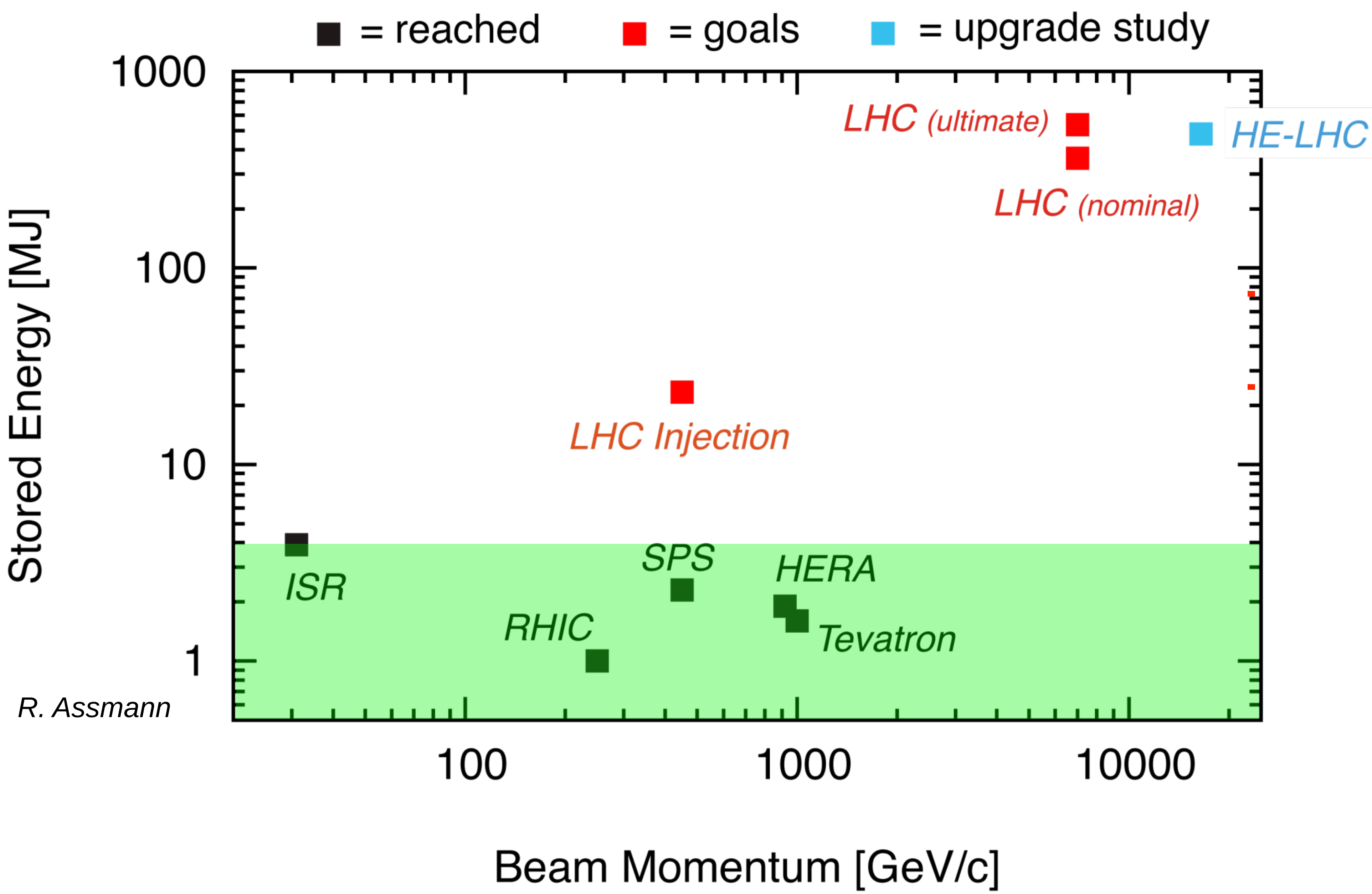
LHC Collimation Review 2011
CERN
Geneva, 14th-15th June 2011

Introduction to LHC Collimation

S. Redaelli for the LHC Collimation Team
CERN, Geneva, Switzerland

LHC stored energy challenge



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<u>Today:</u> **75 MJ per beam (L = 1.2 x 10^{33} cm^{-2} s^{-1})!**

No beam-induced quenches with circulating beams so far.

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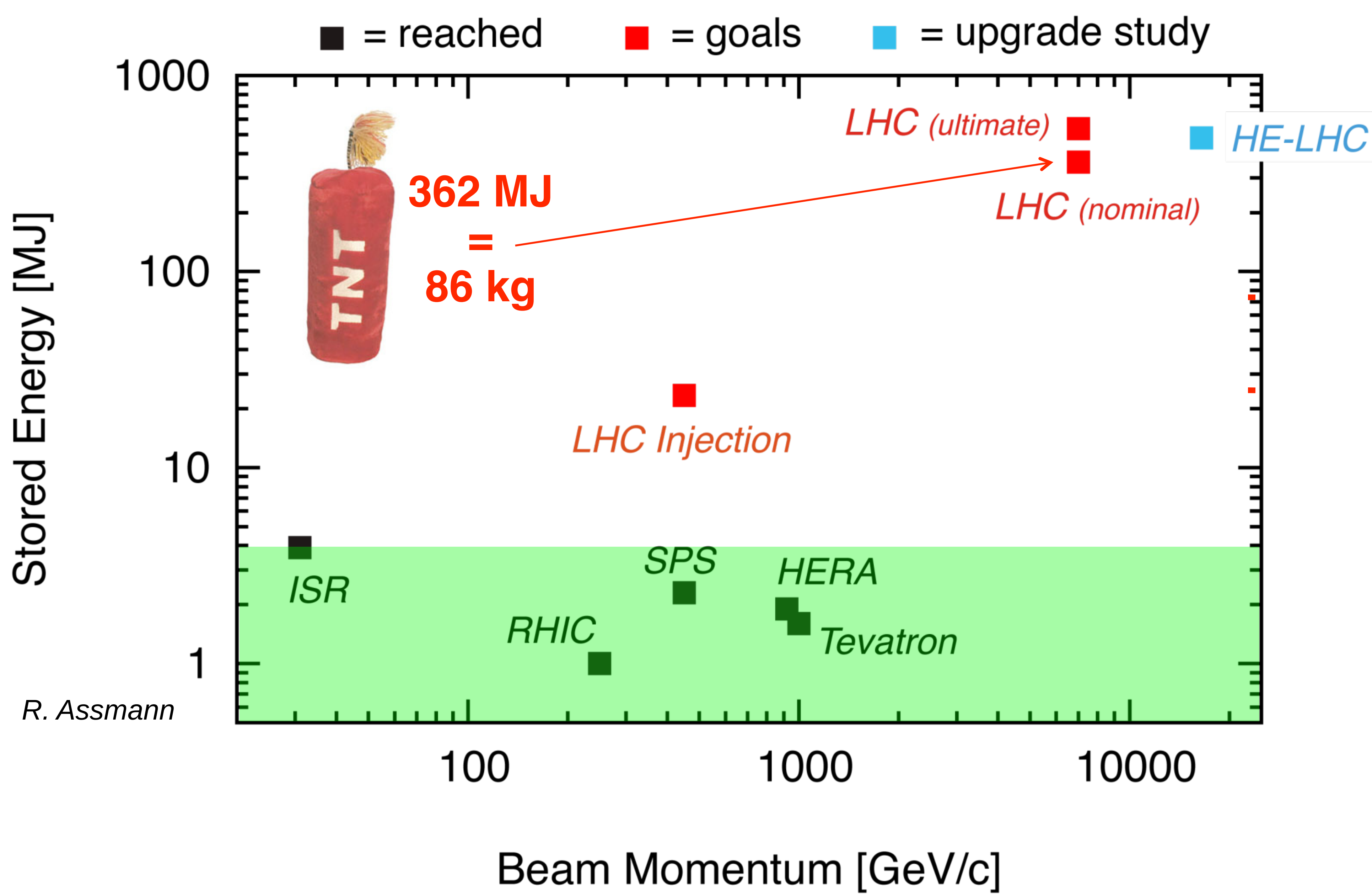

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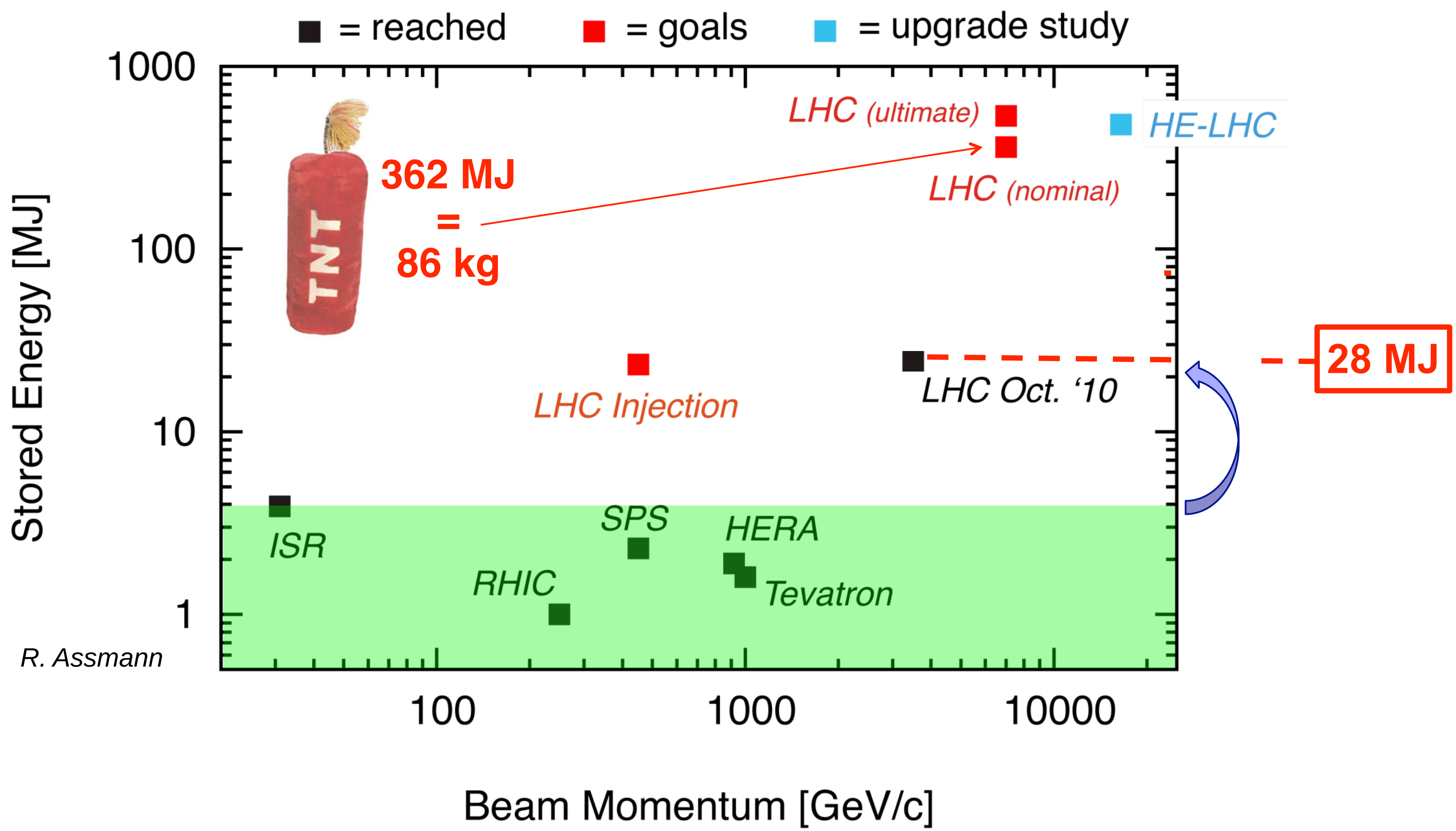

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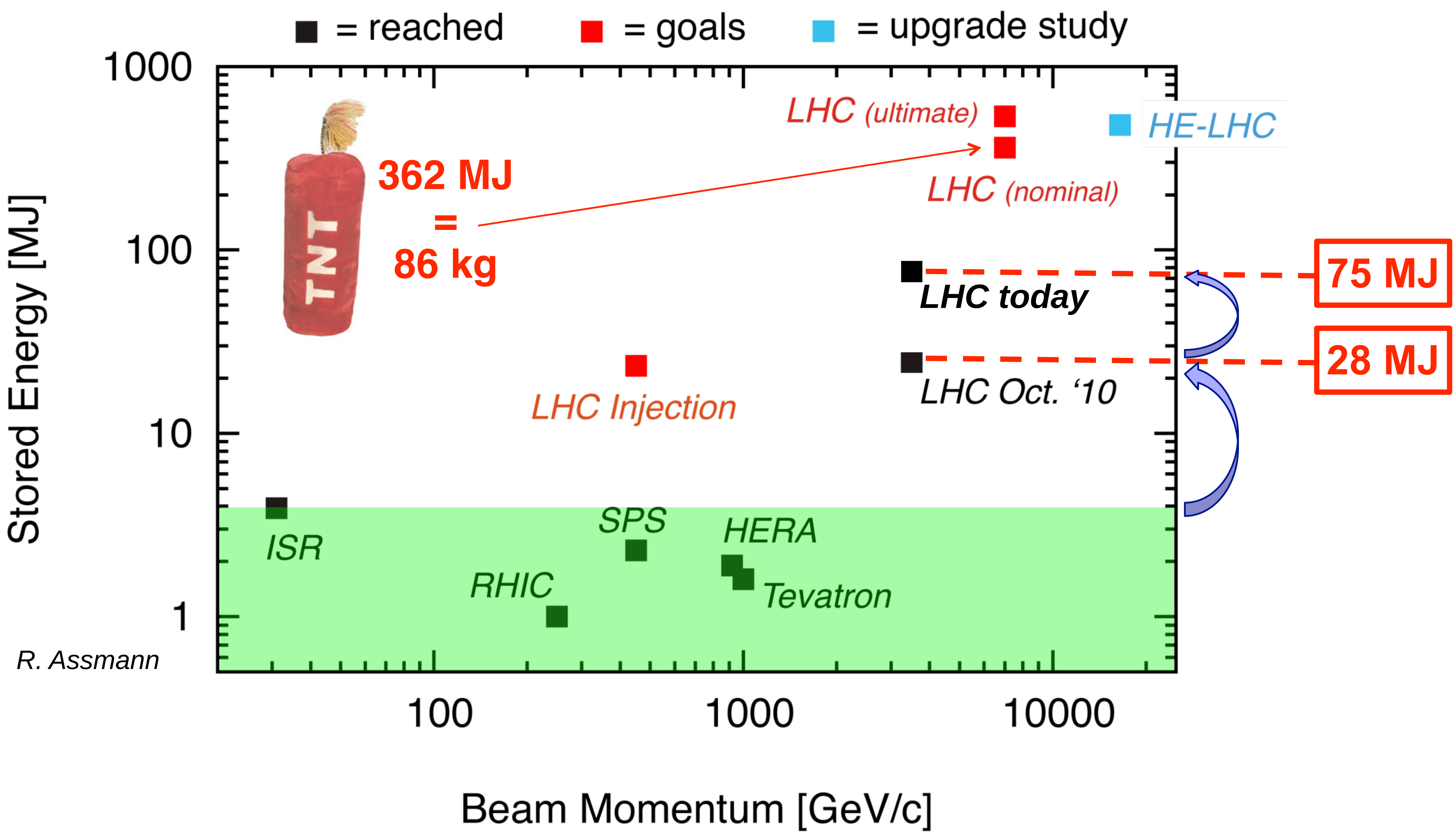

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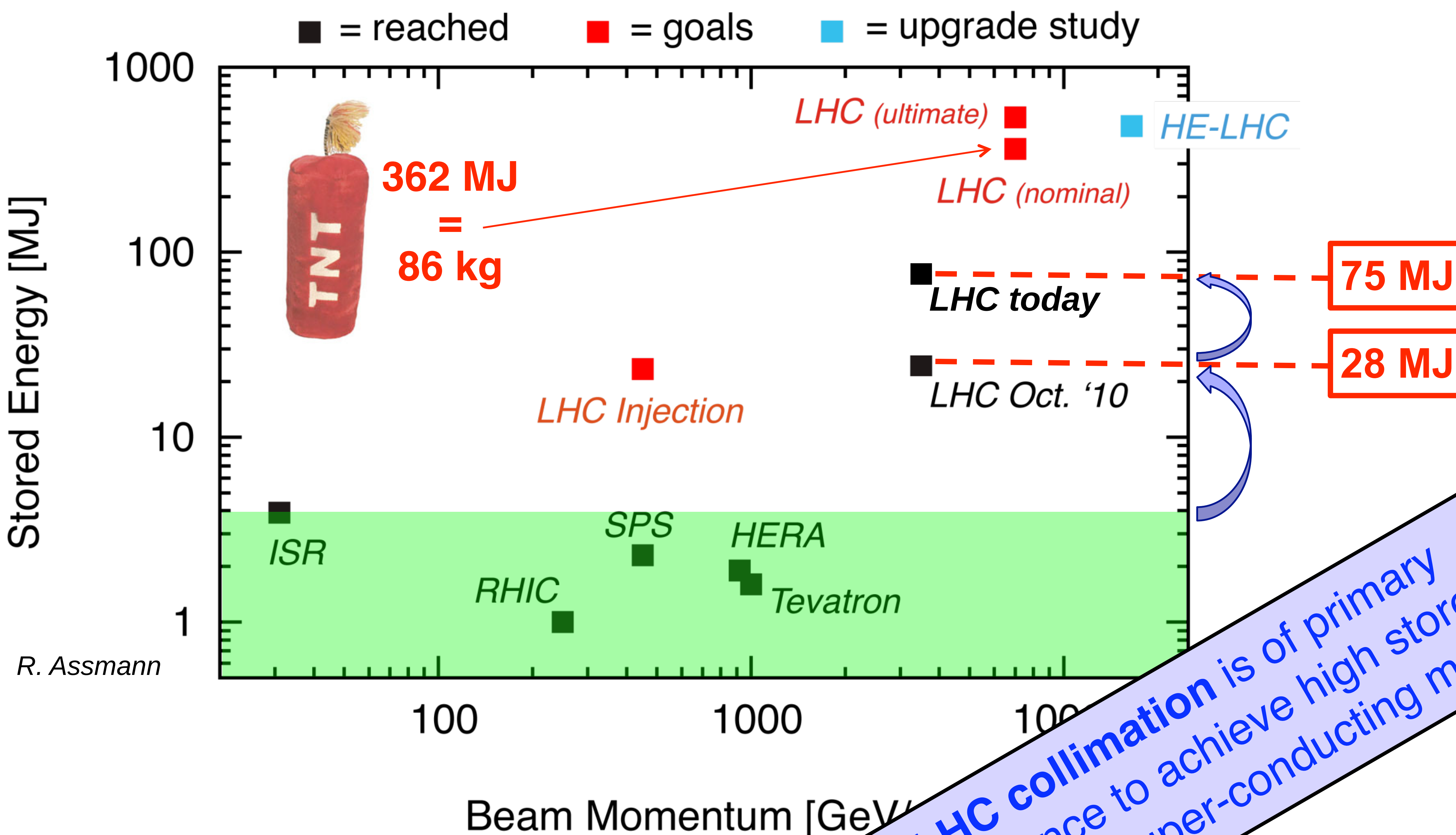

LHC collimation is of primary importance to achieve high stored energies in a super-conducting machine

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Outline

- Introduction
- Design, layouts and settings
- Collimation cleaning
- Operational experience
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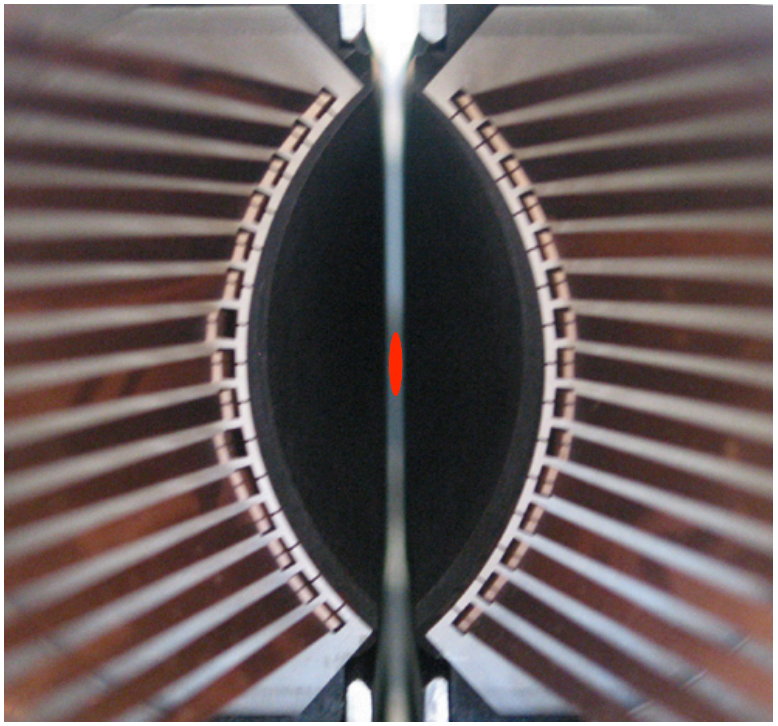
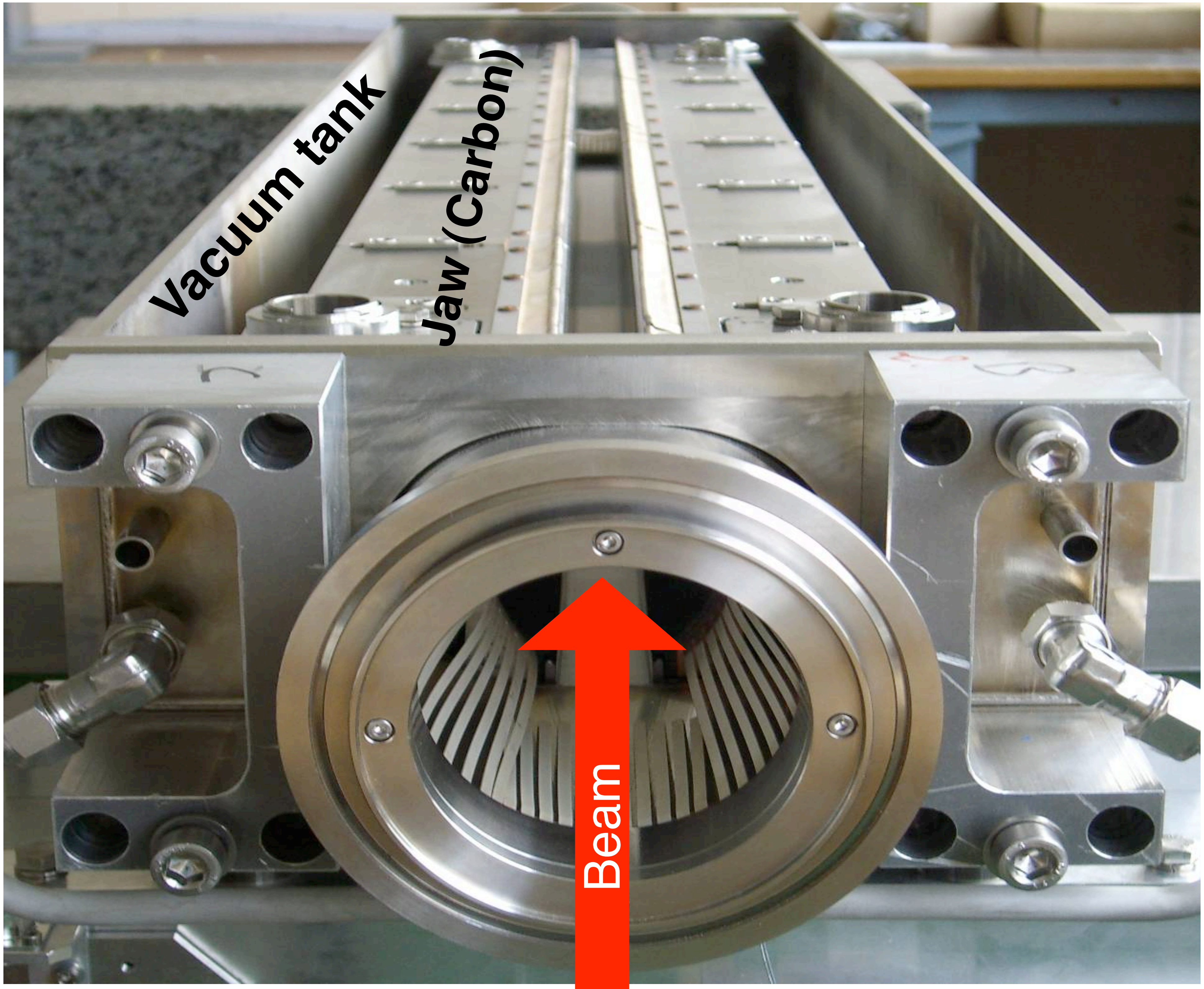
The Phase I LHC collimator

What the beam sees!



