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

The LHC machine protection and beam collimation

Part 3

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Outline

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

Outline - 3rd lecture

- **Main points from 2nd lecture**
- **The LHC collimator design**
  - From conceptual design to hardware
  - The LHC collimators
- **Operational performance at the LHC**
  - How do we operate the system
  - Cleaning performance
- **Simulations of collimation cleaning**
  - Halo tracking and beam loss prediction
- **Advanced collimation concepts**
  - High Luminosity collimation upgrade
  - Crystal collimation
  - Hollow electron lenses

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:
  (1) minimize risk of quenches with 360 MJ stored energy,
  (2) passive machine protection in case of accidental failures.
  Many other important roles (warm vs cold machine, activation, backgrounds, etc...)!
- Collimation is achieved by constraining the transverse amplitudes of halo particles: collimator jaws are set close to the beam to shield the aperture.
- Many sources of beam losses (collisions, gas or beam scattering, operational losses,...) are modelled by looking at the time-dependent **beam lifetime**.
  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!

  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**.*

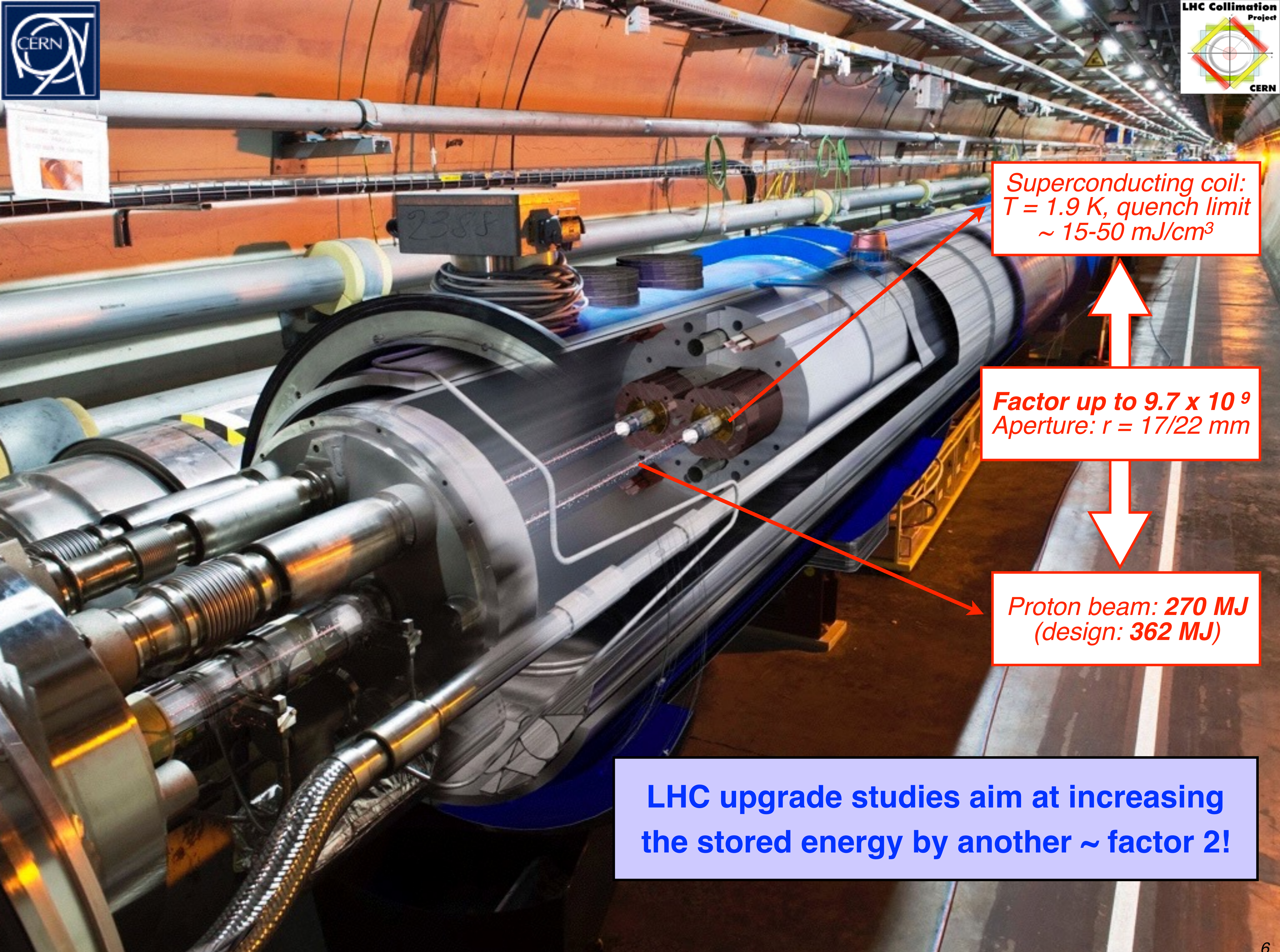
- Dedicated **momentum cleaning** might be needed if energy losses are a concern.

  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 system: **warm insertions**; but collimators also used for **local protection** and **physics debris cleaning**.

- **LHC collimation**: unprecedented complexity in particle accelerators!

  *A total of ~50 collimators per beam, ordered in a pre-defined **collimation hierarchy** as it is needed to shield the (small!) LHC aperture.*



LHC Collimation Project
CERN
Superconducting coil:
T = 1.9 K, quench limit
~ 15-50 mJ/cm³
Factor up to 9.7 x 10 ⁹
Aperture: r = 17/22 mm
Proton beam: 270 MJ
(design: 362 MJ)
LHC upgrade studies aim at increasing the stored energy by another ~ factor 2!

Roles of collimation systems

- **Halo cleaning** versus quench limits (super-conducting machines)
- Passive **machine protection**
  First line of defence in case of accidental failures.
- **Concentration of losses/activation** in controlled areas
  Ease maintenance by avoiding many distributed high-radiation areas.
- **Reduction total doses** on accelerator equipment
  Provide local protection to equipment exposed to high doses (like the warm magnets in cleaning insertions)
- **Cleaning of physics debris** (physics products, in colliders)
  Avoid magnet quenches close to the high-luminosity experiments
- Optimize **background** in the experiments
  Minimize the impact of halo losses on quality of experimental data

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

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

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  Control and probe the transverse

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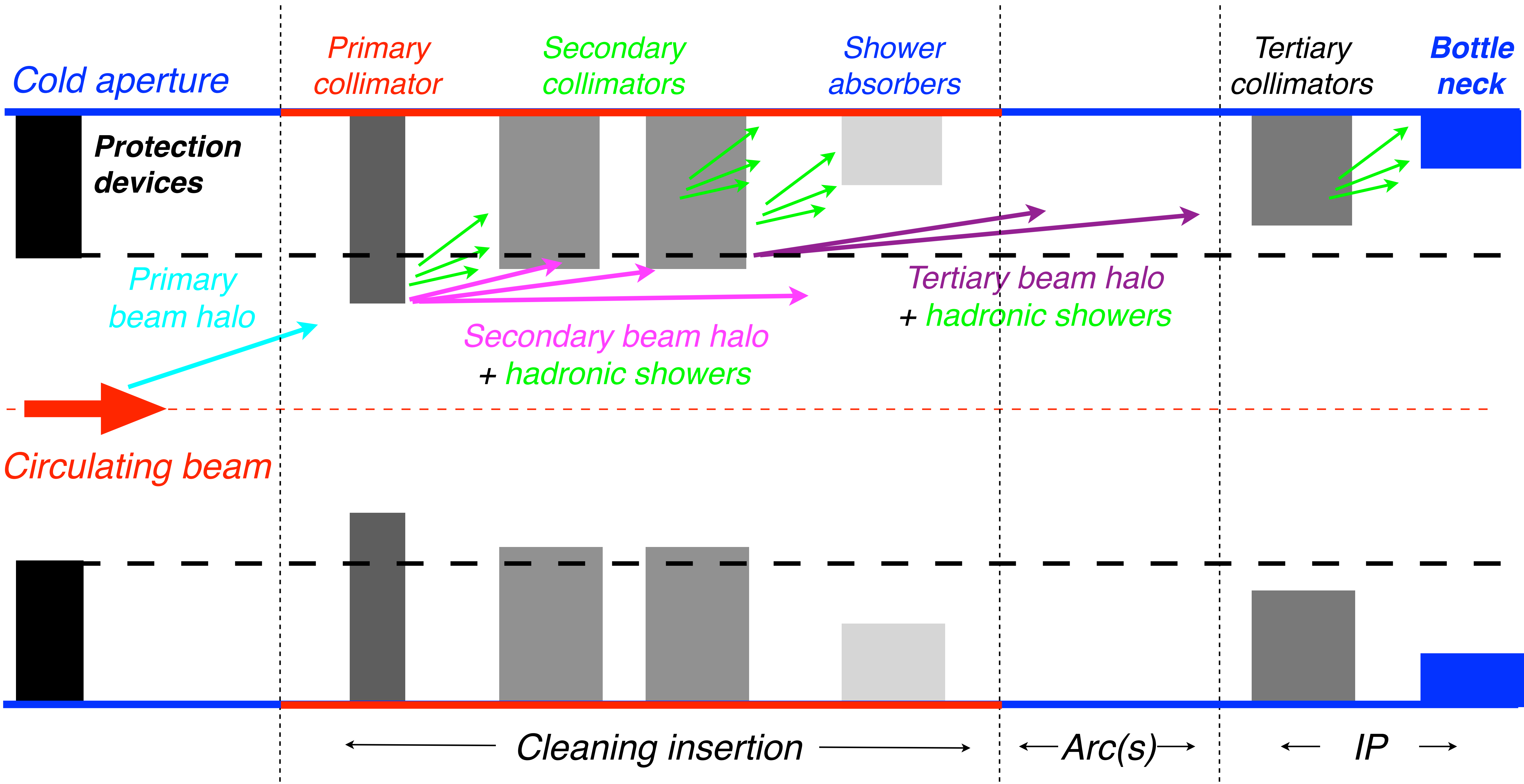
This lecture: focus **collimation cleaning** functionality. LHC examples as a case study because all these roles are addressed !

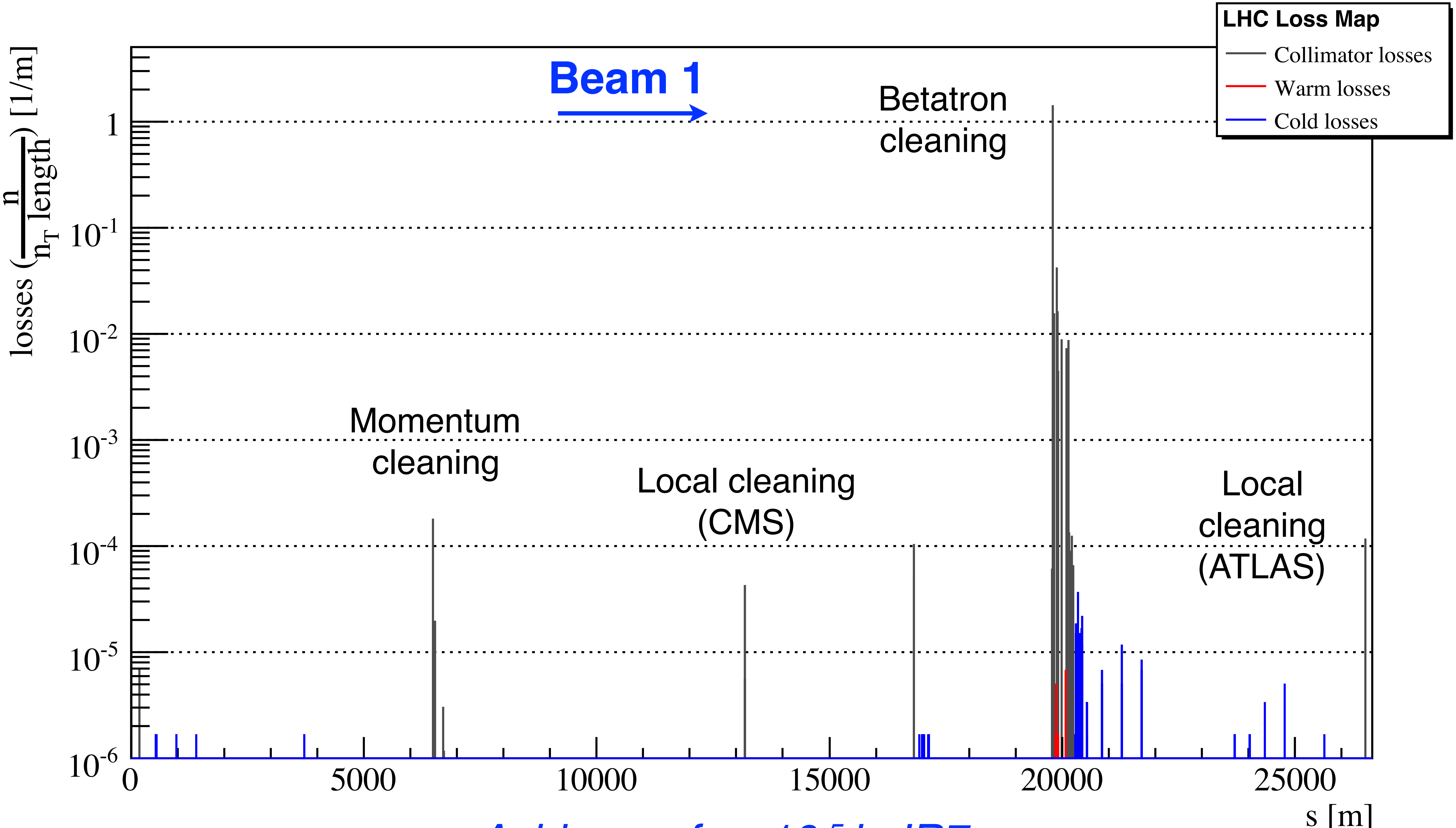
Multi-stage collimation at the LHC



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

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

Simulated 7 TeV performance



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

Cold losses in experiments removed by local protection.

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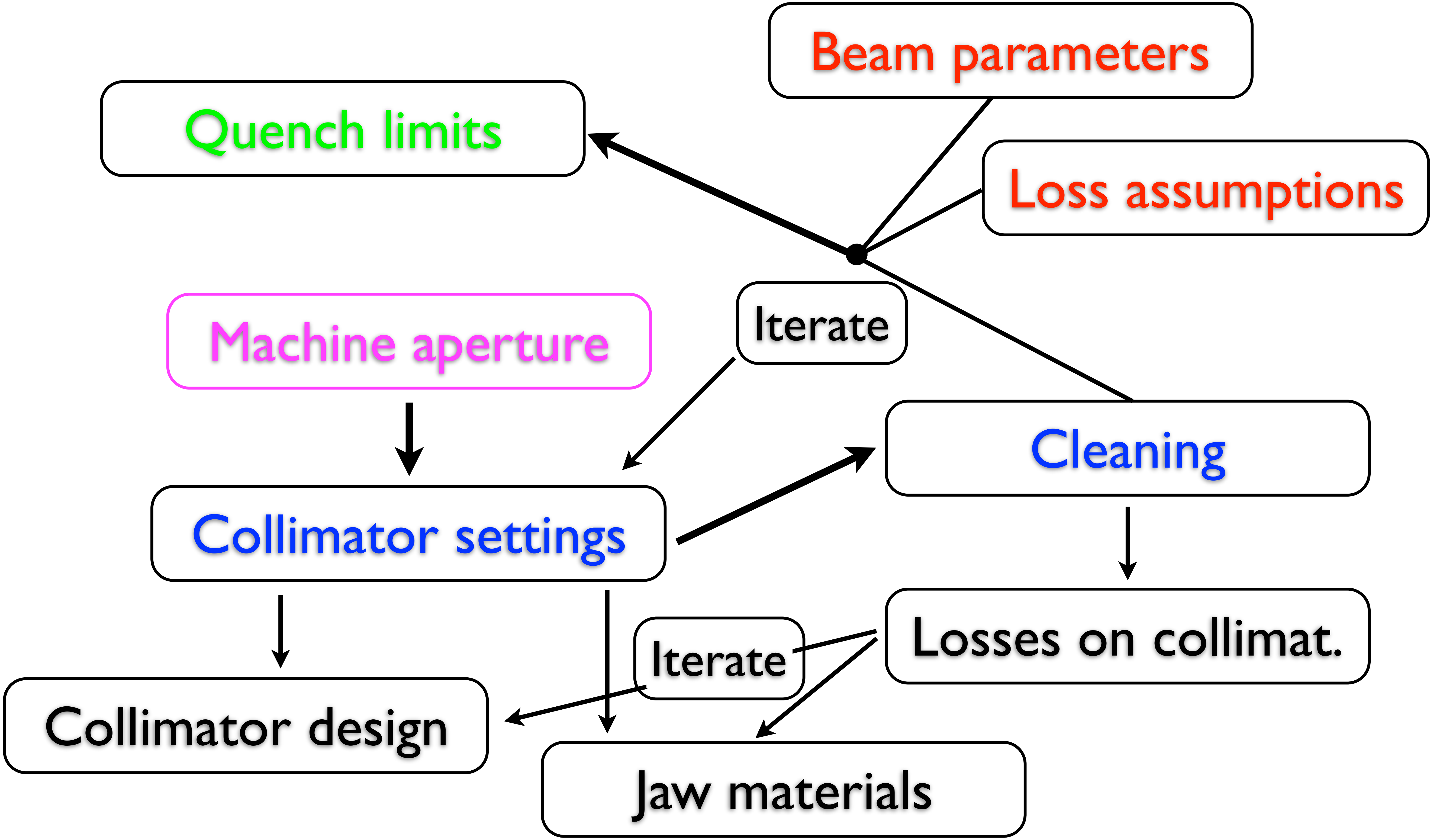
Workflow for collimation design



A multi-disciplinary topic...

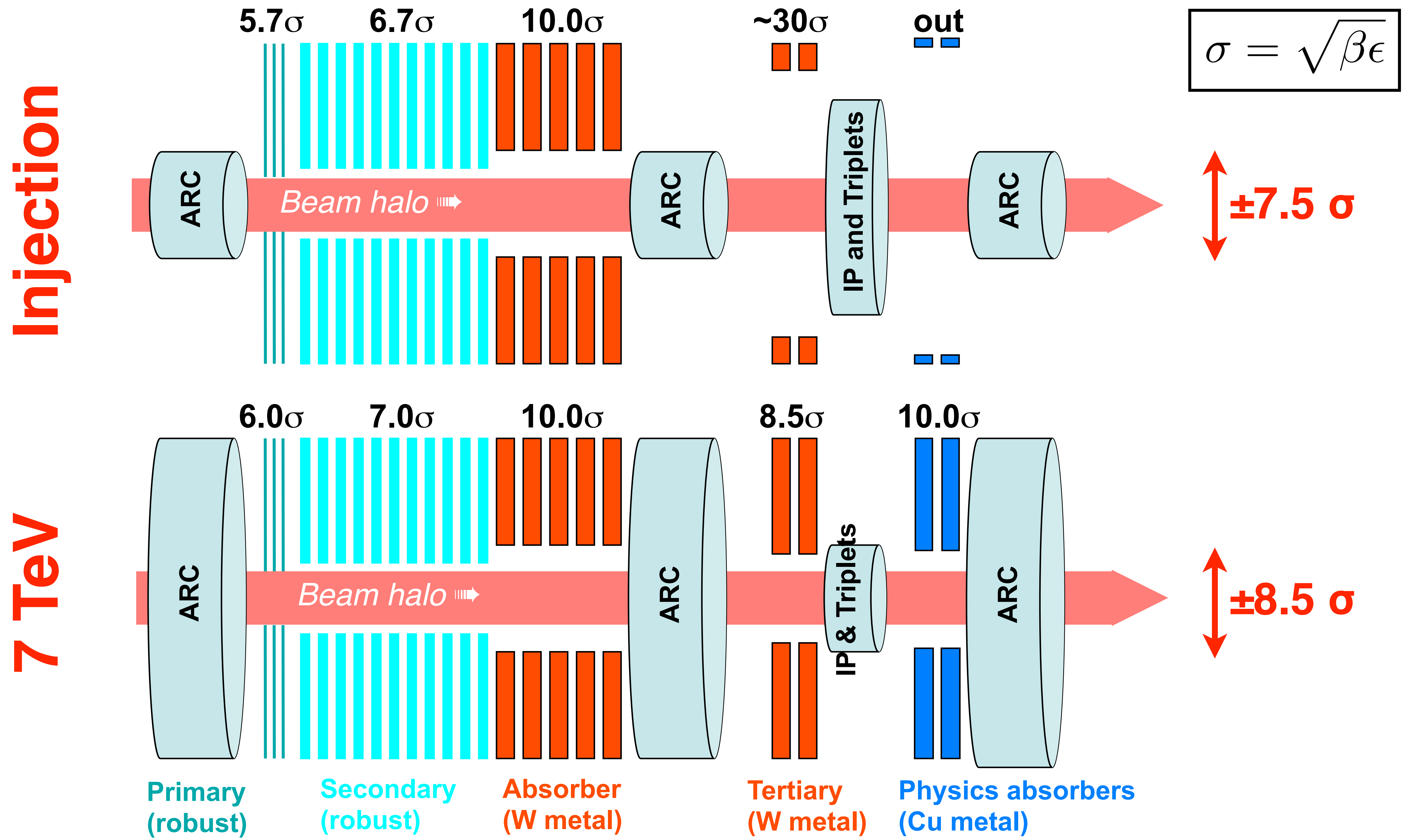
The complete design chain rely on different key ingredients:

- Tracking models
- Collimation scattering models
- Energy deposition simulations
- Thermo-mechanical analysis
- Operational assumptions

Standard chain of tools developed and used at CERN:
(1) SixTrack with collimation
(2) FLUKA
(3) ANSIS / AutoDyn

Important effort worldwide to extend tools:
MARS, Geant4, Merlin, BDSIM, ...
Recent workshop within HiLumi-WP5:
https://indico.cern.ch/event/275446

Aperture design and collimator settings



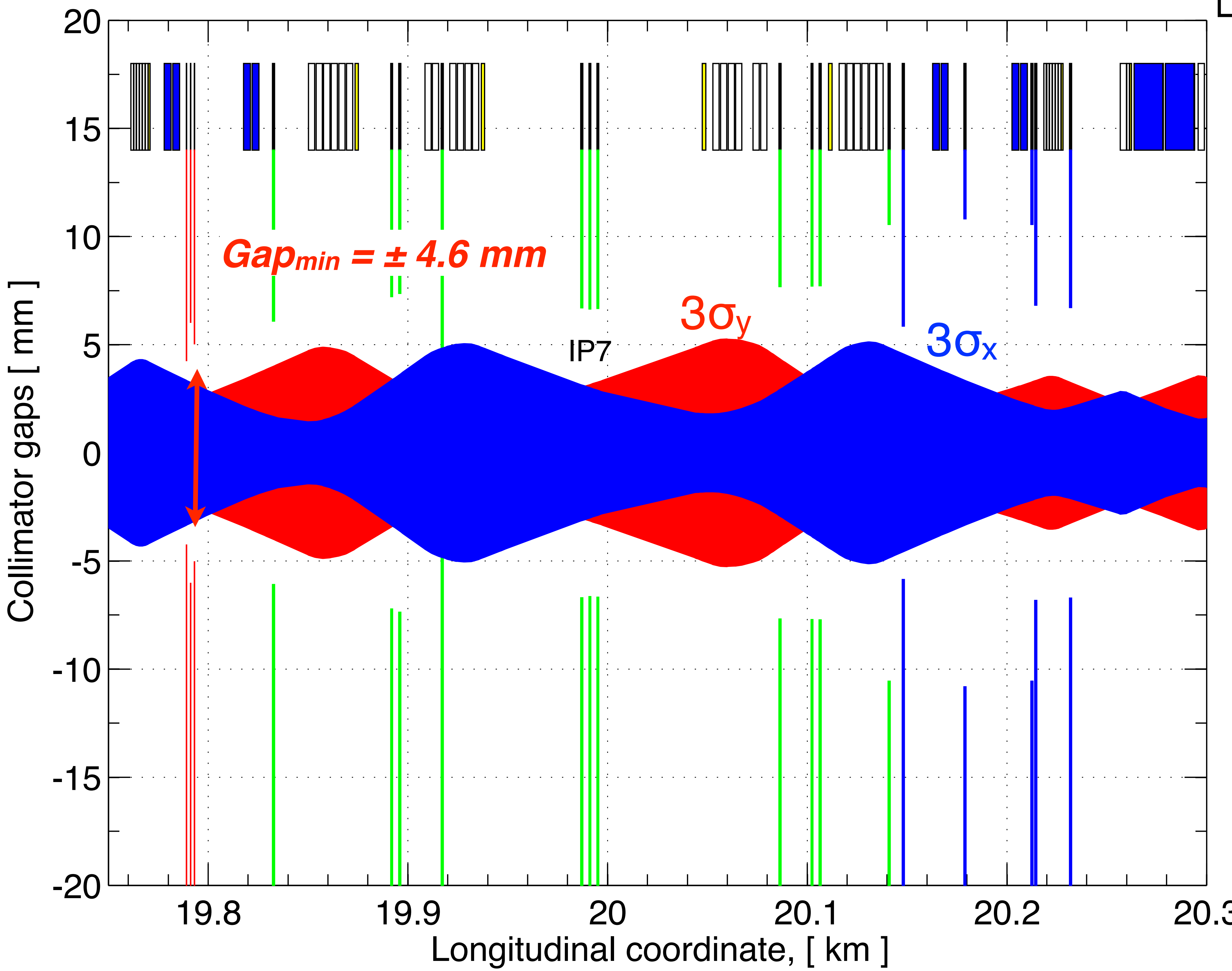
Ramp: beam sizes shrinks like sqrt(E).

Squeeze optics changes introduce bottlenecks triplet.

IR7 collimator settings at 450 GeV

A_{TCP} = 5.7 σ **A_{TCS} = 6.7 σ** **A_{TCLA} = 10 σ**

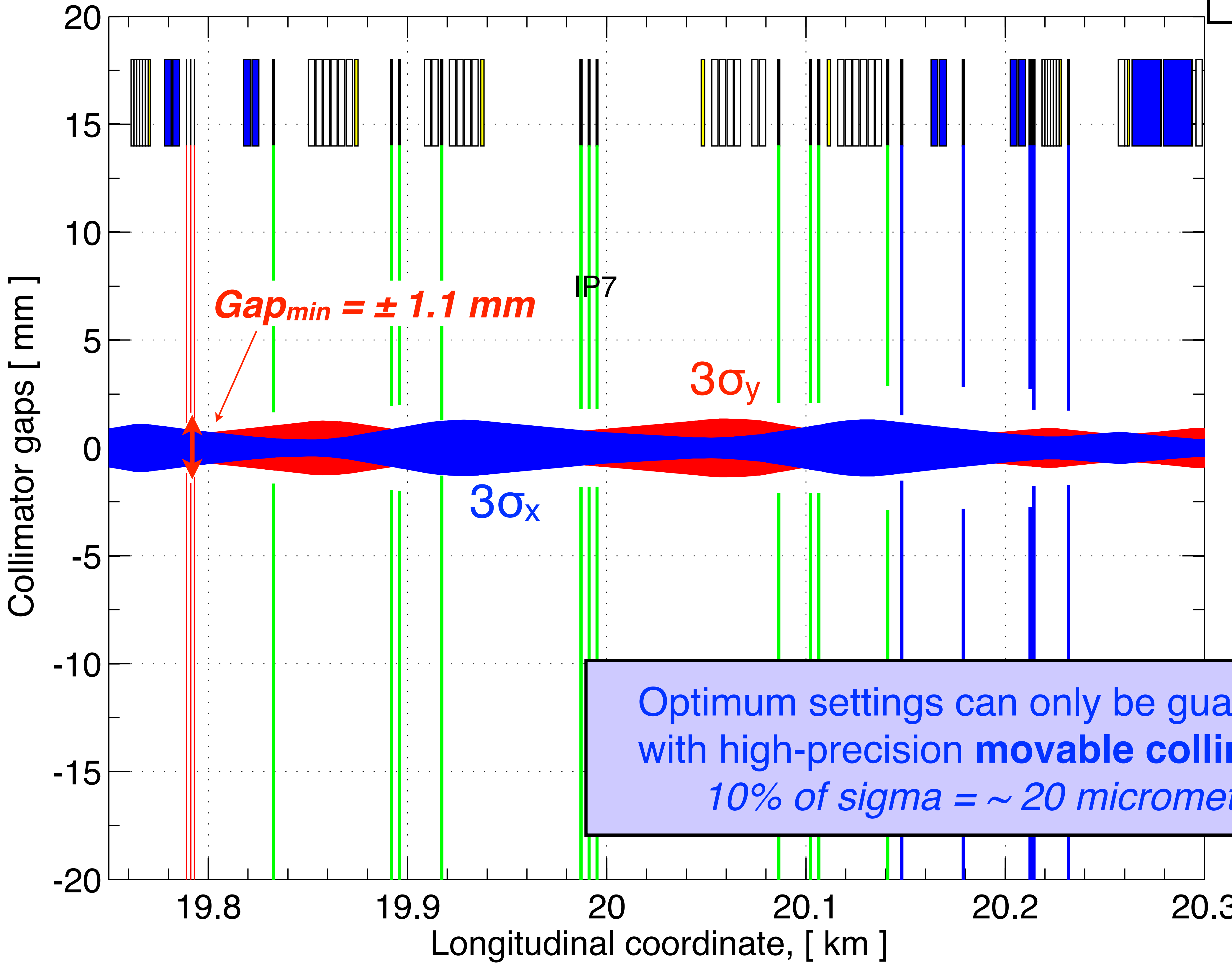
$$\sigma = \sqrt{\beta\epsilon}$$



IR7 collimator settings at 7 TeV

A_{TCP} = 6 σ A_{TCS} = 7 σ A_{TCLA} = 10 σ

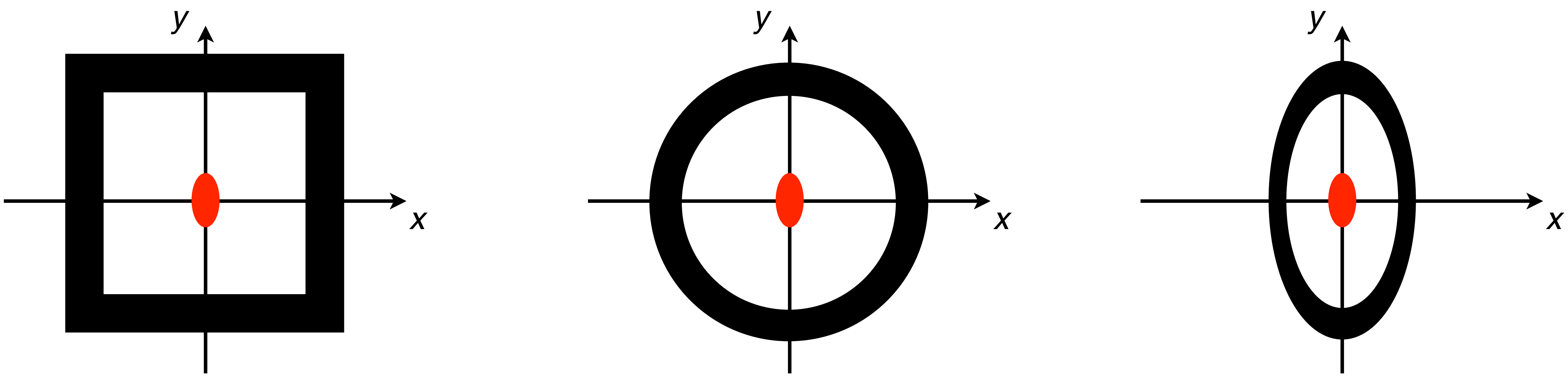
$$\sigma = \sqrt{\beta\epsilon}$$



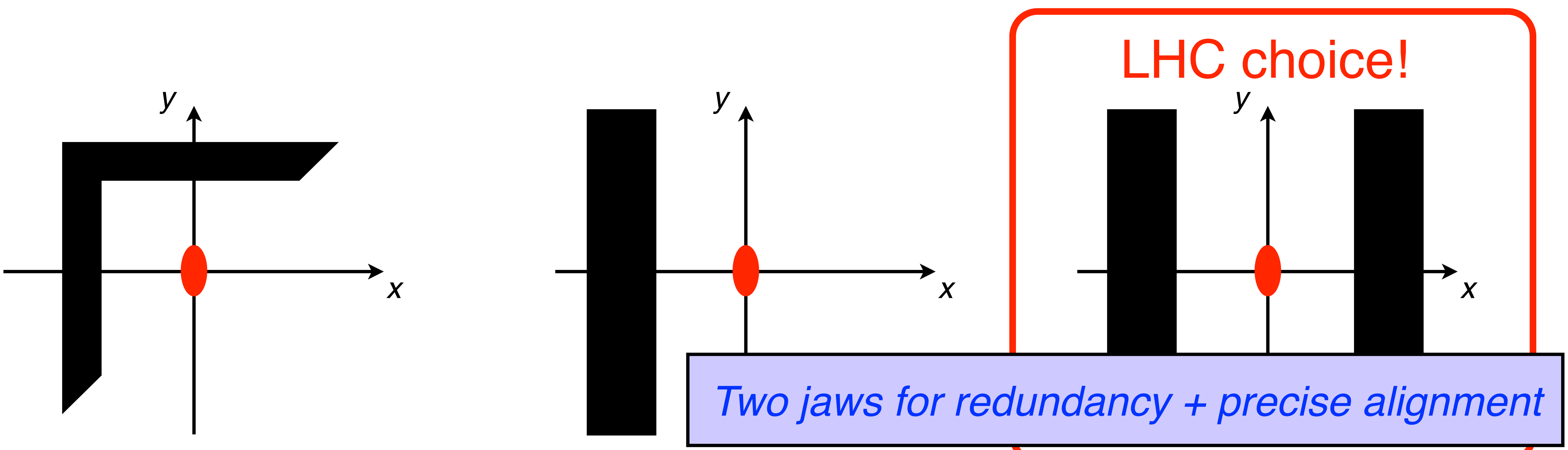
Optimum settings can only be guaranteed with high-precision **movable collimators**!
10% of sigma = ~ 20 micrometers!

Possible collimator designs

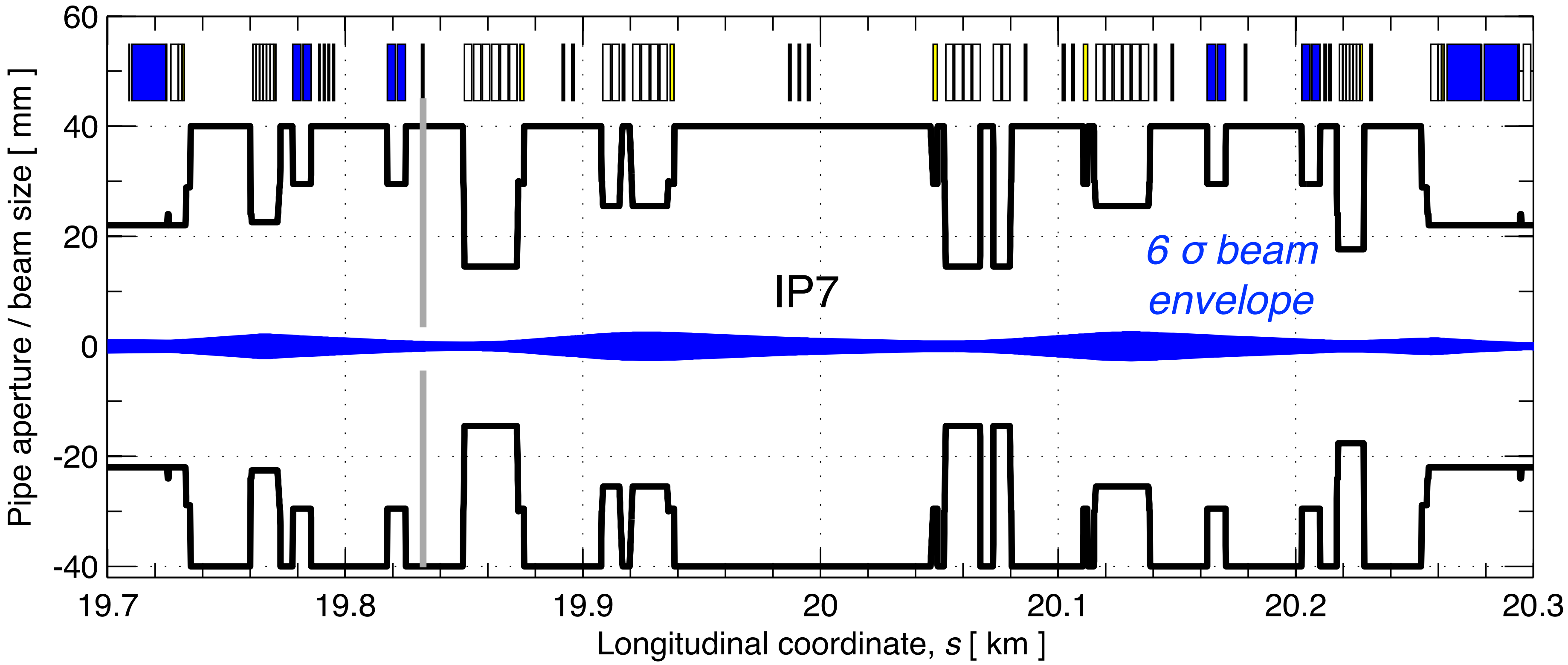
Fixed collimators (masks): square, circular, elliptical, ...

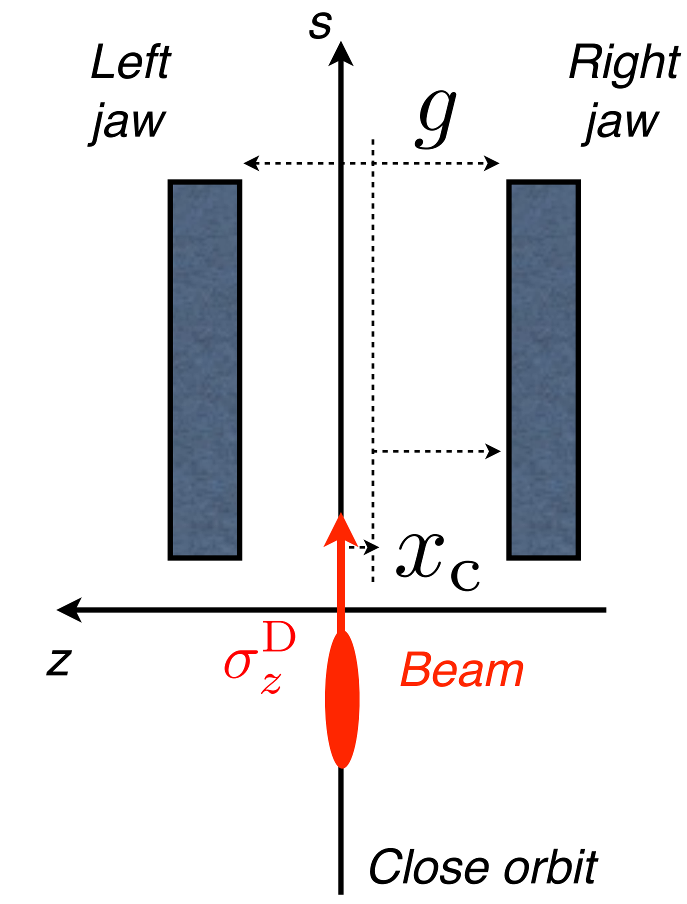


Movable collimators: L-shaped, one-sided, two-sided.



