46th ICFA Advance Beam dynamics Workshop
on High-Intensity and High-Brightness Hadron Beams - HB 2010
Morschach, Switzerland, Sep. 27th - Oct. 1st, 2010

Performance of the LHC collimation system

S. Redaelli, BE-OP
R. Assmann, R. Bruce, D. Wollmann, BE-ABP
CERN, Geneva, Switzerland

Acknowledgments

- Collimation team:

F. Burkart, M. Cauchi, G. Valentino.

- R. Losito and A. Masi: collimator controls team.

- Engineering design team.

- Beam Loss Monitor team.

- LSA (LHC Software Architecture) team.

- LHC-OP crew.

- Injection and dump teams.

Outline

- Introduction
- Layout and challenges
- Collimator settings
- Operation and performance
- Conclusions

Layout of LHC collimation system

Two warm cleaning insertions

IR3: Momentum cleaning
- **1 primary (H)**
- **4 secondary (H,S)**
- **4 shower abs. (H,V)**

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

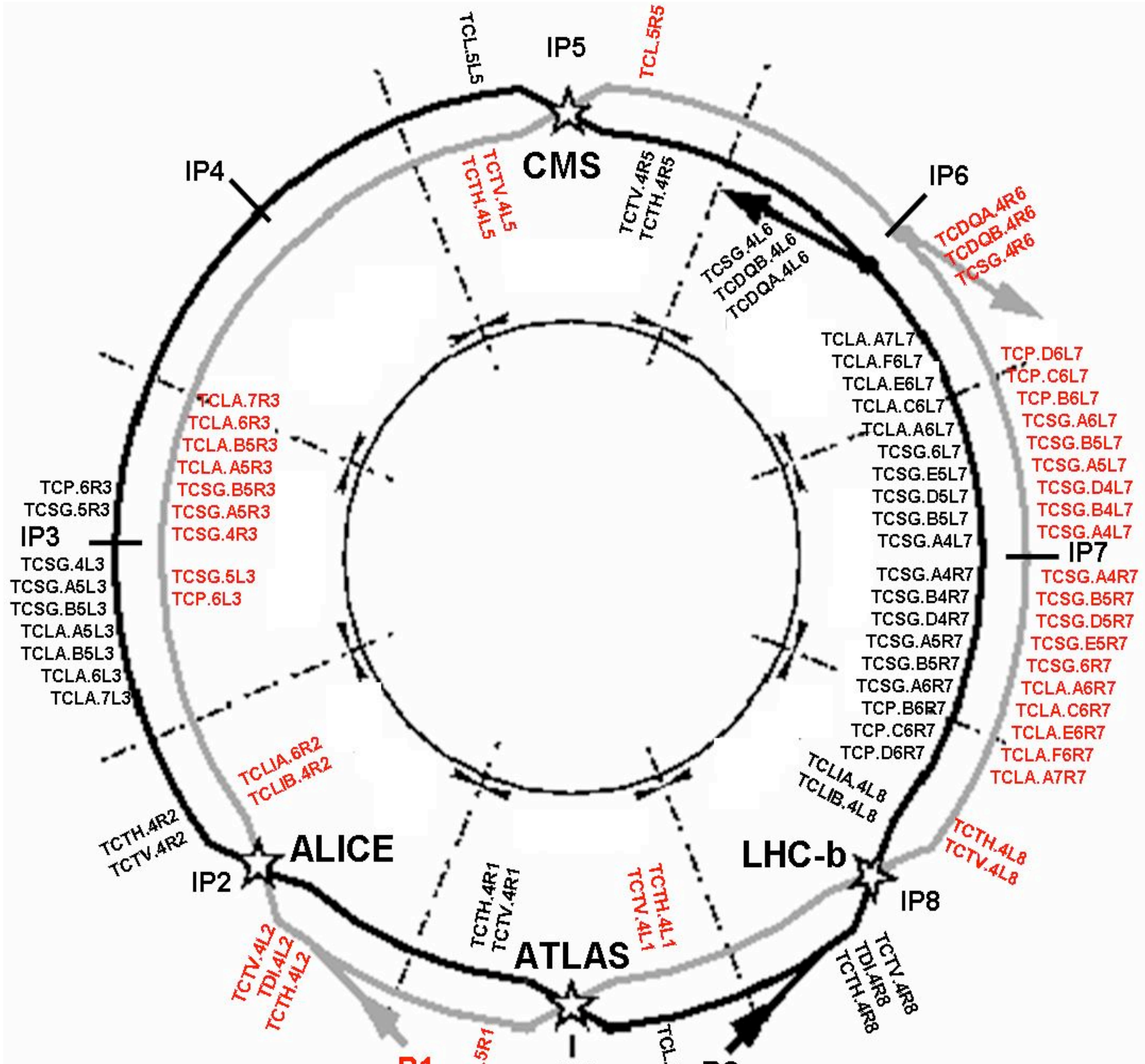
Local cleaning at triplets
- **8 tertiary (2 per IP)**

Passive absorbers for warm magnets

Physics debris absorbers

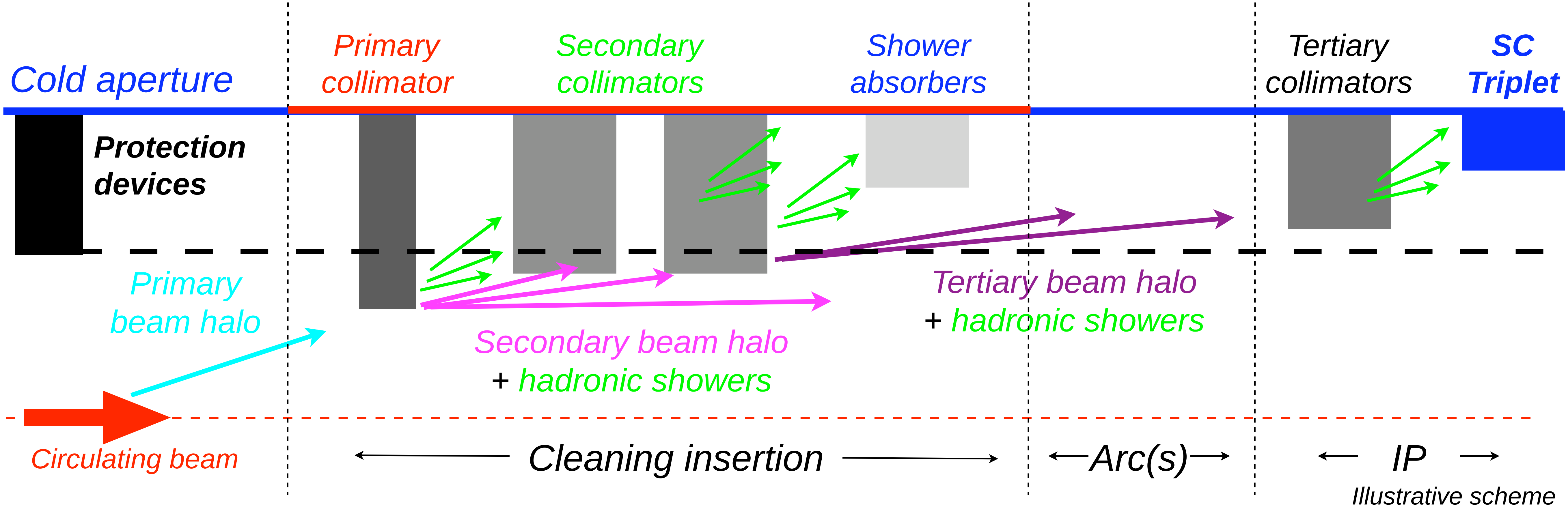
Transfer lines (13 collimators)
Injection and dump protection (10)

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



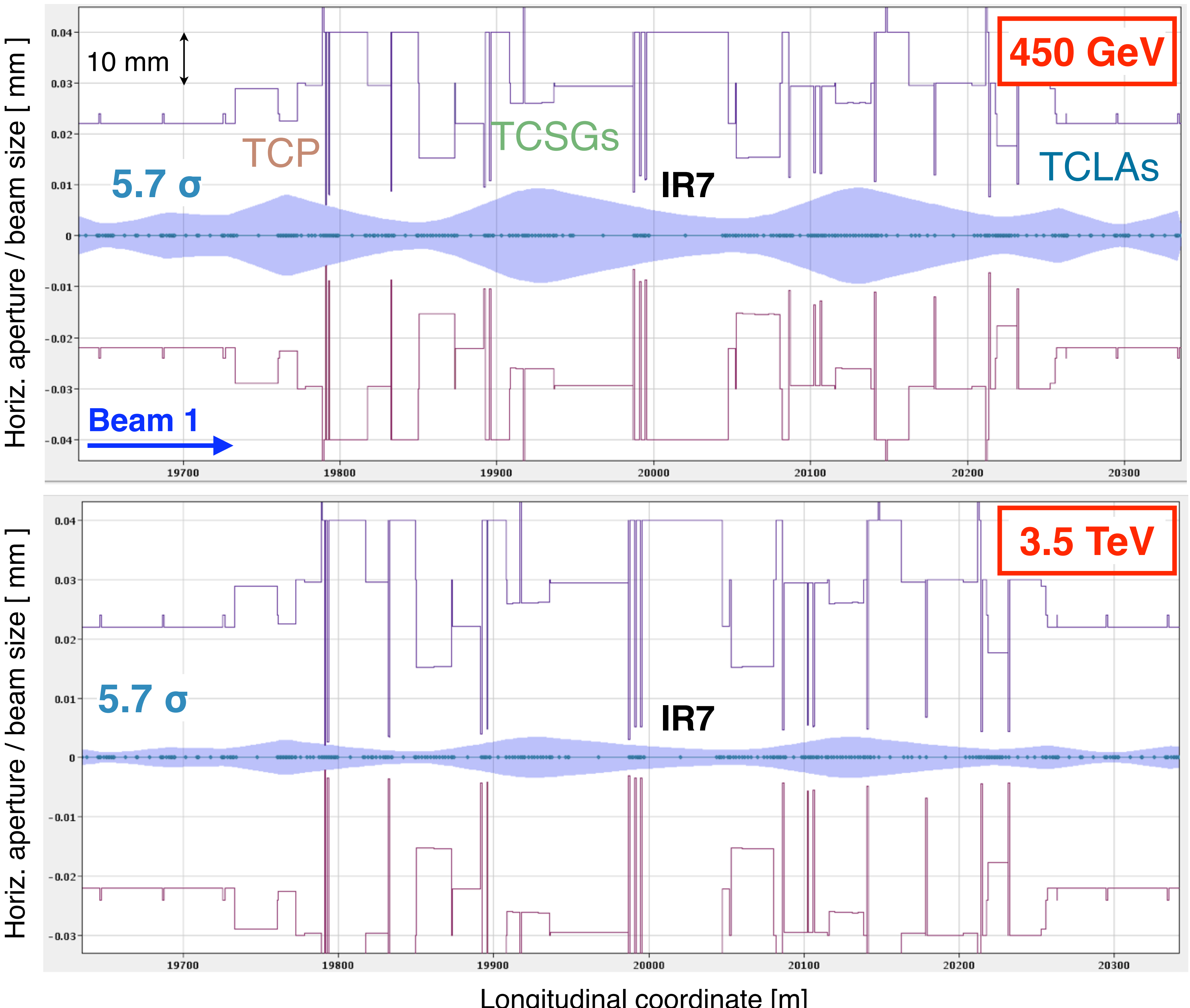
Picture by C. Bracco

LHC multi-stage collimation



- The cold aperture must be in the shade of several layer of collimators.
- **Leakage** to cold aperture must be below quench limit!
- LHC aperture sets the scale: Injection: ≥ 12.5 σ
  3.5 TeV, β*=3.5m: ≥ 15.0 σ
- Primary and secondary collimators are **robust** (Carbon).
  Absorbers and tertiary collimators (Tungsten) are not and must be protected.
- **Beam-based setup** → local beam position and beam size at each collimator.

Example of collimator gaps (i)



Collimator gaps (betatron cleaning):

450 GeV: ±4.3 mm

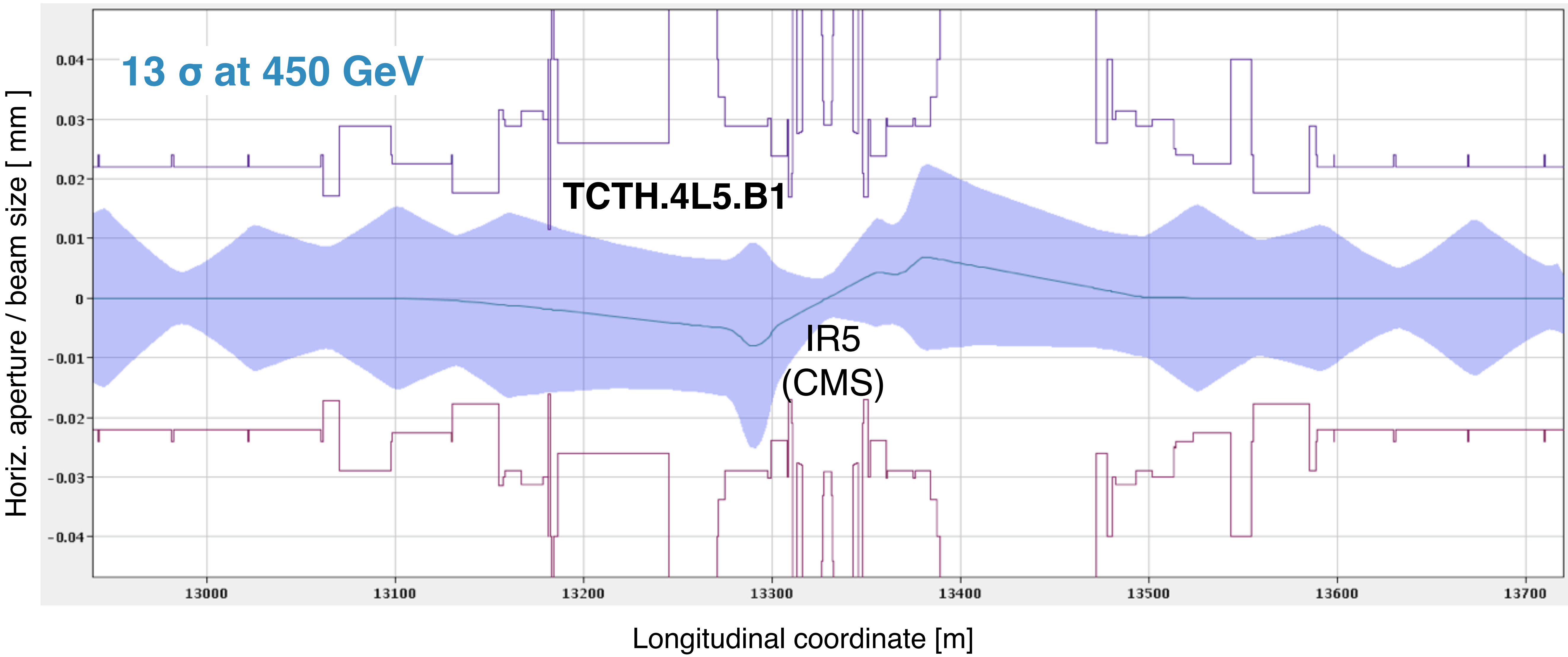
3.5 TeV: ±1.5 mm

Collimator settings depend critically on orbit and beta functions!

Intrinsic safety and redundancy: two-sided collimators!