~ 2 mm



Two-jaw design:
Beam cannot "drift away"!

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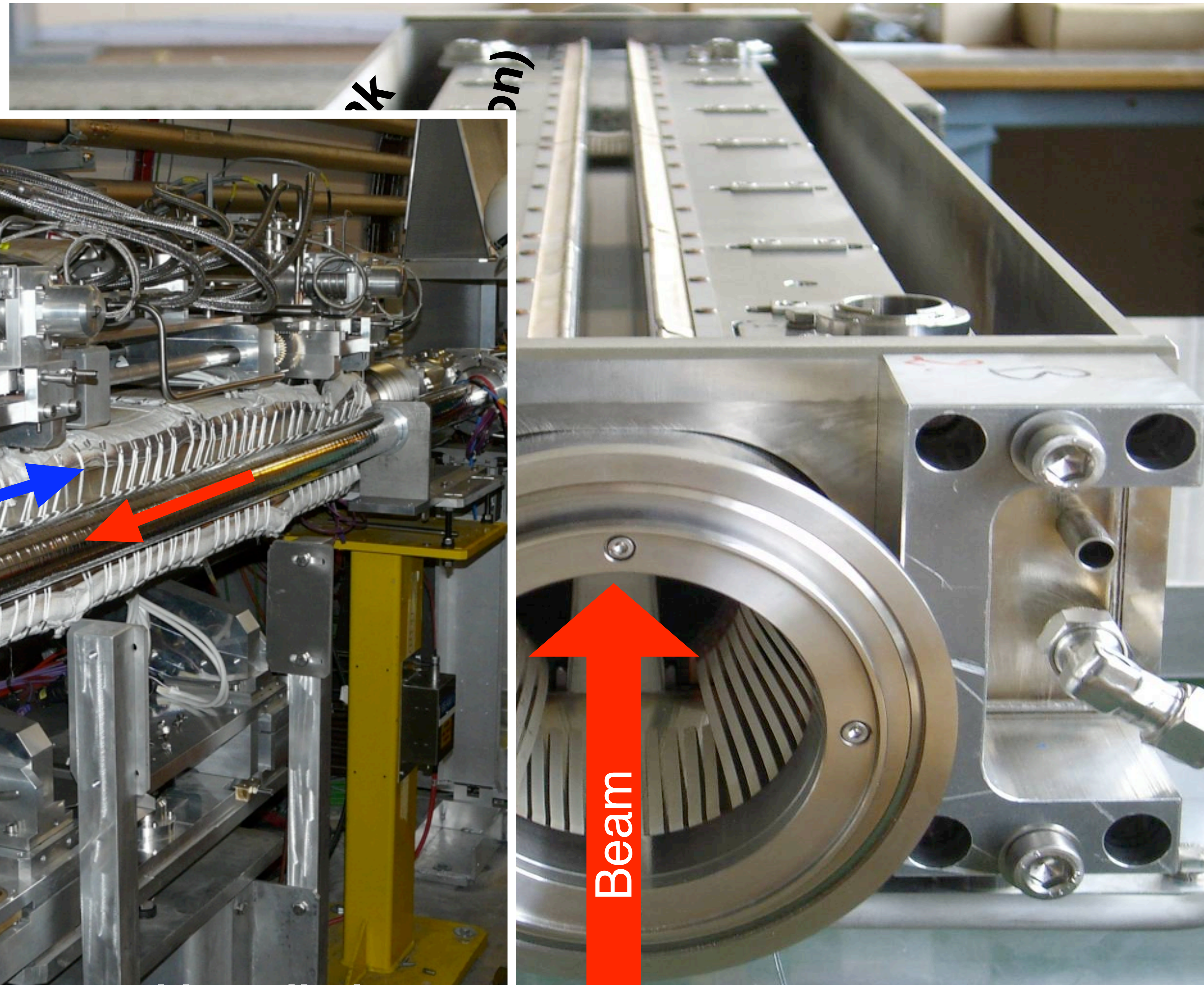

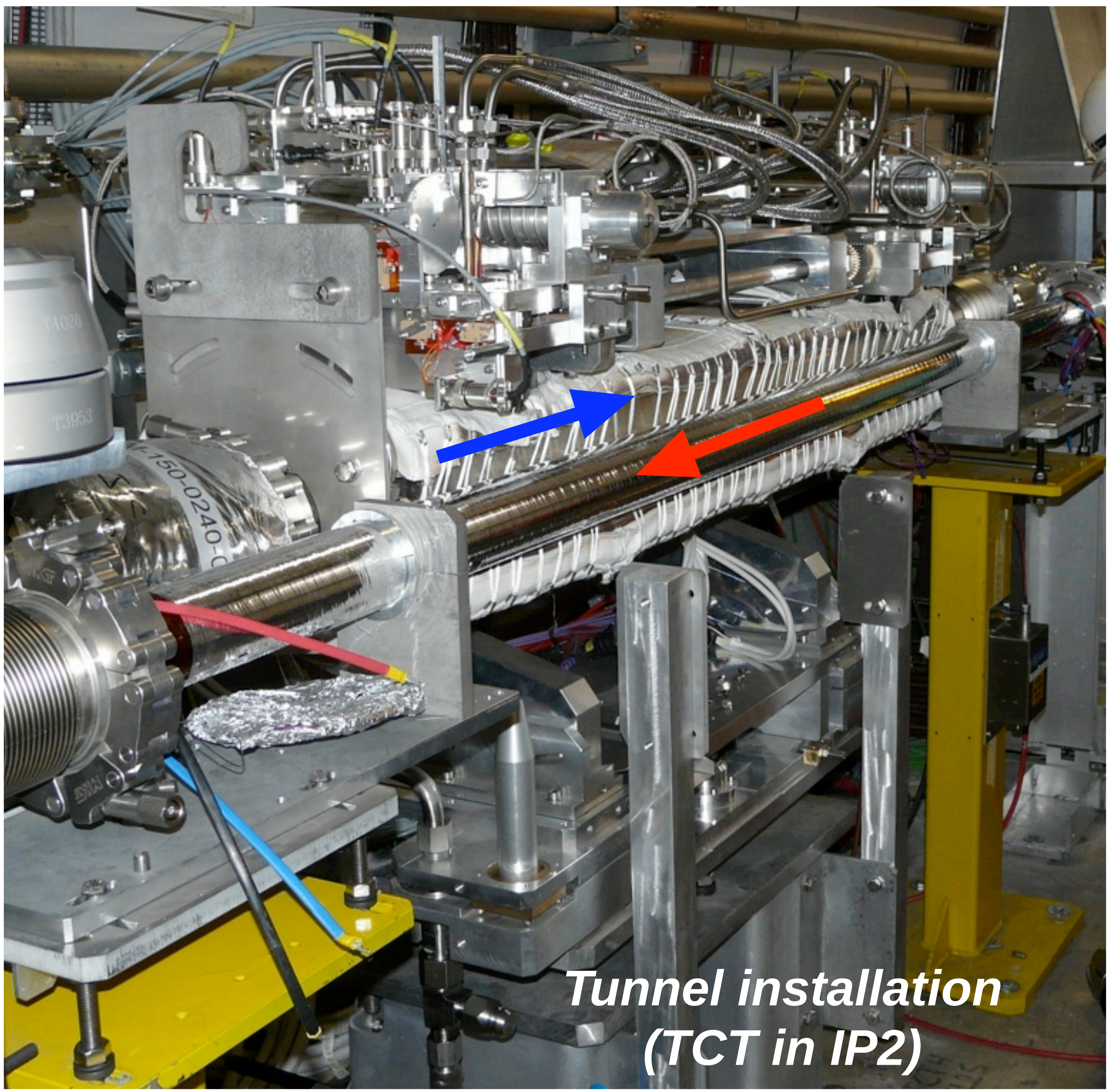

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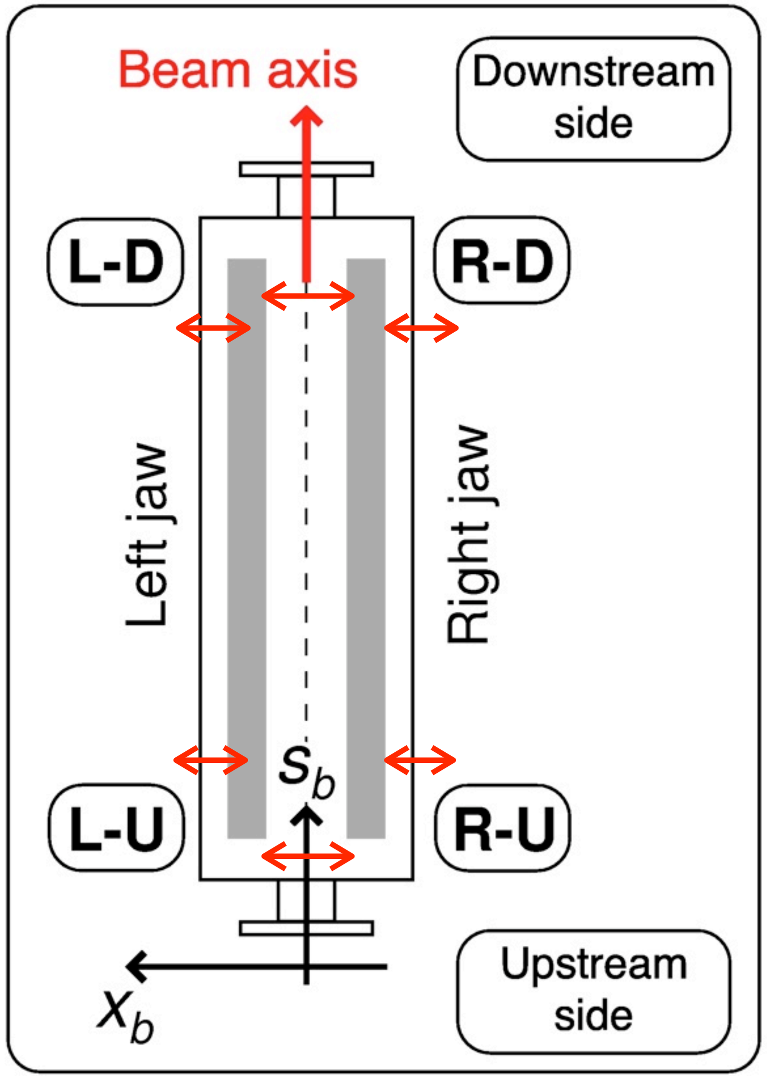
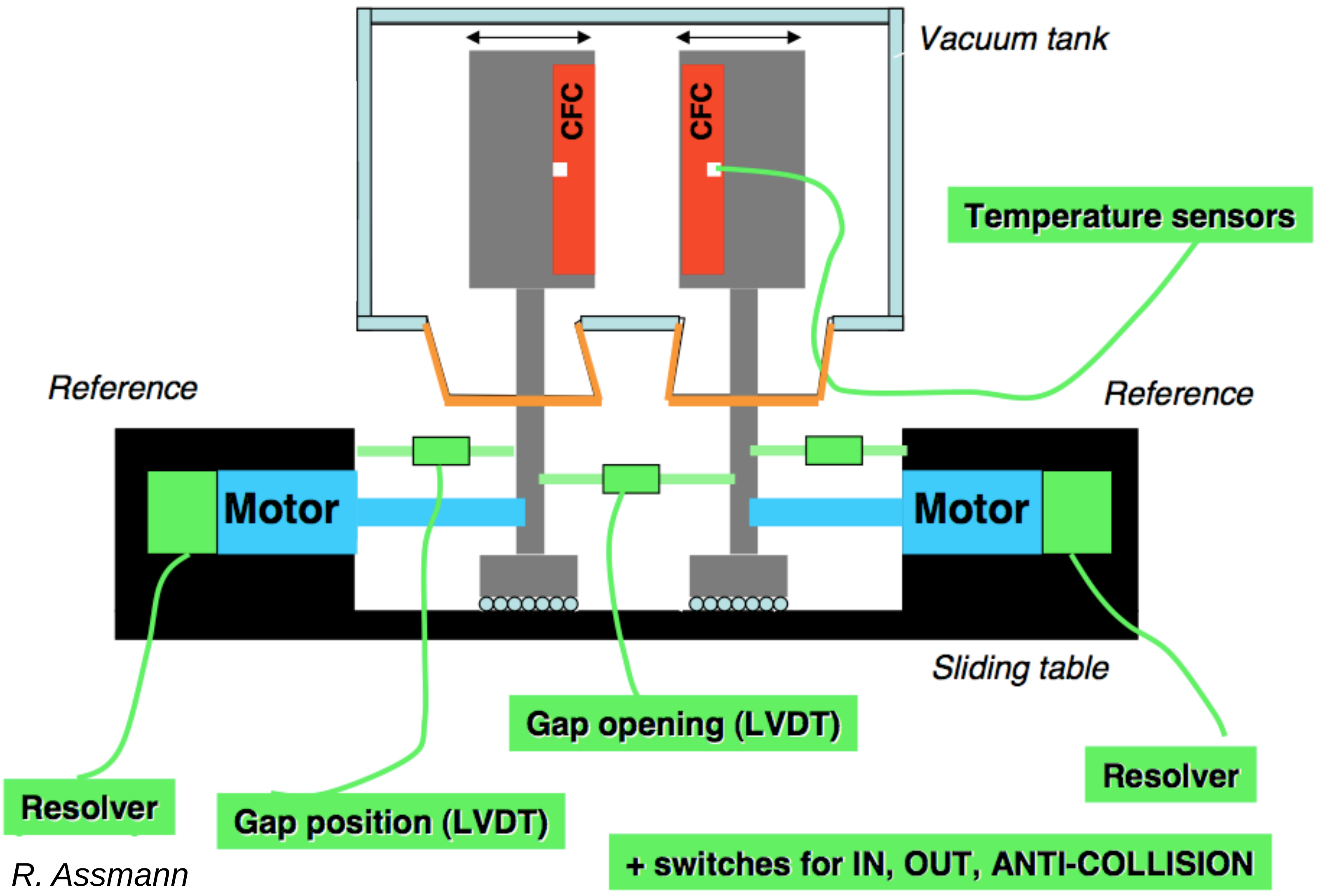
Jaw positions: controls and survey





Settings: **4 stepping motors** for jaw corners + 1 motor for tank position.

Survey: 7 direct measurements: **4 corners** + **2 gaps** + tank

4 resolvers that count motor steps

10 switch statuses (full-in, full-out, anti-collision)

Redundancy: **14 position measurements** per collimator

Layout of LHC collimation system

Two warm cleaning insertions, 3 collimation planes

- **IR3: Momentum cleaning**
  - **1 primary (H)**
  - **4 secondary (H)**
  - **4 shower abs. (H,V)**
- **IR7: Betatron cleaning**
  - **3 primary (H,V,S)**
  - **11 secondary (H,V,S)**
  - **5 shower abs. (H,V)**

Local cleaning at triplets

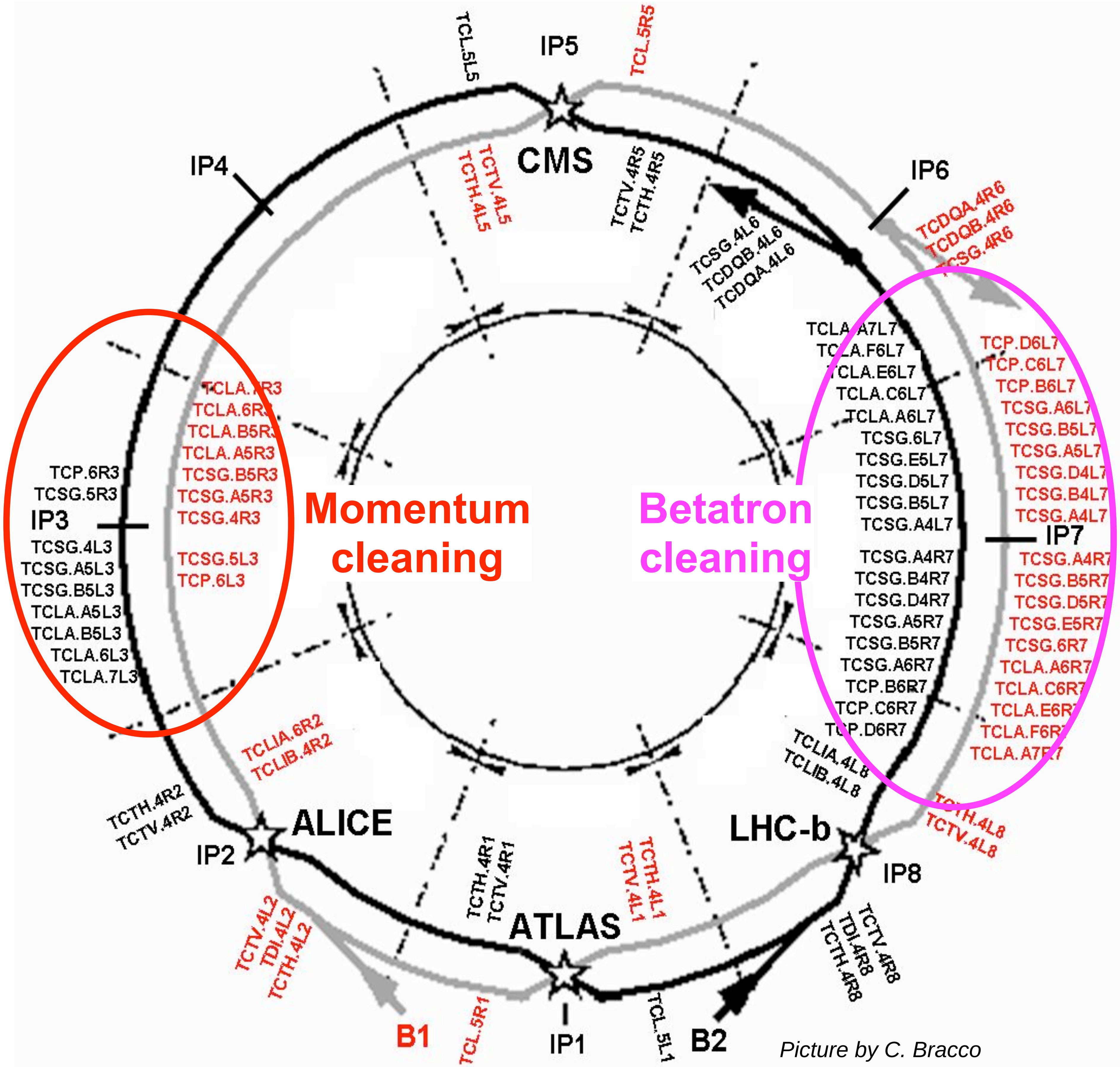
- **8 tertiary (2 per IP)**

Passive absorbers for warm magnets

Physics debris absorbers

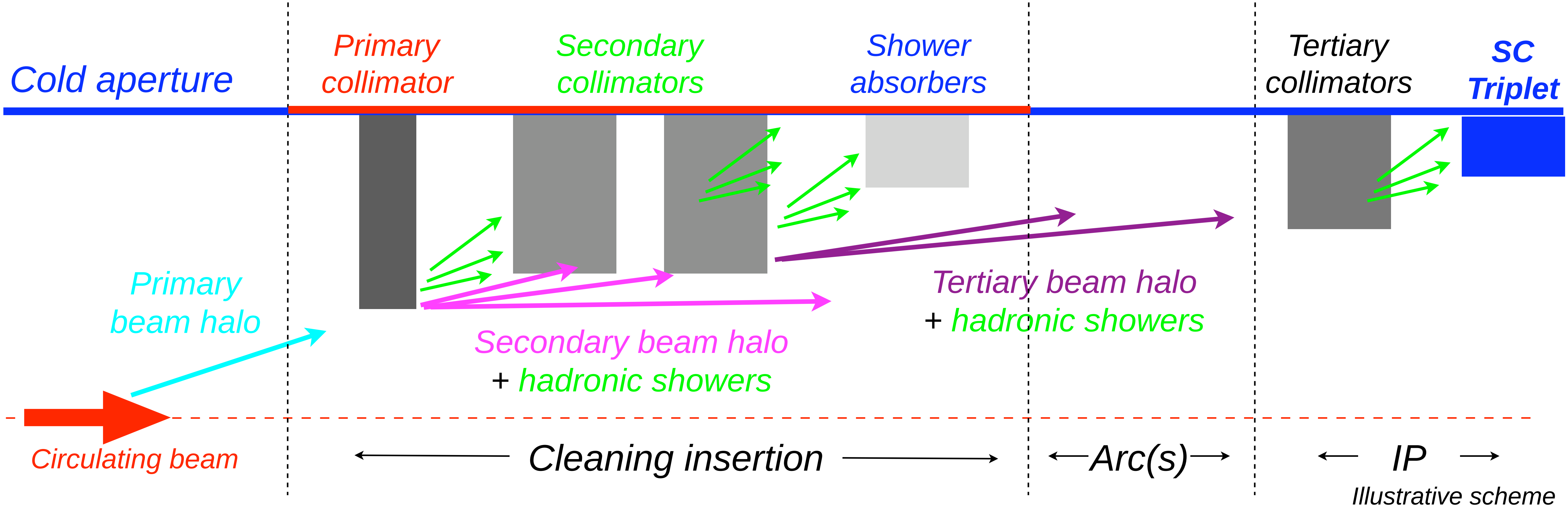
Transfer lines (13 collimators)
Injection and dump protection (10)

Total of 108 collimators (100 movable). Two jaws (4 motors) per collimator!



