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CERN Accelerator School (CAS) — Advanced Accelerator Physics
11-22 November 2024
Spa, Belgium

Beam collimation

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Accelerator Physics Group

The CERN Accelerator School

Outline

- **Introduction**
- **Accelerator physics concepts**
  - Recap. of betatron motion
  - “Aperture” in a circular accelerator
- **Beam collimation**
  - The beam stored energy challenge
  - Beam losses and cleaning requirements
  - Design of a beam halo collimation system
  - The LHC collimation system
- **Collimation design and performance**
  - Design of the LHC collimators
  - Collimation system in operation
  - Simulations and measurements
- **Crystal collimation**

References — i

CERN-2016-002
29 January 2016

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Beam Loss and Accelerator Protection

2014 Joint International Accelerator School

Newport Beach, United States
5–14 November 2014

Proceedings

Editor: R. Schmidt

GENEVA
2016

S. Redaelli: Beam cleaning and Collimation Systems, p. 403
PDF: https://cds.cern.ch/record/2207182/files/arXiv:1608.03159.pdf

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Beam Cleaning and Collimation Systems

S. Redaelli
CERN, Geneva, Switzerland

Abstract
Collimation systems in particle accelerators are designed to dispose of unavoidable losses safely and efficiently during beam operation. Different roles are required for different types of accelerator. The present state of the art in beam collimation is exemplified in high-intensity, high-energy superconducting hadron colliders, like the CERN Large Hadron Collider (LHC), where stored beam energies reach levels up to several orders of magnitude higher than the tiny energies required to quench cold magnets. Collimation systems are essential systems for the daily operation of these modern machines. In this document, the design of a multistage collimation system is reviewed, taking the LHC as an example case study. In this case, unprecedented cleaning performance has been achieved, together with a system complexity comparable to no other accelerator. Aspects related to collimator design and operational challenges of large collimation systems are also addressed.

Keywords
Beam collimation; multi-stage cleaning; beam losses; circular colliders; Large Hadron Collider.

1 Introduction

The role of beam collimation systems in modern particle accelerators has become increasingly important in the quest for higher beam energies and intensities. For reference, the beam stored energy of recent and future particle accelerators is shown in Fig. 1, which includes the design (362 MJ) and achieved (150 MJ) values of the CERN Large Hadron Collider (LHC) [1], as well as the 700 MJ goal for its high-luminosity upgrade (HL-LHC) [2, 3]. High-power accelerators simply cannot operate without adequate systems to control unavoidable losses in standard beam operation. The operation and physics goals of recent superconducting, high-energy hadron colliders, such as the Tevatron [4], the Relativistic Heavy-

References — ii

CERN Yellow Reports:
Conference Proceedings

CERN-2018-011-CP

volume 2/2018

ICFA Mini-Workshop on
Tracking for Collimation in
Particle Accelerators

CERN, Geneva, Switzerland, 30 October 2015

Editor:
S. Redaelli

CERN

https://cds.cern.ch/record/2646800/files/CERN-2018-011-CP.pdf

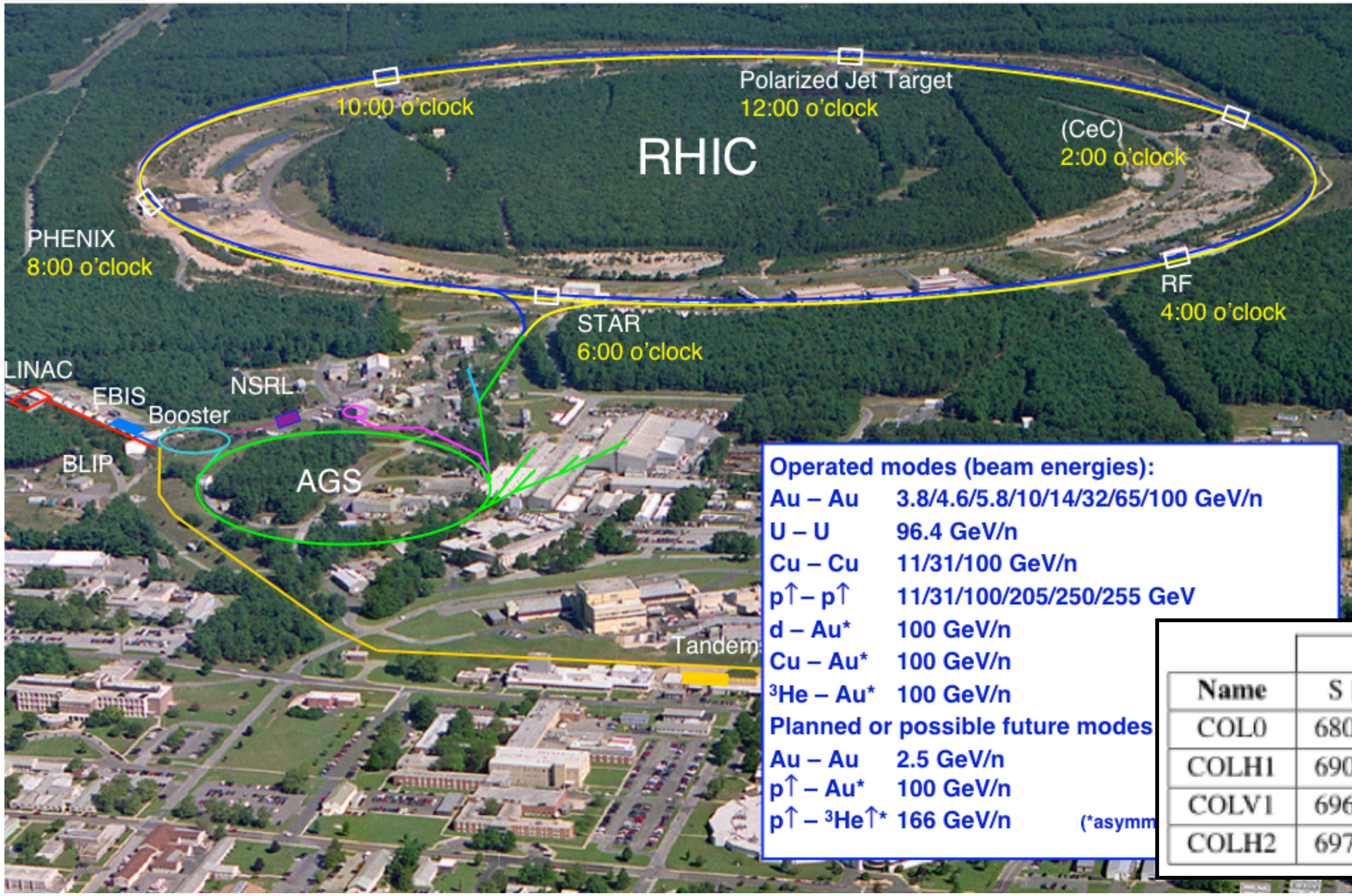
Contents

Always interested to get new students (masters, PhDs) so do not hesitate to contact me if interested in these topics.

Recent effort to update simulations tools:
Xsuite package

Modern accelerators — supercolliders — cannot work without an adequate collimation system…

RHIC collimation system



RHIC beam parameters [p]:

E_b = 255 GeV

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

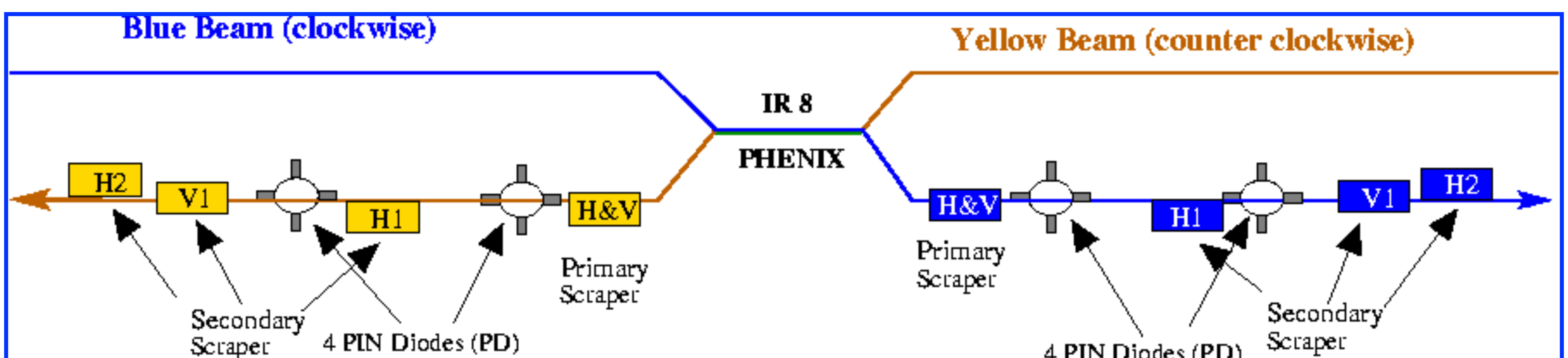
E_{stored} = ~ 440 kJ

Collimation system:

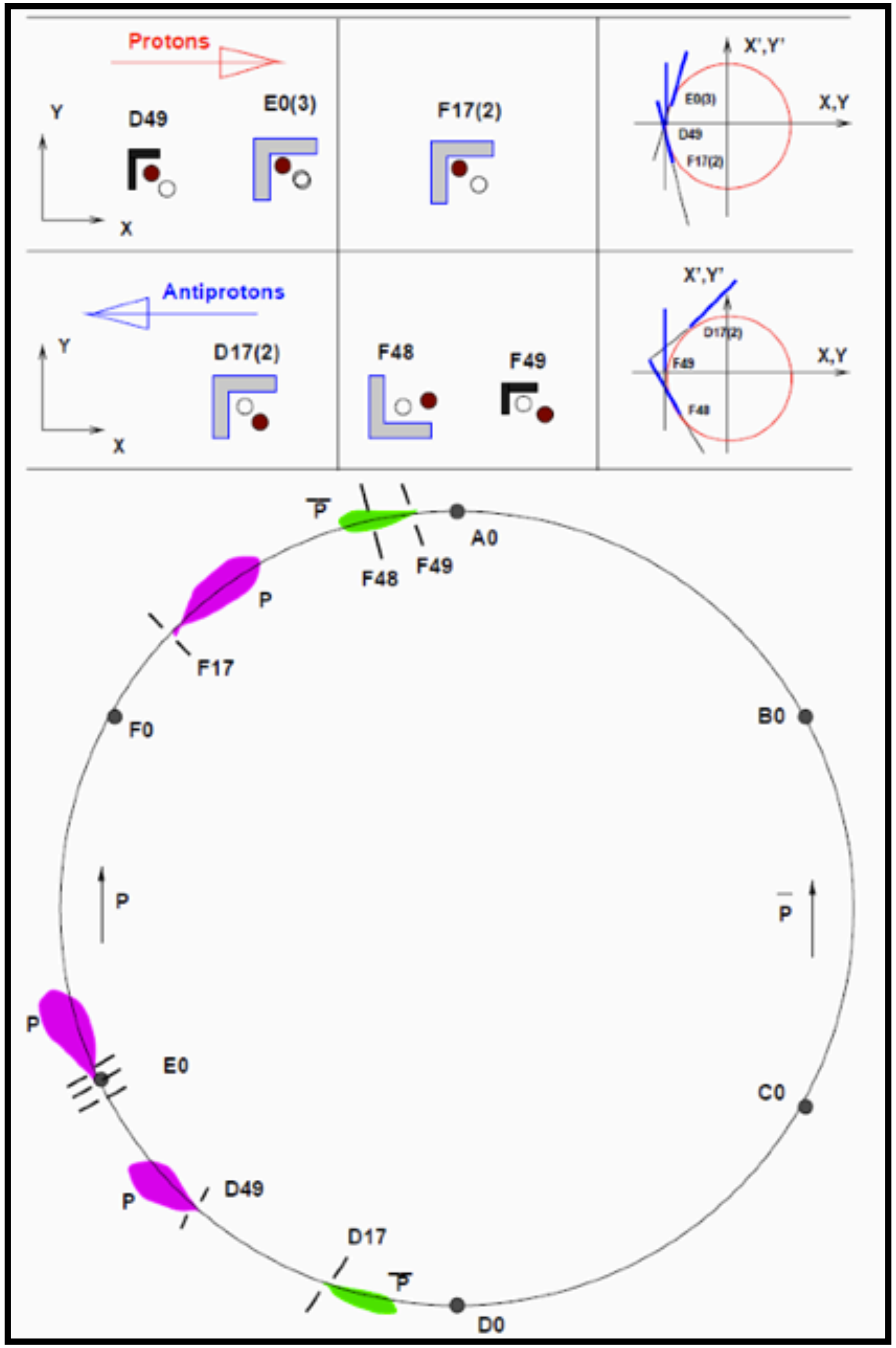
8 collimators

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

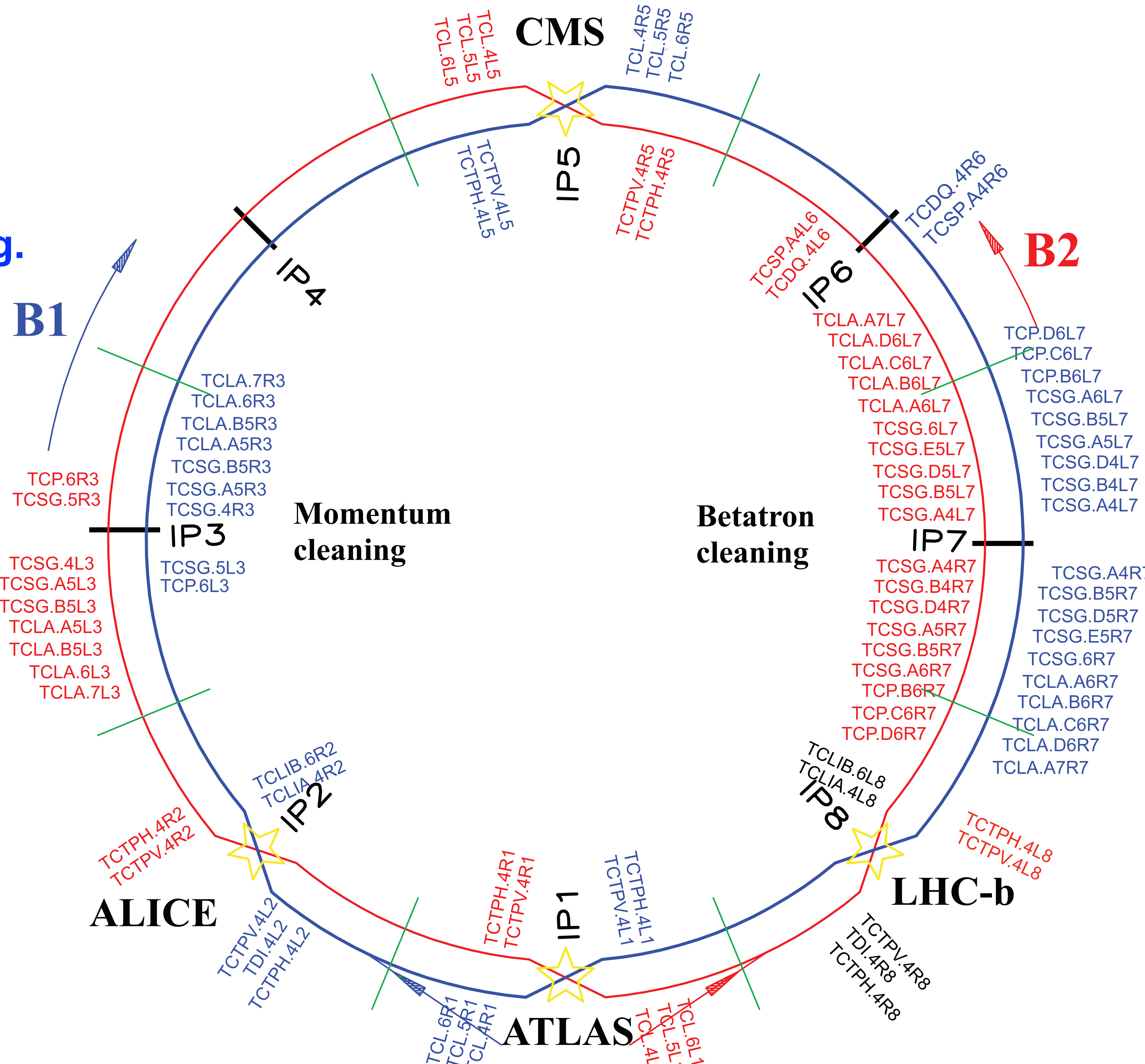
Collimation system:

13 collimators, L shape

26 positional degrees of freedom

LHC collimation system layout

The LHC is the state-of-the-art for high-energy colliders!
Collimators distributed along the 27km LHC ring.

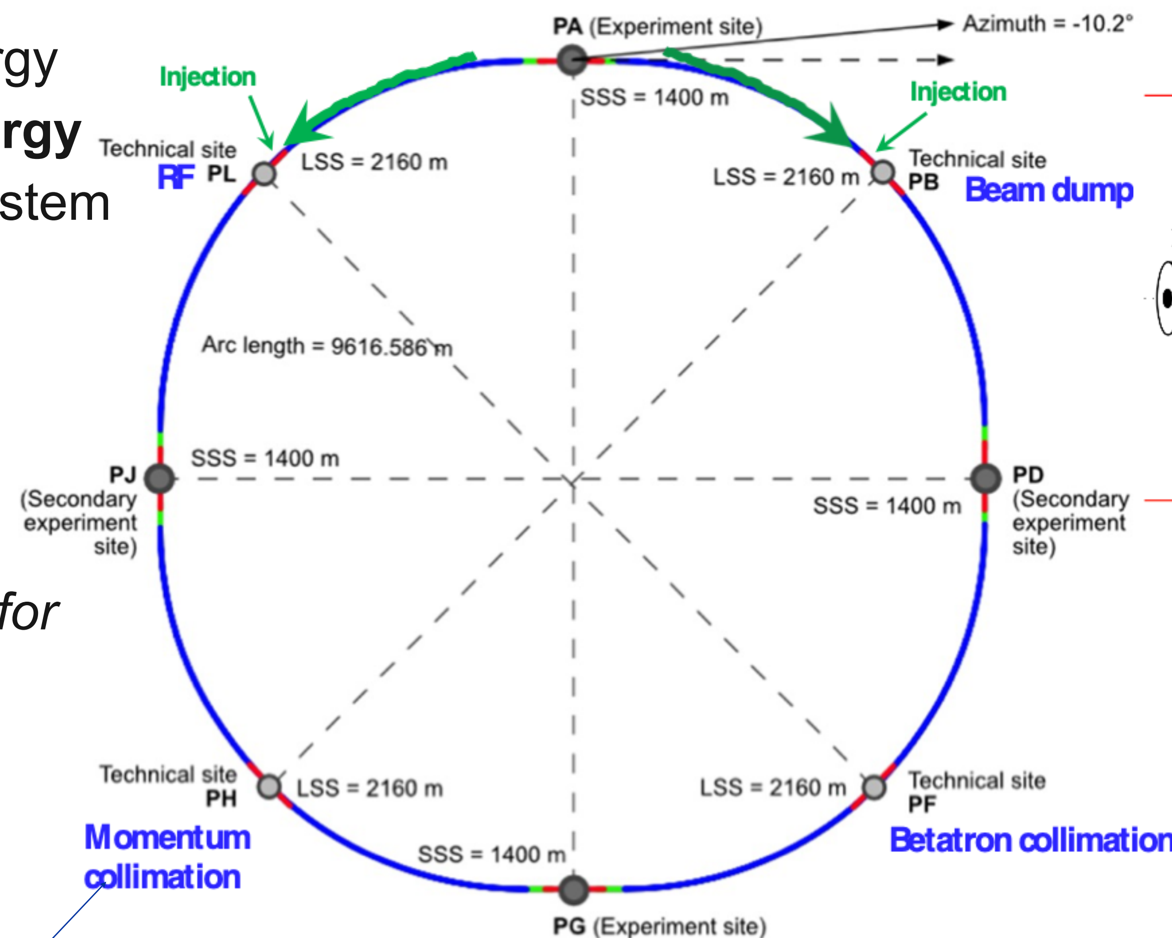


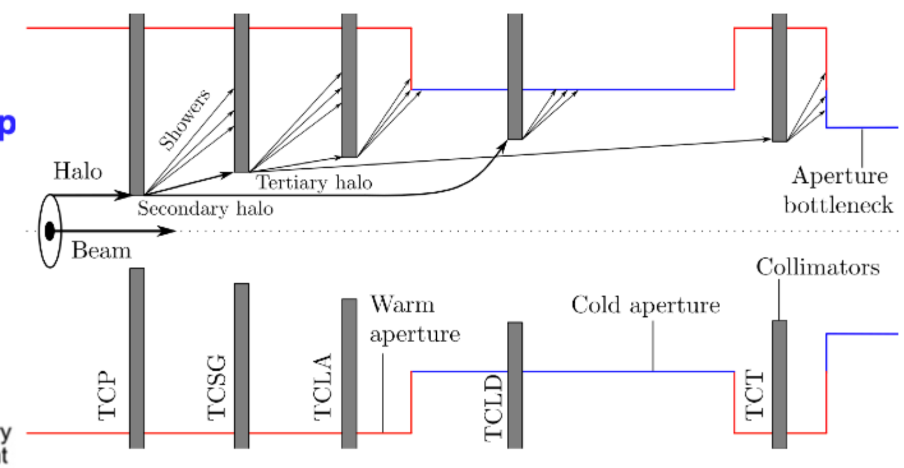
Total of 118 two-sided collimators
(108 are movable, 4 motors each).
LHC Run 2 system

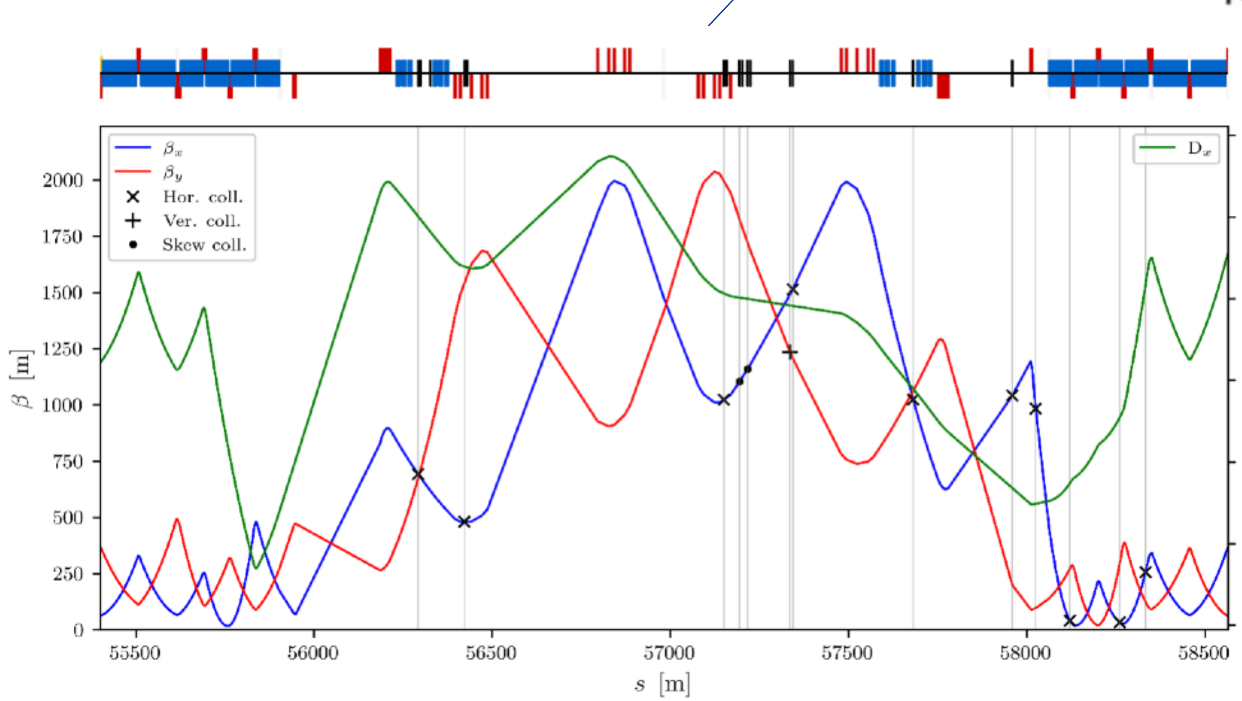
Future Circular Collider, FCC-hh

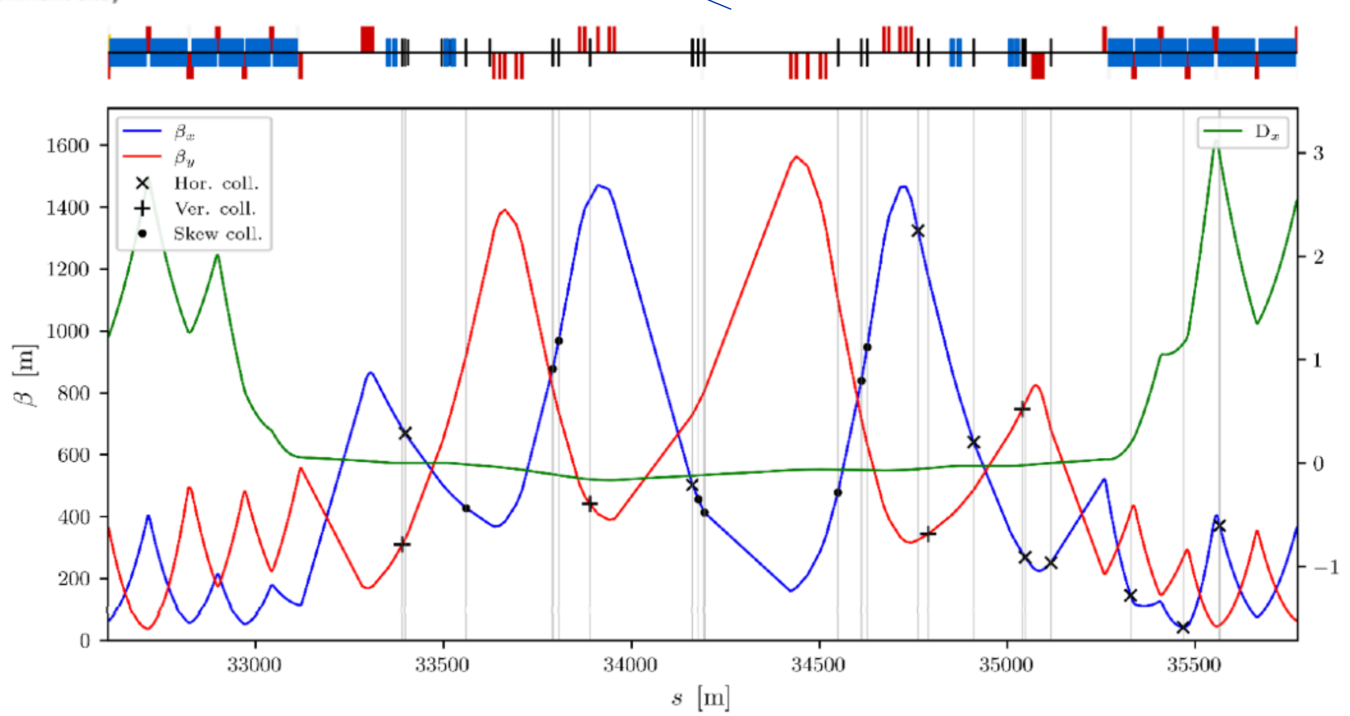
Collimation system:

- 50 TeV proton beam energy
- **8.3 GJ stored beam energy**
- Multi-stage collimation system
  - Based on the LHC
  - Includes dispersion suppressor collimators
- 58 collimators per beam
- *Layout being updated following the siting study for FCC-ee.*



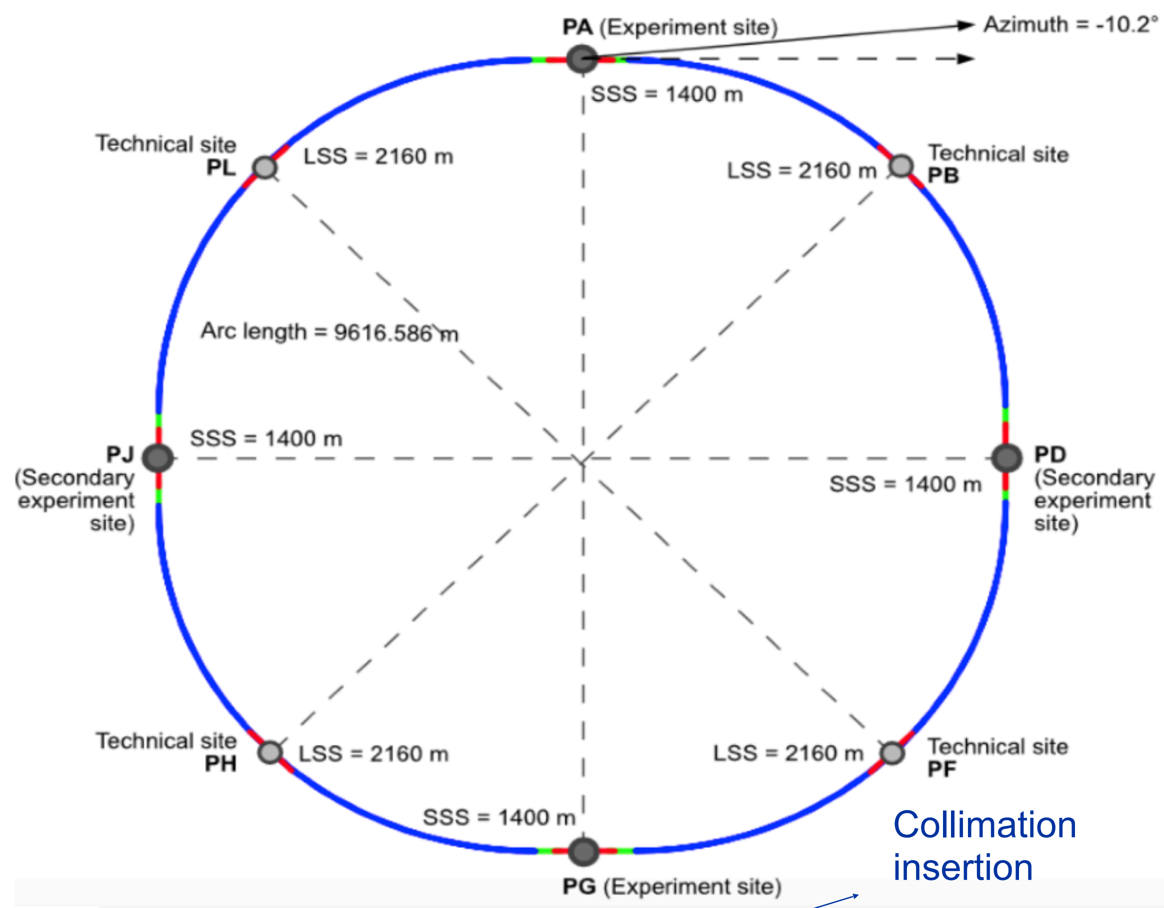


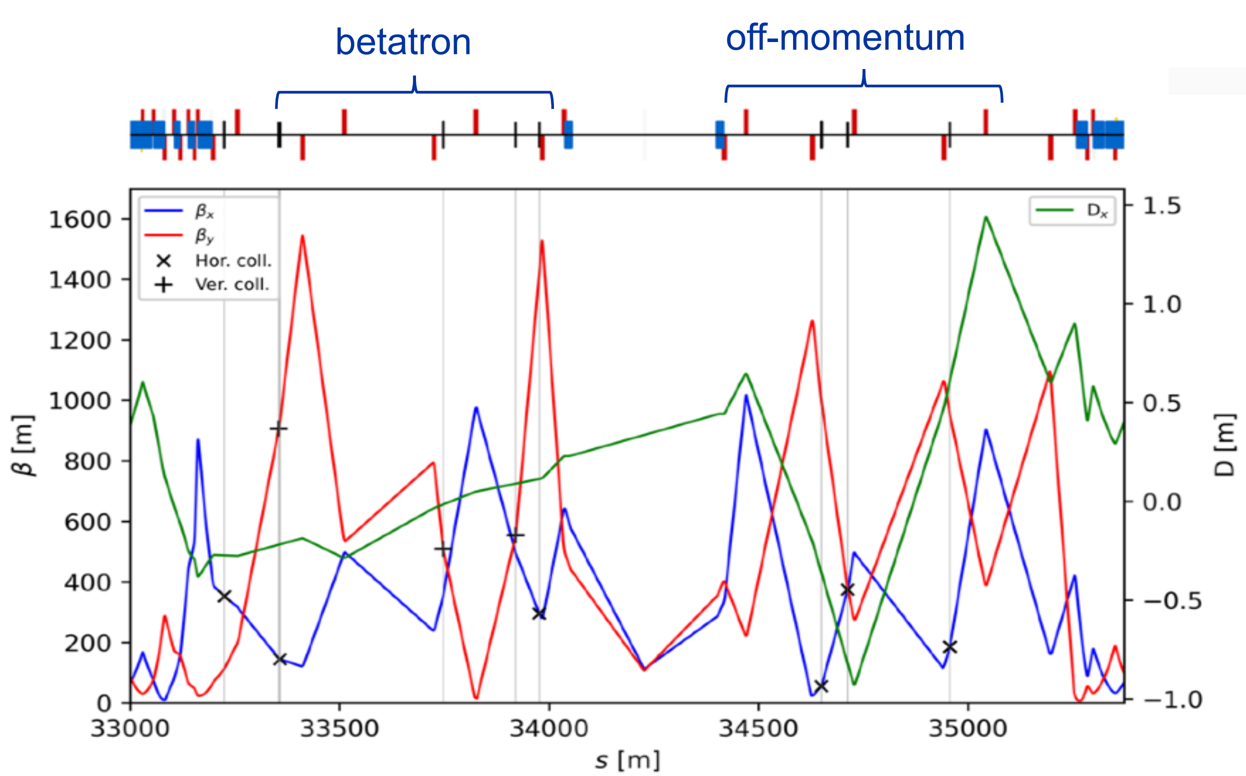




Future Circular Collider, FCC-ee

- **Collimation system:**
  - 45.6-182.5 GeV electron / positron beam energy (4 modes)
  - Up to **20.7 MJ stored beam energy**
  - 2-stage collimation system
    - Betatron and off-momentum in one insertion
  - Additional synchrotron radiation collimators around IPs
  - 32 collimators per beam

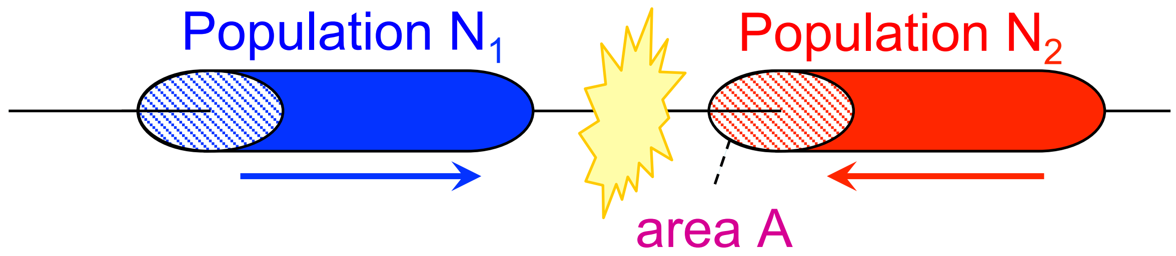




Collimation system are a key to the successful performance of colliders and to the design of future projects.

What do experiments want?

The Large Hadron Collider (LHC): is the state-of-the-art circular collider in operation since 2010 at the European Organisation for Nuclear Research (CERN) that provides high-energy collisions for particle's physics studies.



High energy

B = bending field
ρ = bending radius
p = momentum
e = charge

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

Determined by the maximum field of bending dipoles, B

High luminosity

$$\mathcal{L} = \frac{N^2 n_b f_{\mathrm{rev}}}{4\pi\sigma_x\sigma_y} F$$

N = bunch population
n_b = number of bunches
f_{rev} = revolution frequency
$\sigma_{x,y}$ = colliding beam sizes
F = geometric factor

Depends on machine parameters: charge per bunch (N), num. of bunches (n_b) and transverse beam sizes (σ)

"Thus, to achieve high luminosity, all one has to do is make (lots of) high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible." PDG 2005, chapter 25.

Luminosity and stored beam energy

$$\mathcal{L} = \frac{N^2 n_b f_{\text{rev}}}{4\pi\sigma_x\sigma_y} F$$

$$E_{\text{stored}} = n_b N E_{\text{beam}}$$

$$\mathcal{L} = \frac{1}{4\pi m_0 c^2} f_{\text{rev}} F \frac{N}{\beta^* \epsilon_{\text{n}}} E_{\text{stored}}$$

N = bunch population
n_b = number of bunches
F = geometric factor
f_{rev} = revolution frequency
$\sigma_{x,y}$ = colliding beam sizes
β^* = colliding beta functions
ε_n = normalised emittance
m_0 = proton rest mass
c = speed of light

β^*:
Machine optics
Beam-beam long range
Collimation hierarchy
Protected aperture

ϵ_n:
Injectors
Emittance preservation
Beam stability
...

Pushing the stored beam energy is a key ingredient to the collider's performance, if it can be handled safely and efficiently!

LHC parameters

Nominal LHC parameters			
	Design	2018	2023
Beam injection energy (TeV)	0.45	0.45	0.45
Beam energy (TeV)	7	6.5	6.8
Number of particles per bunch	1.15 x	1.2 x 10^{11}	1.6 x 10^{11}
Number of bunches per beam	2808	2560	2560
Max stored beam energy (MJ)	362	300	~ 430MJ
Beam current (A)	0.58	0.48	0.56
Norm transverse emittance (μm)	3.75	2.1	1.8
Colliding beam size (μm)	16	11	9
Bunch length at top energy (cm)	7.55	7.55	7.55

- How do we handle these unprecedented stored beam energies?

- How do we protect the machine while operating at small β*?

- What are the implication on machine protection?

- Why do we need a halo collimation system?

- How do we design it and operate a collimation system?

LHC parameters

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Similar considerations apply for high-power accelerators, not necessarily colliders for HEP

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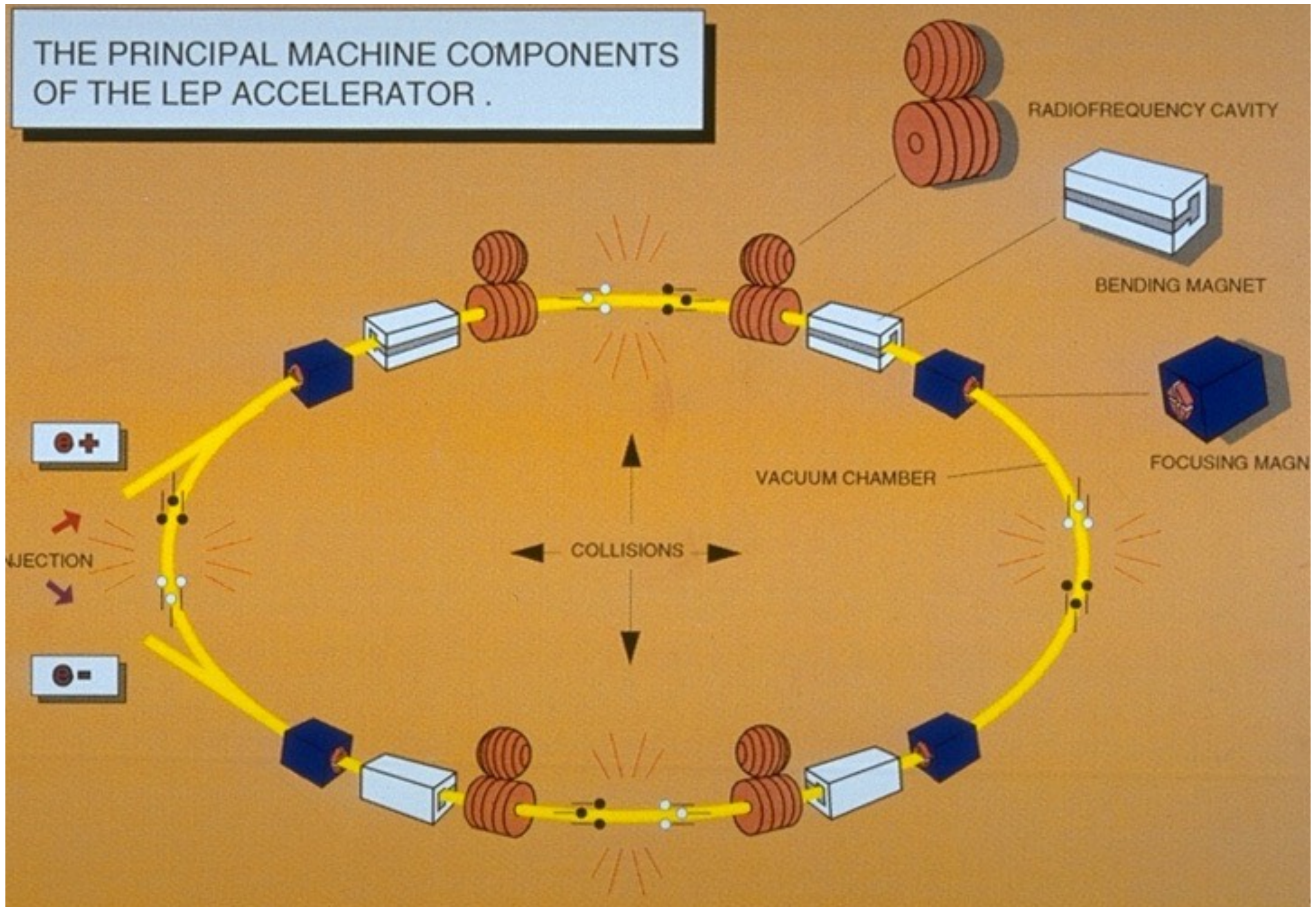
Circular colliders — basic components



Charged particles are accelerated, guided and confined by **electromagnetic fields**.

- Bending: Dipole magnets
- Focusing: Quadrupole magnets
- Acceleration: RF cavities

In synchrotrons, they are “ramped” together synchronously to match beam energy.

- Chromatic aberration: Sextupole magnets

Lorentz force

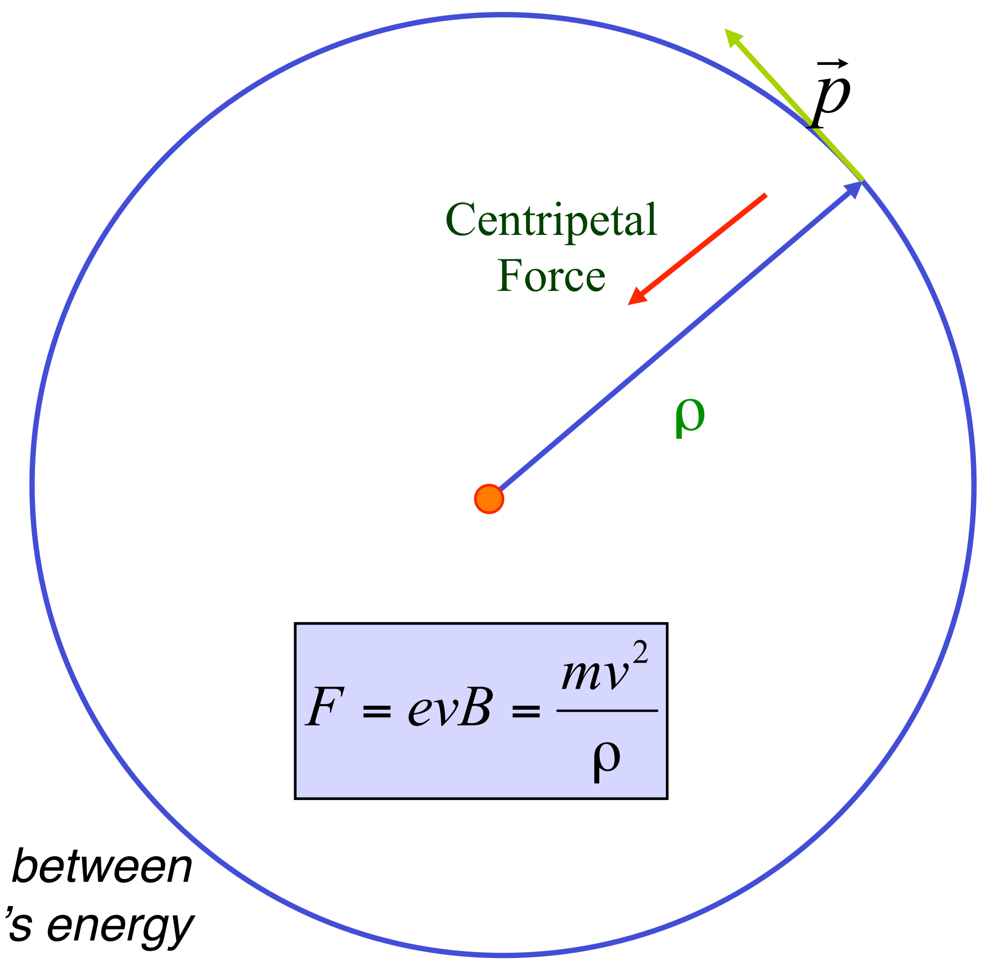
$$\vec{F} = e(\vec{v} \times \vec{B} + \vec{E})$$

Magnetic rigidity

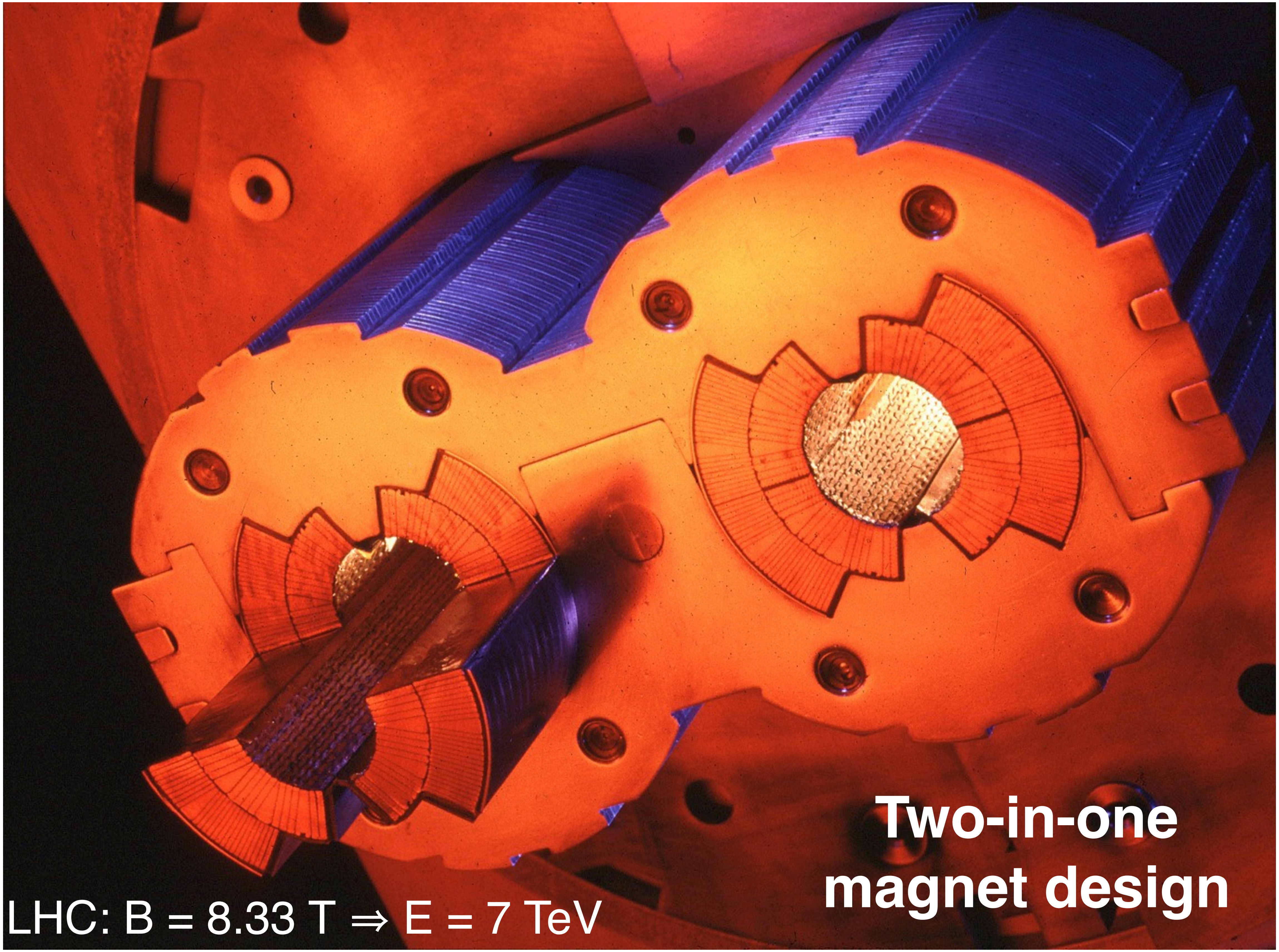
$$B\rho = \frac{mv}{e} = \frac{p}{e}$$

LHC: ρ = 2.8 km
(given by existing LEP tunnel)

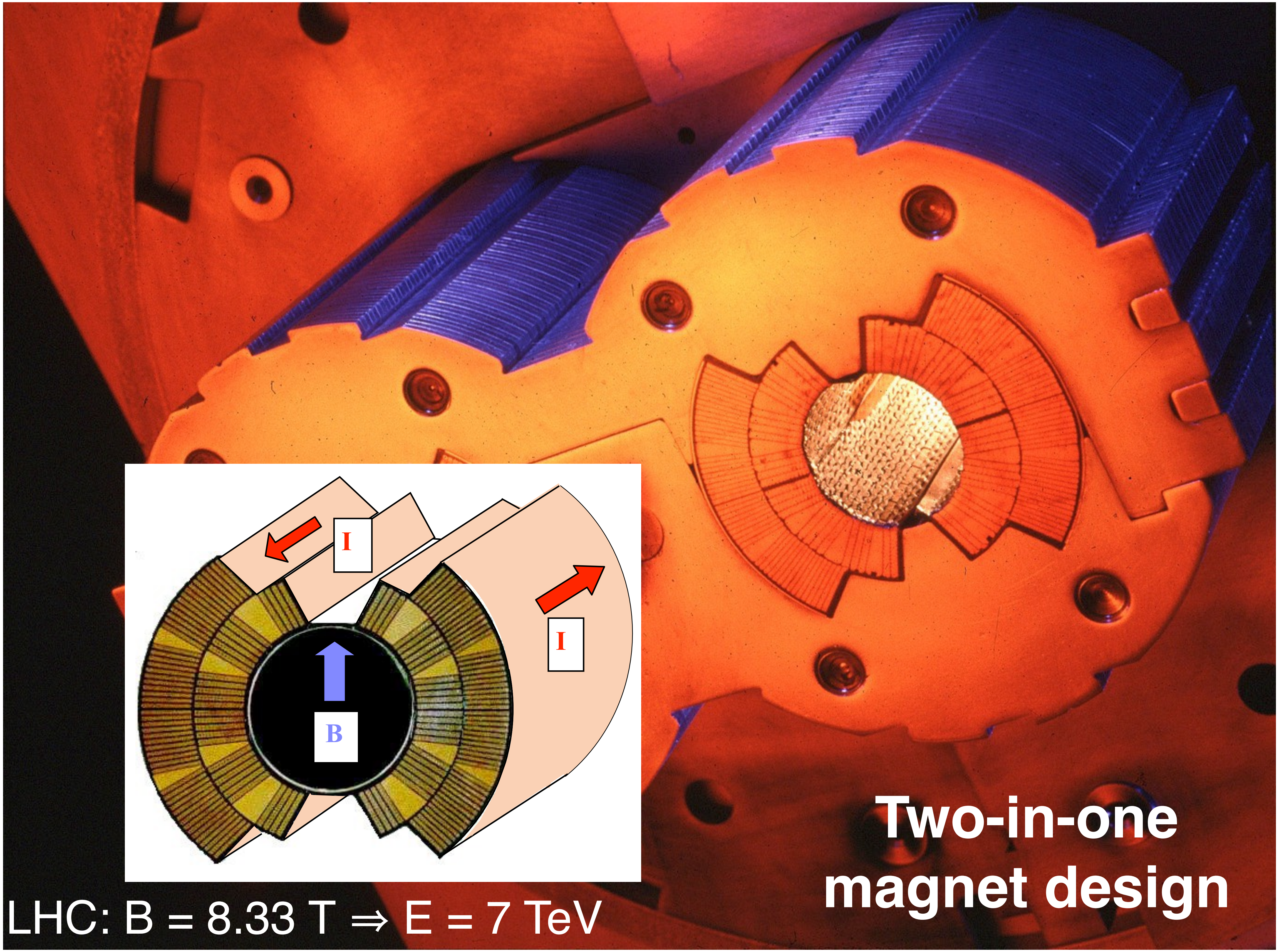
Fixes the relation between magnetic field and particle’s energy



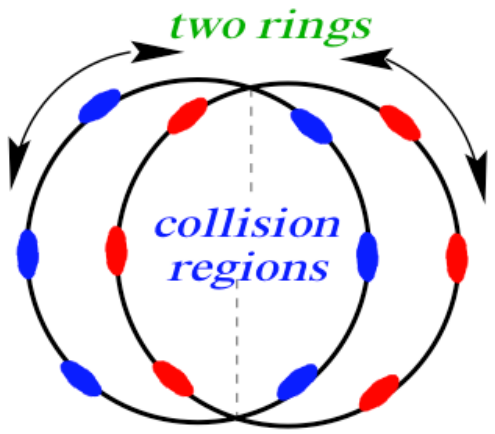
Bending

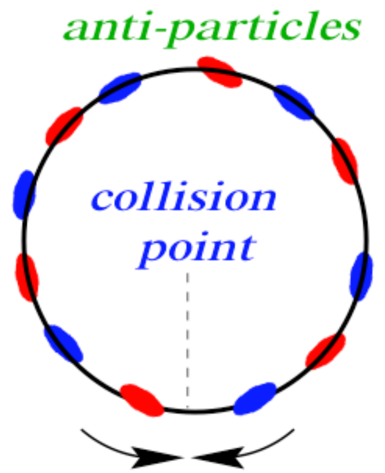


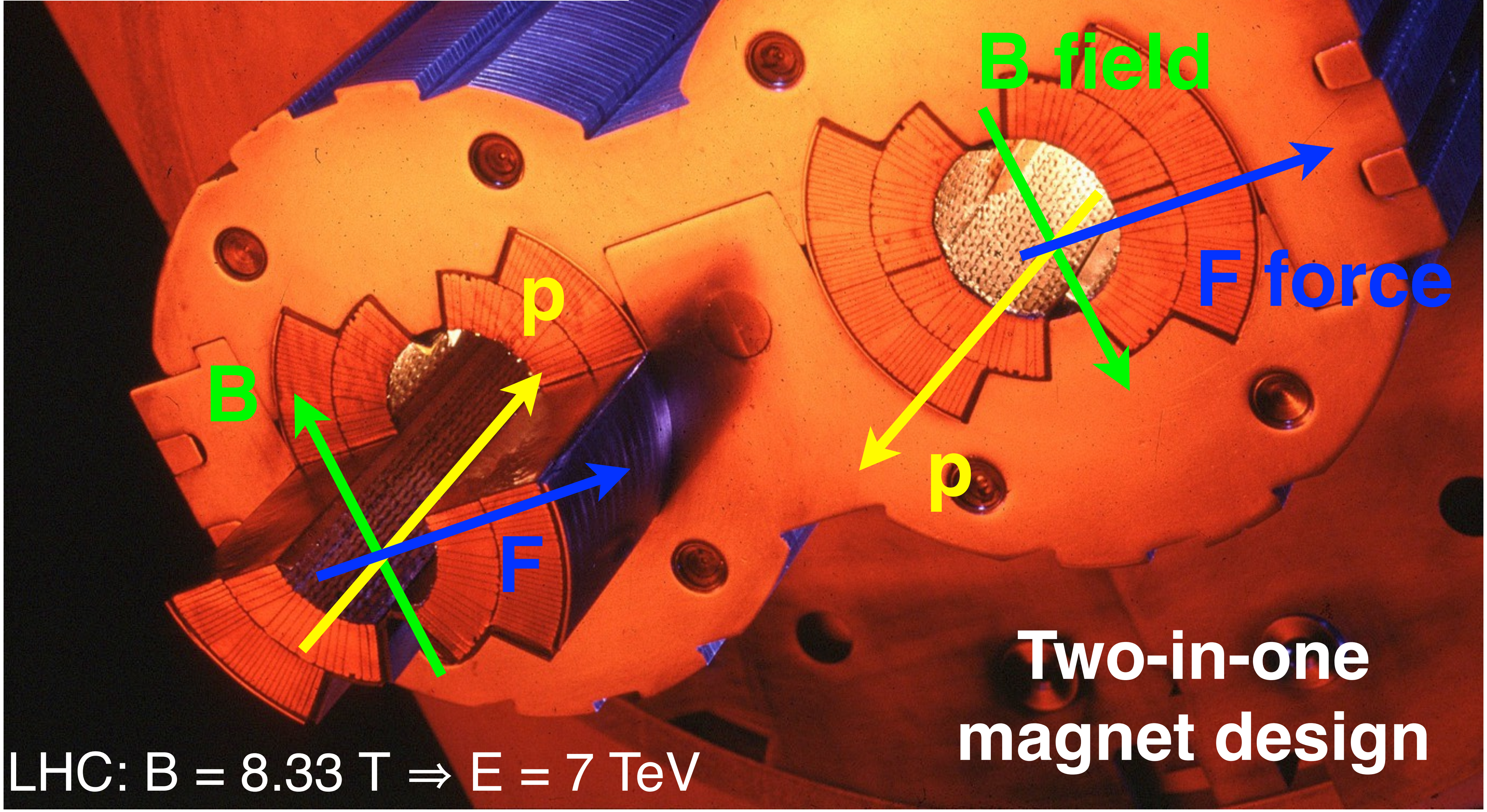
Bending



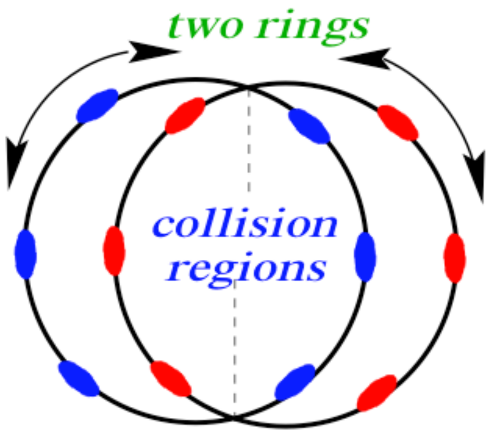
Bending

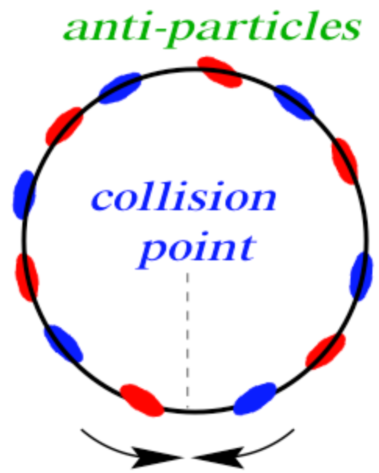

two rings
collision
regions

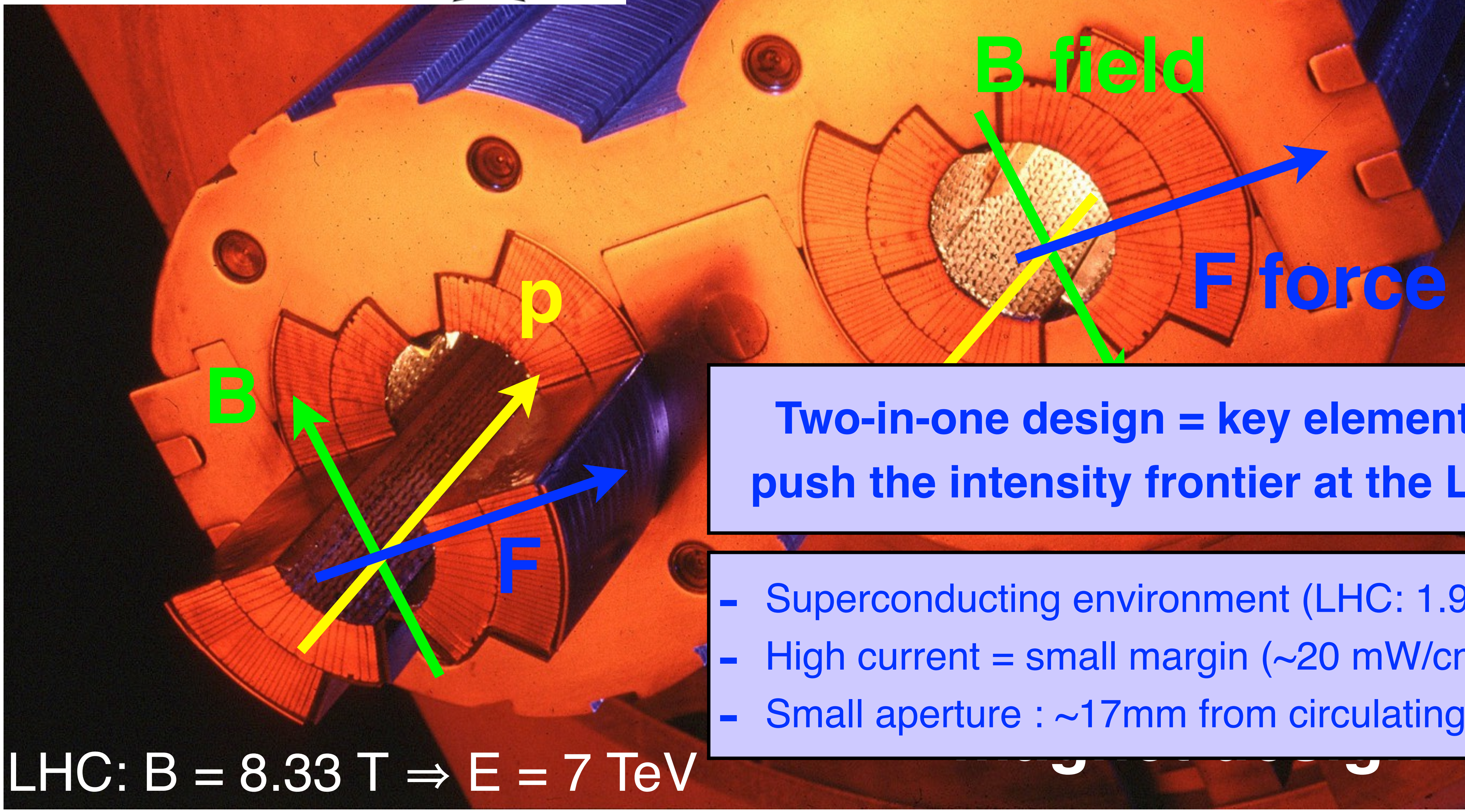

anti-particles
collision
point


B field
F force
p
B
p
F
Two-in-one
magnet design
LHC: B = 8.33 T ⇒ E = 7 TeV

Bending





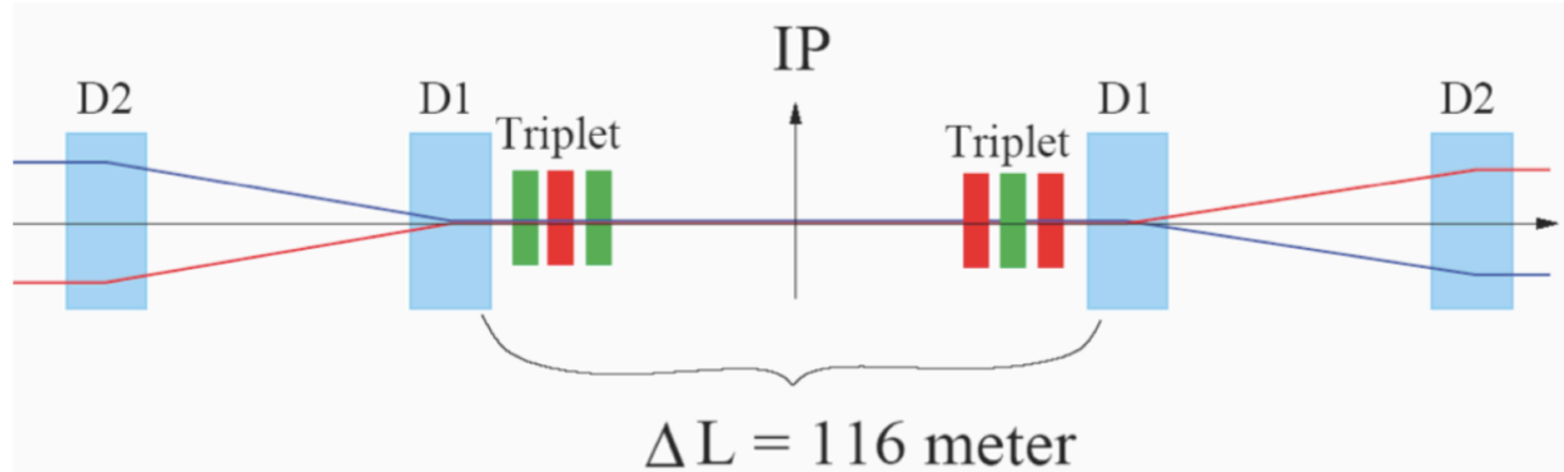


Two-in-one design = key element to push the intensity frontier at the LHC!

