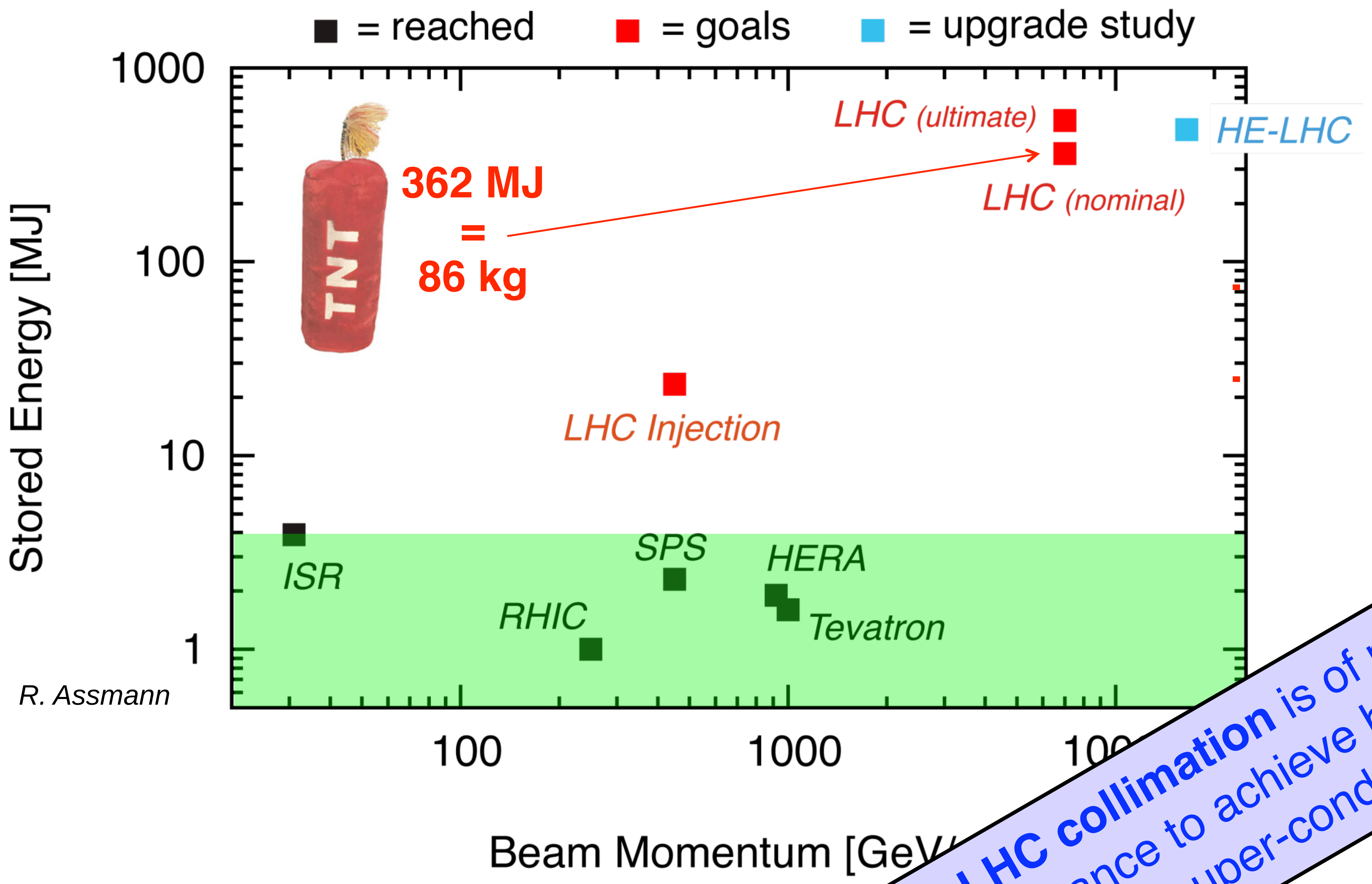
LHC Collimation Review 2011
CERN
Geneva, 14th-15th June 2011

Introduction to LHC Collimation

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

LHC stored energy challenge



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

2010: **Factor ~10 above state-of-th... he Tevatron!**

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

No beam-induced quenches with circulating beams so far.

Outline

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

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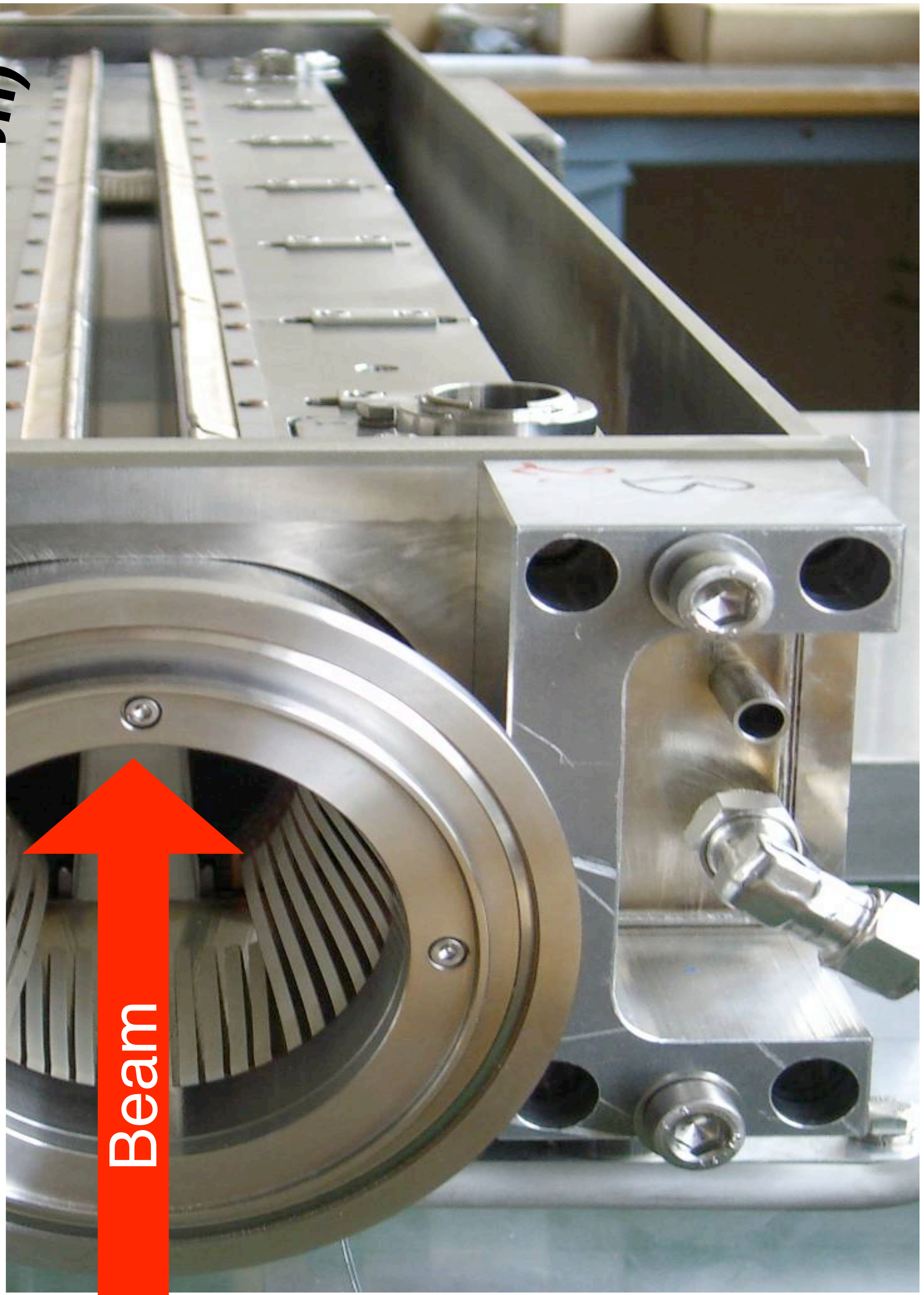
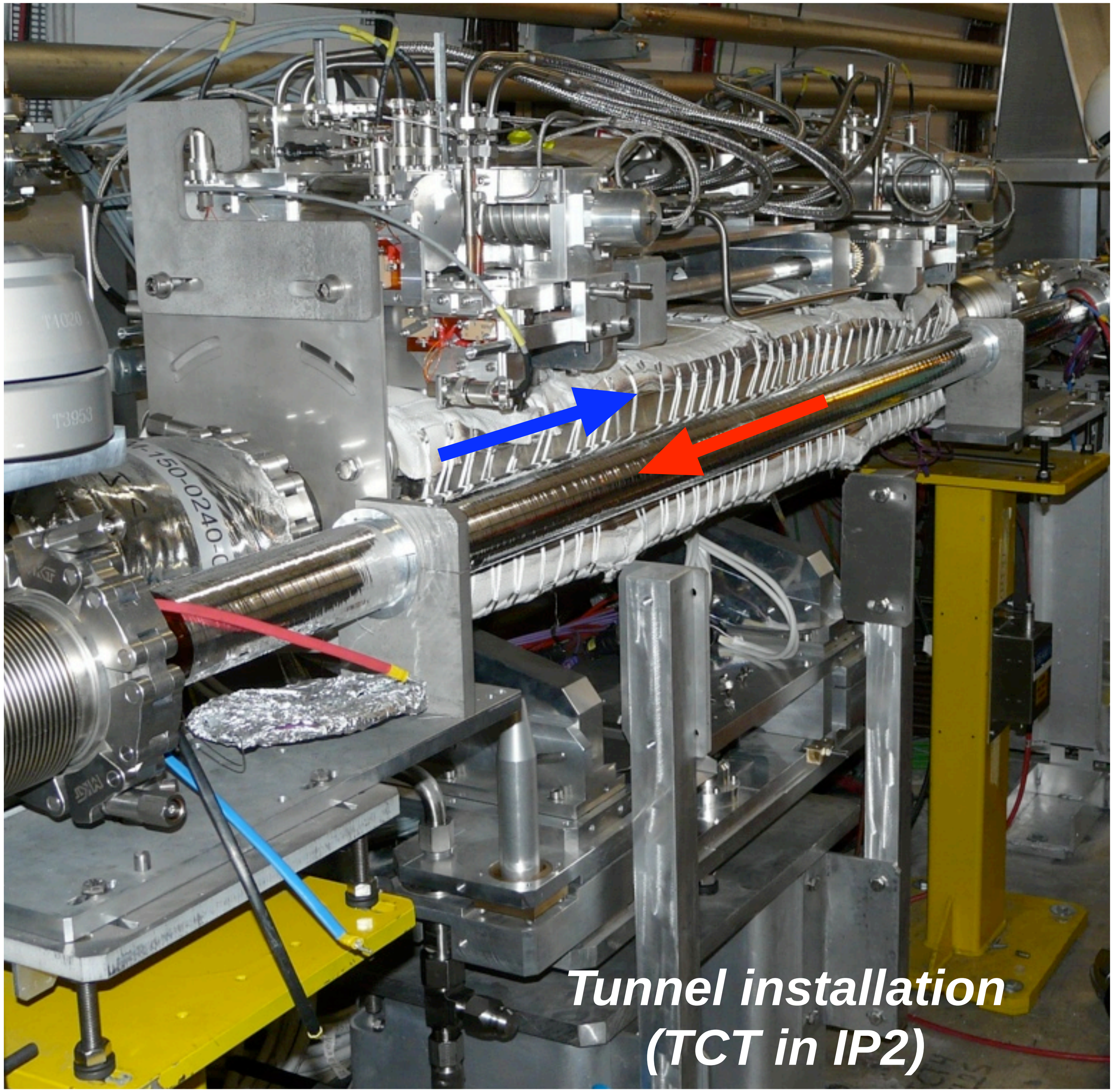
The Phase I LHC collimator

What the beam sees!

