Jörg Wenninger
CERN Beams Department
Operation group / LHC

Beam cleaning, collimation and beam absorbers

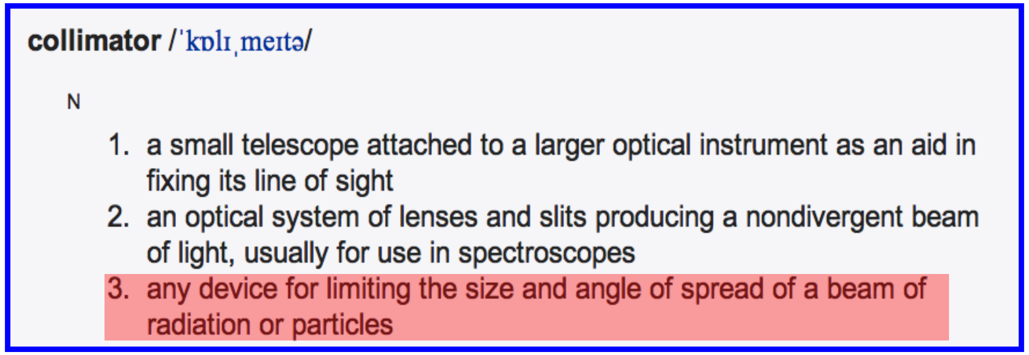
Acknowledgements:
R. Schmidt, D. Mirarchi,
S. Redaelli, A. Bertarelli

USPAS
Machine Protection & Beam Loss
Houston, January 2023

- **Introduction to collimation and absorbers**
- **Collimation requirements and design**
- **Collimator hardware**
- **Collimation system operation**
- **Synchrotron radiation collimation**
- **Novel collimation techniques**
- **Dump absorbers**

Beam collimation - introduction

A collimator is generally viewed as a device positioned at a certain distance to the beam to intercept particles.



collimator /ˈkɒlɪˌmeɪtə/

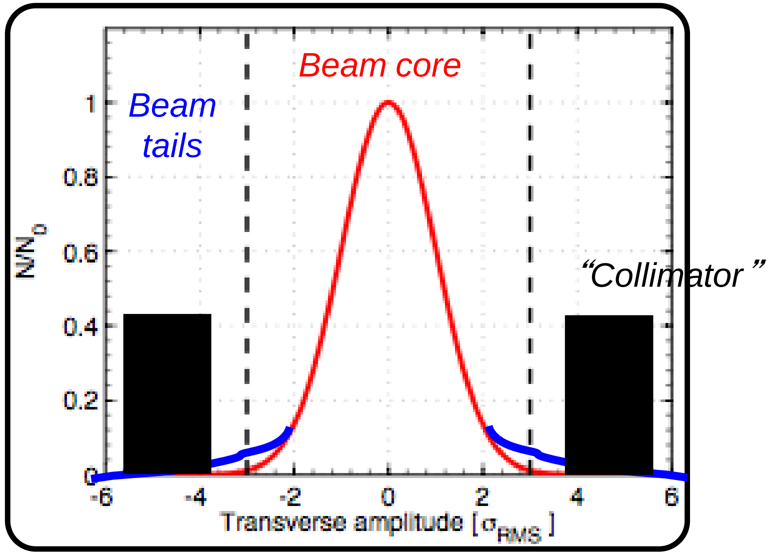
N

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

The *classical* use case is **beam halo collimation:**

Controlled disposal of beam halo particles, which is achieved by reducing the transverse cross section of the beam.

There may be different goals of **collimation systems** depending on the machine



Roles of collimation systems and absorbers

Halo cleaning to protect accelerator components
Superconducting and permanent magnets, superconducting RF cavities etc.

Passive **machine protection** as beam absorbers or interceptors
First line of defense in case of accidental failures.

Concentration of losses/activation in well defined areas
Ease maintenance by avoiding many distributed high-radiation areas.

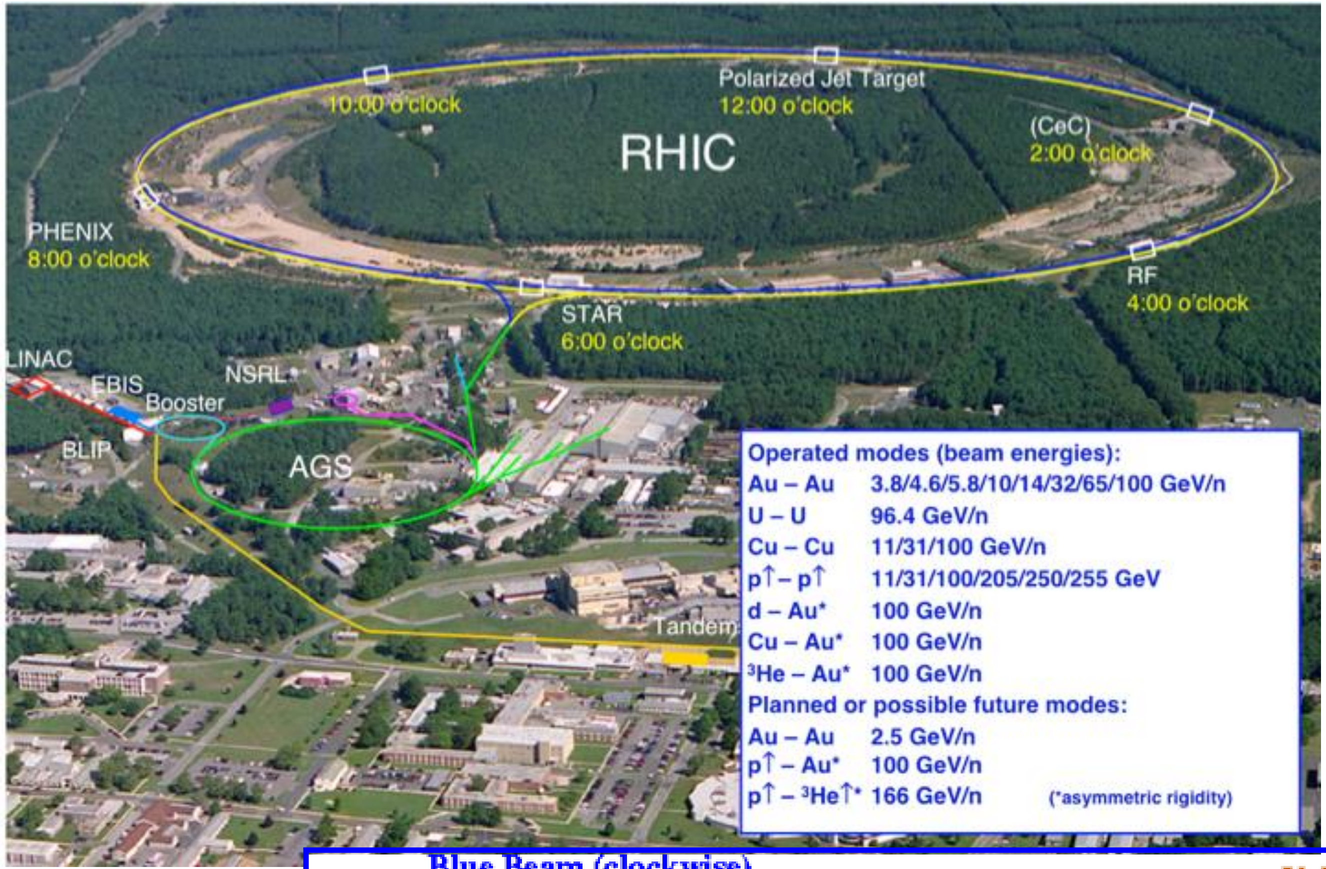
Reduction the radiation doses to accelerator components
Provide local protection to equipment exposed to high doses.

Cleaning of physics debris (physics products, in colliders)
Protect superconducting elements close to high-luminosity experiments.

Background optimization for experiments
Minimize the impact of halo losses or photons (for e+e-) on the quality of experimental data.

Beam **tail/halo scraping** and **diagnostics**
Control and probe the transverse or longitudinal shape of the beam.

Collimation RHIC



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

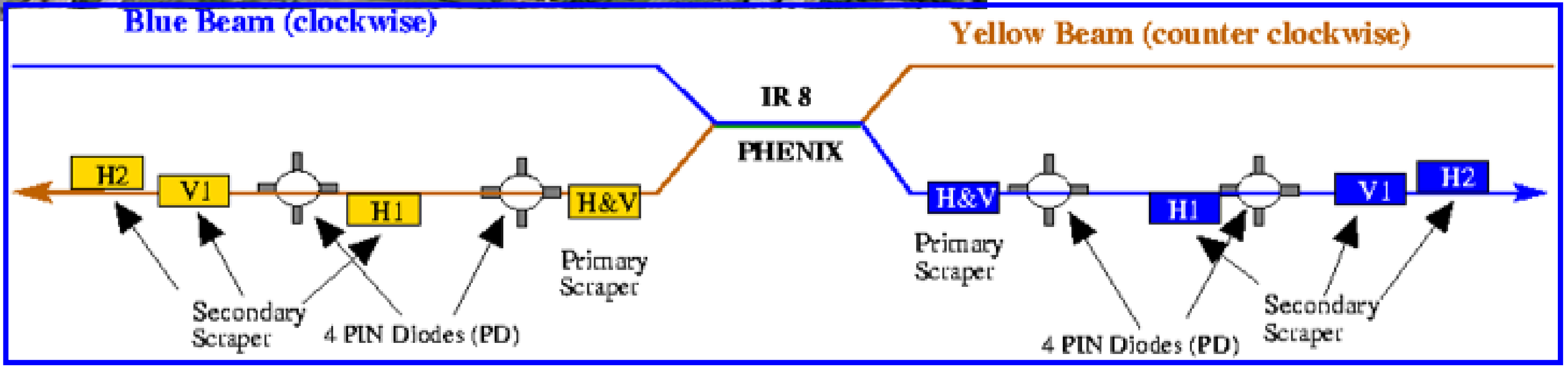
(*asymmetric rigidity)

RHIC beam parameters [p]:

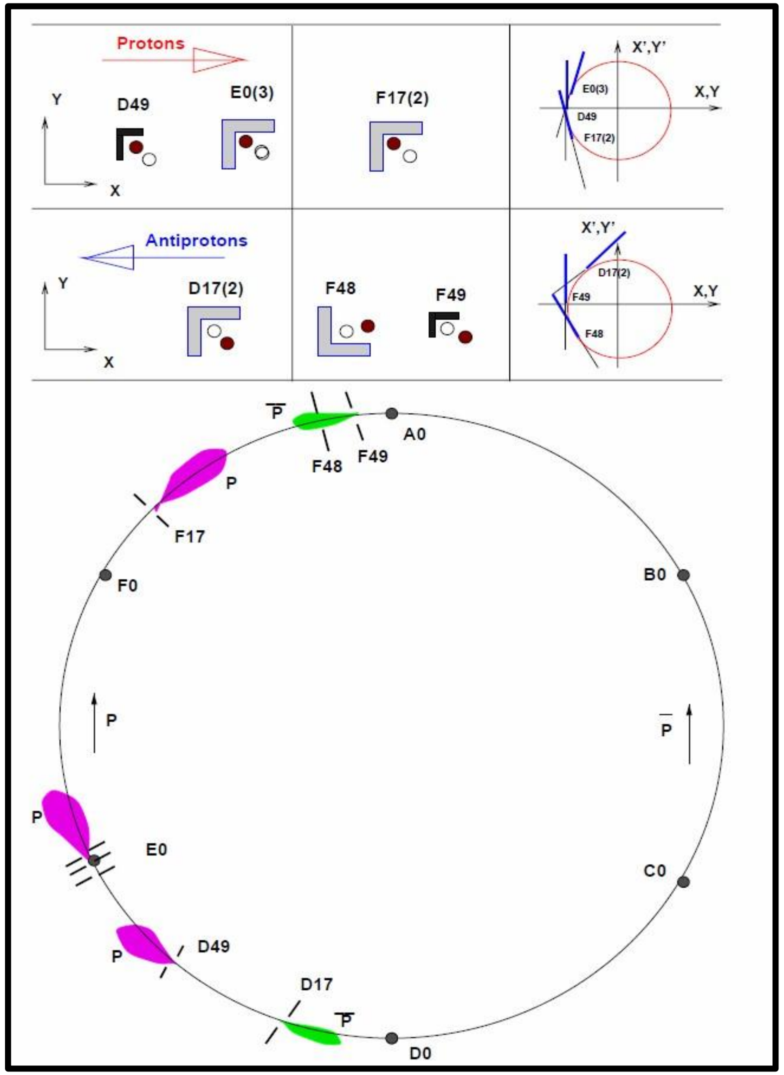
E_b = 250 GeV
N_{tot} = 110 x 10^{11}p
E_{stored} = ~ 440 kJ

Collimation system:

8 collimators
Some with L shape



Collimation Tevatron



Tevatron Run II parameters:

E_b = 1 TeV

E_{stored} = ~ 2 MJ

Collimation system:

13 collimators, L shape

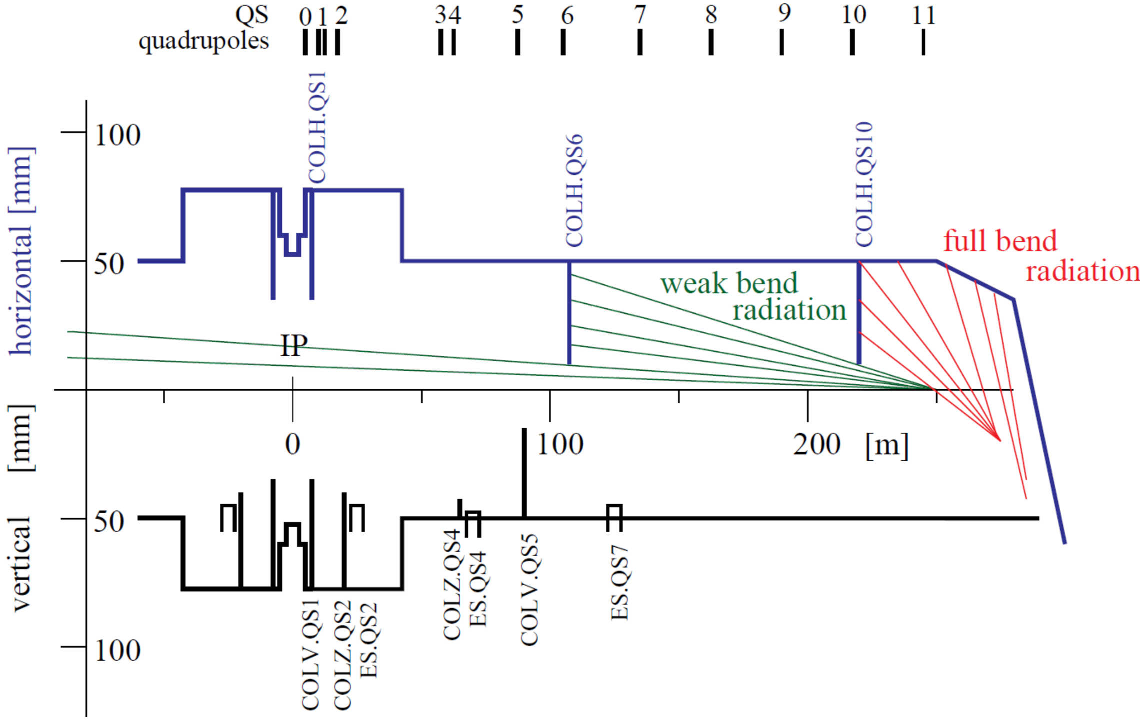
26 degrees of freedom for positioning

N. Mokhov et al, Fermilab-Pub-11-378-APC

Collimation LEP (1989-2000)

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 up to ~15 MW / beam

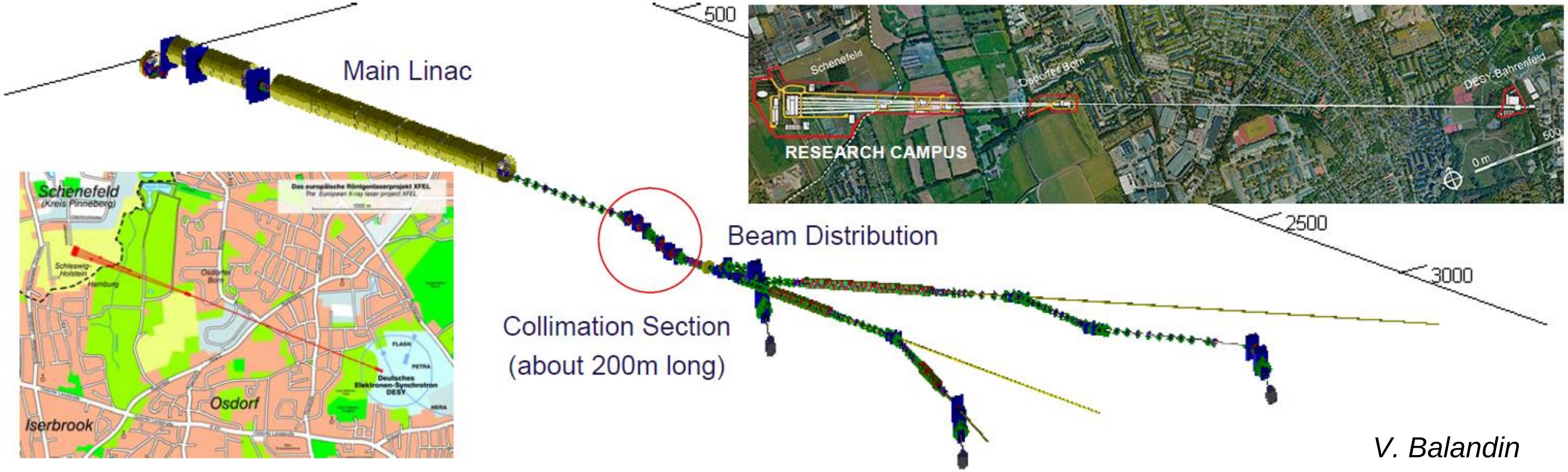


LEP collimation system:

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

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

Collimation at XFEL



Main Linac

Beam Distribution

Collimation Section
(about 200m long)

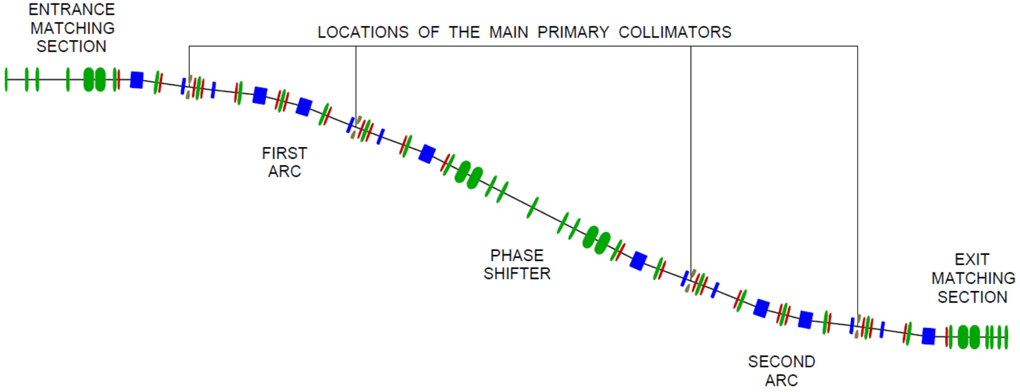
V. Balandin

XFEL parameters:

- $E_b = 17.5$ *GeV*
- $I_b = 1$ *nC* ~ 1.6×10^{10} e$^-$
- $N_b = 3000$
- *Repetition rate = 10 Hz*

XFEL collimation system:

- ~20 double jaw collimators,
- *Primary, supplementing primary & secondary*
- *Made of Titanium alloy*



ENTRANCE MATCHING SECTION

LOCATIONS OF THE MAIN PRIMARY COLLIMATORS

FIRST ARC

PHASE SHIFTER

EXIT MATCHING SECTION

SECOND ARC

V.Balandin et al, TESLA-FEL Report 2007-05

Collimation LHC

LHC parameters (current):

E_b = 6.8 TeV

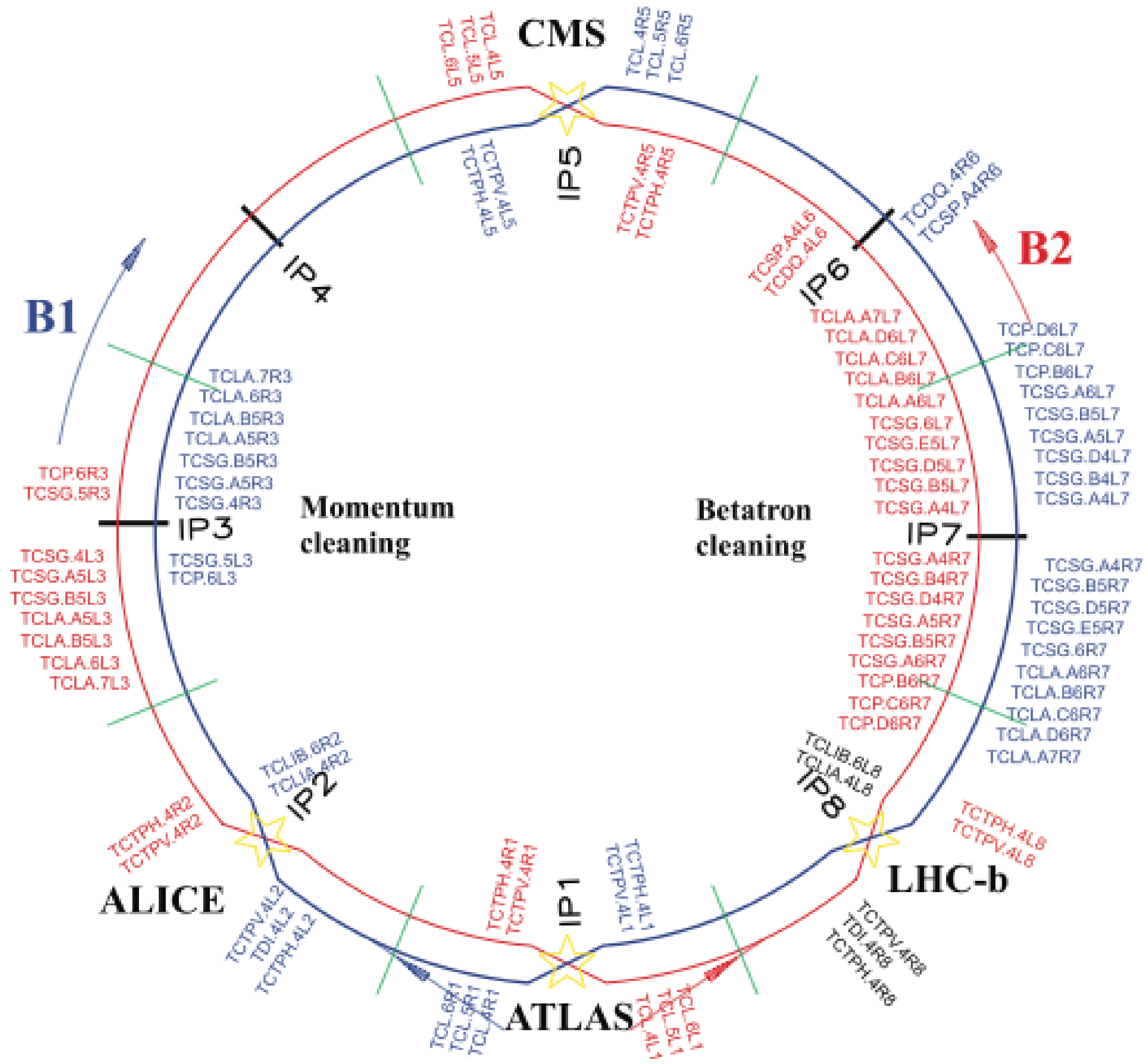
I_{bunch} = 1.5 x 10^{11} p

I_{tot} = 3.6 x 10^{14} p

E_{stored} = 400 MJ

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

Made of graphite, tungsten and copper.