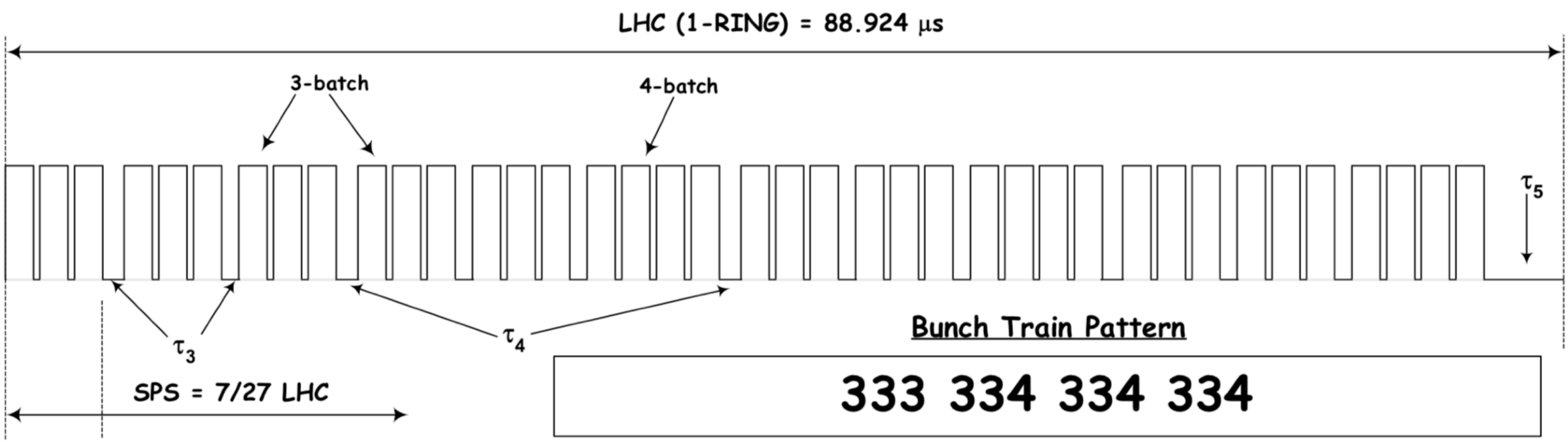
- Superconducting environment (LHC: 1.9k!)
- High current = small margin (~20 mW/cm^3)
- Small aperture : ~17mm from circulating beam

Pushing the beam power

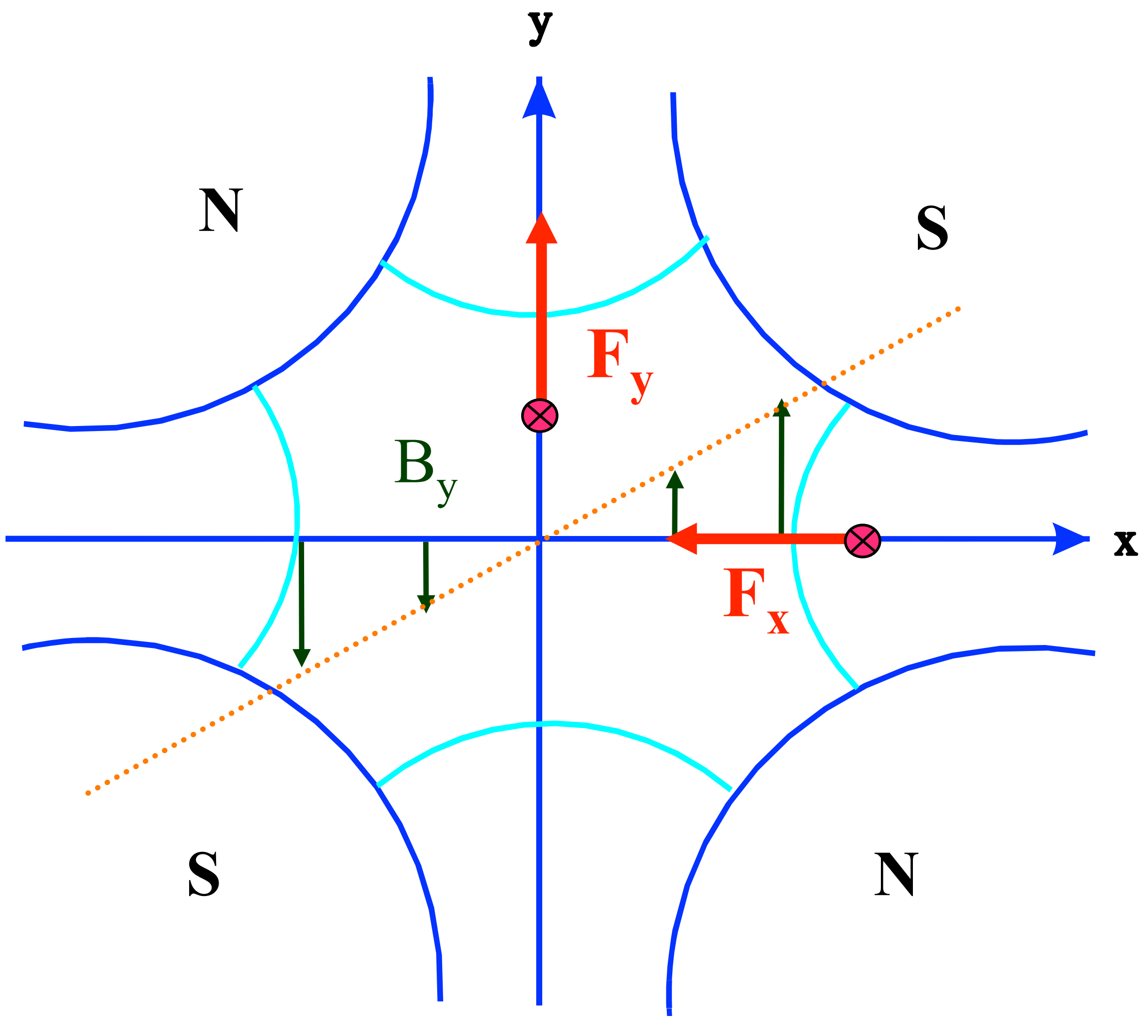
Beams travel in separated vacuum chambers except around the collision points → the LHC beam current is pushed by increasing the number of bunches!

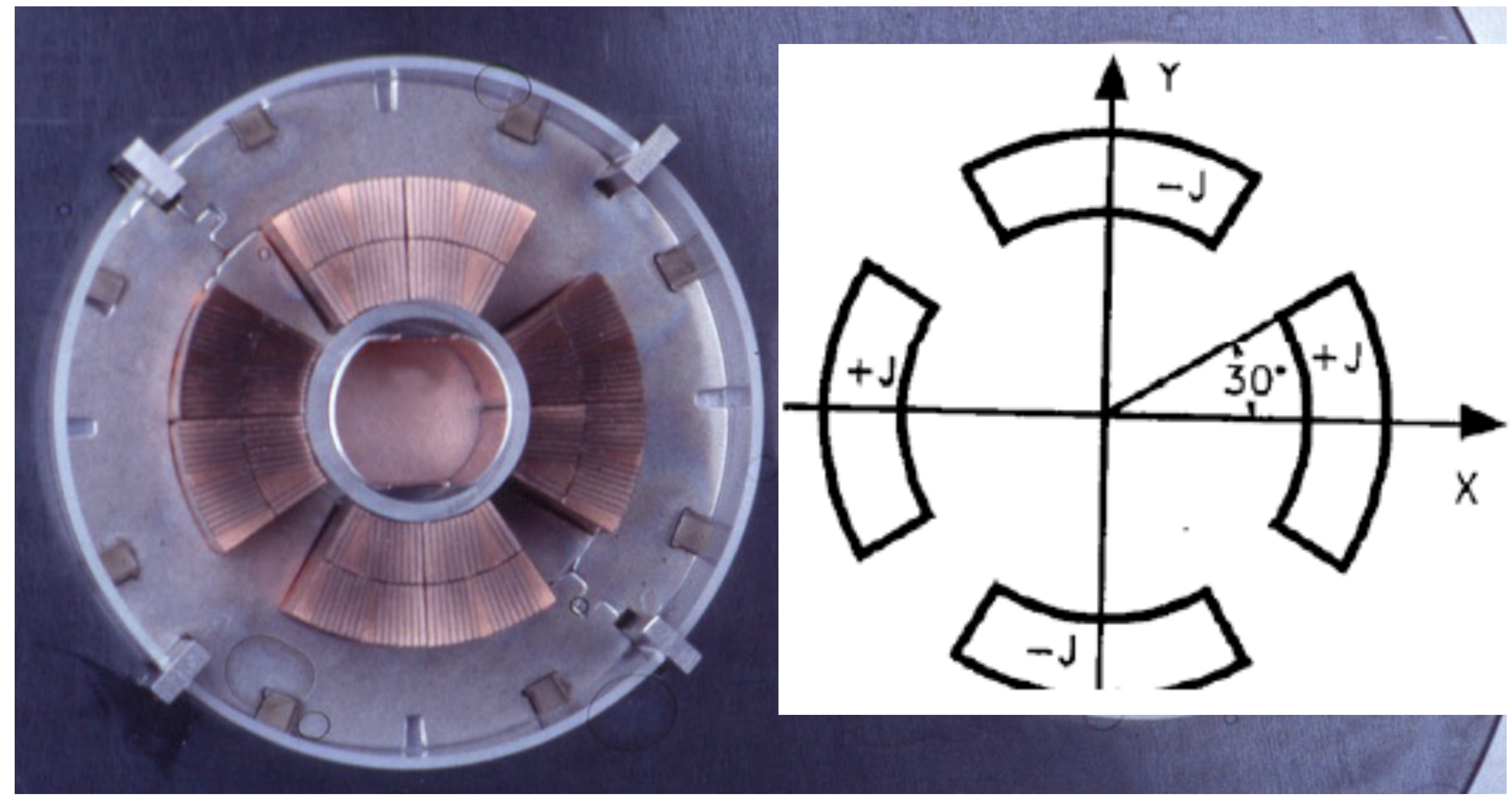


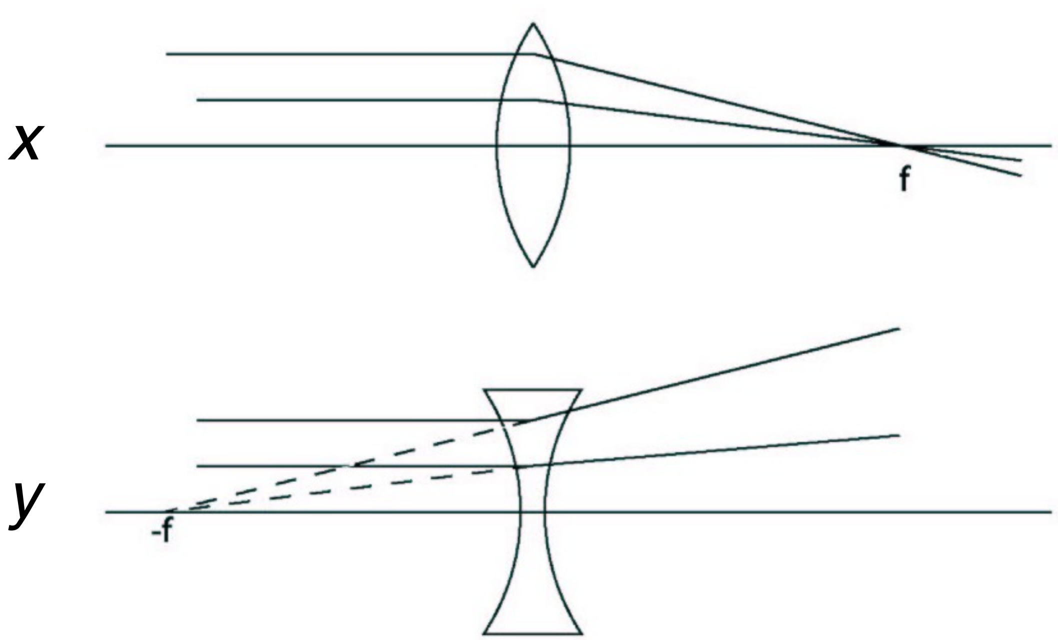
The LHC design filling scheme targeted ~2800 bunches with 25 ns spacing!



Focusing







Transverse focusing is achieved with **quadrupole magnets**, which act on the beam like an optical lens.

Linear increase of the magnetic field along the axes (no effect on axis) — quadrupole **gradient**.

Focusing in one plane, **de-focusing** in the other!

Betatron motion

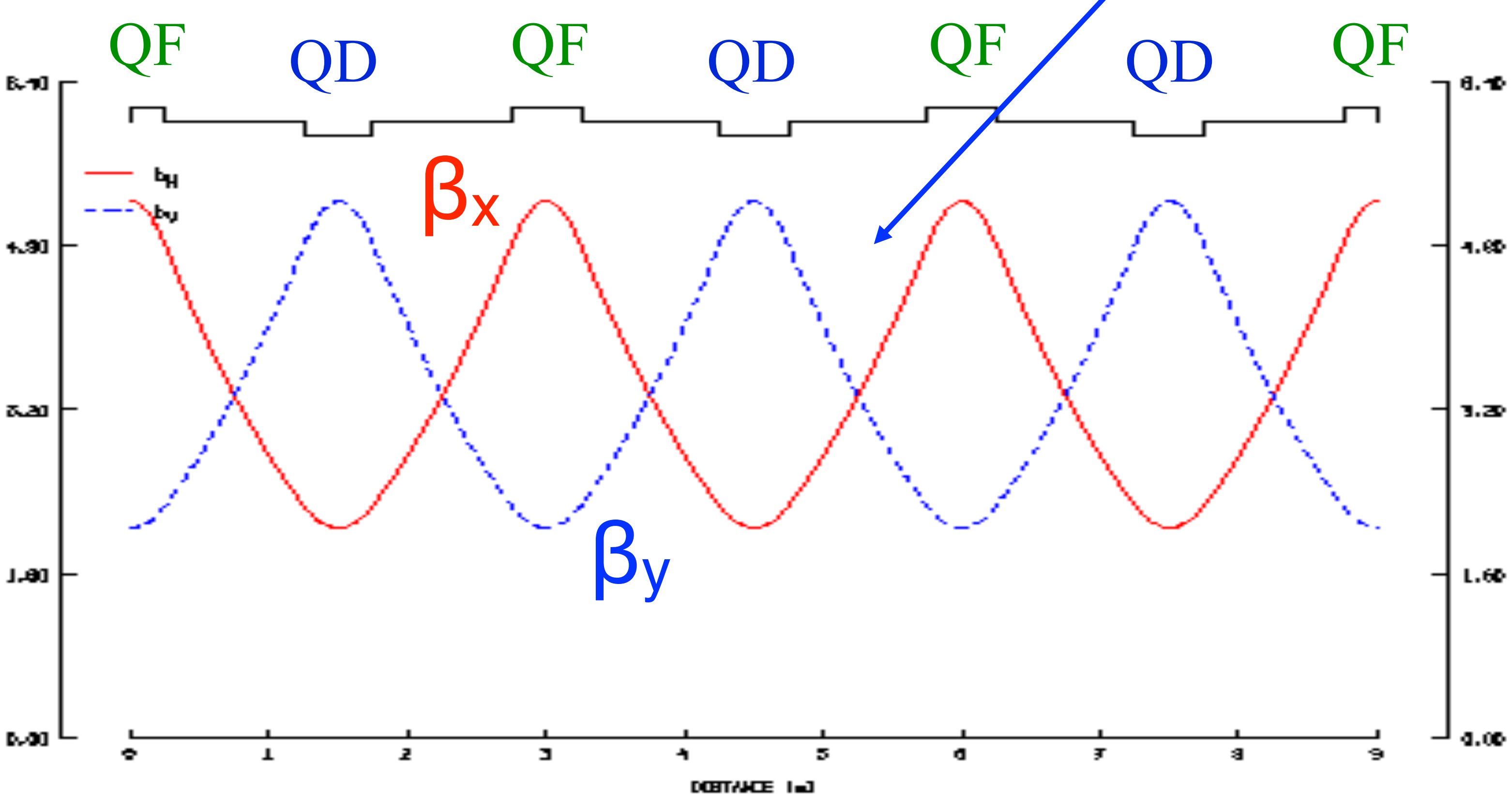
The solution of Hill's equation:

(*s* is the longitudinal coordinate)

$$x(s) = A\sqrt{\beta_x(s)}\cos[\phi(s) + \phi_0]$$

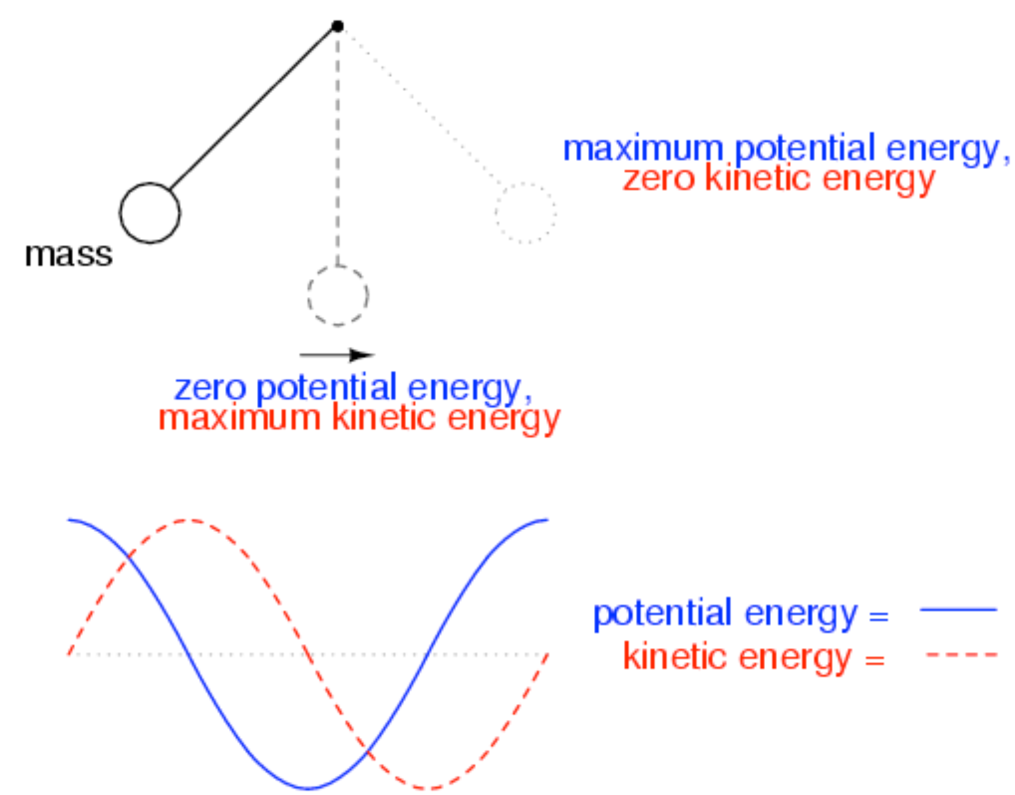
s-dependent amplitude

Oscillatory term



Betatron functions in a simple FODO cell

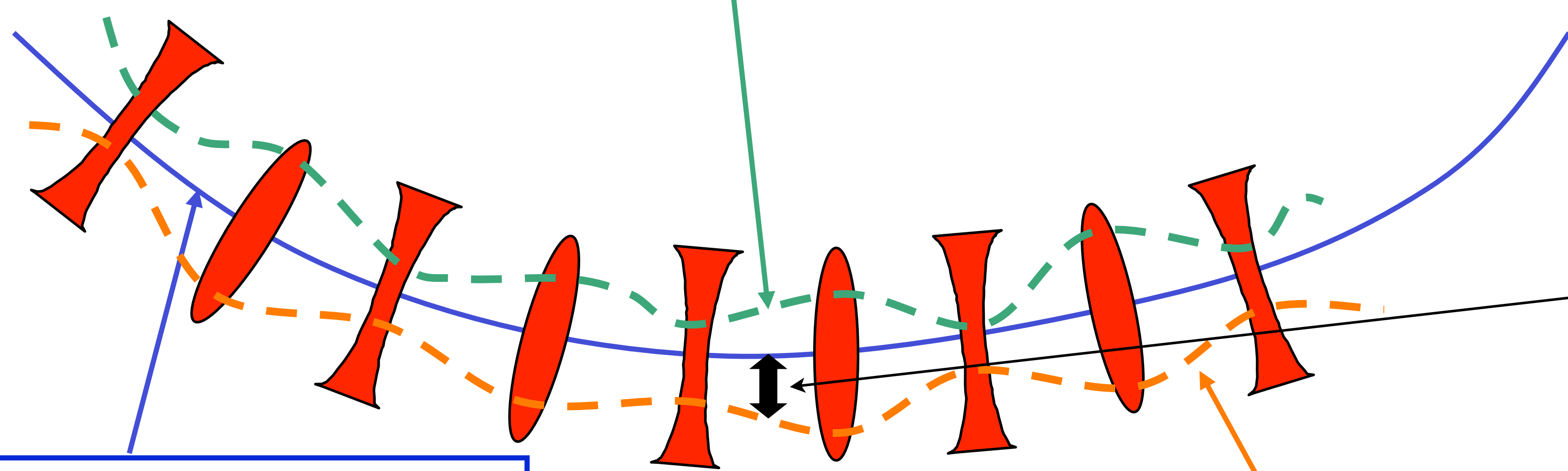
It is analogous to the general solution of a simple harmonic motion:



Dispersion

Dipole = spectrometer

Closed orbit for $p < p_0$



Central design orbit = closed orbit for $p=p_0$

Closed orbit for $p > p_0$

Lattice property

Particle's momentum error

$$\Delta x(s) = D(s) \times \frac{\Delta p}{p}$$

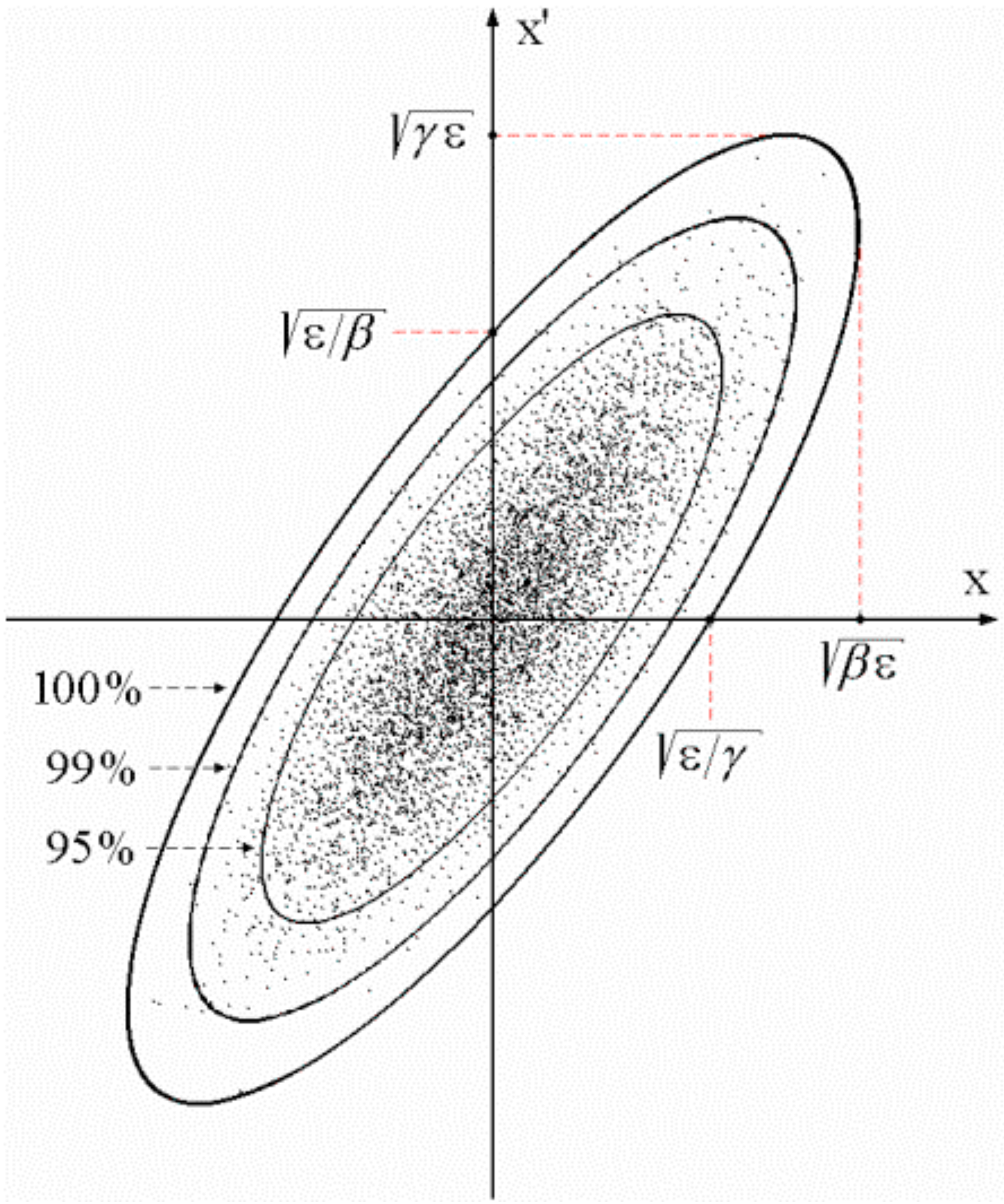
$$x'' + K(s)x = \frac{1}{\rho}\frac{\Delta p}{p_0}$$

Non-homogeneous Hill's equation

$$x(s) = A\sqrt{\beta_x(s)}\cos[\phi(s)+\phi_0] + D(s) \times \frac{\Delta p}{p}$$

D(s) = dispersion function. Periodic in *s*.

Emittance and beam size (i)



Motion of a single particle:

$$x(s) = A\sqrt{\beta_x(s)}\cos[\phi(s)+\phi_0] + D(s)\times\frac{\Delta p}{p}$$

β(s), ϕ(s), D(s) → determined by lattice

A_i, ϕ_i, $\Delta p/p_i$ → define individual trajectories

For an ***ensemble* of particles**:

The **transverse emittance**, **ε**, is the area of the phase-space ellipse.

Usually, 95% confidence level given.

Beam size = projection on *X* (*Y*) axis

Adiabatic damping of **ε** when beams accelerate

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

Bunch energy spread $$\delta = \left(\frac{\Delta p}{p}\right)_{\rm rms}$$

Betatronic contribution

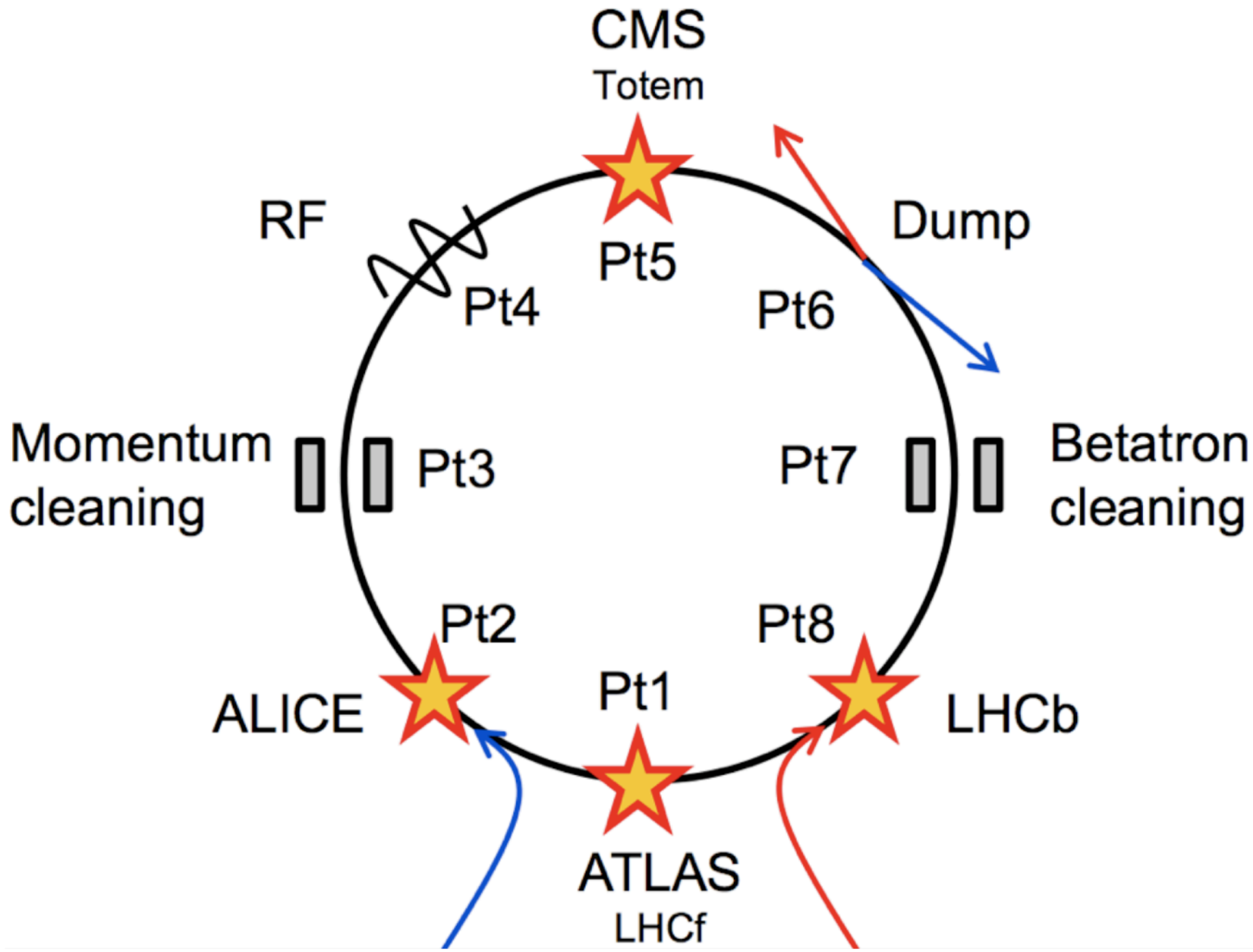
Dispersive contribution

Some examples from the LHC

The Large Hadron Collider (LHC)

LHC Layout

- 8 arcs (~3 km)
- 8 straight sections (~700 m).
- Two-in-one magnet design
- The beams cross in 4 points:
  Pt1: ATLAS, LHCf
  Pt2: ALICE
  Pt5: CMS, TOTEM
  Pt8: LHCb
- Pt2/Pt8: beam injection
- Pt6: beam dump region
- Pt4: RF (acceleration)
- Pt3/Pt7: beam cleaning



Notation:
8 "Points" (Pt) or
"Interaction Regions" (IRs)

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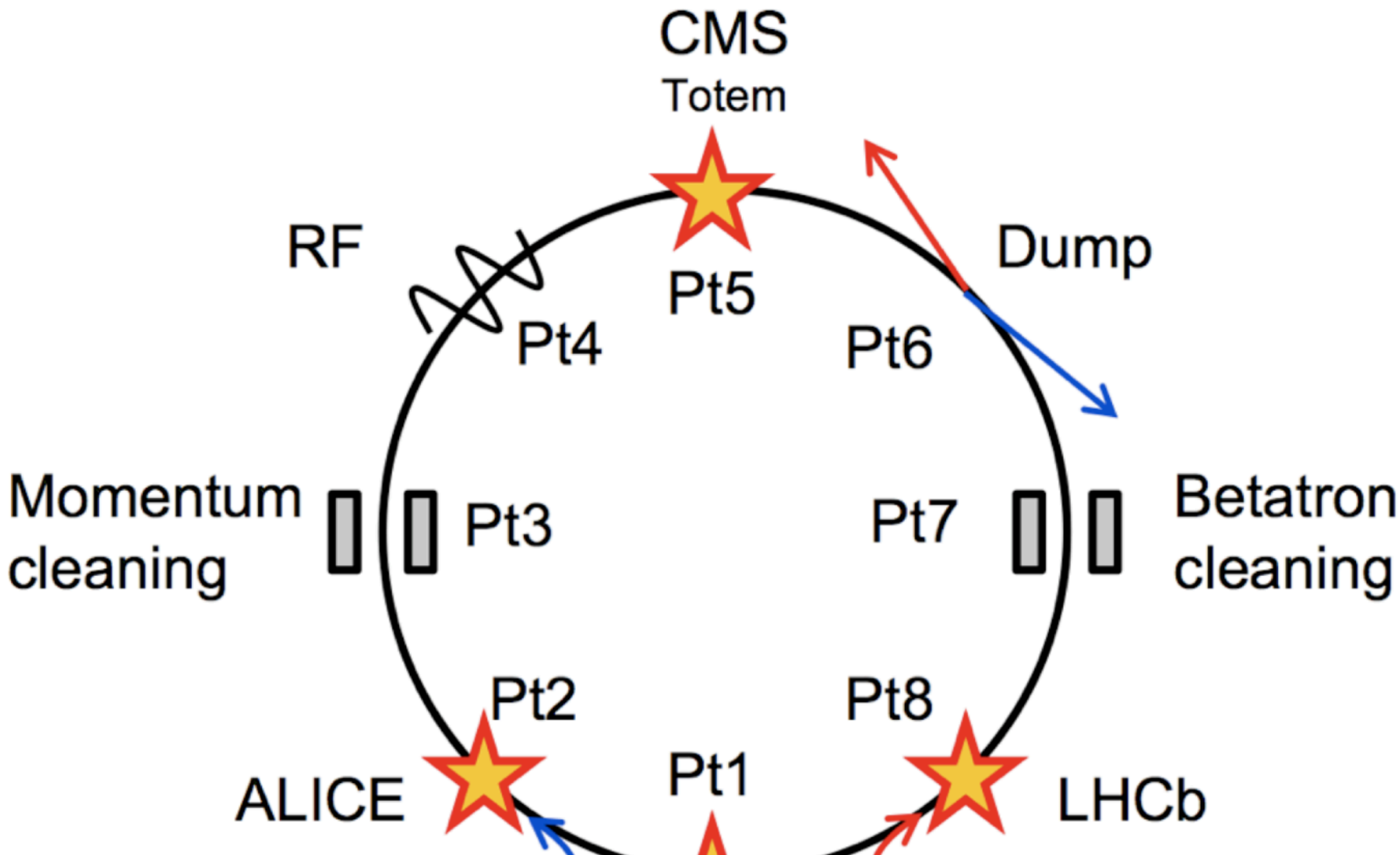
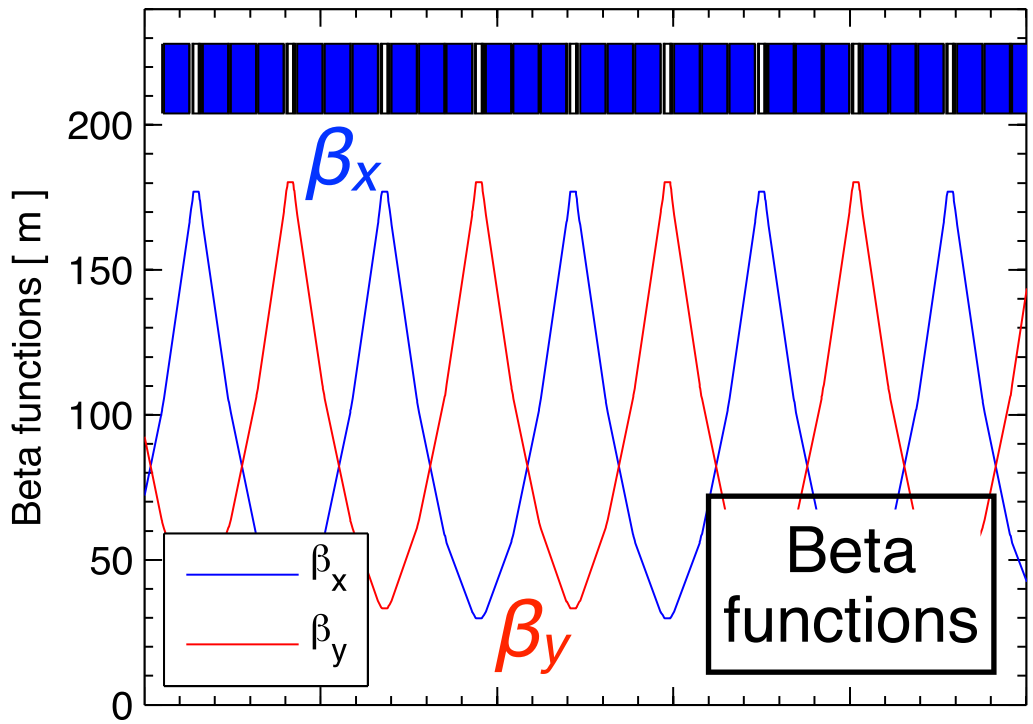
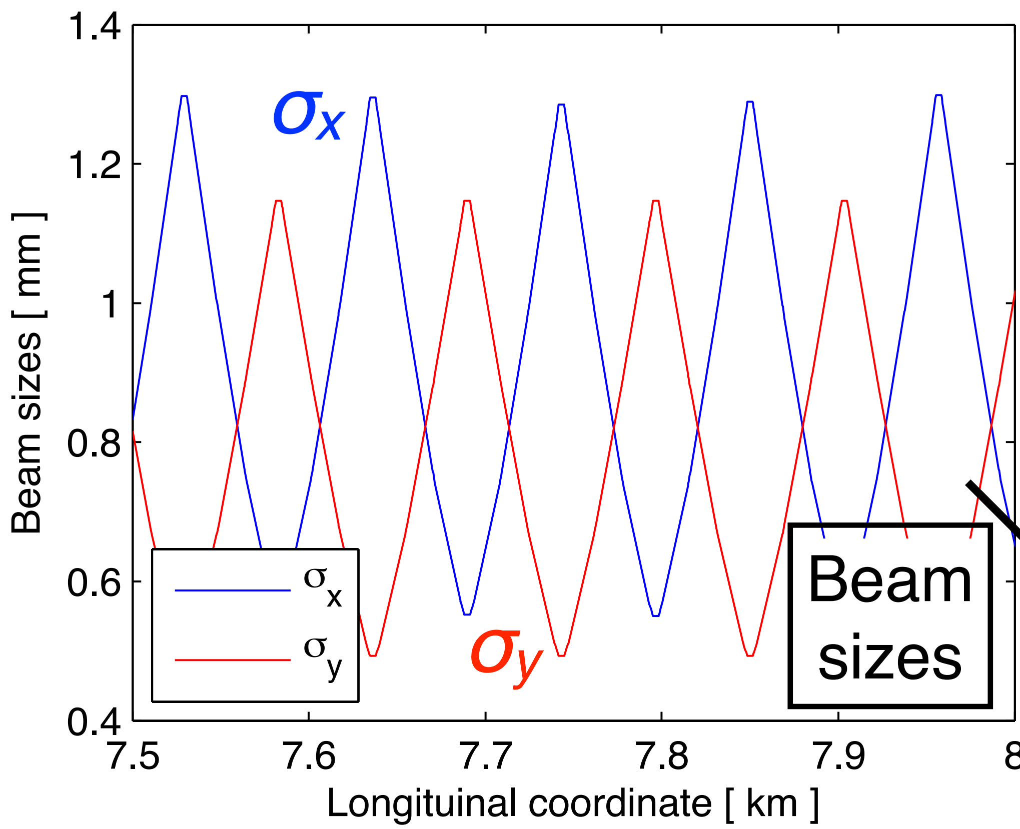


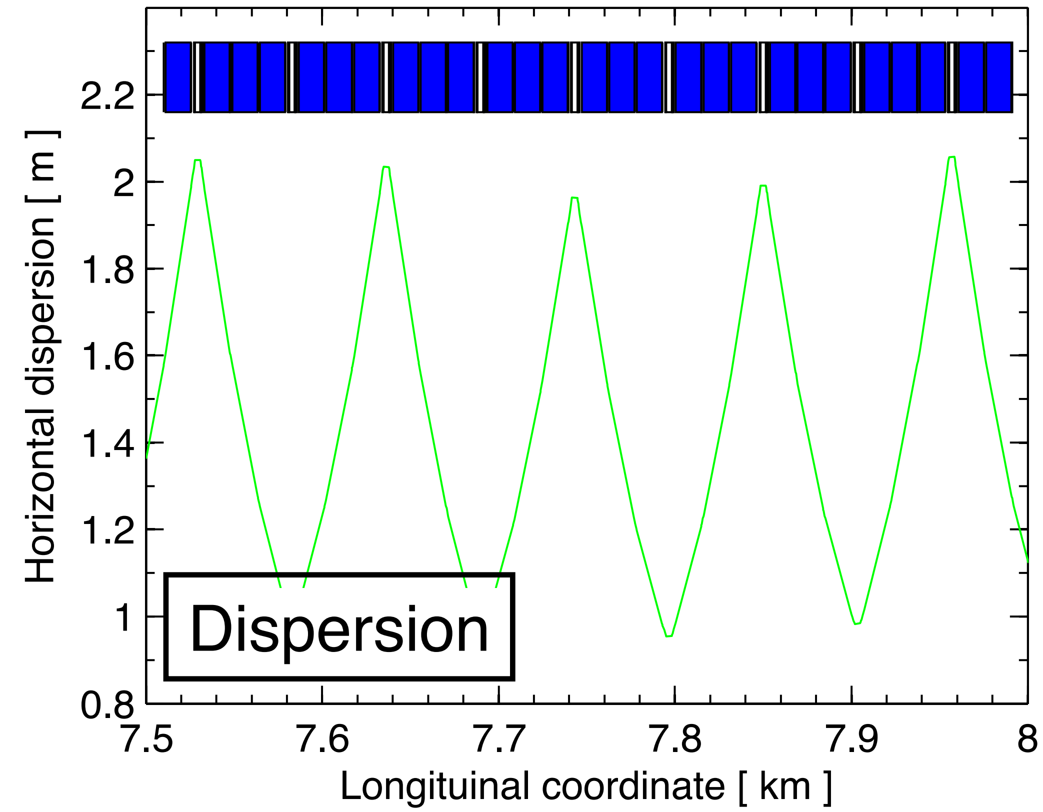
- Optics of 8 arcs: transport with FODO lattice
- Dedicated optics solutions in each interaction region
- Examples: arc, collimation + experiment

Notation:
8 "Points" (Pt) or
"Interaction Regions" (IRs)

Example for the LHC arc (450 GeV)







$$\beta_{x,y} = 30 \div 180\text{m}$$

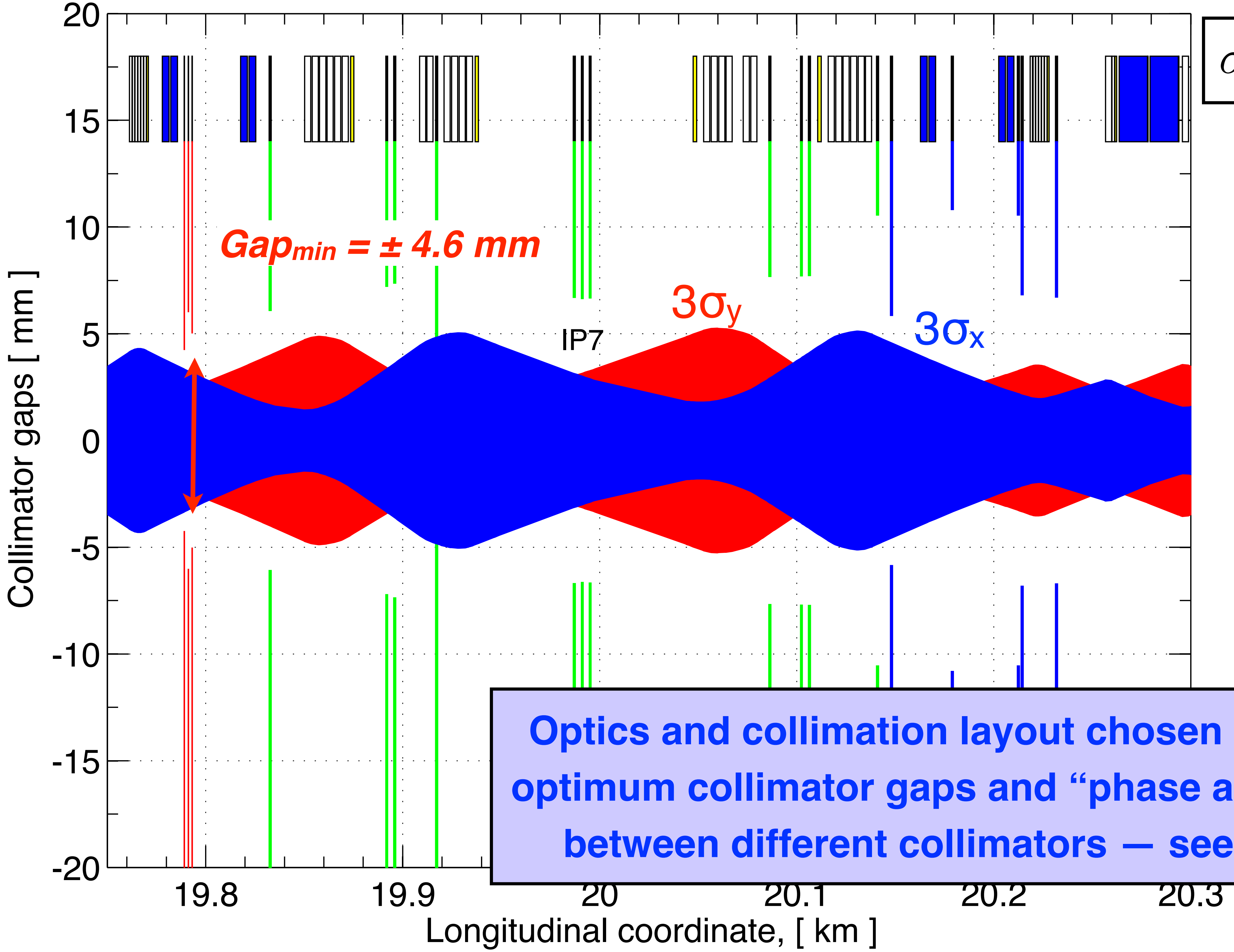
$$\left(\frac{\Delta p}{p}\right)_{\text{rms}} = 3.06 \times 10^{-4}$$

$$D_x^{\text{max}} \approx 2\text{m}$$

Beam sizes ~4 times smaller at 7 TeV (same optics)

IR7: collimation insertion

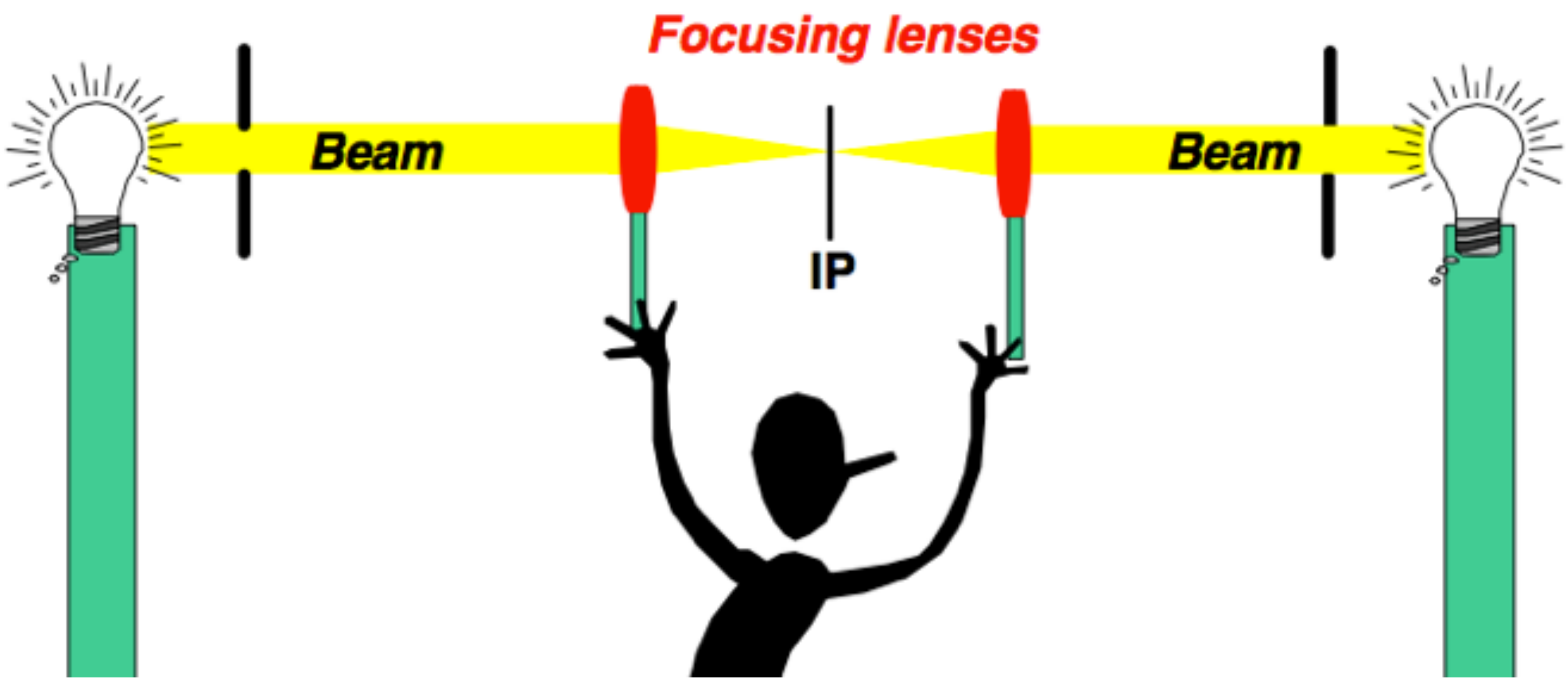
Shown: collimator gaps (primary, secondary, absorbers will be introduced later)



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

Optics and collimation layout chosen to have optimum collimator gaps and "phase advance" between different collimators — see later.

