Graduate Studies in Accelerator Physics — PhD Student lectures
June 5th-7th, 2017
Università La Sapienza, Rome, Italy

The LHC machine protection and beam collimation

Part 2

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Accelerator Physics Group

Outline

- **Introduction to the LHC**
  - Recap. of basic accelerator physics
  - CERN accelerator complex
  - LHC parameters and detailed layouts
- **Machine protection and collimation**
  - Machine protection and collimation system
  - Design of beam halo collimation
  - The LHC beam collimation system
- **Advanced beam collimation**
  - Collimation in practice: LHC operation
  - Simulations and measurements
  - HL-LHC upgrade
  - Advanced concepts: crystals, hollow lenses

Outline - 2nd lecture

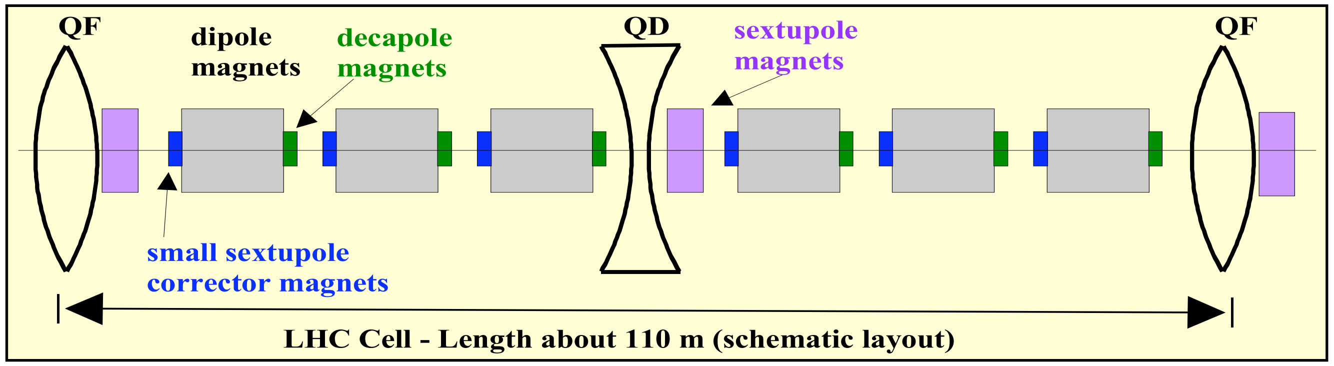
- **Main points from 1st lecture**
- **Machine protection and collimation**
  - — Concepts and LHC implementation
  - — Case study: 2008 event
- **Beam losses and collimation**
  - — Roles of beam collimation systems
  - — Beam losses mechanisms
- **Design of a multi-stage collimation system**
  - — Betatron collimation design
  - — Advanced: off-momentum, local protection
- **The LHC beam collimation system**
  - — Detailed layouts

High-intensity circular hadron accelerators

Basic accelerator physics

Beam rigidity:

$$\boxed{B\rho = \frac{p}{\mathrm{e}}}$$



Equation of motion and its solution:

Beta function

Dispersion

$$x'' + K(s)x = \frac{1}{\rho}\frac{\Delta p}{p_0} \quad \Rightarrow \quad \boxed{x(s) = A\sqrt{\beta_x(s)}\cos[\phi(s) + \phi_0] + D(s) \times \frac{\Delta p}{p}}$$

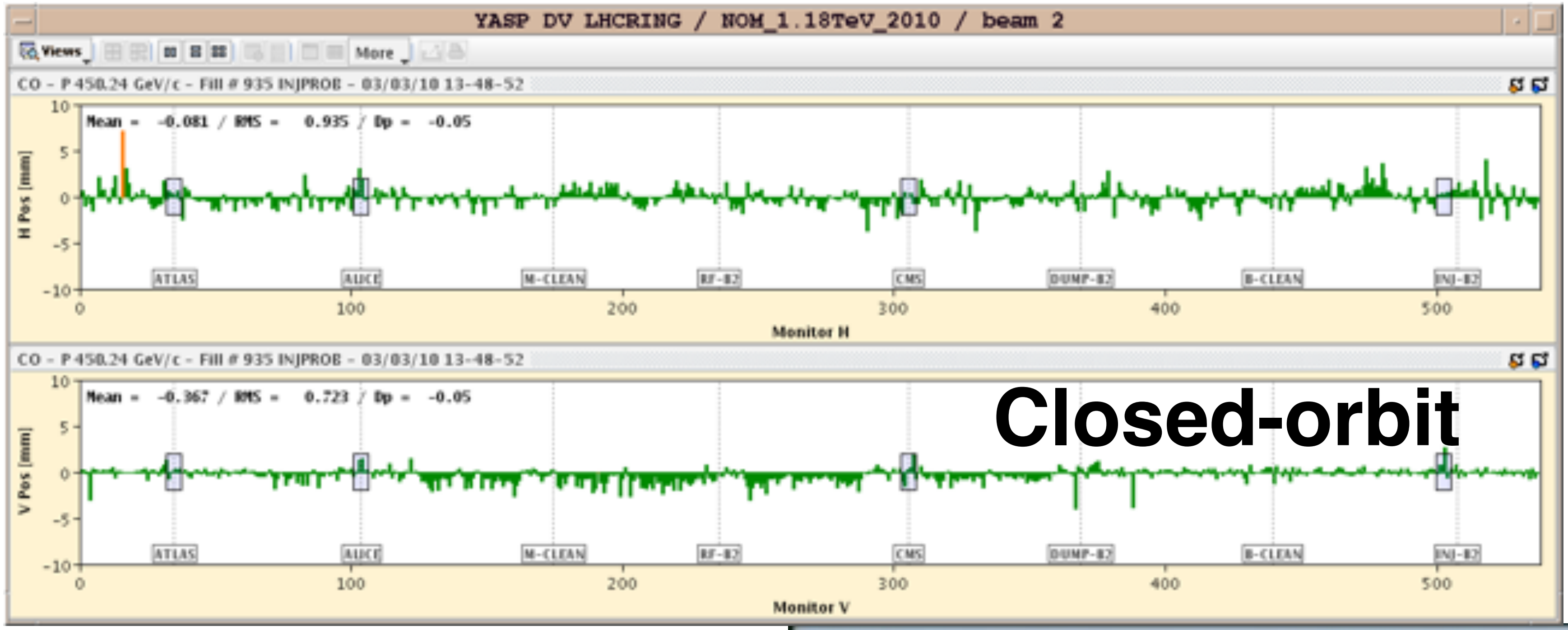
Betatron tune and chromaticity:

$$\boxed{Q = \frac{1}{2\pi}\int\frac{ds}{\beta(s)}} \qquad \boxed{Q' = \frac{\Delta Q}{\Delta p/p}}$$

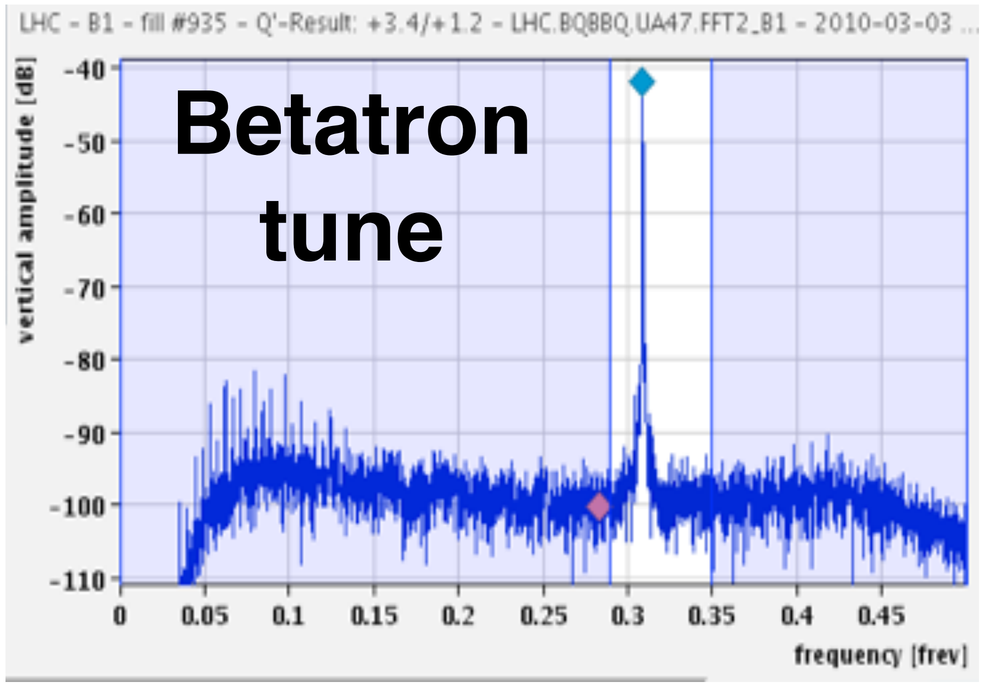
Emittance and beam size:

$$\boxed{\sigma_x(s) = \sqrt{\epsilon\beta_x(s) + [D_x(s)\delta]^2}}$$

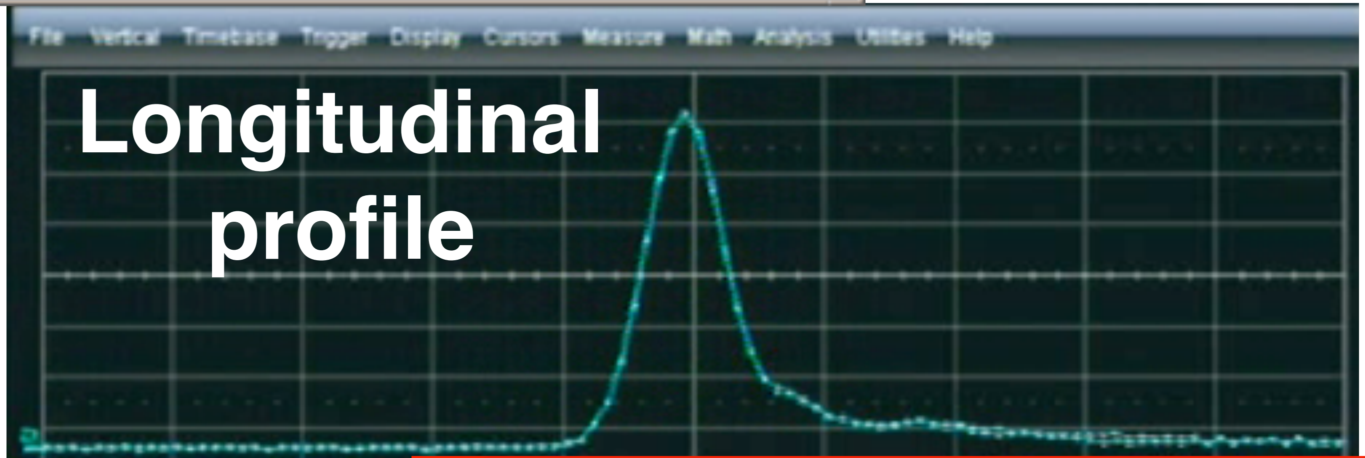
Beam measurements



Closed-orbit

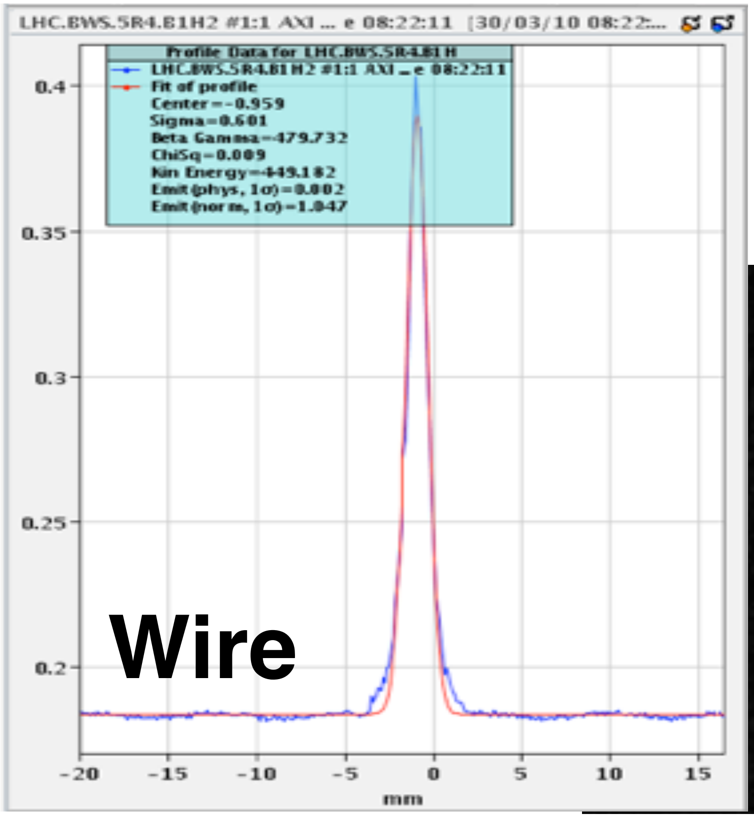


Betatron tune



Longitudinal profile

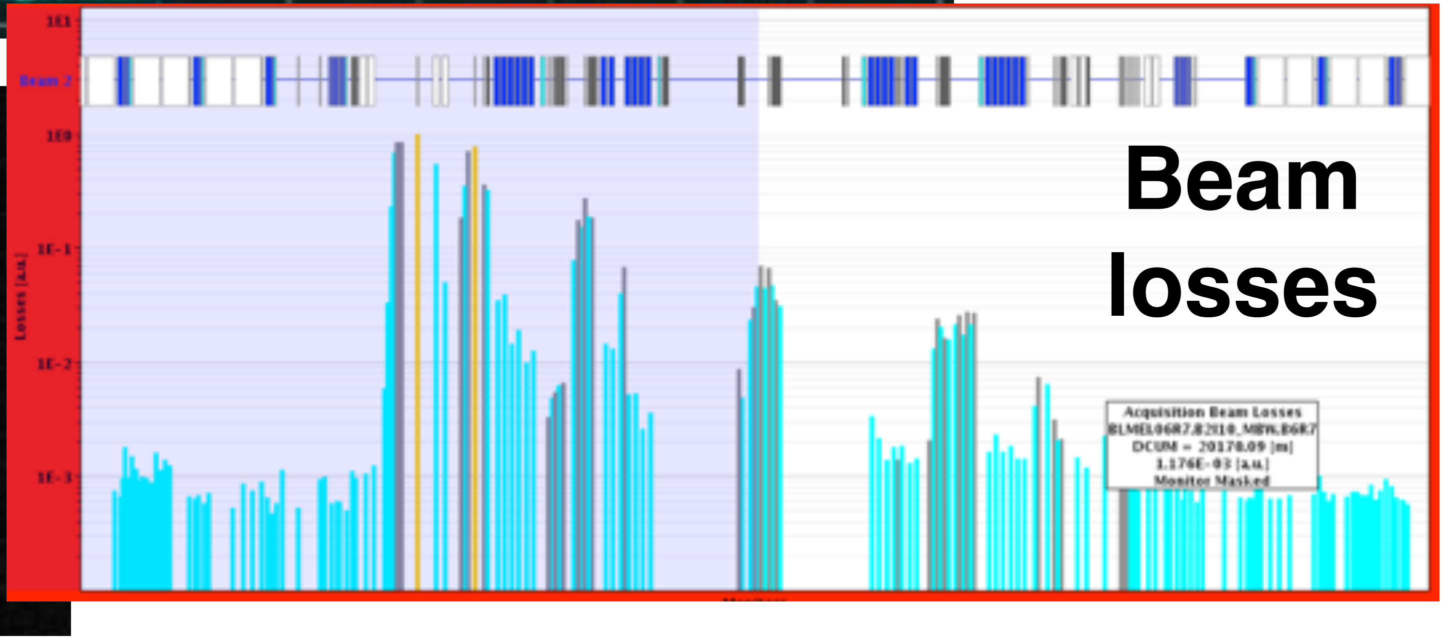
Transverse size



Center=-0.959
Sigma=0.601
Beta Gamma=479.732
ChiSq=0.009
Kin Energy=449.182
Emit (phys, 1σ)=0.002
Emit (norm, 1σ)=1.047

Wire

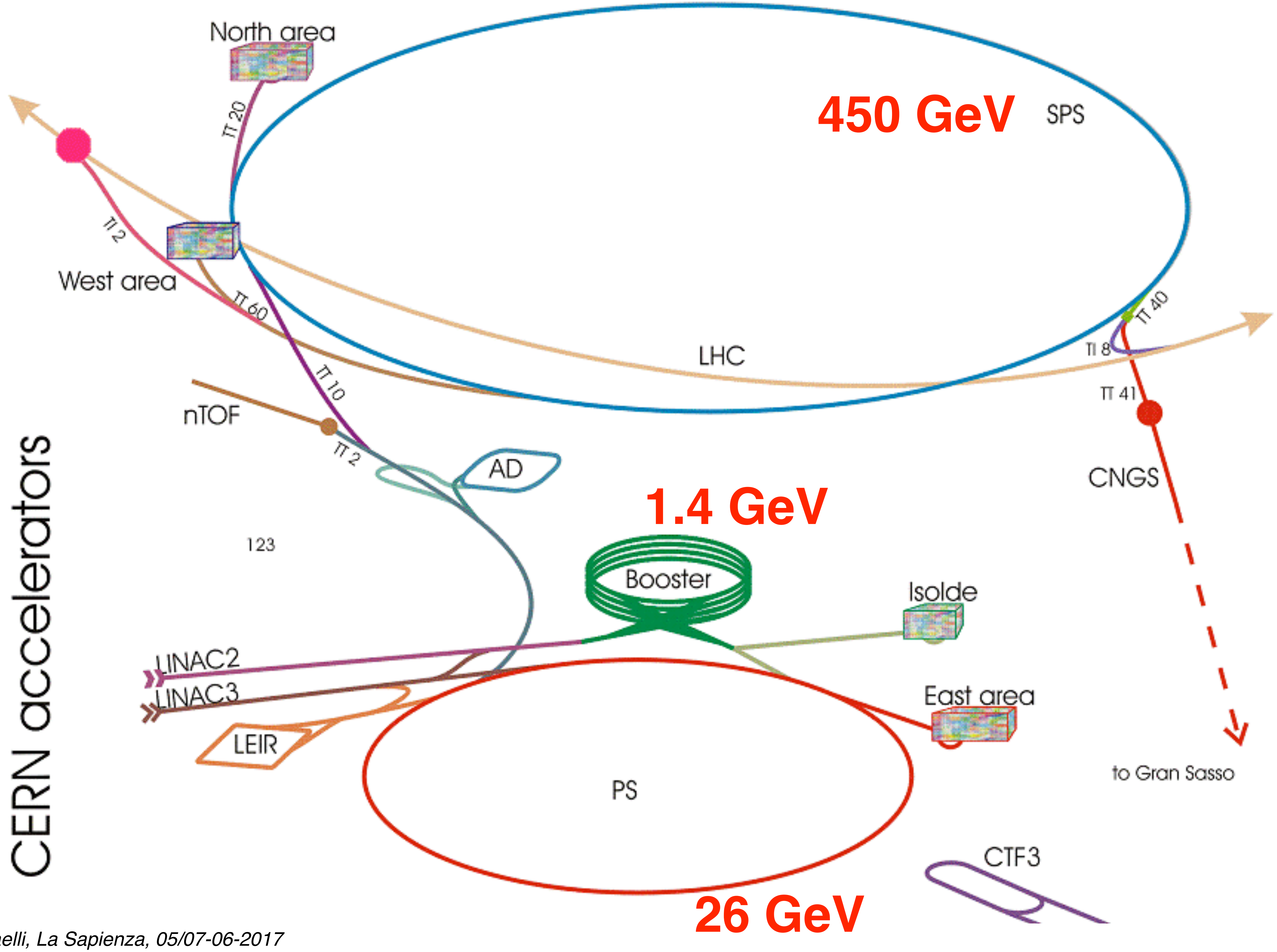
Synch. light



Acquisition Beam Losses
BLMEL06R7.B2I10_MBW.B6R7
DCUM = 20178.09 [m]
1.176E-03 [a.u.]
Monitor Masked

Beam losses

LHC injector complex



The Large Hadron Collider

Eight arcs and
eight straight sessions:

Point 1: Atlas, LHCf

Point 2: Alice, injection

Point 3: Momentum cleaning

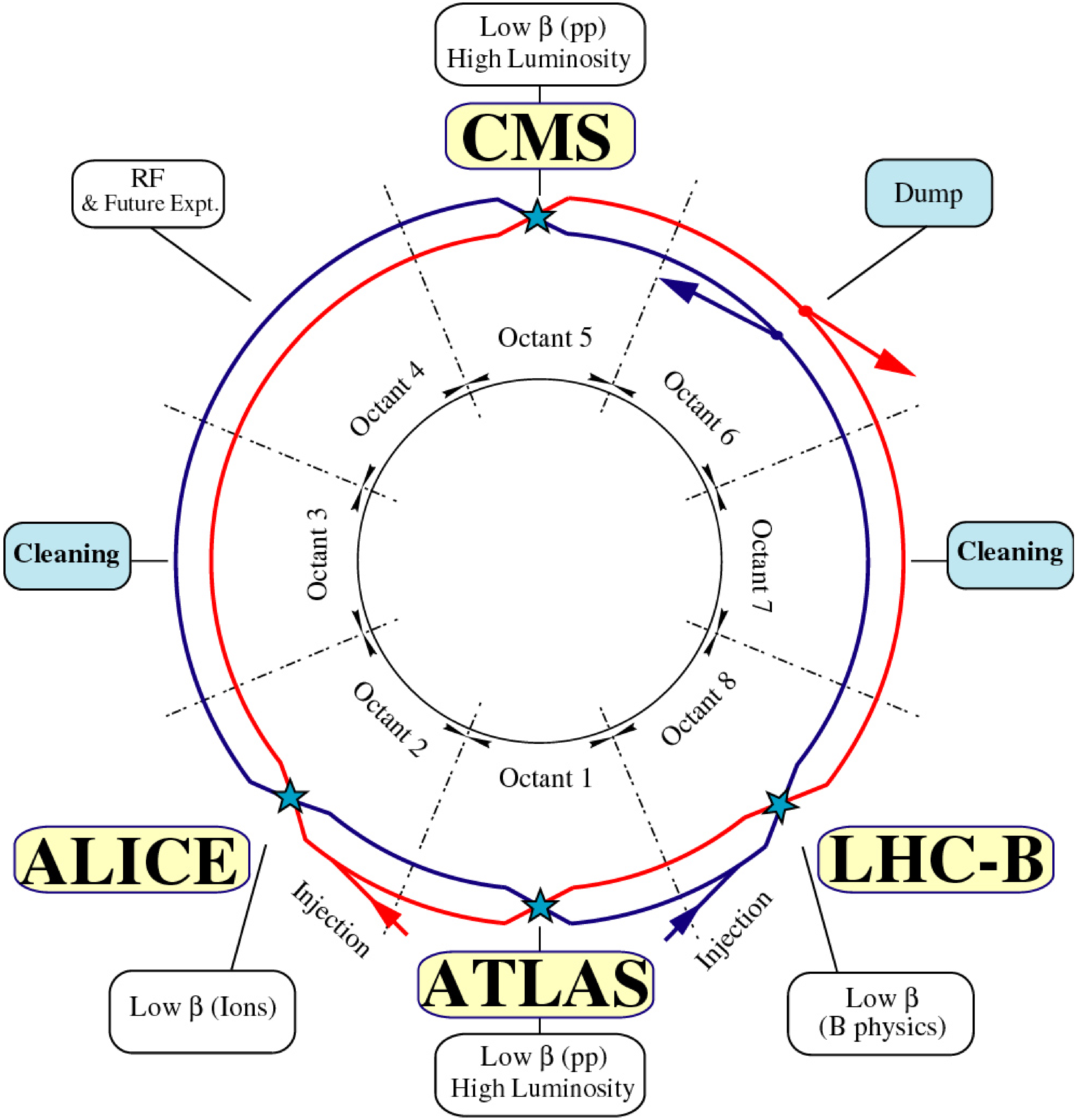
Point 4: RF

Point 5: CMS, TOTEM

Point 6: Beam Dumps

Point 7: Betatron cleaning

Point 8: LHCb, injection



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  - **Concepts and LHC implementation**
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Machine protection

Why do we have to care??

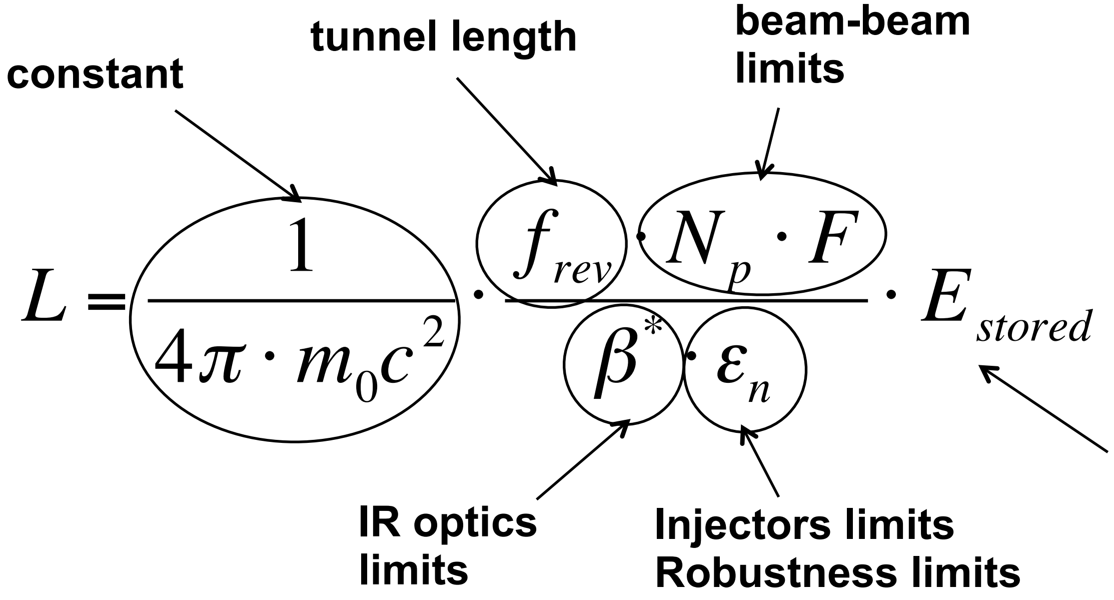
Energy stored in the superconducting magnet **10.4 GJ**

Energy stored in the 7 TeV beams **362 MJ**

We've seen what damage a 2.5 MJ beam, or even 1 bunch at 7 TeV, can do!

Why do we need so much?

Magnet energy is driven by the high-field requirement.
Beam stored energy is driven by luminosity increase!

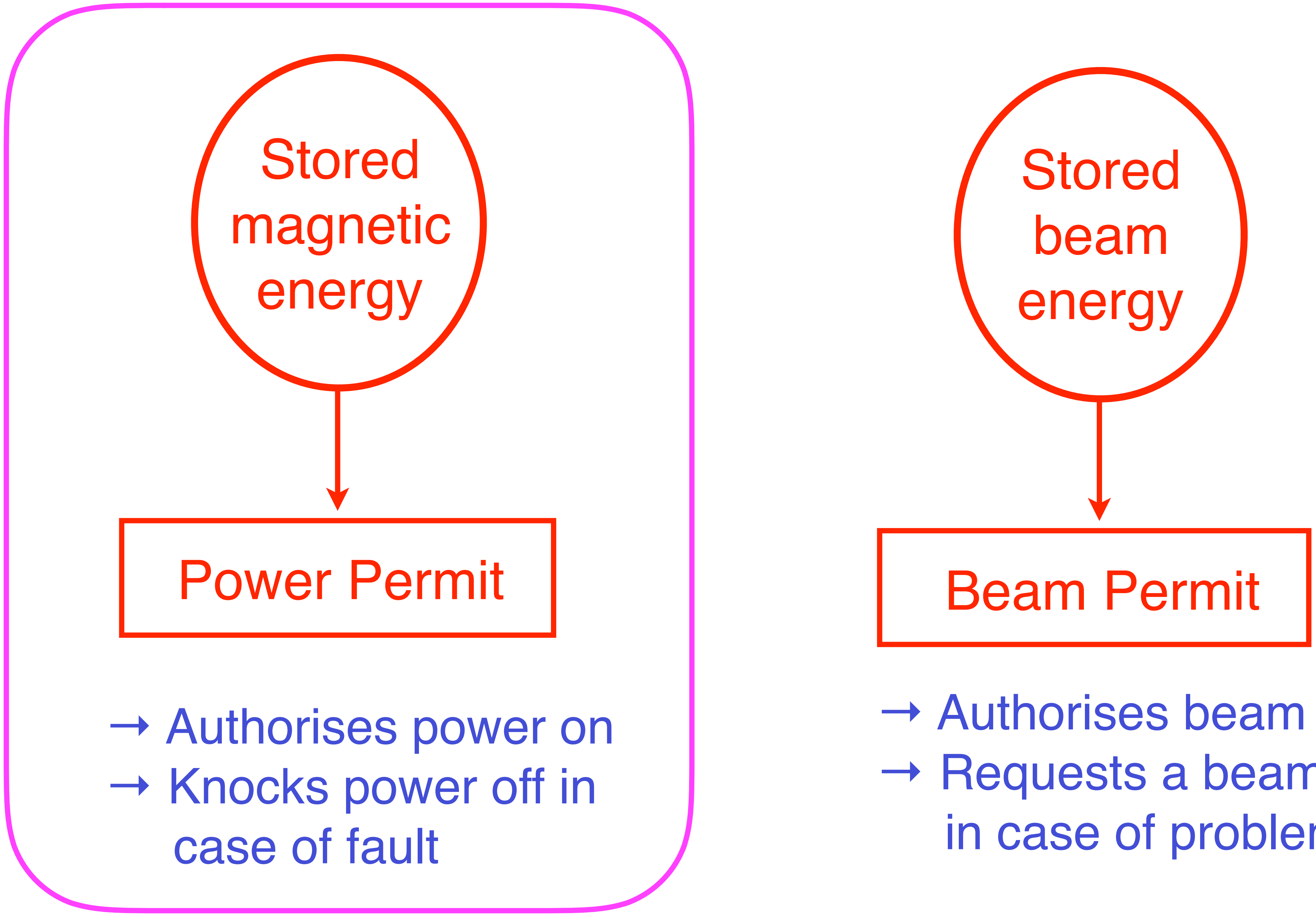


$$L = \frac{1}{4\pi \cdot m_0 c^2} \cdot \frac{f_{rev} \cdot N_p \cdot F}{\beta^* \cdot \varepsilon_n} \cdot E_{stored}$$

β^* = *IP beta function* ($\beta_x=\beta_y$)
ε_n = *norm. transv. emittance*
N_p = *protons per bunch*
f_{rev} = *revolution frequency*
F = *geometrical correction*
m_0 = *rest mass, e.g. of proton*
c = *velocity of light*

LHC luminosity is increased via stored energy!

Two sides of machine protection



Stored magnetic energy

Power Permit

→ Authorises power on

→ Knocks power off in case of fault

Stored beam energy

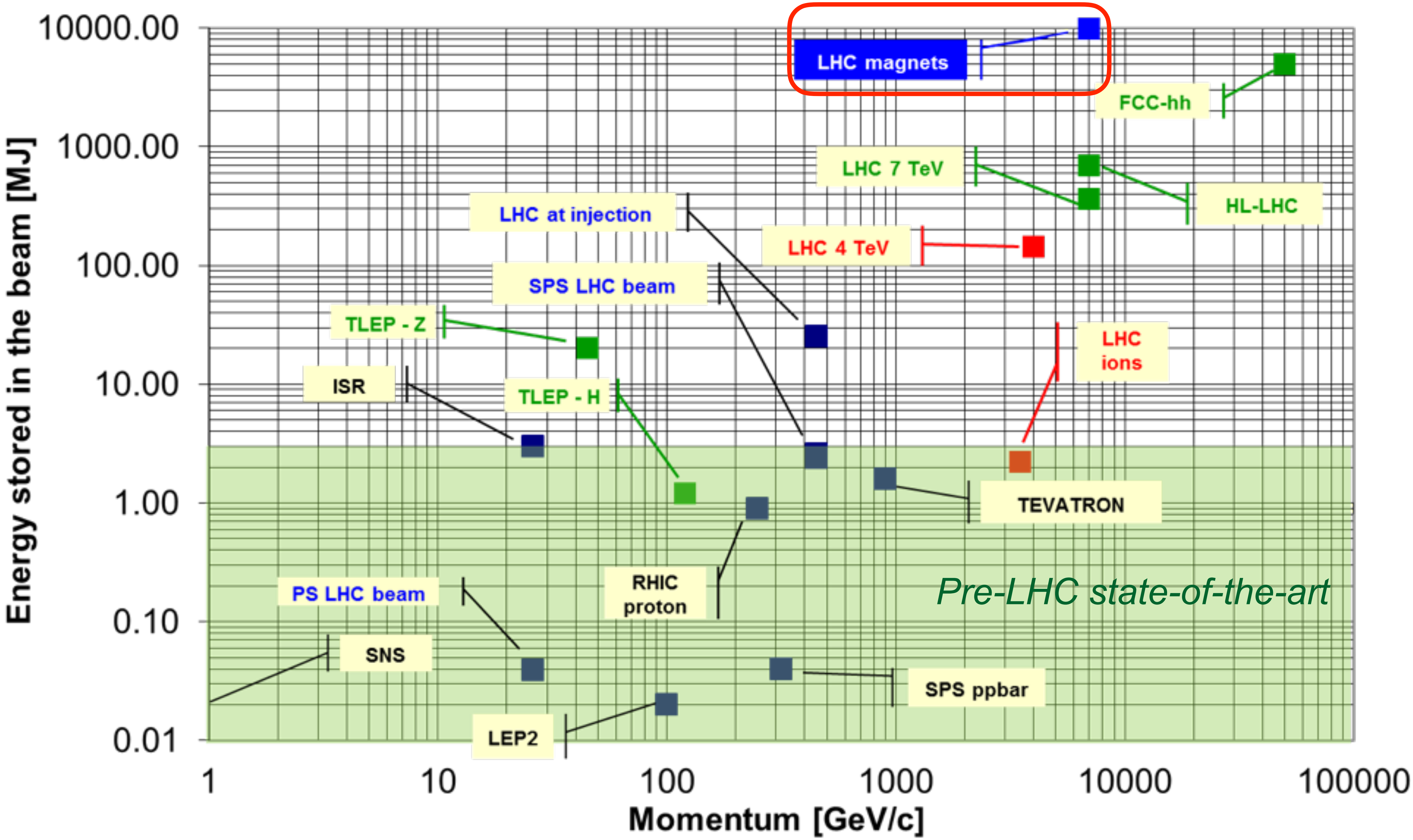
Beam Permit

→ Authorises beam

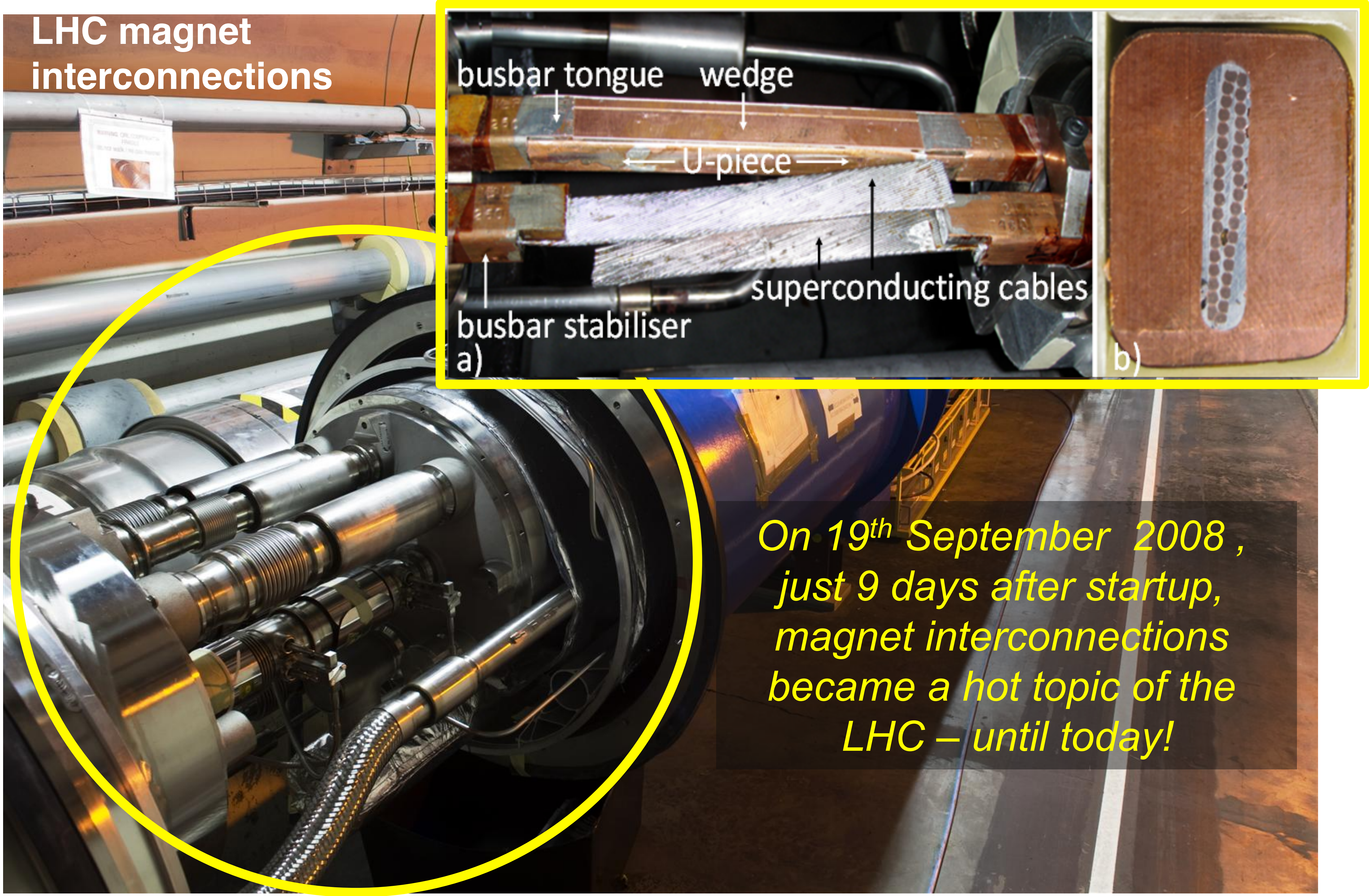
→ Requests a beam dump in case of problems

Remark: aspects relates to people safety and environment protection (legal obligations!) are not treated here.