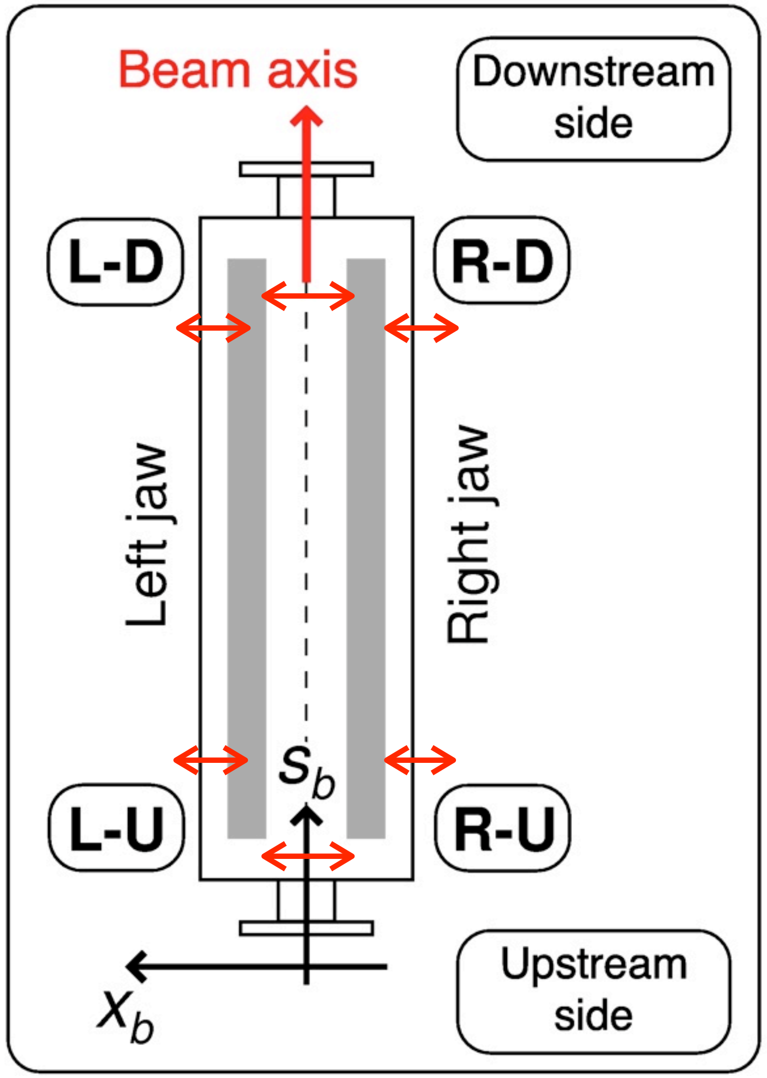


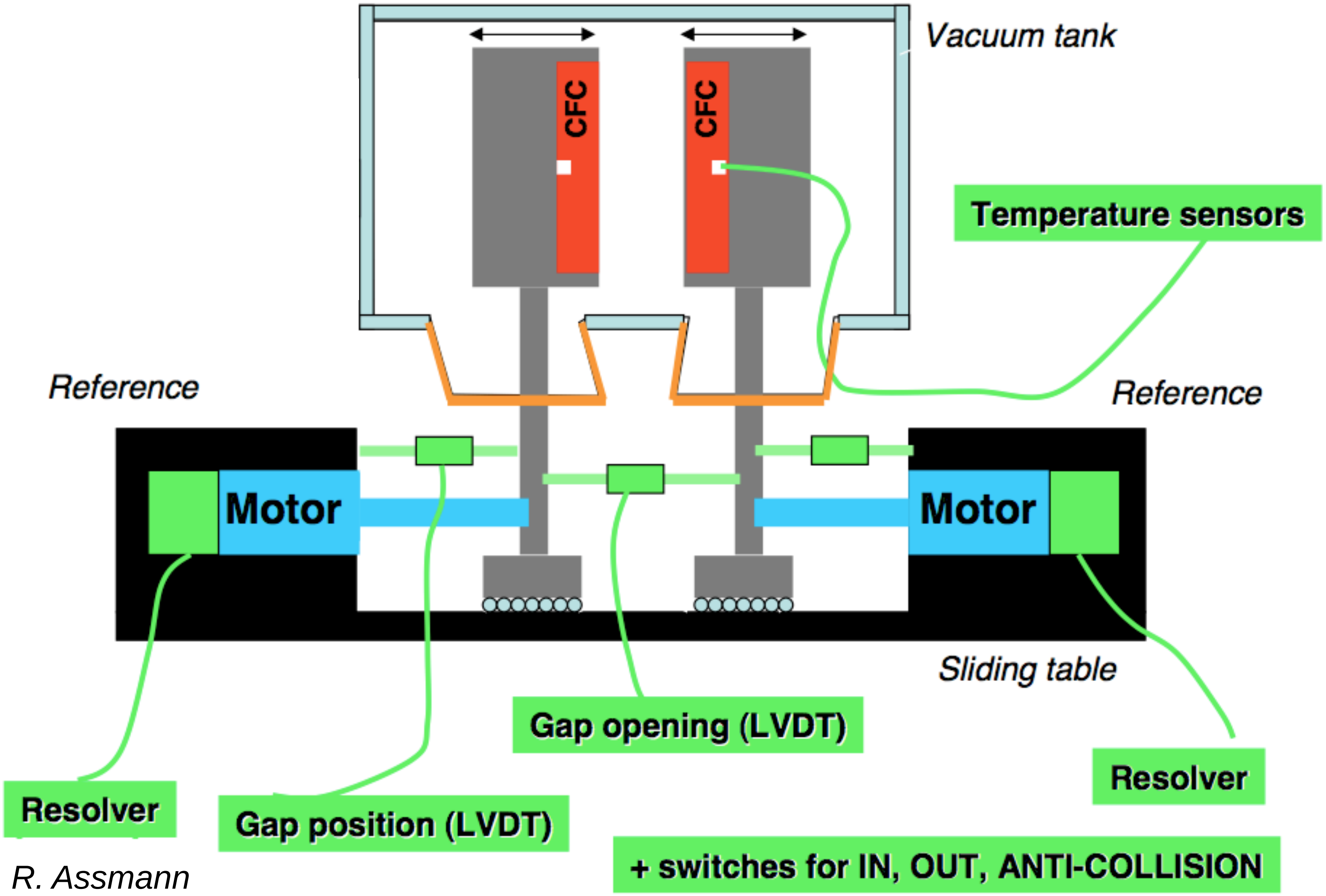


Tunnel installation (TCT in IP2)

Two-jaw design:
Beam cannot “drift away”!

Jaw positions: controls and survey





R. Assmann

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

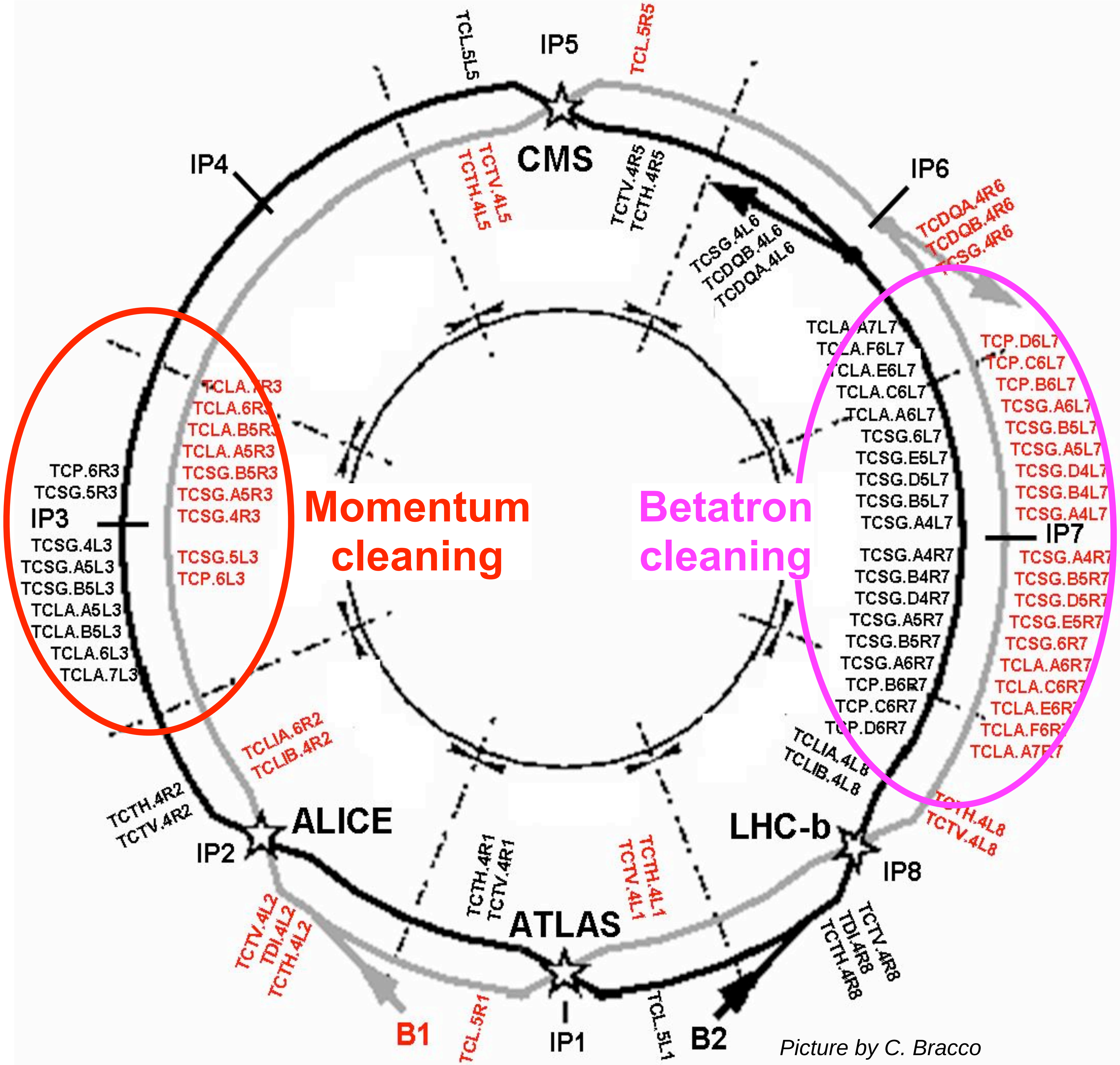
- **8 tertiary (2 per IP)**

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!

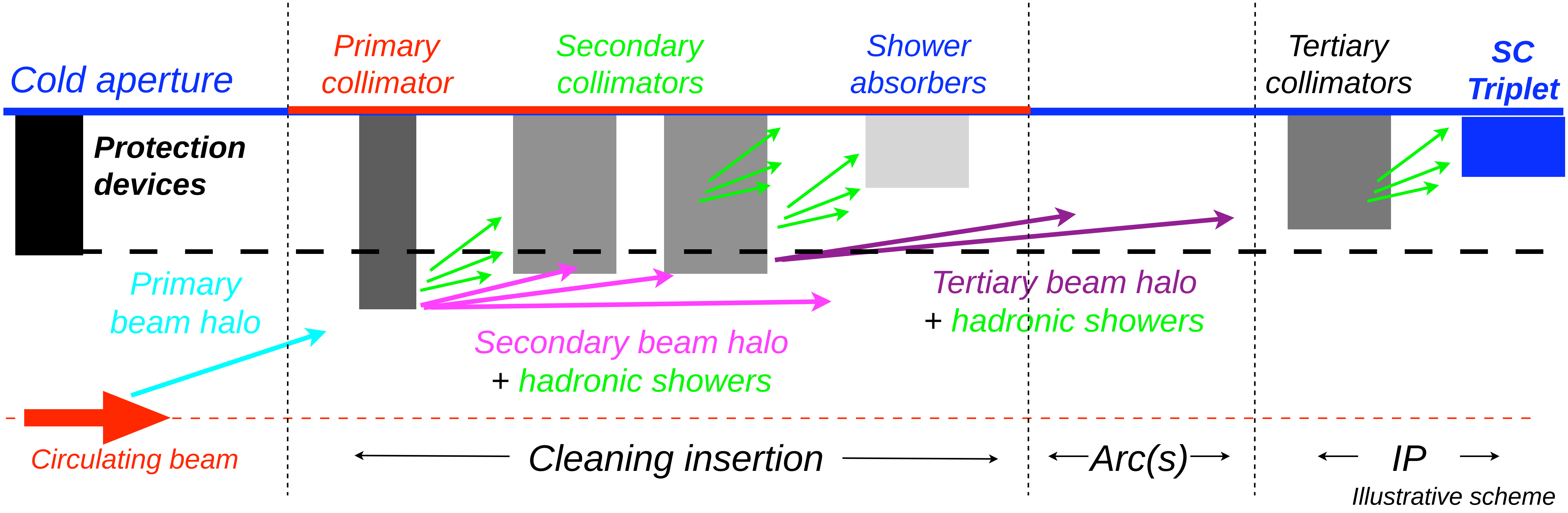


Momentum cleaning

Betatron cleaning

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!

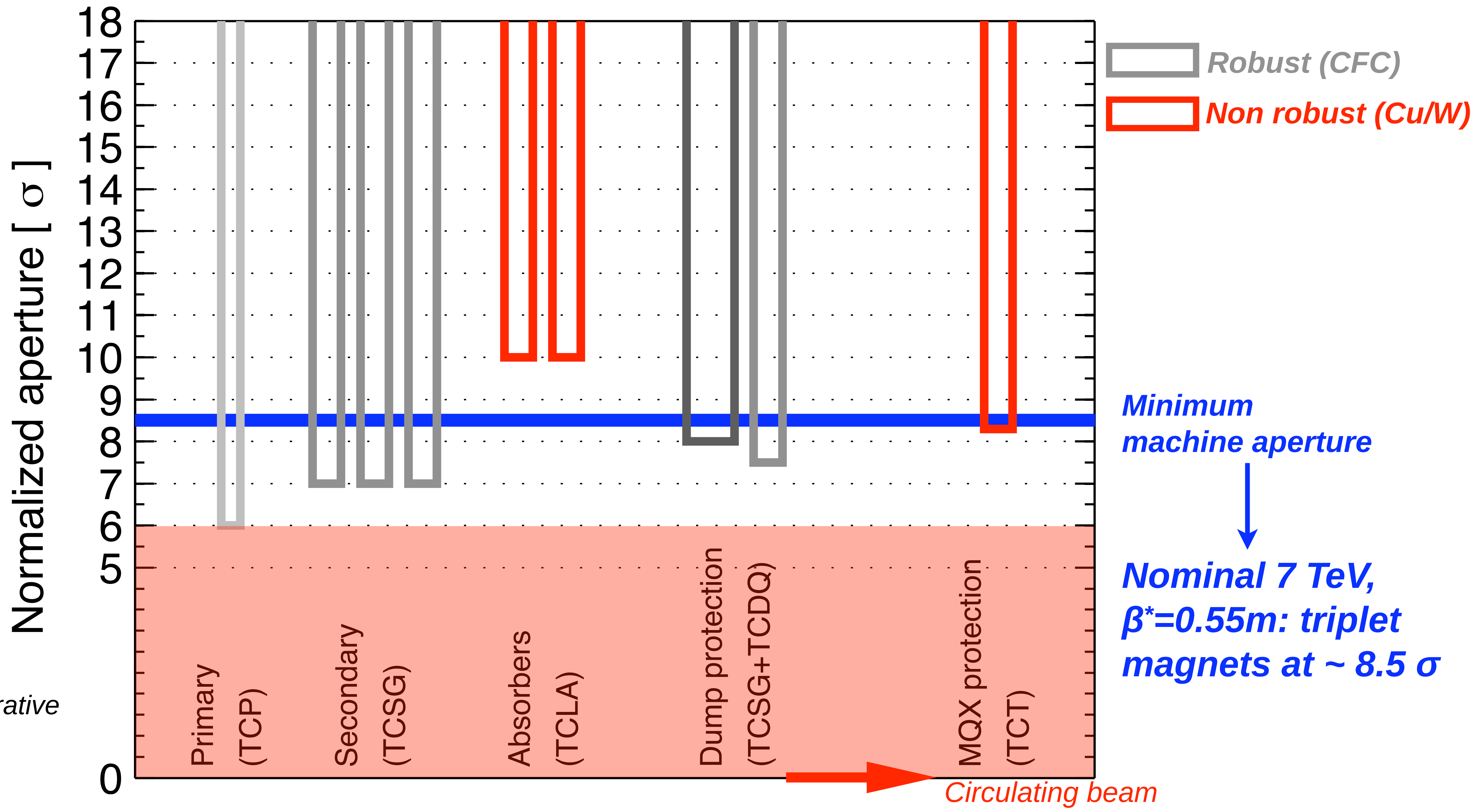
- LHC **aperture** sets the scale: **Injection: ≥ 12.5 σ**

  3.5 TeV, β*=1.5m: ≥ 14.0 σ

- **Beam-based setup** → local beam position and beam size at each collimator.