MADX online: aperture model with measured collimator gaps (G. Müller)

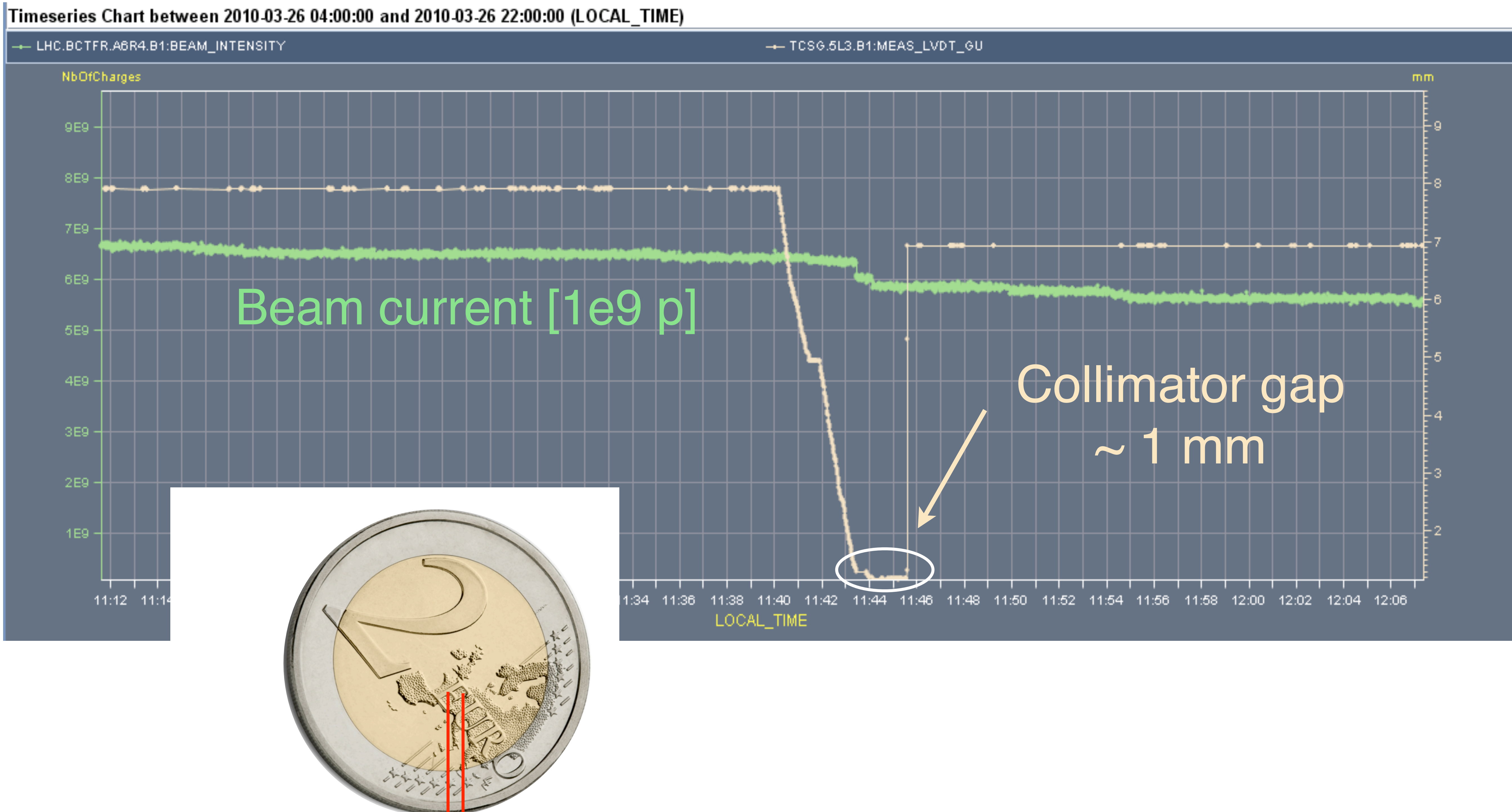
Example of collimator gaps (ii)



In the interaction regions (IRs), tertiary collimators protect the supeconducting triplets.

We have a change of beta during the squeeze, a change of centres from separation and crossing schemes: re-qualification needed if machine configuration changes.

Minimum gap with 3.5 TeV beams



3.5 TeV beam circulating in a gap as wide as the Italy on the 2 euro coin!!

Operational aspects and set-up strategy

- Main **operational challenges**:
  - High stored energy: Collimators needed in all phases *(inj., ramp, squeeze, physics)*; Function-driven controls of jaw positions mandatory;
  - Small gaps: Mechanical precision, reproducibility (< 20 microns);
  - Beam cleaning: Big and distributed system (~ 100 collimators);
  - Machine Protection: Redundant interlock of collimator jaw positions and gaps.

- Collimator settings are given in terms of **local beam size** and **beam position**.

- Once settings are established, the system performance depends **critically** on:
  - the **mechanical precision** of collimator positions;
  - 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.

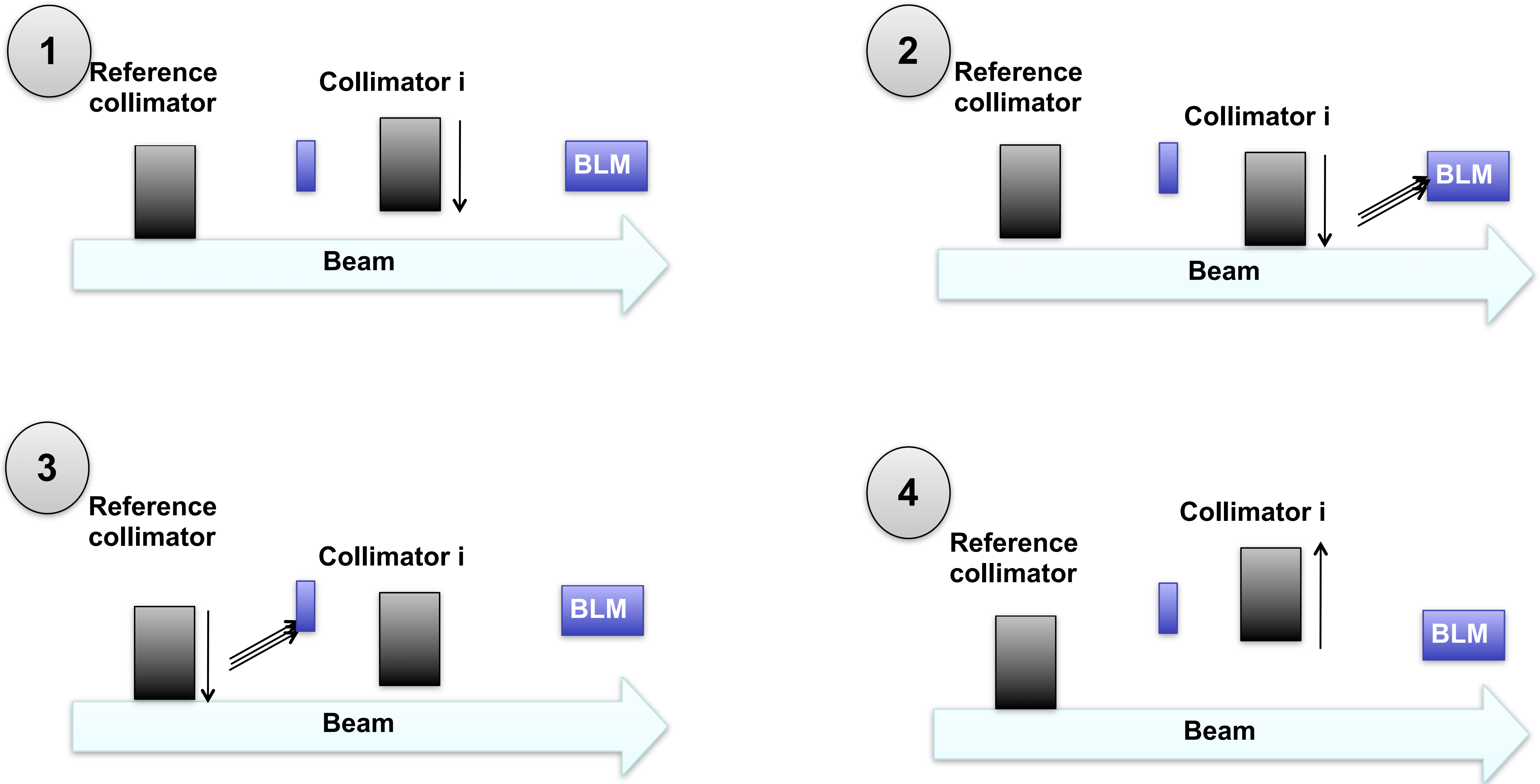
  Dedicated collimator alignment campaigns are done for each machine configuration (injection, flat top, squeeze, stable beams) and then we rely on the reproducibility of machine.

- **Consequences** of this infrequent setup:
  - **constraints** on machine **reproducibility** (orbit stab. fill to fill **< 150 μm**, **$\Delta\beta/\beta$< 20%**)!
  - require regular **monitoring** of cleaning performance.

Outline

- Introduction
- Layout and challenges
- **Collimator settings**
- Operation and performance
- Conclusions

Beam-based collimator set-up



R. Assmann

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

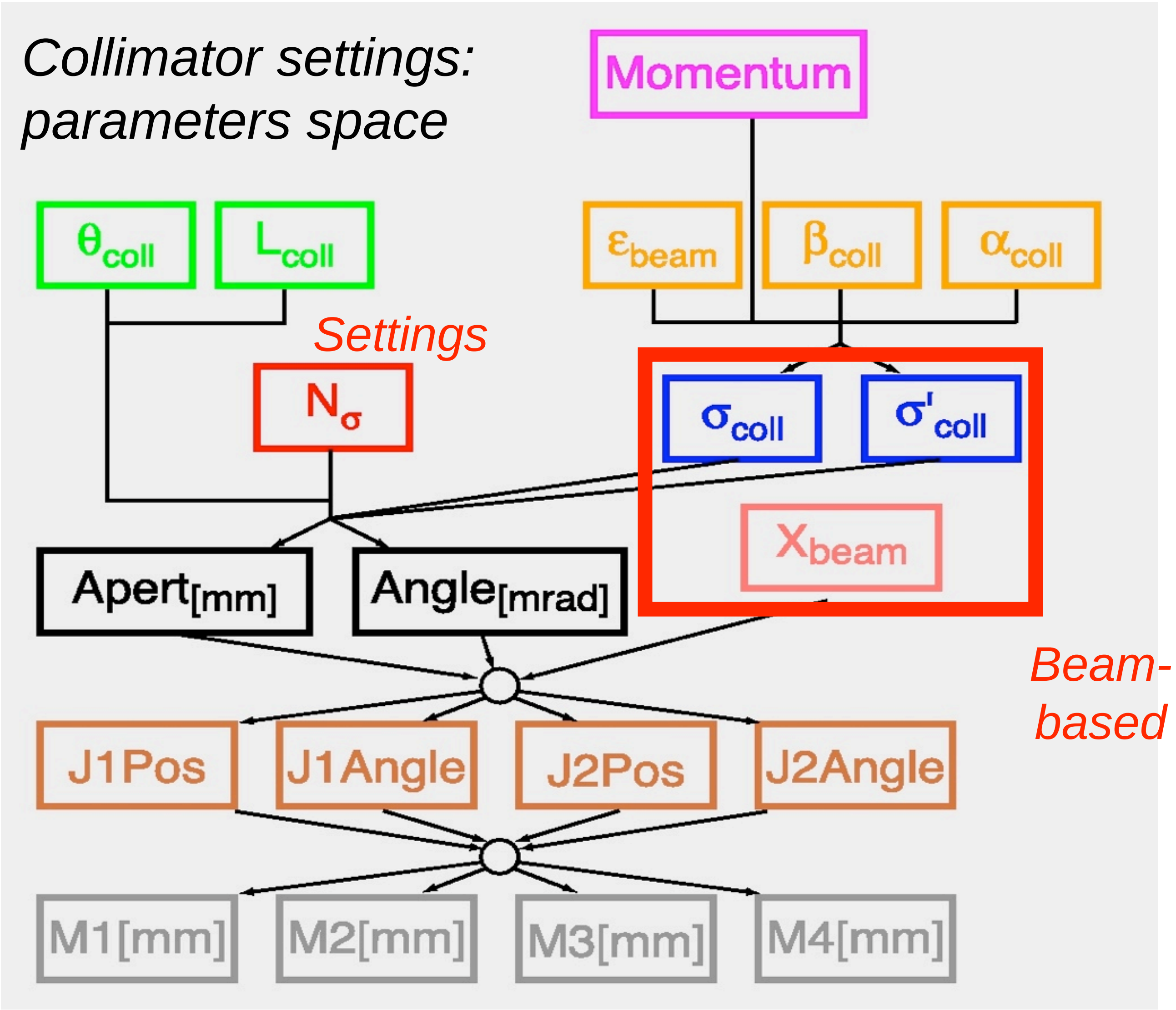
(2) “Touch” the halo with the other collimators around the ring (**both sides**) → <u>local beam position</u>.

(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 is repeated for each machine configuration.

Collimator setting generation



<u>Nominal settings</u>:

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

$$\sigma_x = \sqrt{\frac{\epsilon_n}{\gamma}\beta_x}$$ *: Beam size along collimation axis "x"*

$$n_0^{\mathrm{tcp}} = 6$$

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

$$\ldots.$$

(More complex if angles are taken into account)

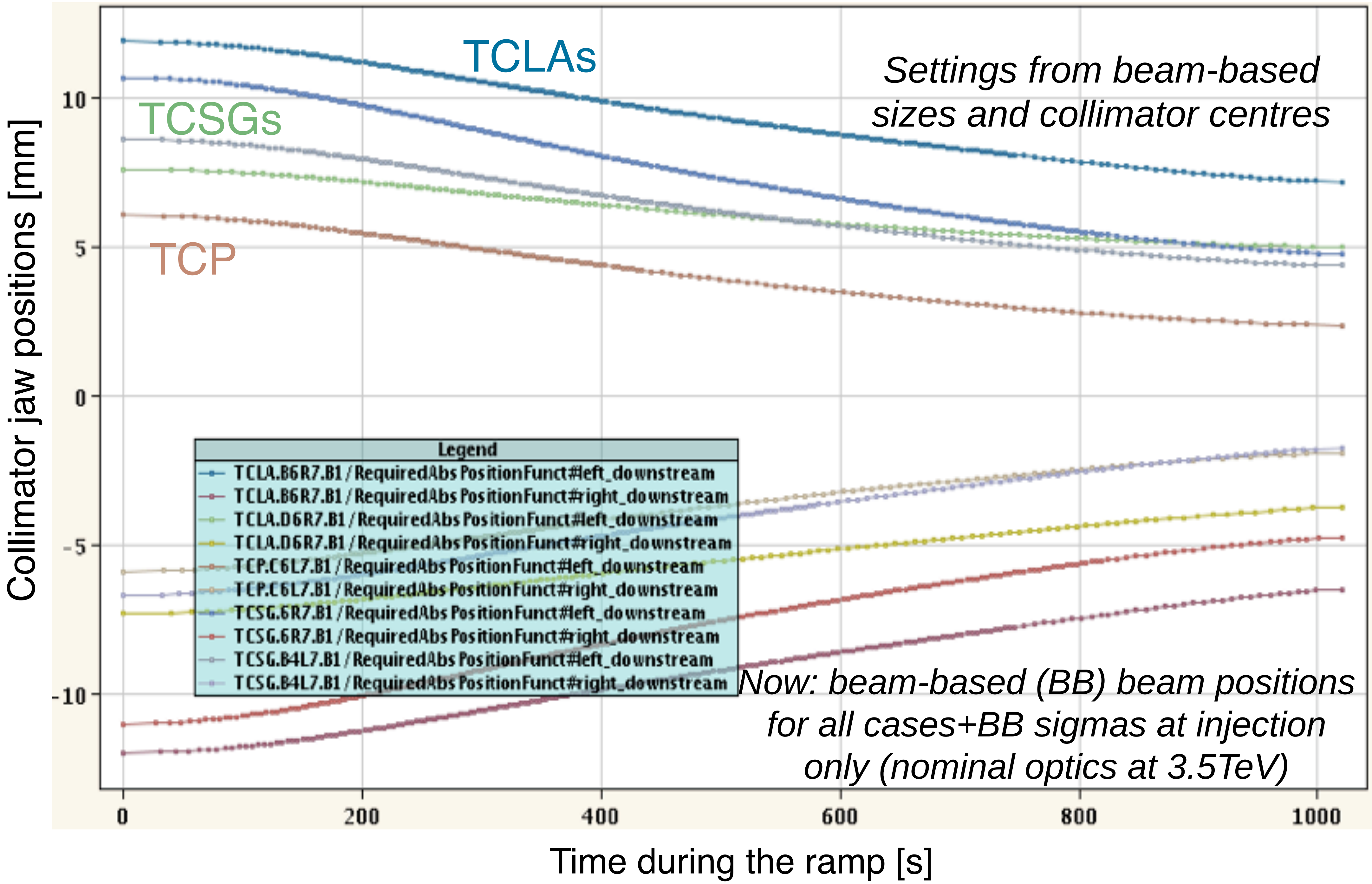
Scaling for ramp settings:

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

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

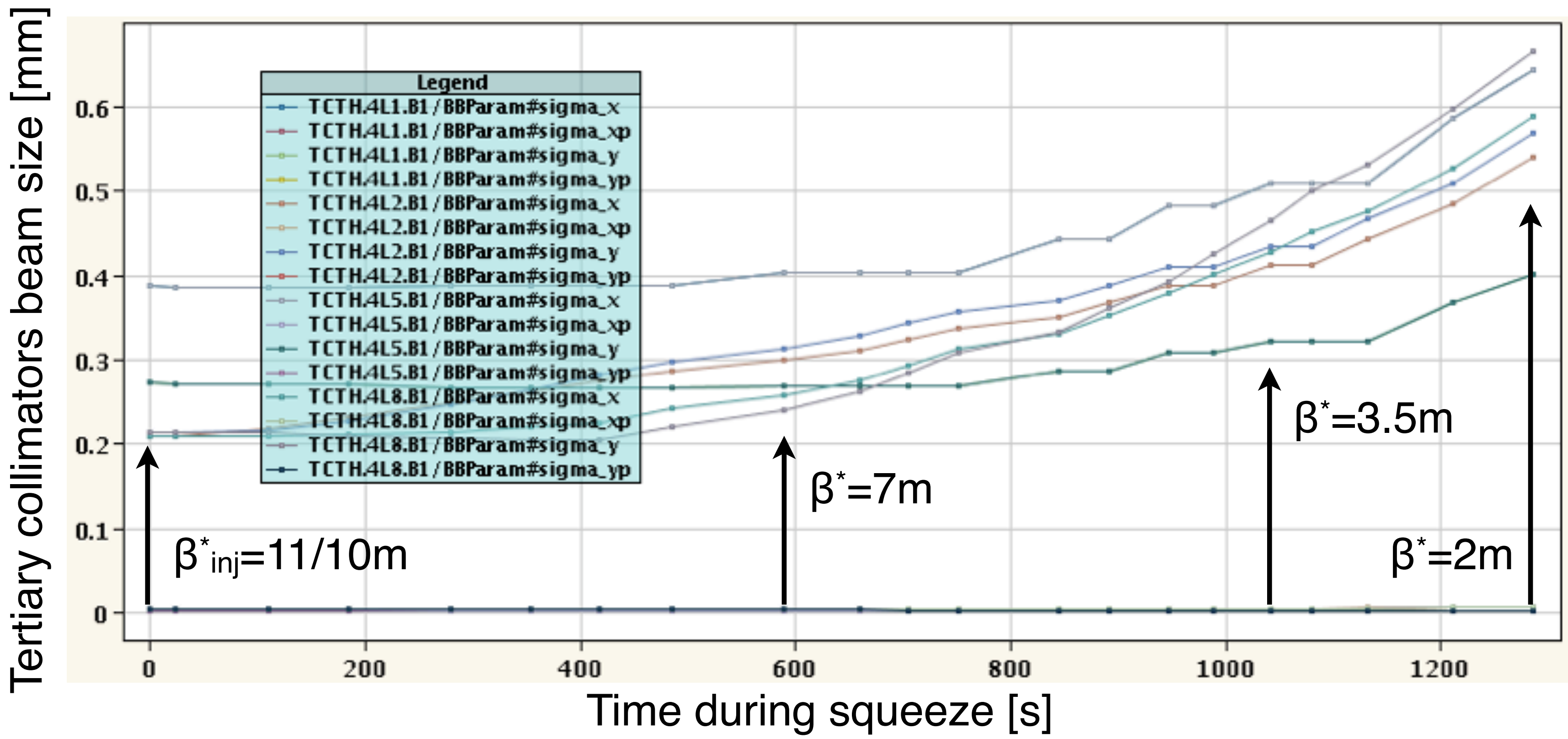
$$\mathrm{jaw}(\gamma) = \left[x_0 + \frac{x_1 - x_0}{\gamma_1 - \gamma_0}(\gamma - \gamma_0)\right] \pm h(\gamma)$$

Ramp settings

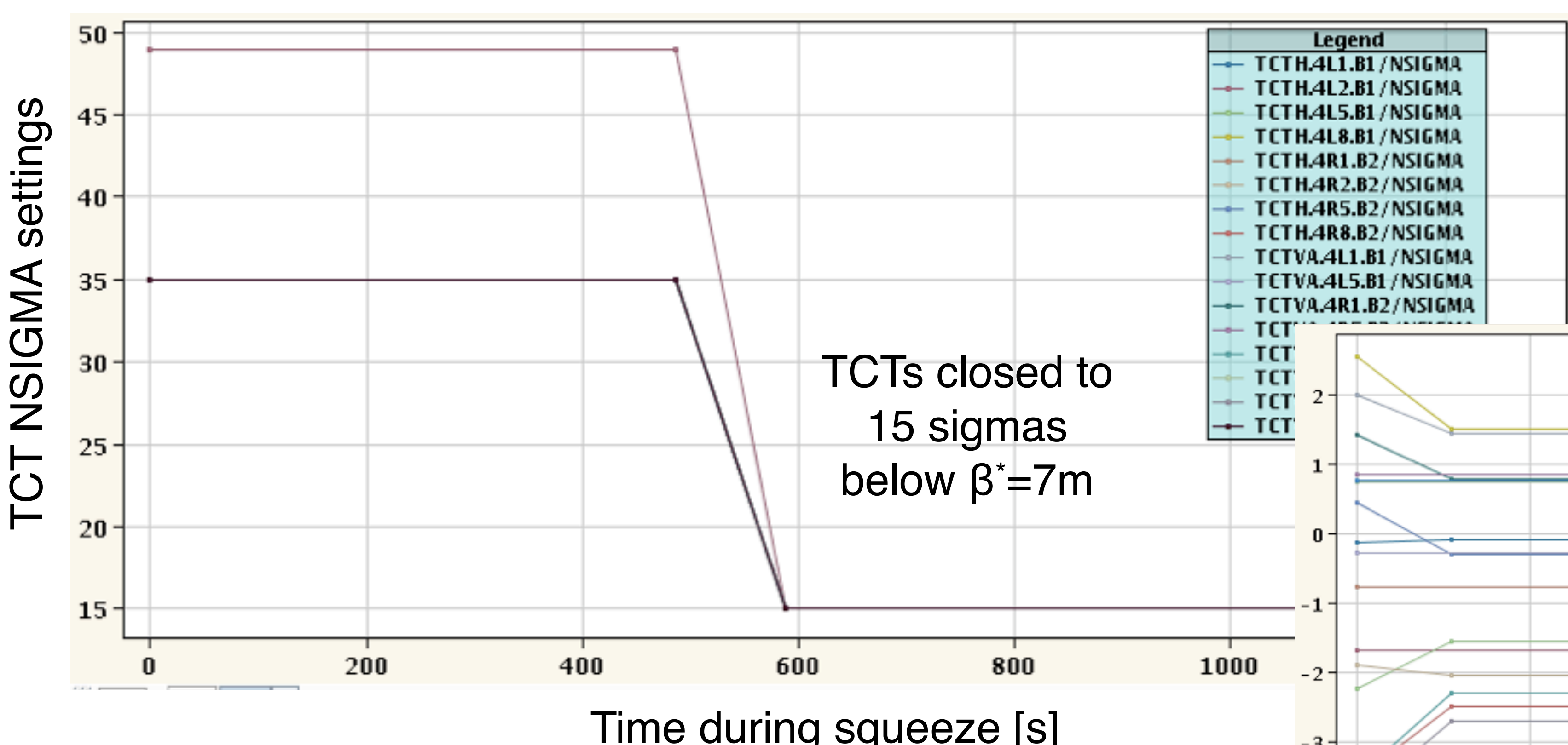


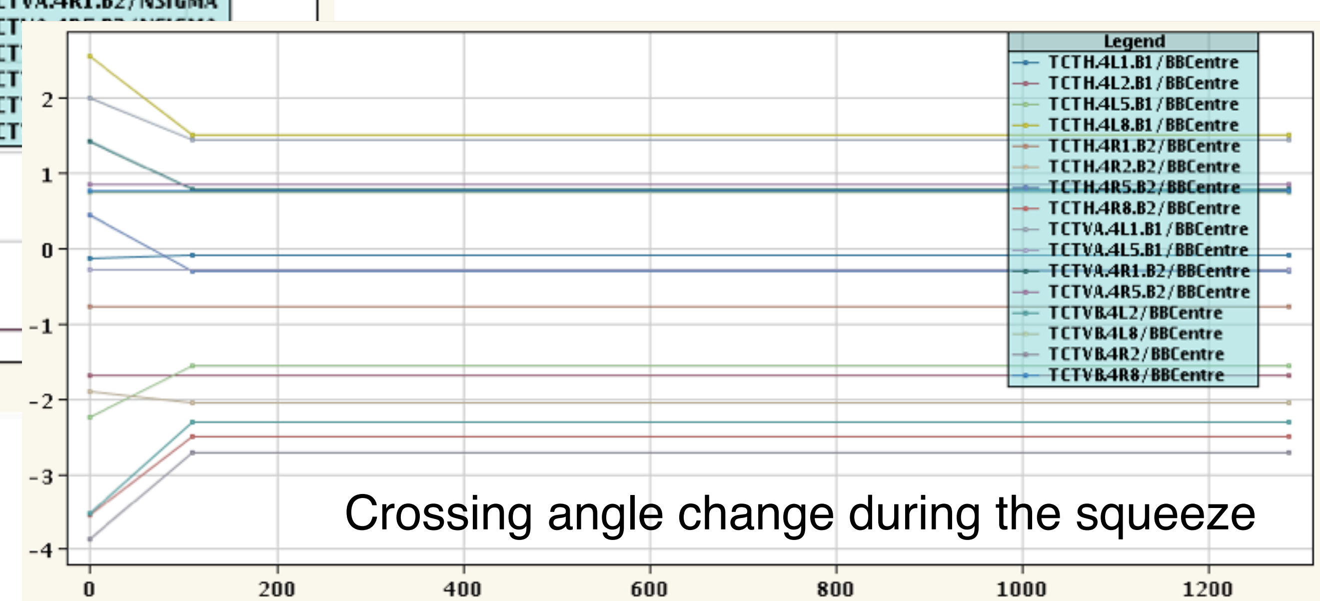
Functions generated for all collimators (R. Bruce) and imported in the control system:
396 functions for motor settings
2376 functions for interlock thresholds
194 gap limits as a function of energy

Squeeze settings

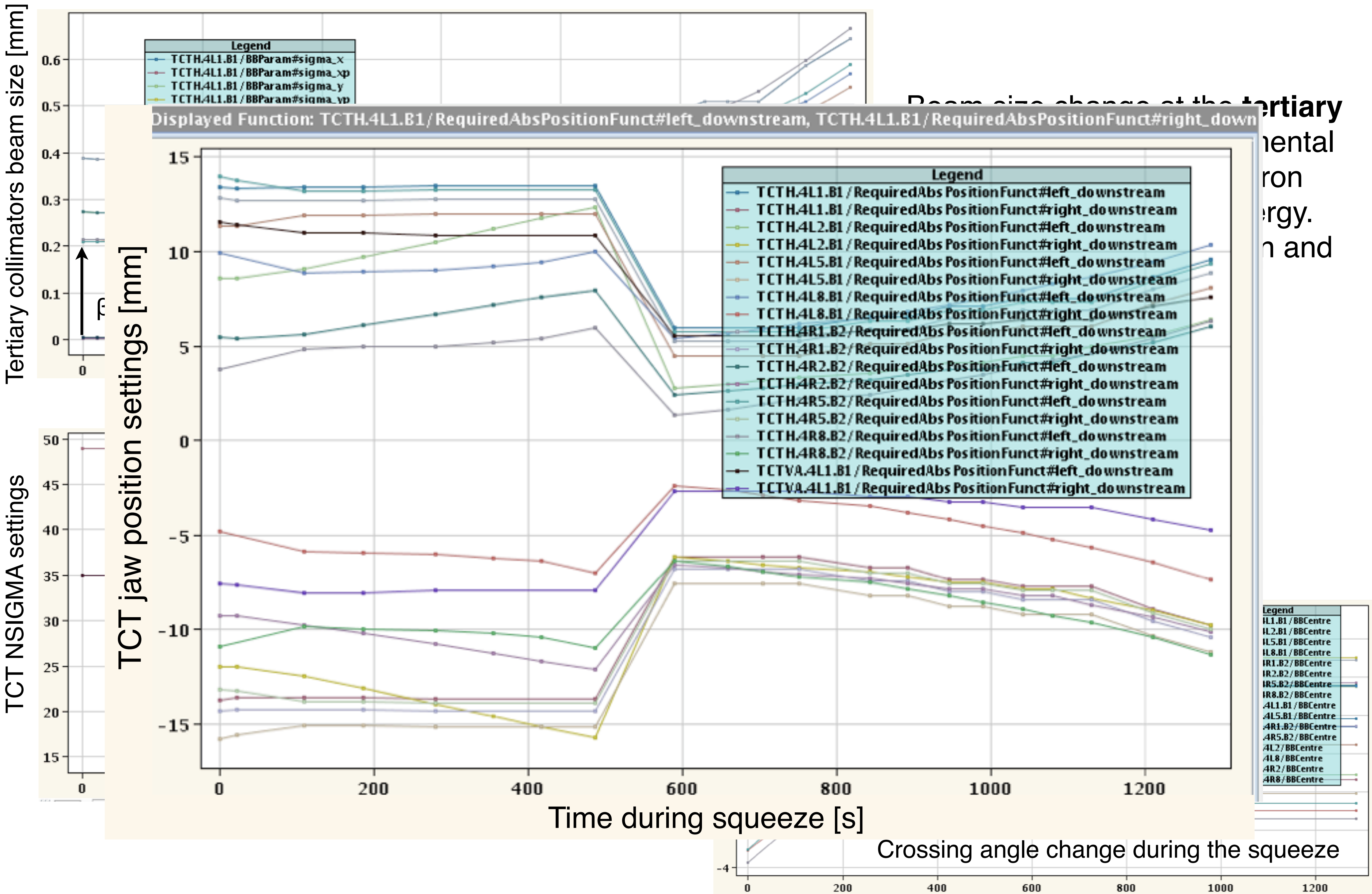


Beam size change at the **tertiary collimators** in the experimental regions during the betatron **squeeze** at constant energy. No changes in the betatron and momentum cleaning.