The stored energy challenge



2008 incident on LHC magnet system



On 19th September 2008, just 9 days after startup, magnet interconnections became a hot topic of the LHC – until today!

List of events

LHC incident on September 19th 2008

- Last commissioning step of one out of the 8 main dipole electrical circuit in sector 34 : ramp to 9.3kA (5.5 TeV).
- At 8.7kA an electrical fault developed in the **dipole bus bar** located in the interconnection between quadrupole Q24.R3 and the neighboring dipole.

  Later correlated to a local resistance of ~220 nΩ – nominal value 0.35 nΩ.
- An electrical arc developed which punctured the helium enclosure.

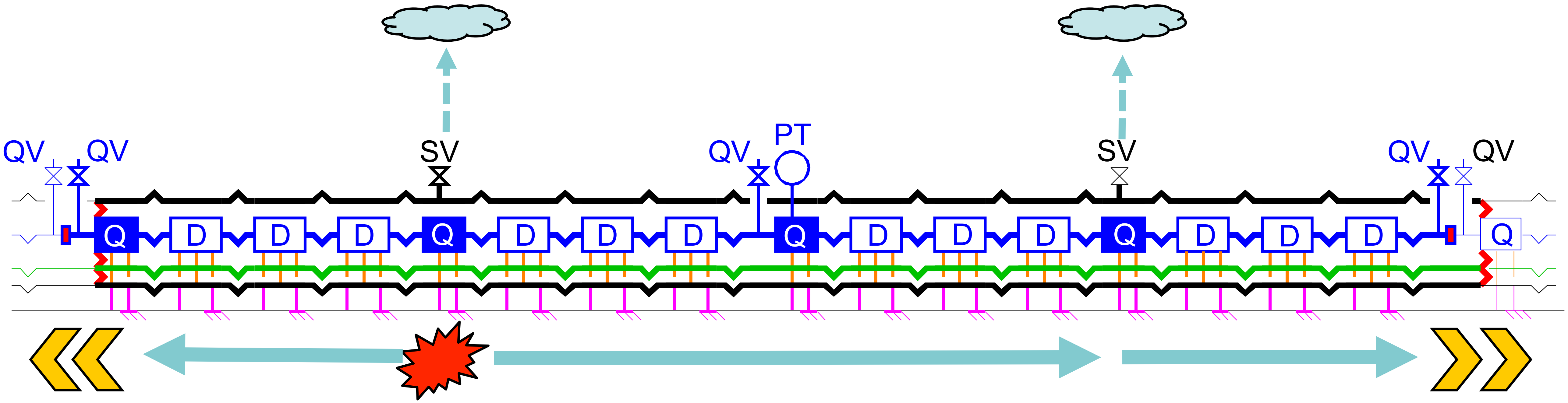
  Secondary arcs developed along the arc.

  Around 400 MJ from a total of 600 MJ stored in the circuit were dissipated in the cold-mass and in electrical arcs.
- Large amounts of Helium were released into the insulating vacuum.

  In total 6 tons of He were released.

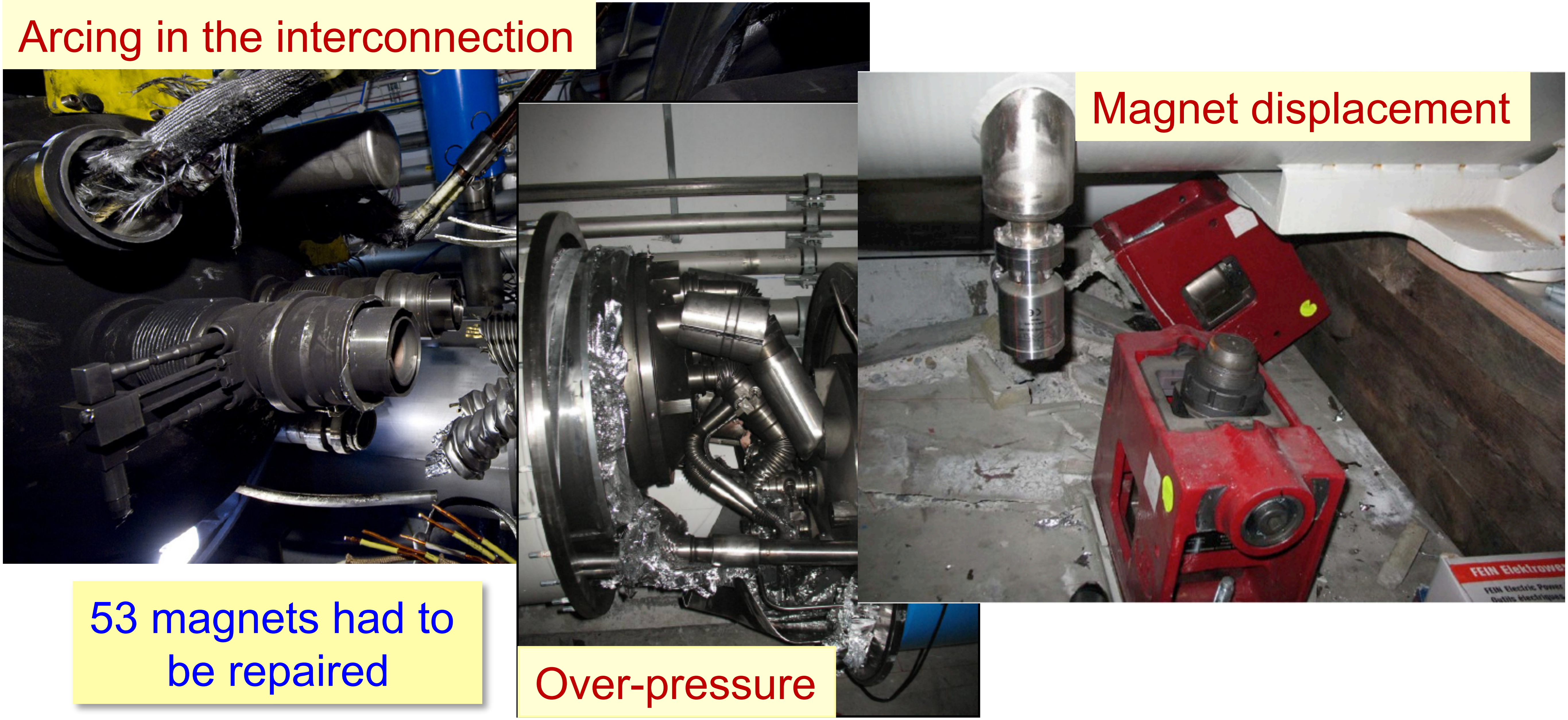
This incident involved magnet powering, but no beam!

Helium pressure wave



- Pressure wave propagates along the magnets inside the insulating vacuum enclosure.
- Rapid pressure rise :
  - Self actuating relief valves could not handle the pressure.
    designed for 2 kg He/s, incident ~ 20 kg/s.
  - Large forces exerted on the vacuum barriers (every 2 cells).
    designed for a pressure of 1.5 bar, incident ~ 8 bar.
  - Several quadrupoles displaced by up to ~50 cm.
  - Connections to the cryogenic line damaged in some places.
  - Beam vacuum to atmospheric pressure.

Damage from 600MJ at the LHC



Arcing in the interconnection

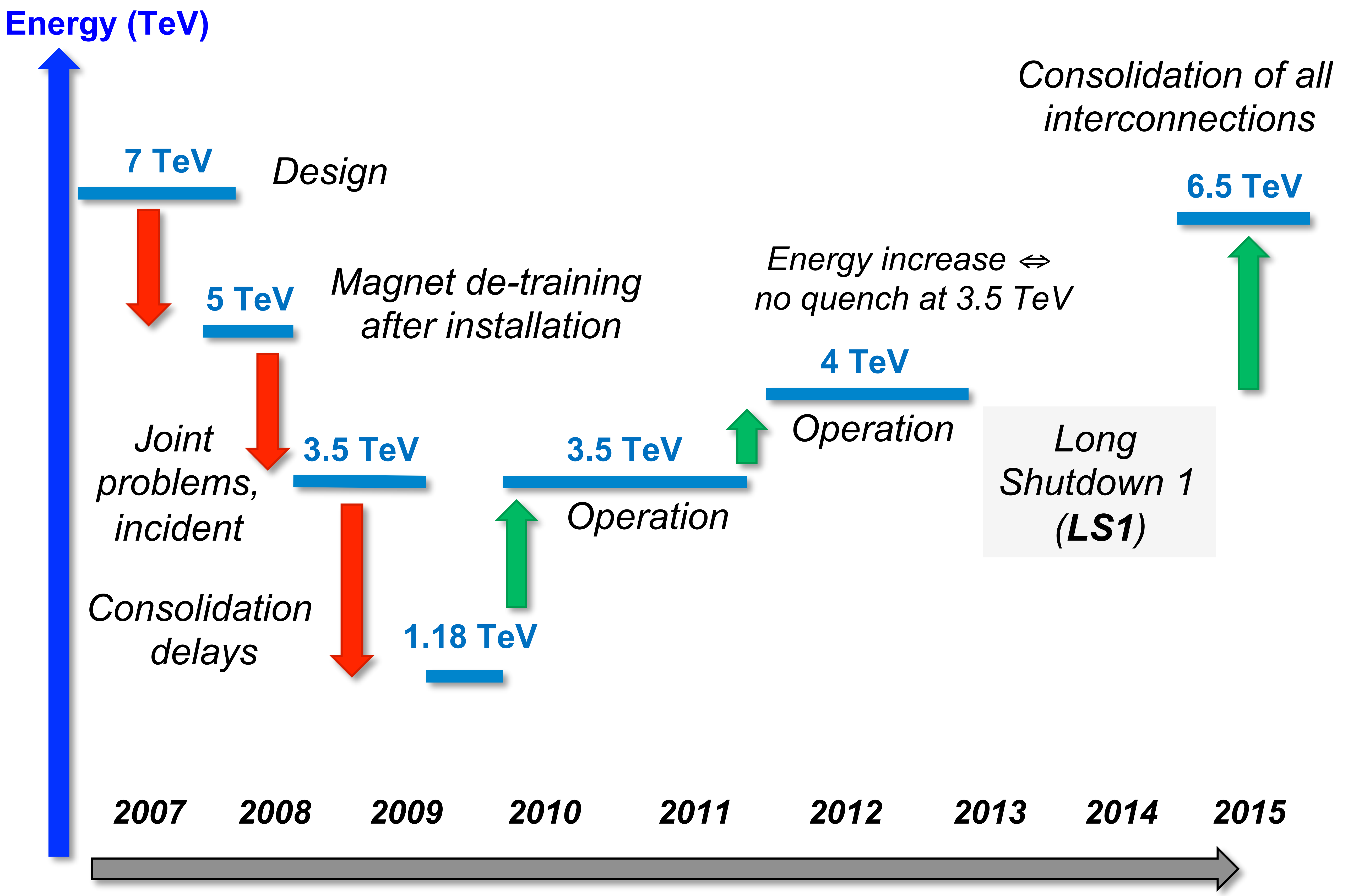
Magnet displacement

53 magnets had to be repaired

Over-pressure

A major event for the LHC that caused (1) Nearly 1 year of delay in the startup with beam; (2) Severe limitations to the operating beam energy in Run I (2010-12); (3) Massive works in 2013-2014 to repair all the 10’000 interconnections! (4) Associated financial implications for delays and repair…

Consequences — energy evolution



Energy (TeV)

7 TeV

Design

Joint problems, incident

5 TeV

Magnet de-training after installation

3.5 TeV

Consolidation delays

1.18 TeV

3.5 TeV

Operation

Energy increase ⇔ no quench at 3.5 TeV

4 TeV

Operation

*Long Shutdown 1 (**LS1**)*

Consolidation of all interconnections

6.5 TeV

2007 2008 2009 2010 2011 2012 2013 2014 2015

Beam damage — Relevant parameters

- ❑ Momentum of the particle
- ❑ Particle type

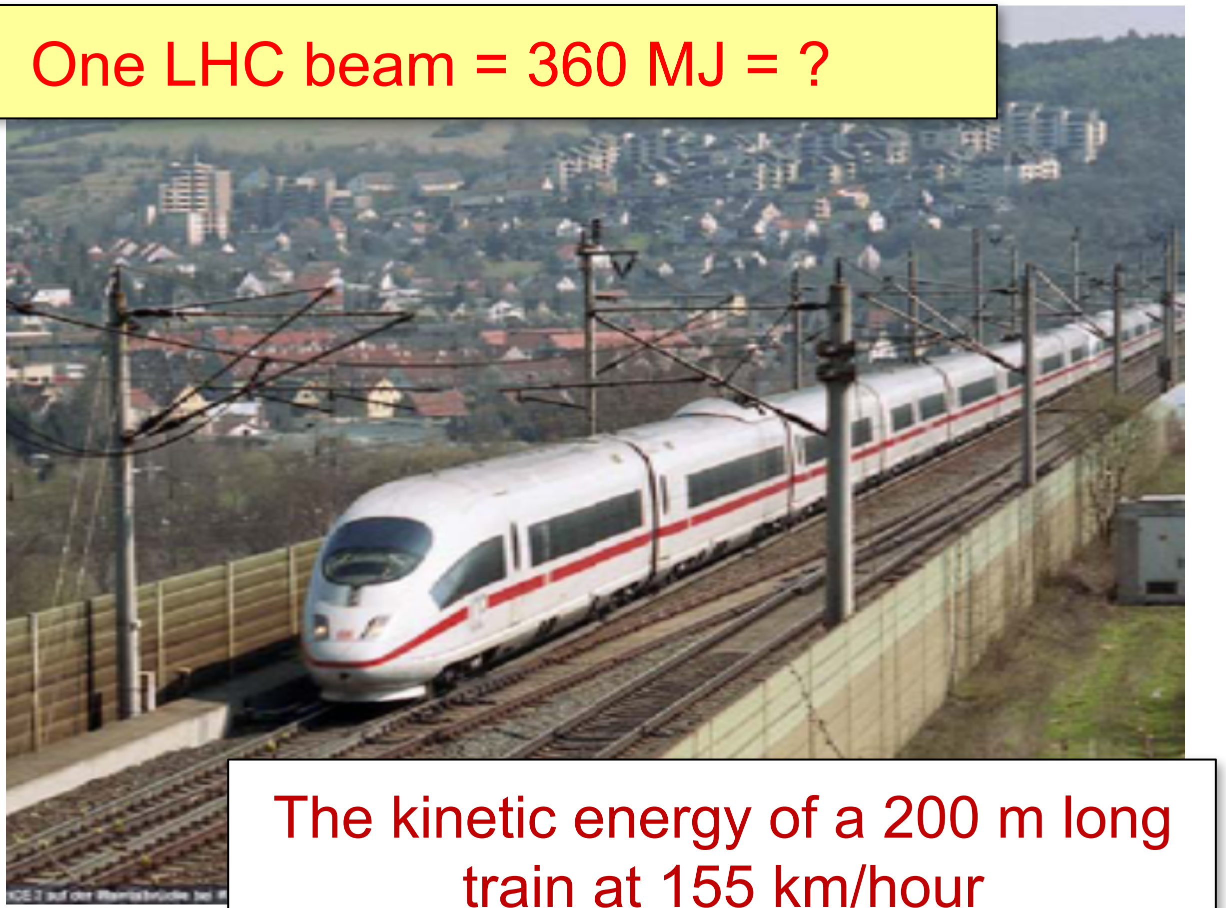
  Activation is mainly an issue for hadron accelerators.
- ❑ Energy stored in the beam

  1 MJ can heat and melt 1.5 kg of copper.

  1 MJ = energy stored in 0.25 kg of TNT.
- ❑ Beam power
- ❑ Beam size
- ❑ Time structure of beam

Key factor :
how easily and how fast
the energy is released !!

One LHC beam = 360 MJ = ?



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

90 kg of TNT

8 litres of gasoline

15 kg of chocolate

Three P’s for machine protection (MP^3)

- Protect the machine
  - Highest priority is to avoid damage of the accelerator.
- Protect the beam
  - Complex protection systems reduce the availability of the accelerator, the number of “false” interlocks stopping operation must be minimized.
  - Trade-off between protection and operation.
- Provide the evidence
  - Clear (post-mortem) diagnostics must be provided when:
    - the protection systems stop operation,
    - something goes wrong (failure, damage, but also ‘near miss’).

Machine protection philosophy

Stored magnetic energy

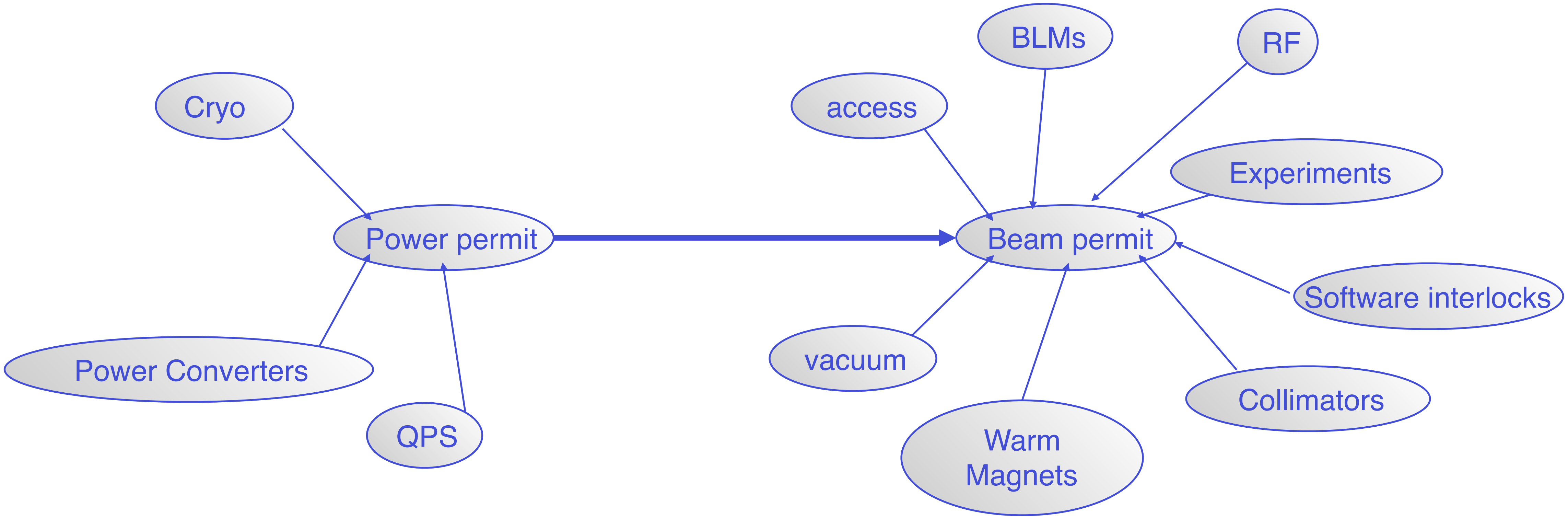
→ **Power Permit**

→ Authorises power on
→ Knocks power off in case of fault

Stored beam energy

→ **Beam Permit**

→ Authorises beam
→ Requests a beam dump in case of problems



Passive and active protection

Active protection

- ○ Equipment surveillance.
- ○ Beam observation.
- ○ Extraction (dump) kickers.

Detection of a failure directly on the equipment or by its effects on the beam.

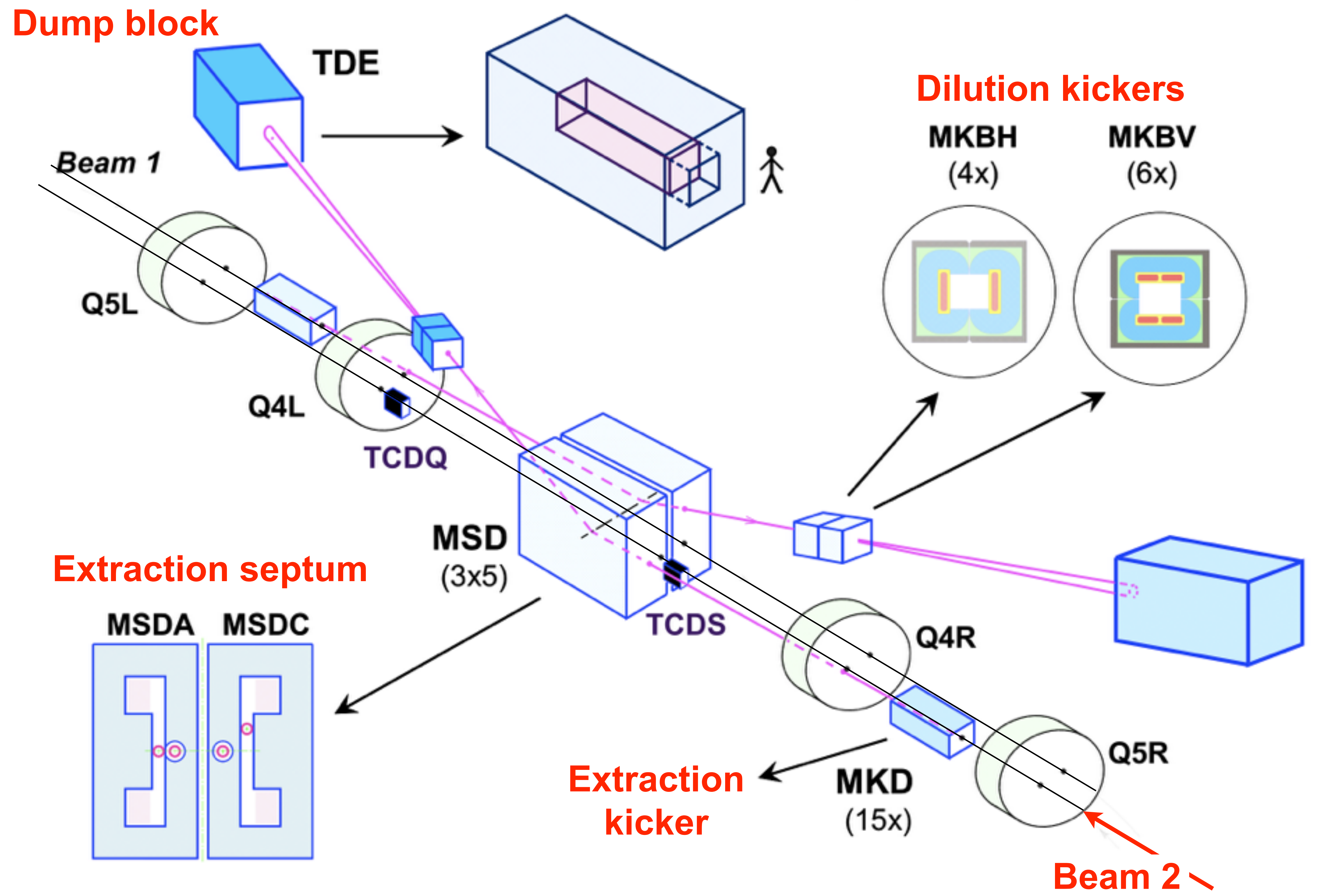
Passive protection

- ○ Collimators.
- ○ Masks.
- ○ Absorbers.
- ○ Dumps.

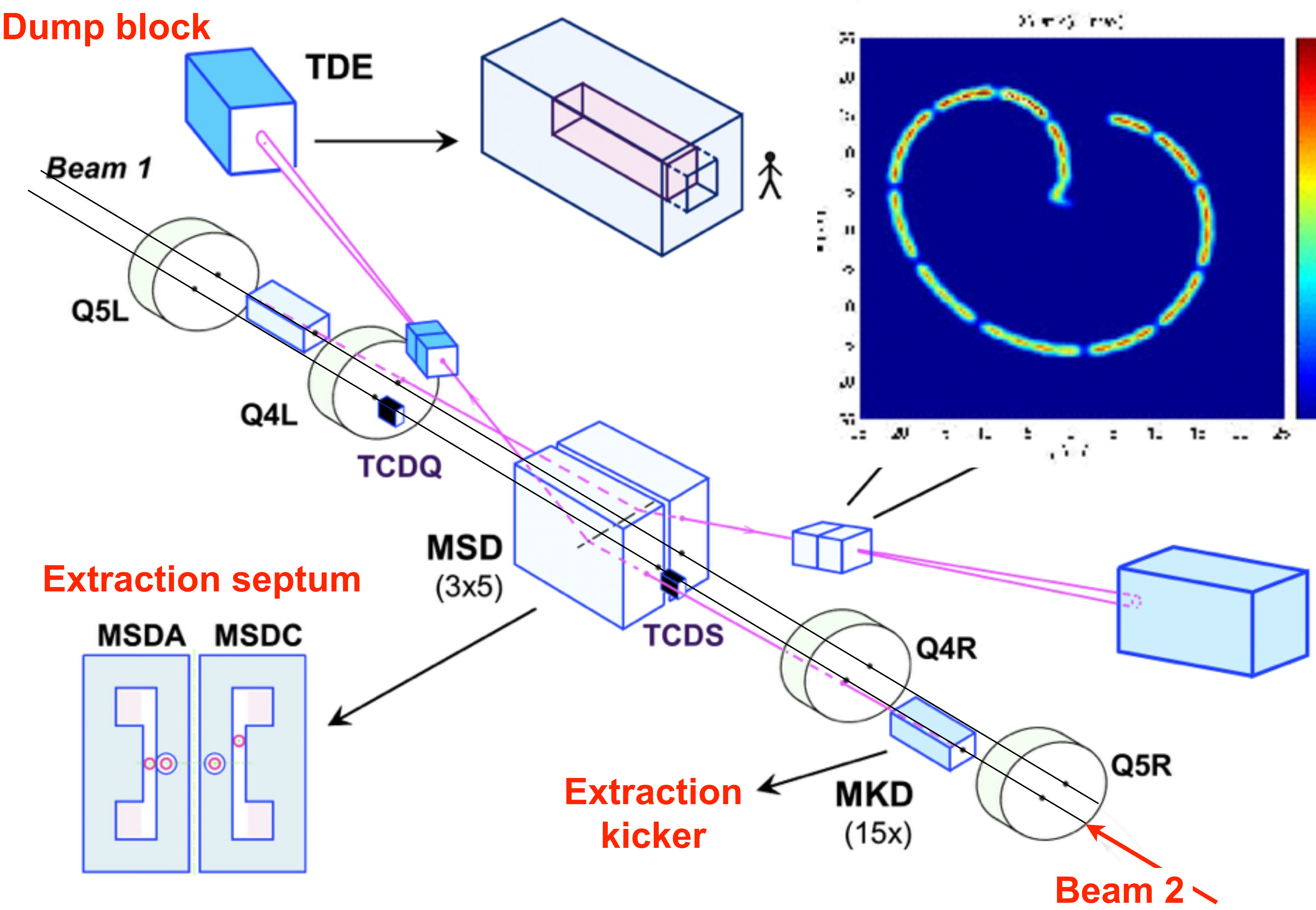
Obstacles to absorb/dilute the energy energy to mitigate risks of damage

Modern MP systems require both passive and active protection to cover all failure cases. The LHC system provided an unprecedented performance needed to meet the specific challenges of 362MJ beams!

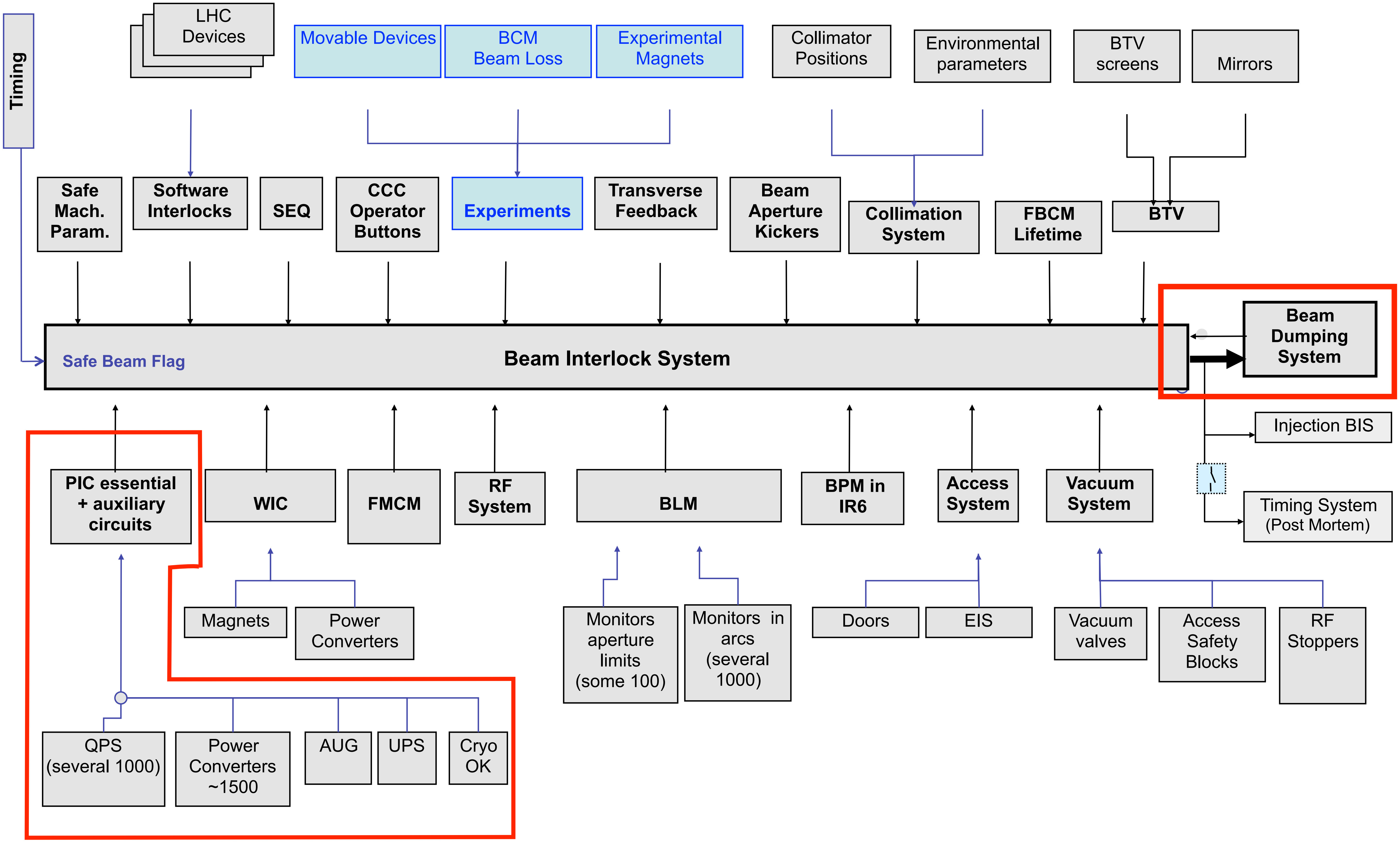
Recap.: LHC beam dump system



Recap.: LHC beam dump system



In practice....



Timing

LHC Devices

Movable Devices

BCM Beam Loss

Experimental Magnets

Collimator Positions

Environmental parameters

BTV screens

Mirrors

Safe Mach. Param.