Picture by C. Bracco

LHC multi-stage collimation



- The minimum LHC aperture is in the shade of several layers of collimators.
  Horizontal, vertical and skew aperture!
- The halo **leakage** to cold aperture must be below quench limit!
- LHC **aperture** sets the scale: **Injection:** **≥ 12.5 σ**
  3.5 TeV, β*=1.5m: **≥ 14.0 σ**
- **Beam-based setup** → local beam position and beam size at each collimator to ensure the collimator **hierarchy**.
- Primary and secondary collimators are **robust** (Carbon-based).
  Absorbers and tertiary collimators (Tungsten) are not and must be protected.

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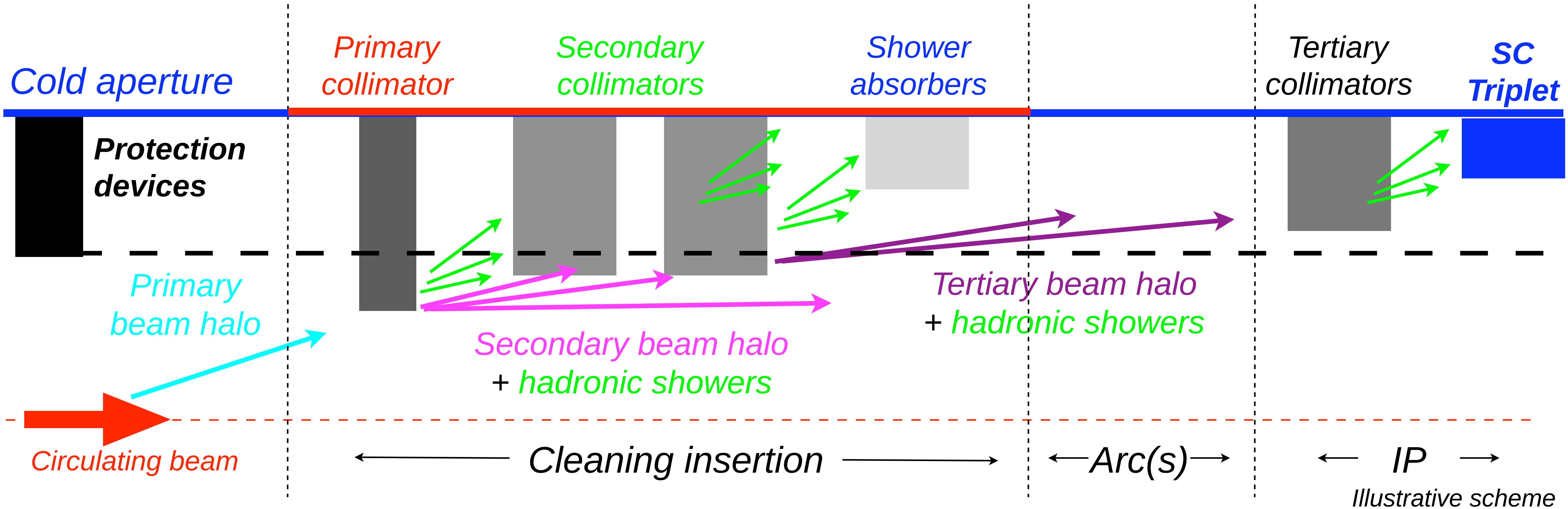

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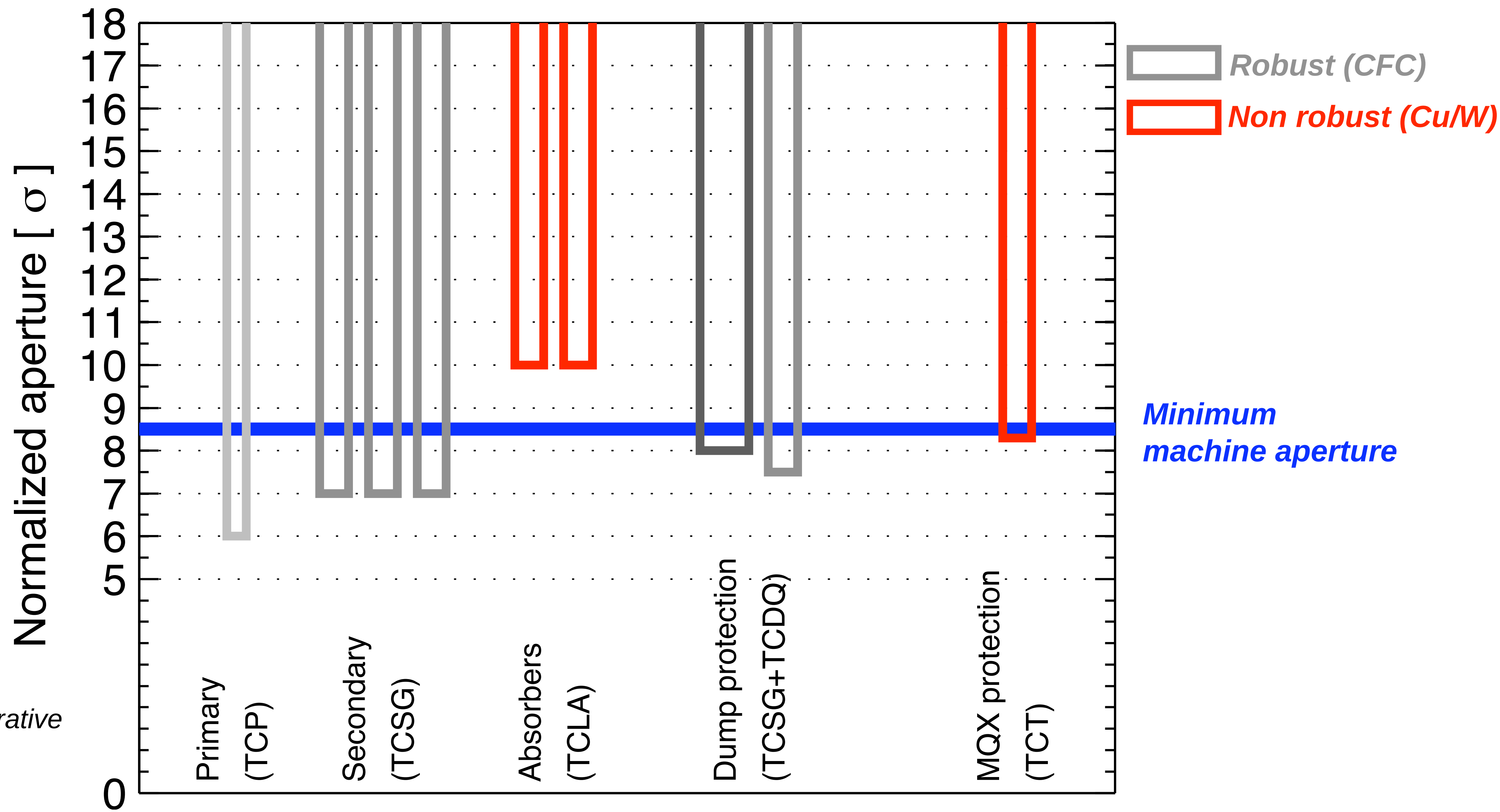
Nominal collimator settings at 7 TeV



An illustrative scheme

- Nominal settings (TCP/TCSG=6/7σ) provide the best cleaning performance.
- Mandatory to push the β^* performance.
- Tightest machine tolerance on orbit and optics. Limited TCT protection.

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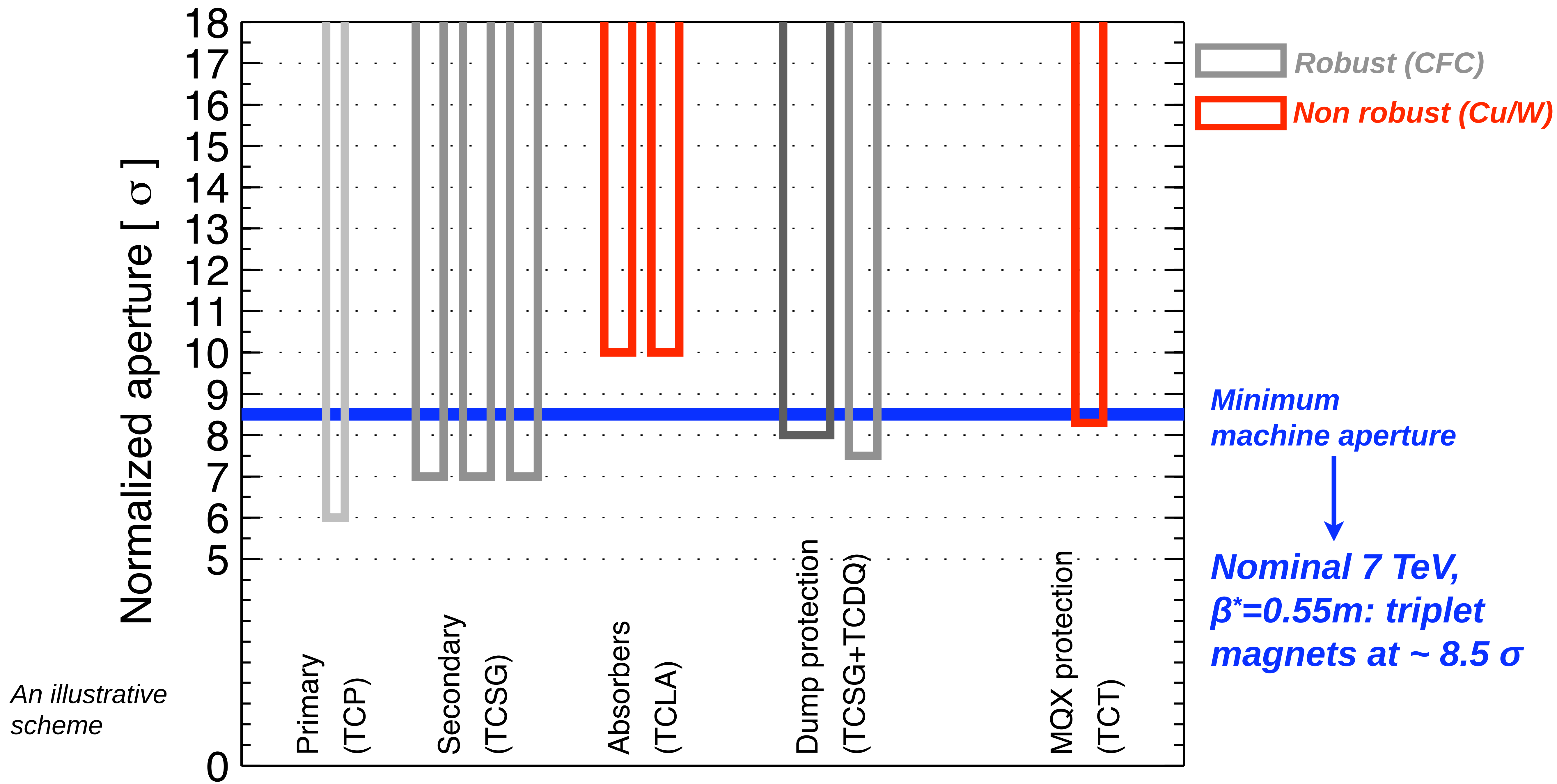

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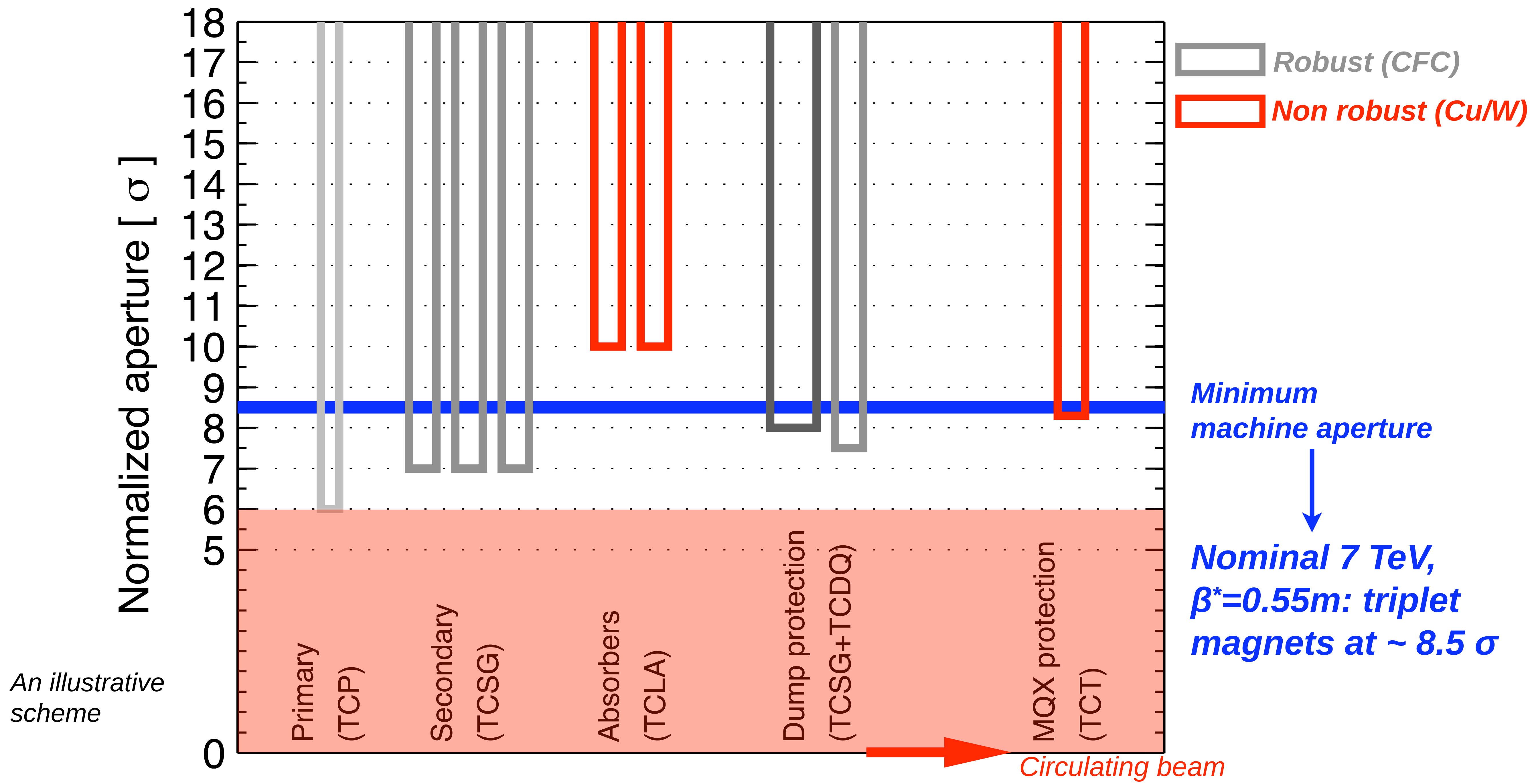

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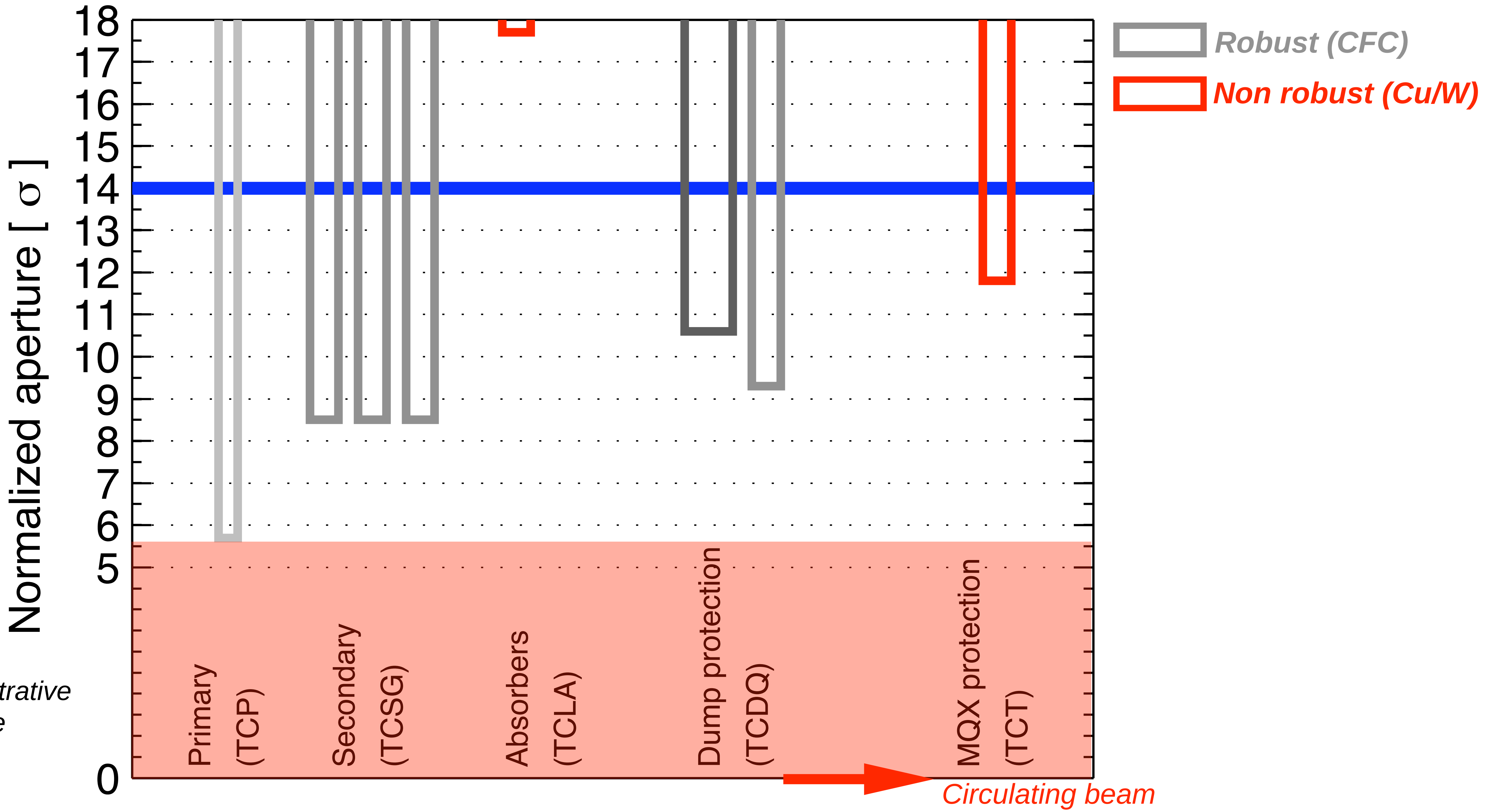

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- Relaxed thresholds on collimator hierarchy: Optimized commissioning!
- Somewhat reduced cleaning, but sufficient for 3.5 TeV operation.
- Limited β^* performance reach (e.g., if orbit worst than foreseen).

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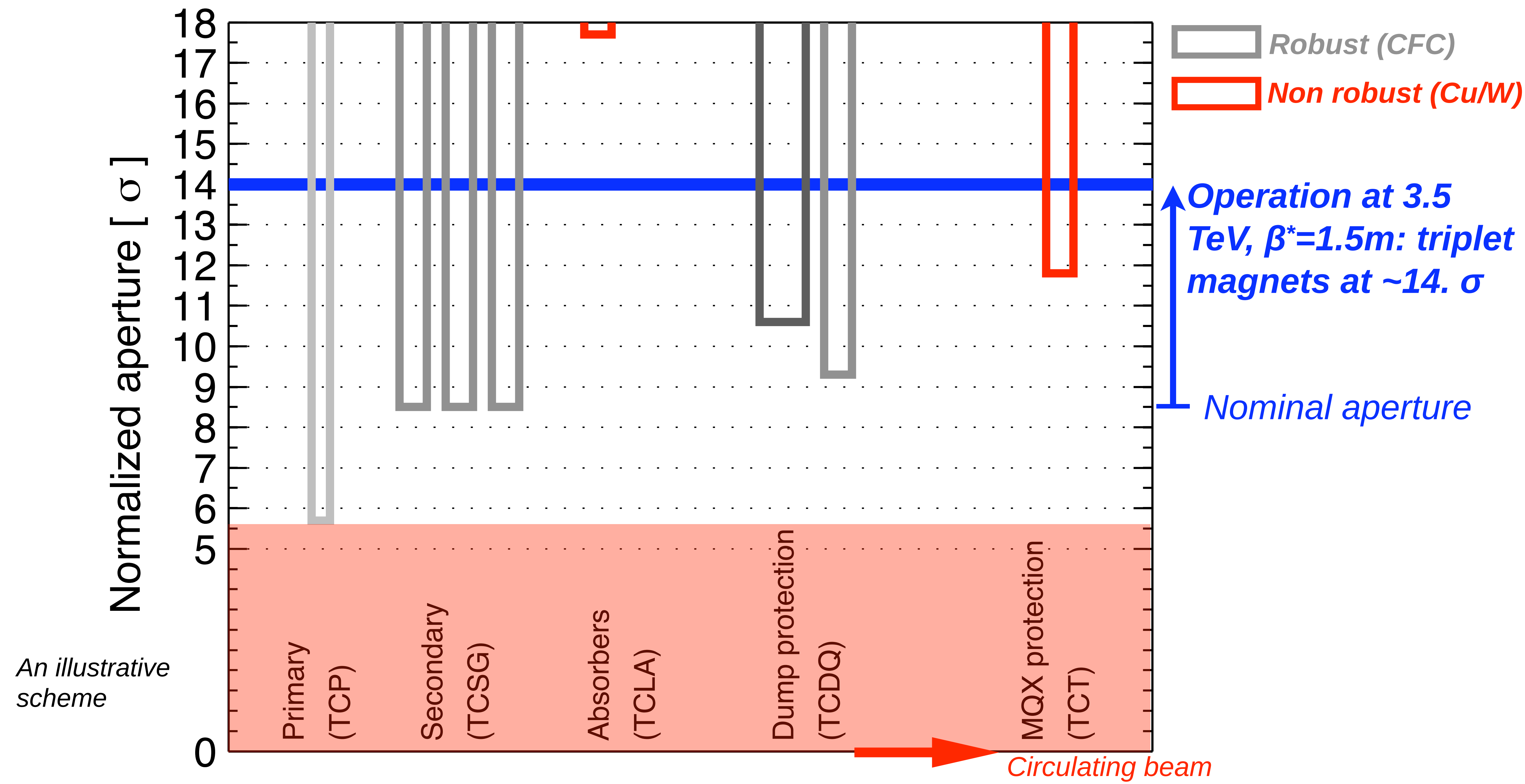