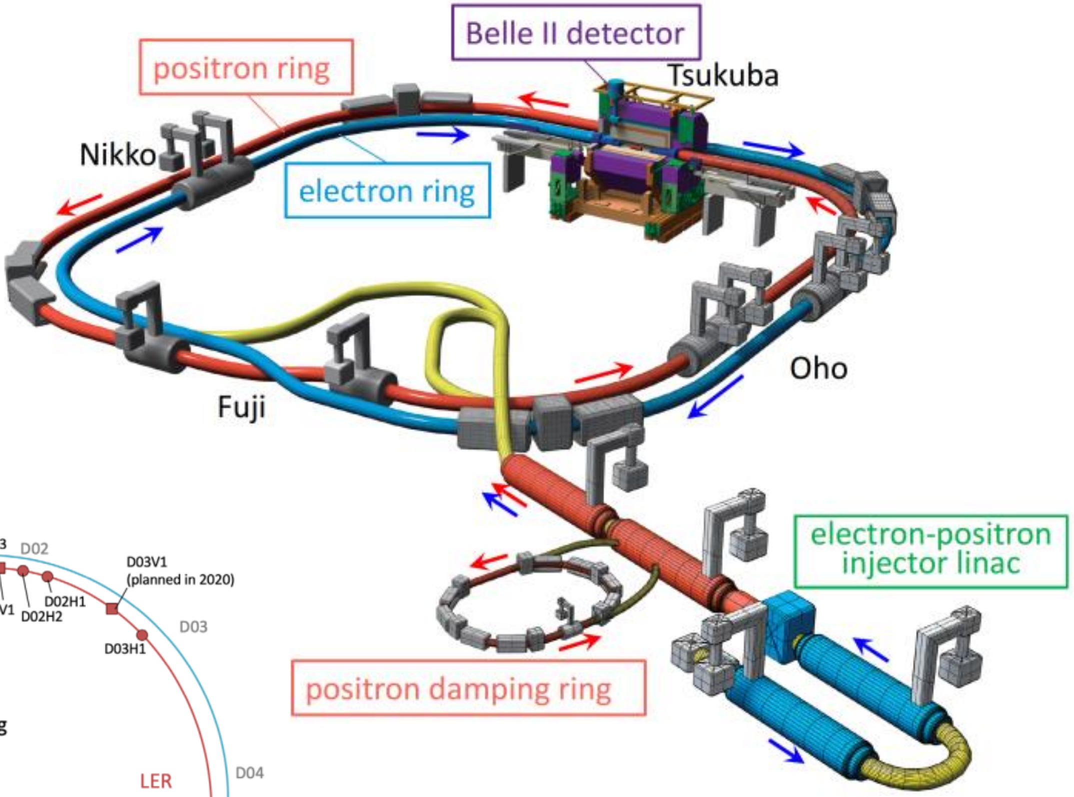


R. Bruce el al, PRSTAB 17, 081004 (2014)

Collimation superKEKB

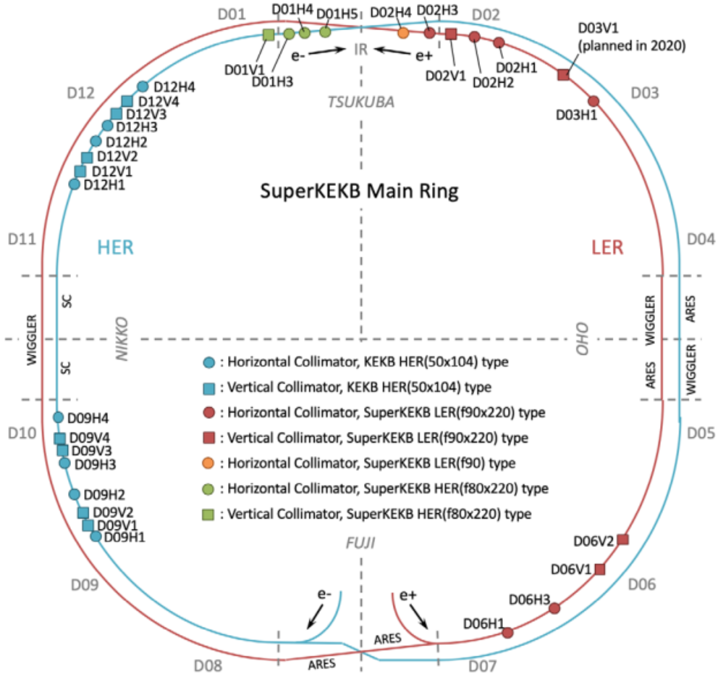
superKEKB parameters (2020):

E_b = 7 GeV e- (HER) / 4 GeV e+ (LER)
Beam currents = 2.6 A (HER) / 3.6 A (LER) – design
1.2 A (HER) / 1.4 A (LER) – achieved
E_{stored} = 182 kJ (HER) / 144 kJ (LER) – design



A large collimation system based on Copper+Tungsten collimators, the system is essential to operate the BELLE detector.

- Beam background control.



T. Ishibashi el al, PRAB 23, 053501 (2020)

- Introduction to collimation and absorbers
- **Collimation requirements and design**
- Collimator hardware
- Collimation system operation
- Synchrotron radiation collimation
- Novel collimation techniques
- Dump absorbers

High powers or stored energy

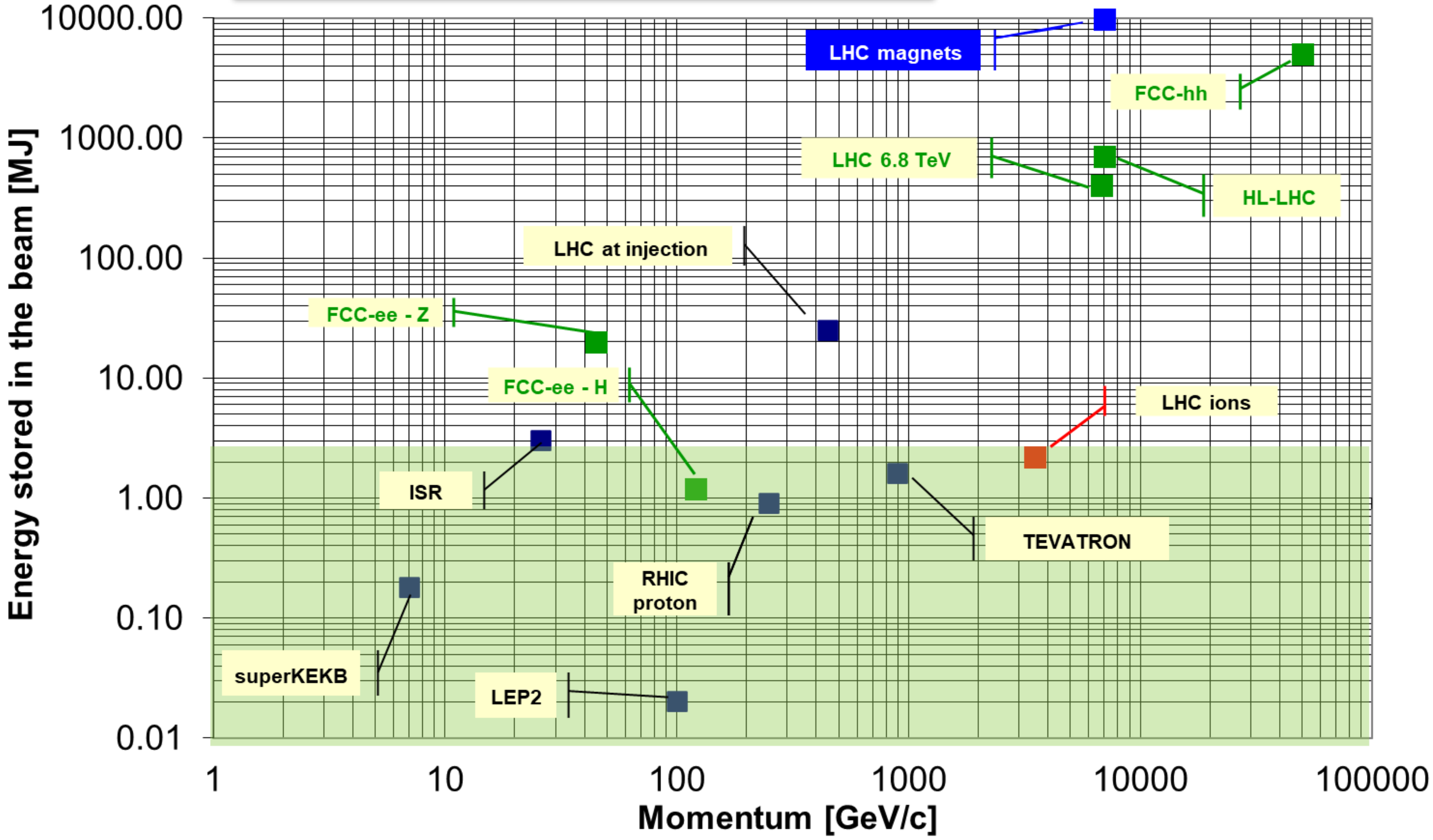
Many current and next generation accelerator facilities are relying on **large stored energy** (colliders like LHC or projects like FCC-hh) or on **high power** (SNS, ESS, ILC, CLIC).

- The machines, often based on **super-conducting elements**, must be protected against failures and against steady state losses to **prevent quenches**.

Current / future e^+e^- colliders like super-KEKB, FCC-ee, CEPC will have to deal with high powers, **synchrotron radiation** or **beam induced heating** are main concerns.

Stored energy – colliders

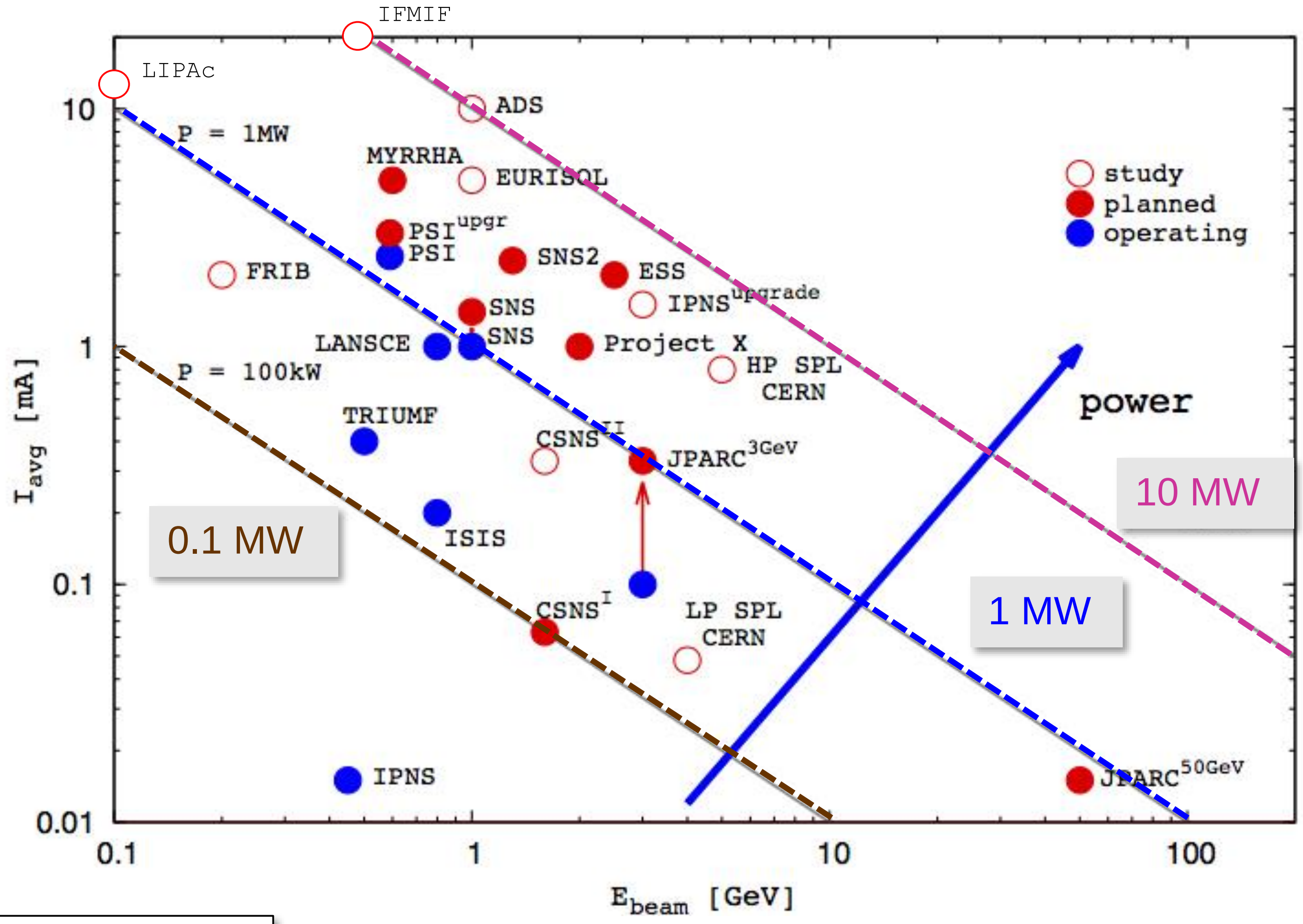
World record @ LHC: 400 MJ @ 6.8 TeV



High power hadrons sources

Planned projects: 1-10 MW range

Courtesy M. Lindroos



ILC ~ 20 MW

Beam losses during operation

In an **ideal world** there is no beam loss throughout the operational cycle of a machine.

- There is no need for a collimation system !

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

- ***Collisions*** *at the interaction points (beam burn up),*
- *Interaction with* ***residual gas*** *and* ***intra-beam scattering,***
- ***Beam instabilities*** *(single-bunch, collective, beam-beam),*
- *Dynamics changes during machine cycle (orbit and optics changes, energy ramps, ...):* ***operational losses****,*
- *Transverse* ***resonances****,*
- *RF noise, RF capture and out-of-bucket losses,*
- *Injection and dump losses,*
- *Synchrotron radiation,*
- *Equipment failures.*

Beam losses occur on many time scales !

Collimation design – proton beams

In machines affected by beam losses, a **collimation system** may be required to intercept the **primary beam losses** ("primary halo") and to absorb the energy.

- *Collimation designed to handle losses that otherwise would occur in an uncontrolled way.*

Design loss rates can be calculated from the **beam intensity** and **beam energy** assuming for example a "**minimum allowed beam lifetime**" (or maximum loss rate) during operation.

- The minimum lifetime corresponds to a steady state loss in a linear accelerator.
- **In LINACs the 1 W/m rule** is often used as upper limit (component activation).

A **collimation (or cleaning) inefficiency** is defined to express the fraction of the total loss that is deposited into sensitive equipment or that escapes the collimators.

- *Superconducting or other sensitive magnets, experiments (background), ...*

Beam lifetime and power loss

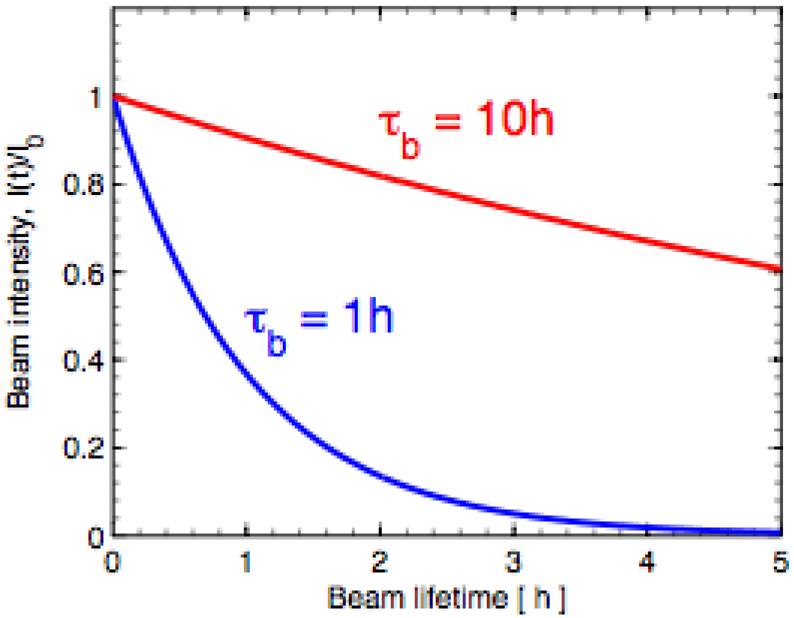
Beam loss mechanisms can be modelled assuming a finite **beam lifetime,** τ_b

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

Beam intensity versus time

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

Particle loss rate



Beam losses mechanisms are characterized by a (time-dependent) beam lifetime. This measures the **beam losses** that a collimation system must handle and defines the **power requirements.**

*Example for the LHC at 7 TeV: a **1h lifetime** at the full intensity of 3.2x10^{14} protons (320 hundred trillion protons!) corresponds to a loss rate of about 90 billion protons per second or **100 kW.***

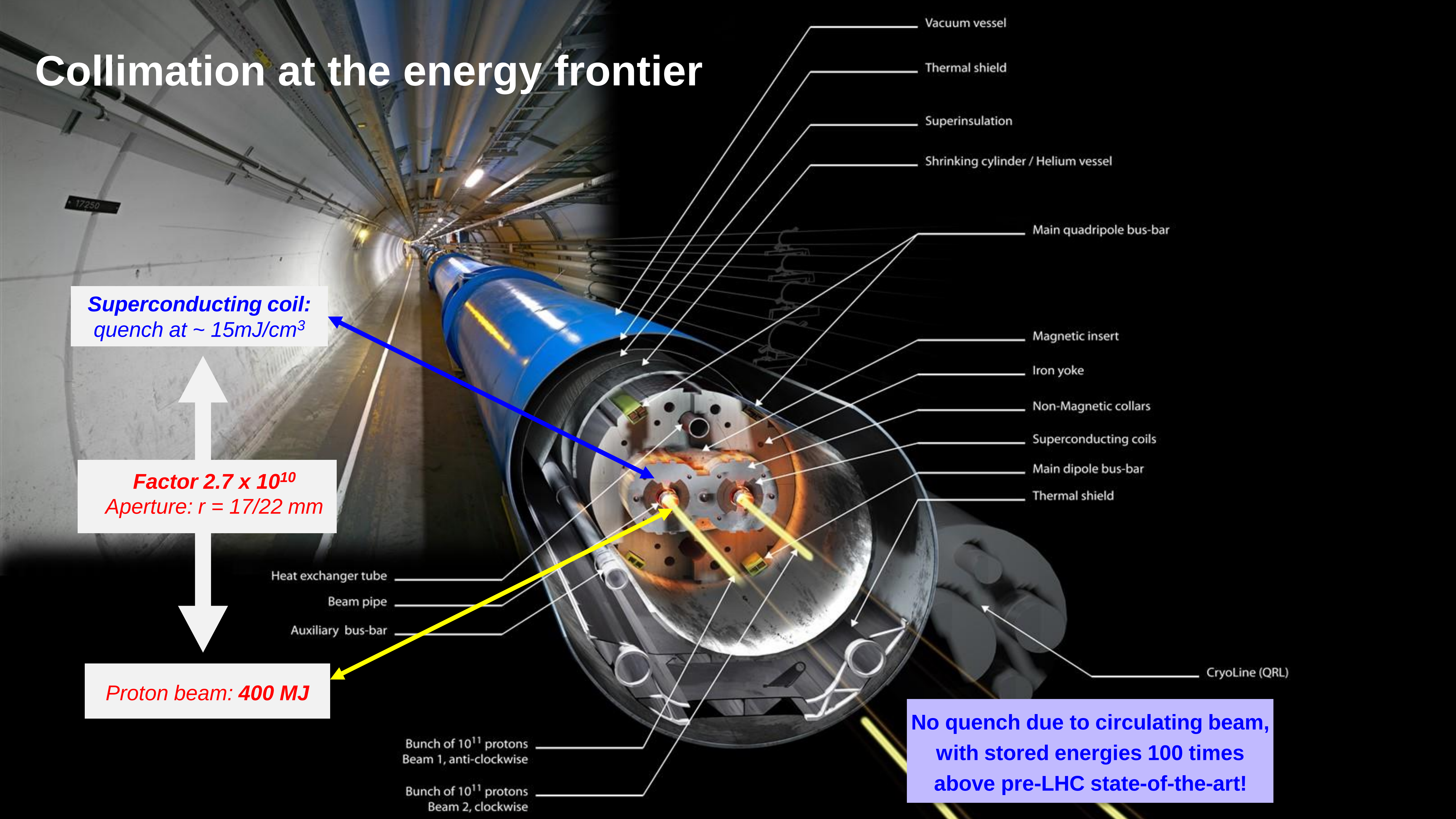
Example – high energy hadron collimation

As an example we consider the case of high energy hadron (protons or ions) collimation.

The collimation system must protect the accelerator against accidental losses and against the continuous losses from halo particles.

Why are some many collimators (100’s) needed at the LHC?

Collimation at the energy frontier



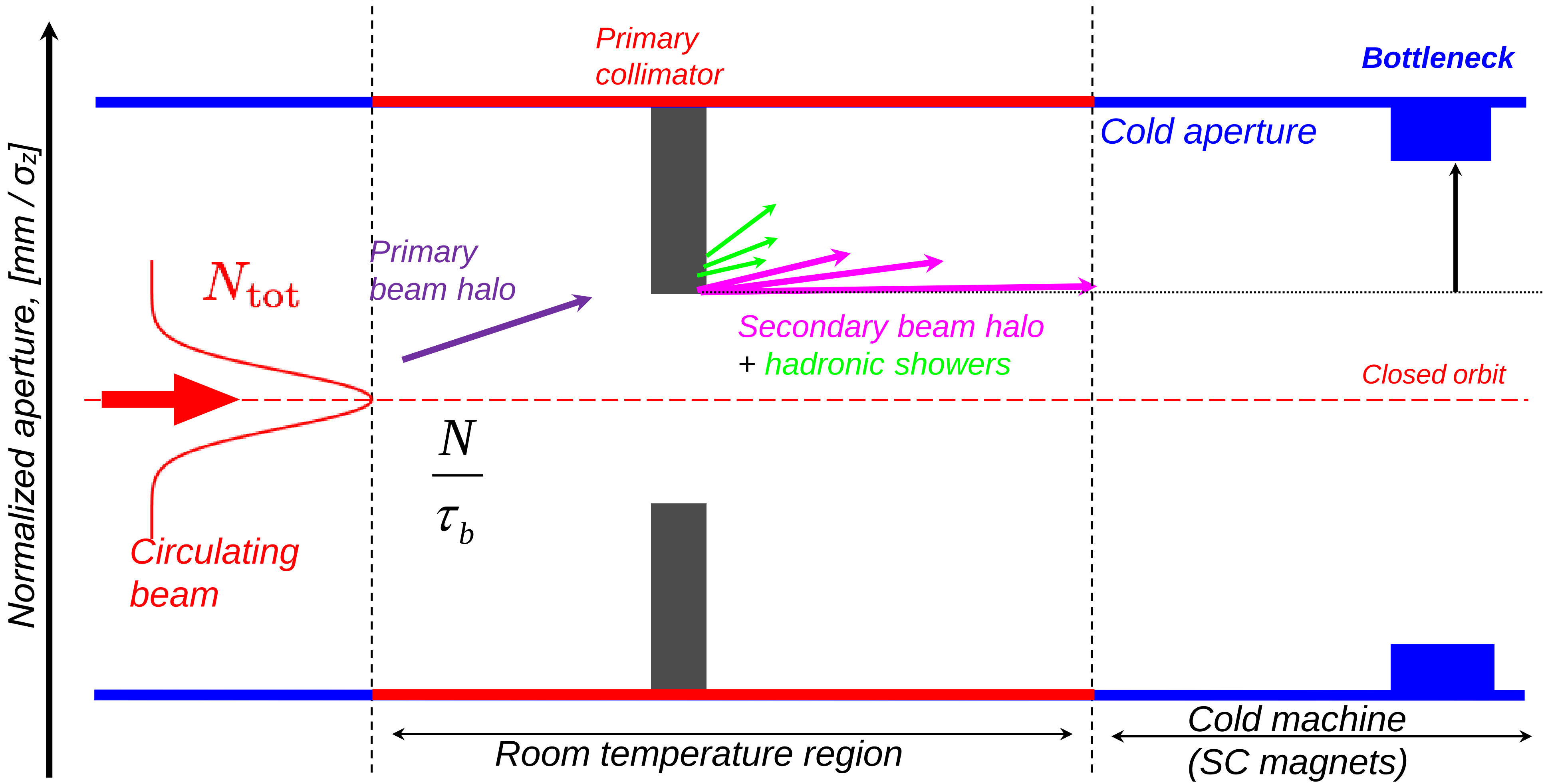
Superconducting coil:
quench at ~ 15mJ/cm^3

Factor 2.7 x 10^{10}
Aperture: r = 17/22 mm

Proton beam: ***400 MJ***

No quench due to circulating beam, with stored energies 100 times above pre-LHC state-of-the-art!

Aperture and single-stage collimation



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

Is it possible to stop them with a single collimator?

Particle interaction with collimators

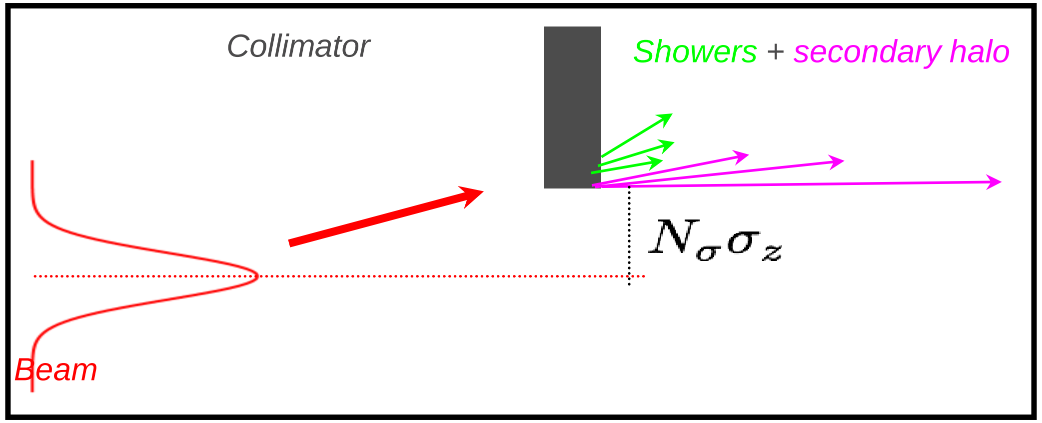
If “primary” collimators were a black absorbers, it would be sufficient to shield the aperture by choosing a gap $N_\sigma \sigma_z$ smaller that the aperture bottleneck !

