External Review on LHC Machine Protection

CERN, Geneva, CH

September 6th-8th, 2010

Introduction to the LHC collimation system

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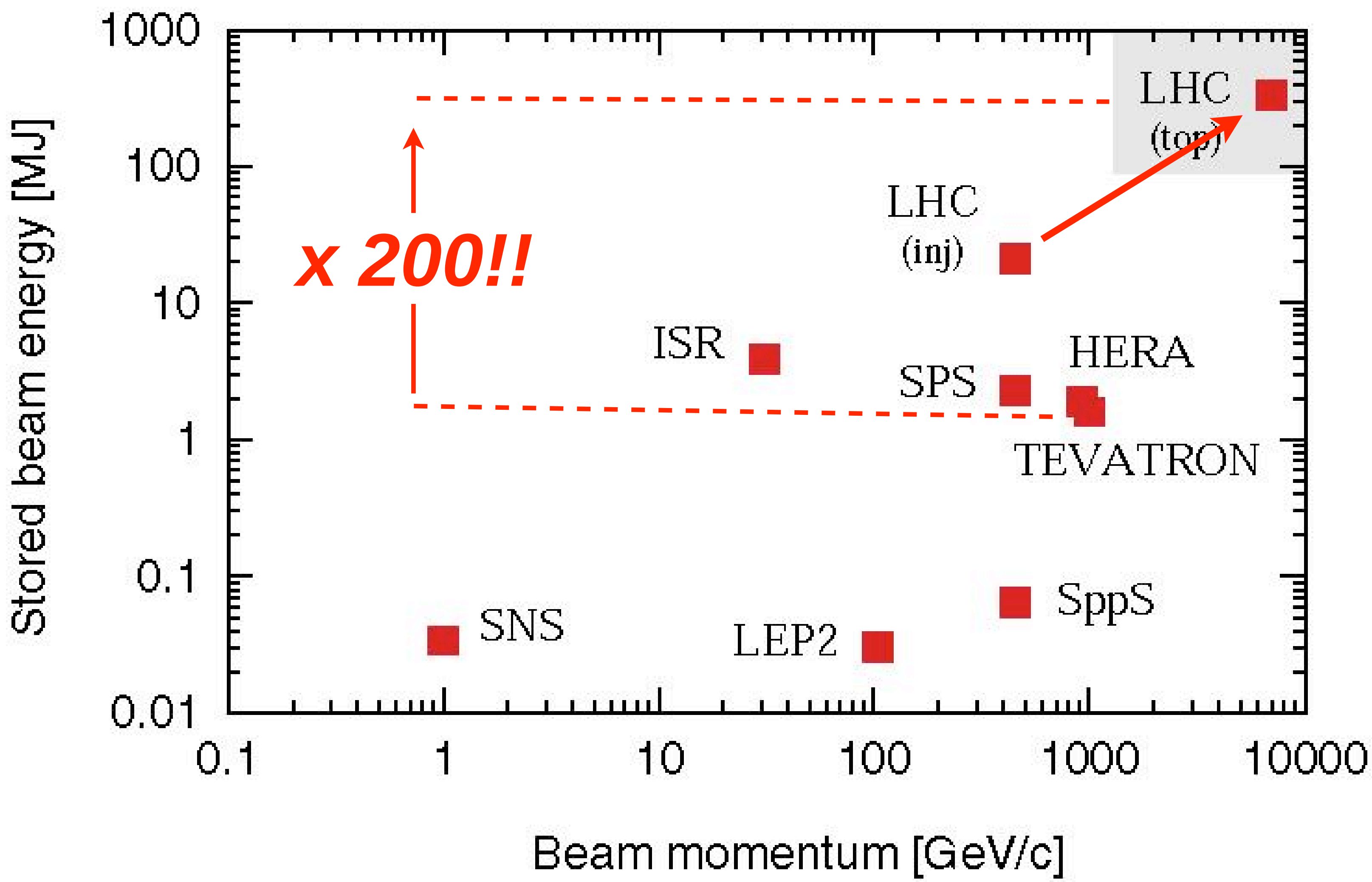
for the LHC Collimation team

Outline

- ☑ Introduction
- ☑ Layout and hierarchy
- ☑ Collimator interlocking
- ☑ Collimation operation
- ☑ Conclusions

Introduction



$E_b = 0.45 \rightarrow 7$ TeV; $I_b = 3.4 \times 10^{14}$

Stored energy	**362 MJ (7 TeV)**
	23 MJ (450 GeV)
Quench limit	~ 10 mJ / cm^3
Damage (metal)	~ 50 kJ / mm^2

LHC enters in a ***new territory*** for handling ultra-intense beams in a super-conducting environment!