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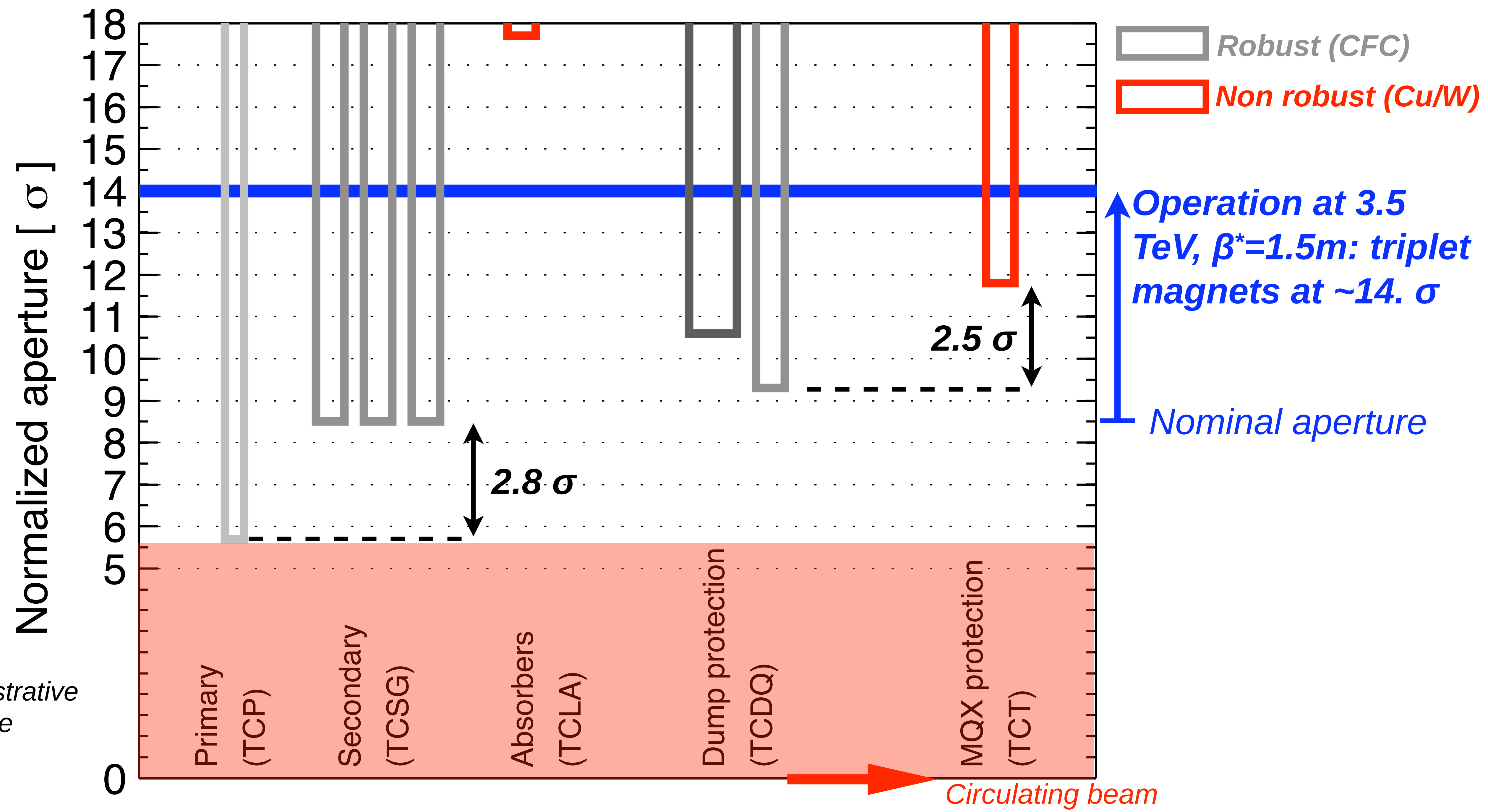

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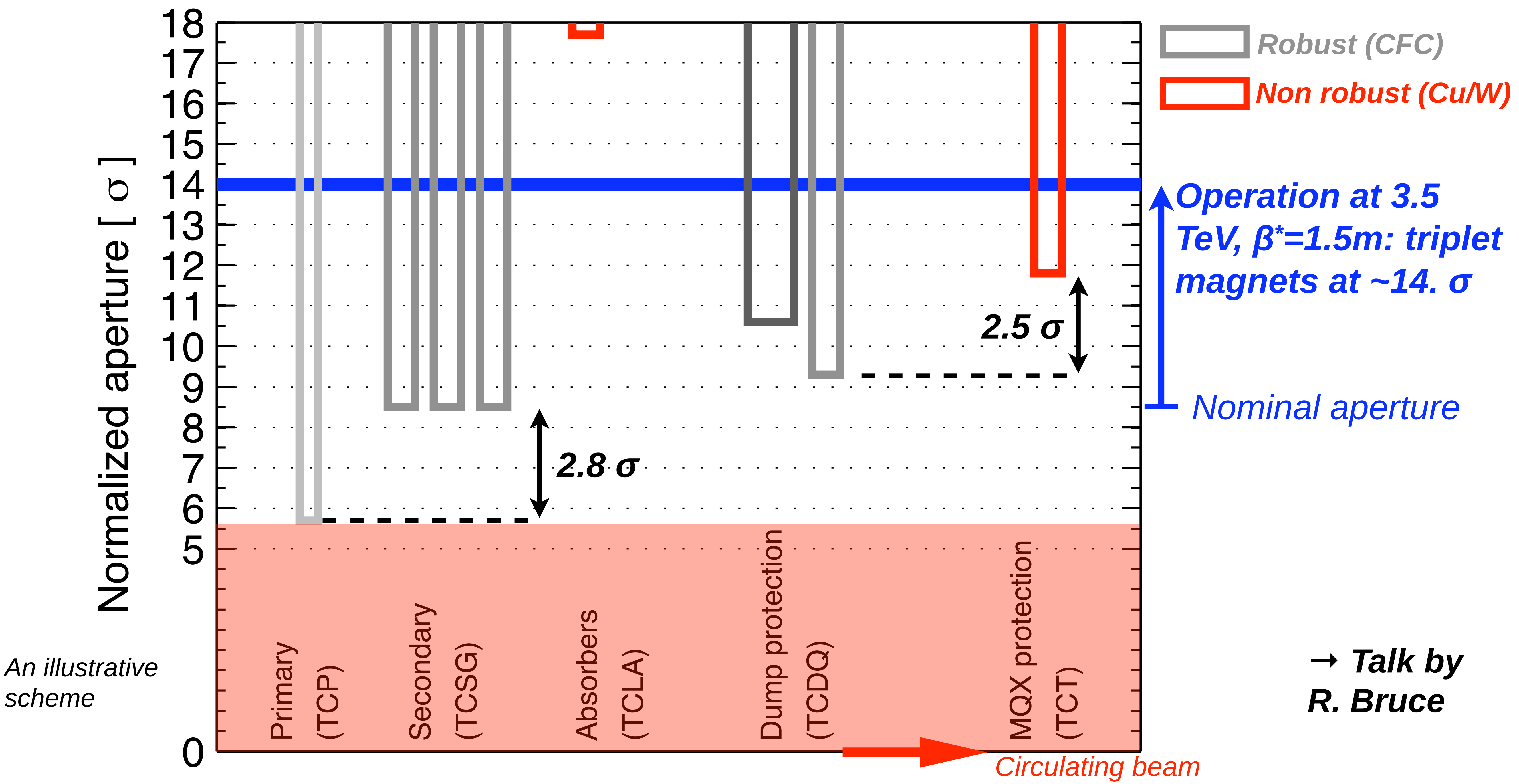

→ ***Talk by R. Bruce***

- Relaxed thresholds on collimator hierarchy: Optimized commissioning!
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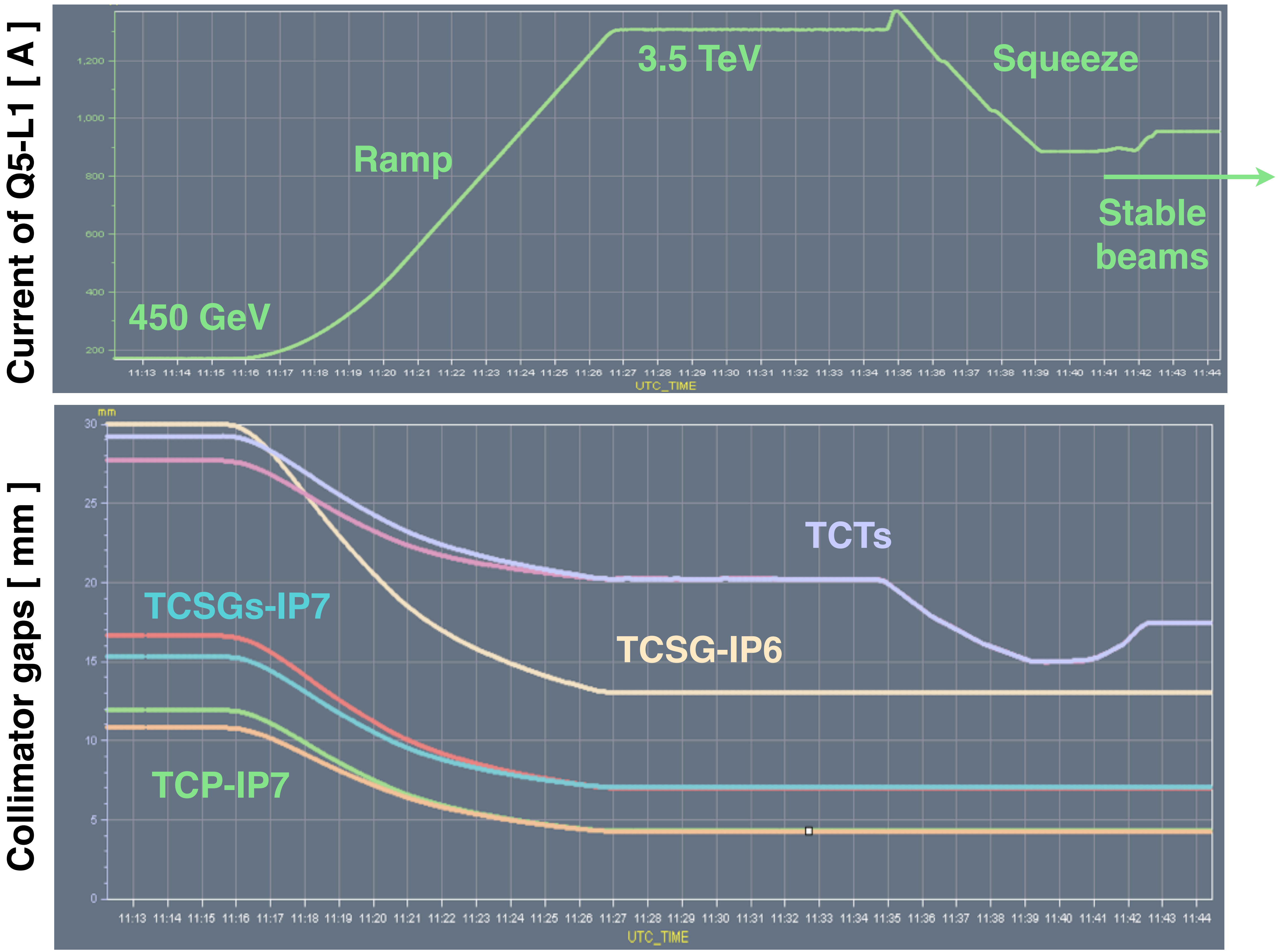
Present operational settings

Parameter	Unit	Plane	Type	Set 1	Set 2	Set 3	Set 4
				Injection	Top energy	Squeeze	Collision
Energy	[GeV]	n.a.	n.a.	450	3500	3500	3500
β^* in IR1/5	[m]	n.a.	n.a.	11.0	11.0	1.5	1.5
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	10.0	10.0
Crossing angle IR1/5	[μrad]	n.a.	n.a.	170	120	120	120
Crossing angle IR2	[μrad]	n.a.	n.a.	170	80	80	80
Crossing angle IR8	[μrad]	n.a.	n.a.	170	250	250	250
Beam separation	[mm]	n.a.	n.a.	2.0	0.7	0.7	0.0
Primary cut IR7	[σ]	H,V,S	TCP	5.7	5.7	5.7	5.7
Secondary cut IR7	[σ]	H,V,S	TCSG	6.7	8.5	8.5	8.5
Quartiary cut IR7	[σ]	H,V	TCLA	10.0	17.7	17.7	17.7
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 experiments	[σ]	H,V	TCT	13.0	26.0	11.8	11.8
Physics debris collimators	[σ]	H	TCL	out	out	out	out
Primary protection IR6	[σ]	H	TCSG	7.0	9.3	9.3	9.3
Secondary protection IR6	[σ]	H	TCDQ	8.0	10.6	10.6	10.6

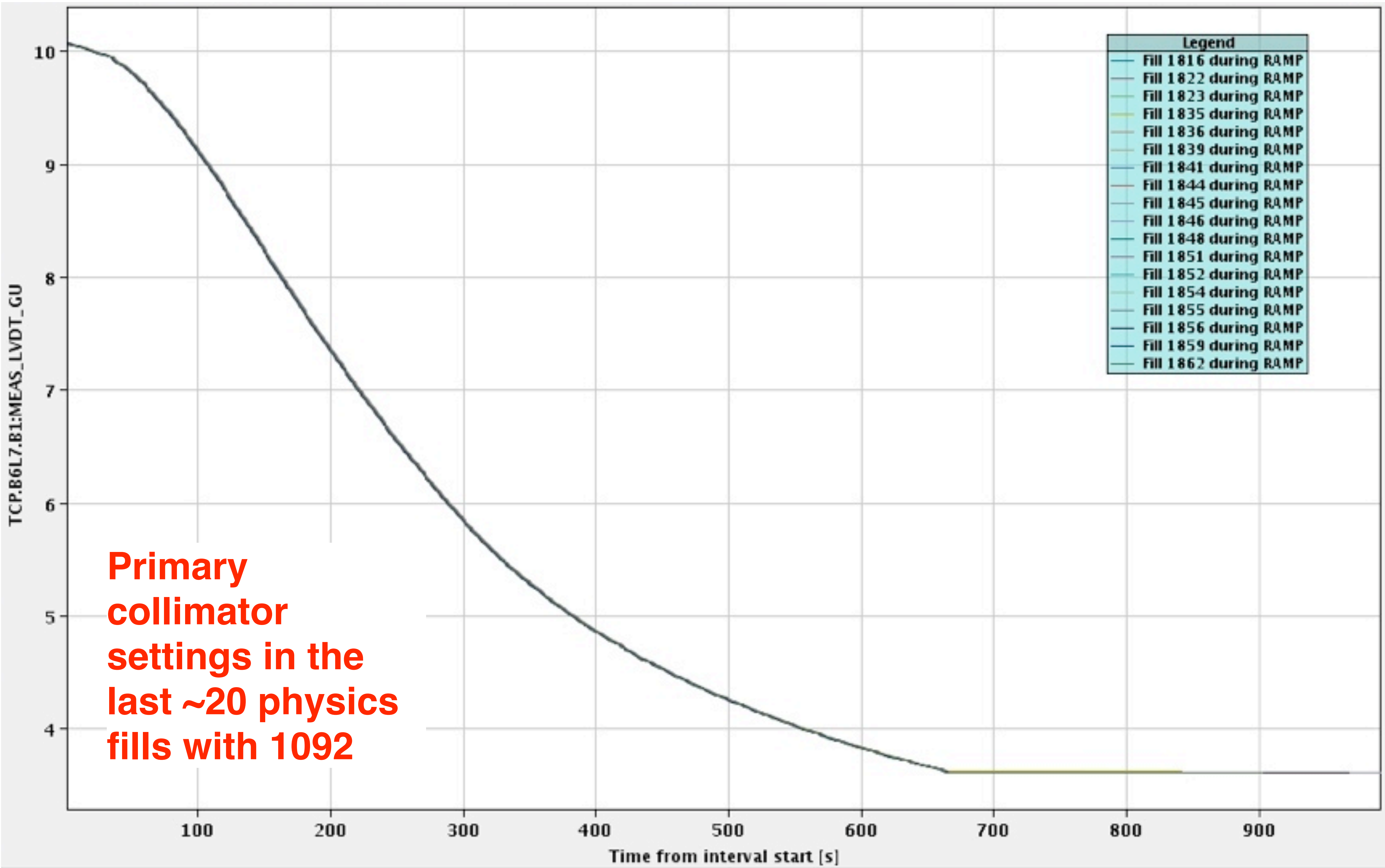
System driven through **functions of time**: smooth transition between setting configurations.

Handling of collimator settings is fully **automated** for the operation crews!

Collimator settings in practice



Reproducibility of settings - TCPs



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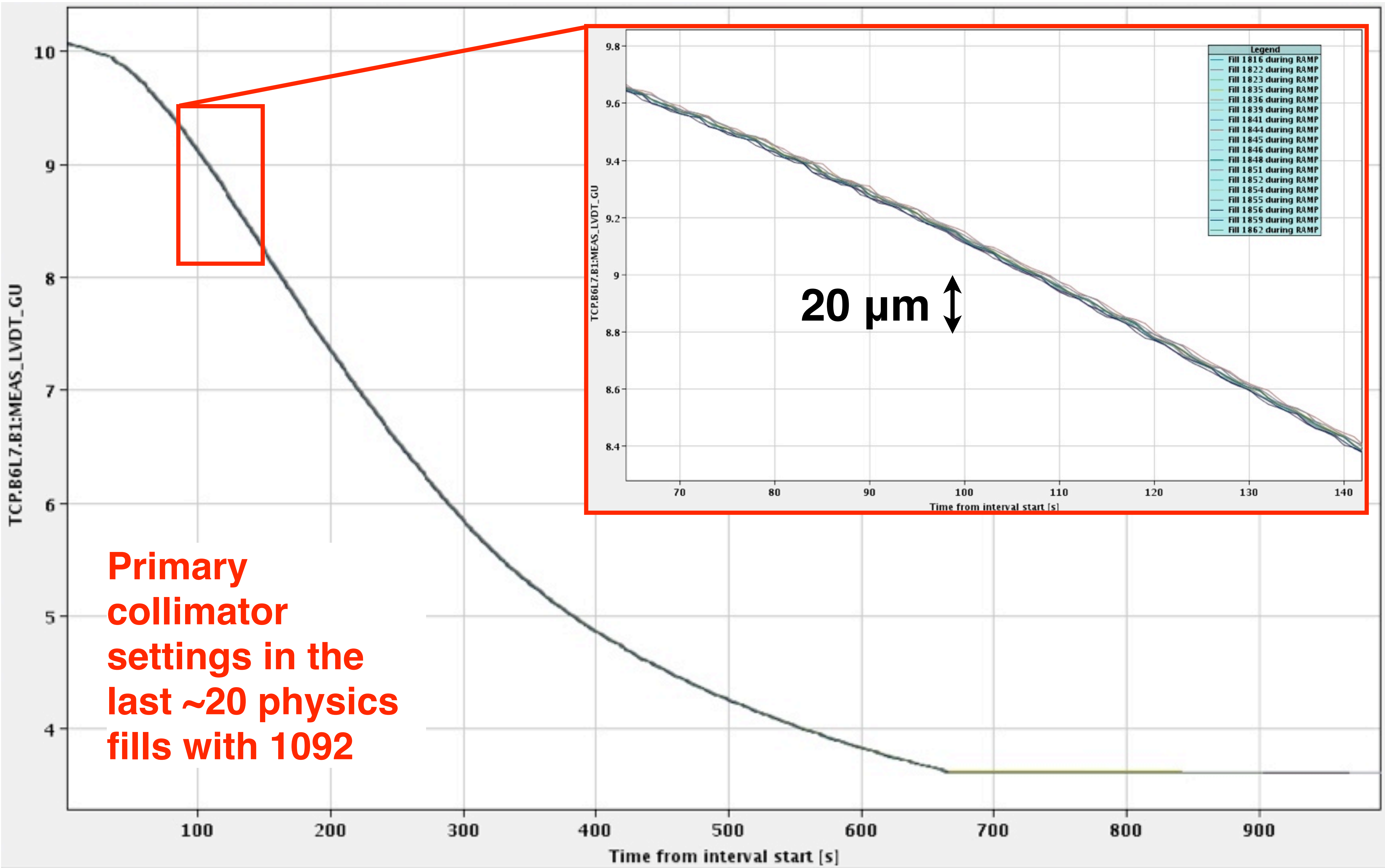
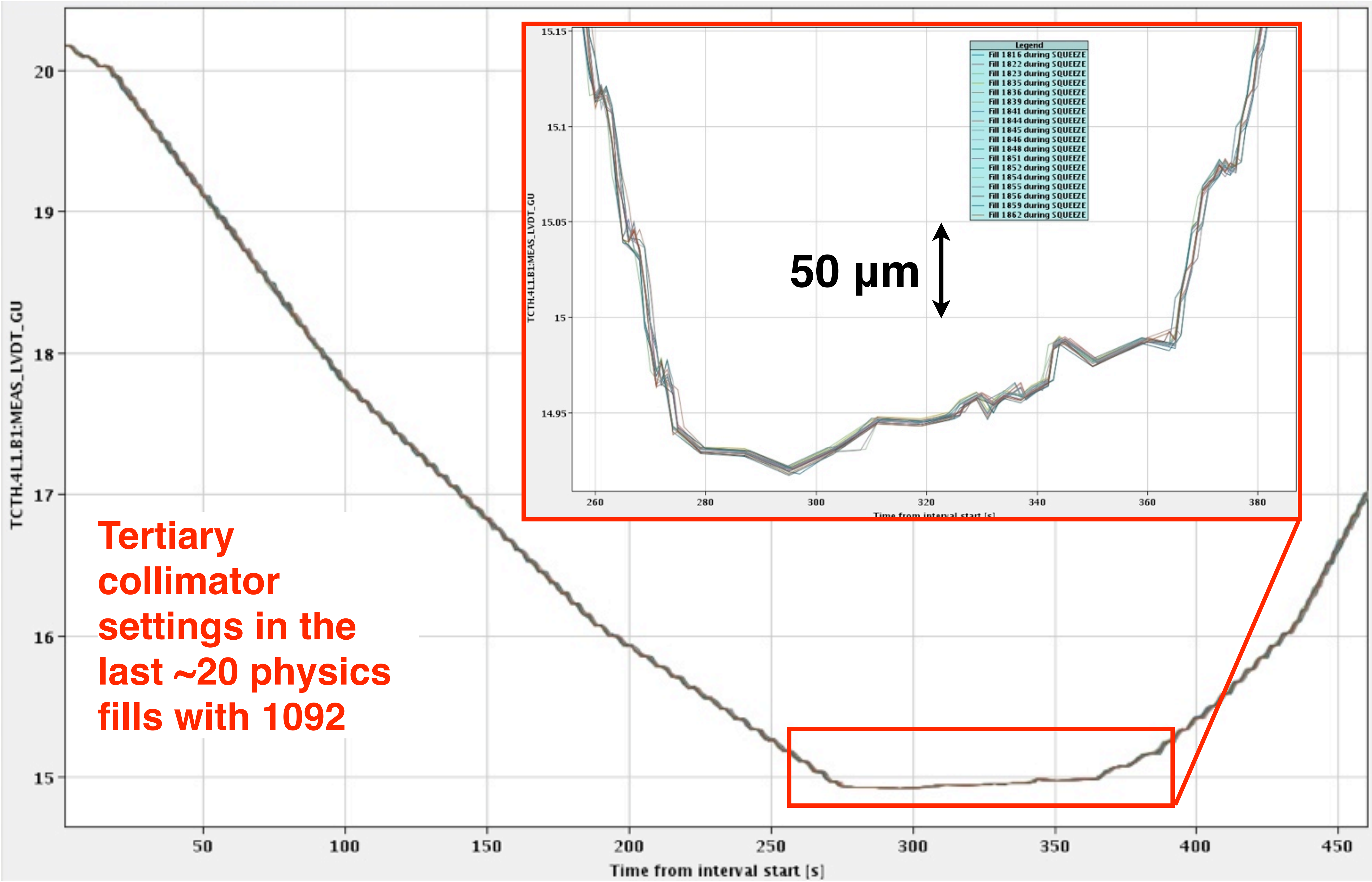


Reproducibility of settings - TCTs



Tertiary collimator settings in the last ~20 physics fills with 1092

Some numbers...