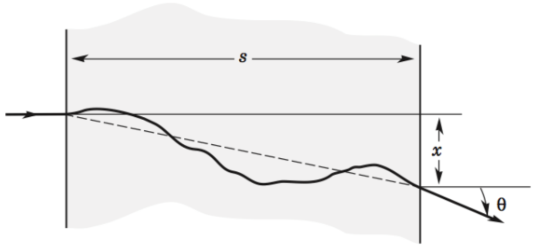
- *In reality, part of the beam energy and a fraction of the incident protons escape from the collimator!*

The primary should be thin as the particle impact parameters can be very small (~µm) and the surface flatness of a long collimator may be an issue.

The aim of the primary is to scatter the particle and increase the particle angle and impact parameter.

- *Usually a multi-turn process !*





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

χ_0 : radiation length

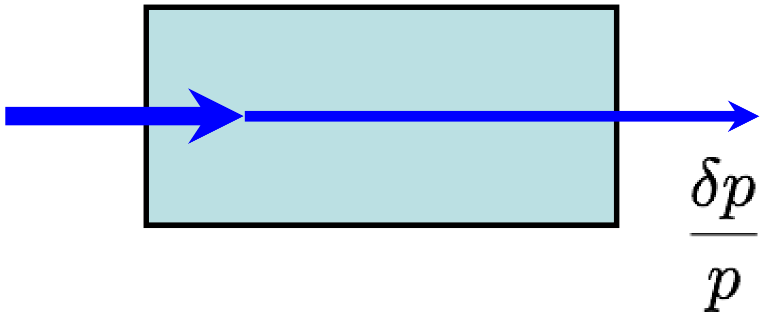
Molière’s multiple-scattering theory: scattered particles gain a **transverse RMS kick**.

Particle interaction with collimators

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

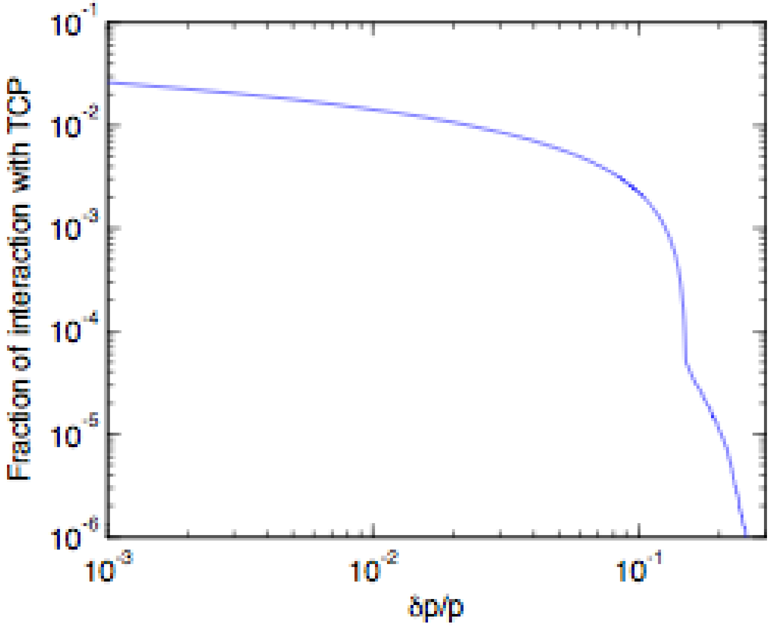
The interaction with collimator materials is itself a **source of halo** (secondary halo).

Particle showers developed by the interaction carry an important fraction of the impacting beam energy that “escapes” from the collimator.

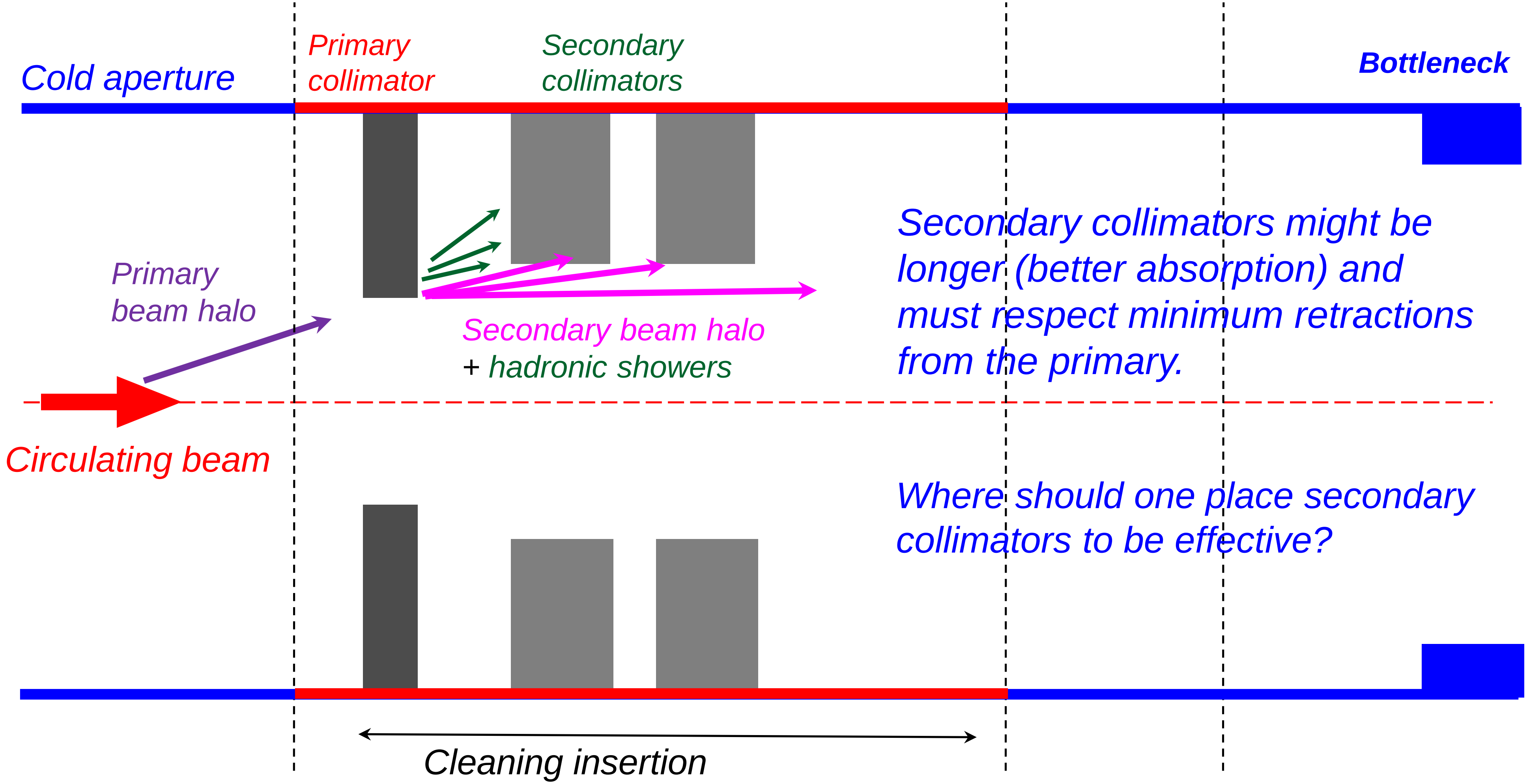

Single-diffractive interactions change the energy!

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

Distribution of energy lost after multi-turn interaction with 60cm long graphite collimator



Two-stage collimation

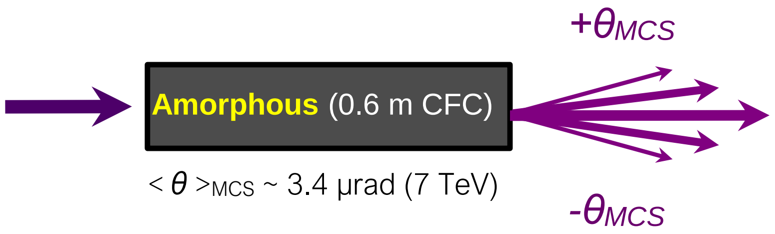


Secondary collimators might be longer (better absorption) and must respect minimum retractions from the primary.

Where should one place secondary collimators to be effective?

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

Optimum secondary collimator locations



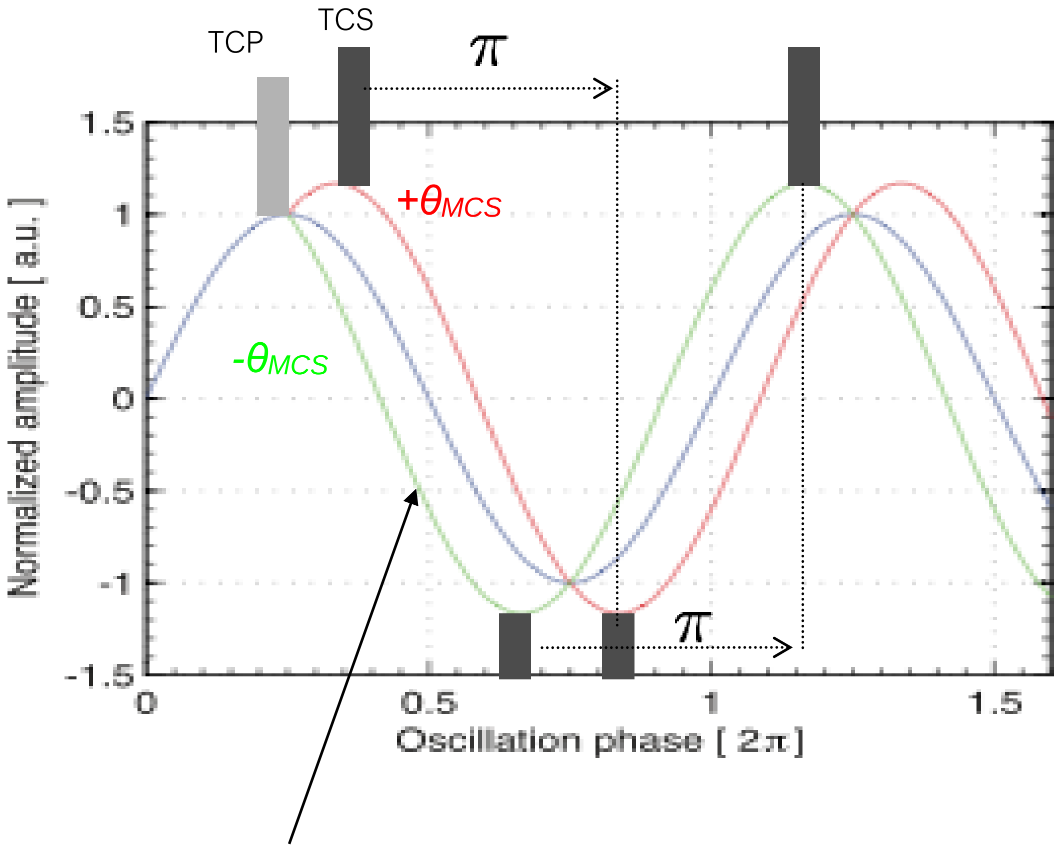
$< \theta >_{MCS}$ ~ 3.4 μrad (7 TeV)

There are optimum phase locations to catch the debris from primary collimators (TCPs).

- **Minimum**: set of 2 **secondary collimators** (TCSs) covering +θ_{MCS} and -θ_{MCS}.
- **Optimum**: 4 secondary (per plane) providing redundant coverage.

Secondary collimators must be placed at **phase** locations where the scattering in the primary translates into the largest transverse offset.

J.B. Jeanneret, PRSTAB 1:081001,1998

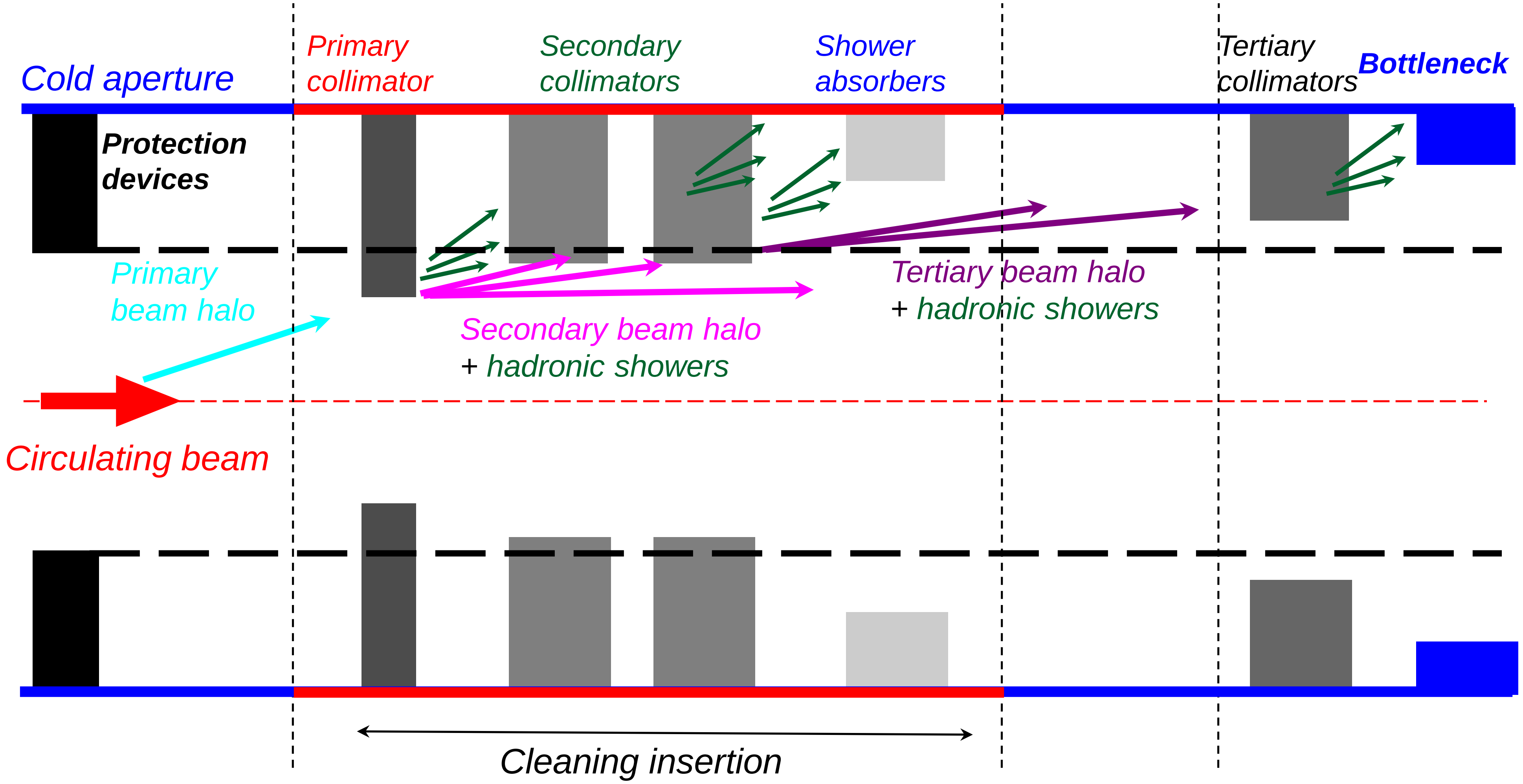


Betatron motion in *z ≡ (x, y)*

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

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

Multi-stage collimation at the LHC



Considering also protection devices, a **5-stage cleaning** is used at the LHC !

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

Why so many?

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

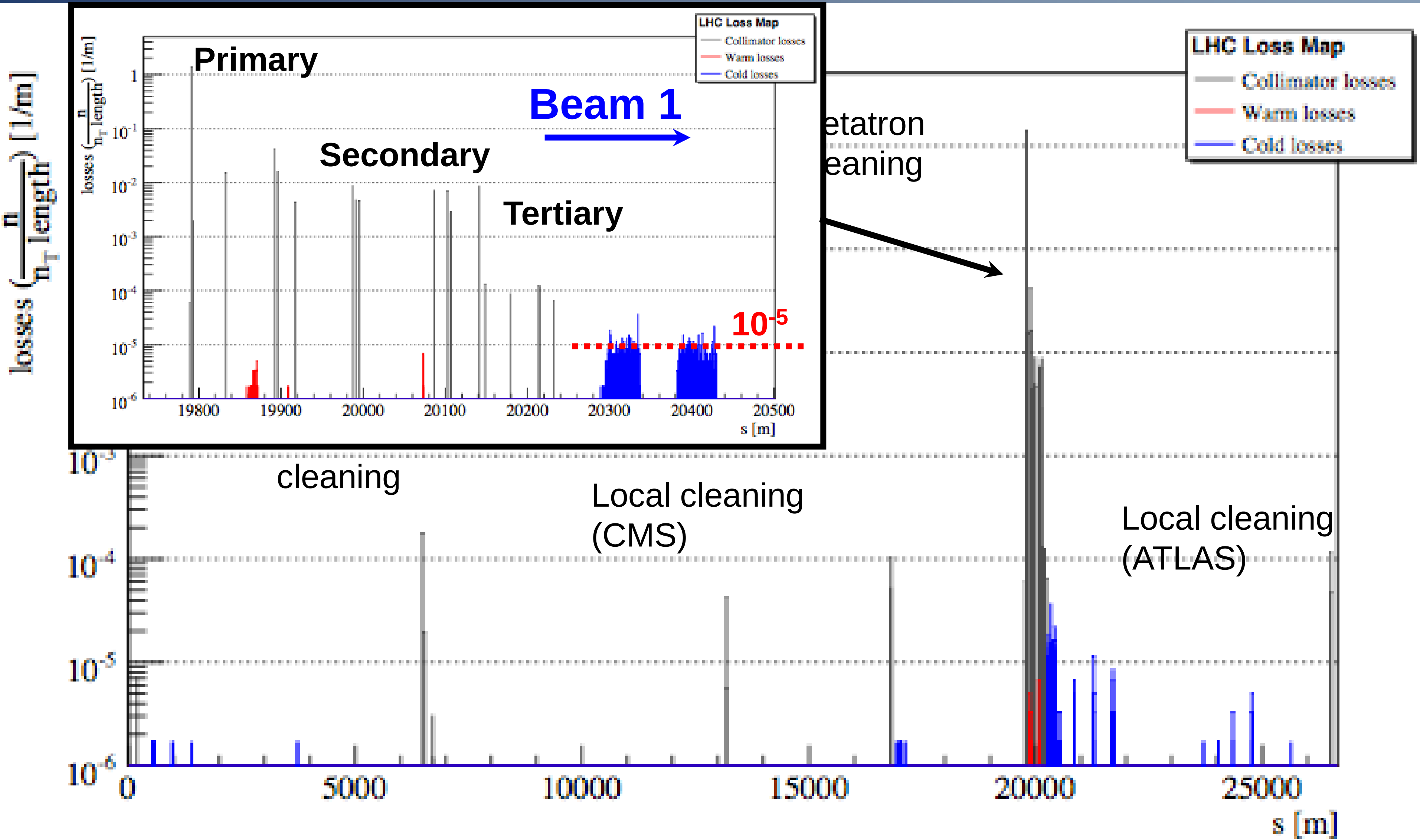
There are **different loss mechanisms** that impose the deployment of **different solutions** for beam collimation, machine protection etc.

- *Betatron (transverse) losses in horizontal, vertical and diagonal planes require full “phase-space” coverage.*
- *Off-energy particle losses occur in different locations than betatron losses.*
- *There are 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 normal conducting magnet insertions.*

Simulated 7 TeV performance



etatron
eaning

cleaning

Local cleaning (CMS)

Local cleaning (ATLAS)

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

Cold losses in experiments removed by local protection.

R. Bruce el al, Phys. Rev. ST Accel. Beams 17, 081004 (2014)

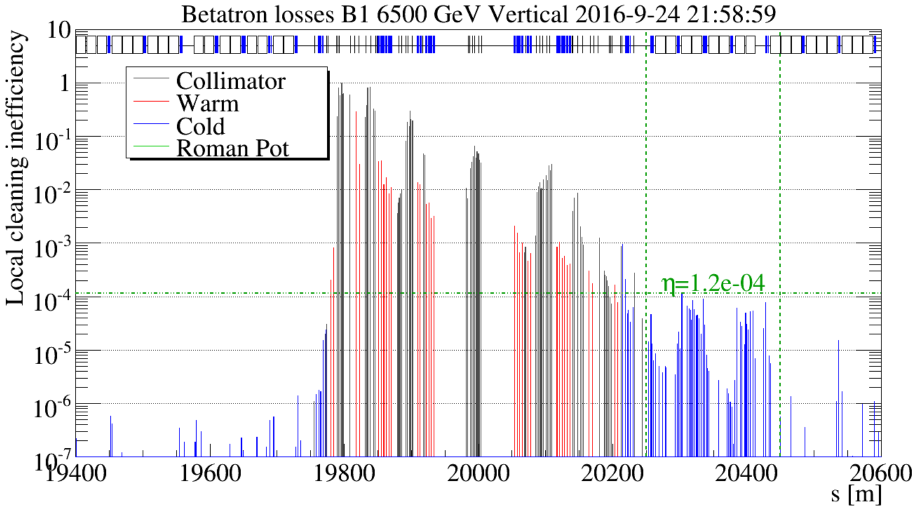
Proton versus ions

Collimation of ion beams is more complex than proton collimation.

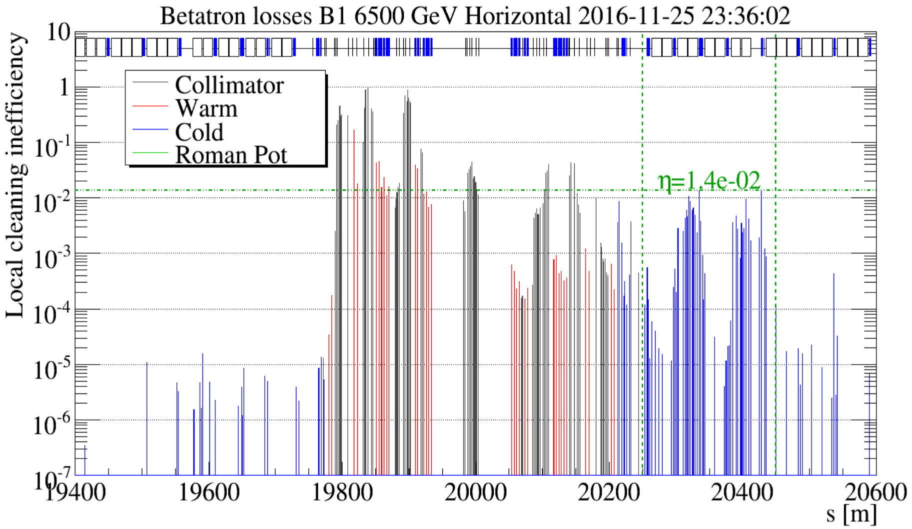
Ions (in particular heavy ions like lead, gold etc) generate **many isotopes by electromagnetic dissociation (EDM) that may escape the collimator and propagate in the accelerator lattice**, escaping for example secondary collimators.

- Increased losses in the downstream arc that acts as a spectrometer and deflects the secondary ions into the accelerator components.

proton collimation



lead ion collimation



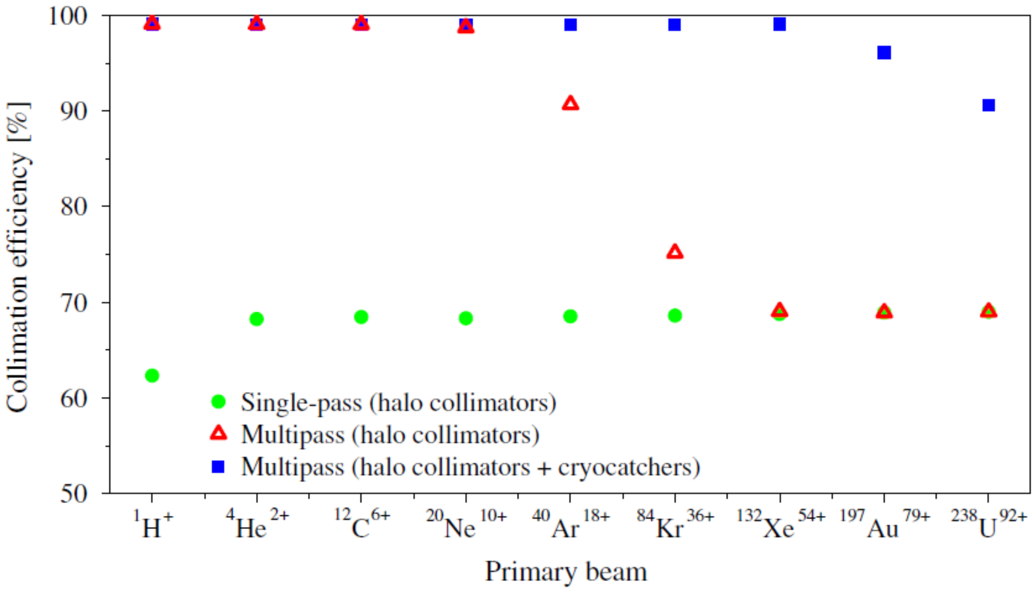
Particle / energy leakage increases by a factor 100 (!) at 6.5 TeV with lead !

Protons versus ions

For the SIS100 accelerator of the FAIR project at GSI in Germany, simulations of collimation system performance were performed for a range of ion species.

- Max. momentum is ~30 Z GeV/c.

The collimation system consists of a primary collimator (1 mm W foil), two secondary collimators (40 cm W blocks) and “cryocatchers” (local absorbers to intercept ions).