- Primary and secondary collimators are **robust** (Carbon-based).
  Absorbers and tertiary collimators (Tungsten) are not and must be protected.

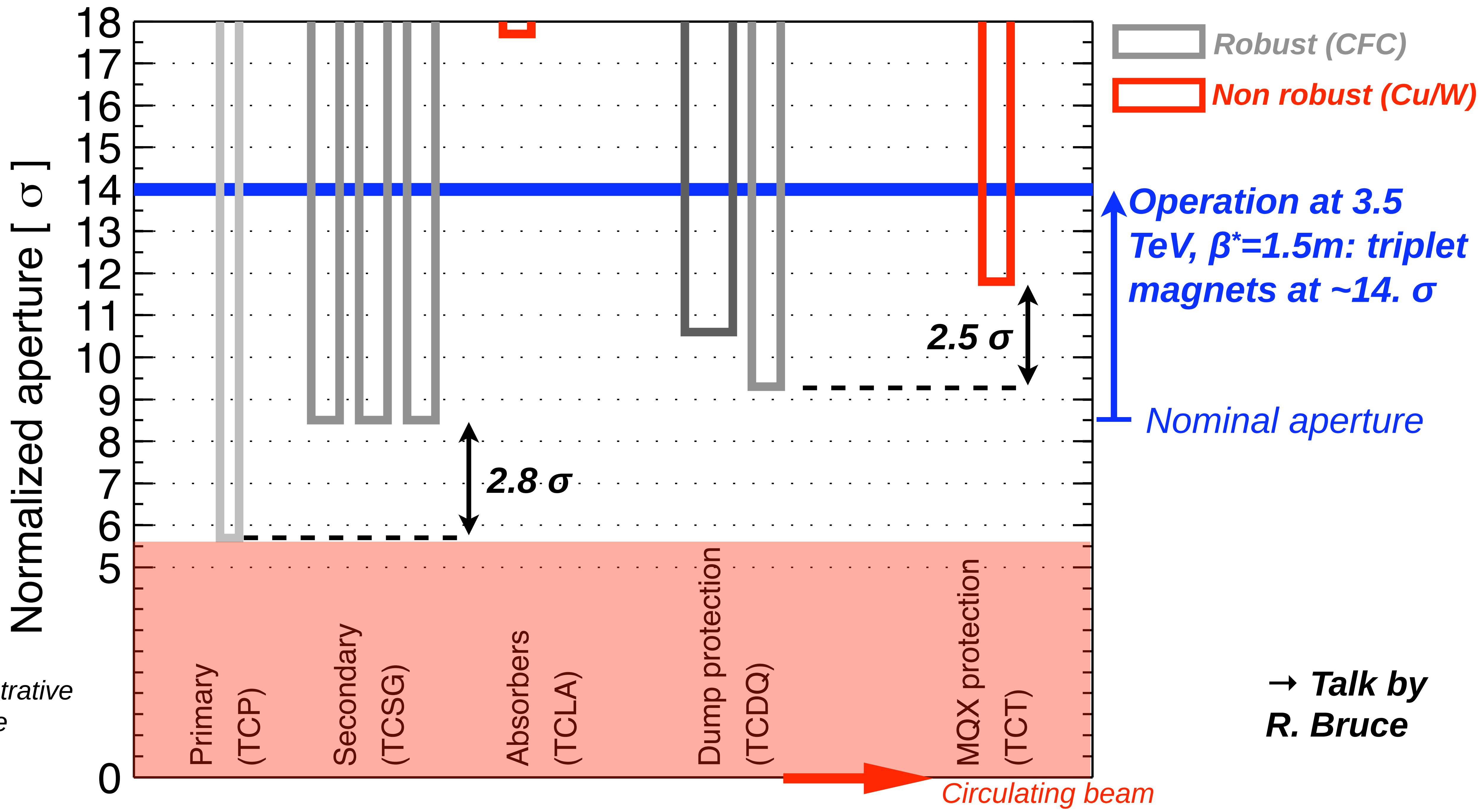
Nominal collimator settings at 7 TeV



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.

Relaxed collimator settings (2010-11)

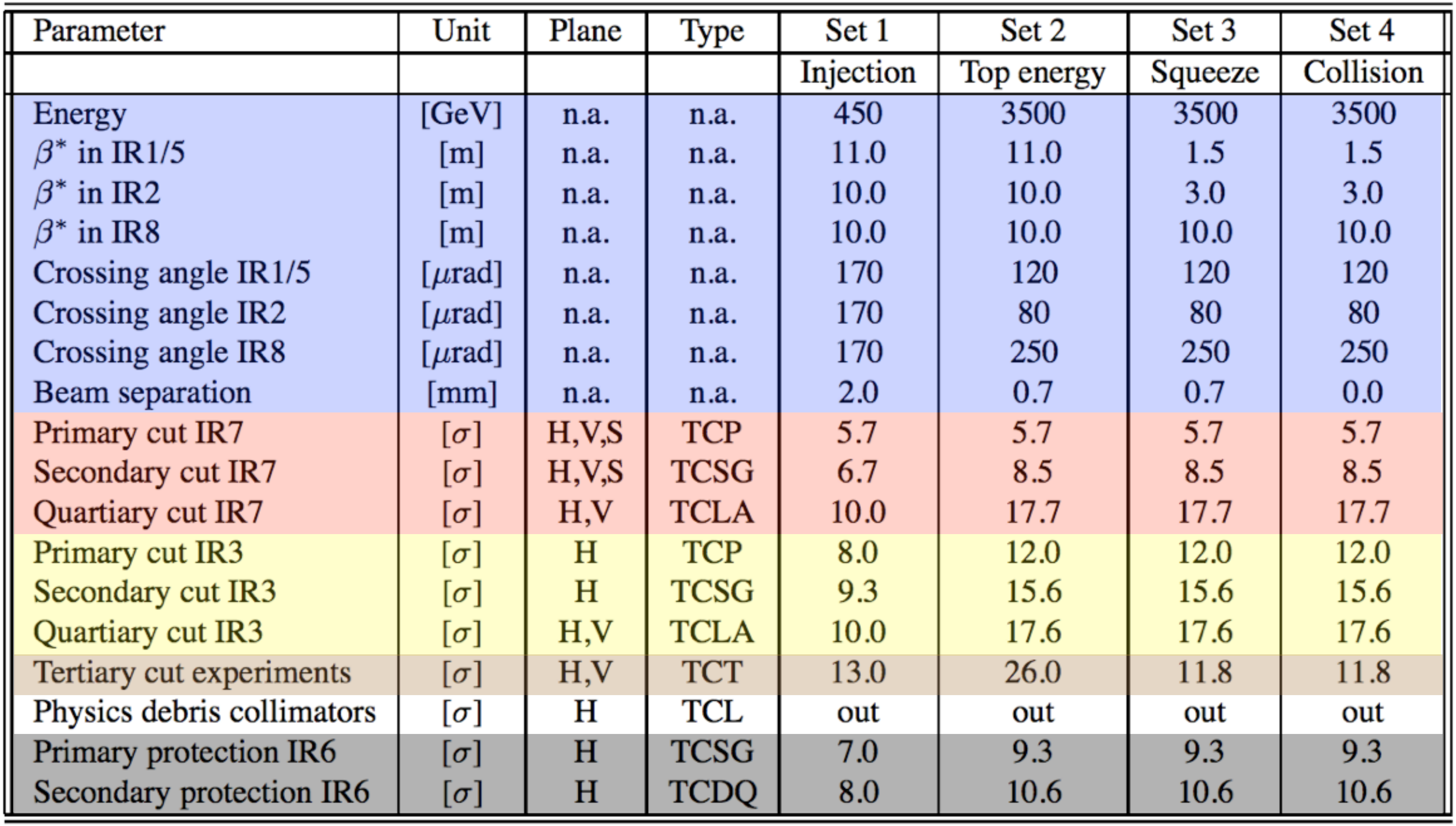


An illustrative scheme

→ ***Talk by R. Bruce***

- 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).

Present operational settings

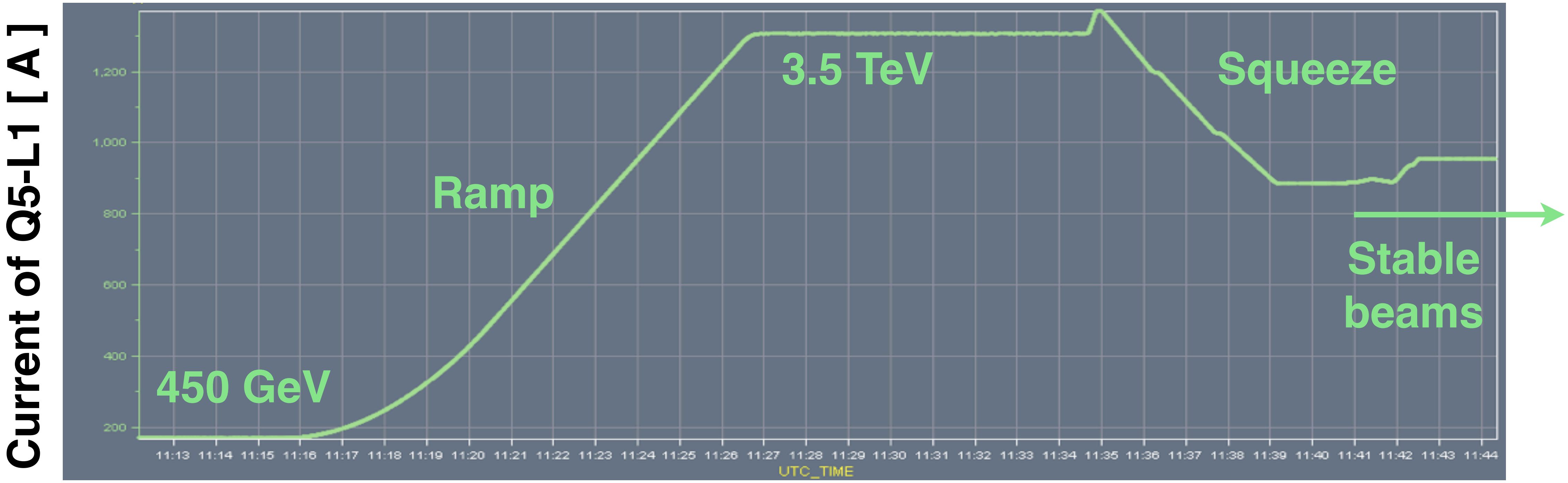


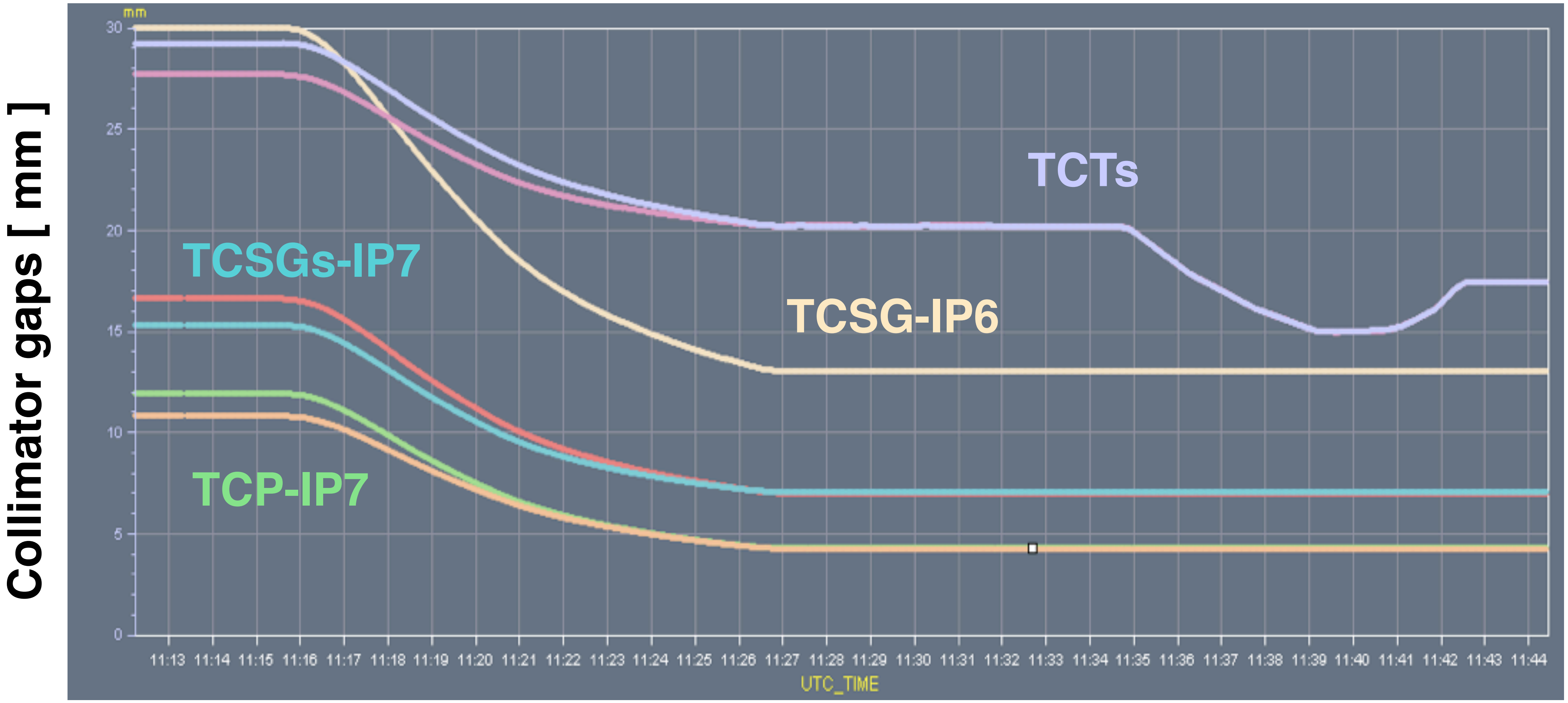
Parameter	Unit	Plane	Type	Set 1	Set 2	Set 3	Set 4
				Injection	Top energy	Squeeze	Collision
Energy	[GeV]	n.a.	n.a.	450	3500	3500	3500
β^* in IR1/5	[m]	n.a.	n.a.	11.0	11.0	1.5	1.5
β^* in IR2	[m]	n.a.	n.a.	10.0	10.0	3.0	3.0
β^* in IR8	[m]	n.a.	n.a.	10.0	10.0	10.0	10.0
Crossing angle IR1/5	[μrad]	n.a.	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.