Table 1: Main system parameters

Parameters	2008	2009
Number of movable collimators	80	100
Degrees of freedom	316	396
Position sensors	788	998
Interlocked position sensors	472	592
Motor settings versus time	316	396
Threshold settings versus time	1896	2376
Threshold settings versus energy	154	194
Collimators with fifth motor	30	46

*They are driven by **functions** of time, triggered synchronously to power converters and RF. **Unique feature** for collimation in particle accelerators!*

Total number of settings to manage in 2011:

396 degrees of freedom x 4 = 1584

2376 limit functions x 4 = 9504

194 energy limit functions x 1 = 194

388 beta* limit functions x 1 = 388

*= **11670 settings***

*Functions of time = **8136***

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Crucial to control tightly the collimator positions in all machine phases!
Important for system upgrades: mechanical and controls choices of Phase I fully validated!

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- ☑ Design, layouts and settings
- ☑ **Collimation cleaning**
- ☑ Operational experience
- ☑ Conclusions

Cleaning efficiency and quench limit

Definitions:

Local cleaning inefficiency

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

Assumed quench limits (loss rates)

$$R_q^{\text{inj}} = 7.0 \times 10^8 \text{ protons/m/s } (450\,\text{GeV})$$
$$R_q^{\text{low}\beta} = 7.6 \times 10^6 \text{ protons/m/s } (7\,\text{TeV})$$

Appropriate scaling vs. beam energy

Critical cleaning at quench limit

$$\tilde{\eta}_c^q = \frac{\eta_c^q}{L_{\text{dil}}} = \frac{\tau R_q}{N_{\text{tot}}}$$

Updated figures based on beam measurements presented by D. Wollmann

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Performance reach of the system

$$N_{\text{tot}} = \frac{\tau R_q}{\tilde{\eta}_c}$$

LHC intensity reach (N_{tot})

Beam lifetime (τ)

Quench limit (R_q)

Collimation cleaning ($\tilde{\eta}_c$)

Design loss assumptions

Performance reach depends on:

- Collimation cleaning inefficiency
- Total beam intensity;
- Peak minimum lifetime;
- Quench limit of magnets;
- Loss dilution length.

$$N_p^{\lim} = \tau_{\min} \cdot \frac{R_q}{\eta_{ineff}} \cdot \frac{F_{BLM} \cdot F_{dilution}}{F_{imperfect}}$$

Intensity Limit

Quench limit, e.g. 8e6 p/m/s

Factor for BLM margin, e.g. 0.33

Factor for shower dilution from FLUKA, e.g. 3.5

Minimum beam lifetime (peak loss): Assumed input

Cleaning inefficiency

Factor for imperfections, e.g. 6

R. Assmann

Our design specification:

Mode	T [s]	τ [h]	R_{loss} [p/s]	P_{loss} [kW]
Injection	cont.	1.0	0.8×10^{11}	6
	10	0.1	8.6×10^{11}	63
Ramp	≈ 1	0.006	1.5×10^{13}	1200
Collision	cont.	1.0	0.8×10^{11}	97
	10	0.2	4.3×10^{11}	487

This figures are being revised based on the beam experience

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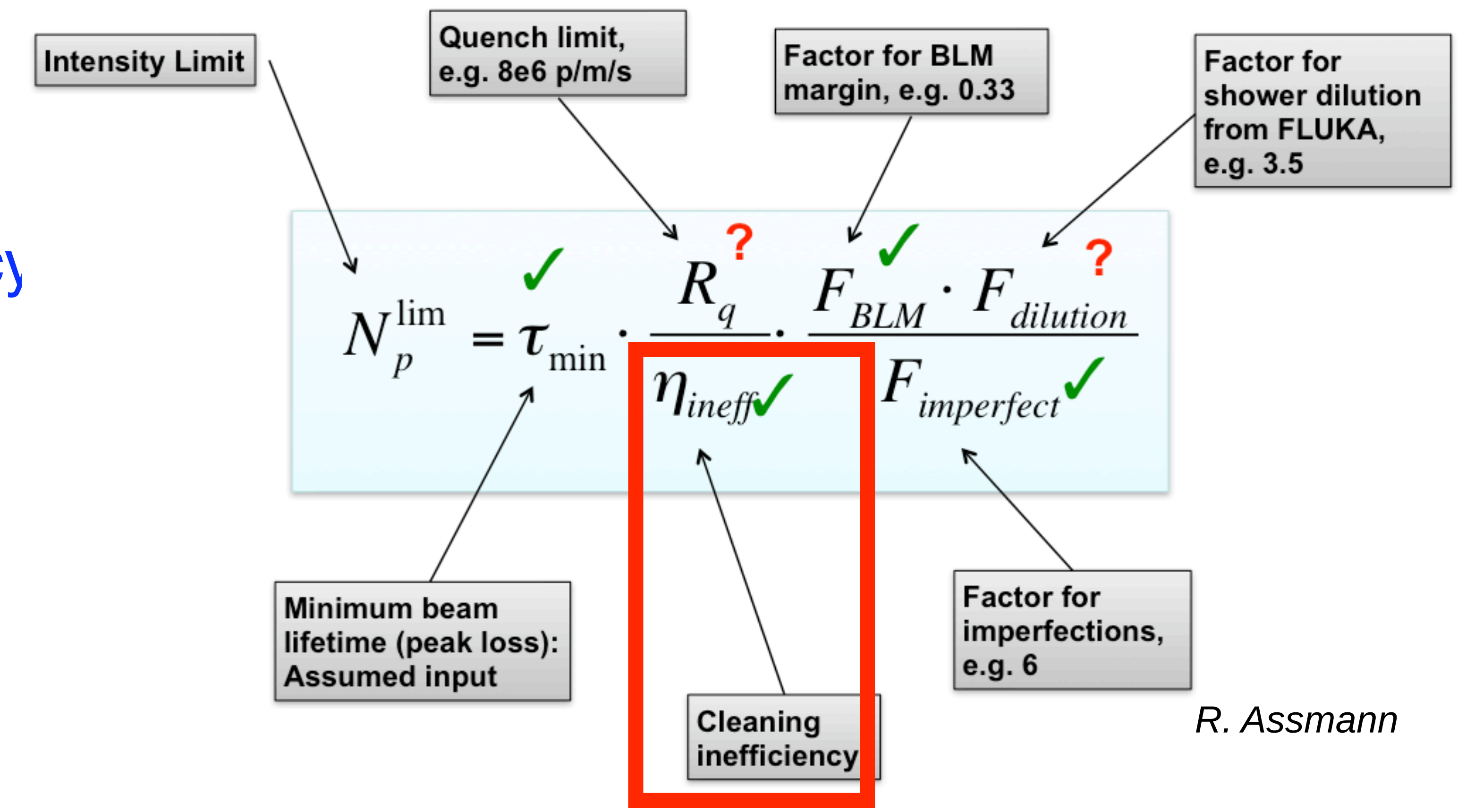

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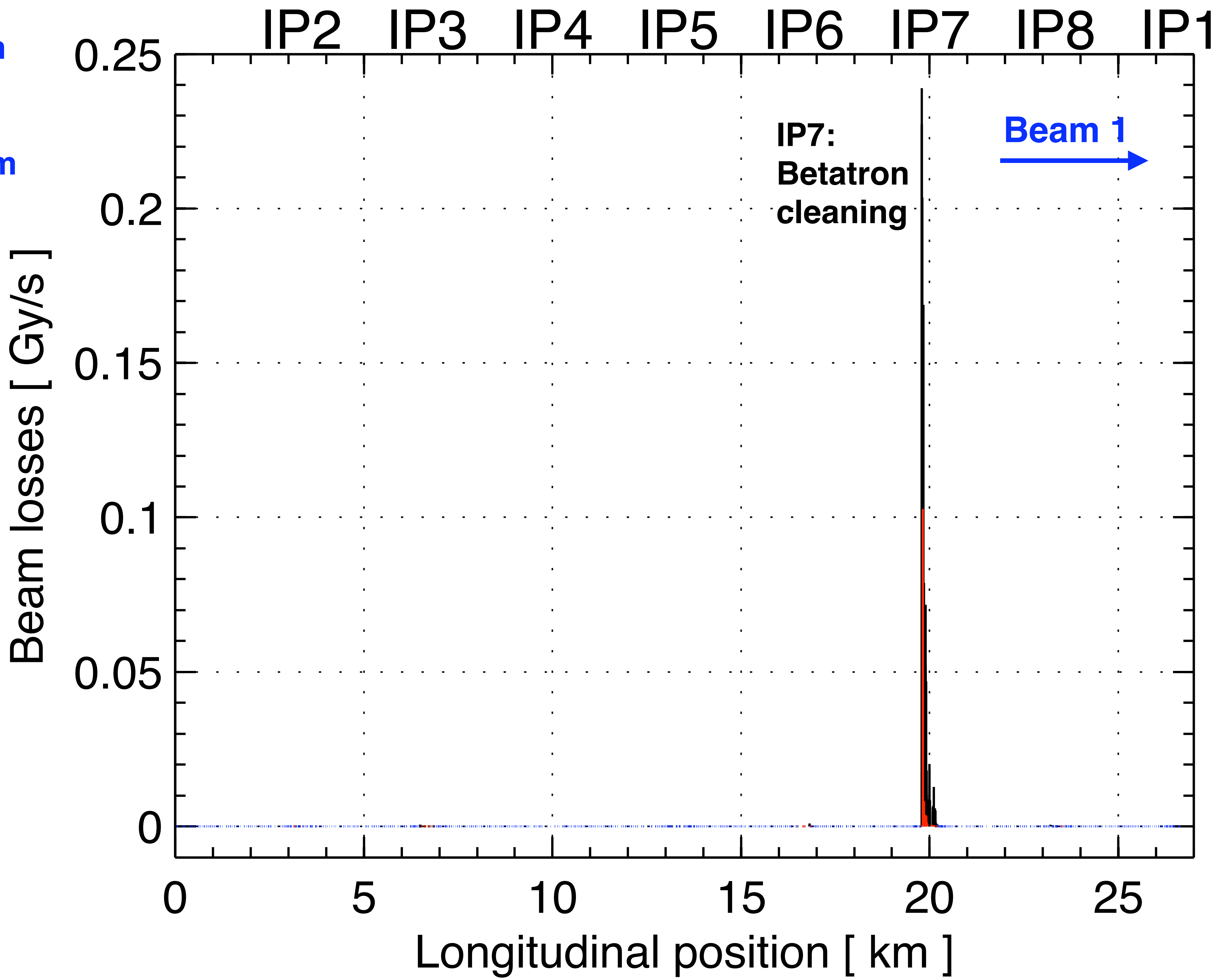
Losses in physics conditions

4000 beam loss monitors along 27 km



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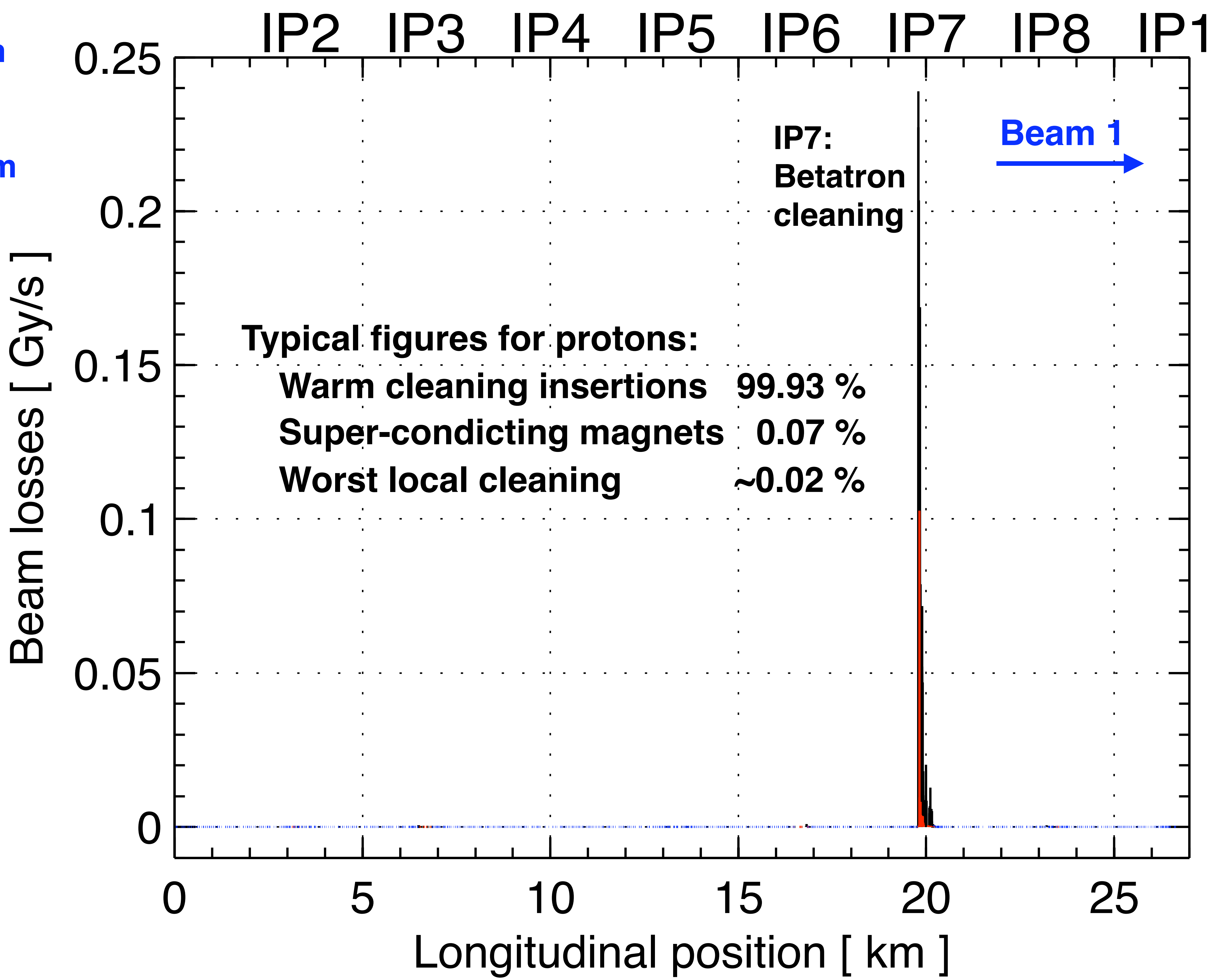

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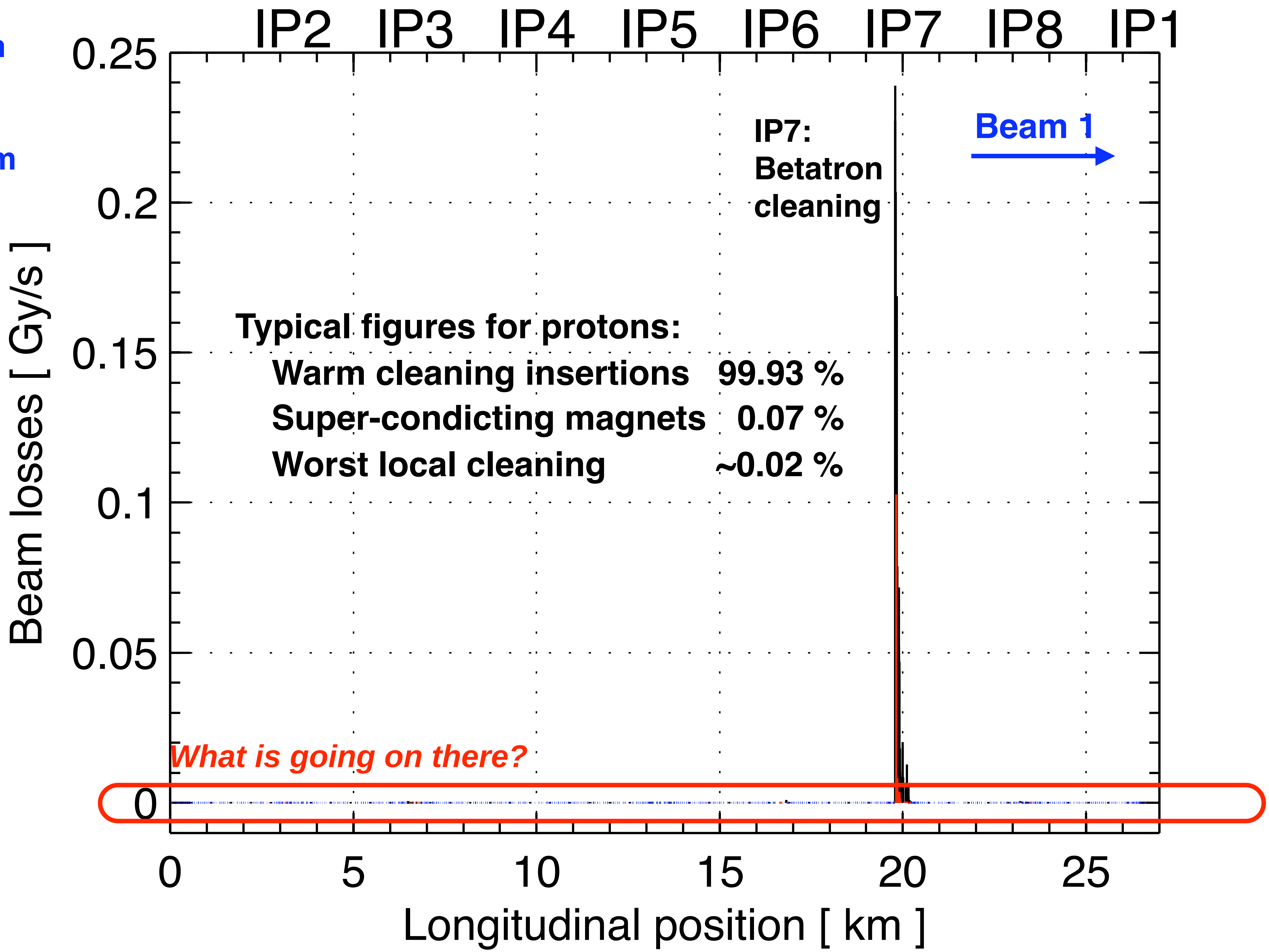
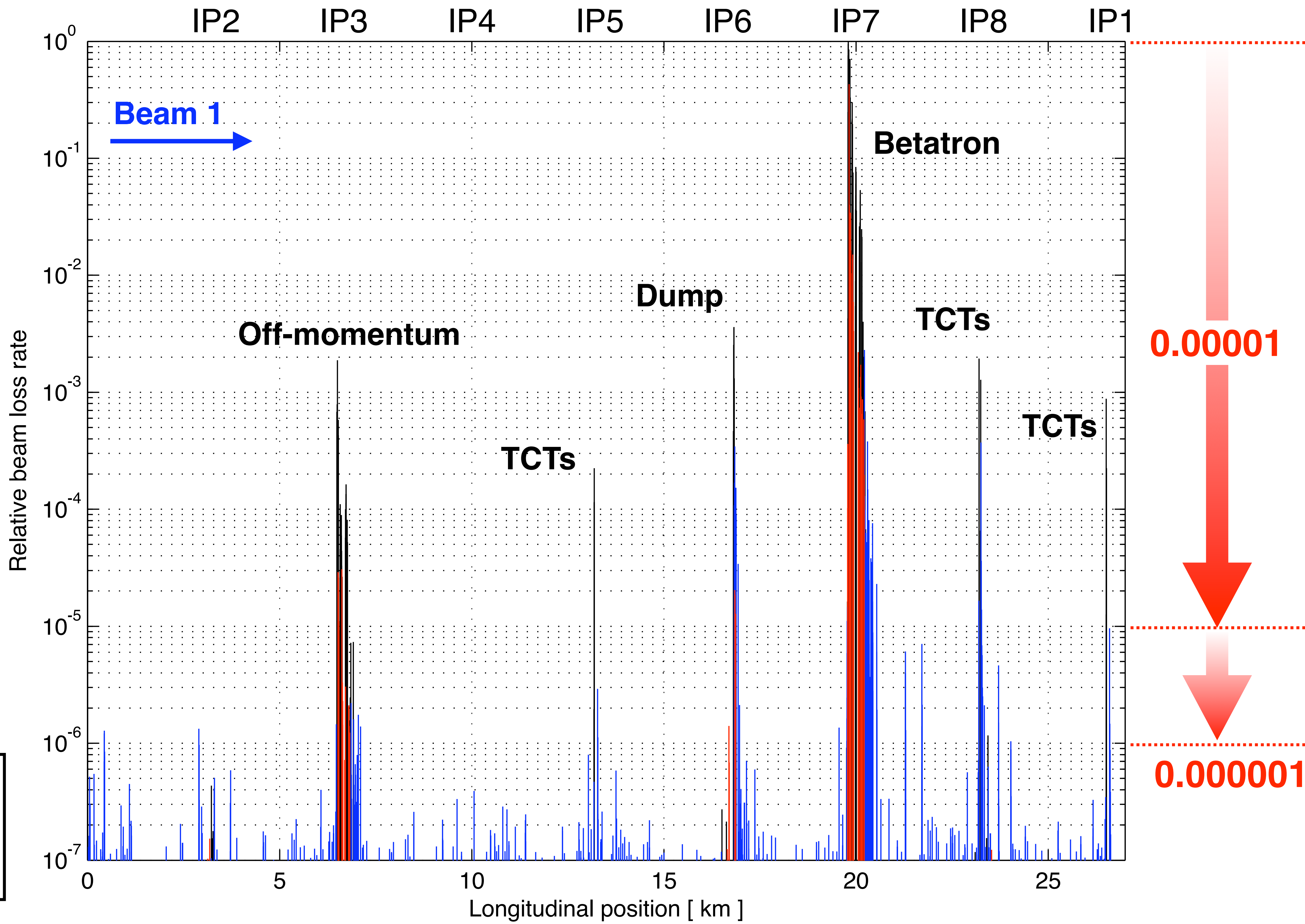


Cleaning performance, 3.5TeV, β^*=1.5m

Higher loss rates: beam across the 3rd order resonance.