- → *Control losses 1000 time better than the state-of-the-art!*
- → *Need collimation at all machine states: injection, ramp, squeeze, physics*
- → *Major role in passive machine protection*

Layout of Phase I 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

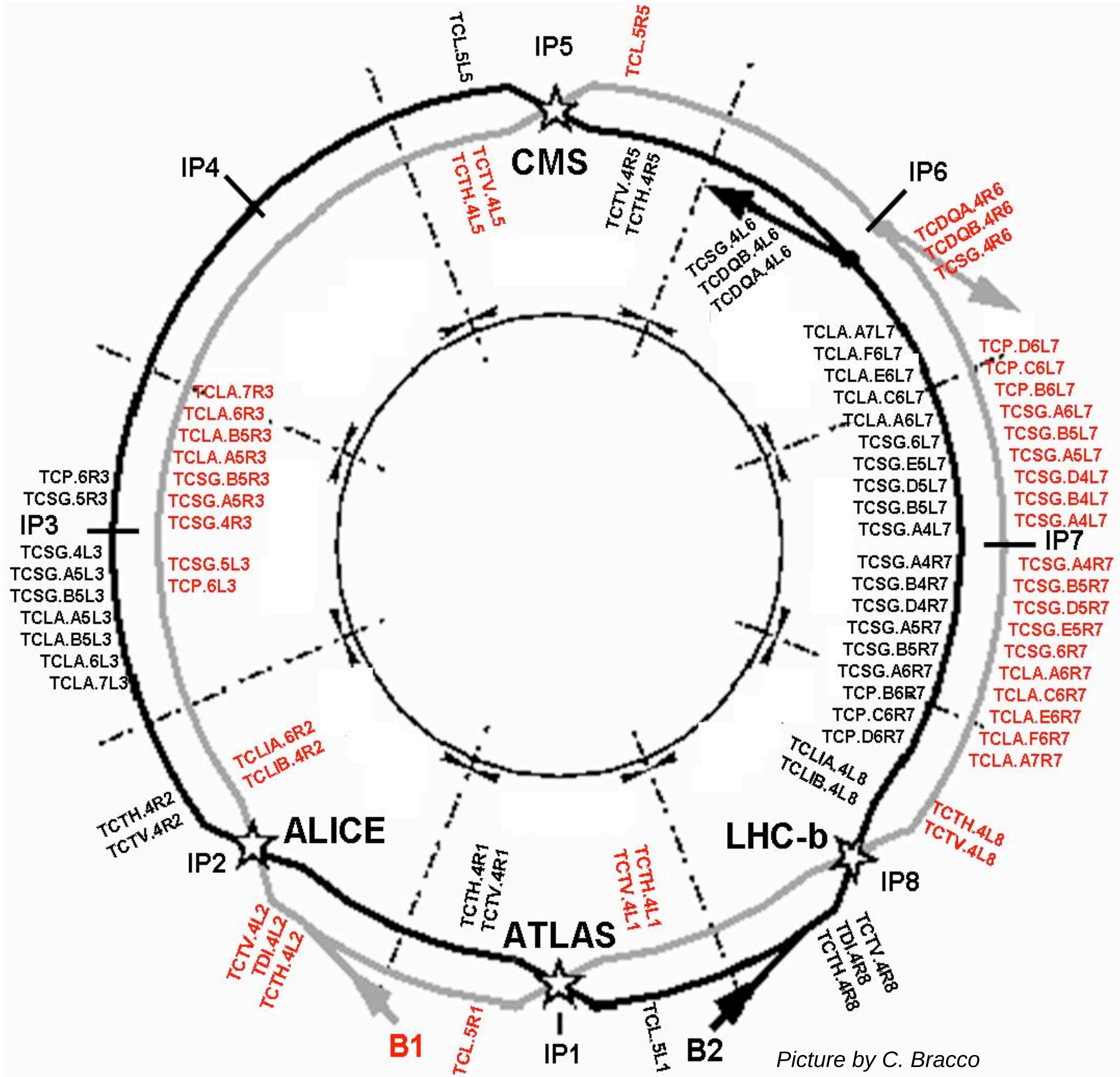
- **8 tertiary (2 per IP)**

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!