Software Interlocks

SEQ

CCC Operator Buttons

Experiments

Transverse Feedback

Beam Aperture Kickers

Collimation System

FBCM Lifetime

BTV

Safe Beam Flag

Beam Interlock System

Beam Dumping System

Injection BIS

Timing System (Post Mortem)

PIC essential + auxiliary circuits

WIC

FMCM

RF System

BLM

BPM in IR6

Access System

Vacuum System

Magnets

Power Converters

Monitors aperture limits (some 100)

Monitors in arcs (several 1000)

Doors

EIS

Vacuum valves

Access Safety Blocks

RF Stoppers

QPS (several 1000)

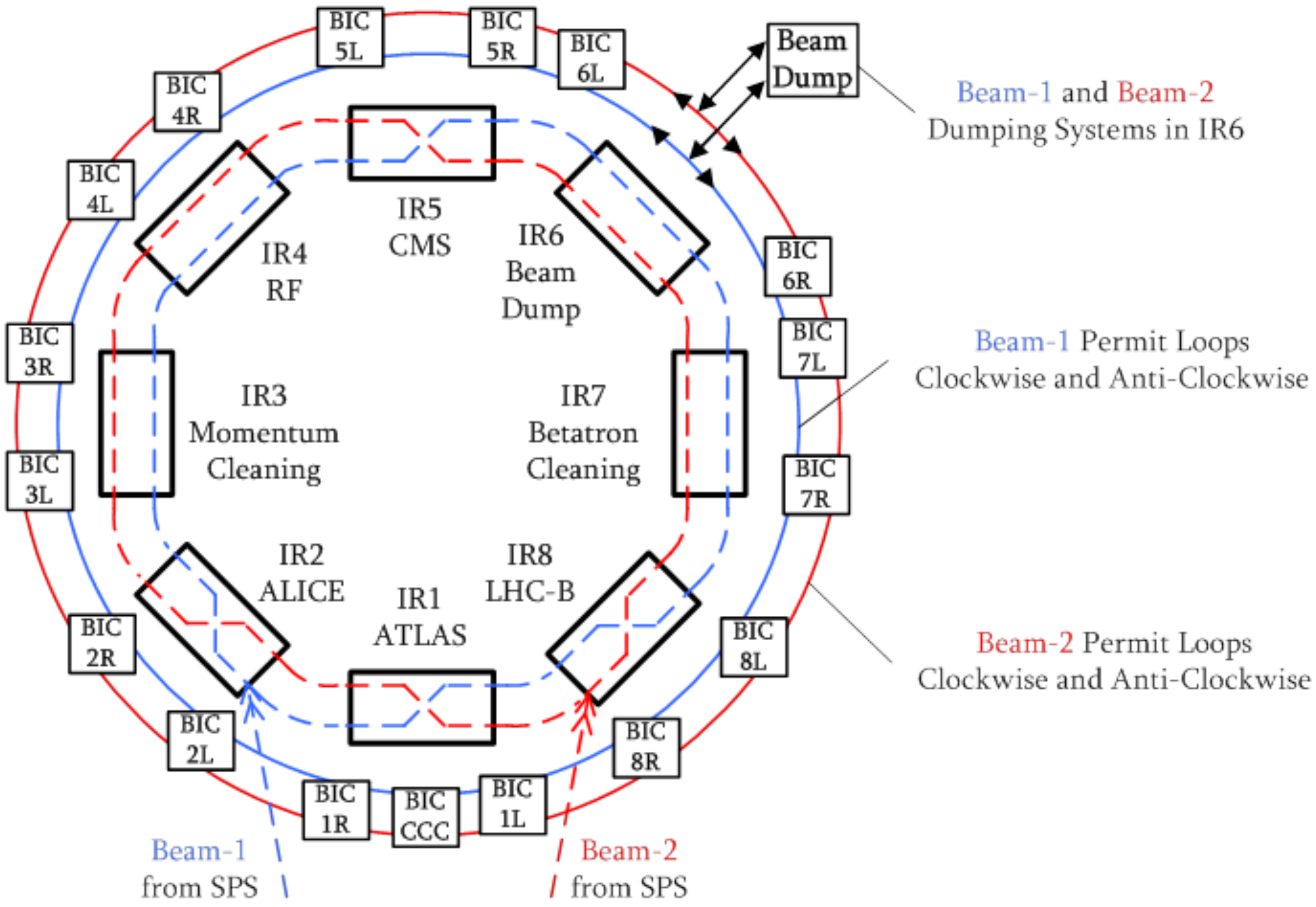
Power Converters ~1500

AUG

UPS

Cryo OK

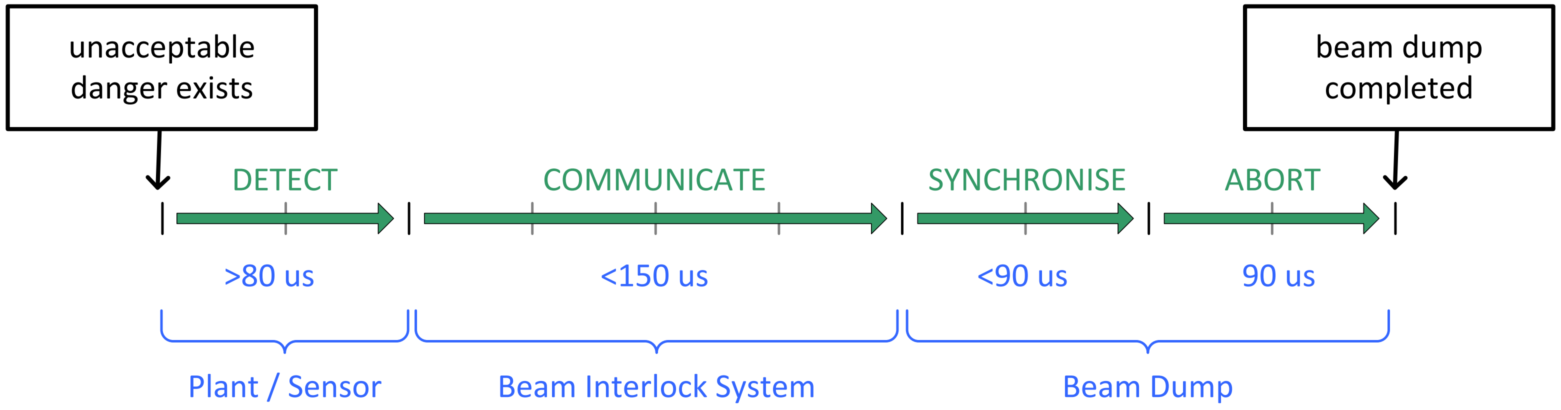
Beam interlock implementation



- ❑ The BPLs are connected to the LHC beam dumping system: a dump is trigger as soon as the signal of a single BPL is stopped.
- ❑ The BPLs are also connected to the LHC injection and SPS extraction interlock systems (same hardware design).

At the LHC the dump delay can reach ~3 turns ~300 μs

Revolution time = 89µs



unacceptable danger exists

beam dump completed

DETECT >80 us

COMMUNICATE <150 us

SYNCHRONISE <90 us

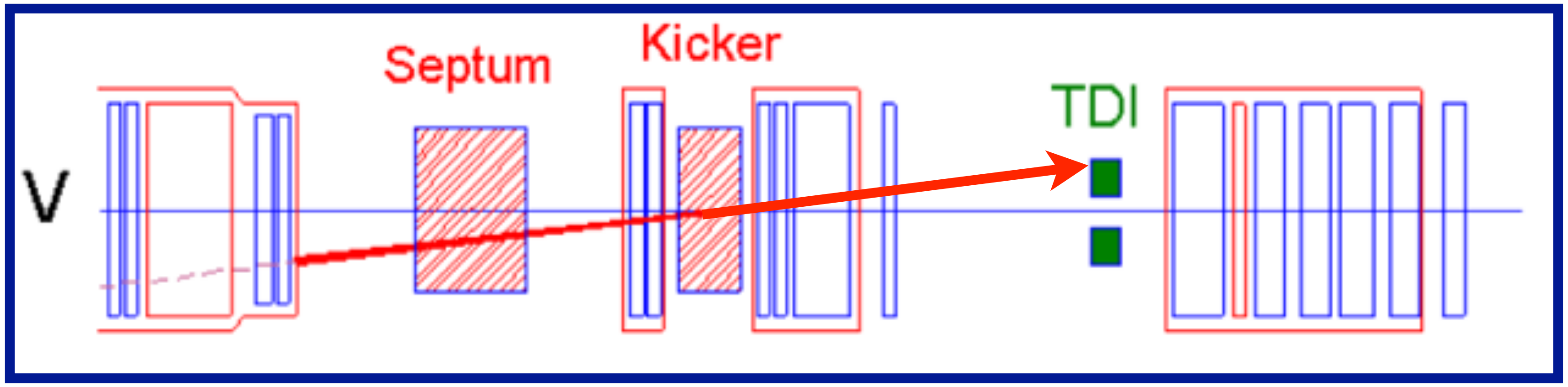
ABORT 90 us

Plant / Sensor

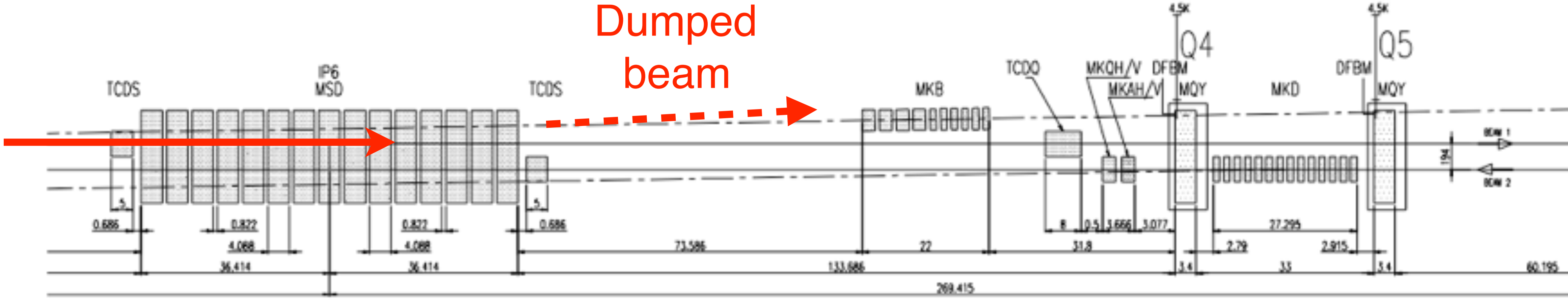
Beam Interlock System

Beam Dump

“Passive” protection



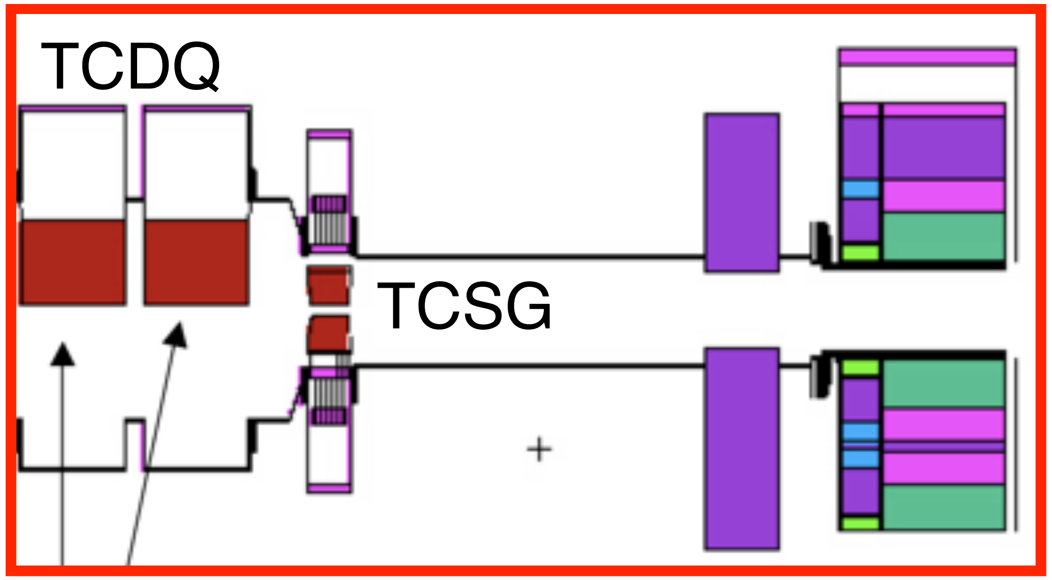
Injection protection
(introduced yesterday)



Circulating beam

Dumped beam

Dump protection elements: movable “TCDQ” and “TCSG” collimators + fixed masks



TCDQ extraction protection

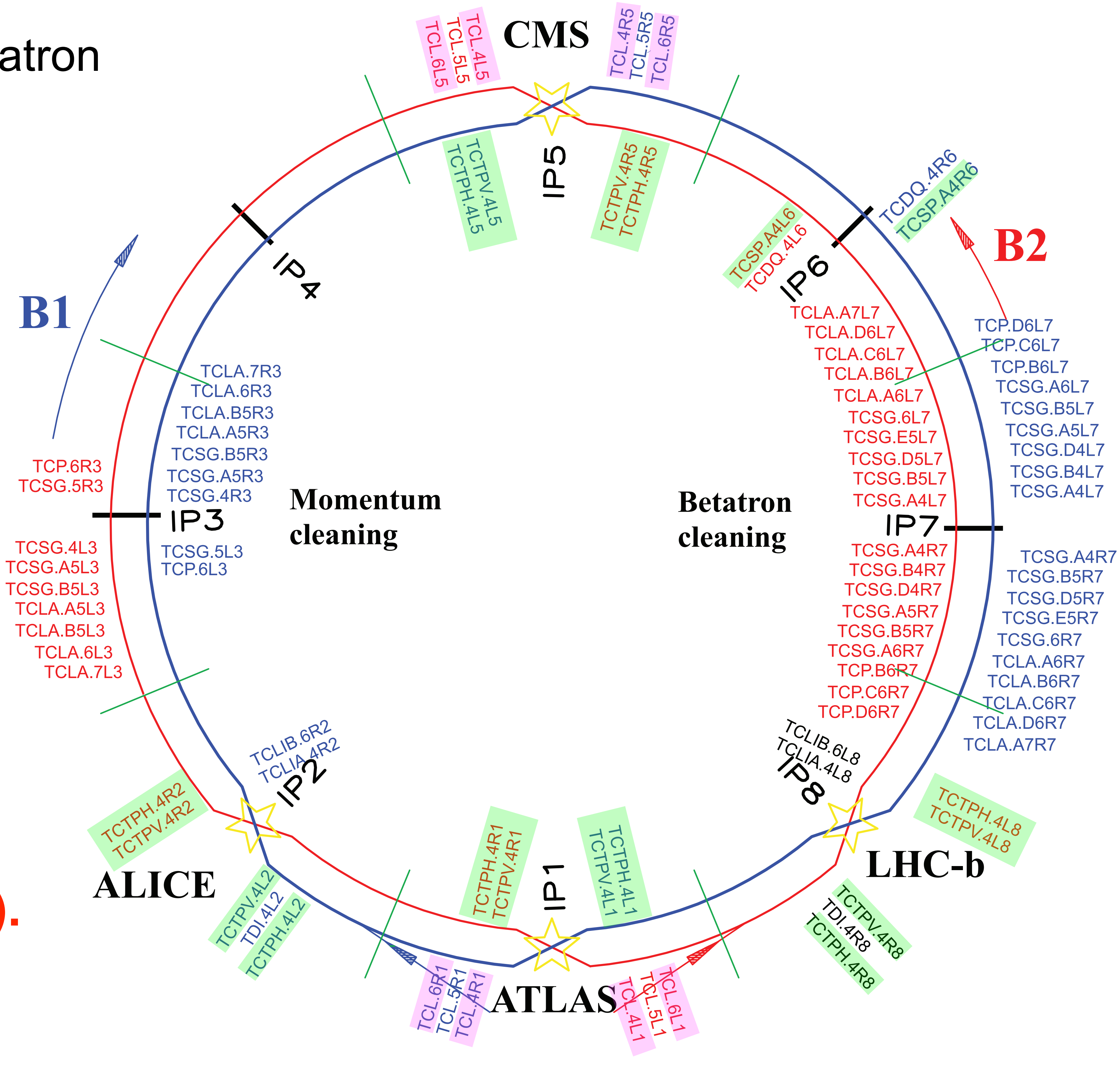
TCDQ = 9-m long collimator based on carbon that intercepts fractions of the beam that might be mis-kicked in case of problems with the beam dump!

LHC collimation system

Dedicated insertions for betatron (IR7) and momentum (IR3) cleaning systems.

Cleaning of incoming beam in all experiments.

Physics debris collimation in the high-lumi IR1/5.



Total of 118 [was 108 in Run I] **collimators (108** [was 100] **movable).**

Where we are

- ☑ We have seen how the LHC beam requirements are met by the CERN accelerator complex
- ☑ We have introduced the main LHC accelerator systems
- ☑ We have introduced the key parameters for the LHC magnet system and for the LHC beam and seen how they determine the machine protection constraints. Driven by the quest for pushing luminosity of high-energy beams!
- ☑ We have presented the basic machine protection philosophy and some key implementations.
- ☑ We have introduced the collimation system as part of the passive protection.

We will now see in detail the LHC collimation system!

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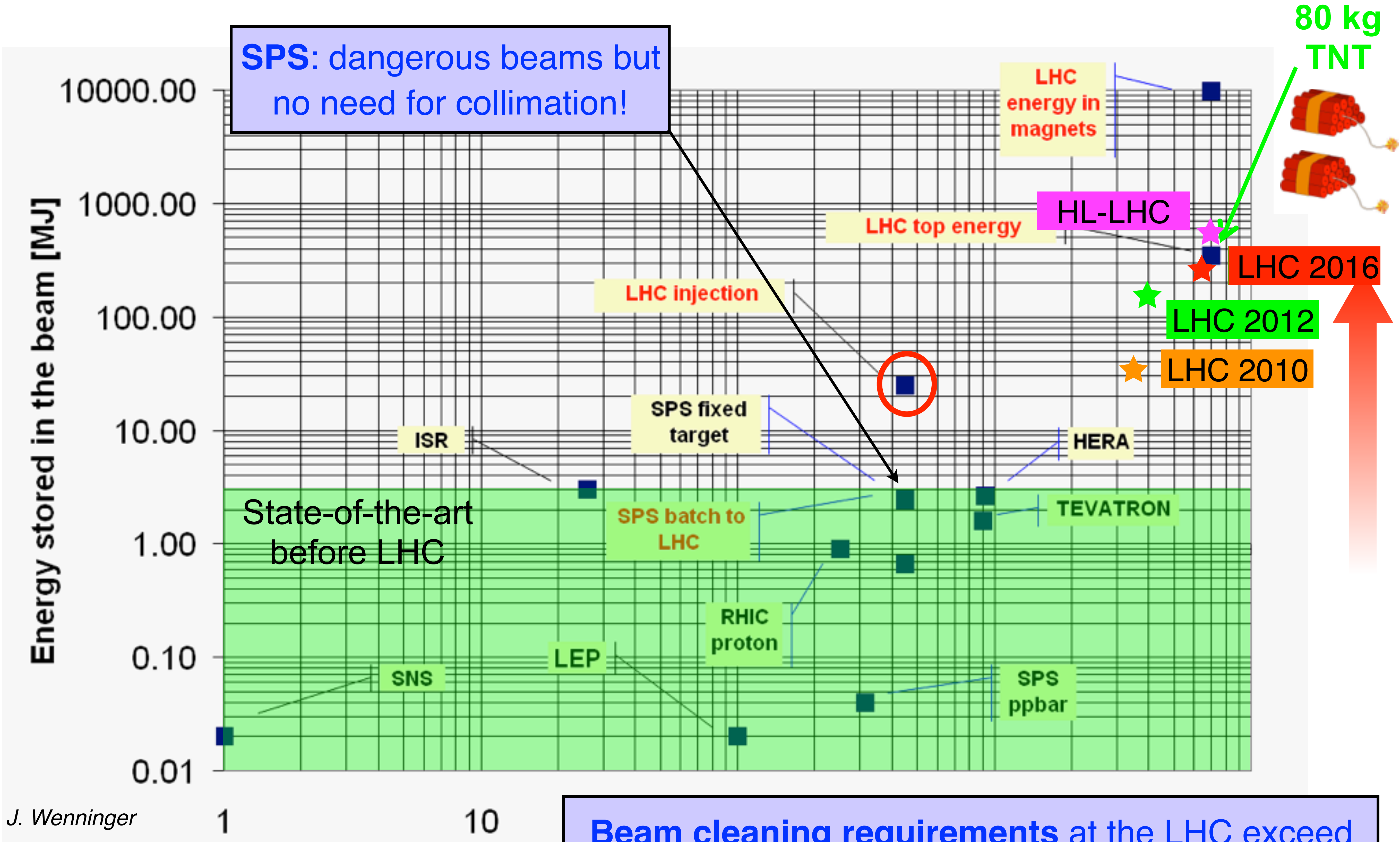
The stored energy challenge

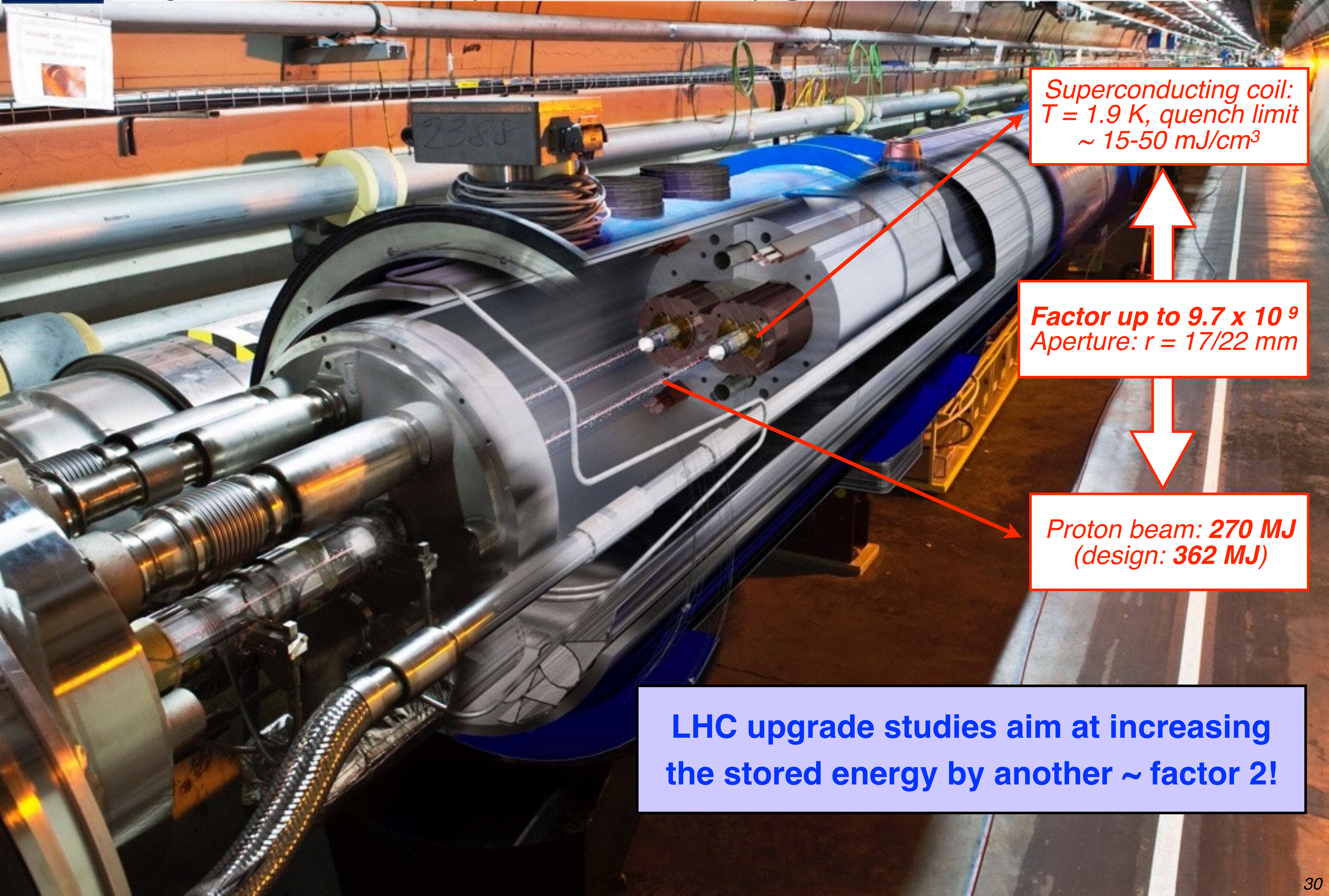
SPS: dangerous beams but no need for collimation!



J. Wenninger

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

1232 NbTi superconducting dipole magnets – each 15 m long
Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium)



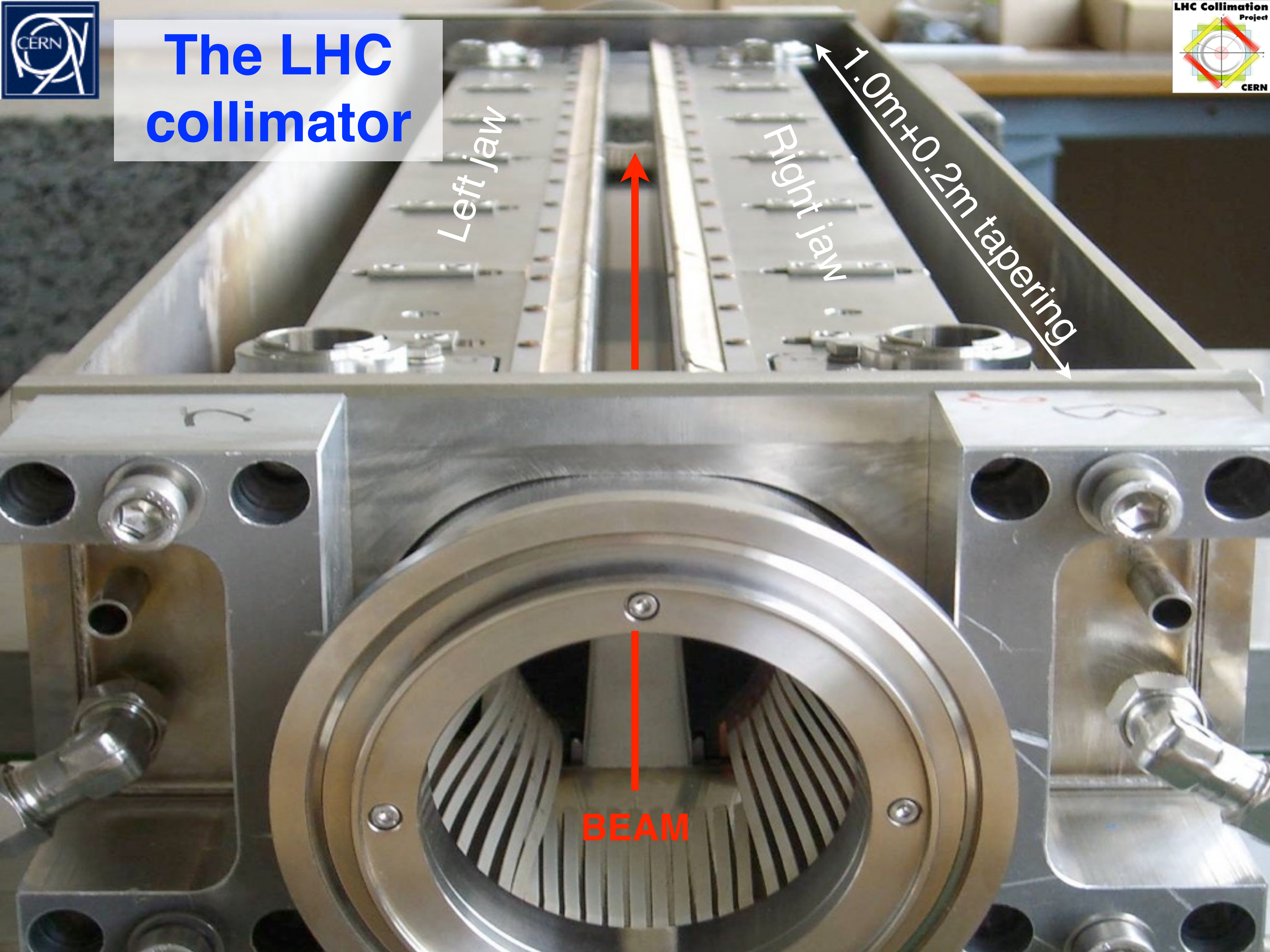
Superconducting coil:
T = 1.9 K, quench limit
~ 15-50 mJ/cm^3

Factor up to 9.7 x 10^9
Aperture: r = 17/22 mm

Proton beam: ***270 MJ***
(design: ***362 MJ****)*

LHC upgrade studies aim at increasing the stored energy by another ~ factor 2!

The LHC collimator



The LHC collimator

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

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

How many collimators are needed?

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

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

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

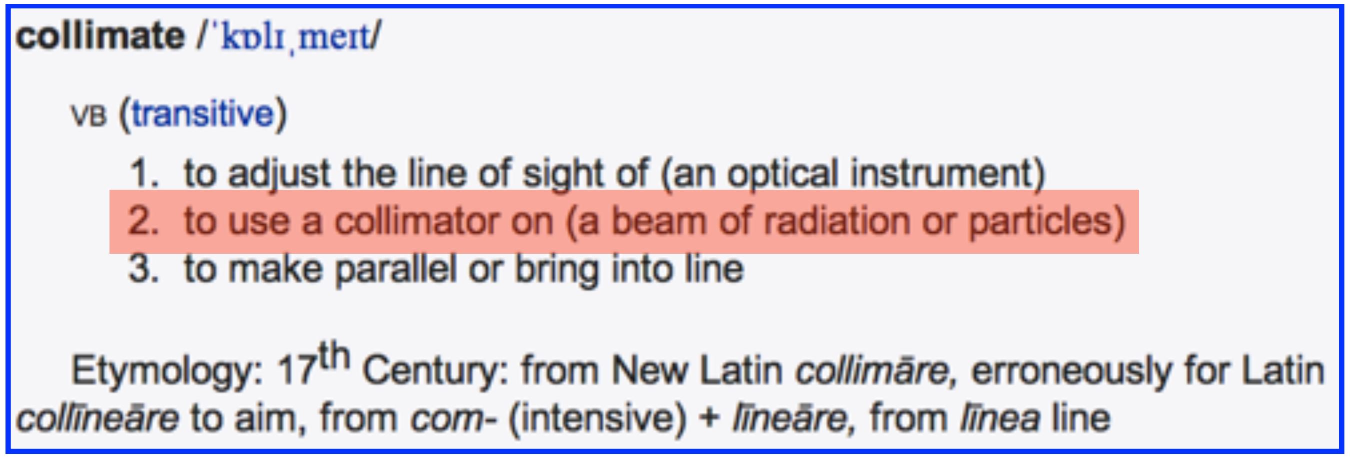
Beam collimation - definitions

Beam halo collimation

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

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

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

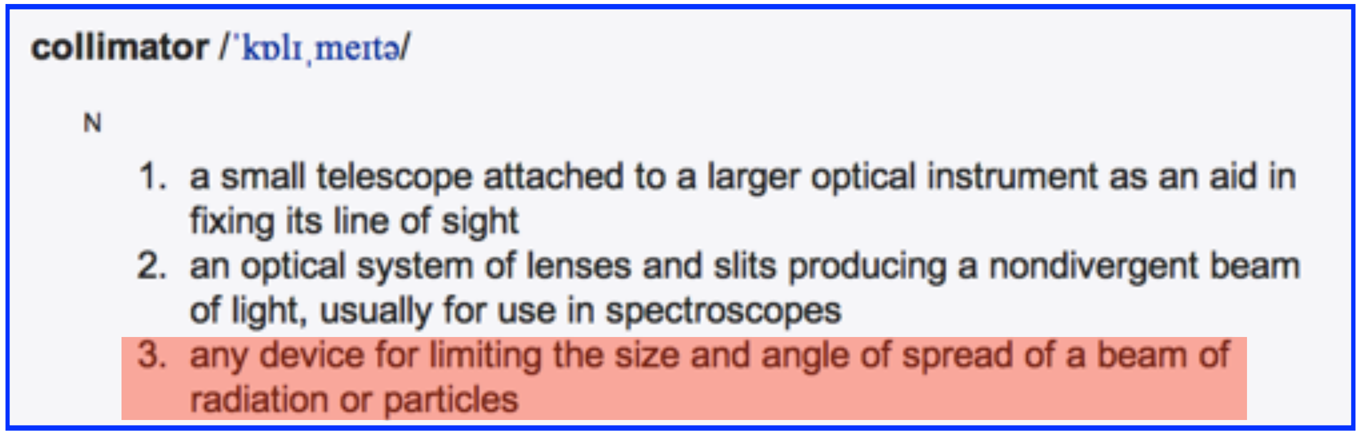


collimate /ˈkɒlɪˌmeɪt/

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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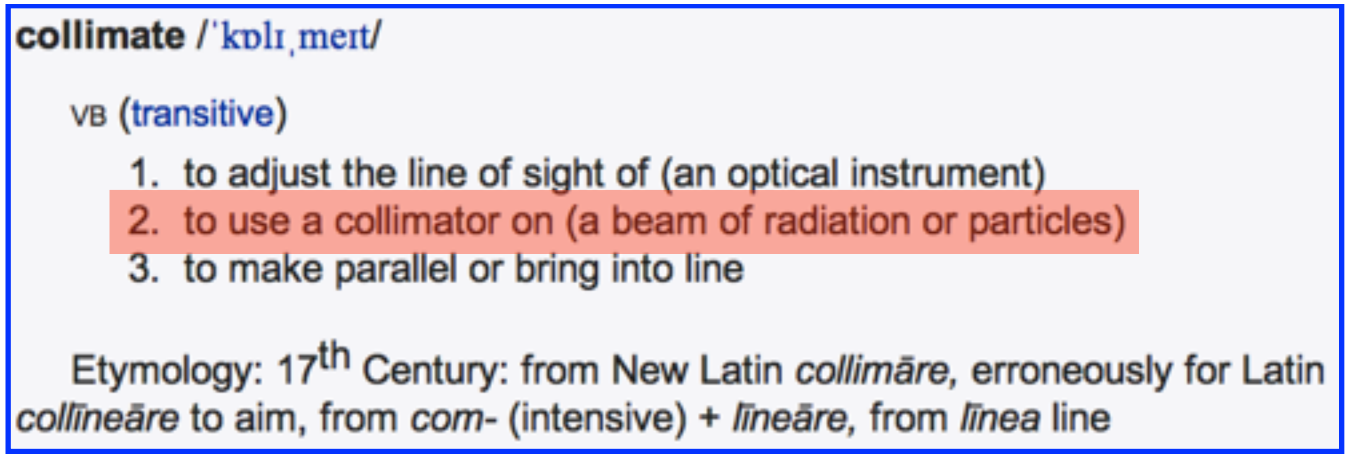

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collima

N

as an aid in

rgent beam

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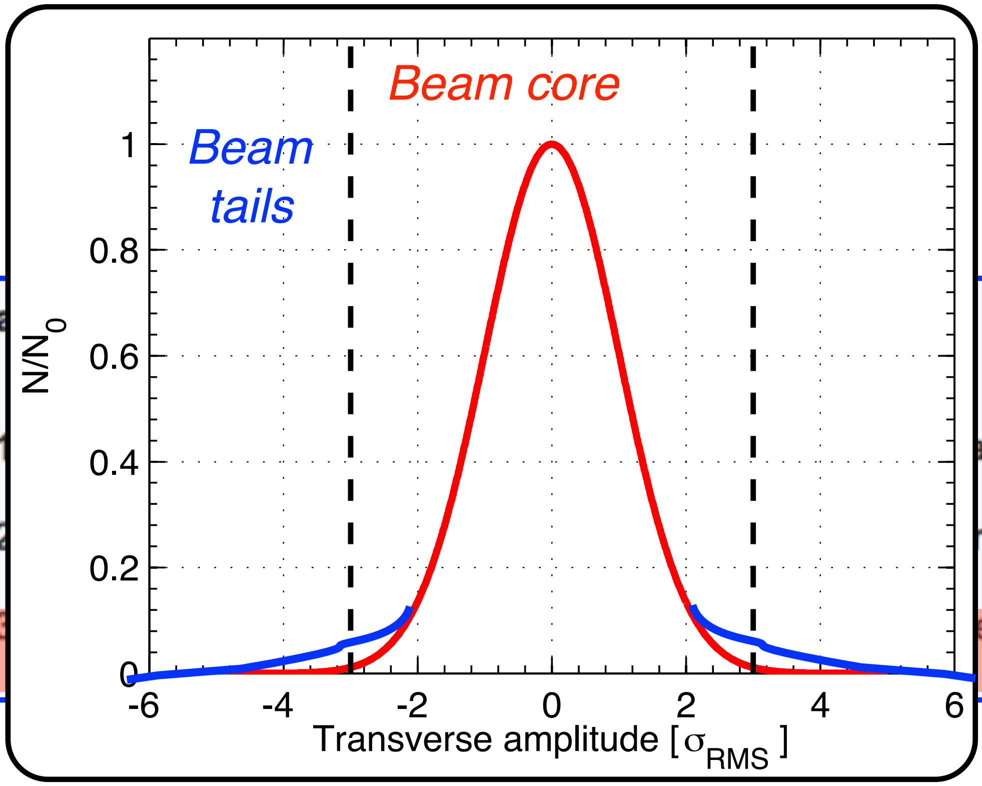

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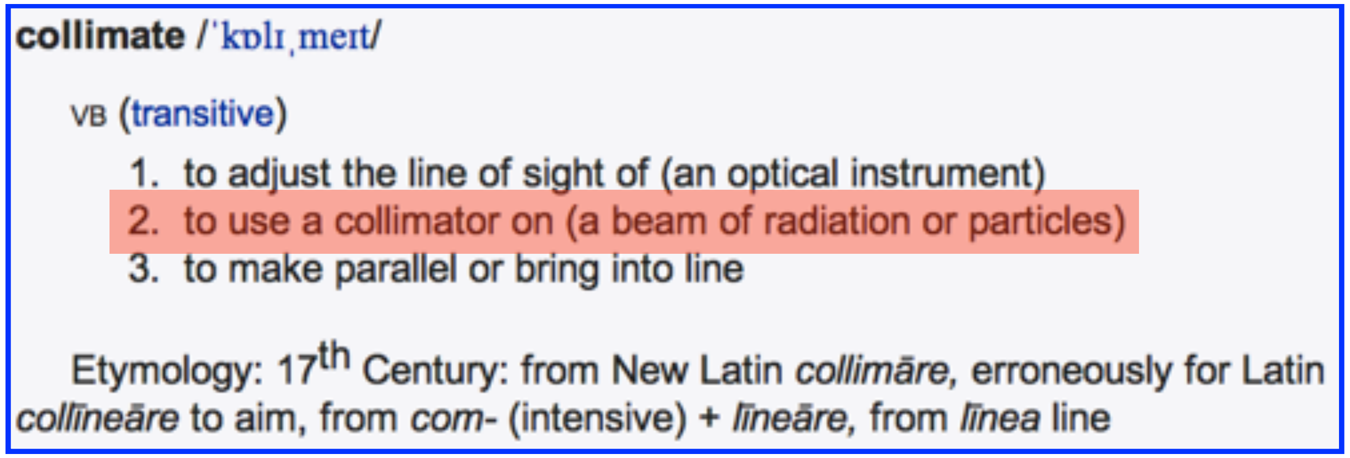
There are different goals of **collimation systems** depending on the machine.