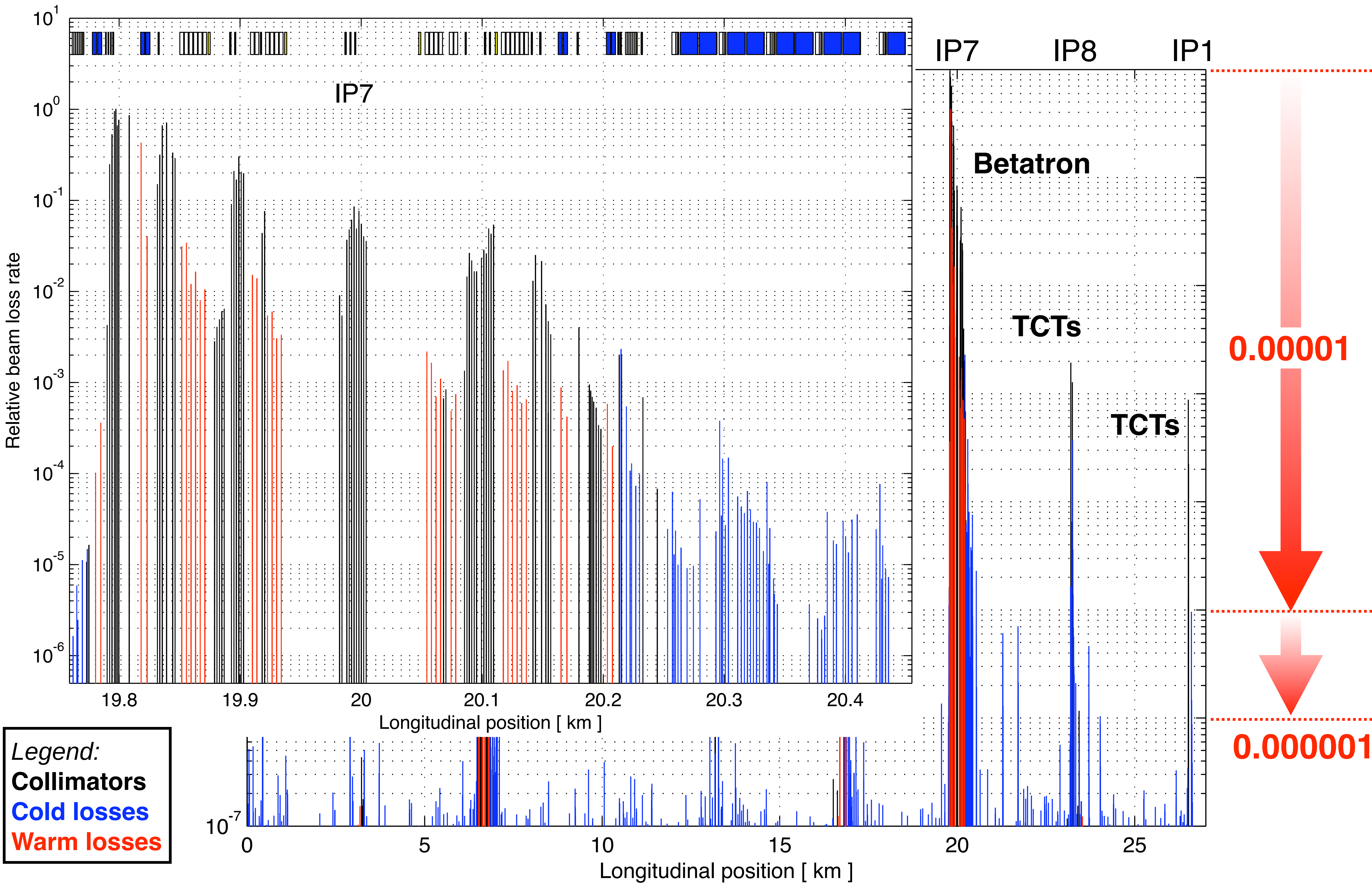
Repeated for ALL run configs.



Legend:
Collimators
Cold losses
Warm losses

Loss maps in physics, 12-04-2011

Cleaning performance, 3.5TeV, β^*=1.5m



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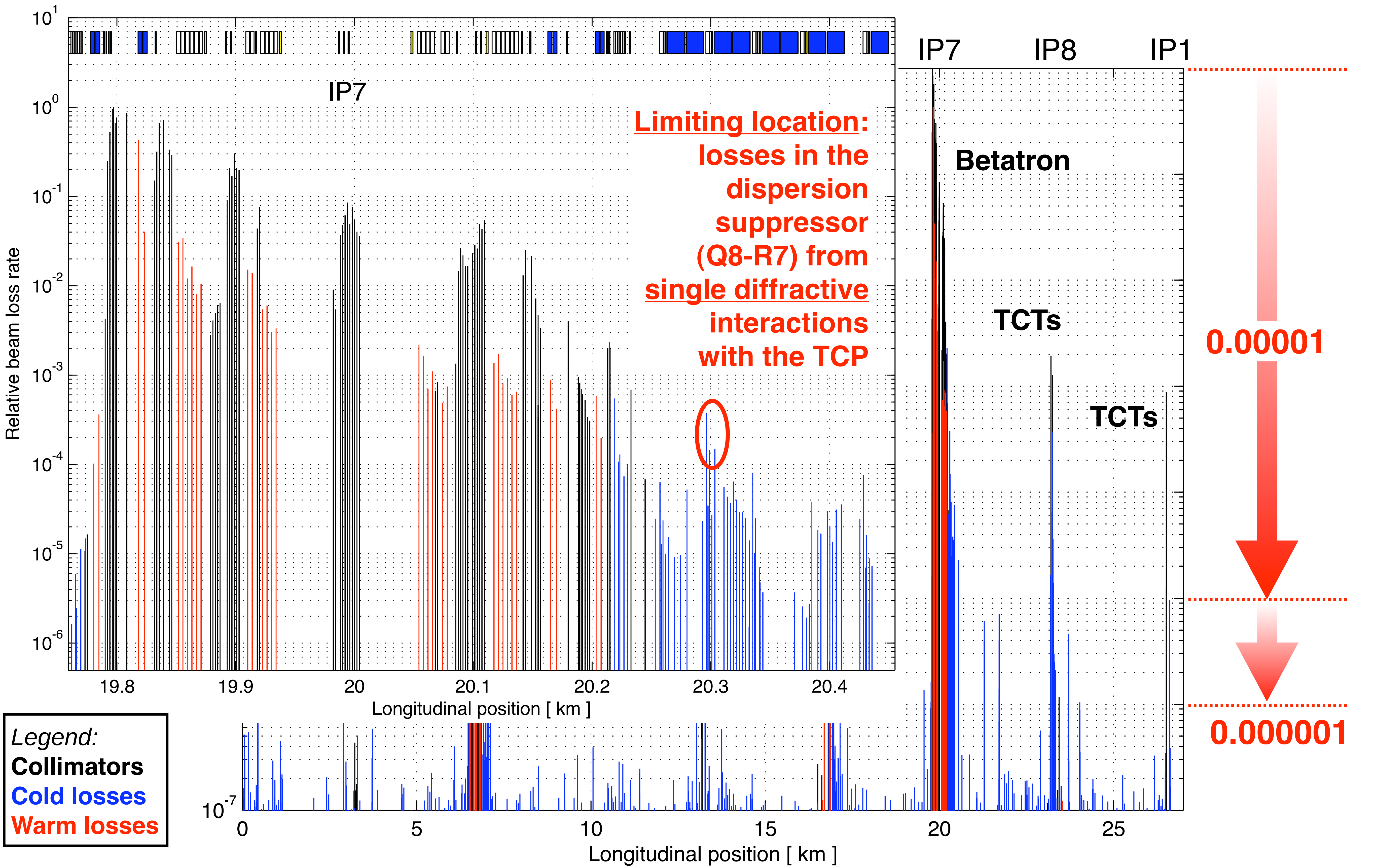
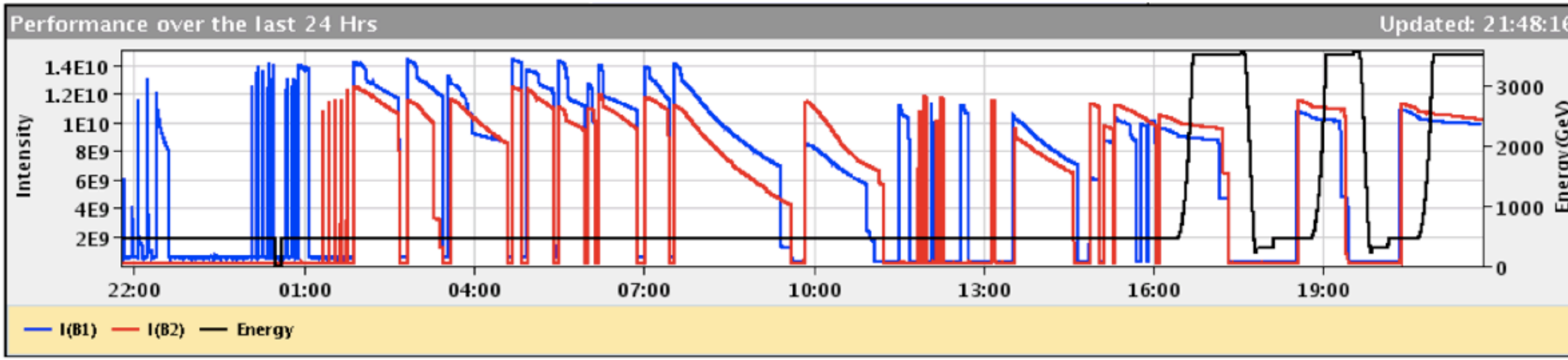


Loss maps in physics, 12-04-2011

A look at ion commissioning

1 day



Beam 1 Inj.,
Circ.
& Capture

Beam 2
Inj., Circ.
& Capture

Optics Checks
BI Checks
Collimation Checks

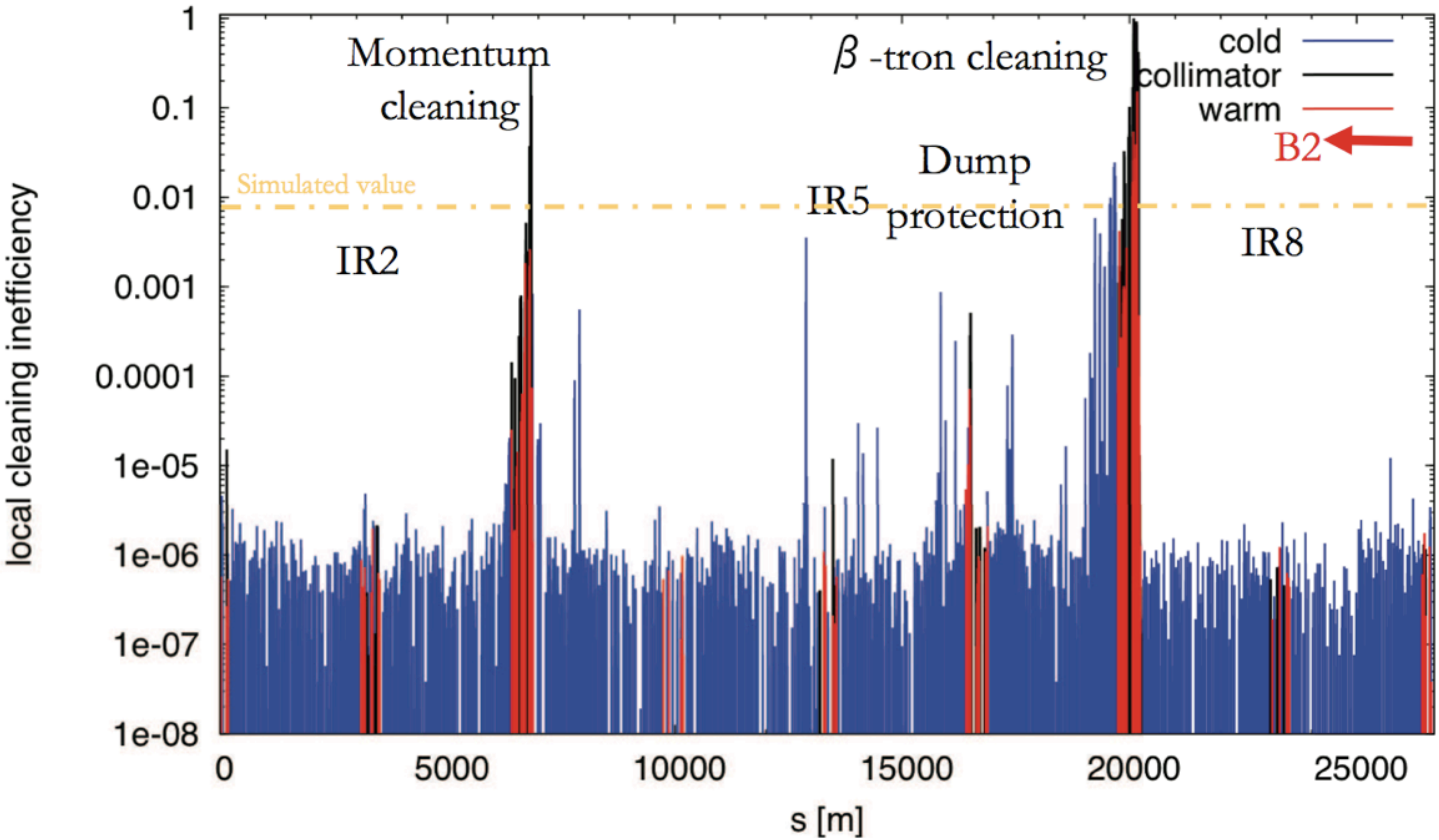
First Ramp
Collimation Checks
Squeeze

Achieved **ion collisions** after **54 hours** of commissioning!

Remarkable maturity and performance of controls, instrumentation, operational experience.

Ion collimation based on the proton settings
(same settings, same machine magnetically).

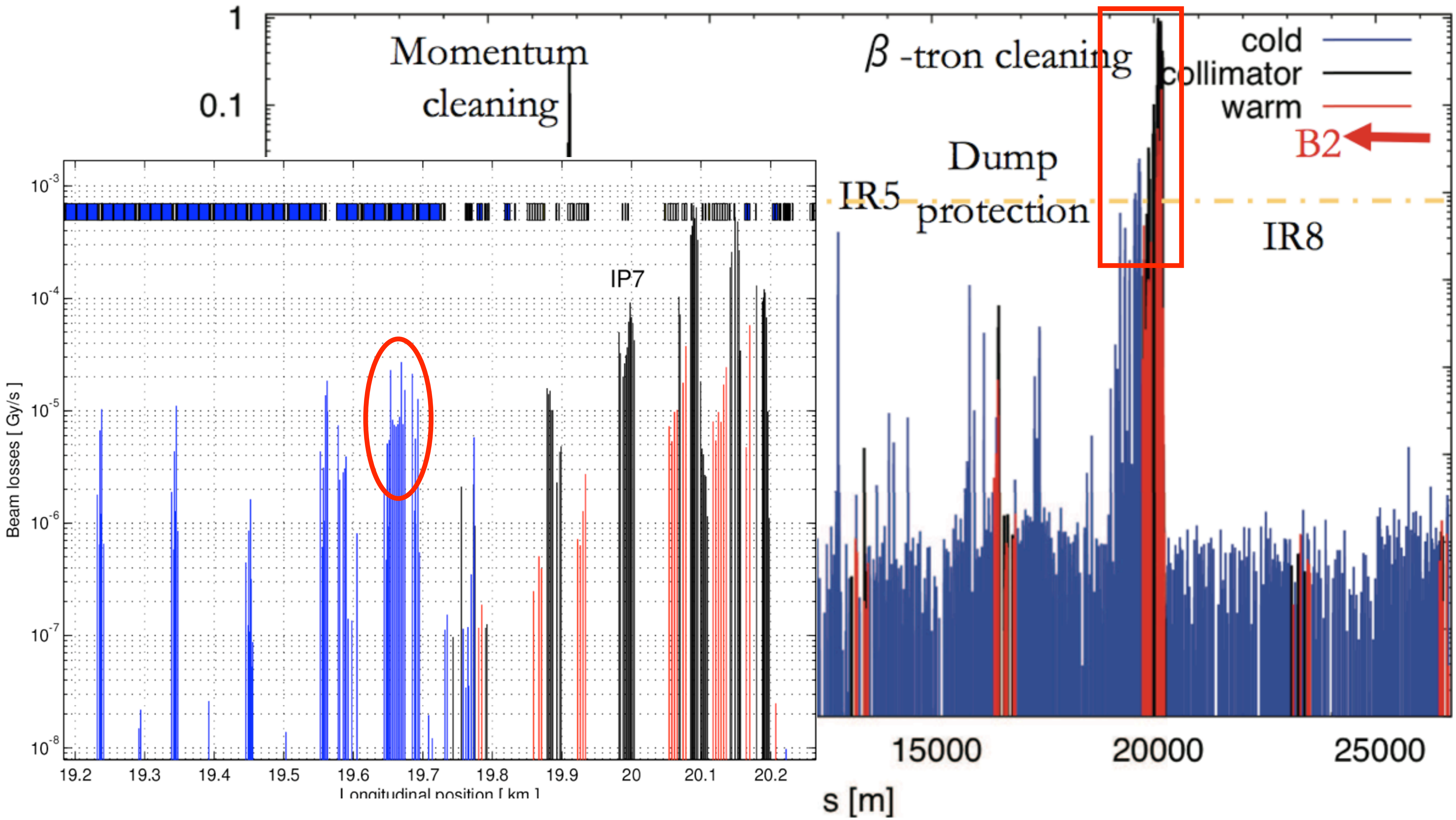
Pb ion cleaning



D. W
Evia

- **Limitation**: **ion fragmentation** and **dissociation** create large effective Dp/p
  → "beams" of different ion species lost at well defined locations.
- Limitation locations are the DS of IR7: losses of a few % (50-100x worst than p!)
- Additional loss locations around the ring not predicted by simulations.

Pb ion cleaning



- **Limitation**: **ion fragmentation** and **dissociation** create large effective Dp/p
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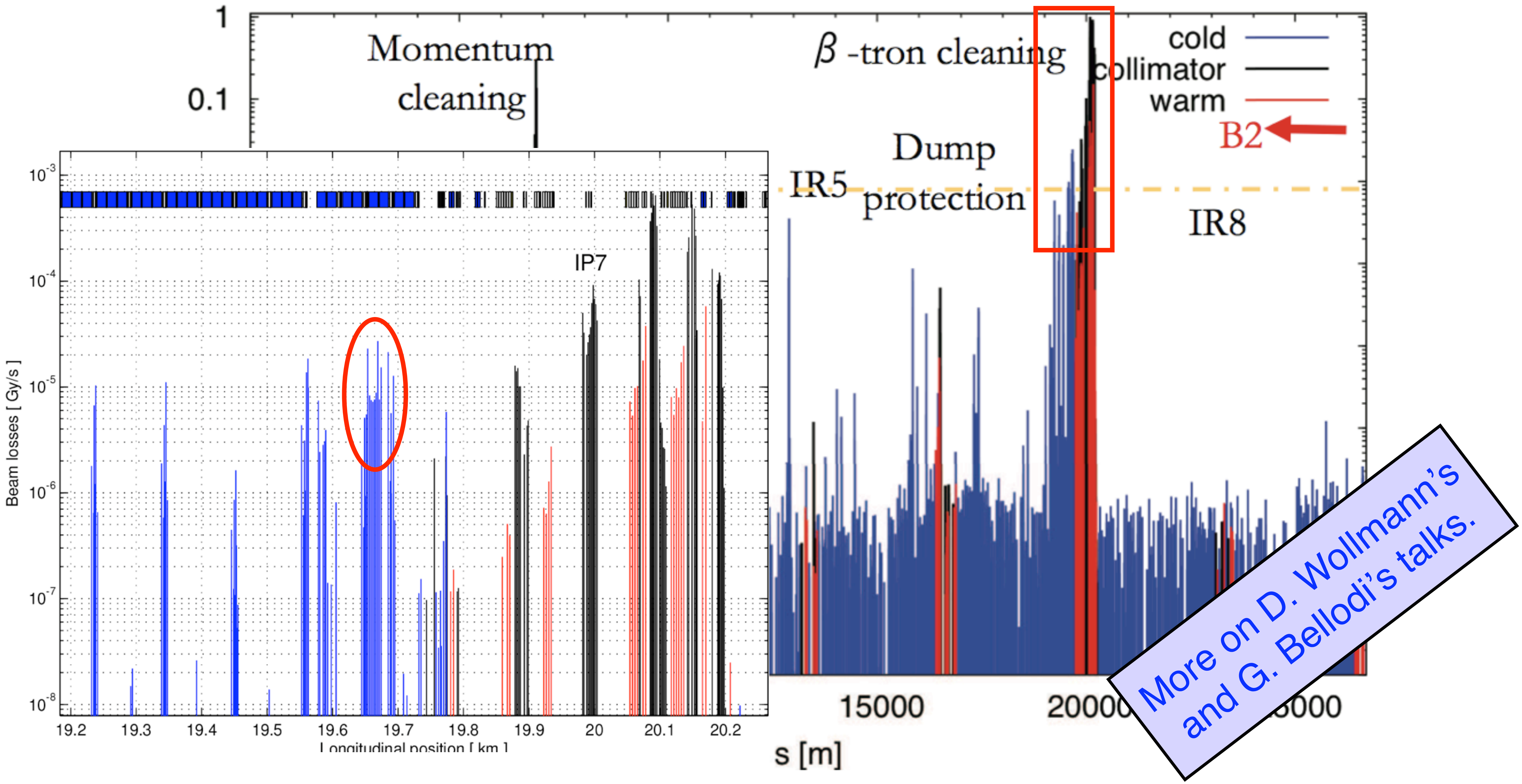

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Outline

- Introduction
- Design, layouts and settings
- Collimation cleaning
- **Operational experience**
- Conclusions

Phase I collimation operation

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  - Beam-based settings valid for 4-5 months according to present experience.
- **Consequences** of this infrequent setup:
  - **constraints** on machine **reproducibility** (orbit stab. fill to fill **< 150 μm**, **$\Delta\beta/\beta$< 20%**)!
  - performance is ensured by regularly **monitoring** the cleaning (dedicated loss maps).
  - **integrated luminosity affected**, e.g. for changes of IP configurations (crossing scheme → in practice, we limit the flexibility).

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  - ***Dispersion suppressor collimators****;*
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  - *Integrated BPM design.*
- **Do we have enough ingredients to take a firm choice for the Phase I upgrade?**

  The performance reach depends critically on many parameters...