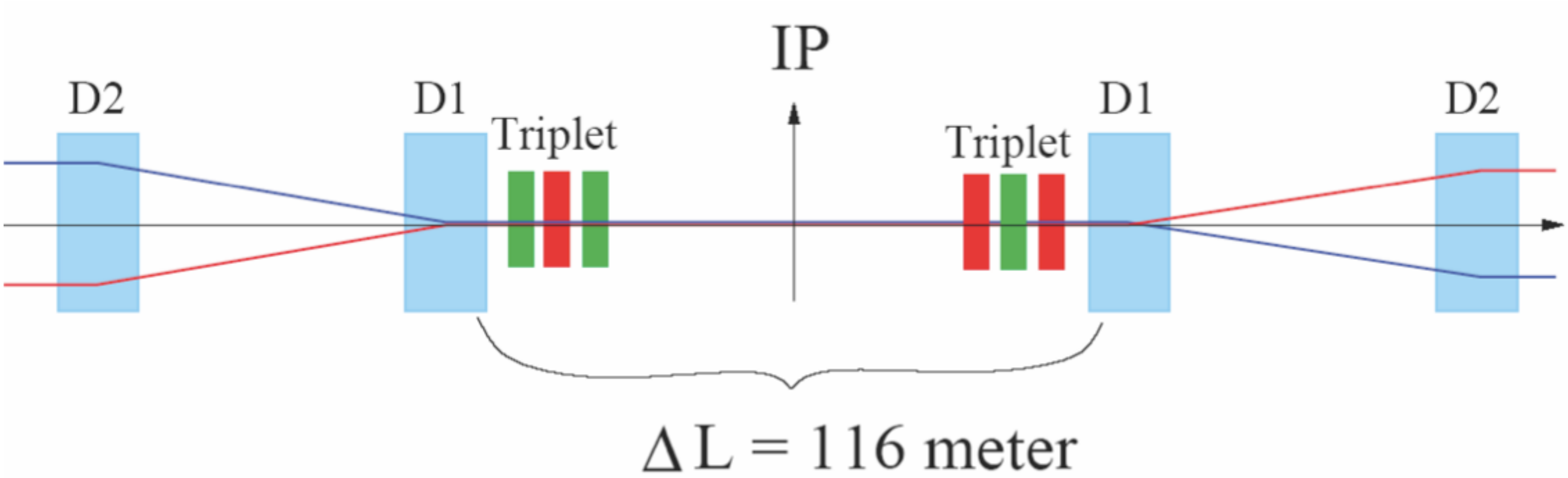
Beam collisions in experimental IRs

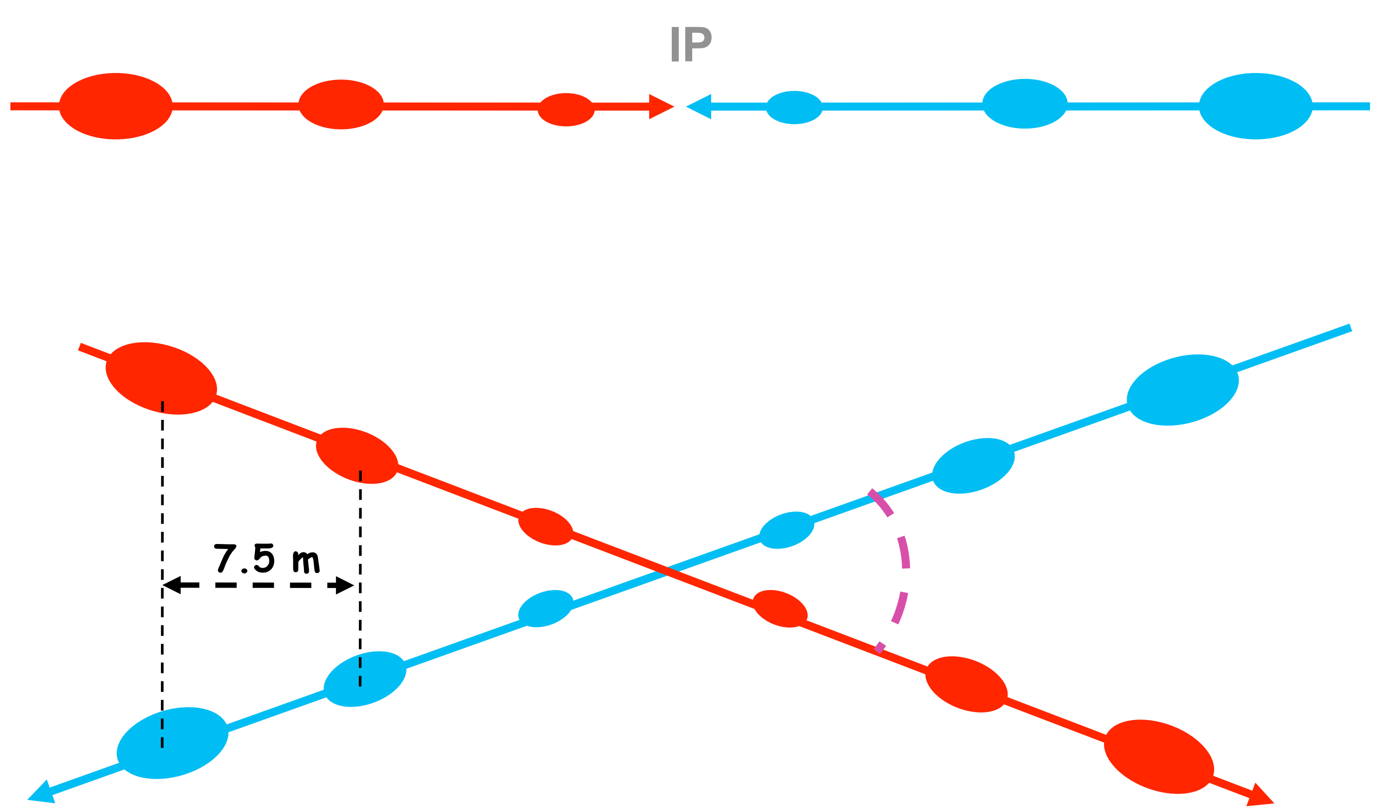


Beam 1→

←Beam 2

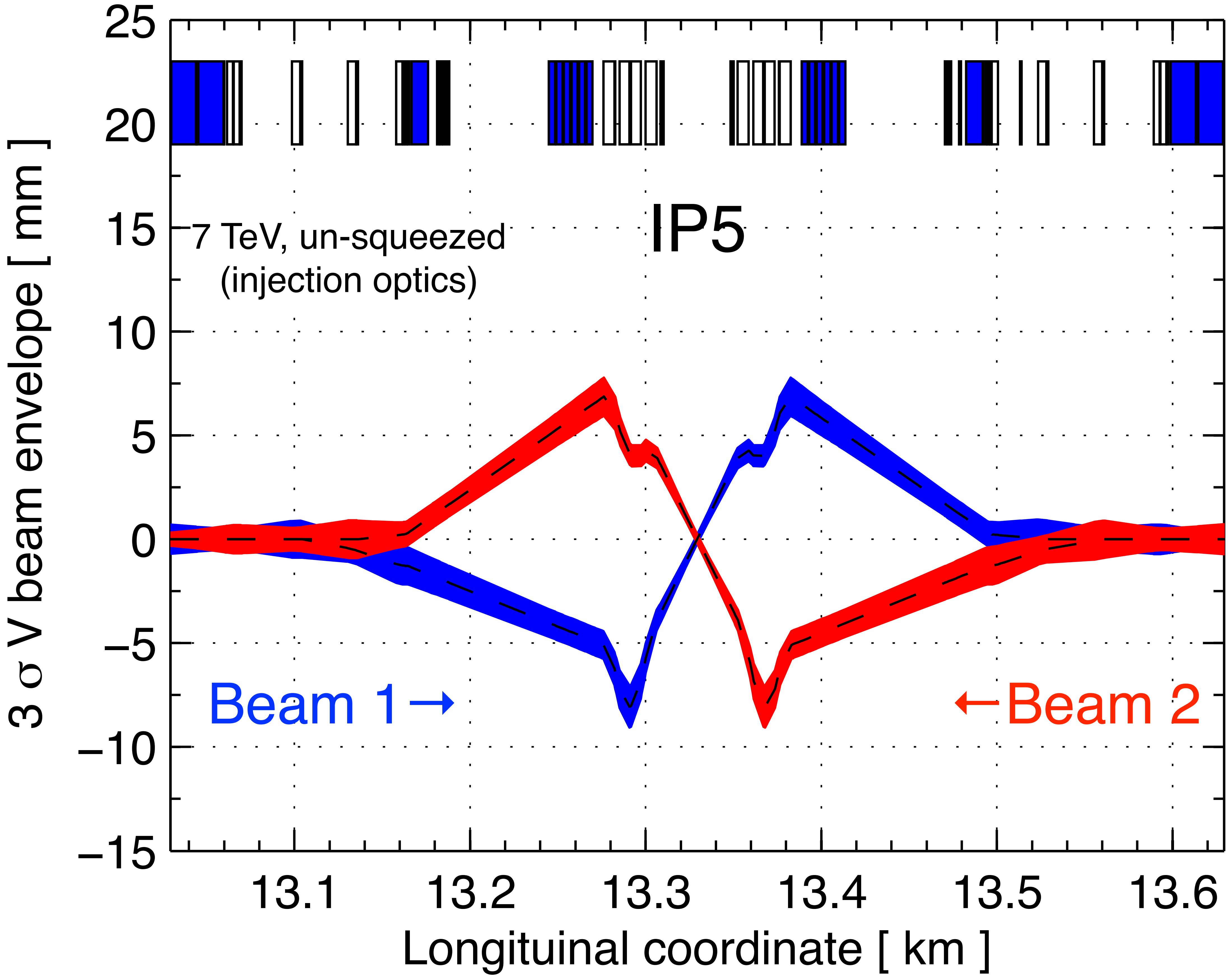
Interaction region layout



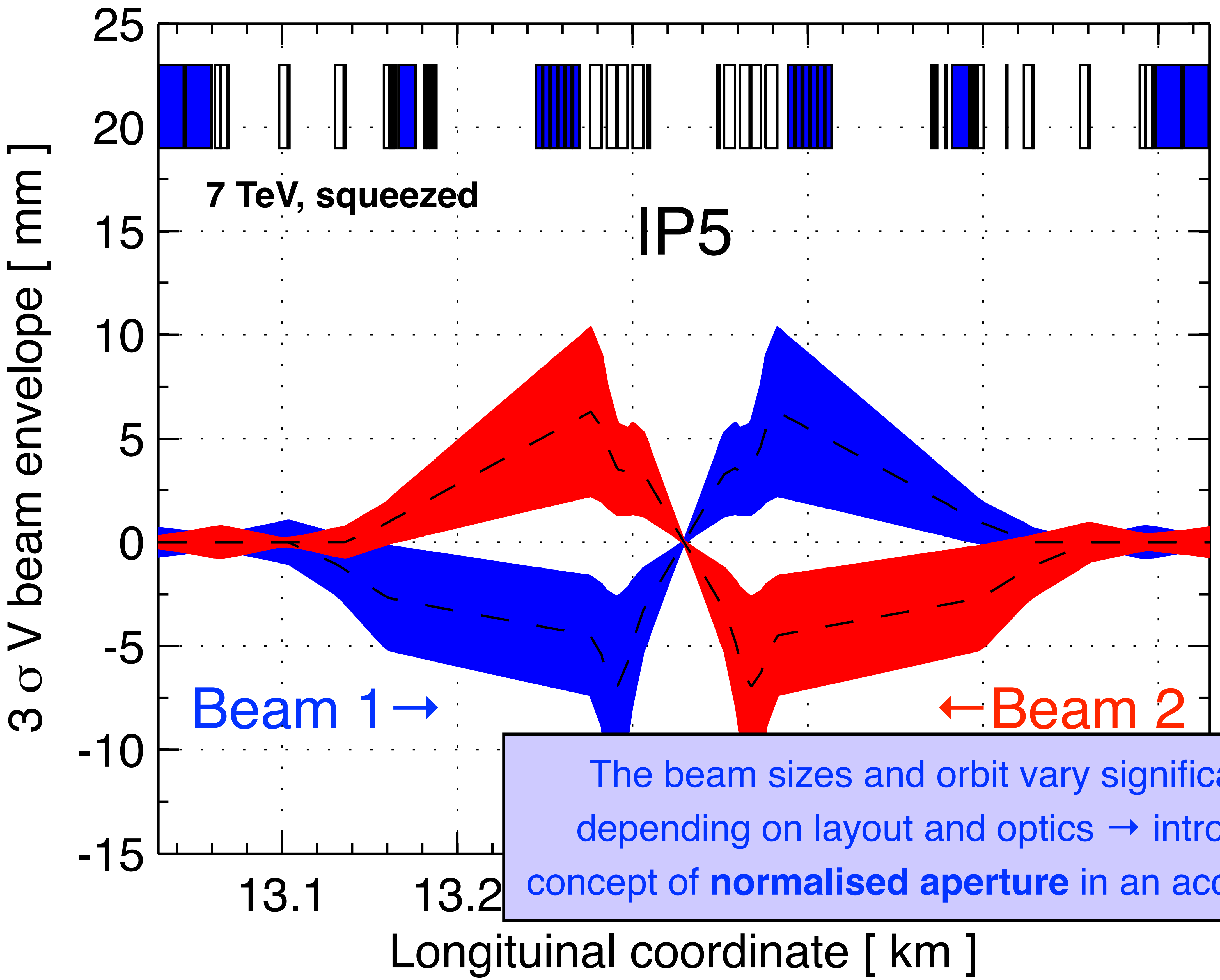


Specific challenges for the collimators that protect the triplet, because local orbit and beam sizes vary during the cycle.

Beam envelope



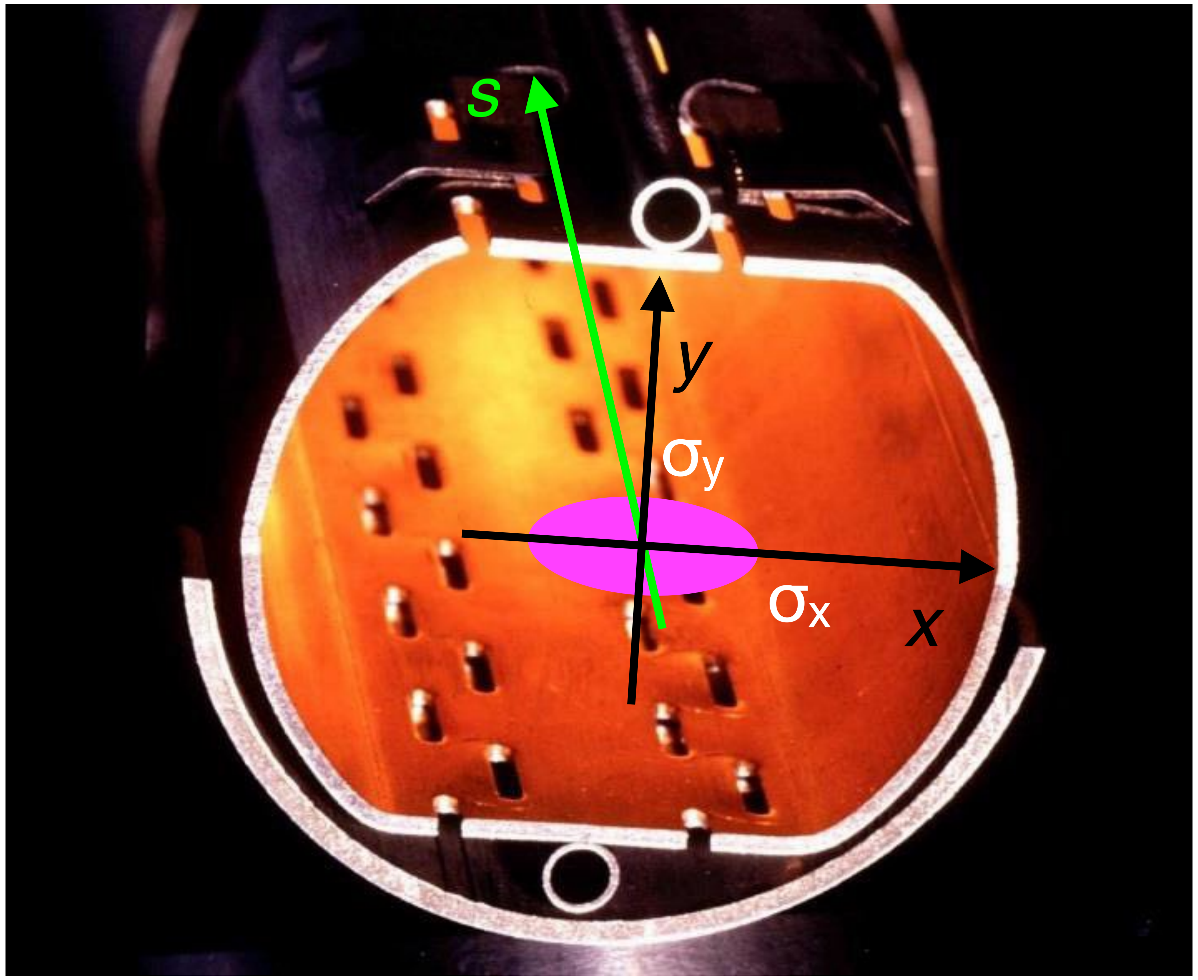
Beam envelope



The beam sizes and orbit vary significantly depending on layout and optics → introduce concept of **normalised aperture** in an accelerator

Aperture in a circular collider

Typical LHC aperture in superconducting magnets ("beam screen"): $r_{x,y}$ = 22/17 mm



It is convenient to introduce a normalised aperture using the varying local beam sizes as a function of *s*

Machine aperture is fundamental for the design of a super-collider: key factor in determining the costs. It needs to be sufficiently large to ensure adequate beam clearance in all operational phases.

Beams must never touch directly the beam pipe: **aperture must be protected.** Primary goal of the collimation system is to ensure this!

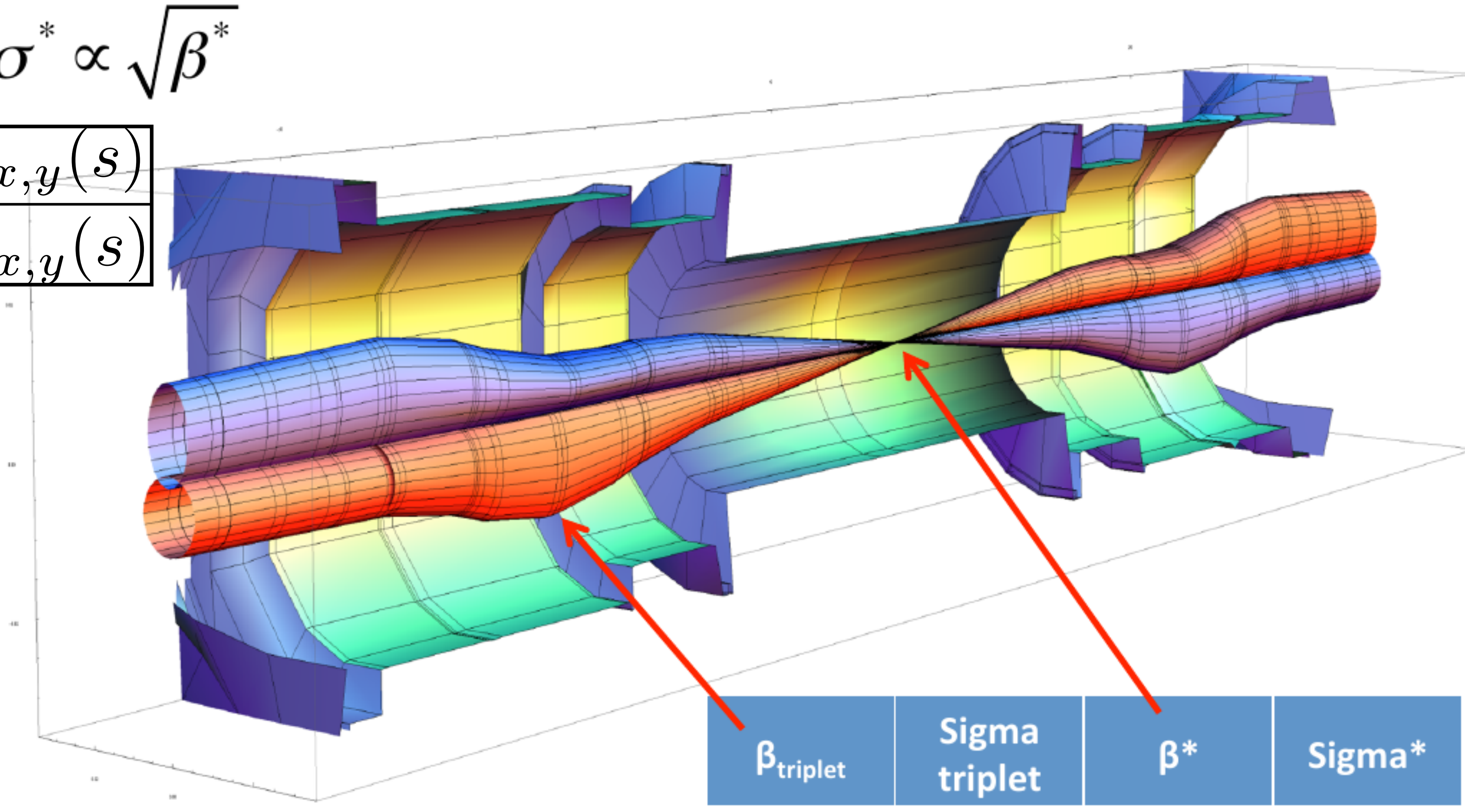
$$A_{x,y}(s) = \frac{r_{x,y}(s)}{\sigma_{x,y}(s)}$$

$$A_{x,y}^{\text{bottleneck}} = \min_s [A_{x,y}(s)]$$

Aperture example

$$\sigma^* \propto \sqrt{\beta^*}$$

$$A_{x,y}(s) = \frac{r_{x,y}(s)}{\sigma_{x,y}(s)}$$

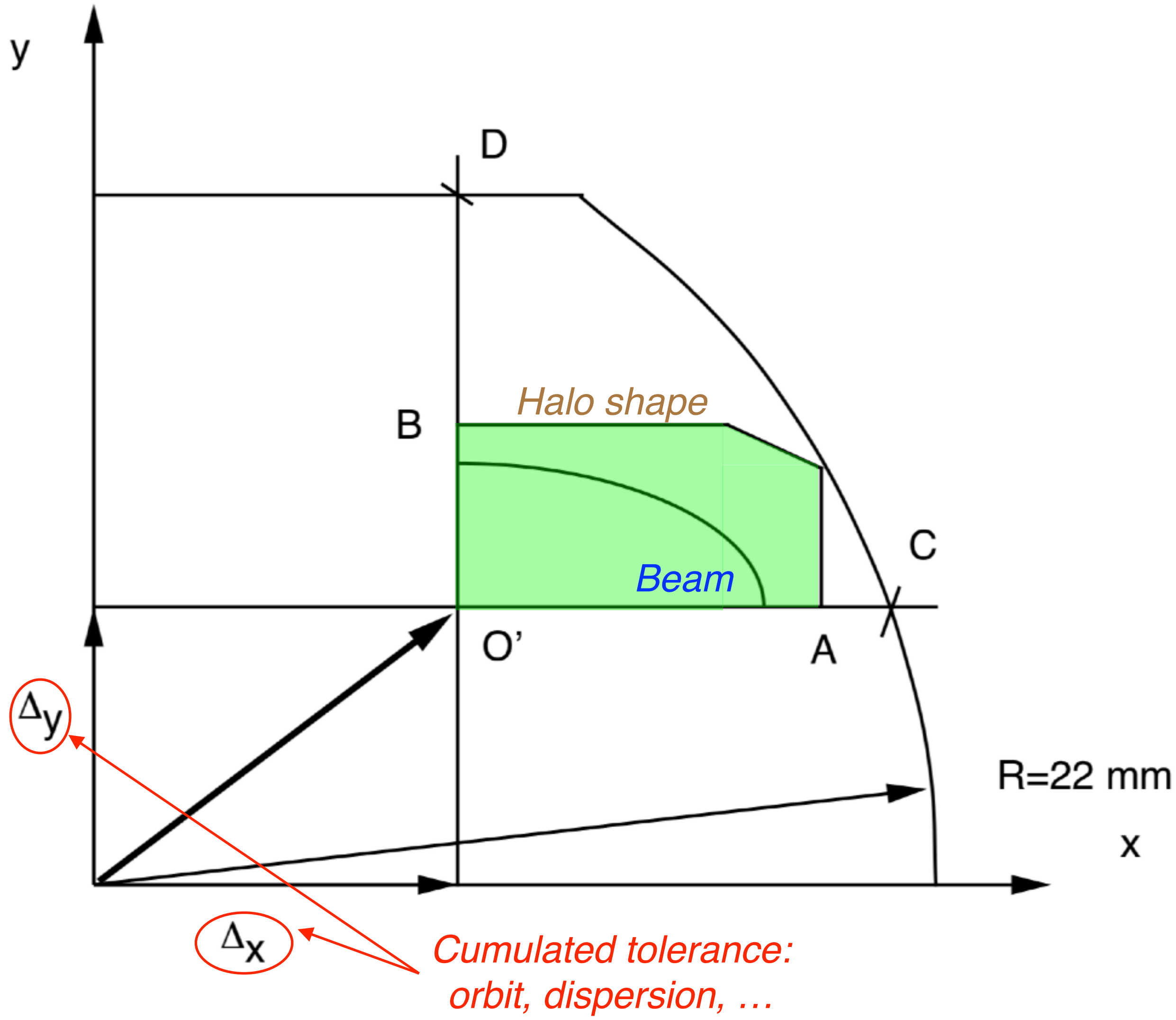


$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	55 cm	17 um

LHC design report parameters

The smallest normalised aperture is the key input parameters for a collimation system design as it defined the normalised collimator settings that protect the accelerator aperture.

Aperture calculations in practise



In reality, the "aperture problem" is quite complex. Many *ad-hoc* tools were developed in the past to account for various error models: beam orbit, optics (betatron and dispersion), manufacturing tolerances, alignment errors, …

We need to build an **"aperture model"** that is used to estimate aperture bottlenecks in the accelerator.

For this lecture, we "only" need to know that there is a minimum aperture values, per beam and plane (x, y), that the collimation system must protect!

$$A^{\mathrm{bottleneck}}_{x,y} = \min_s \left[\frac{r_{x,y}(s)}{\sigma_{x,y}(s)}\right]$$

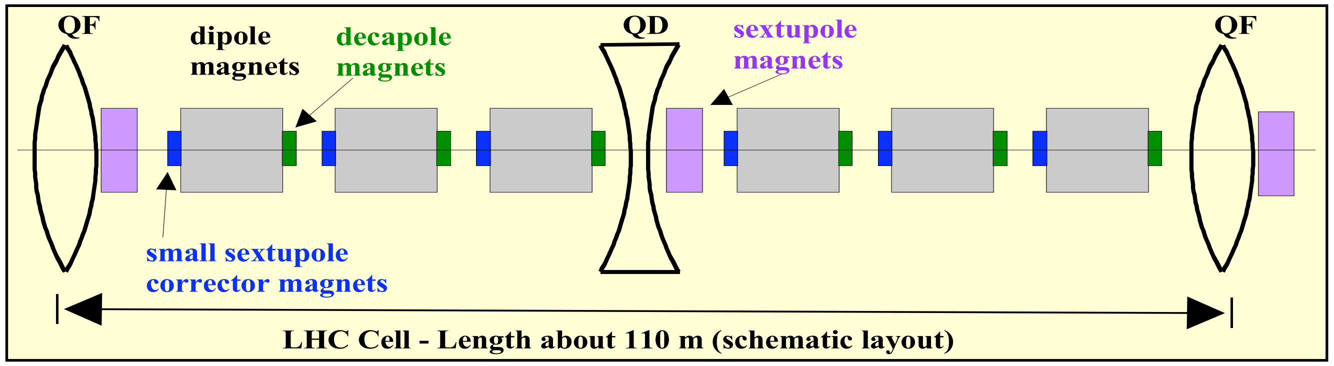
In a similar way, one can compute the off-momentum aperture bottleneck and design a collimation system to protect it — focus this lecture on the betatron case.

Outline

- **Introduction**
- **Accelerator physics concepts**
  — Recap. of betatron motion
  — "Aperture" in a circular accelerator
- **Beam collimation**
  — **The beam stored energy challenge**
  — **Beam losses and cleaning requirements**
  — **Design of a beam halo collimation system**
  — **The LHC collimation system**
- **Collimation design and performance**
  — Design of the LHC collimators
  — Collimation system in operation
  — Simulations and measurements
- **Crystal collimation**

Recap. of what we have seen so far

Beam rigidity: $$B\rho = \frac{p}{\mathrm{e}}$$



Equation of motion and its solution:

Beta function

Dispersion

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

Betatron tune and chromaticity:

$$Q = \frac{1}{2\pi}\int\frac{ds}{\beta(s)}$$

$$Q' = \frac{\Delta Q}{\Delta p/p}$$

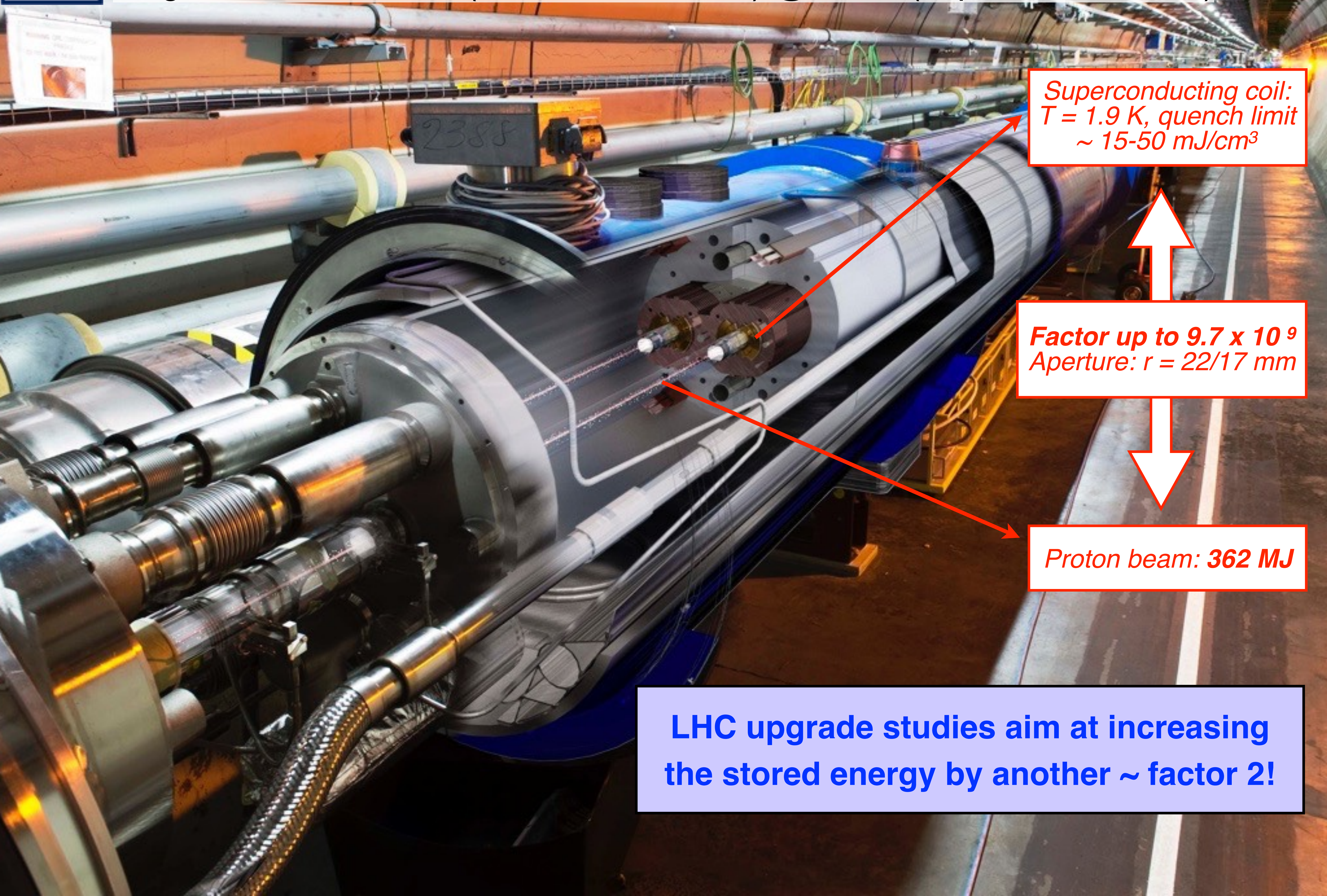
Emittance and beam size:

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

Normalized aperture:

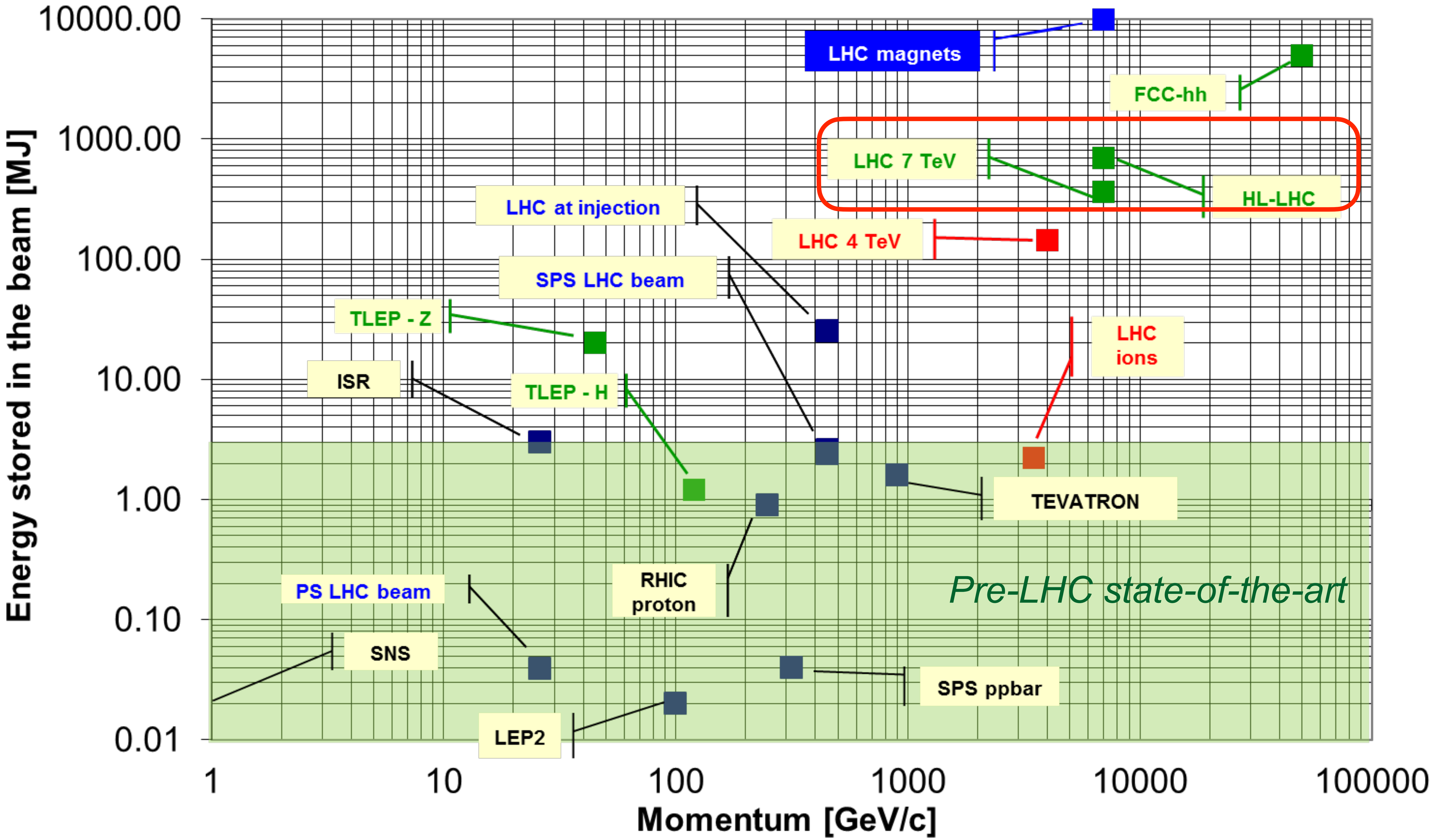
$$A_{x,y}^{\mathrm{bottleneck}} = \min_s\left[\frac{r_{x,y}(s)}{\sigma_{x,y}(s)}\right]$$

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)



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

The LHC stored energy challenge



362 MJ stored energy (LHC design at 7 TeV)

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 while preserving the **superconducting** state!

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****.*
- *Equipment failures & human errors*
- *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

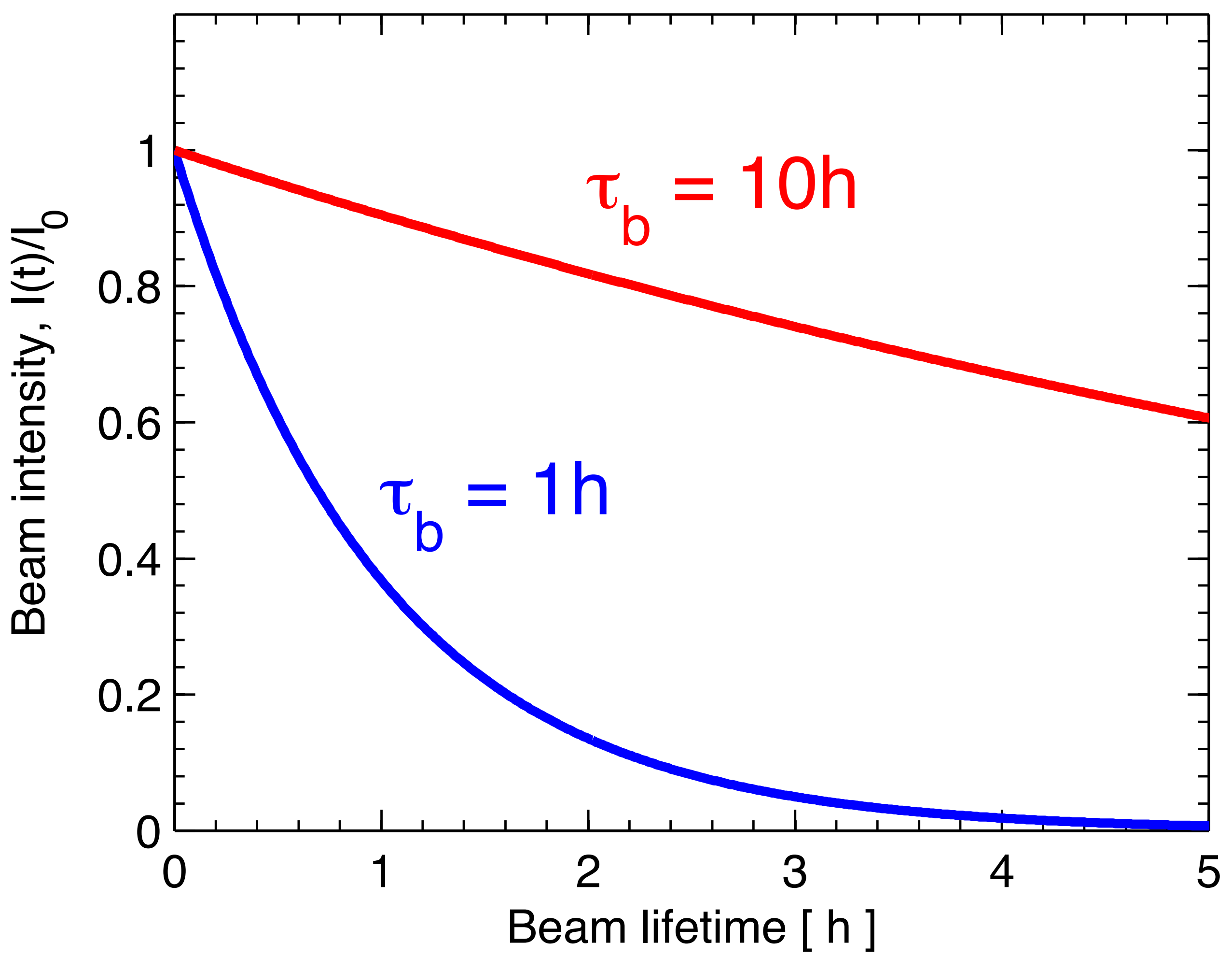
Beam loss mechanisms are modelled by assuming a non-infinite **beam lifetime,** τ_b

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

: Beam intensity versus time

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

: Proton loss rate



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

LHC target driven by quench limits of SC magnet: ***0.2 h lifetime*** *at the full intensity (320 hundred trillion protons!) corresponds to a loss rate of about 450 billion proton per second, i.e.* ***0.5 MJ/s = 500 kW****!*

Collimation design: losses & target

N_{tot} : total beam populations [p]

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

R_q : tolerable loss rates [p/m/s]
(LHC: quench limit)

Criterion for collimation: losses must stay below a target (e.g., quench limits; experimental background; activation…)

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

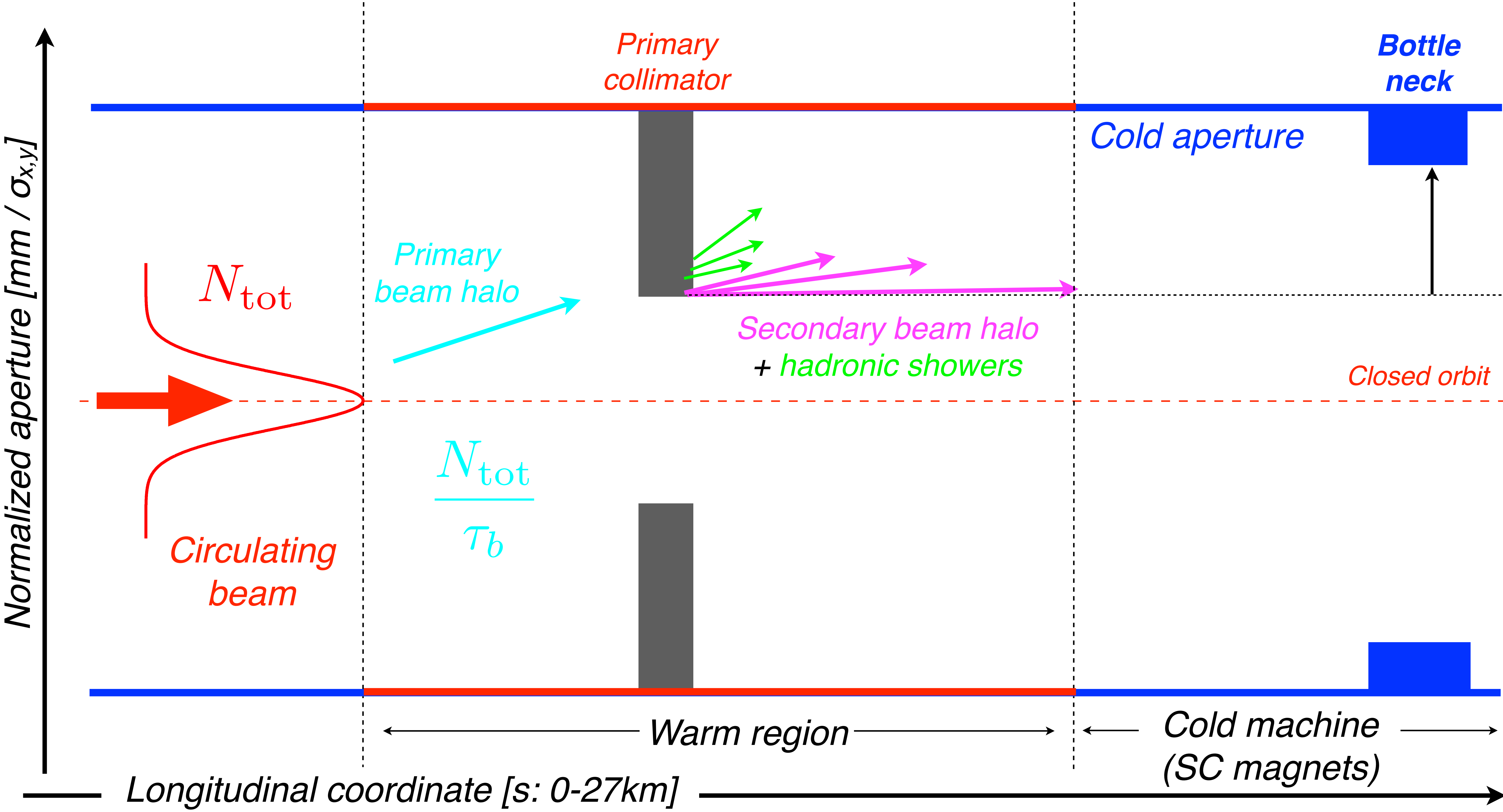
$\tilde{\eta}_c$: local cleaning inefficiency [1/m] → fraction of proton losses that is lost at a certain location.

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

LHC example: magnets must NOT quench. This requires $\eta_c < 0.0001$

Let's start designing a collimation system to protect the aperture

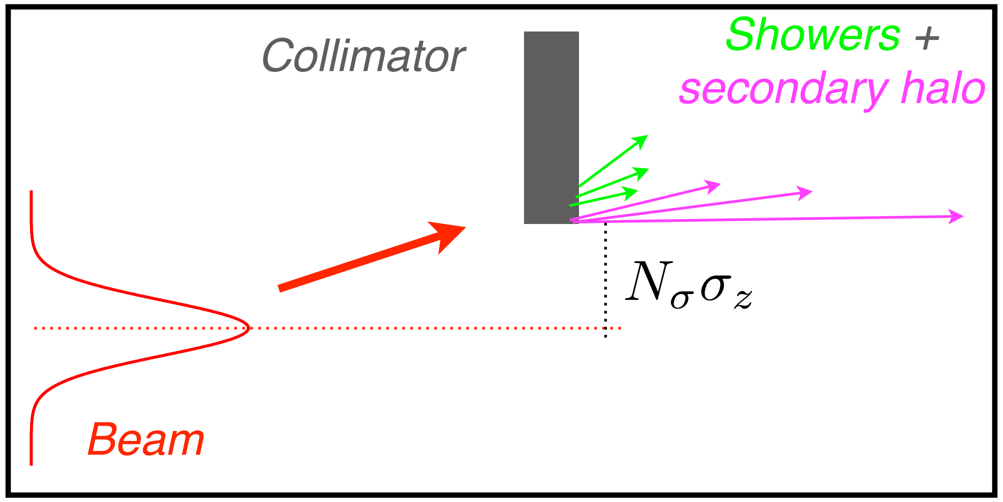
Aperture and single-stage cleaning



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?

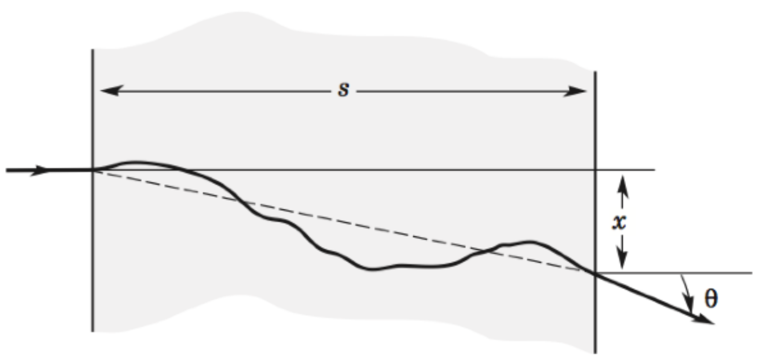
Particle interactions with collimators



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.

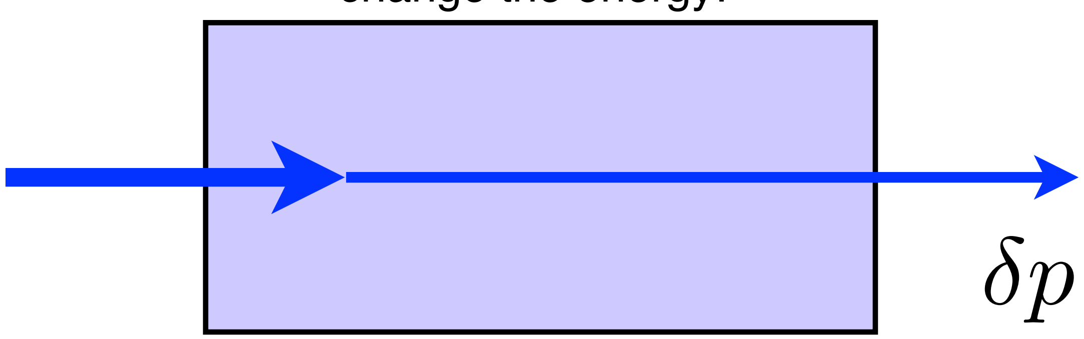


$$\sqrt{\langle \theta_p^2 \rangle} = \frac{13.6}{cp[\mathrm{MeV}]} \sqrt{\frac{s}{\chi_0}} \left(1 + 0.038 \cdot \left(\frac{s}{\chi_0}\right)\right)$$

χ_0 : radiation length

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

Single-diffractive interactions change the energy!



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

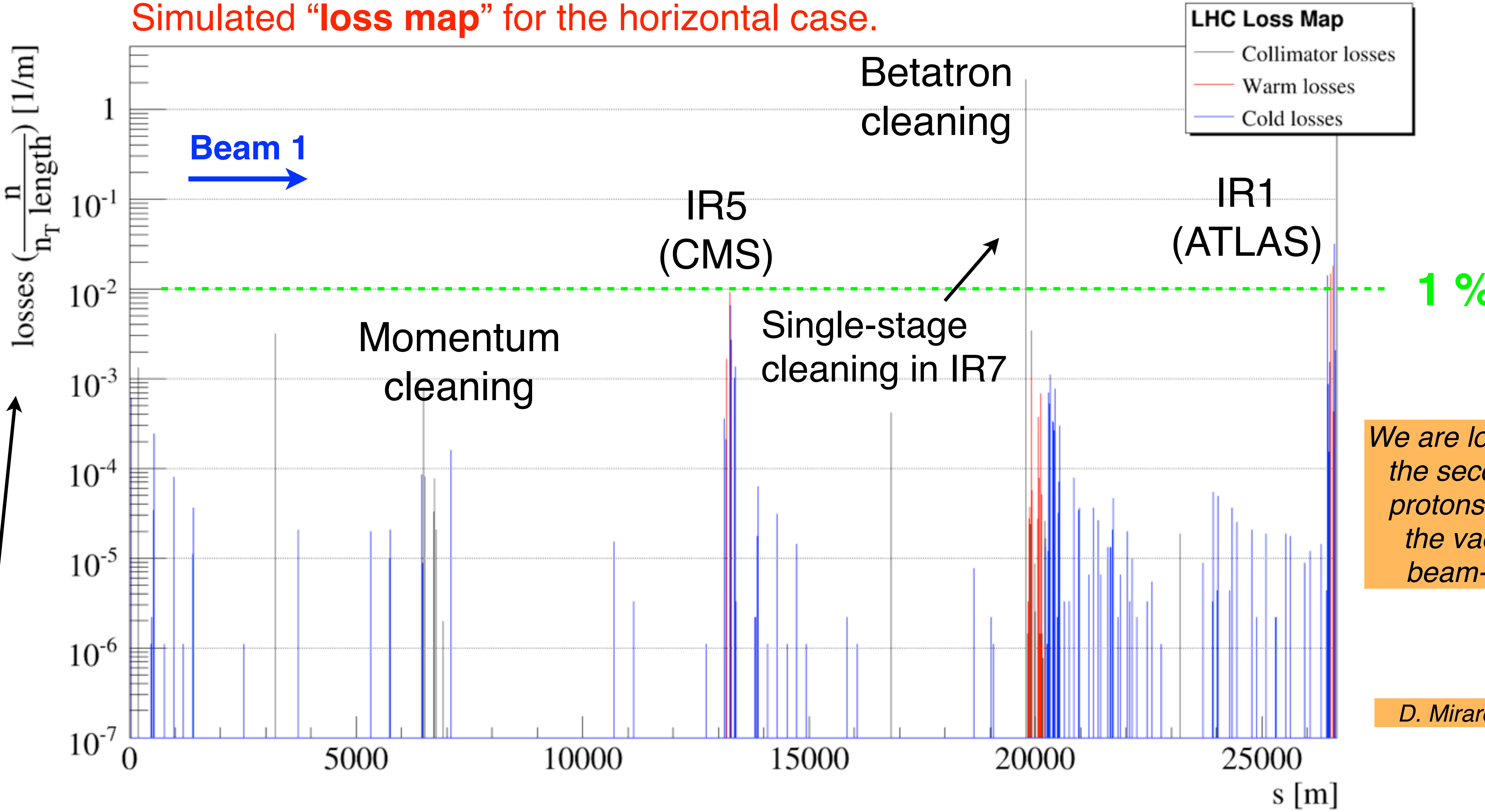
The interaction with collimator materials is itself a source of betatron and off-momentum halo (secondary halo).

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.

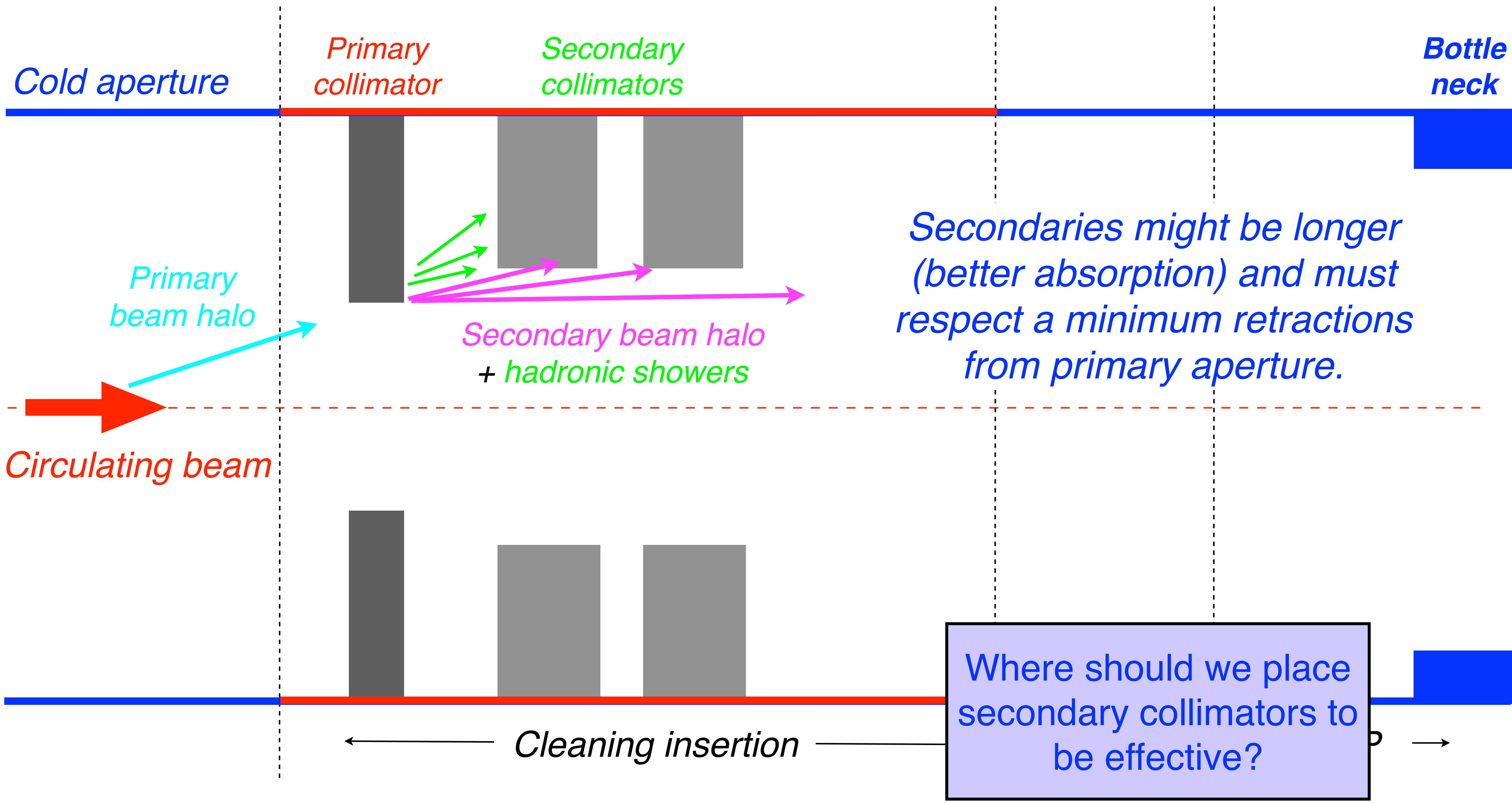
D. Mirarchi

Local cleaning inefficiency

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

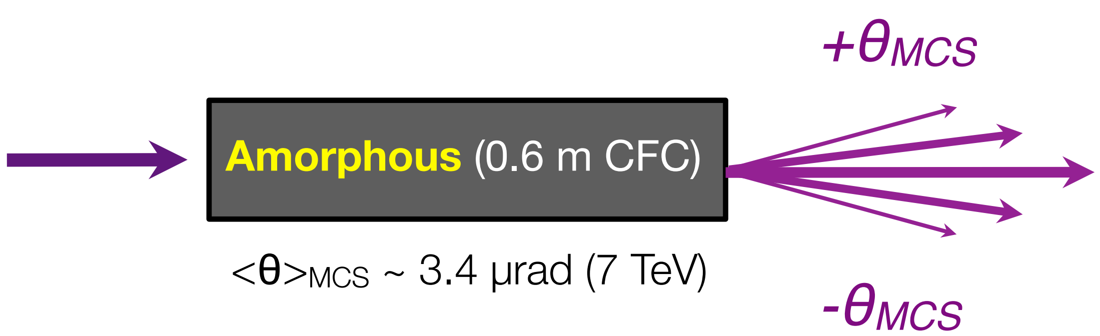
Fraction of proton lost per unit length.