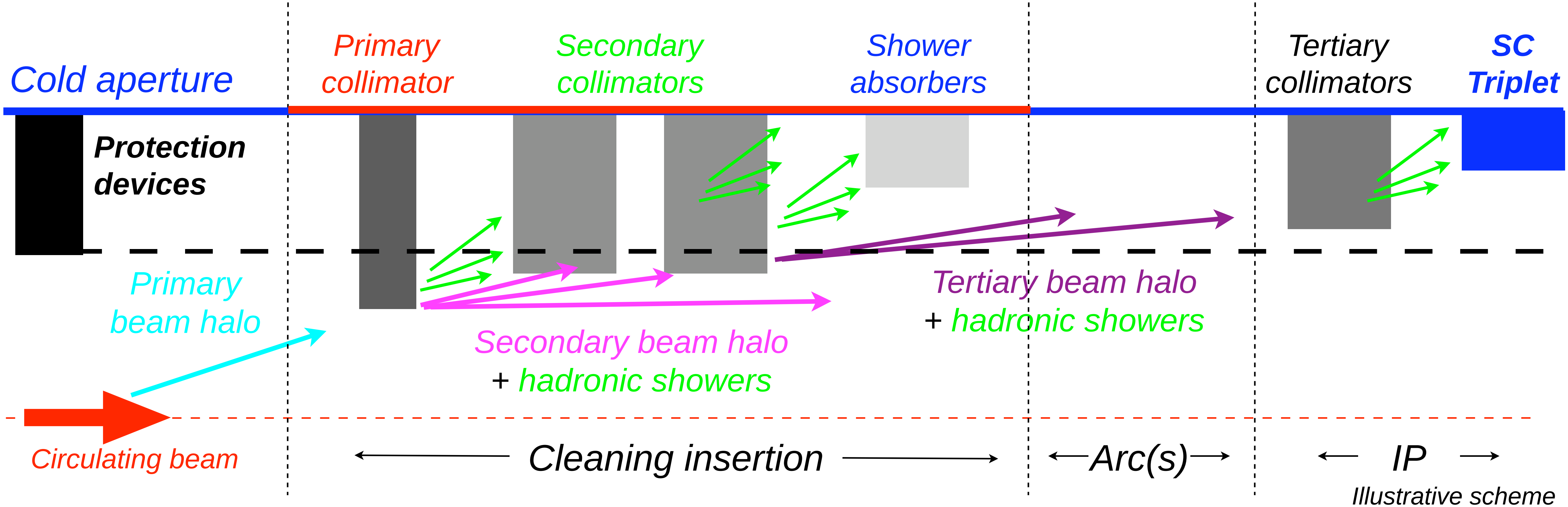


Picture by C. Bracco

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*

LHC multi-stage collimation



In all machine phases, the cold aperture must be in the shade of several layer of collimators. Largest losses are concentrated in warm regions!

Leakage in cold aperture must be below quench limit (and damage level for warm)!

