  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 !

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  - Betatron and mom

Extract from loss scenarios the key design parameters for a **cleaning 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 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__"*
- *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 model all these effects to understand beam collimation!

These effects might increase the beam halo population (create tails) and ultimately cause beam losses!

Losses and beam lifetime

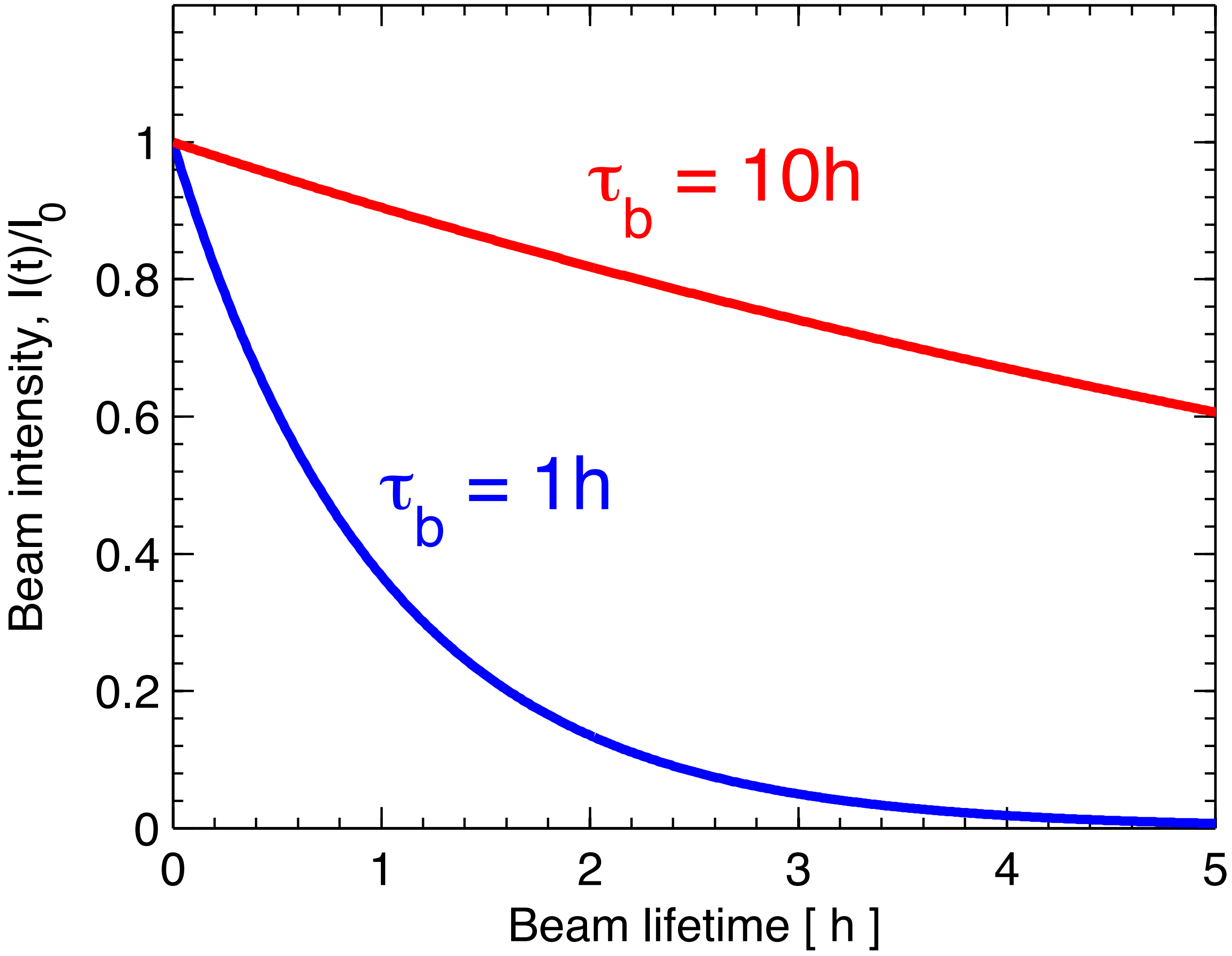
Beam loss mechanisms are modelled by assuming a non-infinite **beam lifetime,** τ_b

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

: Beam intensity versus time

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

: Proton loss rate



Different loss 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.

Some numbers for the LHC at 7 TeV

Each LHC beam consists of $3.2x10^{14}$ protons

(320 hundred trillion protons!),

corresponding to a beam stored energy = ***362 MJ***

1h lifetime *(typical value) corresponds to a loss rate of about 90 billion proton per second, i.e.*

0.1MJ/s = 100 kW*!*

Quench limit at 7TeV = ***20-50mW/cm^3***

Need a very good cleaning efficiency!

More realistic loss scenarios can easily bring losses up to ***500kW*** *(0.2 h lifetime).*

High Luminosity upgrade of the LHC: ***1 MJ.***

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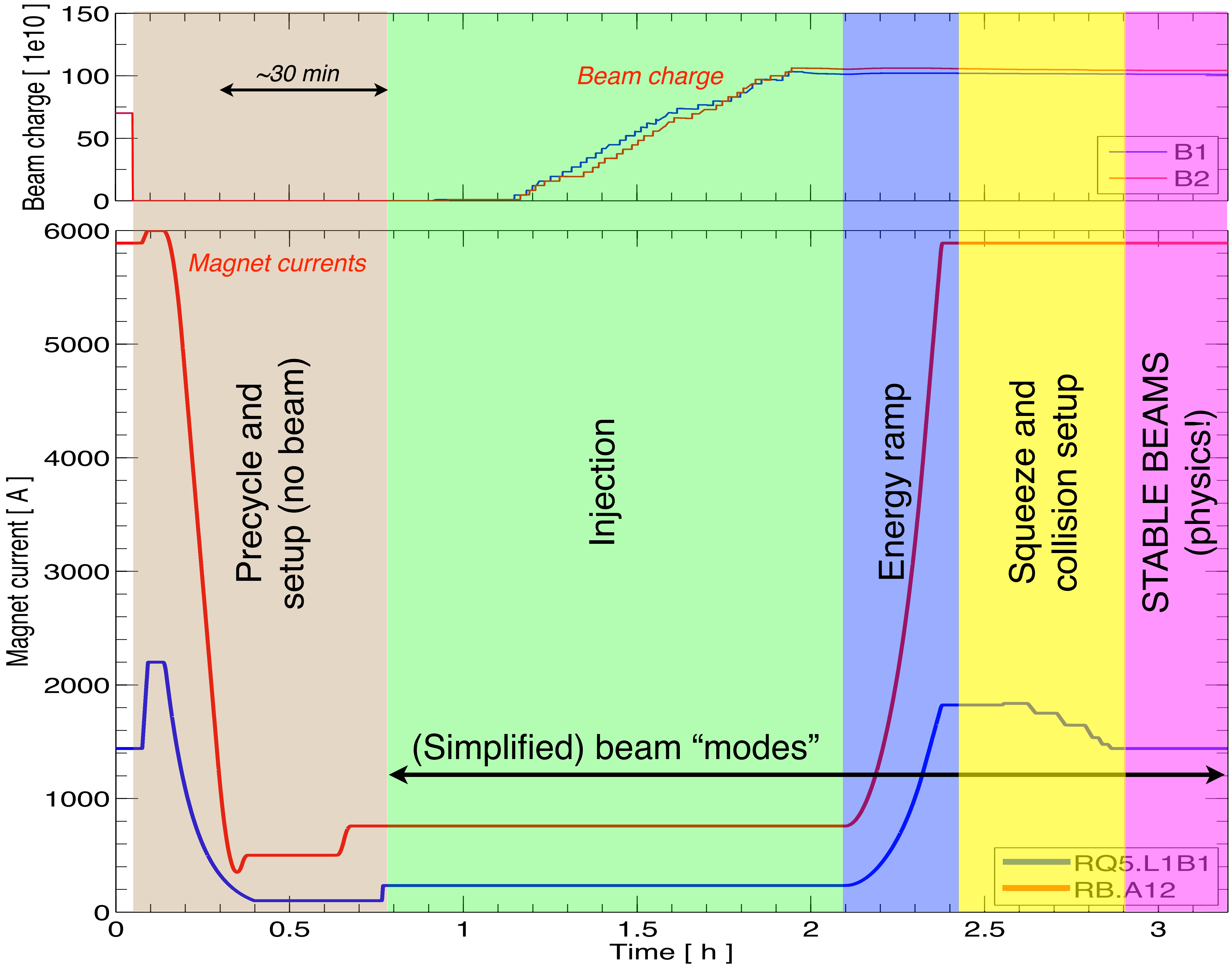
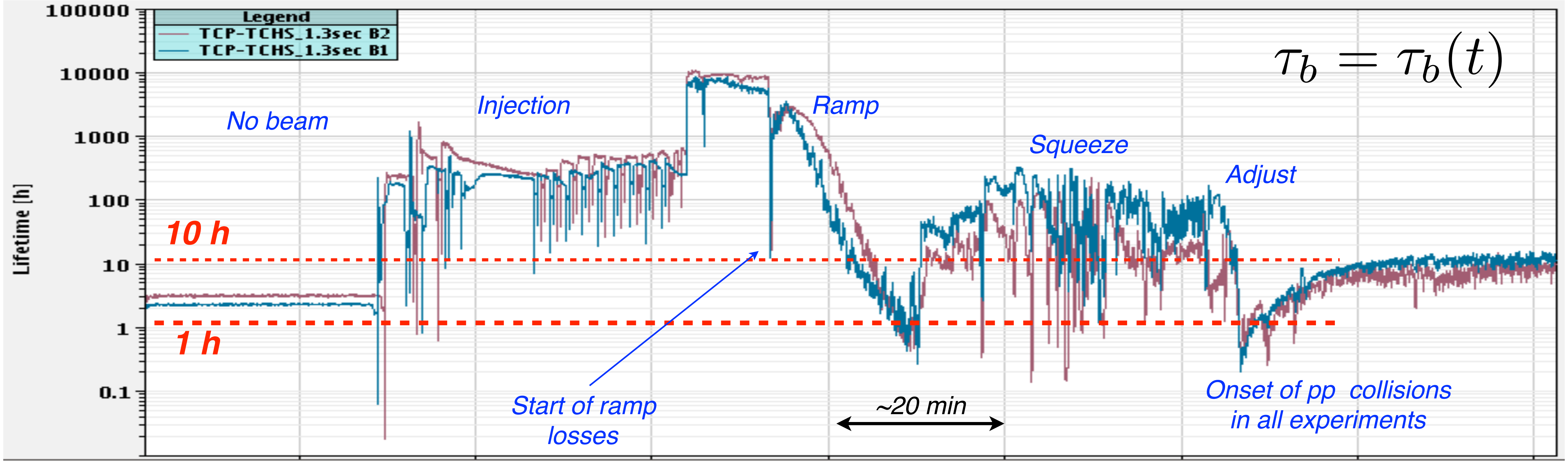
High Luminosity upg

LHC operation demands a very efficient beam cleaning to safely operate below quench limits!

Operational cycle of a collider



LHC lifetime in a physics fill in 2012



$$\tau_b = \tau_b(t)$$

No beam

Injection

Ramp

Squeeze

Adjust

10 h

1 h

Start of ramp losses

~20 min

Onset of pp collisions in all experiments

Example of a typical physics fill in 2012.

The lifetime at top energy can drop well below 1 h!

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

*Goal of the **collimation system: catch these losses** and **ensure that a controlled fraction** of it reaches sensitive equipment.*

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 halos carry.