I. Strašík et al, PRSTAB 18, 081001 (2015)

Introduction to collimation and absorbers

Collimation requirements and design

Collimator hardware

Collimation system operation

Synchrotron radiation collimation

Novel collimation techniques

Dump absorbers

Some requirements of a collimator

The collimator should behave as much as possible as a **black hole** for particles: absorb them entirely !

- In practice absorption is limited by material properties, impacting particle type and particle energy ⇔ shower depth and width.

The collimator should **absorb power** from the beam (loss).

- Possibly limited by energy density and cooling capacity.

The collimator should be **robust** and capable of surviving a beam impact (failures).

- In some cases up to the full beam impact.
- Shock impact as opposed to steady state power (previous req).

The collimator should be **close to be beam** to limit the extend of the halo or shadow accelerator components.

- To mitigate the impact on beam stability, the collimator material should be an excellent conductor.

A multi-disciplinary topic

The complete collimation design chain rely on different ingredients:

Tracking models

Collimation / photon scattering models

Energy deposition simulations

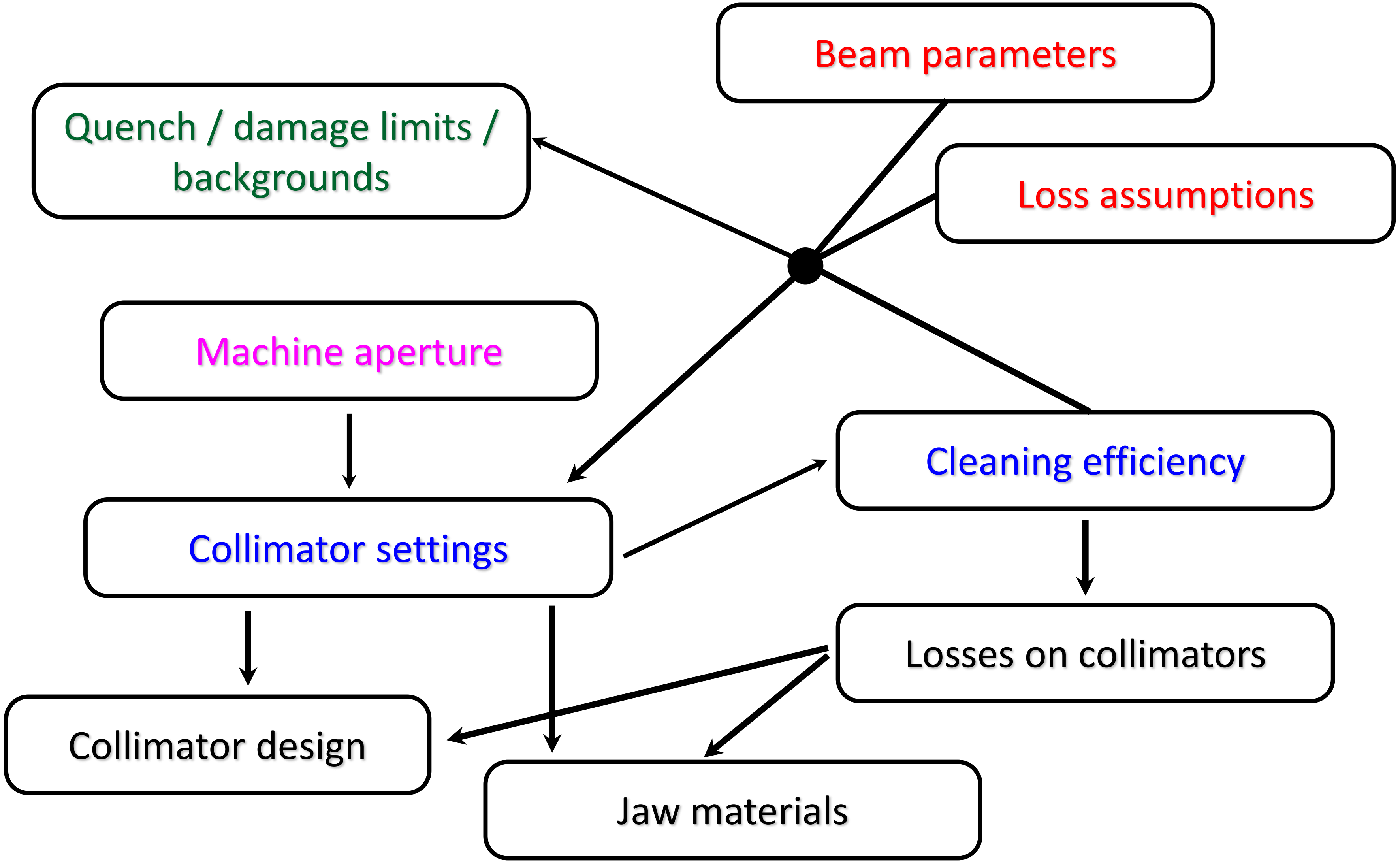
Thermo-mechanical analysis

Operational assumptions

Tools developed and used for LHC:

- Particle tracking with **SixTrack** including collimation – to determine impact points
- Shower simulations with **FLUKA**.
- **ANSIS / AutoDyn** simulations of the collimator material.

Workflow for collimation design



Beam parameters

Quench / damage limits / backgrounds

Loss assumptions

Machine aperture

Cleaning efficiency

Collimator settings

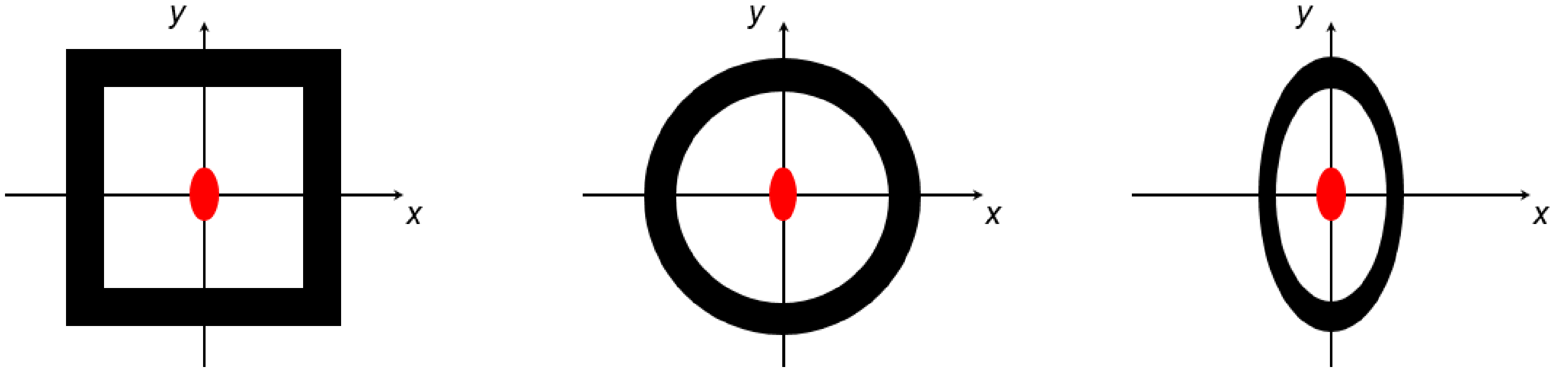
Losses on collimators

Collimator design

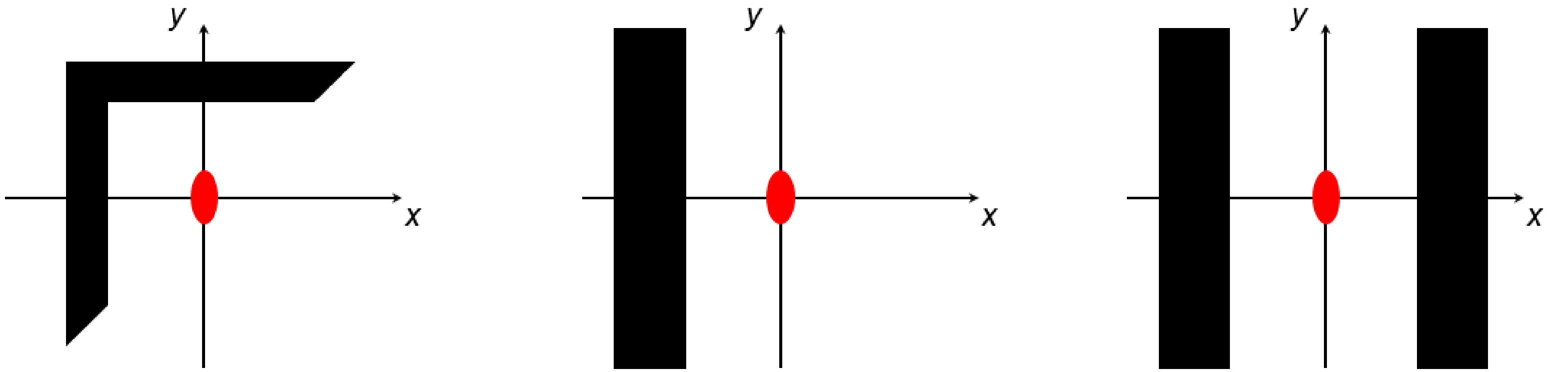
Jaw materials

Collimator designs

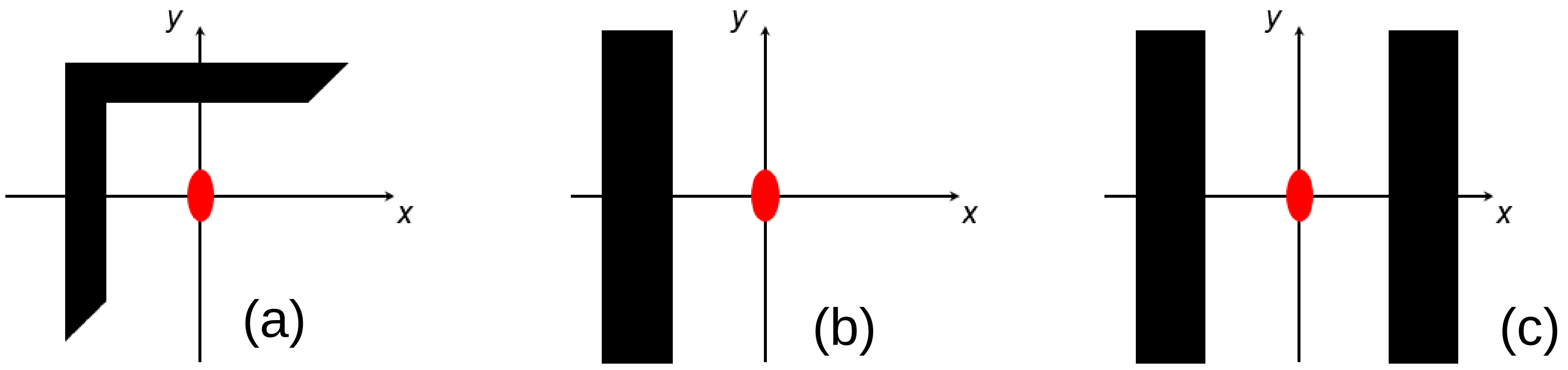
Fixed collimators (masks, absorbers): square, circular, elliptical, ...



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



Movable collimator design



- **Dual plane** (x+y) in one device (cost !),
- **Beam not confined**,
- Alignment more delicate (plane coupling).

- **Single plane** (x) only,
- **Beam not confined**.

- **Single plane** (x) only,
- **Beam confined** by double jaw,

For the single sided systems (a & b), the beam can move away from the jaw (orbit changes) and affect the collimation performance.

Collimator materials

Materials for collimators and absorbers – hadrons:

- Copper (Cu),
  - excellent conductor, medium density (9 g/cm^3), low material resistance.
- Tungsten (W),
  - moderate conductor, high density (19 g/cm^3), high melting temperature.
- Graphite (C) and Carbon (Fiber) Composites (CFC),
  - moderate conductor, low density (1-2 g/cm^3), high melting temperature, robust against shock impacts.
- Molybdenum (Mo)
  - better conductor than graphite, but less robust.
- Beryllium (Be).
  - excellent conductor, low density (2 g/cm^3), low melting temperature.

Materials for photon / e+e- absorbers:

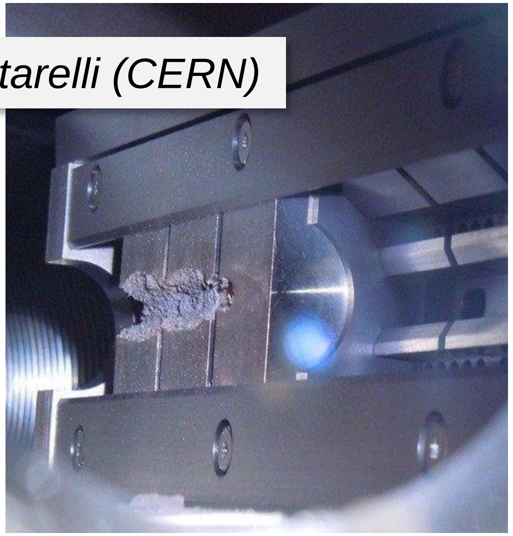
- Copper (Cu).
- Titanium (Ti).
- Tungsten (W).

Search for better materials ongoing !

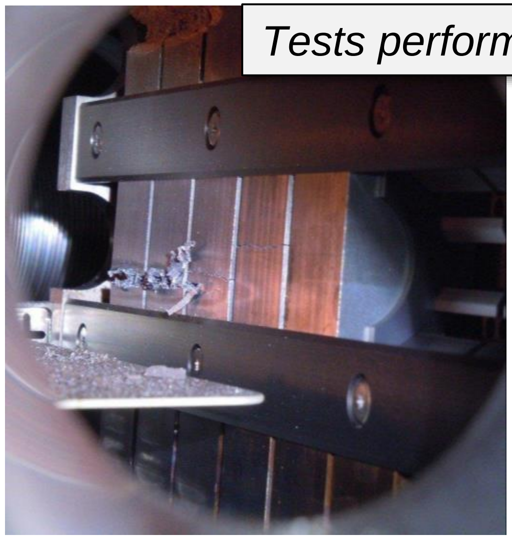
Collimator material tests

Courtesy A. Bertarelli (CERN)

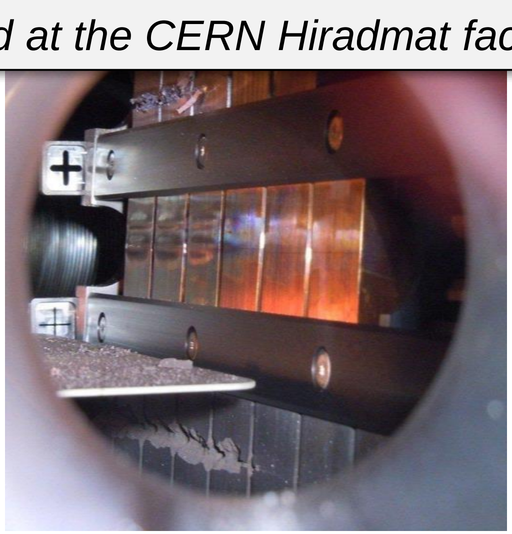
Tests performed at the CERN Hiradmat facility



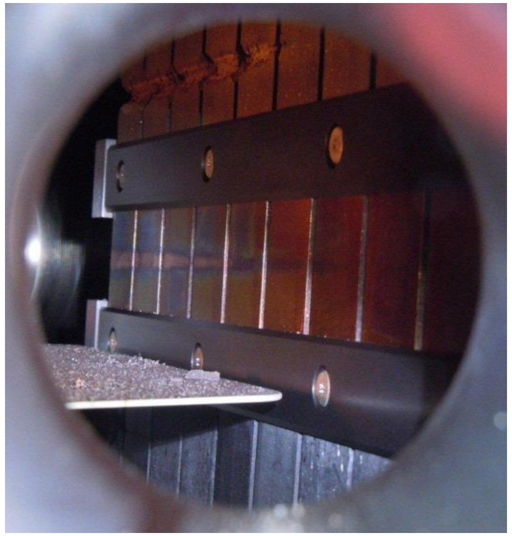
Inermet 180 (W-Ni-Cu), ~0.5 MJ



Molybdenum, ~ 0.5 & 1 MJ



Glidcop, 2 x ~0.5 MJ



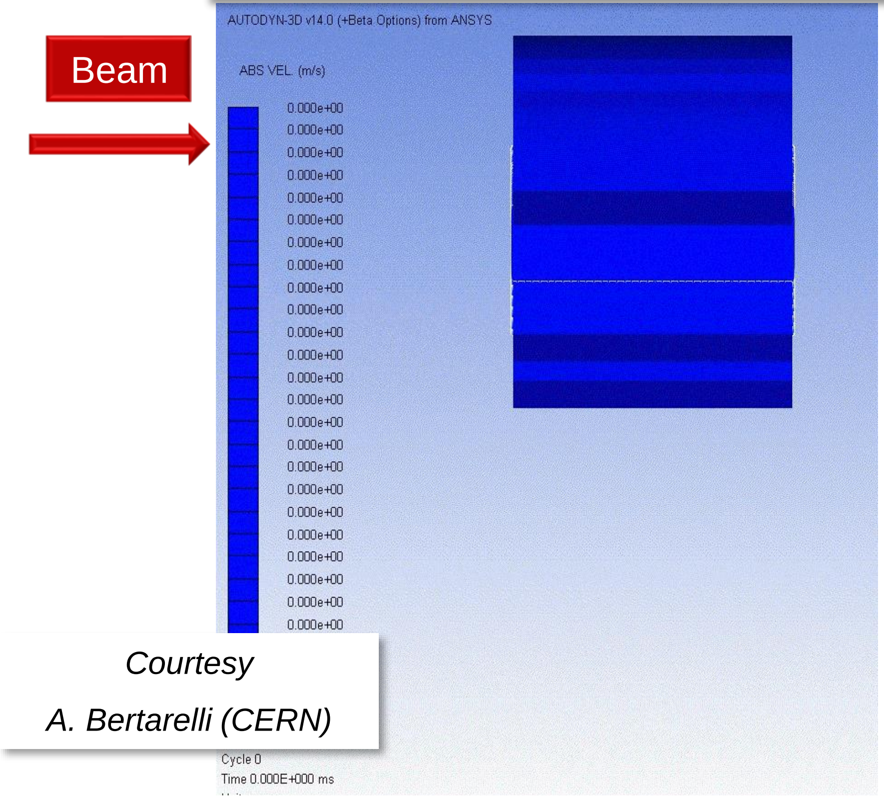
*Copper-Diamond,
~ 1 MJ*

Molybdenum-Copper-Diamond, ~1 MJ

*Molybdenum-Graphite (3 grades)
~ 1 MJ*

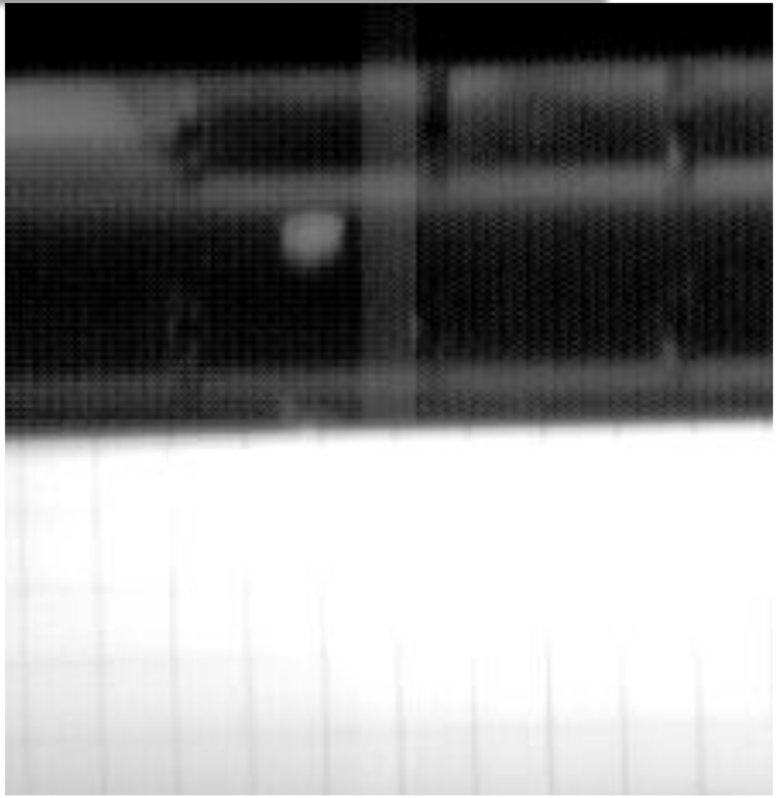
High intensity collimator test

Inermet : comparison between simulation and experiment



Courtesy

A. Bertarelli (CERN)

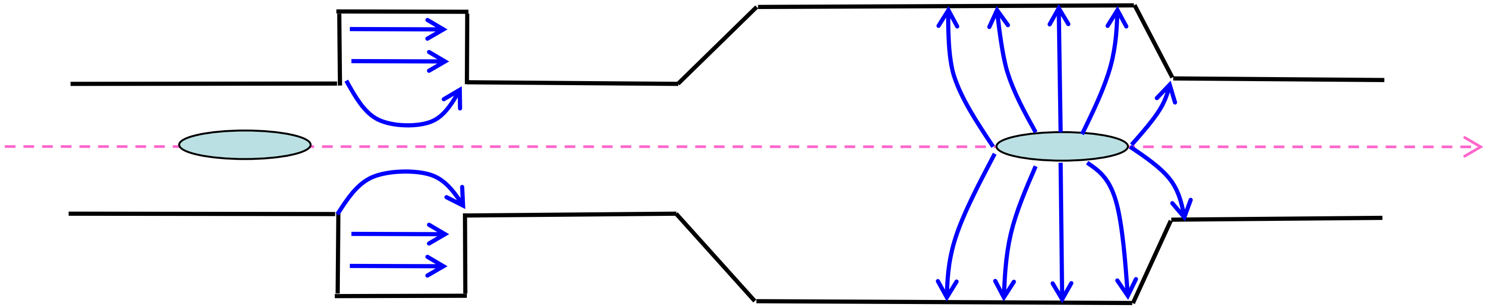


Case	**Bunches**	**p/bunch**	**Total Intensity**	**Beam Sigma**	**Specimen Slot**	**Velocity**
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	**316 m/s**
Experiment	72	1.26e11	9.0e12 p	1.9 mm	8 (partly 9)	**~275 m/s**

Collimator impedance

Collimators are usually positioned very close to the beam where the **wakefields** induced by the beam-collimator interaction may:

- act back on the beam and lead to **beam instabilities** (circular) or **beam break up** (linacs).
- propagate and dissipate energy in accelerator components.



The impact of the collimator scales ∝ $\mathbf{1/b^{2\text{-}3}}$ where **b** is the **collimator gap**.

To minimize the impact of a collimator on beam stability:

- The material should be an **excellent conductor** (surface resistance),
- The jaw should have a **smooth shape** with **gentle transitions** to the neighbouring vacuum chamber.

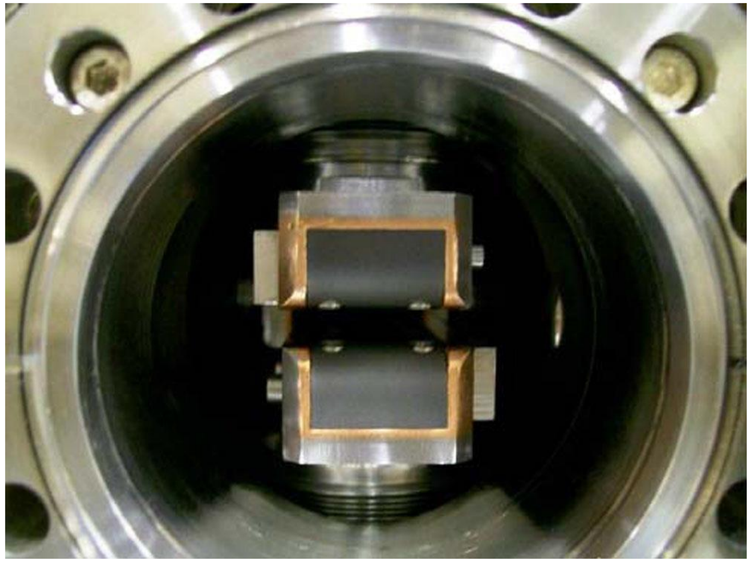
Collimator wake-fields

In linacs with short bunches (e^-/e^+) collimator wakefields can ‘kick’ the beam transversely when the bunches are not centred.

- Kick is in general different for head (~ not affected) and tail → emittance growth.