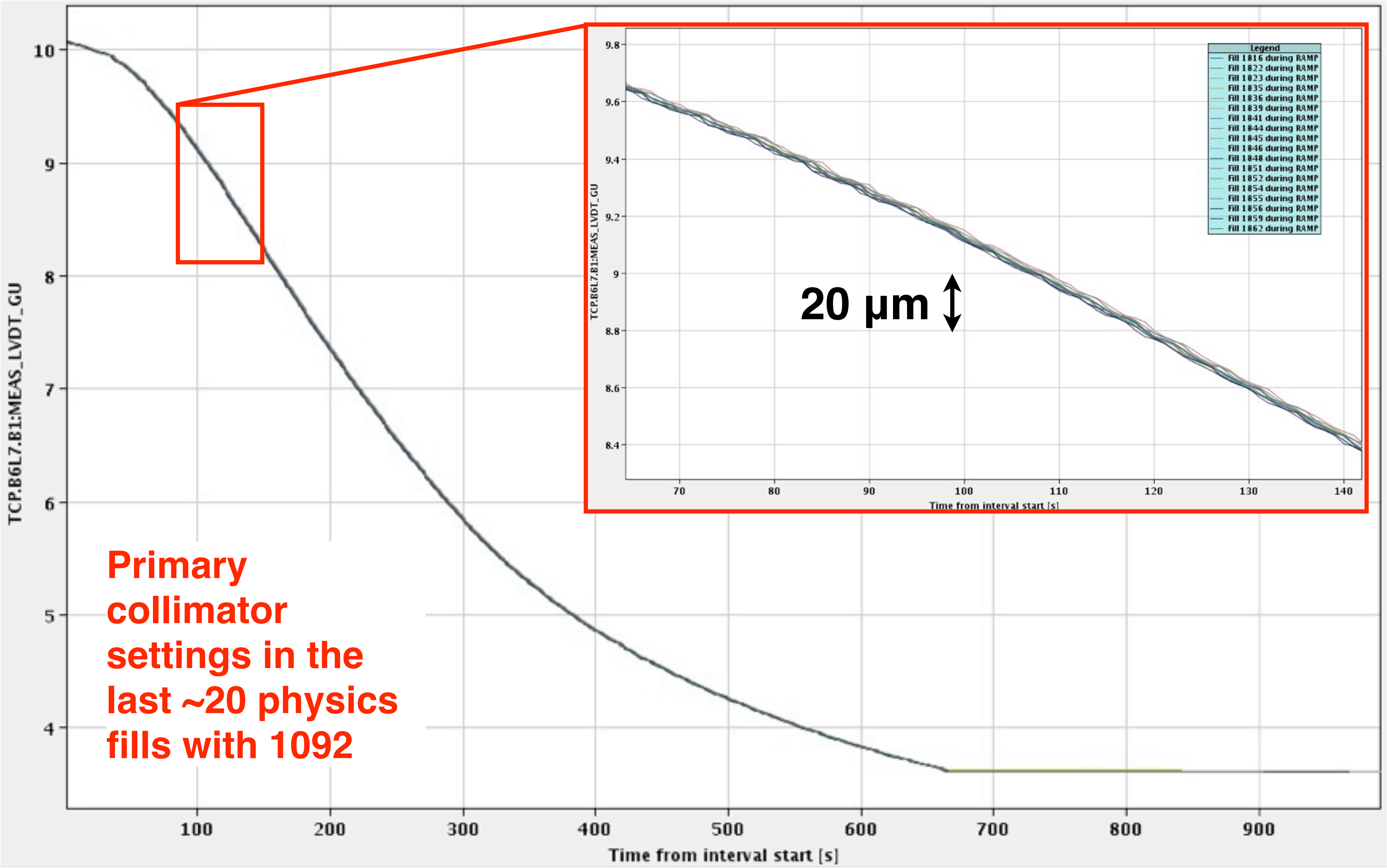
Handling of collimator settings is fully **automated** for the operation crews!

Collimator settings in practice





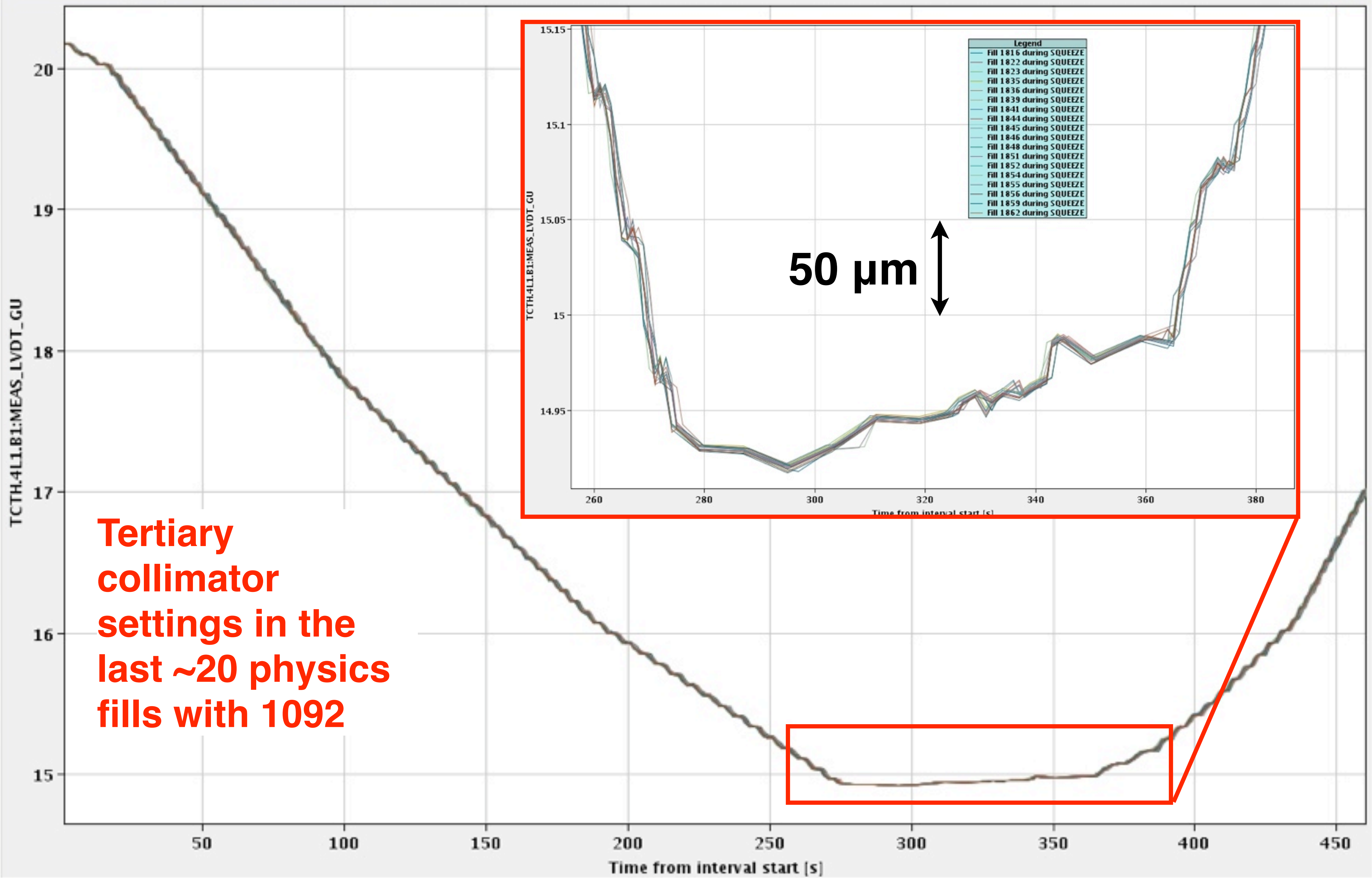
Reproducibility of settings - TCPs



20 µm

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

Reproducibility of settings - TCTs



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

Some numbers...

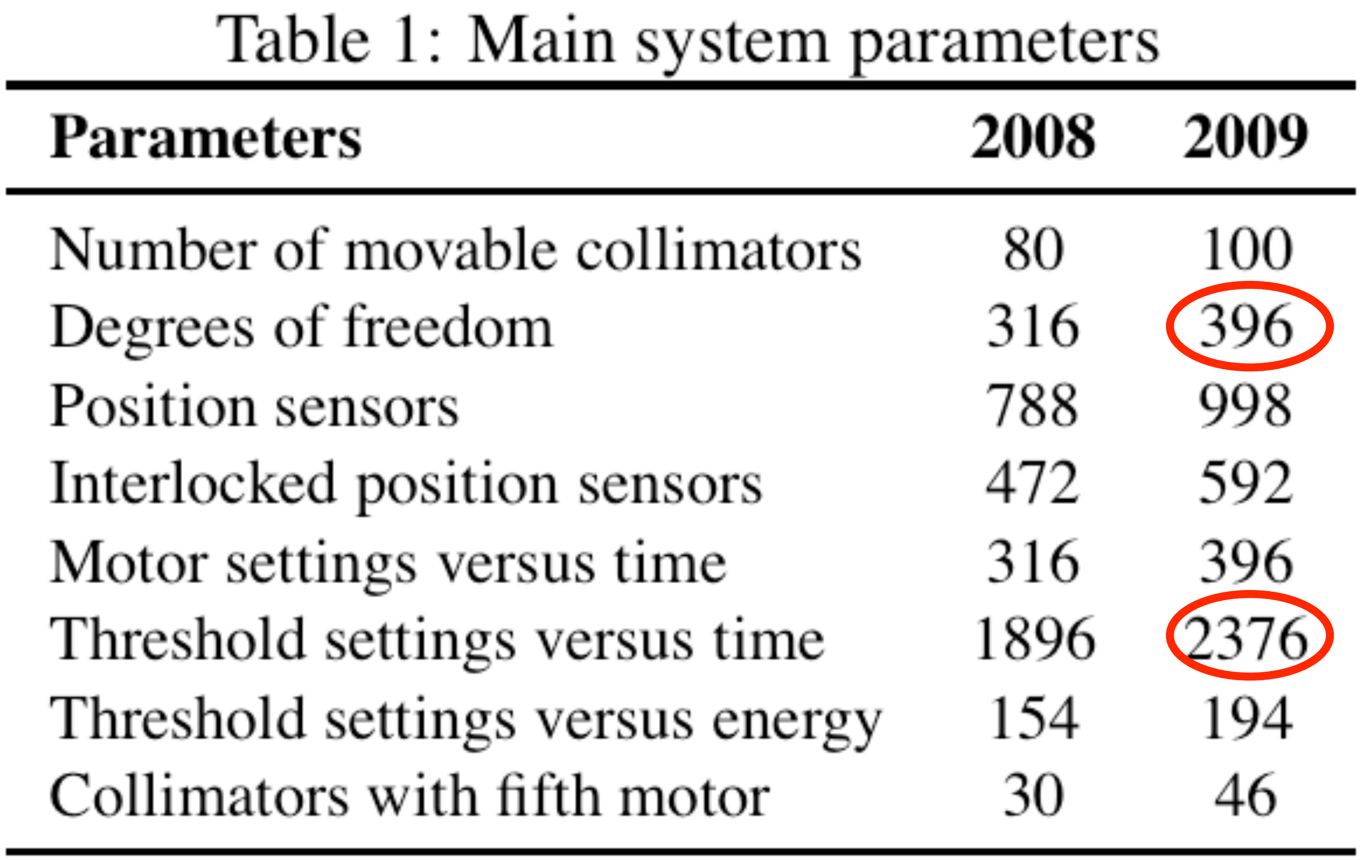


Table 1: Main system parameters

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***

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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Cleaning efficiency and quench limit

Definitions:

Local cleaning inefficiency

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

Assumed quench limits (loss rates)

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

Appropriate scaling vs. beam energy

Critical cleaning at quench limit

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

Updated figures based on beam measurements presented by D. Wollmann

Performance reach of the system

Quench limit

Beam lifetime

LHC intensity reach

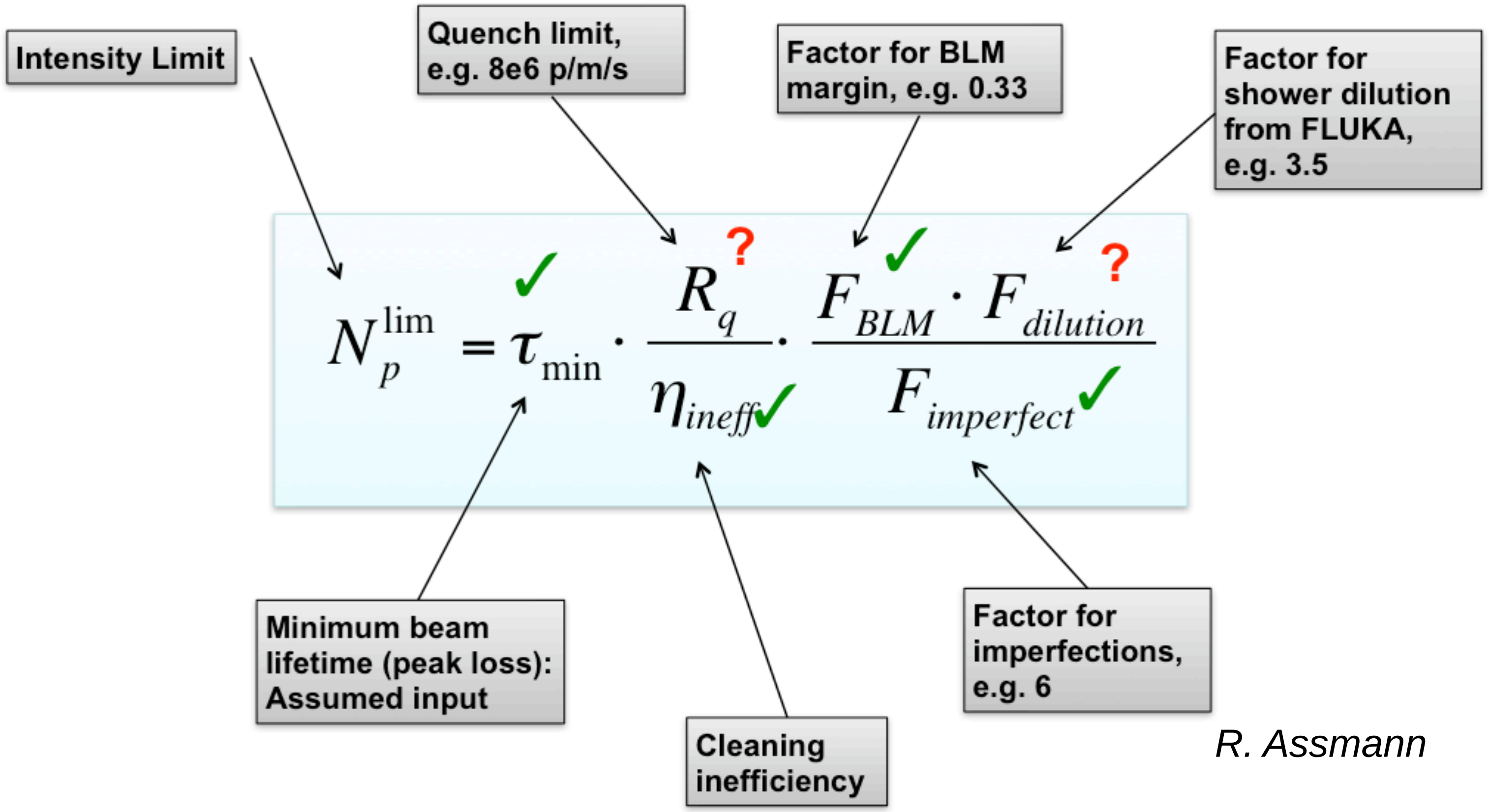
$$\boxed{N_{\mathrm{tot}} = \frac{\tau R_q}{\tilde{\eta}_c}}$$