Two-stage collimation

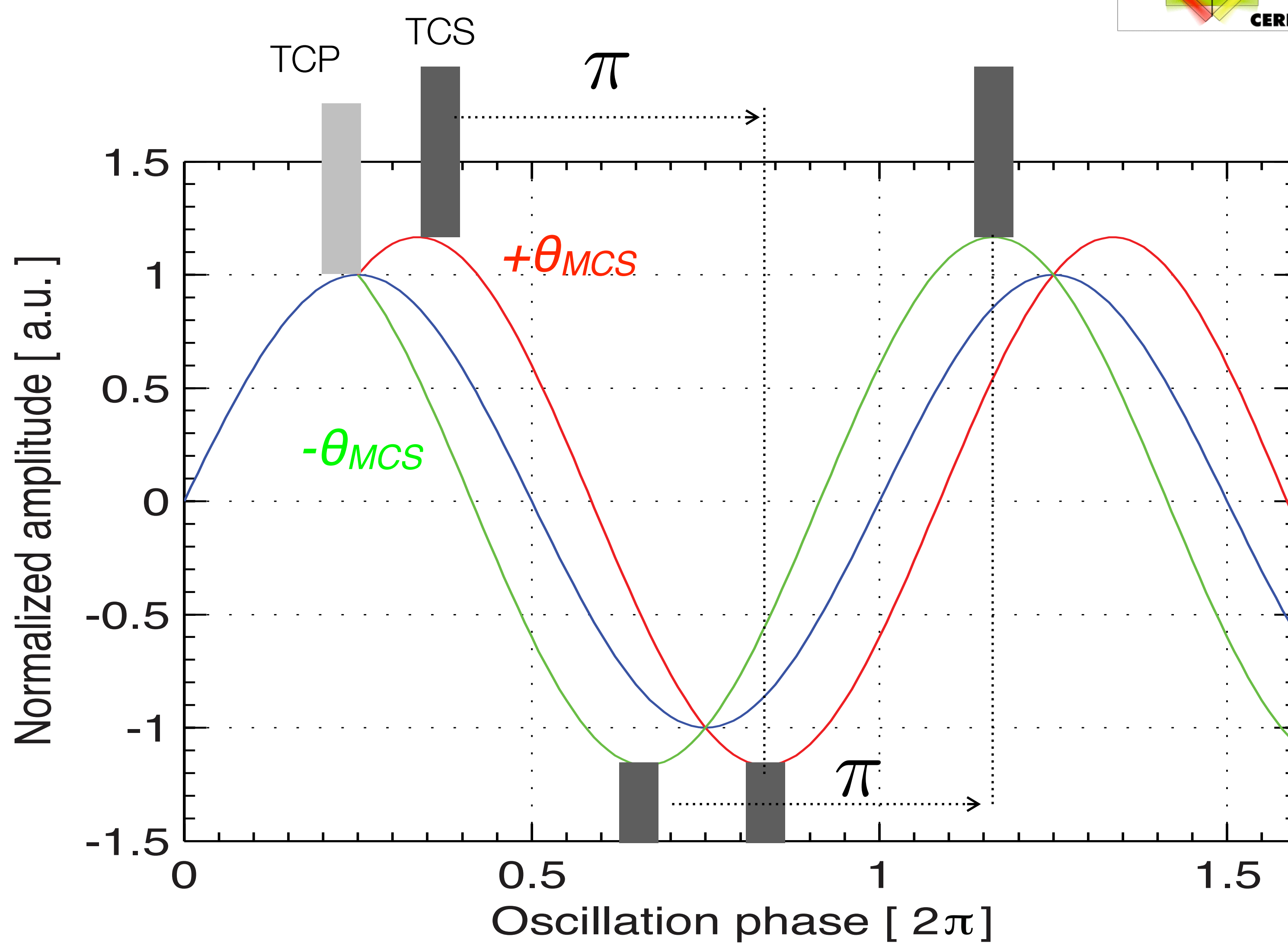


"Secondary" collimators (TCSs) can be added to intercept the secondary halo and the showers that leak out of the primary collimator.

Optimum secondary collimator locations



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



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

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

$\beta(s)$: 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

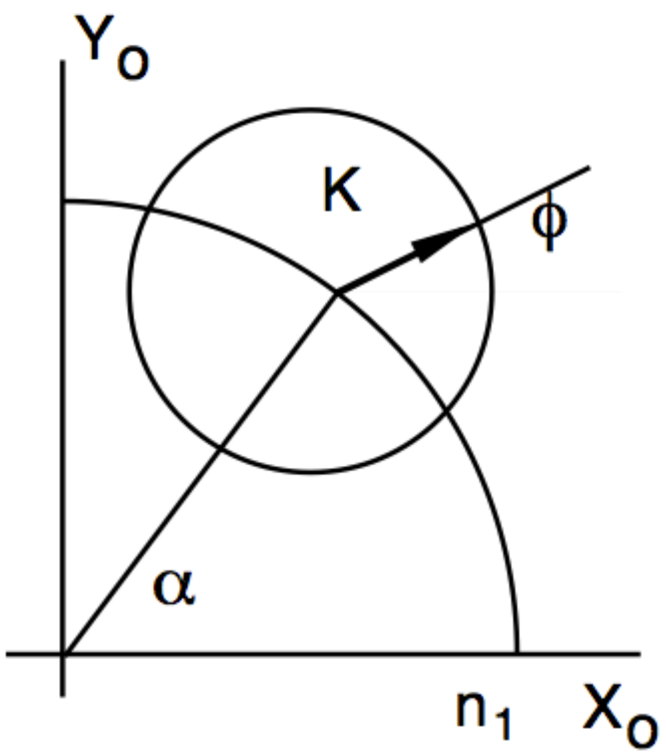
α, ϕ : collimator plane and scattering angle

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

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

Optics of a two-stage collimation system

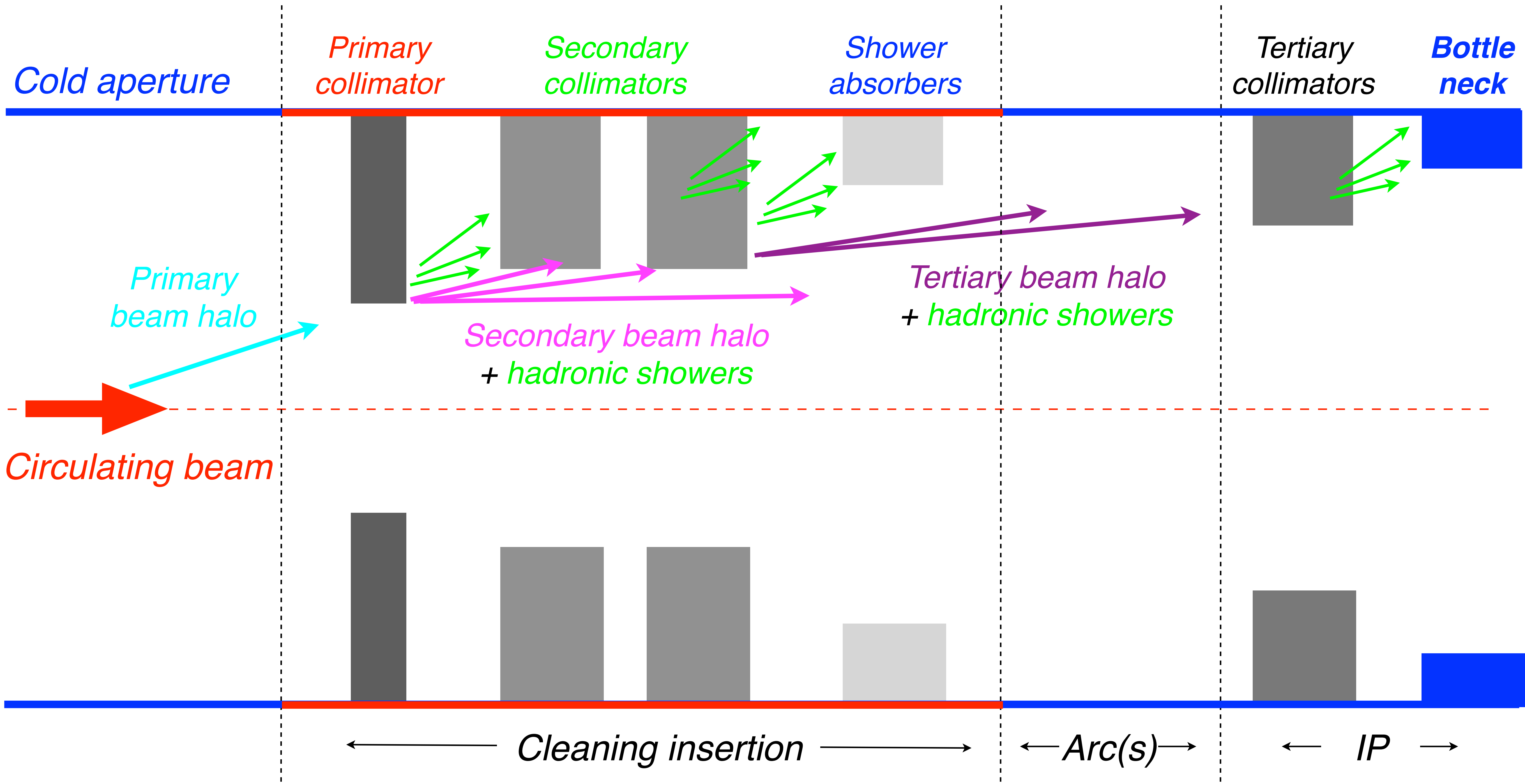
J. B. Jeanneret
CERN, CH-1211 Geneva, Switzerland
(Received 13 October 1998; published 21 December 1998)



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	$\pi/2 + \mu_0$

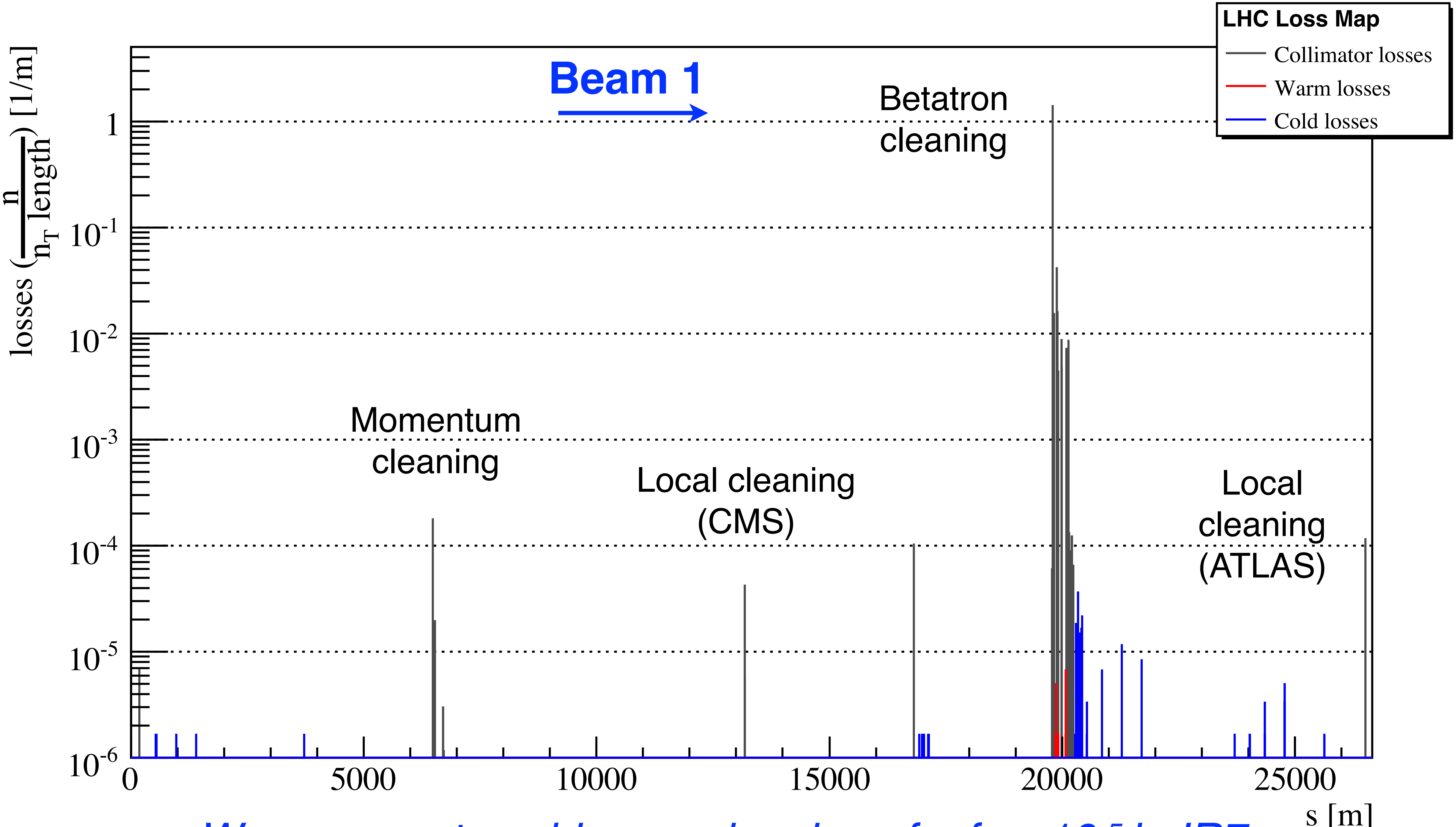
Multi-stage collimation at the LHC



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

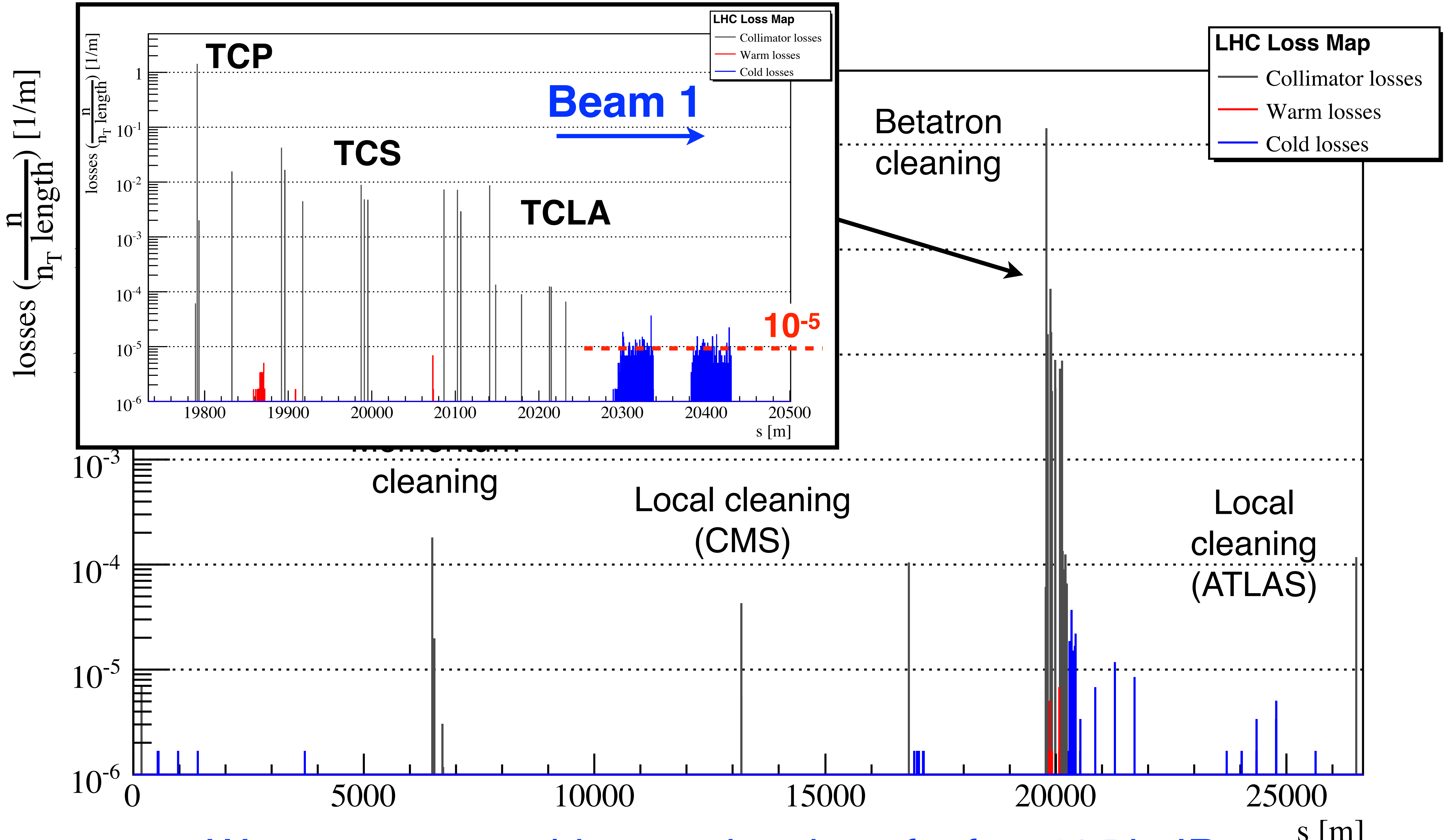
The system performance relies on achieving the well-defined **hierarchy** between different **collimator families** and **machine aperture**.

Simulated 7 TeV performance



We manage to achieve a cleaning of a few 10^{-5} in IR7.
Cold losses in experiments removed by local protection.

Simulated 7 TeV performance



We manage to achieve a cleaning of a few 10^{-5} in IR7.
Cold losses in experiments removed by local protection.

LHC collimation system (Run 2)

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)**

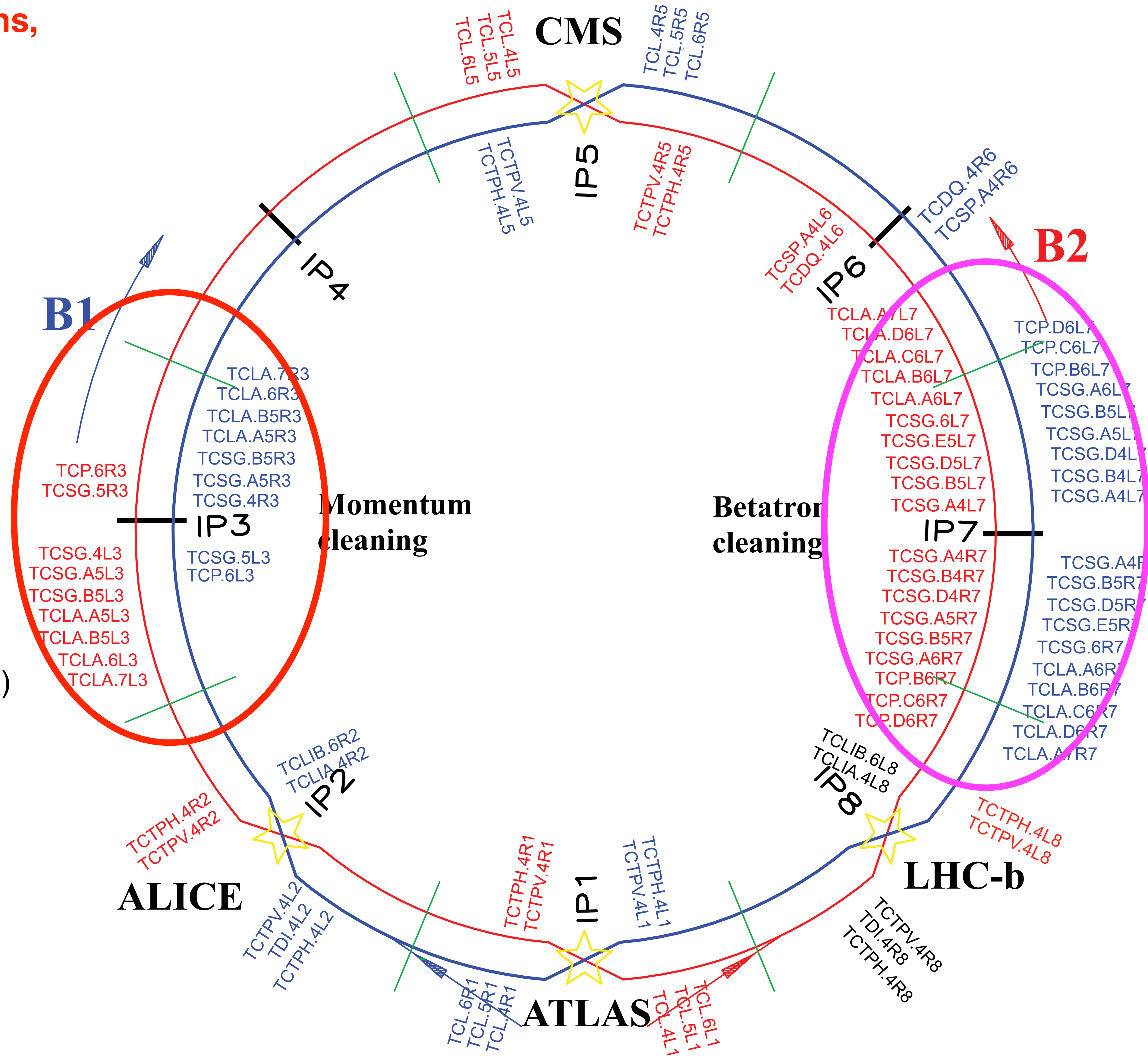
Local cleaning at triplets
- **8 tertiary (2 per IP)**

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!



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Main points to retain (i)

- **Beam collimation** is essential in modern high-power machines to safely dispose of unavoidable beam losses (*beam halo cleaning*).
  LHC main concerns:
  Protect against the risk of quenches with > 300 MJ beam stored energy,
- Collimation is achieved by constraining the transverse amplitudes of halo particles: collimator jaws are set close to the beam to shield the machine aperture bottleneck.
- Many sources of beam losses (collisions, gas or beam scattering, operational losses,...) are modelled by looking at the time-dependent **beam lifetime**.
  Required cleaning depends on minimum allowed beam lifetime [for given quench limit].
- We have see the key parameters involved in the specification of collimation systems (beam intensity and energy, assumed lifetime, ...)
- Single-stage collimation: efficiencies up to ~97-99%. This is not enough: the leakage must be reduced by another factor 100-1000 to avoid quenches.
  Many collimators are needed to catch efficiently high-energy halo particles.

Main points to retain (ii)

- A **multi-stage collimation** can provide the missing factors and fulfil the cleaning challenge (for the LHC)!

  Secondary collimators are placed at optimum locations to catch product of halo interactions with primaries (secondary halo+shower products).

  *Other collimators are needed to achieve ~1e-5 → complex **multi-stage hierarchy**.*

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

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

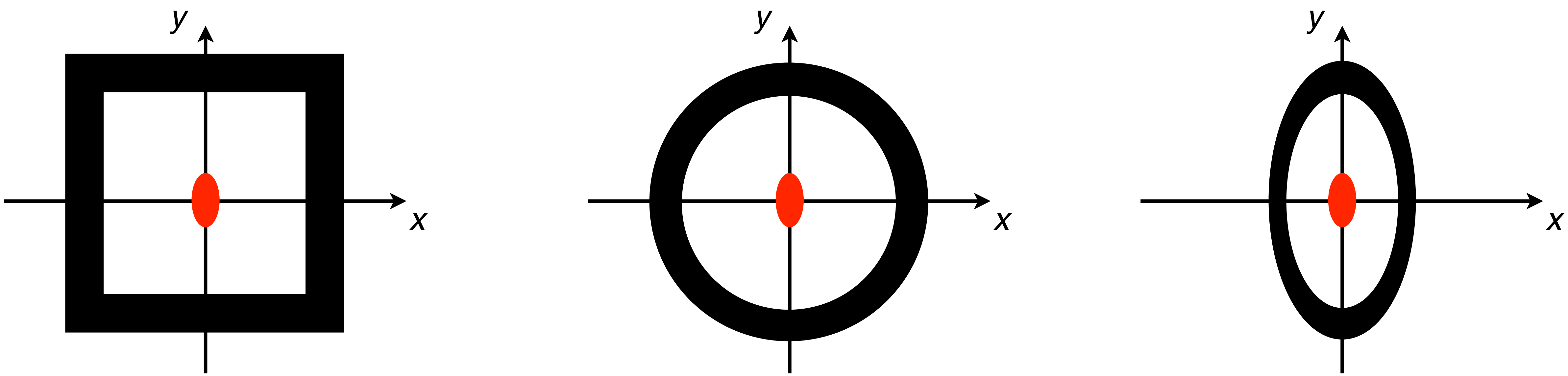
- Back-bone of collimation placed in dedicated **warm insertions**, but some collimators also used for **local protection** of sensitive magnets.

- LHC collimation: unprecedented complexity in particle accelerators!

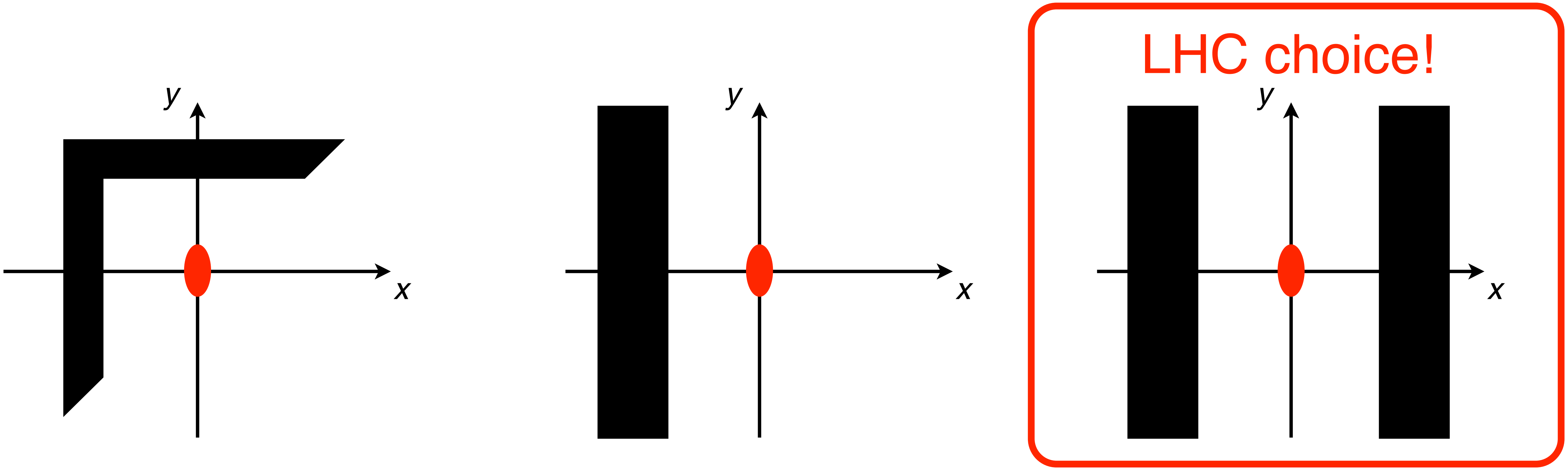
  *A total of 44 collimators per beam, ordered in a pre-defined **collimation hierarchy**: two dedicated warm insertions (2-stage collimation+shower absorbers), local cleaning in experiments, physics debris cleaning and protection collimators.*

Possible collimator designs

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



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



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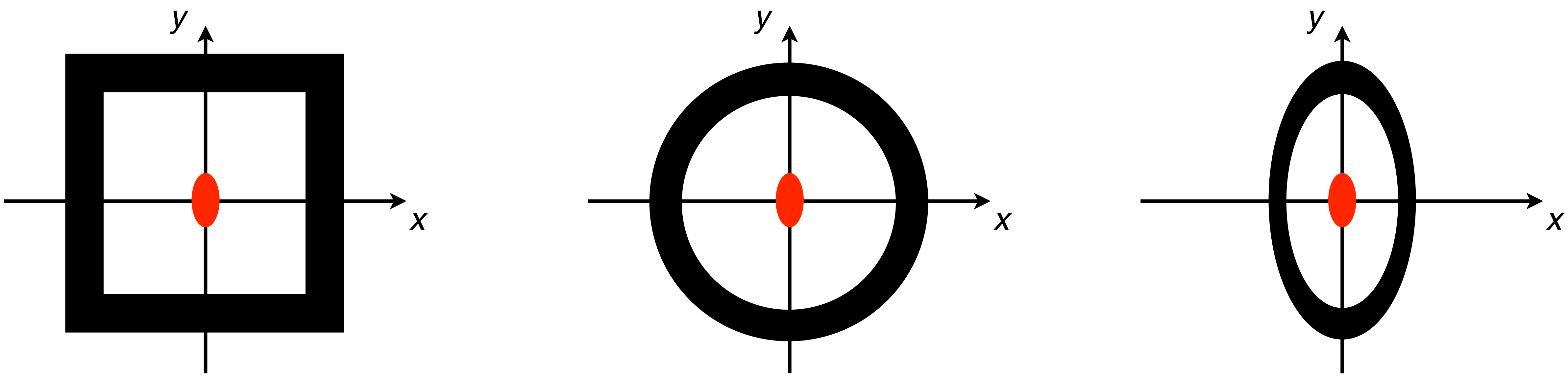
Fixed collimators (masks): square, circular, elliptical, ...



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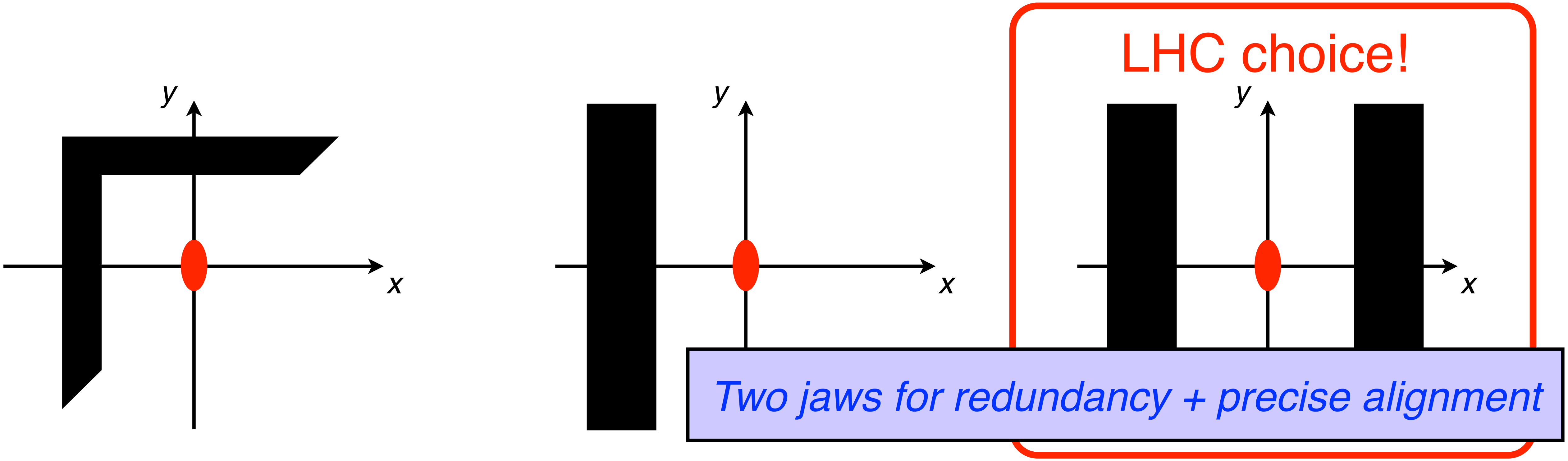
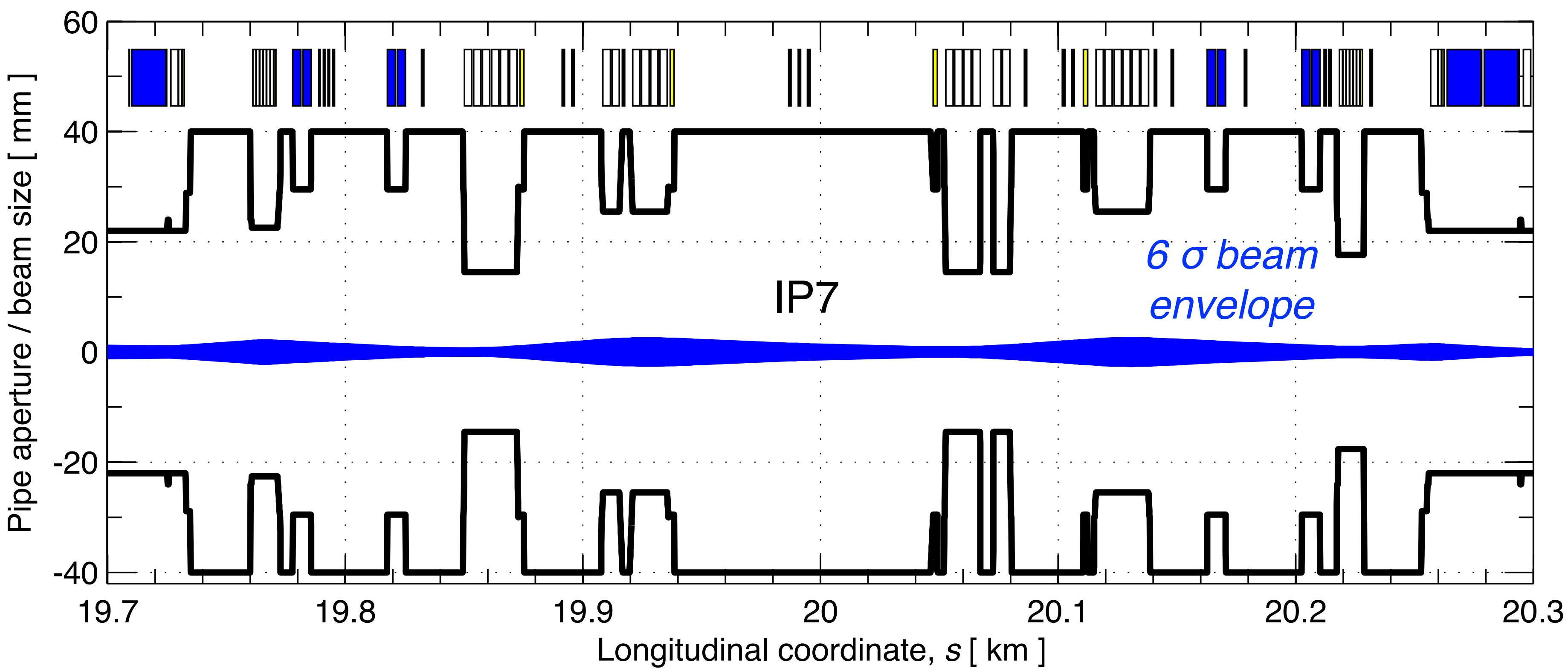


Setting/aperture notations



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

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

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

ϵ_z/γ : normalized emittance

D_z : dispersion function

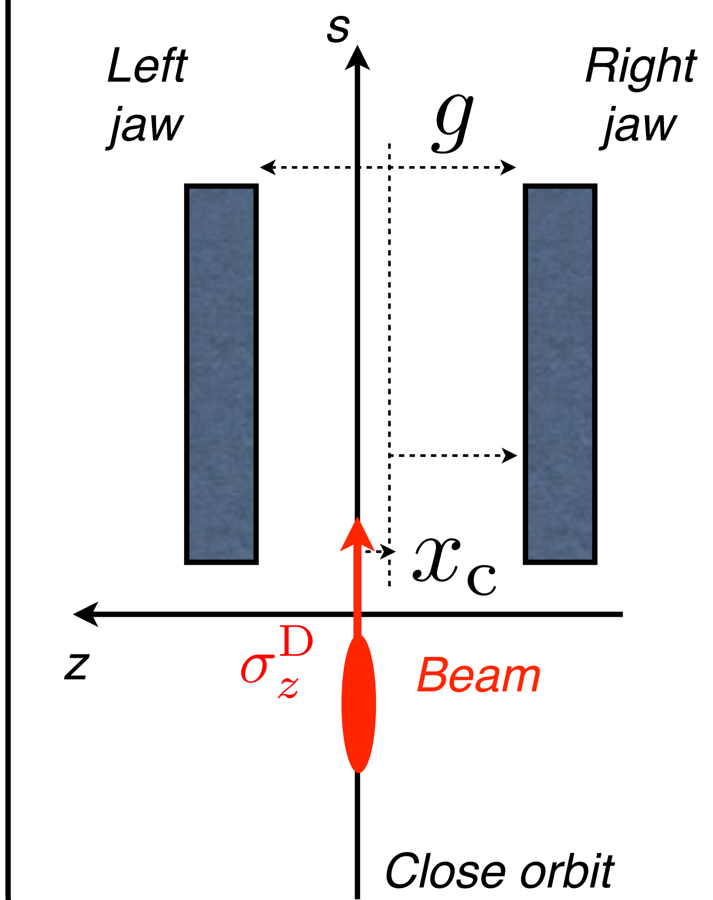
$\delta p/p$: RMS energy spread

g : collimator gap in millimeters

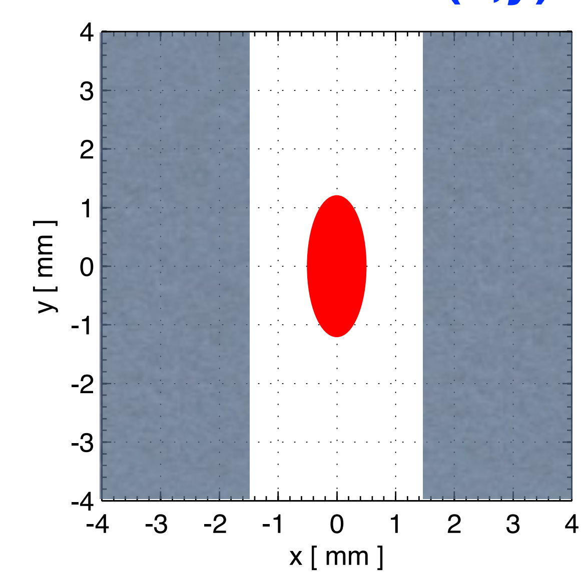
$$N_\sigma = \frac{g}{2}\frac{1}{\sigma_z}$$: **Normalized gap (beam size units)**

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

Top view (*x*,*s*)

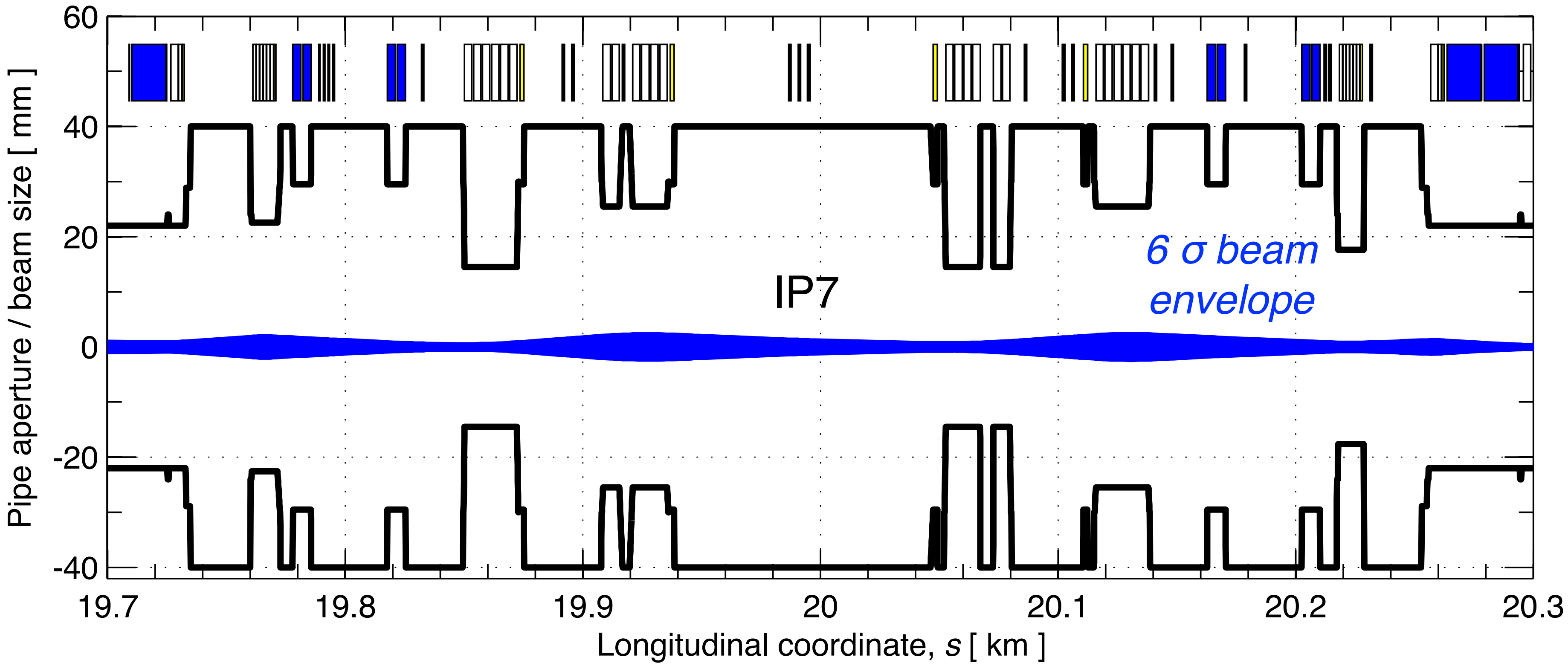


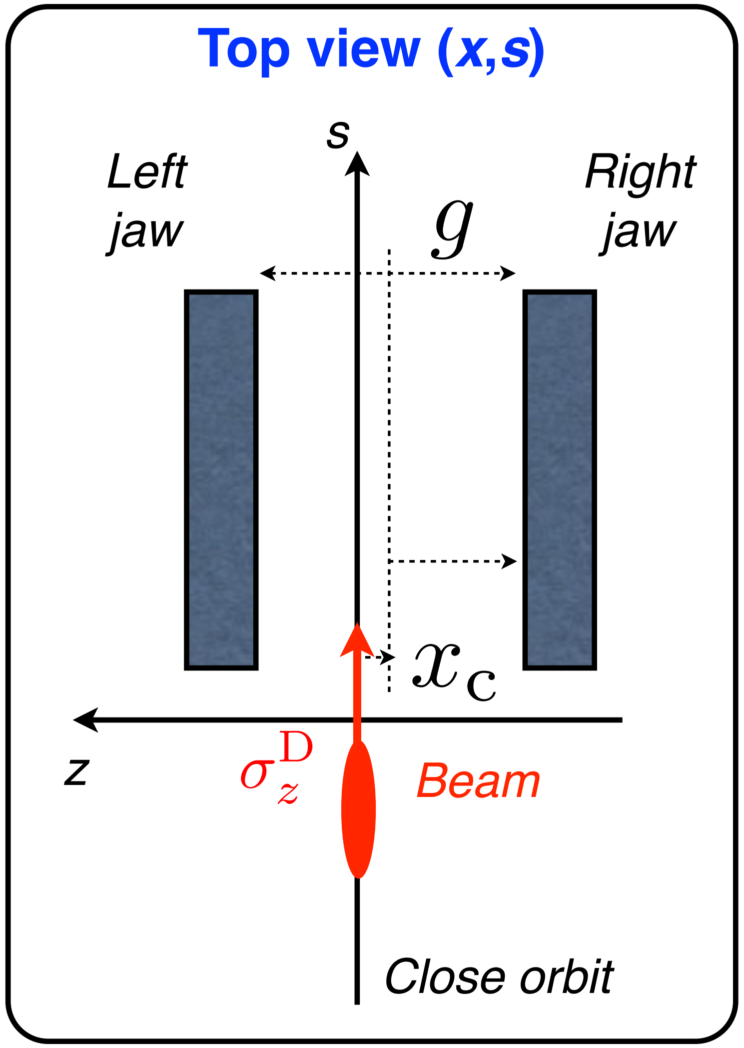
Front view (*x*,*y*)



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

Setting/aperture notations





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

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

$$\sigma_z = \sqrt{\beta_z \frac{\epsilon_z}{\gamma}}$$

: RMS *betatron* beam size

ϵ_z/γ : normalized emittance

D_z : dispersion function

$\delta p/p$: RMS energy spread

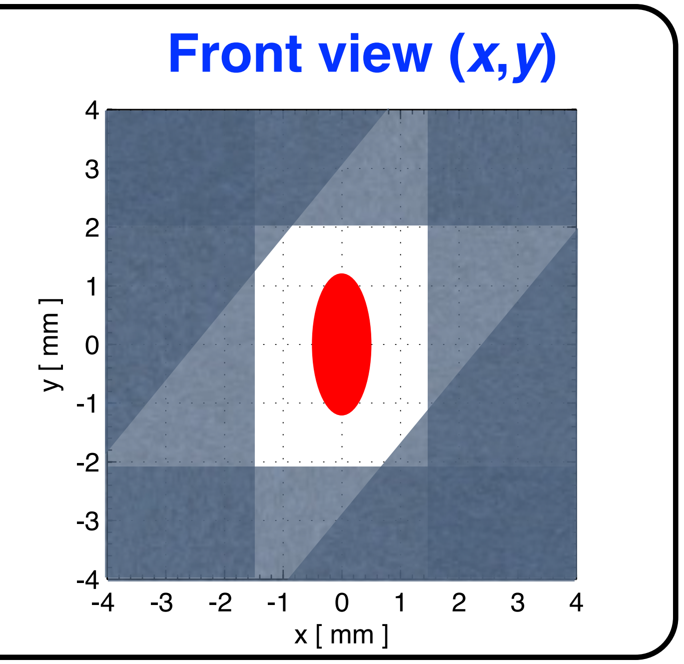
g : collimator gap in millimeters

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

: Normalized gap (beam size units)

$$x_c \pm N_\sigma \cdot \sigma_z$$

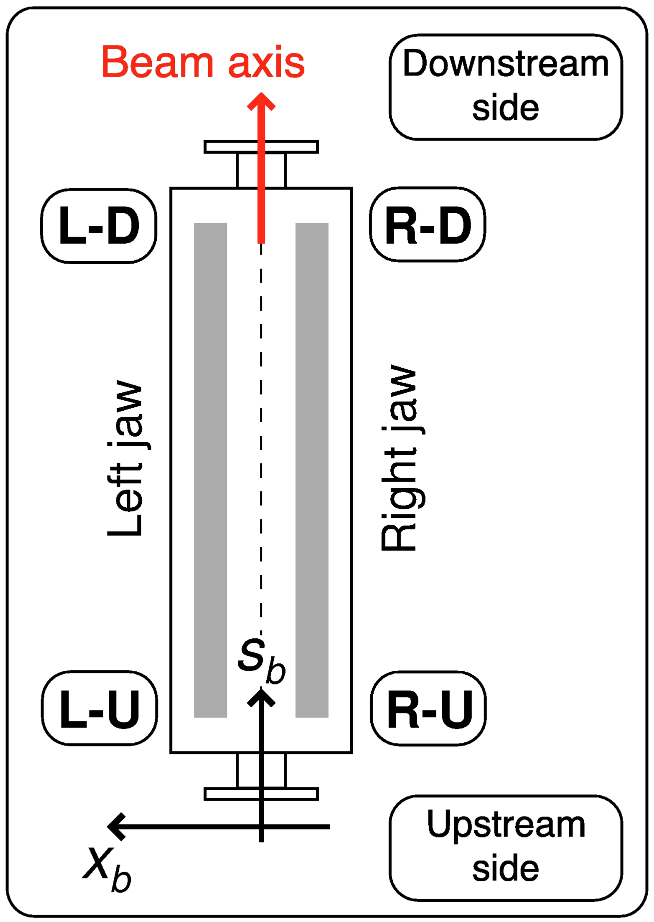
: Collimator jaw positions



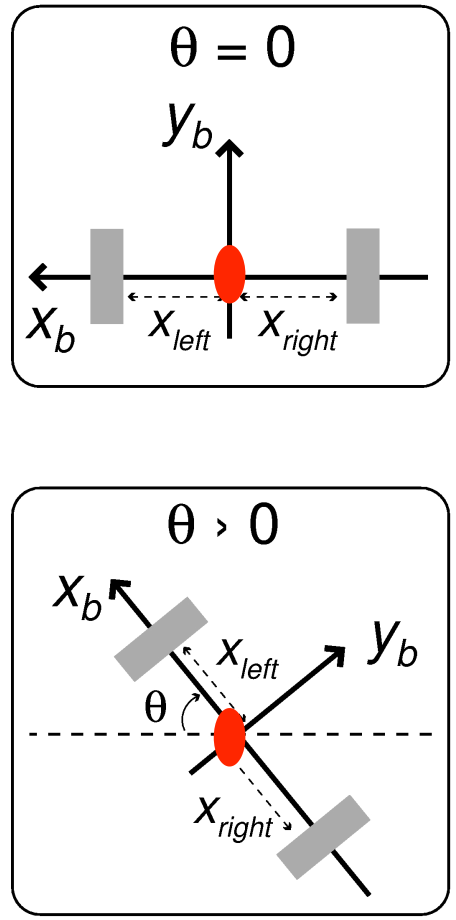
Collimator settings and aperture are expressed in normalized units, using the of local betatron beam size → enable to define the **setting "hierarchy"**!

"Skew" collimators

Top view



Front views

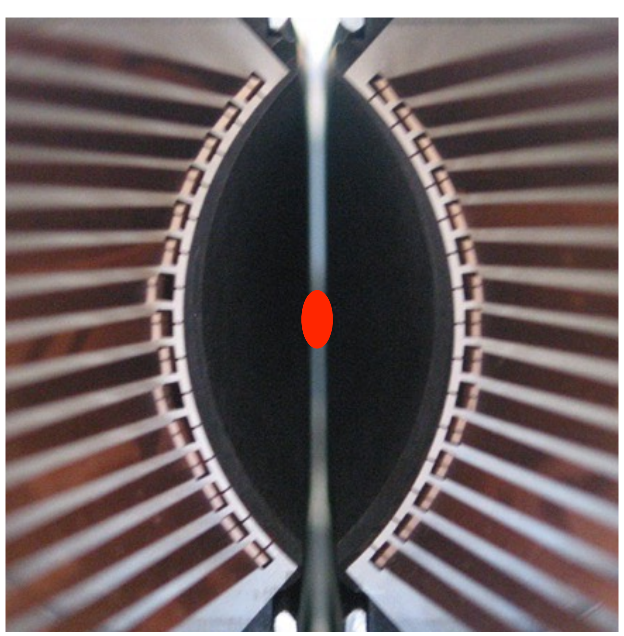


In the LHC, we also have "rotated" collimators that provide collimation in the ***skew plane.***
The collimator jaw movement occurs along the skew axis (still 1D movement). Normalized settings are defined for an appropriate effective beam size.
Same collimator design for all cases: rotate vacuum tank.

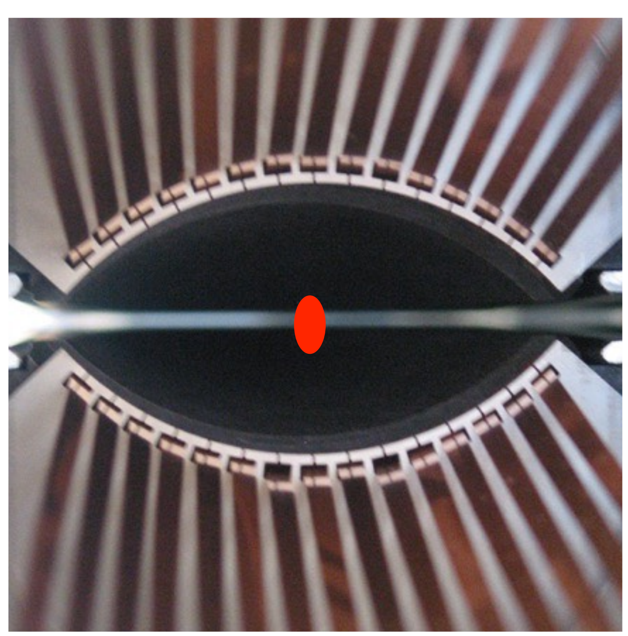
RMS *betatron* beam size in the collimator plane

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

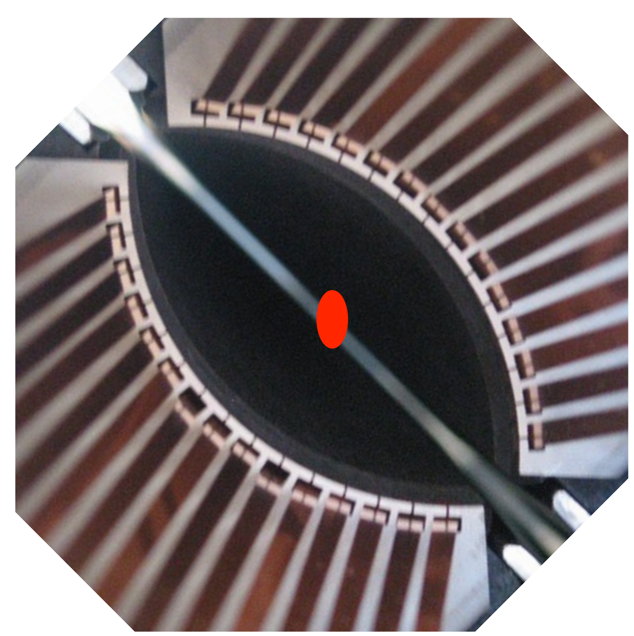
Horizontal



Vertical



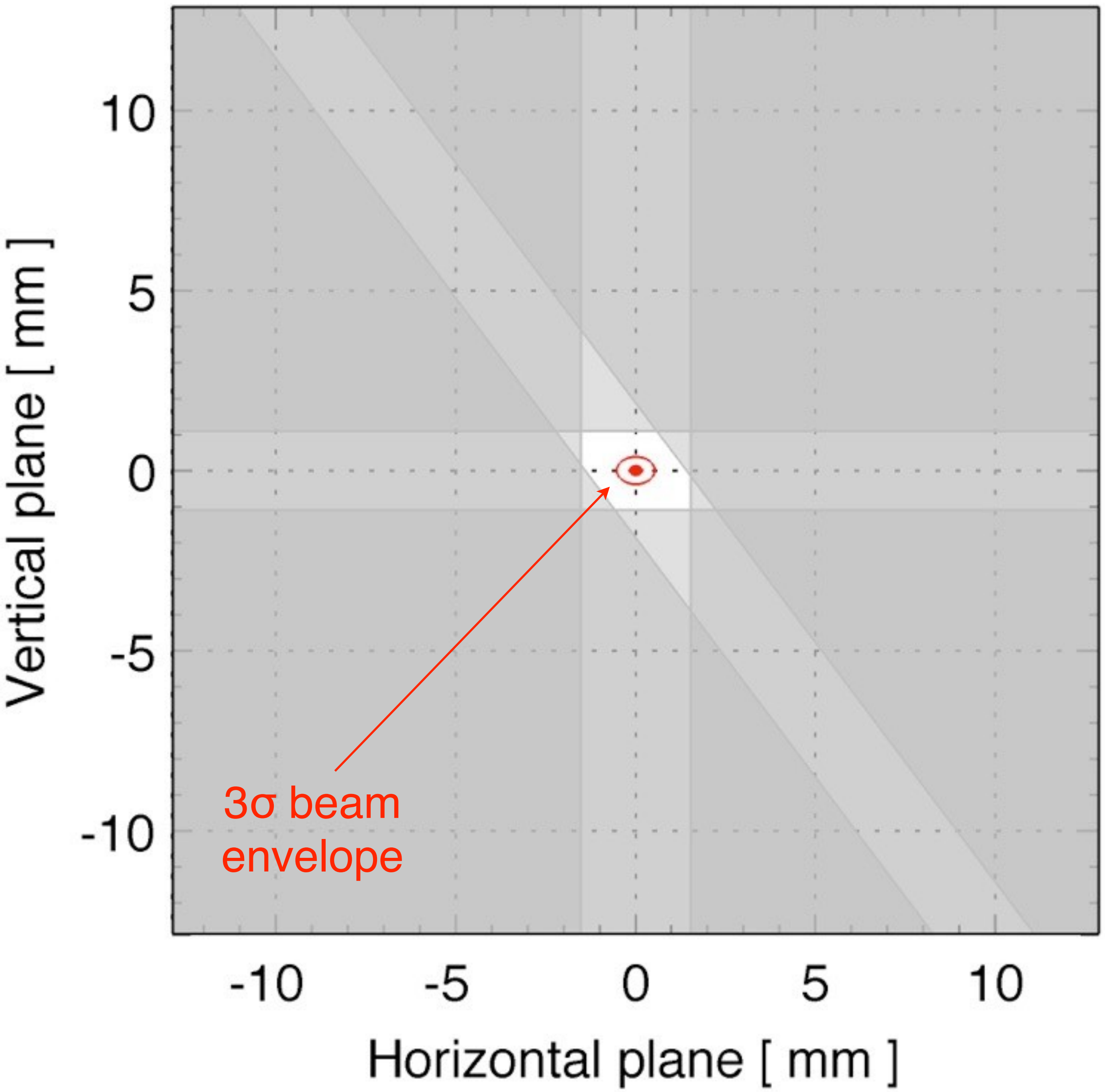
Skew



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

Smallest collimator gaps

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



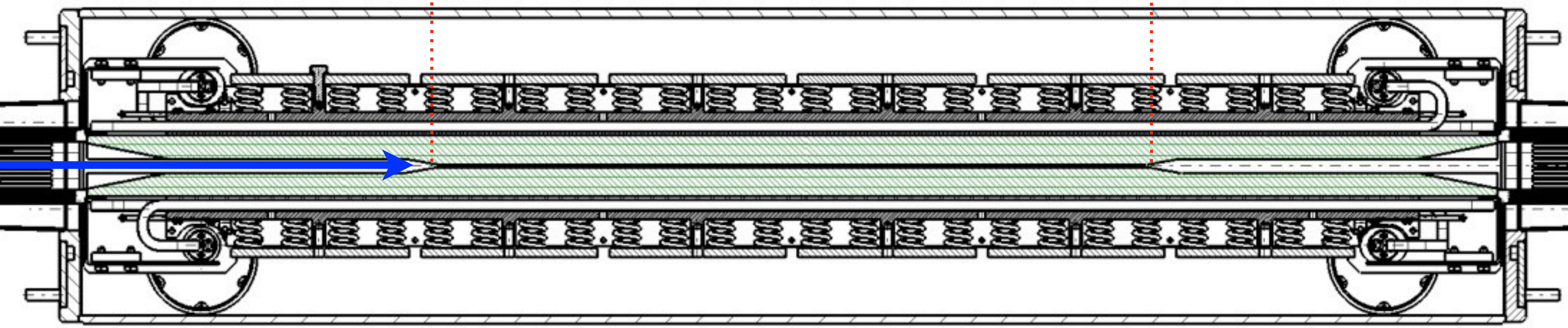
2€ coin

A beam carrying up to >400MJ passes more than 11000 per second in such small collimator gaps!