> *Collimation required to handle losses that otherwise would occur in an uncontrolled way, all around the machine.*

Design loss rates are calculated from the **total beam intensity** by assuming a "**minimum allowed beam lifetime**" that can occur during operation. This specifies the design requirement for the collimation system.

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), ...*

Case study: losses vs quench limits

N_{tot} : total beam populations [p]

$\dfrac{N_{\text{tot}}}{\tau_b}$: 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

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

$\boxed{\tilde{\eta}_c}$: 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).

A beam lifetime of 0.2h corresponds to a loss rate at the LHC of **$4.5\text{x}10^{11}$ p/s**. Assuming a quench limit of ***R_q*** **~ $3.2\text{x}10^{7}$p/m/s** at 7 TeV, one can calculate a **required inefficiency of about 10^{-4}** (if losses over 1 m)!!

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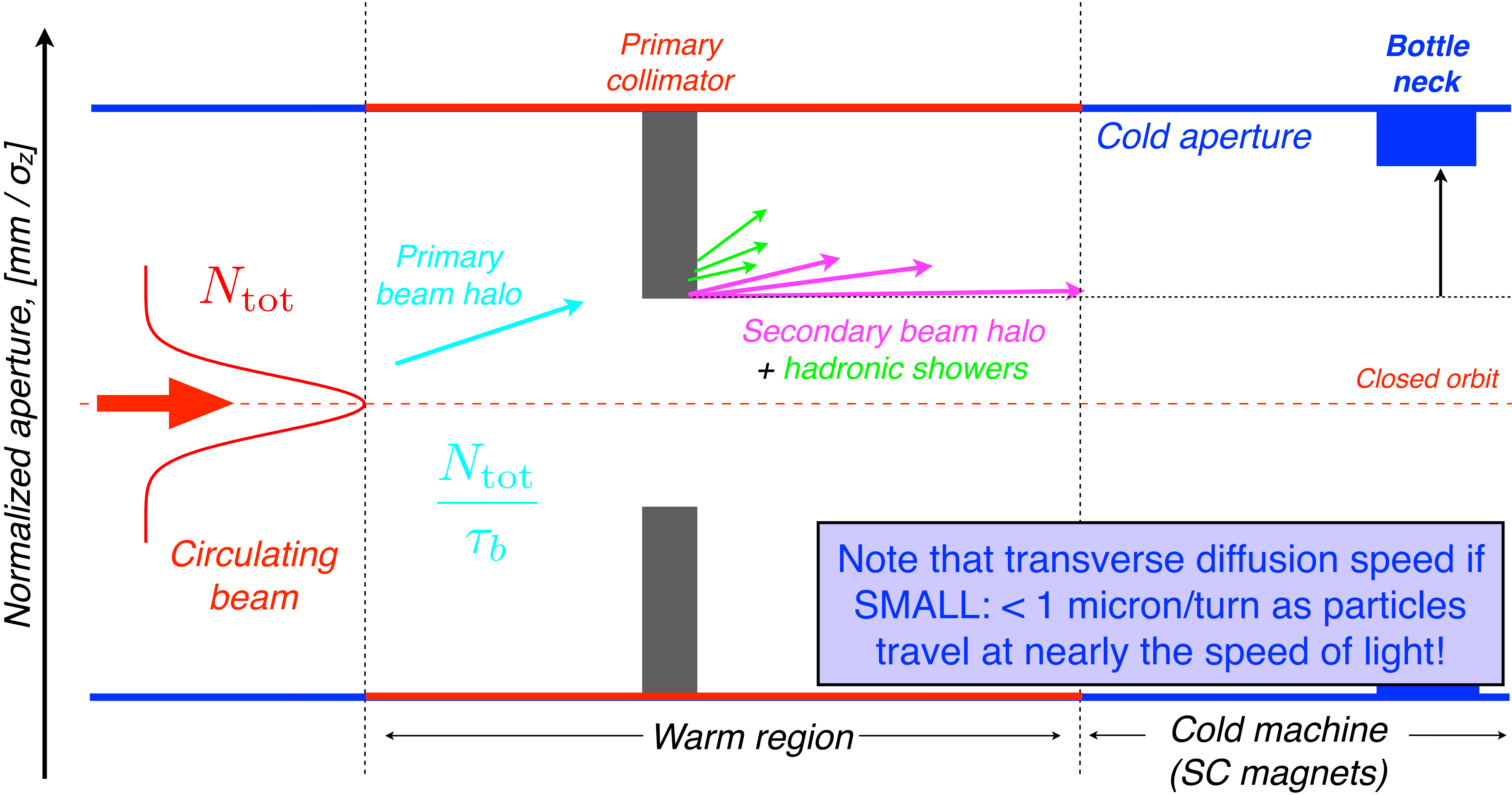
Betatron and momentum

Aperture and single-stage cleaning

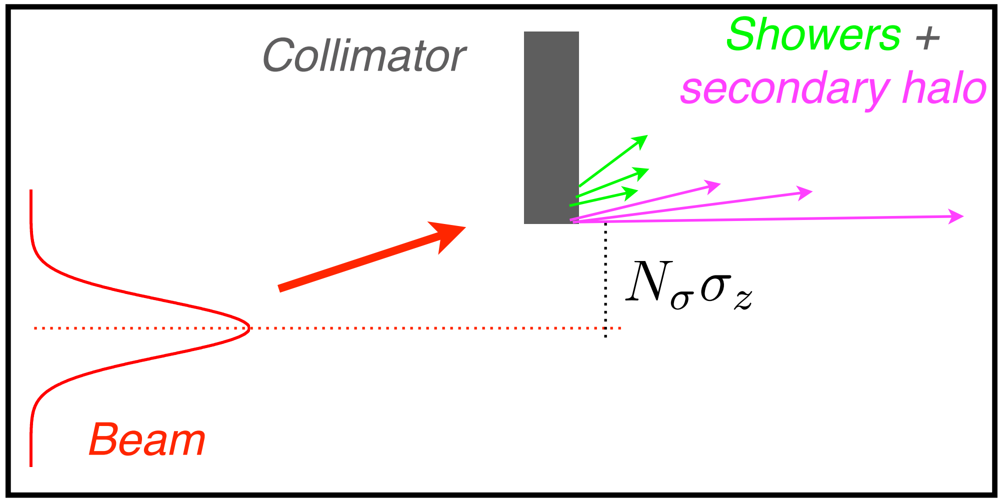


Note that transverse diffusion speed if SMALL: < 1 micron/turn as particles travel at nearly the speed of light!

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?

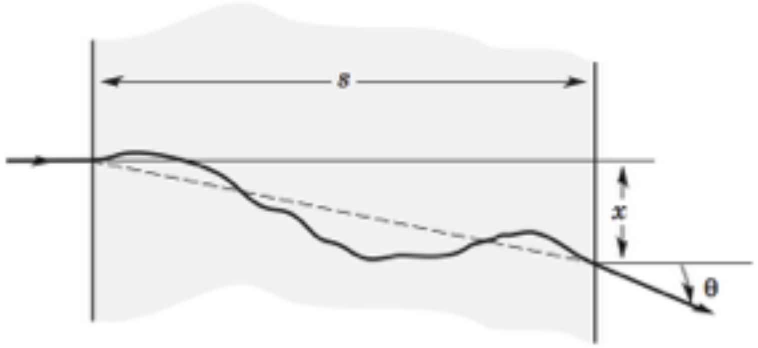
Particle interaction with collimators



If the “primary” collimator were a black absorber, it would be sufficient to **shield the aperture** by choosing a half-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.

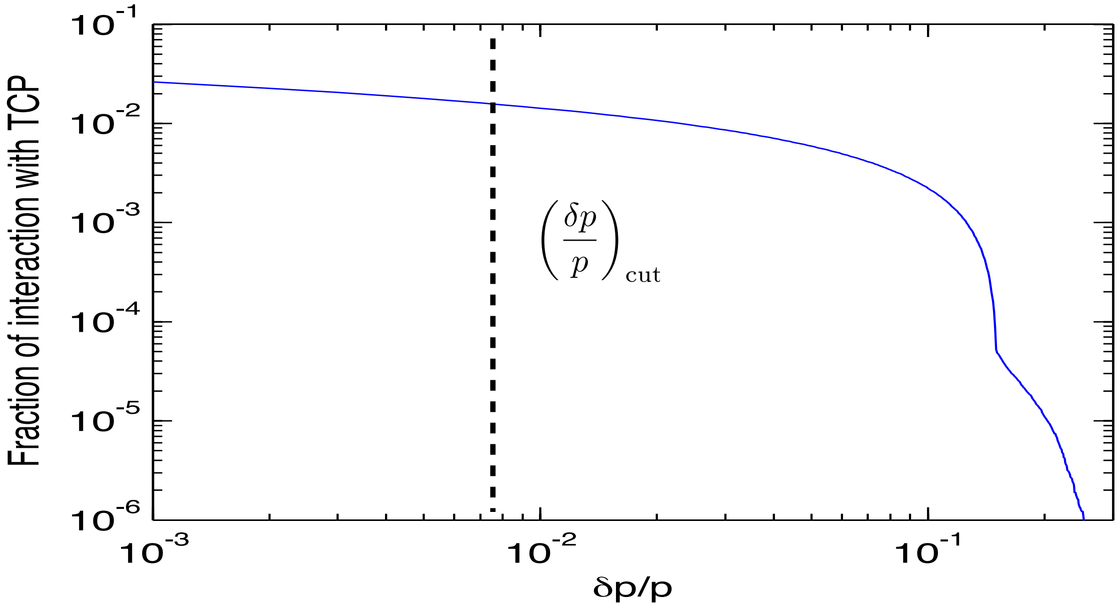


$$\sqrt{\langle \theta_p^2 \rangle} = \frac{13.6}{cp[\mathrm{MeV}]} \sqrt{\frac{s}{\chi_0}} \left(1 + 0.038 \cdot \left(\frac{s}{\chi_0} \right) \right)$$