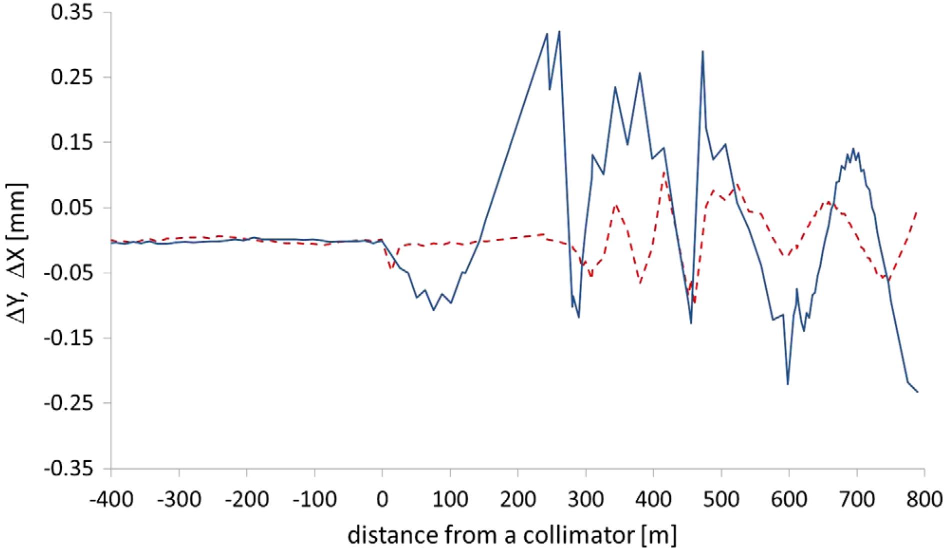
P. Tenenbaum et al, PRSTAB 10, 034401 (2007)

Example of SLAC main linac (→LCLS)



Very strong discontinuity of the vacuum chamber due to the collimator jaws

Transverse deflection when the lower jaw is closer to the beam



A. Novokhatski et al, PRSTAB 17, 124401 (2014)

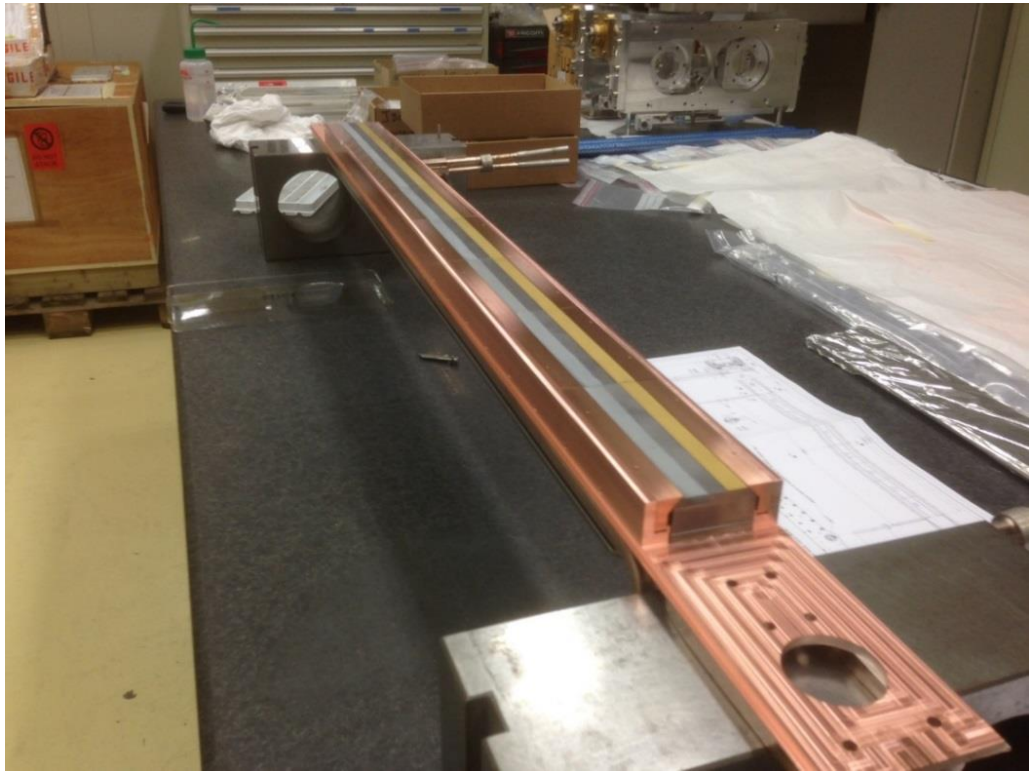
Impedance reduction

The material choice may have to be optimized between electrical resistance and robustness.

- Copper: excellent conductor, not robust (low meting T),
- Graphite: medium quality conductor, very robust (low density & high melting T),
- Tungsten: medium quality conductor, medium robustness, very dense.

New generation collimators are now designed with surface coatings to lower the resistance. In general ~ μm thicknesses is sufficient.

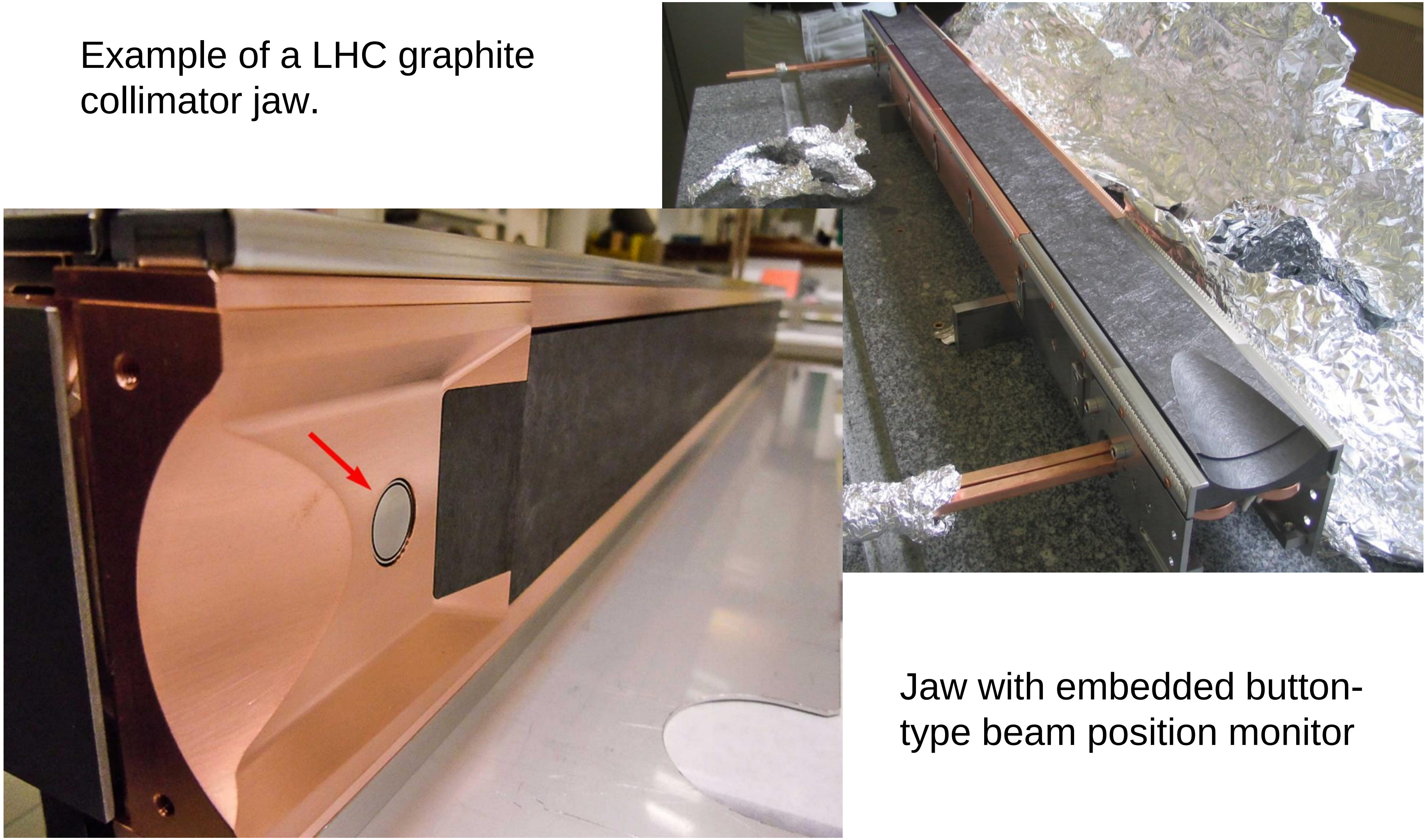
- Key issue: will the coating survive high power (temperatures) and / or shock impacts?



LHC collimator test jaw with 3 different surfaces to test with beam: Titanium nitrite (yellow), Molybdenum (black), Molybdenum graphite (grey – bulk material).

Collimator jaw example

Example of a LHC graphite collimator jaw.

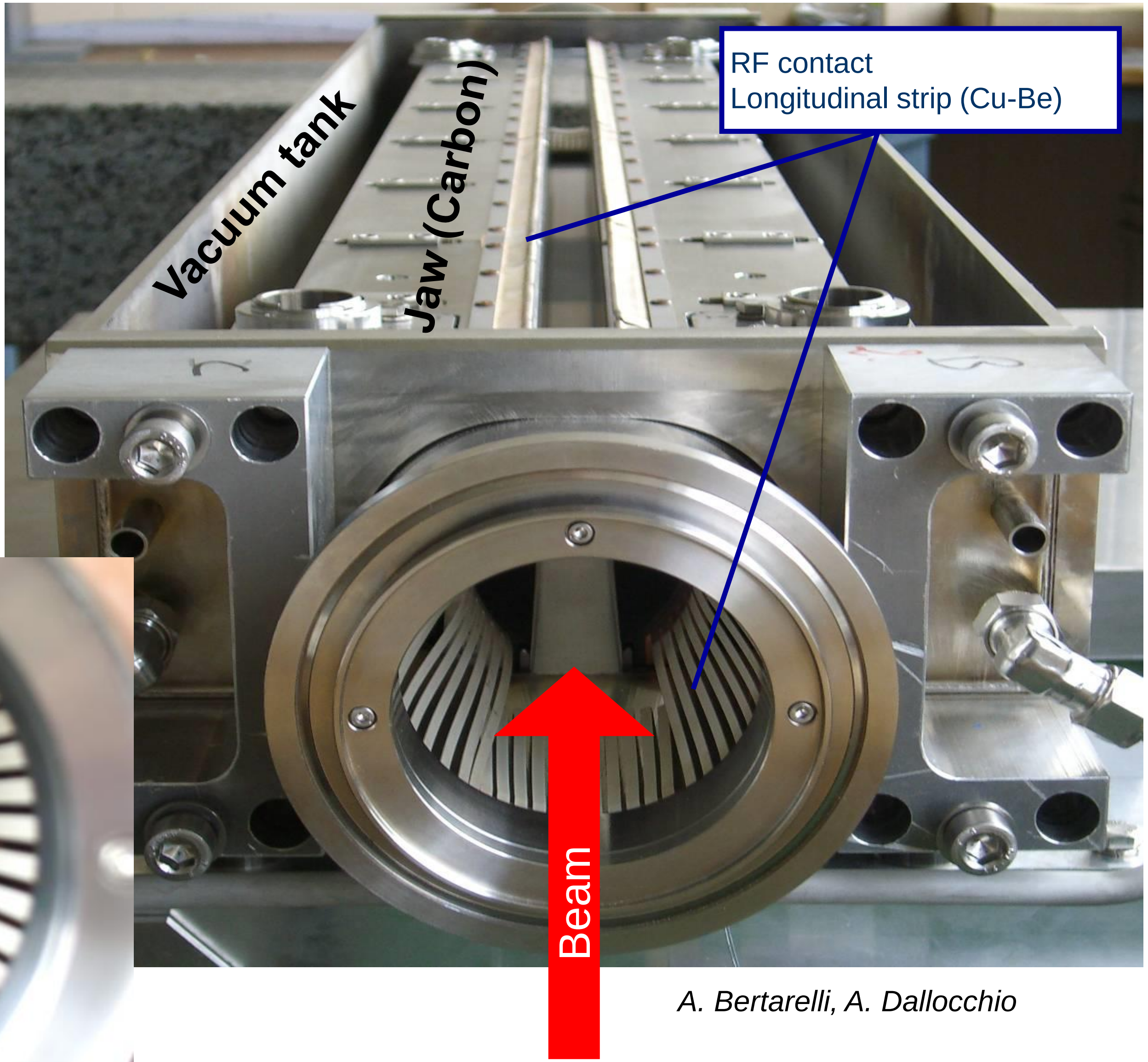


Jaw with embedded button-type beam position monitor

LHC Collimator design

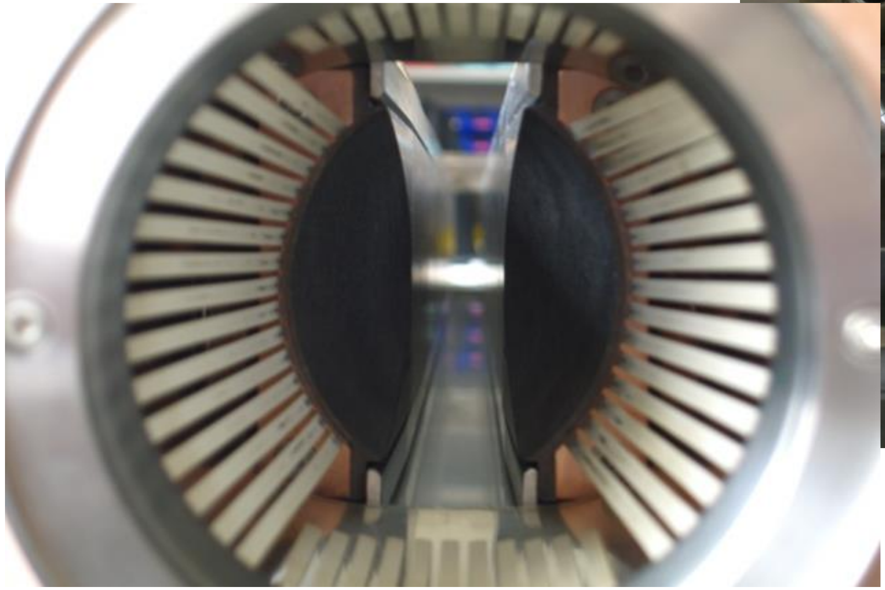
RF fingers and smooth transitions must be foreseen (impedance and heating).

Collimator is cooled (clamped water cooled Cu-alloy plate).



A. Bertarelli, A. Dallocchio

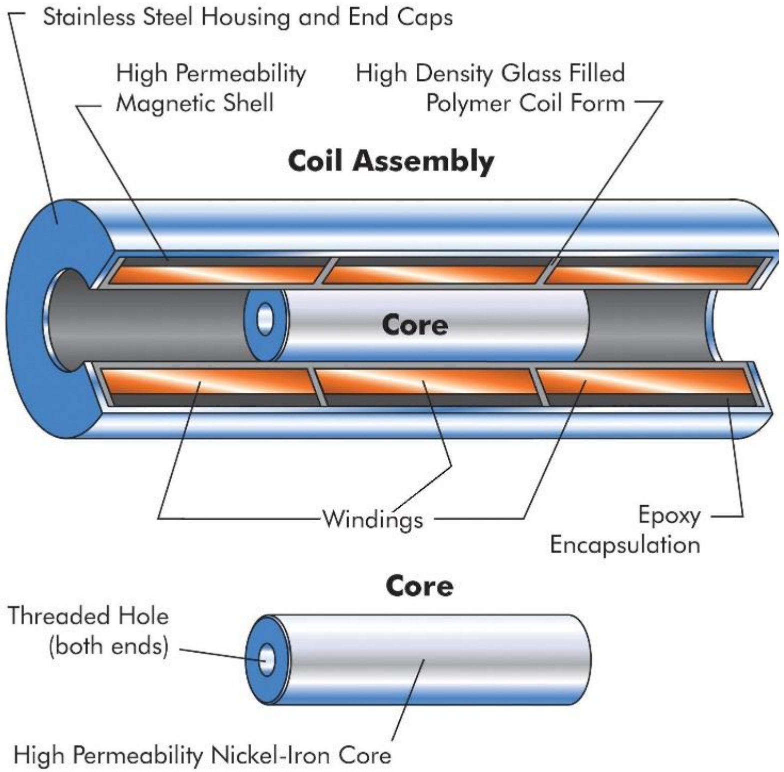
What the beam sees!

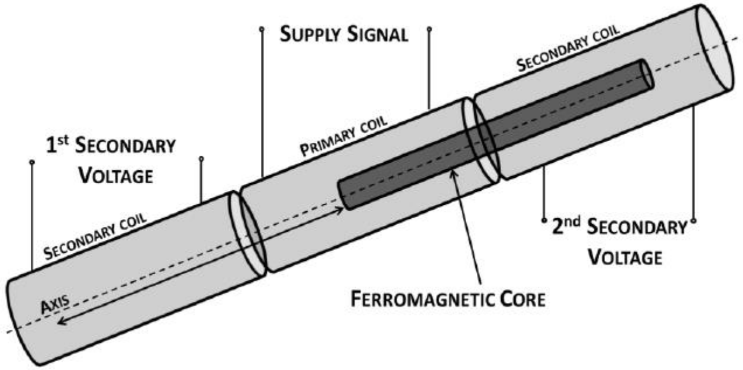


Position monitoring

For movable collimators the position must be known, monitored and interlocked :

- Motor counts and position encoders,
- Linear Variable Differential Transformers (LVDT) are robust, reliable, accurate (~μm) and very linear devices to monitor the jaw positions.
  - For example: each LHC collimator is equipped with 6 LVDTs to measure the jaw positions and the collimator gap – provides redundancy.



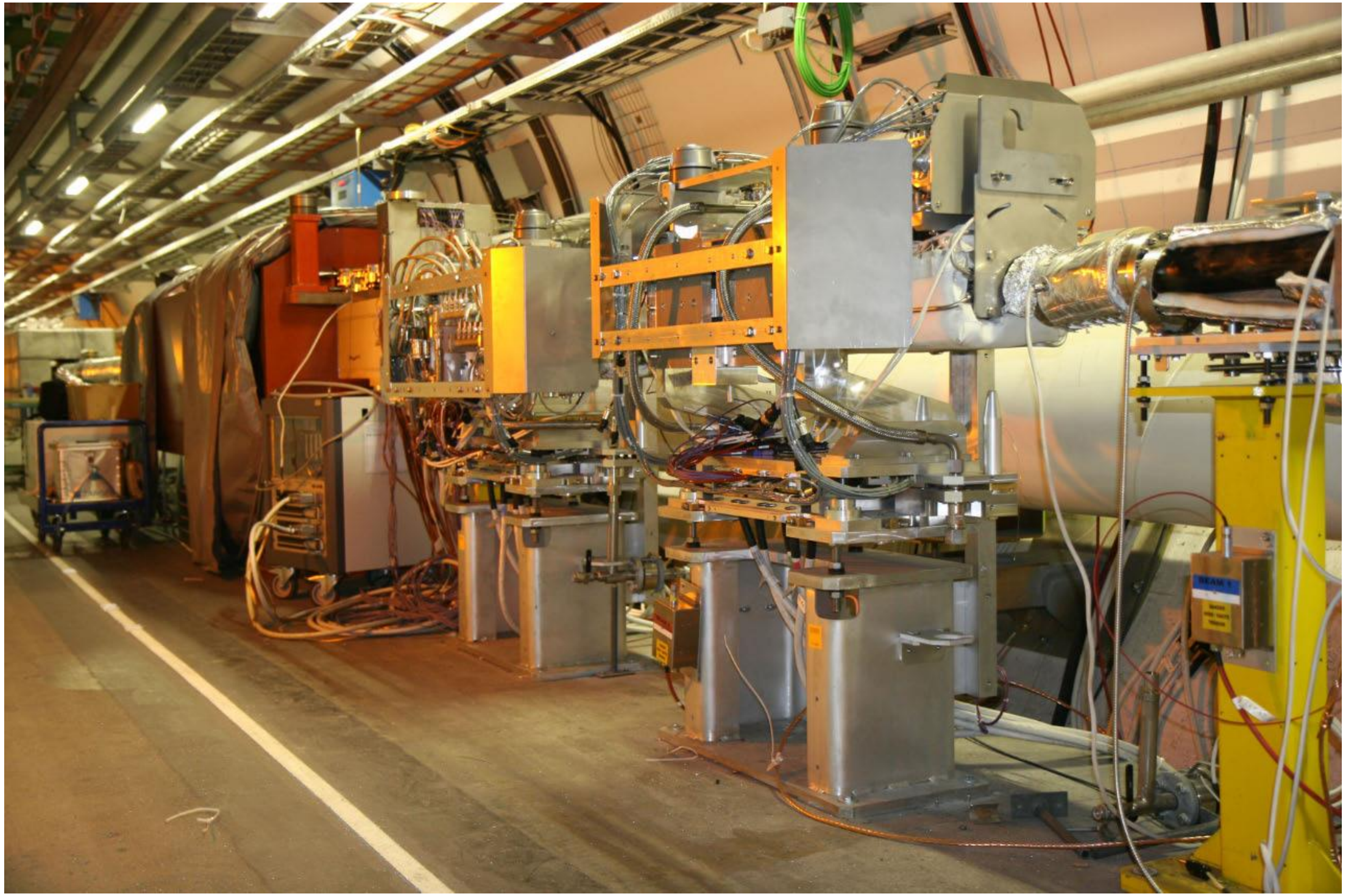


A. Danisi et al, JINST 8 P09005

A. Masi et al, IEEE TRANSACTIONS ON NUCL SCIENCE, VOL. 55, NO. 1, FEB. 2008

The final object

Collimator installed in the LHC tunnel.



Introduction to collimation and absorbers

Collimation requirements and design

Collimator hardware

Collimation system operation

Synchrotron radiation collimation

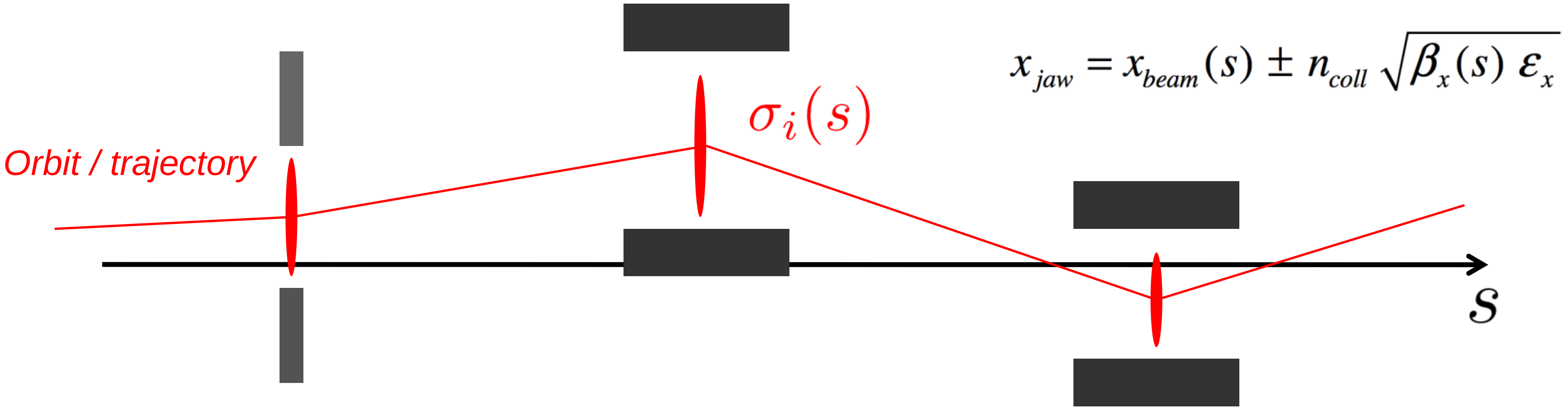
Novel collimation techniques

Dump absorbers

Collimator beam-based alignment

Collimator settings, expressed in units of beam size, must be converted to physical positions in [m] :

- Align / center the collimator jaws ⇒ must know the beam position
- Adjust the gap to the correct setting ⇒ must know the beam size

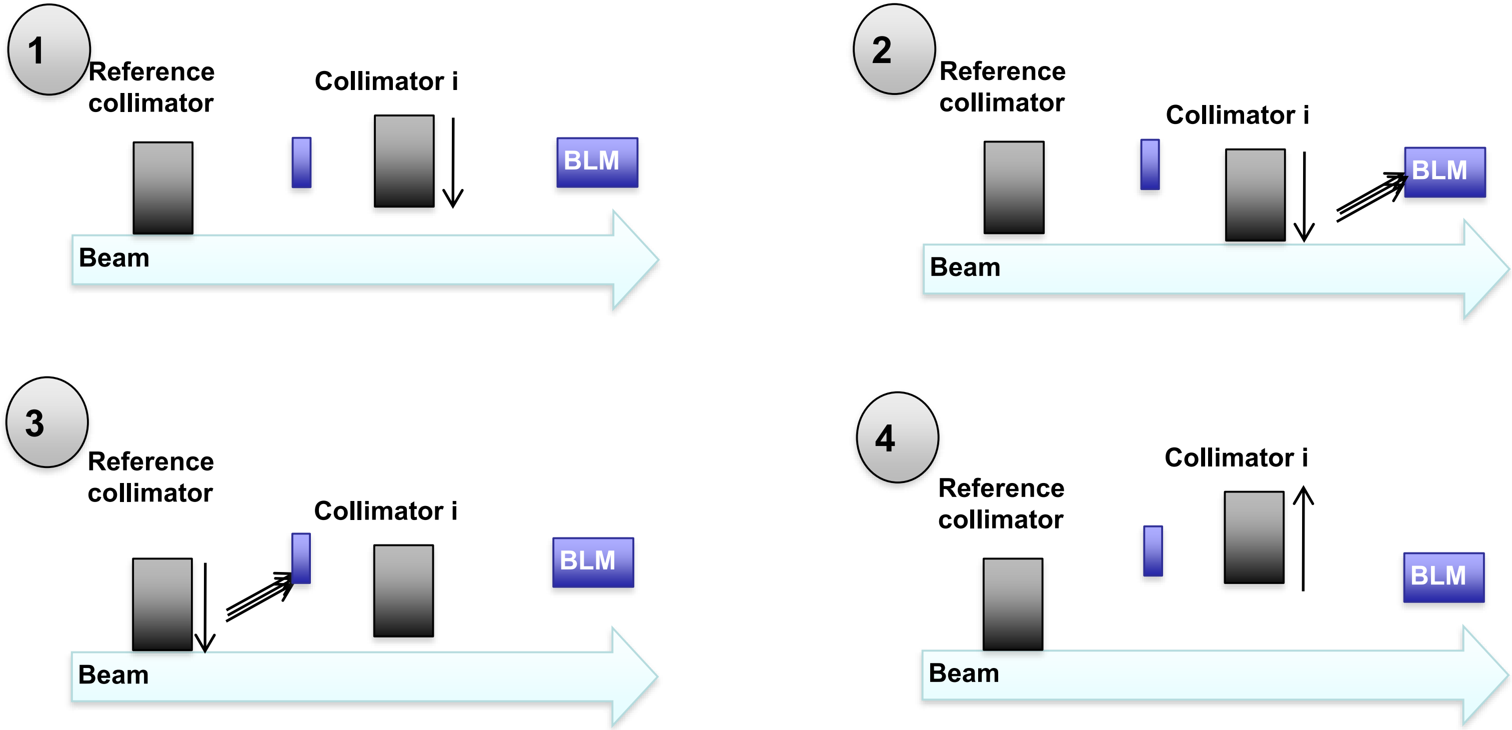


$$x_{jaw} = x_{beam}(s) \pm n_{coll}\sqrt{\beta_x(s)\,\varepsilon_x}$$

When **gaps** are **very small**, collimators may not be set deterministically using design machine parameters: alignment errors, beam position offsets and optics errors cause uncertainties that can be large compared to gaps.