Collimation cleaning

Design loss assumptions

Performance reach depends on:

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



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

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

Minimum beam lifetime (peak loss): Assumed input

Cleaning inefficiency

Factor for imperfections, e.g. 6

R. Assmann

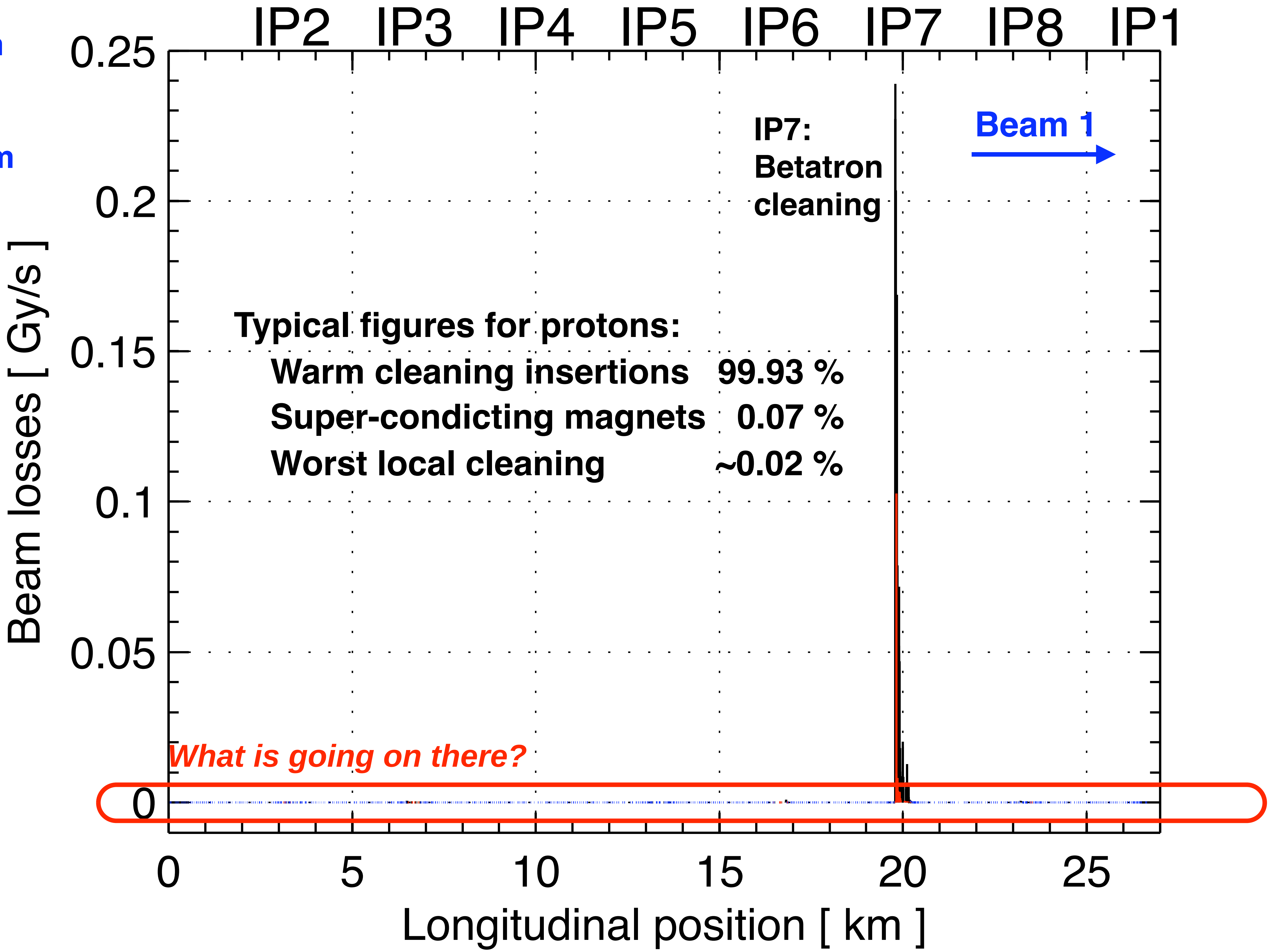
Our design specification:

Mode	**T** [s]	τ [h]	$\mathrm{R}_{\mathrm{loss}}$ [p/s]	$\mathrm{P}_{\mathrm{loss}}$ [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

Losses in physics conditions

4000 beam loss monitors along 27 km



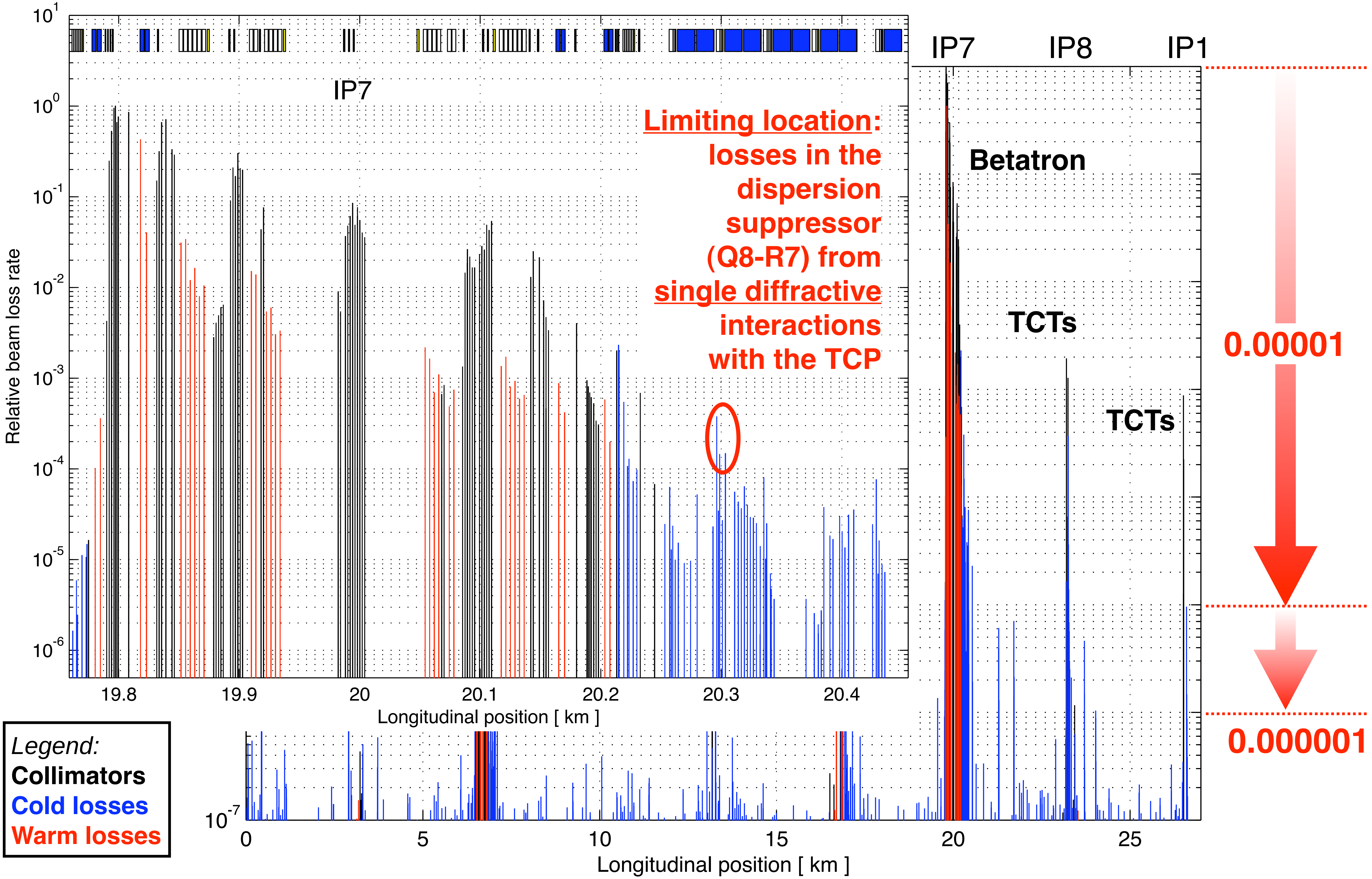
IP7: Betatron cleaning

Typical figures for protons:

Warm cleaning insertions	**99.93 %**
Super-condicting magnets	**0.07 %**
Worst local cleaning	**~0.02 %**

What is going on there?

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



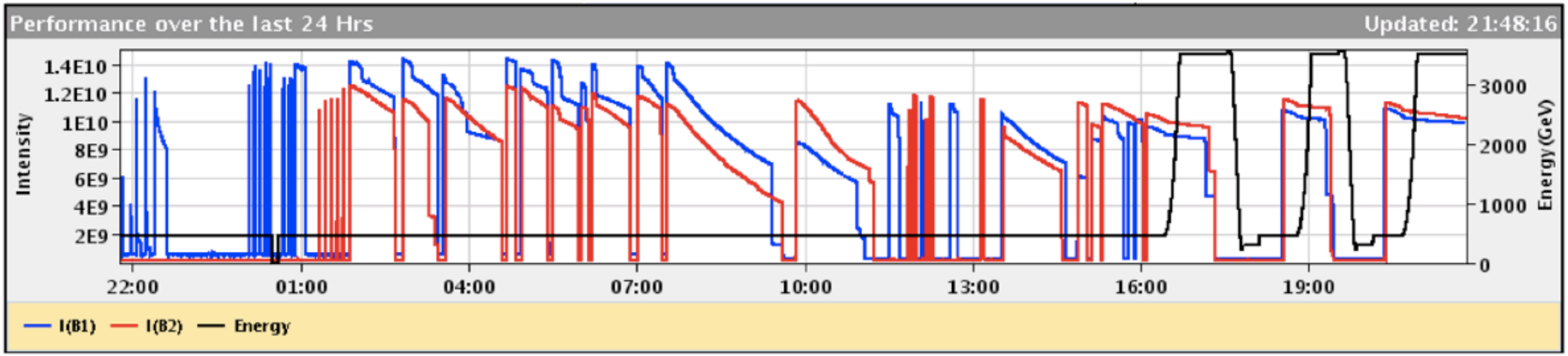
Limiting location: losses in the dispersion suppressor (Q8-R7) from **single diffractive** interactions with the TCP

Legend:
Collimators
Cold losses
Warm losses

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

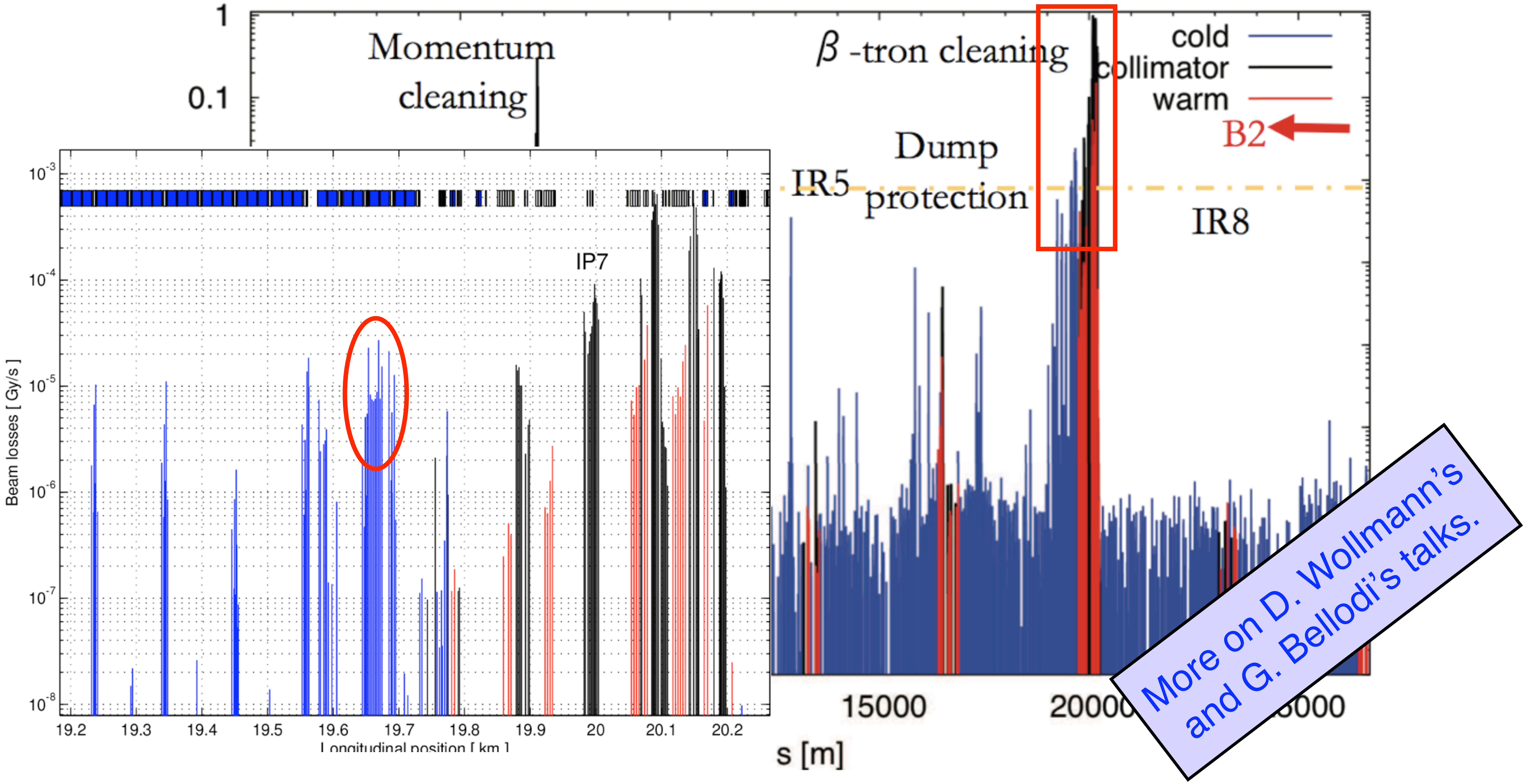
First Ramp
Collimation Checks
Squeeze

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



More on D. Wollmann's and G. Bellodi's talks.