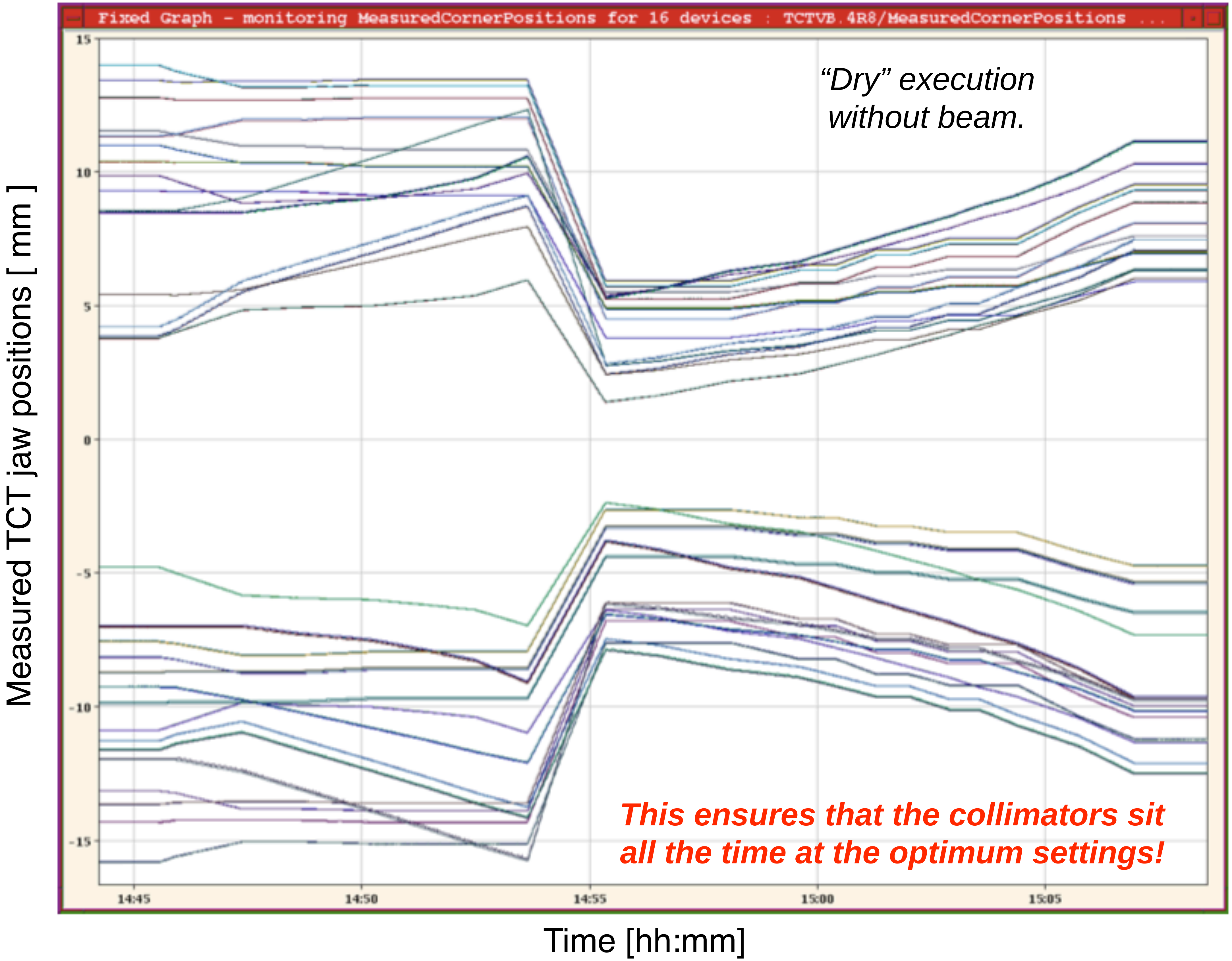




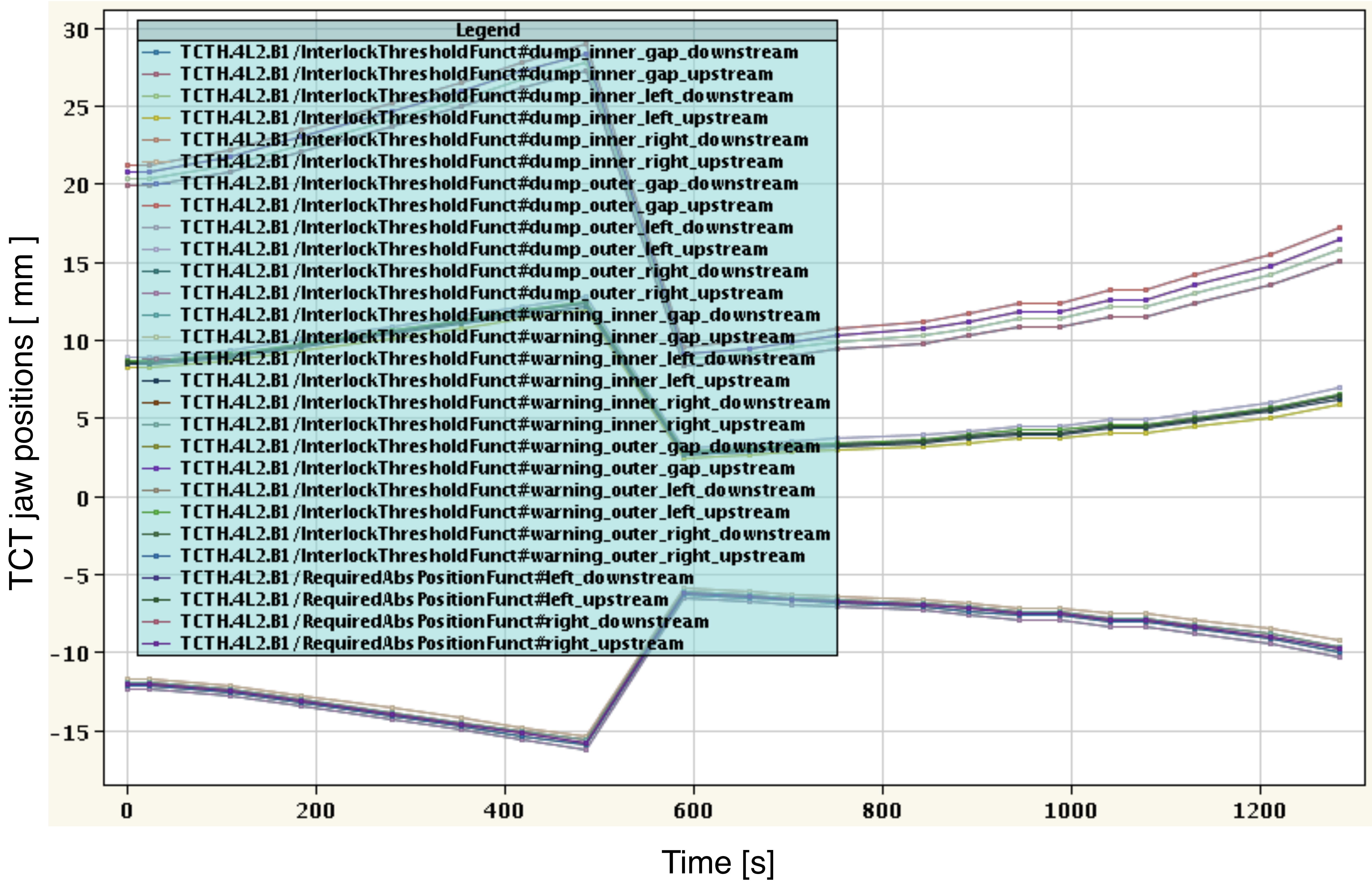
Squeeze settings



Measured jaw positions

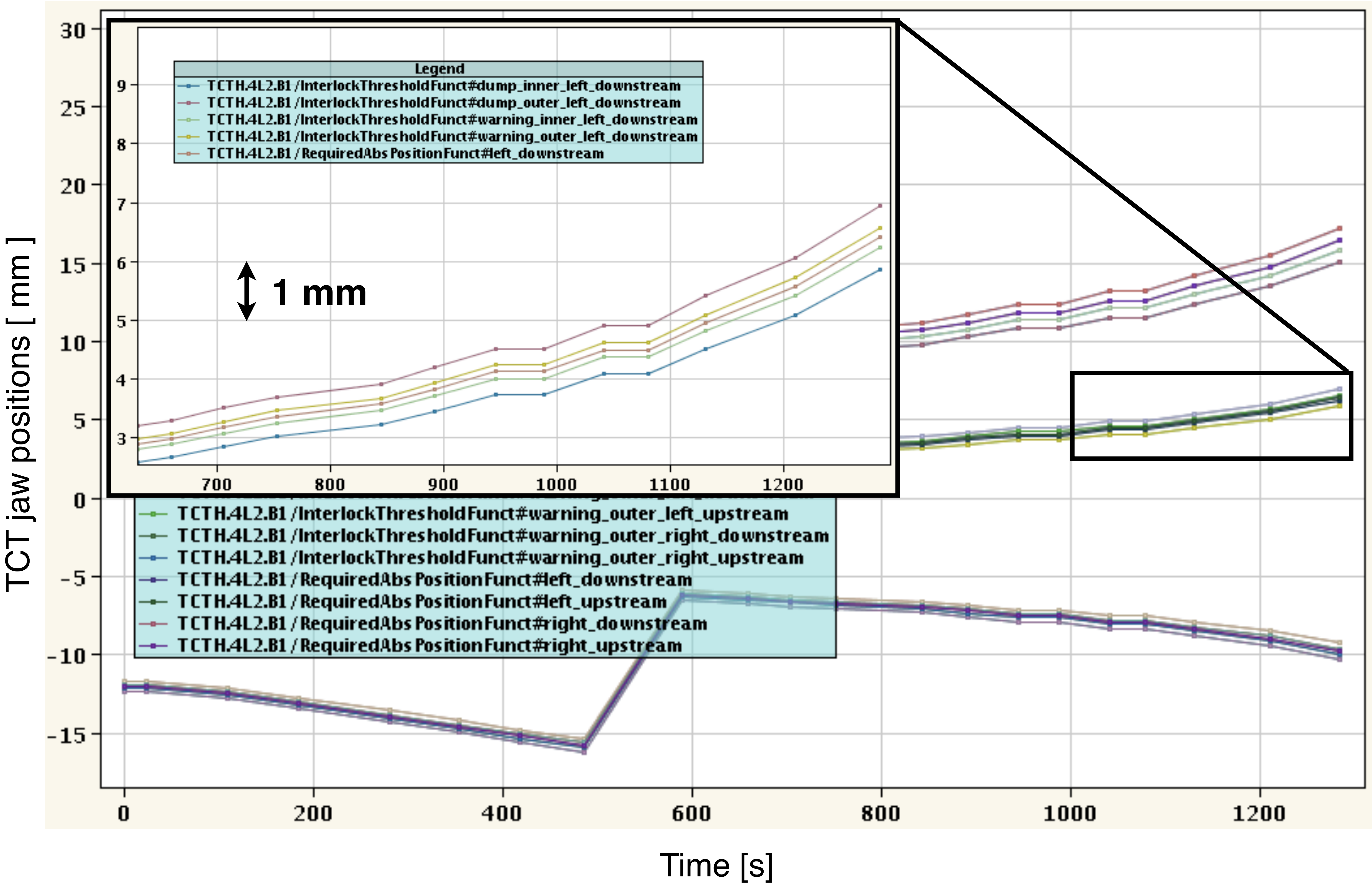


Don’t forget interlock limits!



Dump thresholds of 400-500 microns around each axis and gap (24 functions per collimator) to detect early on unsafe situations!

Don’t forget interlock limits!



Dump thresholds of 400-500 microns around each axis and gap (24 functions per collimator) to detect early on unsafe situations!

Outline

- Introduction
- Layout and challenges
- Collimator settings
- **Operation and performance**
- Conclusions

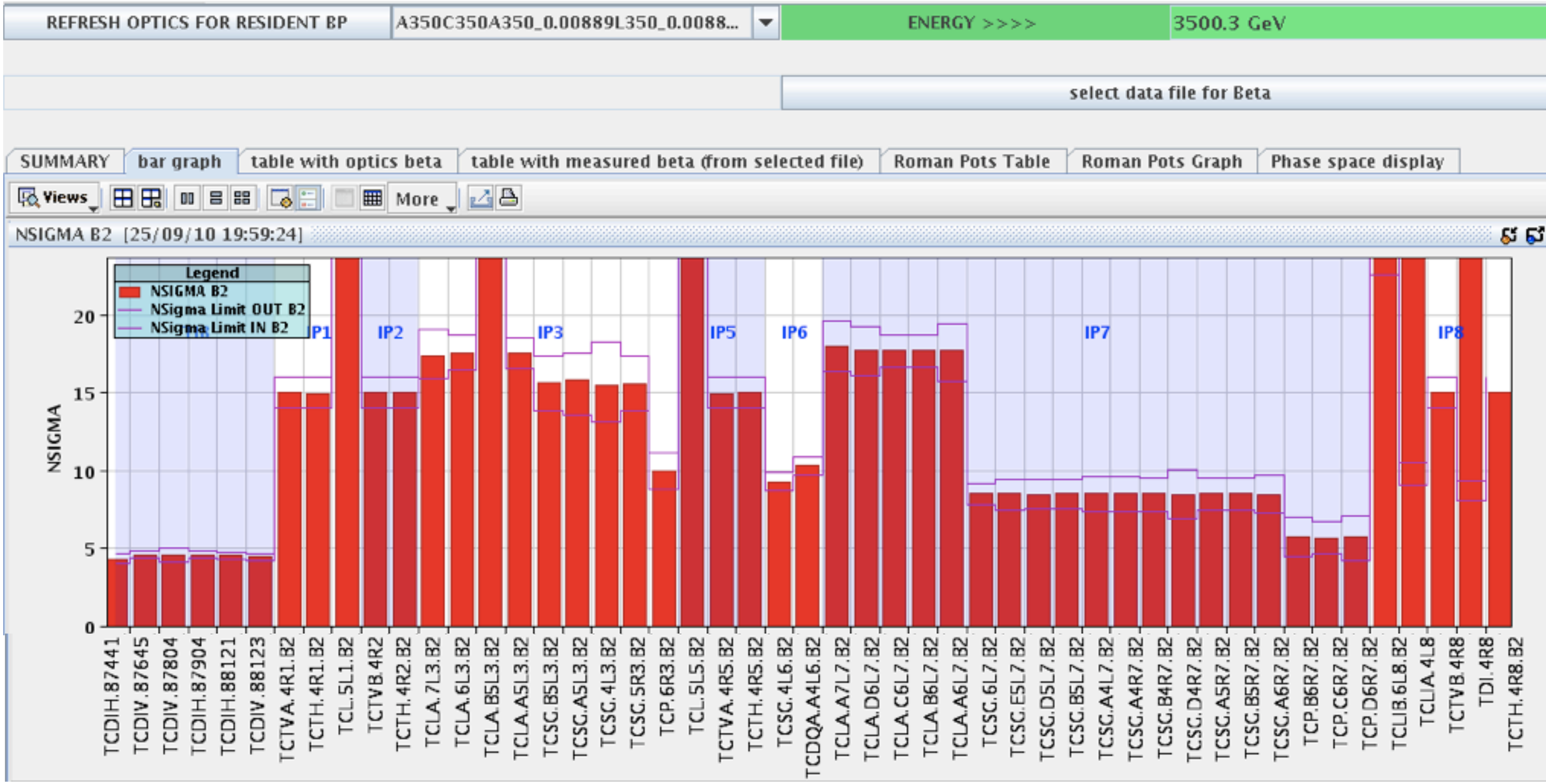
Run configurations and settings

Condition	Unit	Plane	Set 1 Injection	Set 2 Top energy	Set 3 Crossing angle	Set 4 Squeeze	Set 5 Collision
Energy	[GeV]	n/a	450	**3500**	3500	3500	3500
IP beta function β^*	[m]	n/a	10-11	10-11	10-11	**3.5**	3.5
Crossing angle α_c	[μrad]	n/a	**170**	170	**100-110**	100-110	100-110
IR separation	[mm]	n/a	2	2	2	2	**0**
Primary cut IR7	[σ]	H. V, S	5.7	**5.7**	5.7	5.7	5.7
Secondary cut IR7	[σ]	H, V, S	6.7	**8.5**	8.5	8.5	8.5
Quartiary cut IR7	[σ]	H, V	10.0	**17.7**	17.7	17.7	17.7
Primary cut IR3	[σ]	H	8.0	**12.0**	12.0	12.0	12.0
Secondary cut IR3	[σ]	H	9.3	**15.6**	15.6	15.6	15.6
Quartiary cut IR3	[σ]	H, V	10.0	**17.6**	17.6	17.6	17.6
Tertiary cut experiments	[σ]	H, V	**13.0**	35	35	**15.0**	**15.0**$^+$
Physics debris collimators	[σ]	H	out	out	out	out	out
TCSG/TCDQ IR6	[σ]	H	7-8	**9.3-10.6**	9.3-10.6	9.3-10.6	9.3-10.6

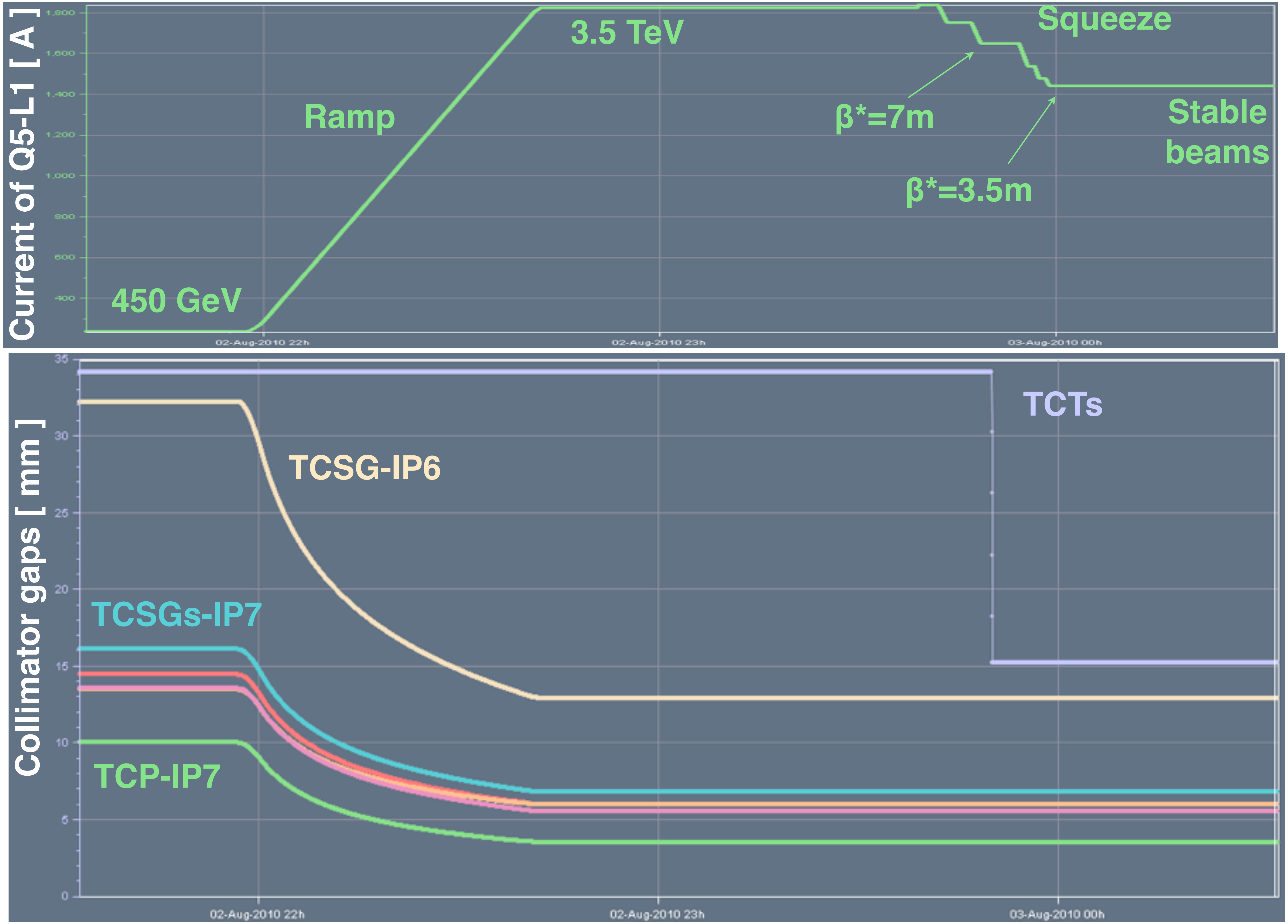
Smooth transition between one configuration and the other with functions.