In such cases both the beam position and the beam size may have to be measured at each collimator with **beam-based alignment techniques**.

Example of an alignment technique



(1) A reference halo is generated with a primary collimators.

(2) The halo is touched with the other collimators (**both sides**) → local beam position.

(3) Re-iterate on the reference collimator to determine the relative aperture → local beam size.

(4) Retract the collimator to the correct settings.

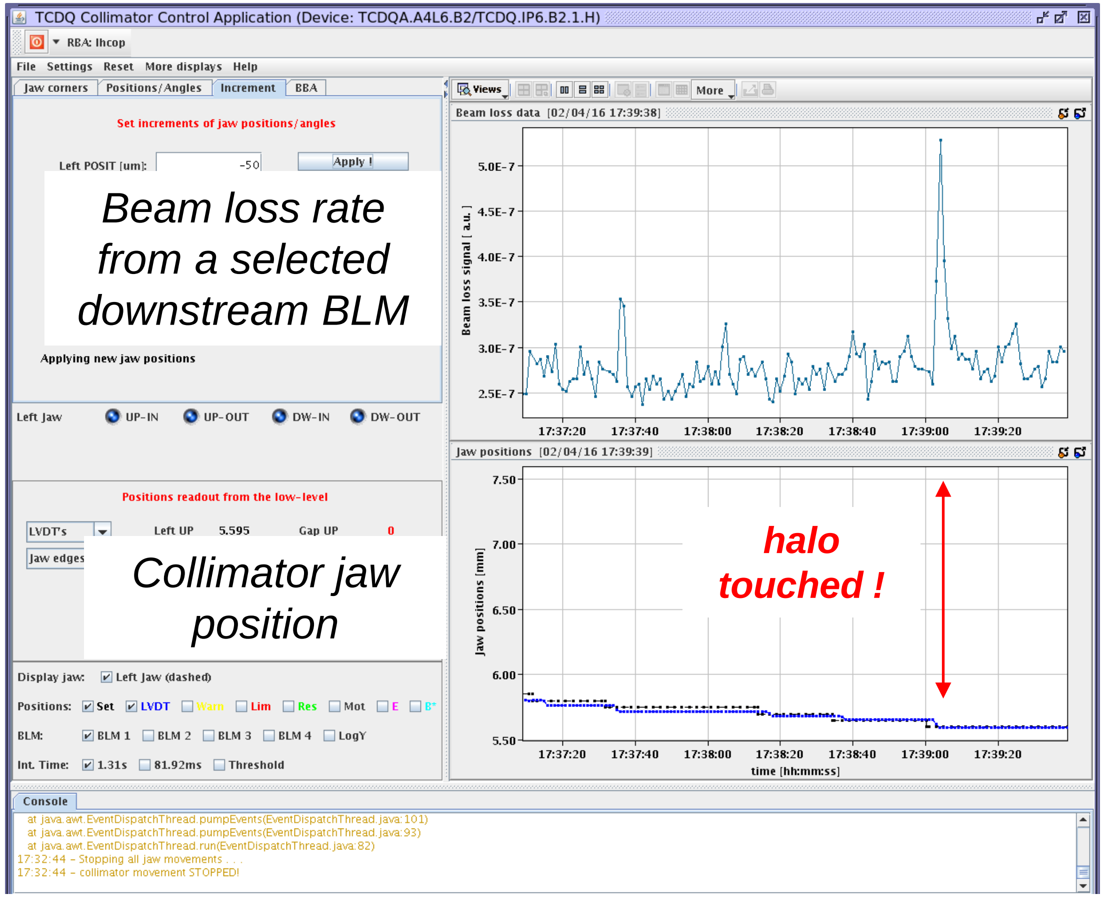
Collimator alignment

The collimator alignment is typically performed with low beam intensity:

- losses are generated during the process,
- the system is not setup (by definition) → not able to handle high power.

LHC collimator alignment

When the halo edge is well defined by a reference collimator, the loss spikes observed during alignment can be used to setup automated and parallel alignment algorithms.



TCDQ Collimator Control Application (Device: TCDQA.A4L6.B2/TCDQ.IP6.B2.1.H)

Set increments of jaw positions/angles

Left POSIT [um]: -50

Applying new jaw positions

Positions readout from the low-level

LVDT's

Jaw edges

Left UP 5.595 Gap UP 0

Display jaw: ☑ Left Jaw (dashed)

Positions: ☑ Set ☑ LVDT ☐ Warn ☐ Lim ☐ Res ☐ Mot ☐ E ☐ B*

BLM: ☑ BLM 1 ☐ BLM 2 ☐ BLM 3 ☐ BLM 4 ☐ LogY

Int. Time: ☑ 1.31s ☐ 81.92ms ☐ Threshold

```
  at java.awt.EventDispatchThread.pumpEvents(EventDispatchThread.java:101)
  at java.awt.EventDispatchThread.pumpEvents(EventDispatchThread.java:93)
  at java.awt.EventDispatchThread.run(EventDispatchThread.java:82)
17:32:44 - Stopping all jaw movements . . .
17:32:44 - collimator movement STOPPED!
```

Beam loss rate from a selected downstream BLM

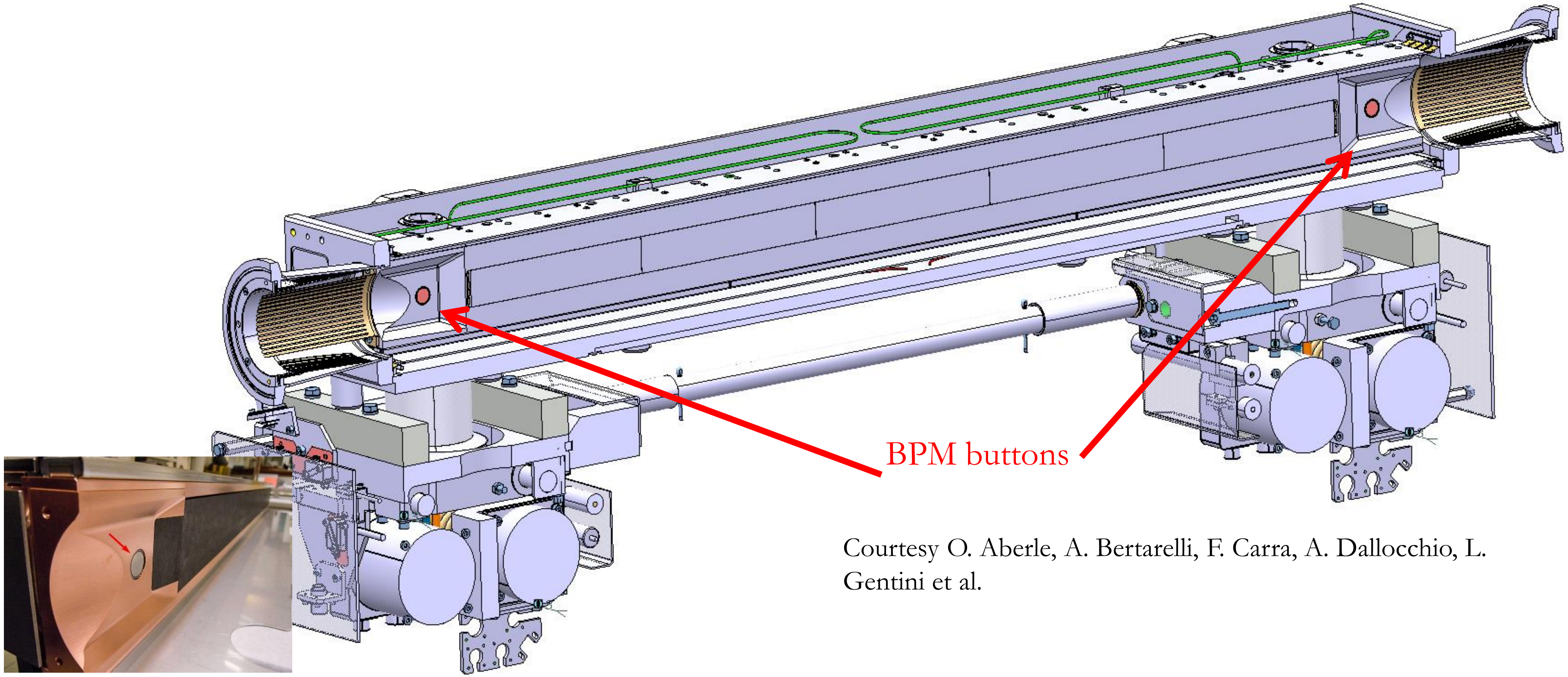
Collimator jaw position

halo touched !

Faster alignment with position monitors

The newest generation collimators of the LHC are now equipped **with beam position monitors integrated into the jaws**.

The alignment time is drastically reduced since it is not necessary to touch the beam to centre the jaws.



Courtesy O. Aberle, A. Bertarelli, F. Carra, A. Dallocchio, L. Gentini et al.

G. Valente et al, PRSTAB ***17****, 021005*

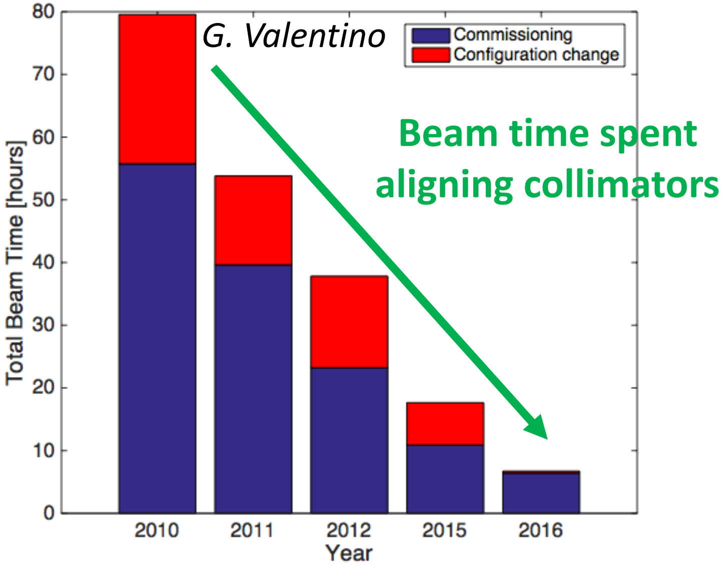
Experience and automation

Over the years, the time required to align the LHC collimation system has been improved massively thanks to automation, parallelism and finally embedded beam position monitors.

A central alignment controller moves the collimators in parallel using **beam loss data acquired at 100 Hz**.

- Defines the step sizes,
- Moves collimators in parallel or one after the other depending on cross-talk information.

Around 20% of the collimators are now equipped with beam position monitors and can be aligned in parallel in less than one minute.



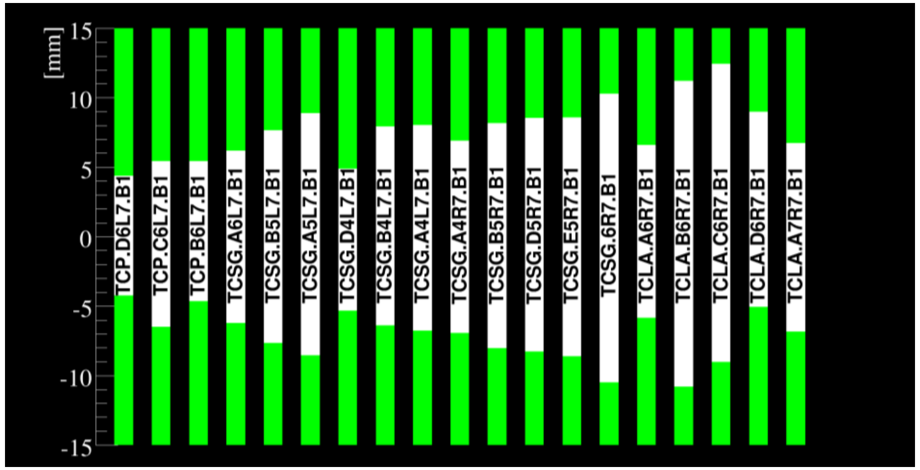
*G. Valente et al, PRSTAB **15**, 051002*

*G. Valente et al, PRSTAB **17**, 021005*

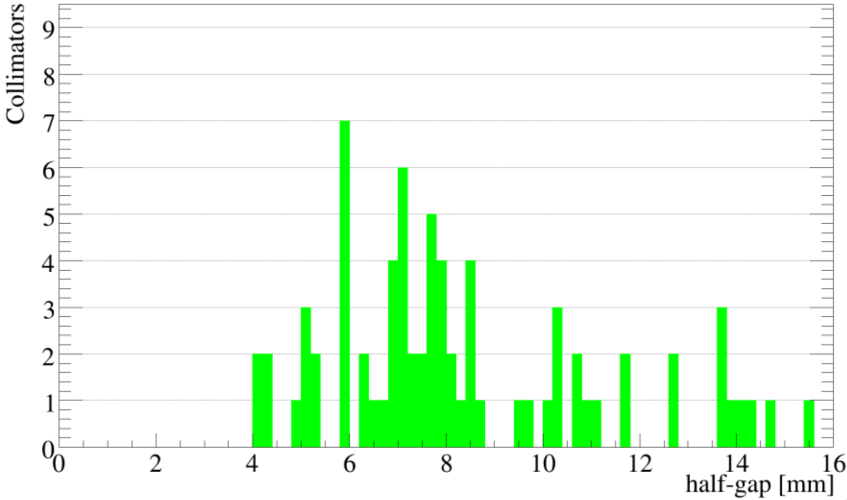
Example of gaps at LHC

Injection

Betatron collimator **gaps**

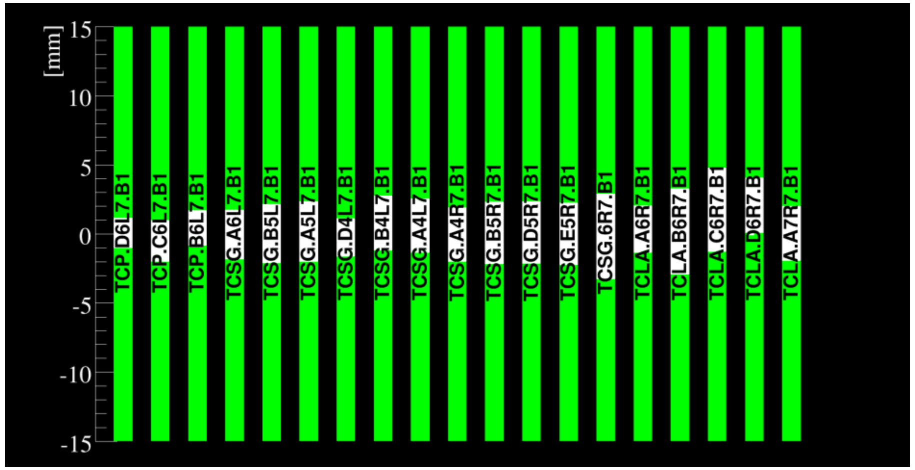


Distribution of **half-gaps for the entire system**

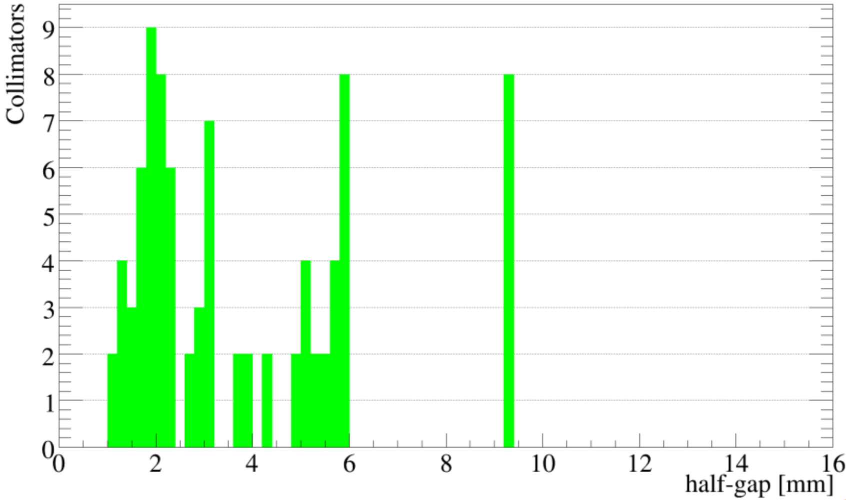


Collisions at 6.5 TeV

Betatron collimator **gaps**



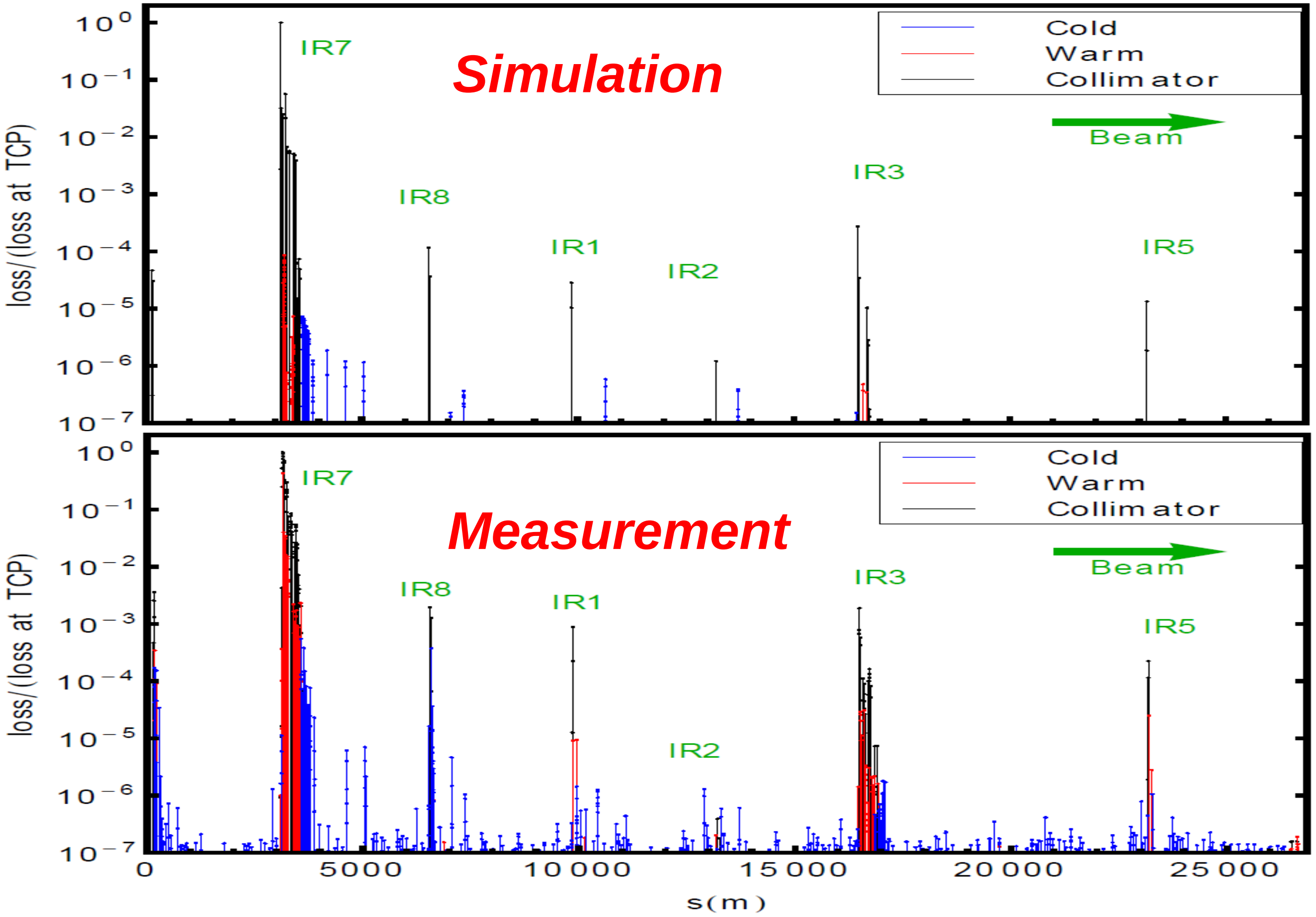
Distribution of **half-gaps for the entire system**



Comparison with measurements

To evaluate the performance of the collimation system, gentle noise excitation of part of the beam is used to generate losses at the collimators.

- The losses generated during that process can be used to estimate the cleaning efficiency of the system.

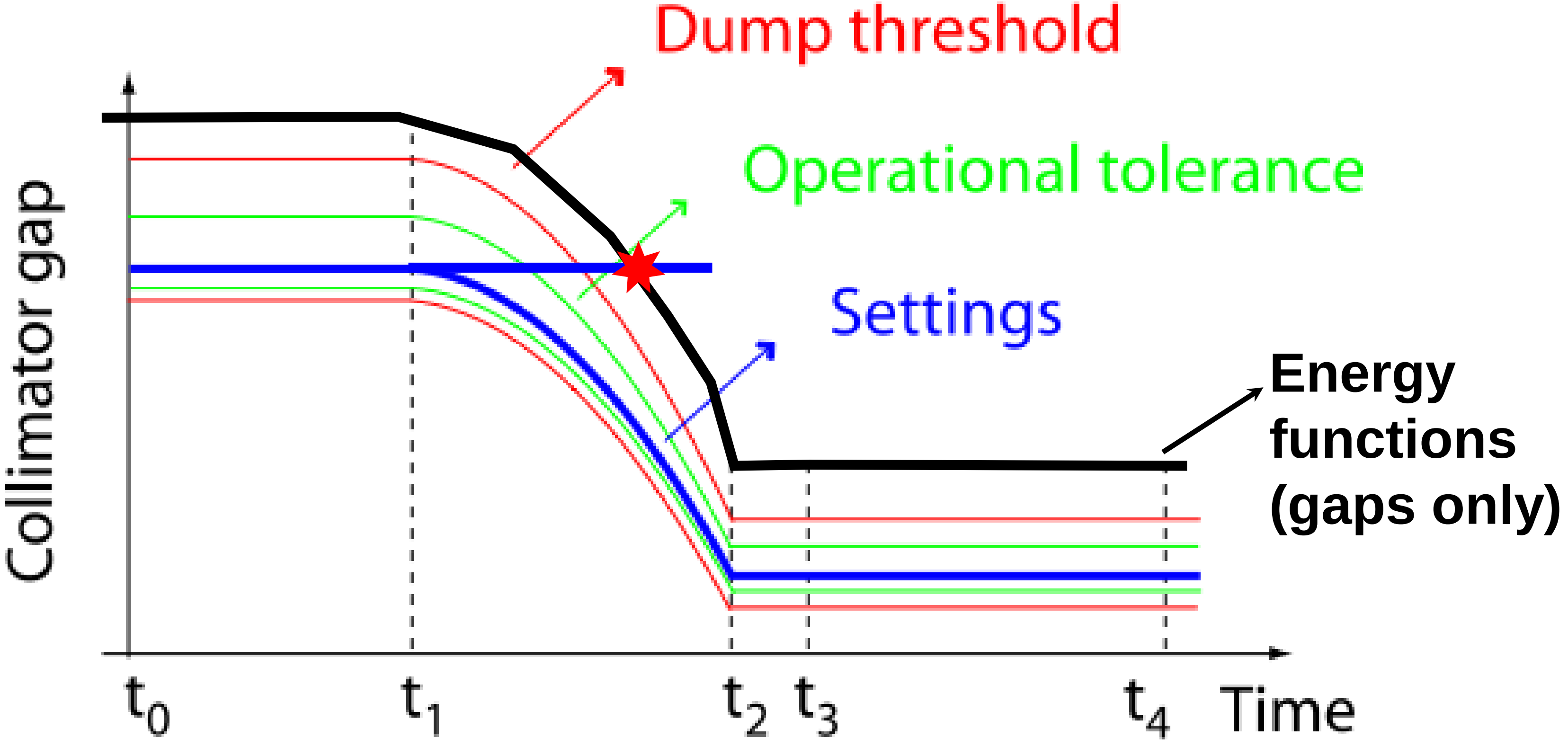


4 TeV proton beam

R. Bruce el al, Phys. Rev. ST Accel. Beams 17, 081004 (2014)

R. Bruce

Collimator position interlocks



For a **cycling** machine (energy, optics etc) collimators may have to move to track beam position or beam size changes: the collimators execute pre-programmed position functions (versus time).