χ_0 : radiation length

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

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



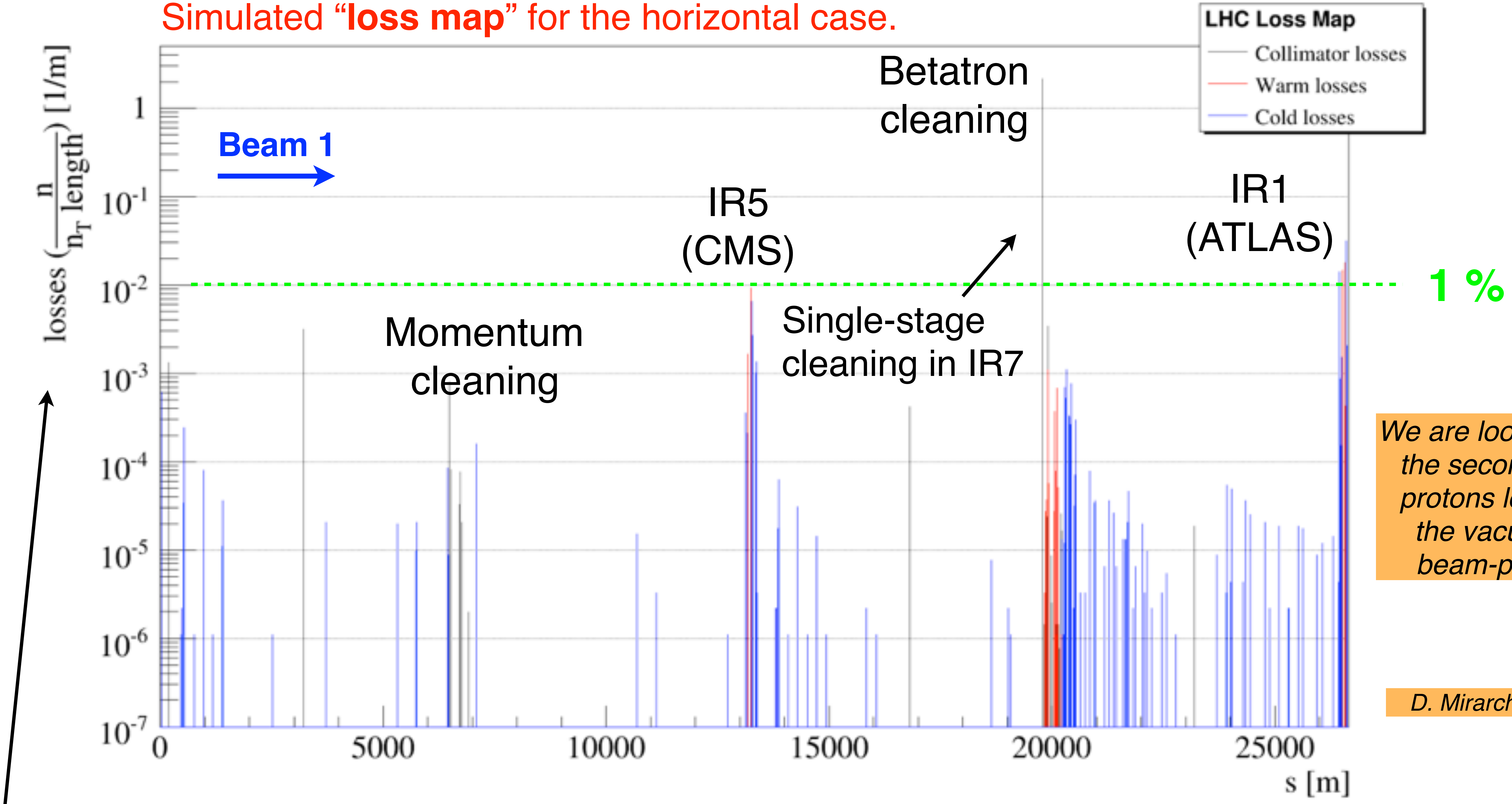
The interaction with collimator materials is itself a source of betatron and off-momentum halo (secondary halo).

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

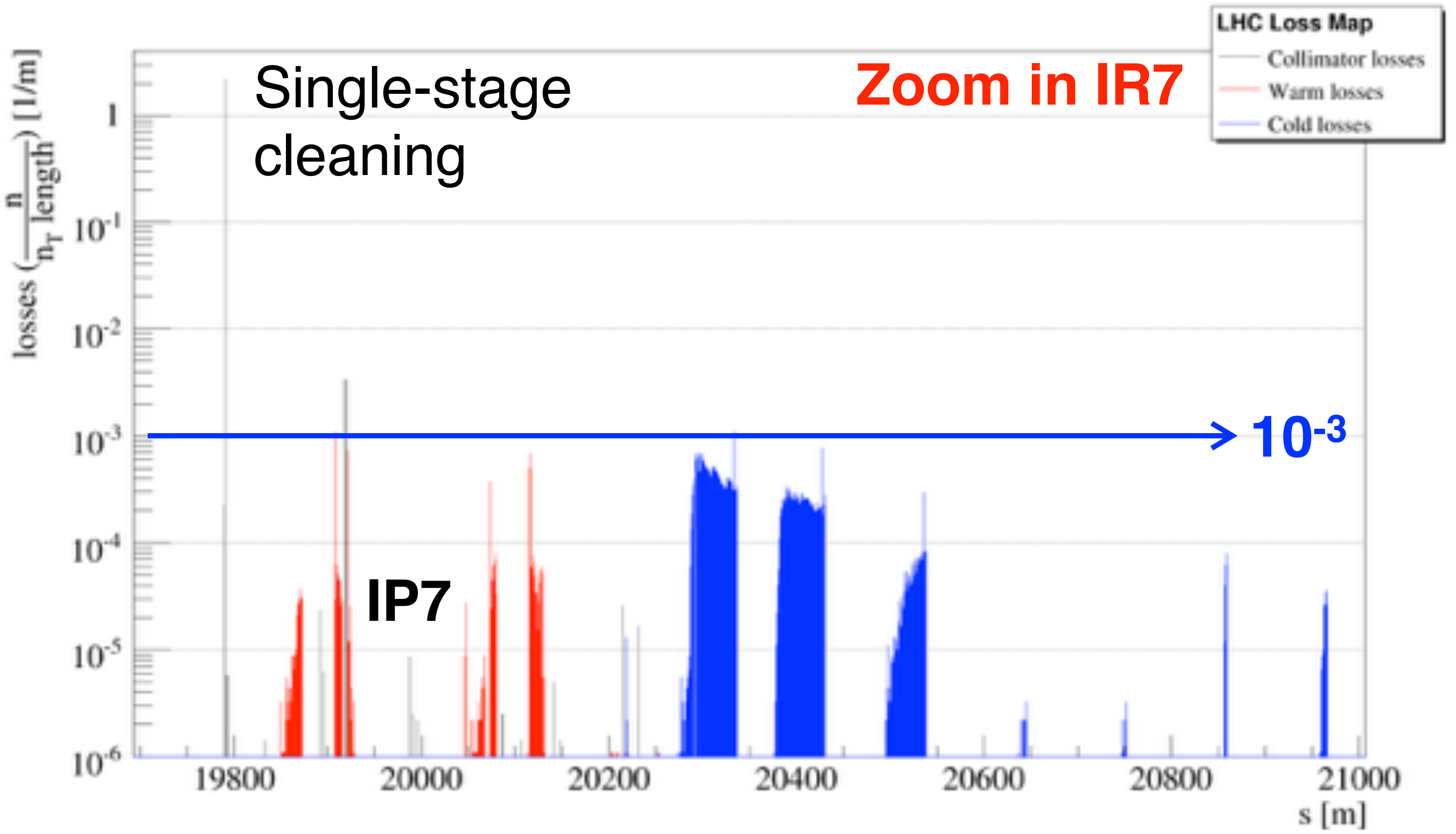
Local cleaning inefficiency

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

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 %**.

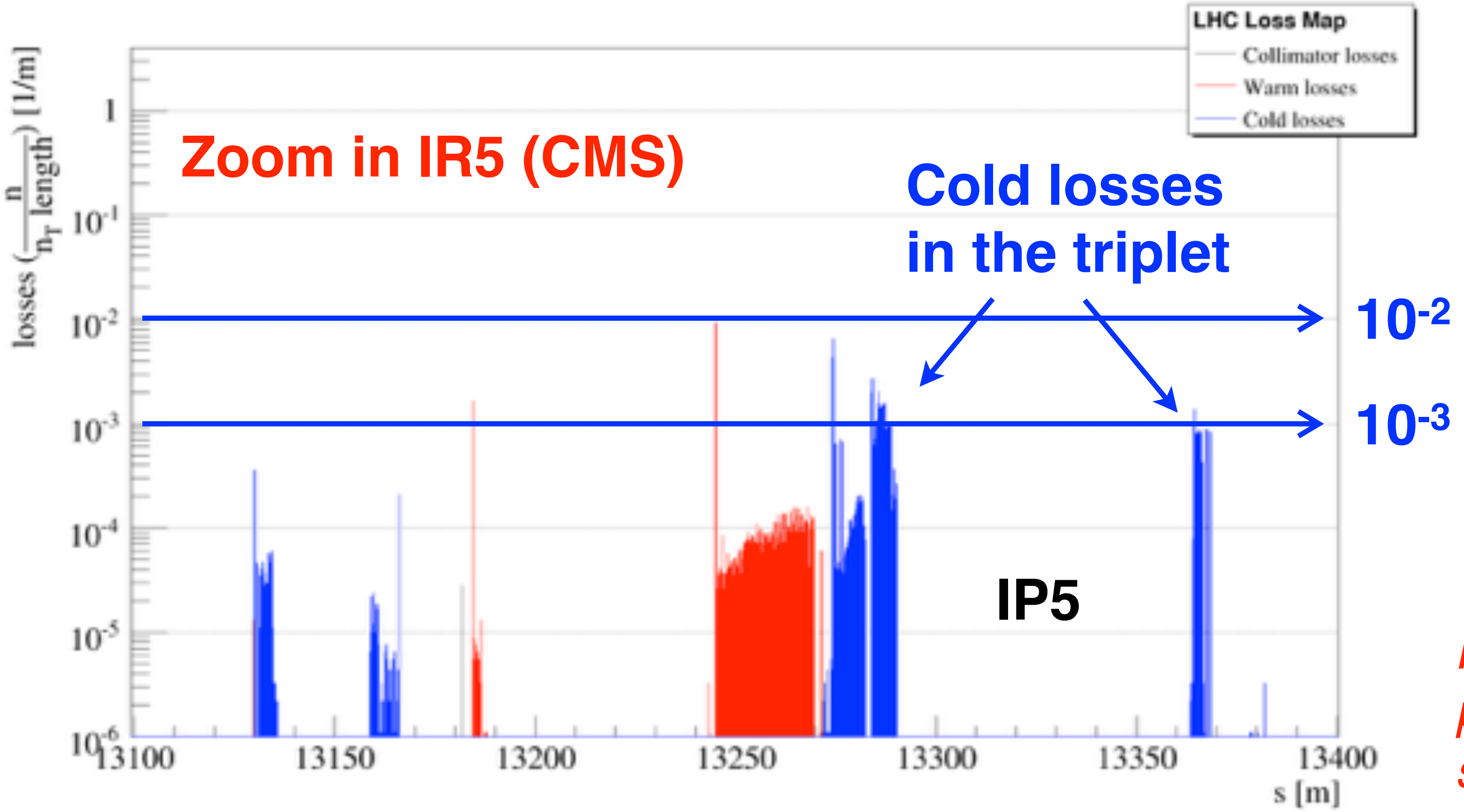
Comparison to quench limits


Single-stage cleaning

Zoom in IR7

IP7

10^{-3}


Zoom in IR5 (CMS)