- **Limitation**: **ion fragmentation** and **dissociation** create large effective Dp/p
  → "beam" 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.

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Phase I collimation operation

- **Manual setup** of **each collimator** (and protection device) is required for every machine configuration (injection, ramp, squeeze, physics, etc.):
  - Tedious alignment campaigns to determine **local beam size** and **beam position**.
  - Procedure based on beam loss measurements when the beam is touched by the jaws → **not possible for high intensities**.
- Once settings are established, the performance depends **critically** on:
  - The **mechanical precision** of collimator positions (very good);
  - Some machine parameters such as **orbit** and **optics**.
- Contrary to other machines, the collimator **alignment** is done **infrequently** and we rely on the **reproducibility** of settings and machine.
  - 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).

Conclusions

- ☑ Introduced the key aspects of the LHC collimation Phase I system.
- ☑ The Phase I collimation system works **very well**!

  Key design choice (controls, mechanical, ...) validated by beam experience

  Close to nominal cleaning with relaxed settings at 3.5 TeV!

  Projected performance show no limitations for 2011-2012 run.
- ☑ We have a good understanding of the present **system limitations.**
- ☑ Various possible **upgrade scenarios** address them **satisfactorily.**

  Dispersion suppressor collimators;

  Combined momentum-betatron cleaning in IR3;

  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 ?

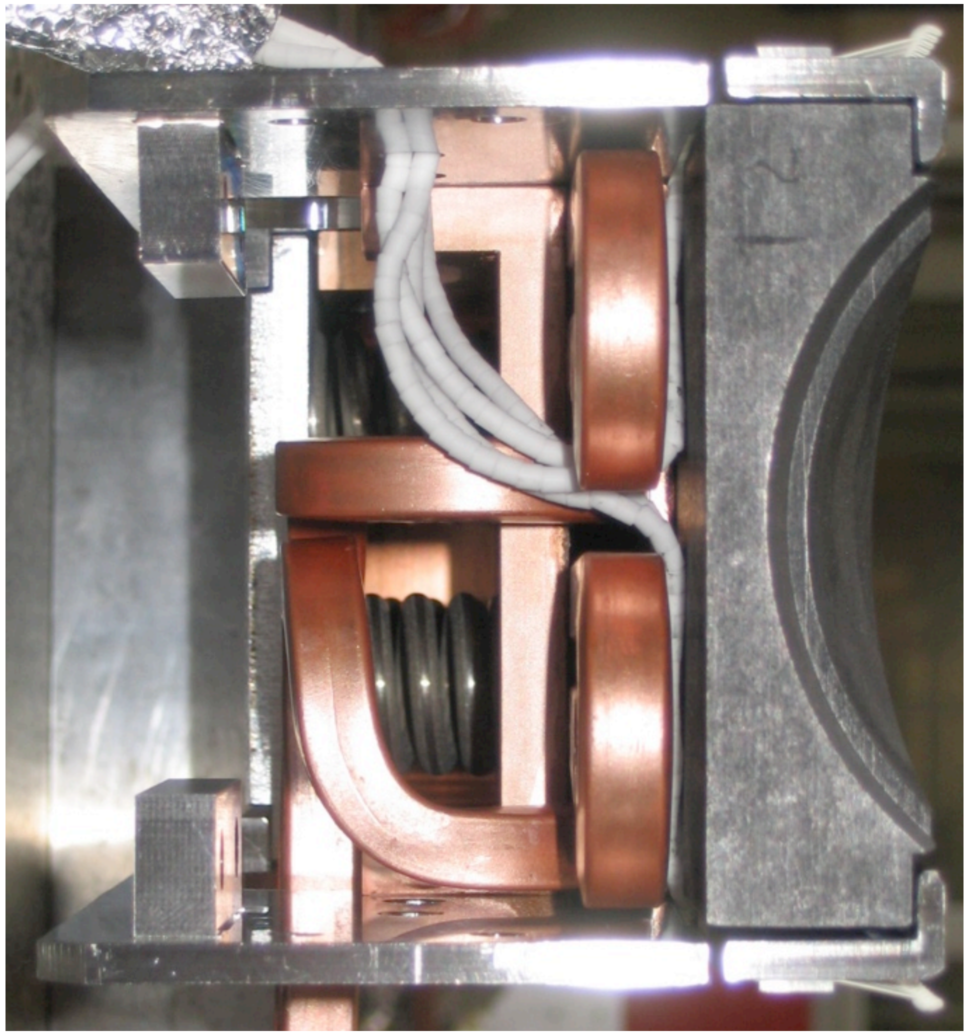
  Better than expected for losses in the DS?
- Is it worth changing the DS for more cleaning?
- What is the scaling of cleaning performance to 7 TeV ?
- Scaling of quench margins to 7 TeV ?
- The minimum beam lifetime, τ, is better than initial assumptions

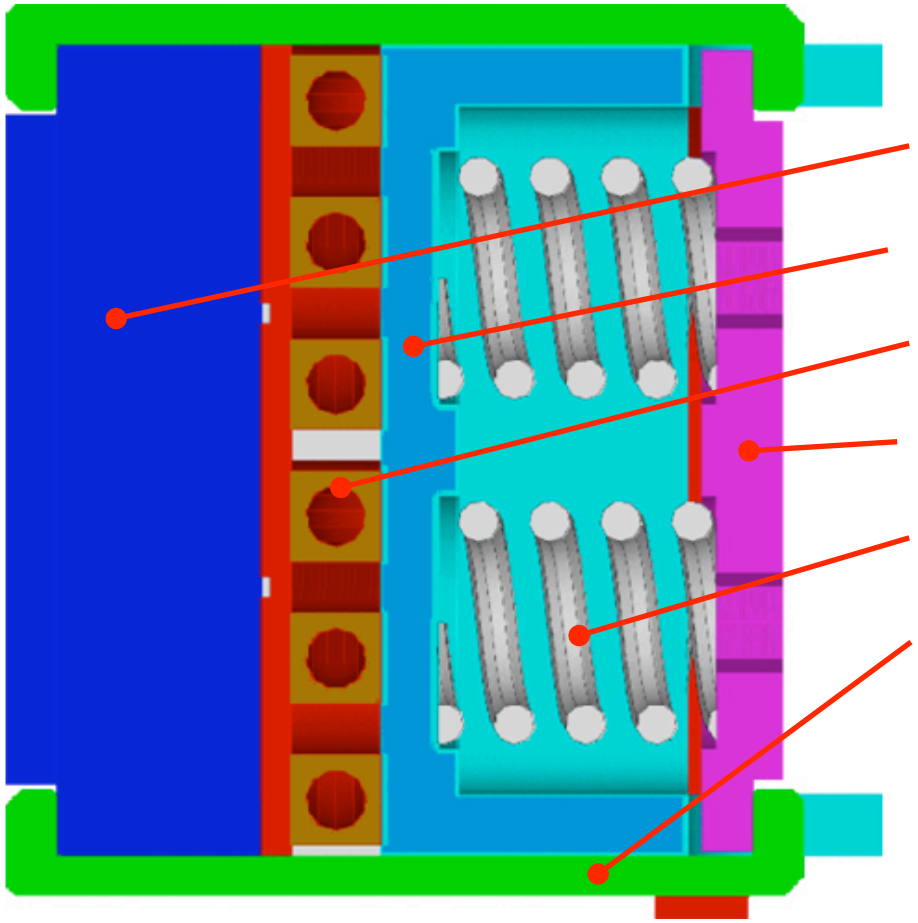
  - *Can we assume that this will be the case at 7 TeV?*
- **Collimator impedance** will limit us ?
- Radiation to electronics ?

All aspects addressed by this review.
Best present knowledge is presented!

Reserve slides

The collimator jaw





Collimating Jaw (C/C composite)

Main support beam (Glidcop)

Cooling-circuit (Cu-Ni pipes)

Counter-plates (Stainless steel)

Preloaded springs (Stainless steel)

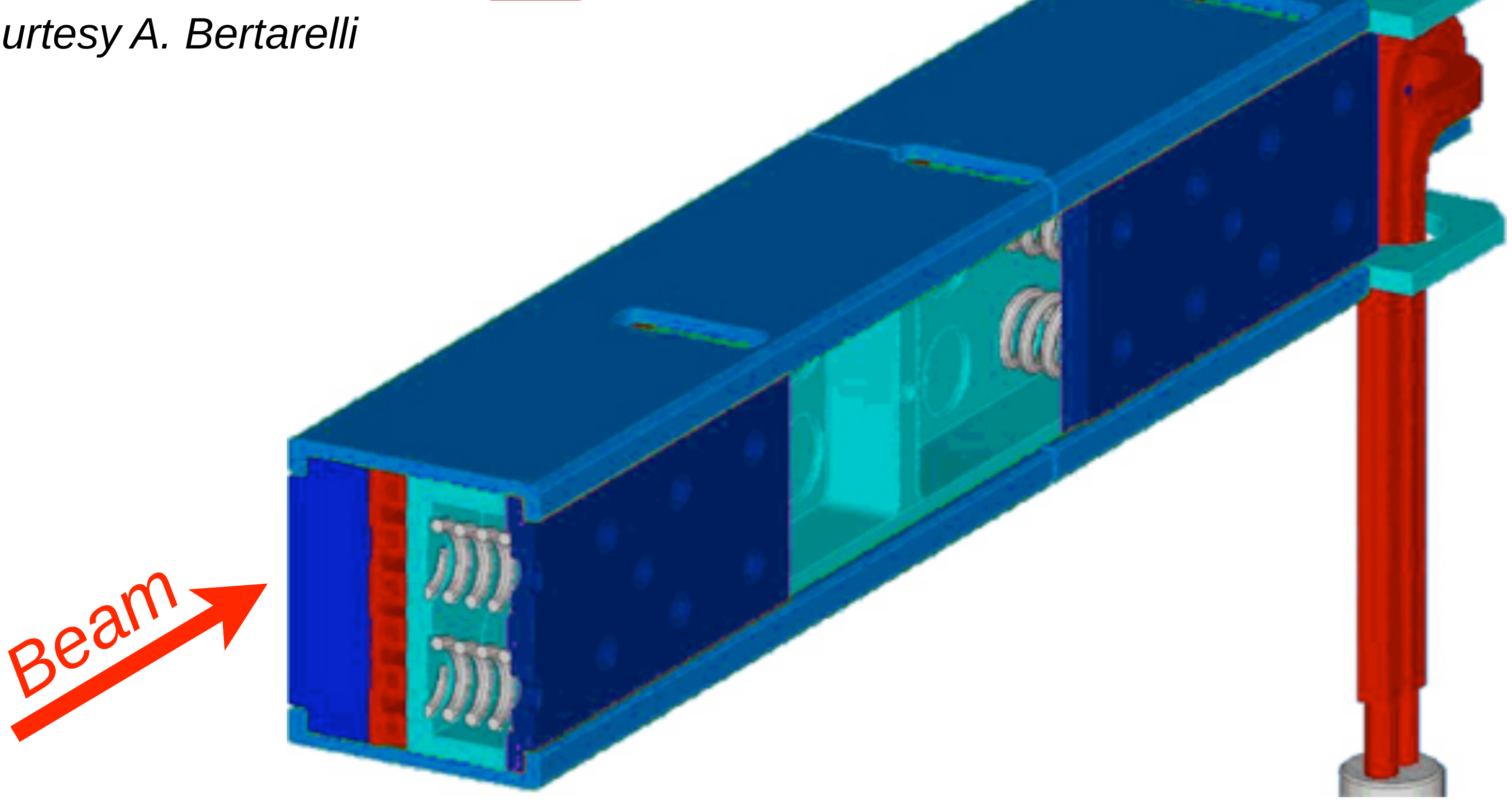
Clamping plates (Glidcop)

Courtesy A. Bertarelli

“Sandwich” design with different layers minimizes the thermal deformations:

Steady (~5 kW) ➝ < 30 μm

Transient (~30 kW) ➝ ~ 110 μm



Beam scraping at the LHC

- Halo scraping:

  Reduces sensitivity on fast loss spikes, which are a known limitation.

- LHC:

  - Space reservations in the ring for 8 scrapers (per beam: 1 in IP3, 3 in IP7);

  - BUT: No technical solution that provides robust scrapers;

  - No material found which is better than the present primary collimators.