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

β_z : beta functions

ϵ_z / γ : normalized emittance

D_z : dispersion function

$\delta p / p$: RMS energy spread

g : collimator gap in millimeters

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

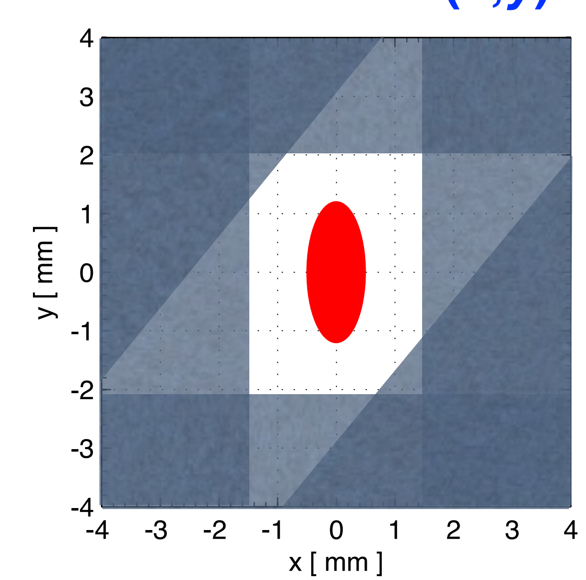
: RMS *betatron* beam size

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

: Normalized gap (beam size units)

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

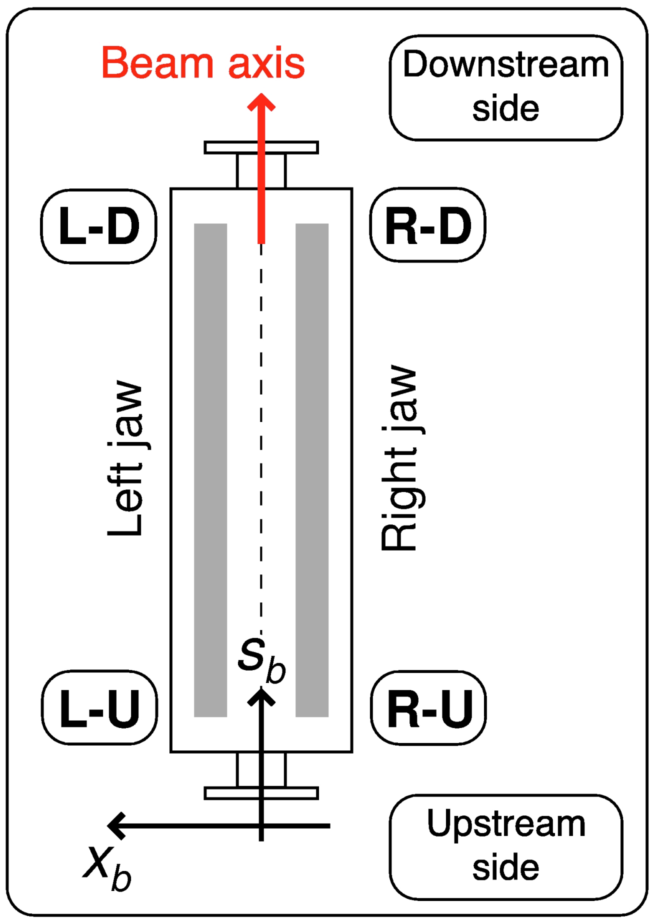
: Collimator jaw positions



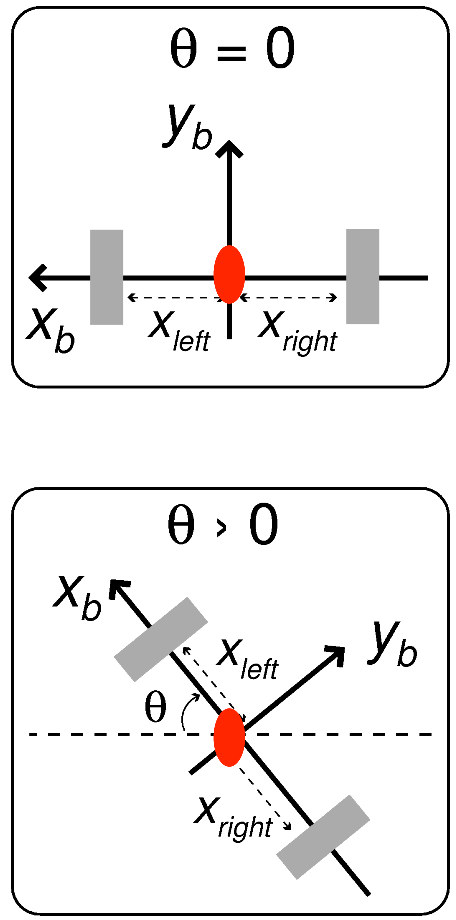
Collimator settings and aperture are expressed in normalized units, using the of local betatron beam size → enable to define the **setting "hierarchy"**!

"Skew" collimators

Top view



Front views

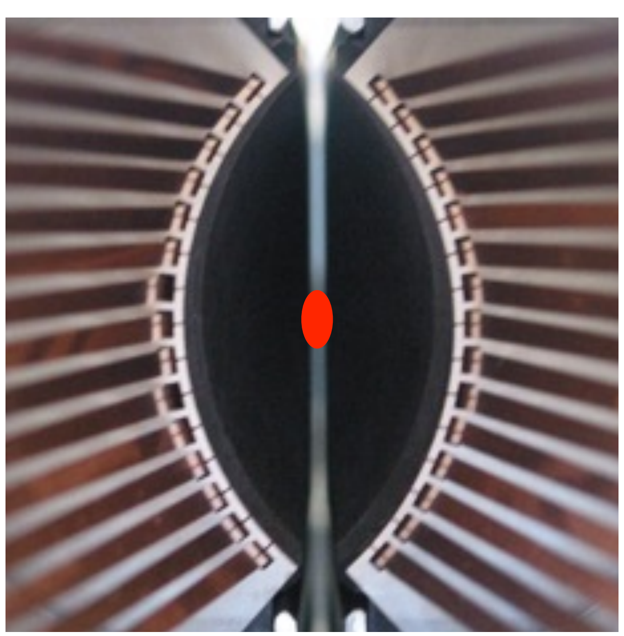


In the LHC, we also have "rotated" collimators that provide collimation in the ***skew plane.***
The collimator jaw movement occurs along the skew axis (still 1D movement). Normalized settings are defined for an appropriate effective beam size.
Same collimator design for all cases: rotate vacuum tank.

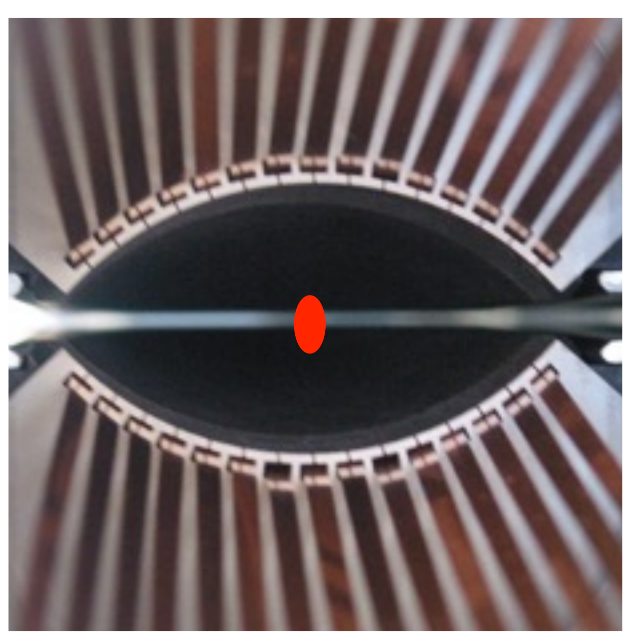
RMS *betatron* beam size in the collimator plane

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

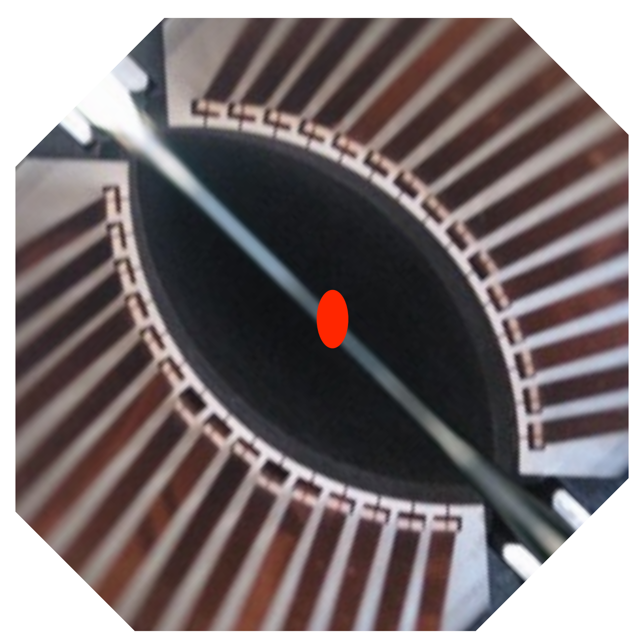
Horizontal



Vertical



Skew



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

Reference design goals

High stored beam energy (melt 500 kg Cu, required for 10^{34} cm^{-2} s^{-1} luminosity)	**~ 360 MJ/beam**
Large transverse energy density (beam is destructive, 3 orders beyond Tevatron/HERA)	**1 GJ/mm²**
High required cleaning efficiency (clean lost protons to avoid SC magnet quenches)	**99.998 % (~10^{-5})**
Activation of collimation insertions (good reliability required, very restricted access)	**~ 1-15 mSv/h**
Small spot sizes at high energy (small 7 TeV emittance, no large beta in restricted space)	**~ 200 μm**
Collimation close to beam (available mechanical aperture is at ~10 σ)	**6-7 σ**
Small collimator gaps (impedance problem, tight tolerances: ~ 10 μm)	**~2.1 mm**
Big and distributed system (coupled with mach. protection / dump)	**~108 movable devices >430 motors**

Quench

Damage

Heating

Activation

Stability

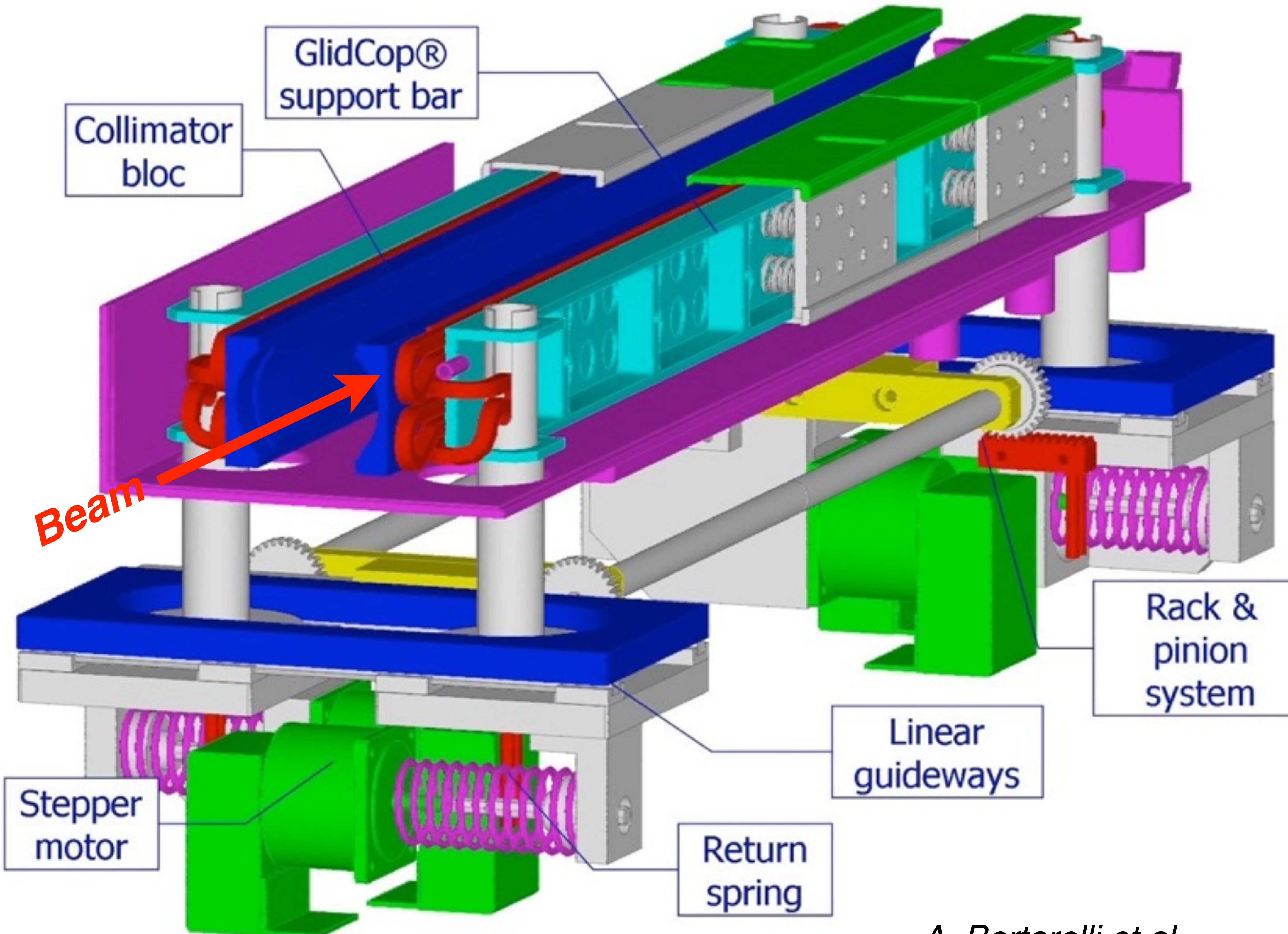
Impedance

Precision

All parameters derived meticulously following the "collimation design flow chart" introduced above...

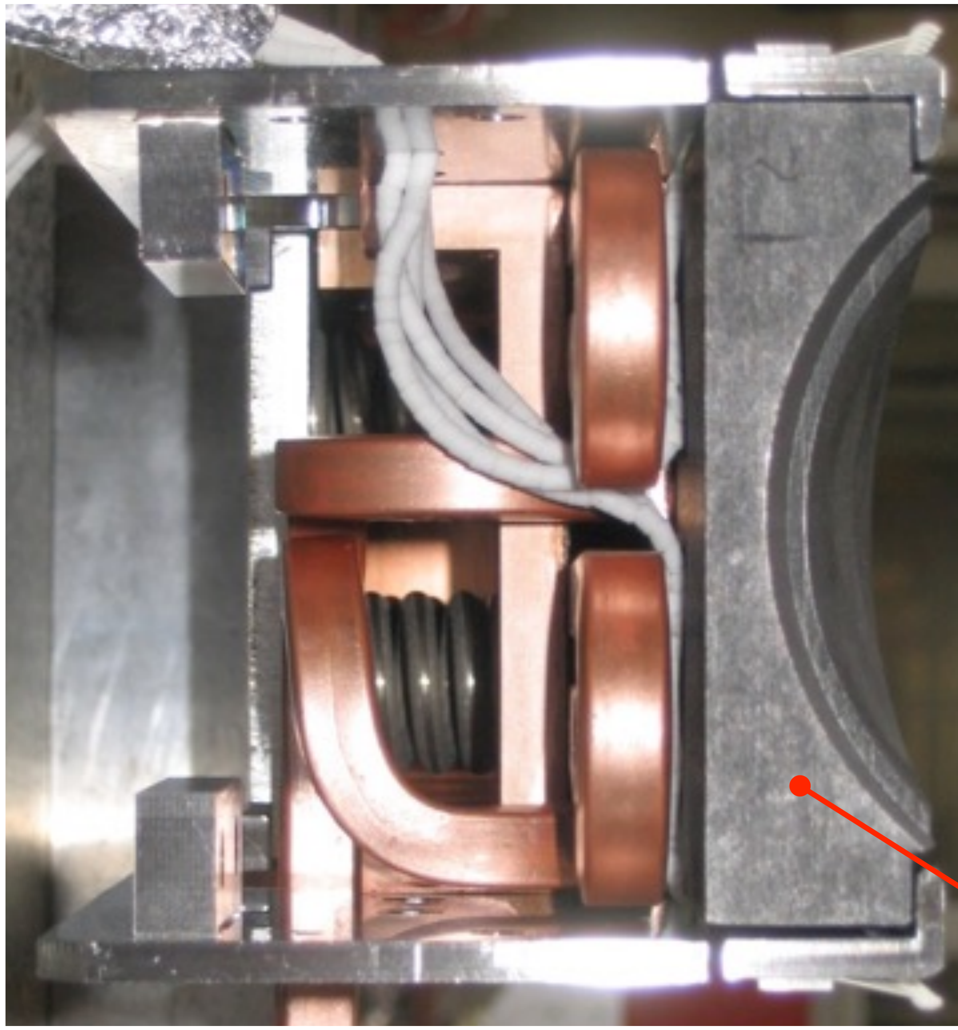
LHC collimator design

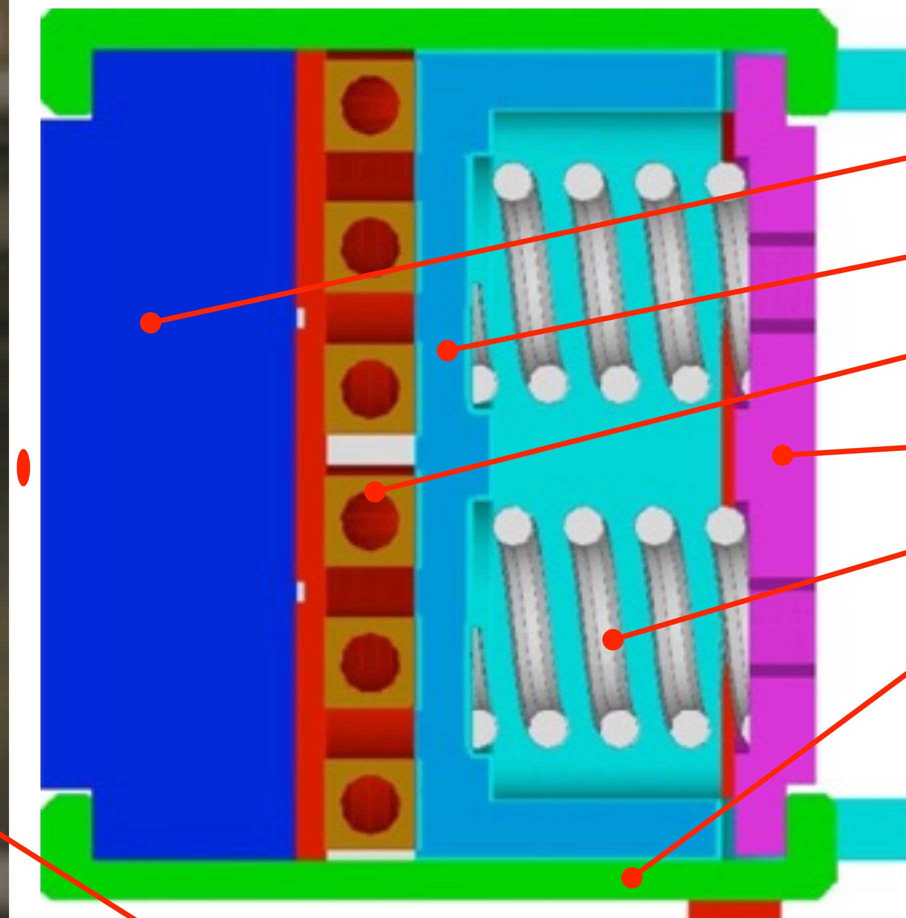
Main design features:
- Two jaws (position and angle)
- Concept of spare surface
- Different angles (H,V,S)
- External reference of jaw position
- Auto-retraction
- RF fingers
- Jaw cooling



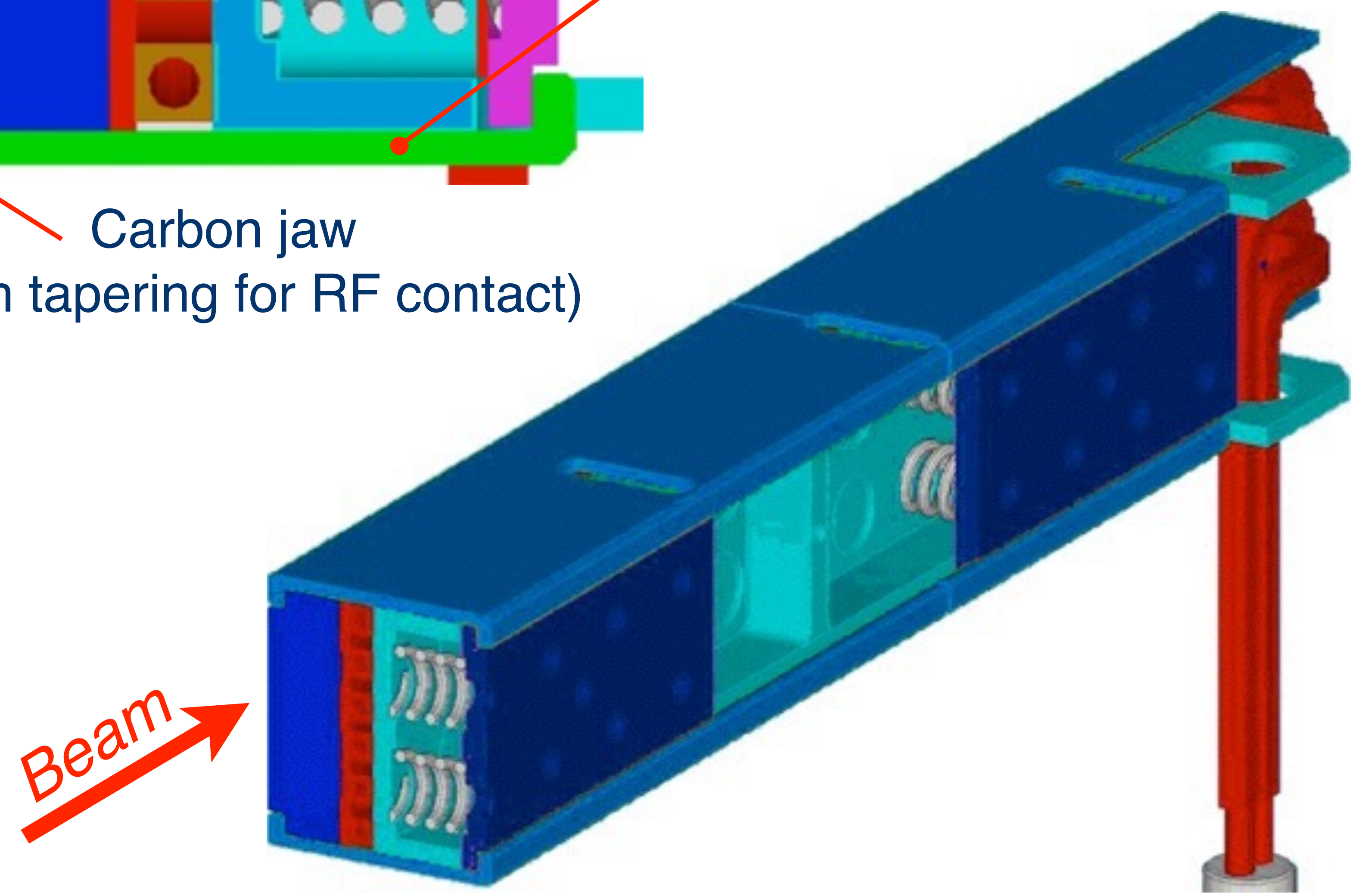
A. Bertarelli et al.

LHC collimator "jaw"

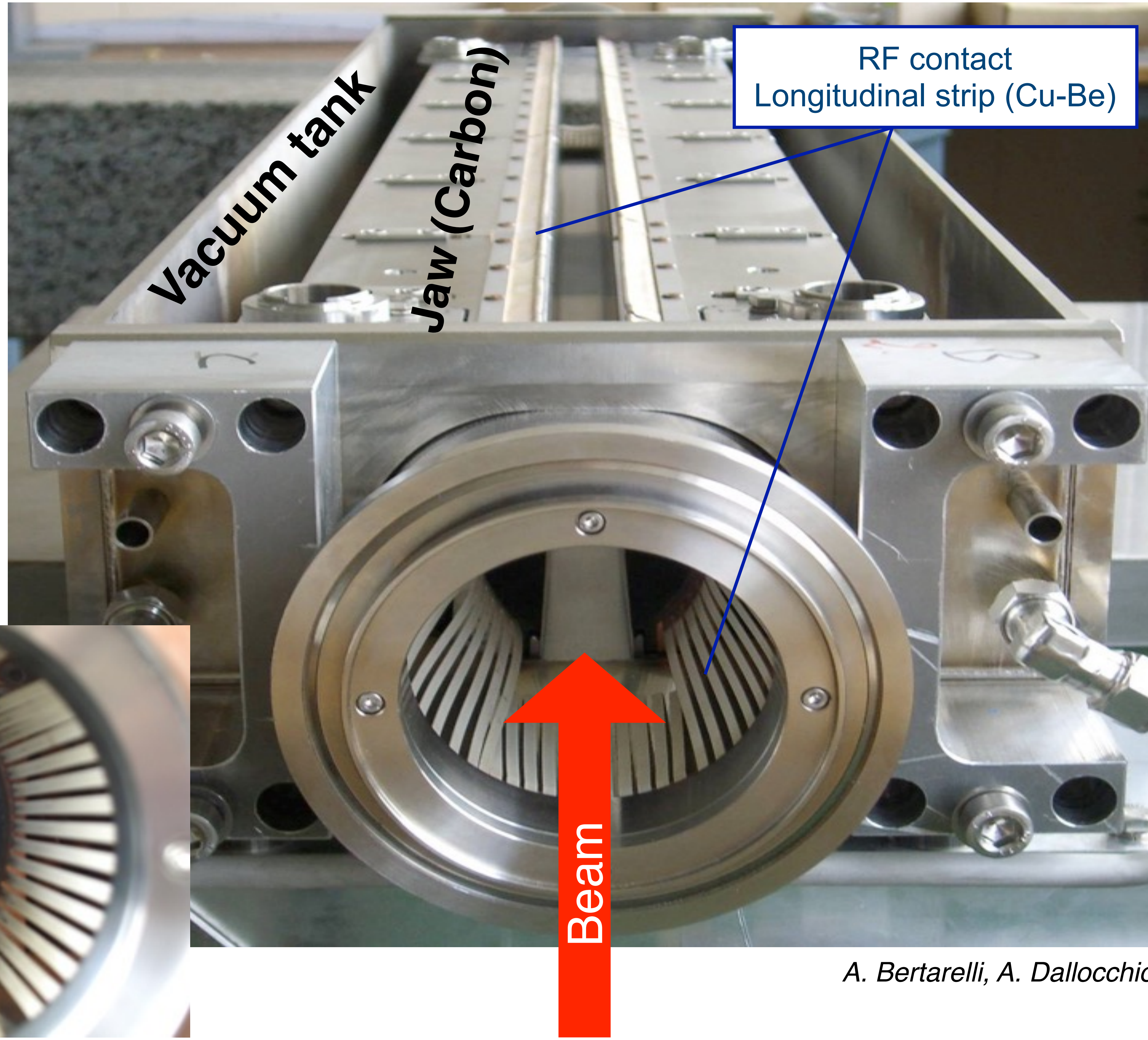




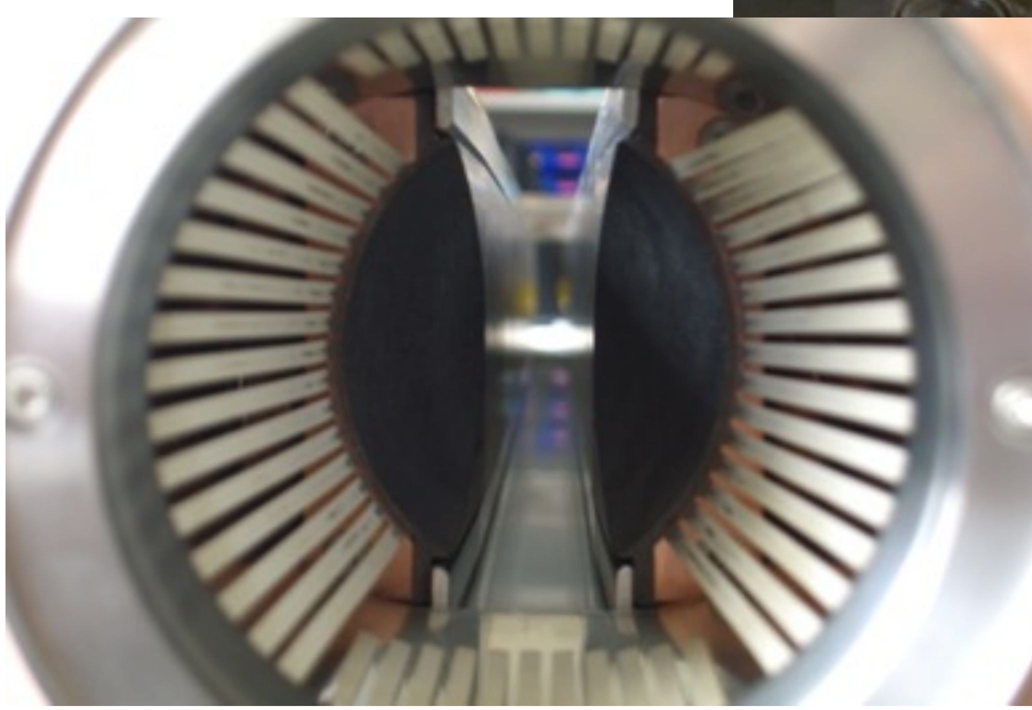
Special "sandwich" design to minimize the thermal deformations:
Steady (~5 kW) → < 30 µm
Transient (~30 kW) → ~ 110 µm
Materials: Graphite, Carbon fibre composites, Copper, Tungsten.



A look inside the vacuum tank

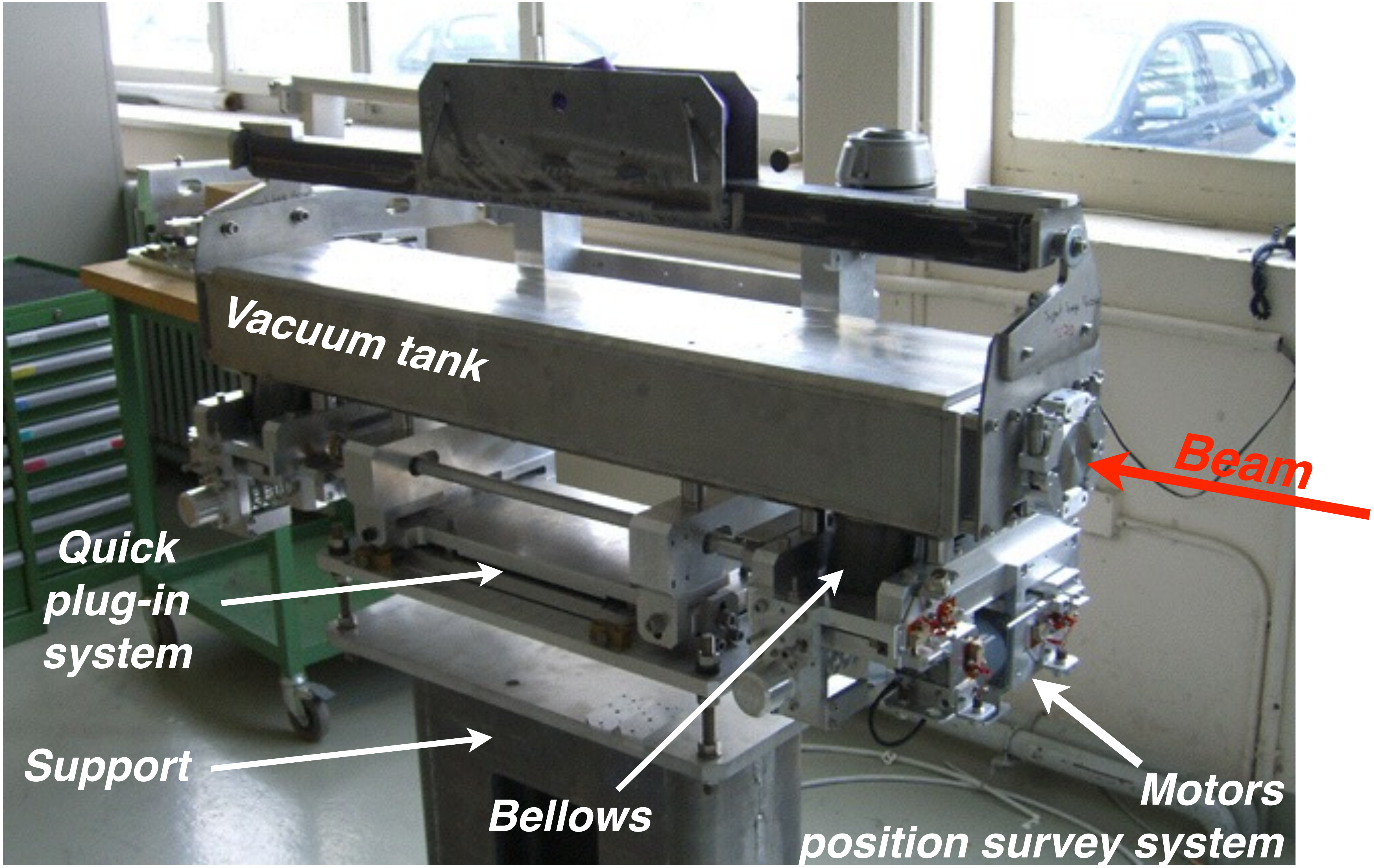


What the beam sees!

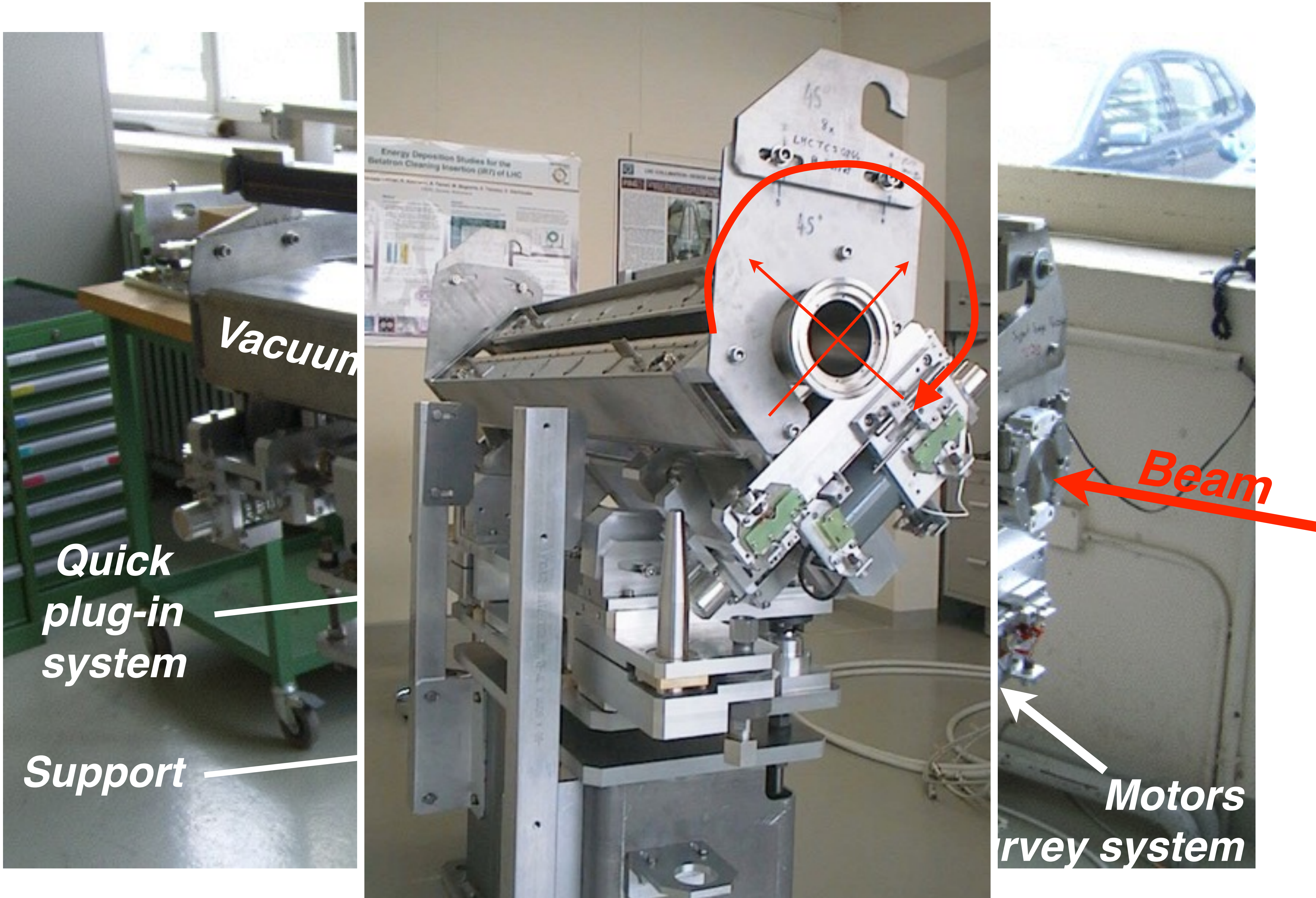


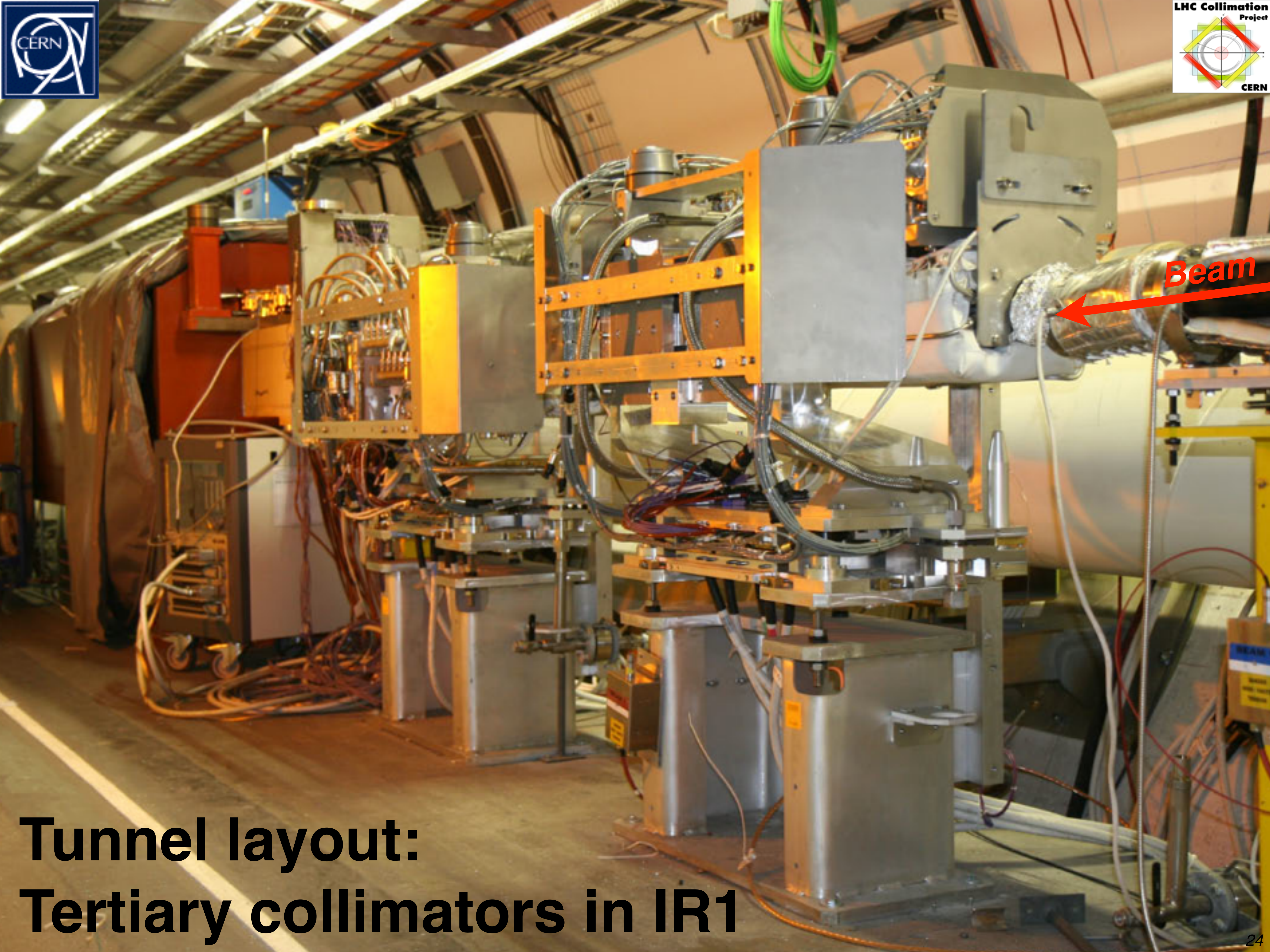
A. Bertarelli, A. Dallocchio

Complete collimator assembly



Complete collimator assembly





Tunnel layout:
Tertiary collimators in IR1

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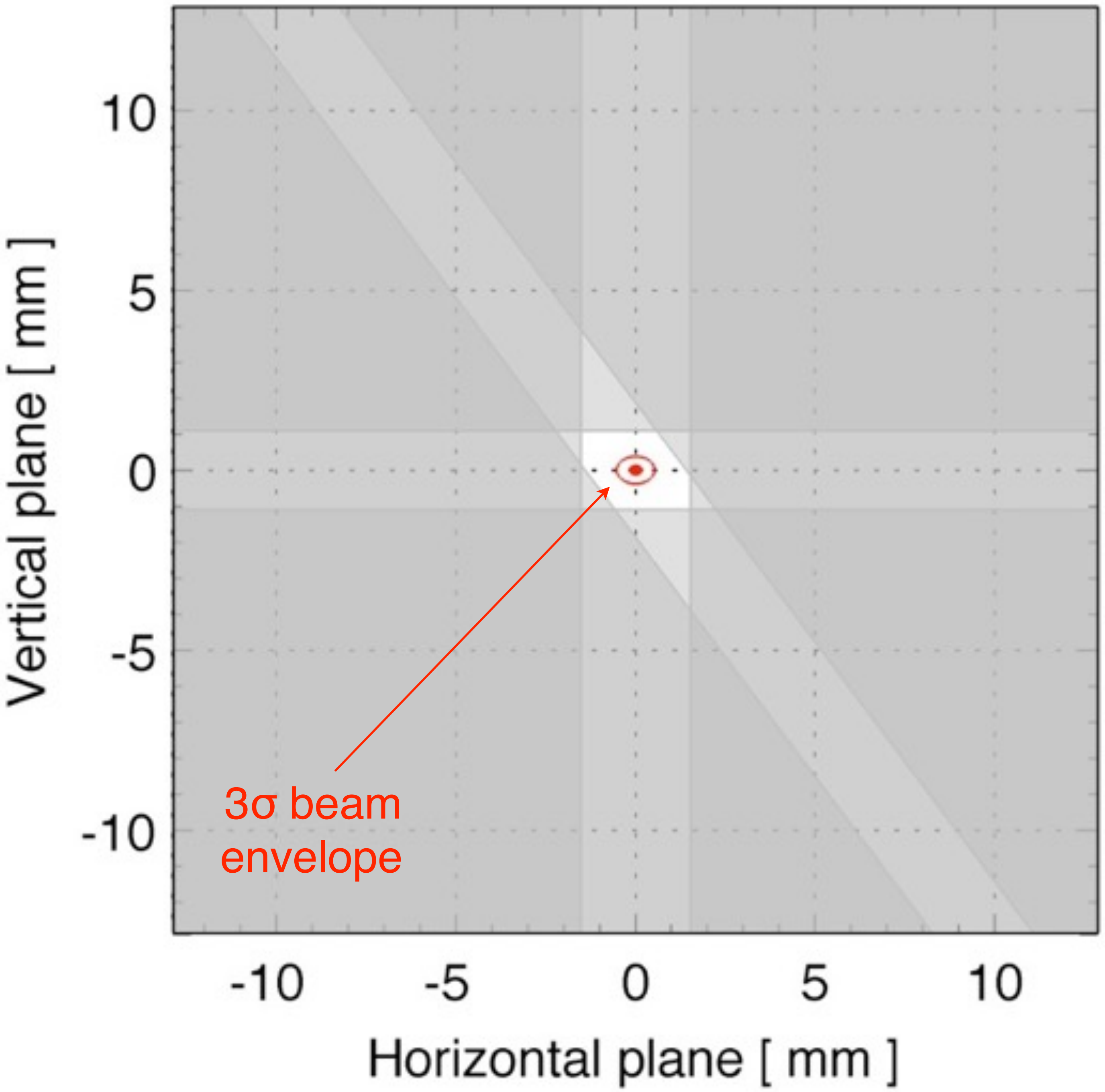
Collimation settings in 2012 at 4 TeV