Cold losses in the triplet

IP5

10^{-2}

10^{-3}

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

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

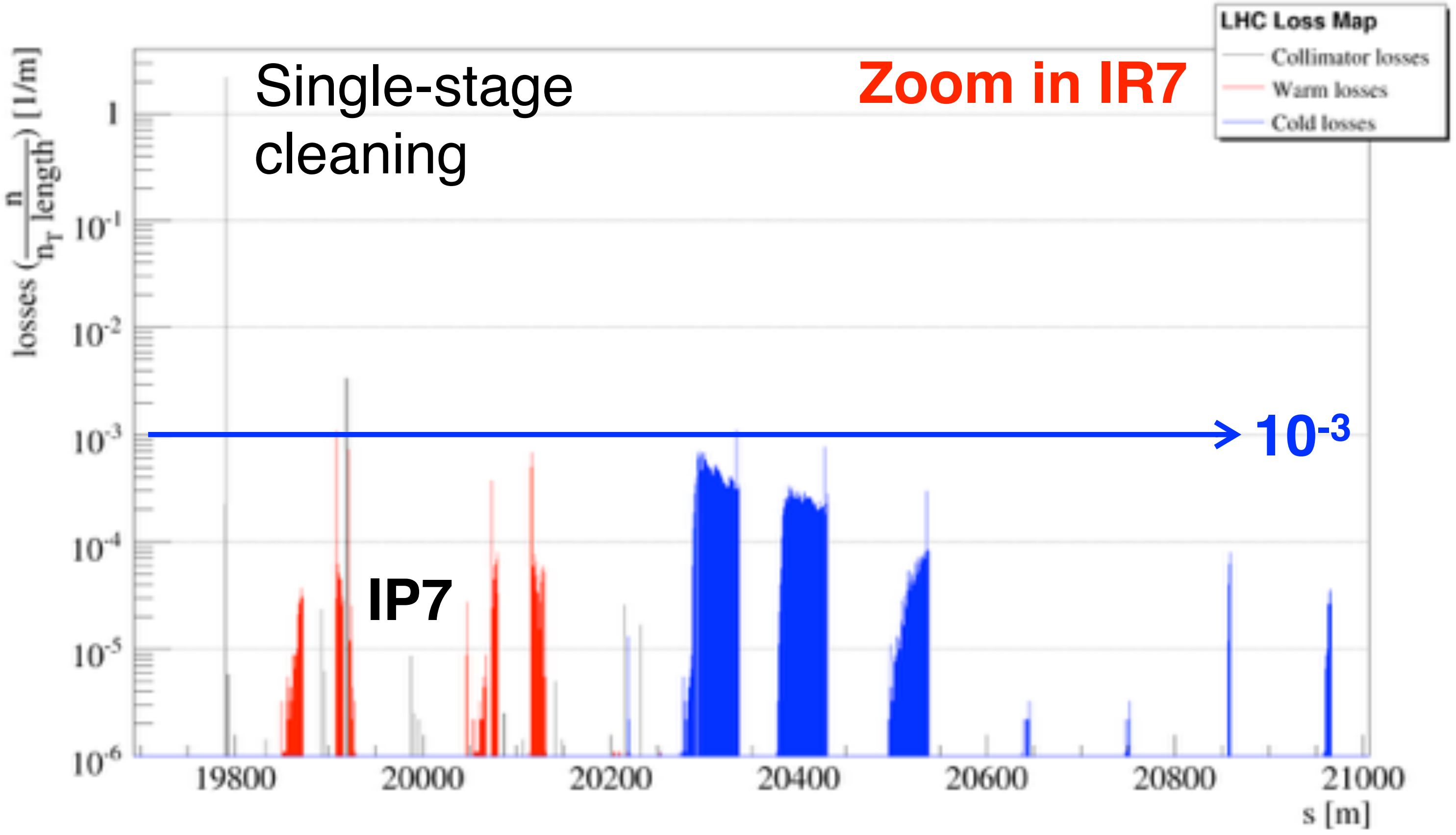
With the single-stage cleaning predicted by this model, losses are up to:

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!*

Comparison to quench limits

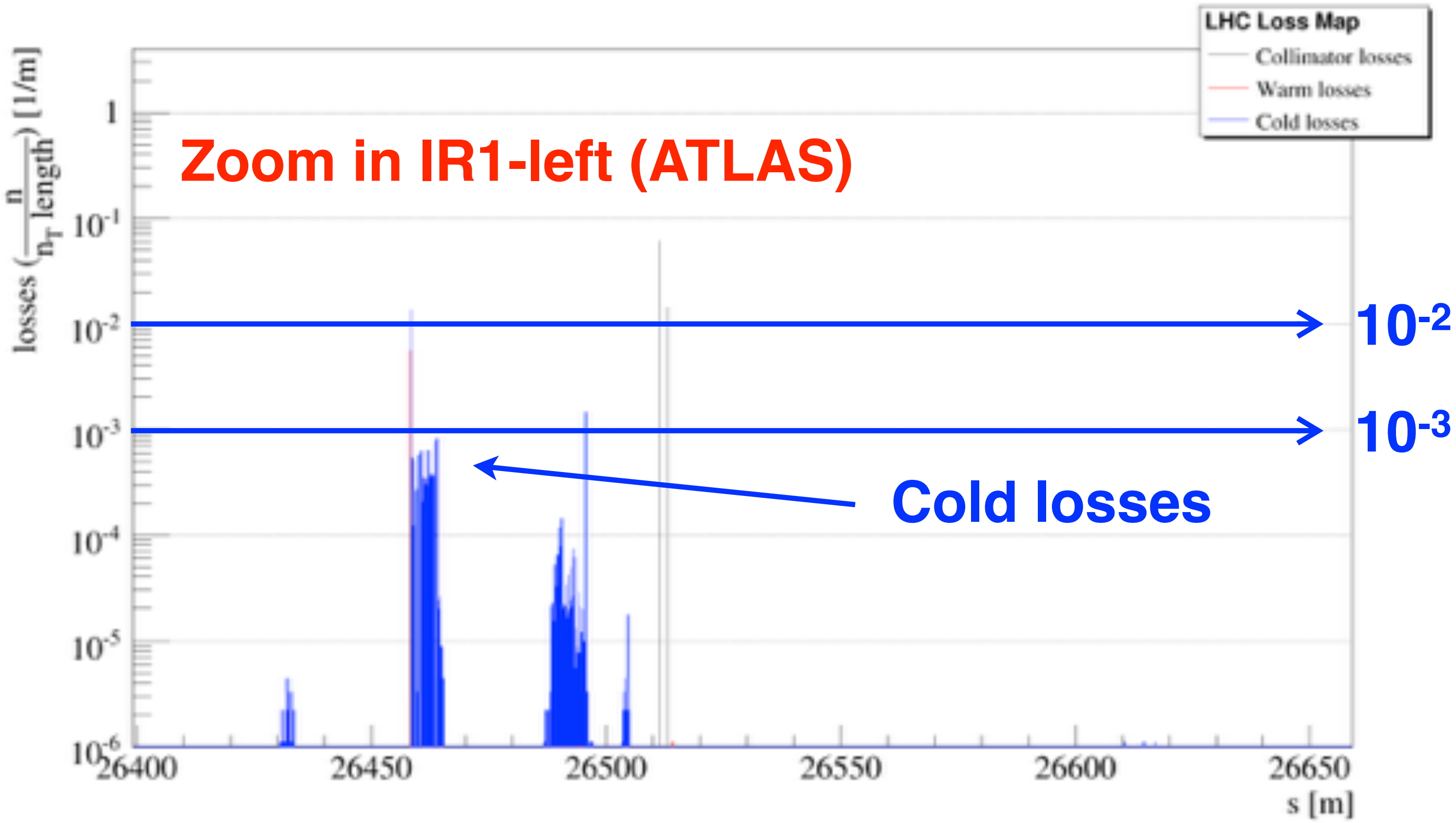


Single-stage cleaning

Zoom in IR7

10^{-3}

IP7



Zoom in IR1-left (ATLAS)

10^{-2}

10^{-3}

Cold losses

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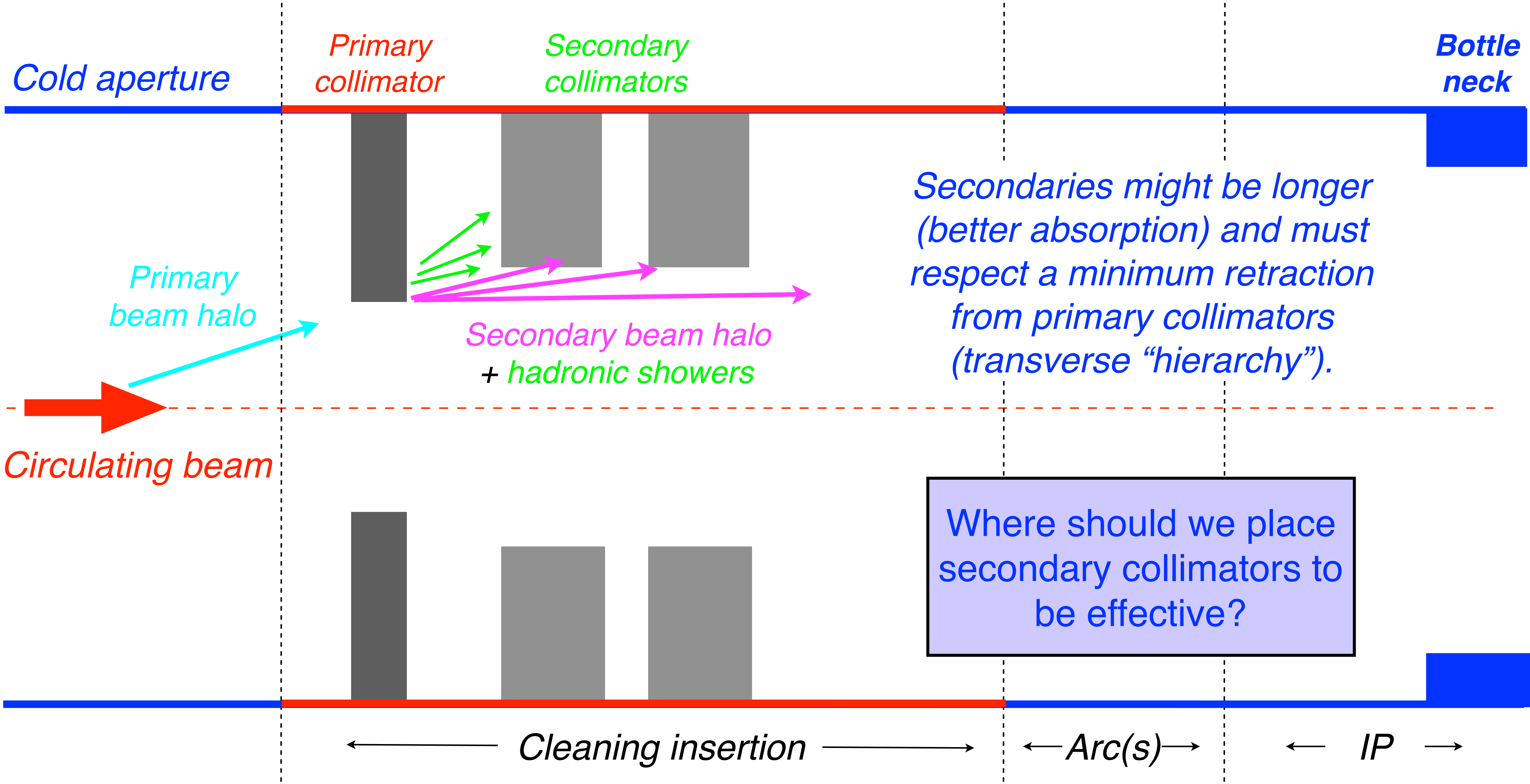
Two-stage collimation

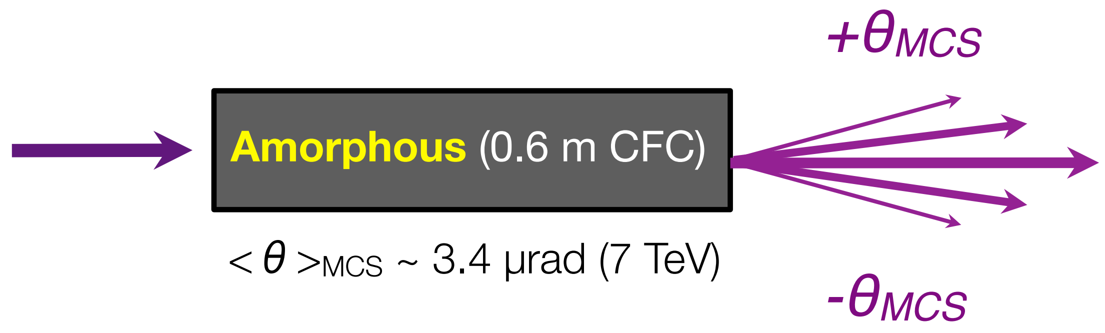


Secondaries might be longer (better absorption) and must respect a minimum retraction from primary collimators (transverse "hierarchy").

Where should we place secondary collimators to be effective?