To interlock the positions **inner** and **outer thresholds** must also be defined as functions of time for each motor **axis** and **gap**.

Introduction to collimation and absorbers

Collimation requirements and design

Collimator hardware

Collimation system operation

Synchrotron radiation collimation

Novel collimation techniques

Dump absorbers

Synchrotron radiation in electron machines

Synchrotron radiation poses specific problems for collimation, for example for the protection of experiments in e+e- colliders.

- When the photons energy reach energies of ~ 1 MeV, neutron production sets in, creating additional issues (LEP, future FCC-ee and CEPC e+e- colliders).

The large number of photons generated in the machine elements close to experimental detectors may pose a significant challenge and requires very careful design not just of collimators and absorbers but also of the **complete accelerator layout**.

In general the energy of e+e- beams is lower than for hadrons (until some ILC-CLIC will be build) and the **electromagnetic interaction of the leptons is much stronger than that of hadrons.**

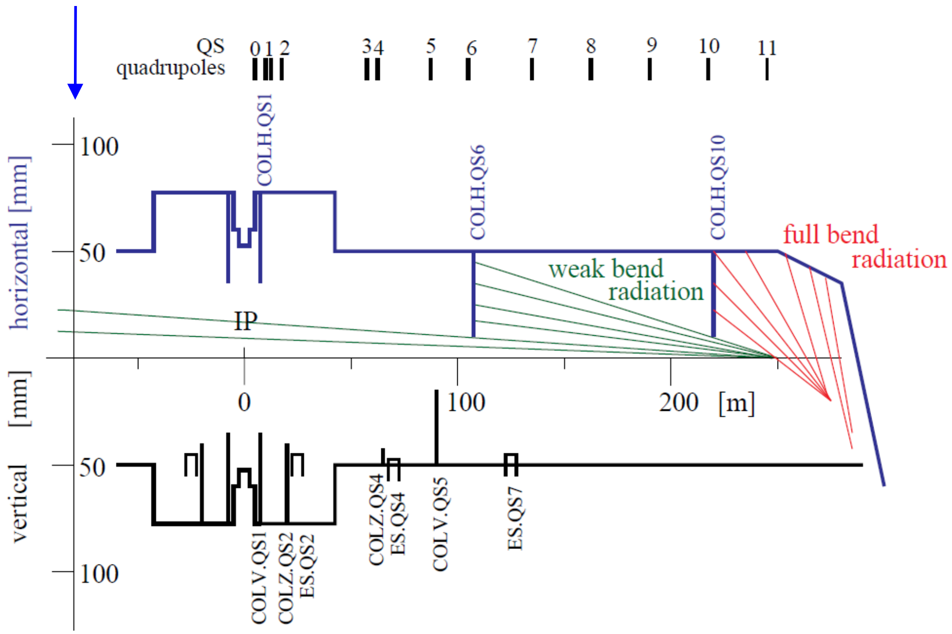
- much lower probably of particles escaping and propagating over long distances,
- more compact collimation system designs.

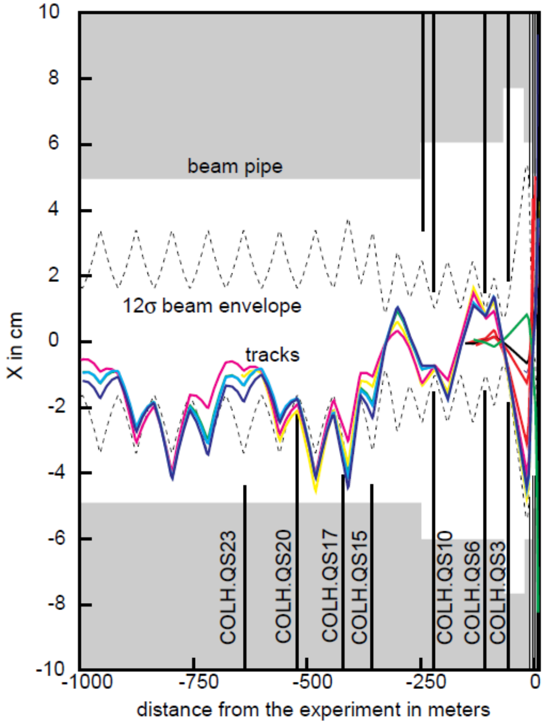
LEP collimators

At the Large Electron Position collider (LEP, 1989-2000, 20 - 105 GeV) many collimators were installed between the curved arc sections that were important sources of SR and off-energy particles and the experimental straight sections.

- Weaker bending magnets were used to lower the photon energy and the number of photons emitted close to the experiment.

Interaction point





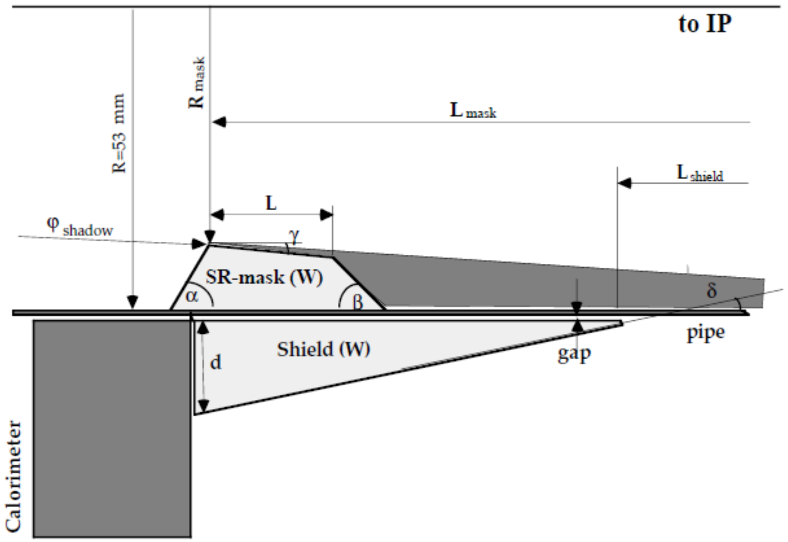
G. von Holtey et al, CERN-SL 97-40

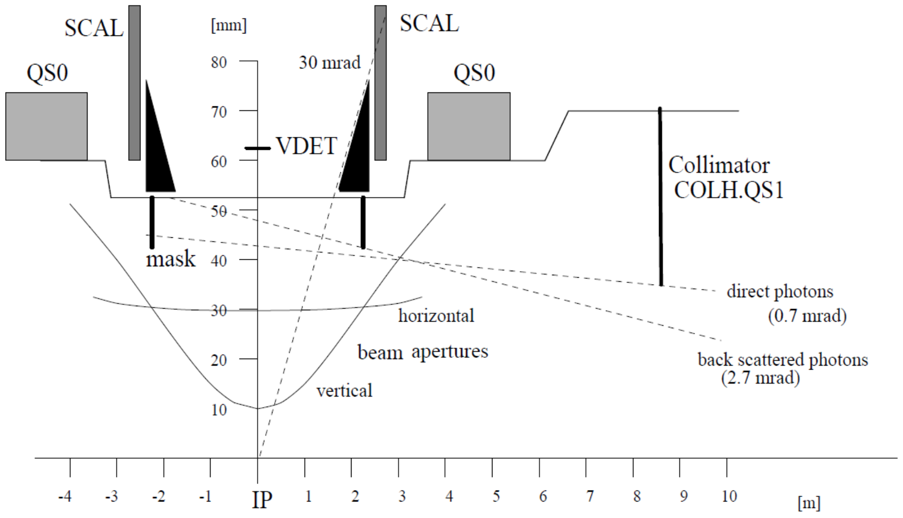
LEP local masks

To protect the experiments against photons emitted in the vicinity of the interaction point, local masks were installed next to the experiments to effectively absorb this radiation.

- Careful design of the shape is required to avoid reflections of photons into the detector (up to ~ 100 keV).

LEP (tungsten) synchrotron mask





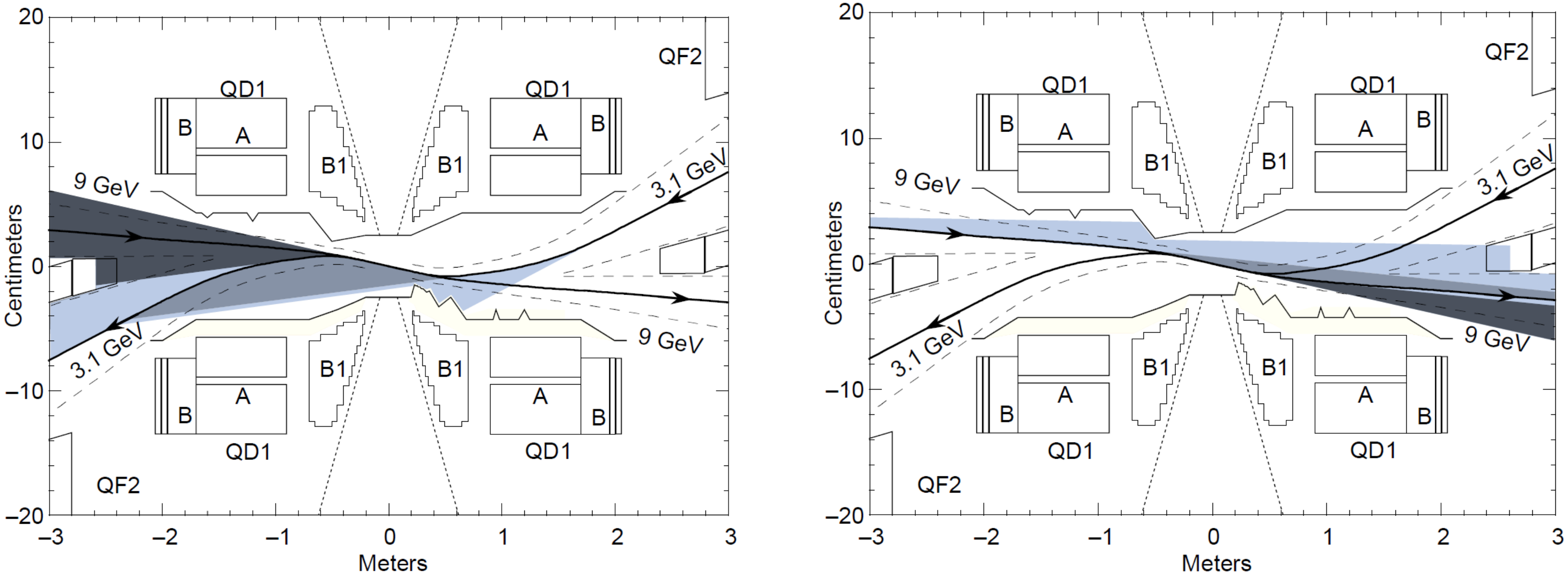
G. von Holtey et al, Proc. PAC 1999, IEEE 1999

PEPII

SLAC’s PEPII B-factory asymmetric e+e- collider (1999-2008) operated with beams currents of 2-3 A at 3 Gev and at 9 GeV.

The design of the interaction region was complex to accommodate the combination-separation of the beams without flooding the BABAR detector with SR photons.

PEPII SR fans & masks around the detector



M. Sullivan, SLAC-PUB-7725 (1997)

superKEKB

A large collimation system is used to cope with the synchrotron radiation load and to ensure operation of the detector.

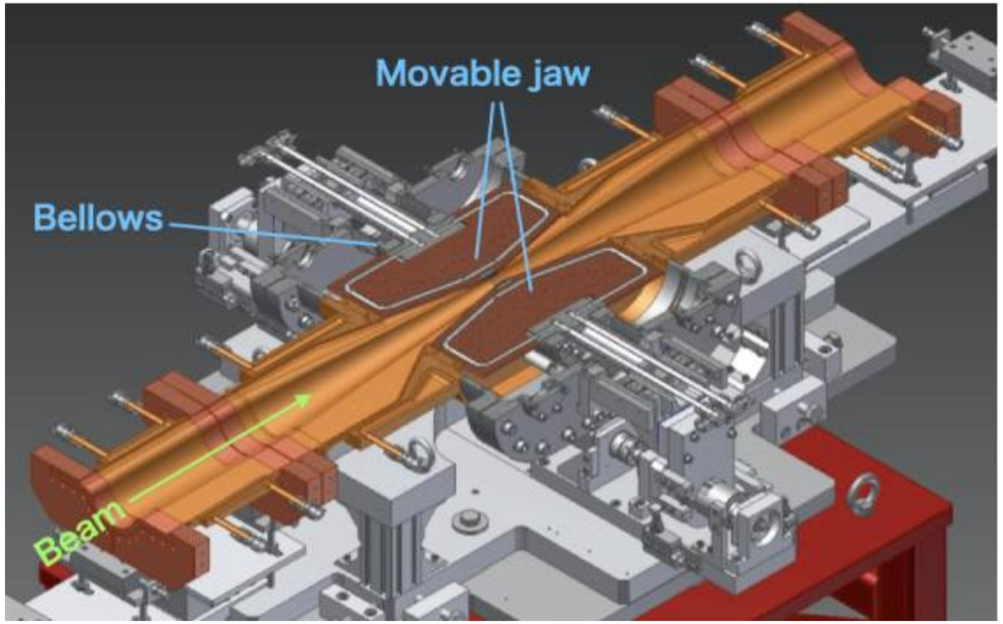
Impedance to the beam is a worry to reach design beam currents.

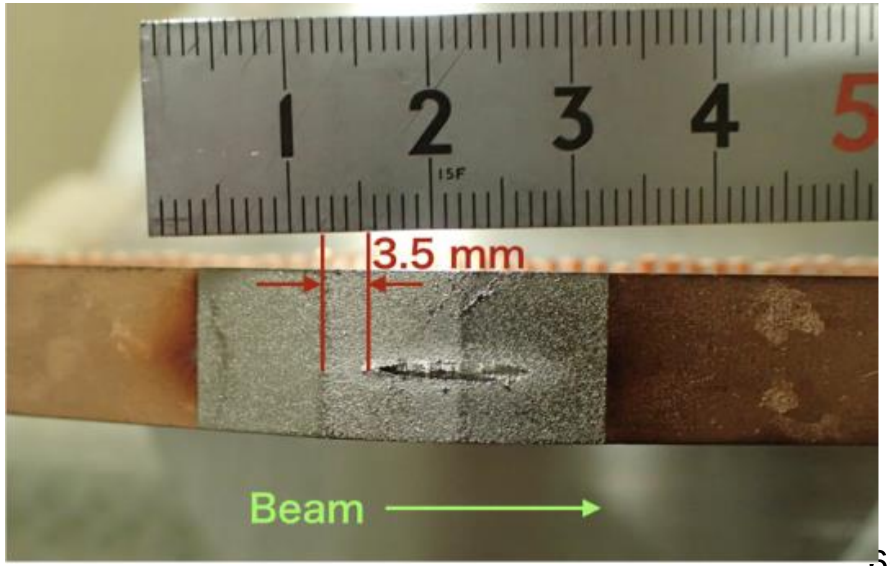
Copper collimators with Tungsten tips to increase the absorption of e+- & photons.

- Very effective in reducing the number of quenches of the superconducting final focus quadrupoles.

The Tungsten tips have been found occasionally damaged by beam impact for beam currents above 0.5 A – cause not understood.

- New generation collimators based on Titanium or Carbon under consideration.





T. Ishibashi el al, PRAB 23, 053501 (2020)

- Introduction to collimation and absorbers
- Collimation requirements and design
- Collimator hardware
- Collimation system operation
- Synchrotron radiation collimation
- **Novel collimation techniques**
- Dump absorbers

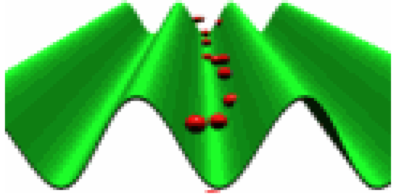
Crystal channelling

Inside a crystal particles (e.g. protons) feel a potential well from the crystalline planes.

If its transverse momentum is small enough, the particle may be trapped between the crystal planes – **channelling**.

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

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



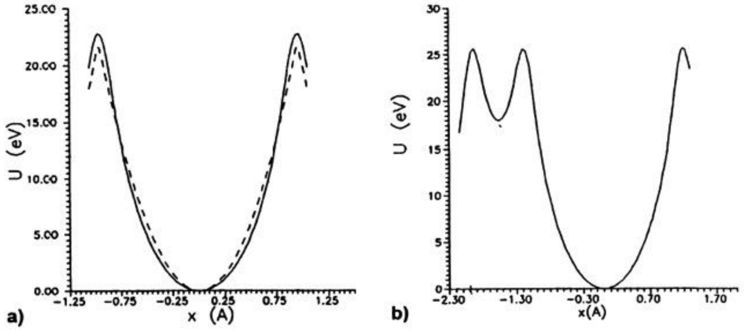
Forced to oscillate in a relatively empty space

$$x(z) = \frac{d_p}{2}\sqrt{\frac{E_t}{U_{max}}}\sin(\frac{2\pi z}{\lambda} + \phi)$$

***Values** at high energies*

Case	Energy [GeV]	θ_c [μrad]	λ [μm]
SPS coast	120	18.3	33.0
SPS coast	270	12.2	49.6
H8	400	10.0	60.3
LHC inj.	450	9.4	64.0
LHC top	6500	2.5	243.2
LHC top	7000	2.4	252.3

Potential seen by protons from a crystalline plane

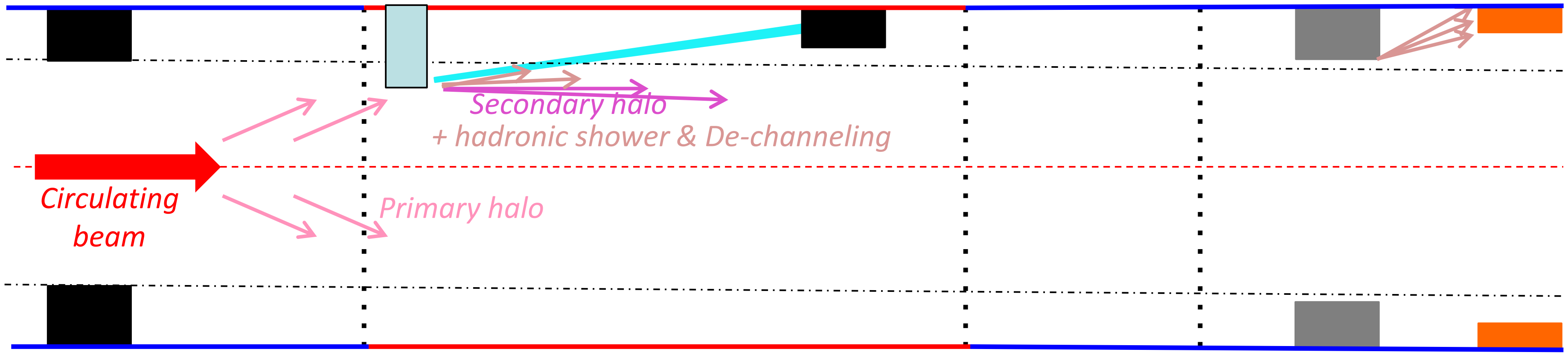


Courtesy D. Mirarchi

Bending the crystal generates an asymmetry in the potential and reduces the acceptance / acceptable transverse momentum.

- But the particle can be deflected by a large angle.

Crystal collimation concept



Possible gains:

Large deflection angle by primary (crystal).

Fewer inelastic collisions in the primary.

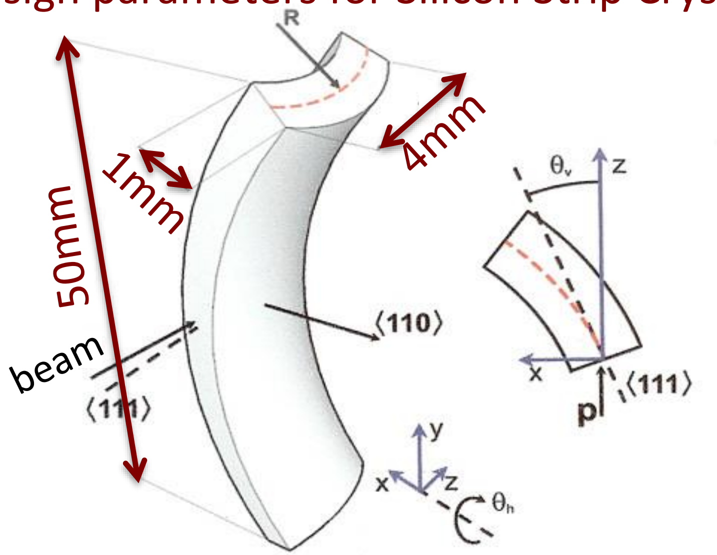
- Smaller energy leakage.

Fewer collimators.

- Reduced impedance.

Better efficiency for ions.

LHC design parameters for Silicon Strip Crystals



Bending 50µrad ≡ B ≈ 300 T @ 7 TeV!

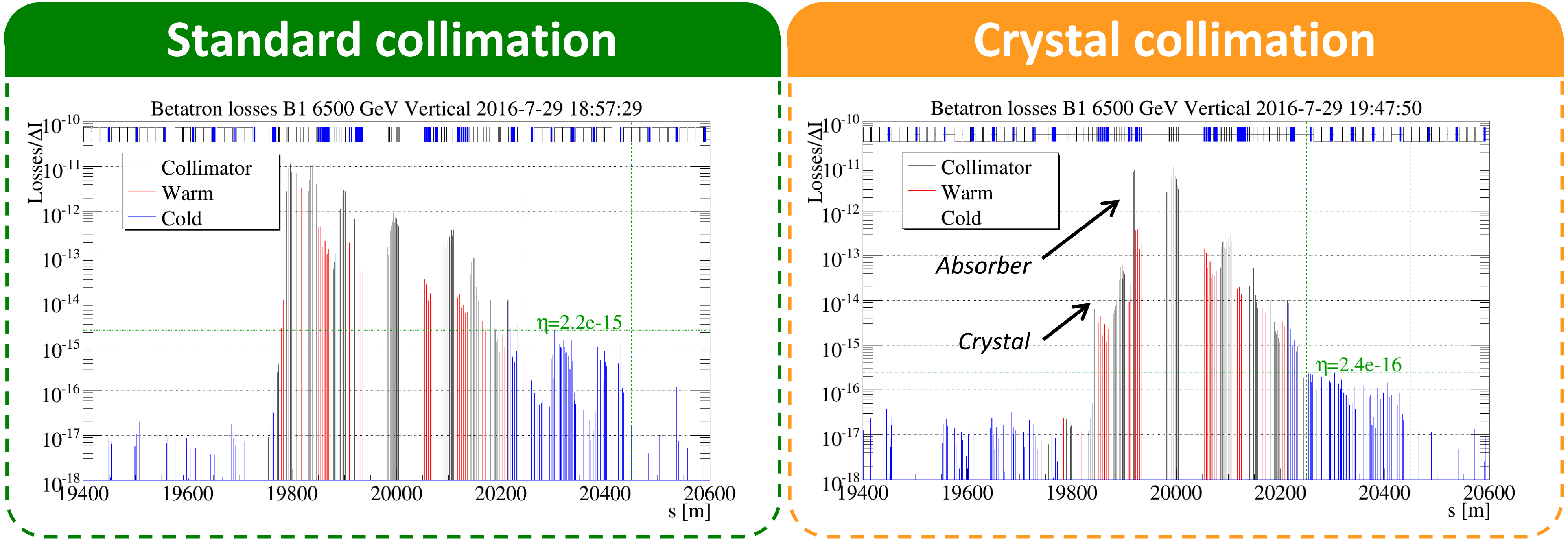
Recent LHC results for crystal collimation

Tests of crystal collimation at the LHC are encouraging, indicating possible **gains for the collimation leakage by a factor ~5-10** for protons and ions.

A program to better understand the sensitivity to beam position errors and other ‘operational imperfections’ is in progress.