Parameter	Unit	Plane	Type	Set 1	Set 2	Set 3	Set 4
				Injection	Top energy	Squeezed	Collision
Energy	[GeV]	n.a.	n.a.	450	4000	4000	4000
β^* in IR1/5	[m]	n.a.	n.a.	11.0	11.0	0.6	0.6
β^* in IR2	[m]	n.a.	n.a.	10.0	10.0	3.0	3.0
β^* in IR8	[m]	n.a.	n.a.	10.0	10.0	3.0	3.0
Crossing angle IR1/5	[μrad]	n.a.	n.a.	170	145	145	145
Crossing angle IR2	[μrad]	n.a.	n.a.	170	220 (H)	220 (H)	100 (V)
Crossing angle IR8	[μrad]	n.a.	n.a.	170	90	90	90
Beam separation	[mm]	n.a.	n.a.	2.0	0.65	0.65	0.0
Primary cut IR7	[σ]	H,V,S	TCP	5.7	4.3	4.3	4.3
Secondary cut IR7	[σ]	H,V,S	TCSG	6.7	6.3	6.3	6.3
Quartiary cut IR7	[σ]	H,V	TCLA	10.0	8.3	8.3	8.3
Primary cut IR3	[σ]	H	TCP	8.0	12.0	12.0	12.0
Secondary cut IR3	[σ]	H	TCSG	9.3	15.6	15.6	15.6
Quartiary cut IR3	[σ]	H,V	TCLA	10.0	17.6	17.6	17.6
Tertiary cut IR1/5	[σ]	H,V	TCT	13.0	26.0	9.0	9.0
Tertiary cut IR2/8	[σ]	H,V	TCT	13.0	26.0	12.0	12.0
Physics debris collimators	[σ]	H	TCL	out	out	out	10.0
Primary protection IR6	[σ]	H	TCSG	7.0	7.1	7.1	7.1
Secondary protection IR6	[σ]	H	TCDQ	8.0	7.6	7.6	7.6

Smallest collimator gaps in 2012

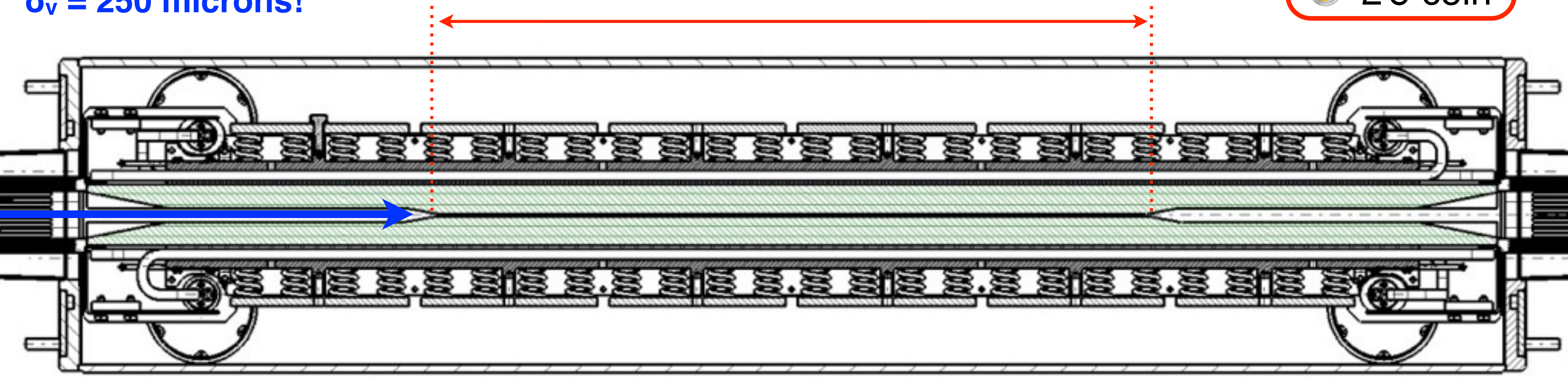
Transverse cuts from H, V and S primary collimators in IR7



2€ coin

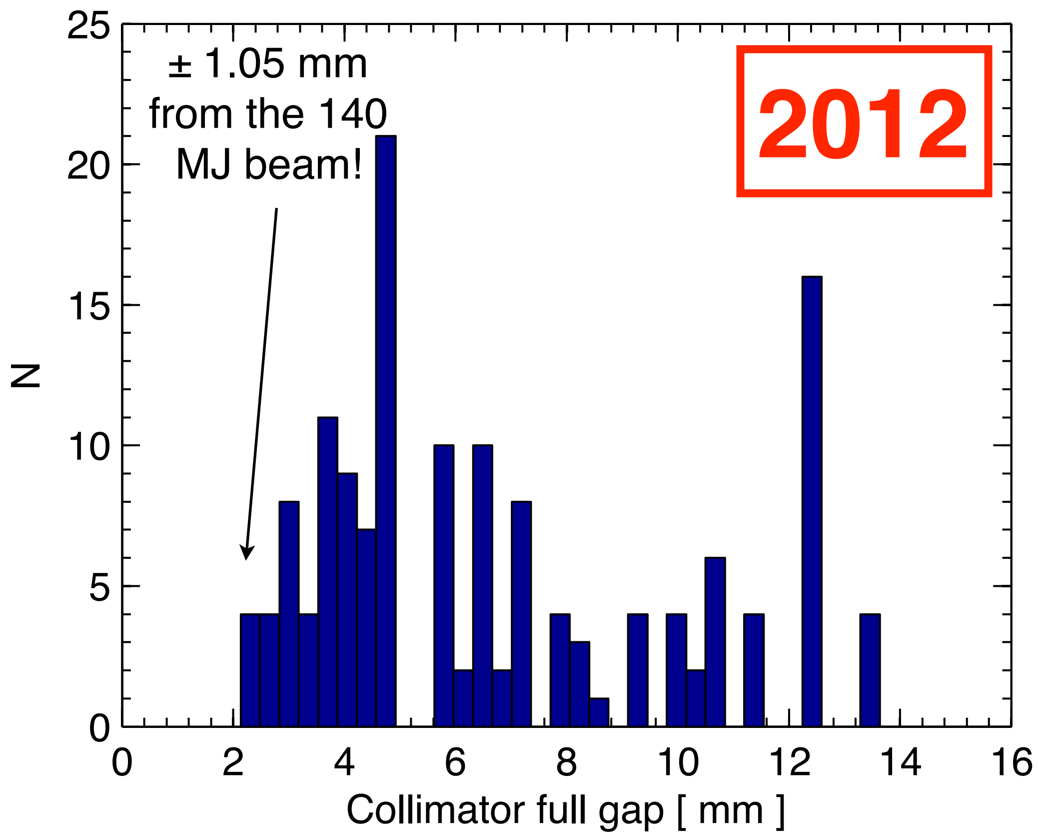
Side view of the vertical TCP

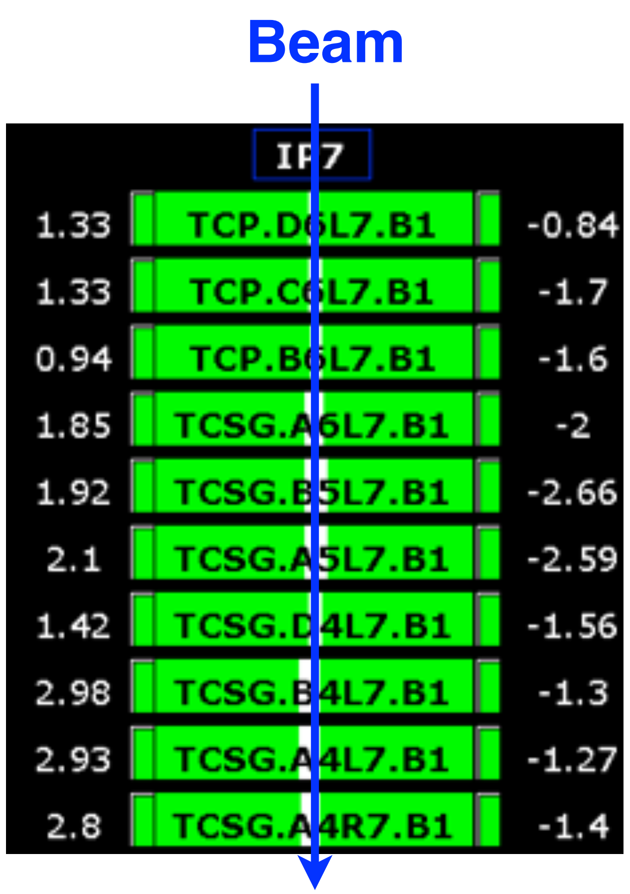
Beam: RMS beam size
σ_v = 250 microns!



L. Gentini

Distribution of collimator gaps in 2012





Demonstration of the feasibility of collimation with 40 micron flatness jaws!

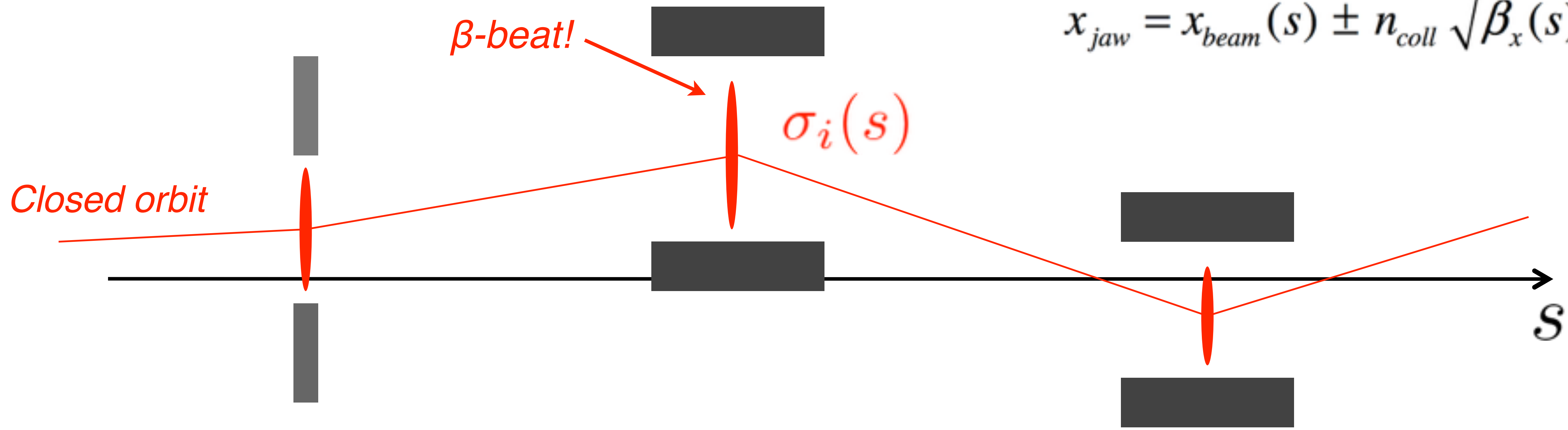
Fixed display in the LHC control room showing the IR7 collimator gaps.

Collimator beam-based alignment

Normalized collimator settings must be converted to positions in [mm]:

- Center the two collimator jaws → Need the orbit!
- Adjust the gap to the correct setting → Need the beam size!

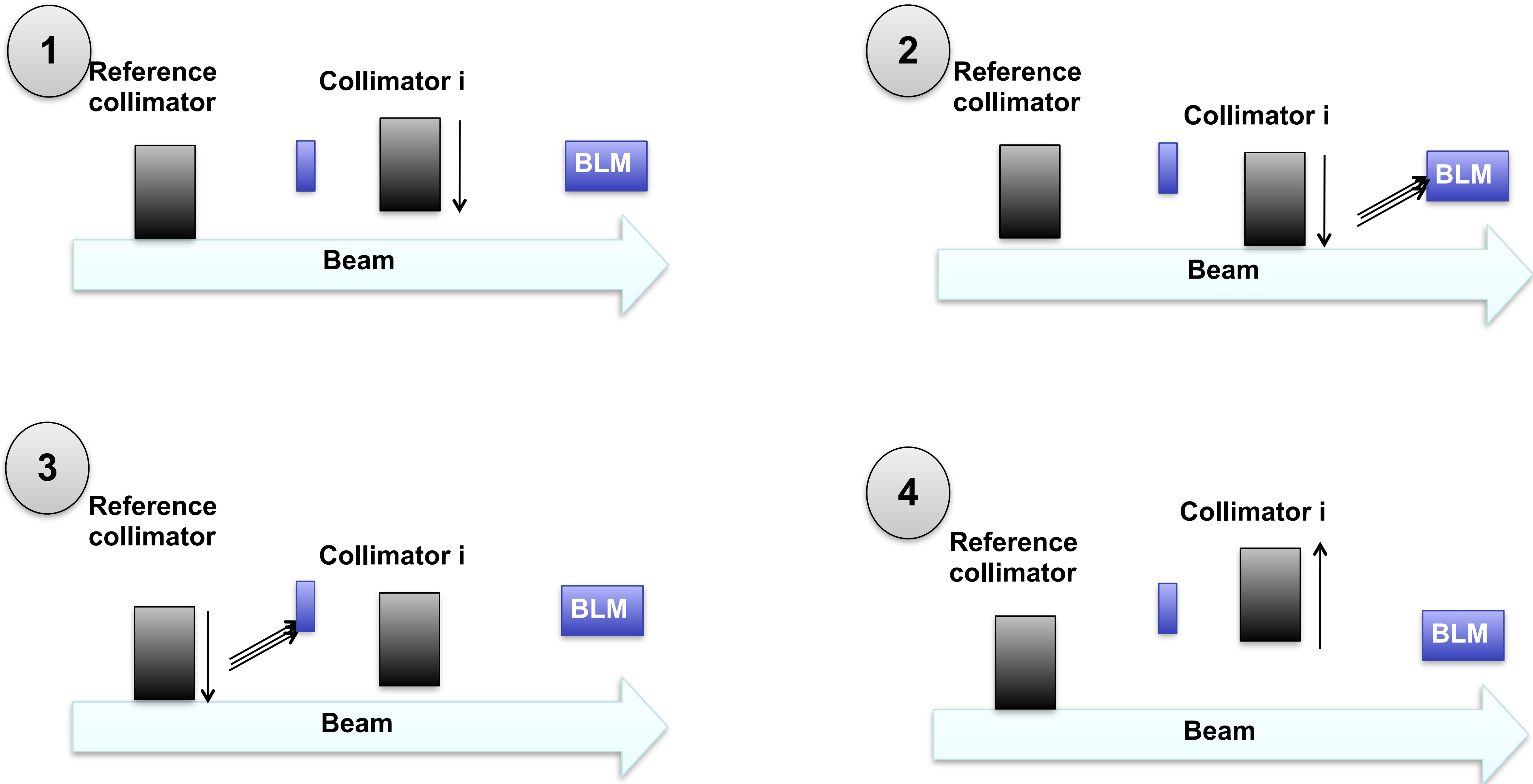
$$x_{jaw} = x_{beam}(s) \pm n_{coll} \sqrt{\beta_x(s)\ \varepsilon_x}$$



Due to the **very small gaps** involved, collimators cannot be set deterministically using nominal orbit and beam sizes: alignment errors, orbit imperfections and optics errors entail uncertainties larger than the gaps.

Beam orbit and beam size at each collimator is measured with **beam-based alignment techniques** in **every phase of the operational cycle** (injection, ramp, squeeze, collisions).

LHC alignment technique



(1) Reference halo generated with primary collimators (TCPs) close to 3-5 sigmas.

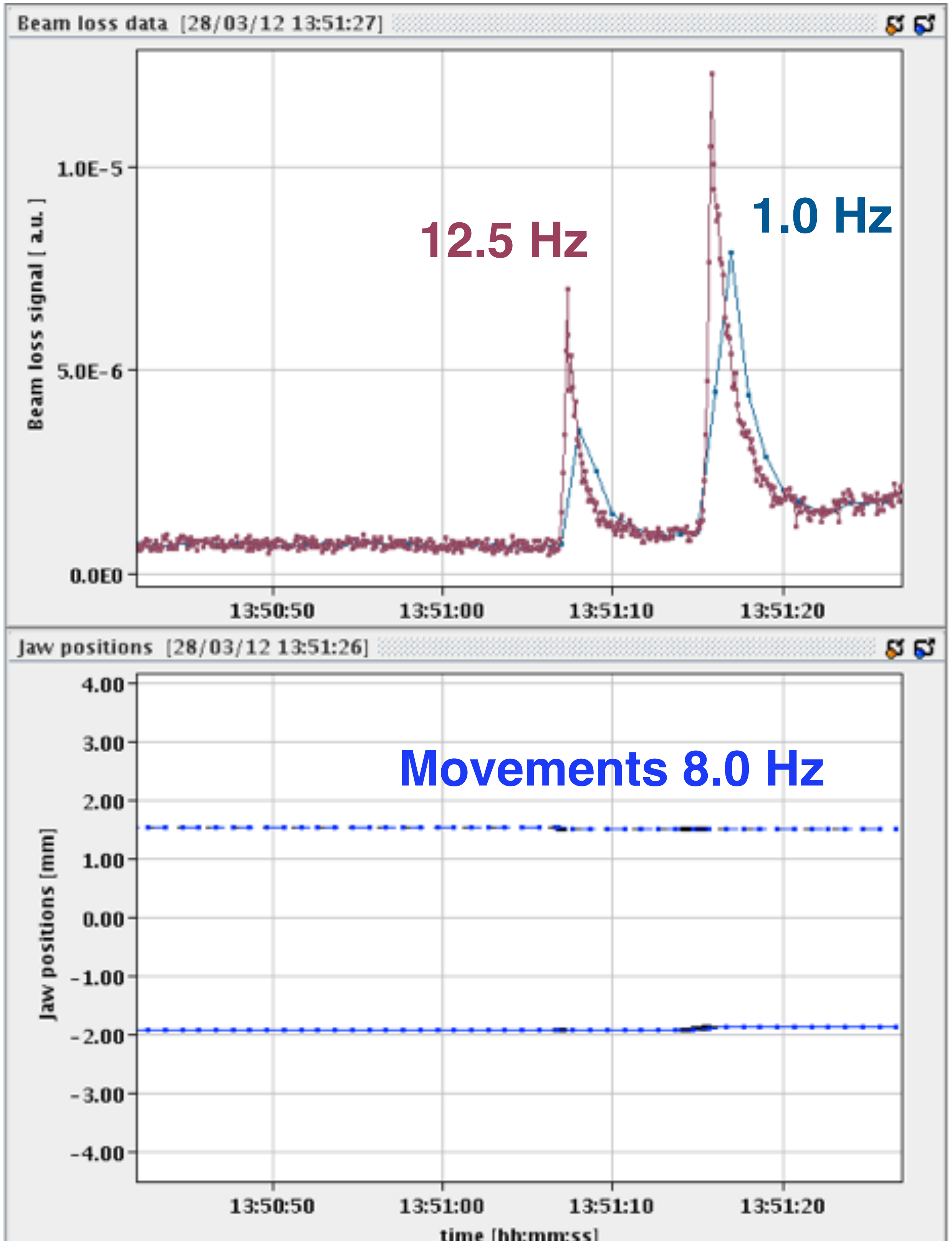
(2) "Touch" the halo with the other collimators around the ring (**both sides**) → local beam position.

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

(4) Retract the collimator to the correct settings.

Tedious procedure that is repeated for each machine configuration.

Can we make it faster?



1) 2010: fully manual procedure > 15 min/device

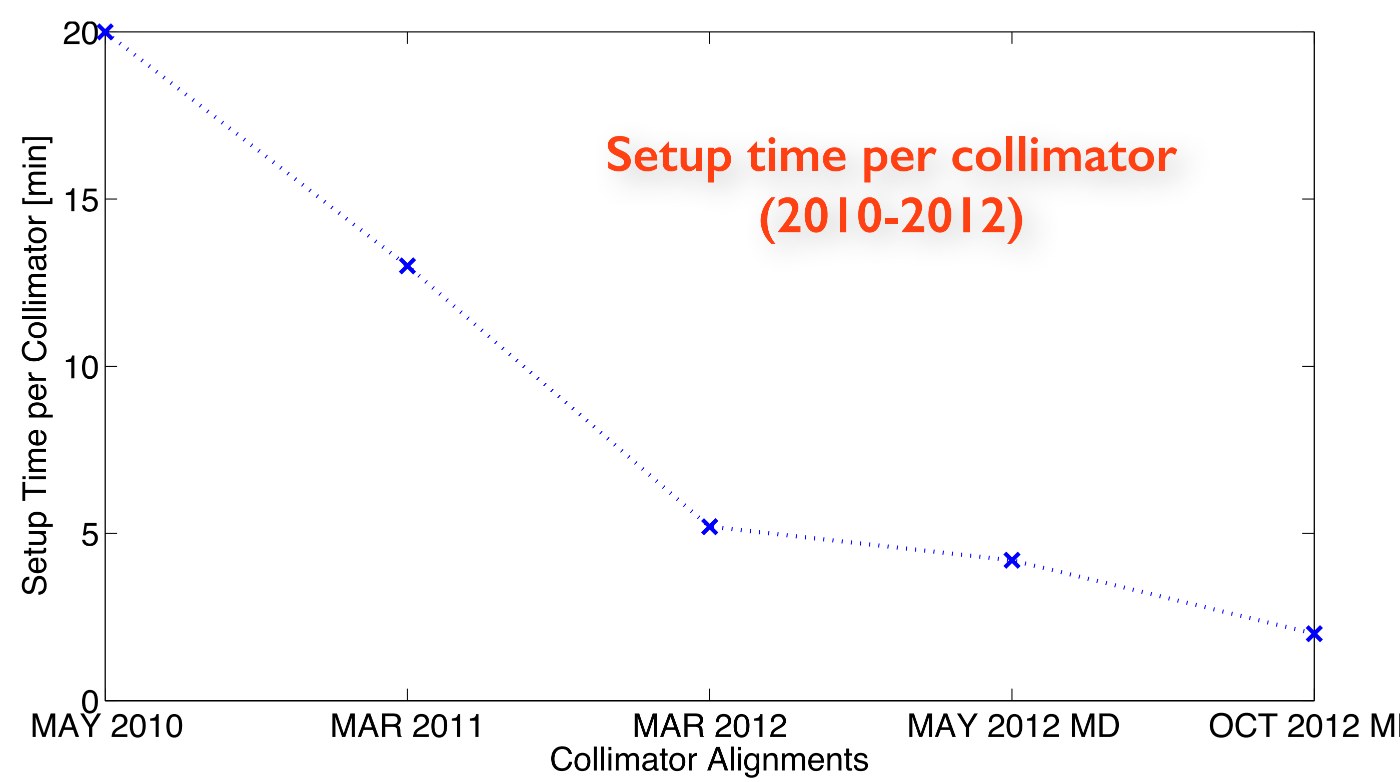
   Limitation of operational efficiency

2) 2011: automated procedure based on feedback loop between BLM and motors

3) 2012: further improved algorithms, faster rates of BLM acquisition and settings trims

4) 2015-17: Faster BLM data (100Hz vs 12.5Hz)

Note: only done in low-intensity fills, then rely on the machine and setting reproducibility.



PhD thesis work G. Valentino

Can we make it even faster?

- **16 tungsten TCTs** in all IRs and the **2 Carbon TCSGs in IR6** have been replaced in 2014 by new collimators with **integrated BPMs**.

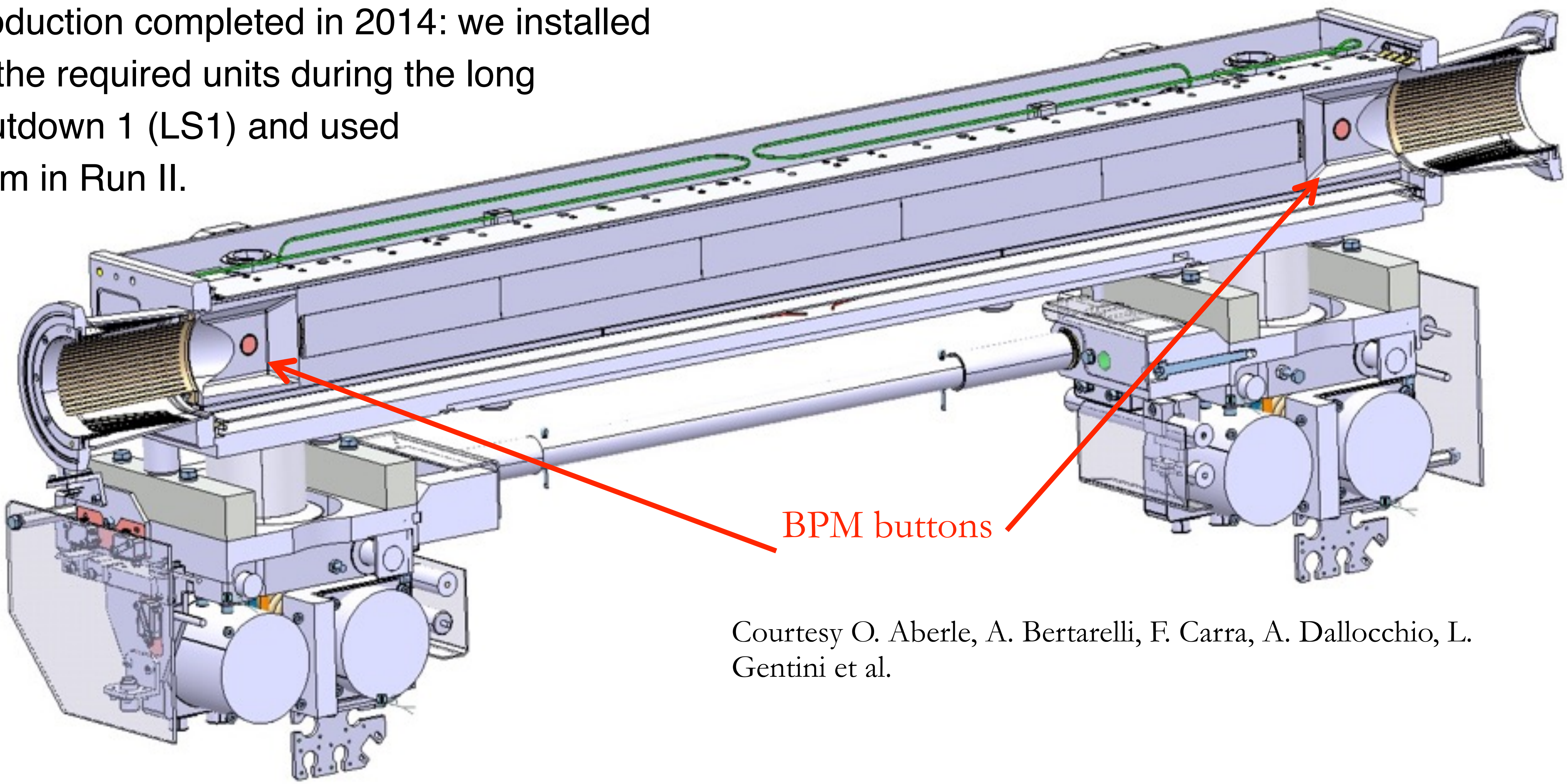
  Gain: can align the collimator jaw without "touching" the beam ➝ no dedicated low-intensity fills.

  ➝ *Drastically reduced setup time => more flexibility in IR configurations*

  ➝ *Reduced orbit margins in cleaning hierarchy*

  ➝ *Improved monitoring of local orbit and interlocking strategy*

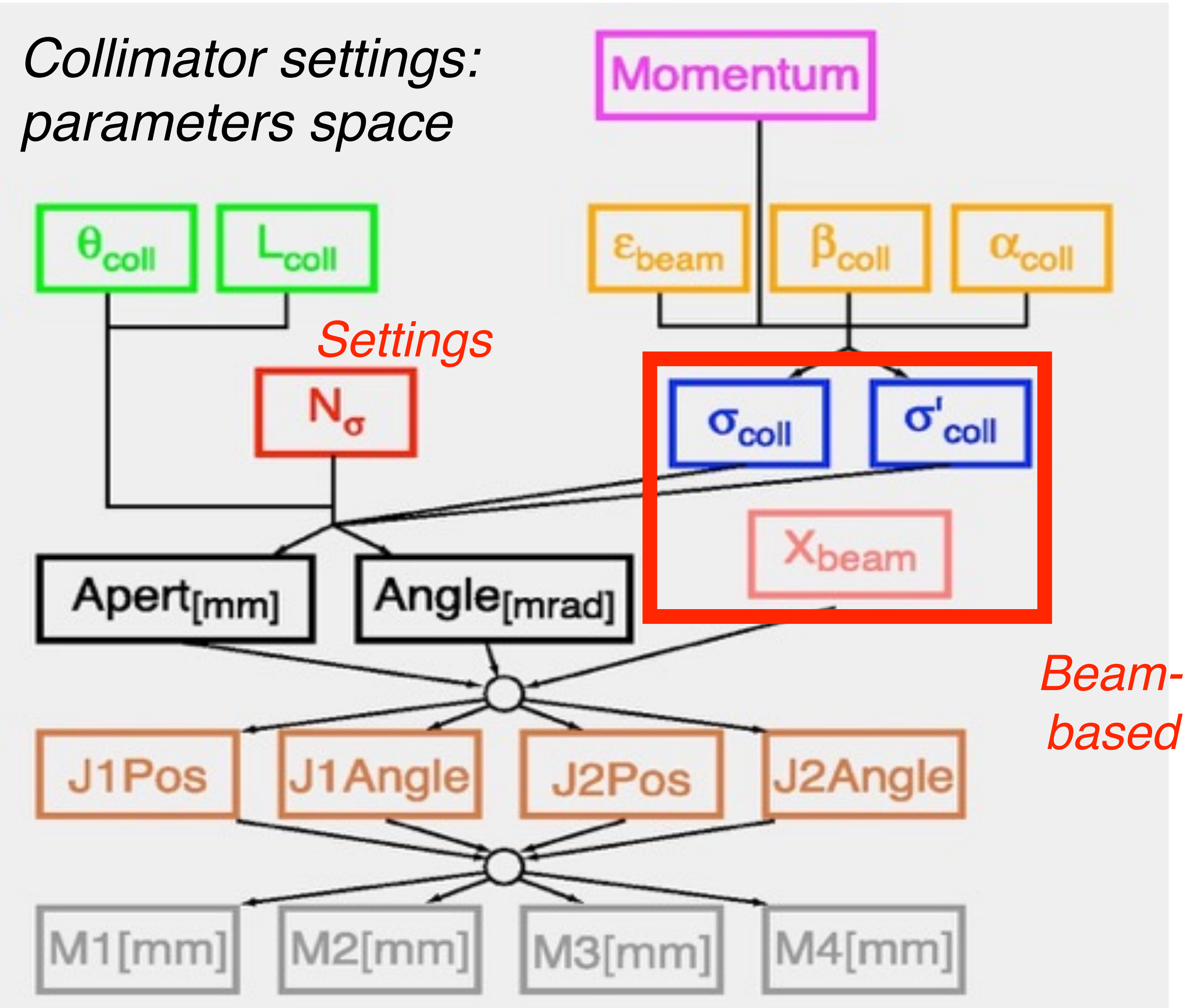
- Production completed in 2014: we installed all the required units during the long shutdown 1 (LS1) and used them in Run II.