Handling of collimator settings is managed by the LHC sequencer.

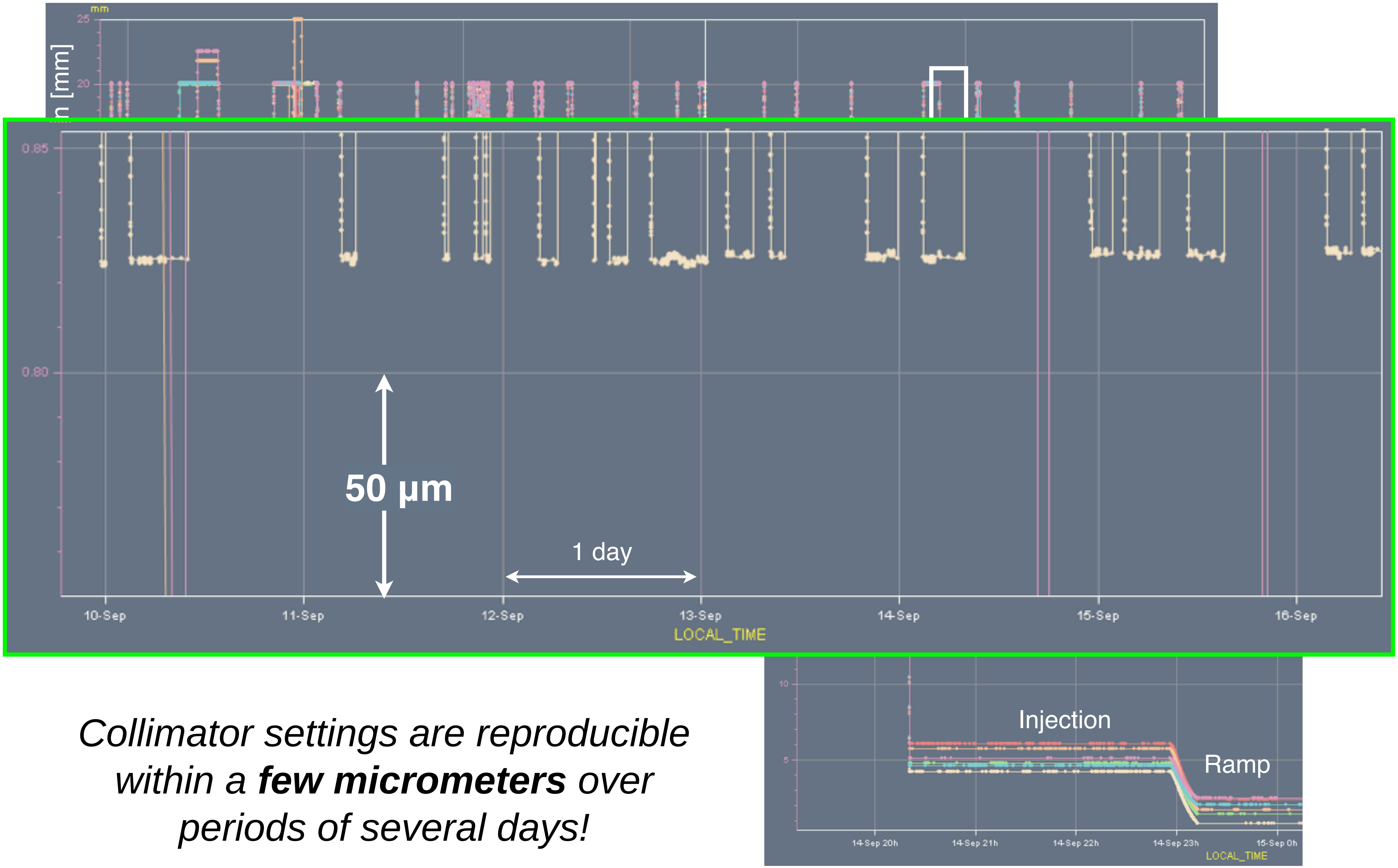
Collimator settings in physics



Operation during inj, ramp & squeeze

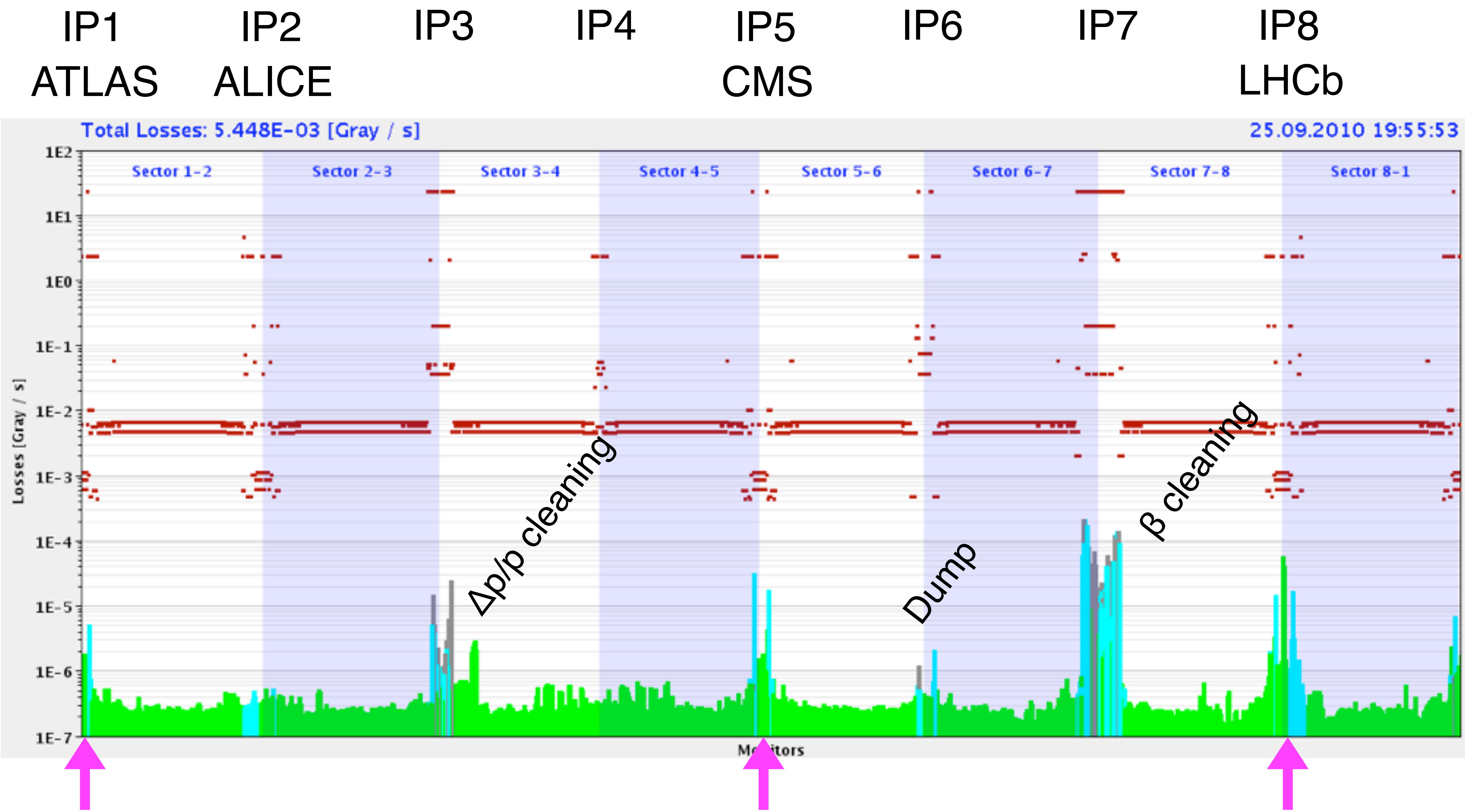


Reproducibility of settings



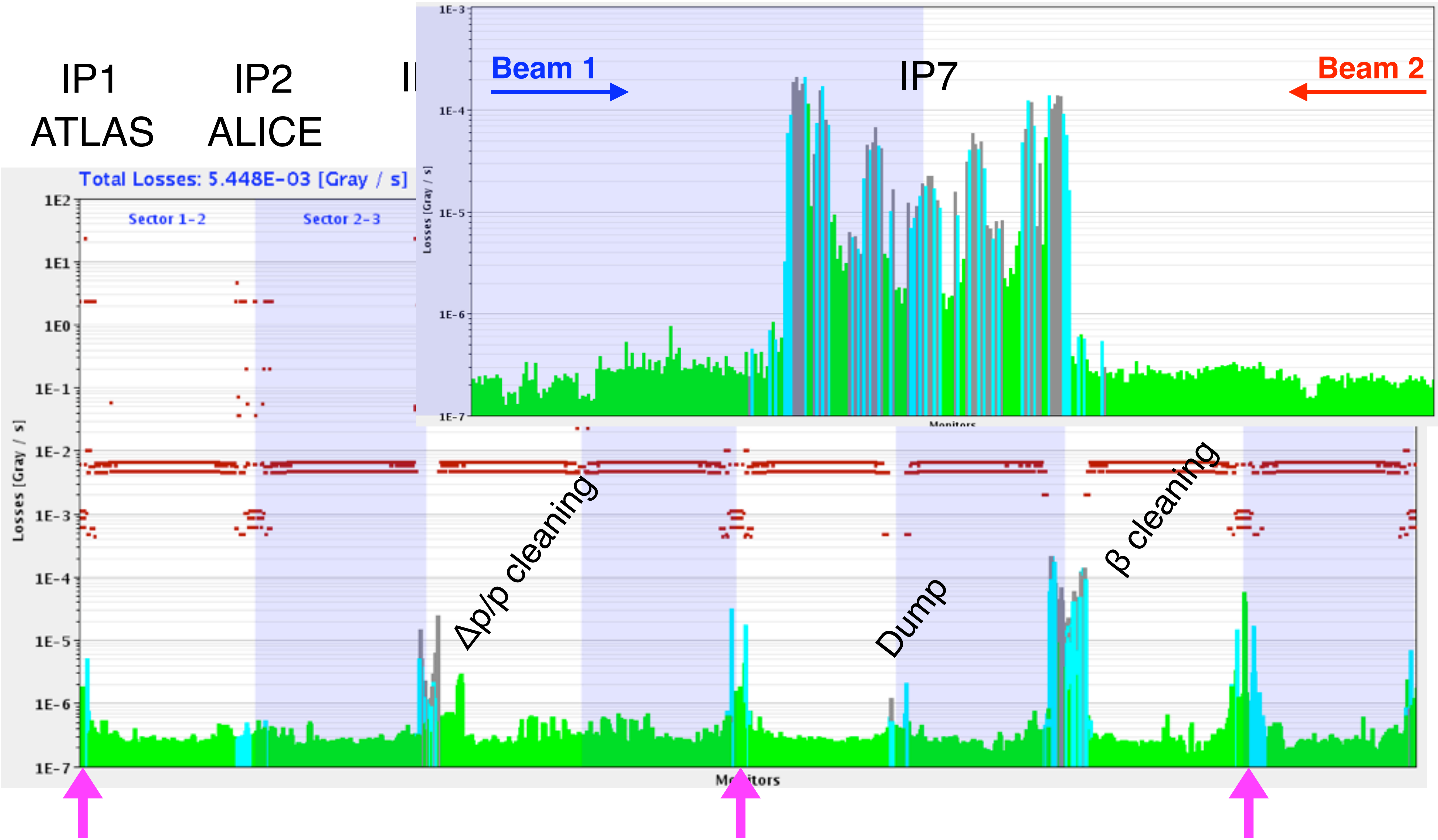
Collimator settings are reproducible within a ***few micrometers*** *over periods of several days!*

Beam losses in collision



Luminosity debris (0.35 x 10^{32} $cm^{-2}s^{-1}$)

Beam losses in collision

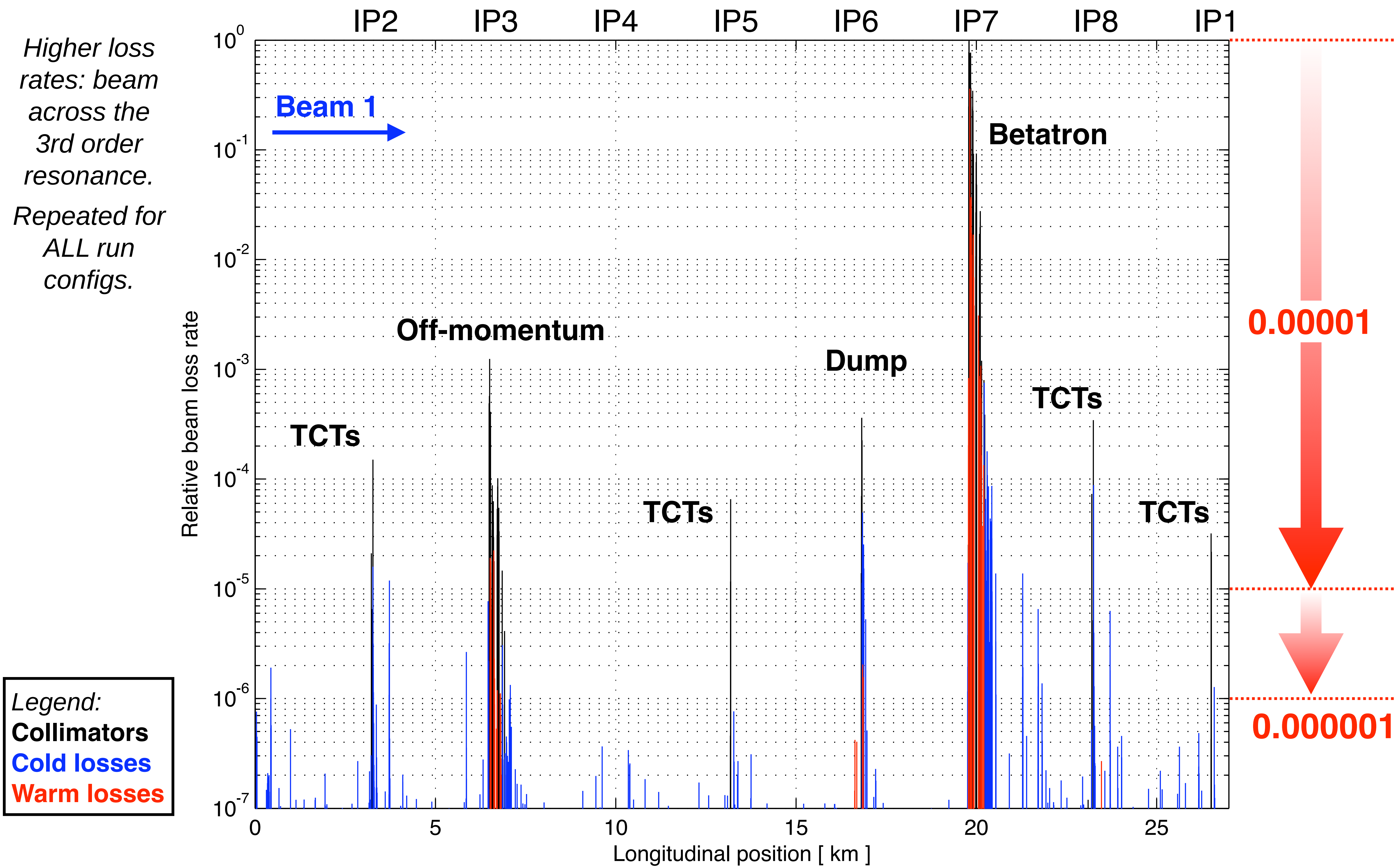


Luminosity debris (0.35 x 10^{32} $cm^{-2}s^{-1}$)