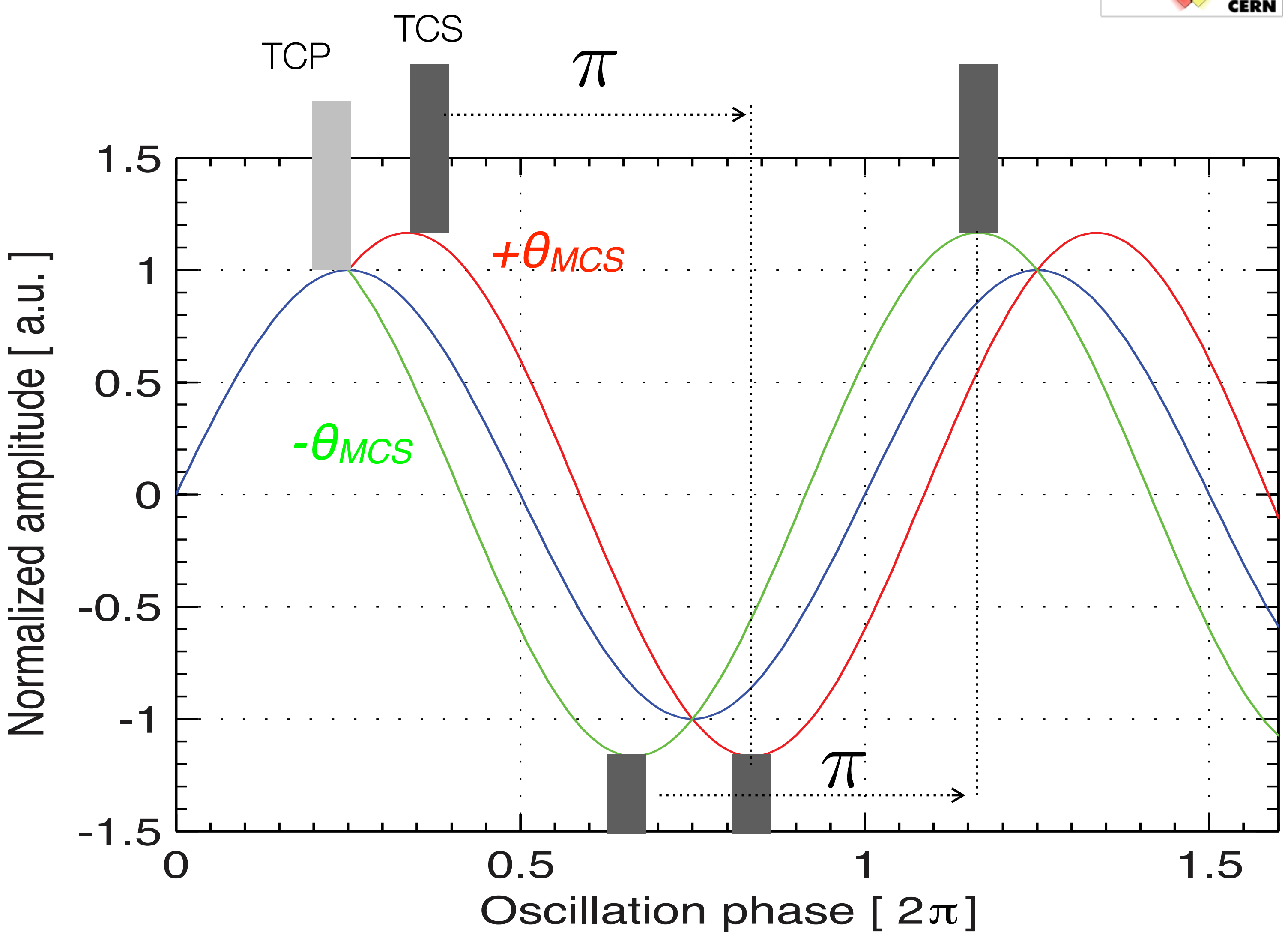
"Secondary" collimators (TCSs) can be added to intercept the secondary halo and the showers that leak out of the primary collimator.

Optimum secondary collimator locations



$< \theta >_{MCS} \sim 3.4\ \mu\text{rad}$ (7 TeV)

There are **two optimum phase locations** to catch the particles scattered out of 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 $z \equiv (x, y)$

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

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

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

TCSs must be retracted at larger gaps than the TCP in order to **avoid** a single-stage cleaning.

Reality is quite more complex...

Optimum phases depend on TCP/TCS retraction

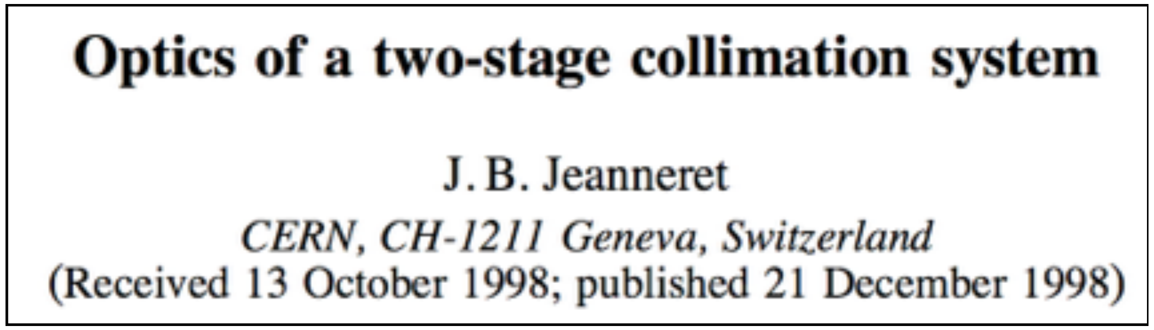
$$\tan\mu_x = \frac{\sqrt{n_{\mathrm{TCP}}^2 - n_{\mathrm{TCS}}^2}}{n_{\mathrm{TCP}}^2}\,\frac{\cos\phi}{\cos\alpha}$$

$n_{\mathrm{TCP}}, n_{\mathrm{TCS}}$: 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

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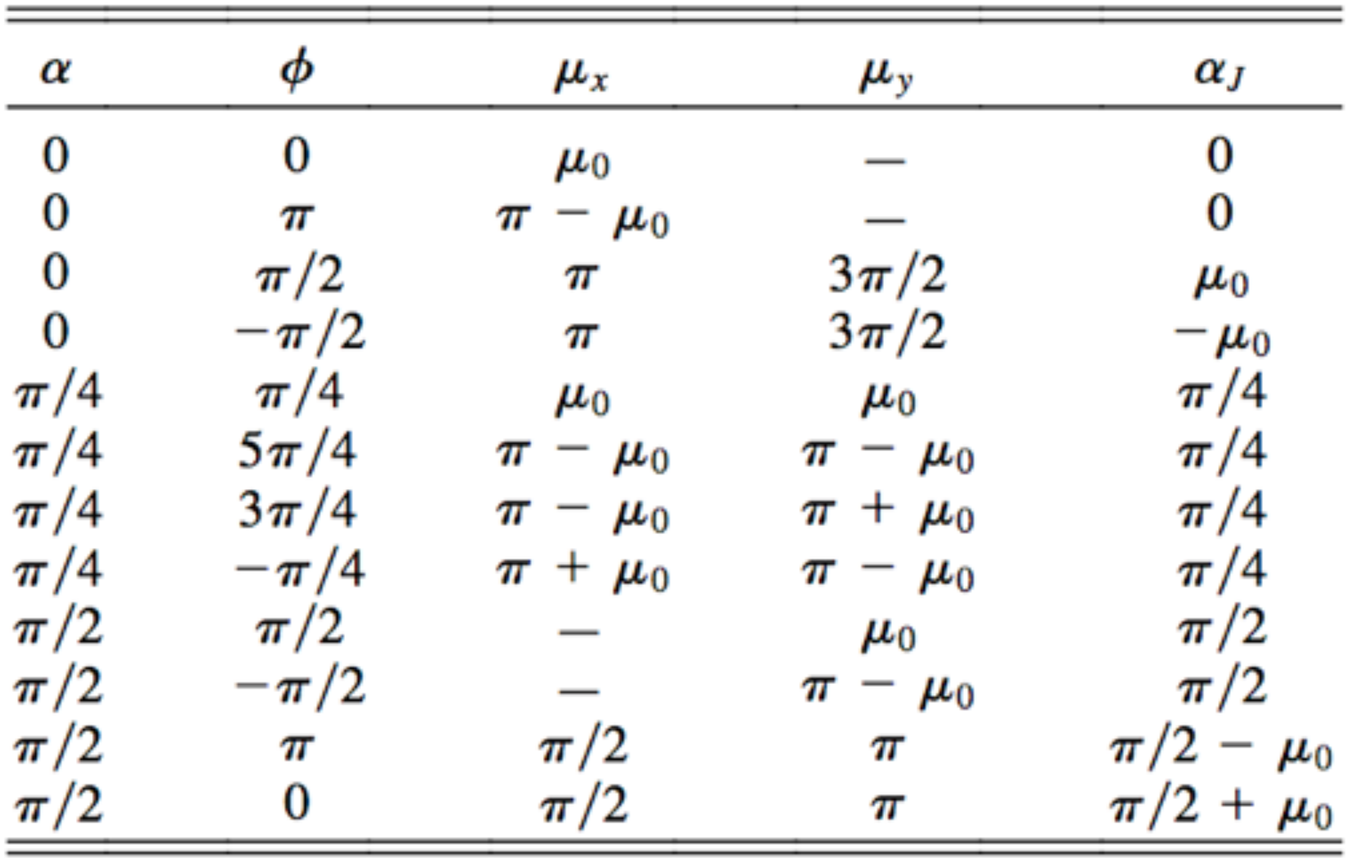
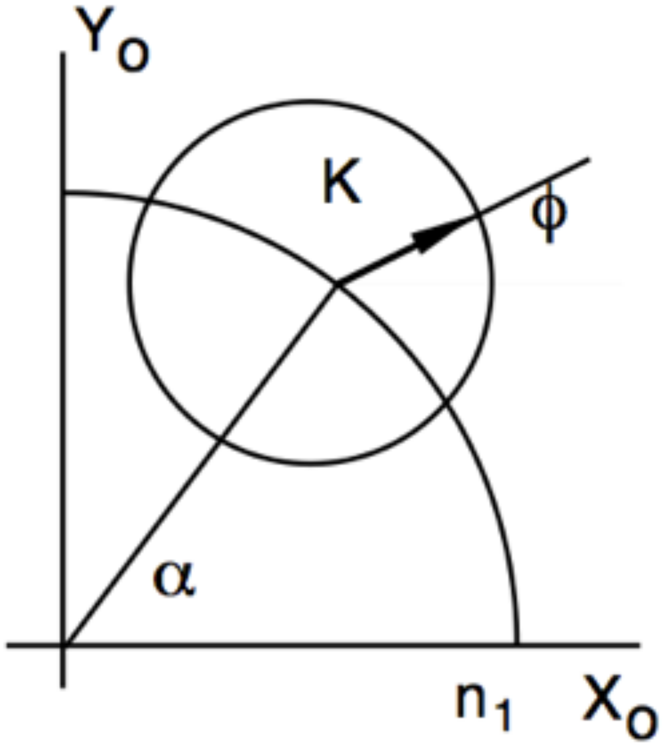
Phase locations (μ_x, μ_y) and jaw orientation (α_J) to catch different scattering angle (ϕ) for horizontal (α=0), vertical (α=π/2) and skew (α=π/2) scattering source locations.