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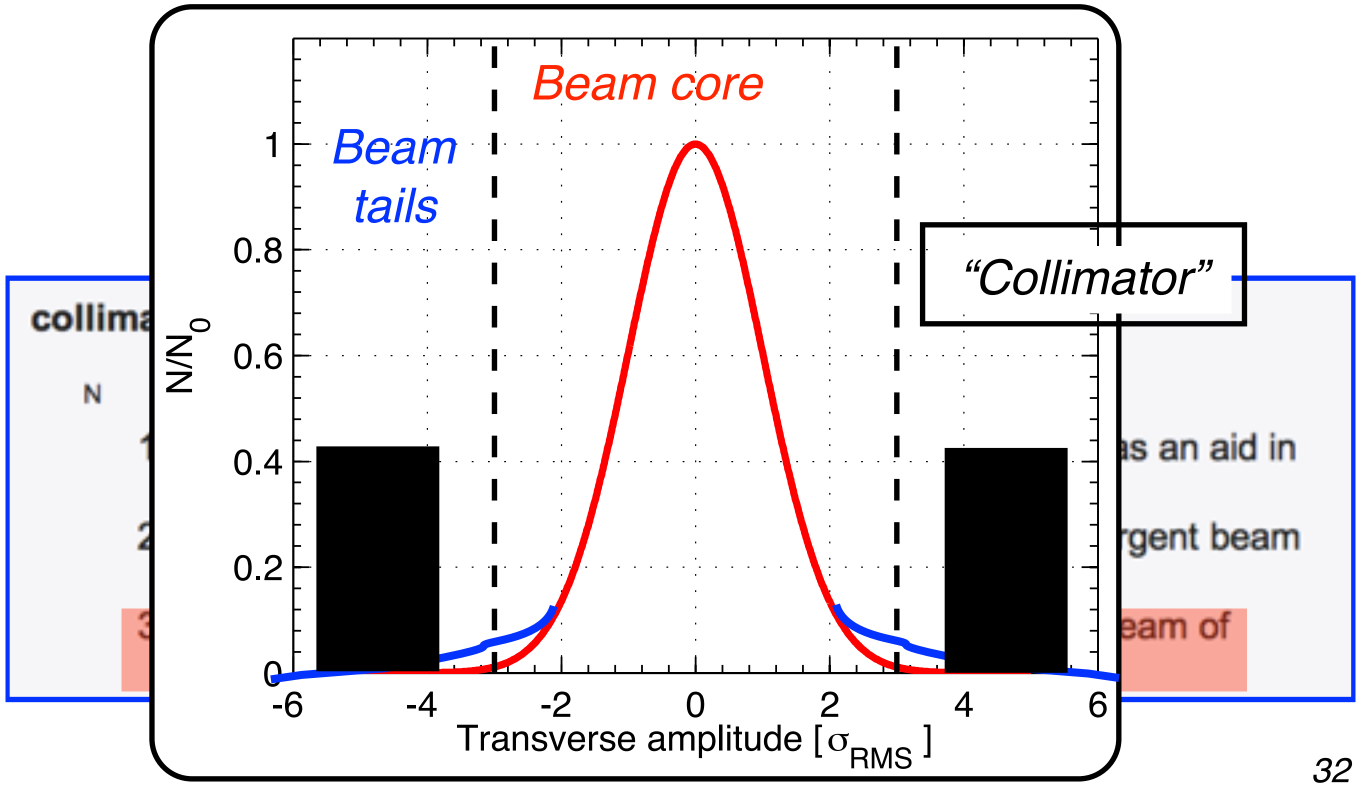
3. to make parallel or bring into line

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



Roles of collimation systems

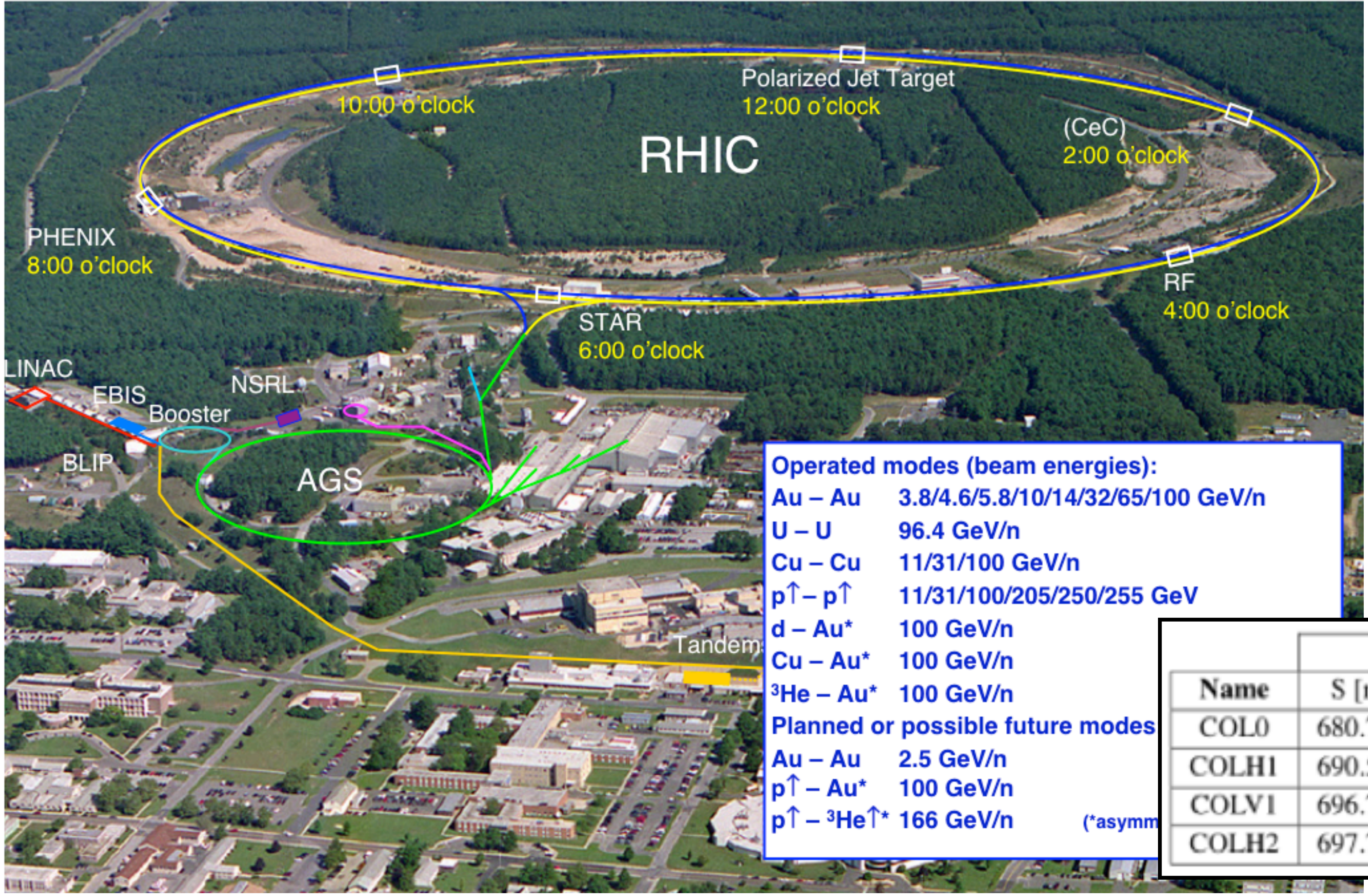
- **Halo cleaning** versus quench limits (super-conducting machines)
- Passive **machine protection**
  First line of defence in case of accidental failures.
- **Concentration of losses/activation** in controlled areas
  Ease maintenance by avoiding many distributed high-radiation areas.
- **Reduction 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**, **halo**
  Control and probe the transverse

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

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

Why is the LHC so special for collimation matters?

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

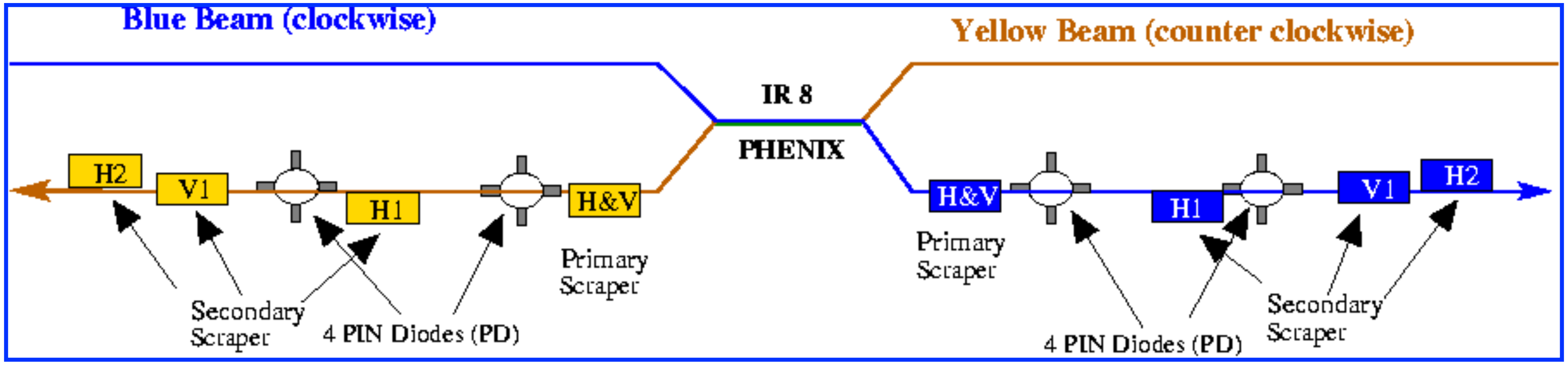
RHIC beam parameters [p]:

E_b = 250 GeV
N_{tot} = 110 x 10^{11}p
E_{stored} = ~ 440 kJ

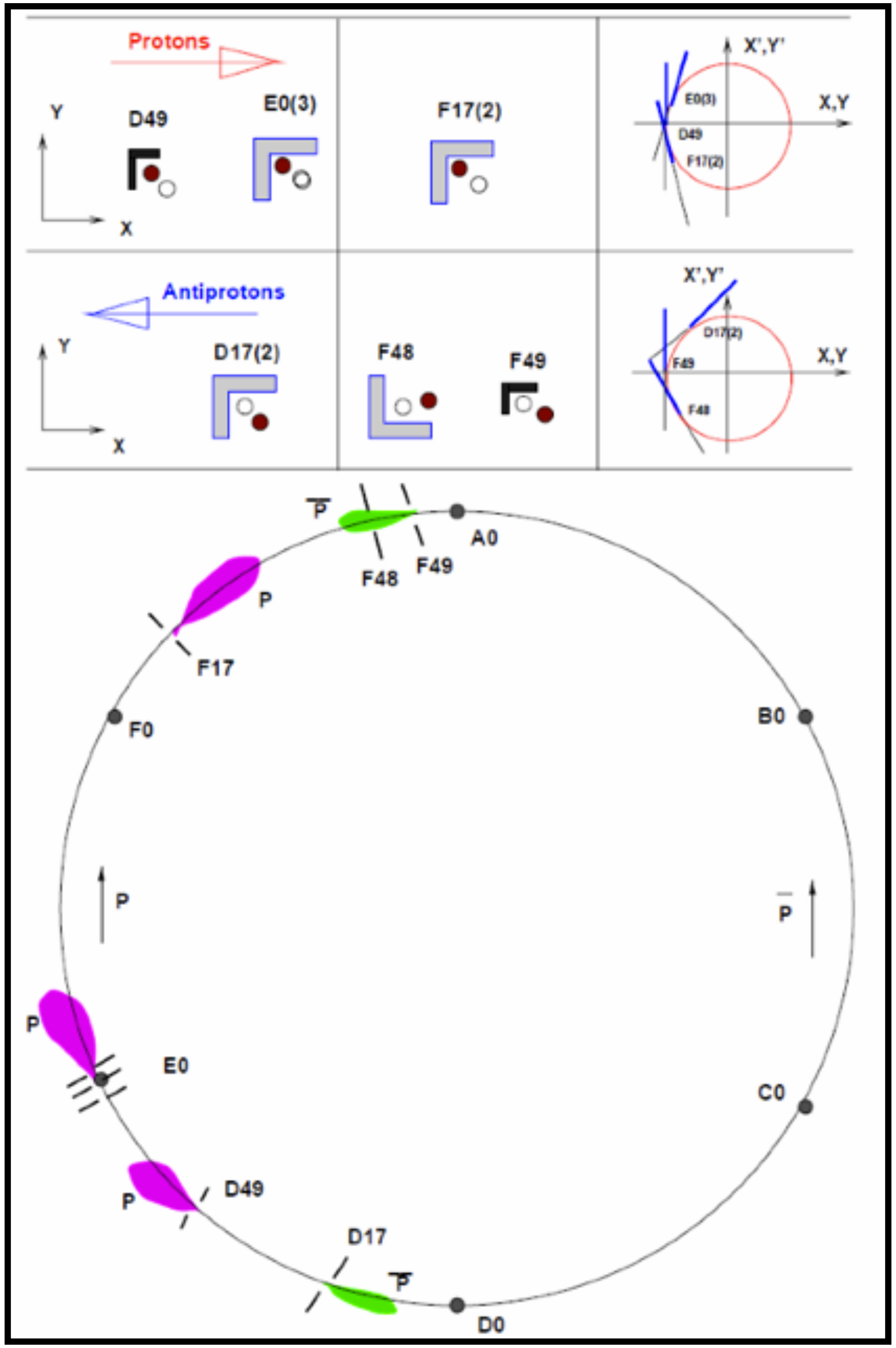
Collimation system:

8 collimators
Some with L shape

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



Tevatron Run II collimation system



Tevatron Run II parameters:

E_b = 1 TeV

E_{stored} = ~ 2 MJ

Collimation system:

13 collimators, L shape

26 positional degrees of freedom

Collimation of LEP collider

LEP parameters - e^+e^- collider:

E_b = 45-105 GeV

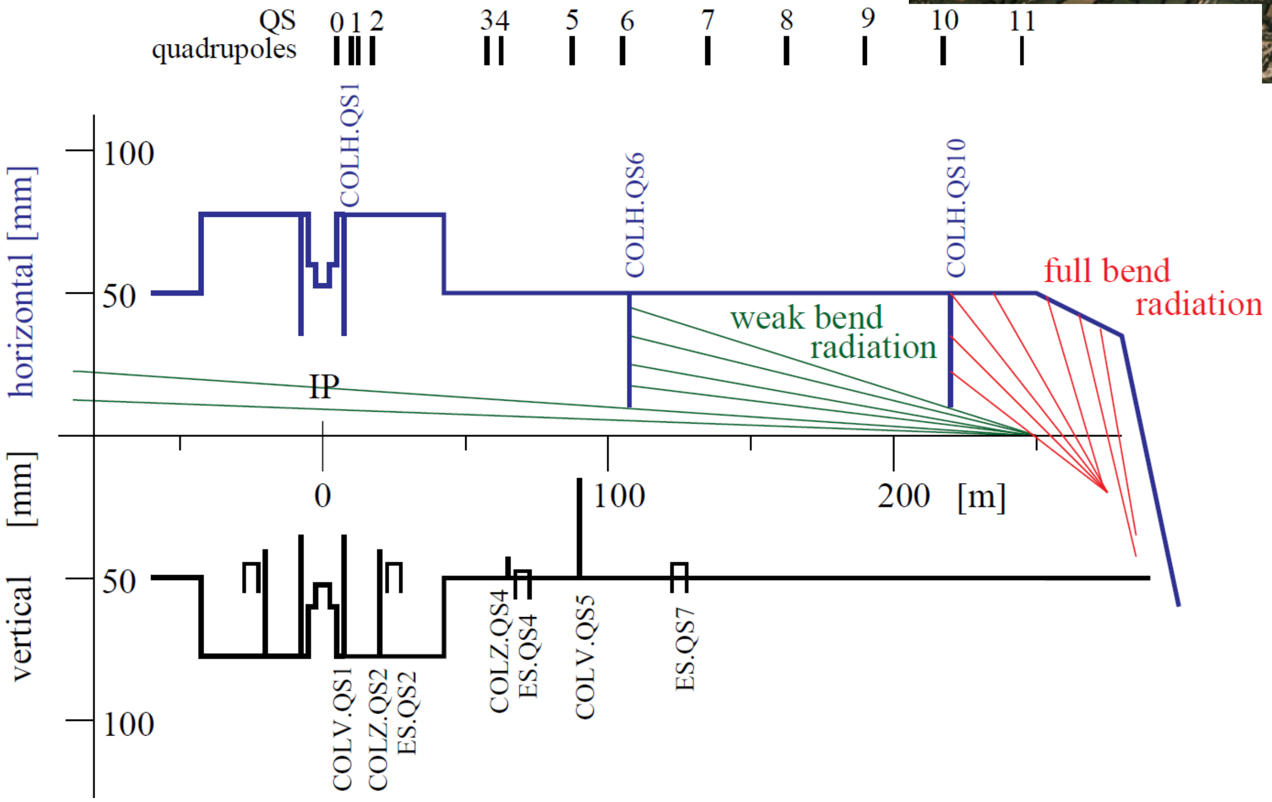
$I_{bunch} = 4 \times 10^{11}$ e^+/e^-

$I_{tot} = 1.6 \times 10^{12}$ e^+/e^-

E_{stored} = ~25 kJ

Bunch spacing = 11 μs

Synchrotron radiation power
~10 MW / beam



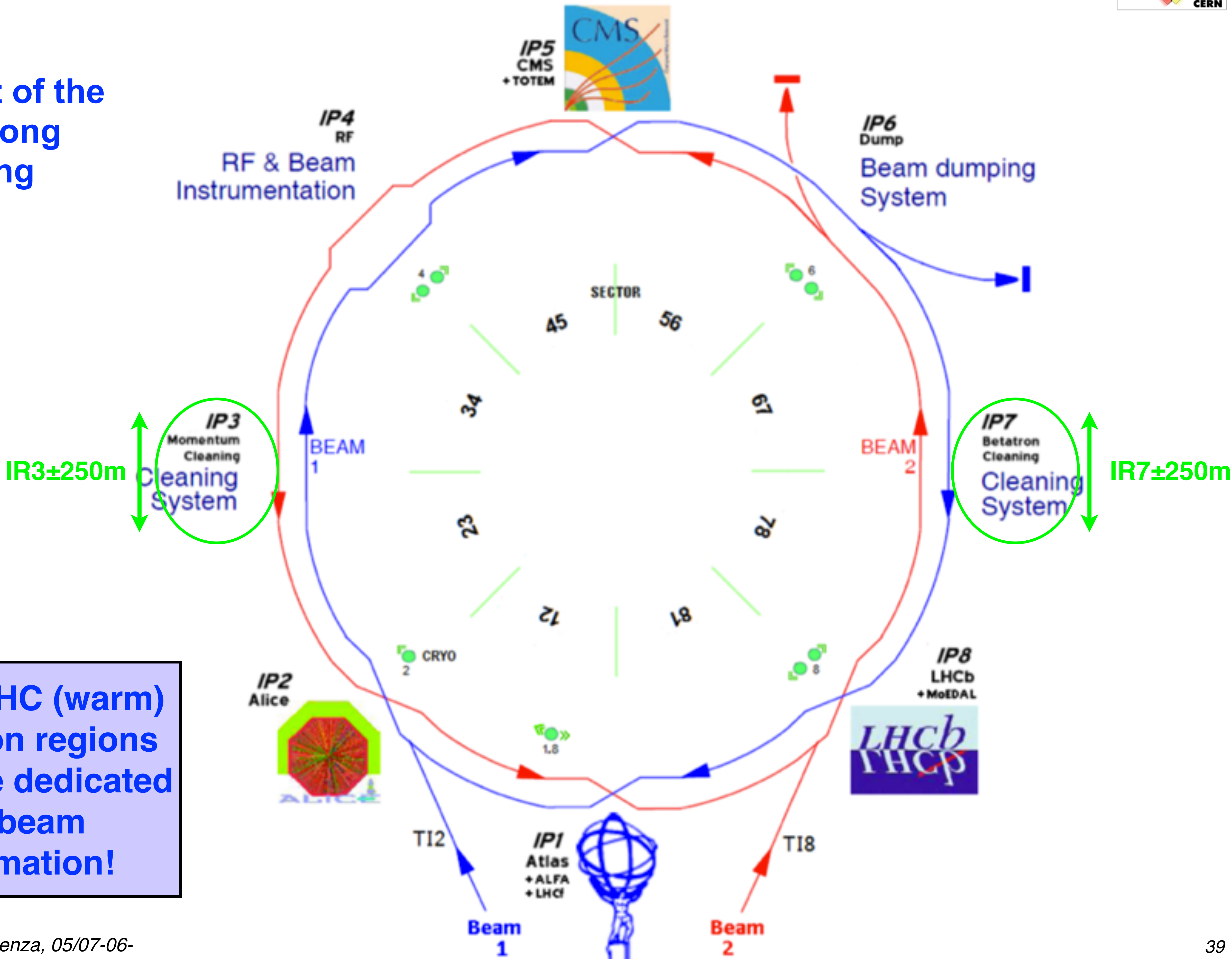
LEP collimation system:

96 collimators (mostly 2 jaw),
Betatron and off-energy,
Local masks at the experiments

G. von Holtey et al, CERN-SL 97-40

LHC ring layout

Layout of the 27km-long LHC ring



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

LHC collimation layout

Collimation designed for nominal LHC design parameters:

E_b = 7 TeV

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

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

E_{stored} = 362 MJ

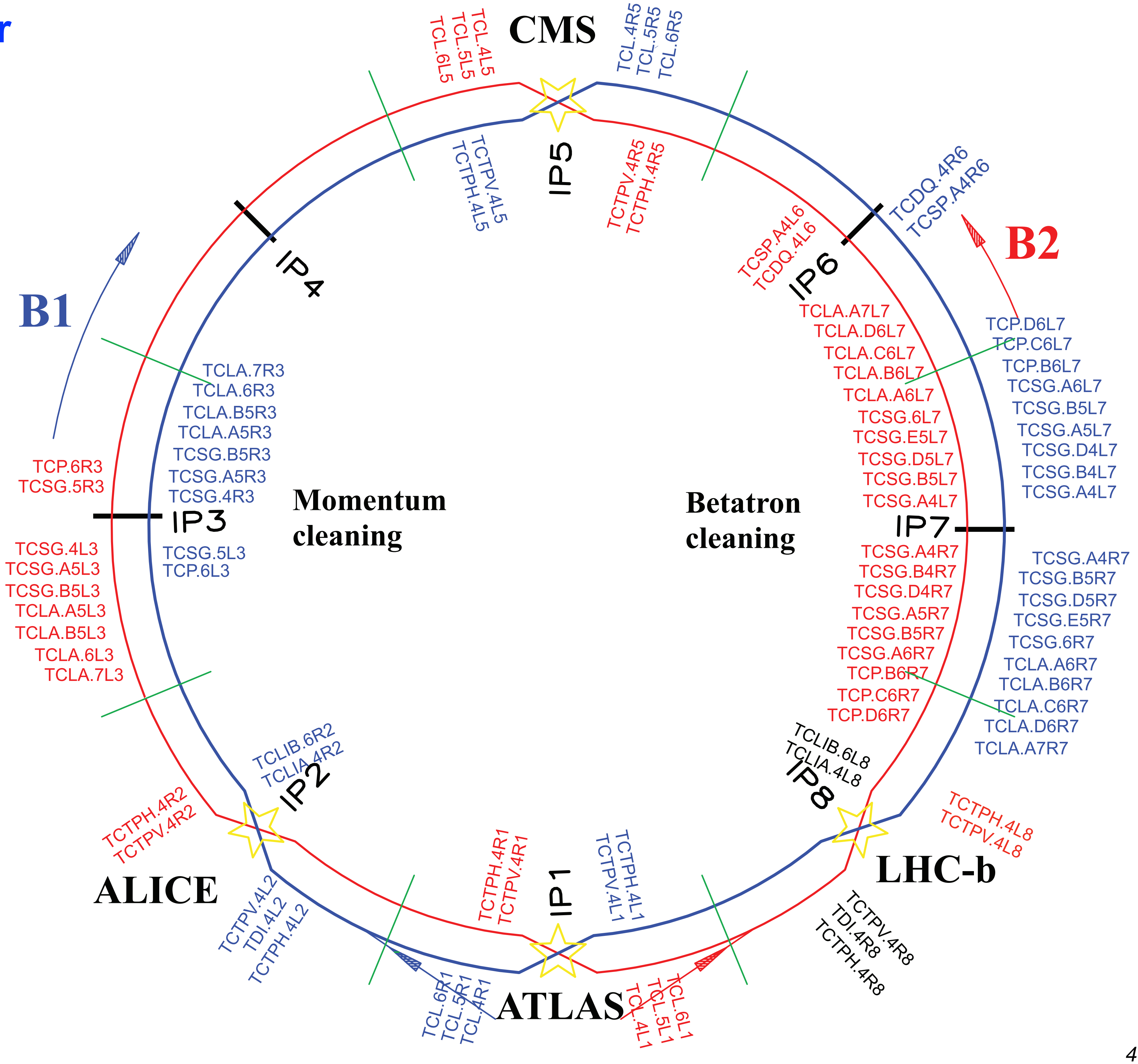
Bunch spacing = 25ns

Achieved:

E_b = 6.5 TeV

E_{stored} = 270 MJ

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



Why so many collimators?

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

You have seen that in previous lectures...

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

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

Momentum losses occur in different locations than betatron's.

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

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

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

Outline

- Main points from 1st lecture
- Machine protection and collimation
  - Concepts and LHC implementation
  - Case study: 2008 event
- **Beam losses and collimation**
  - Roles of beam collimation systems
  - **Beam losses mechanisms**
- Design of a multi-stage collimation system
  - Betatron collimation design
  - Advanced: off-momentum, local protection
- The LHC beam collimation system
  - Detailed layouts and collimator design

Beam losses vs. collimation

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

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

No need for a collimation system!

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

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

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

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

Beam losses through lifetime

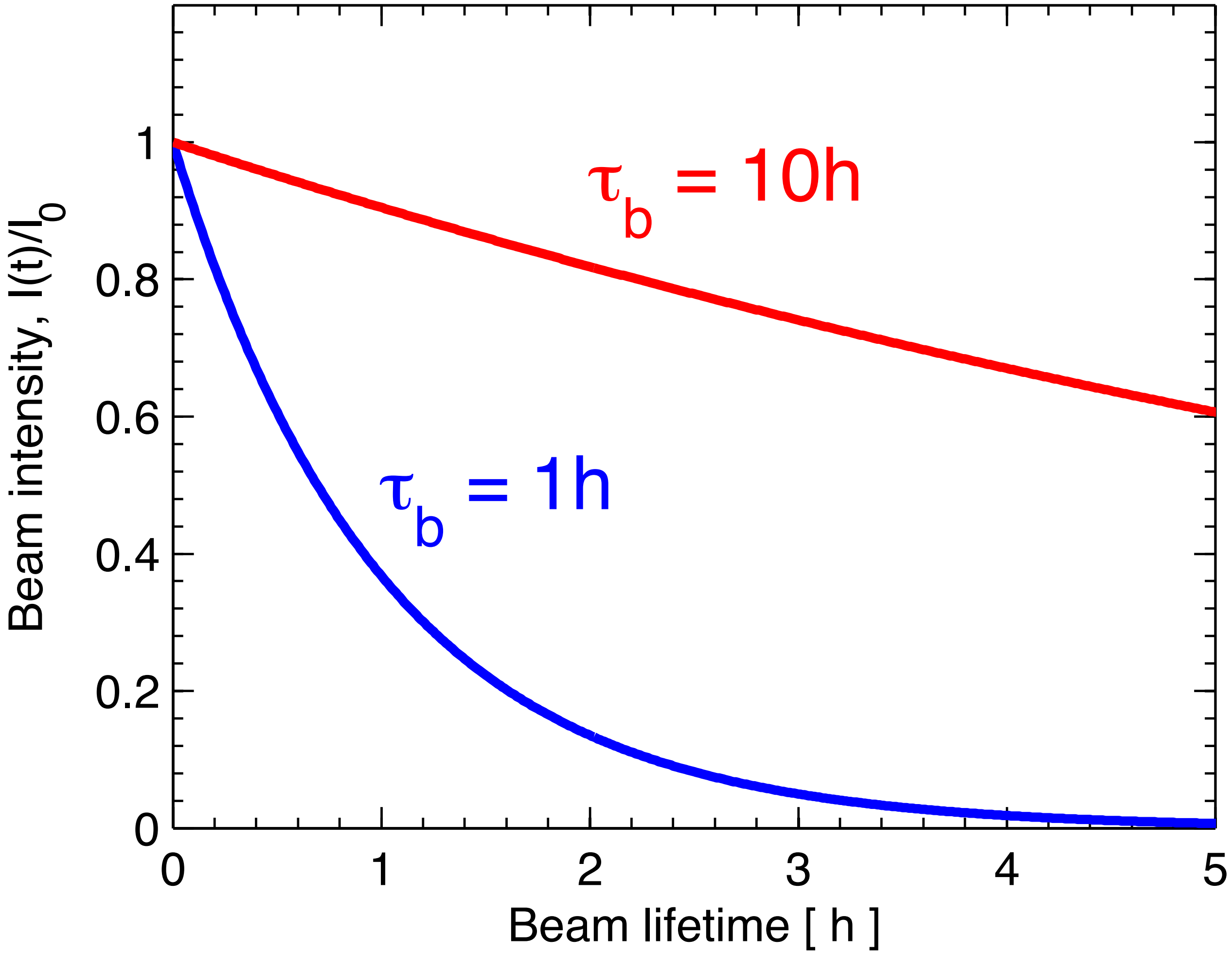
Beam loss mechanisms are modelled by assuming a non-infinite **beam lifetime,** τ_b

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

: Beam intensity versus time

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

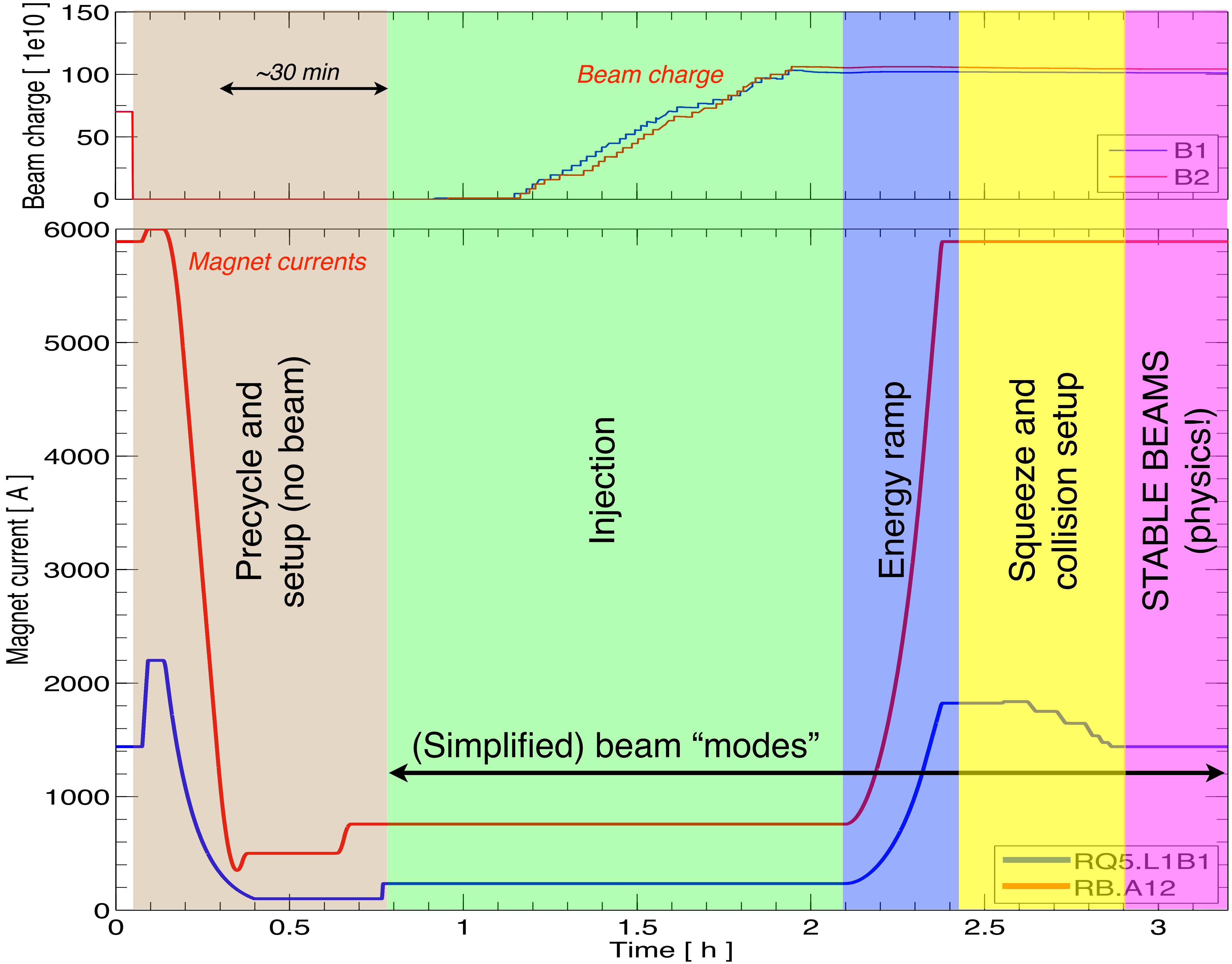
: Proton loss rate



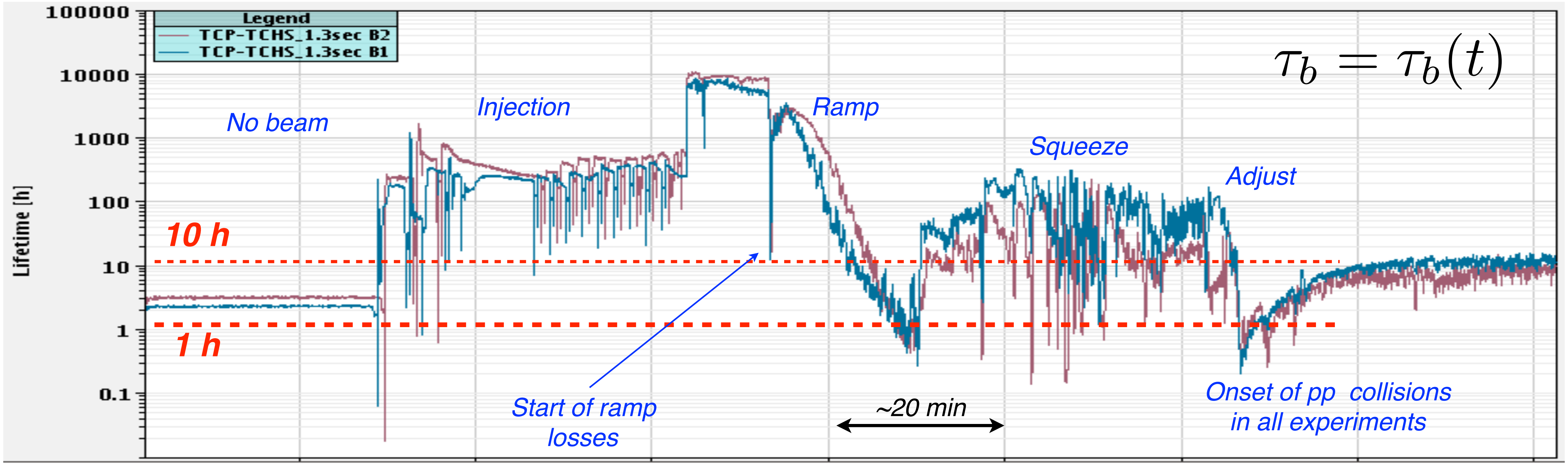
Beam losses mechanisms are characterized by a time-dependent beam lifetime during the machine cycle. This measures the **total beam losses** that a collimation system must handle.