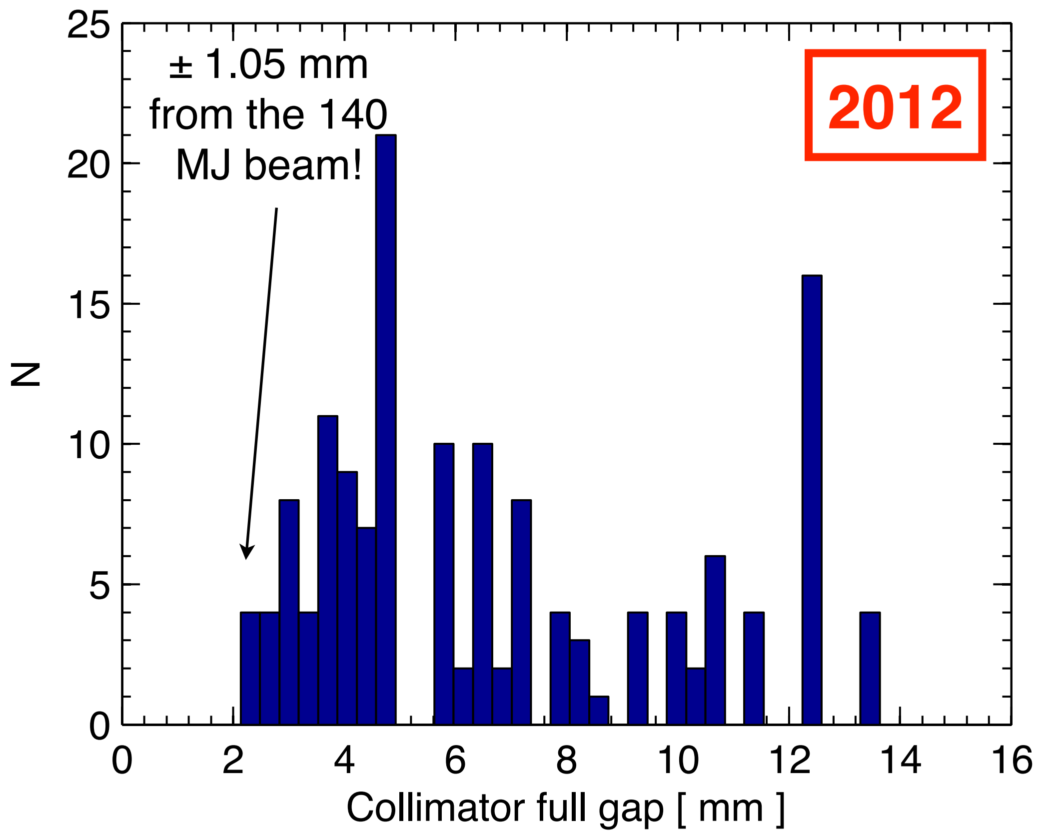
Side view of the vertical TCP

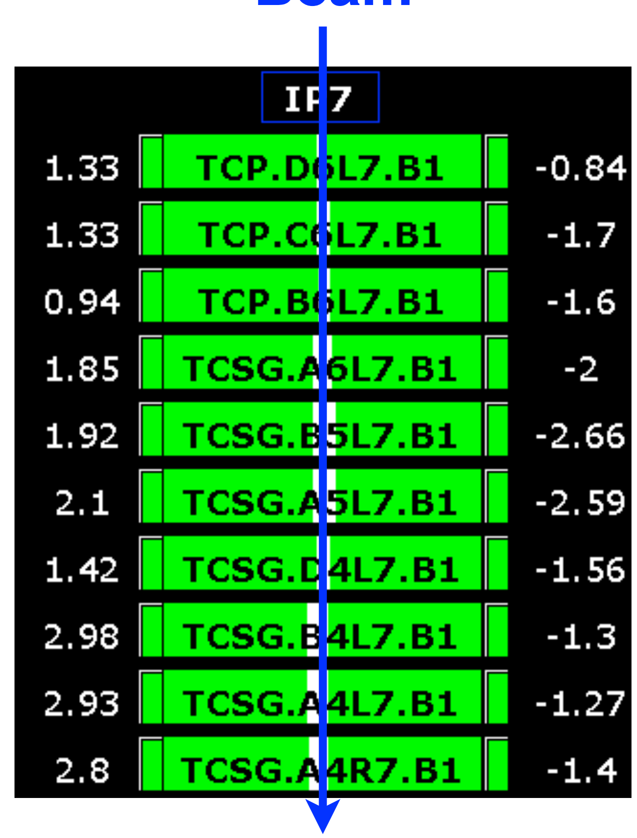
Beam: RMS beam size
σ_v = 250 microns!

60 cm flat active length, gap = ± 1.05 mm



Distribution of collimator gaps in 2012





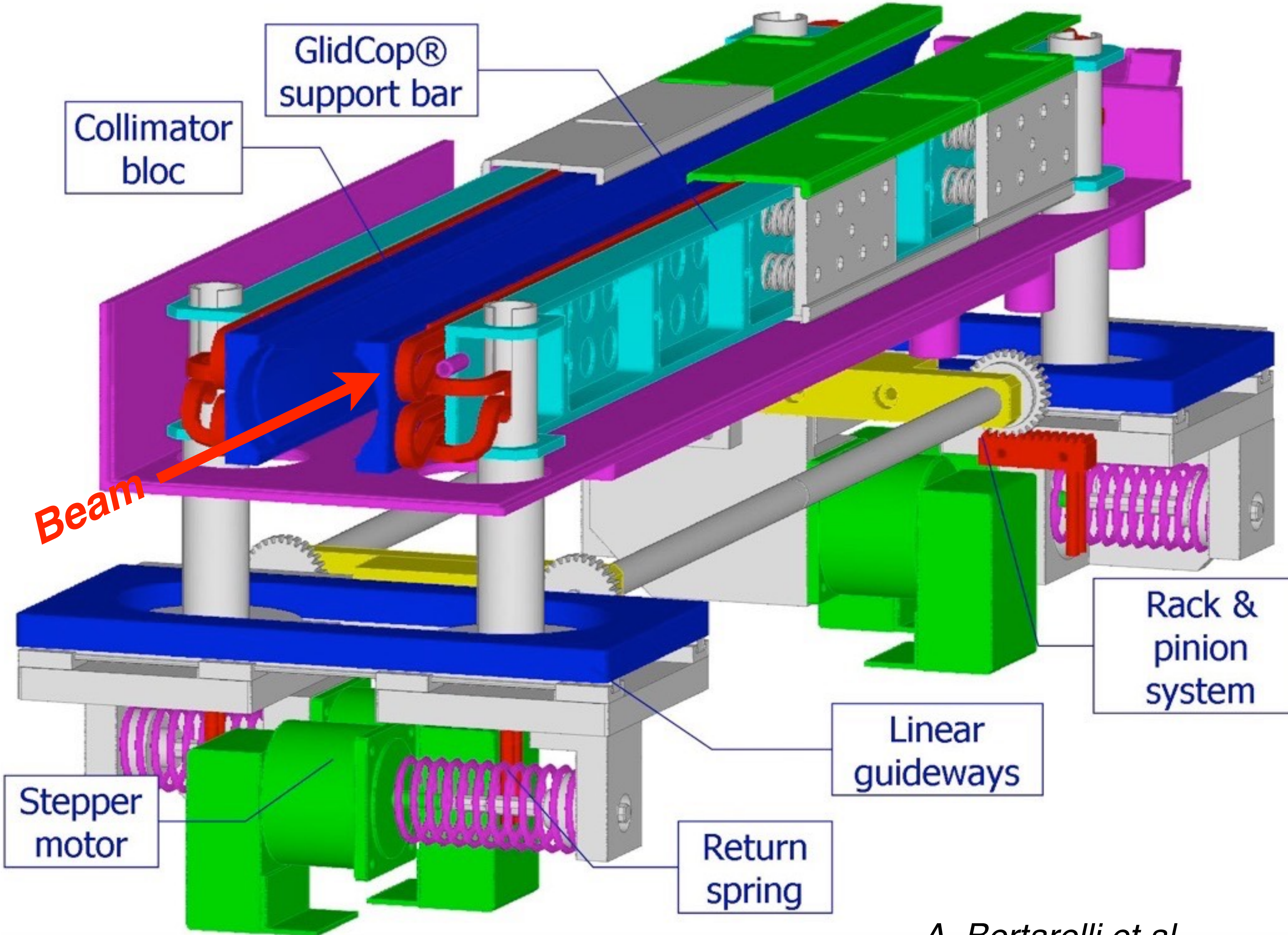
*Collimation **impedance** is a concern because of small gaps → rich R&D on collimation materials to minimise this.*

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

LHC collimator design

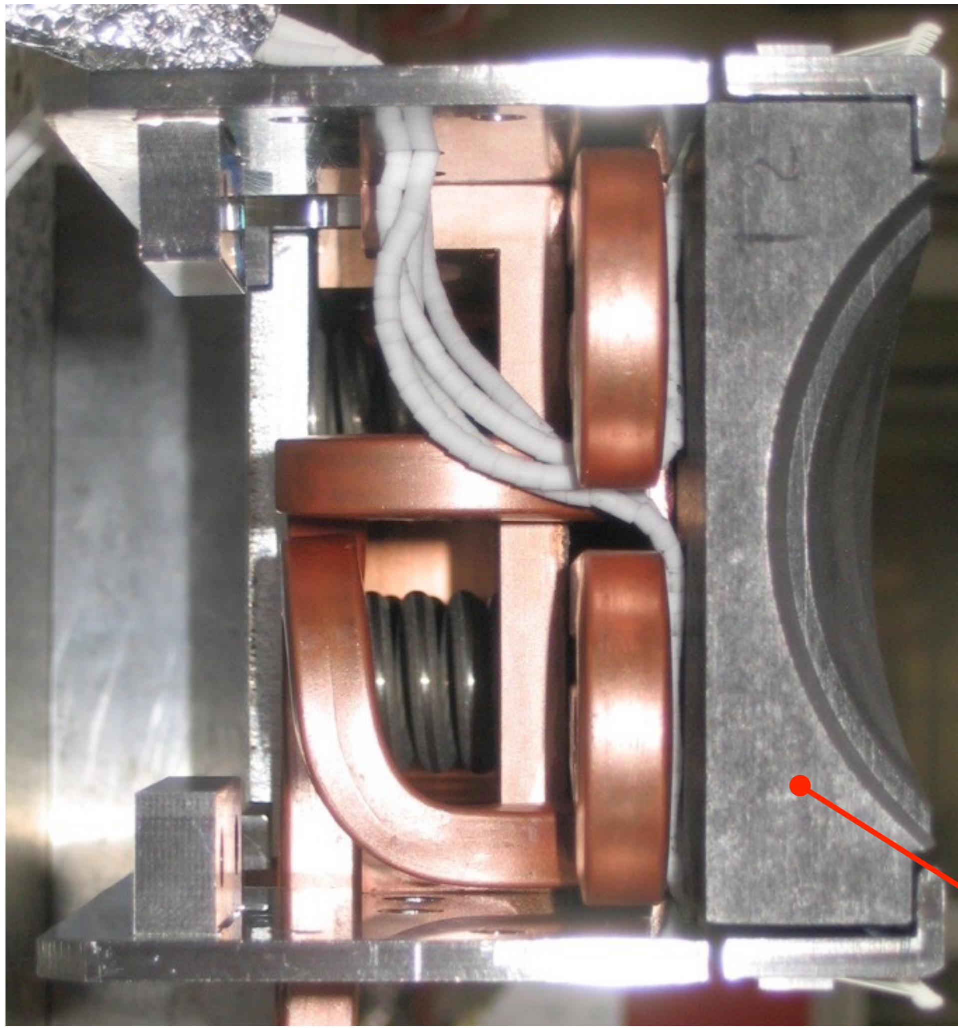
Main design features:

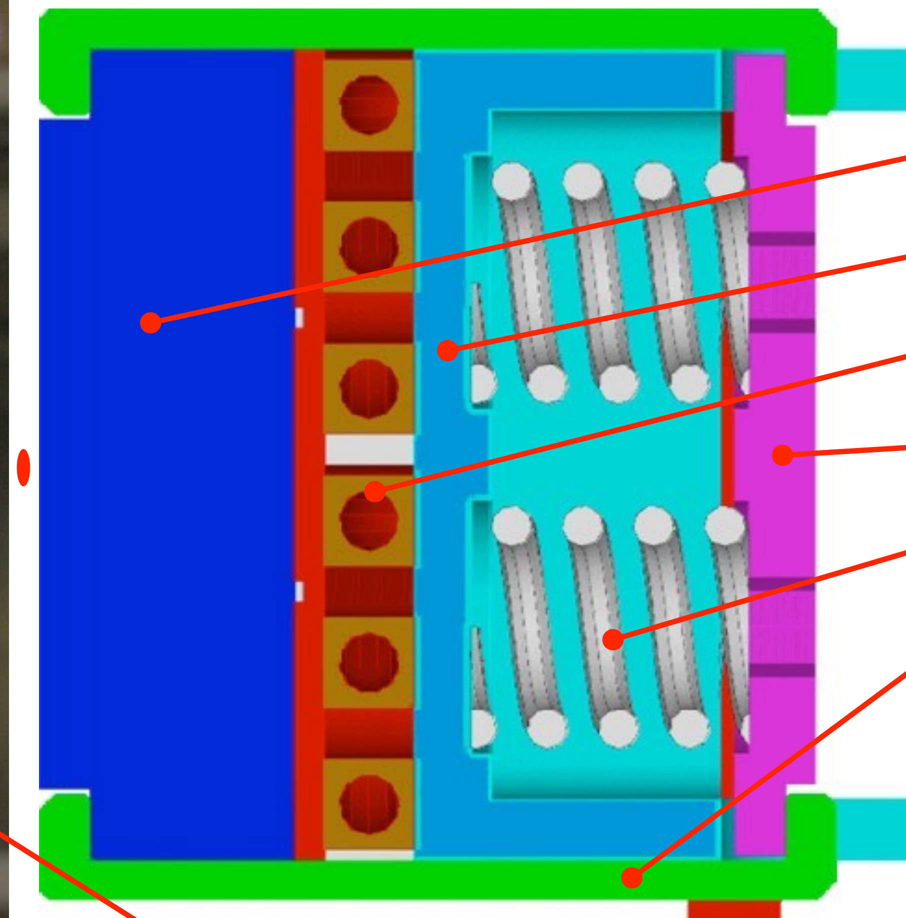
- Two jaws (position and angle)
- Concept of spare surface
- Different angles (H,V,S)
- External reference of jaw position
- Auto-retraction
- RF fingers
- Jaw cooling



A. Bertarelli et al.

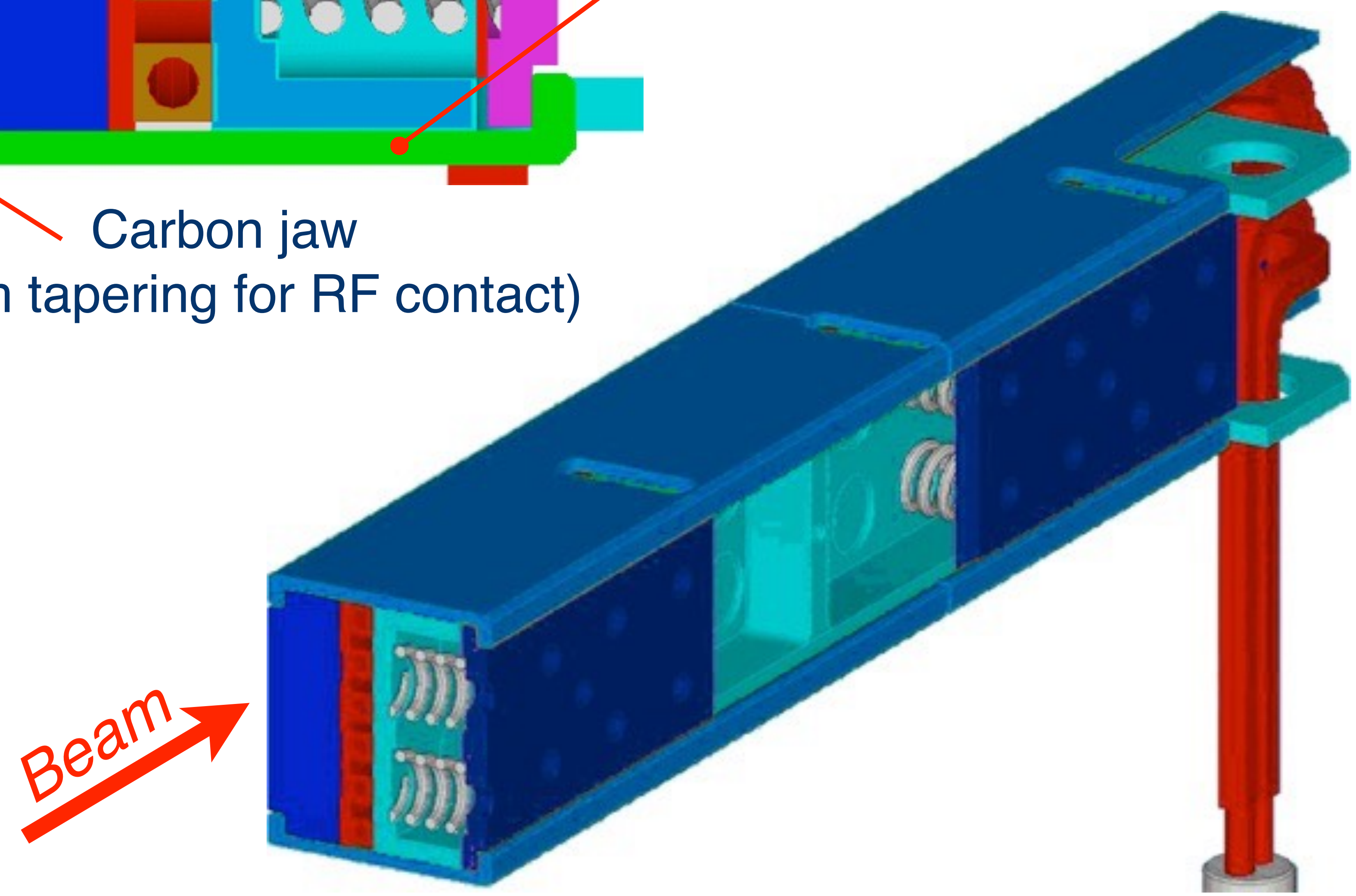
LHC collimator "jaw"



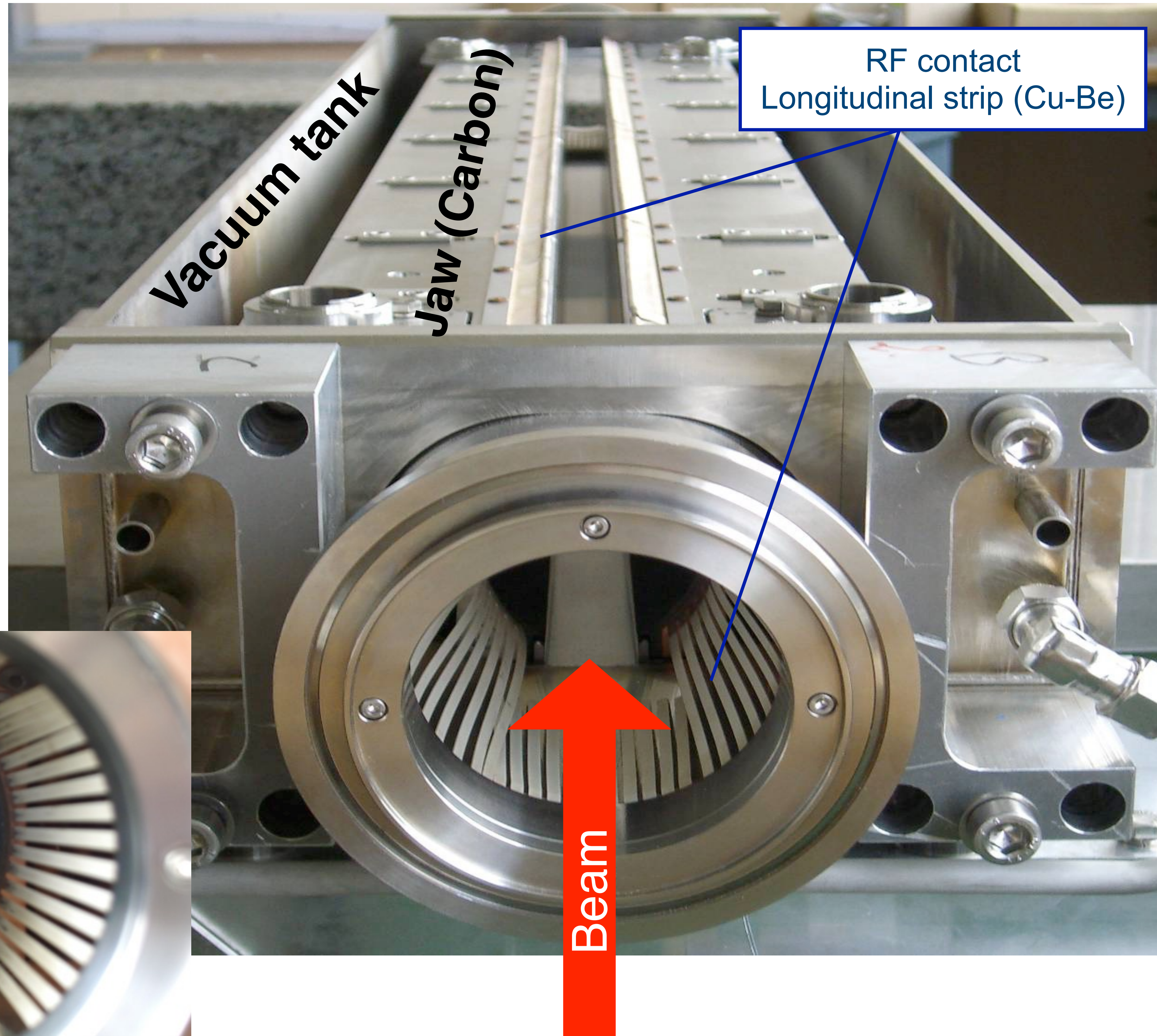


Carbon jaw
(10cm tapering for RF contact)

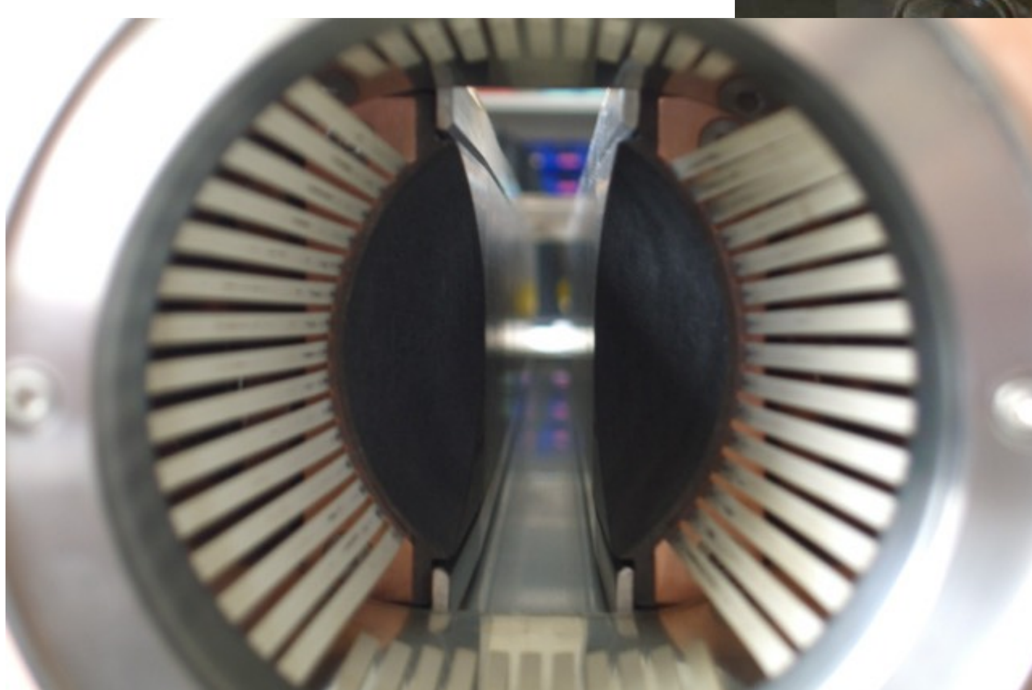
Special "sandwich" design to minimize the thermal deformations:
Steady (~5 kW) ➙ < 30 μm
Transient (~30 kW) ➙ ~ 110 μm
Materials: Graphite, Carbon fibre composites, Copper, Tungsten.



A look inside the vacuum tank



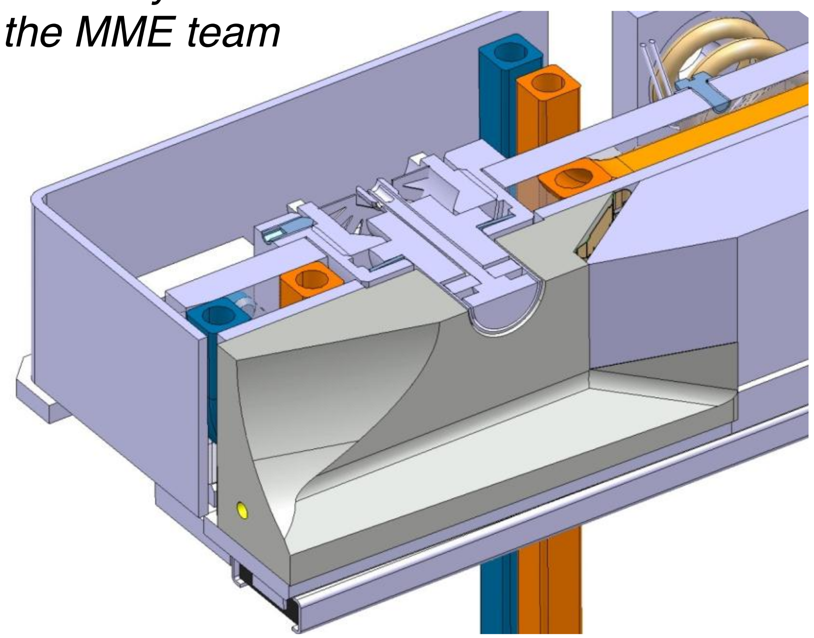
What the beam sees!

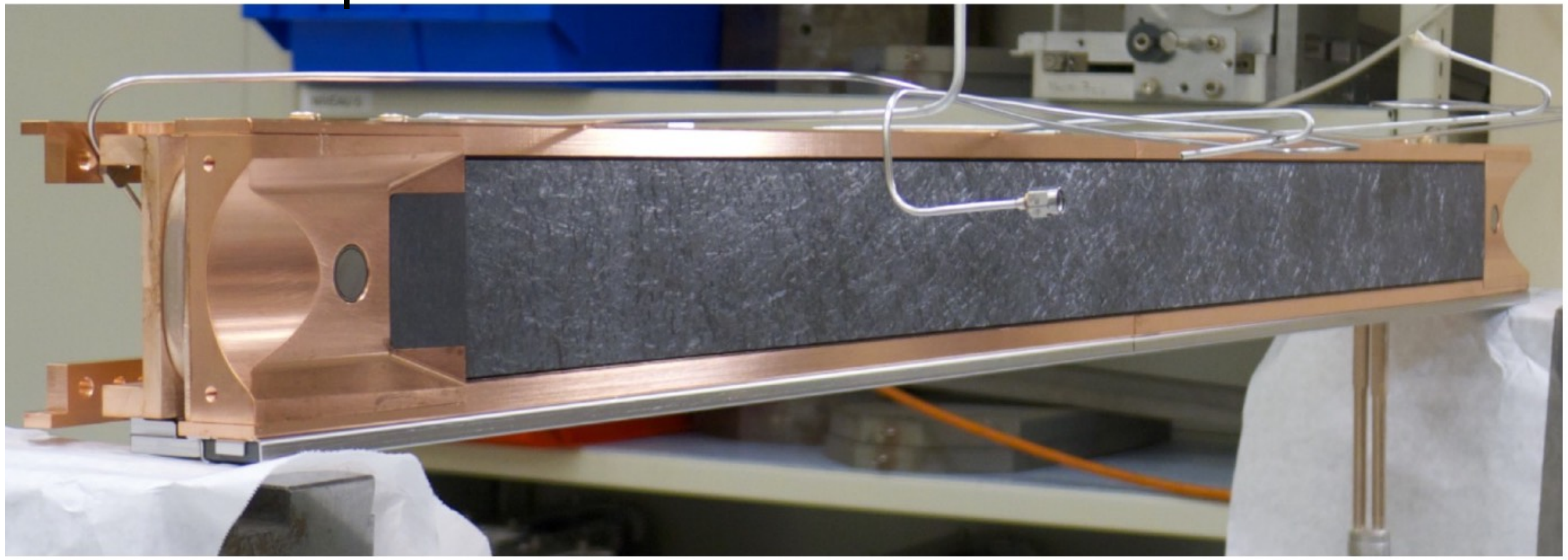


Newest design: in-jaw BPMs!

BPM: beam position monitor

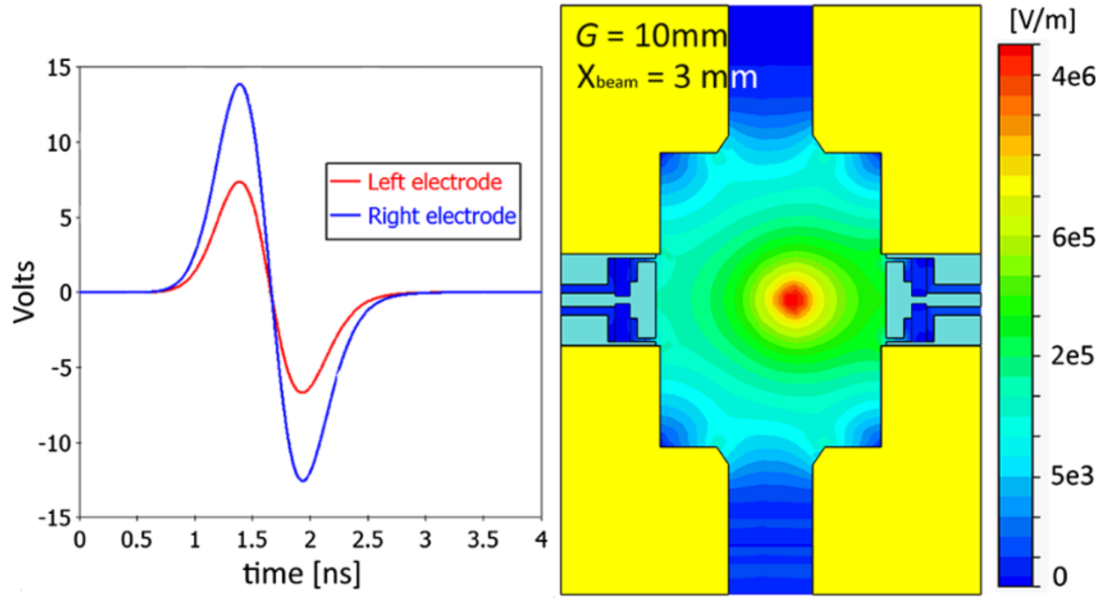
Courtesy of A. Dallocchio for the MME team

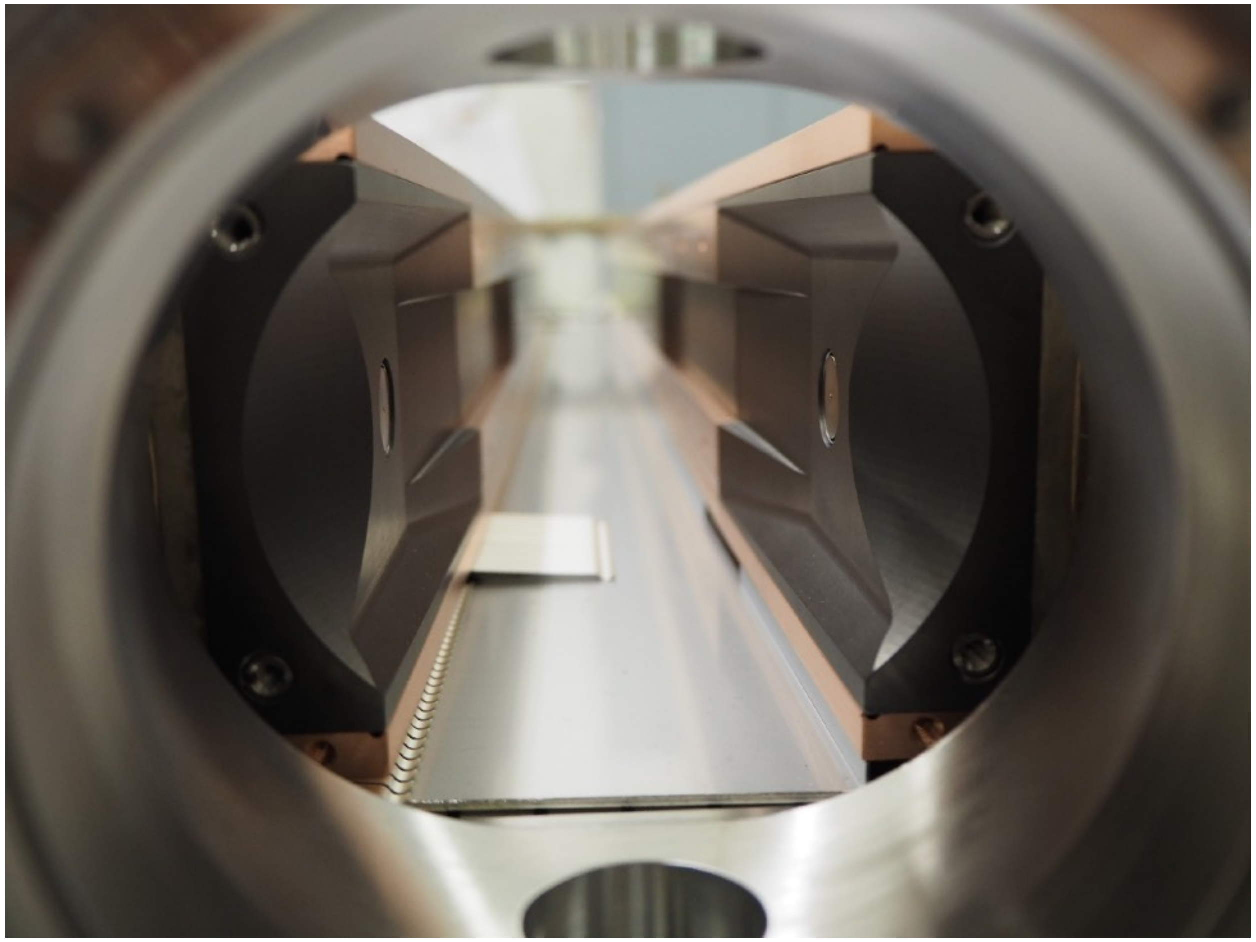




Aims:

- Faster & precise alignment to the circulating beam: crucial for operation at small gaps (see above)
- continuous orbit monitoring.





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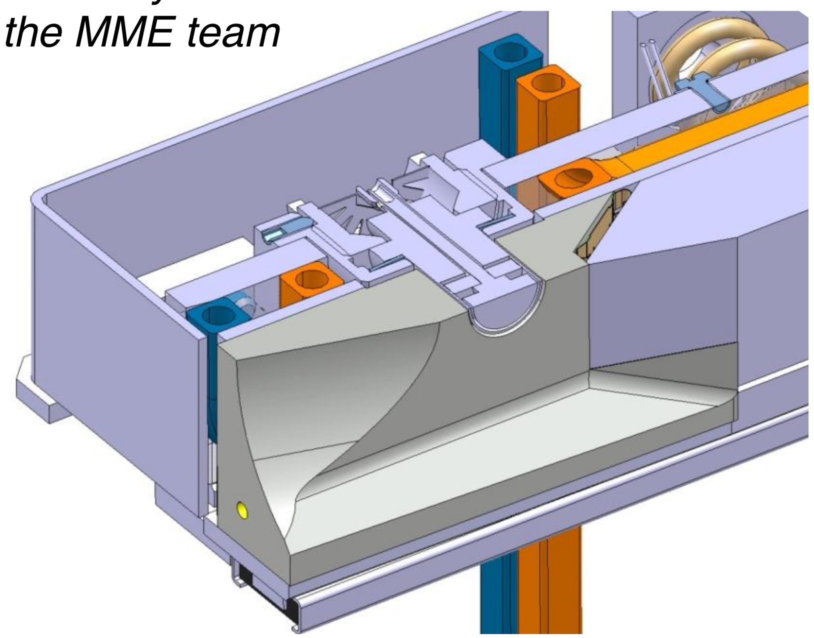

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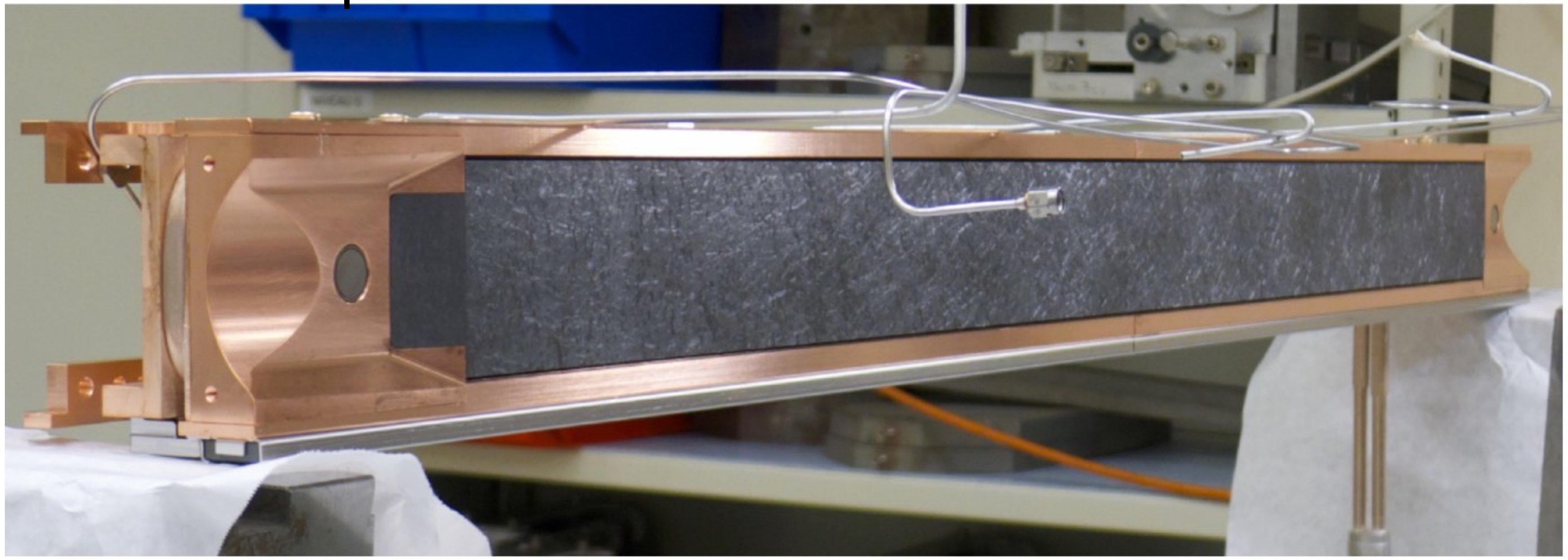

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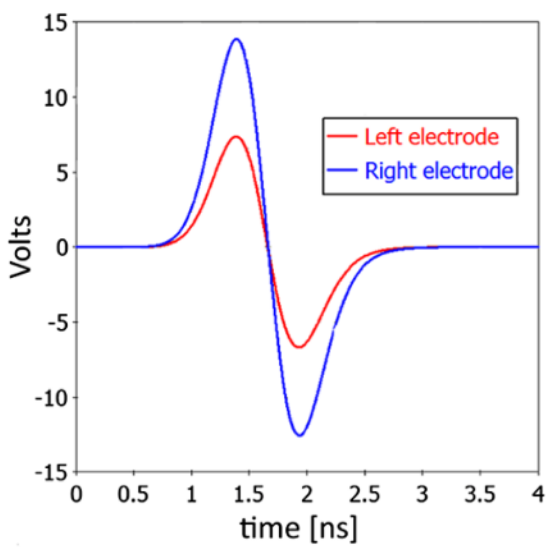
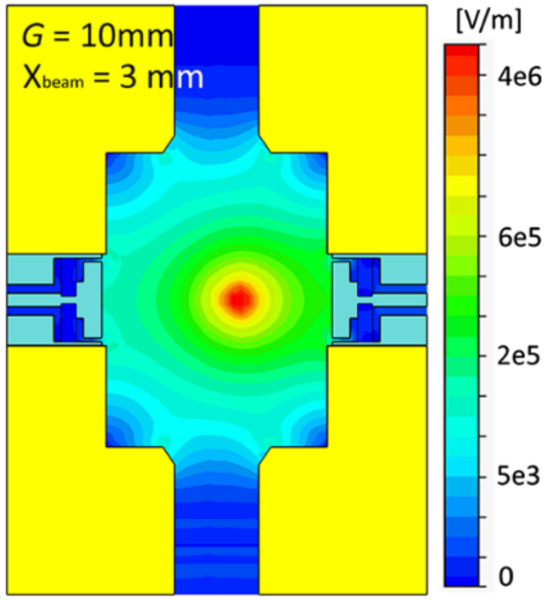
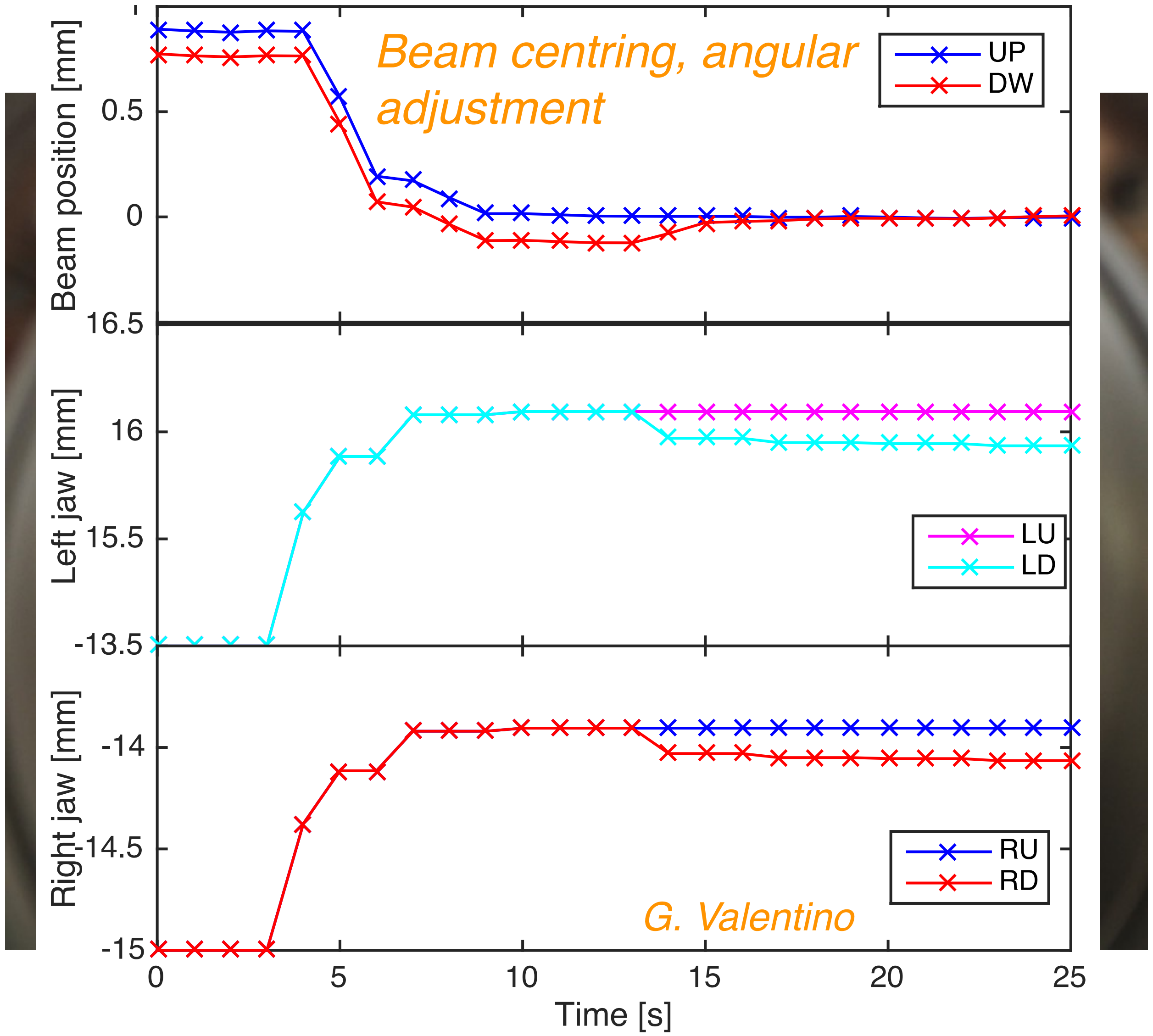
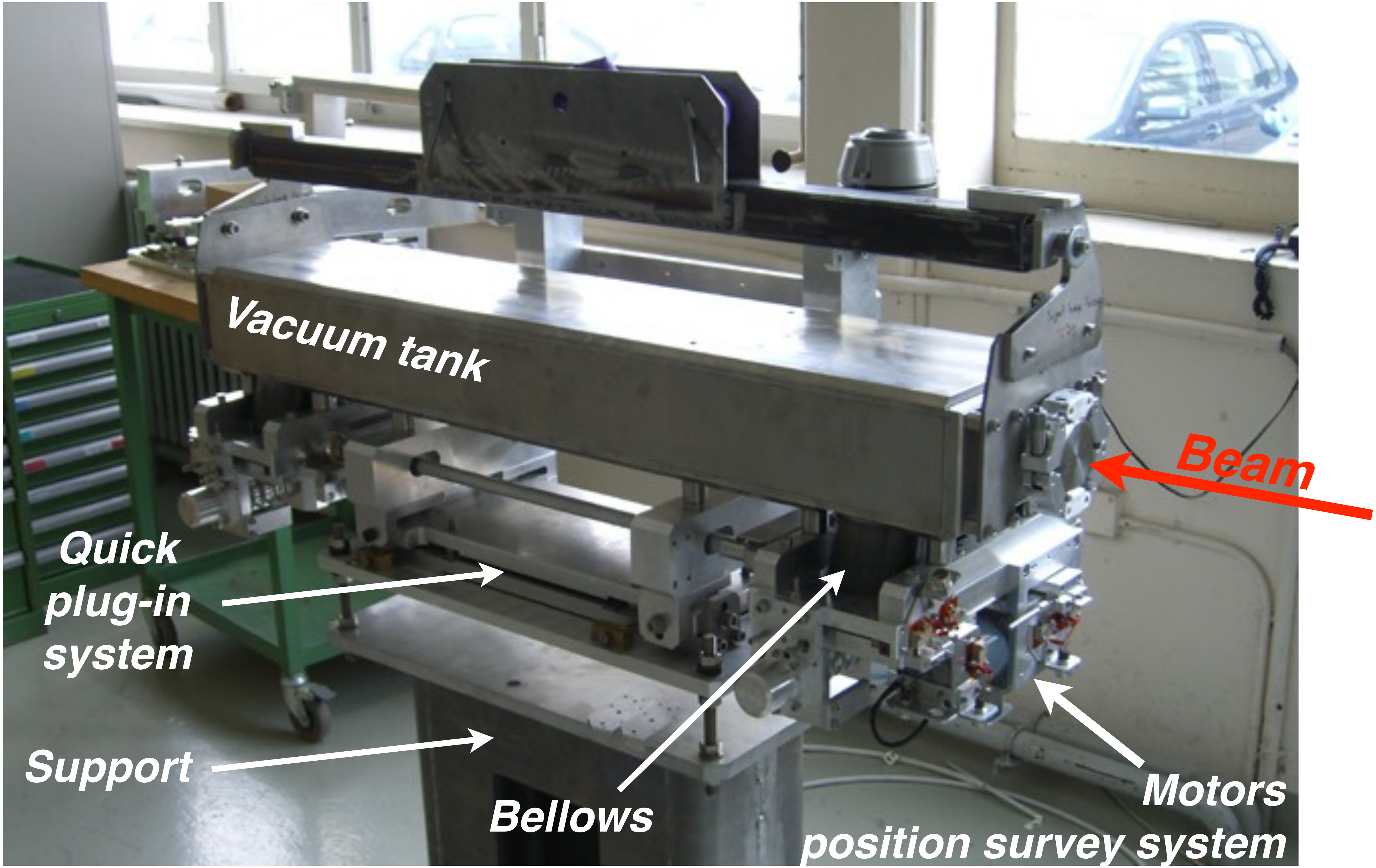