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

Setting generation

What do we do when we have **orbit** and **beam size** at every collimator during the cycle?



$$\mathrm{jaw} = x_{\mathrm{beam}} \pm n_0 \times \sigma_x$$

$$\sigma_x = \sqrt{\frac{\epsilon_n}{\gamma}\beta_x}$$ *: Beam size in coll. plane*

$$n_0^{\mathrm{tcp}} = 6$$
$$n_0^{\mathrm{tcsg}} = 7$$ *: Normalized settings*

<u>Energy ramp</u>: all parameters change as a function of gamma (BB sigma at 450GeV, nominal optics at flat-top)
<u>Betatron squeeze</u>: additional change of beam size for different optics

Scaling for ramp settings:

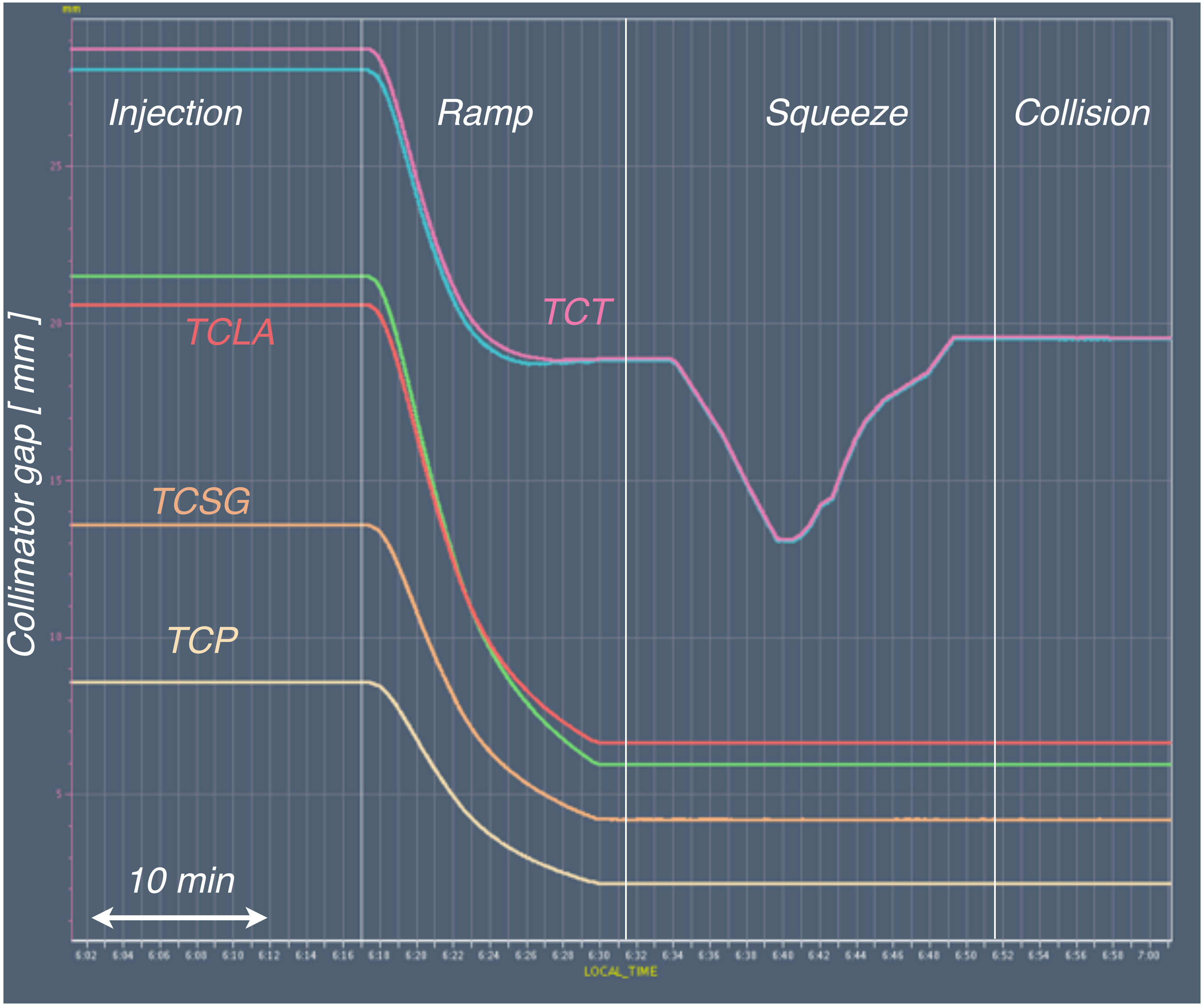
$$n_0 = n_0(\gamma) \qquad \sigma_x = \sigma_x(\gamma) \qquad h(\gamma) = n_0(\gamma) \times \sigma_x(\gamma)$$

$$h(\gamma) = \left[n_0 + \frac{n_1 - n_0}{\gamma_1 - \gamma_0}(\gamma - \gamma_0)\right] \times \frac{1}{\sqrt{\gamma}}\left[\frac{\sqrt{\epsilon_1\beta_1} - \sqrt{\epsilon_0\beta_0}}{\gamma_1 - \gamma_0}(\gamma - \gamma_0)\right]$$

$$\mathrm{jaw}(\gamma) = \left[x_0 + \frac{x_1 - x_0}{\gamma_1 - \gamma_0}(\gamma - \gamma_0)\right] \pm h(\gamma)$$

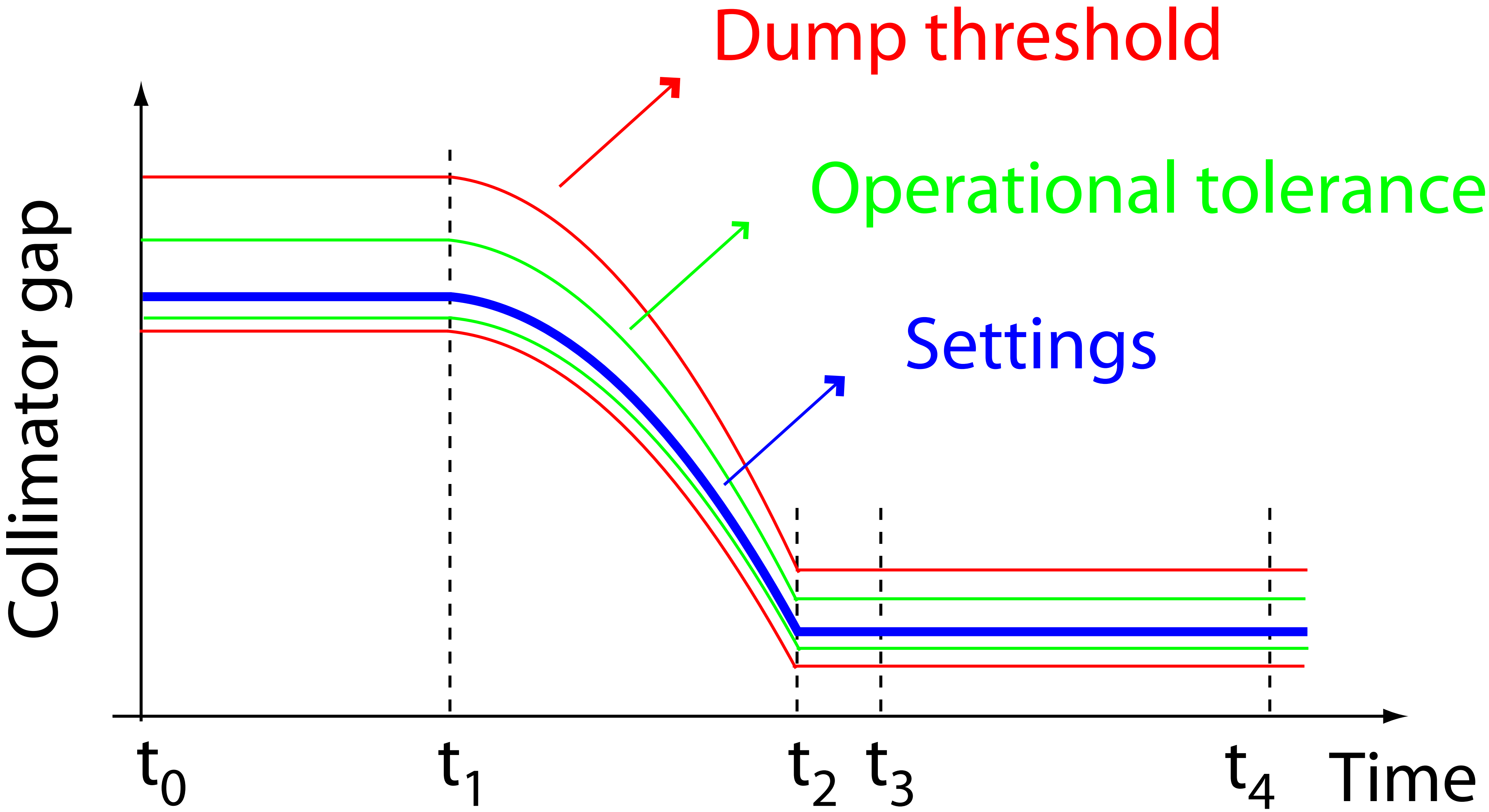
Collimation during cycle

Example from 2012



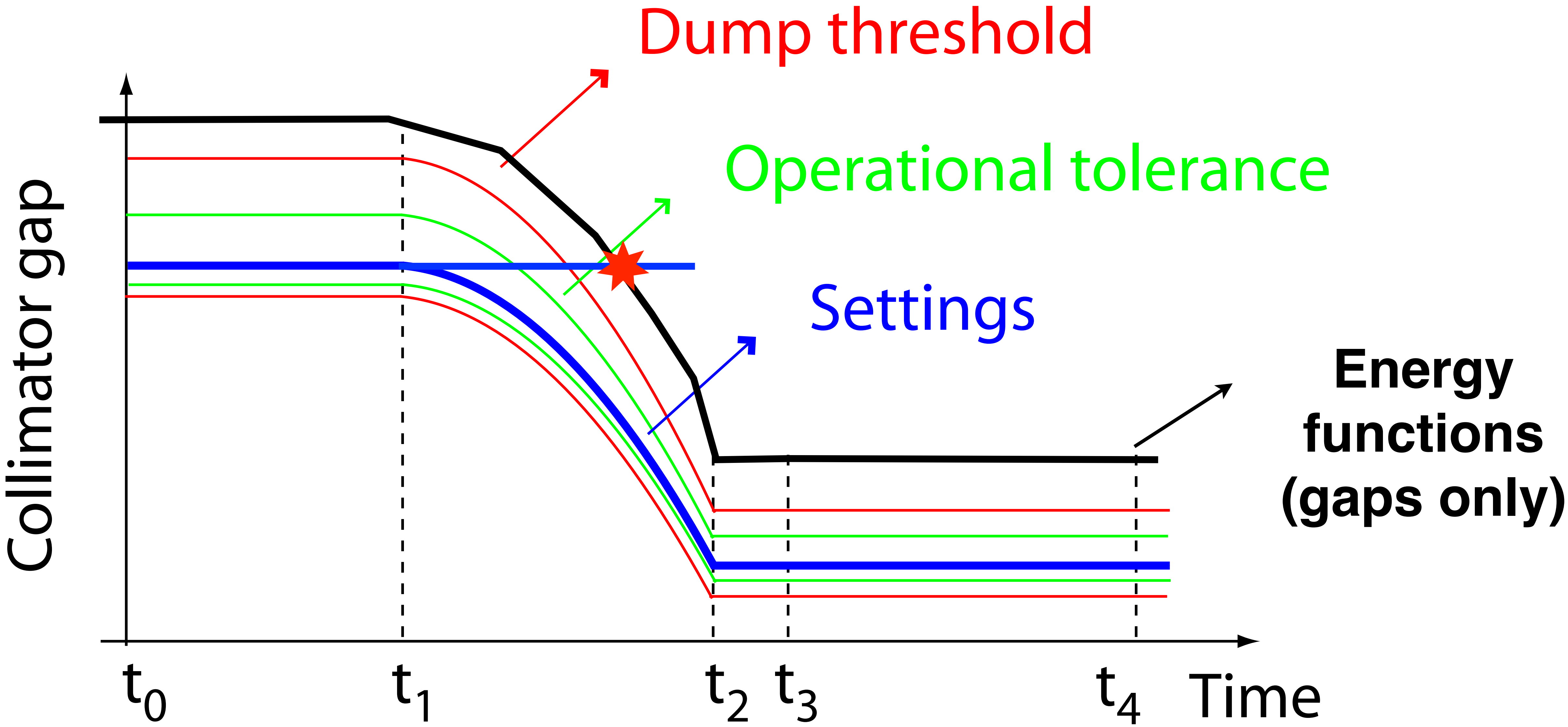
At the LHC, collimator are moved through setting functions versus time.

Gap and position interlocks



- **Inner** and **outer thresholds** as a function of **time** for each motor **axis** and **gap** (24 functions per collimator). Triggered by timing event (e.g. start of ramp).
  "Double protection" → beam interlock AND jaws stopped
- Redundancy: **maximum allowed gap versus energy** (2 per collimator: OUT)
  Beams dumped if a collimator does not start its ramp function.
- Redundancy: **max. and min. allowed gap versus beta*** (4 per collimator: IN/OUT)
  Beams dumped if a collimator does not start its squeeze function.

Gap and position interlocks



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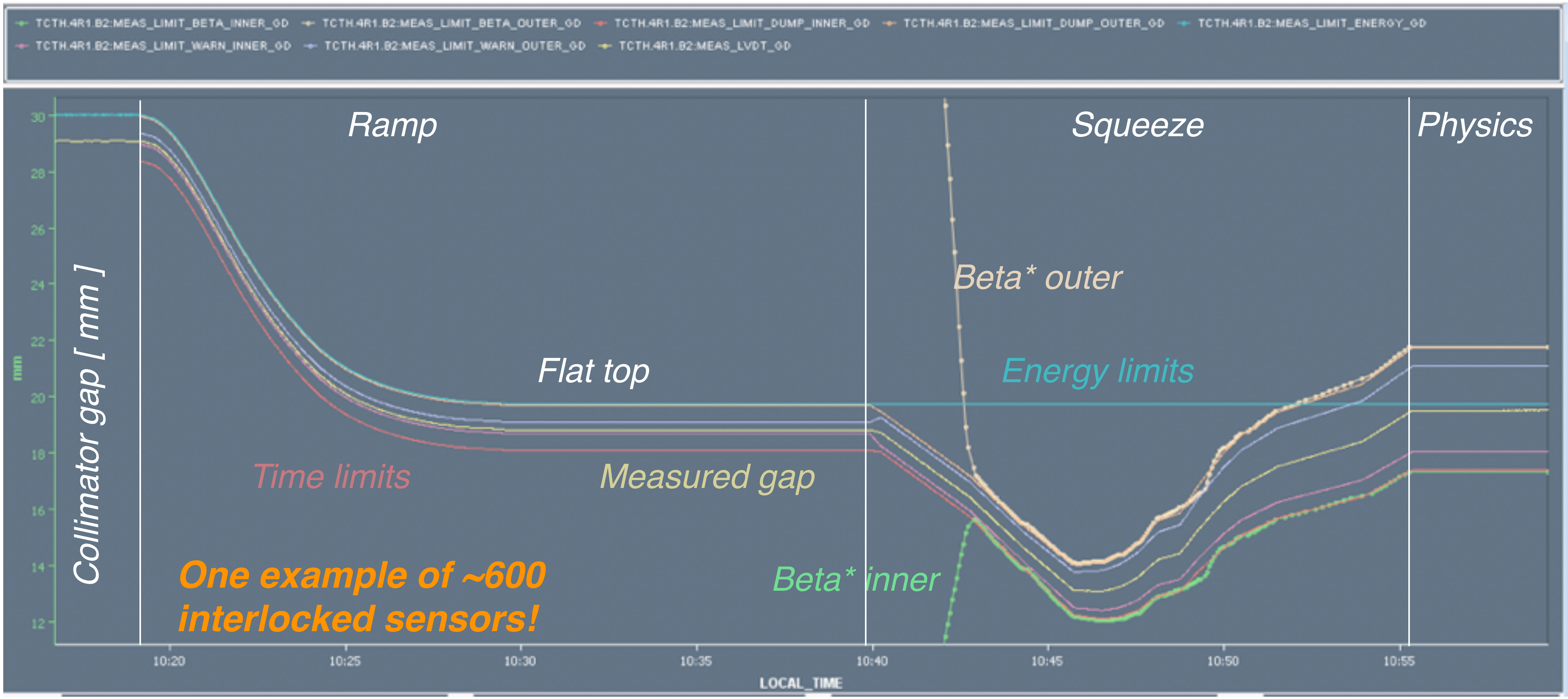
- Redundancy: **max. and min. allowed gap versus beta*** (4 per collimator: IN/OUT)
  Beams dumped if a collimator does not start its squeeze function.

Interlock limits in practice...



Energy limits active already at injection:

- Prevent injection of unsafe beams if collimators are open!
- Test at every fill the interlock chain, when collimators go to parking.
- They dump the beams if a collimator does not start ramp functions.

Beta* limits became active for the TCTs at the first squeeze step to 9m.

Physics: 3 redundant limits (vs time, energy and beta*active at the same time!!

Collimator control challenge

Table 1: LHC collimators for the 2010-2013 run.

Functional type	Name	Plane	Num.	Material
Primary IR3	TCP	H	2	CFC
Secondary IR3	TCSG	H	8	CFC
Absorbers IR3	TCLA	H,V	8	W
Primary IR7	TCP	H,V,S	6	CFC
Secondary IR7	TCSG	H,V,S	22	CFC
Absorbers IR7	TCLA	H,V	10	W
Tertiary IR1/2/5/8	TCT	H,V	16	W/Cu
Physics absor. IR1/5	TCL	H	4	Cu
Dump protection IR6	TCSG	H	2	CFC
	TCDQ	H	2	C
Inj. prot. (lines)	TCDI	H,V	13	CFC
Inj. prot. IR2/8	TDI	V	2	C
	TCLI	V	4	CFC
	TCDD	V	1	CFC

Table 2: 2012 collimation parameters table.

Parameters	**Number**
Movable collimators in the ring	85
Transfer line collimators	13
Stepping motors	392
Resolvers	392
Position/gap measurements	584
Interlocked position sensors	584
Interlocked temperature sensors	584
Motor settings: functions / discrete	448/1180
Threshold settings versus time	9768
Threshold settings versus energy	196
Threshold settings versus β^*	384
Temperature thresholds	490

*The controls system of the LHC collimation reached an unprecedented complexity. This is necessary to redundantly ensure that collimators are at the good positions: a **beam dump** is requested if any **abnormal behaviour** is detected within the system.*

Are internal system checks enough to ensure that the performance is adequate?

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.

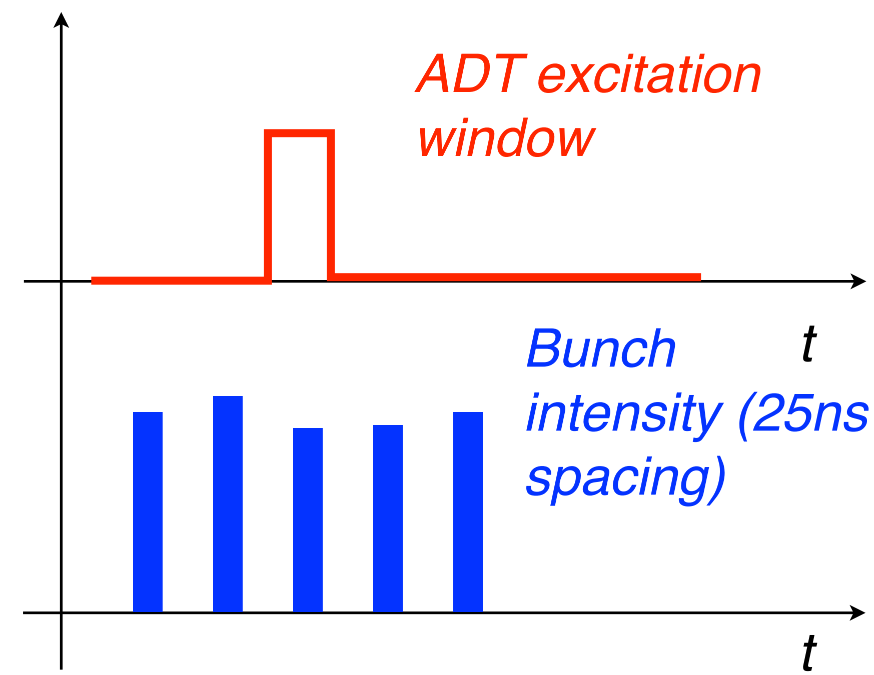
Excite beam resonances by changing the tunes;

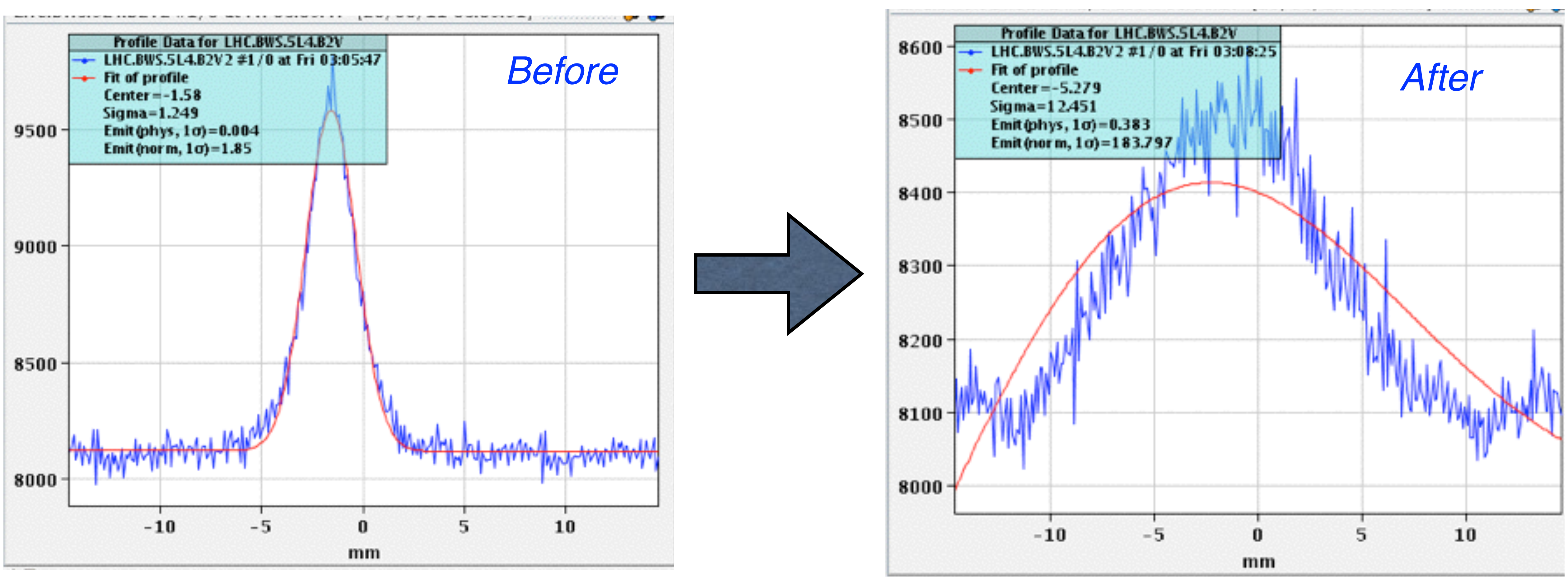
*controlled blow-up with **transverse damper**.*

Excitation with transverse damper

The LHC transverse damper ("ADT") uses fast kicker magnets to stabilize the beams.

We also use it to "inject" noise into the beam, causing an emittance blow-up that leads to fast losses!

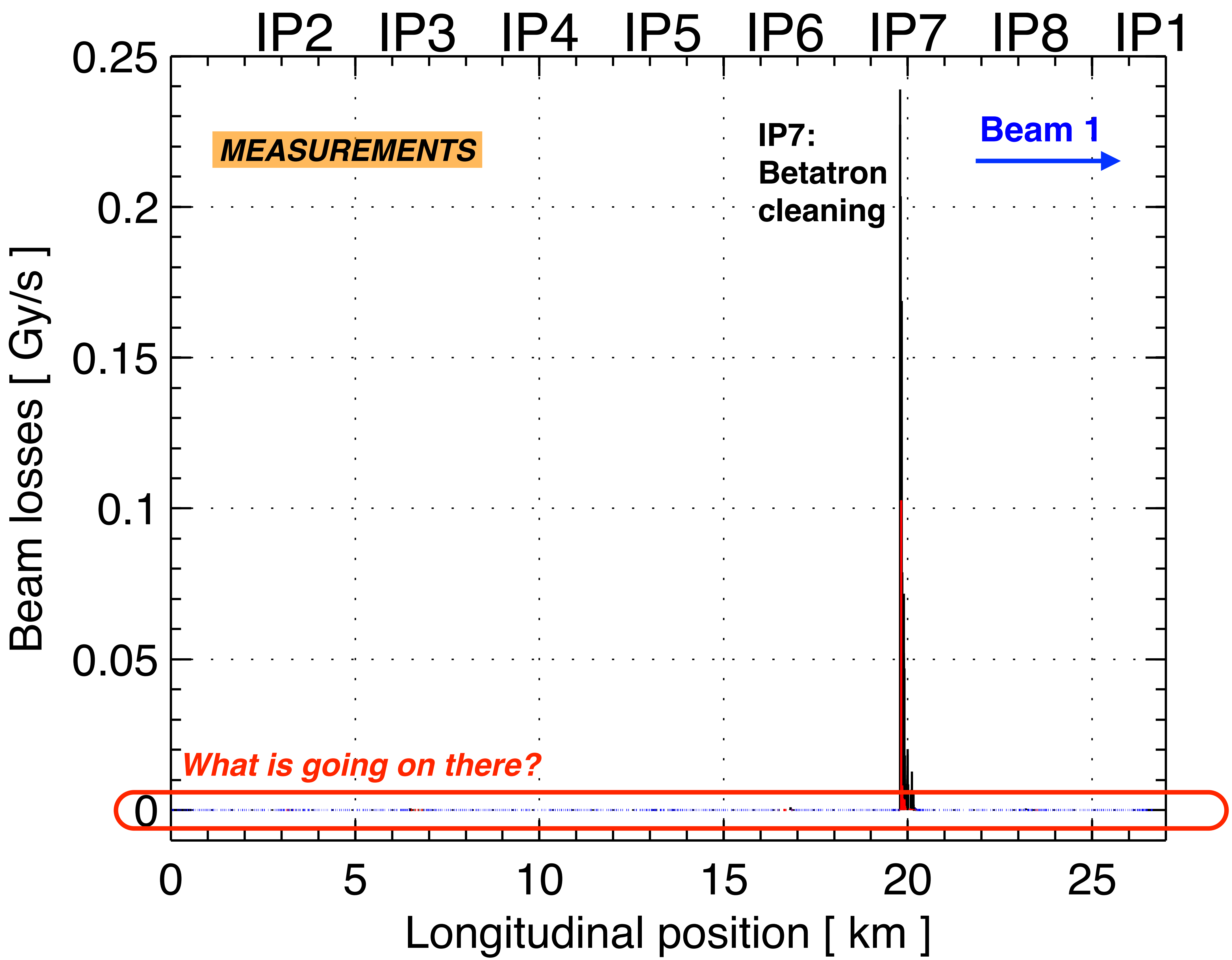




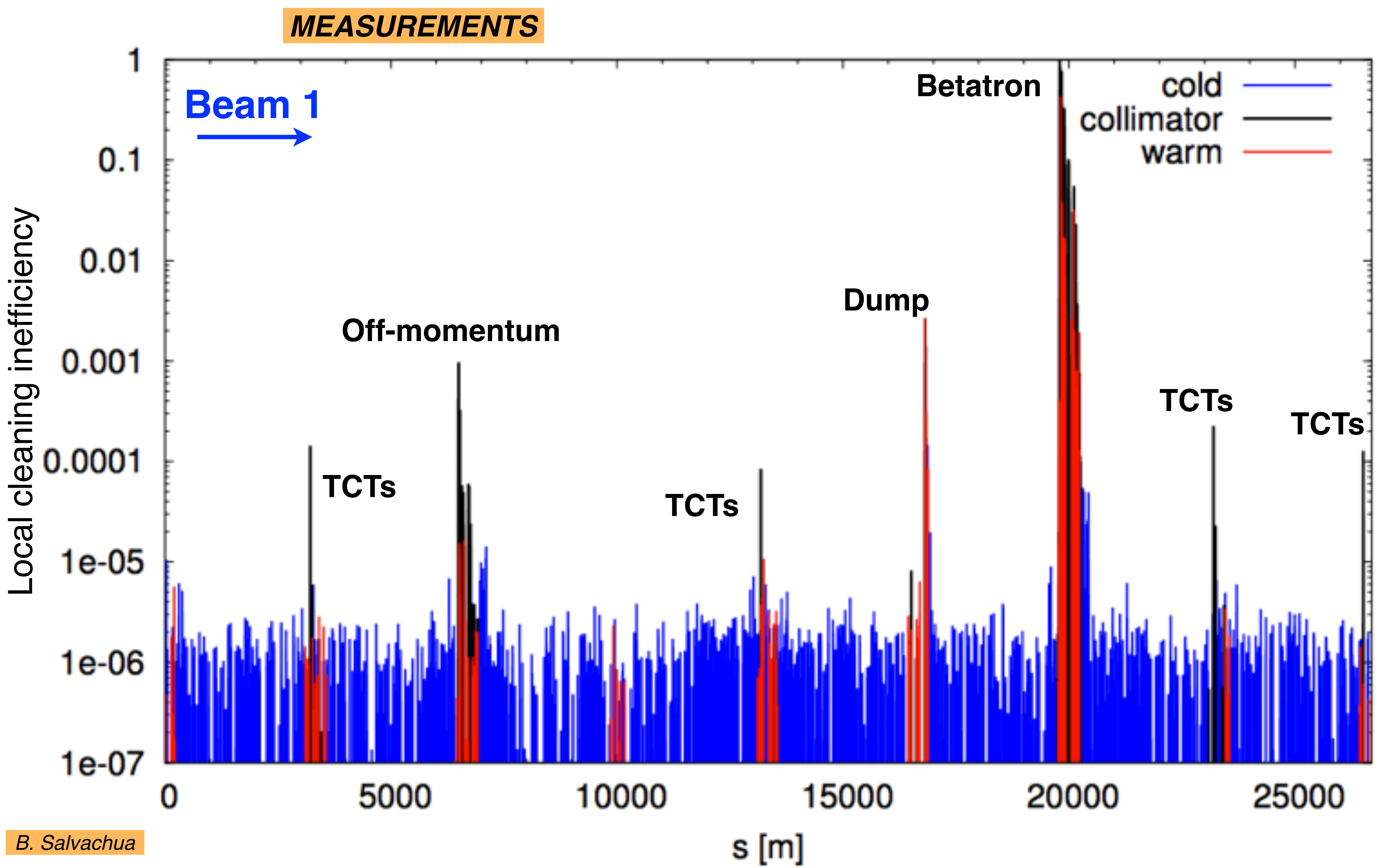
Emittance measurement through wire scanners of an individual bunch within a train.

Collimation cleaning

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

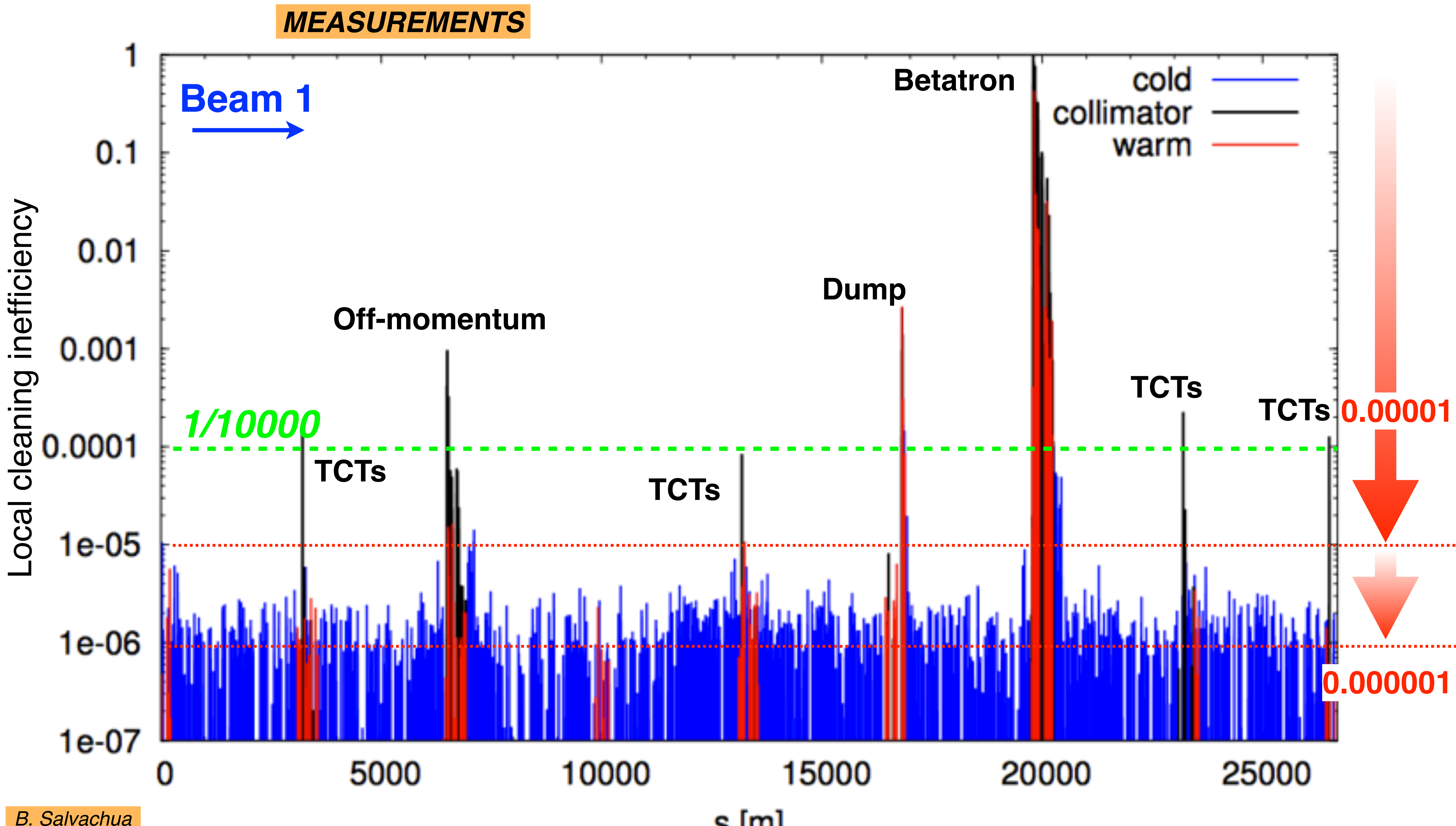


Collimation cleaning: 4.0 TeV, β^*=0.6 m



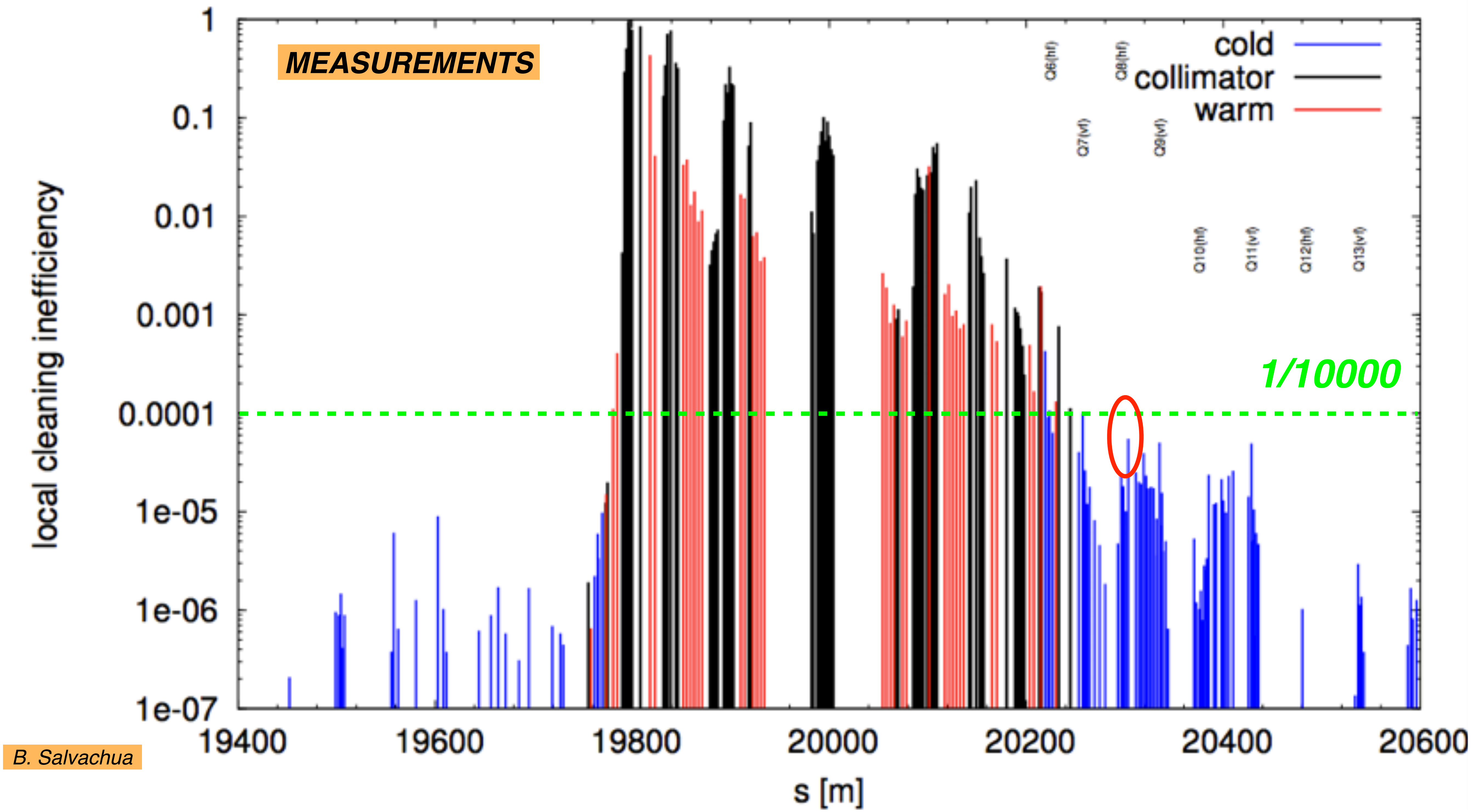
B. Salvachua

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



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

Zoom in IR7

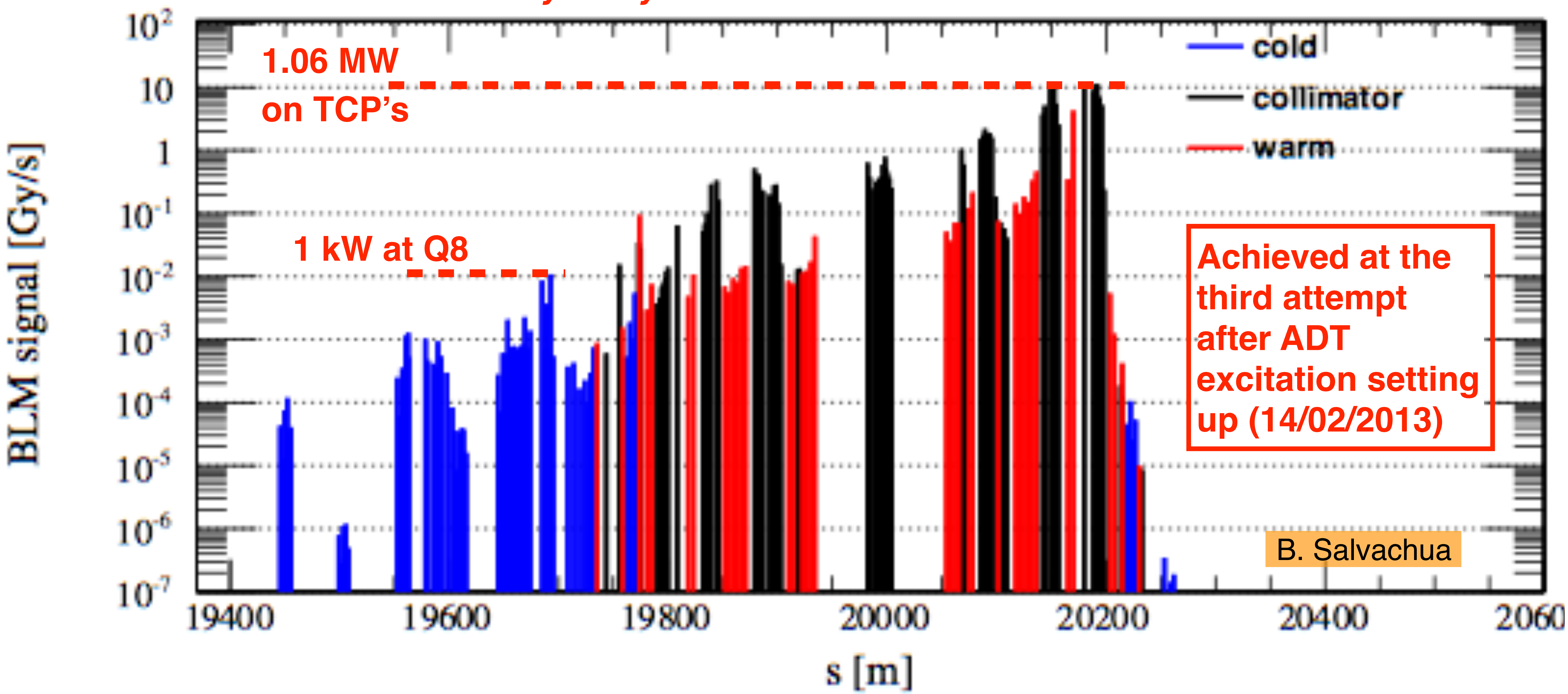


<u>Critical location</u> (both beams): losses in the "dispersion suppressor".

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

One extreme example: quench test

Preliminary analysis of beam tests done on 14/02/2013



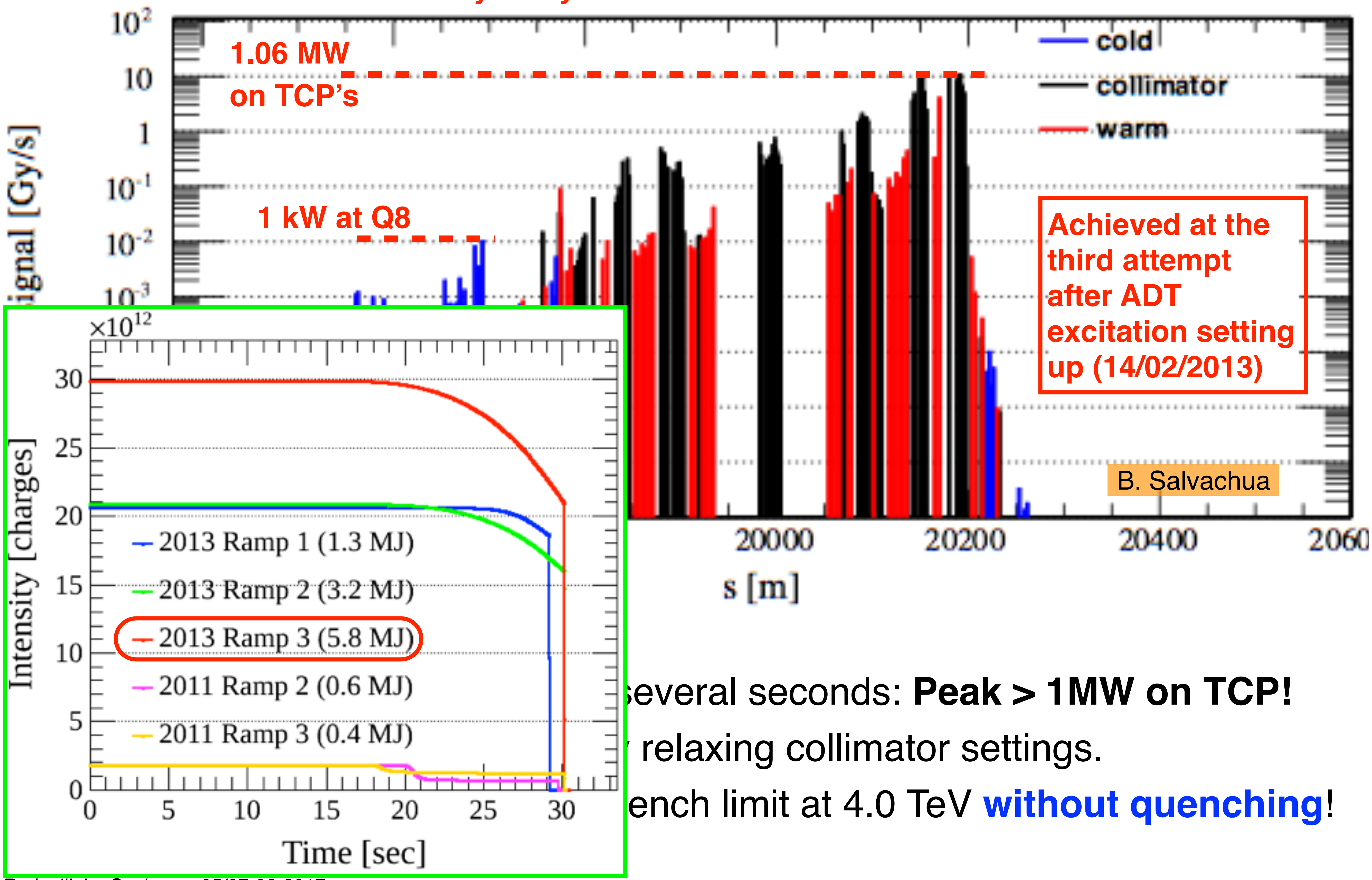
Controlled beam excitation over several seconds: **Peak > 1MW on TCP!**

Worsened cleaning by relaxing collimator settings.