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

Operational cycle of a collider



LHC lifetime in a physics fill in 2012



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

Example of a typical physics fill in 2012.

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

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

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

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

Key collimation design parameters

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

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

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

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

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

Example: losses versus quench limits

N_{tot} : total beam populations [p]

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

R_q : quench limit [p/m/s]

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

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

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

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

For the 1h lifetime case shown before, we get a loss rate at the LHC of 90x10^9 p/s. Assuming a quench limit of $R_q \sim$ 3.2x10^7p/m/s at 7 TeV, one can calculate a **required inefficiency of a few 10-4**!!

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

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

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

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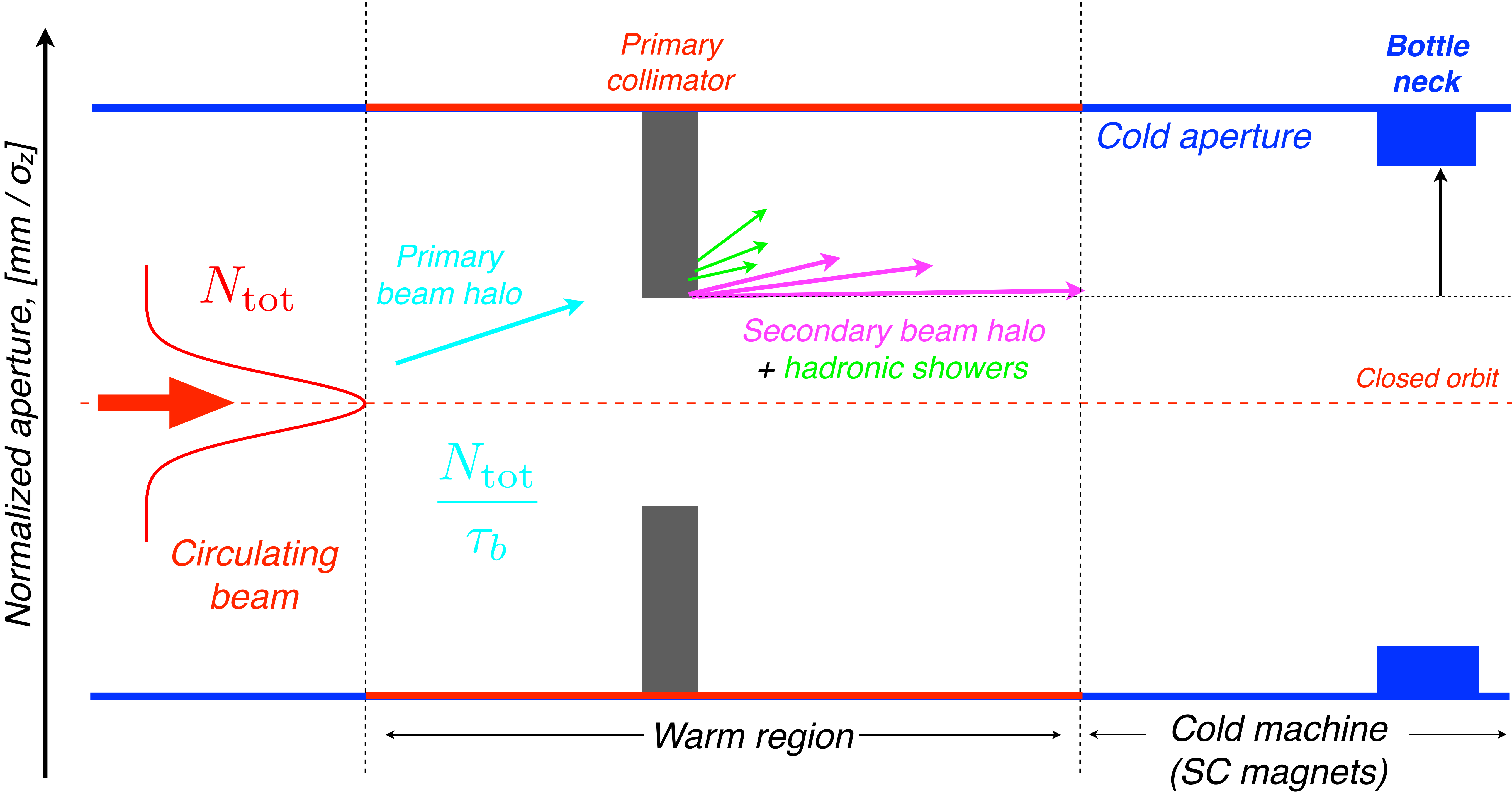
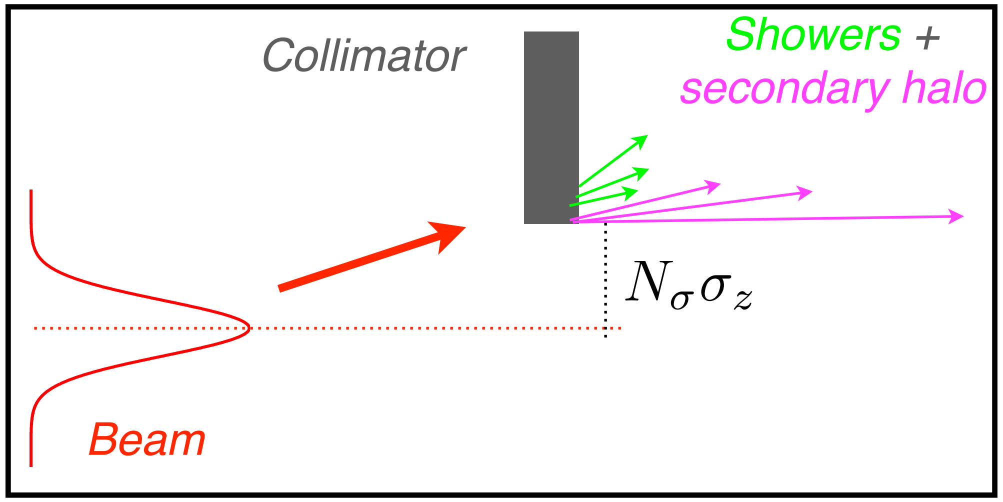
Aperture and single-stage cleaning



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

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

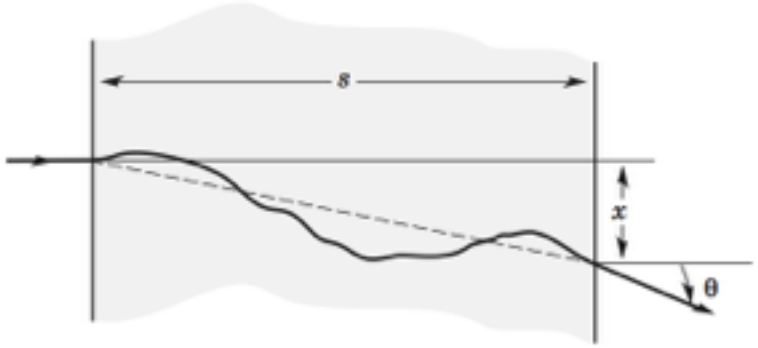
Particle interaction with collimators



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

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

For “cleaning” what matters is the energy leakage.

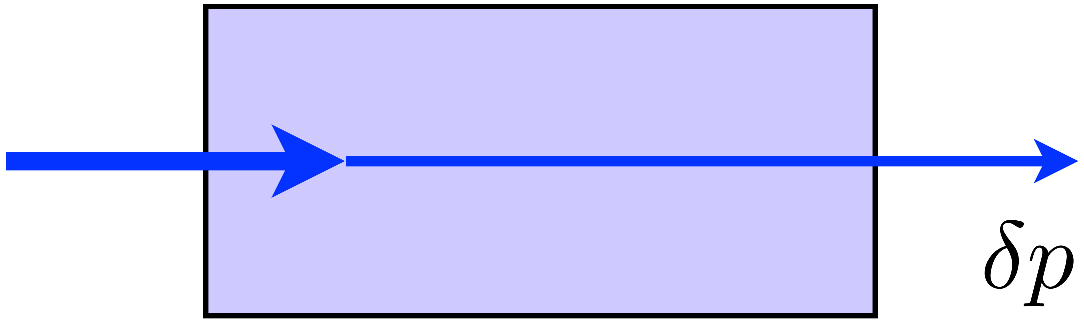


$$\sqrt{\langle\theta_p^2\rangle} = \frac{13.6}{cp[\mathrm{MeV}]}\sqrt{\frac{s}{\chi_0}}\left(1+0.038\cdot\left(\frac{s}{\chi_0}\right)\right)$$

χ_0 : radiation length

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

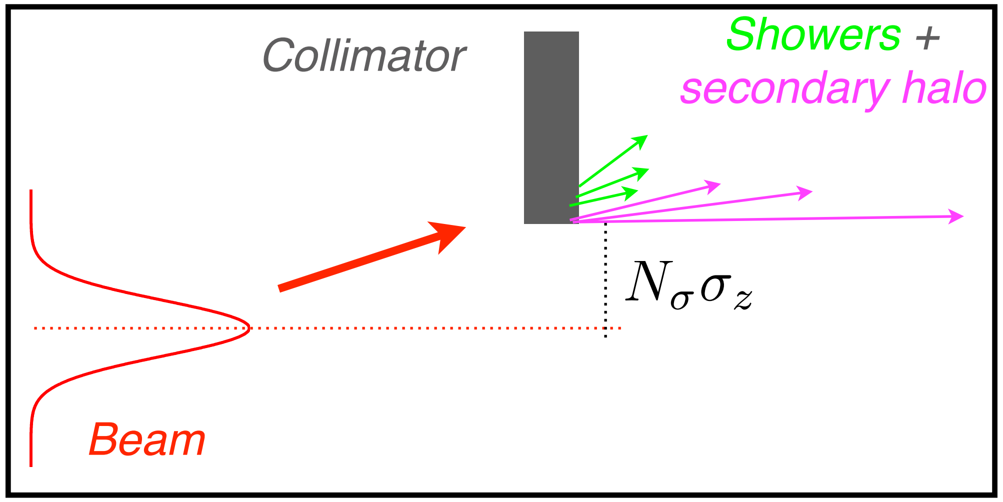
Single-diffractive interactions change the energy!



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

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

Particle interaction with collimators



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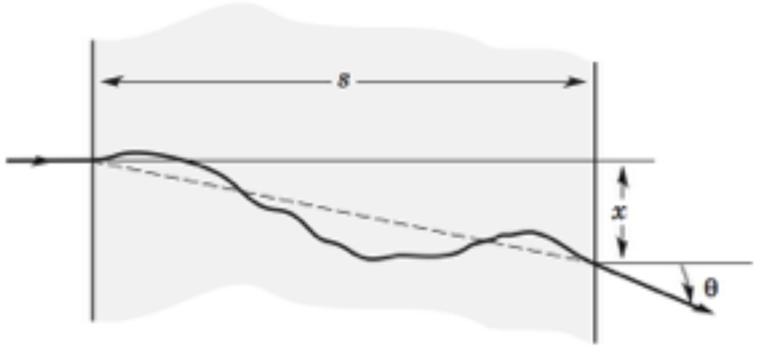

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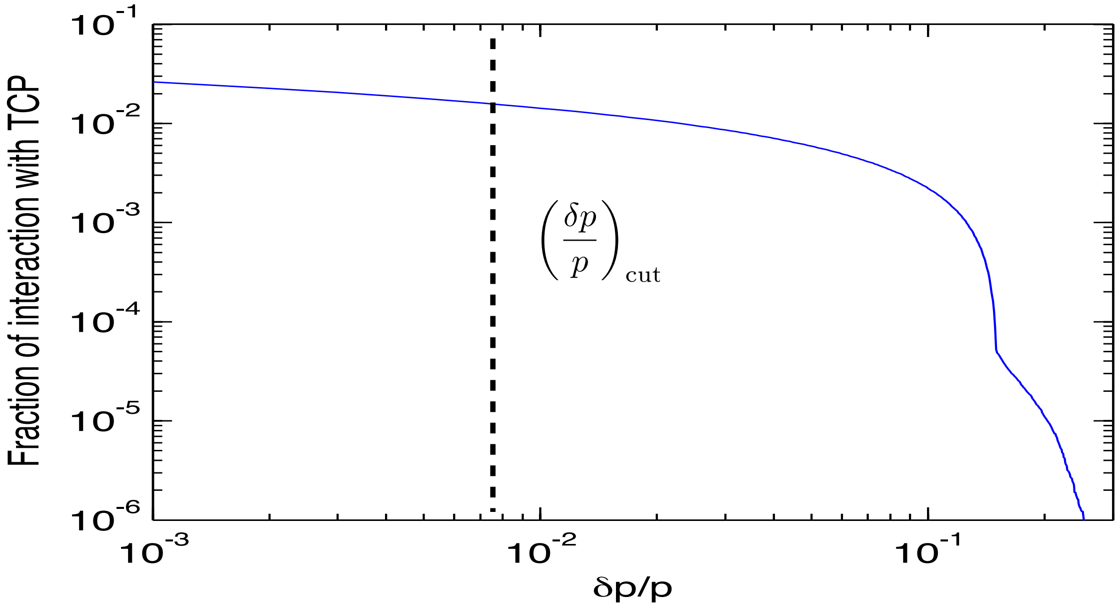
Distribution of energy lost after multi-turn interaction with 60cm TCP



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

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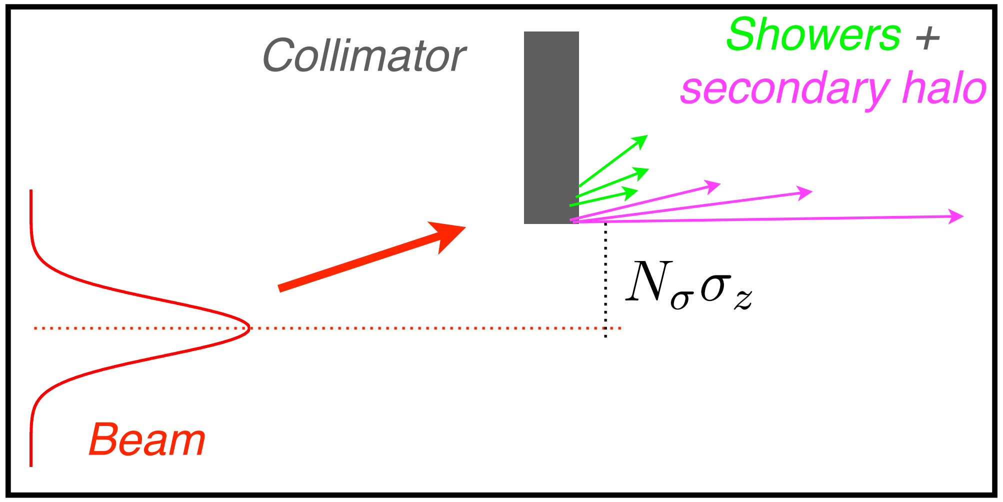
Particle interaction with collimators



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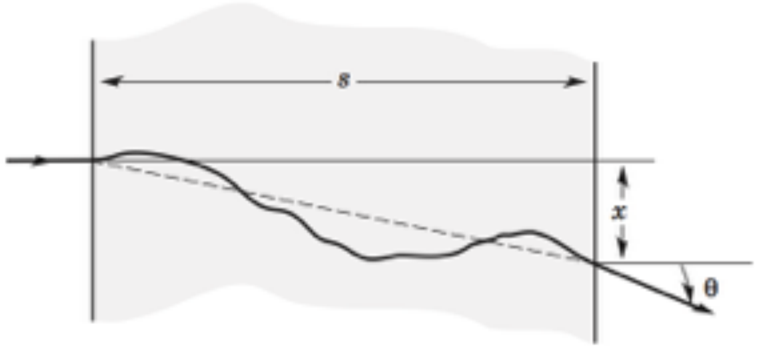

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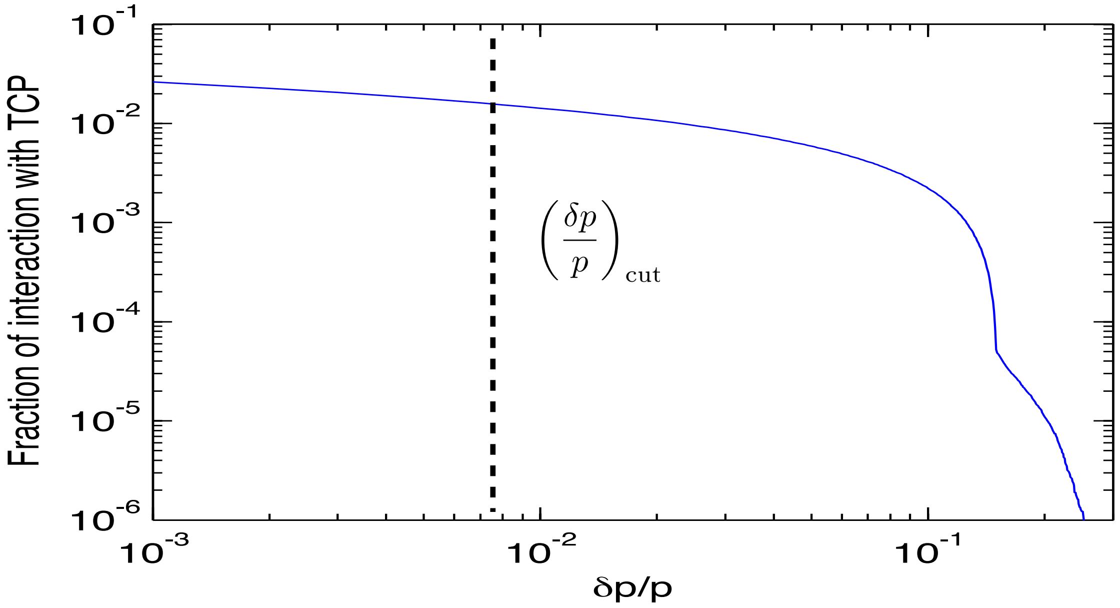


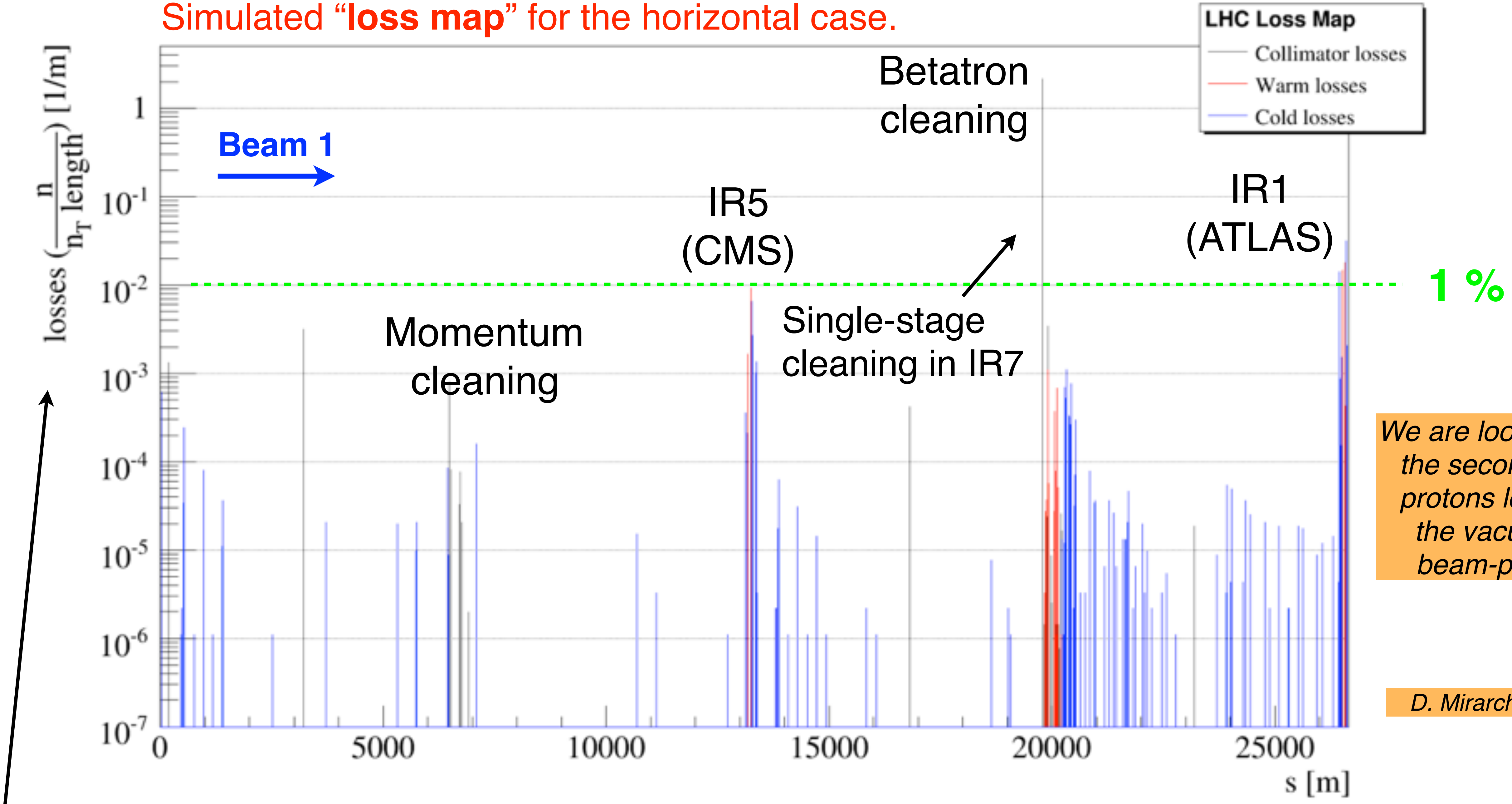
The interaction with collimator materials is itself a source of betatron and off-momentum halo (secondary halo).

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

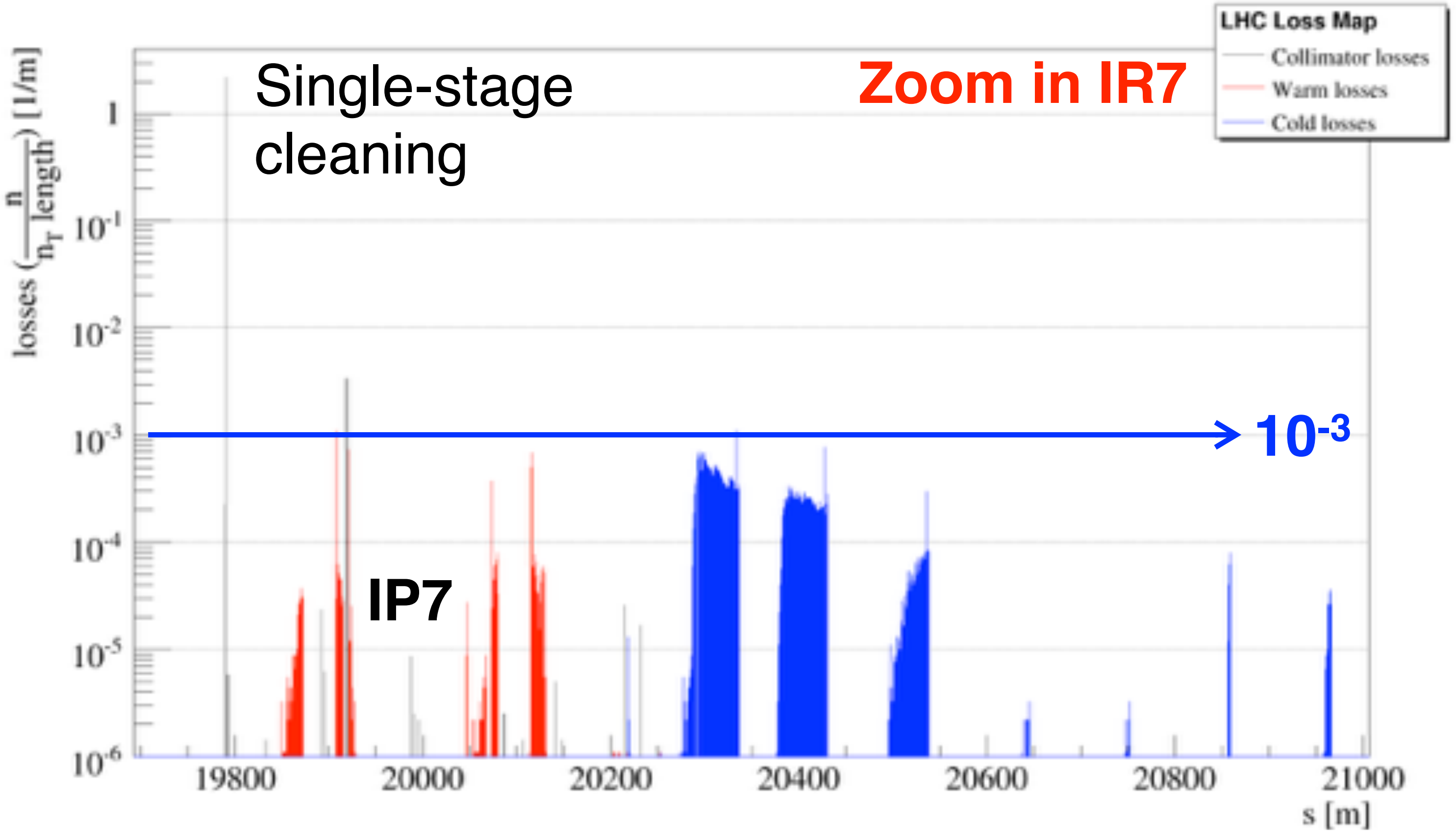
Local cleaning inefficiency

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

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

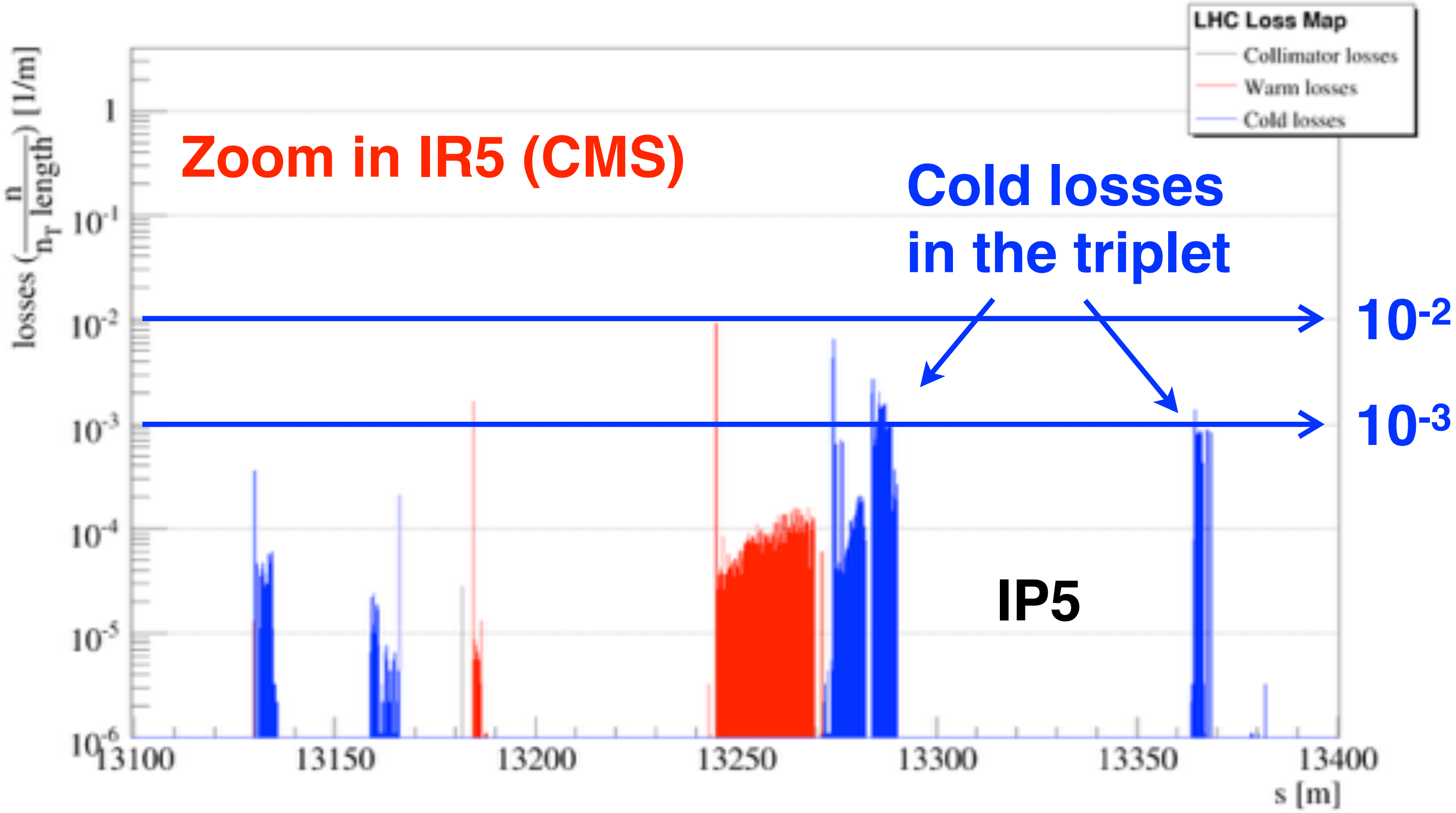


Single-stage cleaning

Zoom in IR7

10^{-3}

IP7



Zoom in IR5 (CMS)

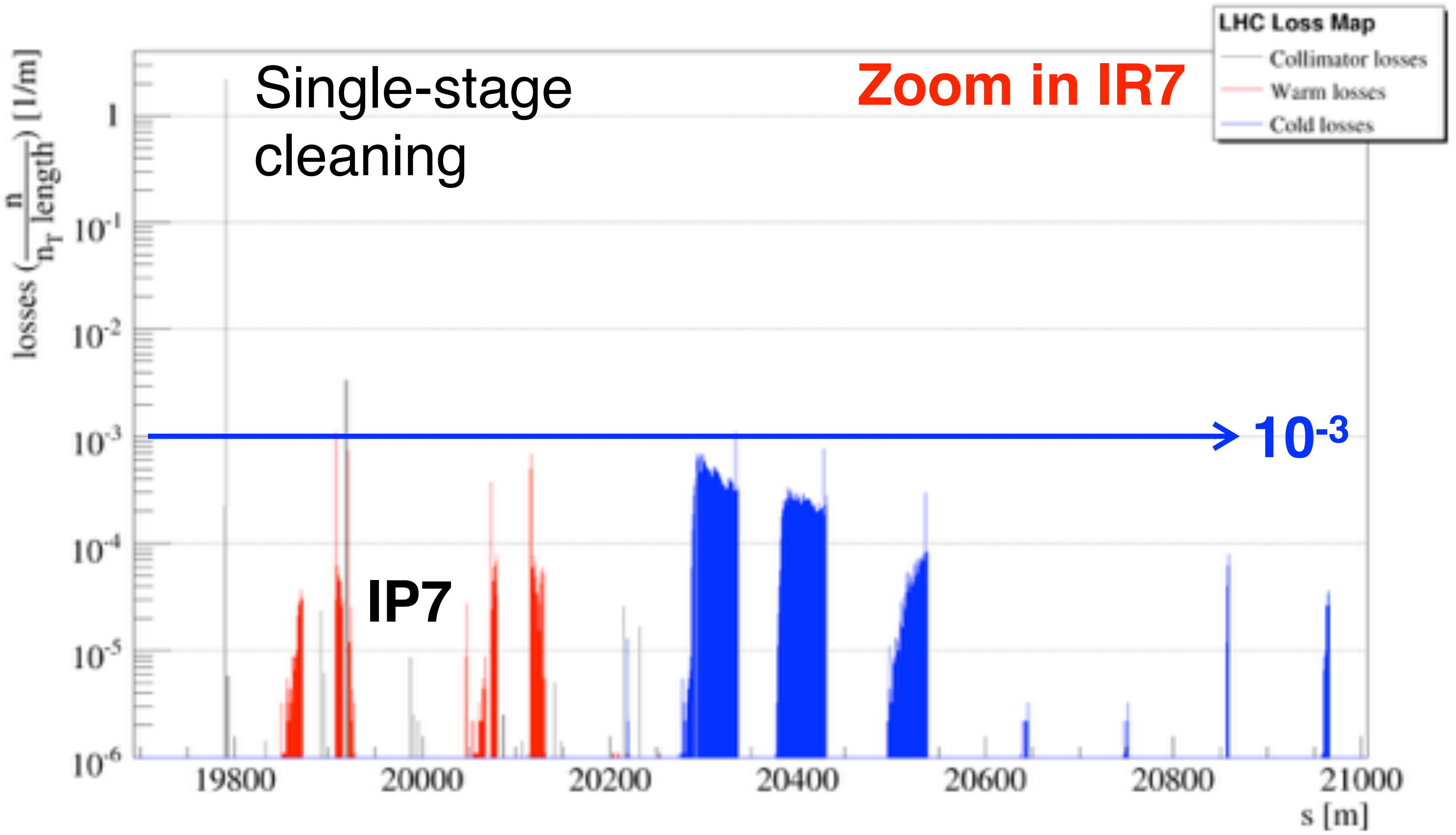
Cold losses in the triplet

10^{-2}

10^{-3}

IP5

Comparison to quench limits

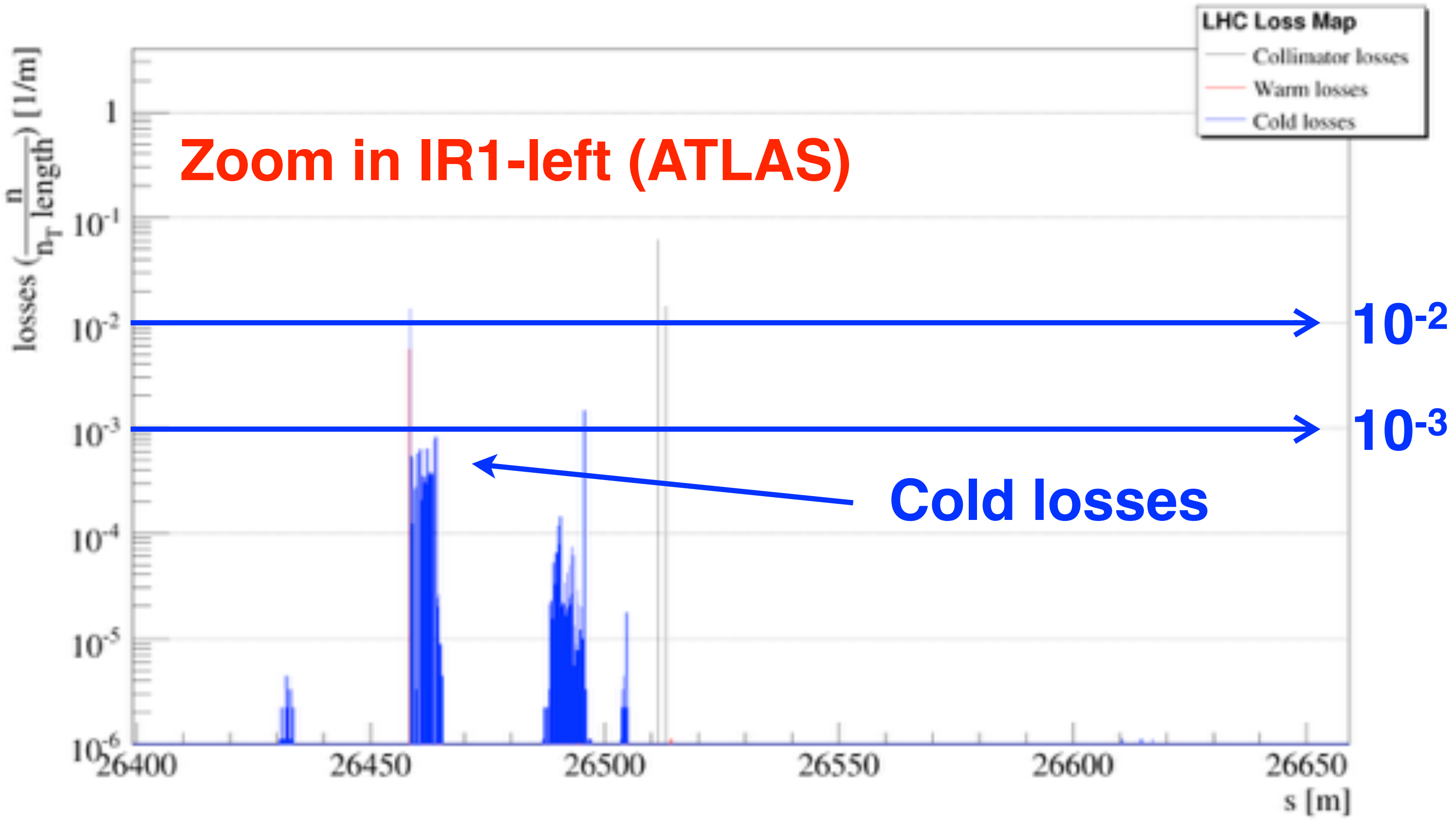


Single-stage cleaning

Zoom in IR7

10^{-3}

IP7



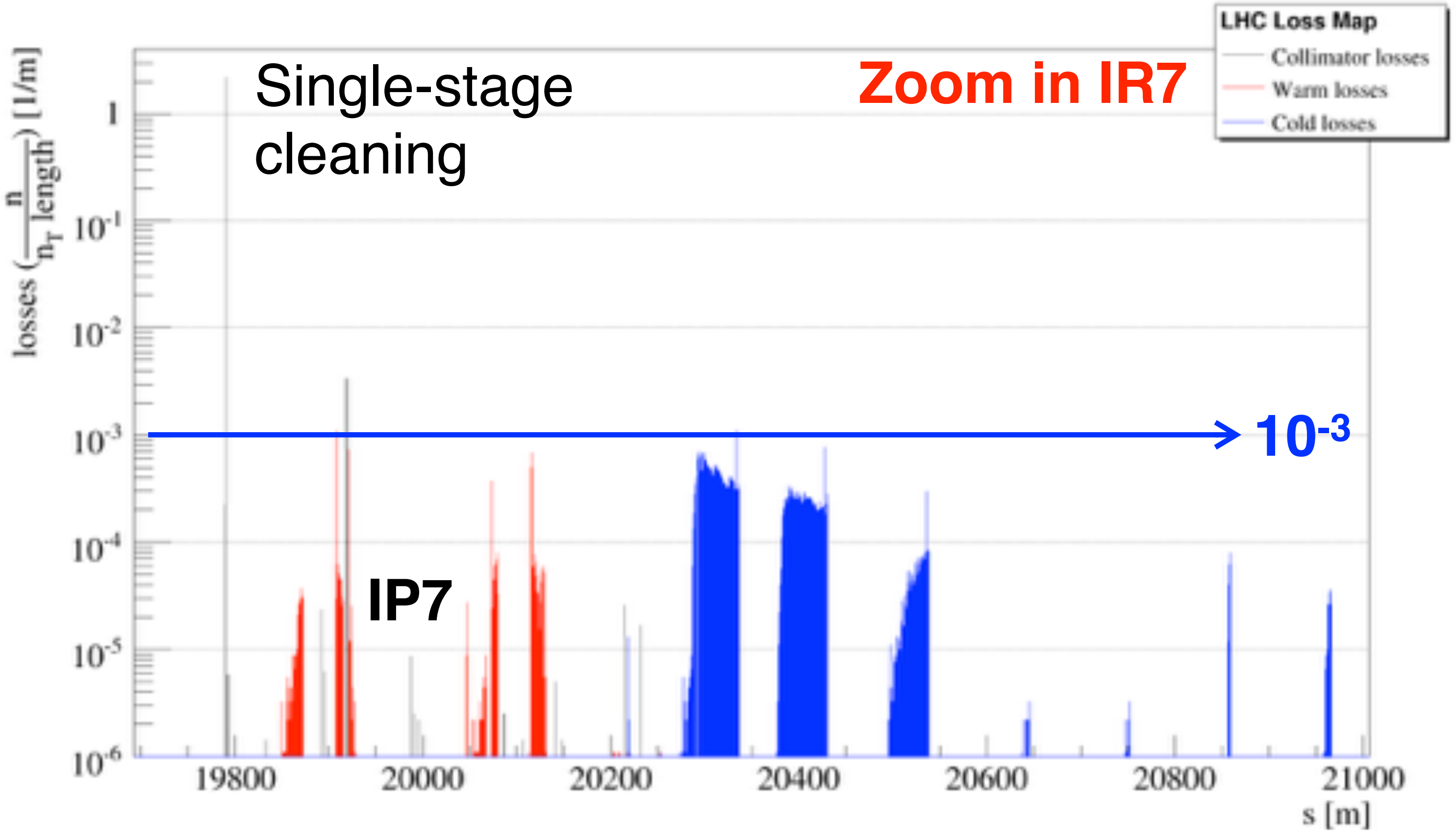
Zoom in IR1-left (ATLAS)