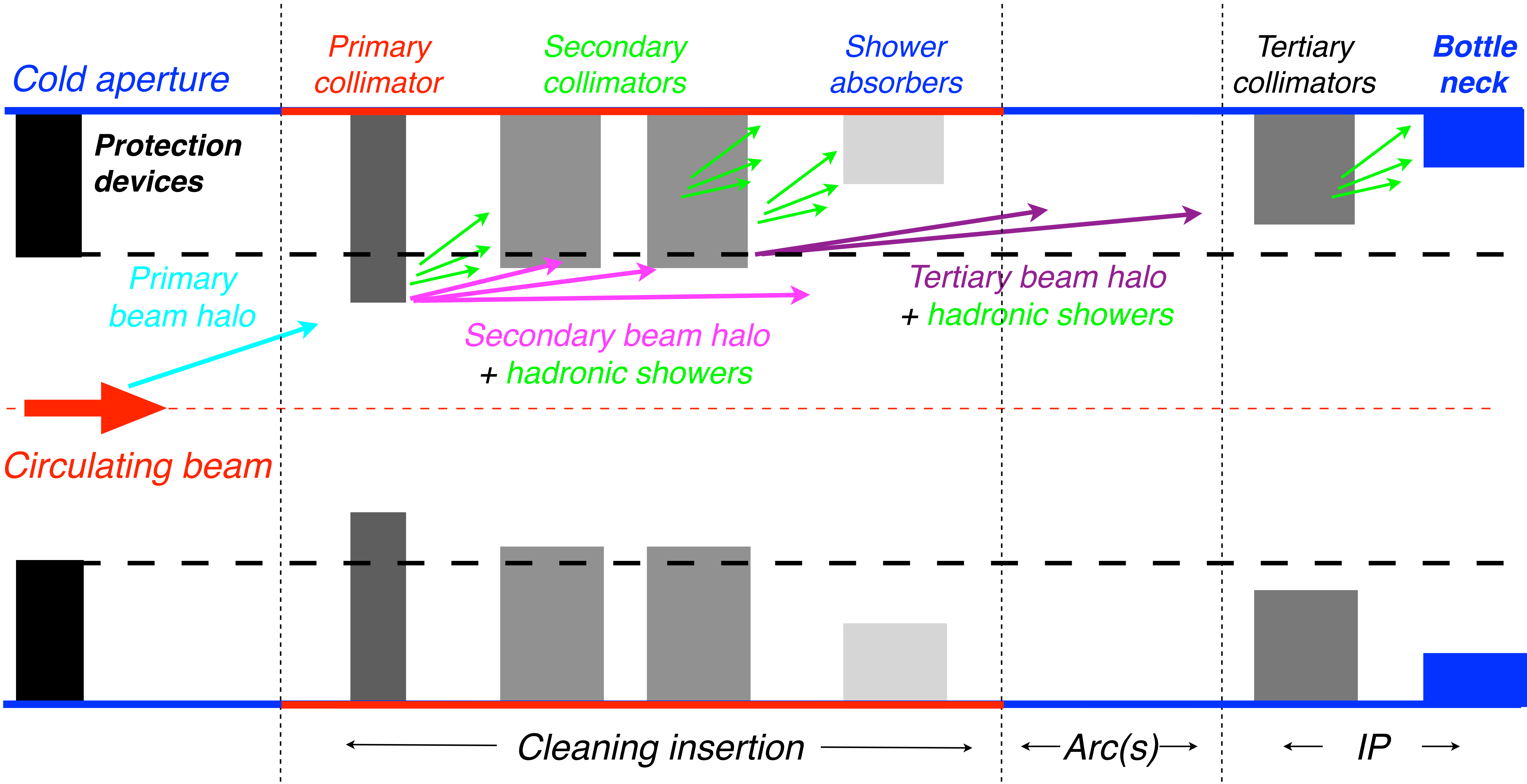


α	ϕ	μ_x	μ_y	α_J
0	0	μ_0	—	0
0	π	$\pi - \mu_0$	—	0
0	$\pi/2$	π	$3\pi/2$	μ_0
0	$-\pi/2$	π	$3\pi/2$	$-\mu_0$
$\pi/4$	$\pi/4$	μ_0	μ_0	$\pi/4$
$\pi/4$	$5\pi/4$	$\pi - \mu_0$	$\pi - \mu_0$	$\pi/4$
$\pi/4$	$3\pi/4$	$\pi - \mu_0$	$\pi + \mu_0$	$\pi/4$
$\pi/4$	$-\pi/4$	$\pi + \mu_0$	$\pi - \mu_0$	$\pi/4$
$\pi/2$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



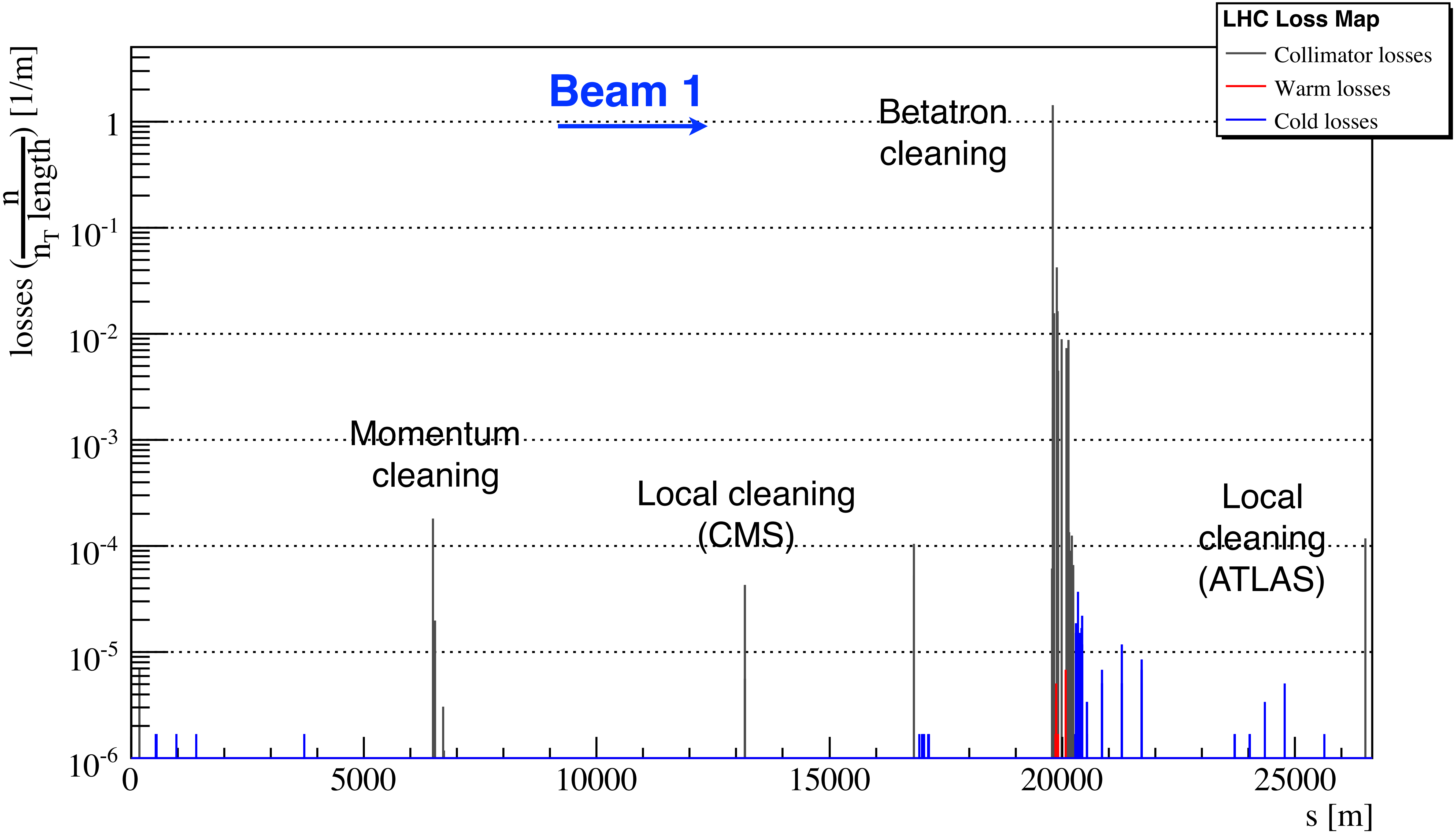
A finite number of secondary collimators can be used to catch efficiently the halo with three primary collimator orientation, in a ***multi-turn process****.*

Multi-stage collimation at the LHC



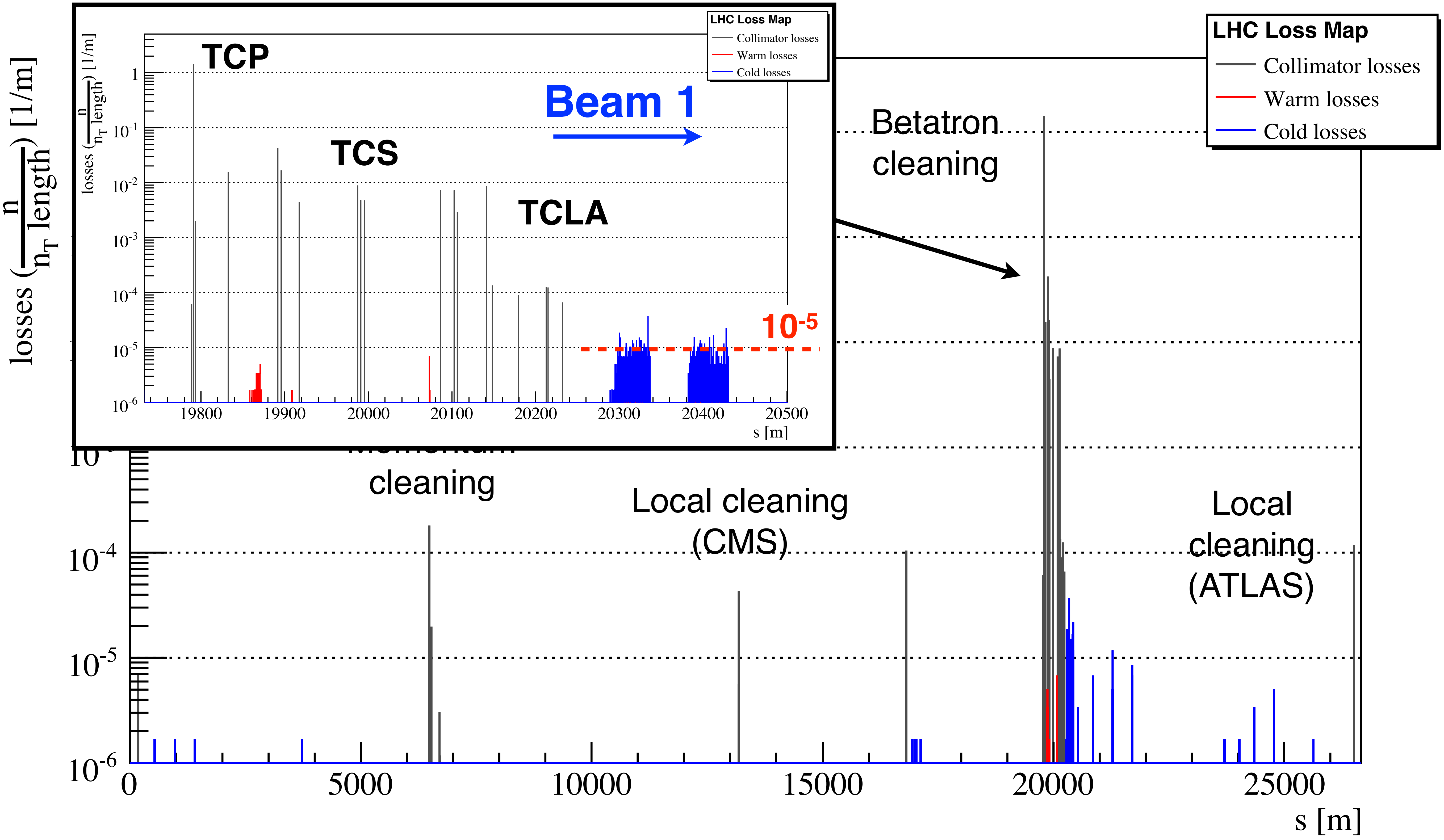
Including protection devices, a **5-stage cleaning** is required!
The system performance relies on achieving a well-defined **hierarchy** between different **collimator families** and **machine aperture**.