Challenge for the review

- "Geometrical" cleaning η_c well understood.
  - *Accurate simulations benchmarked with experimental data;*
  - *Limiting location predicted well: limits consistently found in dispersion suppressors*
- Quench limit, R_q ?
  Better than expected for losses in the DS?
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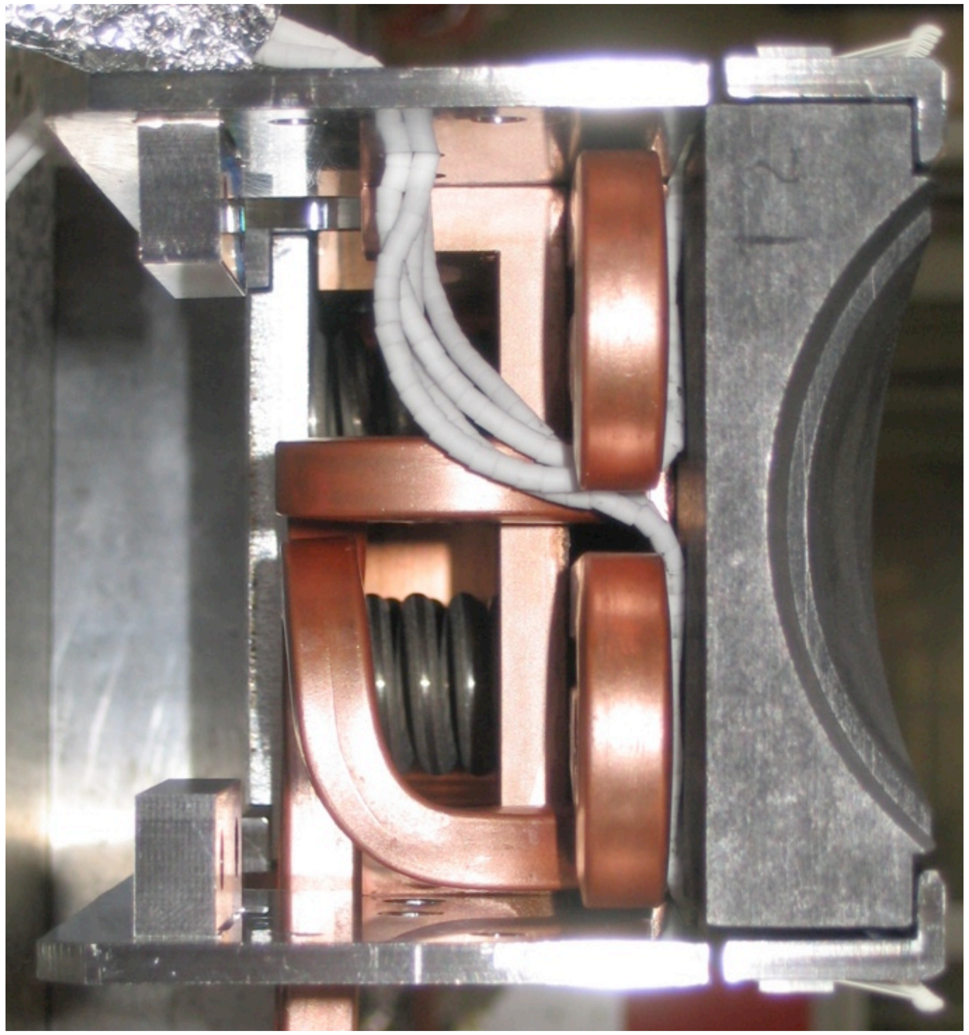
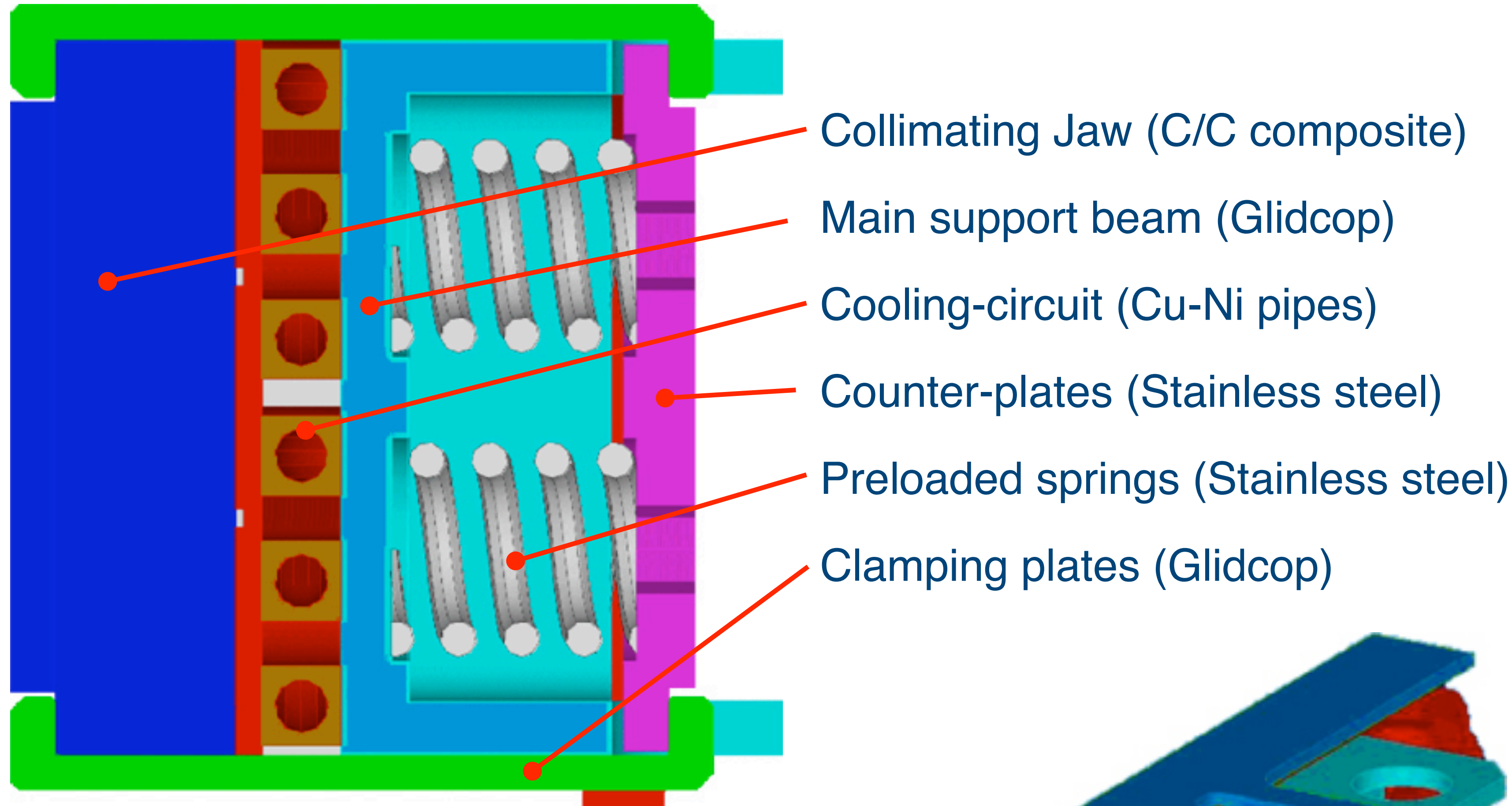
All aspects addressed by this review.
Best present knowledge is presented!

Reserve slides

The collimator jaw



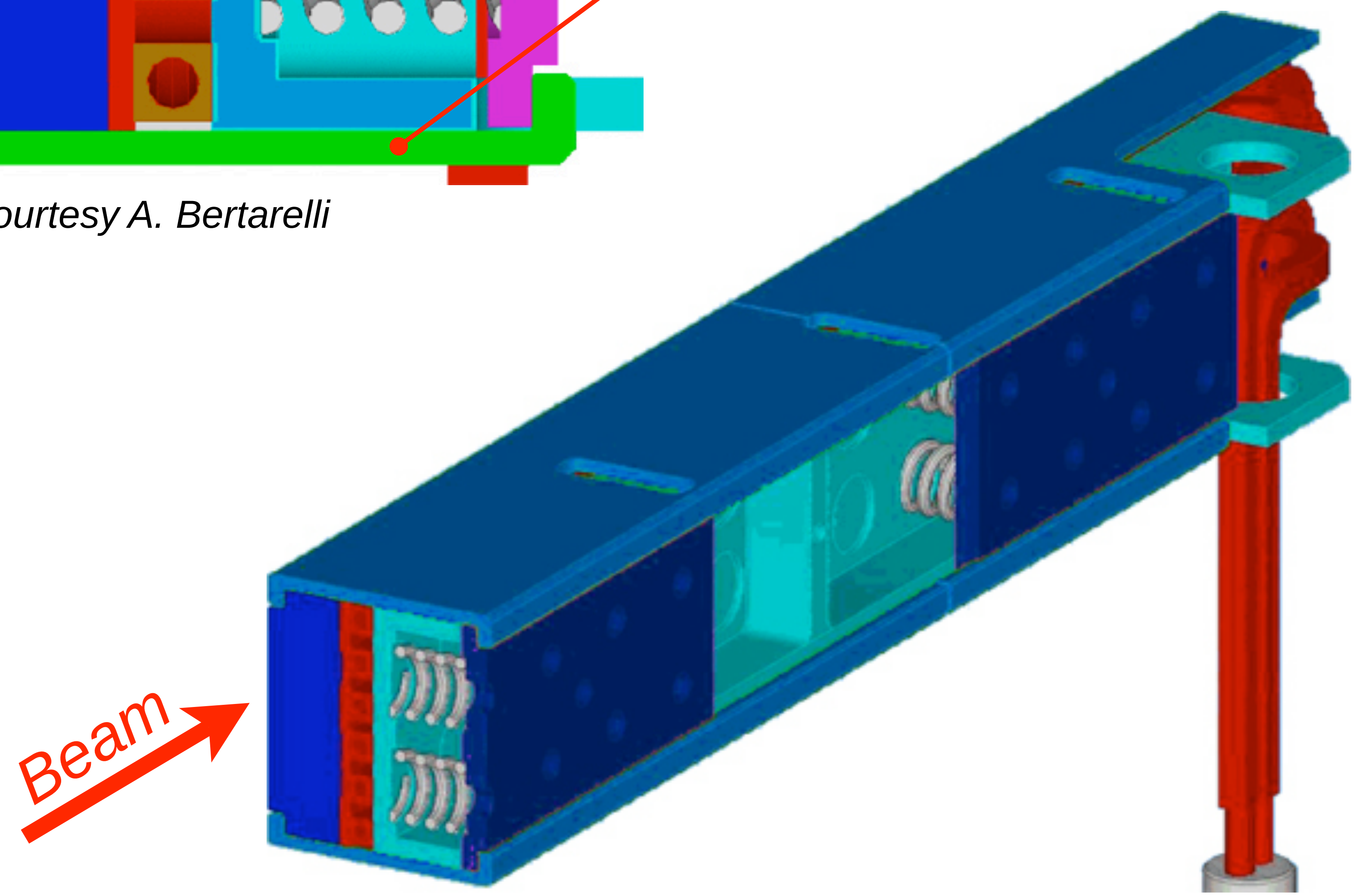


Courtesy A. Bertarelli

"Sandwich" design with different layers minimizes the thermal deformations:

Steady (~5 kW) ➙ < 30 μm

Transient (~30 kW) ➙ ~ 110 μm



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- **Hollow electron beams**:
  - Electron beam cannot be destroyed!
  - Very encouraging experimental results from Tevatron.

- Alternative methods are under investigation.

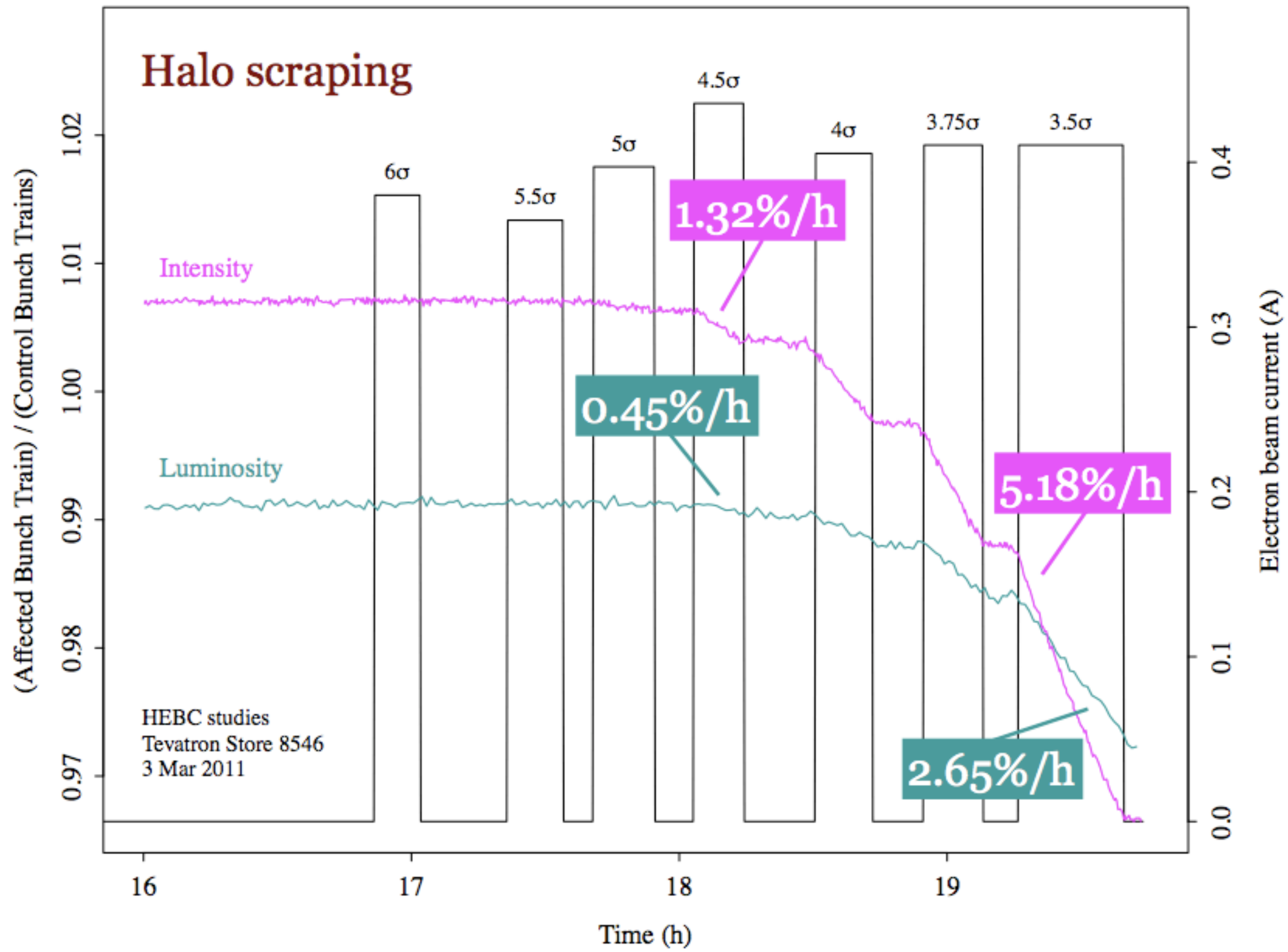
Hollow e-beam studies at Fermilab

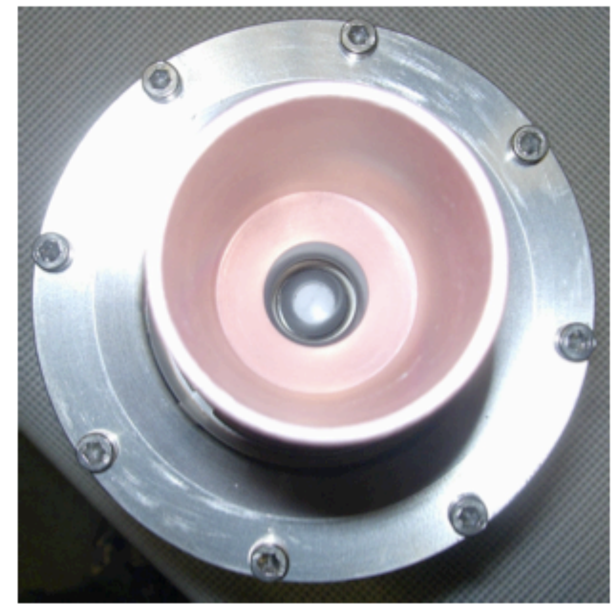
Paper submitted to Phy. Rev. Letter

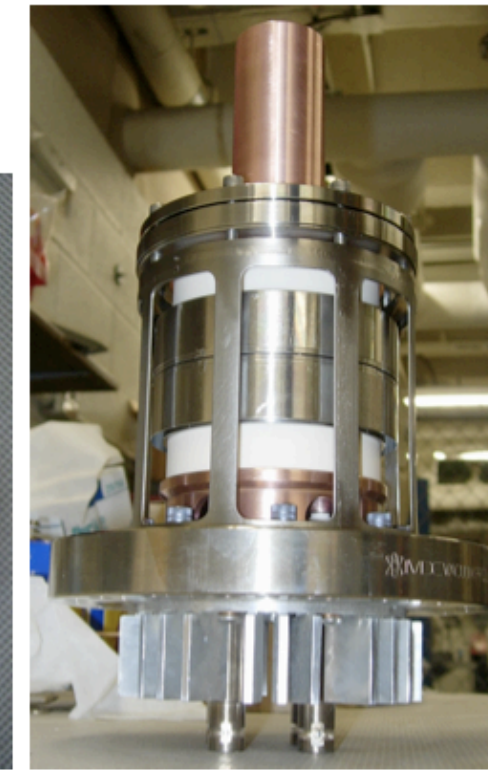
Collimation with hollow electron beams

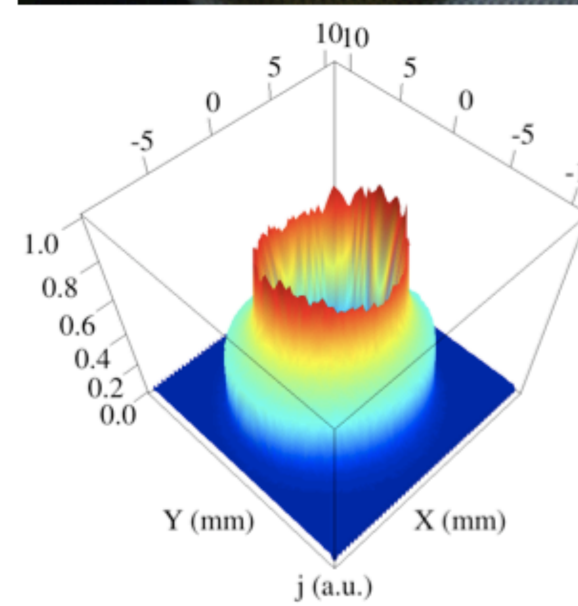
G. Stancari,* A. Valishev, G. Annala, G. Kuznetsov,† V. Shiltsev, D. A. Still, and L. G. Vorobiev
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, U.S.A.
(Dated: May 16, 2011)

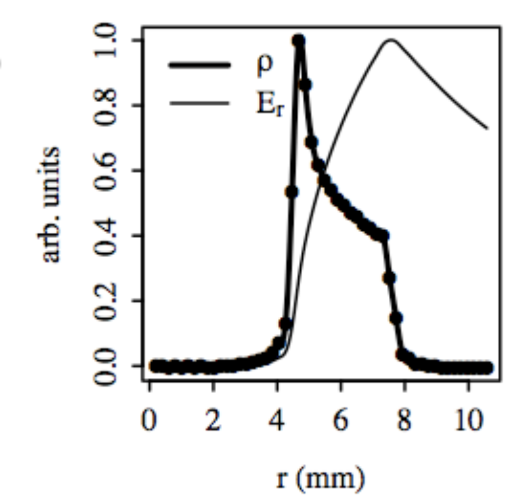
A novel concept of controlled halo removal for intense high-energy beams in storage rings and colliders is presented. It is based on the interaction of the circulating beam with a 5-keV, magnetically confined, pulsed hollow electron beam in a 2-m-long section of the ring. The electrons enclose the circulating beam, kicking halo particles transversely and leaving the beam core unperturbed. By acting as a tunable diffusion enhancer and not as a hard aperture limitation, the hollow electron beam collimator extends conventional collimation systems beyond the intensity limits imposed by tolerable losses. The concept was tested experimentally at the Fermilab Tevatron proton-antiproton collider. The first results on the collimation of 980-GeV antiprotons are presented.





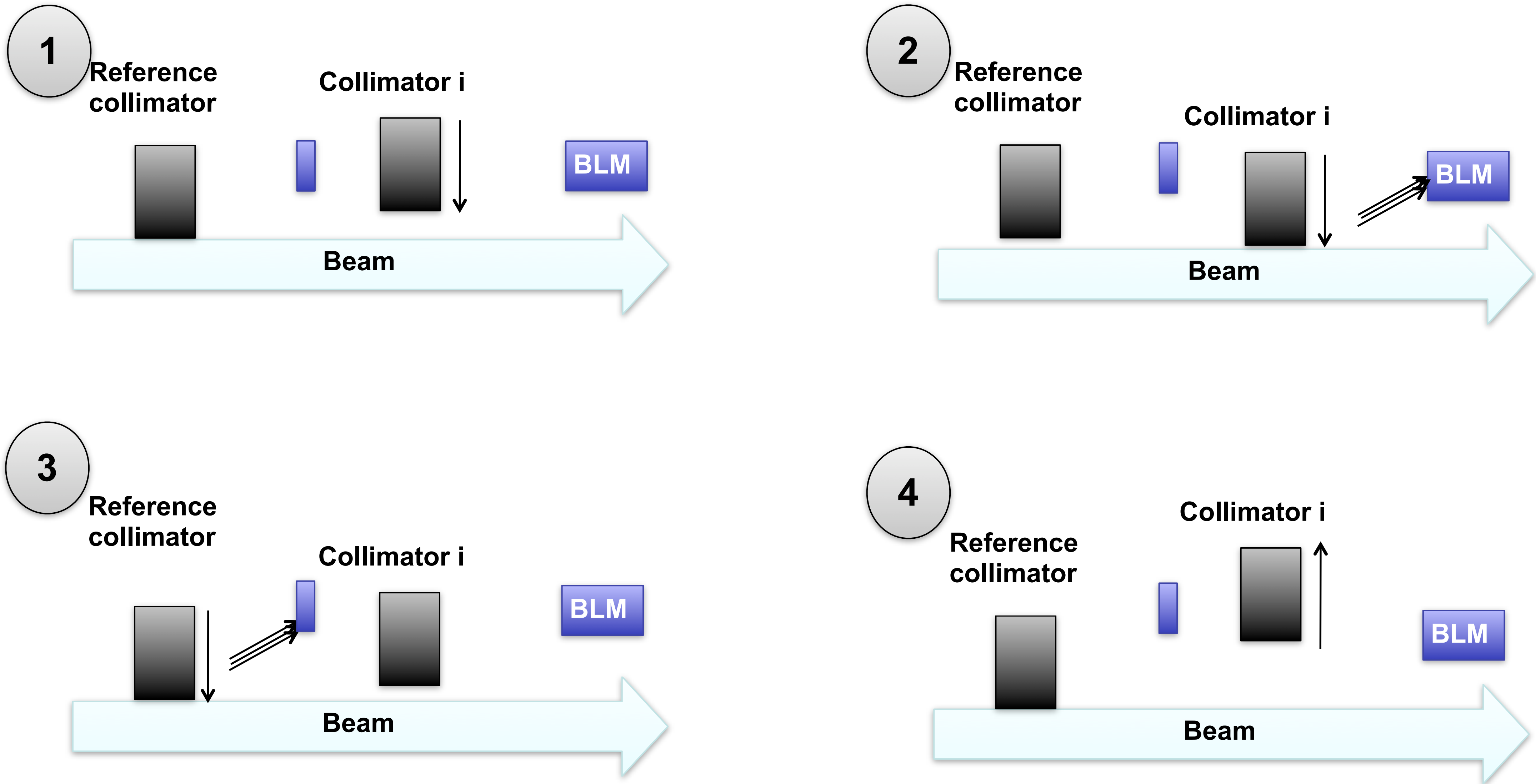






Courtesy of G. Stancari, Fermilab.

Collimator beam-based setup



R. Assmann

(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**) → <u>local beam position</u>.