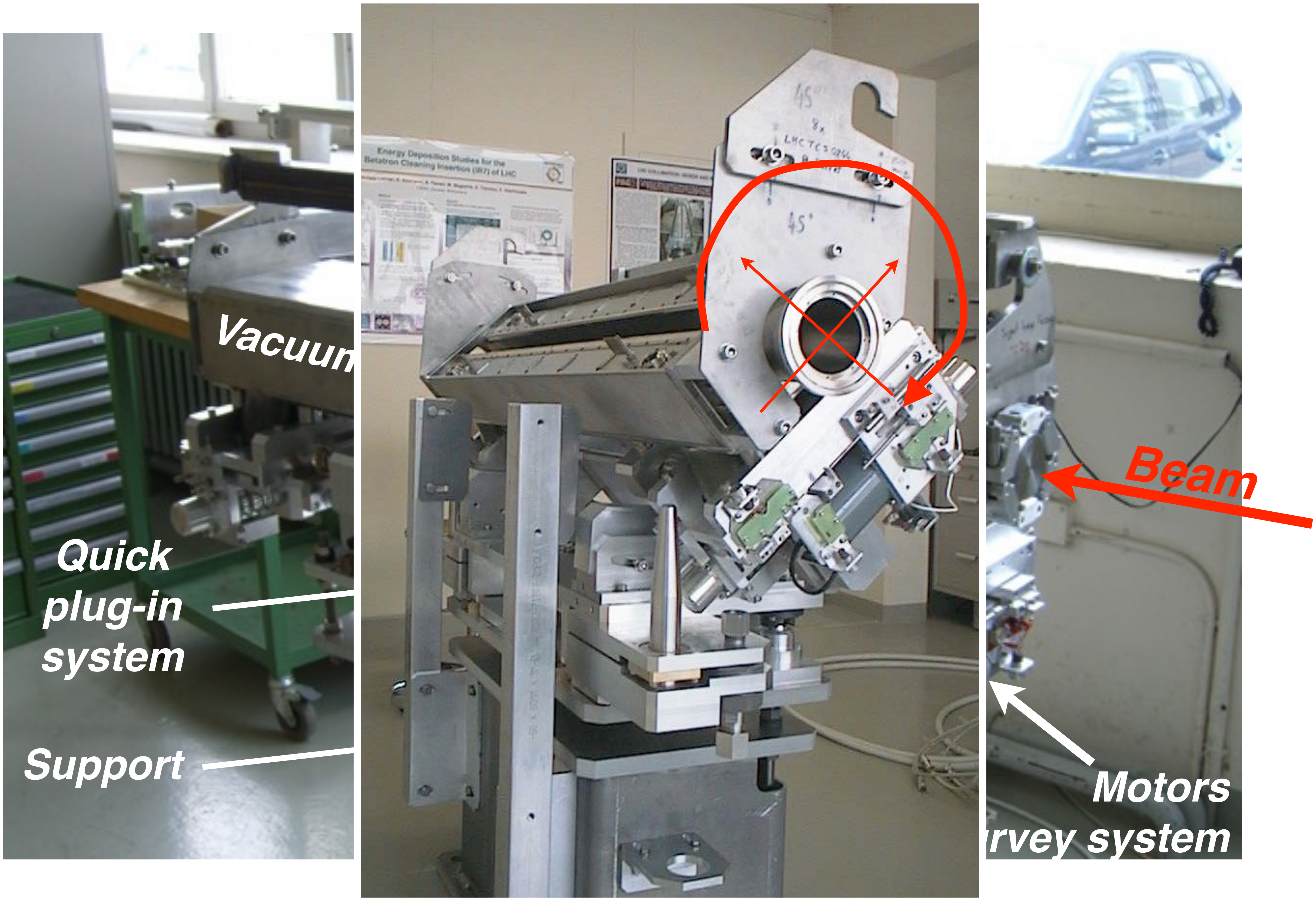


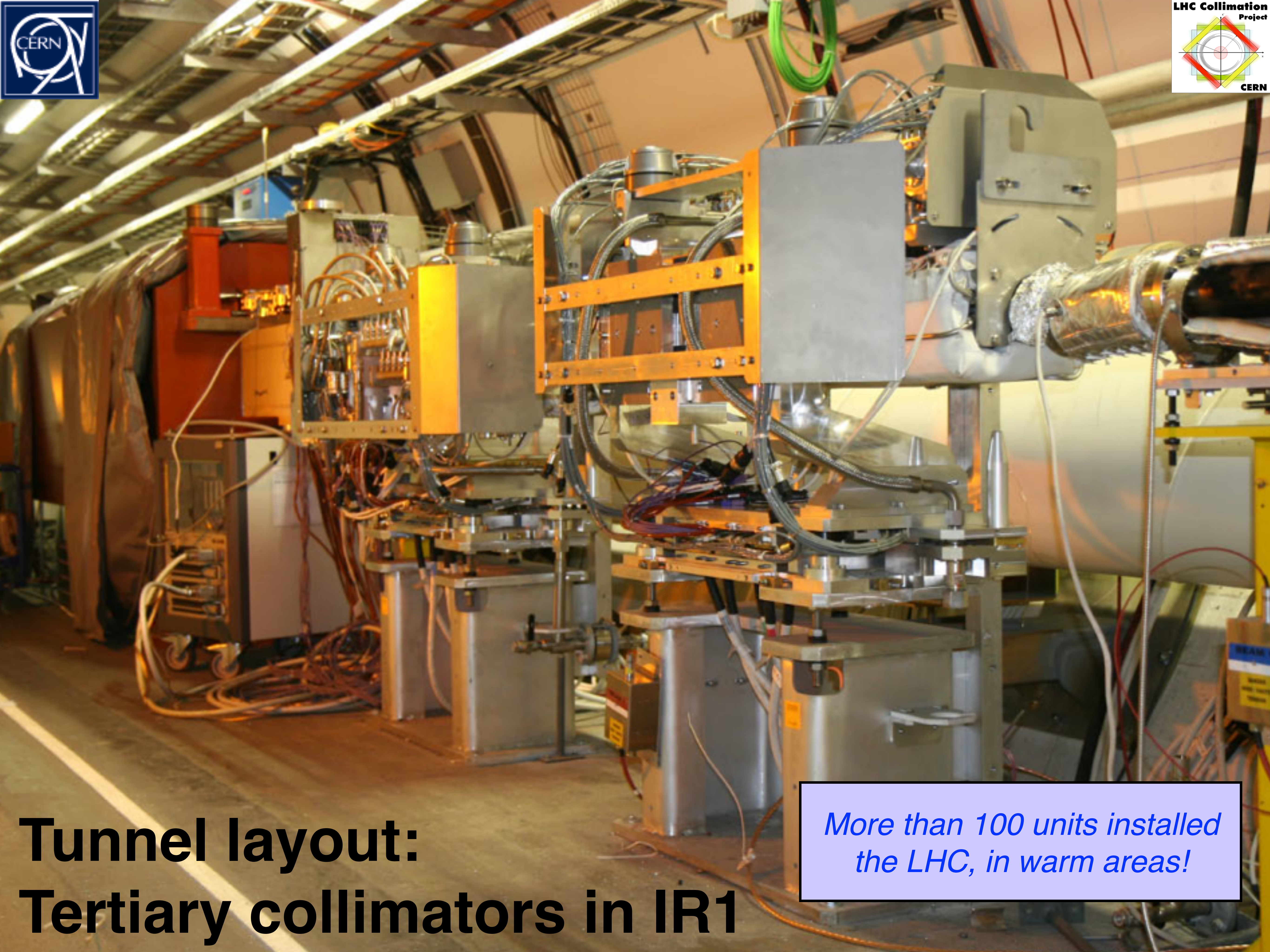


Complete collimator assembly



Complete collimator assembly

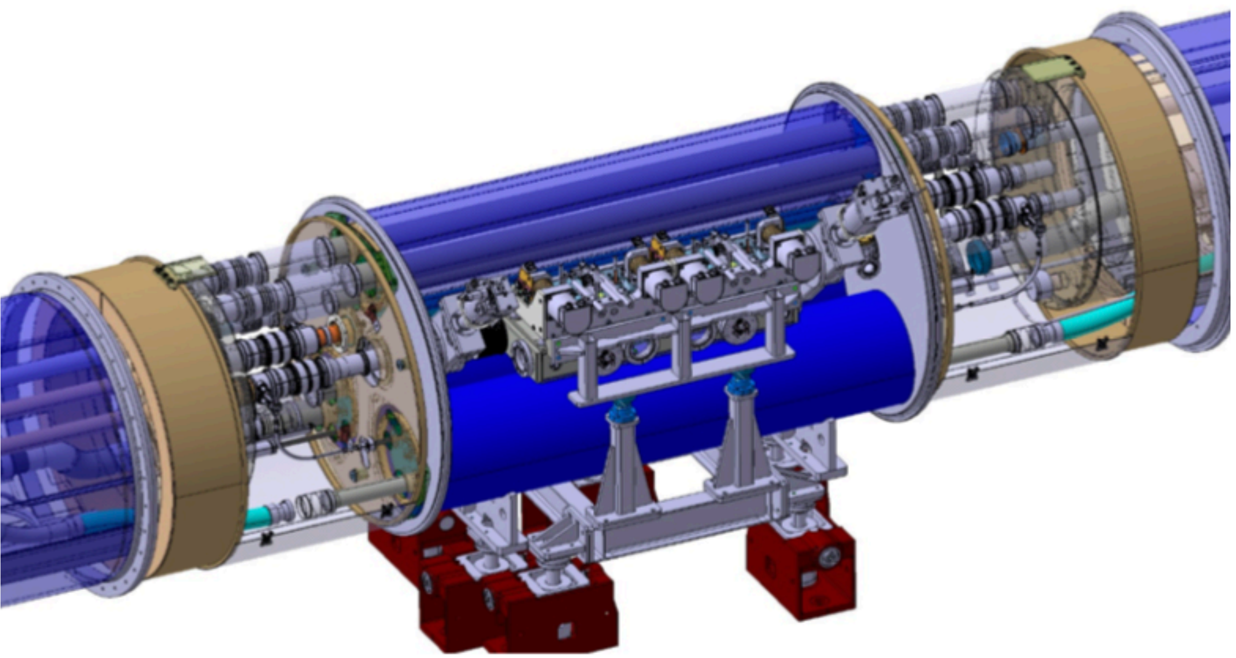


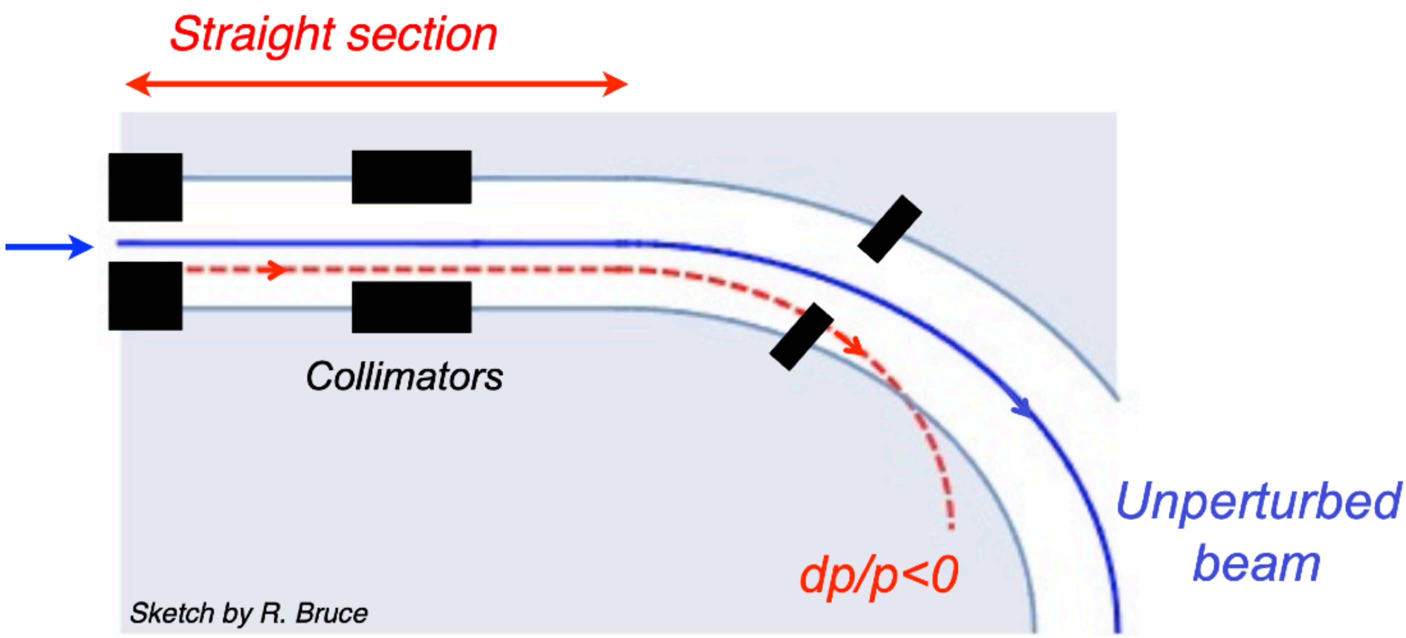


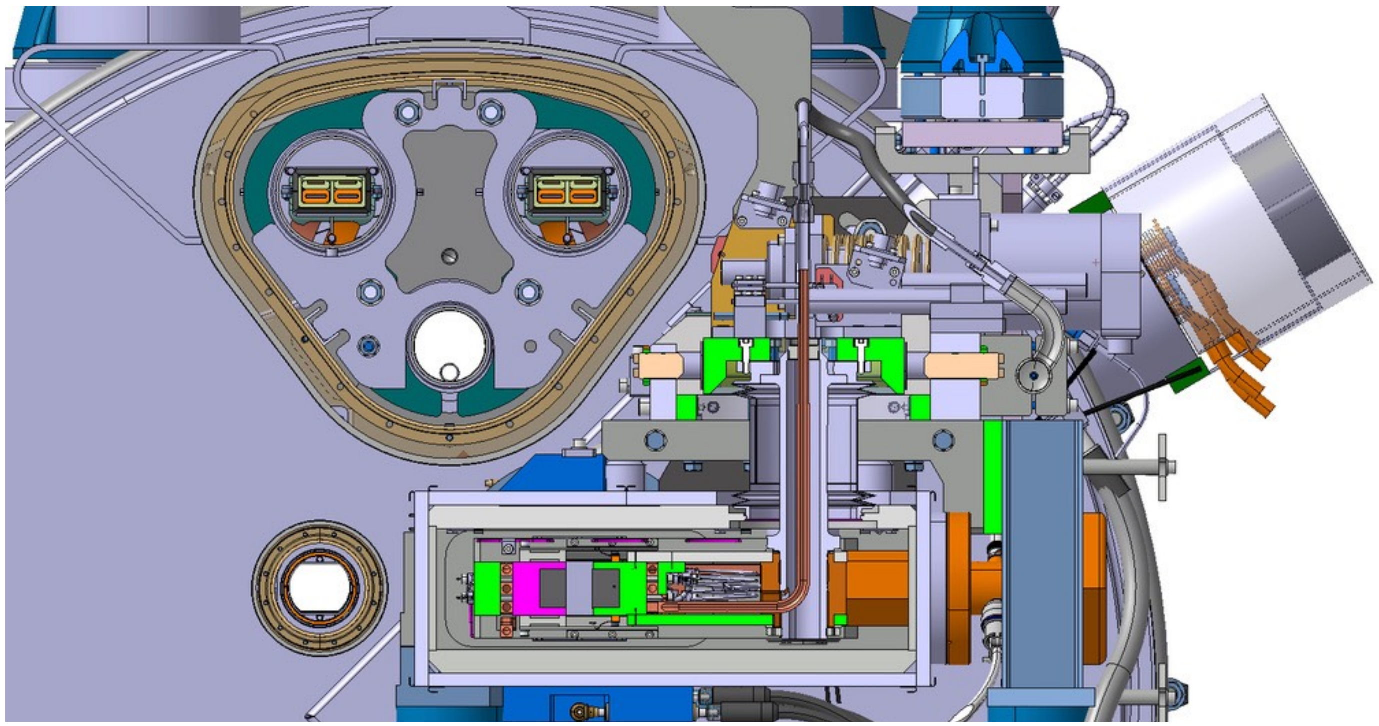
Tunnel layout: Tertiary collimators in IR1

More than 100 units installed the LHC, in warm areas!

Special collimation design — TCLD

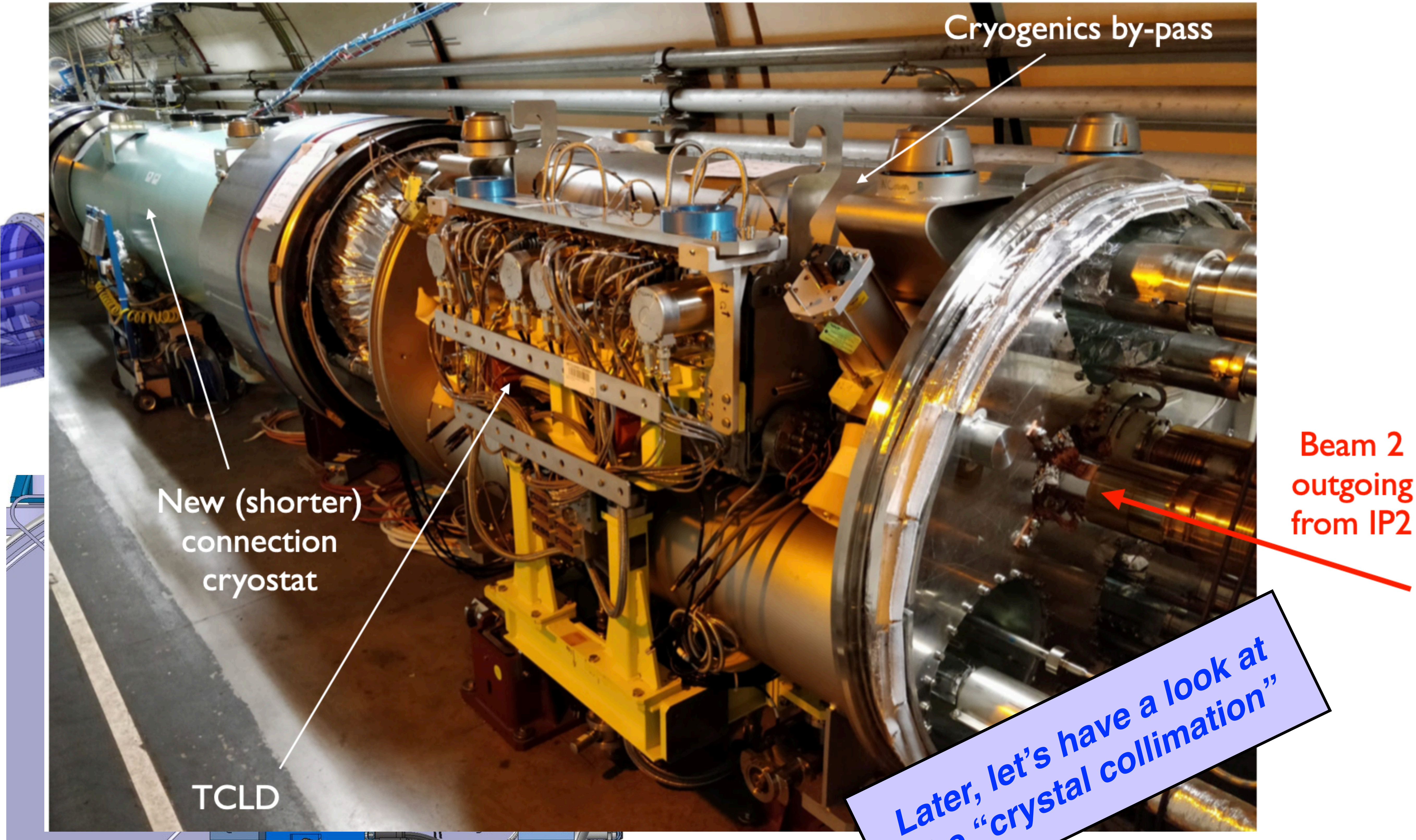






Special design of a warm collimator in the cold region to cure local losses at the "dispersion suppressors" at the beginning of the LHC arcs.

Special collimation design — TCLD



Later, let's have a look at the "crystal collimation"

Outline

- **Introduction**
- **Accelerator physics concepts**
  - Recap. of betatron motion
  - “Aperture” in a circular accelerator
- **Beam collimation**
  - The beam stored energy challenge
  - Beam losses and cleaning requirements
  - Design of a beam halo collimation system
  - The LHC collimation system
- **Collimation design and performance**
  - Design of the LHC collimators
  - **Collimation system in operation**
  - **Simulations and measurements**
- **Crystal collimation**

Collimation hierarchy

LHC collimation fixed display

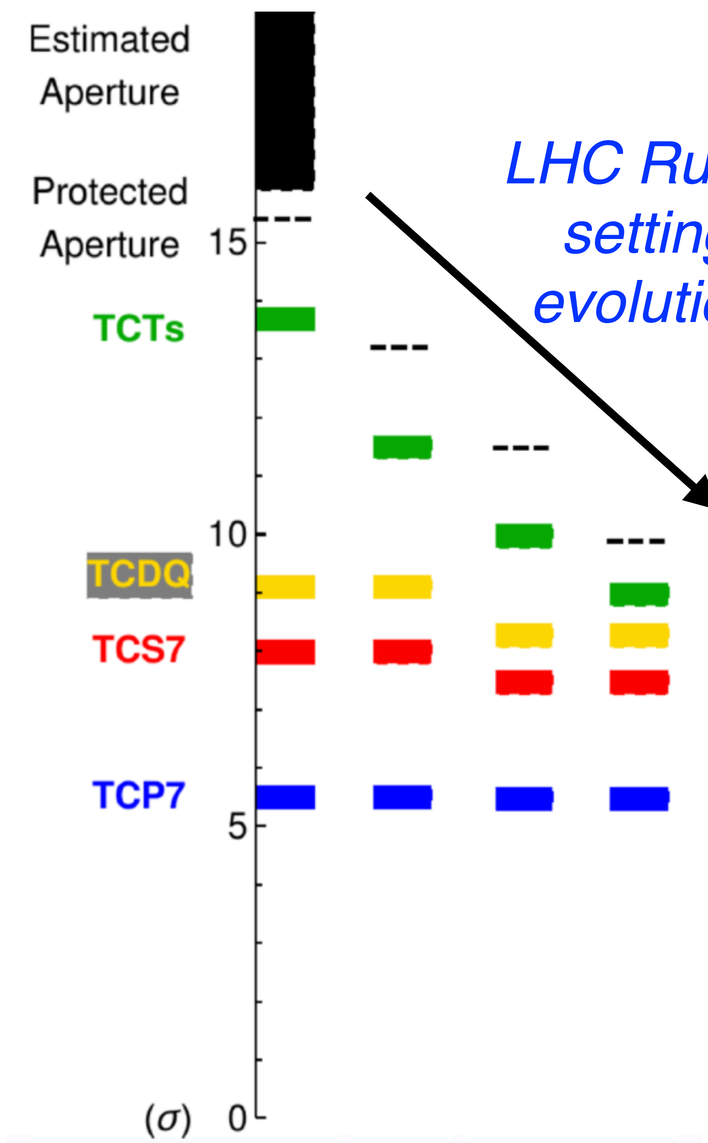
HW GROUP: COLLIMATORS_VISTAR_B1 — Beam Mode: ADJUST — Energy: 6800 GeV

MDC PRS	L (mm)	IR1	R (mm)
	8.75	TCTPH.4L1.B1	-8.11
	7.48	TCTPV.4L1.B1	-4.79
	25.00	TCL.4R1.B1	-25.00
	25.00	TCL.5R1.B1	-25.00
	24.98	TCL.6R1.B1	-25.01
MDC PRS	L (mm)	IR2	R (mm)
	5.33	TCTPH.4L2.B1	-5.20
	4.57	TCTPV.4L2.B1	-6.93
	53.43	TDISA.A4L2.B1	-53.58
	53.41	TDISB.A4L2.B1	-53.46
	53.50	TDISC.A4L2.B1	-53.50
	20.45	TCDD.4L2	-20.51
	27.98	TCLIA.4R2	-27.98
	24.83	TCLIB.6R2.B1	-24.99
	20.00	TCLD.A11R2.B1	-20.03
MDC PRS	L (mm)	IR3	R (mm)
	4.10	TCP.6L3.B1	-3.49
	3.05	TCSG.5L3.B1	-2.82
	1.74	TCSG.4R3.B1	-2.26

MDC PRS	L (mm)	Collimator	R (mm)
	2.42	TCSG.A5R3.B1	-2.85
	2.51	TCSG.B5R3.B1	-3.39
	6.03	TCLA.A5R3.B1	-5.63
	4.98	TCLA.B5R3.B1	-5.86
	5.21	TCLA.6R3.B1	-4.80
	3.81	TCLA.7R3.B1	-3.29
MDC PRS	L (mm)	IR5	R (mm)
	8.06	TCTPH.4L5.B1	-8.81
	6.28	TCTPV.4L5.B1	-6.01
	25.00	TCL.4R5.B1	-25.00
	24.99	TCL.5R5.B1	-24.99
	25.00	TCL.6R5.B1	-25.01
MDC PRS	L (mm)	IR6	R (mm)
	3.70	TCDQA.A4R6.B1	
	3.77	TCSP.A4R6.B1	-3.59
MDC PRS	L (mm)	IR7	R (mm)
	1.20	TCP.D6L7.B1	-0.68
	1.58	TCP.C6L7.B1	-1.02
	1.32	TCP.B6L7.B1	-0.84
	1.58	TCSG.A6L7.B1	-1.40

	L (mm)	Collimator	R (mm)
	63.89	TCPCV.A6L7.B1	Closed
	1.94	TCSG.B5L7.B1	-1.72
	2.12	TCSG.A5L7.B1	-1.58
	1.11	TCSG.D4L7.B1	-1.30
	58.28	TCPCH.A4L7.B1	Closed
	22.97	TCSG.B4L7.B1	-22.97
	1.93	TCSPM.B4L7.B1	-1.36
	1.77	TCSG.A4L7.B1	-1.55
	1.71	TCSG.A4R7.B1	-1.67
	1.84	TCSG.B5R7.B1	-1.98
	2.00	TCSG.D5R7.B1	-1.84
	23.01	TCSG.E5R7.B1	-23.01
	1.75	TCSPM.E5R7.B1	-2.11
	22.99	TCSG.6R7.B1	-22.98
	2.23	TCSPM.6R7.B1	-2.68
	2.33	TCLA.A6R7.B1	-0.90
	3.15	TCLA.B6R7.B1	-2.07
	4.16	TCLA.C6R7.B1	-1.14
	3.24	TCLA.D6R7.B1	-0.06
	1.66	TCLA.A7R7.B1	-1.70

Hierarchy expressed in σ units and LHC protected aperture



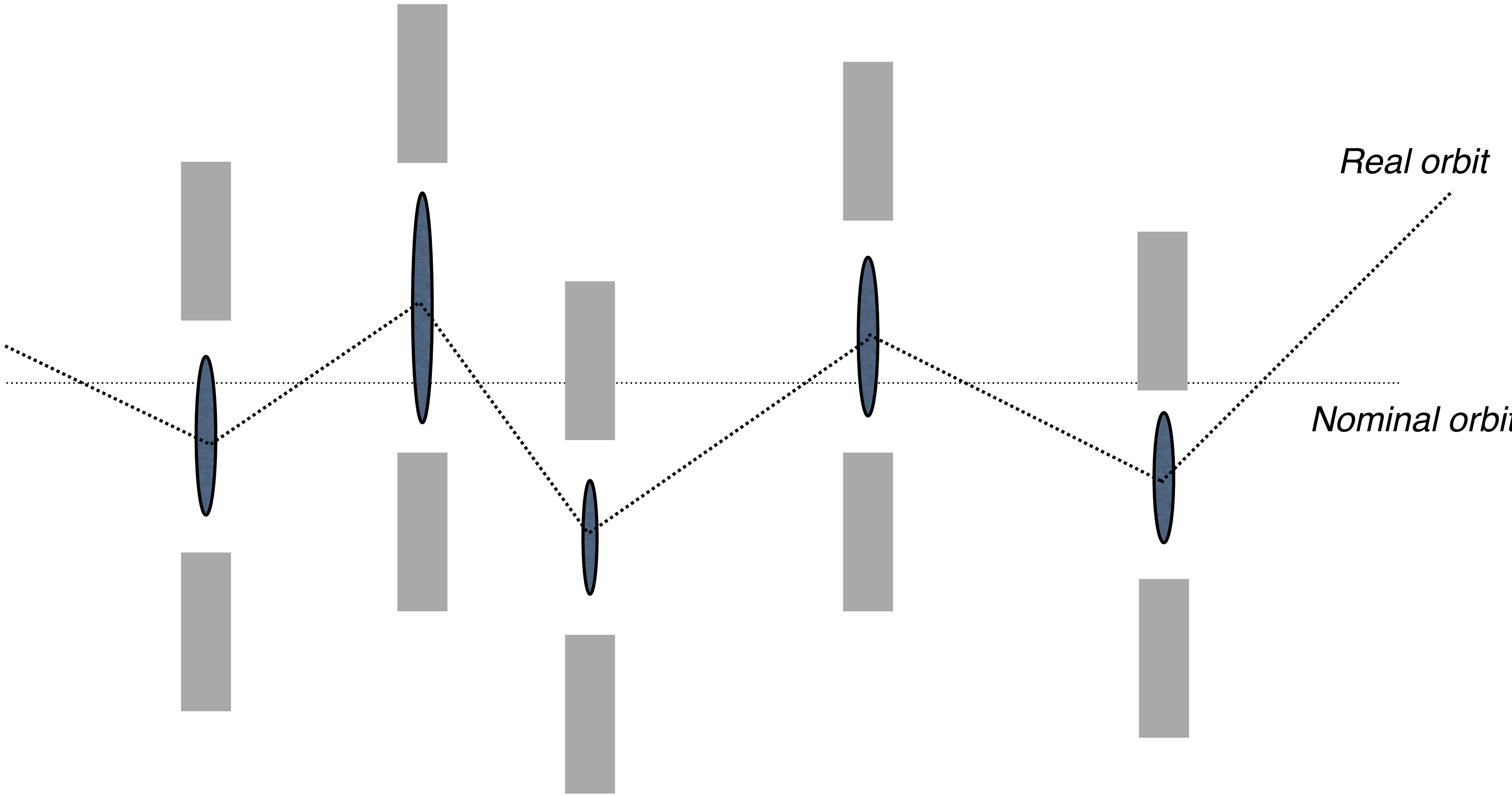
Smaller (triplet) aperture = smaller β* = more collisions

Tight hierarchy frees space in the triplet for smaller β reach.*

Collimators are grouped in “families” that build a strict transverse hierarchy to protect, through multiple stages, the machine aperture.

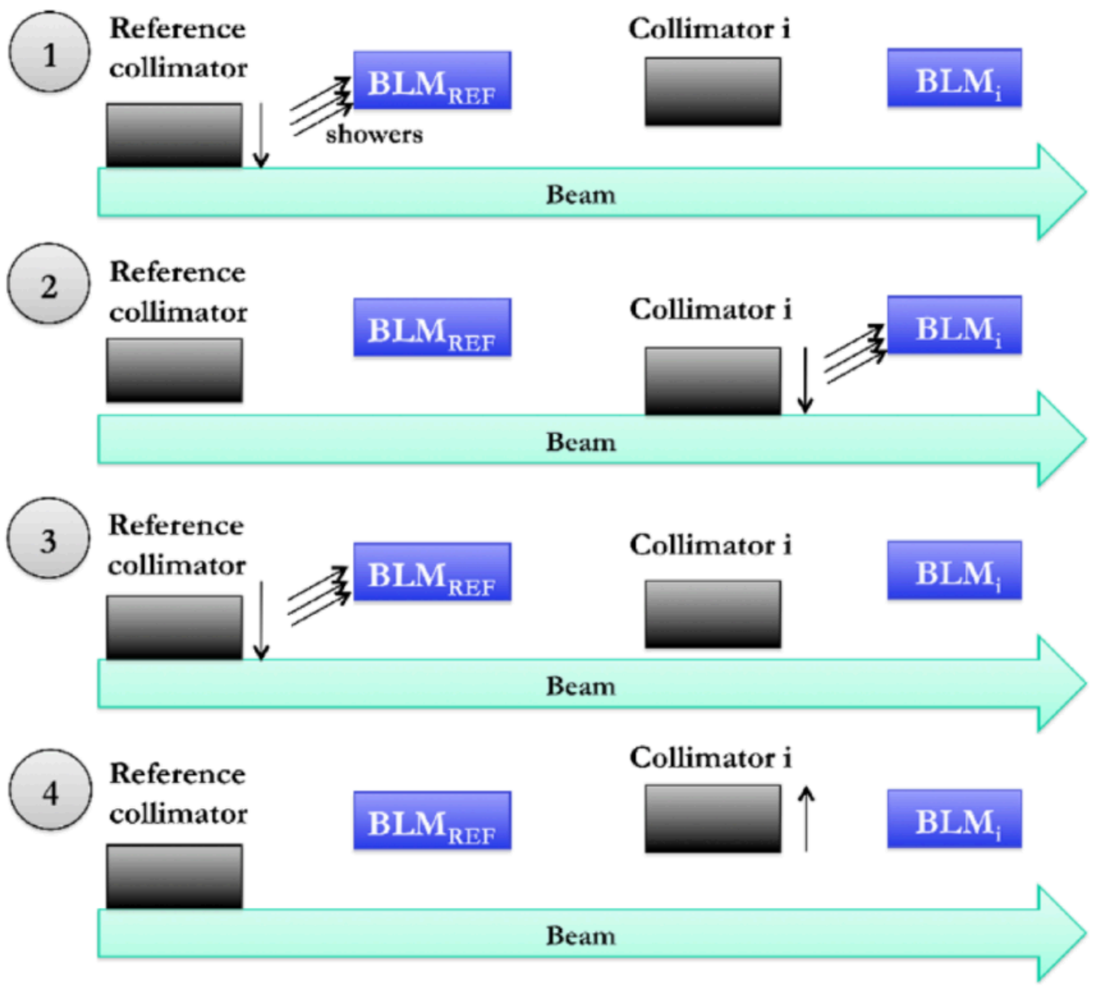
Some acronyms: TCP: primaries; TCS: secondaries; TCT: tertiaries; TCDQ: dump protection; …

Collimation alignment

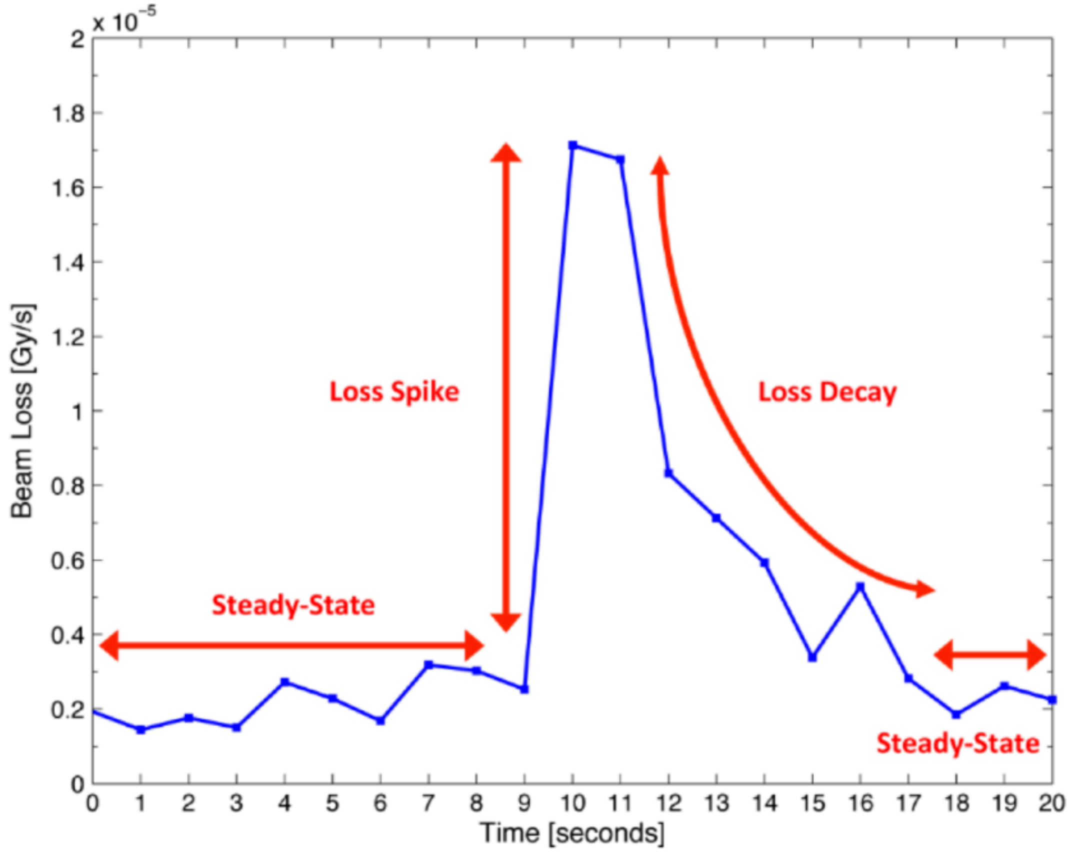


Detailed procedures for the "beam-based alignment" collimation were established to find local beam position and establish the relative transverse hierarchy.
Need to be repeated for each individual collimator!

Machine learning for alignment



Time signal of losses when the collimator "touches" the beam



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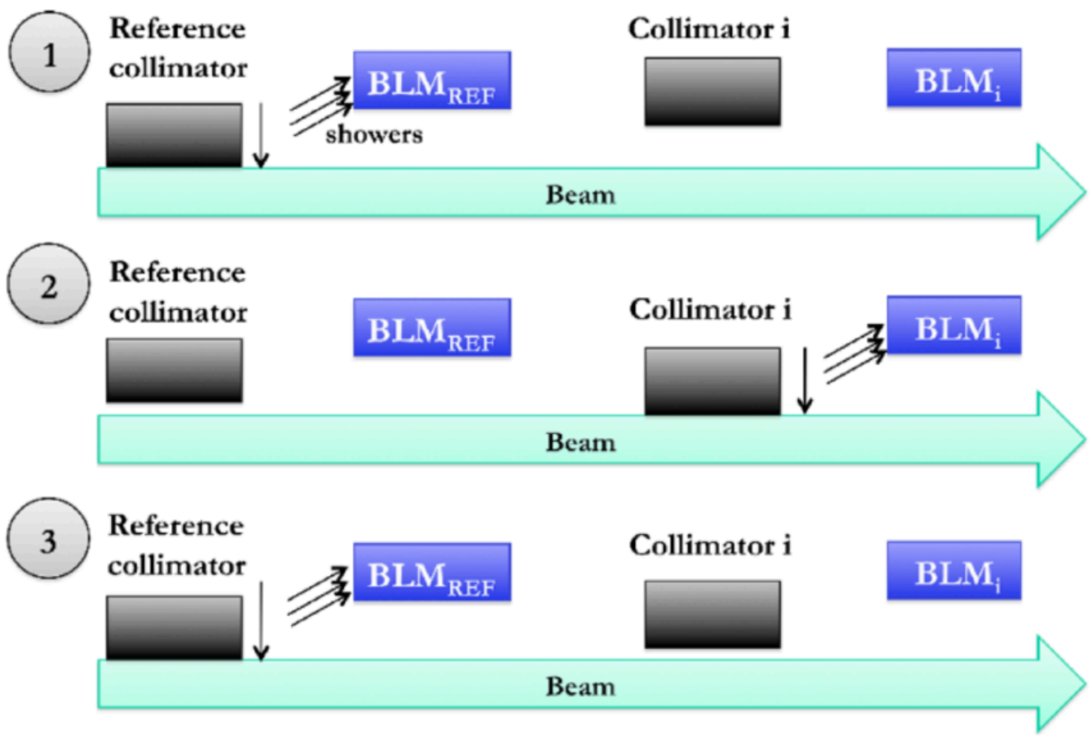
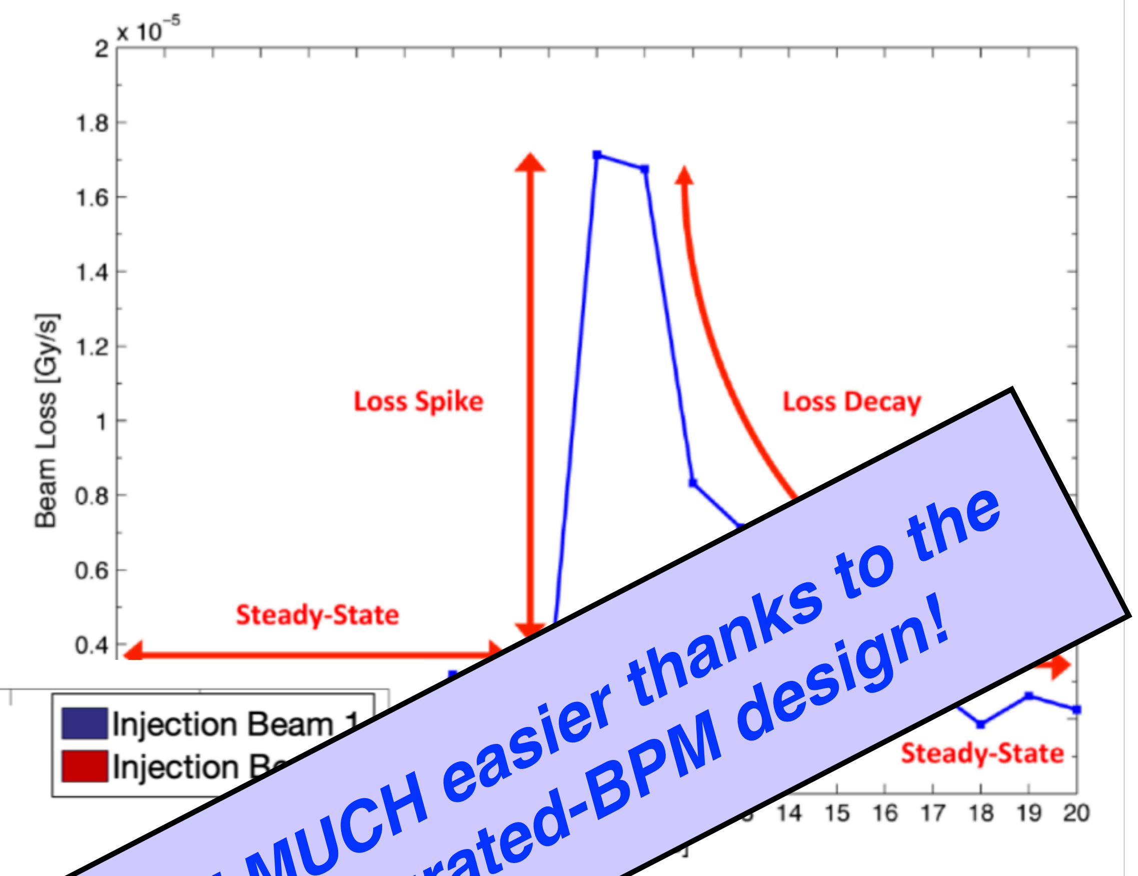
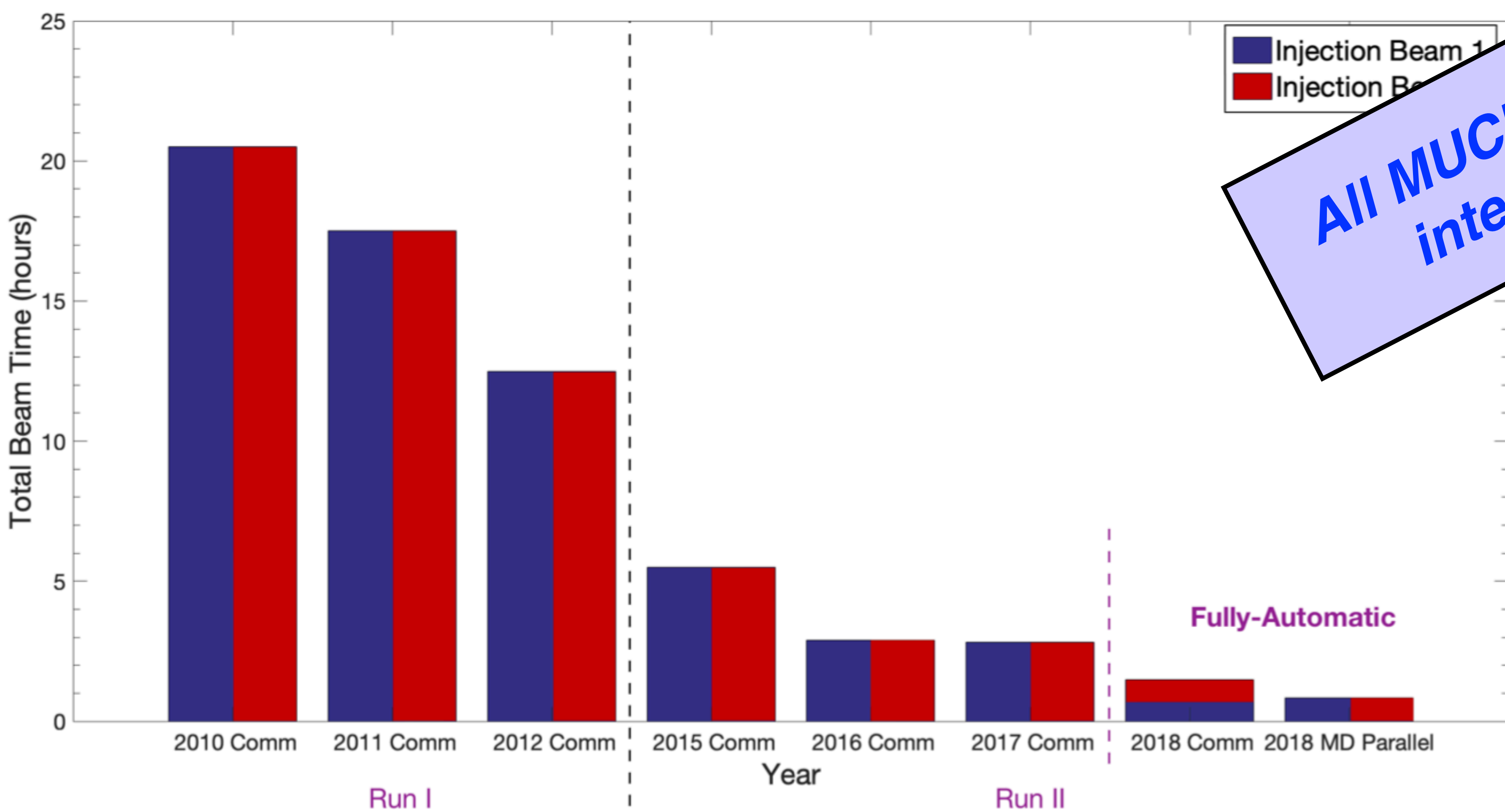


Time signal of losses when the collimator "touches" the beam



All MUCH easier thanks to the integrated-BPM design!



Loss spike detection and orchestration of the 100+ collimators automatised and made faster by using ML applications
PhD thesis: G. Azzopardi

Beam validation through "loss maps"

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

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

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

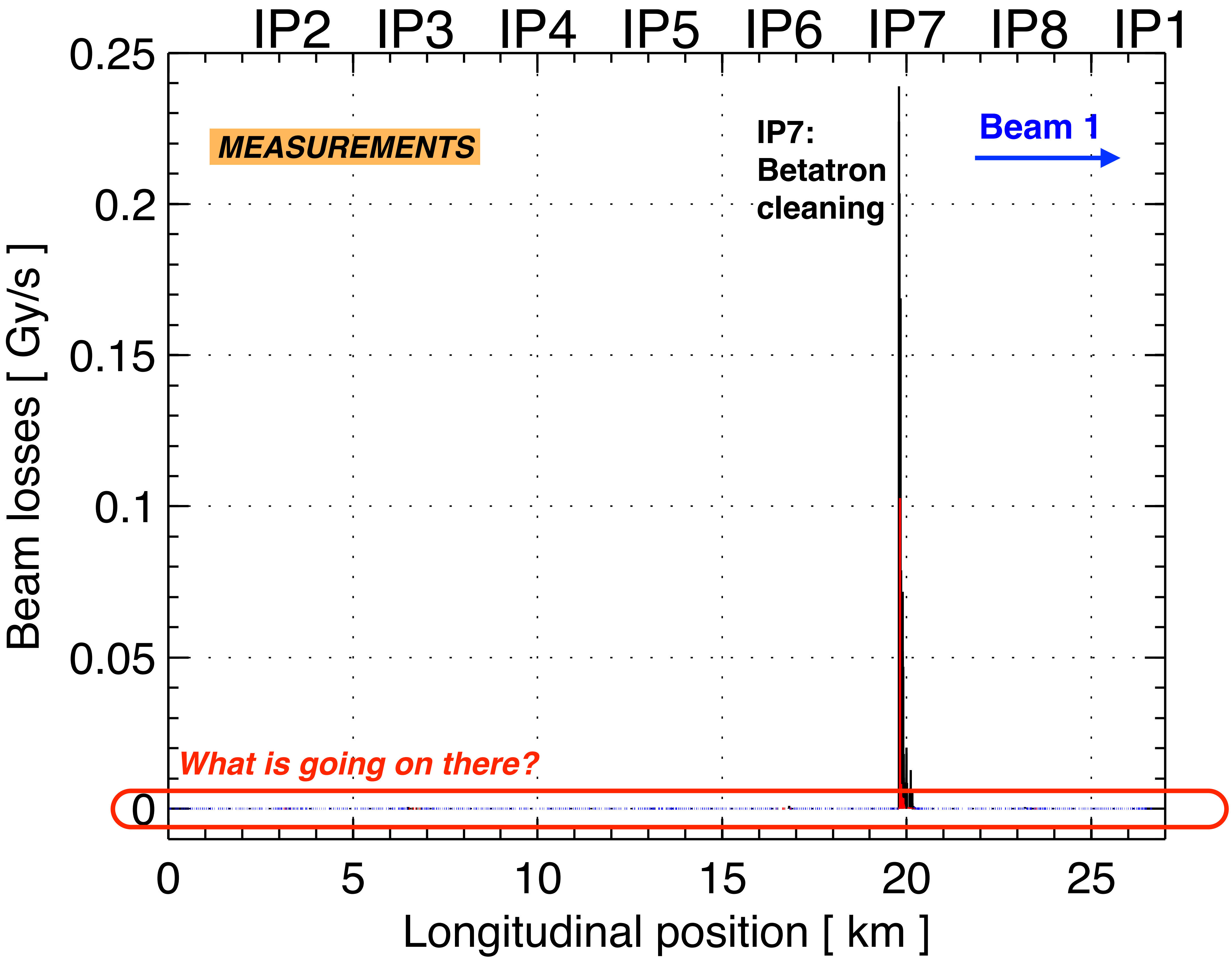
→ Each set of settings of the collimation system is validated through loss maps with low-intensity beams (few bunches)

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

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

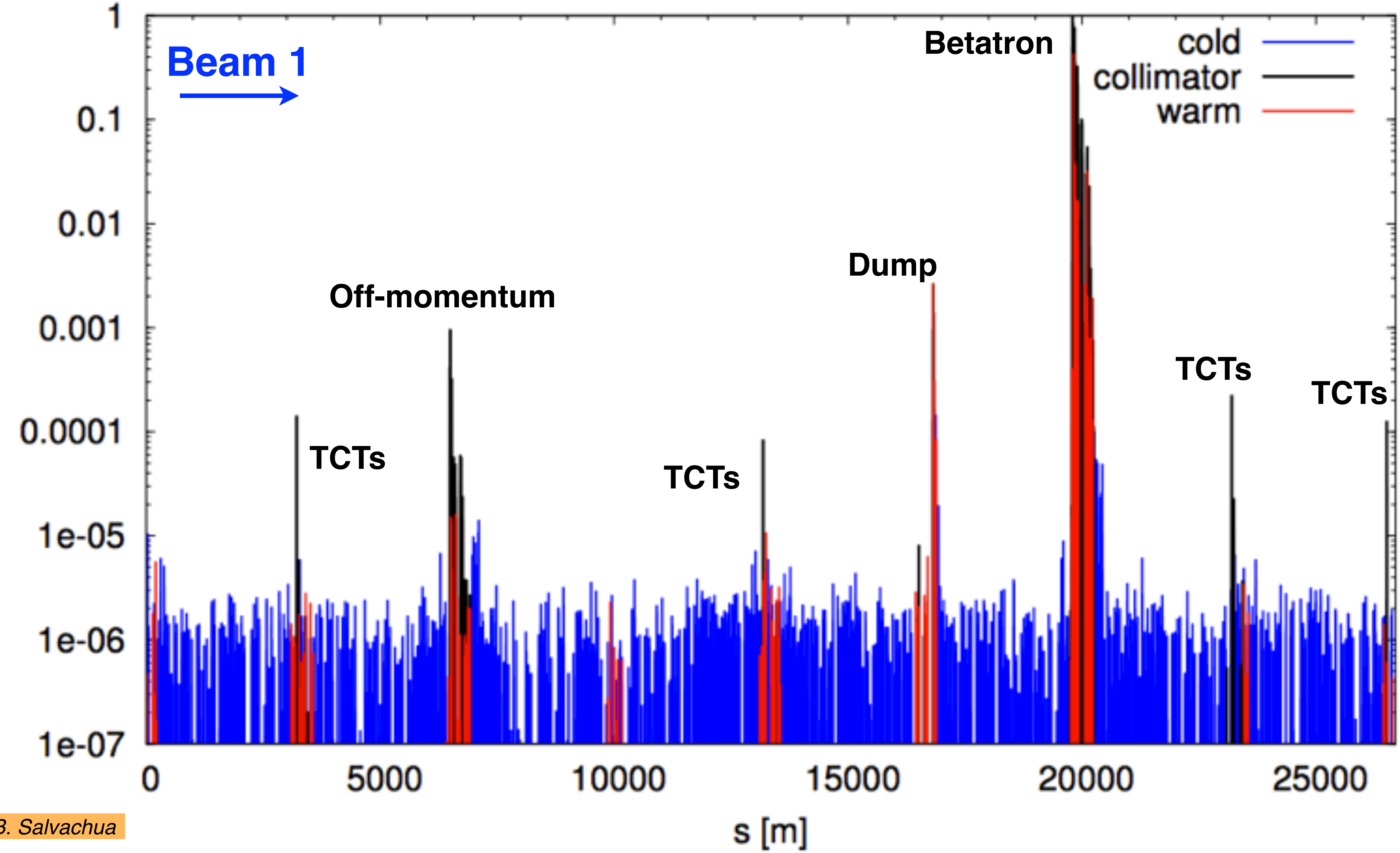
Collimation cleaning

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



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

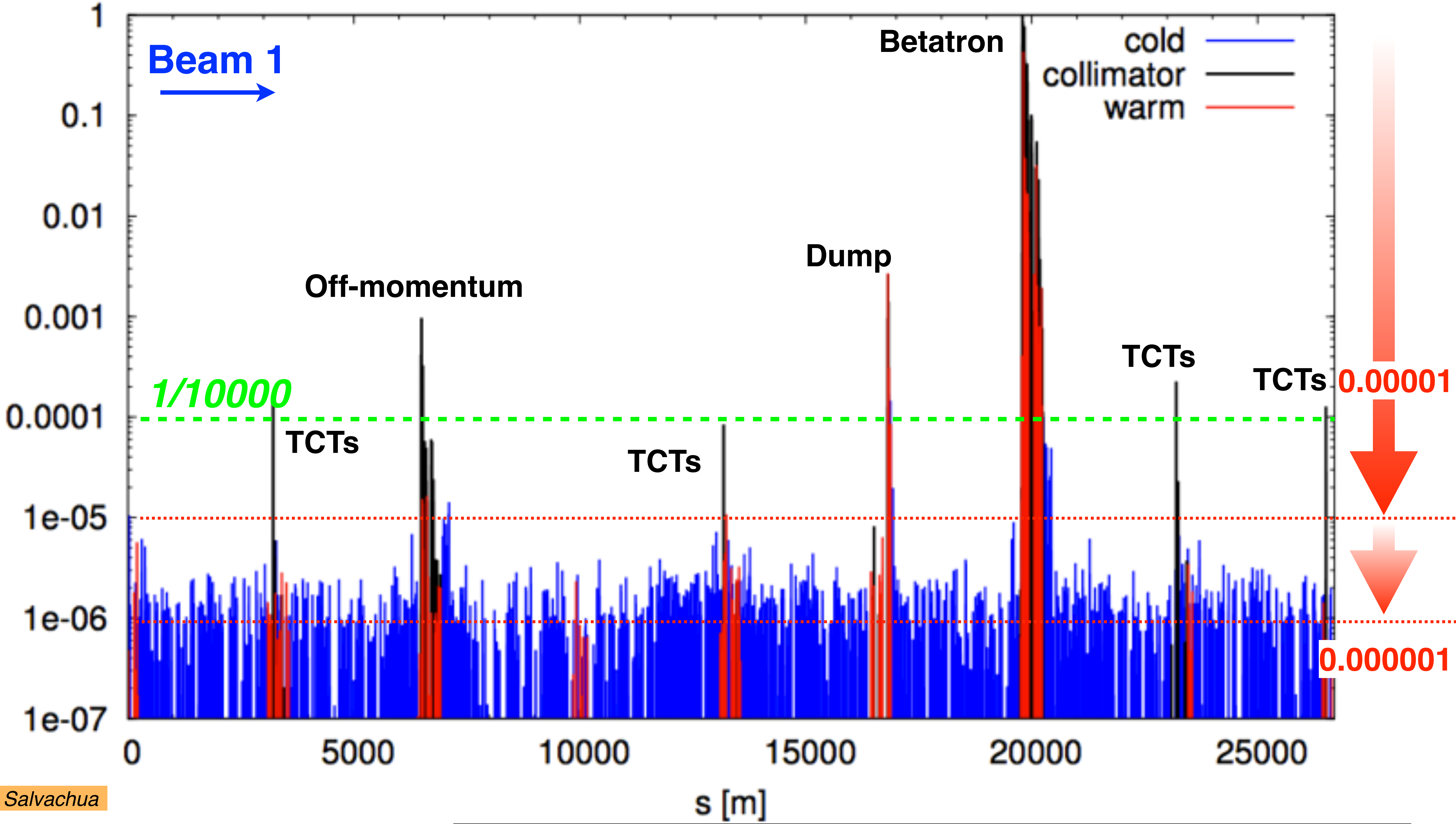
MEASUREMENTS



B. Salvachua

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

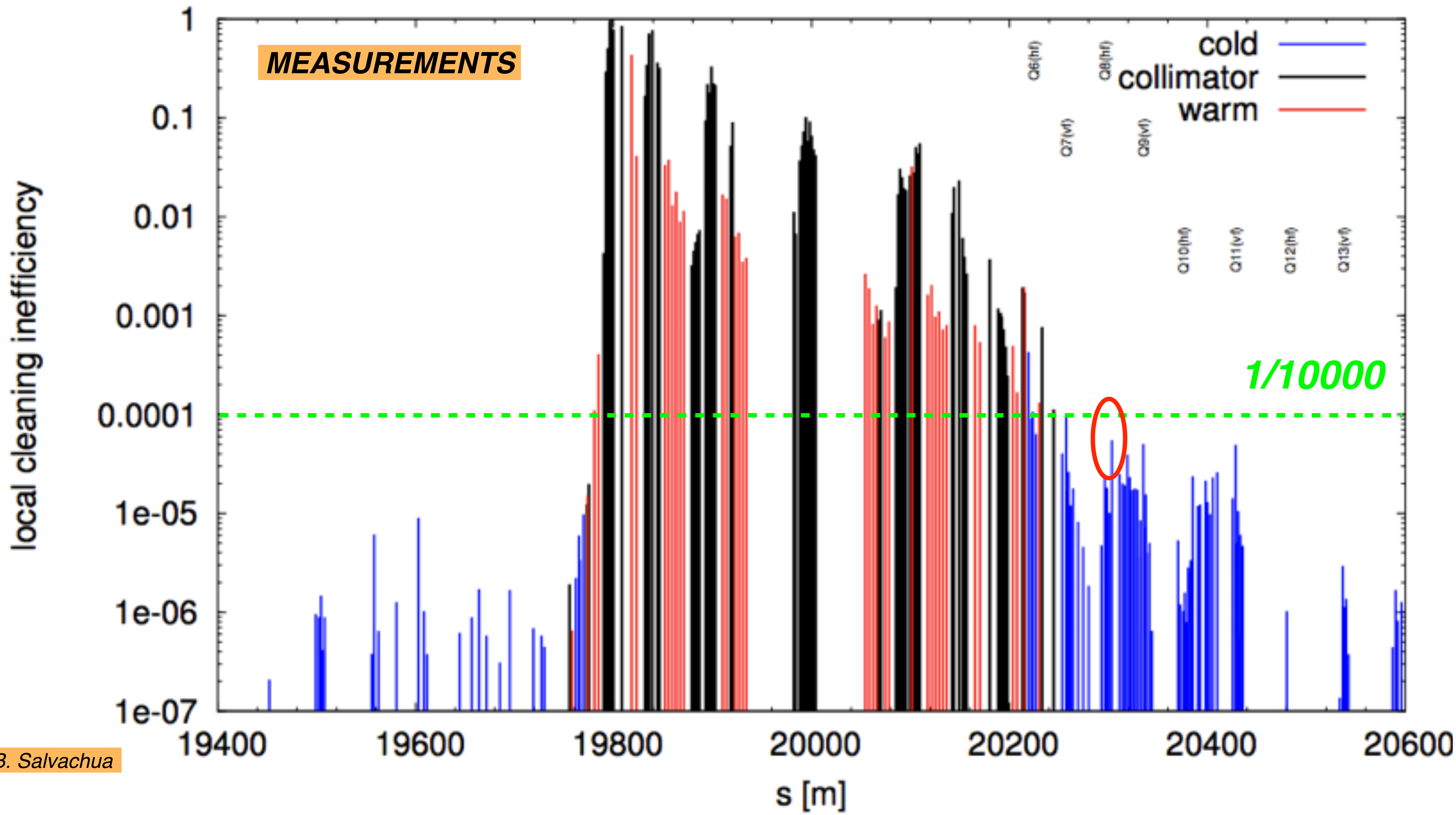
MEASUREMENTS



B. Salvachua

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

Betatron cleaning: zoom in IR7



B. Salvachua

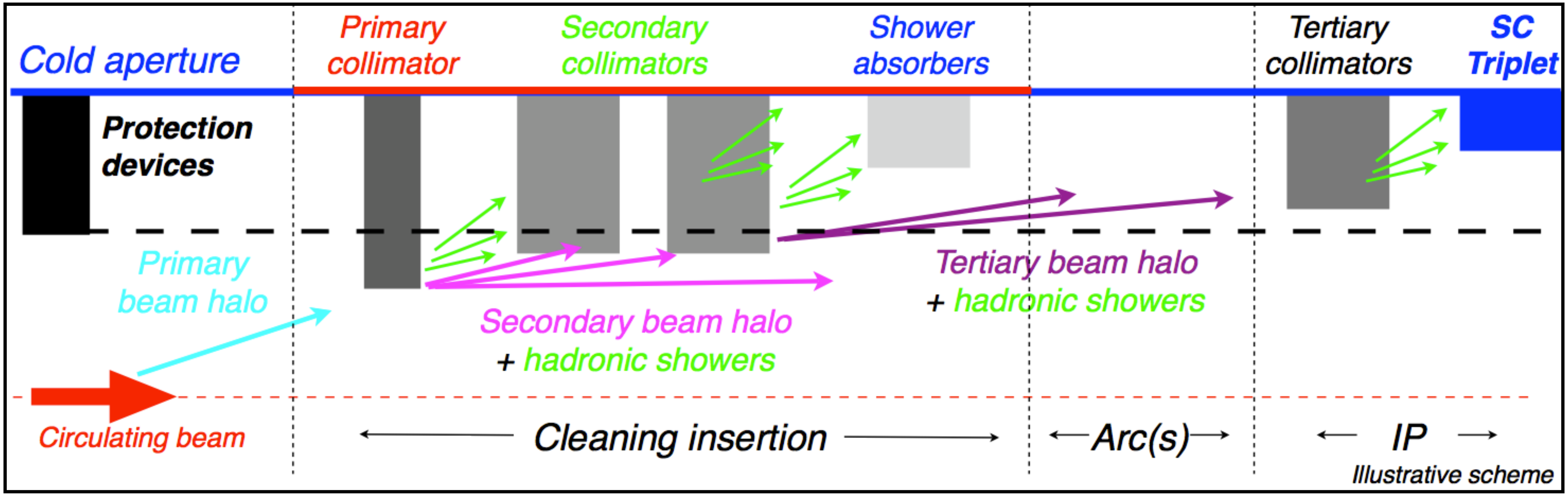
<u>Critical location</u> (both beams): losses in the "dispersion suppressor".