Achieved 3.4 times the assumed quench limit at 4.0 TeV **without quenching**!

One extreme example: quench test

Preliminary analysis of beam tests done on 14/02/2013

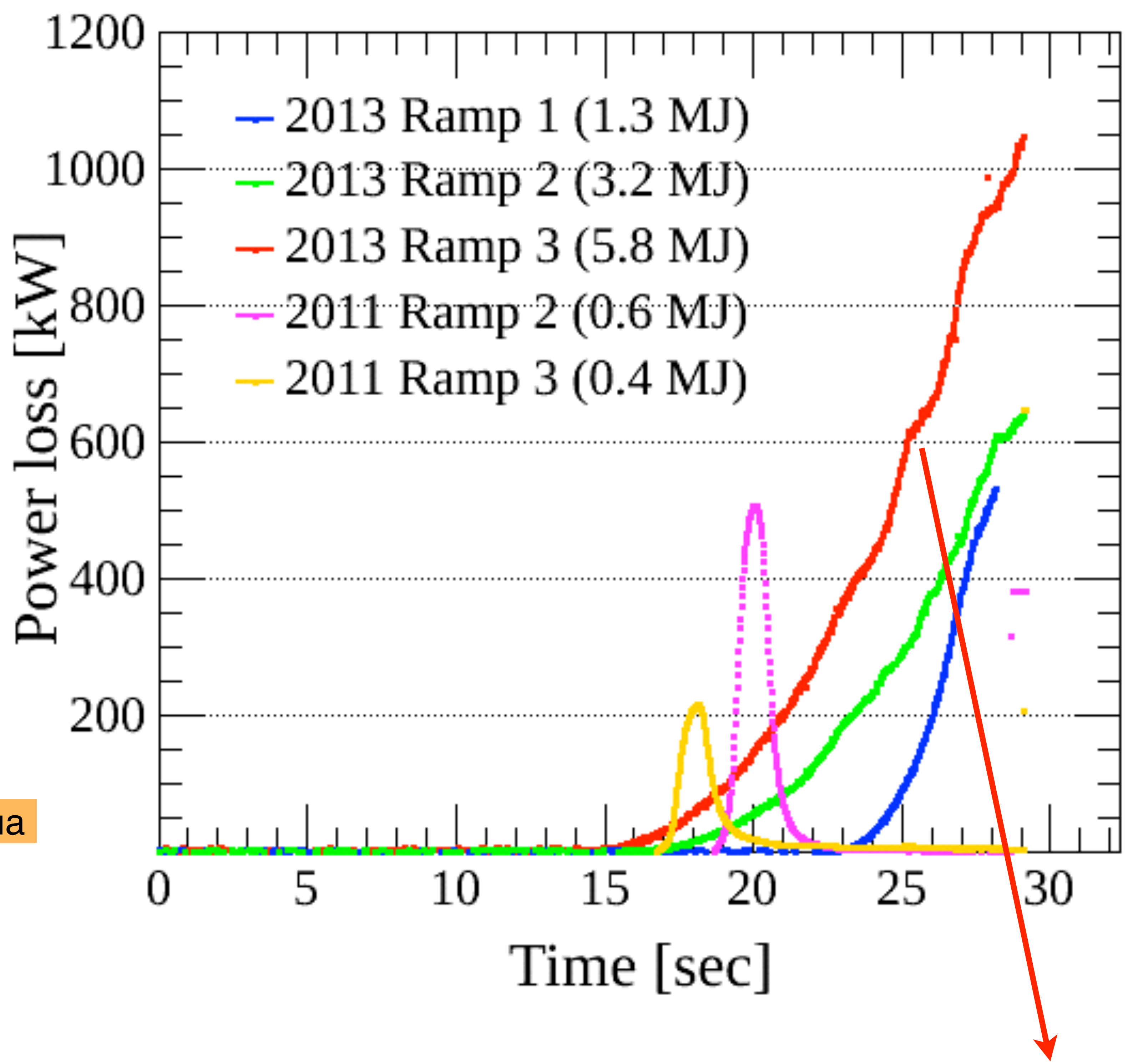


several seconds: **Peak > 1MW on TCP!**

relaxing collimator settings.

ench limit at 4.0 TeV **without quenching**!

Handling 1 MW losses



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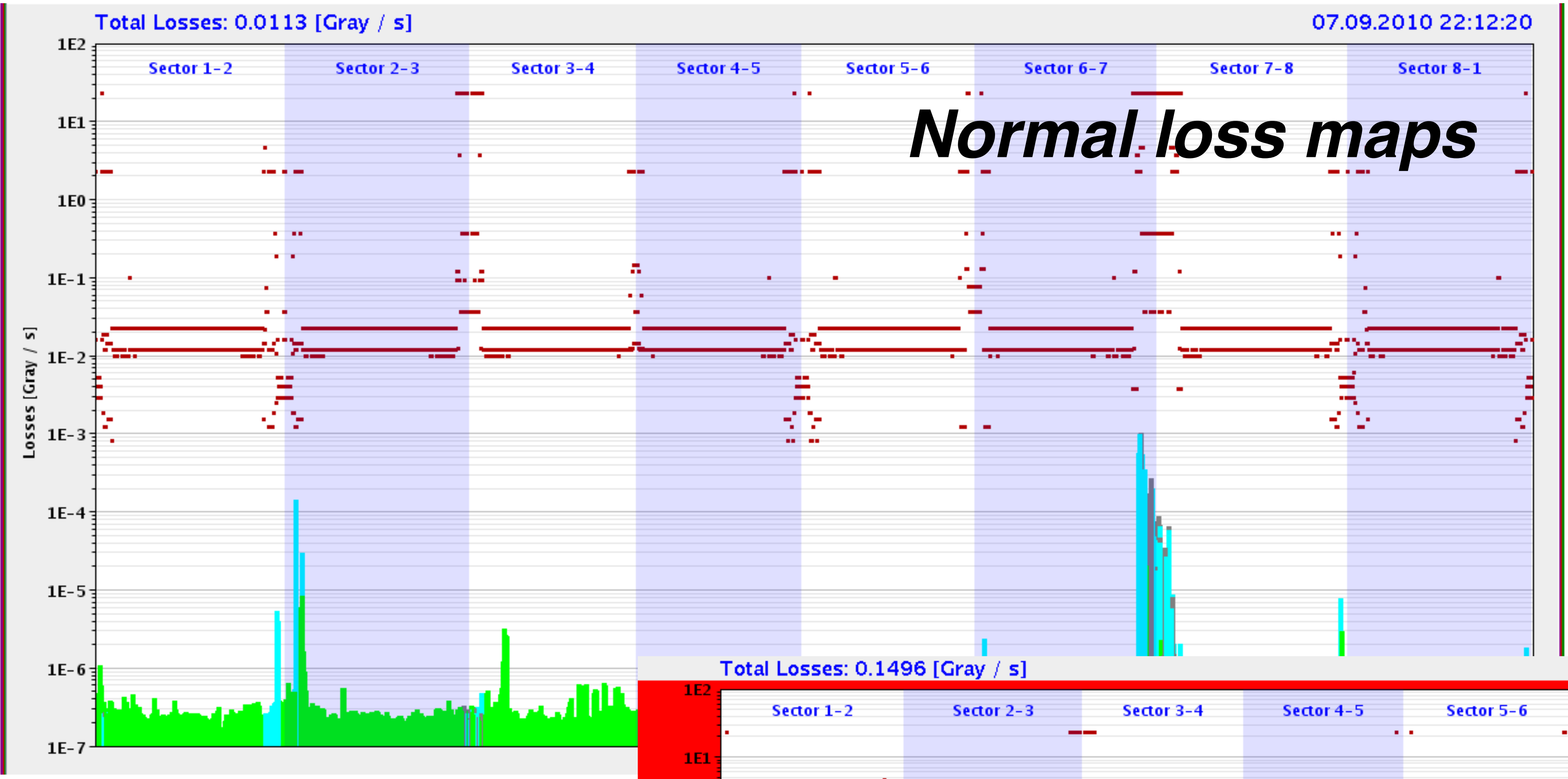
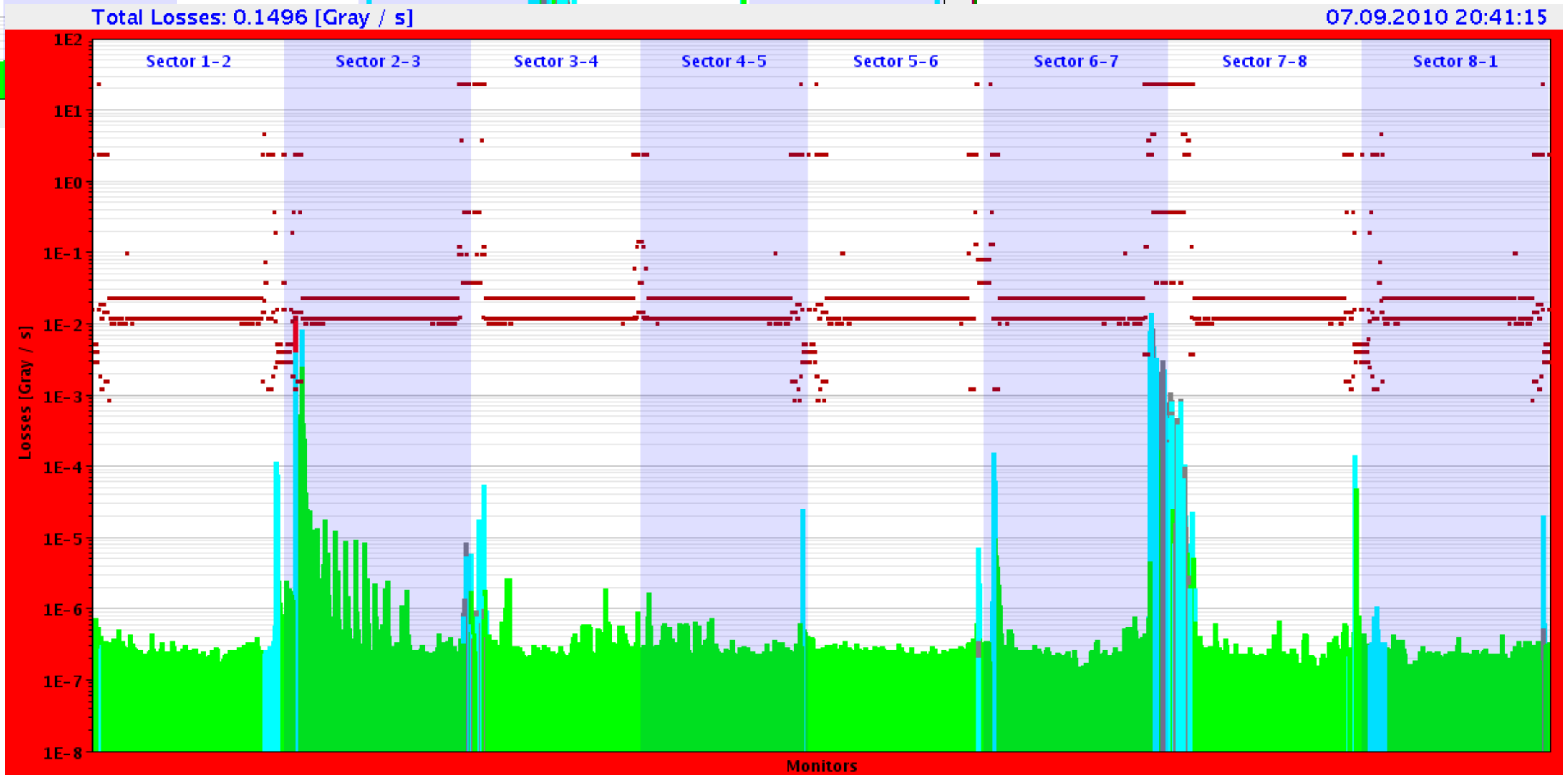
Primary beam losses equivalent to the stored energy of > 3 Tevatron beams (but energy 4 times larger!) lost without quenching!

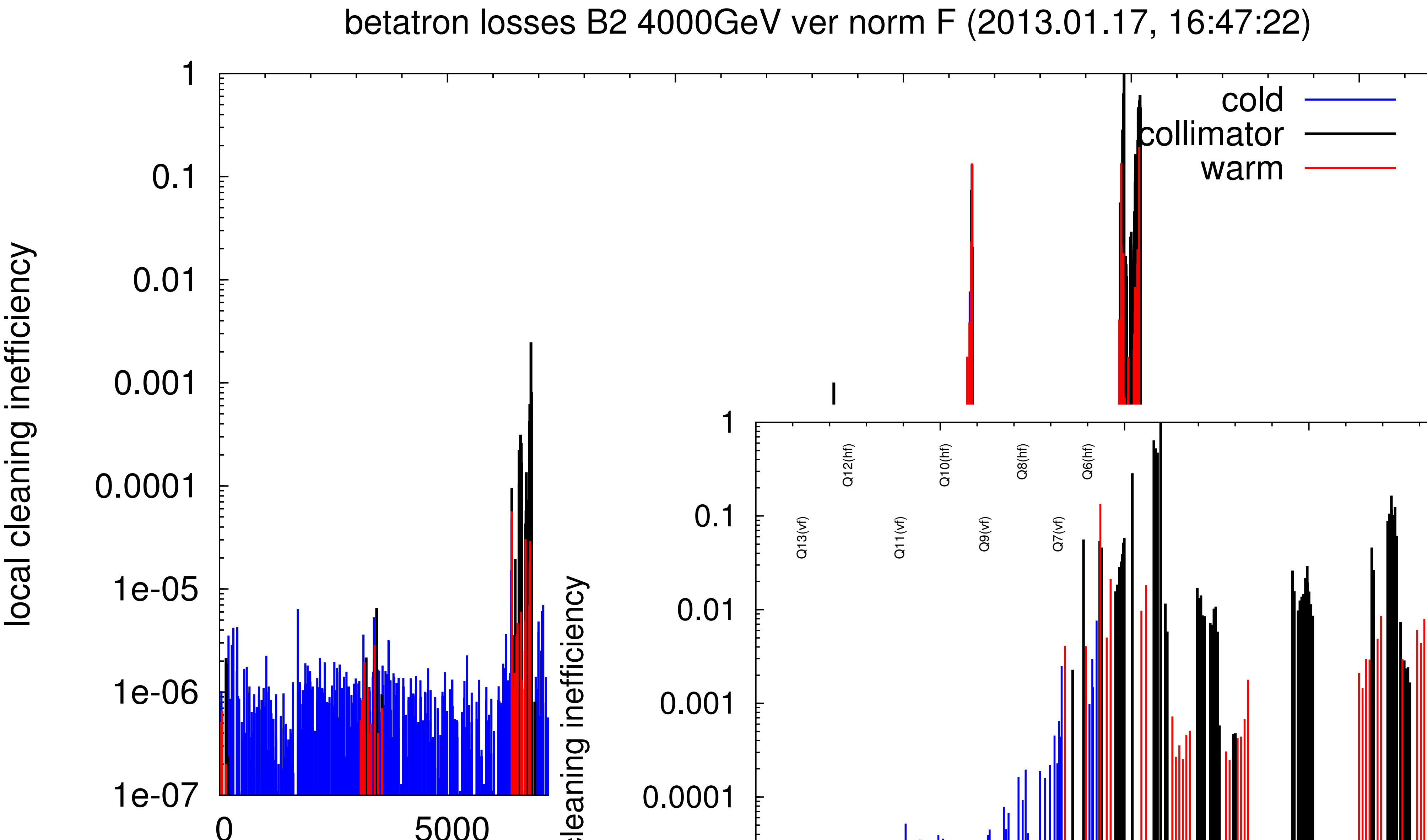
Can something go wrong?

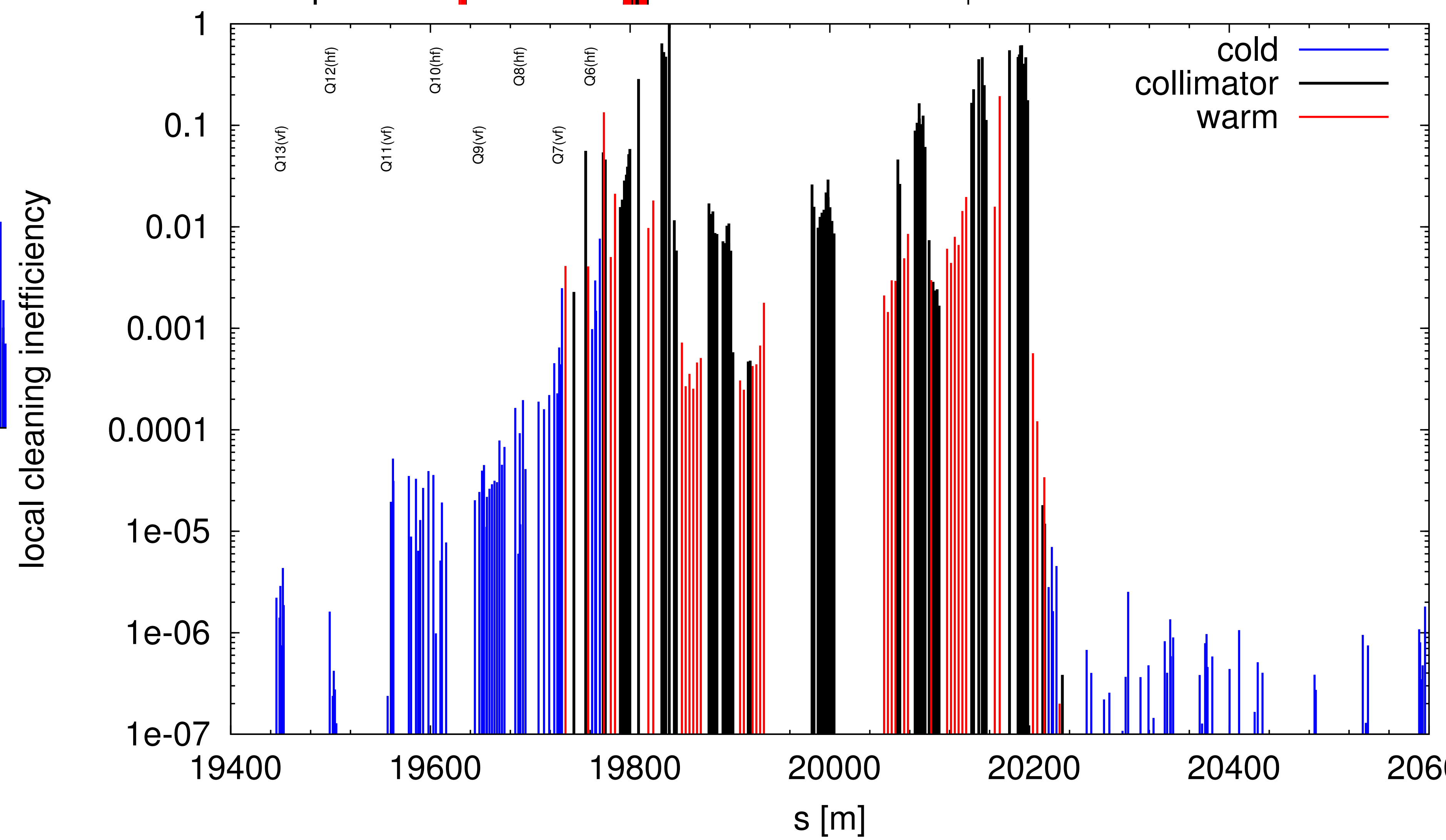




One injection protection collimator in IR2 forgot in...

Catching setting errors



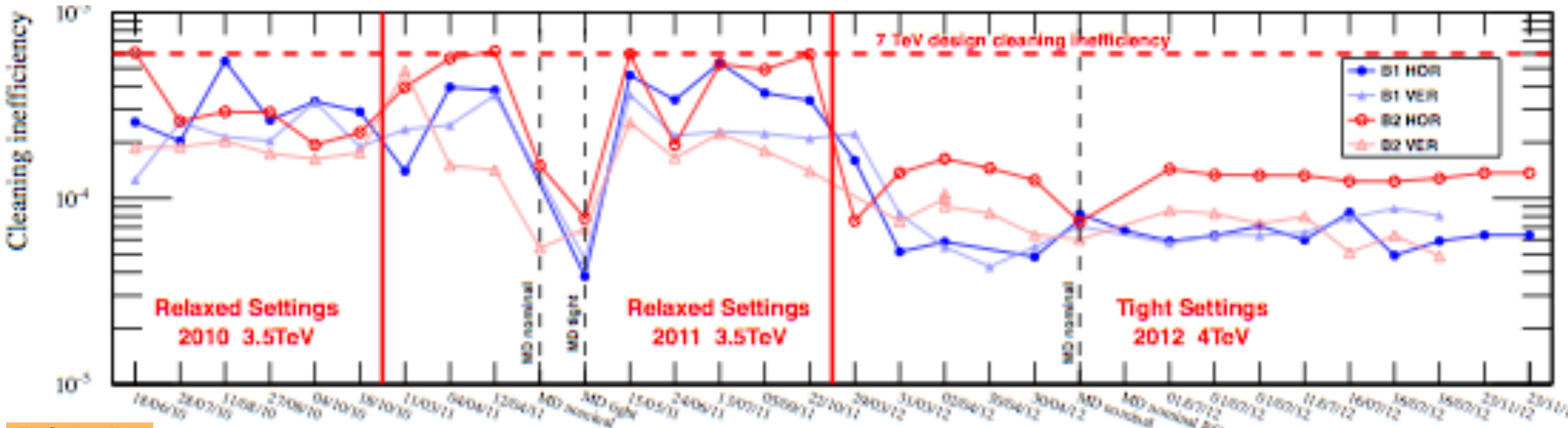


Alignment error of one TCLA collimators

G. Valentino

Can catch small settings errors. Student working on detailed analysis

Continuous performance monitoring



B. Salvachua

- The loss maps are regularly performed to **validate the system functionality**.
  Shown here: cleaning at the highest COLD loss location of the ring (DS in IR7)
- We can monitor the performance stability within a few 1e-4.
- **Excellent stability** of cleaning performance observed!
  Steps in the graph determined by changes of collimator settings.
- Collimators (and protection devices) must be re-aligned in case of abnormal issues with the cleaning performance.
  *So far, **1 alignment per year** proved to be sufficient thanks to the excellent stability of the machine and of the collimator settings.*

Outline

- Main points from 2nd lecture
- The LHC collimator design
  - From conceptual design to hardware
  - The LHC collimators
- Operational performance at the LHC
  - How do we operate the system
  - Cleaning performance
- **Simulations of collimation cleaning**
  - **Halo tracking and beam loss prediction**
- Advanced collimation concepts
  - High Luminosity collimation upgrade
  - Crystal collimation
  - Hollow electron lenses

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.*

LHC collimation: simulation challenges

- **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.*

LHC collimation: simulation challenges

- Detailed description of the **LHC aperture** all along the 27 km

  → *10 cm binning, i.e. 270000 check points.*

LHC collimation: simulation challenges

- Accurate tracking of particles with large **orbit** and **energy deviations**

    → *need state-of-the-art tools for multi-turn tracking.*

LHC collimation: simulation challenges

- 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.*

LHC collimation: simulation challenges

- 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.*

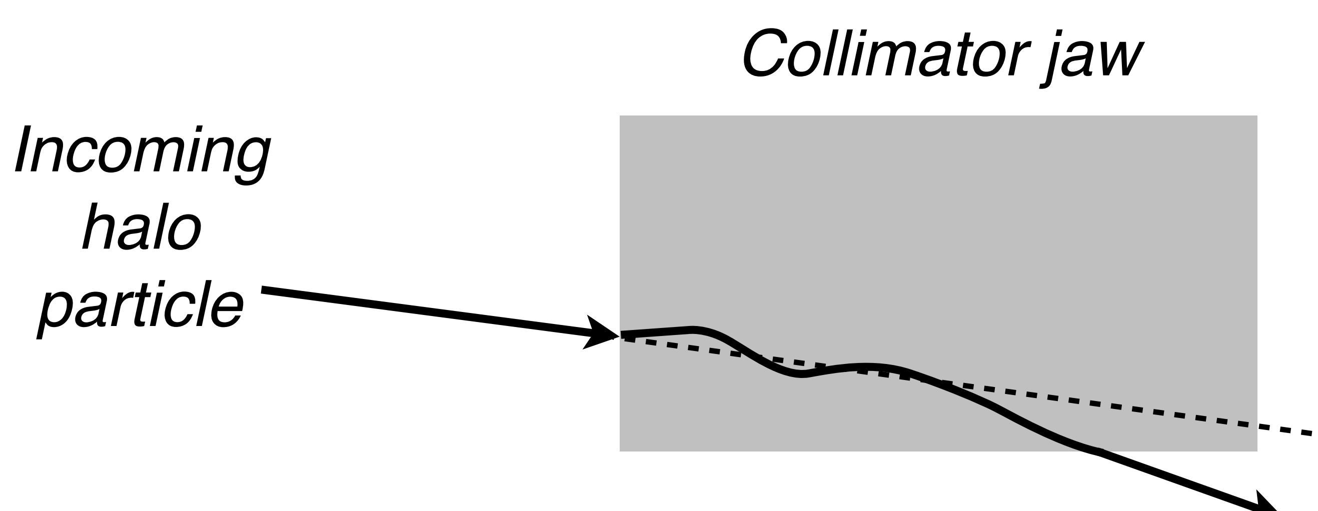
Simulation goal: determine energy lost in (cold) magnets for given beam intensity impinging on collimators.

Simulation tools

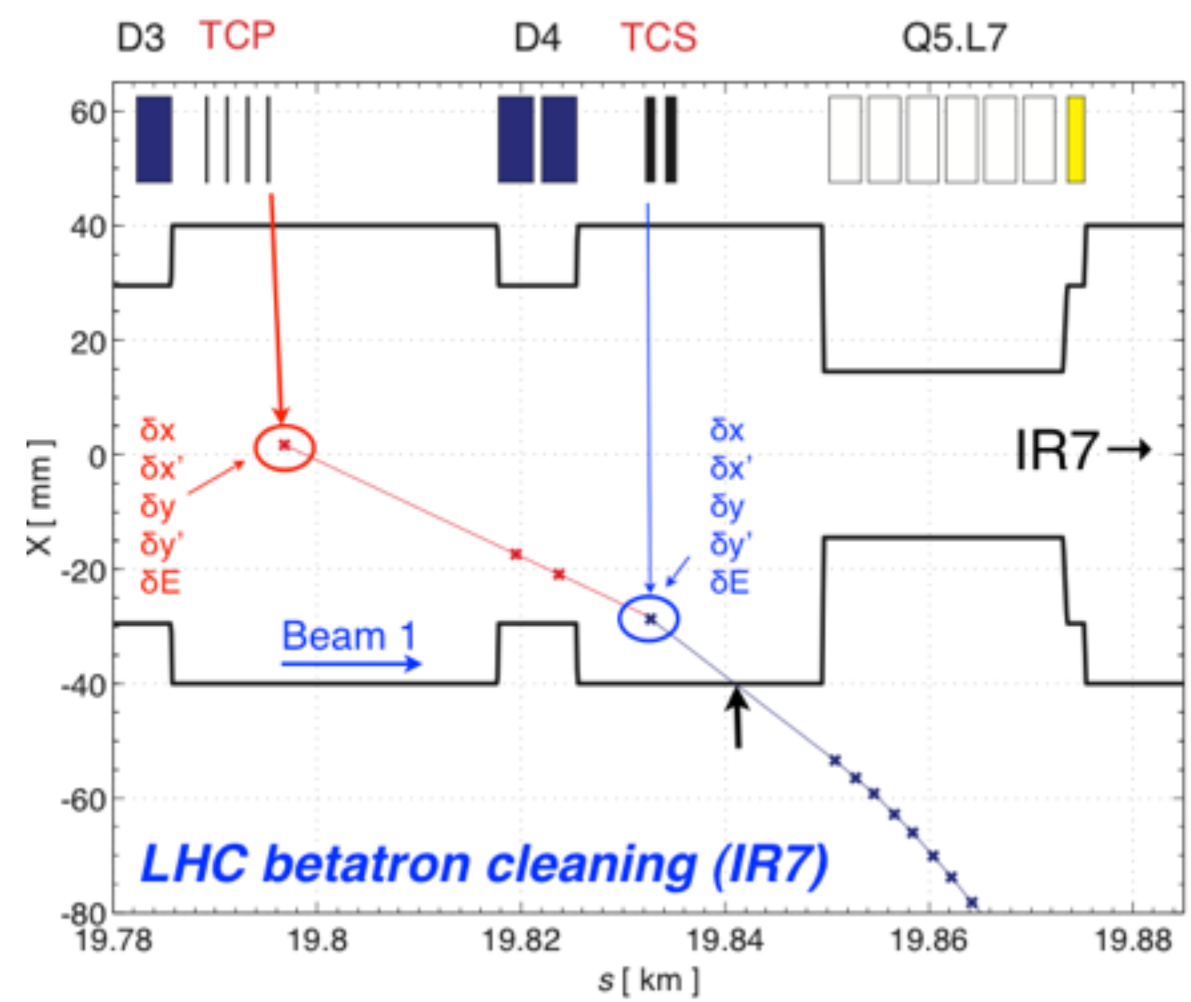
Accurate tracking of halo particles 6D dynamics, chromatic effects, δp/p, high order field errors, ...	**SixTrack**[†]
Detailed collimator geometry Implement all collimators and protection devices, treat any azimuthal angle, tilt/flatness errors	
Scattering routine Track protons inside collimator materials	**K2**
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

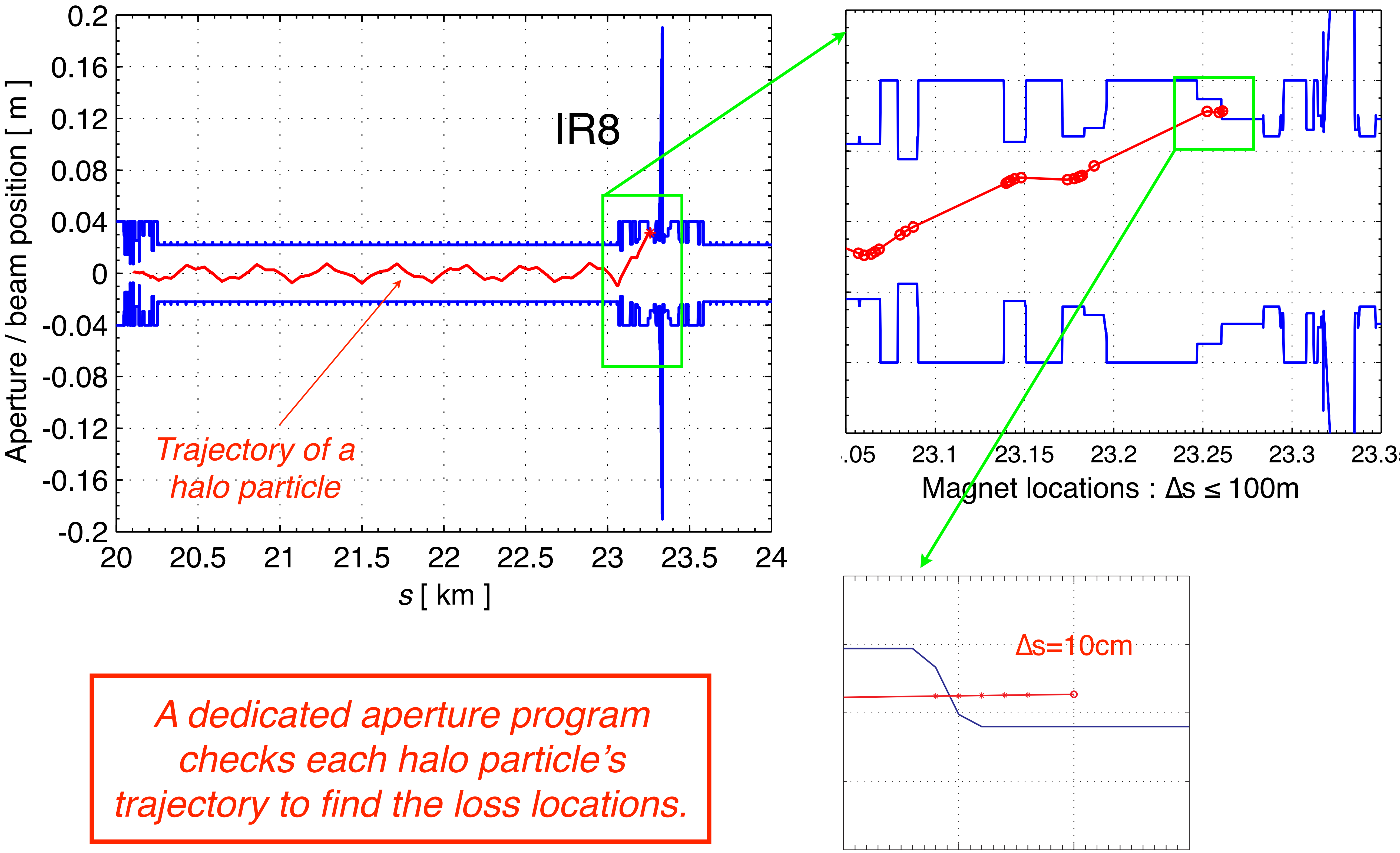
† See also talk by F. Schmidt .



An illustrative scheme



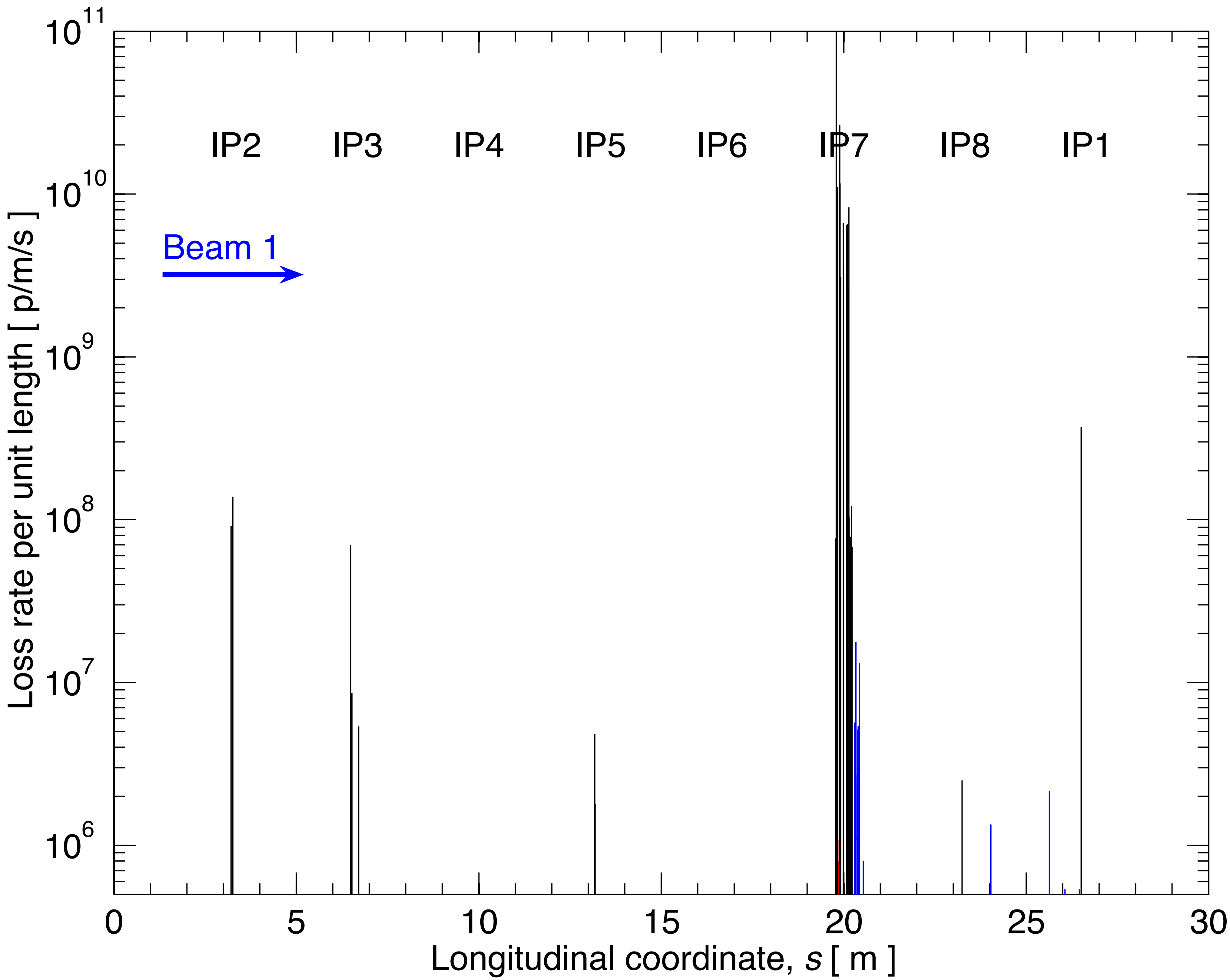
Example: trajectory of a halo particle



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

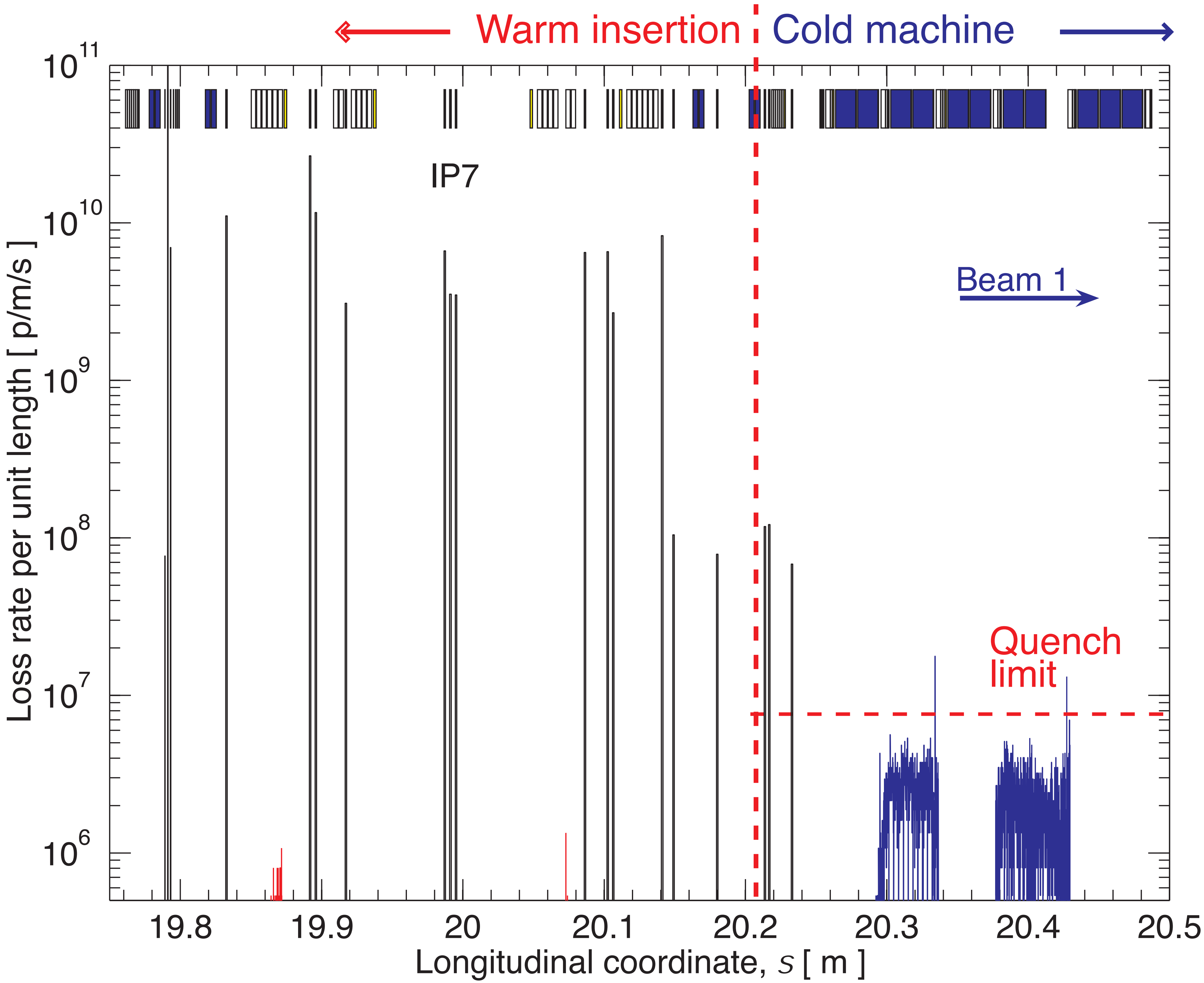
Interpolation: Δs=10cm
(270000 points!)