10^{-2}

10^{-3}

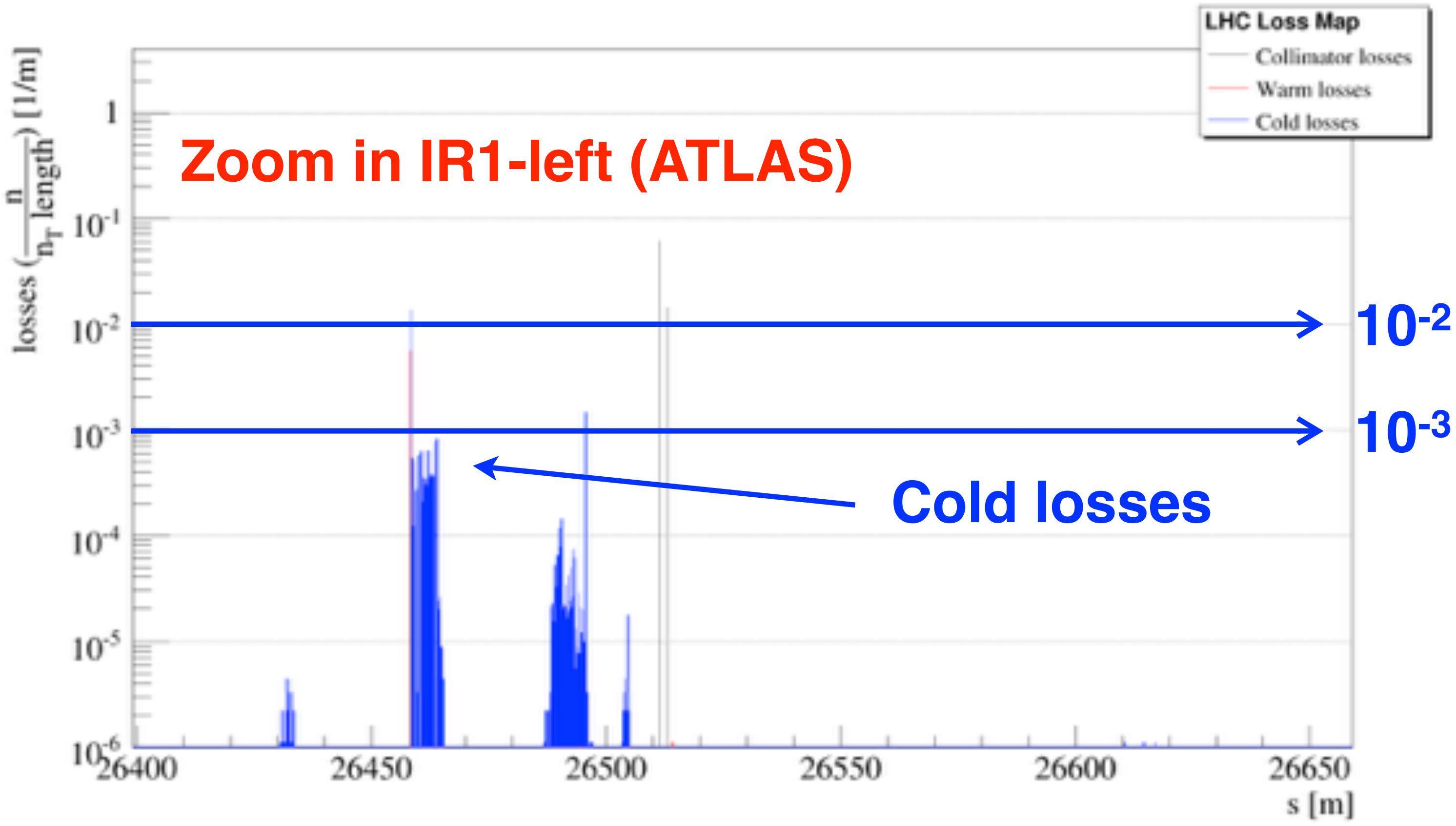
Cold losses

Comparison to quench limits



Single-stage cleaning

Zoom in IR7



Zoom in IR1-left (ATLAS)

Cold losses

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

R_q (7 TeV) = 3.2×10^7 p/m/s

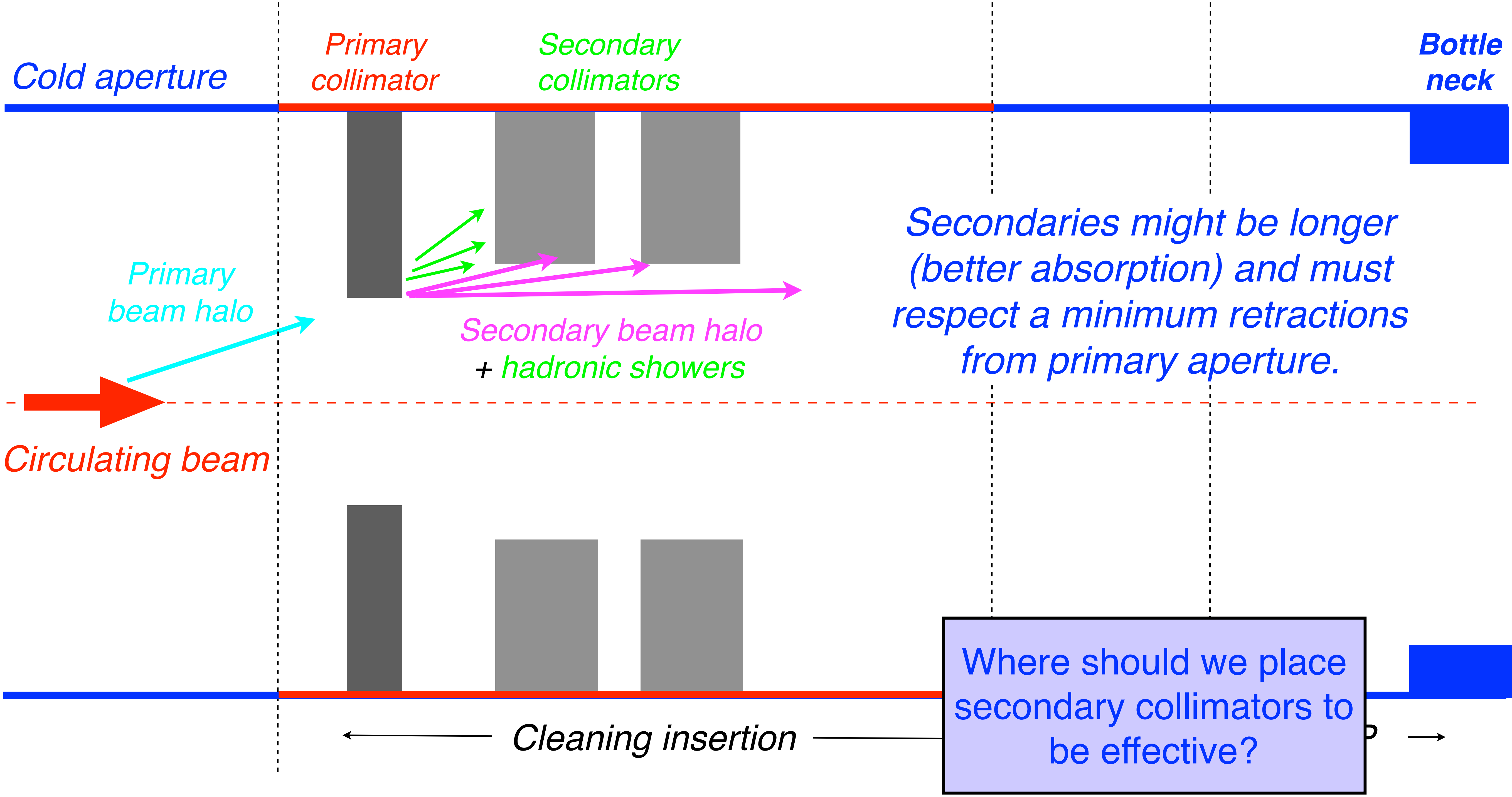
With the single-stage cleaning predicted by this model, losses are up to:

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



Cold aperture

Primary collimator

Secondary collimators

Bottle neck

Primary beam halo

Secondary beam halo

+ hadronic showers

Circulating beam

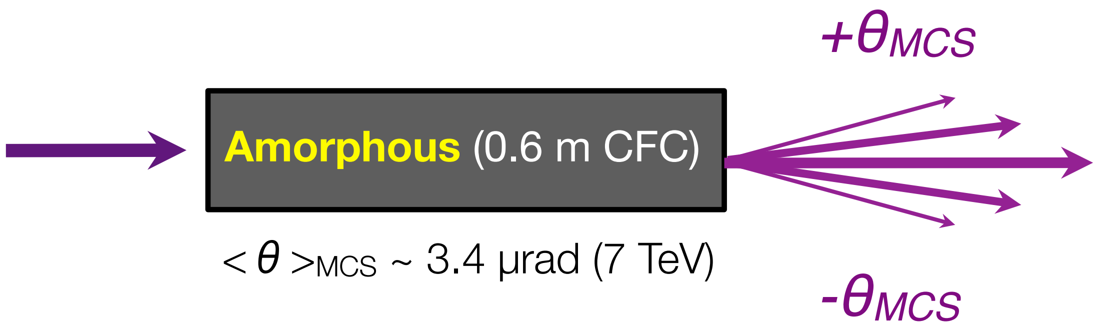
Cleaning insertion

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

Where should we place secondary collimators to be effective?

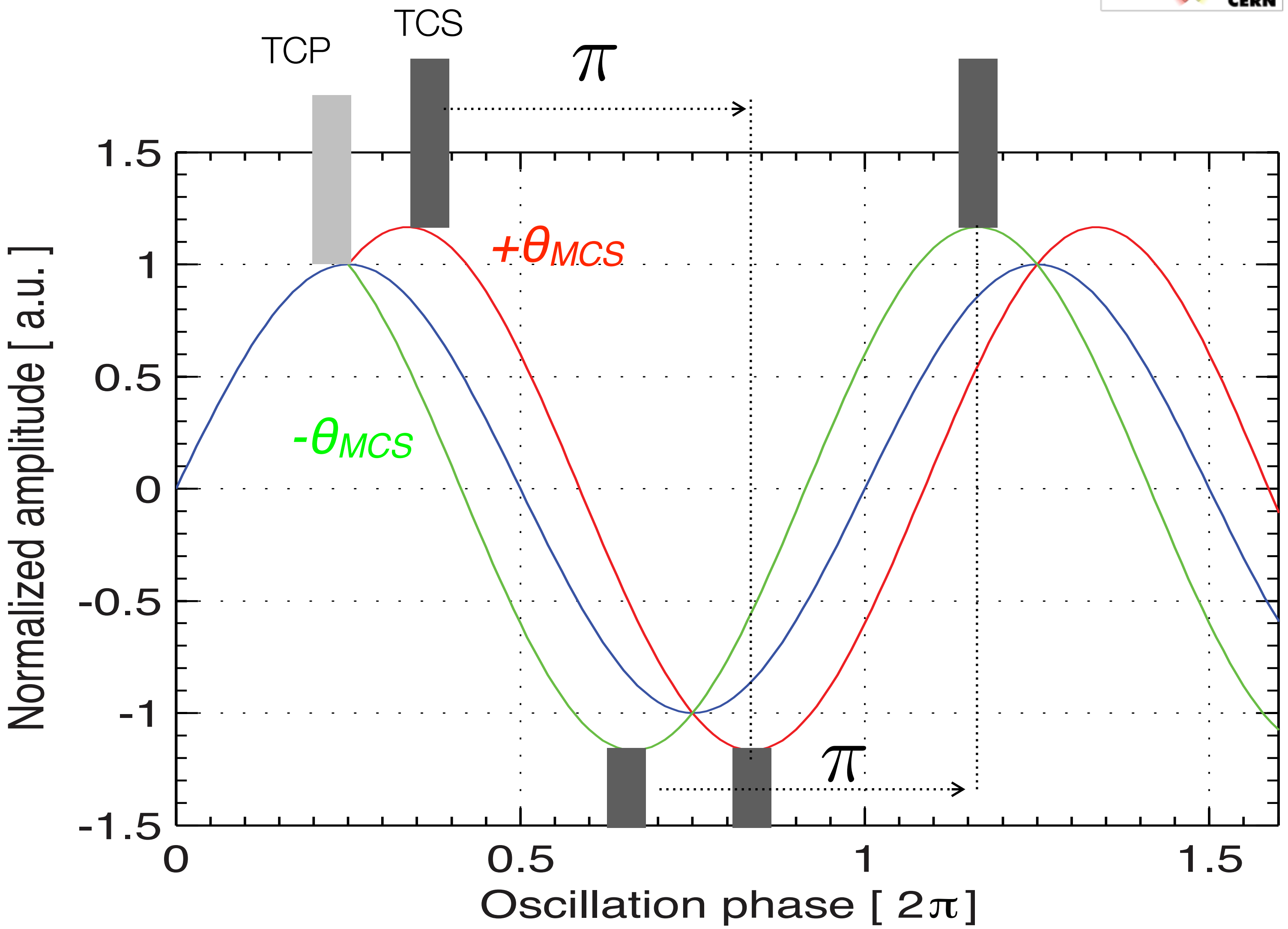
“Secondary” collimators (TCSs) can be added to intercept the secondary halo and the showers that leak out of the primary collimator.

Optimum secondary collimator locations



$< \theta >_{MCS}$ ~ 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 +θ_{MCS} and -θ_{MCS}.
Optimum: 4 TCSs (per plane) providing redundant coverage.



Betatron motion in *z ≡ (x, y)*

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

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

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

Reality is a bit more complicated...

Optimum phases depend on TCP/TCS retraction

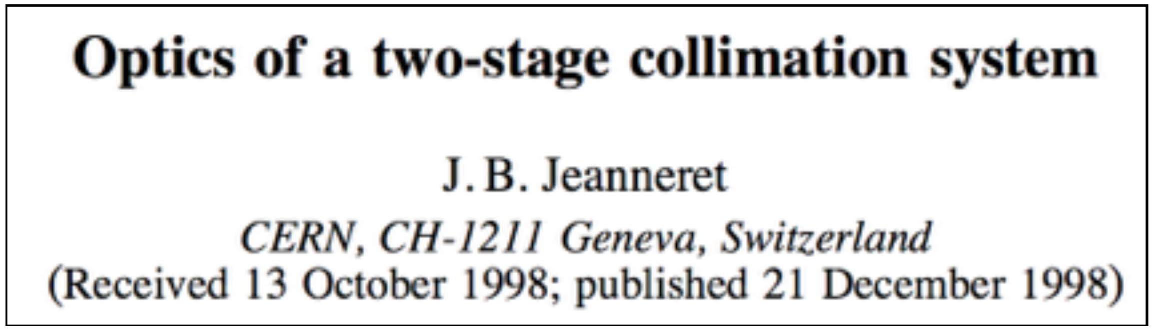
$$\tan\mu_x = \frac{\sqrt{n_{\mathrm{TCP}}^2 - n_{\mathrm{TCS}}^2}}{n_{\mathrm{TCP}}^2}\,\frac{\cos\phi}{\cos\alpha}$$

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

α, ϕ : collimator plane and scattering angle

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

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

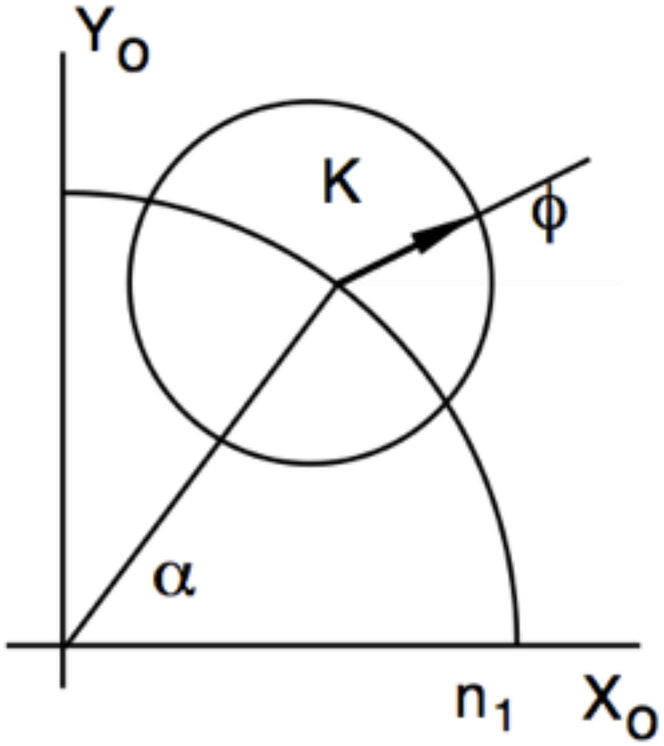


Optics of a two-stage collimation system

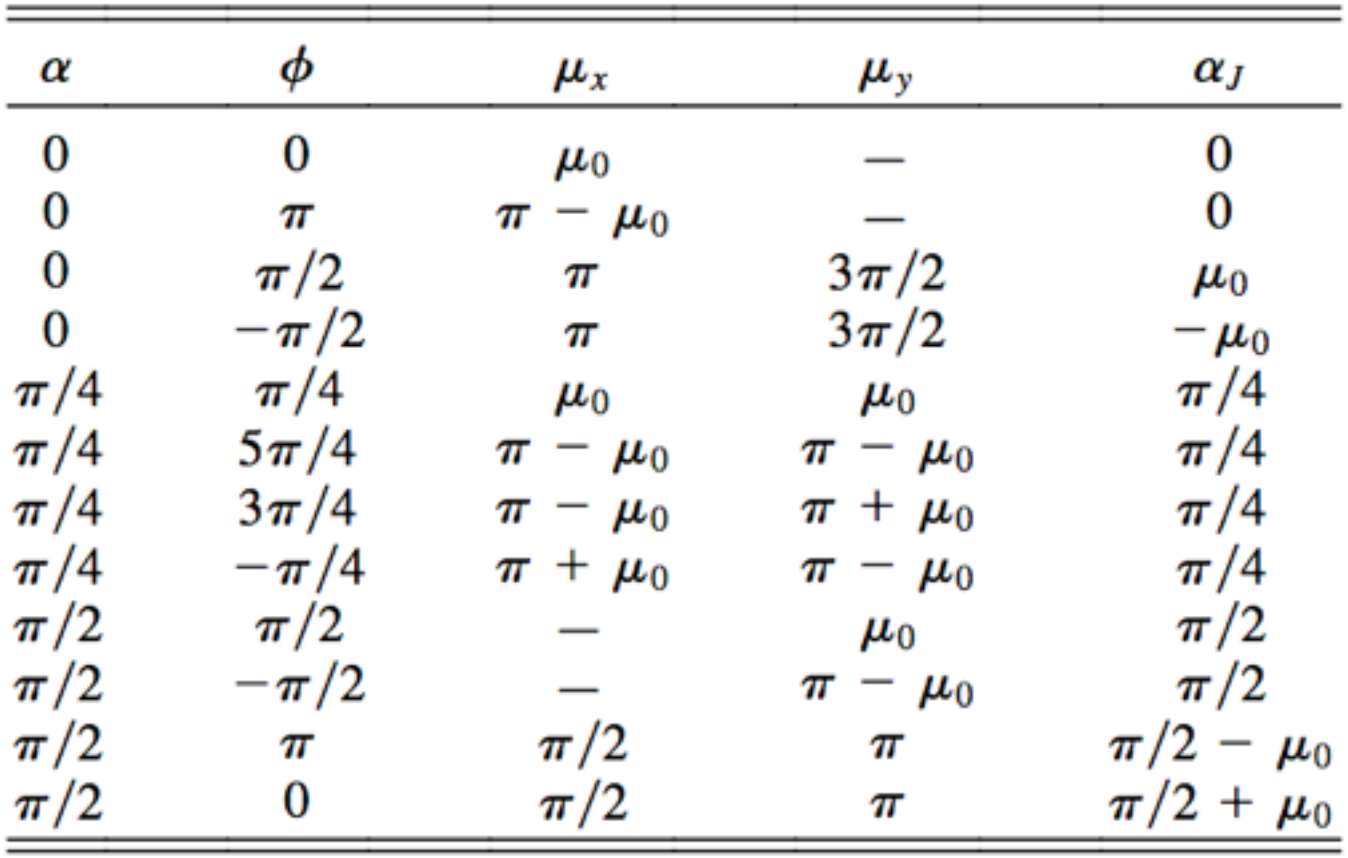
J. B. Jeanneret

CERN, CH-1211 Geneva, Switzerland

(Received 13 October 1998; published 21 December 1998)



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	$\pi/2 + \mu_0$

Reality is a bit more complicated...

Optimum phases depend on TCP/TCS retraction

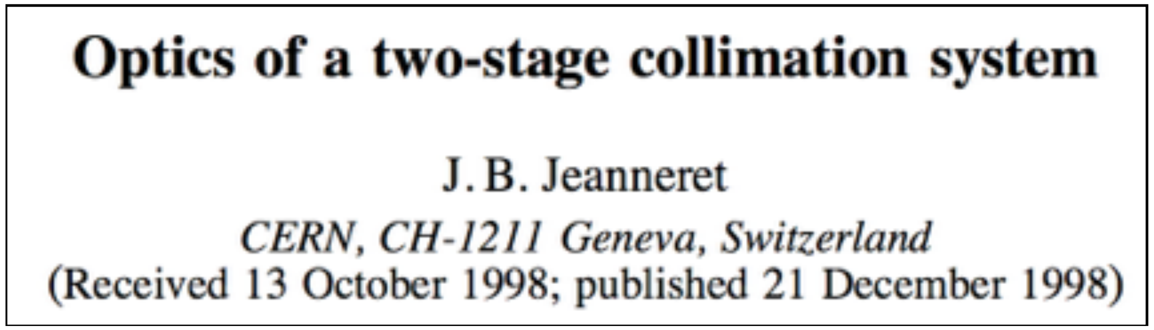
$$\tan \mu_x = \frac{\sqrt{n^2_{\mathrm{TCP}} - n^2_{\mathrm{TCS}}}}{n^2_{\mathrm{TCP}}} \frac{\cos \phi}{\cos \alpha}$$

$n_{\mathrm{TCP}}, n_{\mathrm{TCS}}$: 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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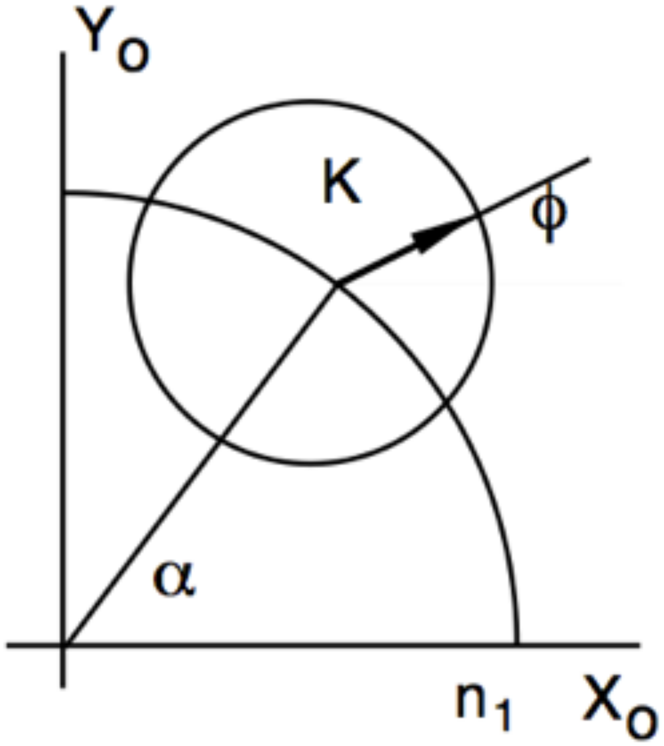
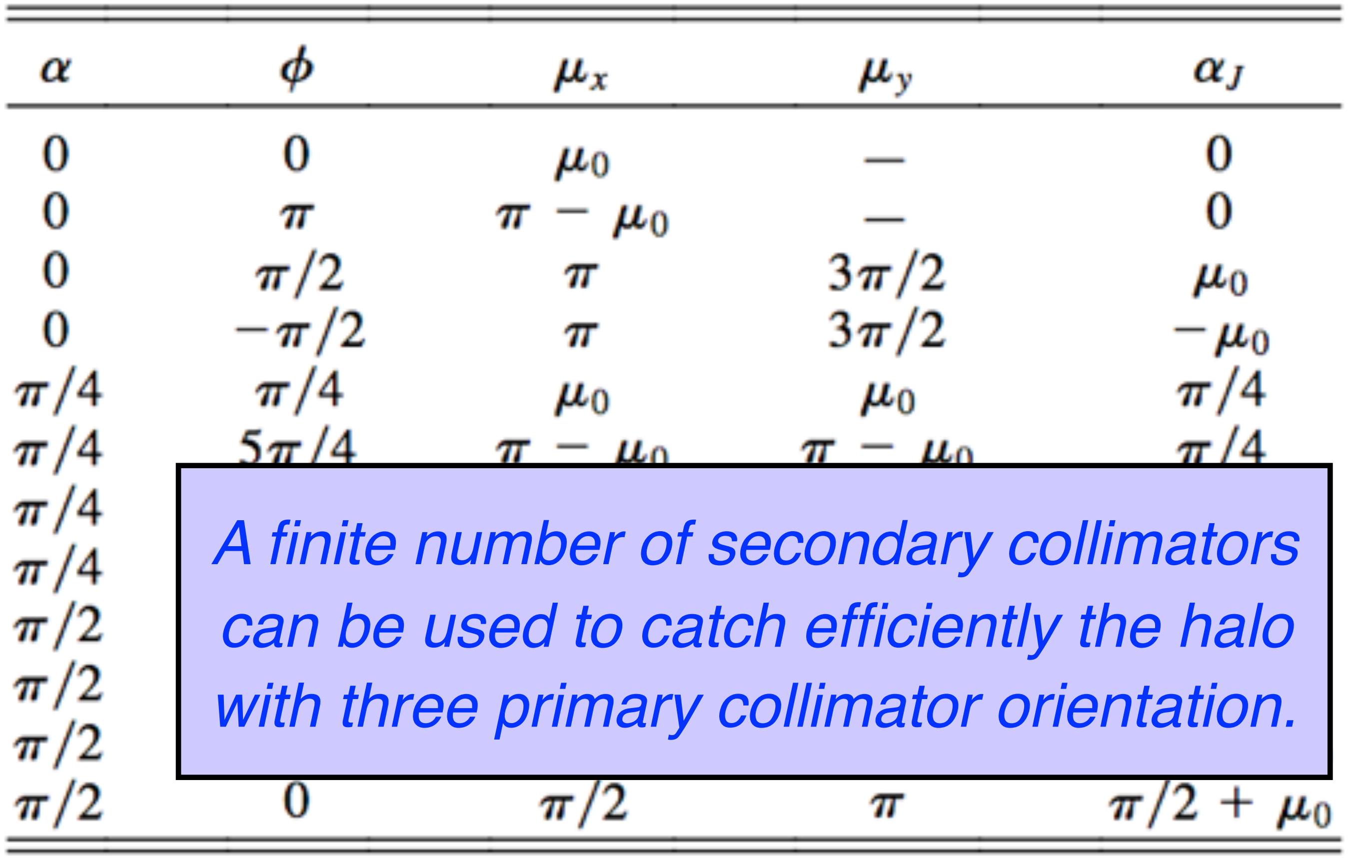
(Received 13 October 1998; published 21 December 1998)



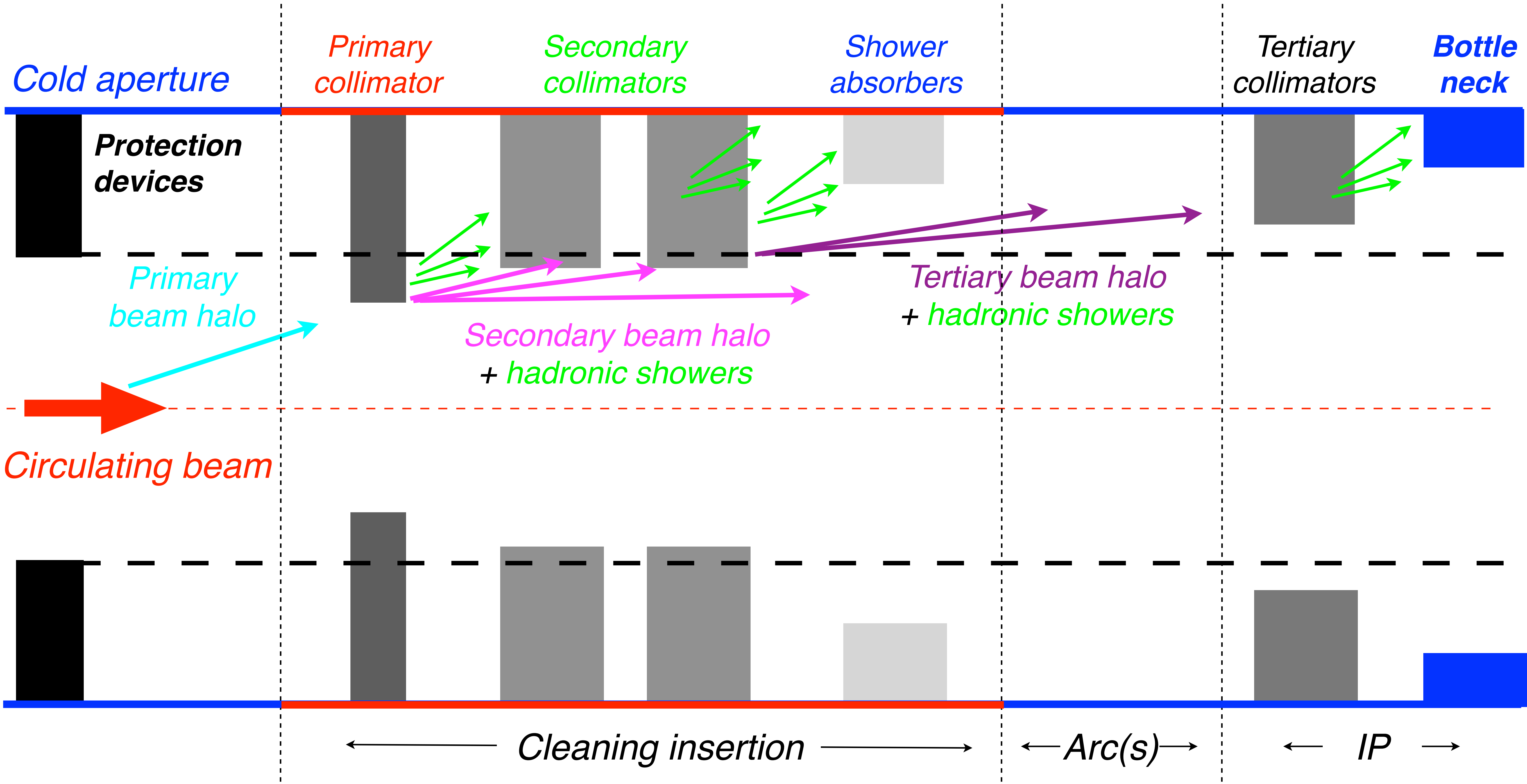
Phase locations (μ_x, μ_y) and jaw orientation (α_J) to catch different scattering angle (ϕ) for horizontal (α=0), vertical (α=π/2) and skew (α=π/2) scattering source locations.