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

Do we understand the observed collimation losses?

LHC collimation: simulation challenges

- Model precisely the **complex** and **distributed collimation** system
  - → *44 collimator per beam along 27 km;* ***multi-stage cleaning****;*
  - → *2 jaw design for* ***3 collimation planes****: horizontal, vertical and skew;*
  - → *impact parameters in the sub-micron range;*
  - → *beam proton* ***scattering*** *with different collimator materials.*
- **Collimation** is designed to provide cleaning efficiencies > 99.99%
  - → *need* ***good statistical accuracy*** *at limiting loss locations;*
  - → *simulate only halo particles that interact with collimators, not the core.*



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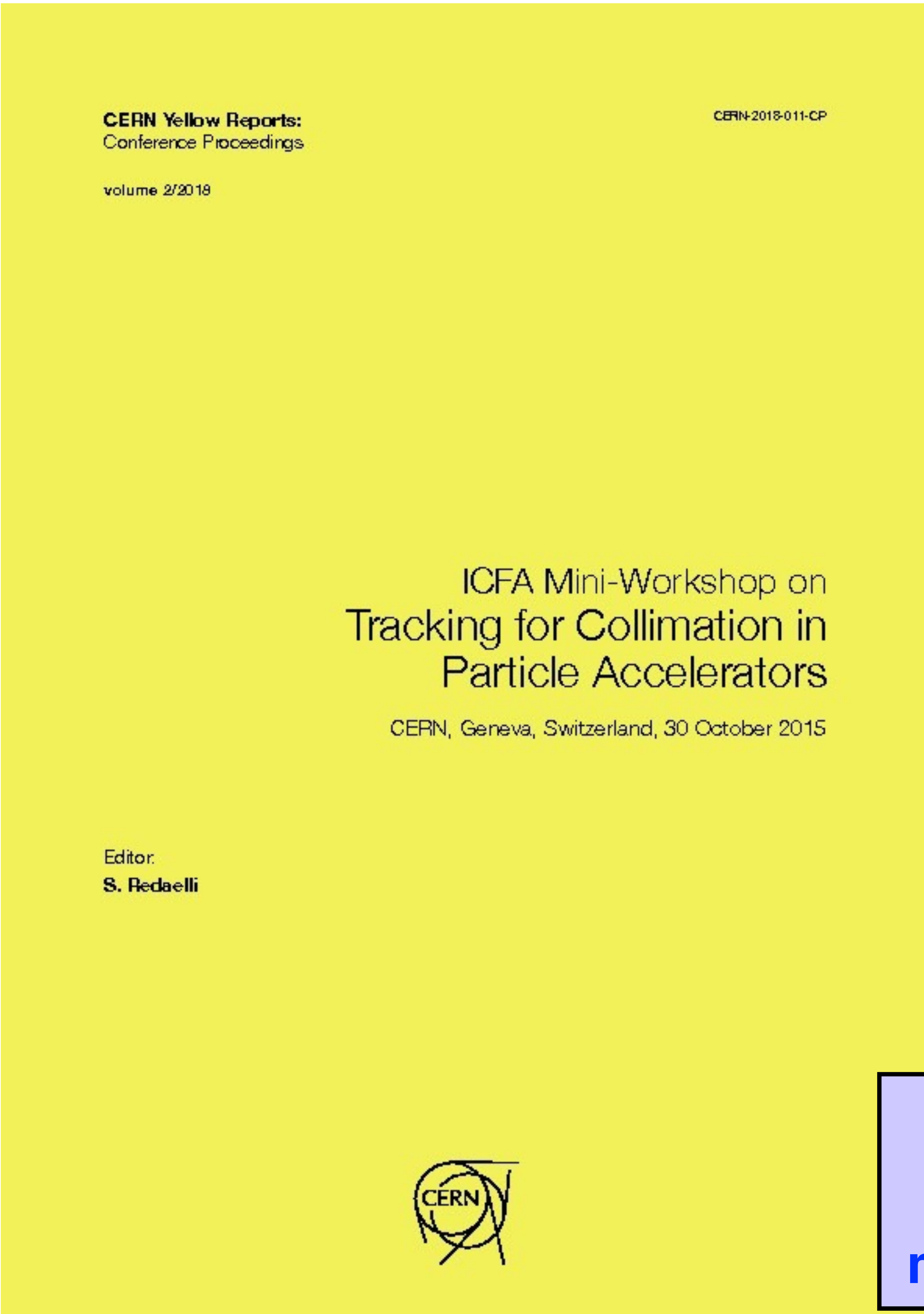
- **Collimation** is designed to provide cleaning efficiencies > 99.99%
  - → *need **good statistical accuracy** at limiting loss locations;*
  - → *simulate only halo particles that interact with collimators, not the core.*
- Detailed description of the **LHC aperture** all along the 27 km
  - → *10 cm binning, i.e. 270000 check points.*
- Accurate tracking of particles with large **orbit** and **energy deviations**
  - → *need state-of-the-art tools for multi-turn tracking.*
- At the scale of 7 TeV beam sizes (~200 microns), small errors matter! Need to **model the relevant imperfections**
  - → *Jaw flatness of the order of 40 microns;*
  - → *Jaw positioning (gap/angles);*
  - → *Machine optics and orbit errors.*

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

Ref.: “tracking for collimation”



Published CERN Yellow Book: CERN-2018-011-CP

The PDF version available on the CERN CDS side.
A few printed copies available for who is interested.

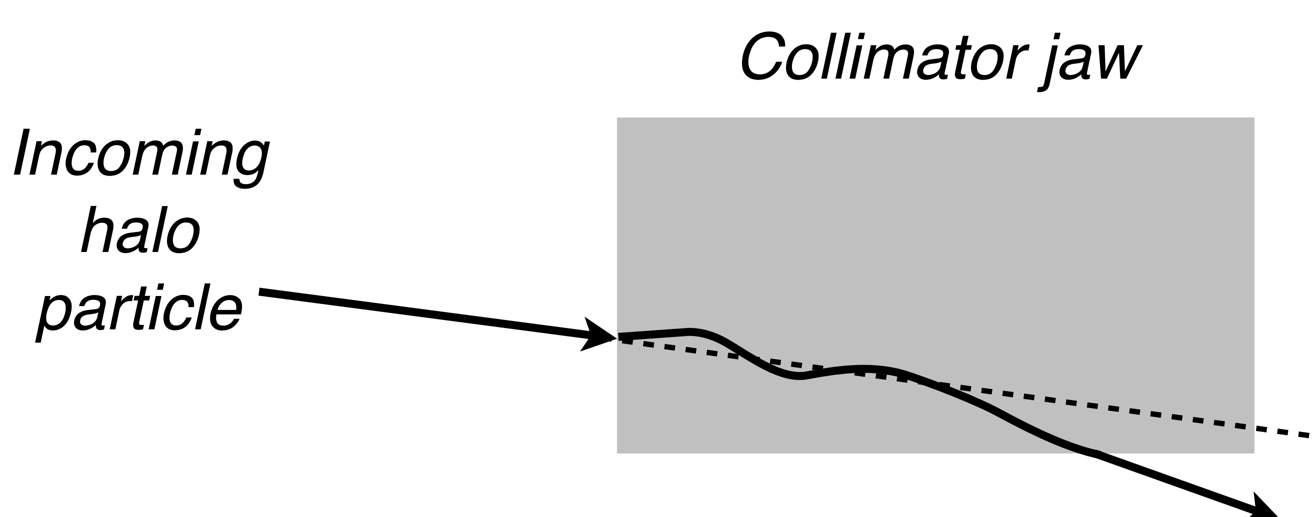
Link to the workshop:
https://indico.cern.ch/event/455493

Presently: ongoing effort in the CERN Accelerator Physics group to renew and modernise the simulation tools — stay tuned!

Simulation tools

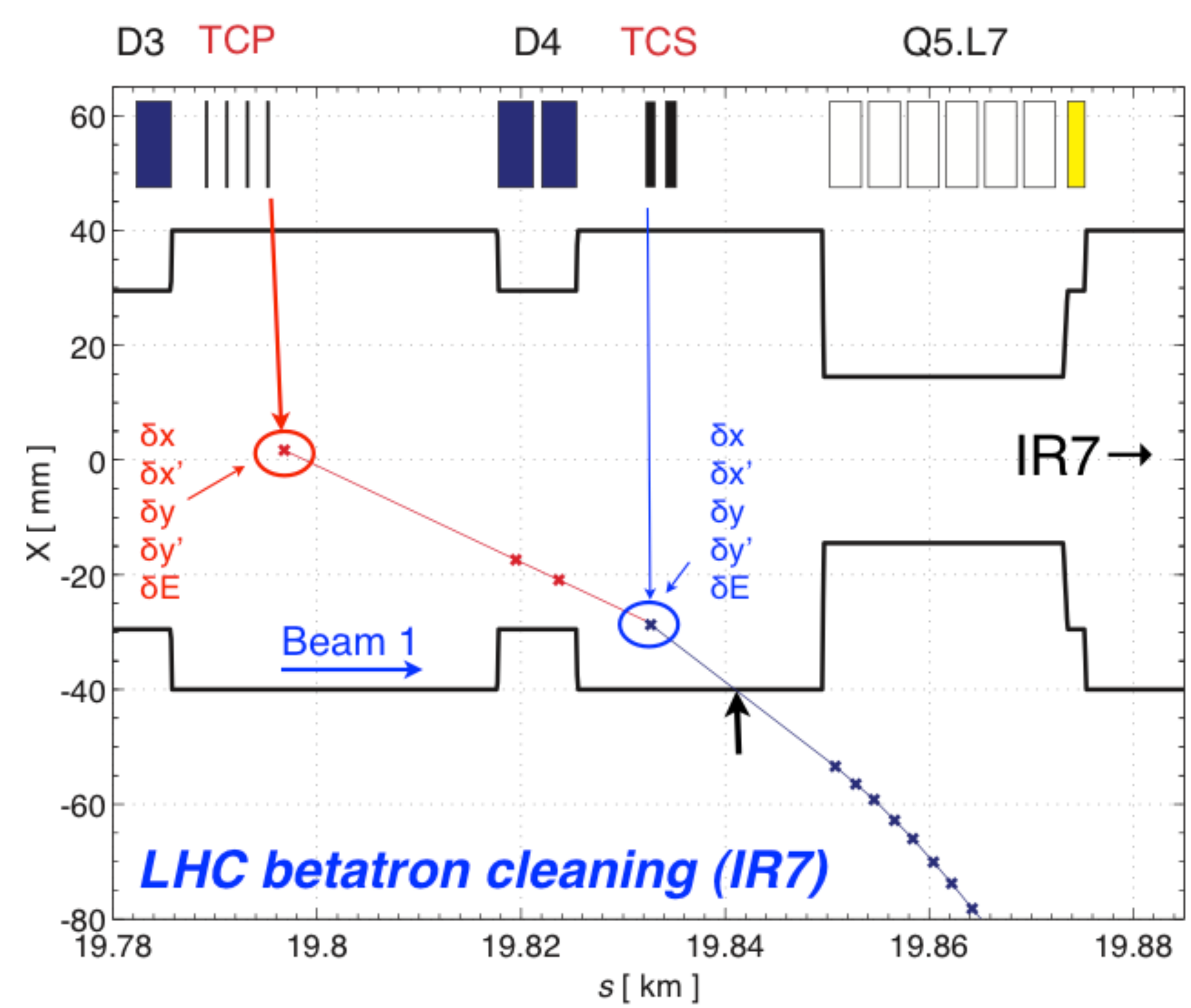
Accurate tracking of halo particles 6D dynamics, chromatic effects, δp/p, high order field errors, ...	**SixTrack xTrack**
Detailed collimator geometry Implement all collimators and protection devices, treat any azimuthal angle, tilt/flatness errors	
Scattering routine and collimator geometry Track protons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

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

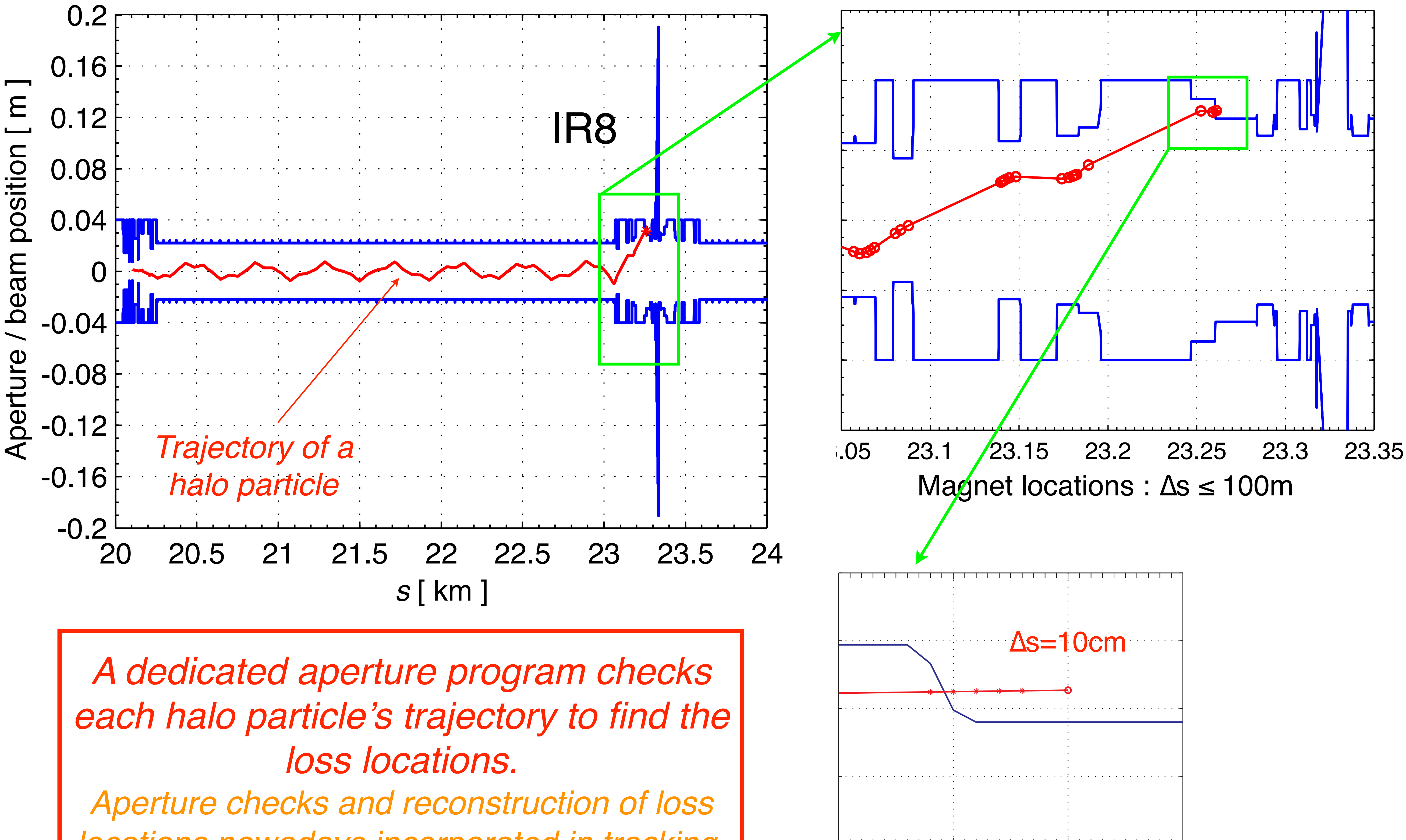


An illustrative scheme

Various possible integrations of different tools are available nowadays for these complex simulations.



Example: trajectory of a halo particle

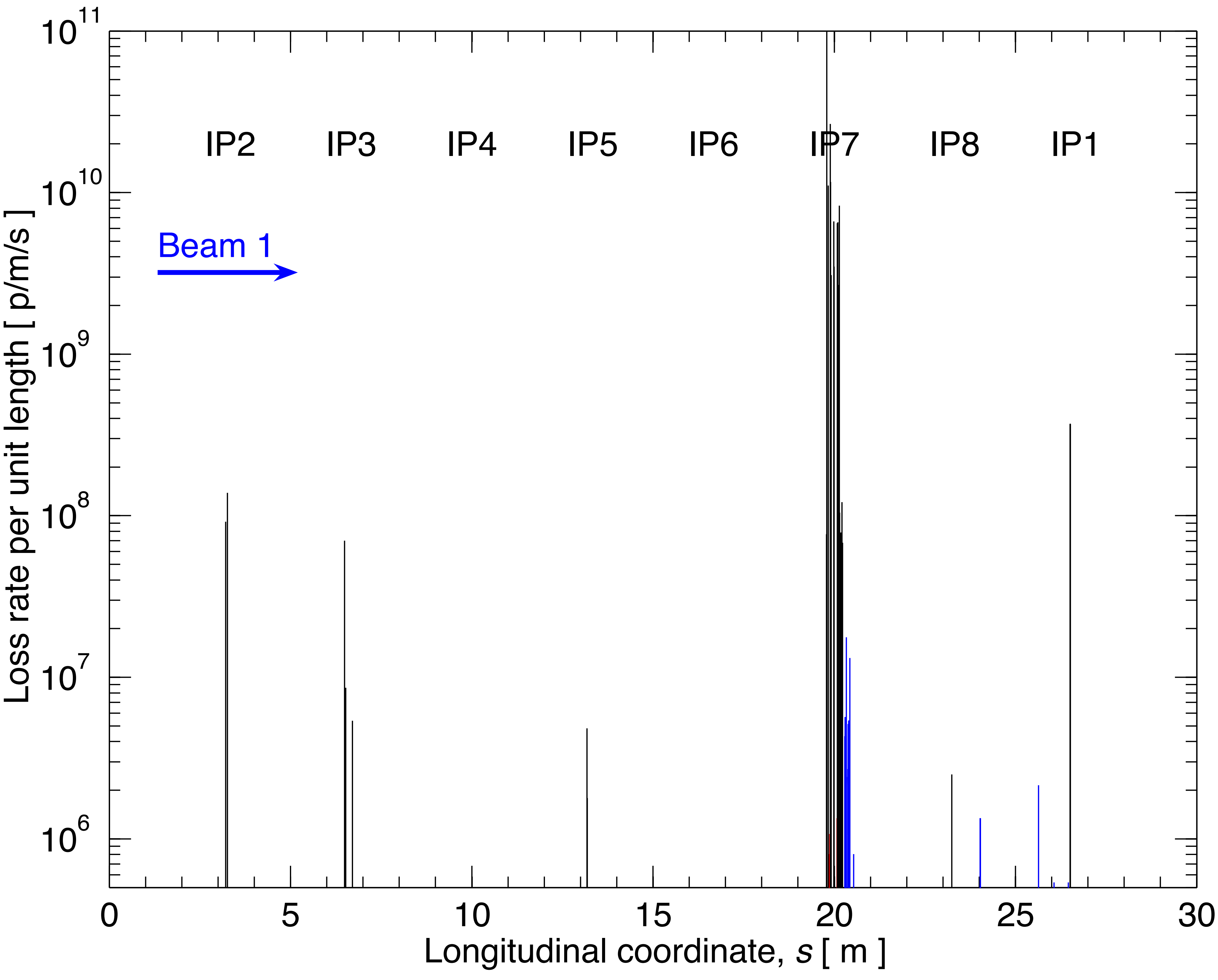


Interpolation: Δs=10cm
LHC: 270000 points!
FCC: ~1000000 points!!

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

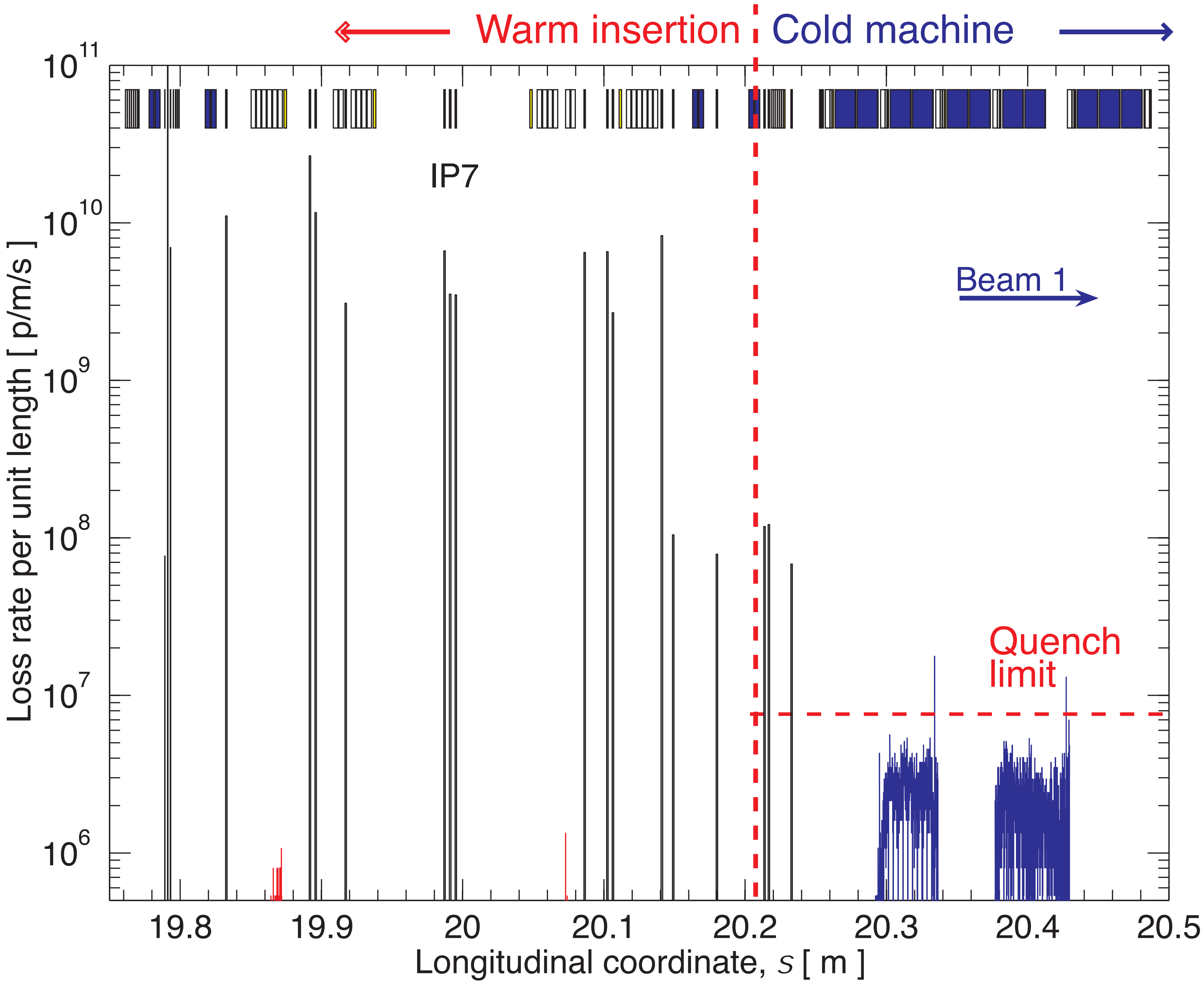
Aperture checks and reconstruction of loss locations nowadays incorporated in tracking.

Example of simulated “loss map”



Nominal 7 TeV case, perfect machine

Example of simulated “loss map”



Nominal 7 TeV case, perfect machine

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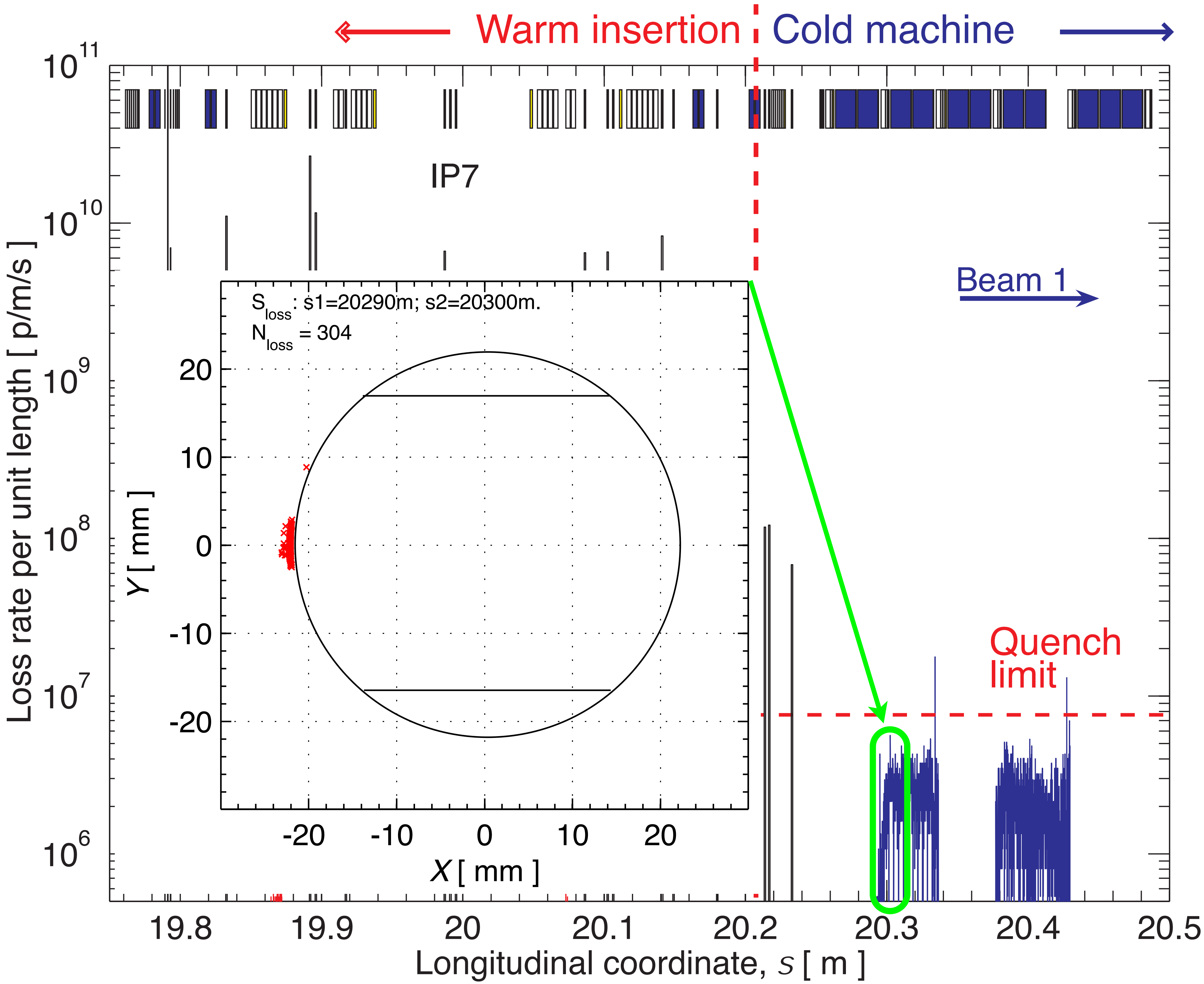

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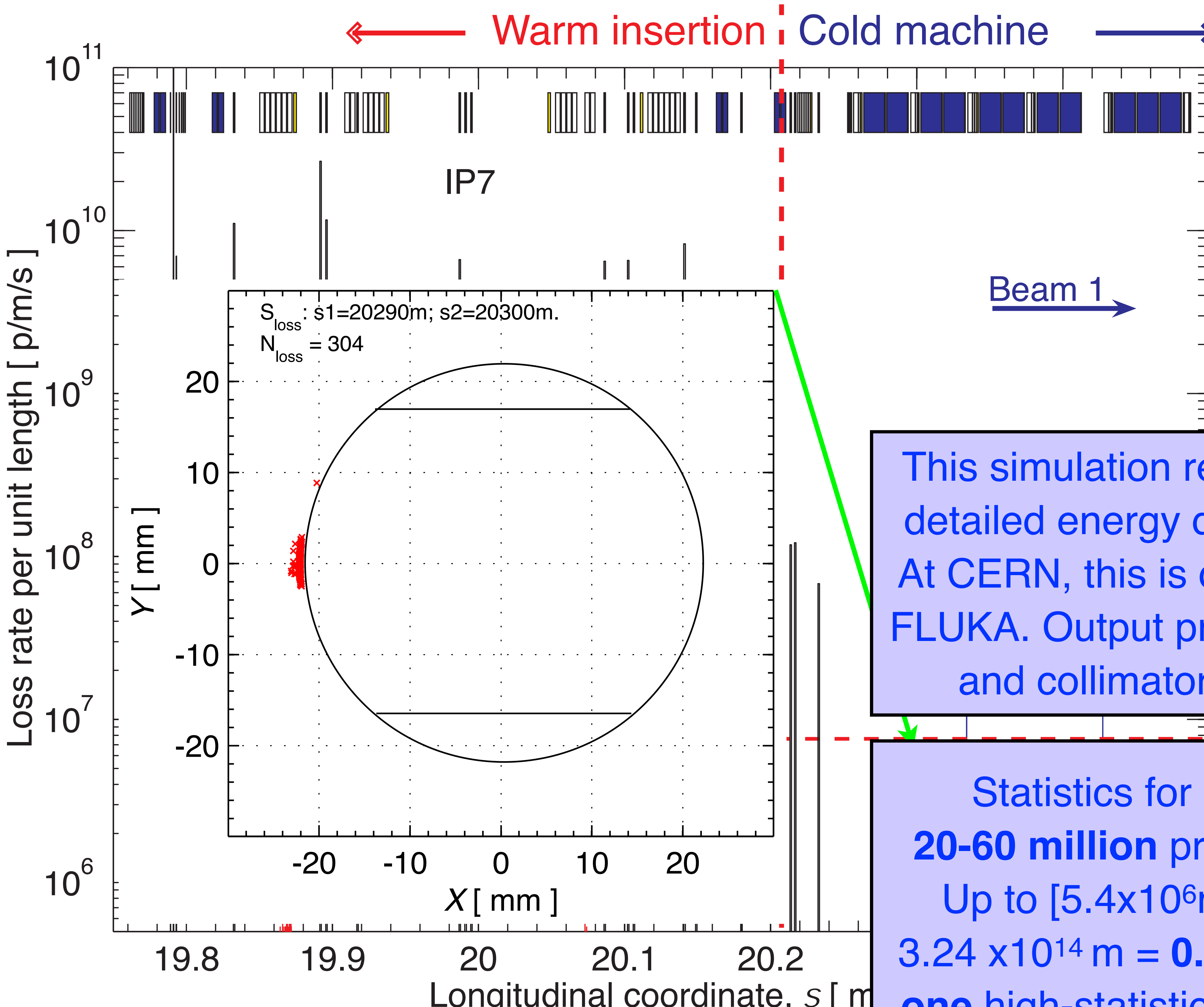
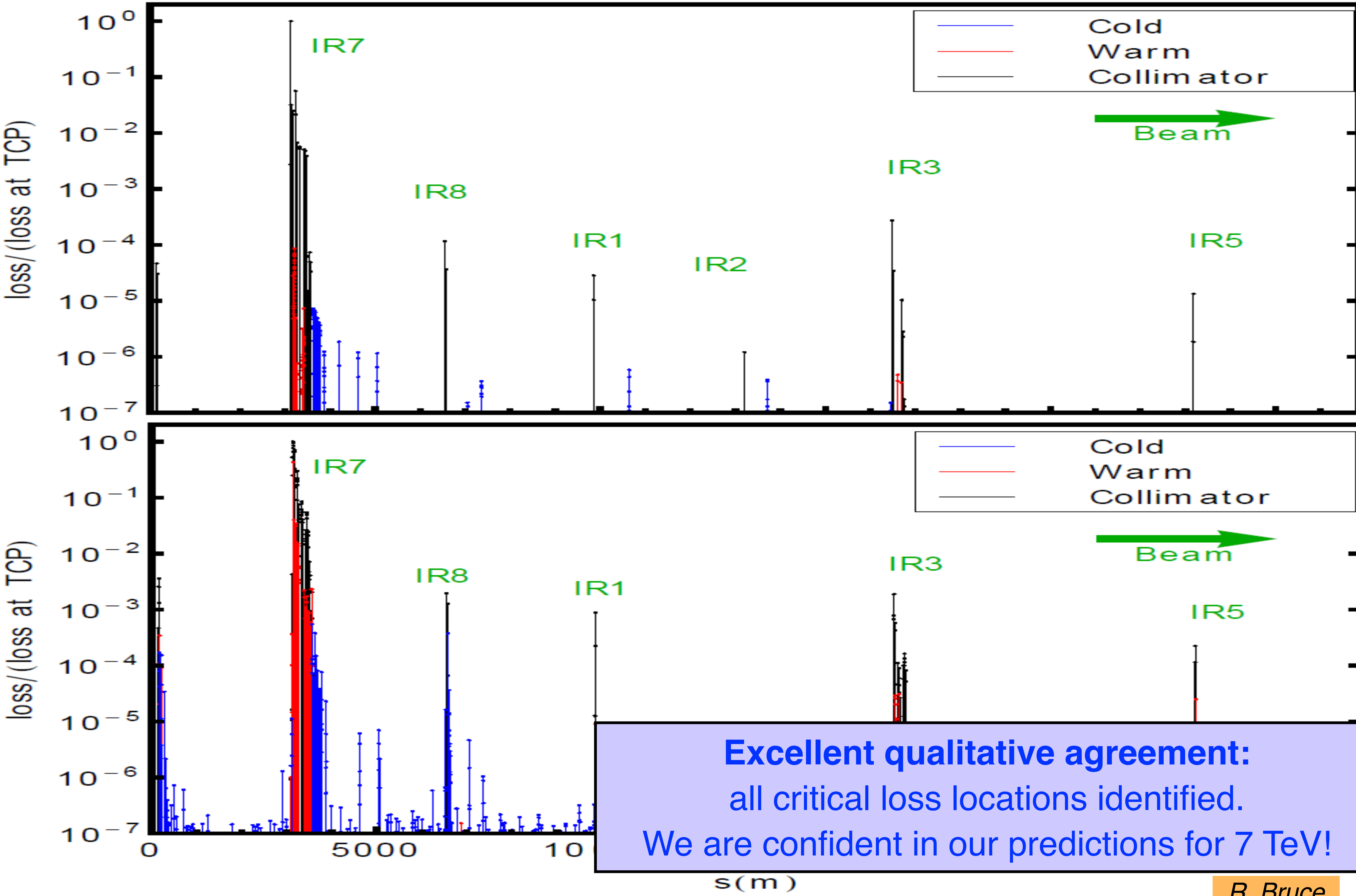


Nominal 7 TeV case, perfect machine

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

Statistics for a typical case:
20-60 million protons, **200 turns**.
Up to [5.4x10^6m] x [60x10^6p] = 3.24 x10^{14} m = **0.034 lightyears** for **one** high-statistics simulation case!

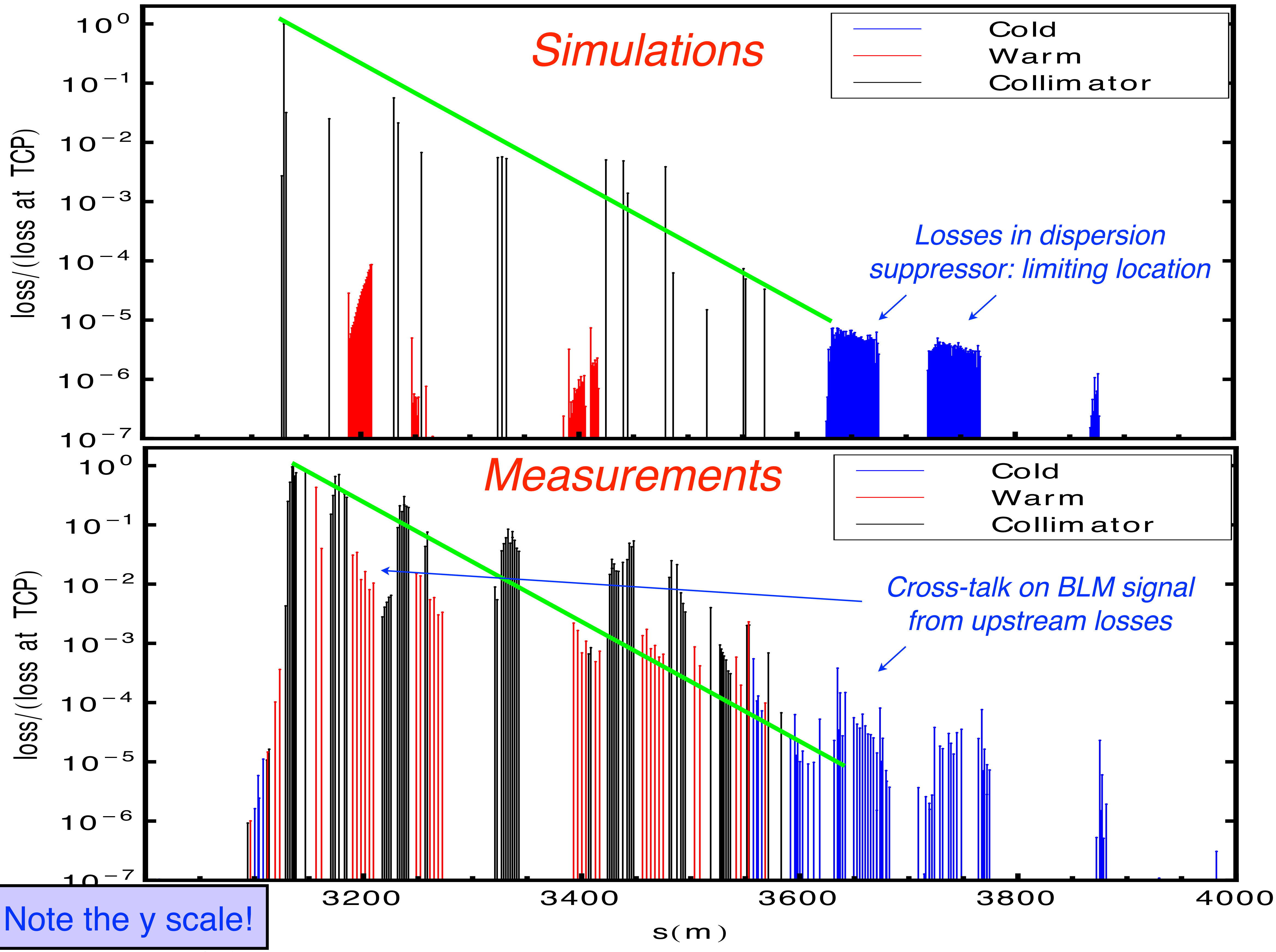
Comparison with measurements



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

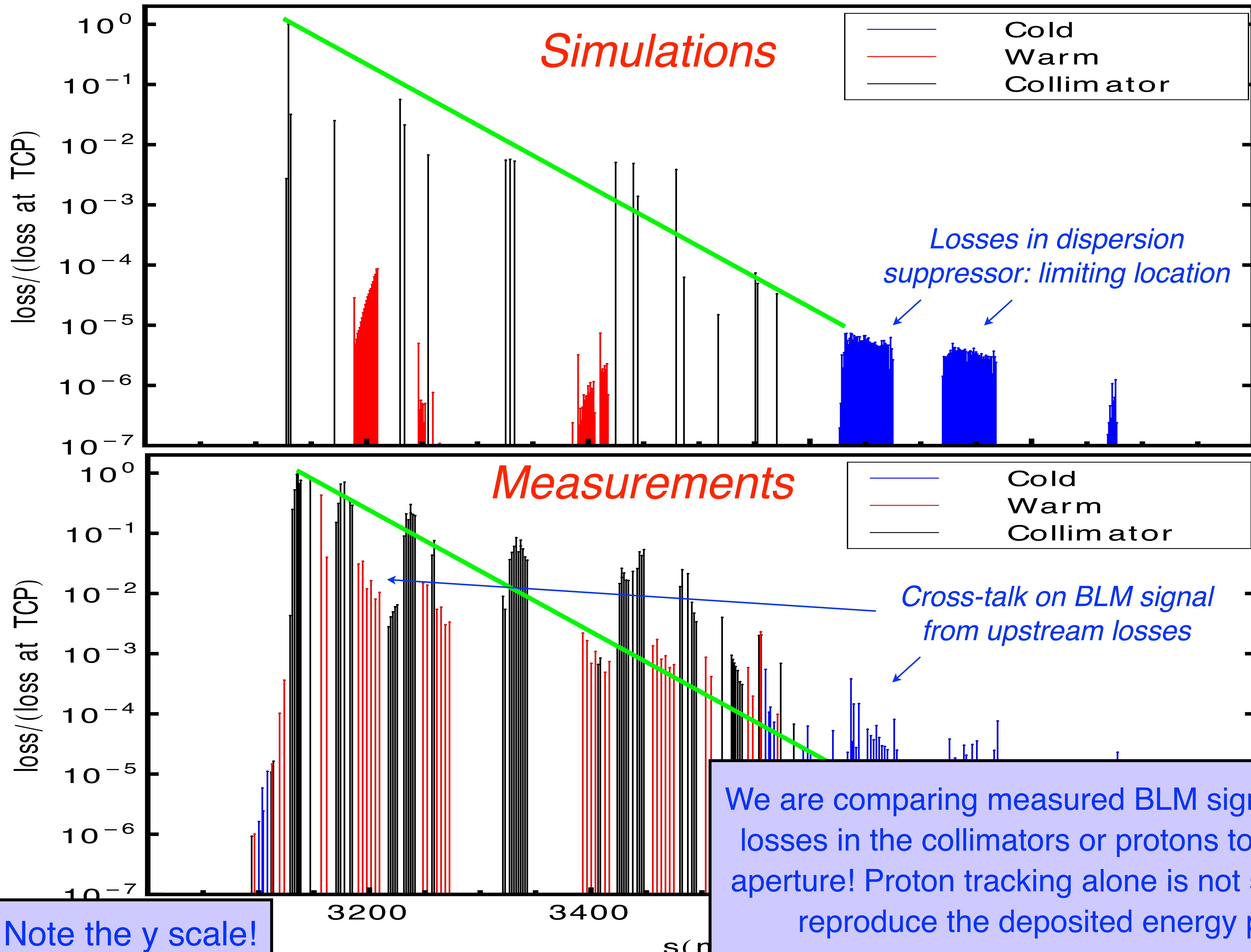
R. Bruce

Comparison in the betatron cleaning



Note the y scale!

Comparison in the betatron cleaning

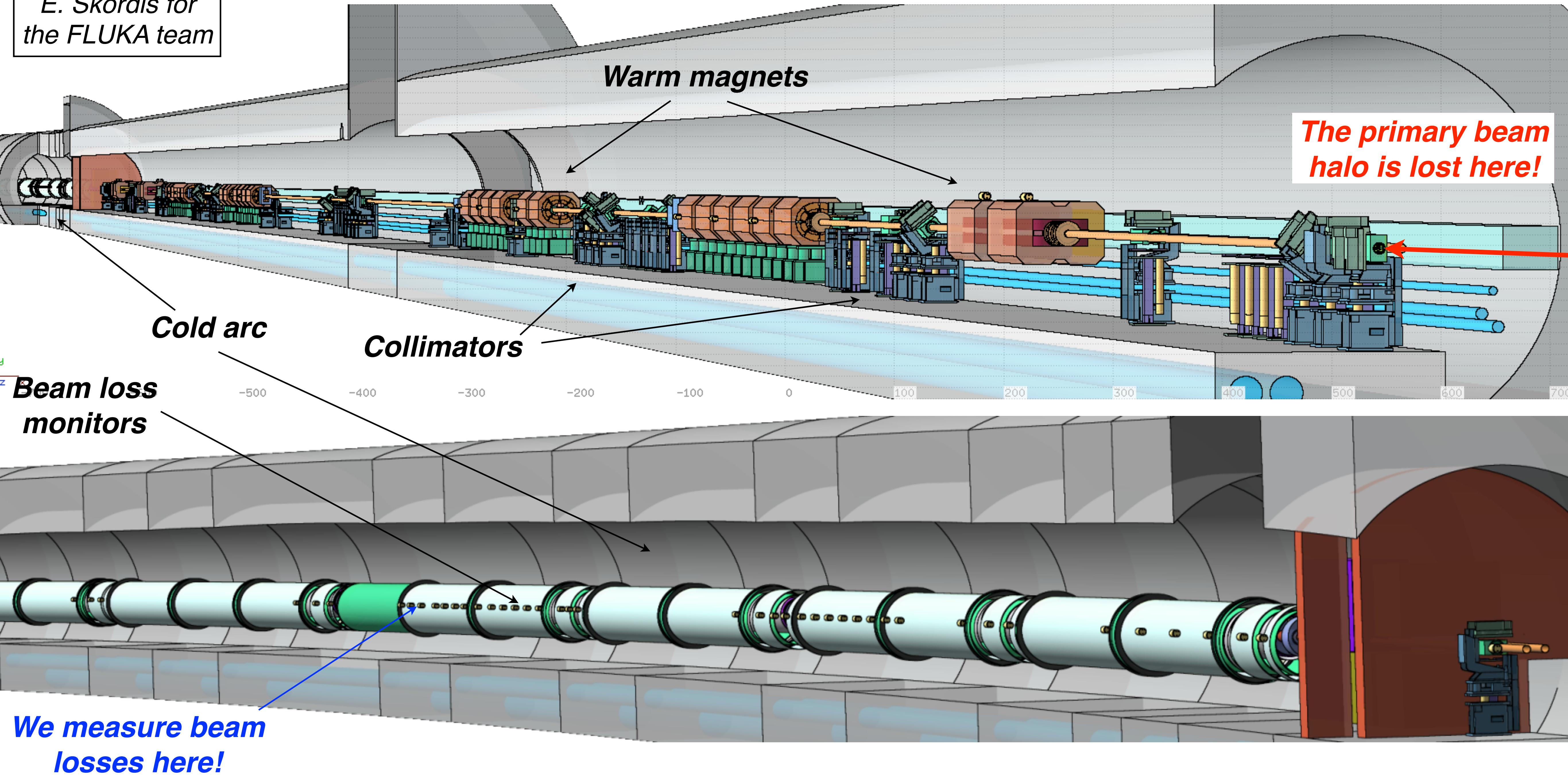


Note the y scale!

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

Integrated simulations

E. Skordis for the FLUKA team

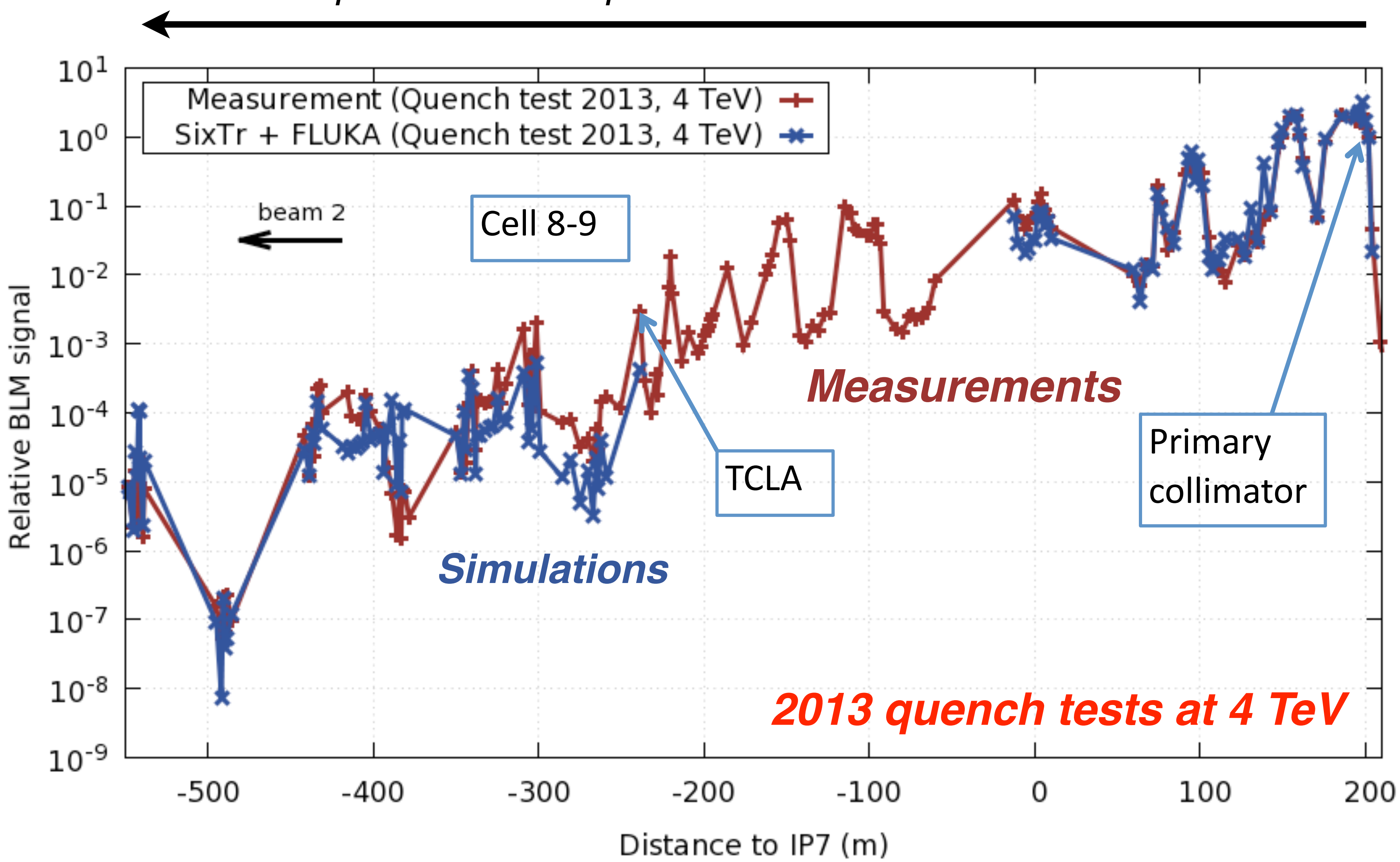


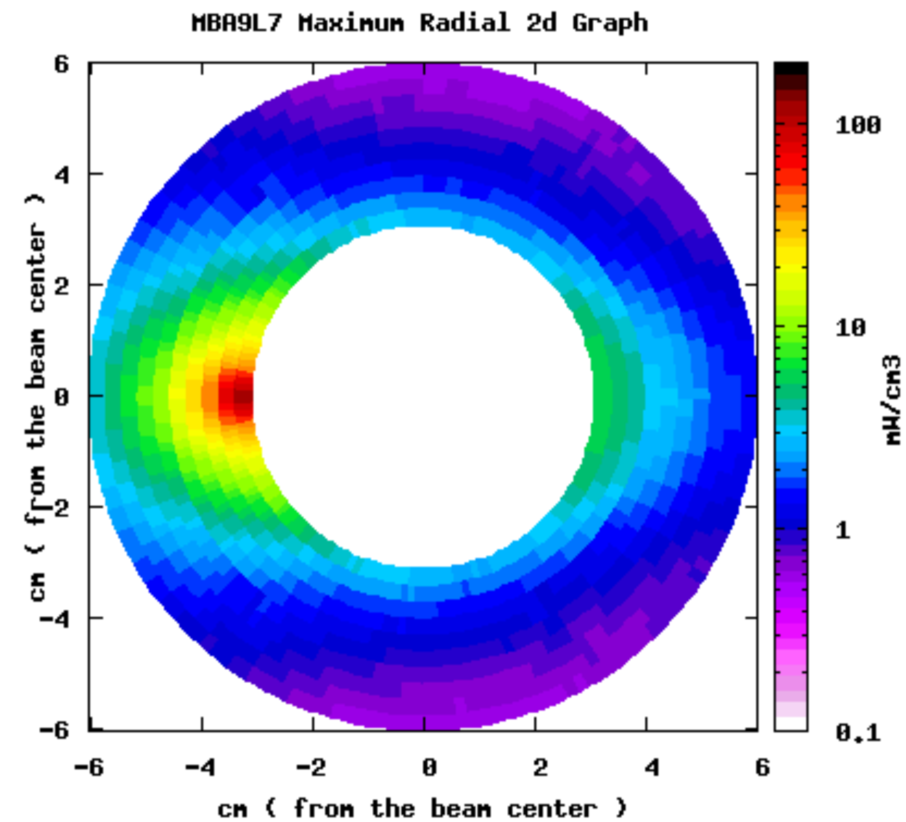
- Impressive machine model for **energy deposition studies** for collimation! This is required to reproduce the details observed in the measurements...

Energy deposition at selected beam loss monitors done with the code FLUKA

Comparison against measurements

Transport of shower products over more than 700 metres!





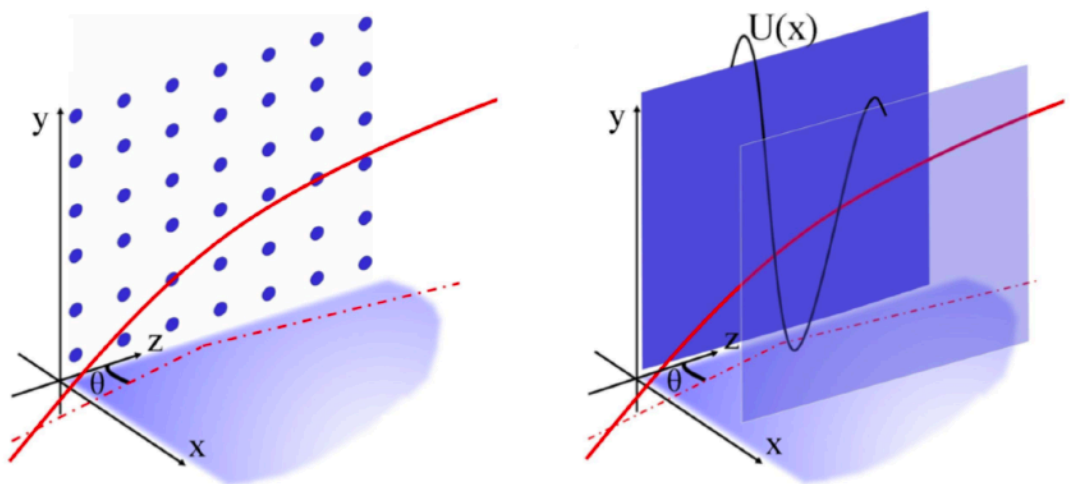
E. Skordis et al.