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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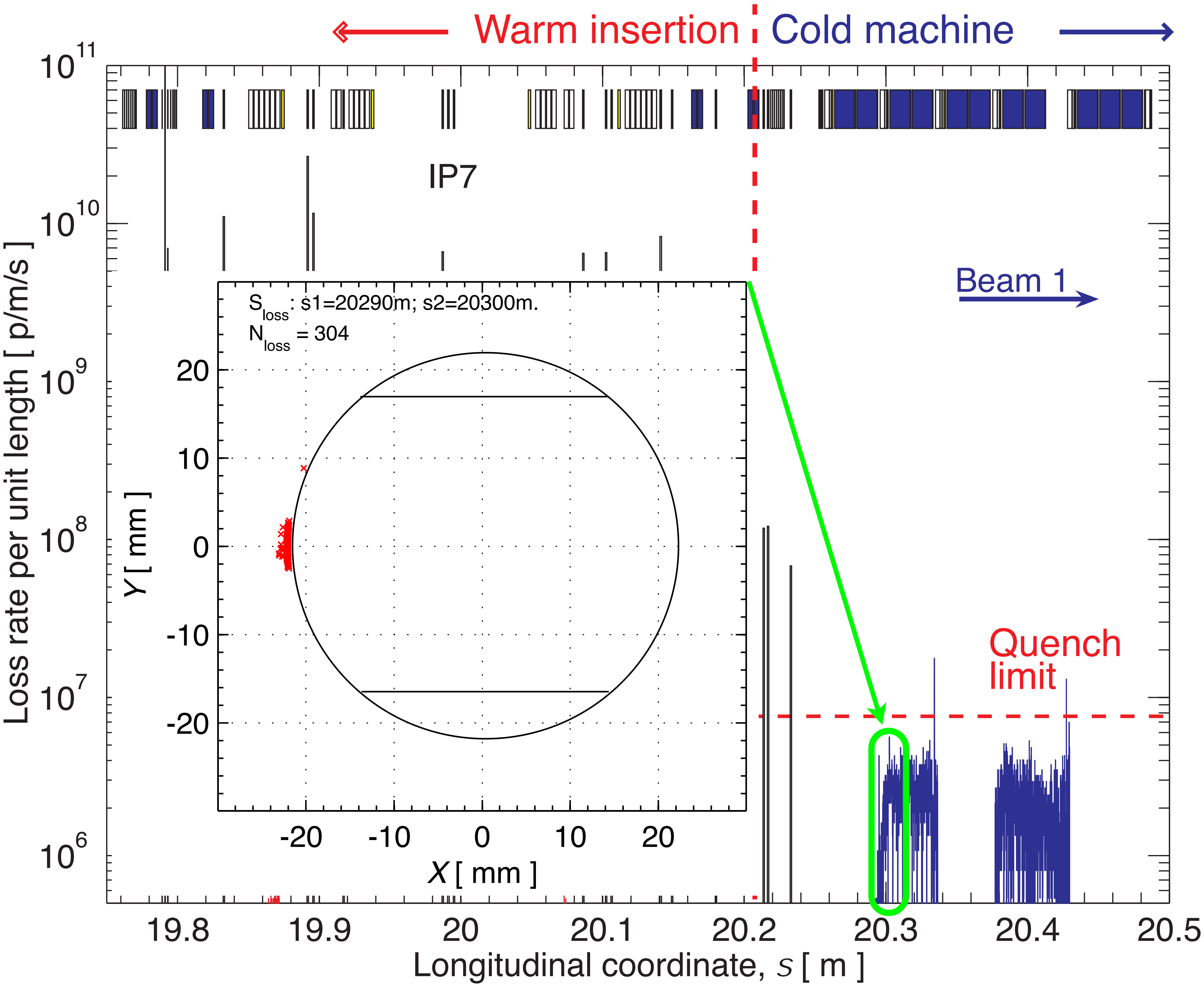
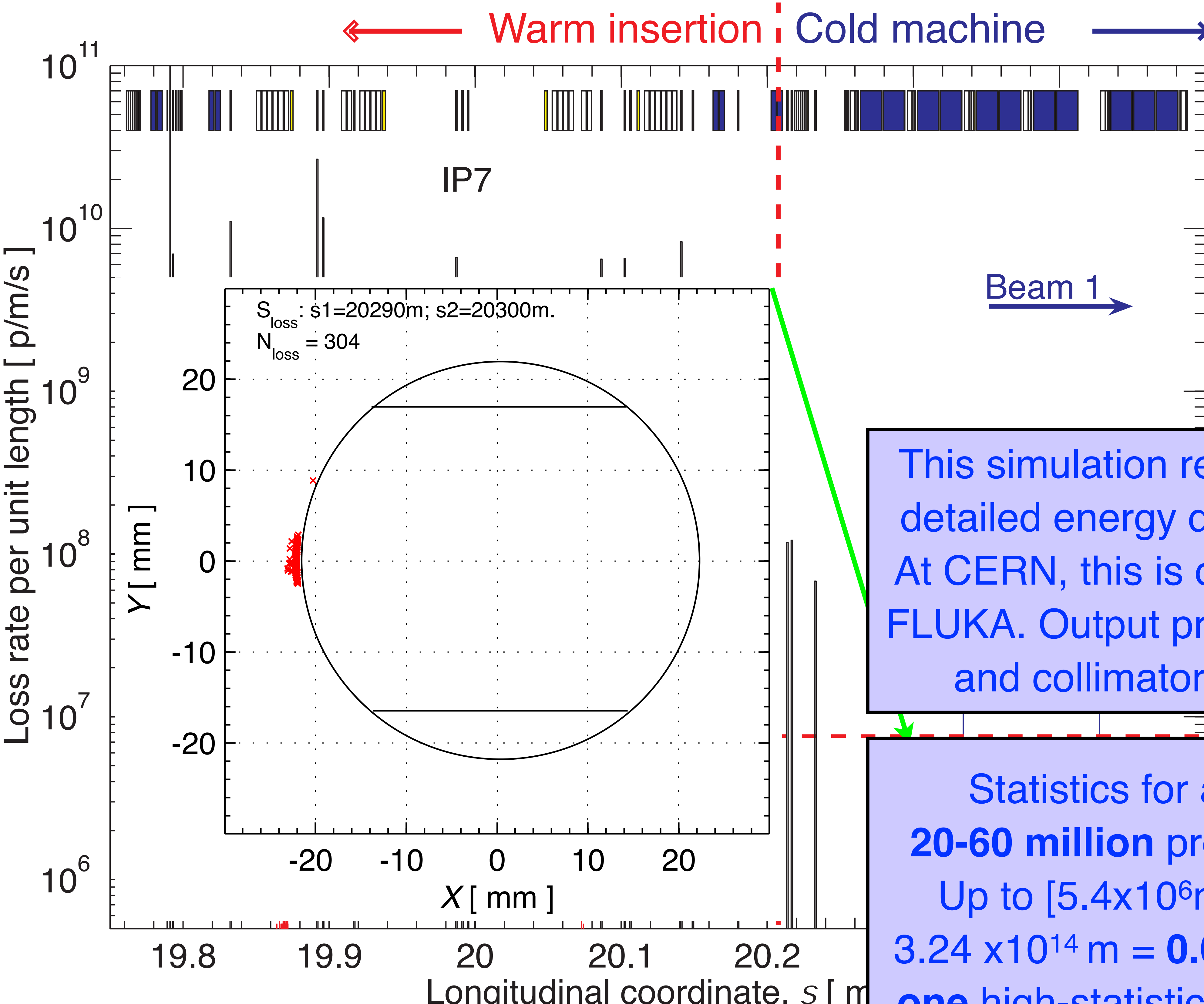


Nominal 7 TeV case, perfect machine

Example of simulated "loss map"



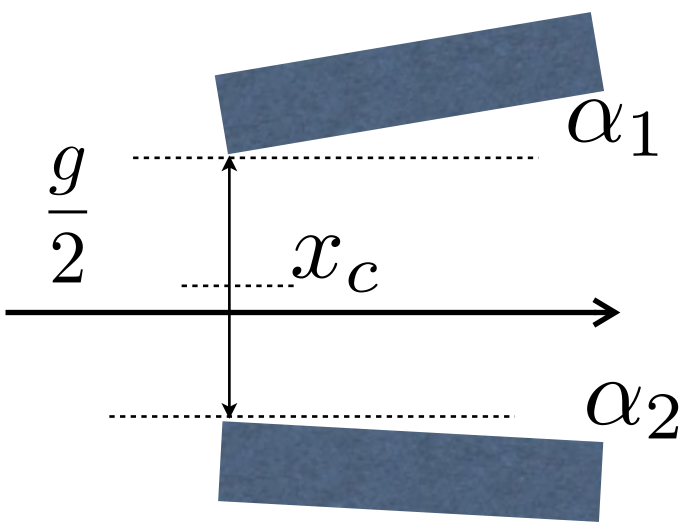
Nominal 7 TeV case, perfect machine

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 [5.4×10^6 m] x [60×10^6 p] = 3.24×10^{14} m = **0.034 lightyears** for **one** high-statistics simulation case!

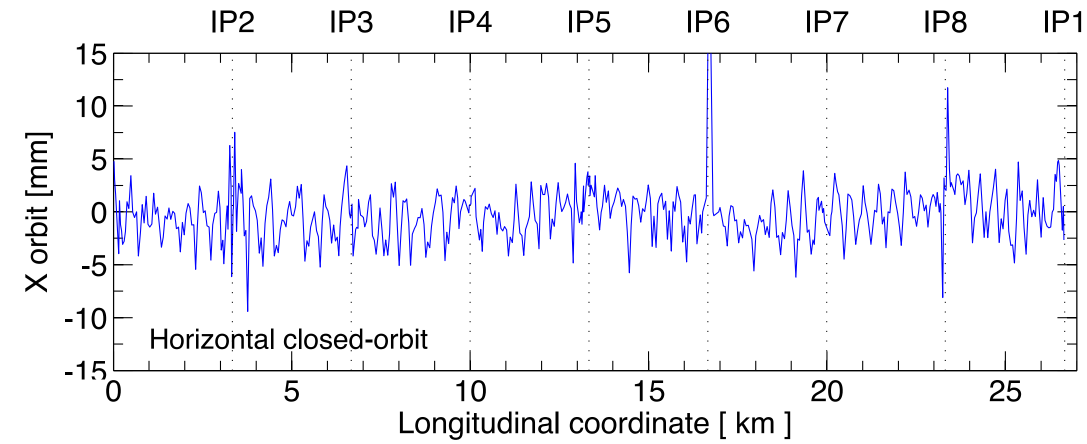
Importance of error models

Collimator positioning with respect to the beam



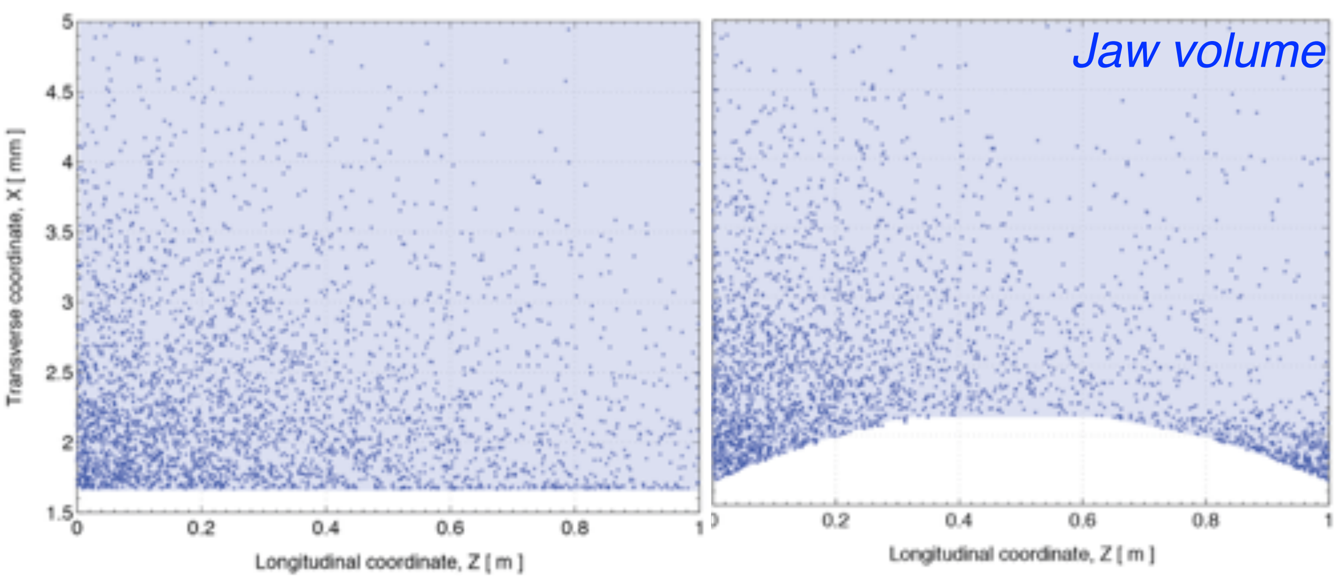
Can apply random errors to collimator geometry.
Typical RMS values:
Collimator centre = 50μm
Gap = 0.1 σ
Jaw tilt angle = 200 μrad

Closed-orbit errors around the ring



Design value: +/- 3-4mm peak-to-peak

Collimator jaw flatness



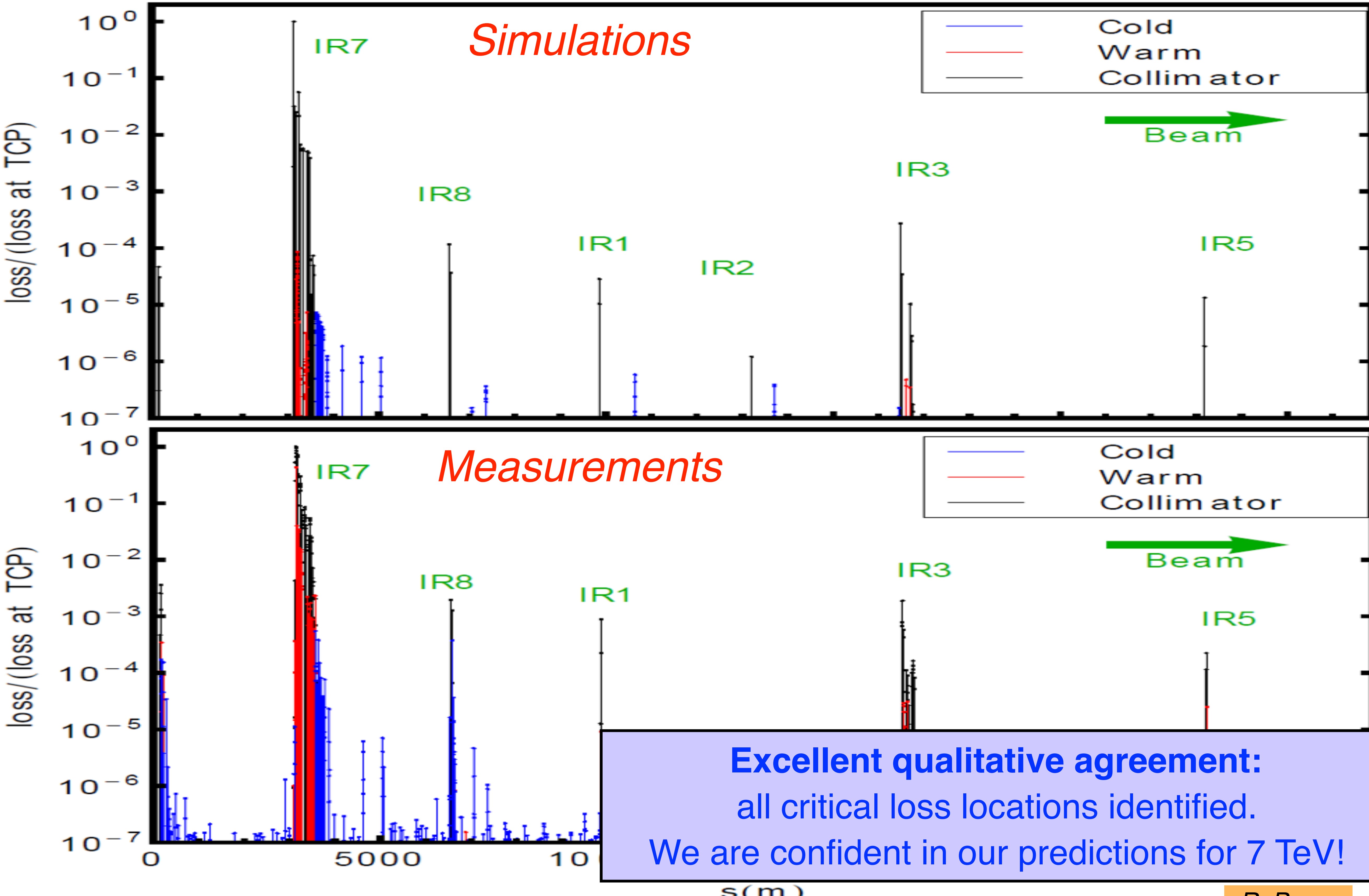
5th order polynomials to fit measured flatness of all Carbon collimators: ≥ 40 µm

Machine aperture misalignments

Element type	Description	Design		Measured	
		$\sigma_{\Delta x}$ [mm]	$\sigma_{\Delta y}$ [mm]	$\sigma_{\Delta x}$ [mm]	$\sigma_{\Delta y}$ [mm]
MB	main dipole	2.40	1.56	1.83	1.10
MQ	arc quadrupole	2.00	1.20	1.36	0.76
MQX	triplet quadrupole	1.00	1.00	1.53	1.53
MQWA	warm quadrupole	2.00	1.20	0.67	0.41
MQWB	warm quadrupole	2.00	1.20	0.67	0.41
MBW	warm dipole	1.50	1.50	1.96	1.49
BPM	beam position monitor	0.50	0.50	1.36	0.76

In addition, all optics and multipole errors well established for the standard MADX / sixtrack interface can be applied.

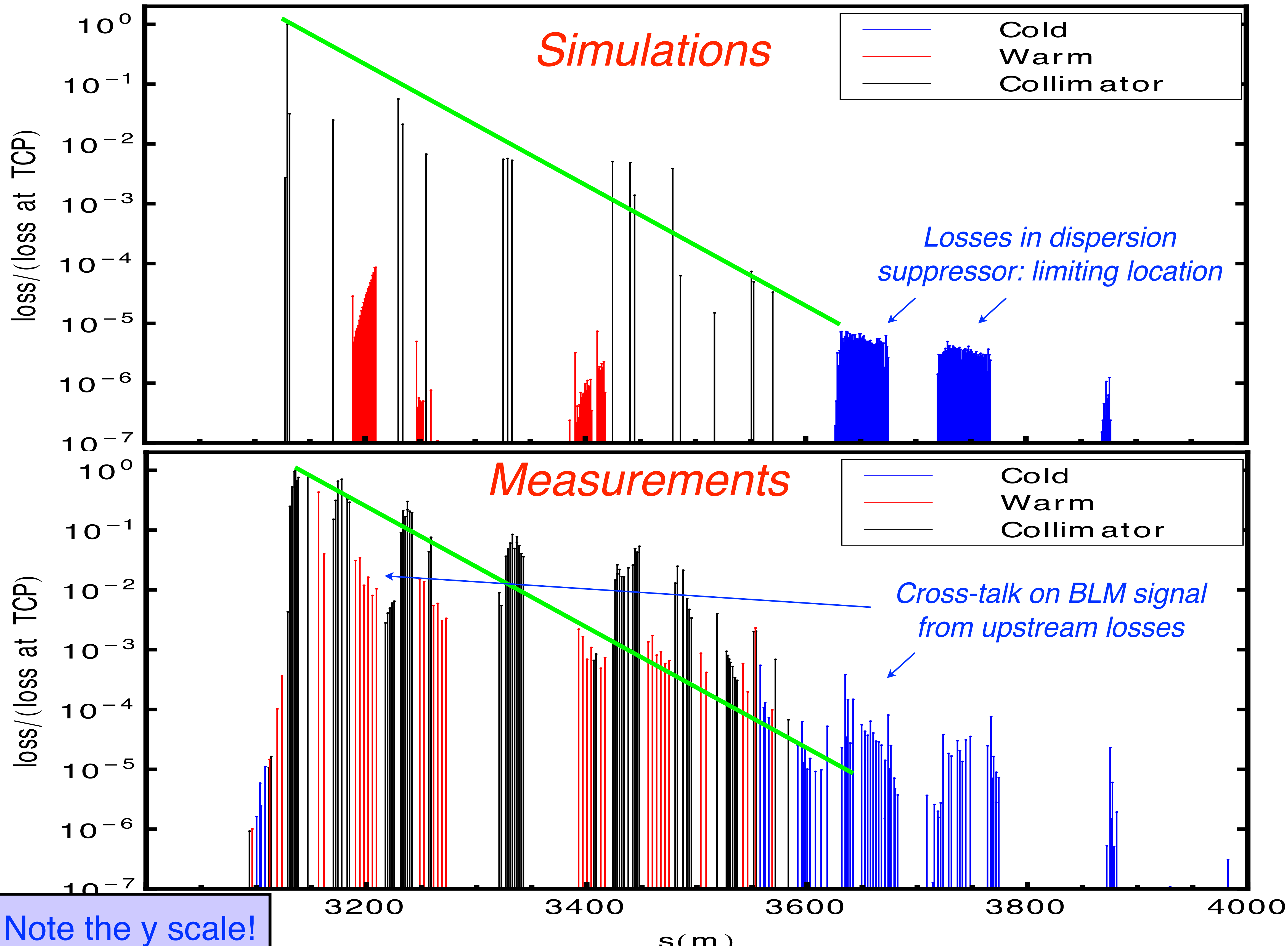
Comparison with measurements



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

R. Bruce

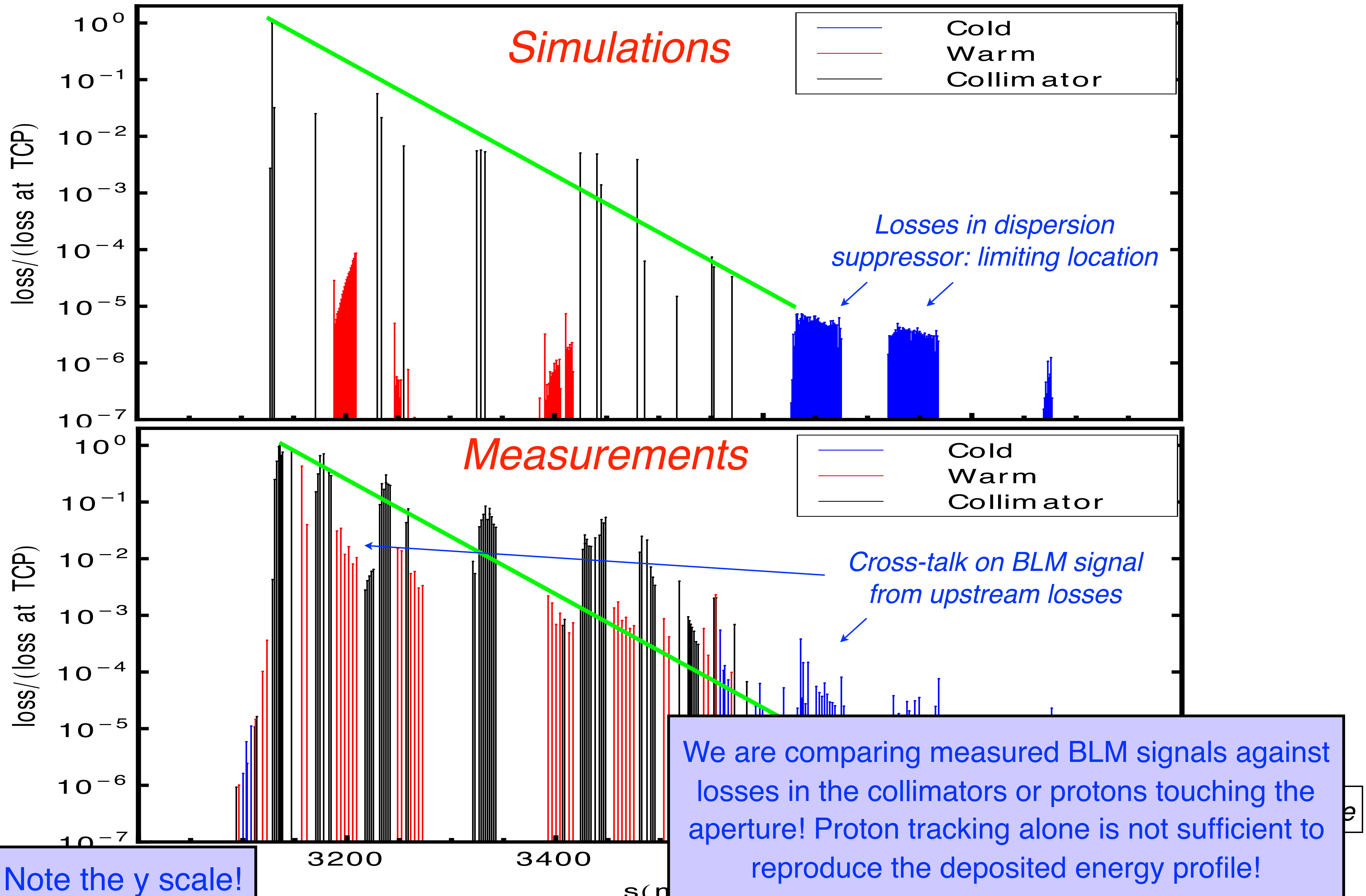
Comparison in the betatron cleaning



R. Bruce

Note the y scale!

Comparison in the betatron cleaning

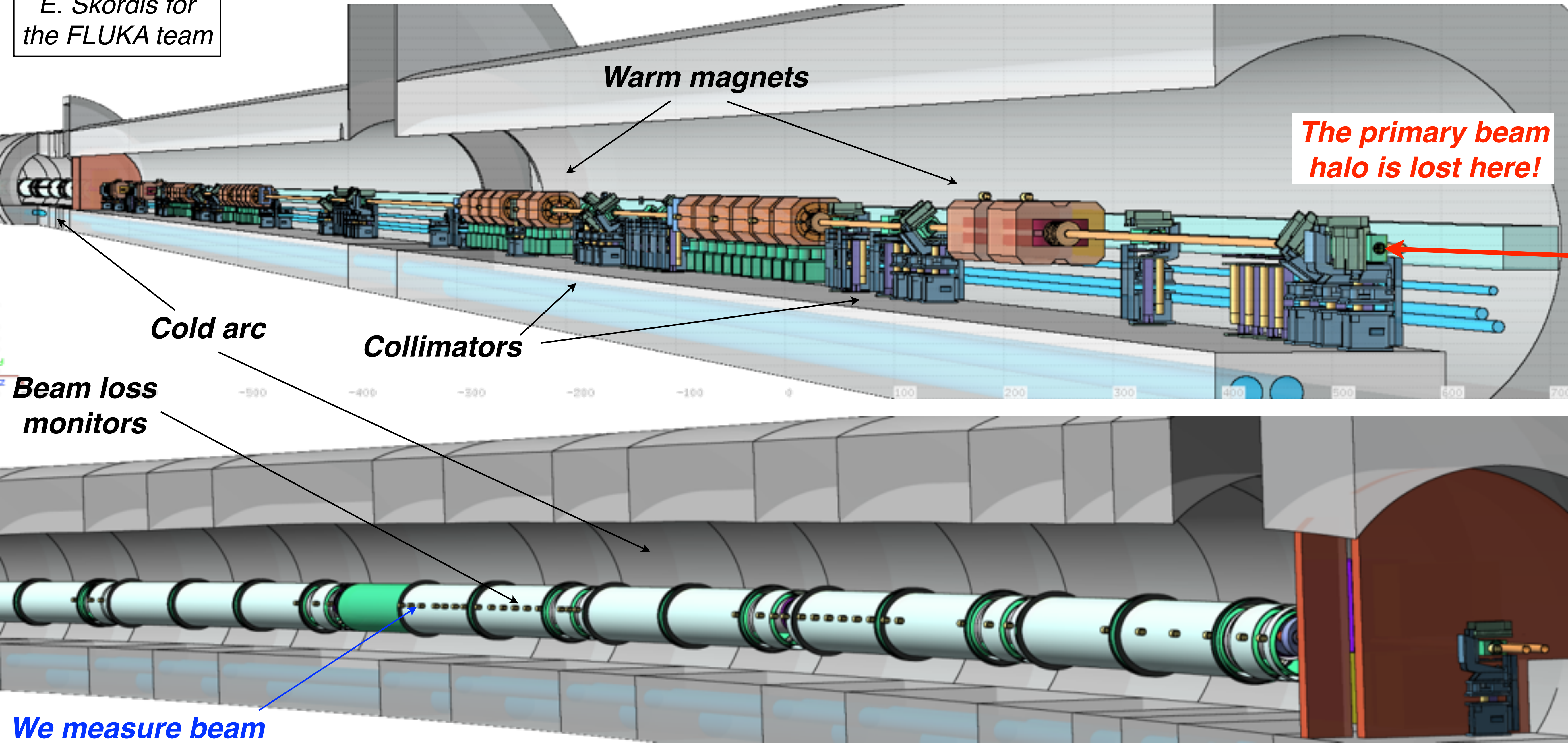


We are comparing measured BLM signals against losses in the collimators or protons touching the aperture! Proton tracking alone is not sufficient to reproduce the deposited energy profile!

Note the y scale!

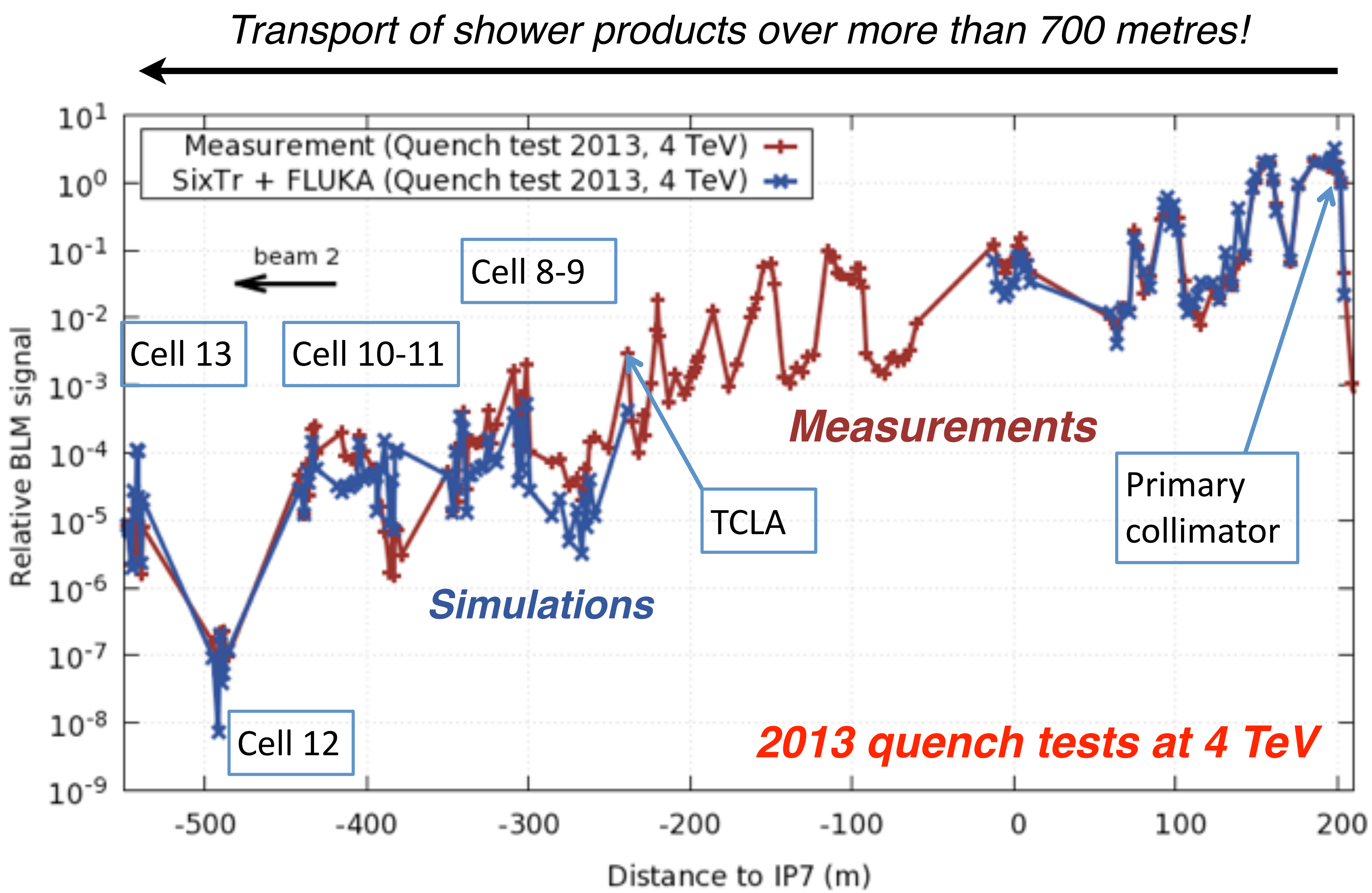
Integrated simulations

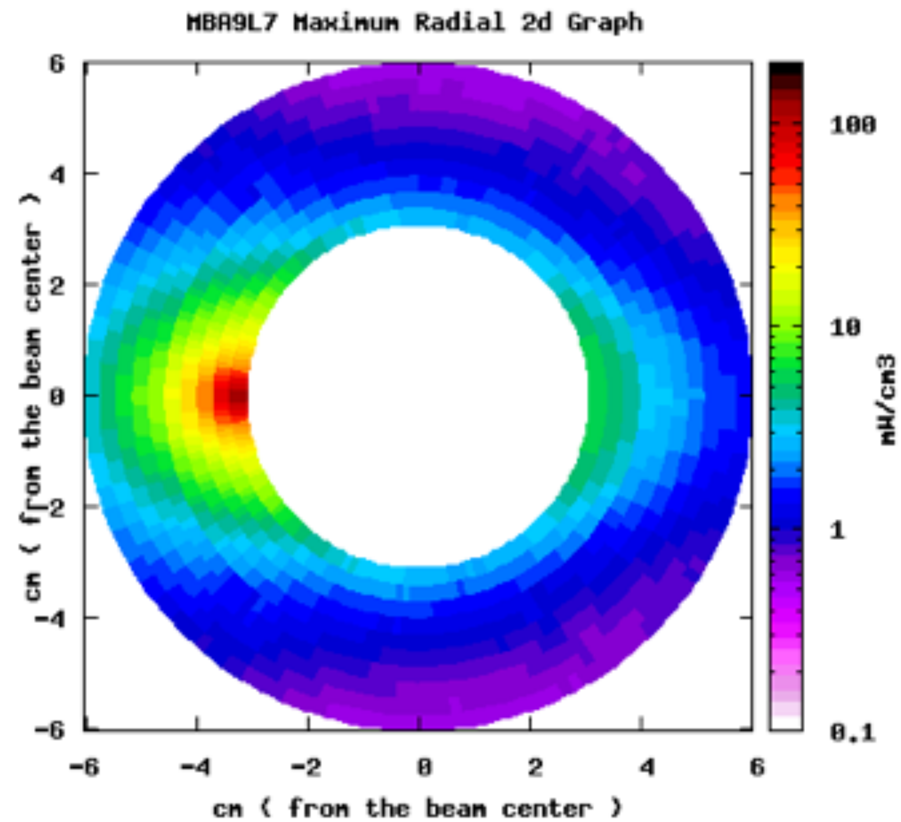
E. Skordis for the FLUKA team



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

Comparison against measurements





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.

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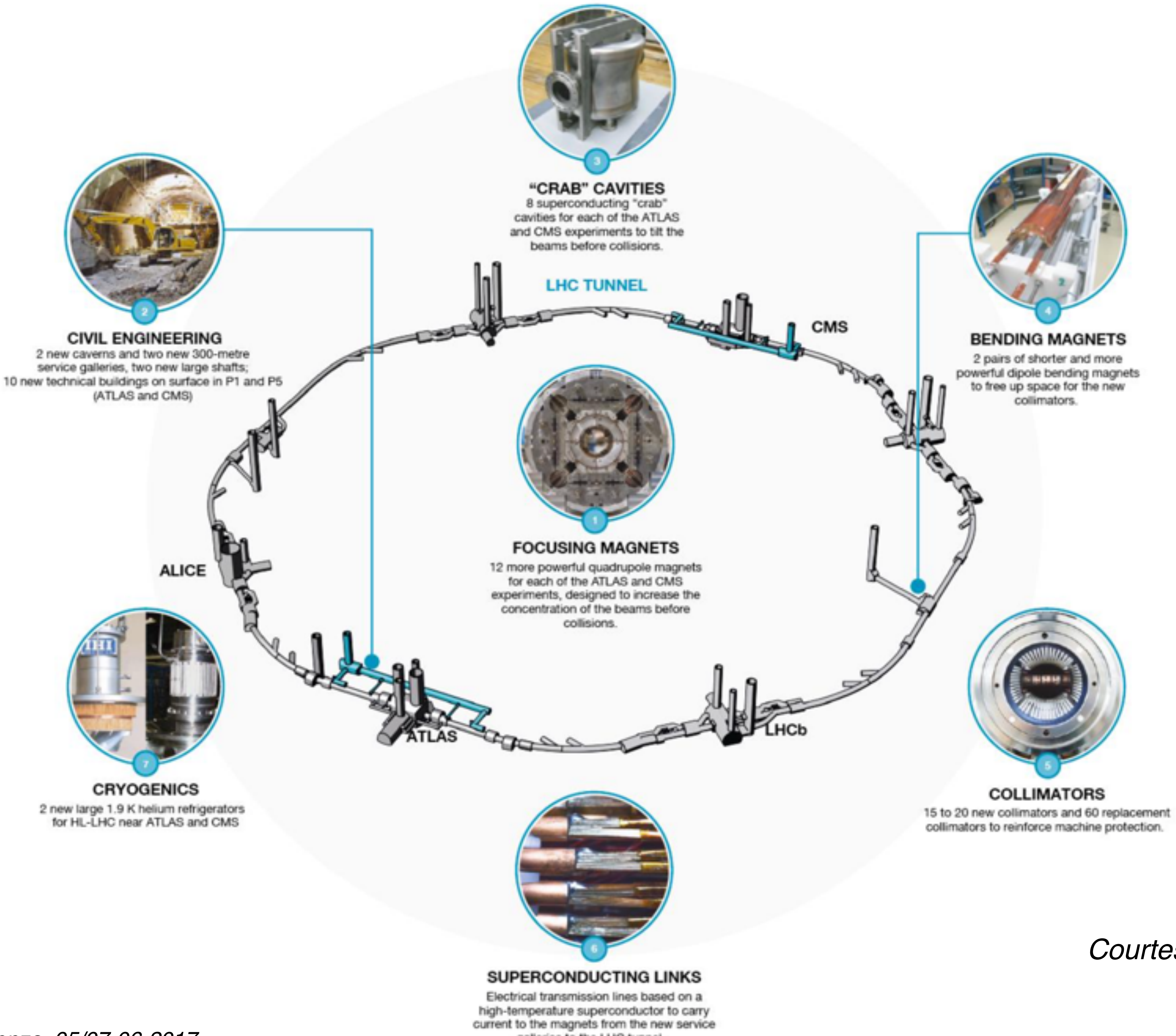
  - **High Luminosity collimation upgrade**
  - **Crystal collimation**
  - **Hollow electron lenses**

Possible limitations the present system

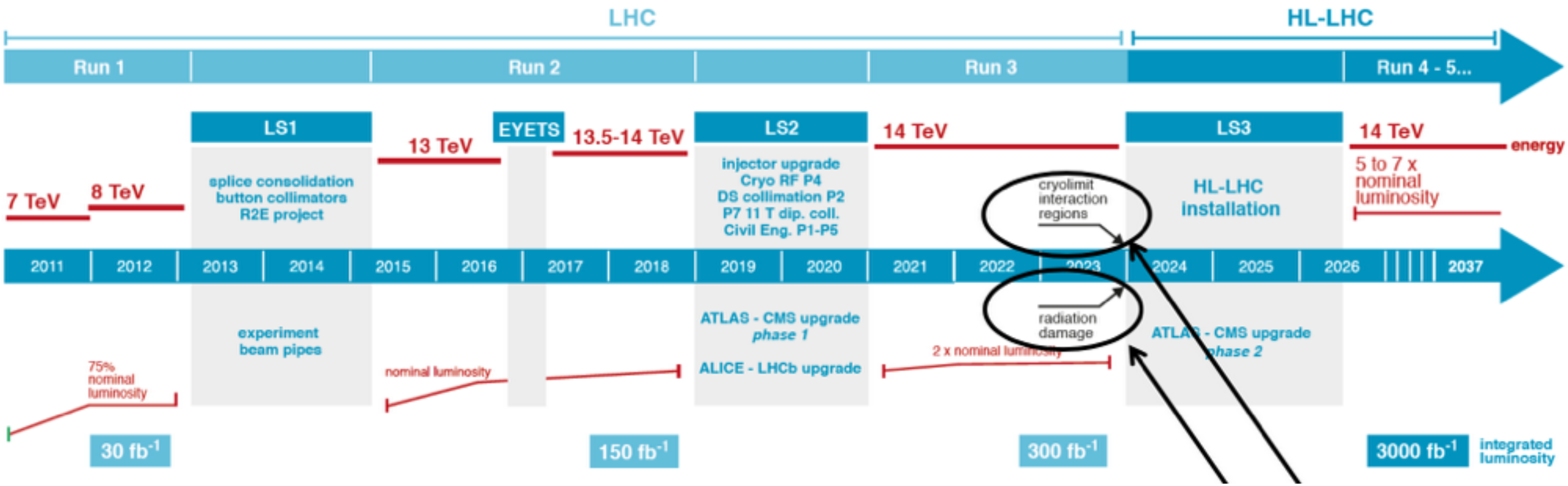
- We are happy with the present system performance but are actively working on **advanced collimation concepts** and designs for the challenges of future upgrades.
- Novel collimator materials: more robust and low impedance.
- Crystal collimation as a way to improve cleaning.
- Hollow electron lenses for active control of primary halo.
- New collimators in the cold regions will be used to overcome the cleaning limitations in the dispersion suppressors.
- Continue improving the system performance and alignment techniques for efficient operation (BPM collimators).
- Rotatable collimator concept in case of frequent damage.