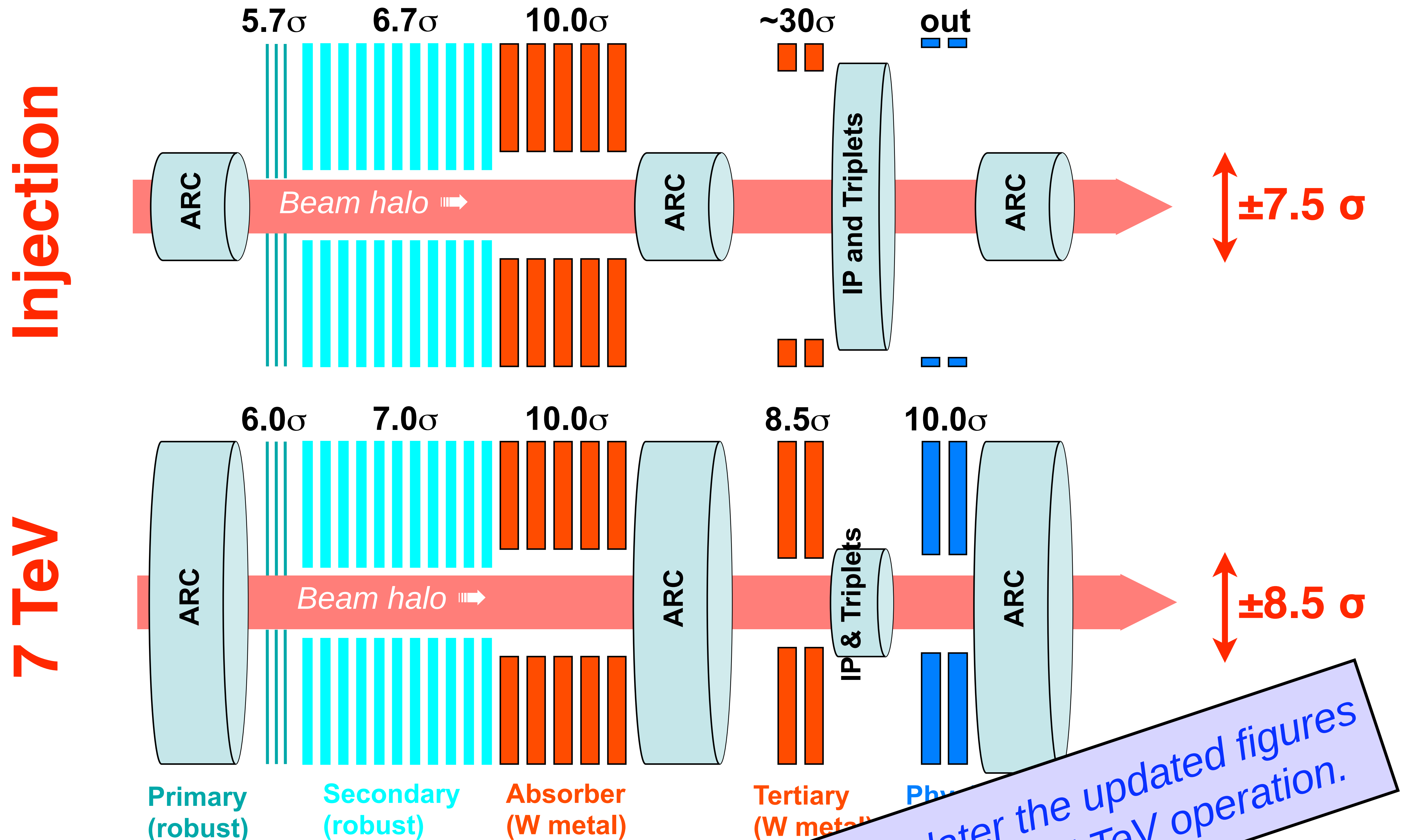
The cold aperture sets the scale for the collimator settings. Different for injection and top energy with squeezed beams (*see next slide*).

Only primary and secondary collimator are robust (Carbon). Absorbers and tertiary collimators (Tungsten) must be protected by the protection devices.

Cleaning and **passive protection** rely on the **good hierarchy** of collimator families.

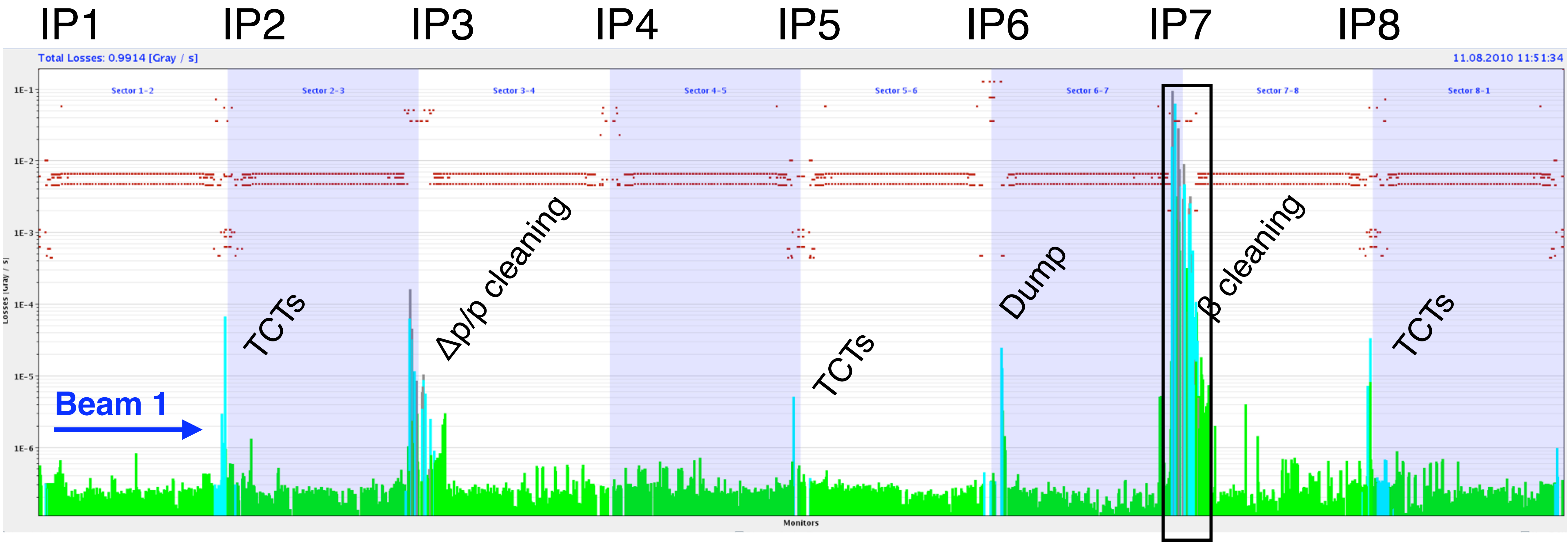
This is achieved with a **beam-based setup** of the collimators to centre the jaws around the beam orbit for a given optics (not discussed here).