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

Crystal collimation

Planar channeling in bent crystals

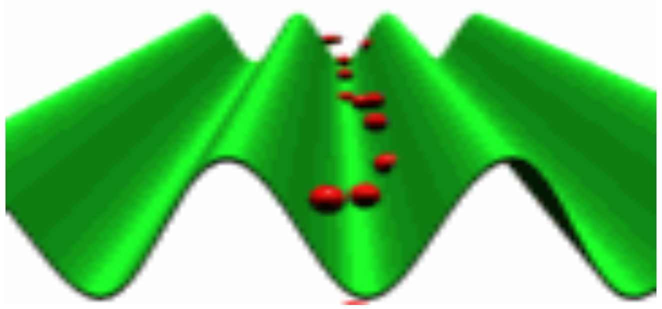
Pure crystals with regular lattices



If the protons ***have*** $\boldsymbol{p_T < U_{max}}$

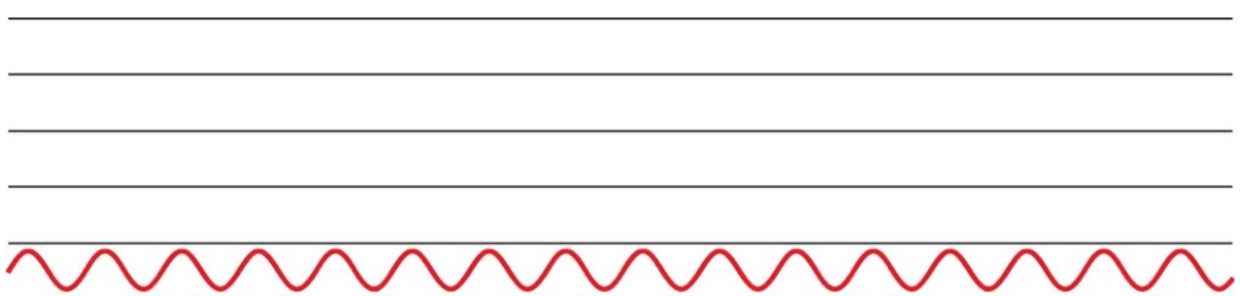
$$\theta_c = \sqrt{\frac{2U_{max}}{pv}}$$

Critical angle

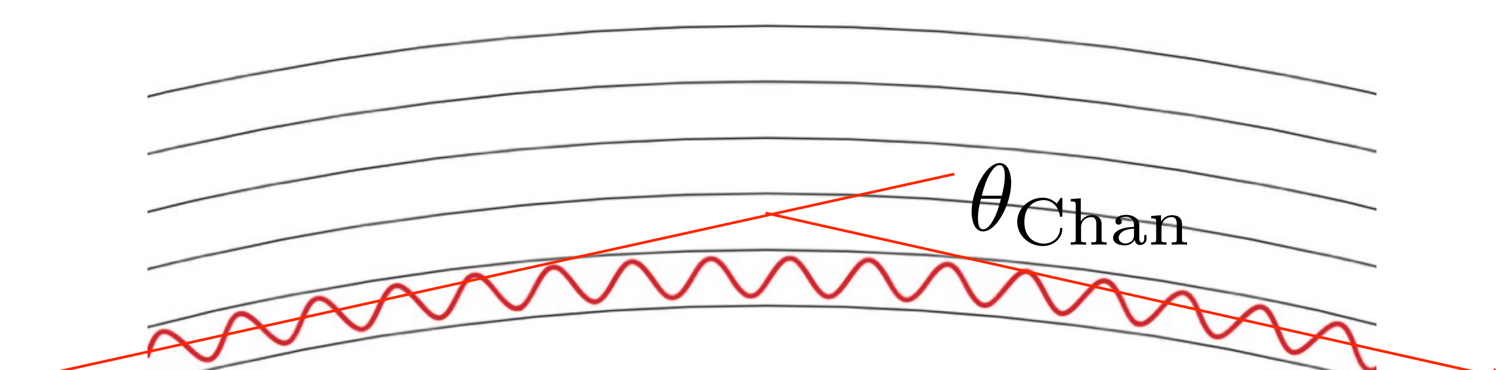


LHC 450 GeV	=	9.4 µrad
LHC 6.5 TeV	=	**2.4 µrad**
FCC-hh 50 TeV	=	0.9 µrad

Straight crystal: hadron oscillate, "trapped" between planes



Bent crystal

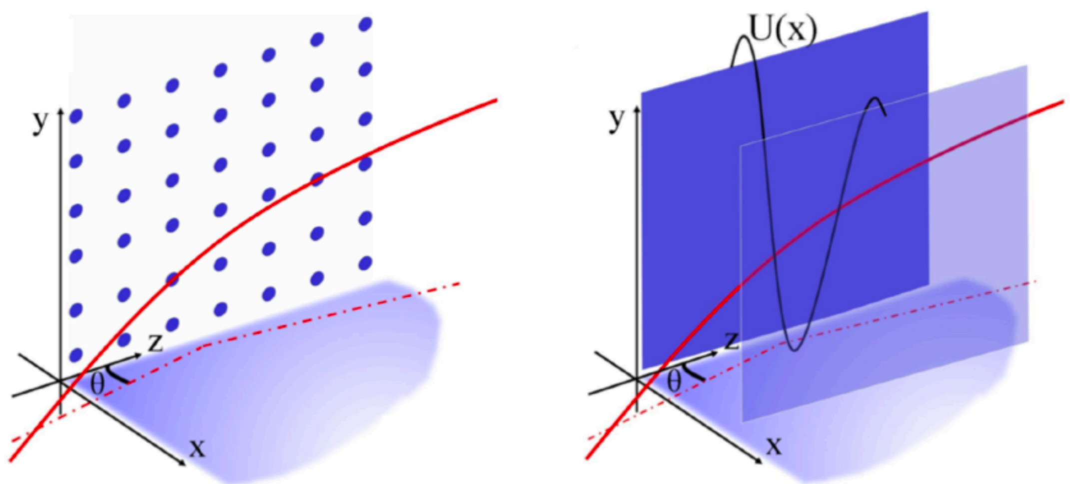


Mechanical bending of crystal produces a net kick of trajectories of the particles trapped between planes.

Equivalent magnetic field for **50µrad** at **7 TeV** proton beams: **310 T** (4 mm crystal)

Planar channeling in bent crystals

Pure crystals with regular lattices



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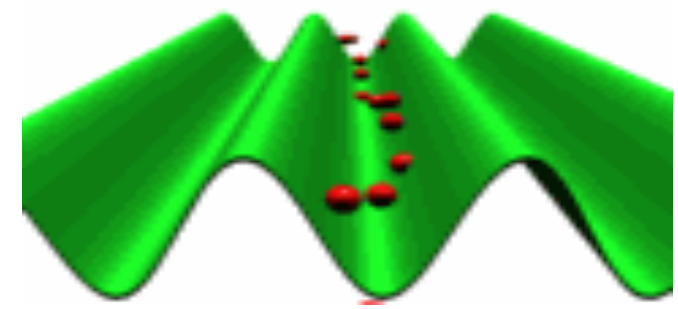

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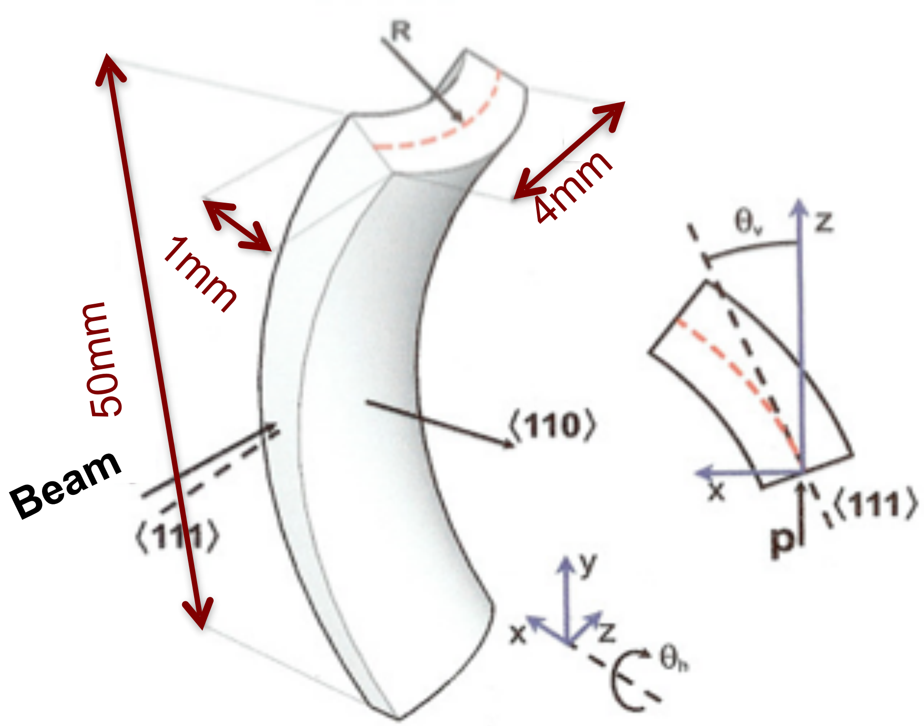
LHC design parameters for **Silicon crystals**



Bending 50μrad

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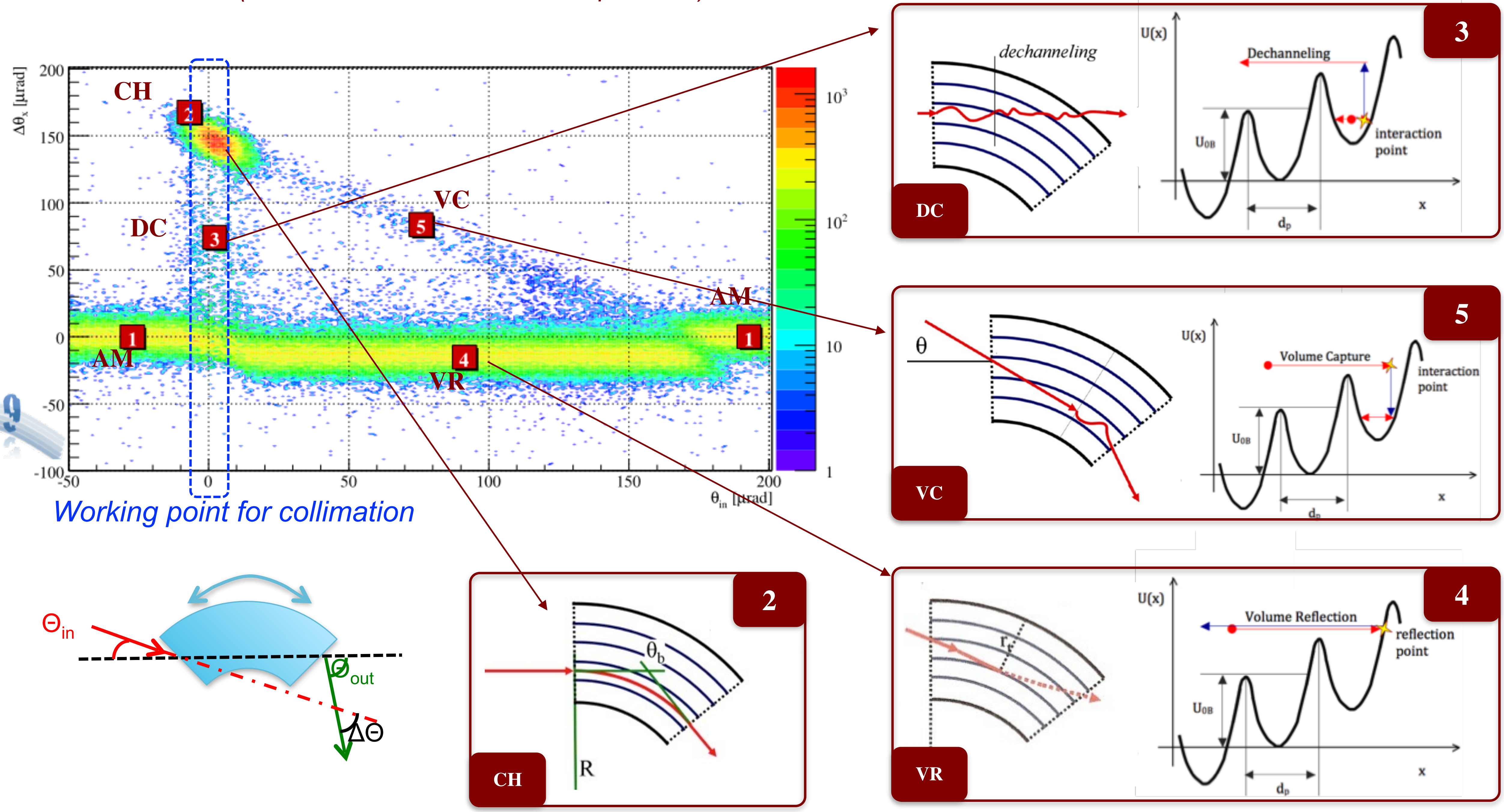
Crystal-hadron coherent interactions

***From test beam** on the CERN-SPS extraction line H8:*
(in the framework of the UA9 experiment)



Working point for collimation

See for an extensive overview Phys. Rept. 815 (2019) 1-107

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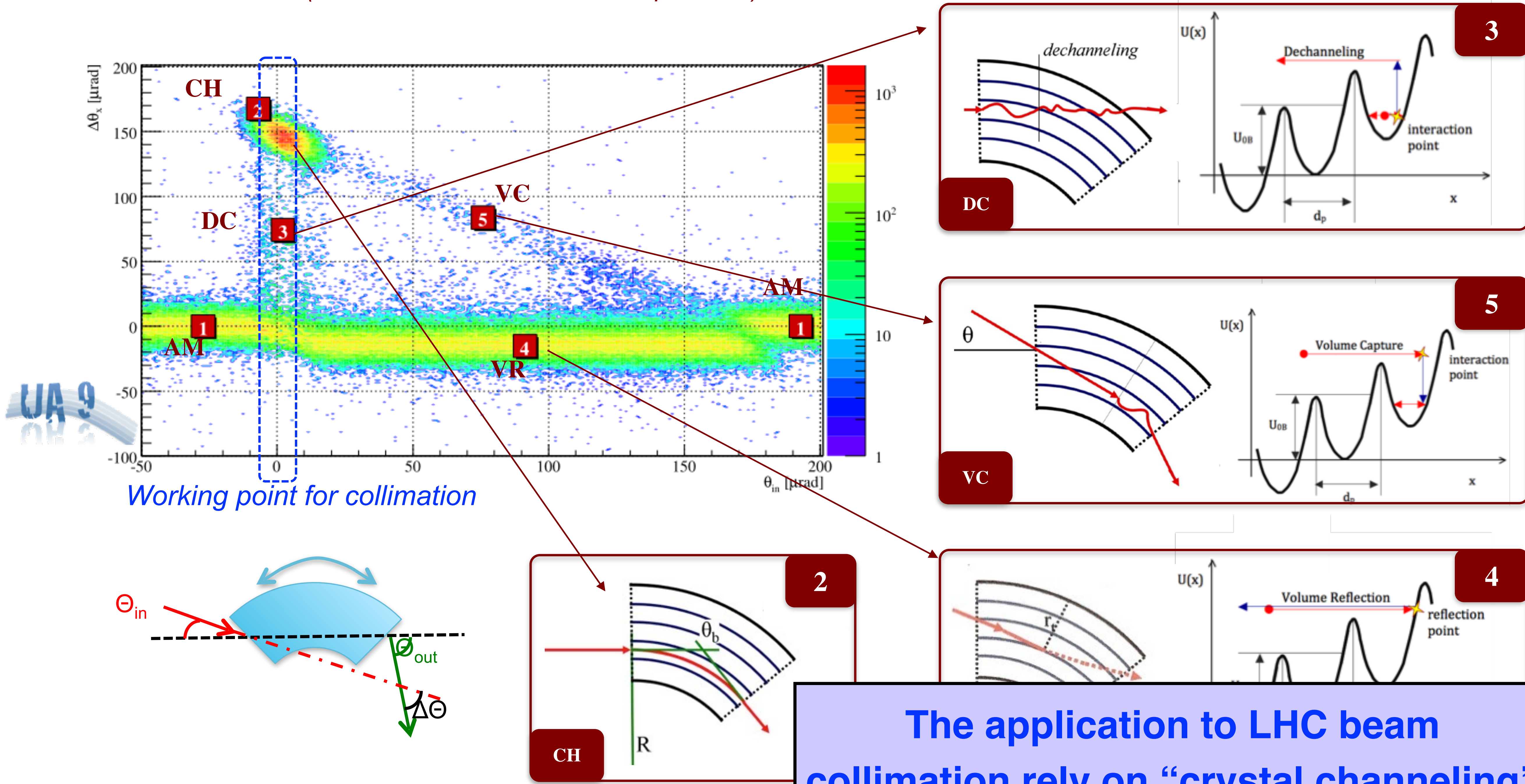
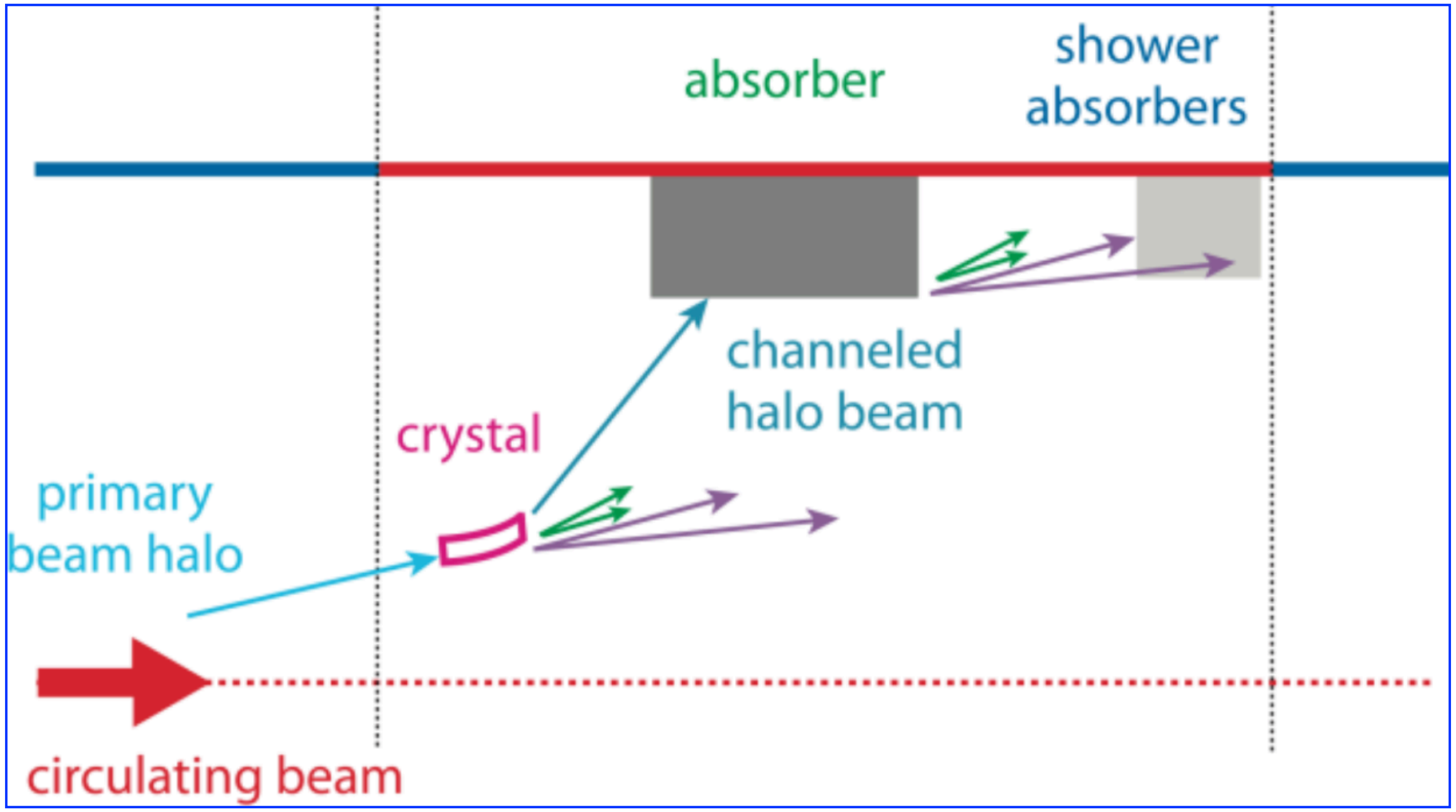


The application to LHC beam collimation rely on "crystal channeling"

See for an extensive overview Phys. Rept. 815 (2019) 1-107

The crystal collimation concept

(replacing the 3-stage betatron cleaning)



The rest of the hierarchy (protection, inner triplet, etc…) remains needed!

Crystal-based betratron halo cleaning

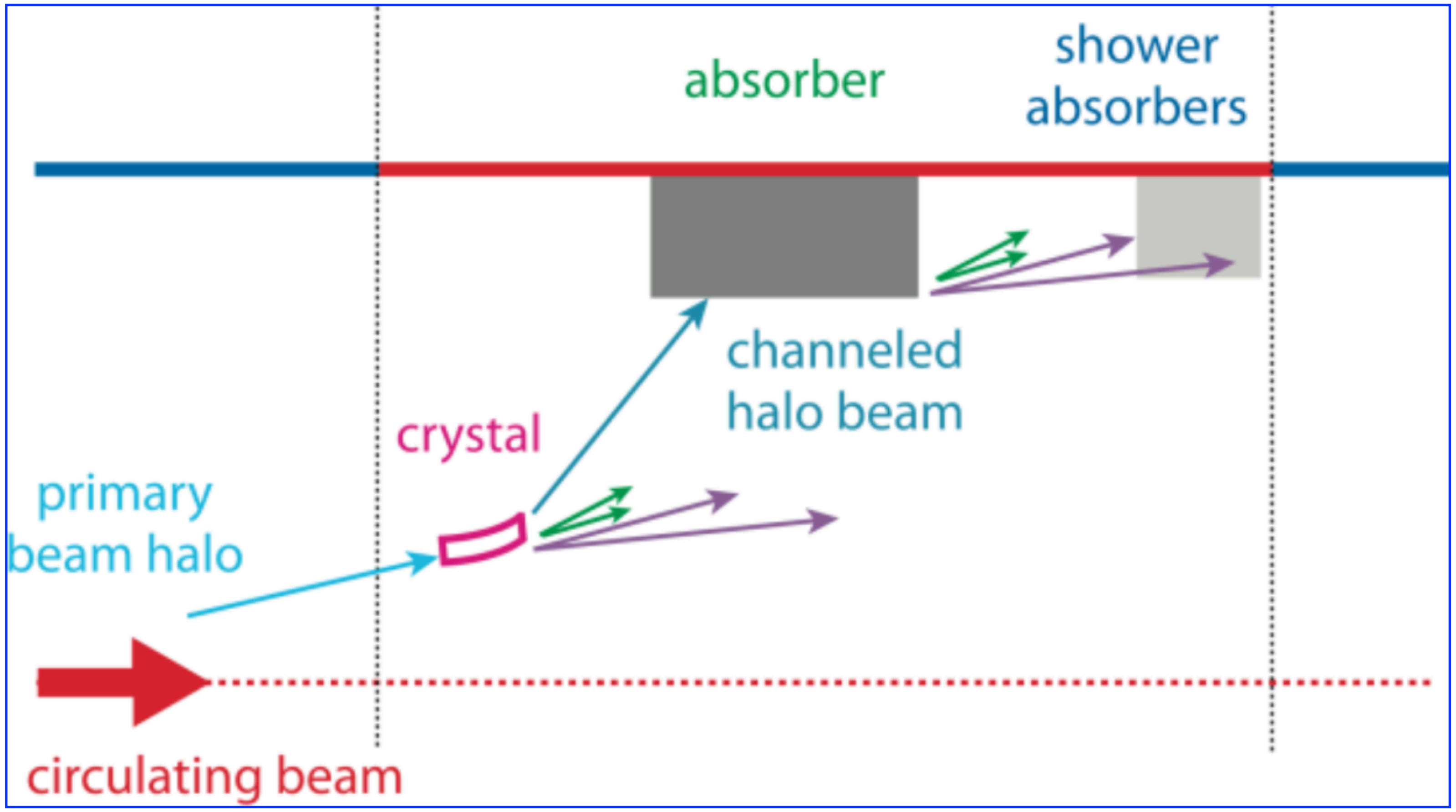
- Bent crystal replaces horizontal and vertical primary collimators
- A single massive absorber (per plane) intercepts the channeled halo
- Needs additional shower absorbers, but "cleaner" disposal of primary losses

Promises: Improvement of cleaning, with fewer collimators, in particular for heavy ion beams (suppress of fragmentation/dissociation!)

Challenges: Quality and performance of crystal assembly (new energy regime)
Angular control within sub-micro radiants
Safe and efficient disposal of channeled halo

The crystal collimation concept

(replacing the 3-stage betatron cleaning)



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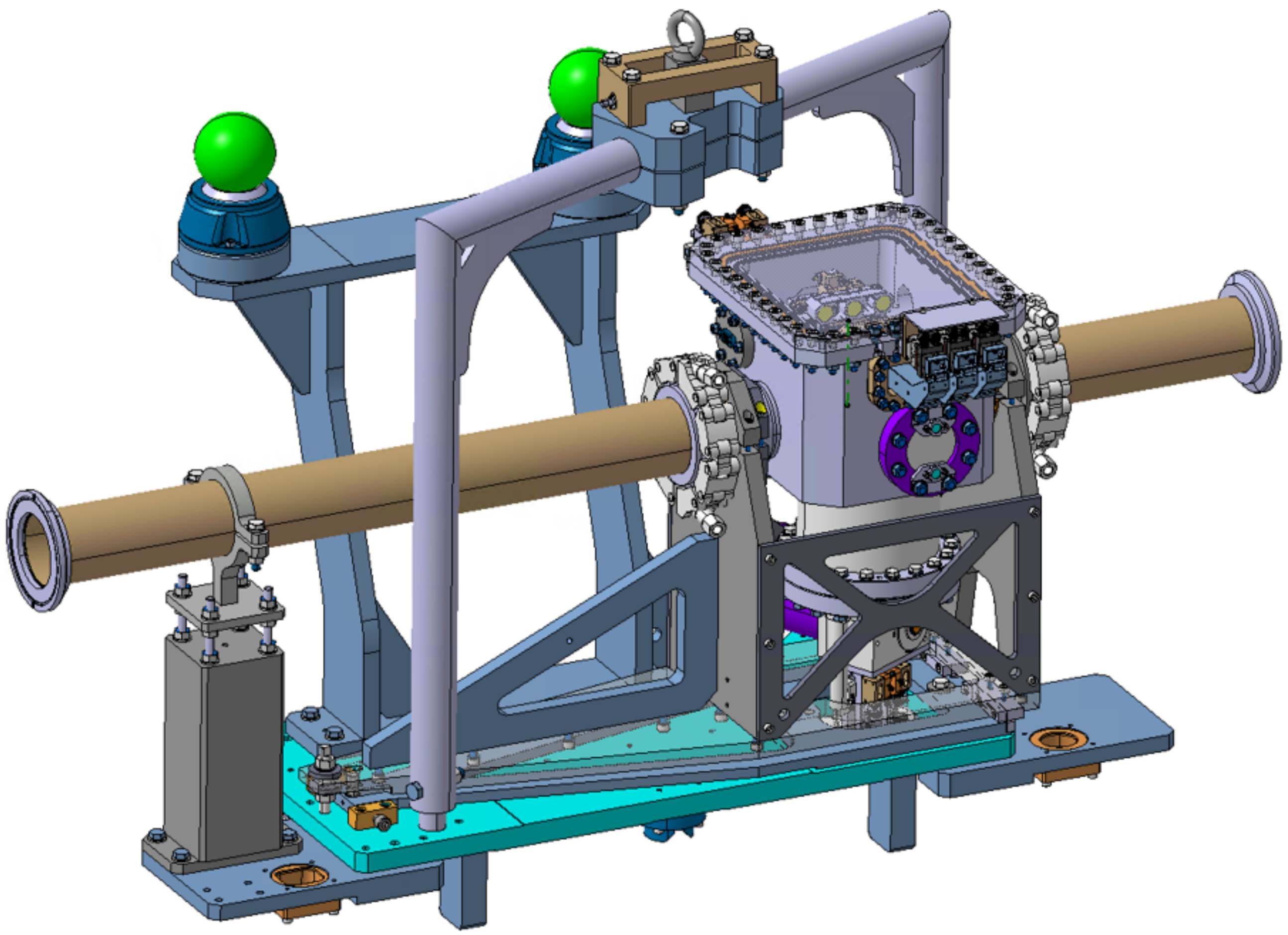
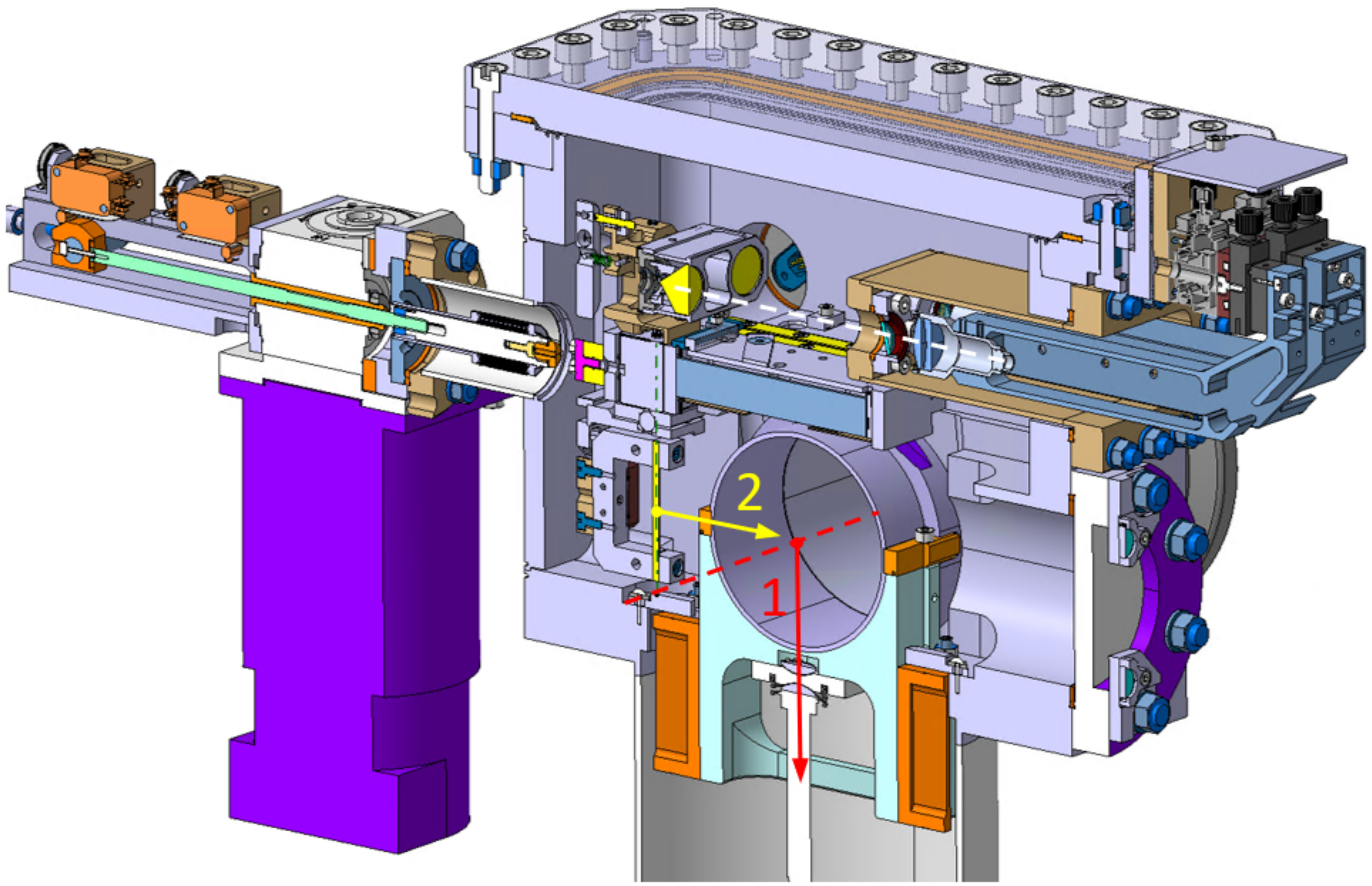
Promises: Improvement of cleaning, with fewer collimators, in particular for

Challenges: Qu ne)
An
Sa

Never used operationally in colliders until 2023.
Decision to install a **crystal collimation test stand** as part of the LHC collimation betatron system to assess performance benefit and operational aspects with **LHC conditions**.

The crystal collimator





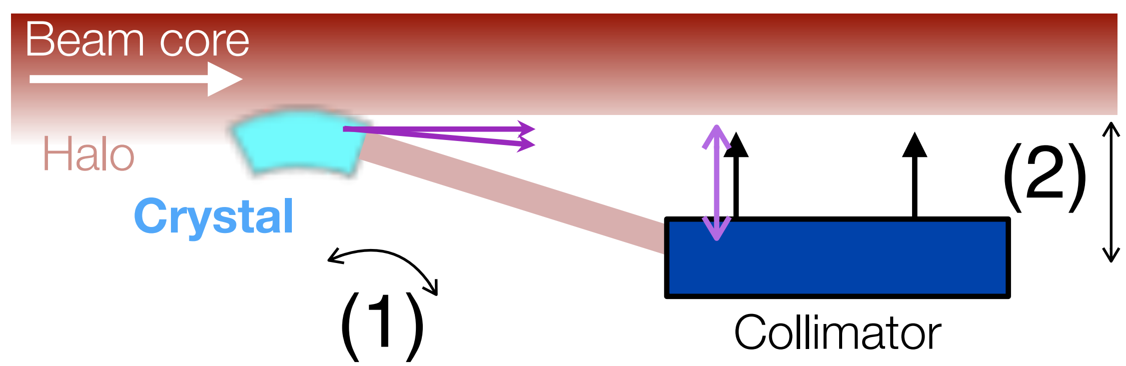
4mm along the beam direction give 50μrad

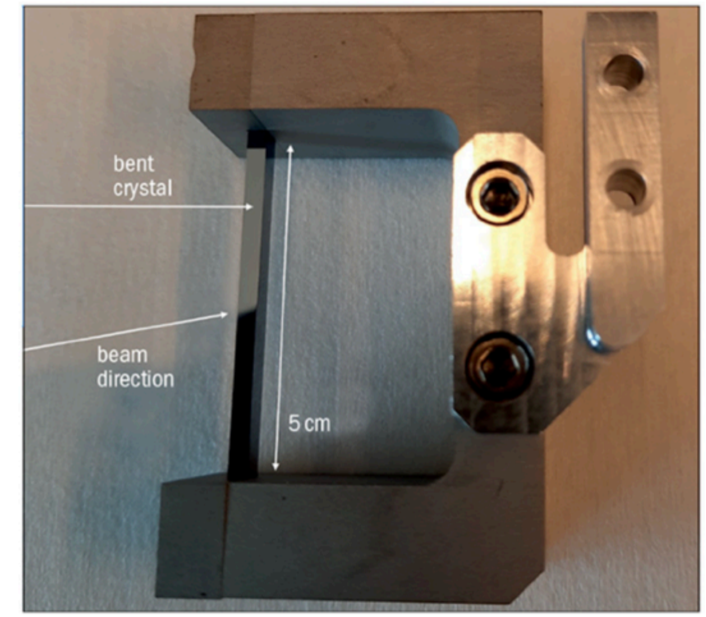
Courtesy SY/STI, BE/CEM, INFN-Fe

Channeling observations at the LHC

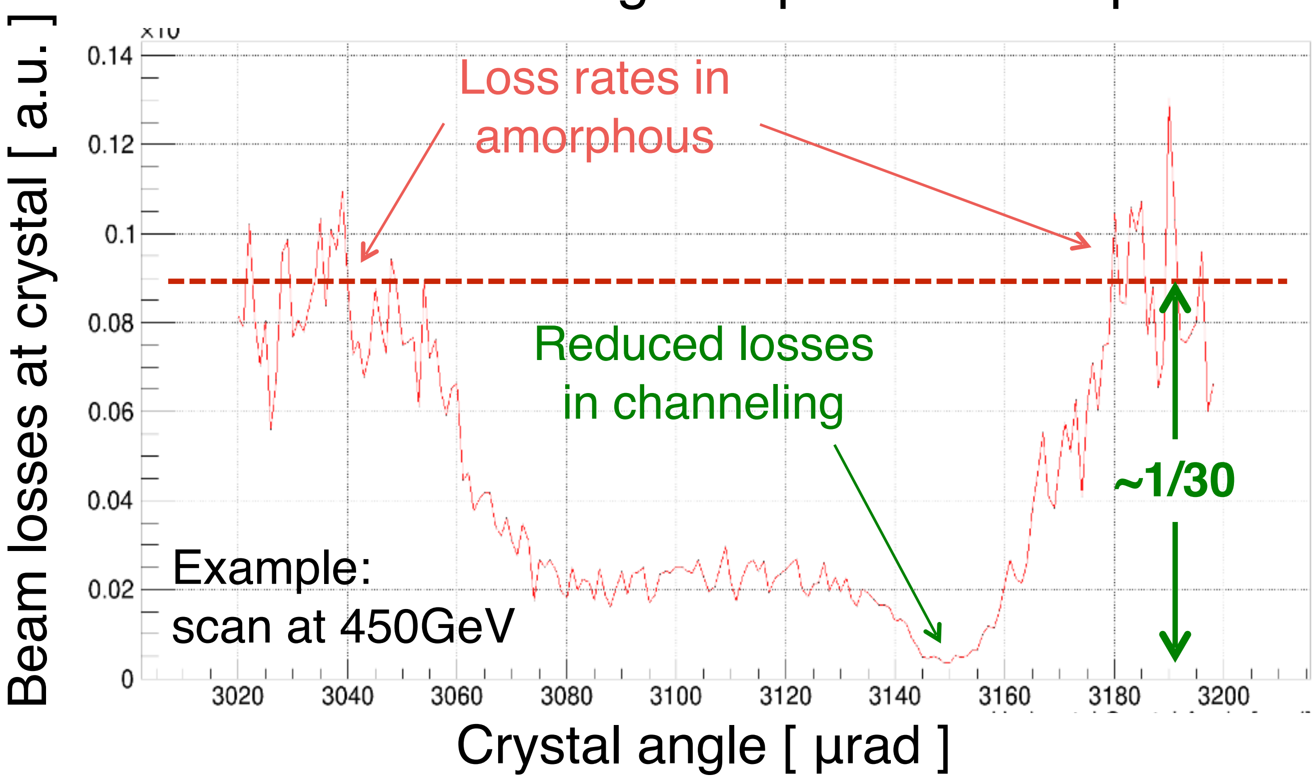
Key measurements: crystal angular scans and linear collimator scans

Established in other circular accelerators, in particular: useful operational experience at the SPS (UA9 setup).

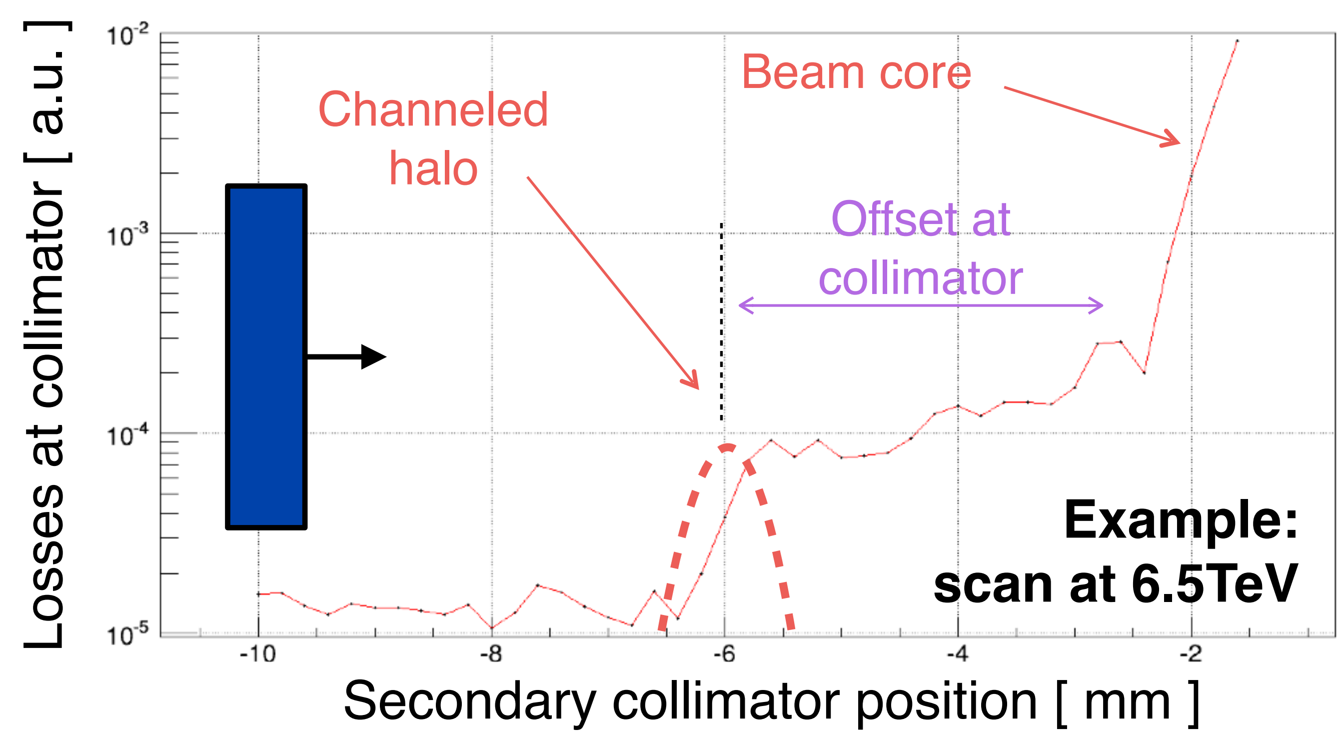




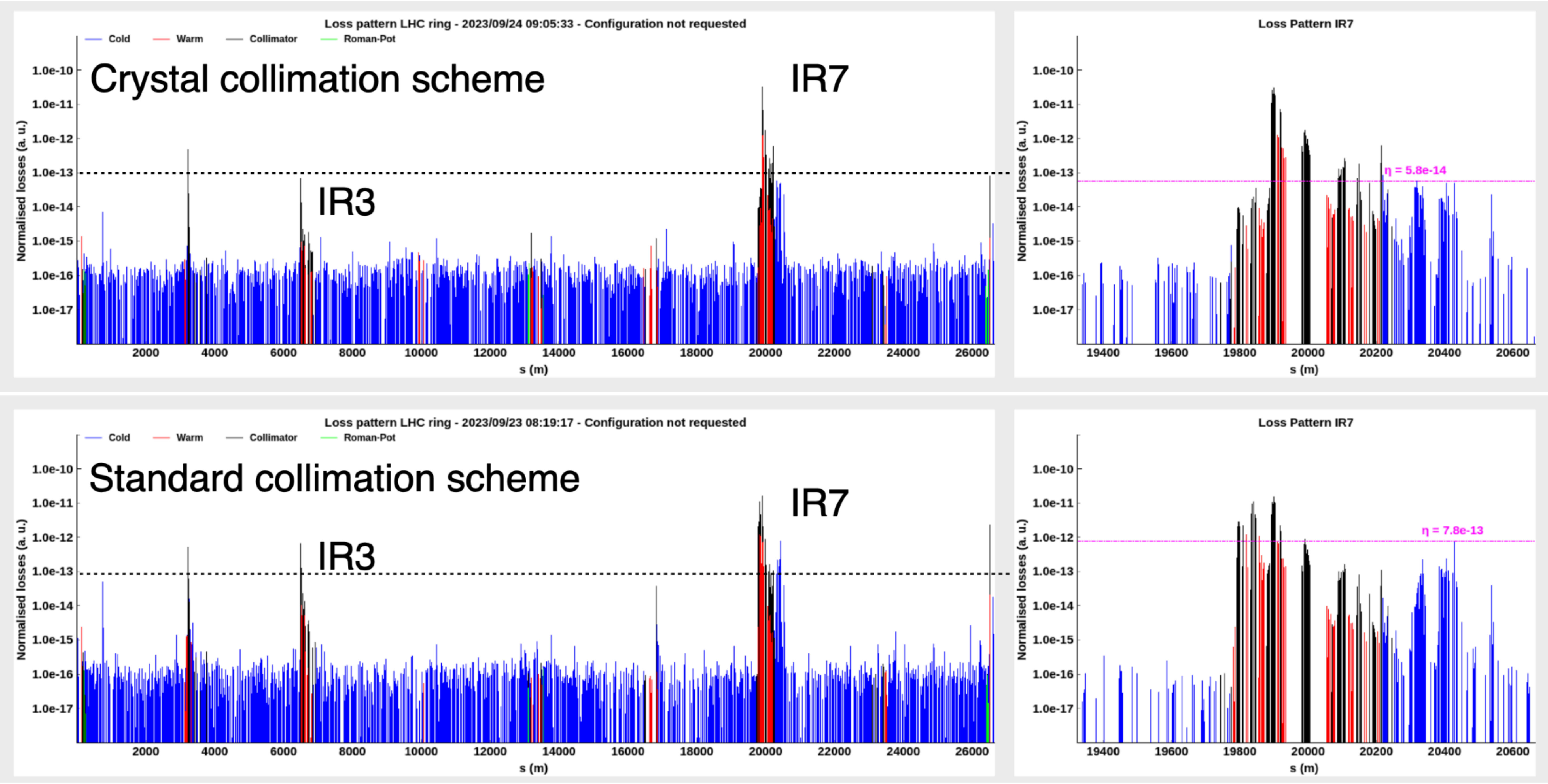
(1) **Angular scan**: strong reduction of local losses in channeling compare to amorphous.



(2) **Linear collimator scan**: measures the profile of the channeled halo.



Collimation performance Pb beams



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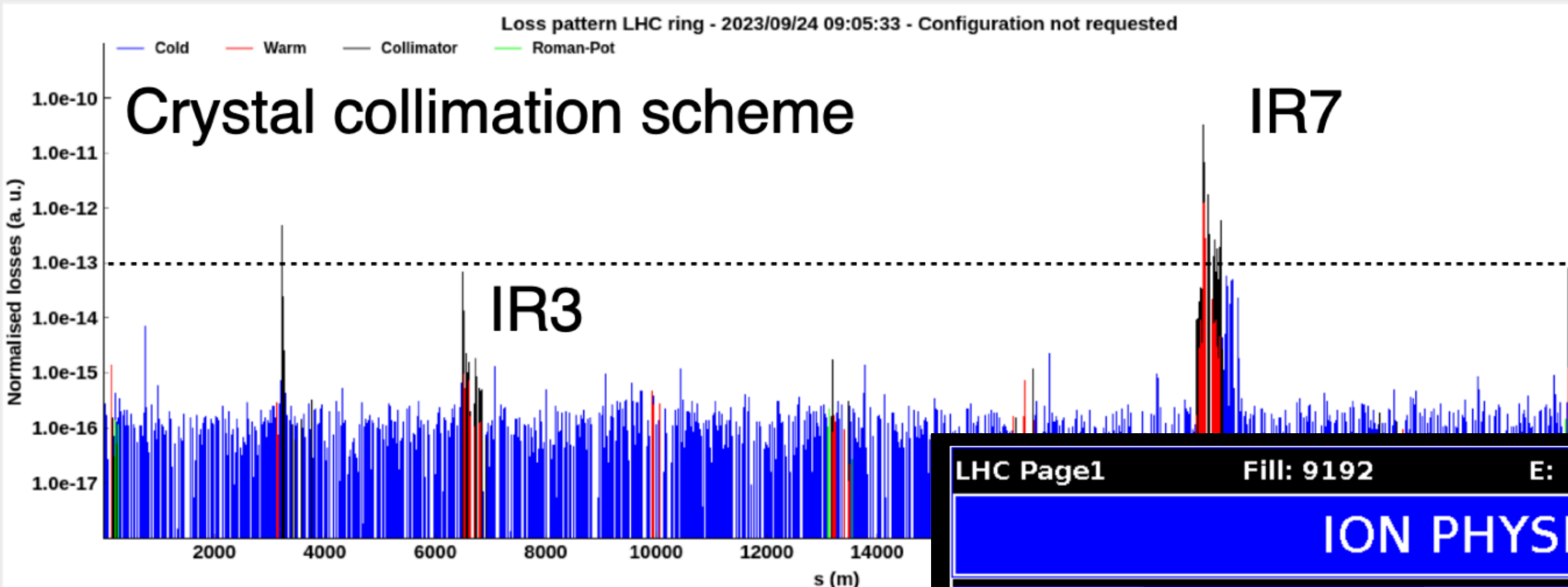
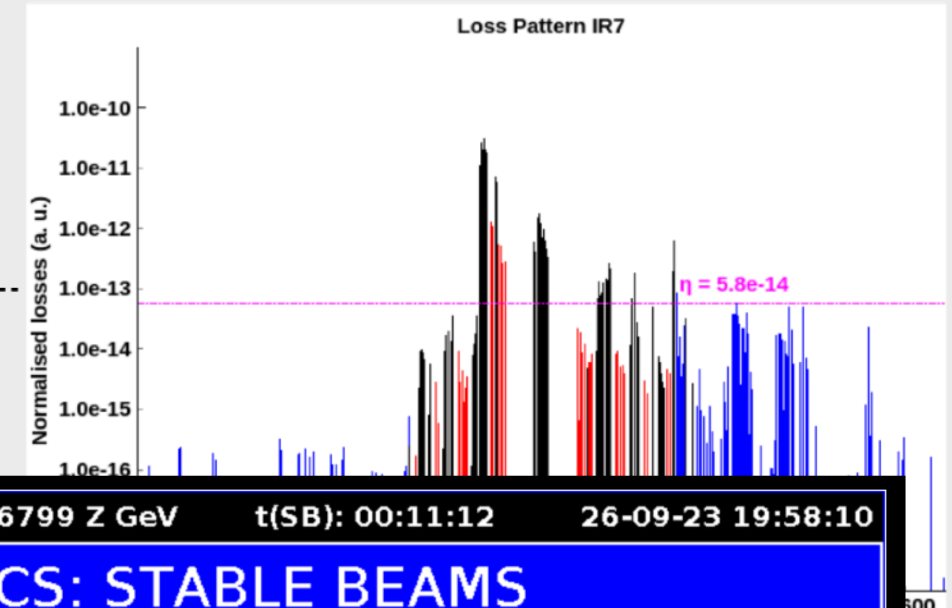
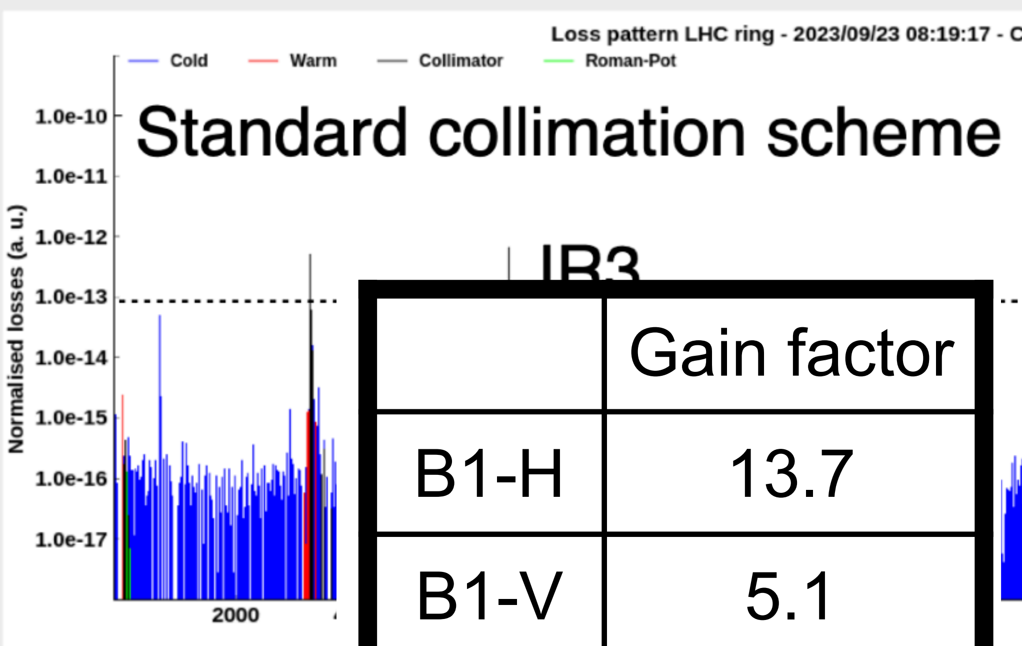
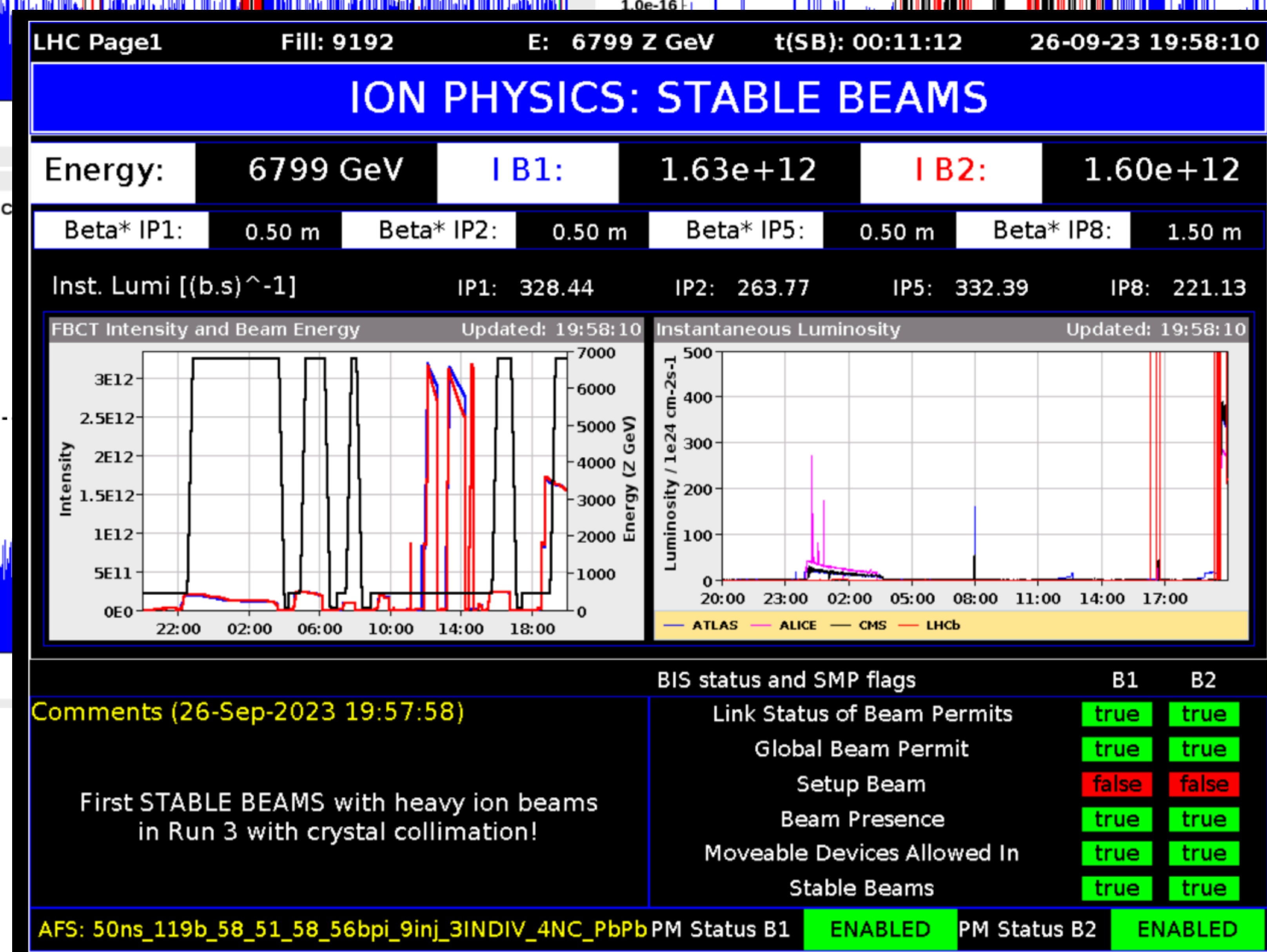






	Gain factor
B1-H	13.7
B1-V	5.1
B2-H	4.9
B2-V	6.5



Thanks for your attention!