- **Hollow electron beams**:

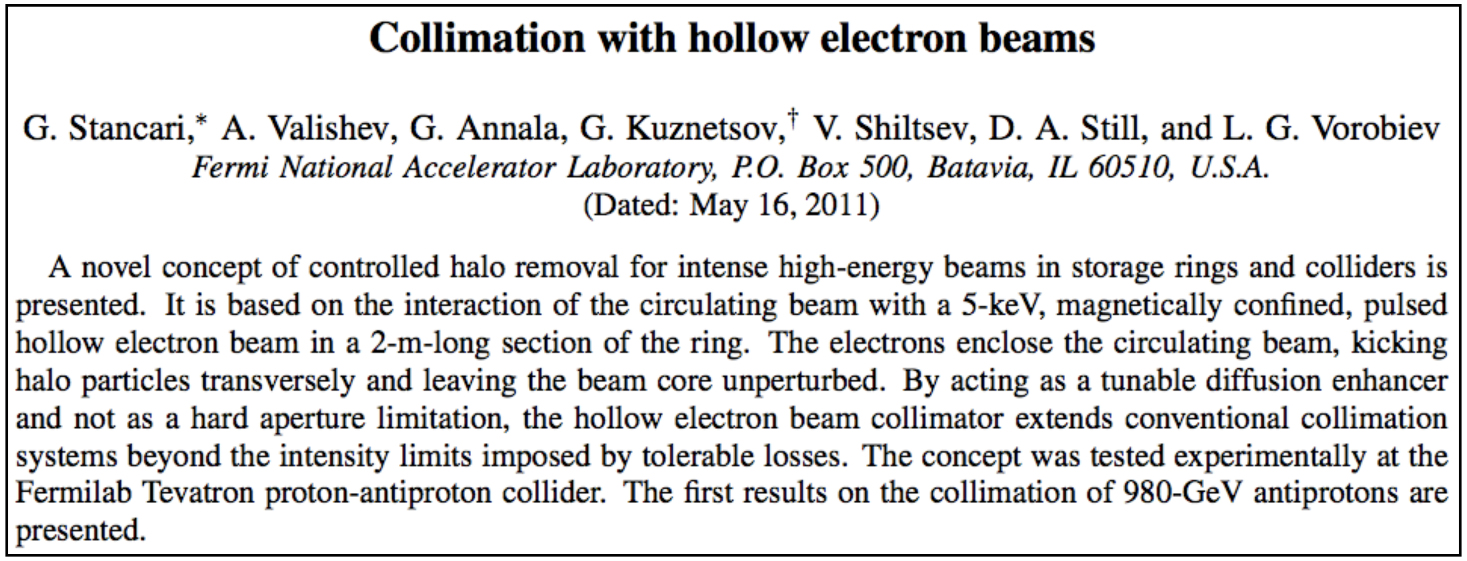
  - Electron beam cannot be destroyed!

  - Very encouraging experimental results from Tevatron.

- Alternative methods are under investigation.

Hollow e-beam studies at Fermilab

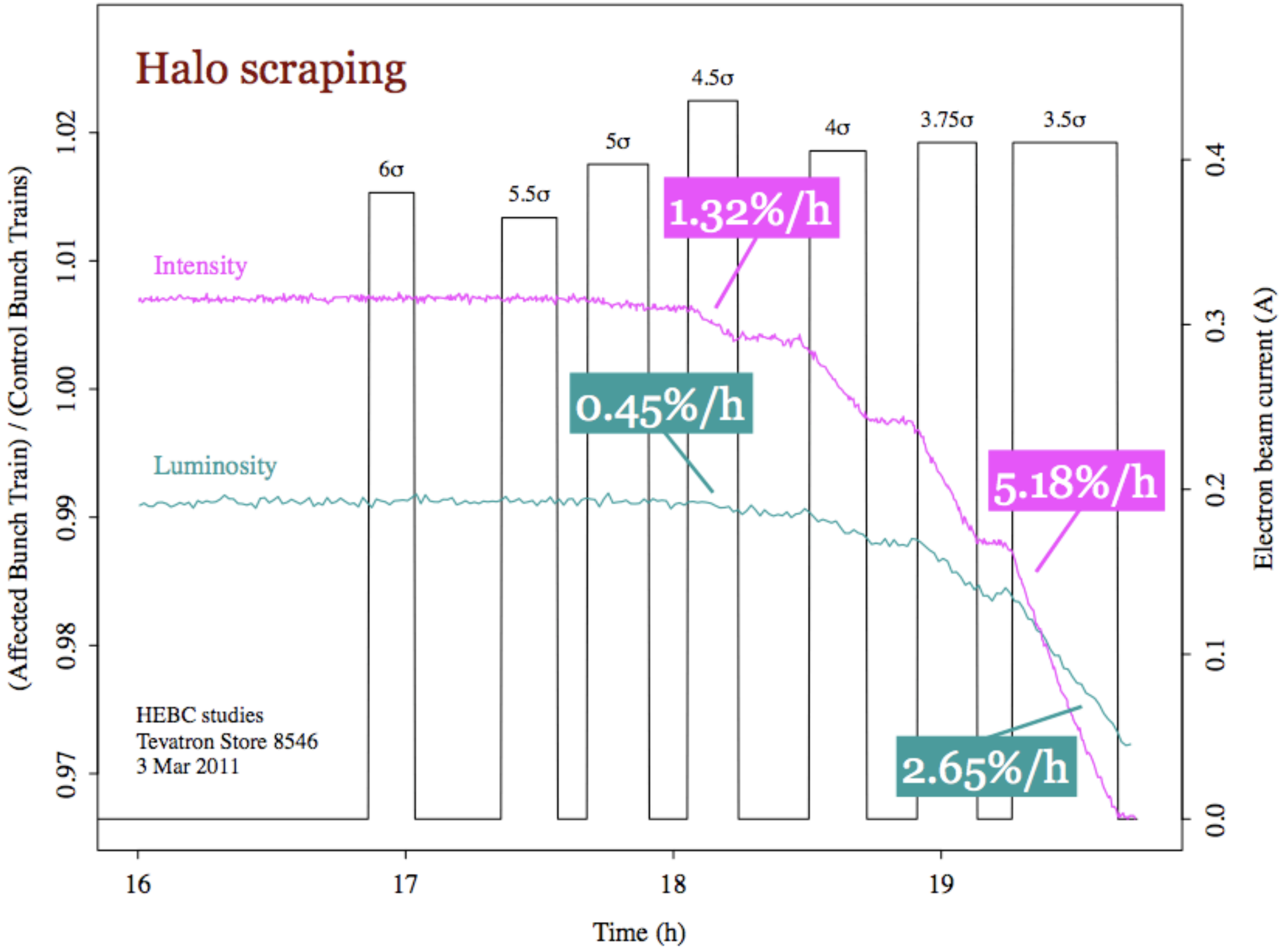
Paper submitted to Phy. Rev. Letter

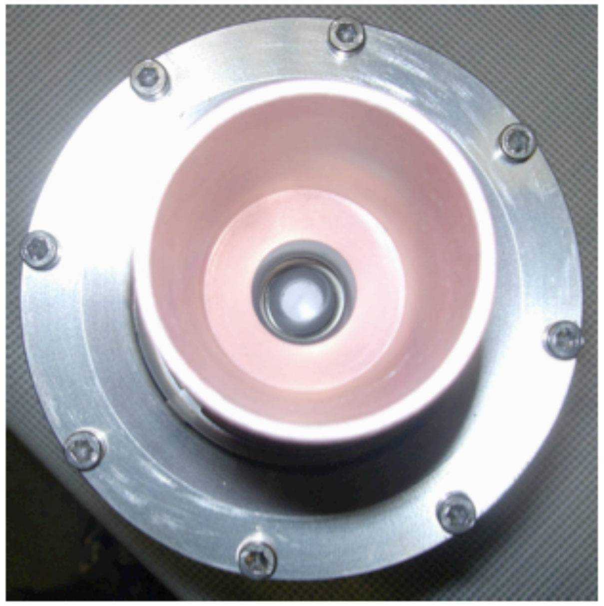


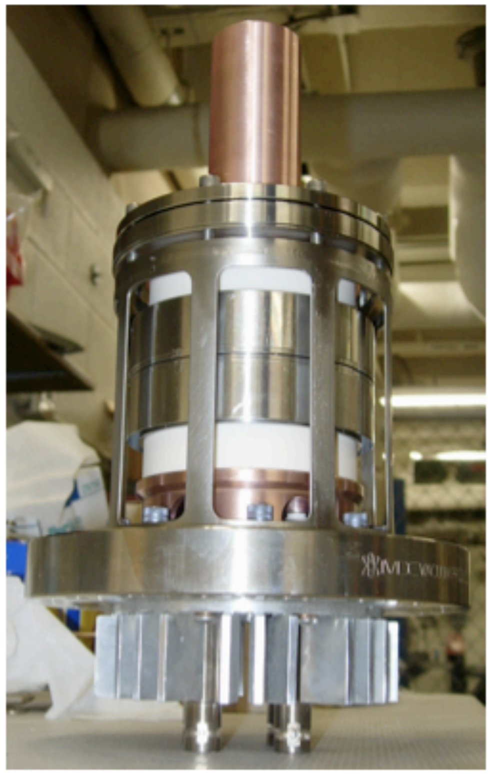
Collimation with hollow electron beams

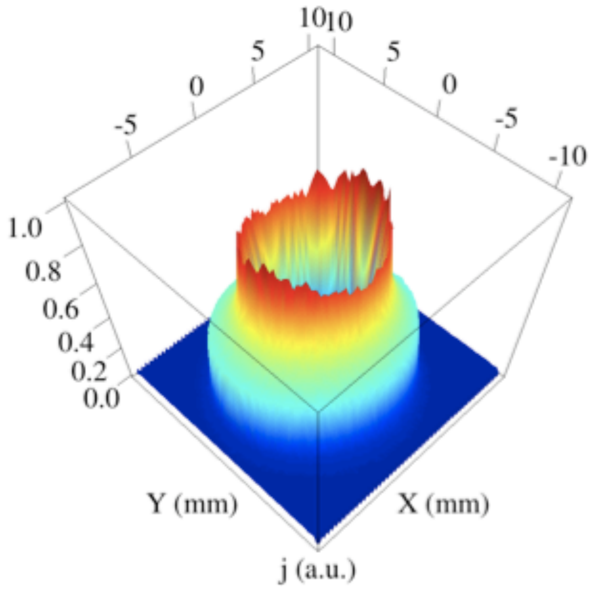
G. Stancari,* A. Valishev, G. Annala, G. Kuznetsov,† V. Shiltsev, D. A. Still, and L. G. Vorobiev
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, U.S.A.
(Dated: May 16, 2011)

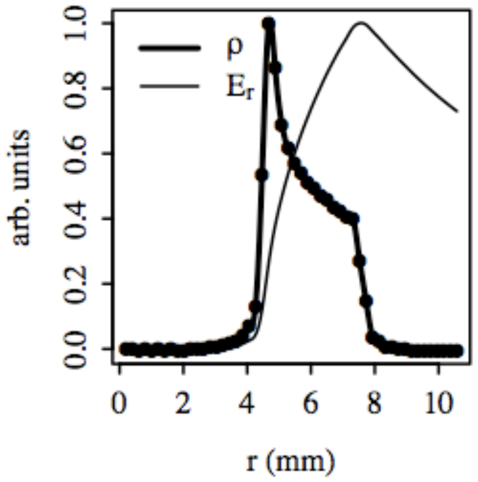
A novel concept of controlled halo removal for intense high-energy beams in storage rings and colliders is presented. It is based on the interaction of the circulating beam with a 5-keV, magnetically confined, pulsed hollow electron beam in a 2-m-long section of the ring. The electrons enclose the circulating 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.





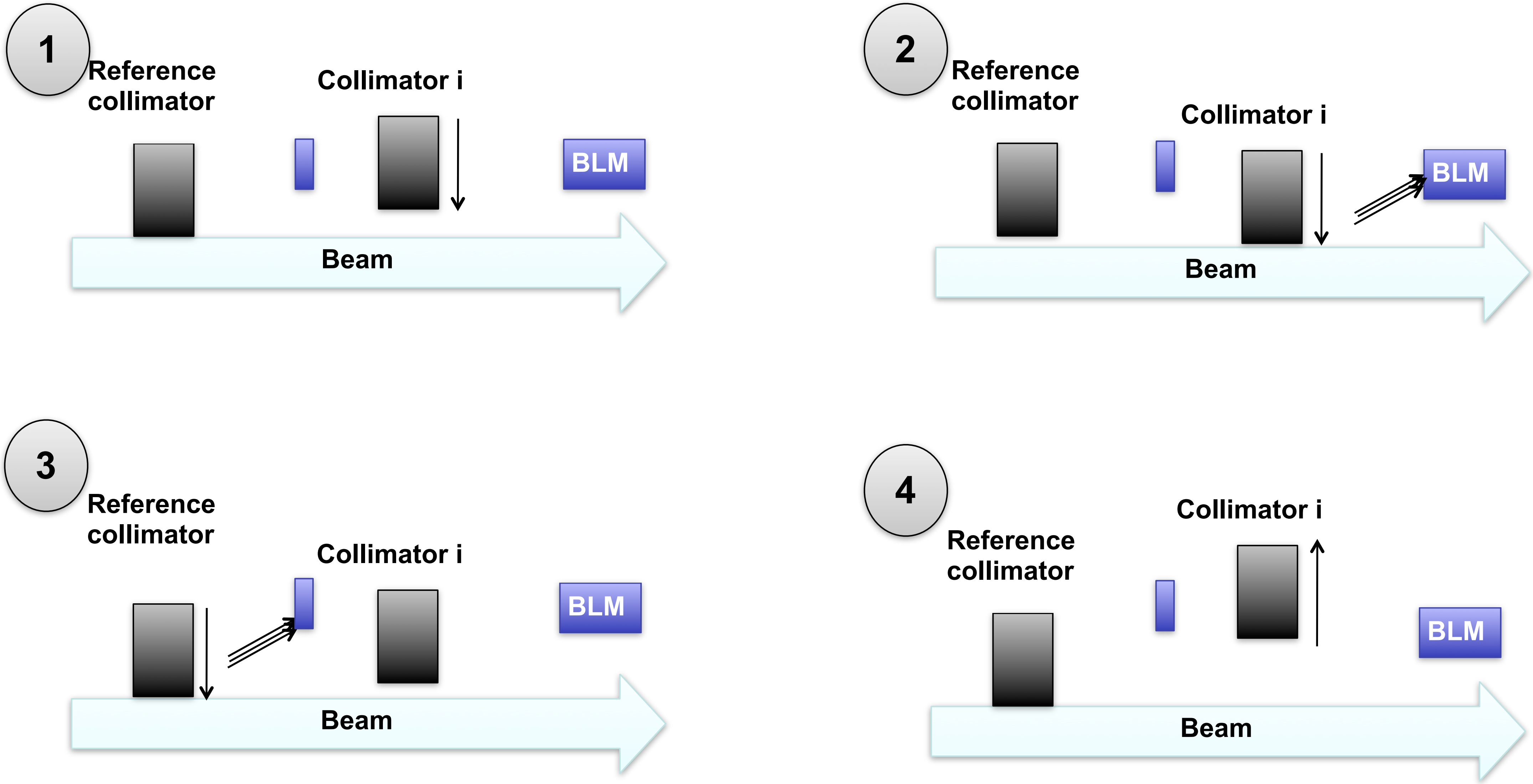






Courtesy of G. Stancari, Fermilab.