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	$\pi/4$
$\pi/4$	$5\pi/4$	$\pi - \mu_0$	$\pi - \mu_0$	$\pi/4$
$\pi/4$				
$\pi/4$				
$\pi/2$				
$\pi/2$				
$\pi/2$				
$\pi/2$	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.

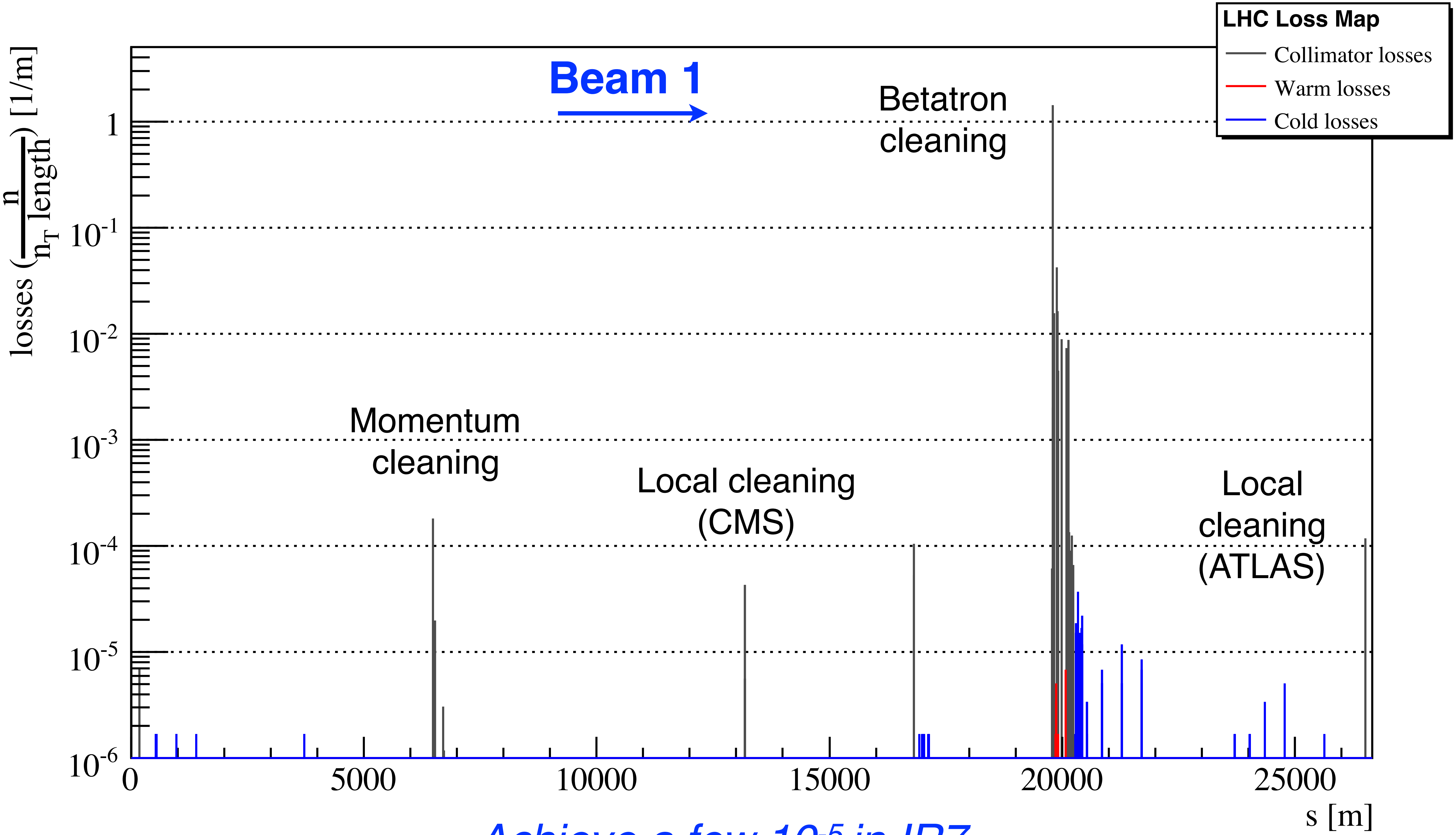
Multi-stage collimation at the LHC



Including protection devices, a **5-stage cleaning** in required!

The system performance relies on achieving the well-defined **hierarchy** between different **collimator families** and **machine aperture**.

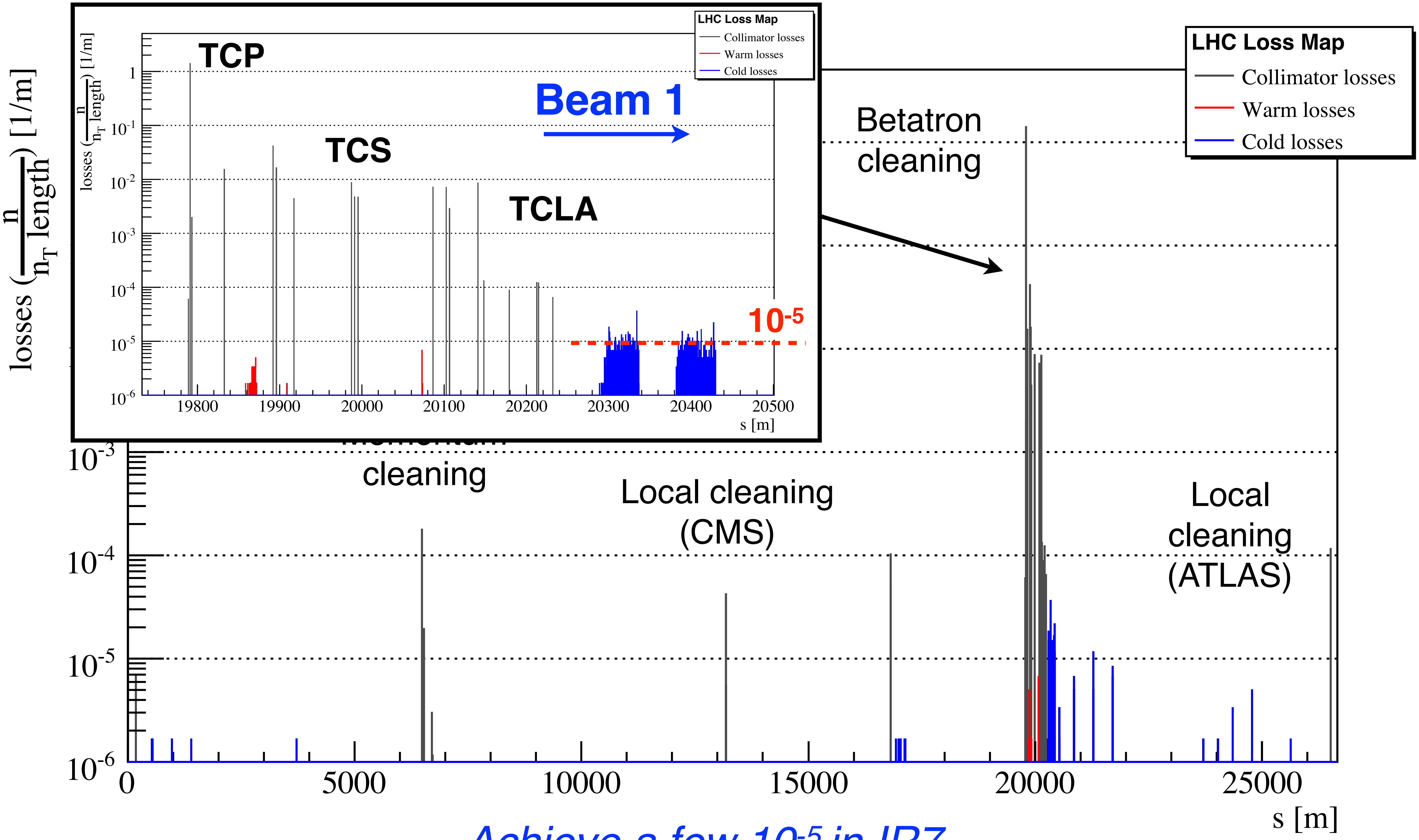
Simulated 7 TeV performance



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

Cold losses in experiments removed by local protection.

Simulated 7 TeV performance



Betatron cleaning

Momentum cleaning

Local cleaning (CMS)

Local cleaning (ATLAS)

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

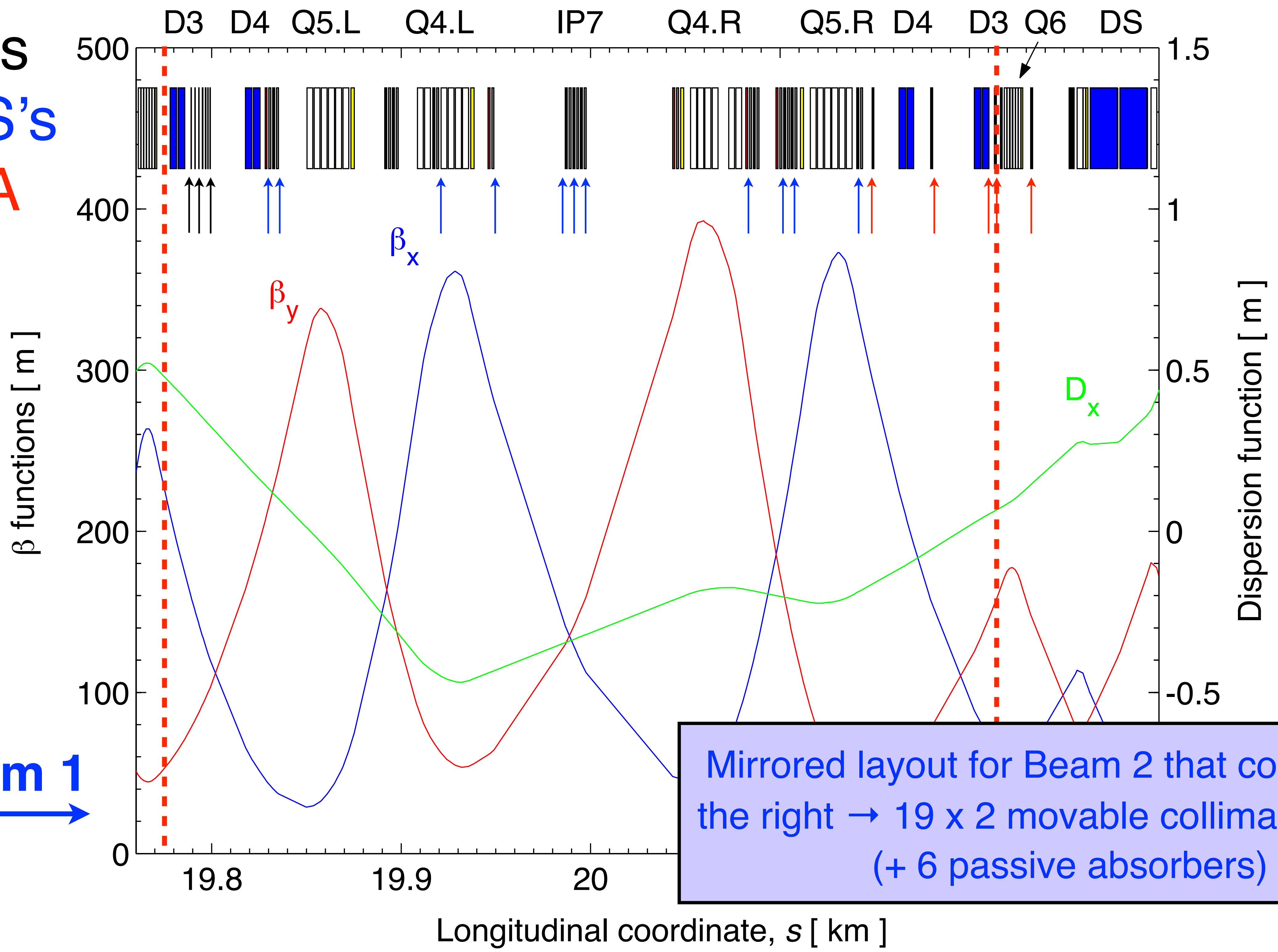
Cold losses in experiments removed by local protection.

Betatron cleaning insertion

3 TCP's

11 TCS's

5 TCLA



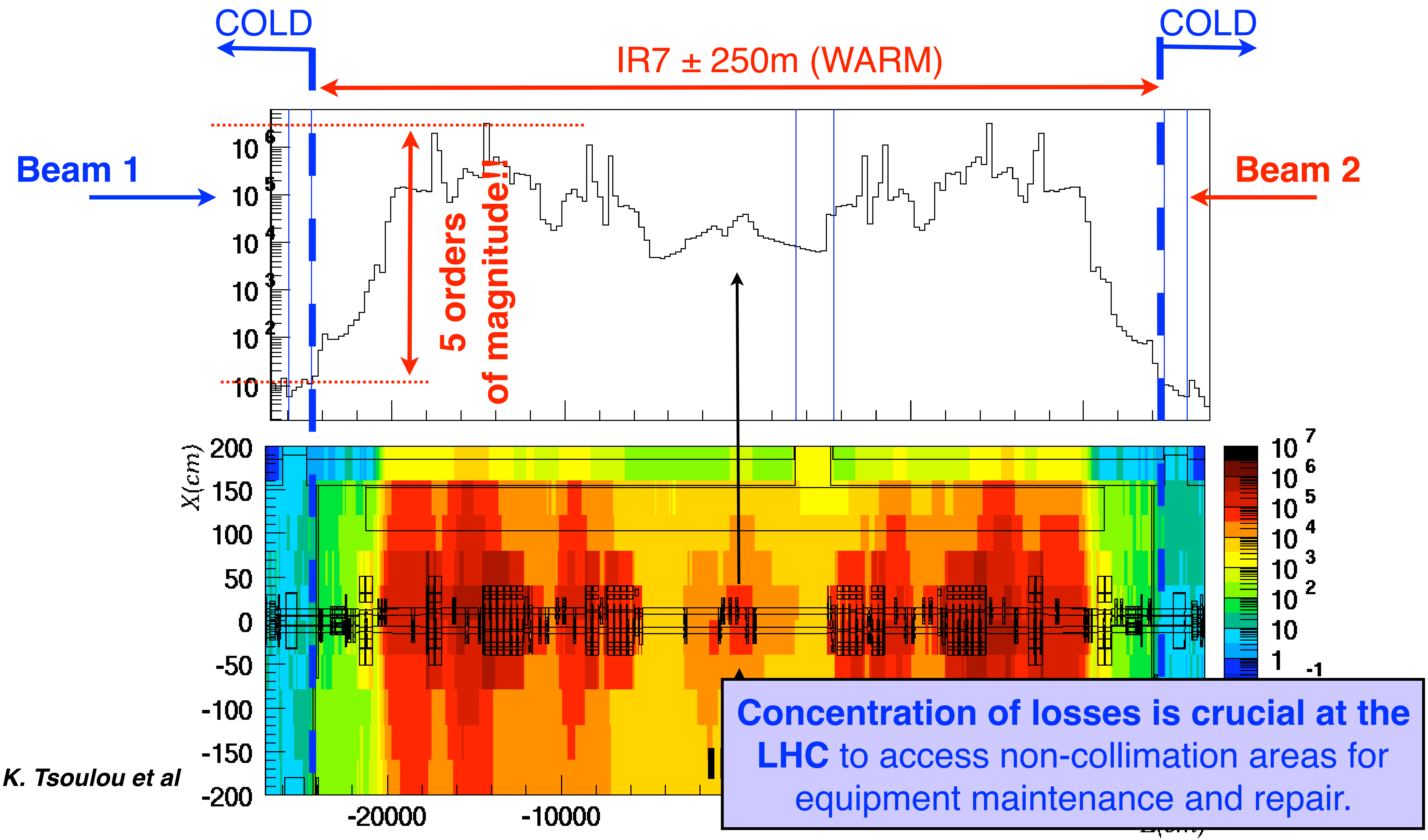
Beam 1 →

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

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

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

Radiation doses in collimation region



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

K. Tsoulou et al

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

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- The LHC beam collimation system
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Off-momentum cleaning systems

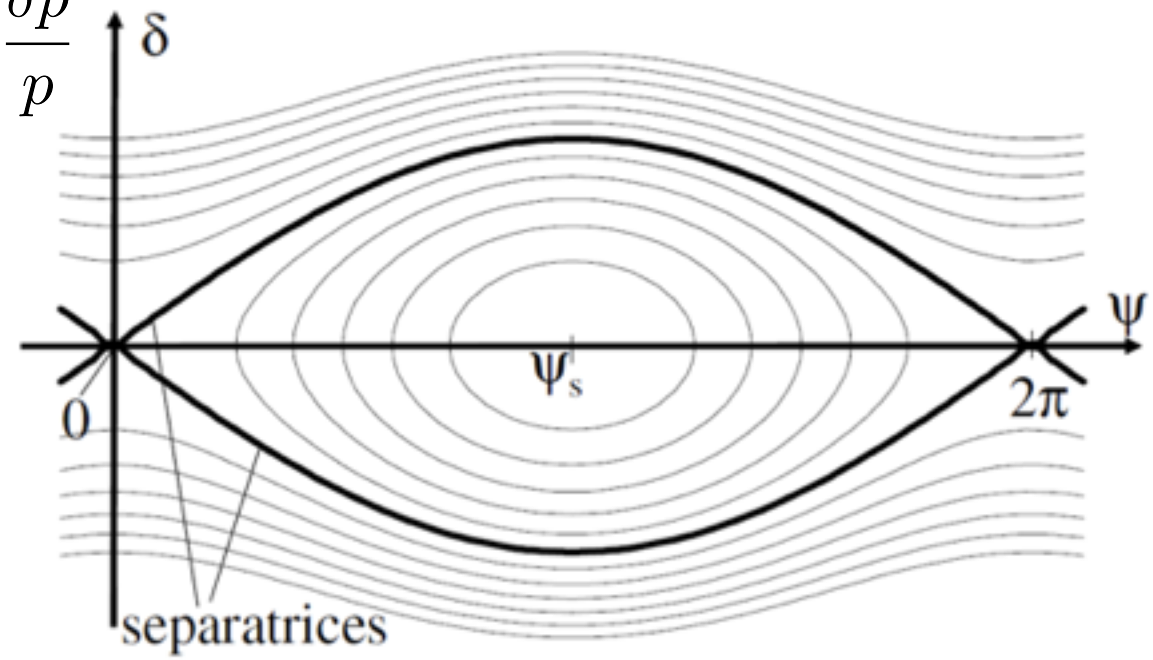
"**Off-momentum losses**" = losses occurring when beam particles lose the energy matching compared to the reference particle.

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

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.

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

How do we collimate these particles?



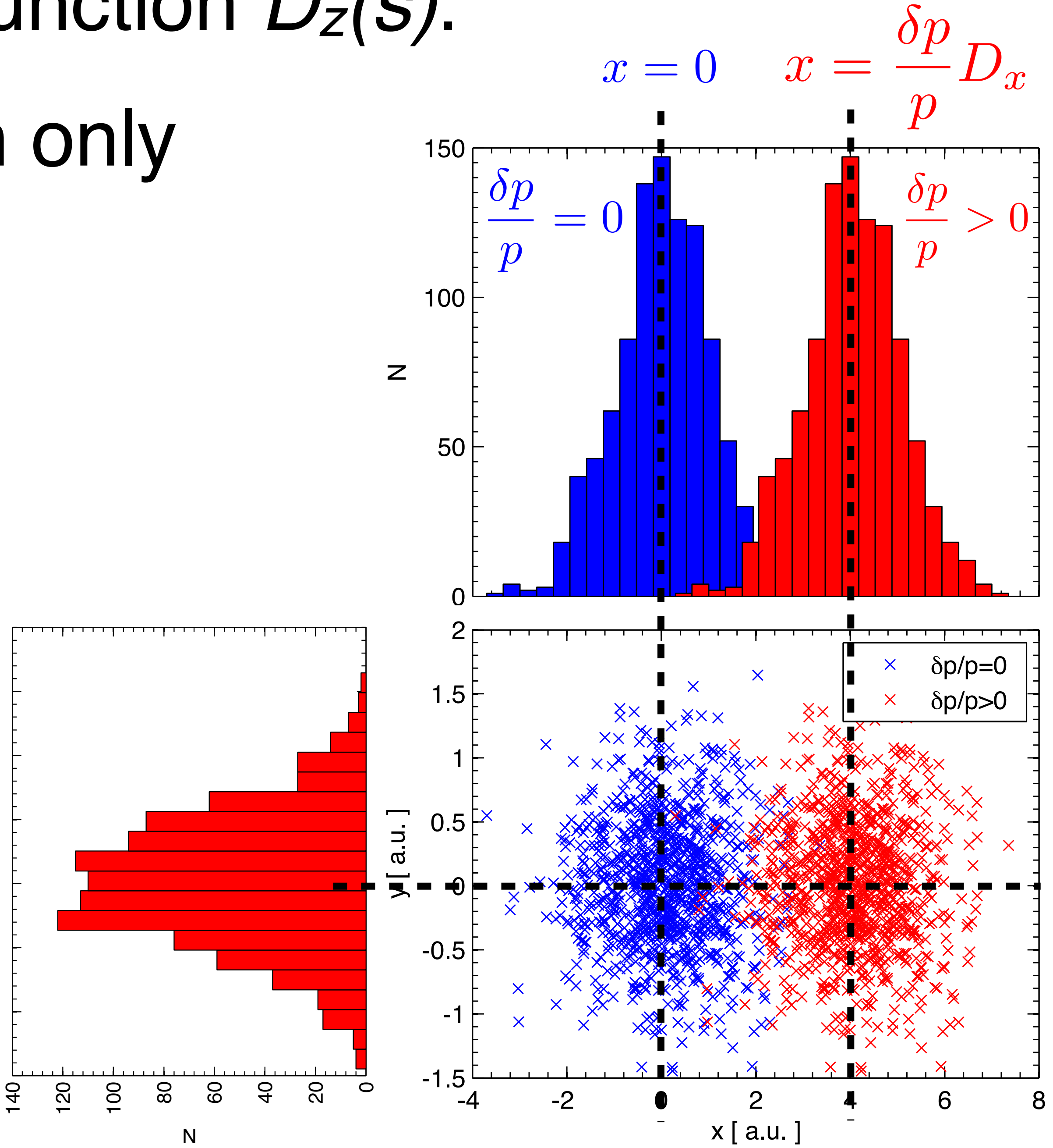
Catching off-momentum particles

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

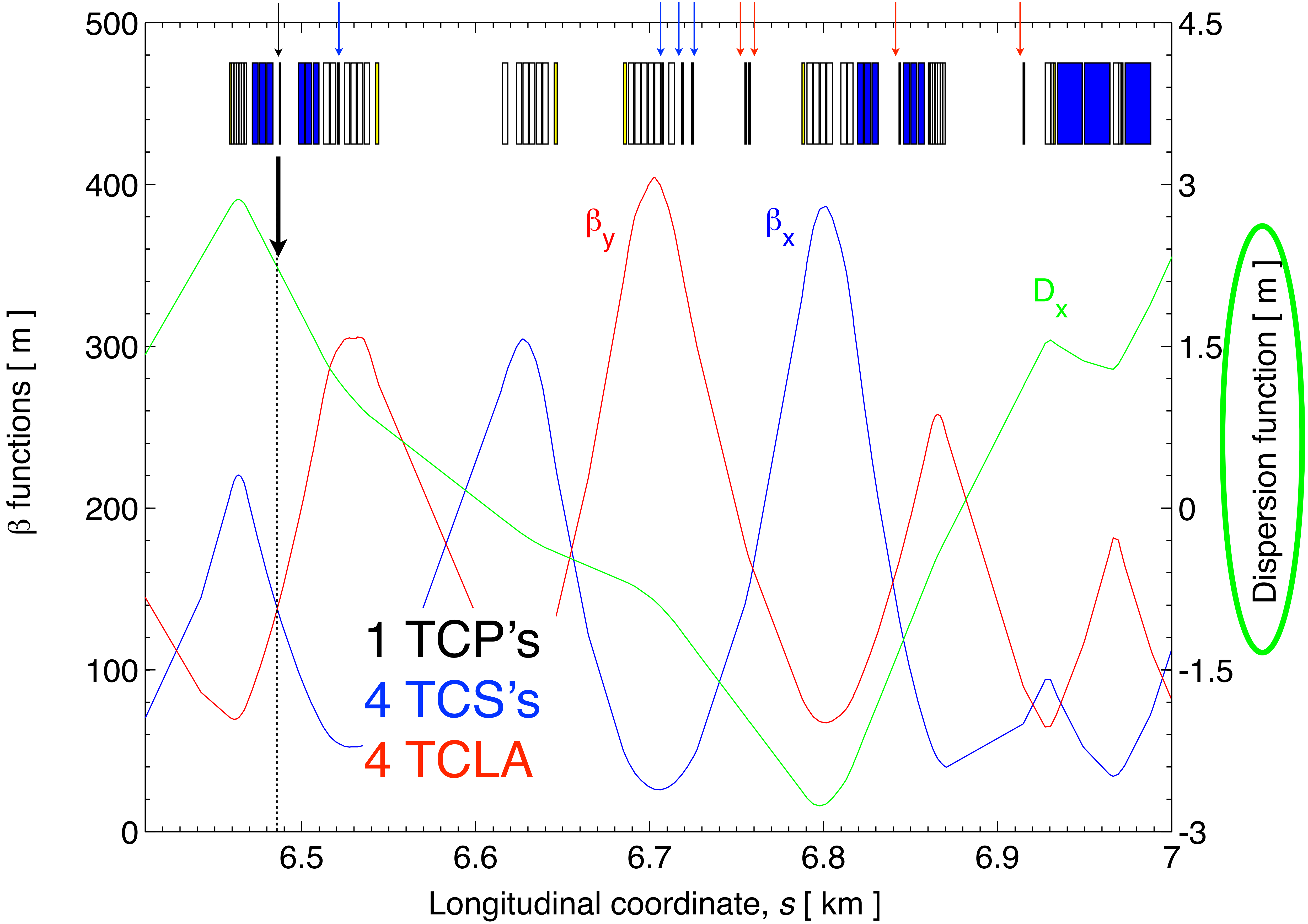
The **mismatch in energy** translates into a **shift of position** that follows the periodic dispersion function *D*$_z$*(s)*.

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

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

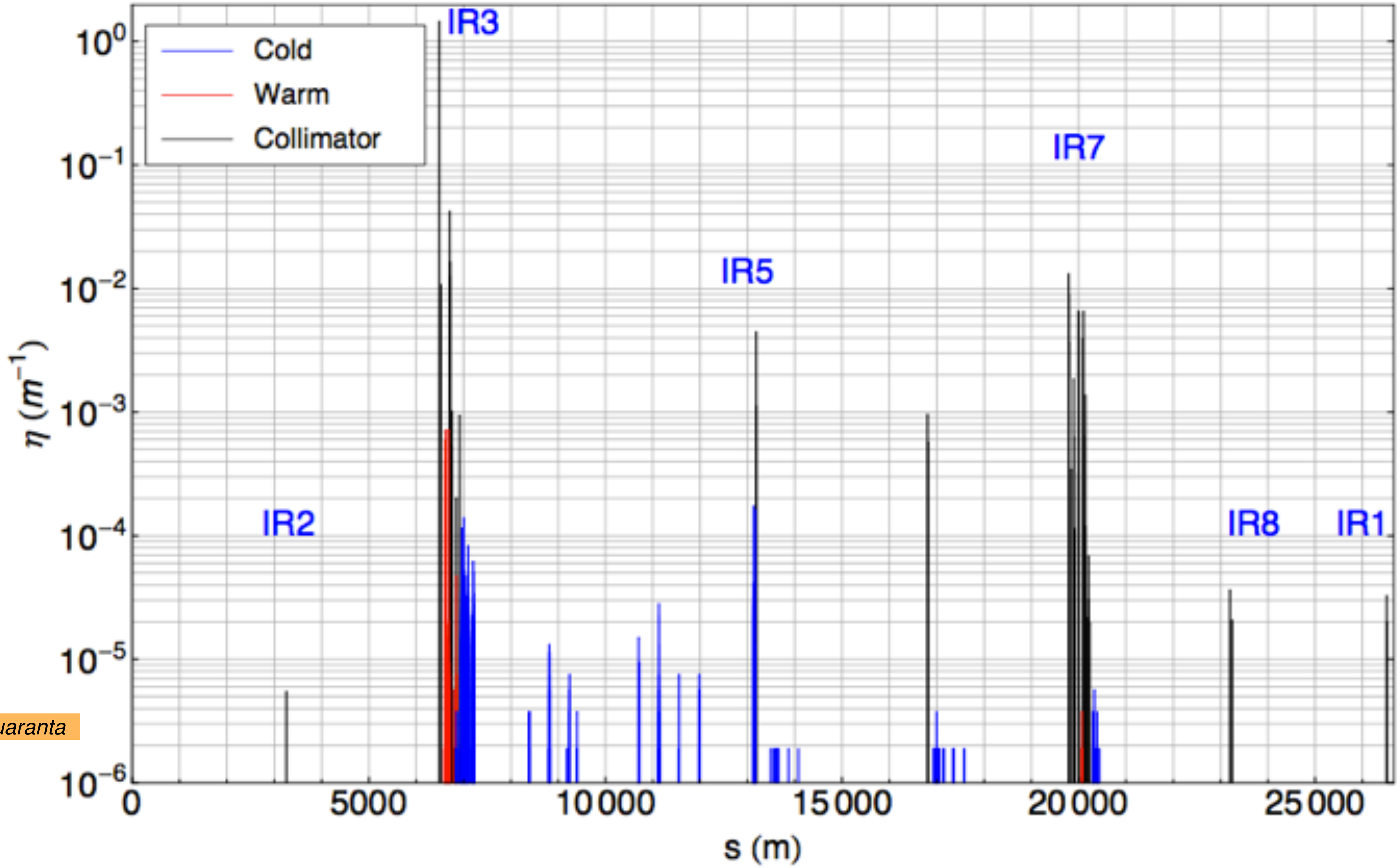


Momentum cleaning optics



1 TCP's
4 TCS's
4 TCLA

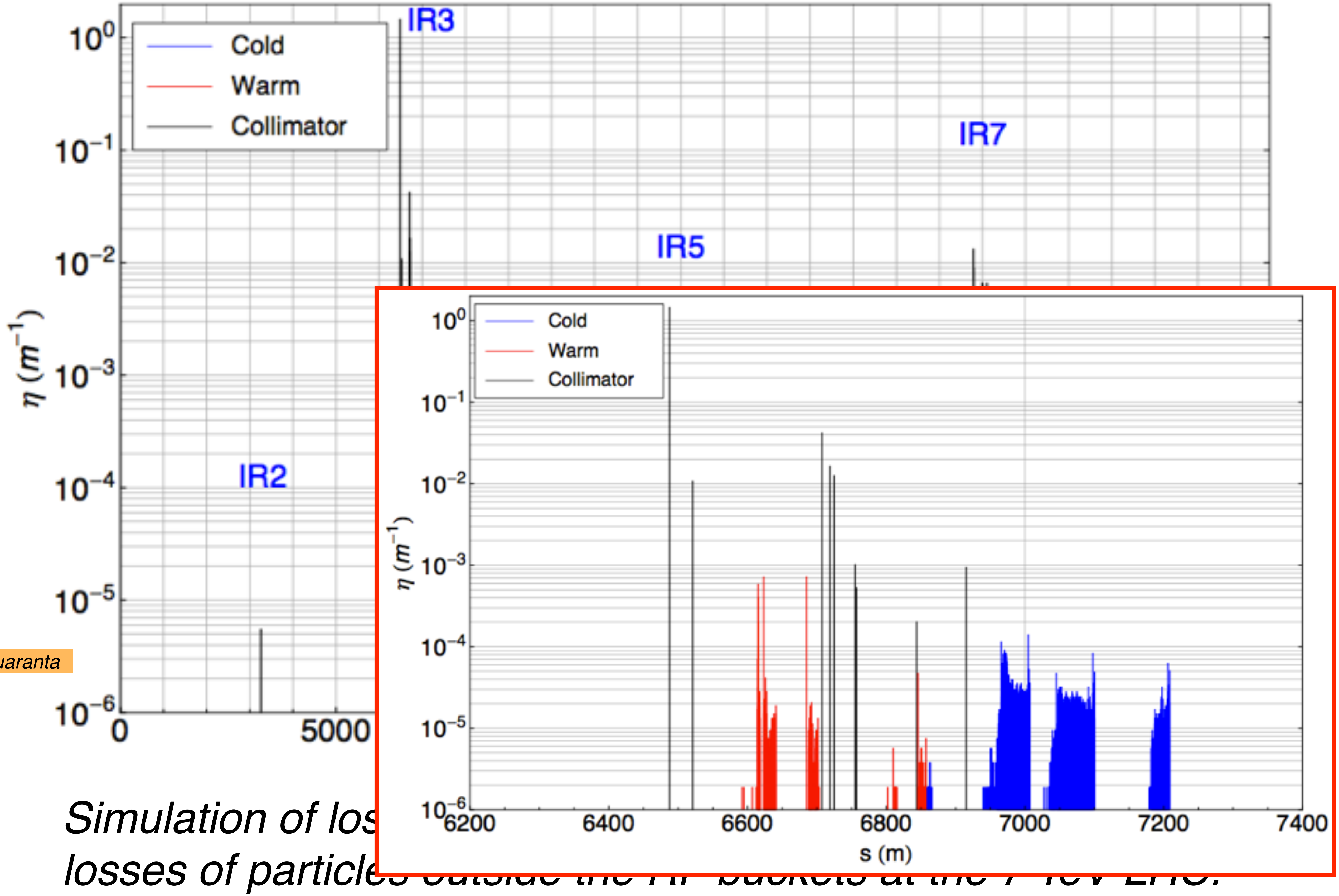
IR3 loss maps: synch. radiation losses



E. Quaranta

Simulation of losses in IR3 caused by synchrotron radiation losses of particles outside the RF buckets at the 7 TeV LHC.

IR3 loss maps: synch. radiation losses

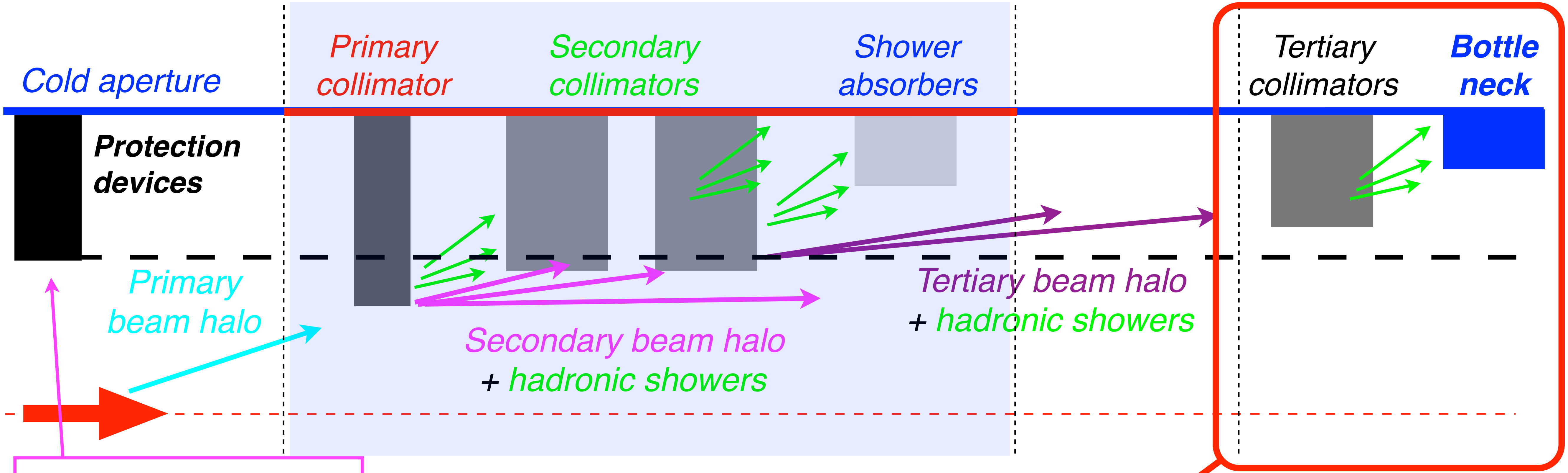


E. Quaranta

Simulation of los

losses of particle

Local cleaning and protection



Protection devices covered in another lecture.