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

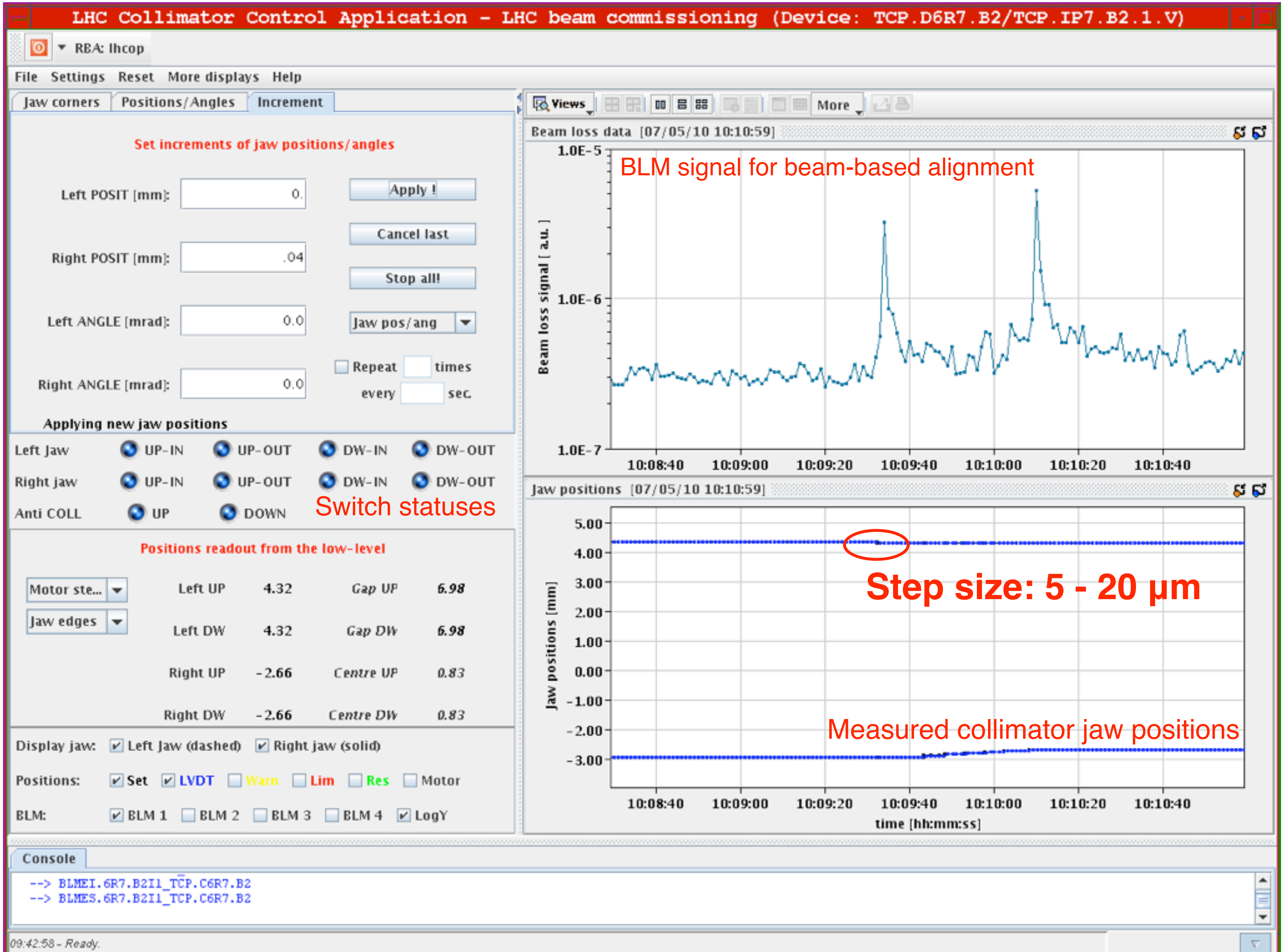
(4) Retract the collimator to the correct settings.

Tedious procedure that must be repeated for each machine configuration.

Beam-based parameters entered manually in big tables used for function setting generation.

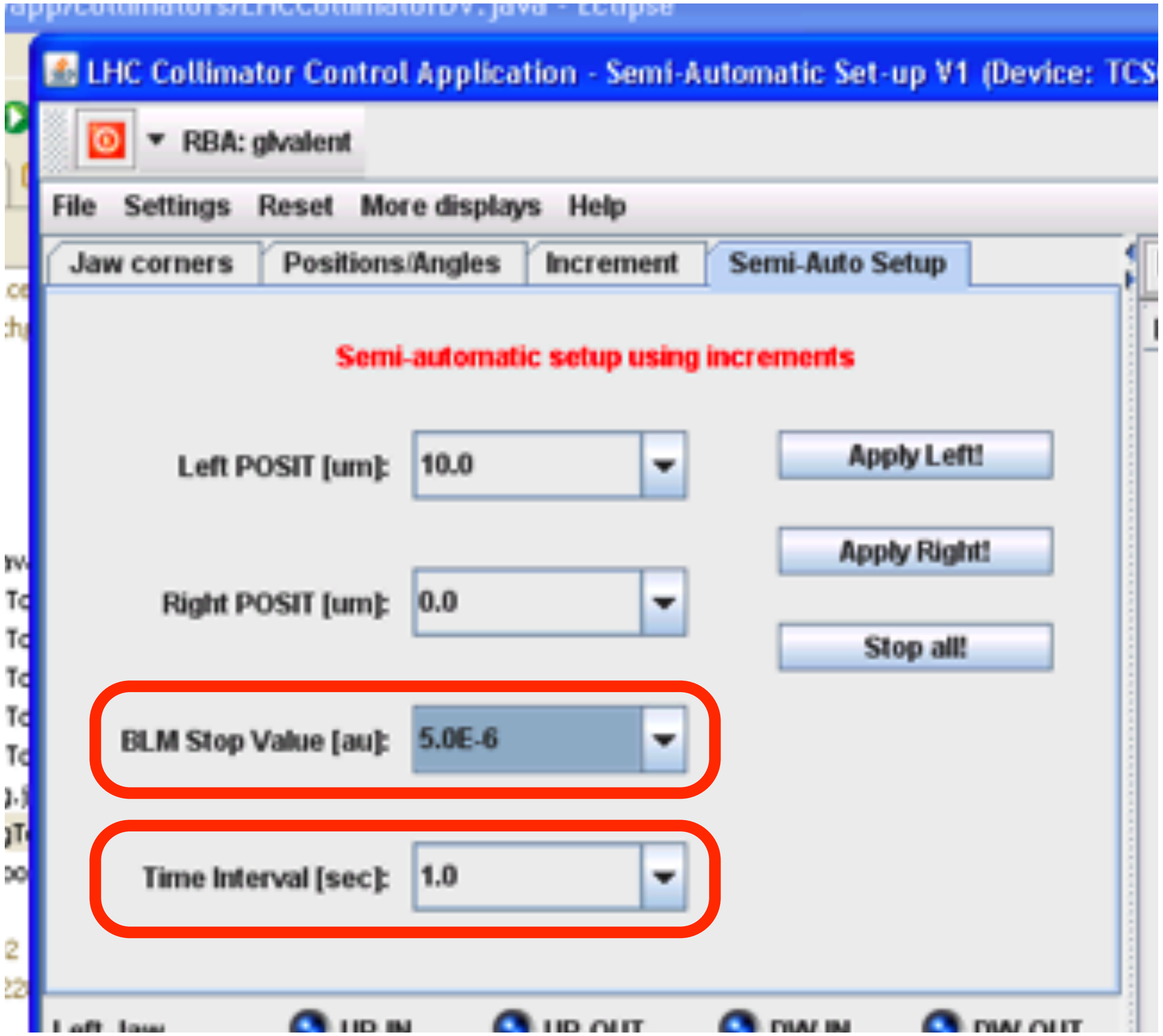
Setup in practice

Settings panel



Semi-automated alignment tool

New application panel under development



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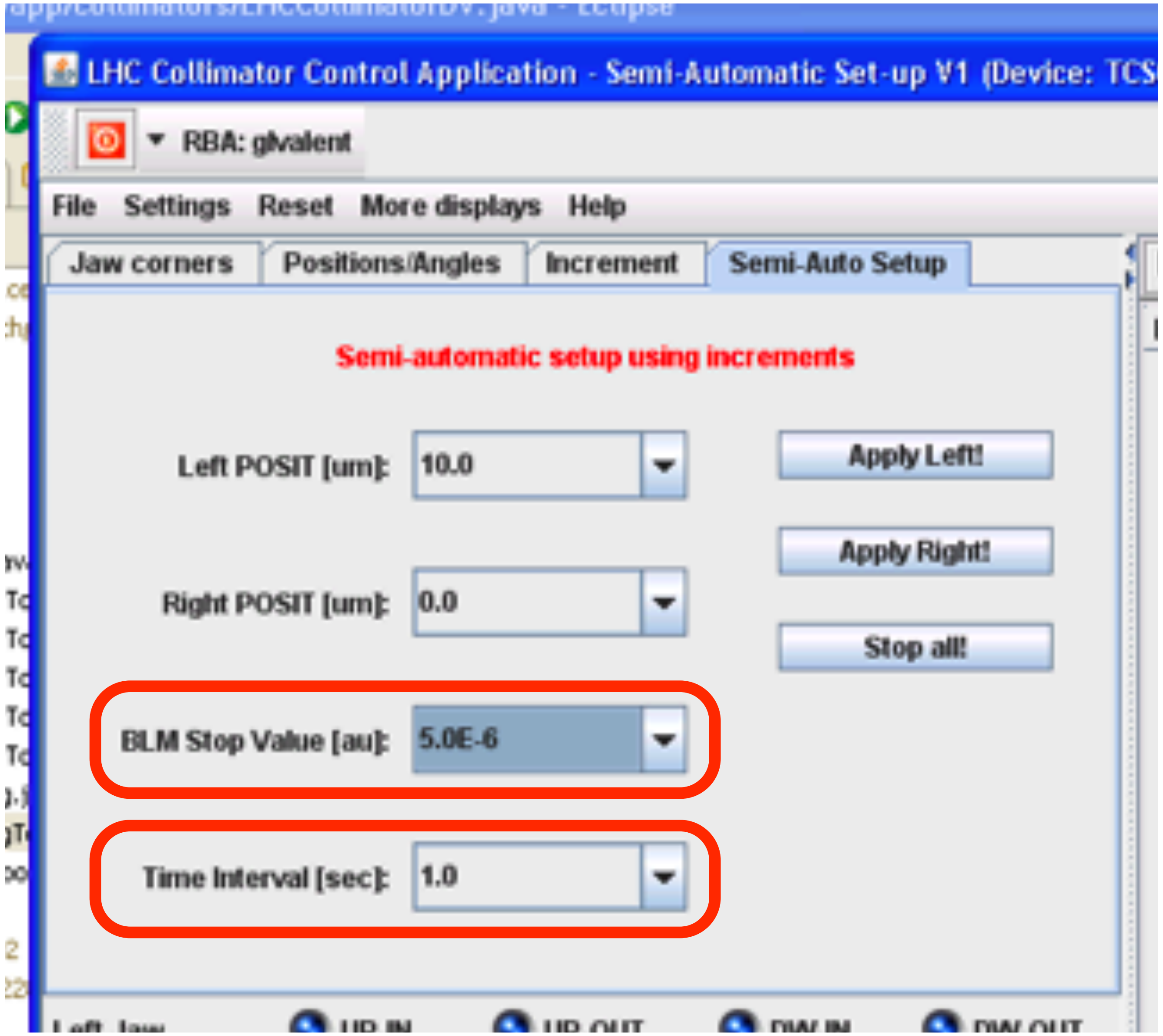
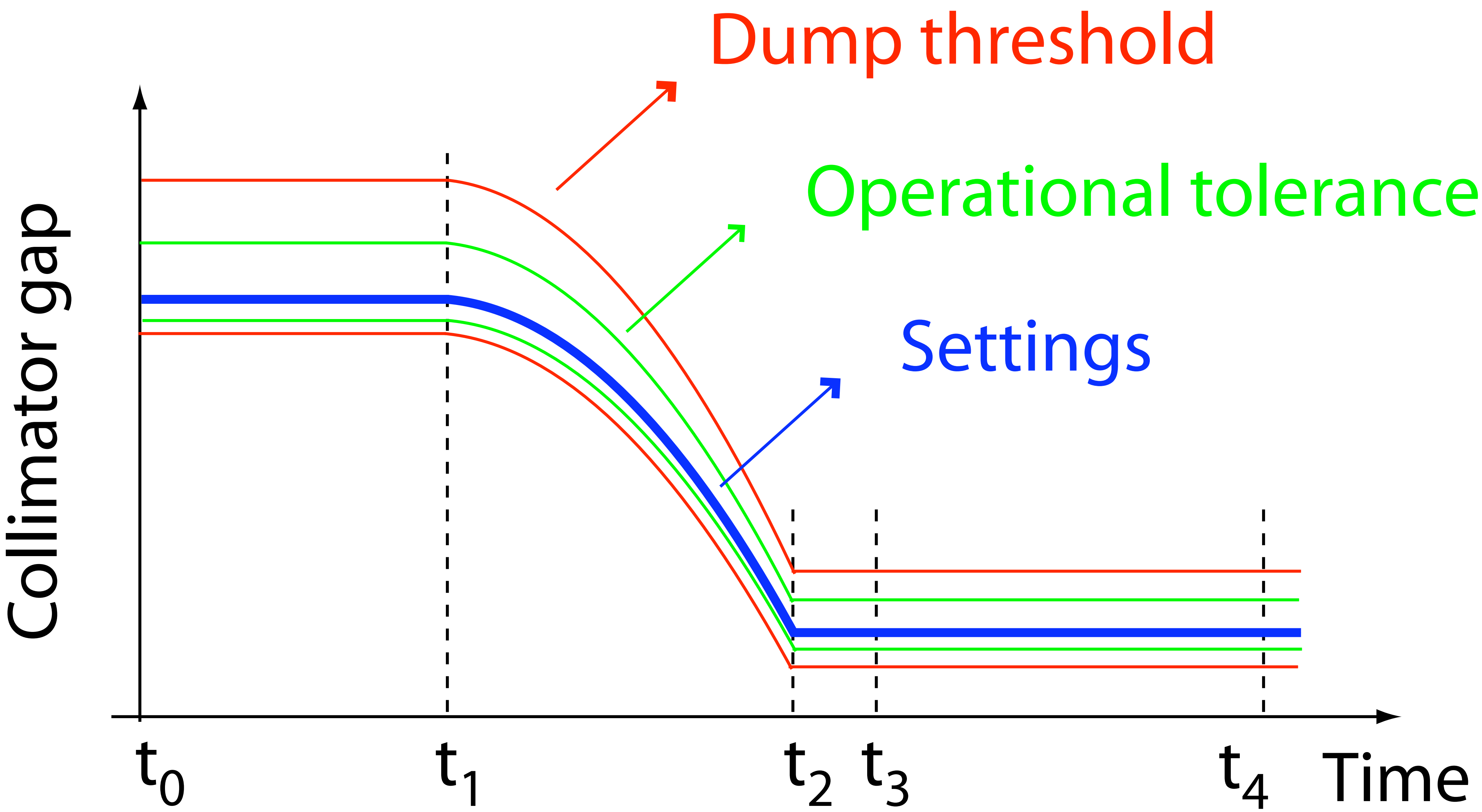


- Semi-automated setup functionality:
  - Choose BLM threshold;
  - Choose repetition rate;
  - Choose jaw and step size.
- Automated collection of beam-based parameters for whole system.
- Need tuning up...
- Working on full automated for 2012 (direct data from BLM system).
- PhD thesis work by G. Valentino.

Collimator dump thresholds



- **Inner** and **outer thresholds** as a function of **time** for each motor **axis** and **gap** (24 per collimator). Triggered by timing event (e.g. start of ramp).
- Internal clock: check at 100 Hz!
- "Double protection" → BIC loop broken AND jaw stopped.
- Redundancy: **maximum allowed gap versus energy** (2 per collimator).
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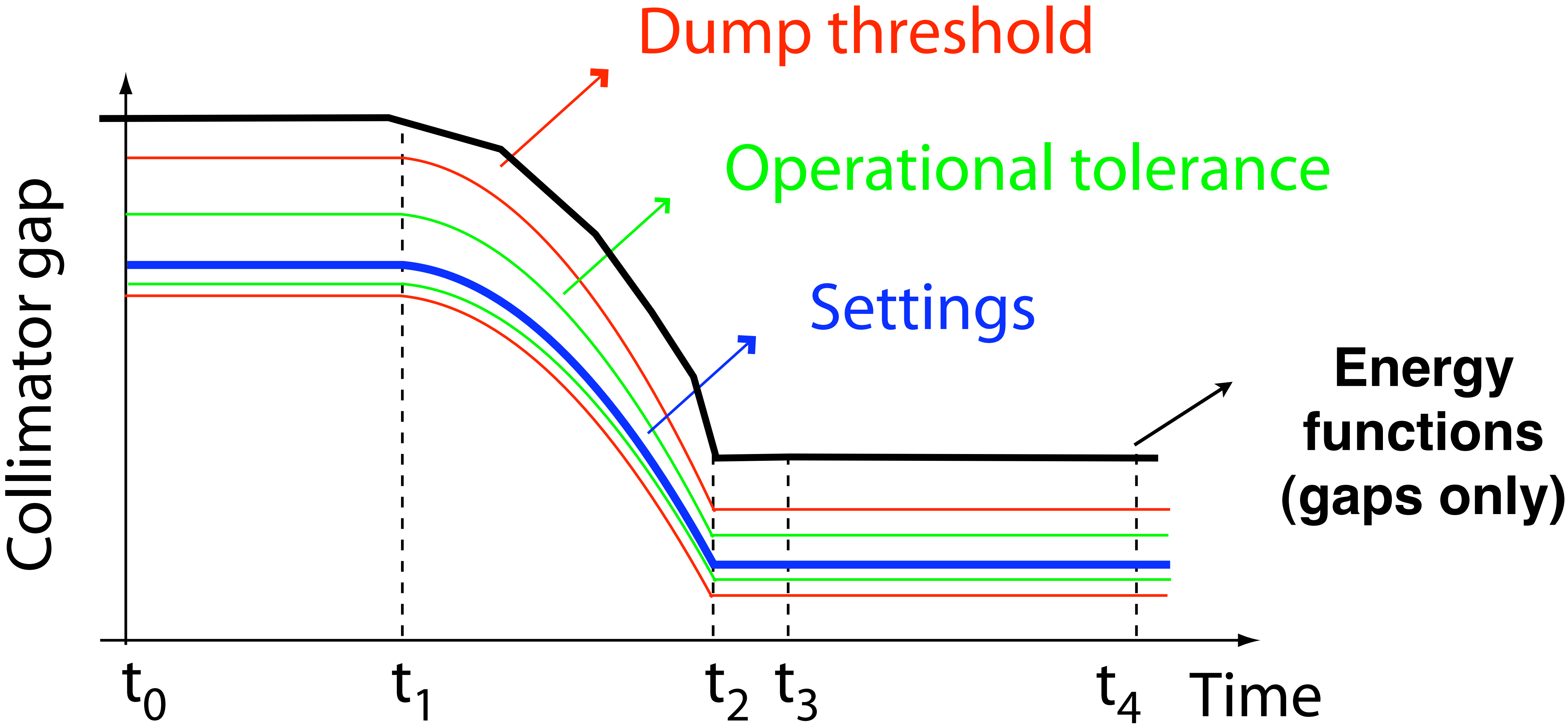

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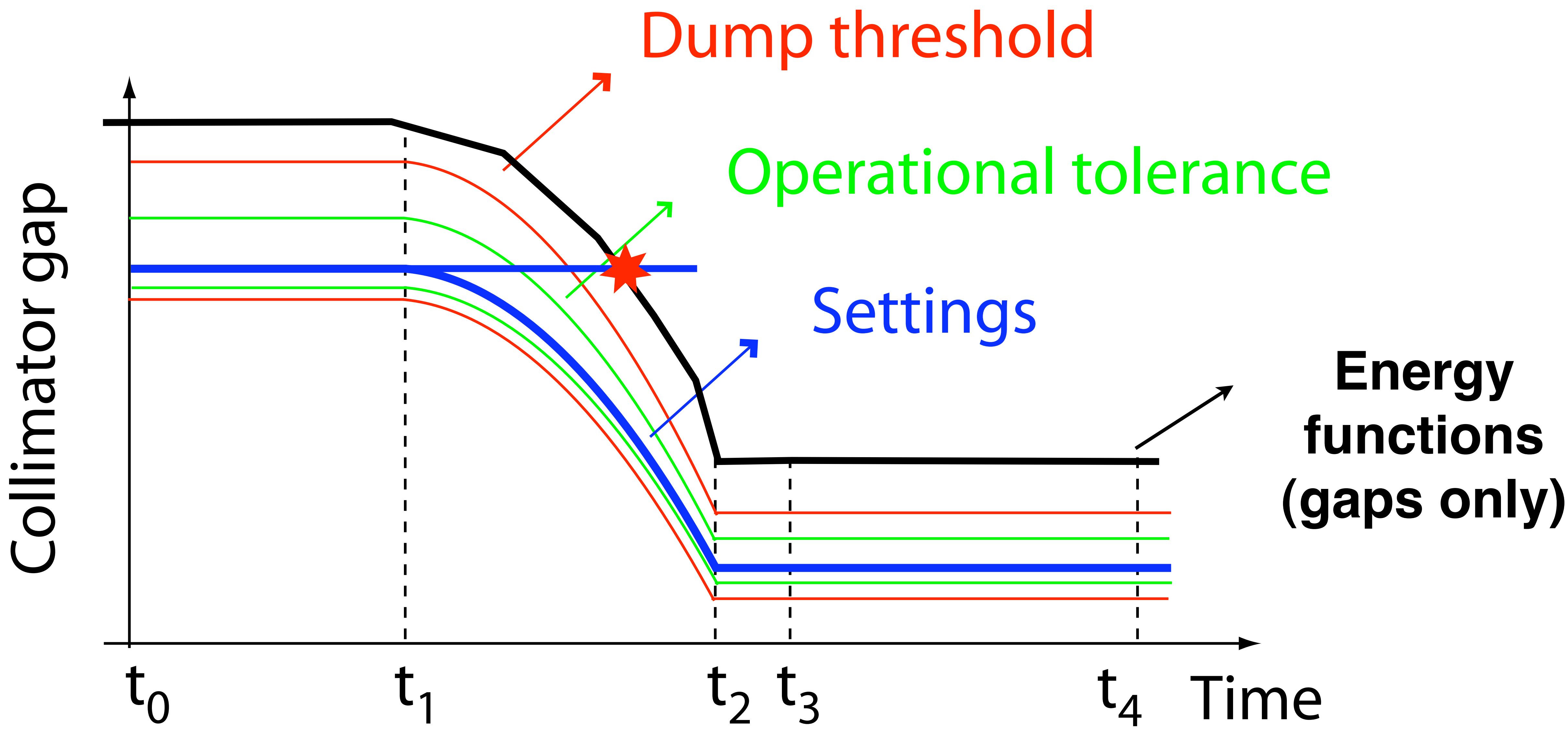

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