Simulated 7 TeV performance



Did achieve, on paper, cleaning inefficiencies of a few 10^{-5} in IR7.
Cold losses in experiments removed by local protection.

Simulated 7 TeV performance



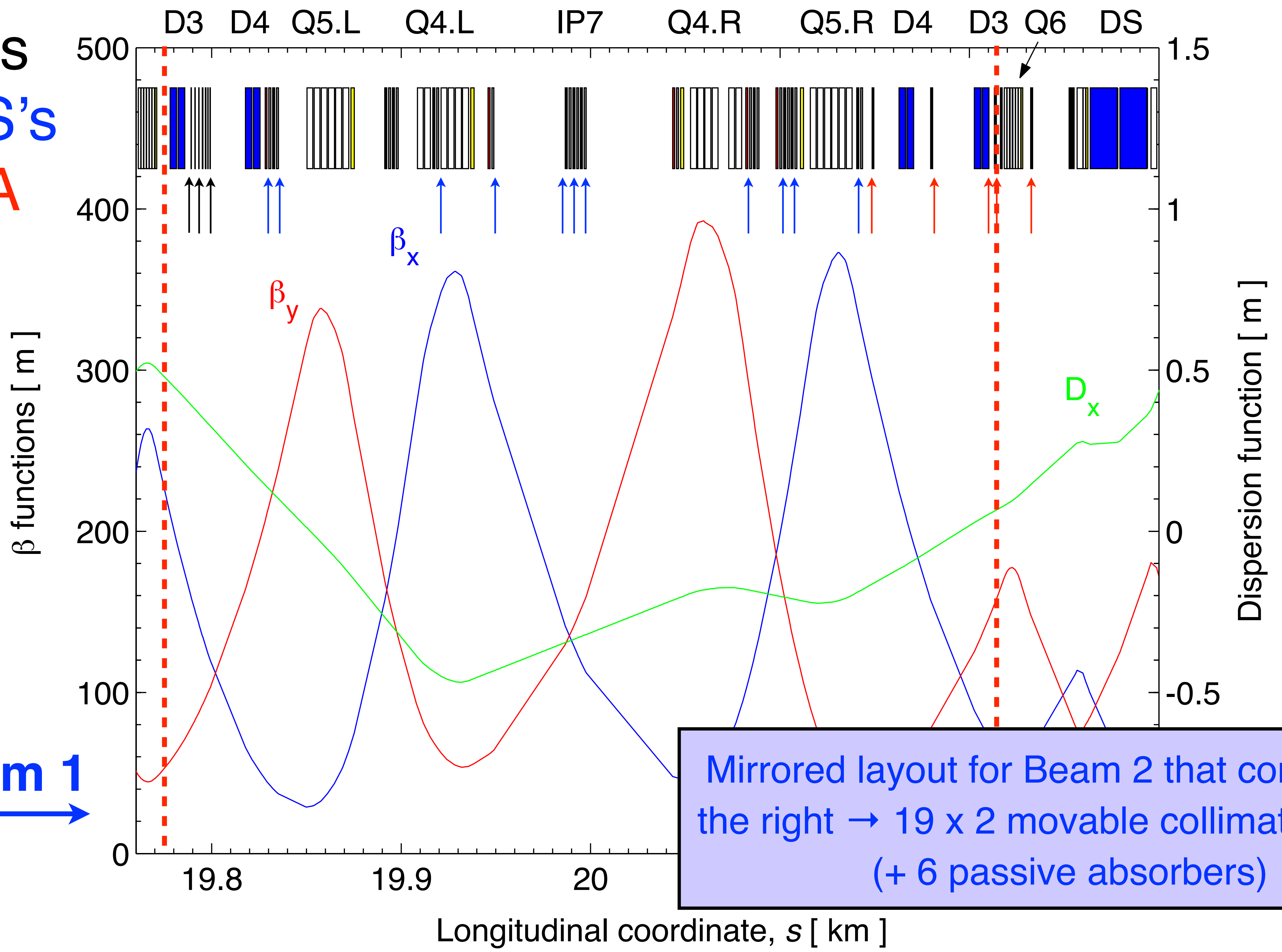
Did achieve, on paper, cleaning inefficiencies of a few 10^{-5} in IR7. Cold losses in experiments removed by local protection.

Betatron cleaning insertion

3 TCP's

11 TCS's

5 TCLA



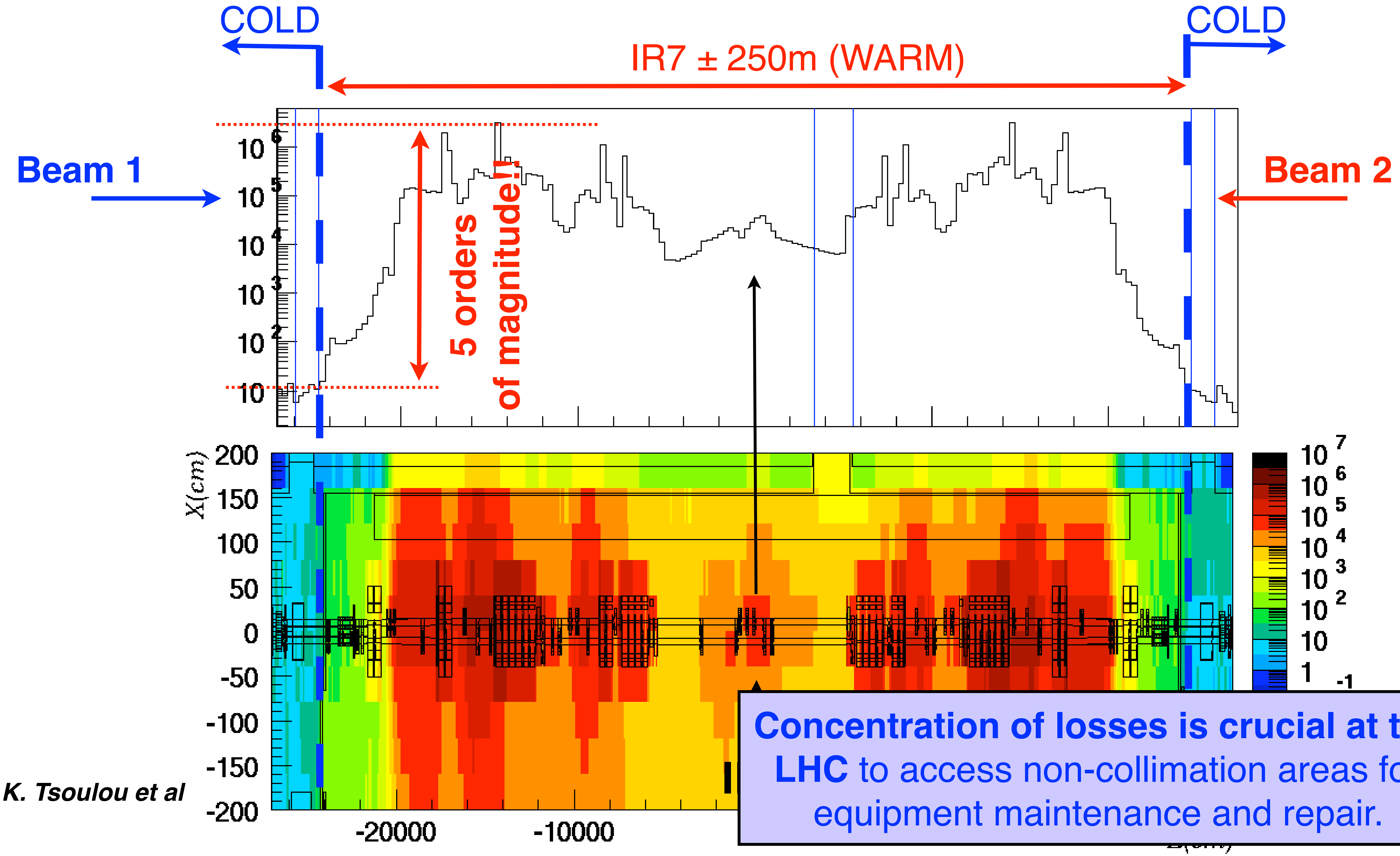
Mirrored layout for Beam 2 that comes from the right → 19 x 2 movable collimator in total (+ 6 passive absorbers)

Beam 1 →

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

Optics provides one full betatron oscillation to achieve the optimum TCS phases in warm section

Radiation doses in collimation region



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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!

Off-momentum cleaning systems

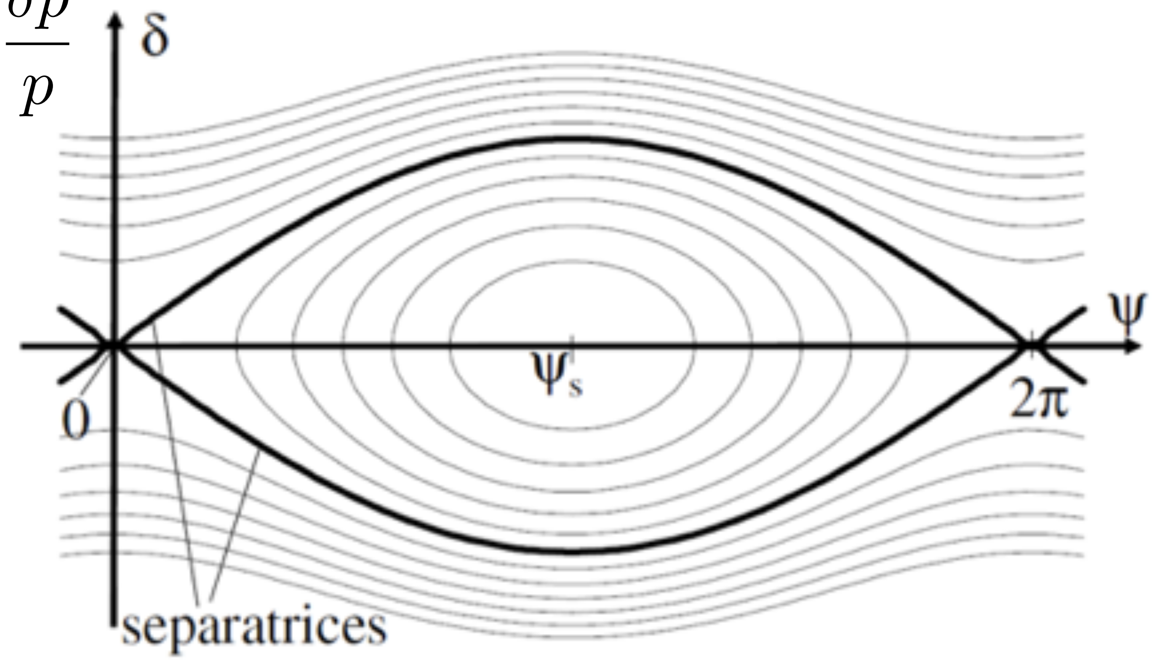
“**Off-momentum losses**” = losses occurring when beam particles lose the energy matching compared to the reference particle.

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

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?