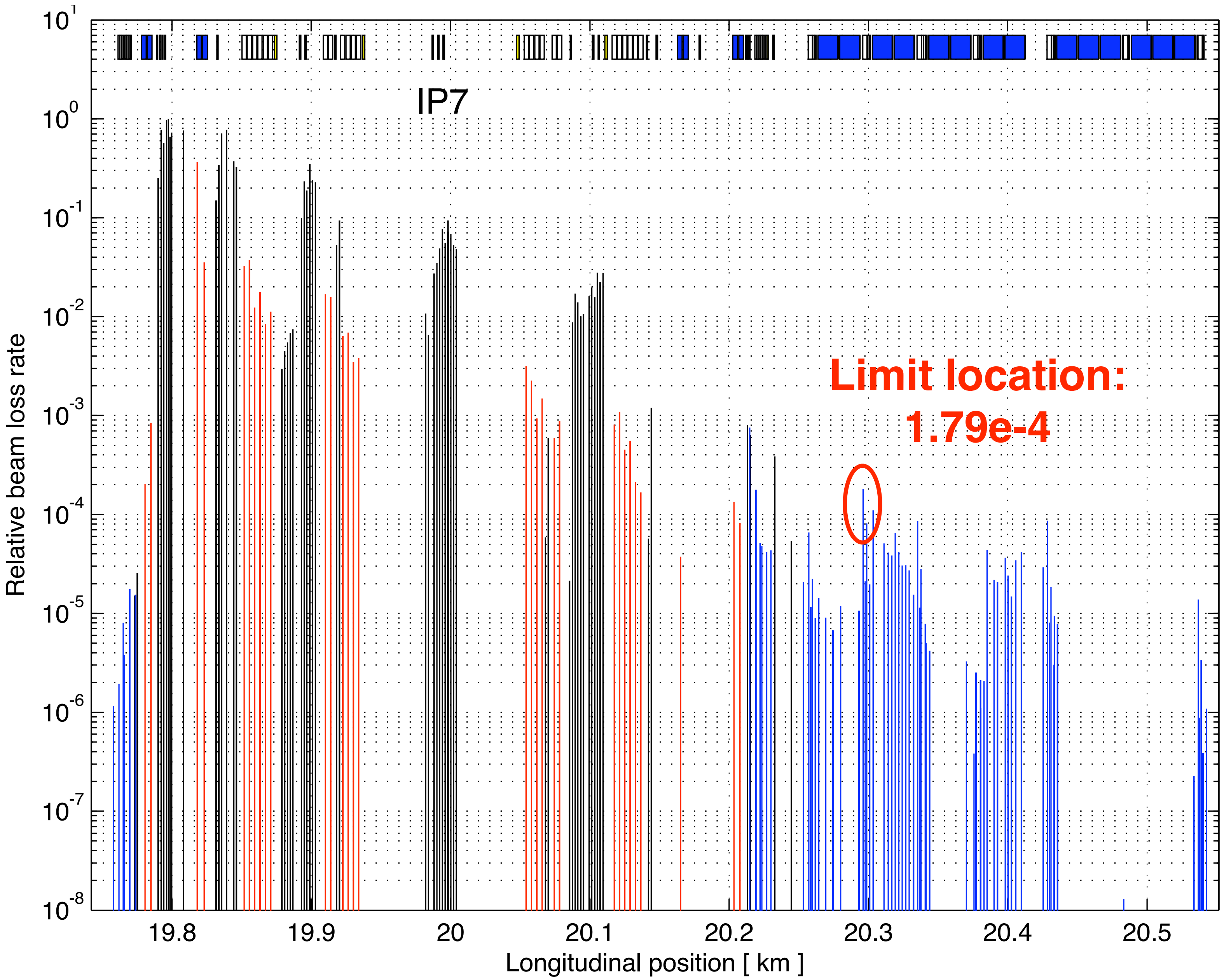
Cleaning performance: 3.5 TeV, β^*=3.5m

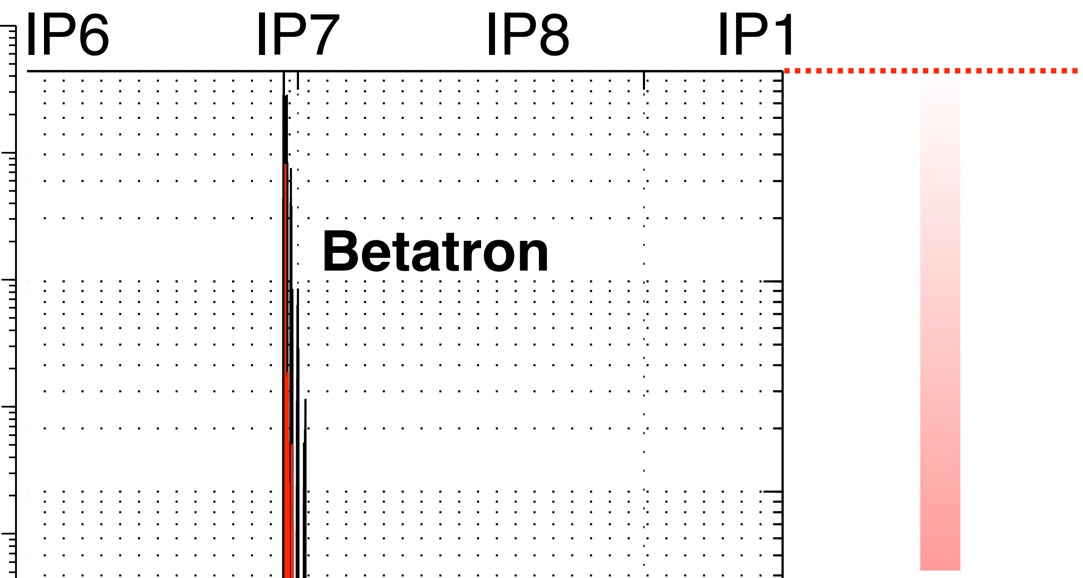
Higher loss rates: beam across the 3rd order resonance.

Repeated for ALL run configs.



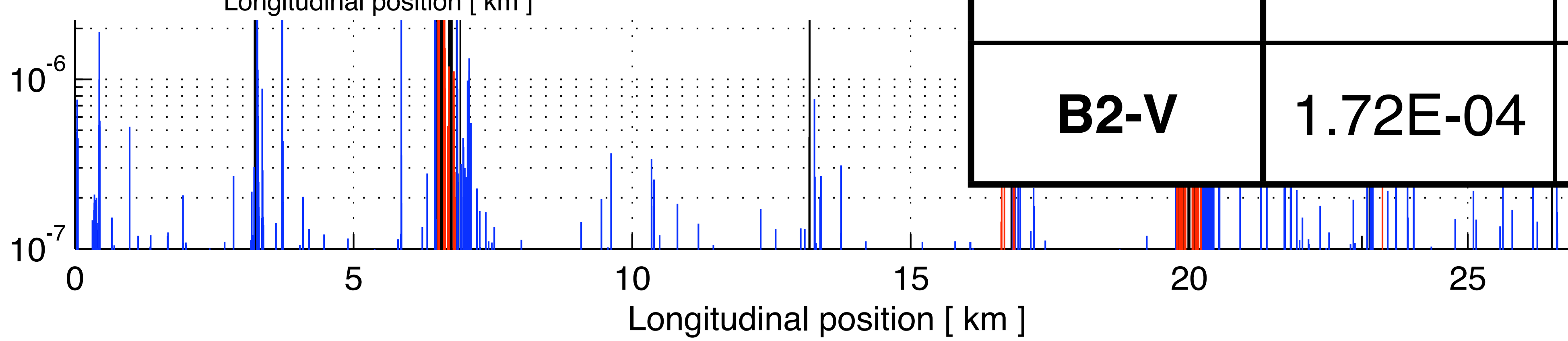
Cleaning performance: 3.5 TeV, β^*=3.5m



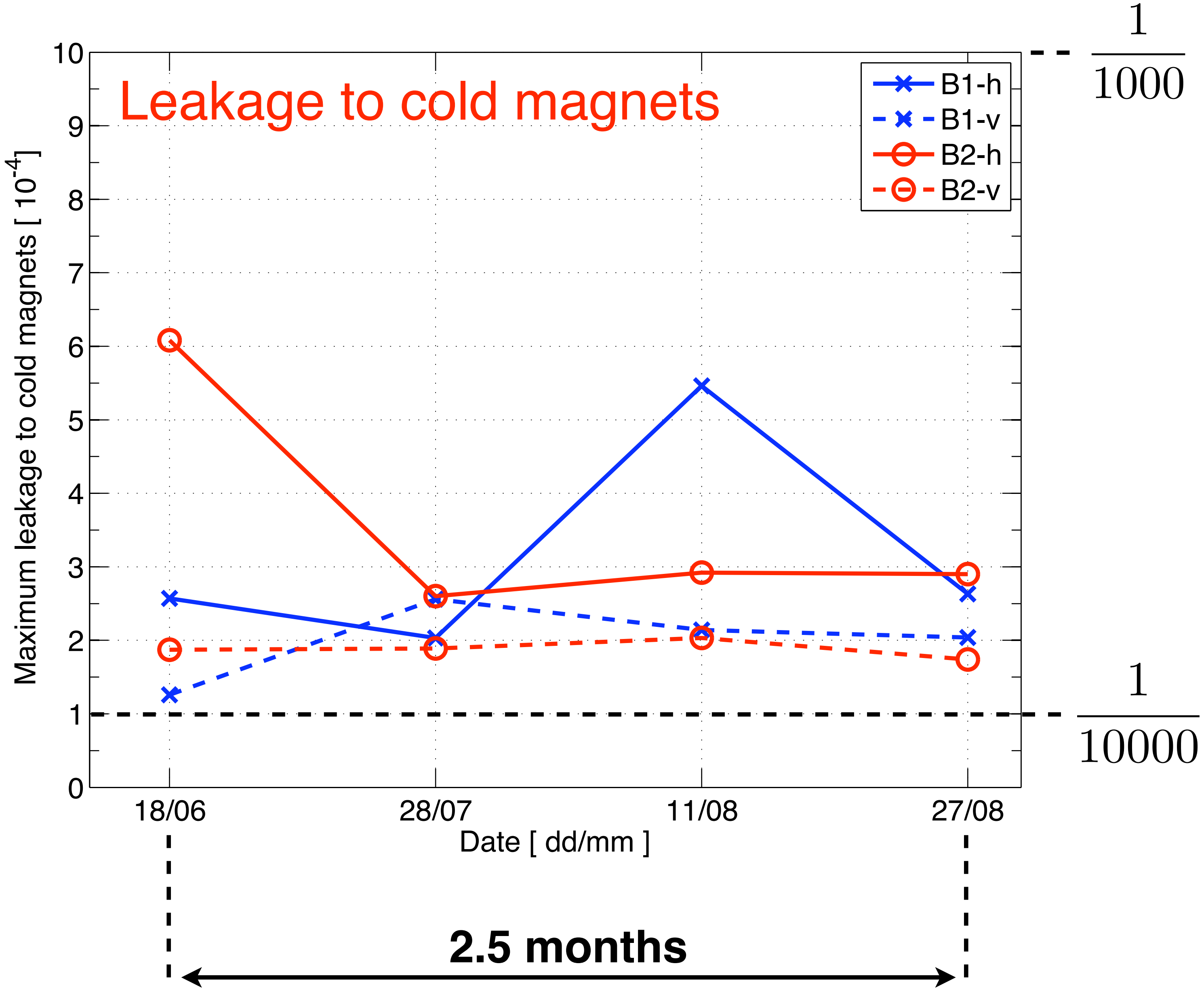


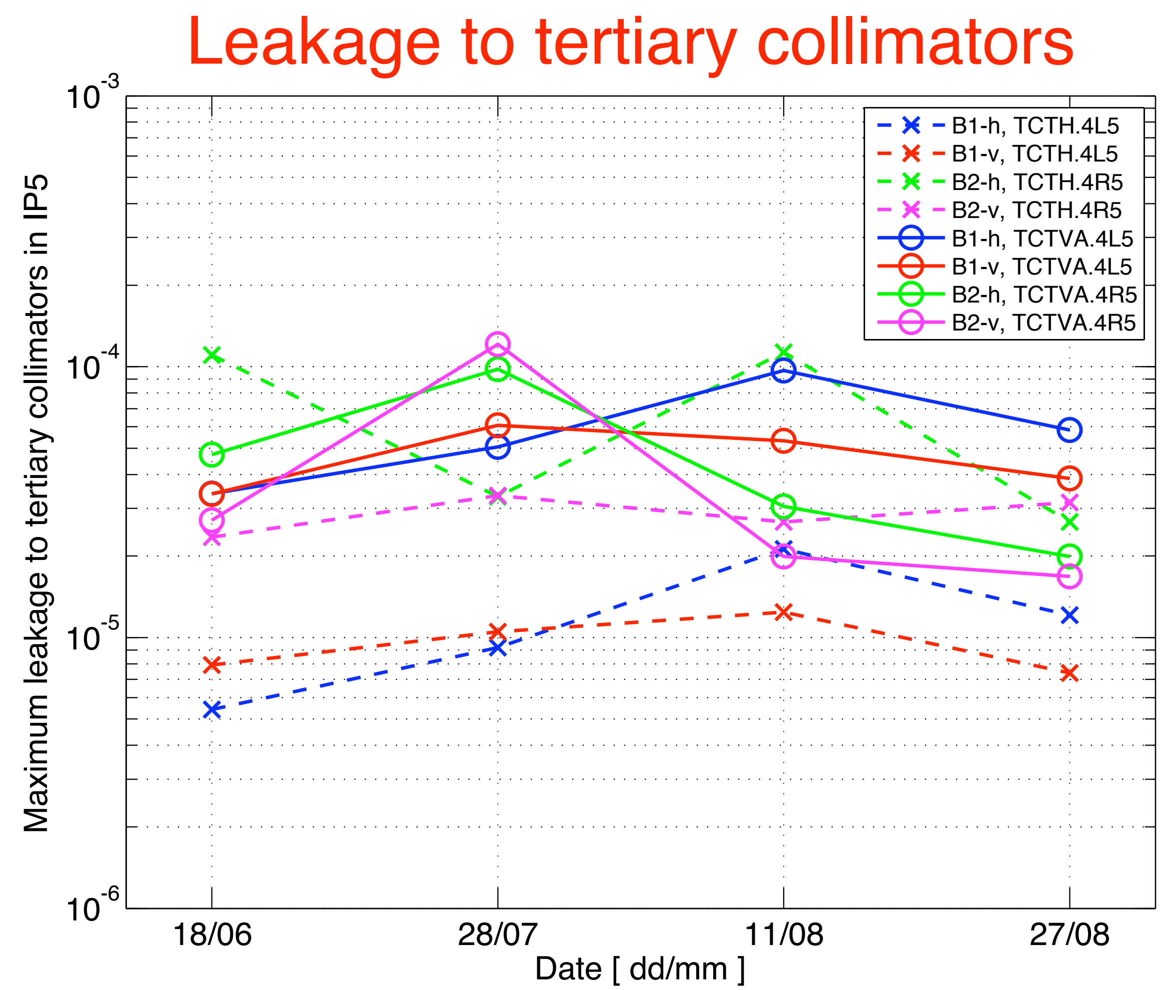
	Leakage	Efficiency
B1-H	2.37E-04	99.976
B1-V	1.79E-04	99.982
B2-H	3.86E-04	99.961
B2-V	1.72E-04	99.983

Legend:
Collimators
Cold losses
Warm losses



Stability of cleaning performance





Set-up established in **mid-June** remained valid until end of August.

Betatron cleaning setup at 3.5 TeV: still valid now after **3.5 months**!