The High Luminosity LHC



Courtesy of L. Rossi

The HL-LHC timeline



Goal: increase the integrated luminosity by a factor 10 by ~2035.

Challenging: required ~doubling the stored beam energy!

Parameters and collimation challenges

- Increased beam stored energy: 362MJ → 700MJ at 7 TeV

  Collimation cleaning *versus quench limits of superconducting magnets.*
  Machine protection constraints from ***beam tail*** *population*
  (7 MJ above 3 sigmas even for perfect Gaussian tails!).

- Larger bunch intensity (Ib=2.3x10^{11}p) in smaller emittance (2.0 μm)

  Collimation impedance *versus beam stability.*
  Collimator robustness *against regular and abnormal beam losses at injection as well as top energy.*

- Larger p-p luminosity (1.0 x $10^{34}cm^{-2}s^{-1}$ → 5.0-7.5 x $10^{34}cm^{-2}s^{-1}$)

  Need to improve the ***collimation*** *of* ***physics debris****.*

  Overall upgrade of the ***collimation layouts*** *in the insertion regions.*

- Much smaller β^* in the collision points (55 cm → 15 cm)

  Cleaning and protection of high-luminosity insertions and physics background.

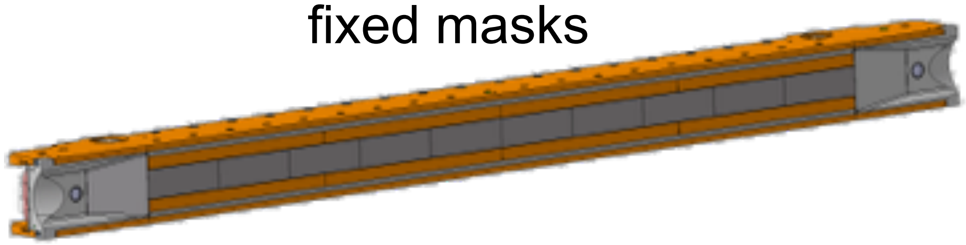
- Operational efficiency is a must for HL-LHC!

  Reliability of high precision devices in high radiation environment; alignment.

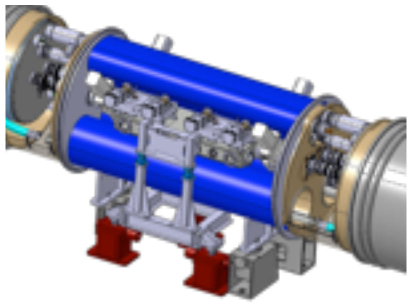
- Upgraded ion performance (6 x $10^{27}cm^{-2}s^{-1}$, i.e. 6 x nominal)

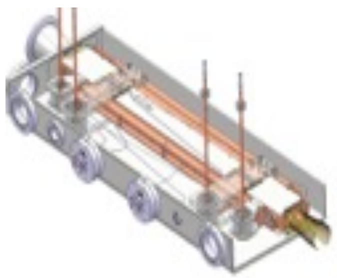
The collimation upgrade baseline

Completely new layouts
Novel materials: TCTs in CuCD
IR1+IR5, <u>per beam</u>:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks

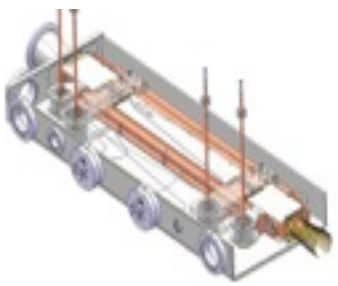


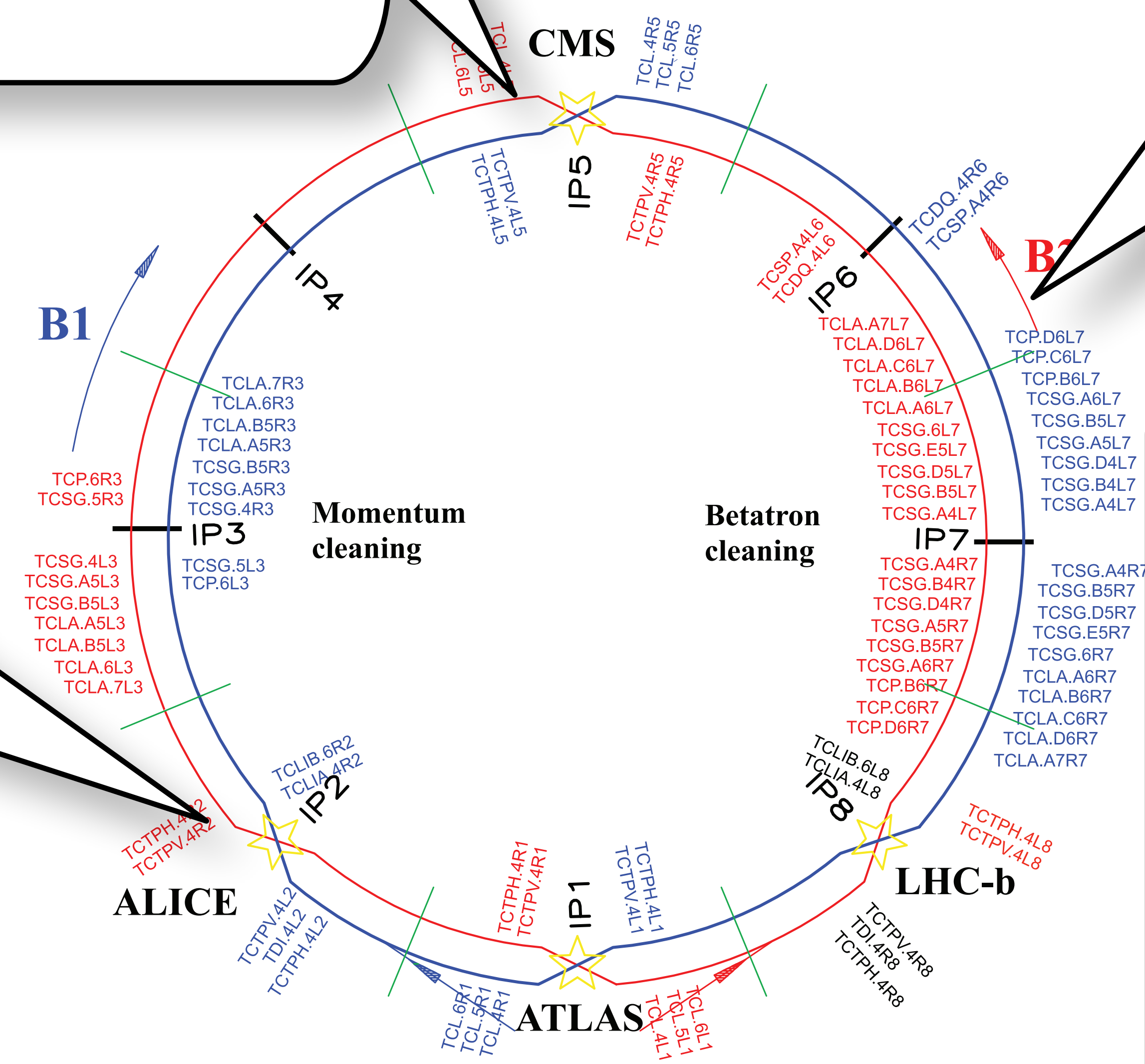
Cleaning: DS coll. + 11T dipoles, 2 units per beam



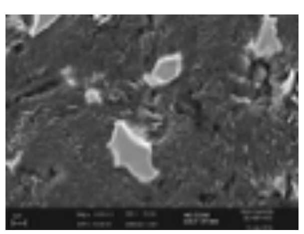


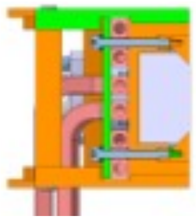
Ion physics debris: DS collimation

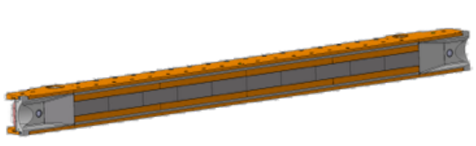




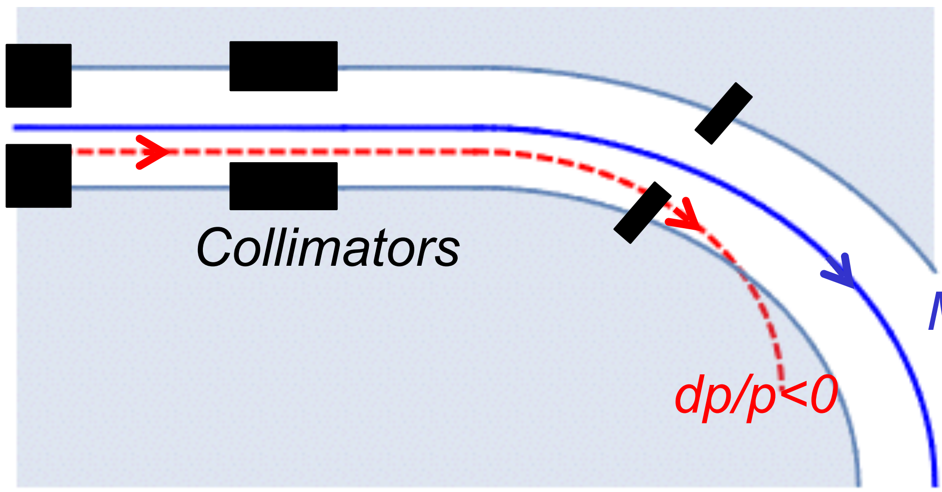
Low-impedance, high robustness secondary collimators: Mo coated MoGr

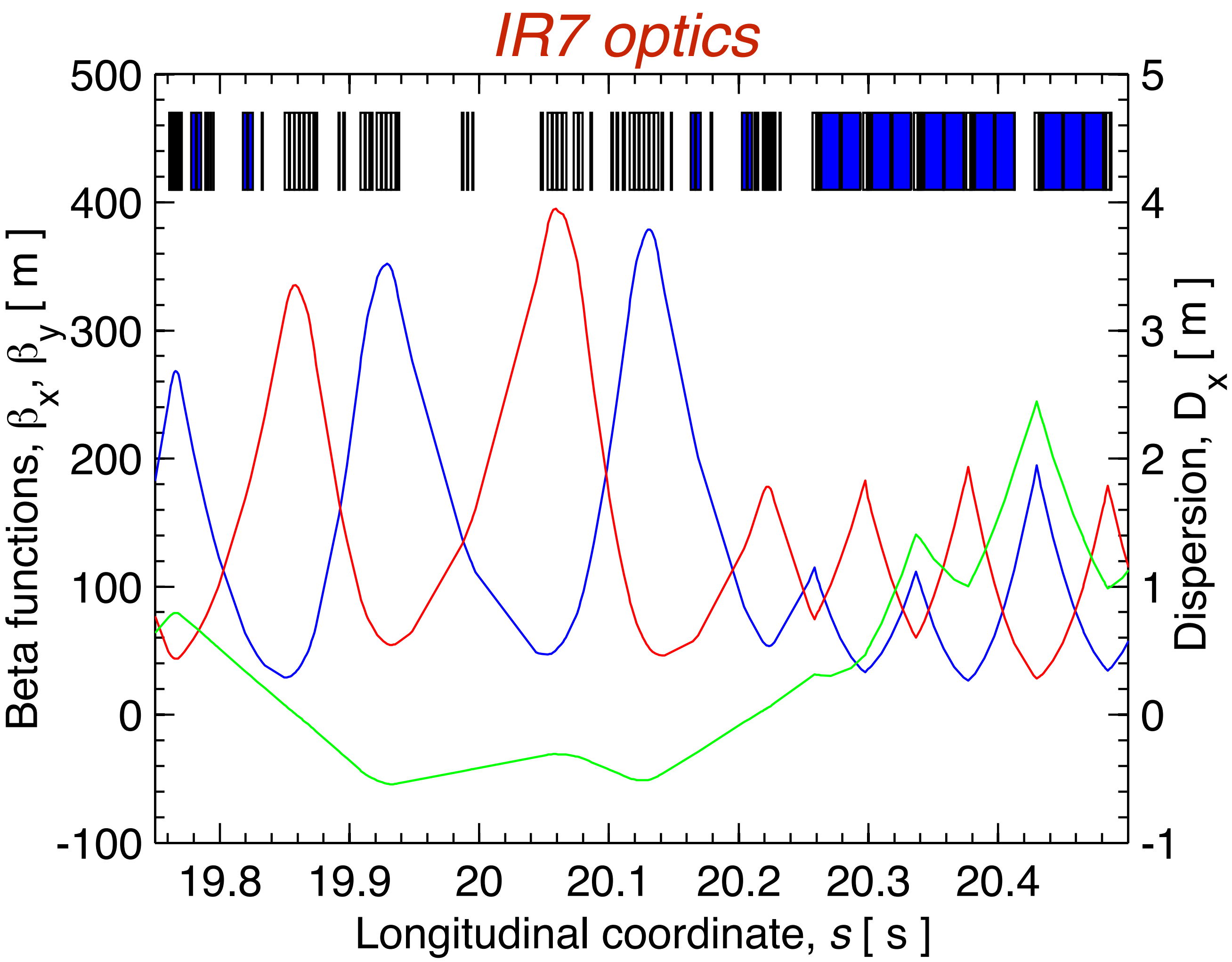






Dispersion suppressor losses





Out-scattered off-energy particles have different bending radius than main beam

Qualitatively similar behaviour in collimation insertion and experiments:

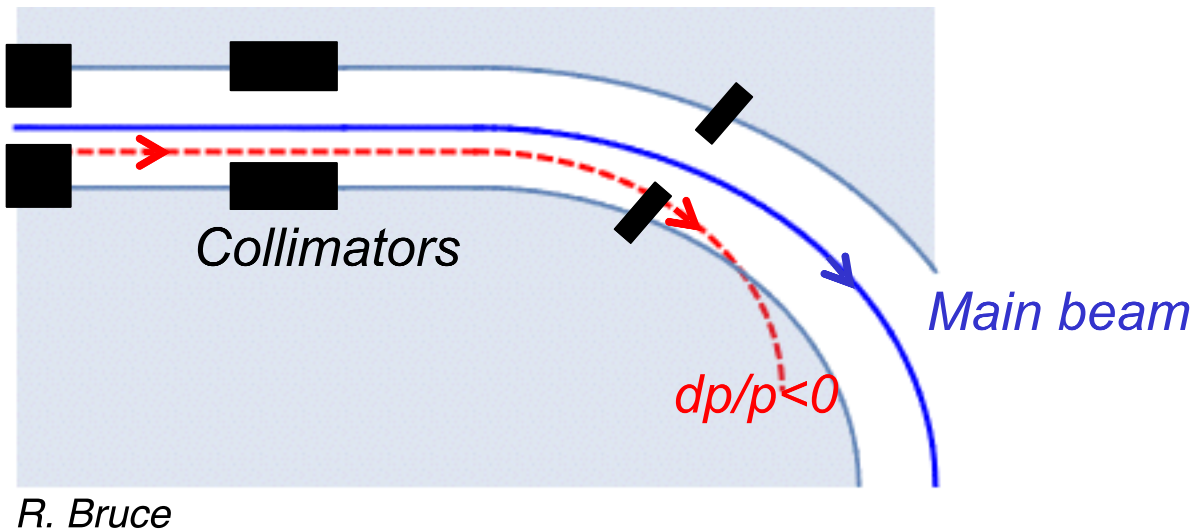
Start deviating significantly only in first bends, downstream of collimators.

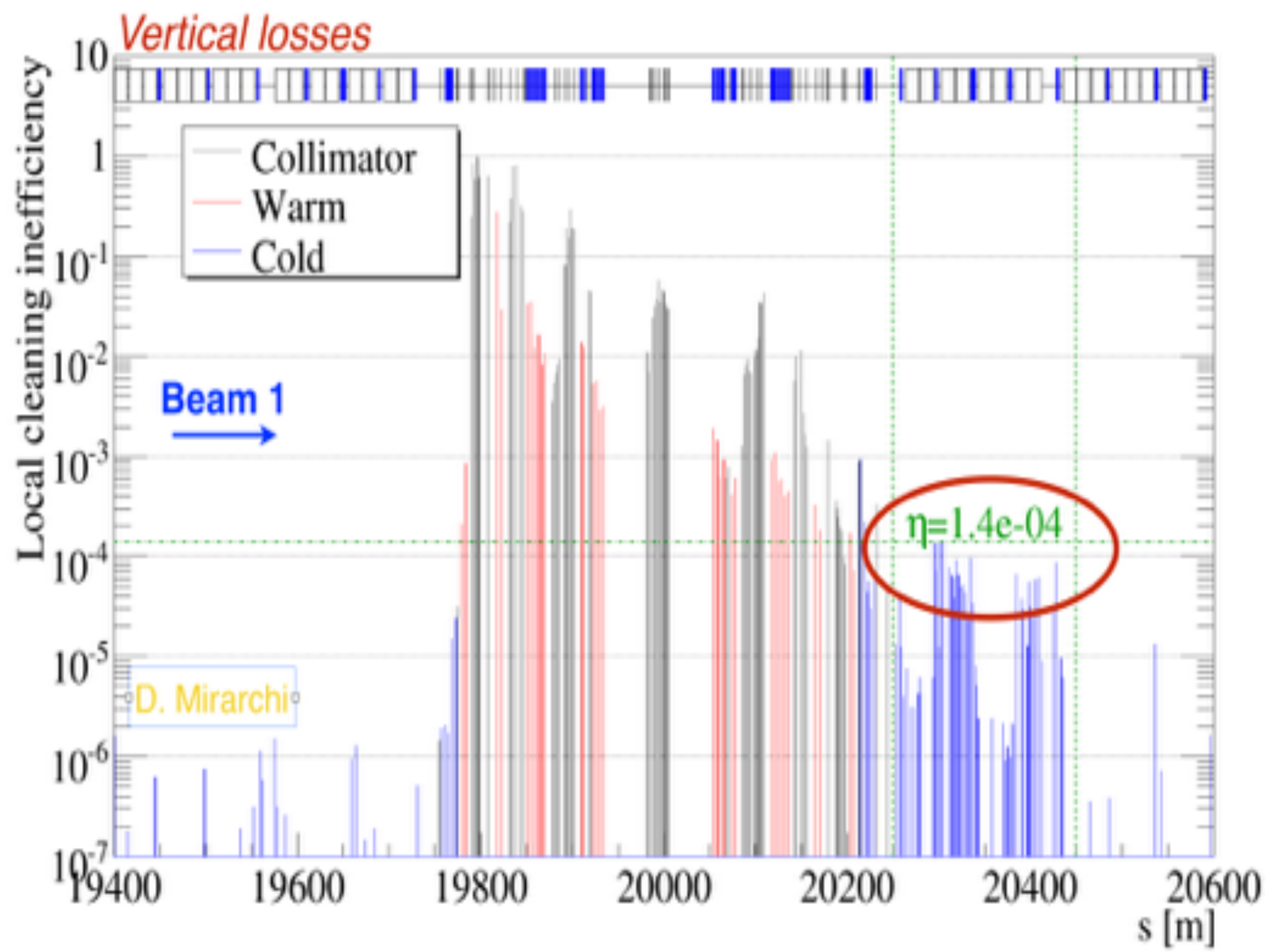
Present multi-stage system is <u>not</u> optimised to catch these dispersive losses.

<u>Idea</u>: Install new collimators (TCLD) in front of exposed magnets, where there is already separation from main beam.

Need two jaws: ion beams; better shower absorption; more precise alignment.

Dispersion suppressor losses





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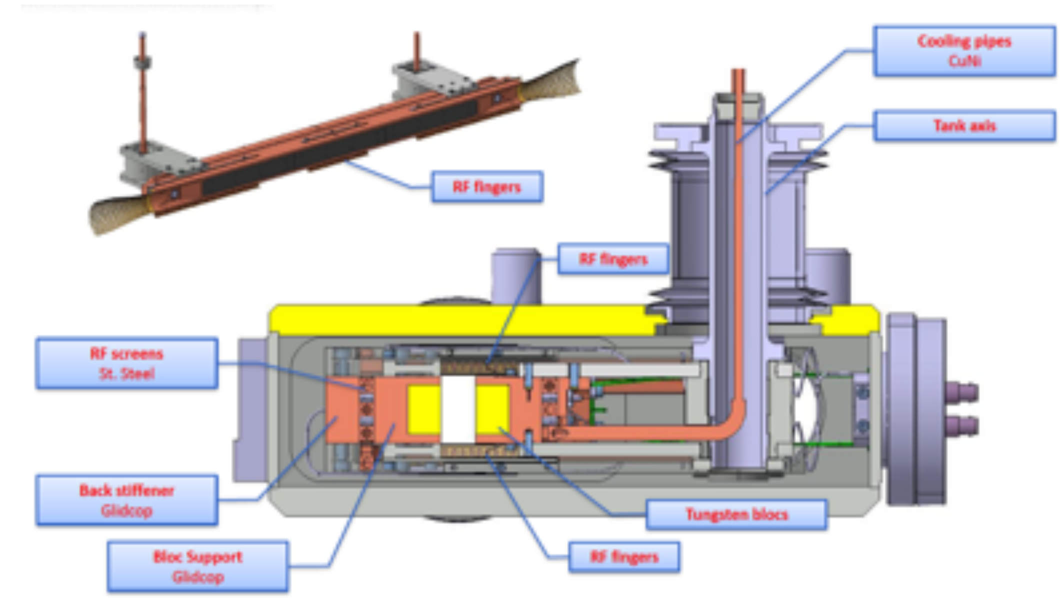
TCLD design and status

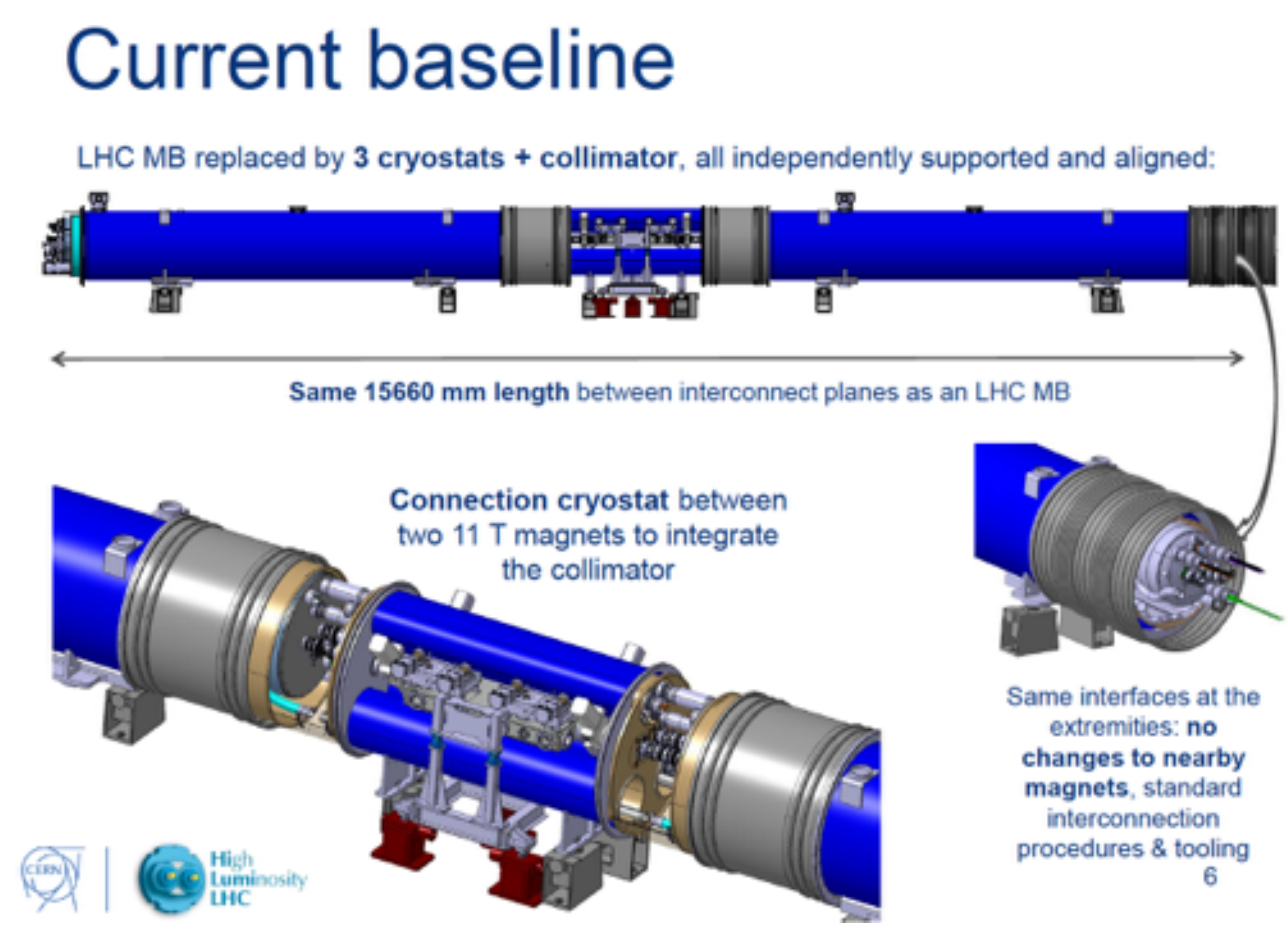
60cm baseline agreed.

Final design for integration between 11T dipoles: ok

Preparing production of 4+1 collimators for LS2

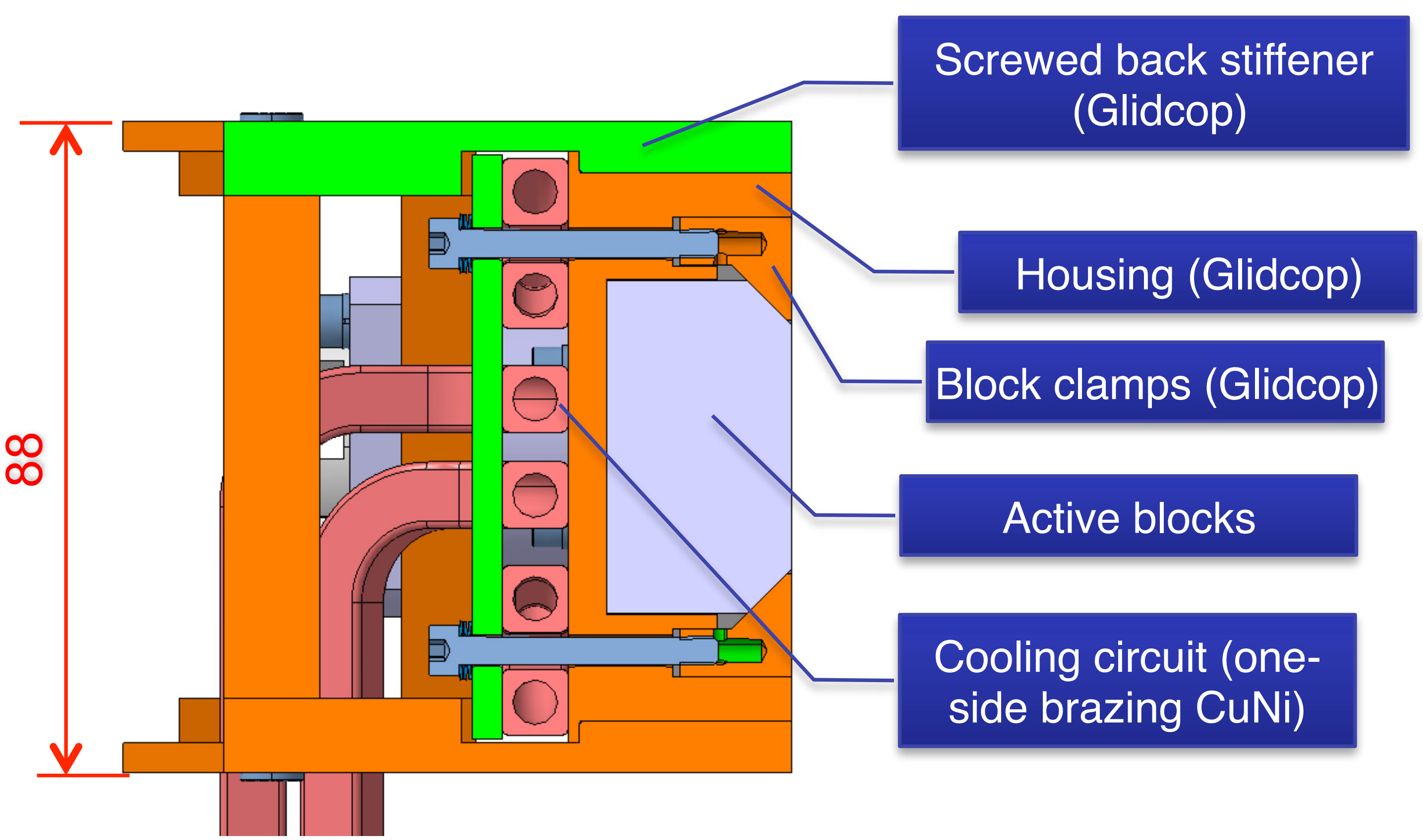
Two variants: without (IR2) and with (IR7) 11T dipoles.

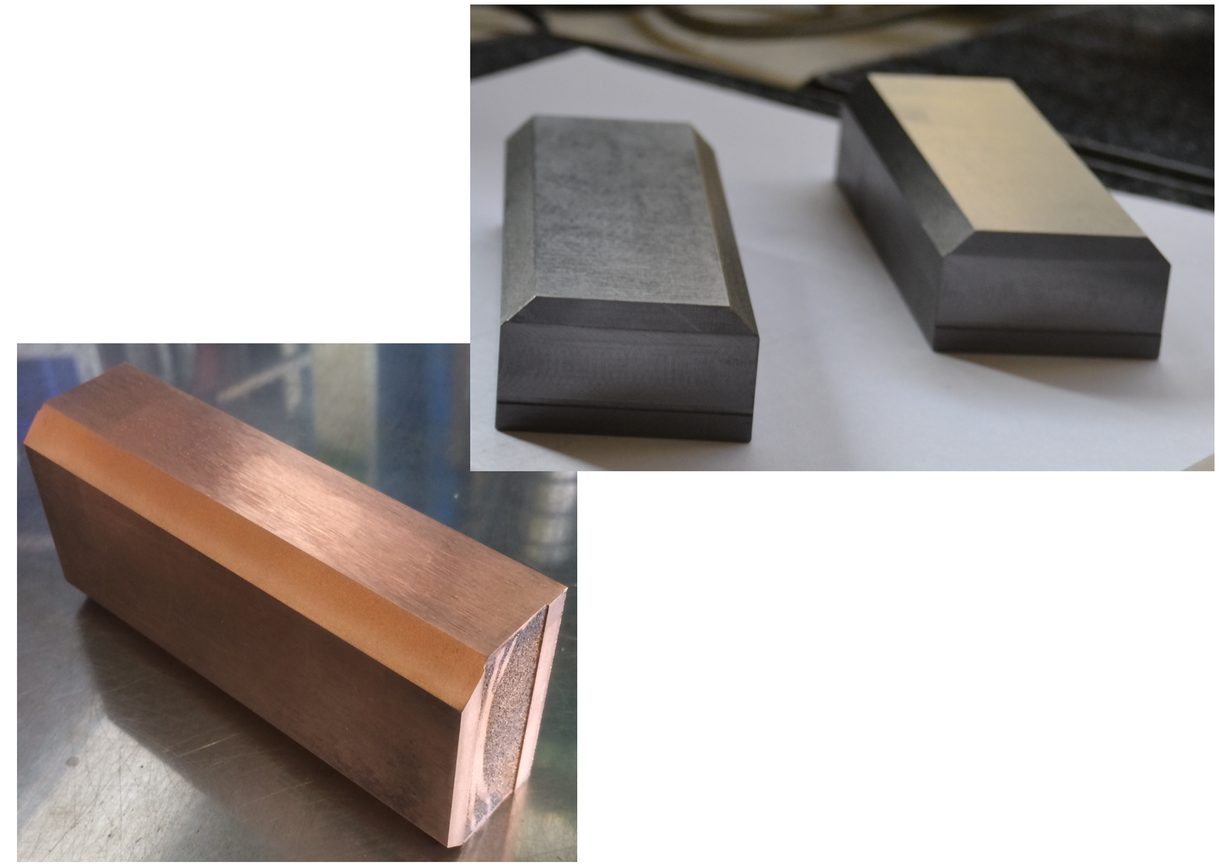


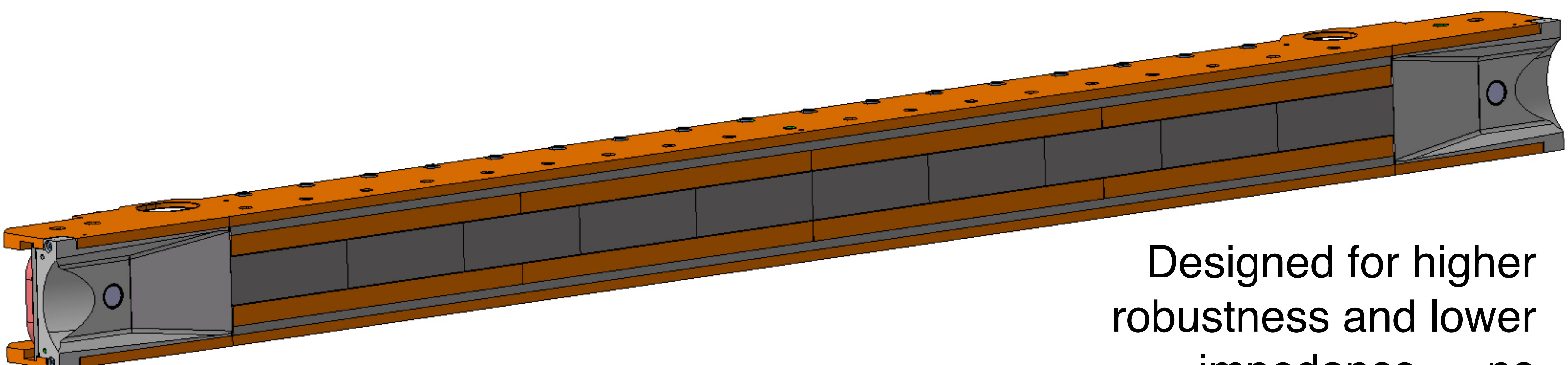


Courtesy Delio Duarte and Luca Gentini

New materials







Designed for higher robustness and lower impedance — no details here.