LHC aperture and collimator settings

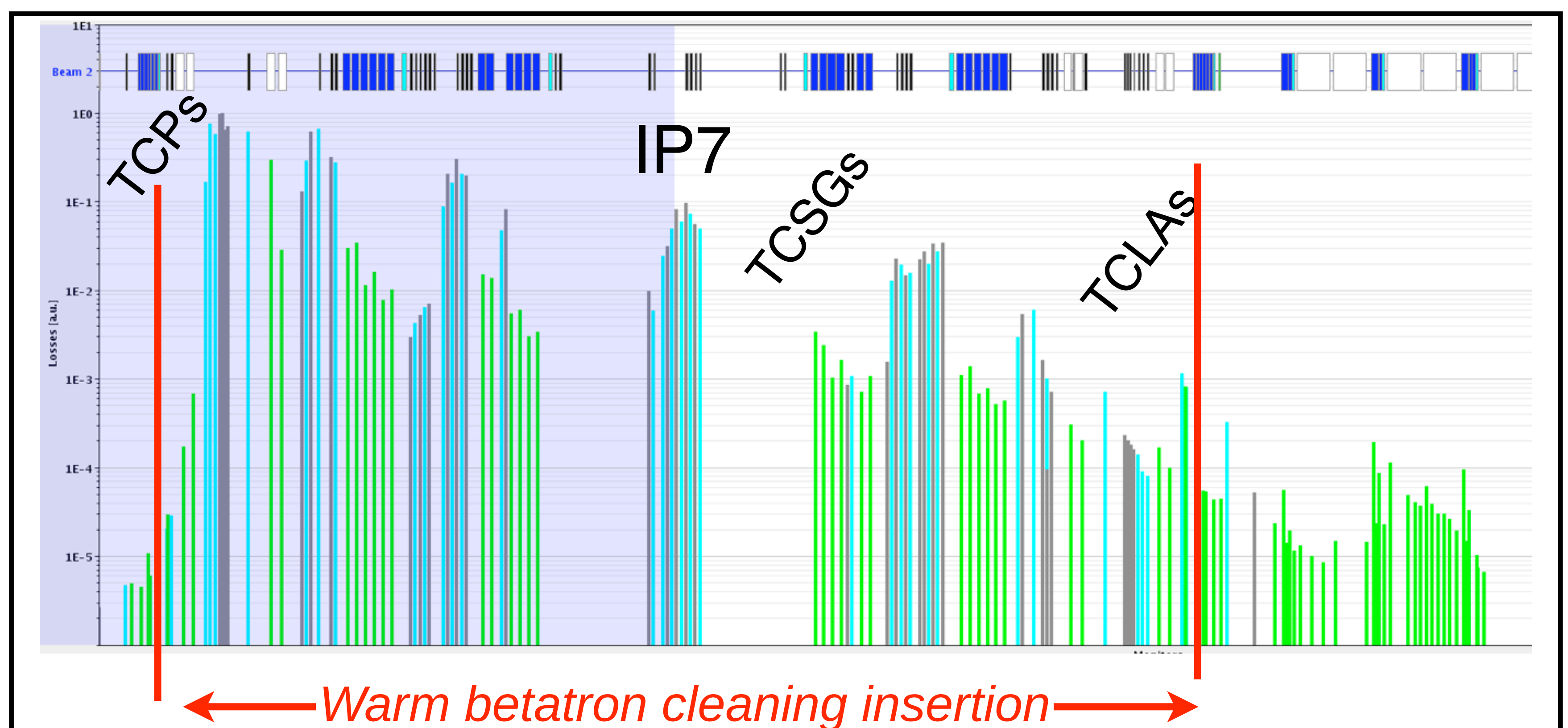


We will see later the updated figures for the present 3.5 TeV operation.