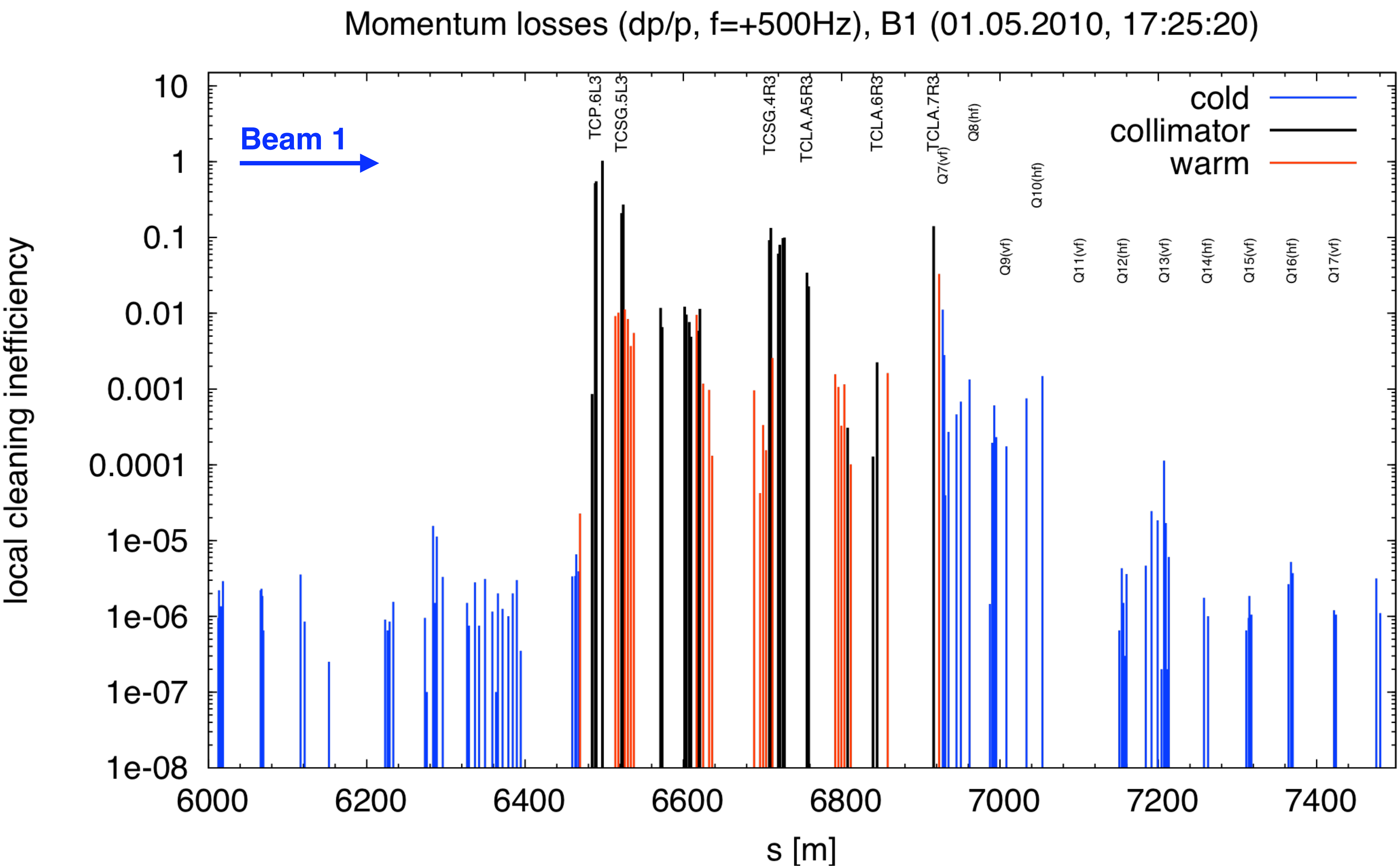
We have just prepared the new settings in preparation for the ~30 MJ operation!

Conclusions

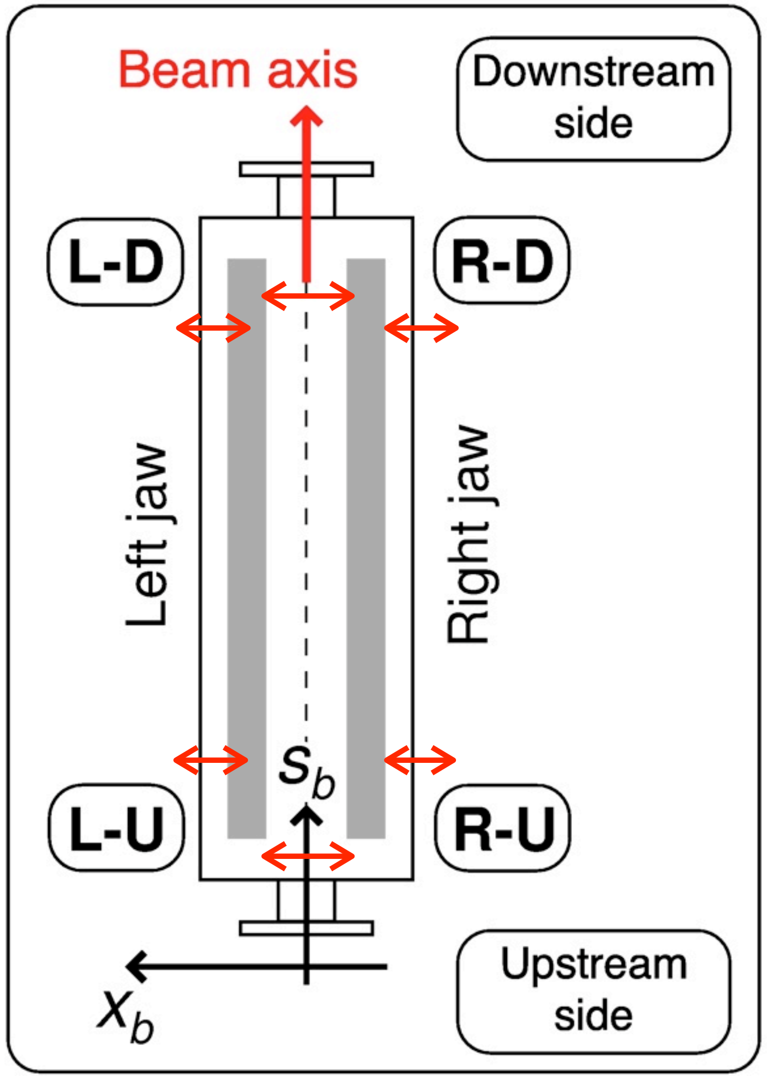
- ☑ **LHC collimation system has seen an exciting commissioning!**
  - *- Full system of ~100 collimators commissioned and operational.*
  - *- Meticulous preparation without beam has ensured a smooth and safe startup!*
- ☑ **LHC collimation works essentially as specified:**
  - *- Confirmed all basic design choices (layout, controls, mechanics, survey,...).*
  - *- It is operated as foreseen in all machine phases, from injection to physics.*
- ☑ **Cleaning performance: leakage in cold magnets is a few 1e-4.**
  - *- No single quench with circulating beams up to 6 MJ stored energy!!*
  - *- Machine aperture is shielded by the collimators in all conditions.*
  - *- Flexible and safe operation is ensured (could handle losses 200x design).*
- ☑ **Setting strategy: infrequent beam-based set-ups+reproducibility**
  - *- Long alignment campaigns, but then ok for months (3.5 months in IR7).*
  - *- Validation campaigns for machine protection + performance monitoring needed.*
- ☑ **The LHC collimation is ready for the operation in 30 MJ regime. Looking forward to achieving the luminosity goal of 10^{32} $cm^{-2}s^{-1}$!**

Reserve slides

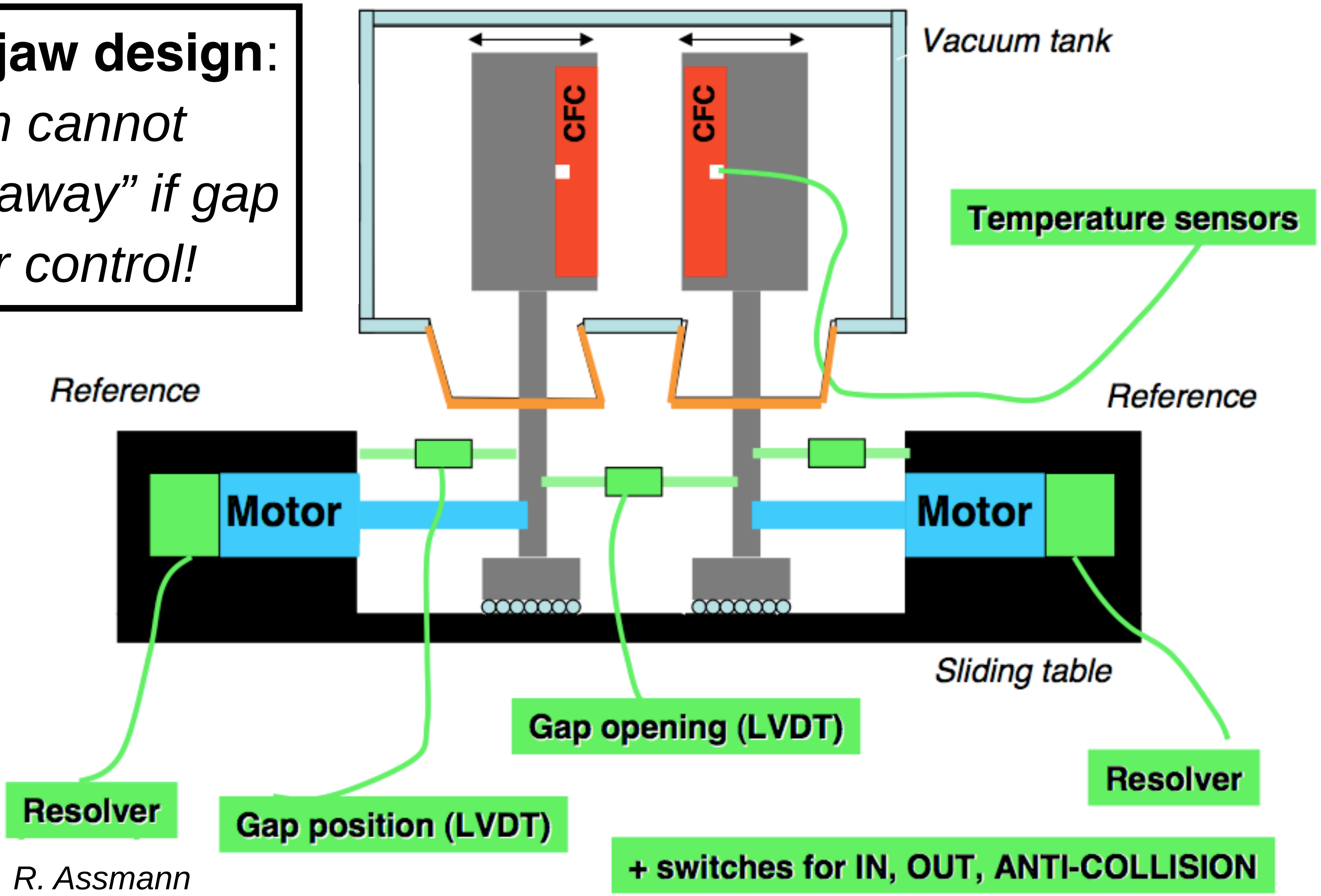
Momentum cleaning



Collimator positioning system



Two-jaw design:
Beam cannot "drift away" if gap under control!

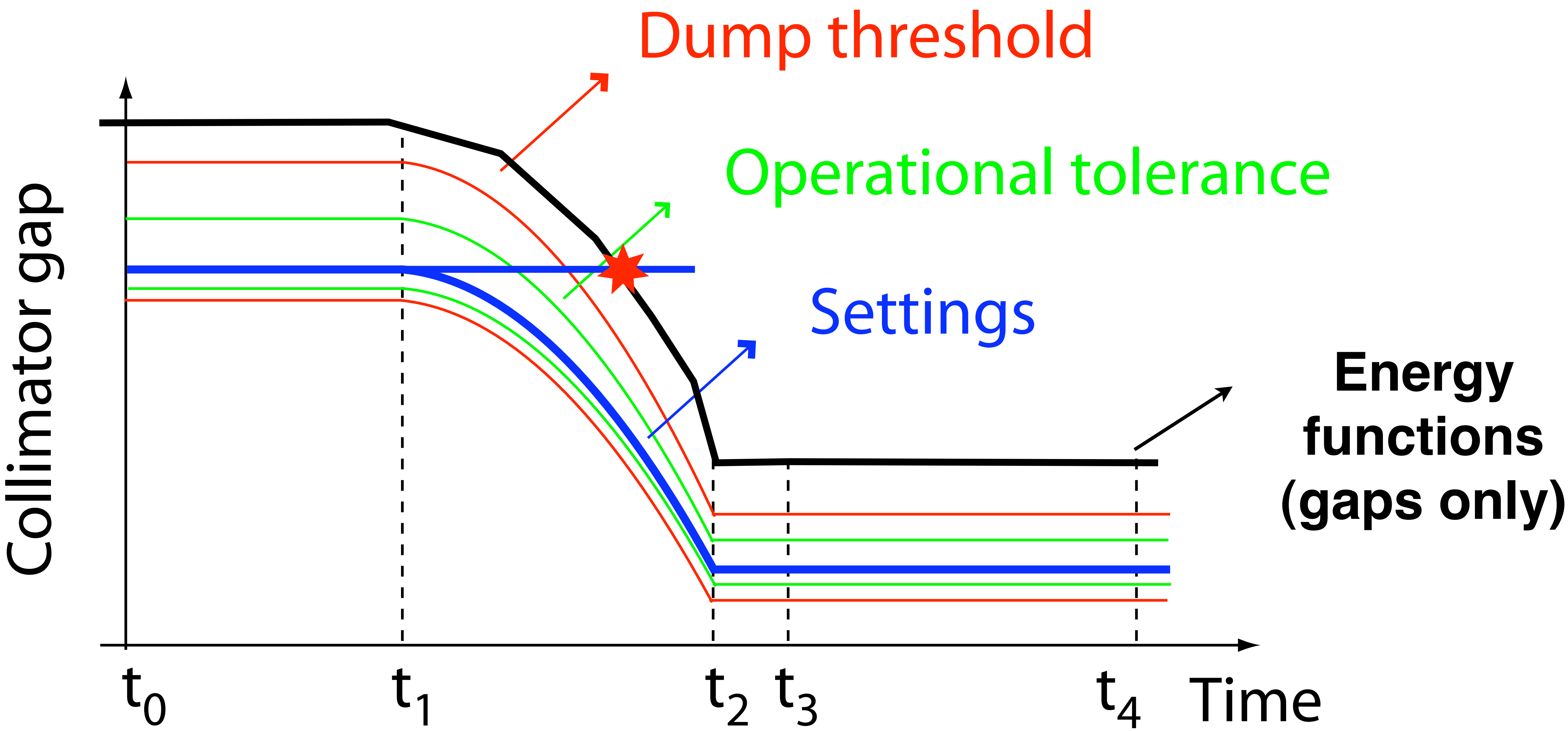


Settings: **4 stepping motors** for jaw corners - 1 motor for tank position.