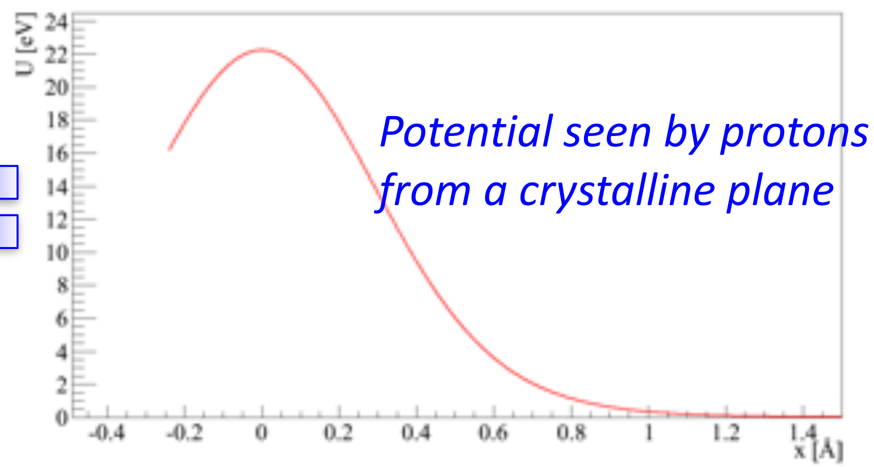
Crystal collimation — i

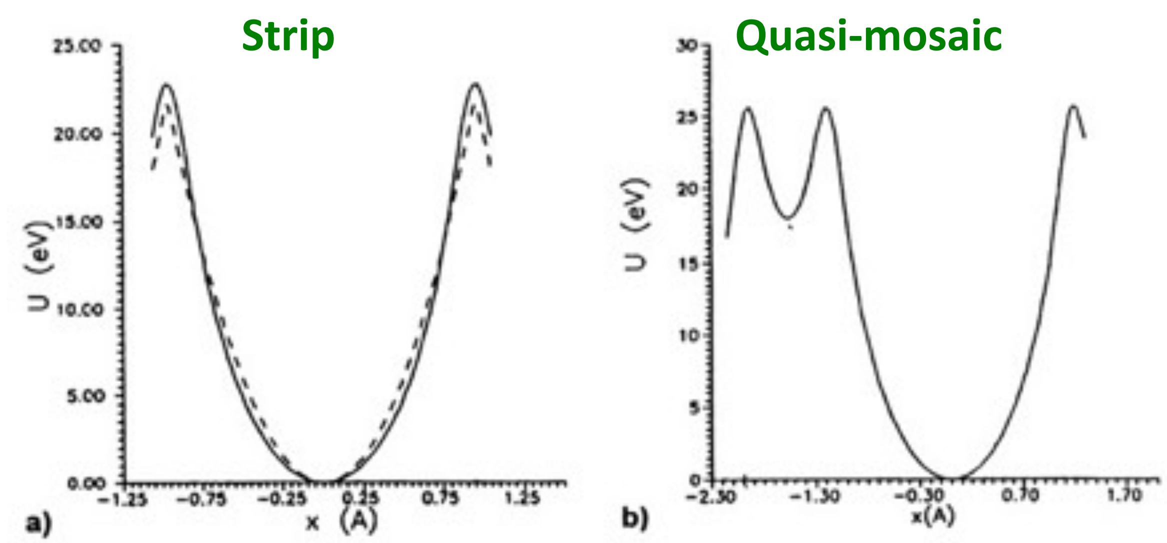
Potential between a **particle** and an **atom** described by the **Thomas-Fermi model:**

$$V(r) = \frac{Z_i Z e^2}{r}\Phi(\frac{r}{a_{\text{TF}}})$$

Continuous approximation:

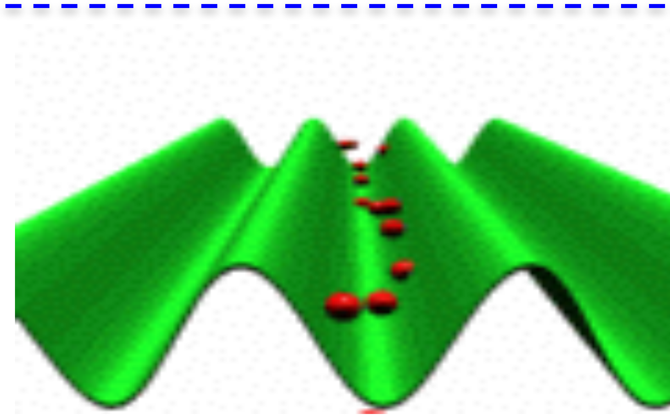
$$U_p(x) = Nd \iint_{-\infty}^{+\infty} V(x,y,z)dydz$$





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

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



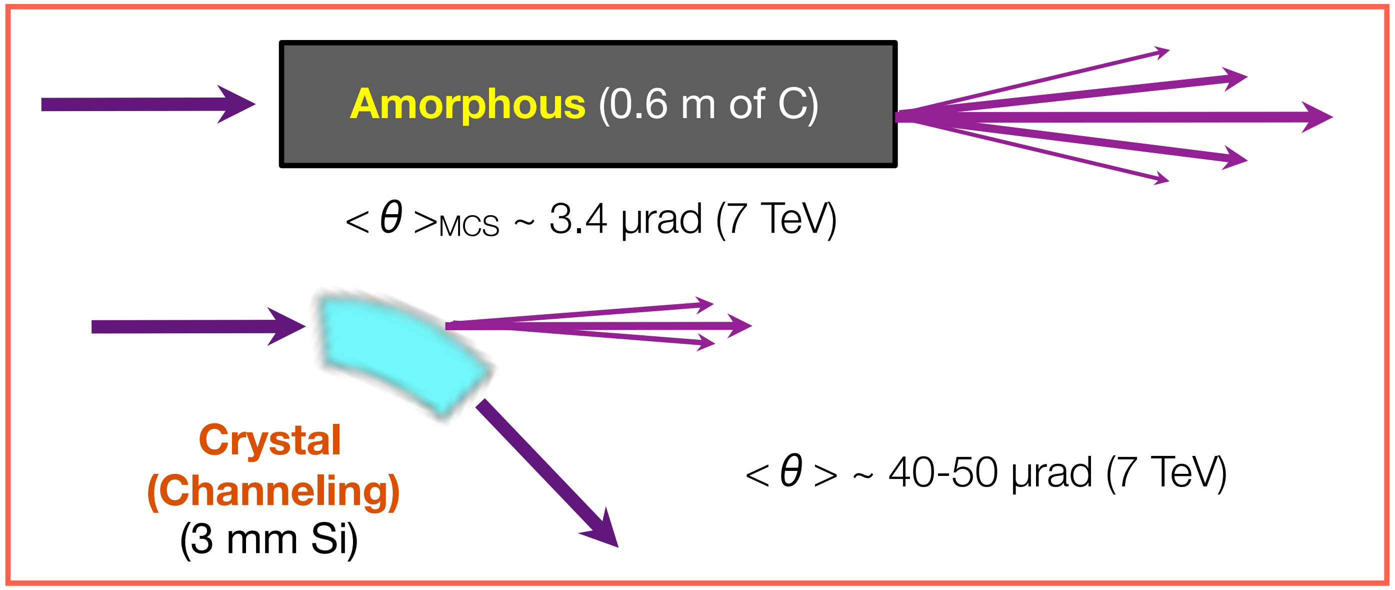
Forced to oscillate in a relatively empty space

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

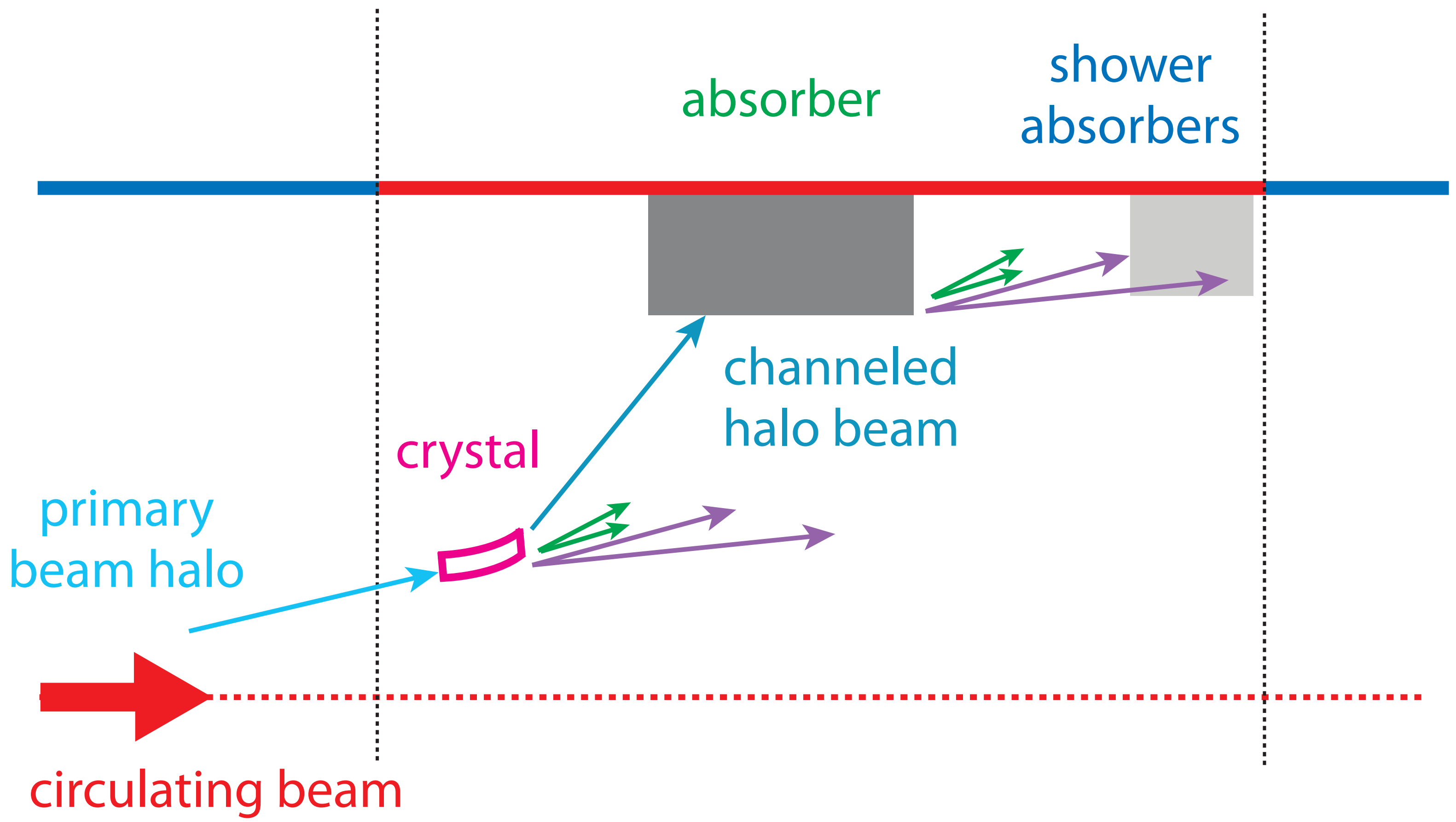
***Typical values** at energies of our interest:*

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

Crystal collimation — ii

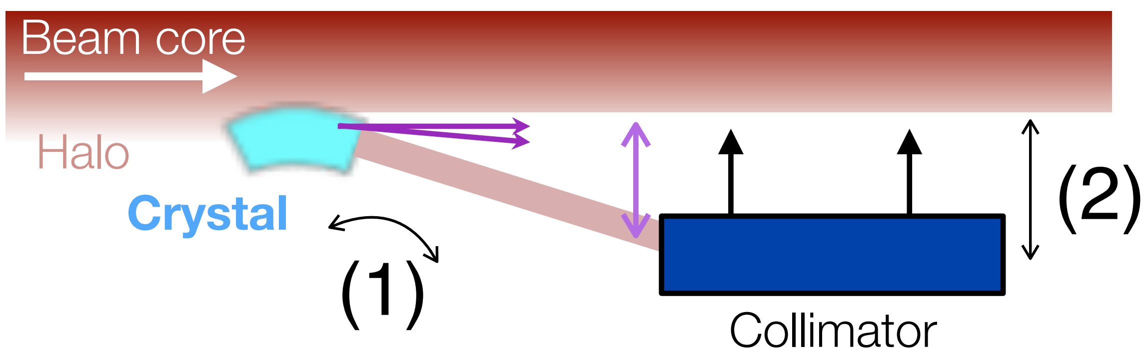


Bent crystals allow bending high-energy particles trapped between lattice planes.

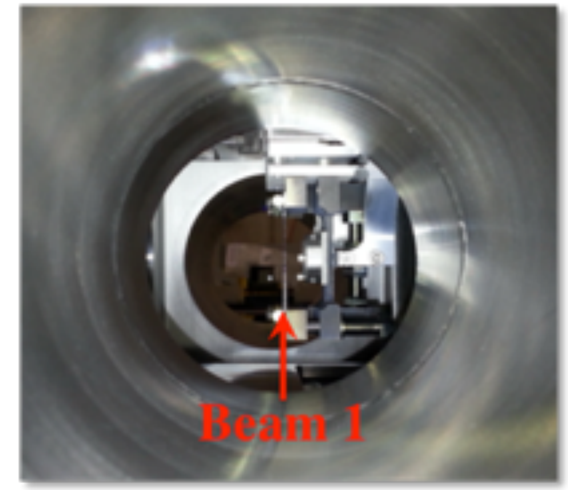


Crystal collimation — iii

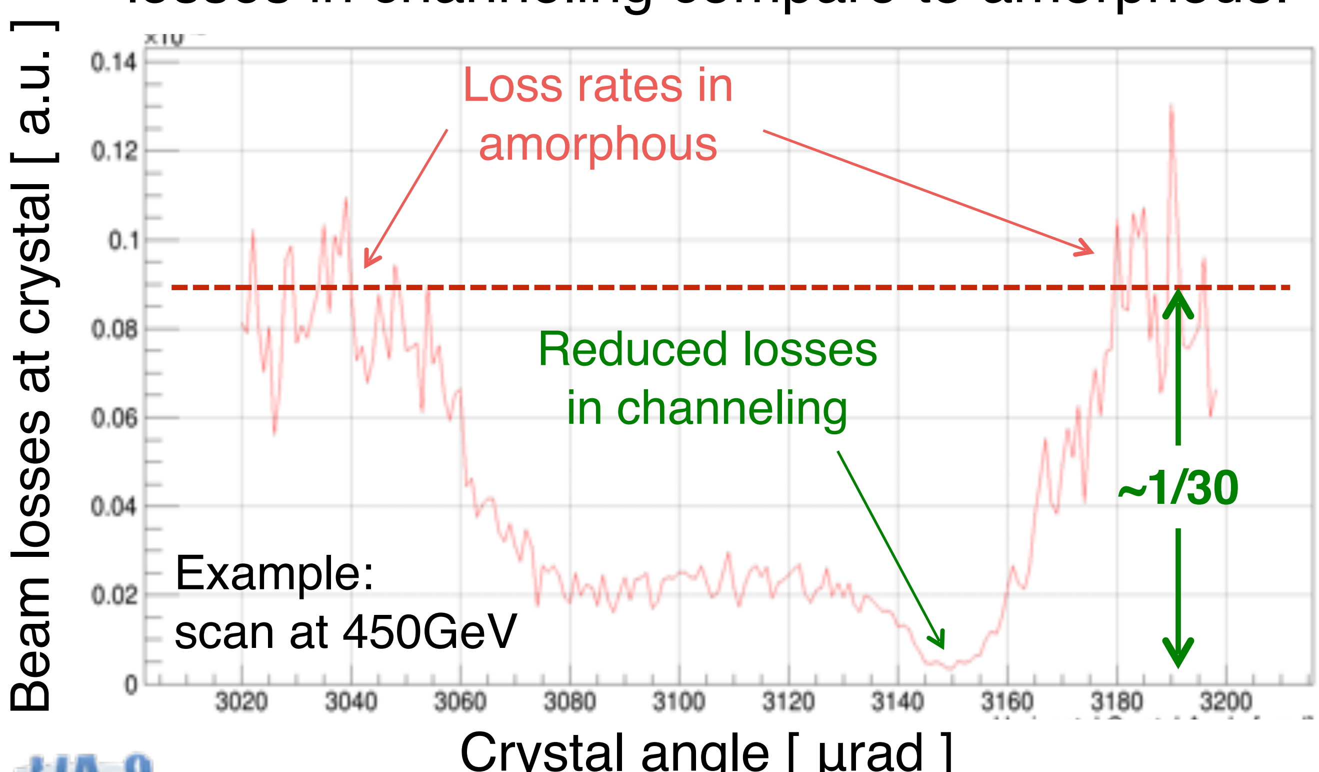
Concept of crystal-based halo collimation



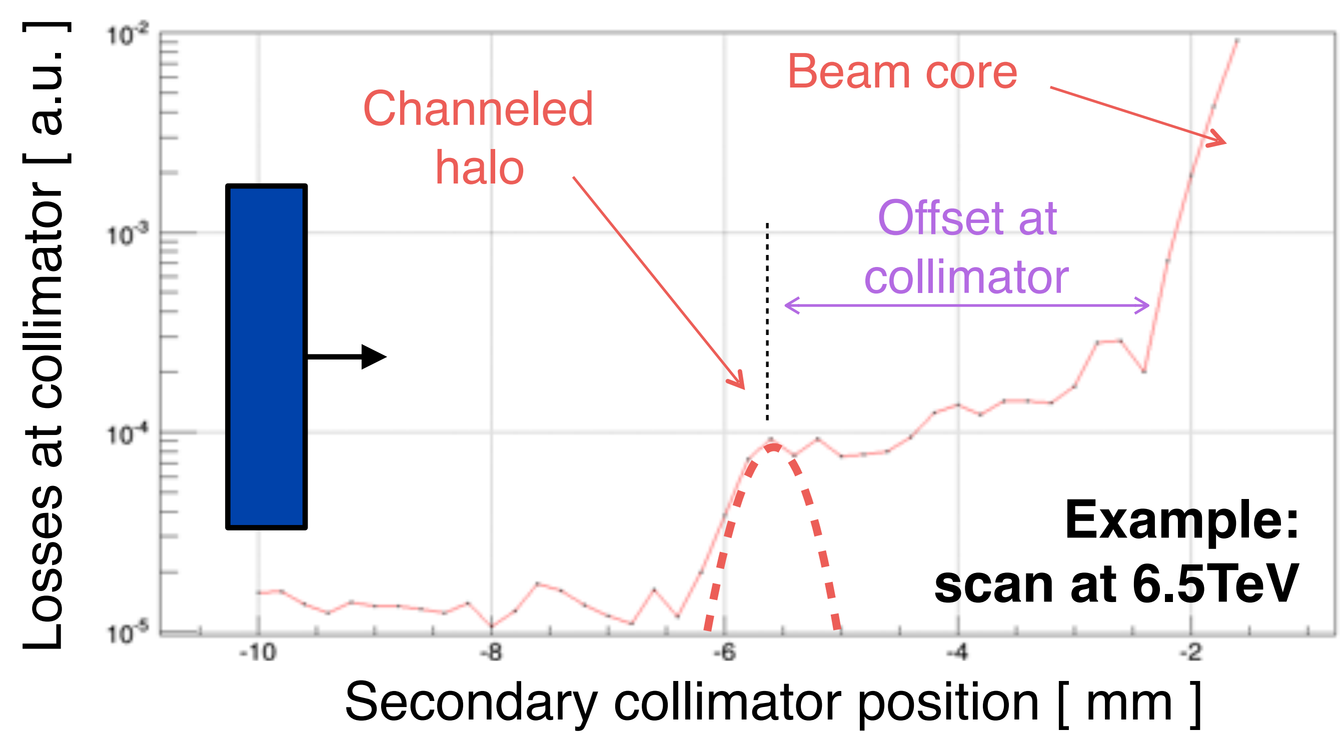
Test stand for crystal collimation studies in IR7
Goniometer with micro-rad control (EN/STI)



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

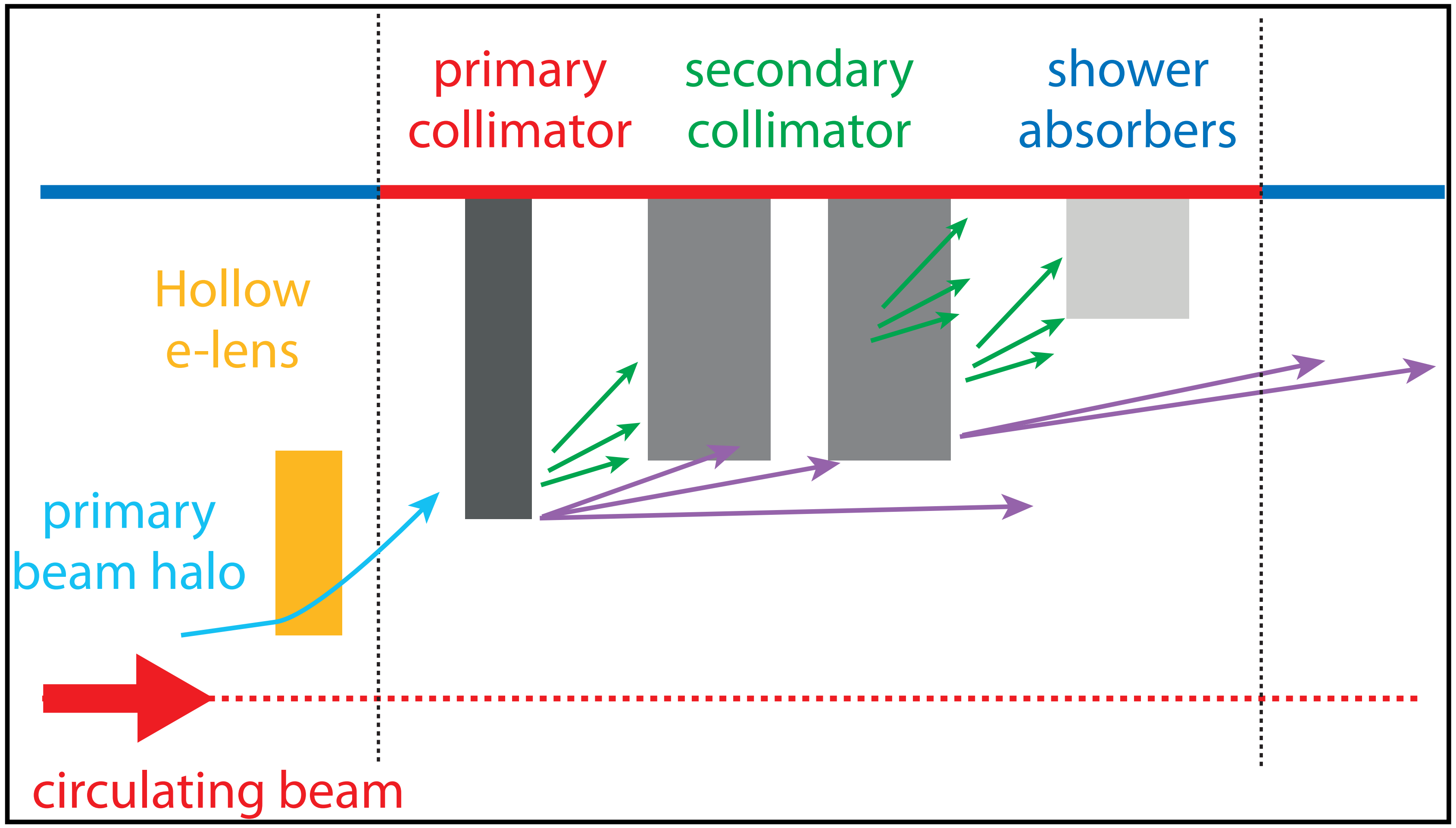


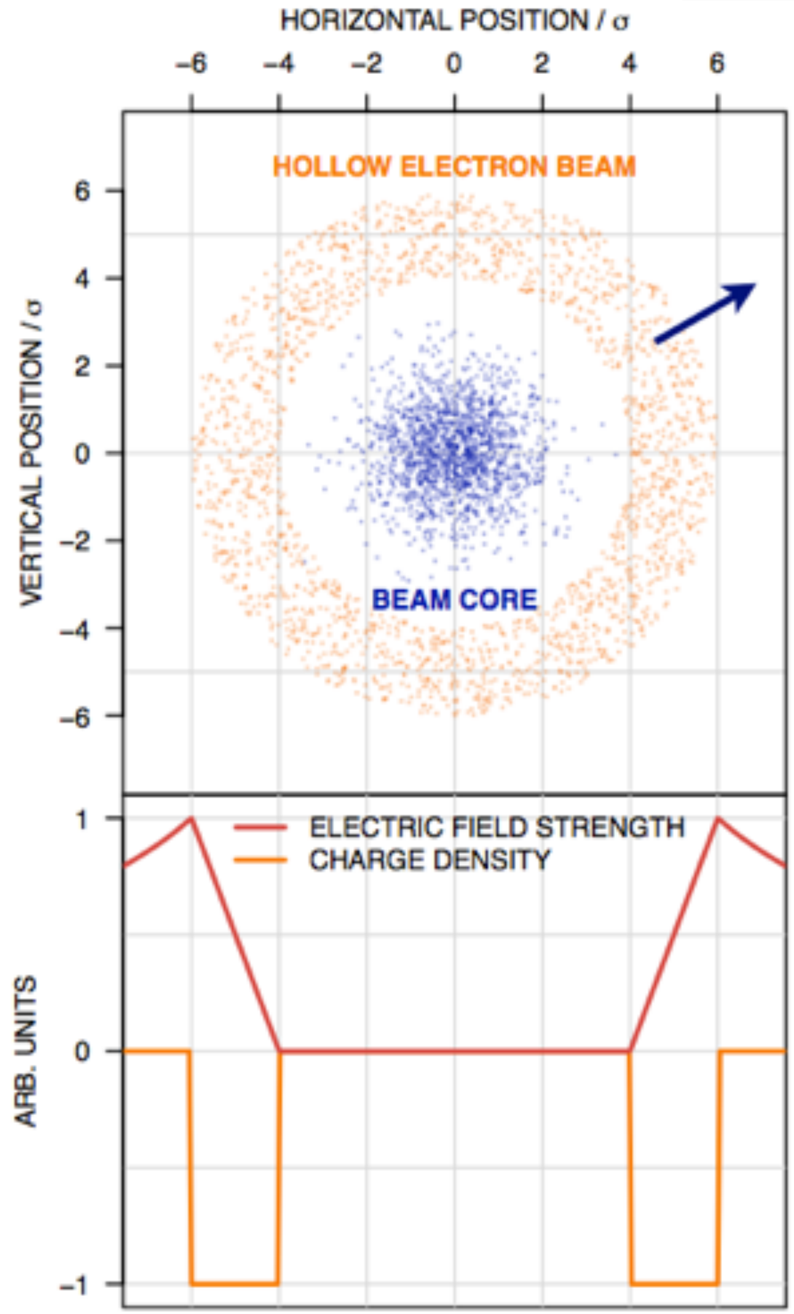
(2) **Linear collimator scan**: measures the profile of the channeled halo.



Crystal channeling observed for the first time at 6.5 TeV!

Hollow electron lenses — i





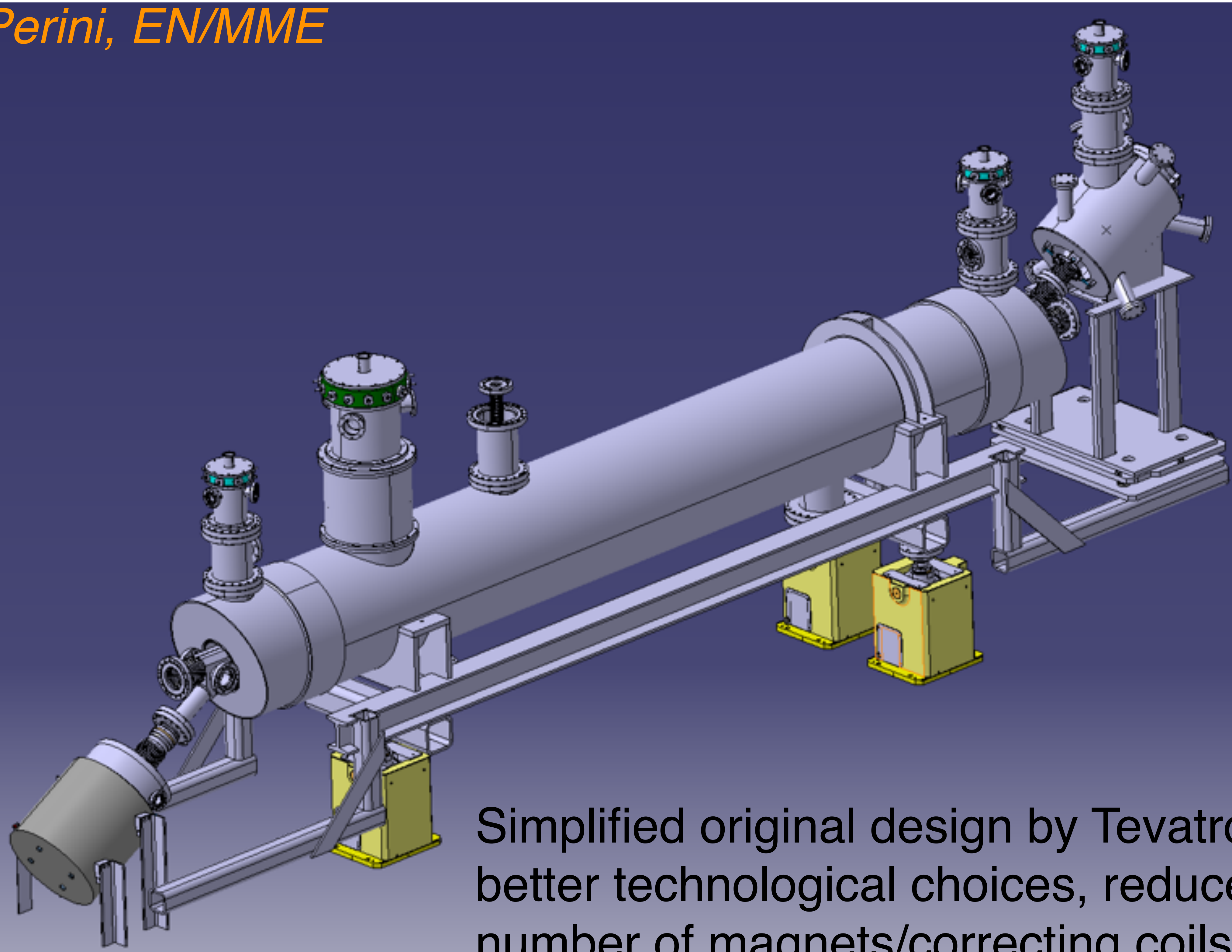
"Non-material" scraper — adds scraping functionality but particles are disposed of by the present collimation system.

Can be installed in other points than IR7, because kicks per turn are small.

Require overlap of e- and proton beam over ~3 meters.

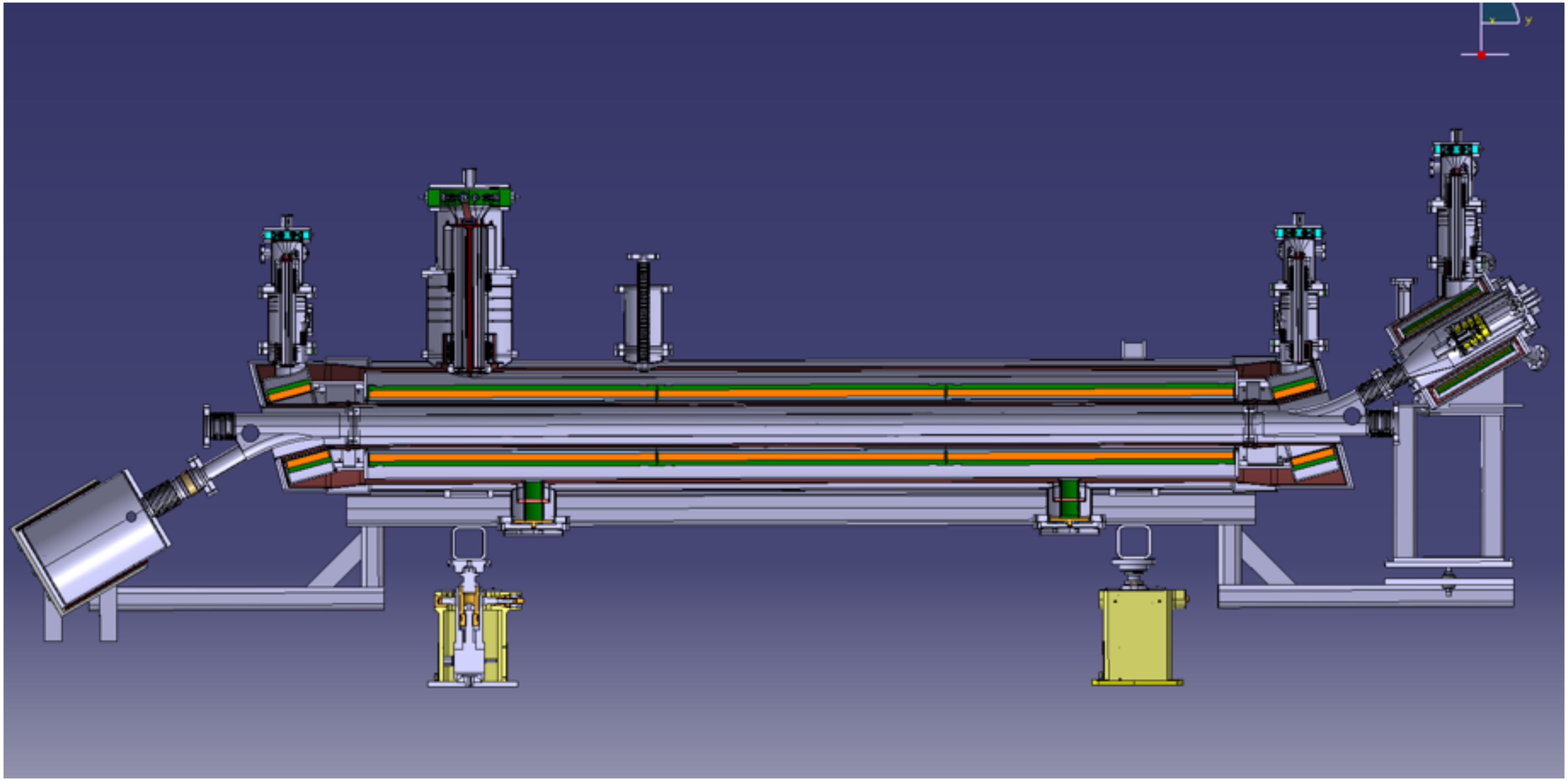
Hollow electron lenses — ii

D. Perini, EN/MME



Simplified original design by Tevatron: better technological choices, reduced number of magnets/correcting coils.

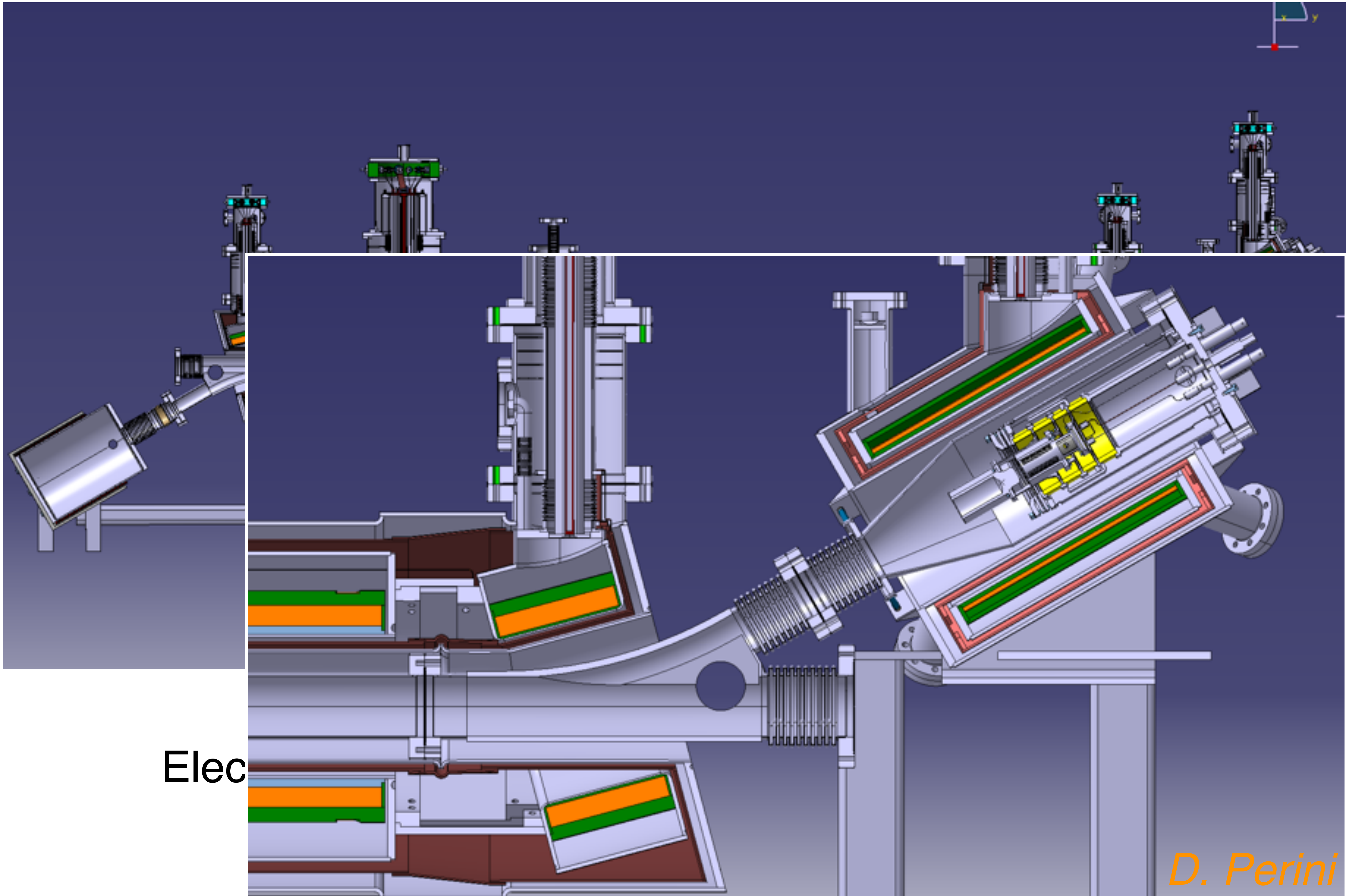
Hollow electron lenses — iii



Electron beam generation and transport: BE/BI

D. Perini

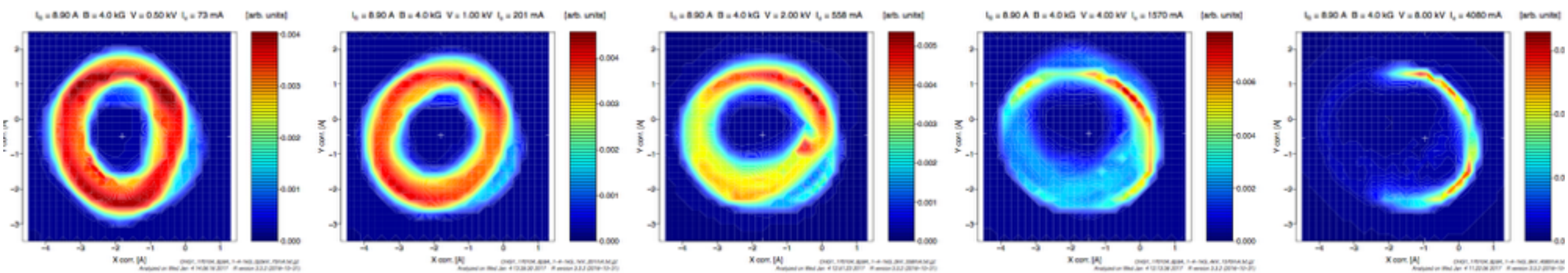
Hollow electron lenses — iii



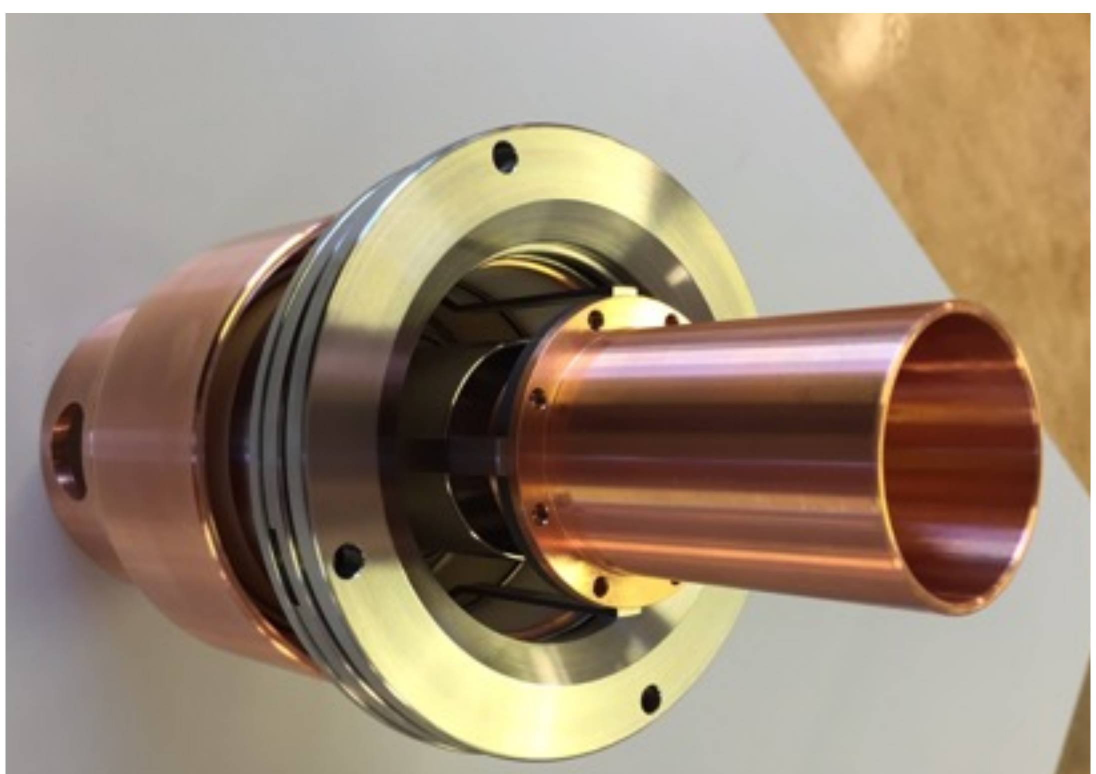
Elec

Hollow electron lenses — iv

Electron beam tests ongoing at Fermilab with a CERN-built hollow gun



0.5 kV, 73 mA | 1 kV, 201 mA | 2 kV, 558 mA | 4 kV, 1.57 A | 8 kV, 4.08 A



Hopefully inserted as part of the LHC upgrade baseline in 2018!

Conclusions

- Reviewed aspects of machine protection and beam halo collimation for the Large Hadron Collider
- They are key assets for present and future super-colliders that must be accounted for early in the accelerator design.
- The LHC collimation system has grown to a large complexity that is required to achieved unprecedented cleaning goals.
- The operational experience proves that the collimation system works as required for the LHC operation.
- On the other hand, further improvements are mandatory for the new challenges of the High-Luminosity LHC!
- Various advanced designs are part of the HL-LHC baseline.
- Exciting topics like crystal and hollow e-lens collimation are being tested actively for future implementations.