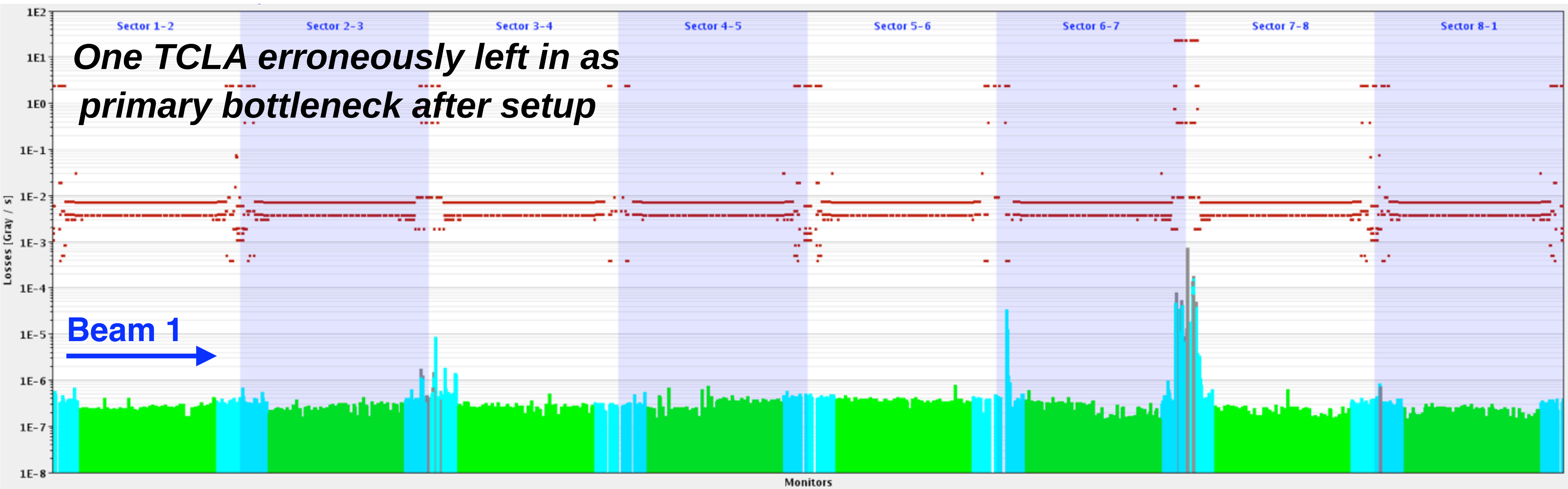
Good setup: hierarchy respected

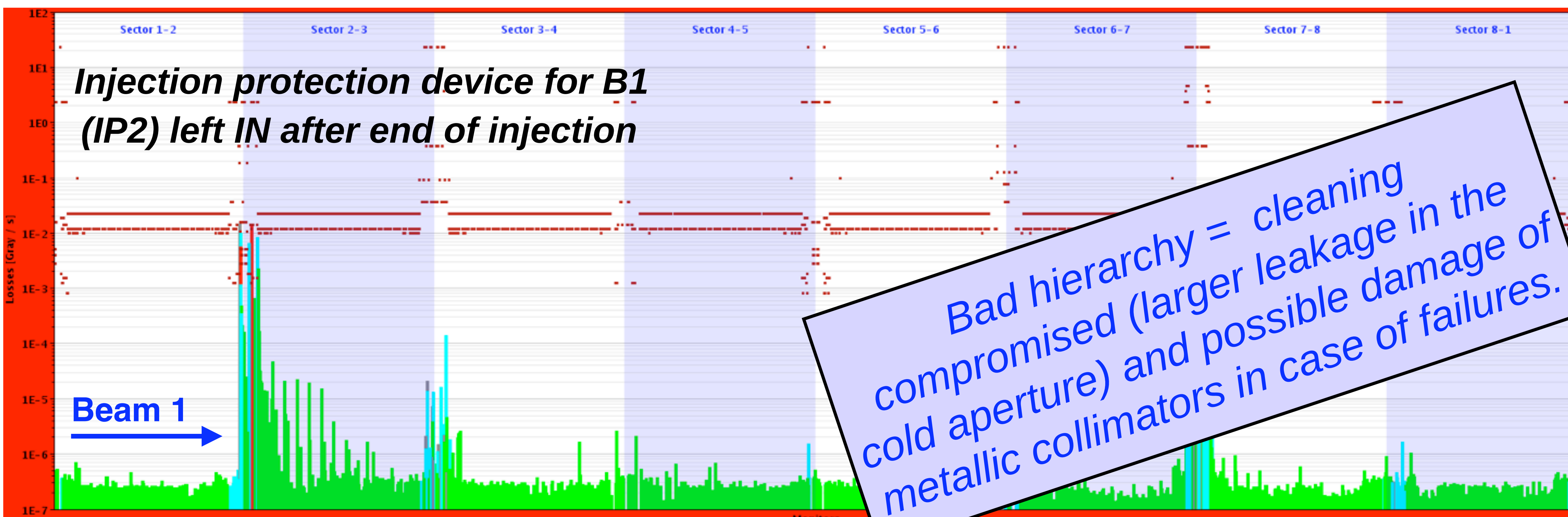


Collimator hierarchy *around the ring is verified after setup with* ***dedicated loss maps*** *induced by artificially high loss rates: record beam losses around the ring while crossing betatron resonances.*
Loss maps compared against simulations to assess system performance.



Bad setup: hierarchy violated





Bad hierarchy = cleaning compromised (larger leakage in the cold aperture) and possible damage of metallic collimators in case of failures.

Considerations on hierarchy

- The collimator **hierarchy** must always be respected with unsafe beams:
  - to ensure **cleaning** (no quenches);
  - to ensure **protection** (no damage)

  Only robust collimators (TCPs, TCSGs) might be exposed to high loss.
- Collimator settings are given in terms of **local beam size** and **beam position**.