Survey: 7 direct measurements: **4 corners** + **2 gaps** + tank
4 resolvers that count motor steps
10 switch statuses (full-in, full-out, anti-collision)

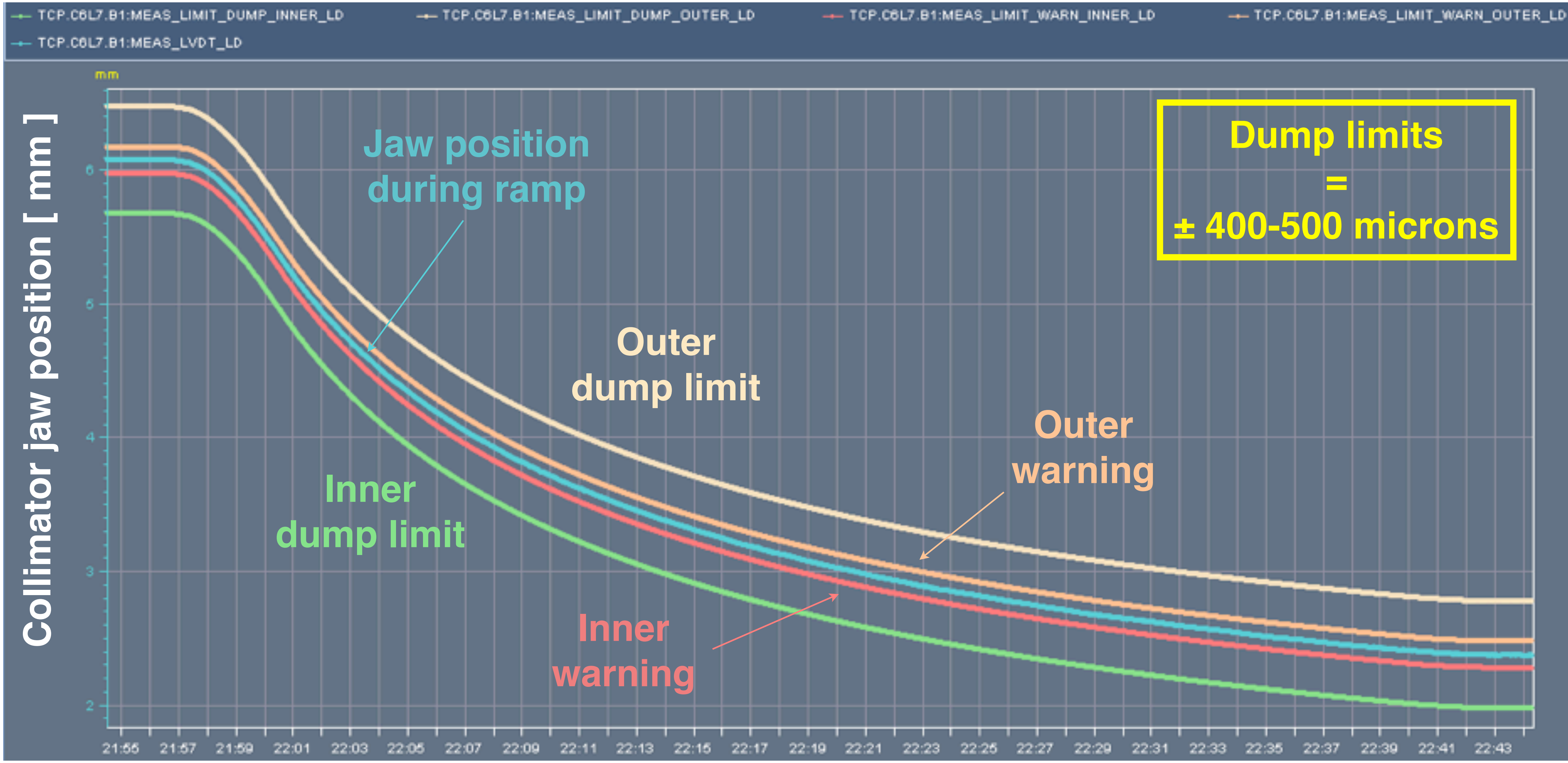
Redundancy: motors+resolvers+LVDT's (*Linear Variable Differential Transformer*) =
14 position measurements per collimator

Position and gap interlocks



- **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).

Time-dependent limit functions

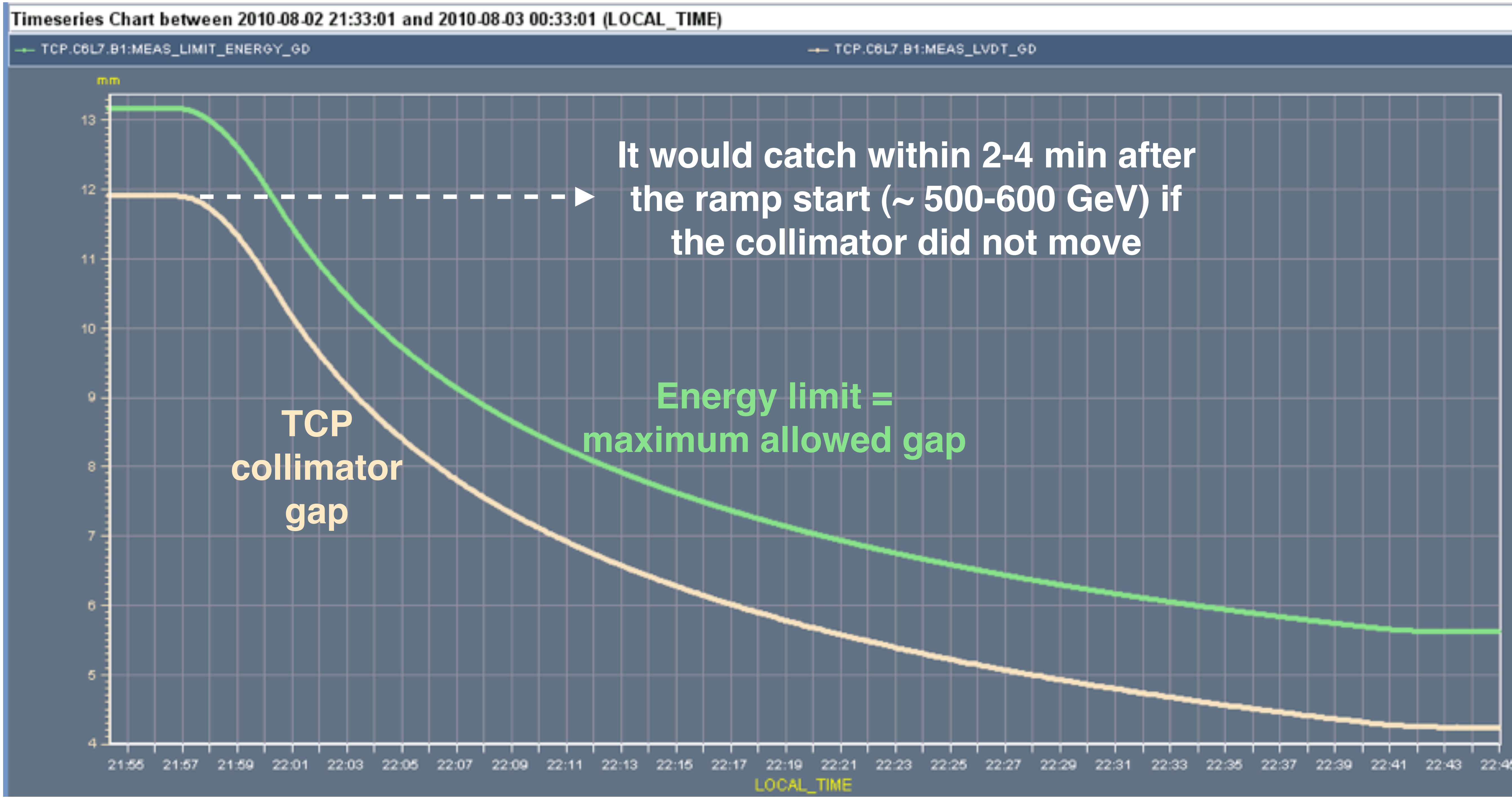


Limit functions (24 per collimator!!) are loaded for all ring collimators.

Constant limits remain active also for collimators that do not move (TCTs).

Function execution is triggered by the ramp timing event.

Gap energy limits

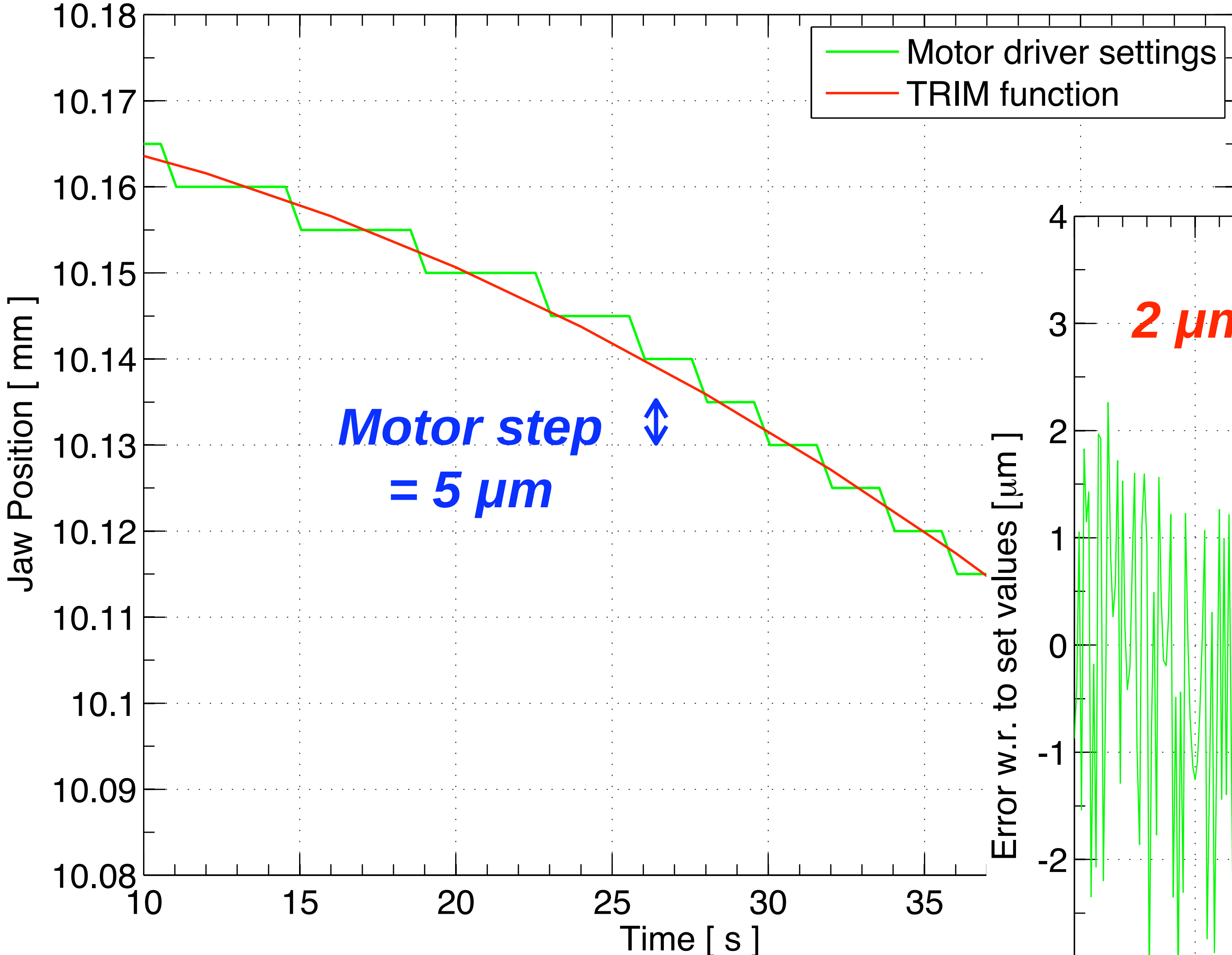


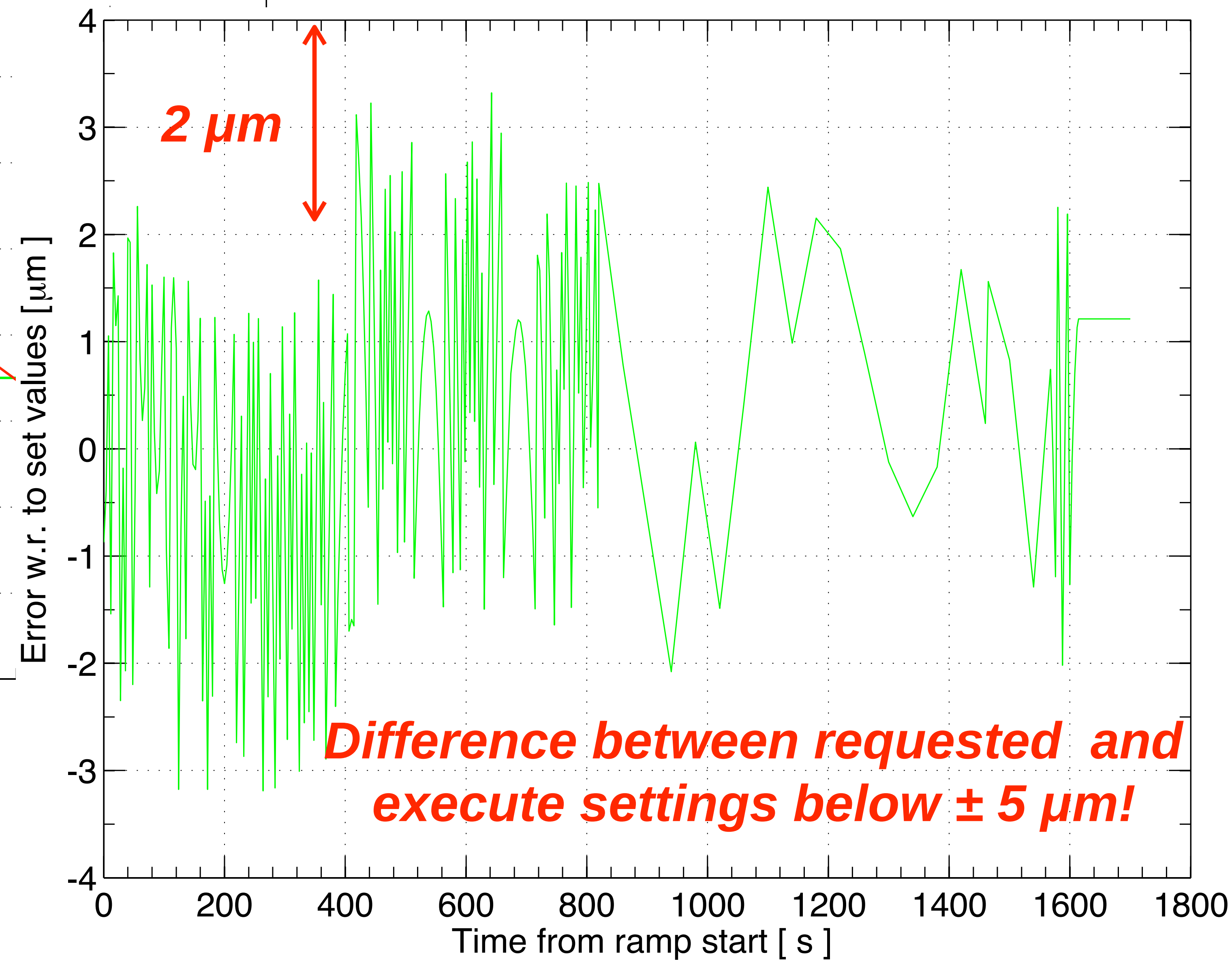
Redundant interlock, independent on trigger: it uses the safe machine parameters.

Beam dumped if a collimator does not start moving during the ramp (and sits happily within time-dependent limits).

Accuracy of function execution

Requested/executed settings vs. time





- Motor step = **5 µm**
- Operational motor speed = 2 mm/s
- “Slow” functions are interpolated with the appropriate rate of step execution

Low-level implementation in the PXI system by A. Masi

List of acronyms

Phase	Acronym	Material	Length [m]	Number	Locations	INJ	TOP	Purpose
	Scrapers							
2	***TCHS***	tbd	tbd	6	**IR3, IR7**			Beam scraping
2	***TCHS***	tbd	tbd	2	**IR3, IR7**			*Skew beam scraping*
	Collimators							
1	**TCP**	C-C	0.2	8	**IR3, IR7**	**Y**	**Y**	Primary collimators
1	**TCSG**	C-C	1.0	30	**IR3, IR7**	**Y**	**Y**	Secondary collimators
1	**TCSG**	C-C	1.0	2	**IR6**	**Y**	**Y**	Help for TCDQ set-up
2	***TCSM***	tbd	tbd	30	**IR3, IR7**			*Hybrid secondary collimators*
4	***TCS4***	tbd	tbd	10	**IR7**			*Phase 4 collimators*
	Diluters							
1	**TDI**	Sandwich	4.2	2	**IR2, IR8**	**Y**		Injection protection
1	**TCLI**	C	1.0	4	**IR2, IR8**	**Y**		Injection protection
1	**TCDI**	C	1.2	14	**TI2, TI8**	**Y**		Injection collimation
1	**TCDQ**	C-C	6.0	2	**IR6**	**Y**	**Y**	Dump protection
	Movable Absorbers							
1	**TCT**	Cu/W	1.0	16	**IR1, IR2, IR5, IR8**		**Y**	Tertiary collimators
1	**TCLA**	Cu/W	1.0	16	**IR3, IR7**	**Y**	**Y**	Showers from collimators
1	**TCL/TCLP**	Cu	1.0	4	**IR1, IR5**		**Y**	Secondaries from IP
3	***TCL/TCLP***	Cu	1.0	4	**IR1, IR5**		**Y**	*Secondaries from IP*