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

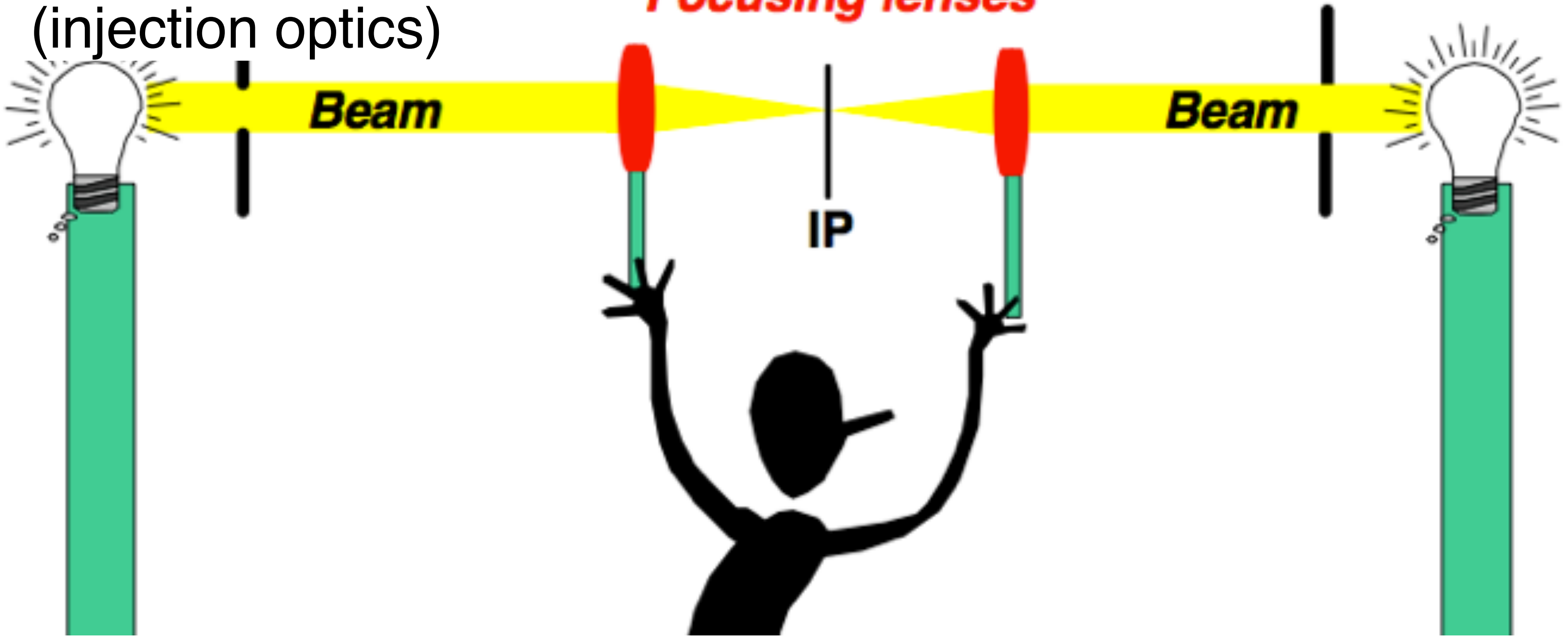
When do we need local protection?

How is the collimator position chosen in these cases?

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

Optics in high-luminosity points

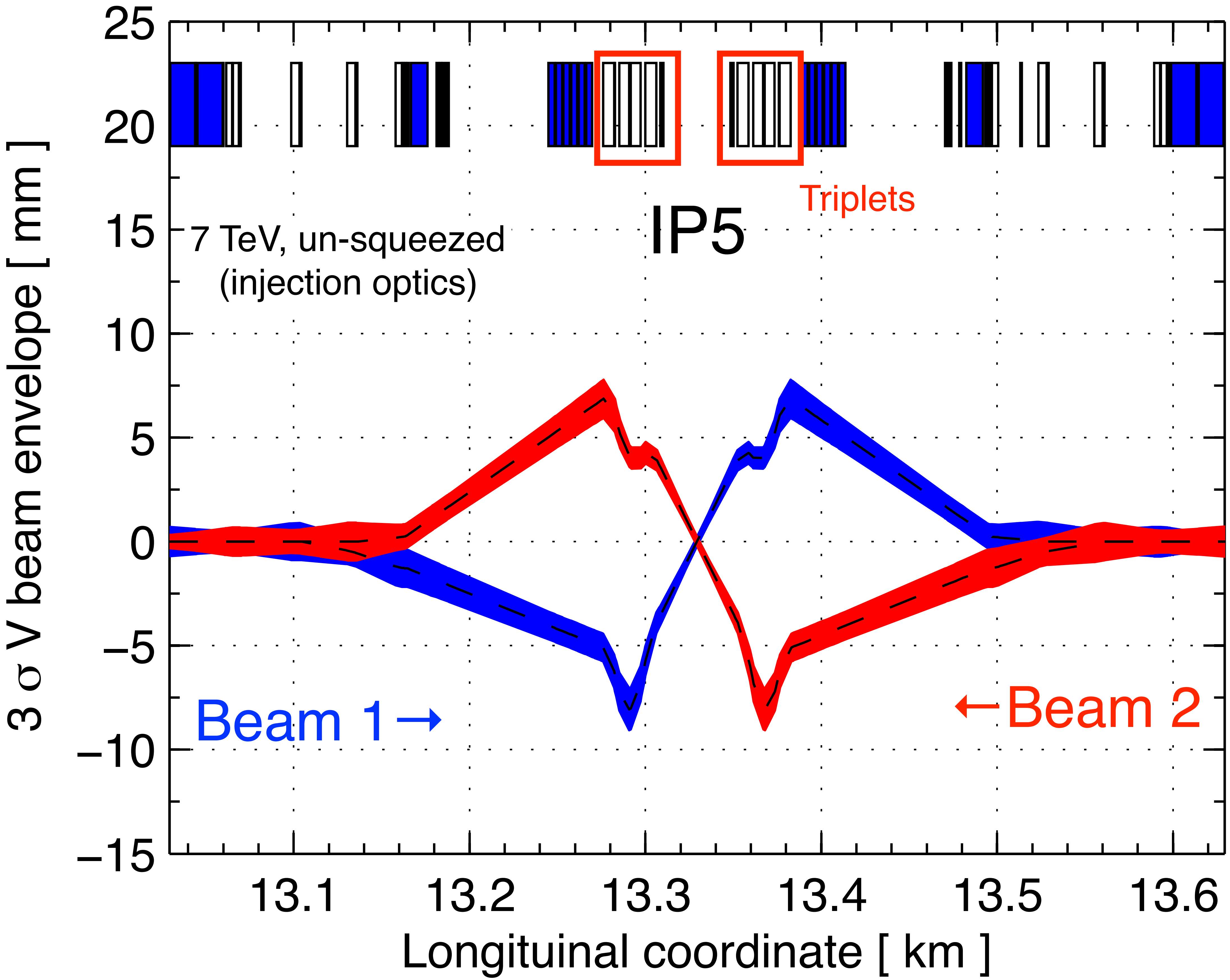
7 TeV, un-squeezed
(injection optics)



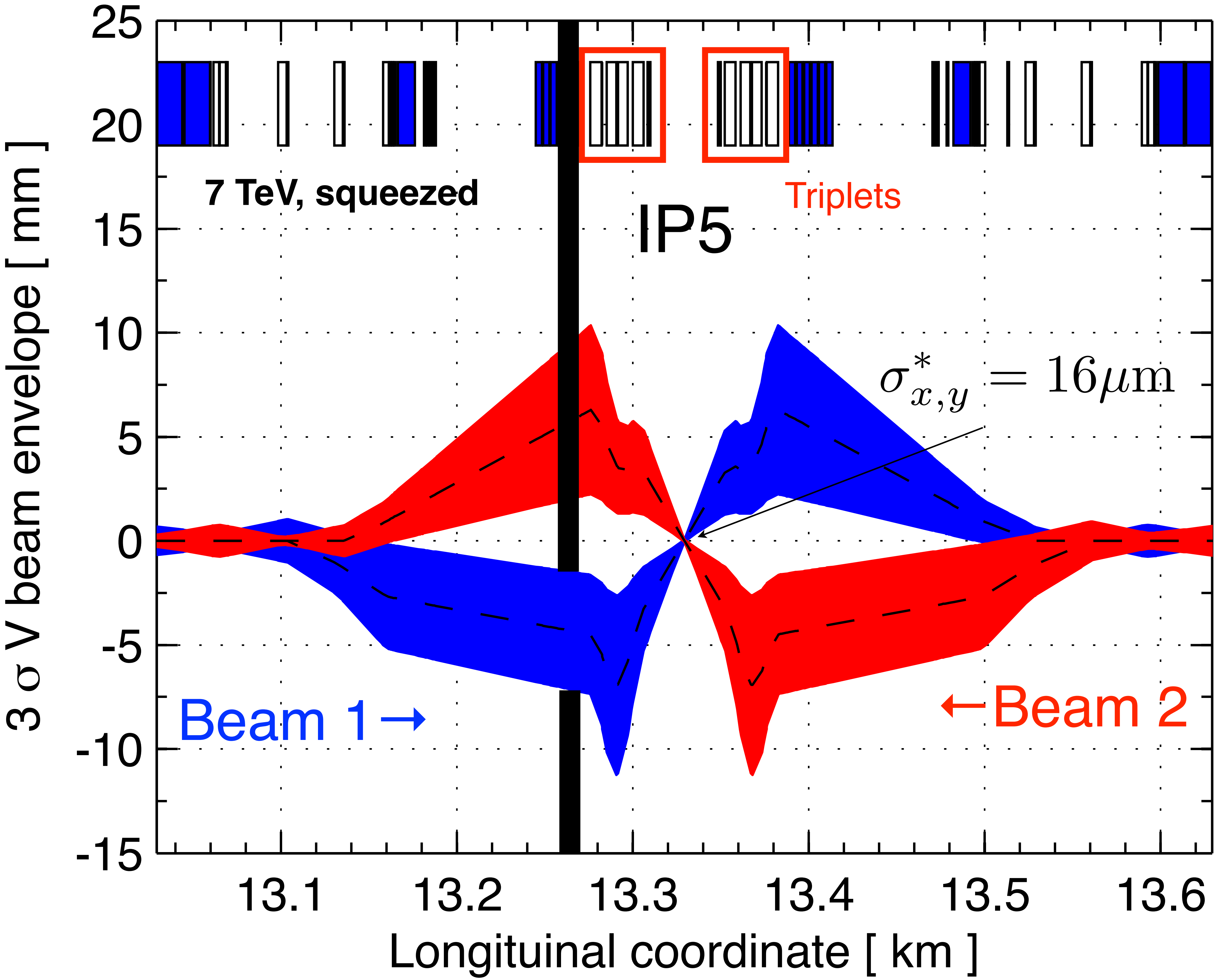
Beam 1→

←Beam 2

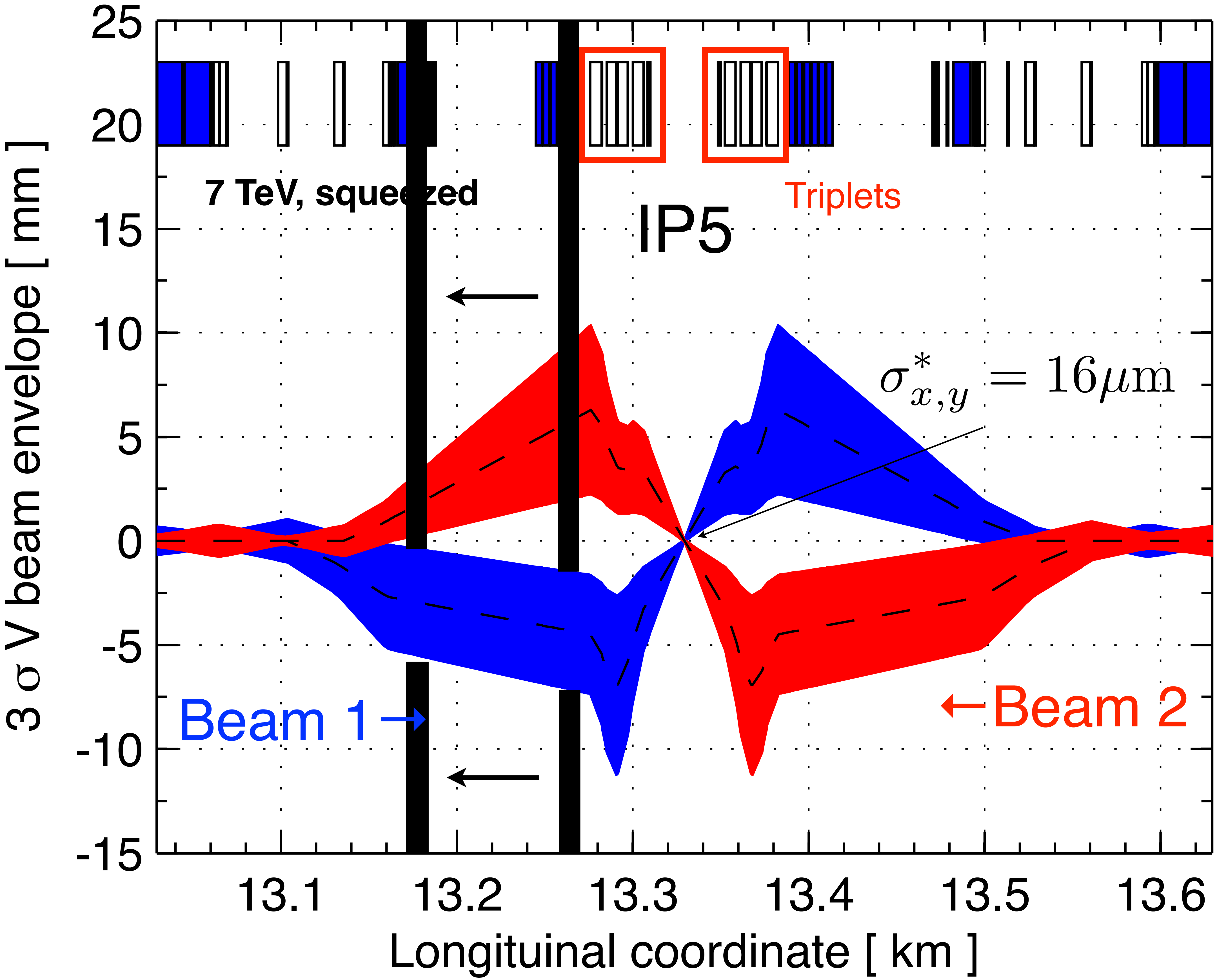
Optics in high-luminosity points



Optics in high-luminosity points



Optics in high-luminosity points



Role of LHC tertiary collimators

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

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

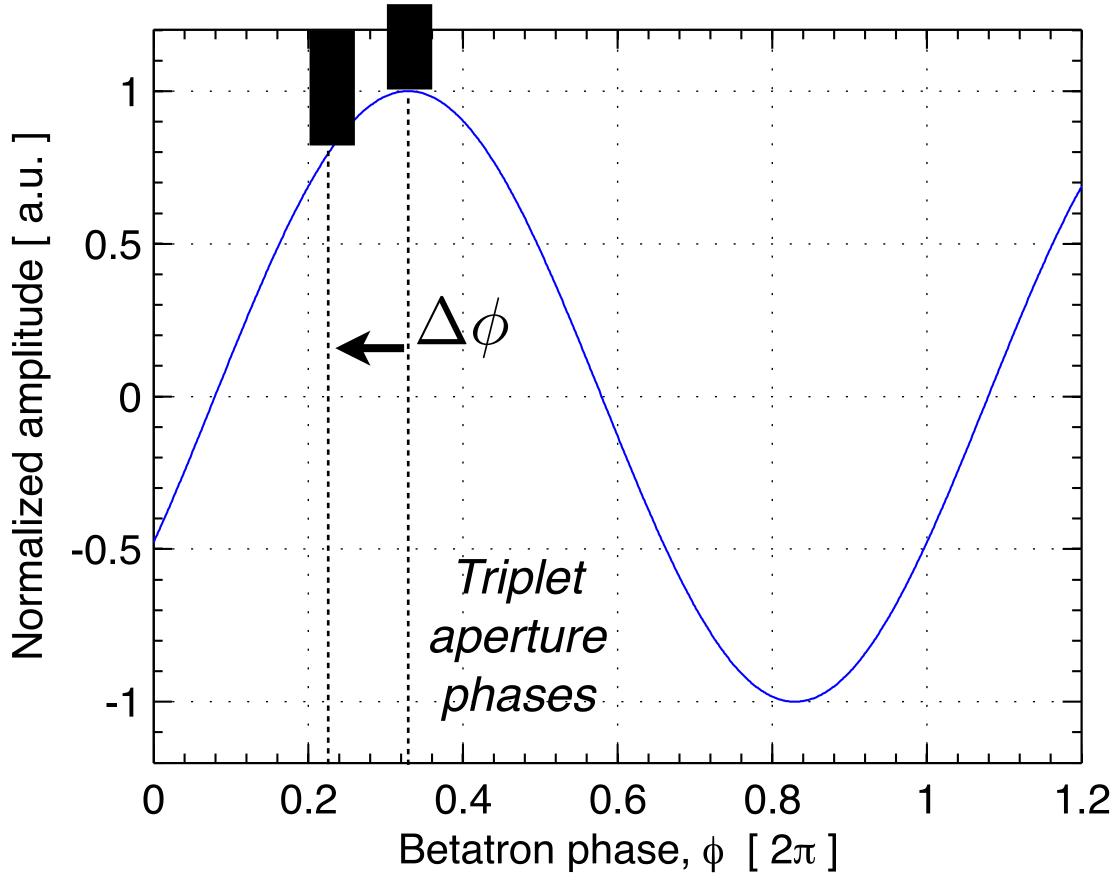
Triplet protection with "squeezed" beams is maximized by

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

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

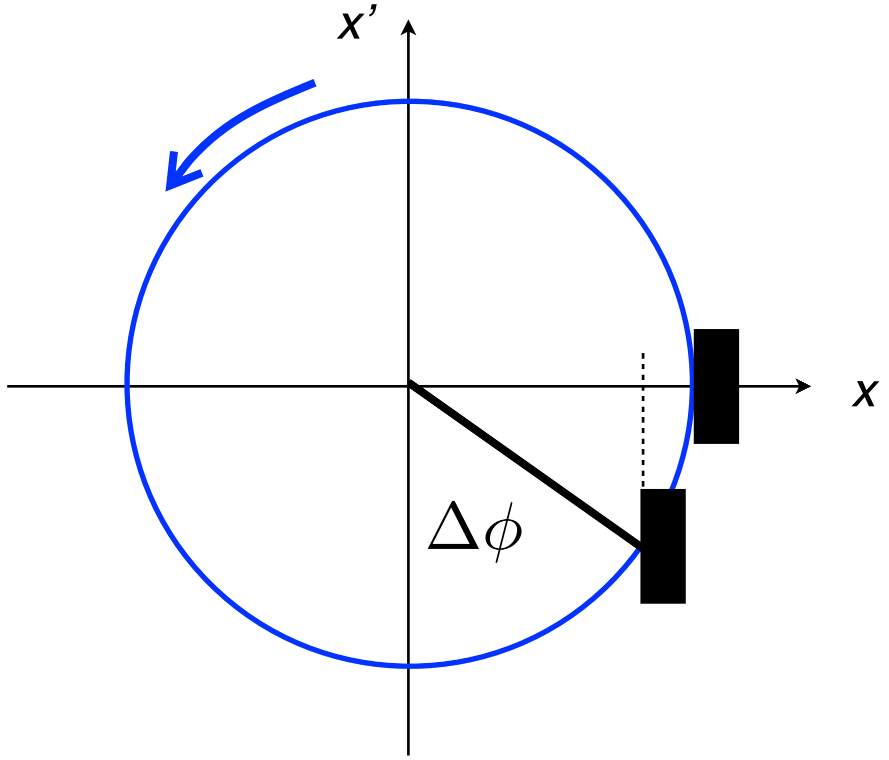
What if we cannot place TCT's at same phase of the triplet?

TCT settings versus aperture



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

Exercise: calculate the required TCT settings changes versus the phase difference.



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

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

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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)**

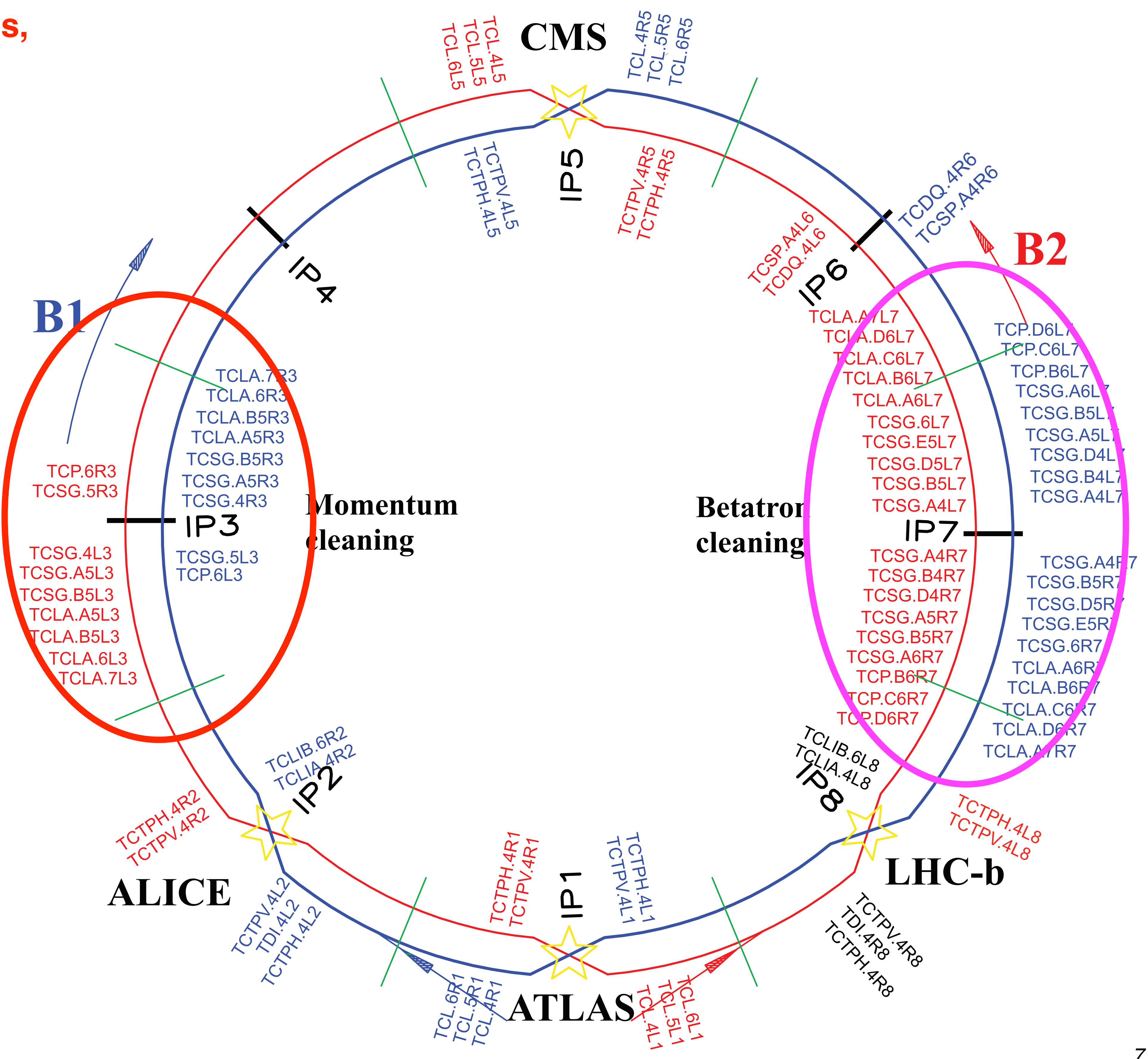
Passive absorbers for warm magnets

Physics debris absorbers

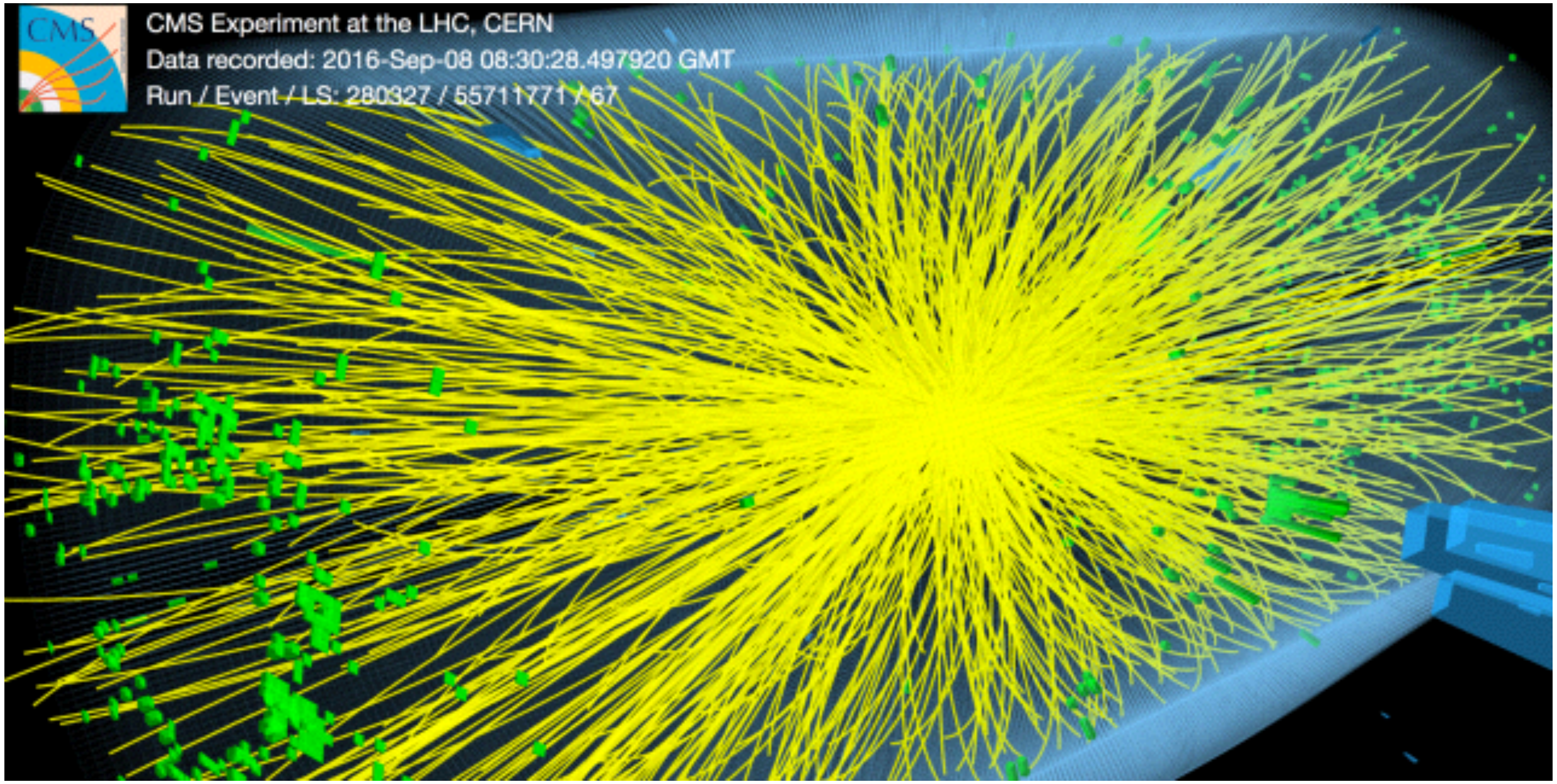
Transfer lines (13 collimators)

Injection and dump protection (10)

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



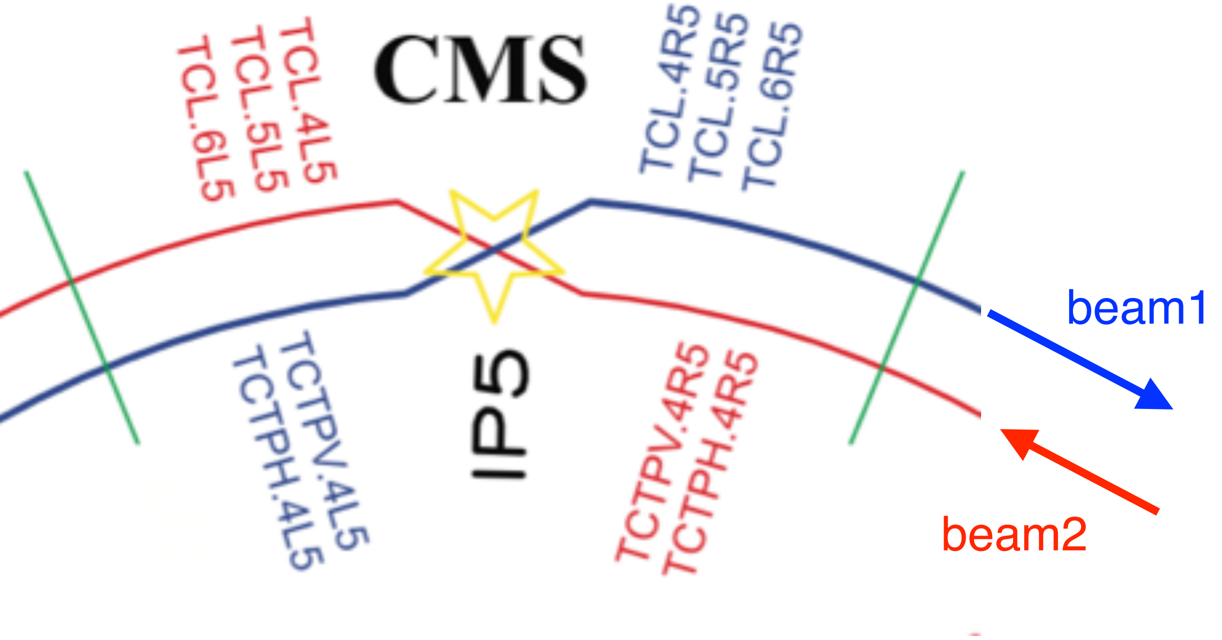
Physics debris collimation — i



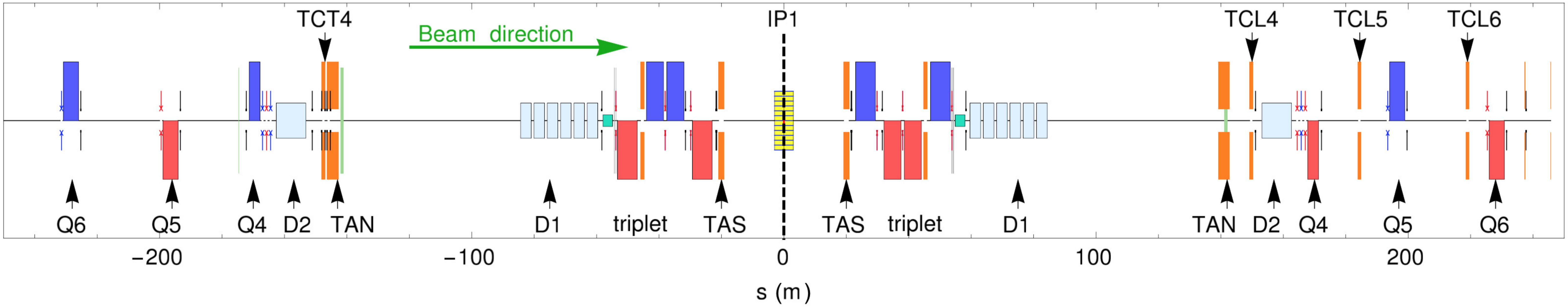
High-energy protons emerge from the collision points with perturbed trajectories — transverse kicks and energy deviations caused by elastic and inelastic collision with the opposite beam.

At the large luminosities, they risk to quench the cold magnets around ATLAS and CMS!

Physics debris collimation — ii

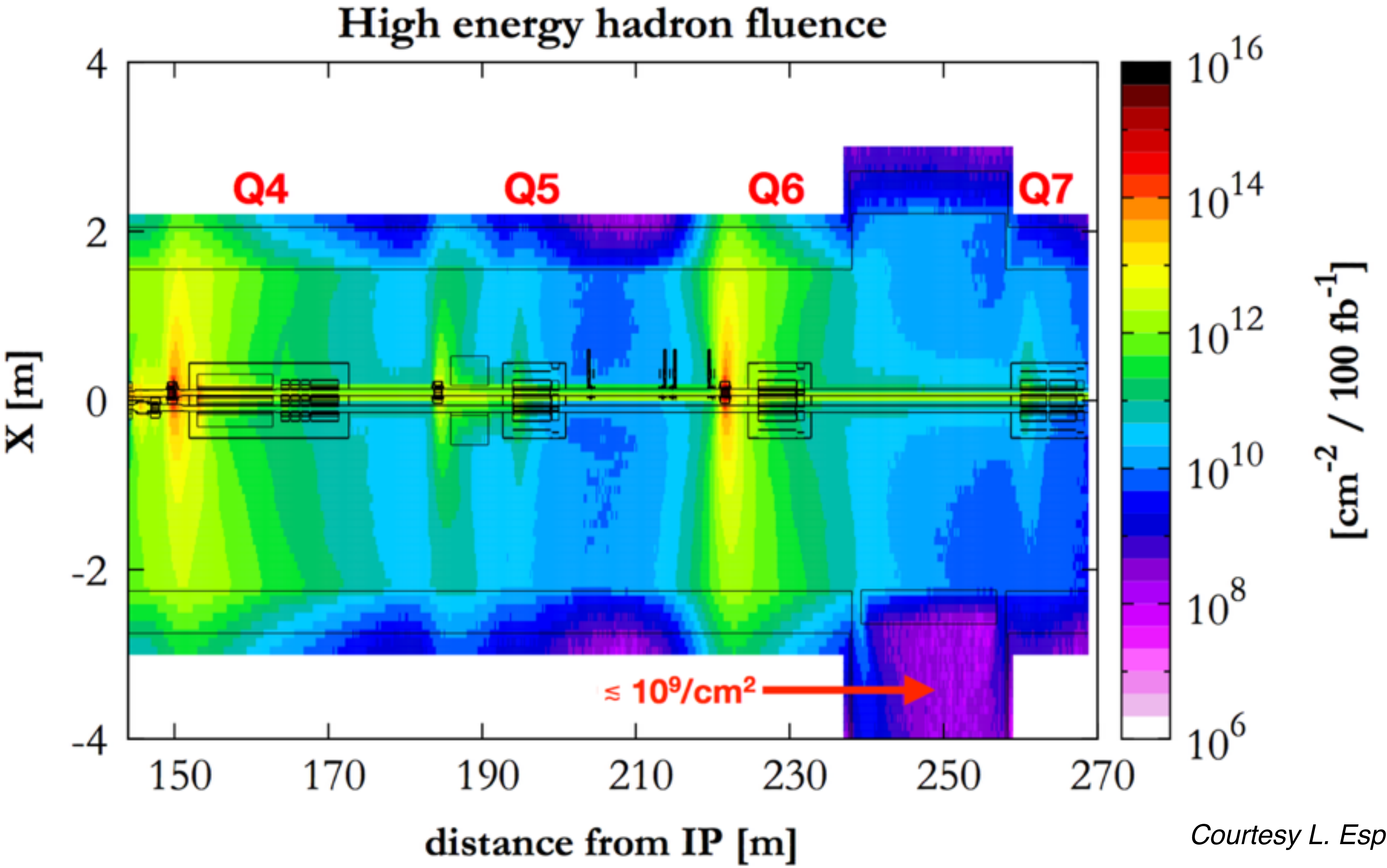


Protection of the “matching section” magnets and (partially) of the first magnets of the arcs around the experiments is done with dedicated collimators (3 per beam).



Courtesy R. Bruce

Physics debris collimation — iii



Courtesy L. Esposito