- Once settings are established, the preservation of hierarchy depends **critically** on:
  - the **mechanical precision** of collimator positions →*detailed discussion later;*
  - 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.
  - Presently using settings established on June 12th (~ 3 months ago)
- **Consequences** of this infrequent setup:
  - tight constraints on **reproducibility** of machine parameters!
  - require regular **monitoring** of cleaning performance → *talk by D. Wollmann*.
- Note that if one runs with **violated hierarchy** the risk is not immediately apparent but might only show up if there are problems like an asynchronous dump.

Considerations on hierarchy

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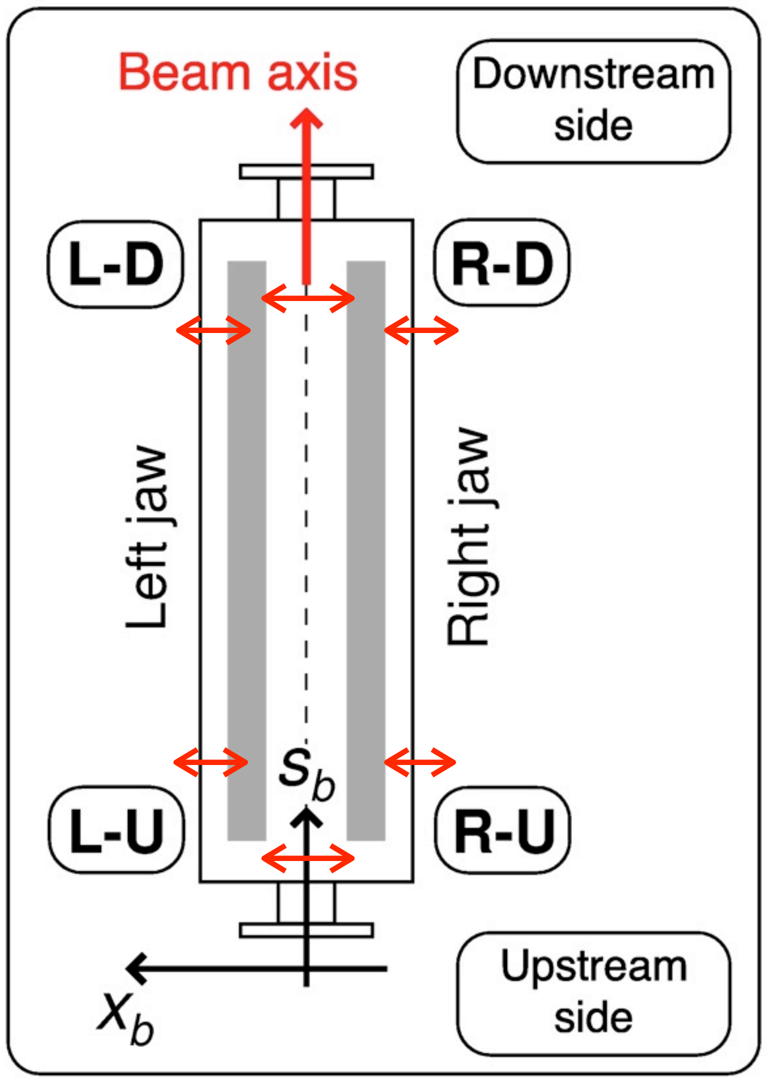
These aspects will be treated in detail in the next talks. Here, present specific aspects of machine protection of collimators and operation of the system.