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



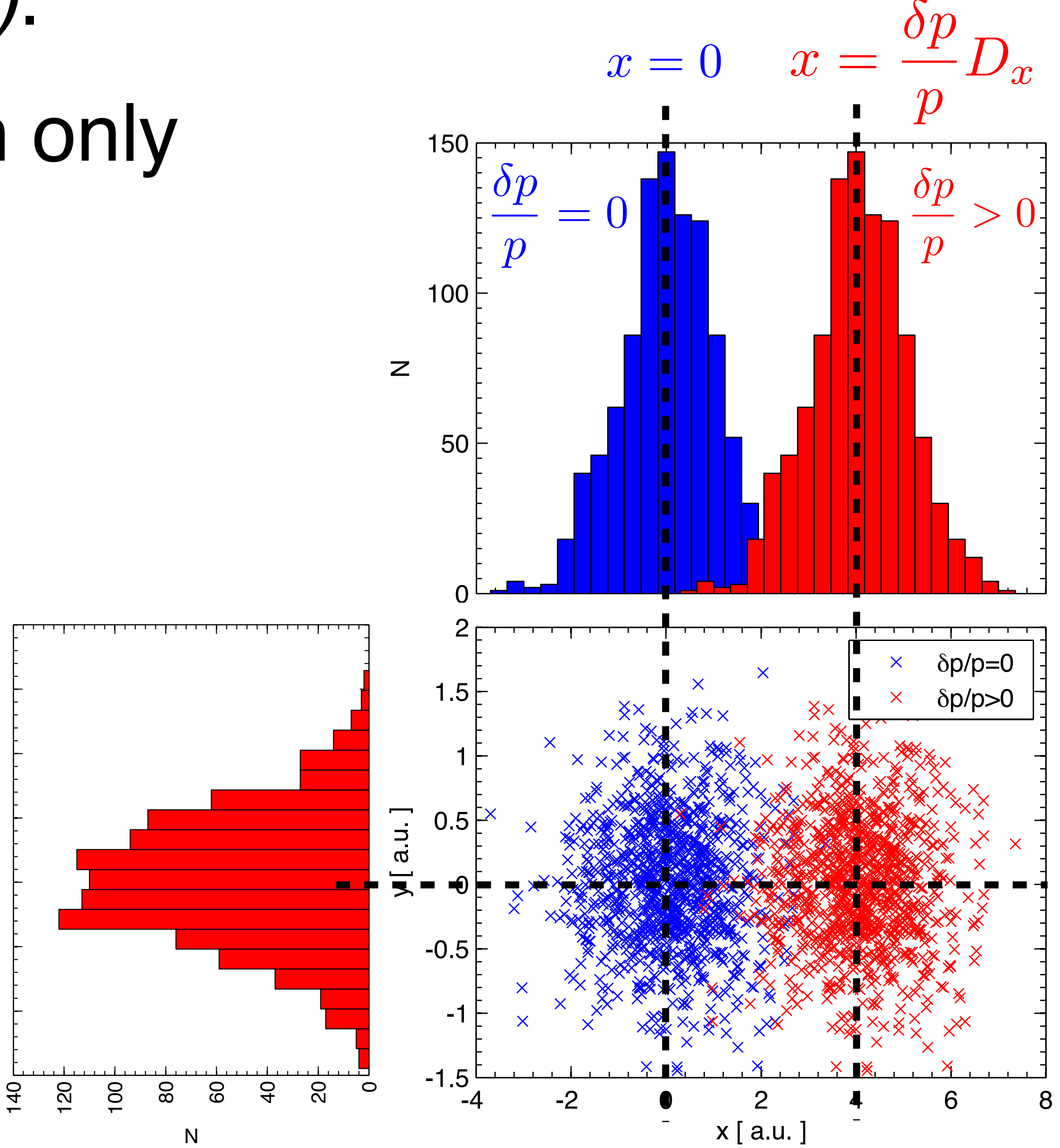
Catching off-momentum particles

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

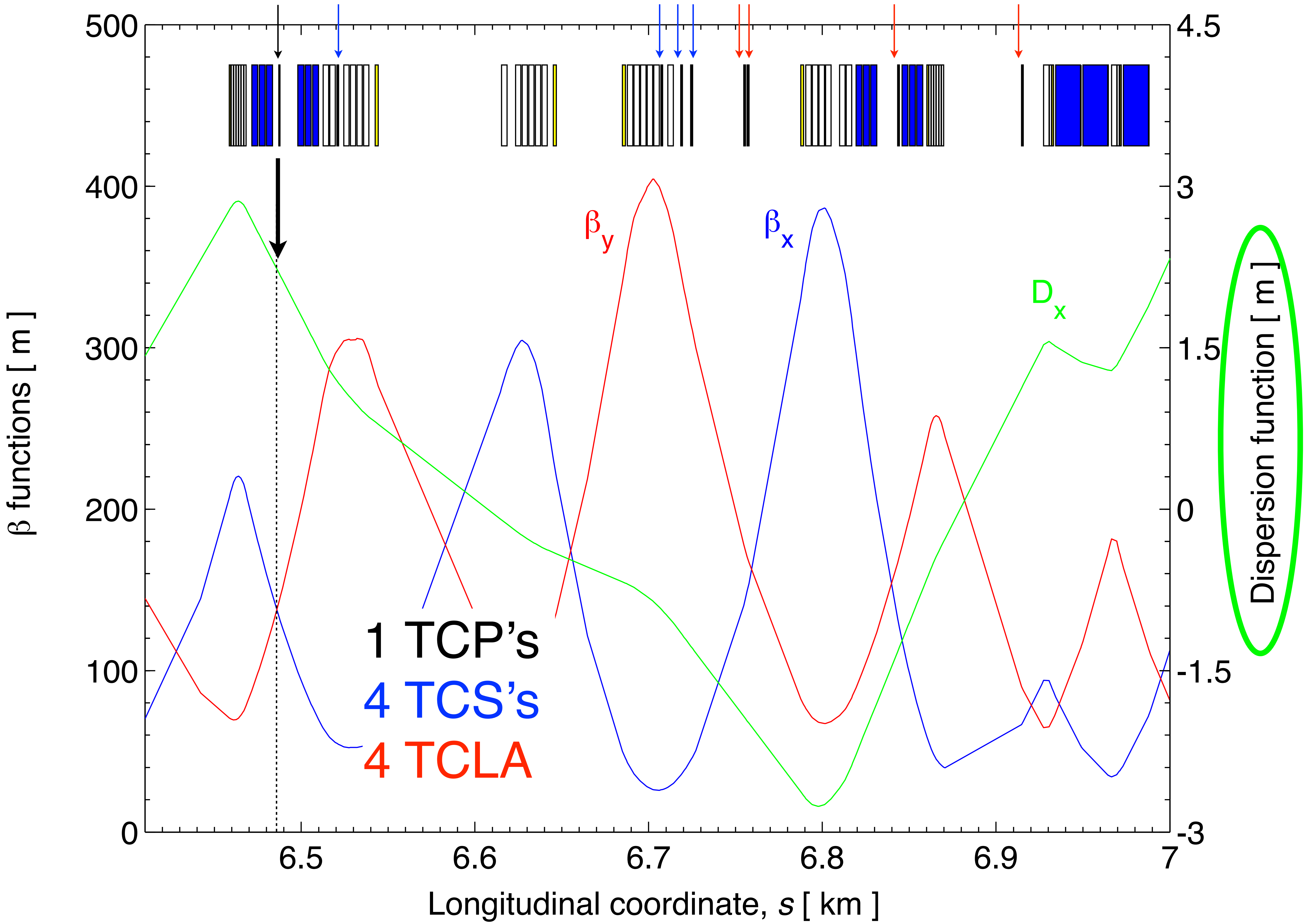
Energy errors translate into **shifts of position** that follows the periodic dispersion function $D_z(s)$.

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



How does the final LHC system look like?

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

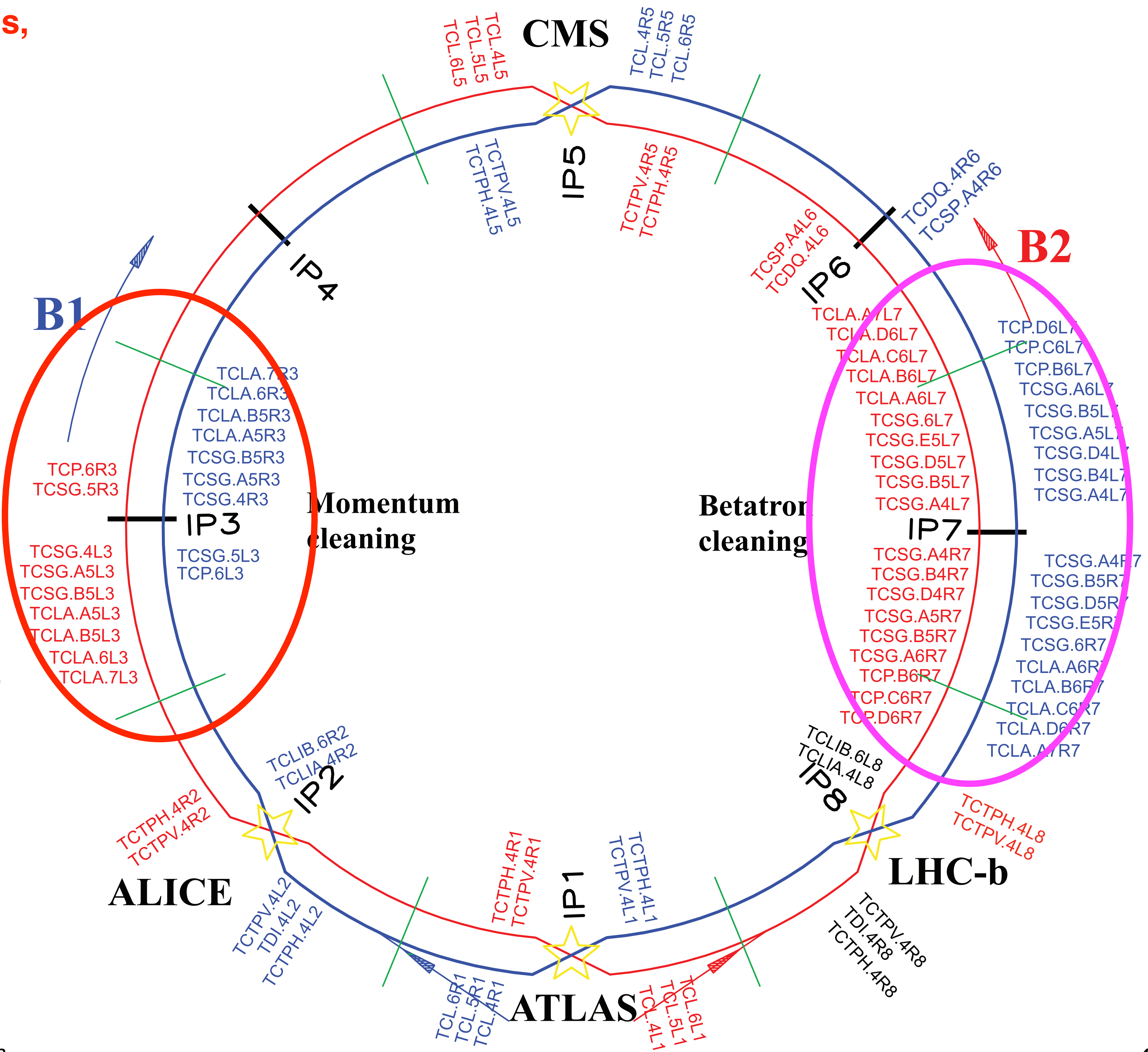
- **8 tertiary (2 per IP)**

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!



Plans for tomorrow

- ☑ LHC collimation design
- ☑ Operational performance at the LHC
- ☑ Collimation simulations
- ☑ Advanced collimation concepts
- ☑ Outlook