Courtesy D. Mirarchi

Standard collimation **Crystal collimation**

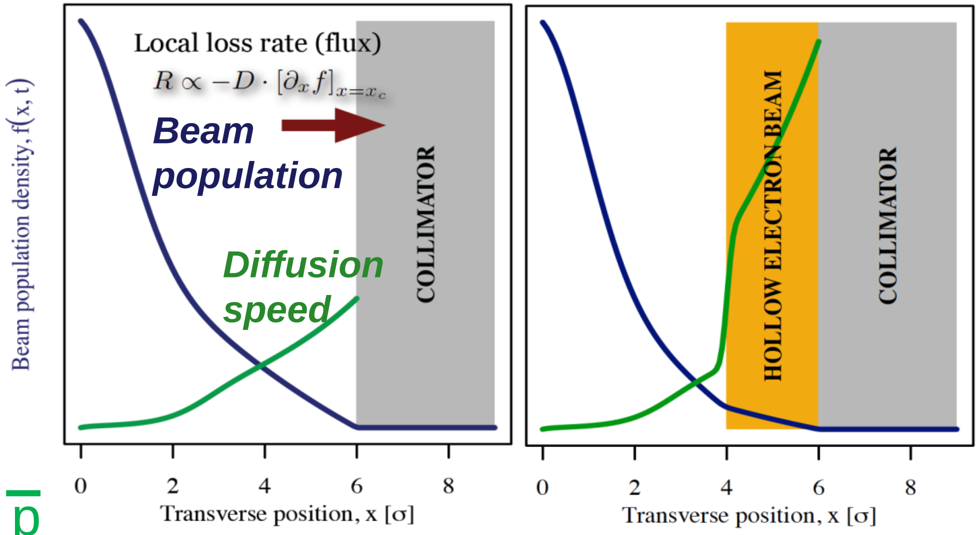


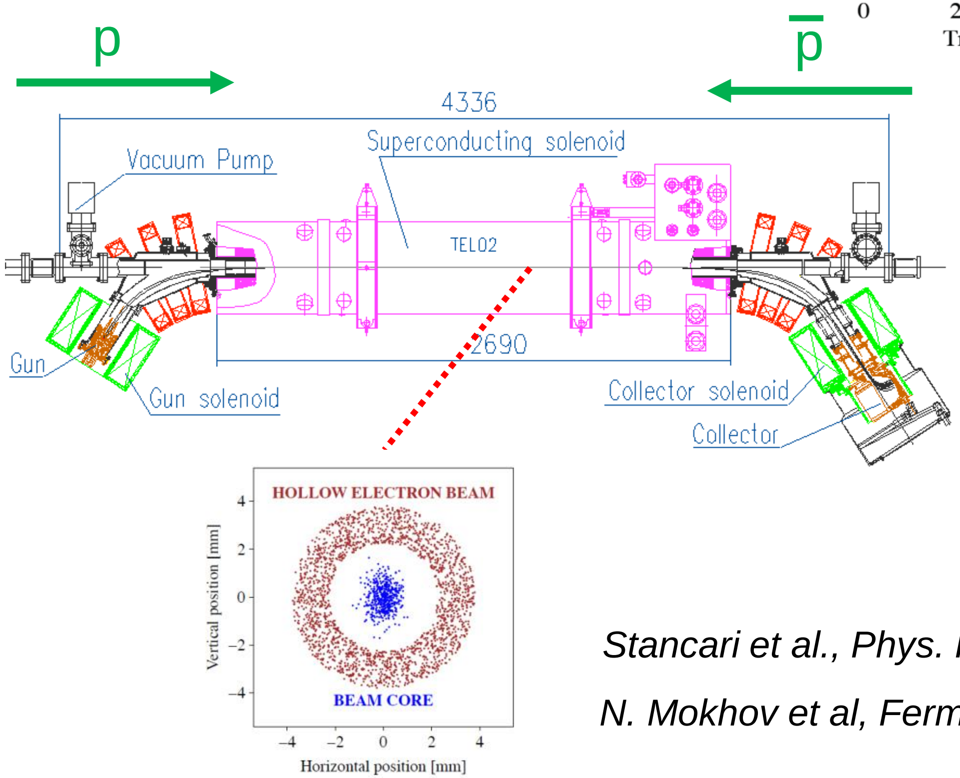
Observed about a **factor 10 better cleaning (η) using crystal**, as expected from simulations!

Hollow electron lens

Halo cleaning by electron lens demonstrated at Tevatron.

- *Acts as a soft scrapper,*
- *No material damage,*
- *Tunable strength – diffusion speed*





Such a lens is considered as an option for LHC upgrades to be able to control the beam halo.

Stancari et al., Phys. Rev. Let. 107, 084802

N. Mokhov et al, Fermilab-Pub-11-378-APC

- Introduction to collimation and absorbers
- Collimation requirements and design
- Collimator hardware
- Collimation system operation
- Synchrotron radiation collimation
- Novel collimation techniques
- **Dump absorbers**

Dumps

The **beam dump** is by definition the device in an accelerator that must **withstand the impact of the entire beam**.

The beam dump may be internal to the accelerator (i.e. part of the lattice) or external to the accelerator.

- In the later case an extraction region and beam transfer are also required.

At the highest energies external dumps are generally the only option due to space and radiation considerations.

In cases of extreme energy density, it may be necessary to dilute the beam by spreading it over the dump surface.

- Painting with kicker magnets.

Dump design considerations

The dump and its entrance window must with stand the impact of one beam.

- Dilution of the beam
- Segmentation of the dump material to spread out energy deposition

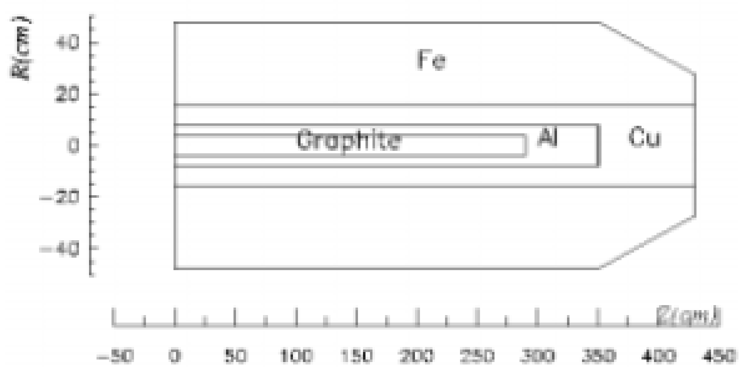
The dump must withstand repetitive beam impacts.

- Dump temperature, cooling.

3 MJ transfer line dump

CERN mobile transfer line dump for 450 GeV proton beams, stored beam energy ~3 MJ.

Inner core of graphite, aluminium and copper, surrounded by an iron shielding.



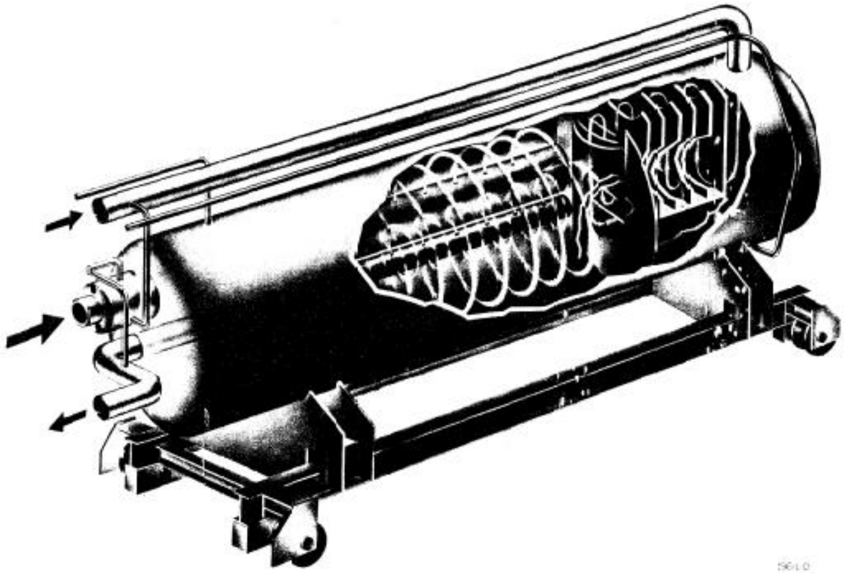
SLAC high power water dumps

At the SLC two 2 MW water dump were installed in 1966 the e^- beams experimental program (up to 25 GeV), in service for ~40 years.

- Advantage of water is that it is not destroyed: a transient phase change may occur, but eventually the water comes back to its original ‘form’.
- Such a dump must be well confined as radioactive water leaks must be prevented !

One of the dumps still exits, but is not used. A new design with larger acceptance is now in place, but the power need is very low.

Courtesy, D.Waltz



The water depth is ~ 10 radiation lengths (followed by ~20 RLs of water cooled Cu plates)

Entrance window 1.25 mm thick chrome plated Cu

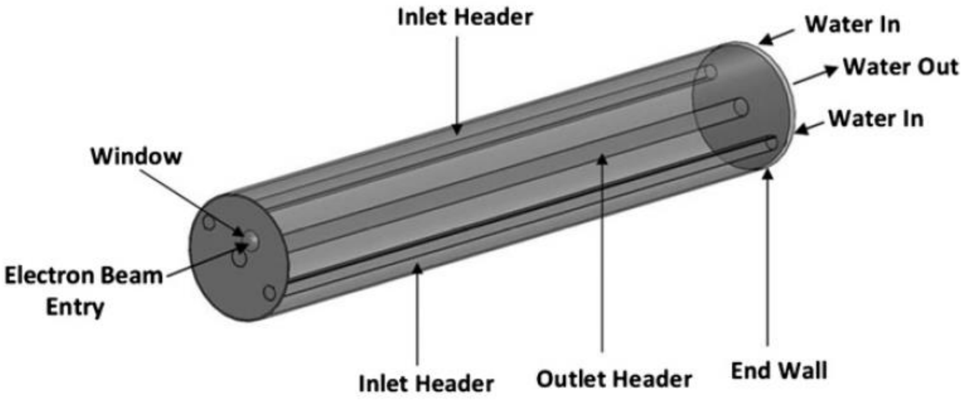
D.Waltz, PAC 1967, IEEE TRANSACTIONS ON NUCL. SCIENCE, JUNE 1967

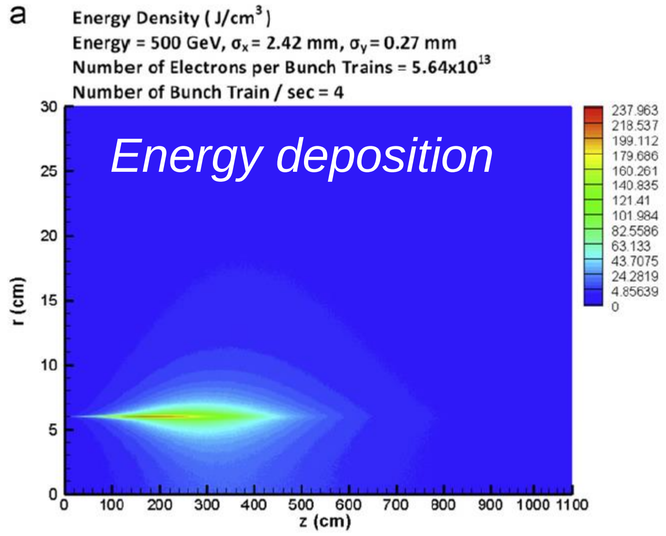
18 MW ILC dump

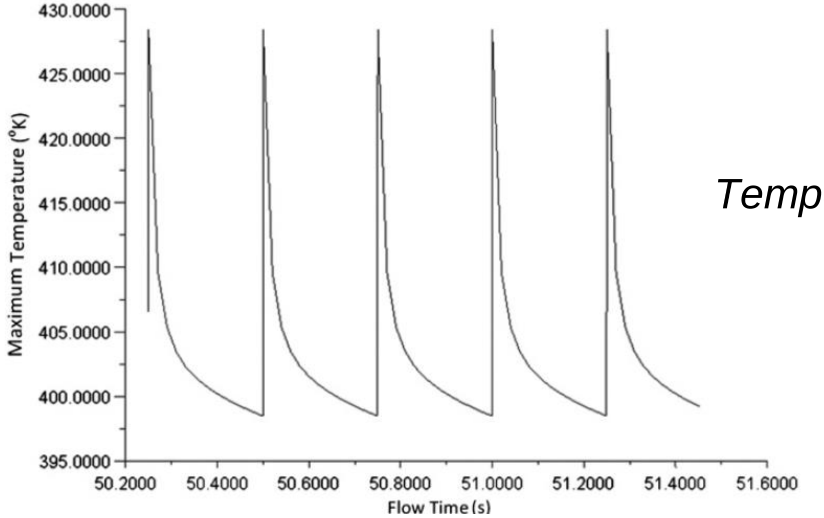
ILC design of a 18 MW water dump for the 500 GeV e^+/e^- beams.

- Based on the SLC water dump design.

Dump vessel length is 11 m.







Temperature cycle, max T ~ 155^{o} C

P.Satyamurthy et al, NIM A679(2012)67–81

D. Walz et al, Proc IPAC10, WEPE003.

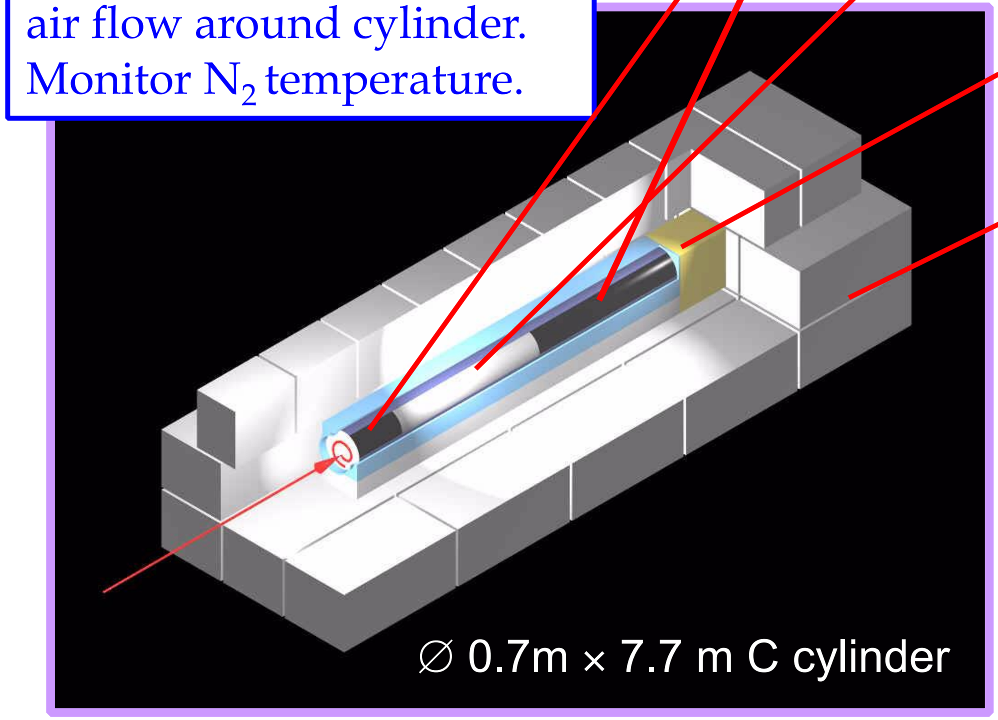
LHC beam dump block

Dump block design consideration: robustness, dump repetition rate,…

At the LHC: only sufficient robustness with **beam dilution**.

Steel cylinders under N_2 overpressure.

No water cooling; forced air flow around cylinder. Monitor N_2 temperature.


∅ 0.7m × 7.7 m C cylinder

0.7 m and 3.5 m of Graphite, 1.73 g/cm^3 density

3.5 m of Graphite with 1.1 g/cm^3 density

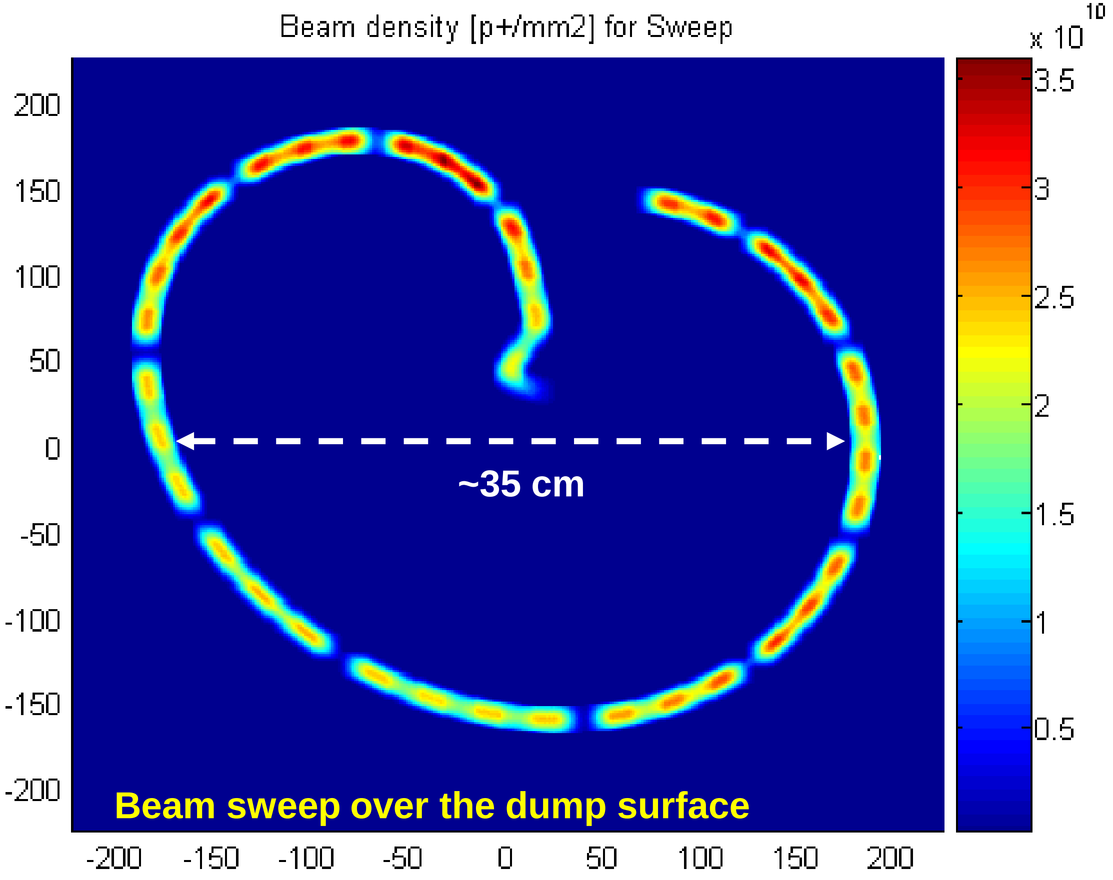
1 m Al, 2 m Fe

~900 T of radiation shielding blocks

Design such that no structural damage to be expected during 20 years of operation with ultimate LHC intensities

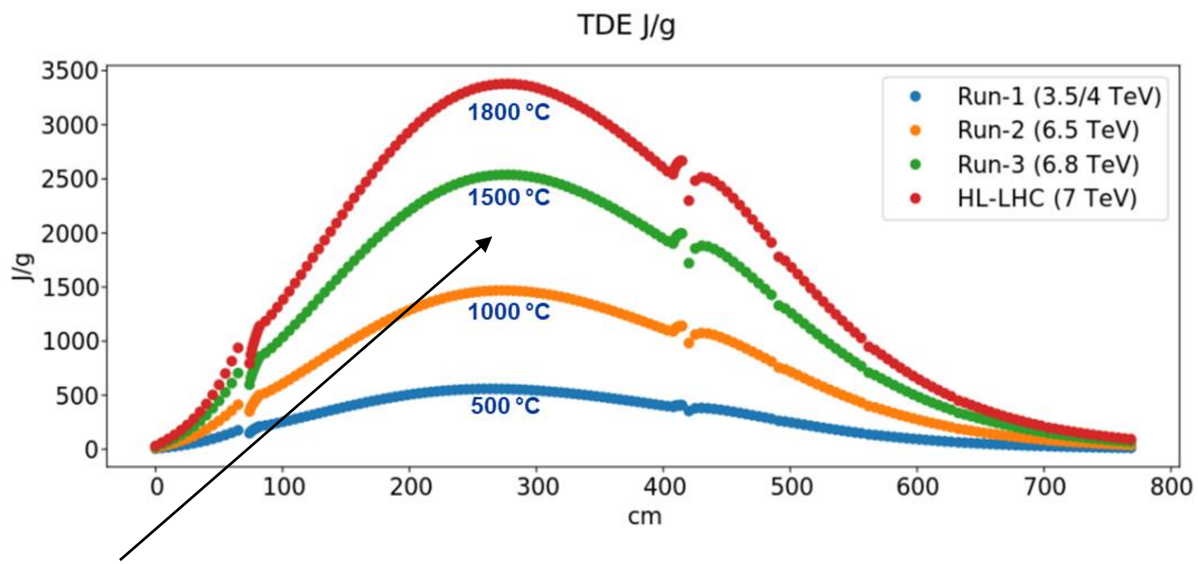

LHC beam dump block - dilution

A set of vertical and horizontal **dilution kickers** installed in the extraction channel sweep the beam over the section of the dump block – this sweep is essential to **prevent damage** to the **graphite core** and to the **dump windows**.



Beam sweep over the dump surface

Peak energy density and temperature

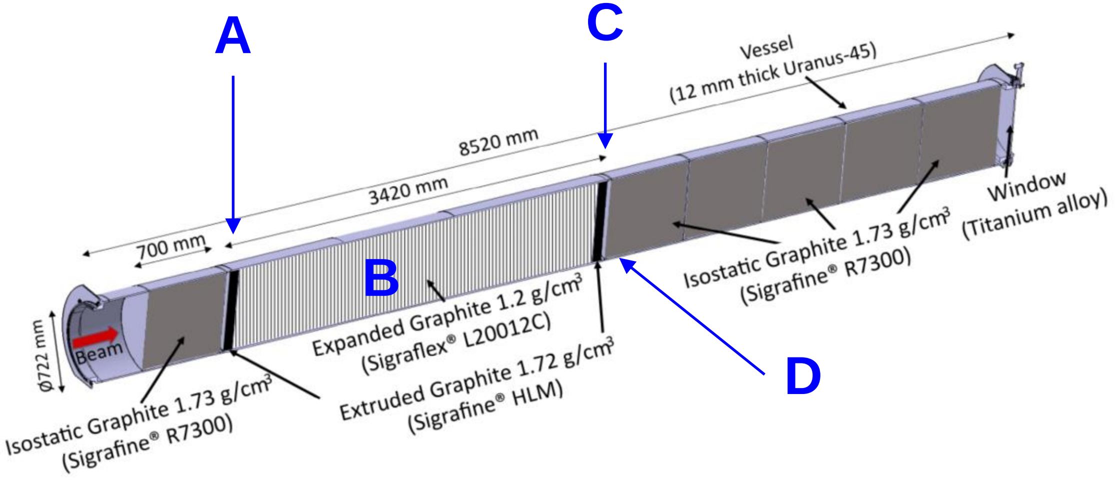


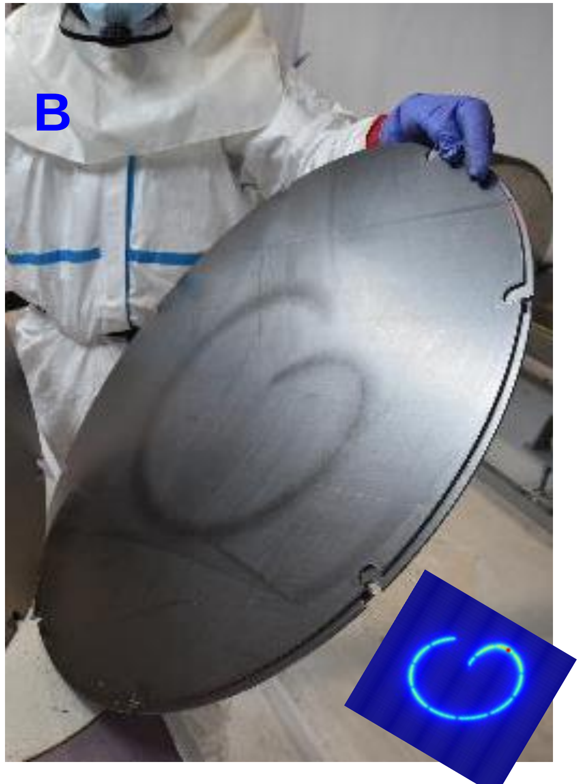
LHC 2022

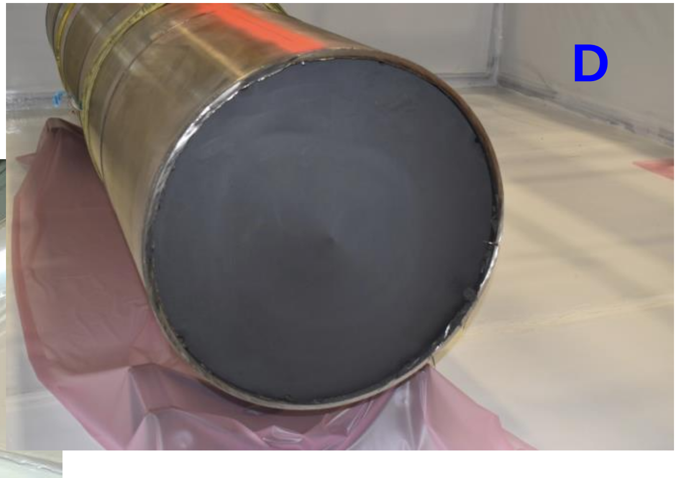
Dump autopsy

During a recent shutdown one dump core was opened to perform an “autopsy” due to worries on integrity after ~300 MJ operation for multiple years.

- The core material was found in good condition.
- Fractures on inner graphite windows, but not critical for dump operation.







Summary

Collimators play many important roles for high intensity machines for halo control, machine and radiation protection.

The design of collimators and absorbers requires careful optimizations involving particle tracking, shower simulations and material study.

- The collimator material may have to satisfy to a number of sometimes conflicting constrains.

Modern collimation system usually involve more than one stage and the integration of the collimators into the machine design must be done at an early stage.

Operational aspects of a collimation system should be considered at an early stage, which involves position sensors, alignment methods and controls aspects.