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>.

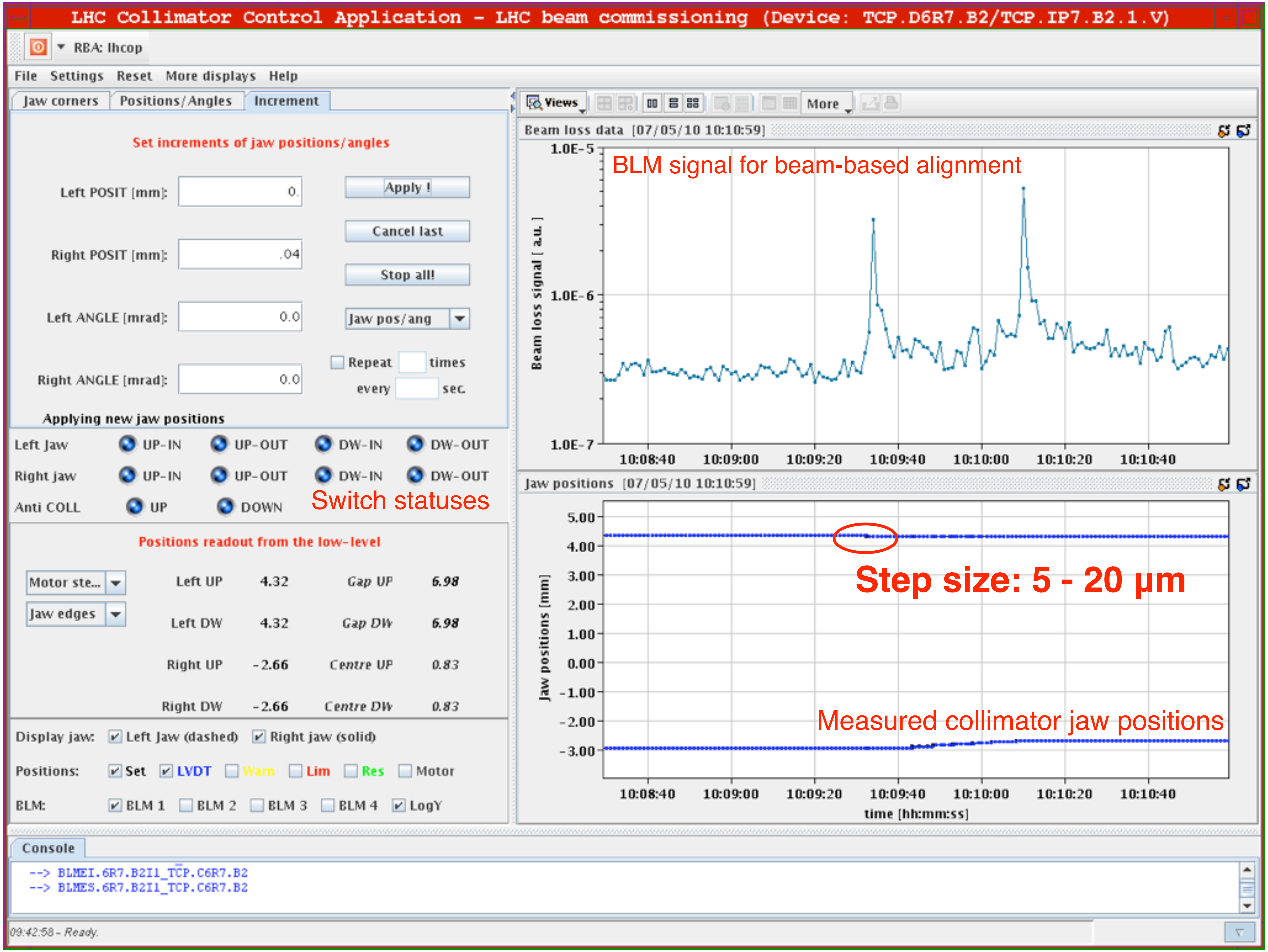
(4) Retract the collimator to the correct settings.

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



LHC Collimator Control Application - LHC beam commissioning (Device: TCP.D6R7.B2/TCP.IP7.B2.1.V)

RBA: lhcop

Set increments of jaw positions/angles

Left POSIT [mm]: 0.

Right POSIT [mm]: .04

Left ANGLE [mrad]: 0.0

Right ANGLE [mrad]: 0.0

Jaw pos/ang

☐ Repeat times every sec.

Applying new jaw positions

Left Jaw	● UP-IN	● UP-OUT	● DW-IN	● DW-OUT
Right jaw	● UP-IN	● UP-OUT	● DW-IN	● DW-OUT
Anti COLL	● UP	● DOWN		

Switch statuses

Positions readout from the low-level

Motor ste...

Jaw edges

Left UP	4.32	*Gap UP*	*6.98*
Left DW	4.32	*Gap DW*	*6.98*
Right UP	-2.66	*Centre UP*	*0.83*
Right DW	-2.66	*Centre DW*	*0.83*

Display jaw: ☑ Left Jaw (dashed) ☑ Right jaw (solid)

Positions: ☑ Set ☑ LVDT ☐ Warn ☐ Lim ☐ Res ☐ Motor

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

Beam loss data [07/05/10 10:10:59]

BLM signal for beam-based alignment

Jaw positions [07/05/10 10:10:59]

Step size: 5 - 20 μm

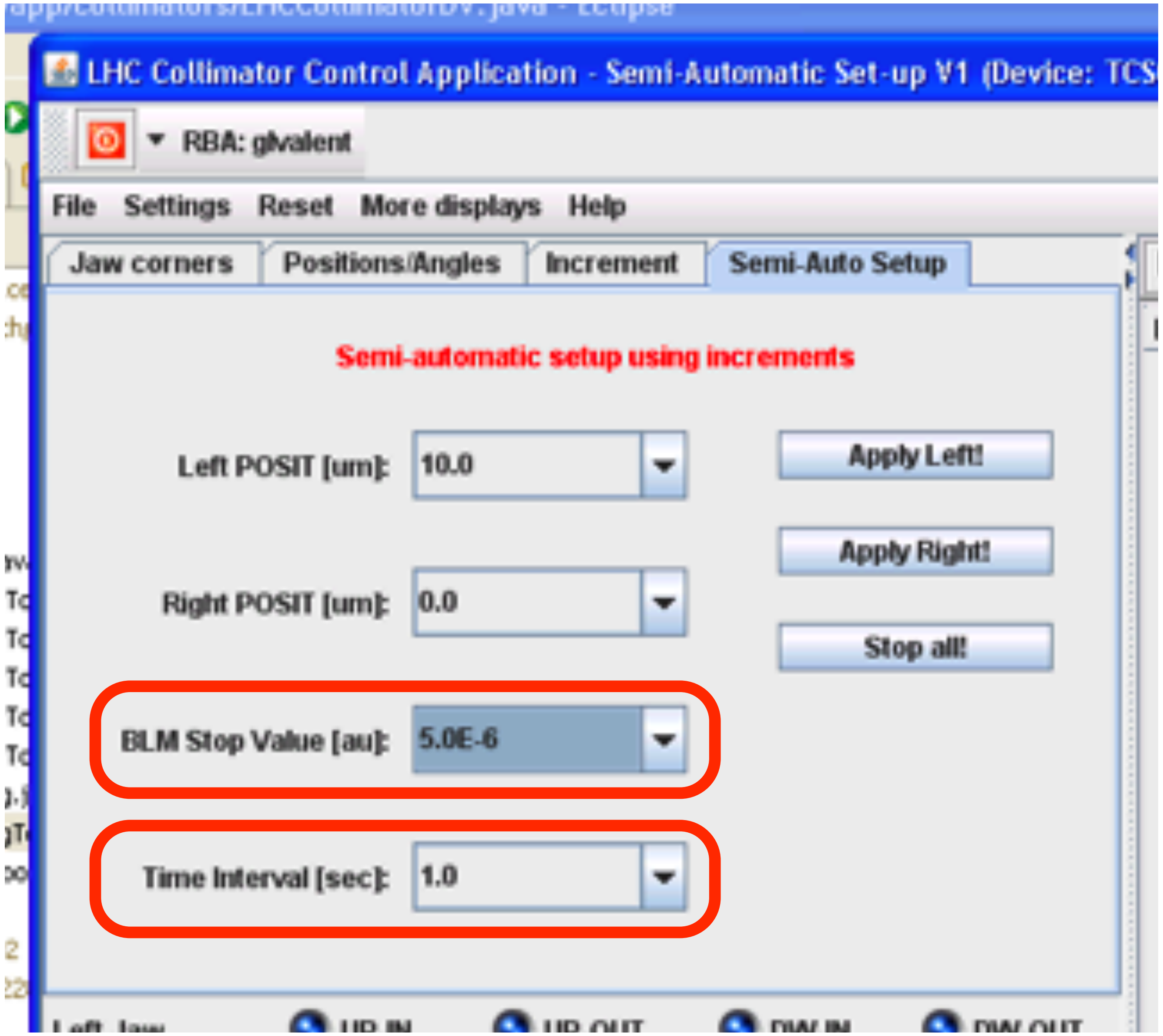
Measured collimator jaw positions

```
 --> BLMEI.6R7.B2I1_TCP.C6R7.B2
 --> BLMES.6R7.B2I1_TCP.C6R7.B2
```

09:42:58 - Ready.

Semi-automated alignment tool

New application panel under development



LHC Collimator Control Application - Semi-Automatic Set-up V1 (Device: TCS

Semi-automatic setup using increments

Left POSIT [um]: 10.0

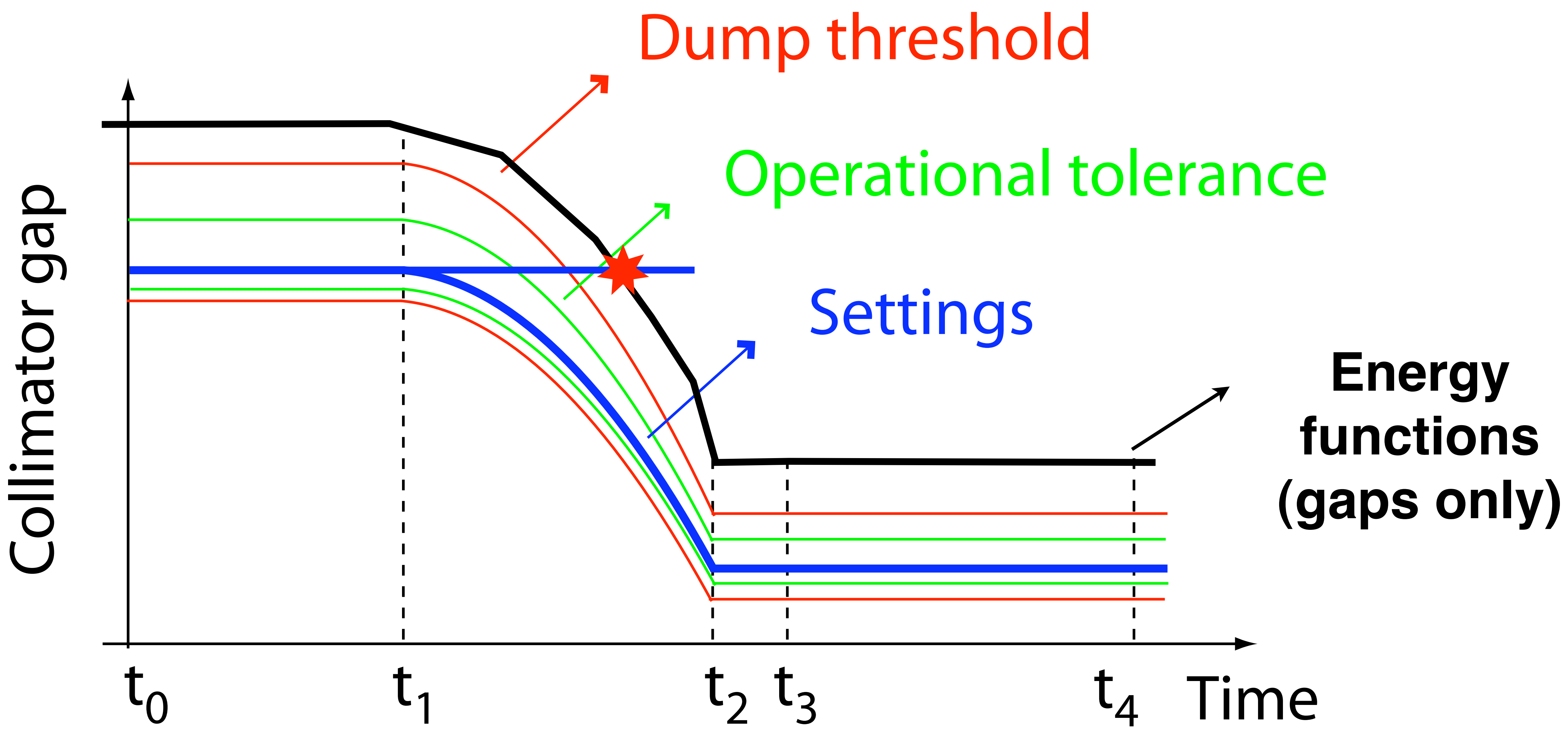
Right POSIT [um]: 0.0

BLM Stop Value [au]: 5.0E-6

Time Interval [sec]: 1.0

- 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).
- ☑ Redundancy: **min/max allowed gap versus beta*** (4 per collimator).