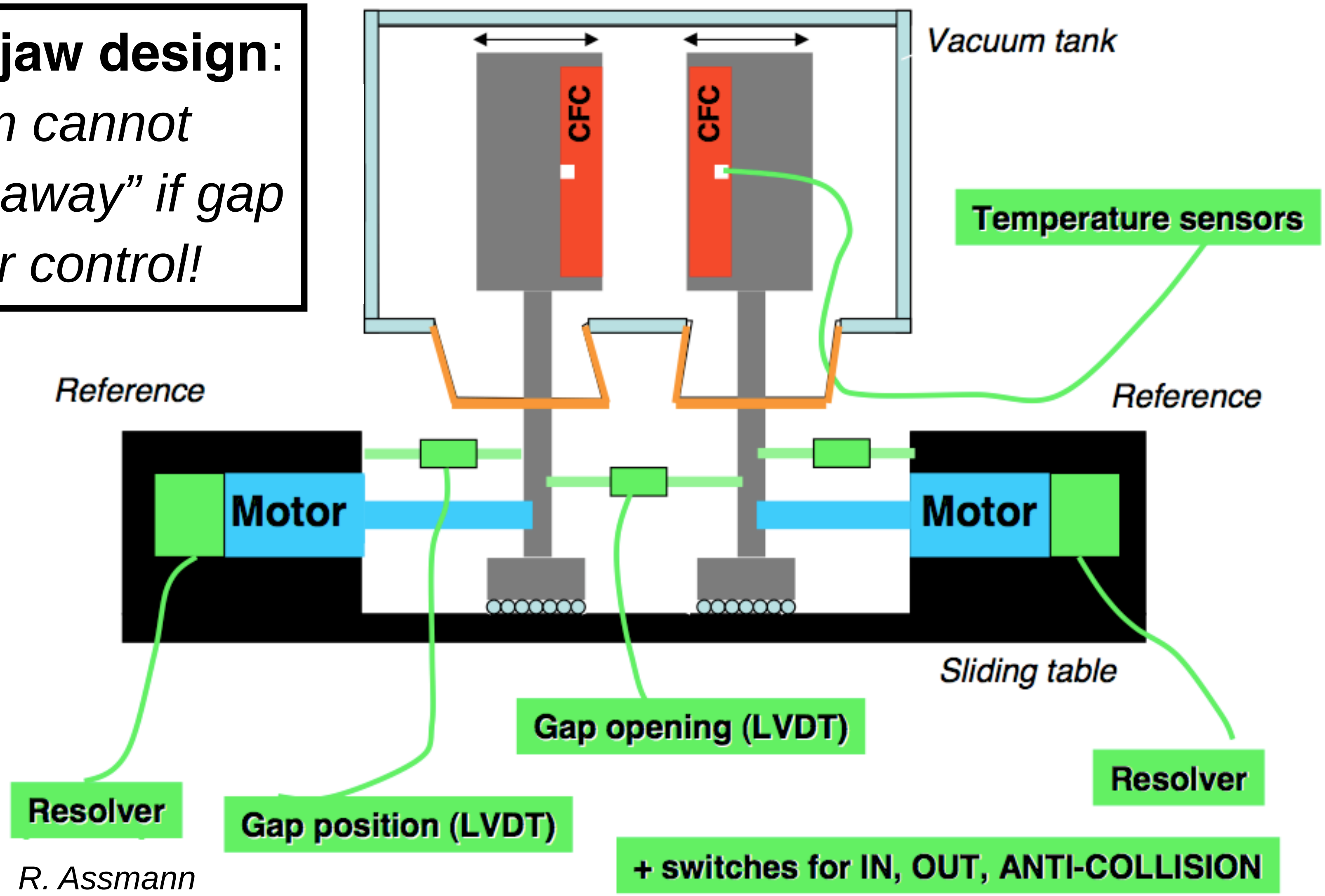
Outline

- ☑ Introduction
- ☑ Layout and hierarchy
- ☑ **Collimator interlocking**
  - **- Positioning survey**
  - **- Interlock strategy**
  - **- MP tests**
- ☑ Collimation operation
- ☑ Conclusions

Collimator positioning system



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

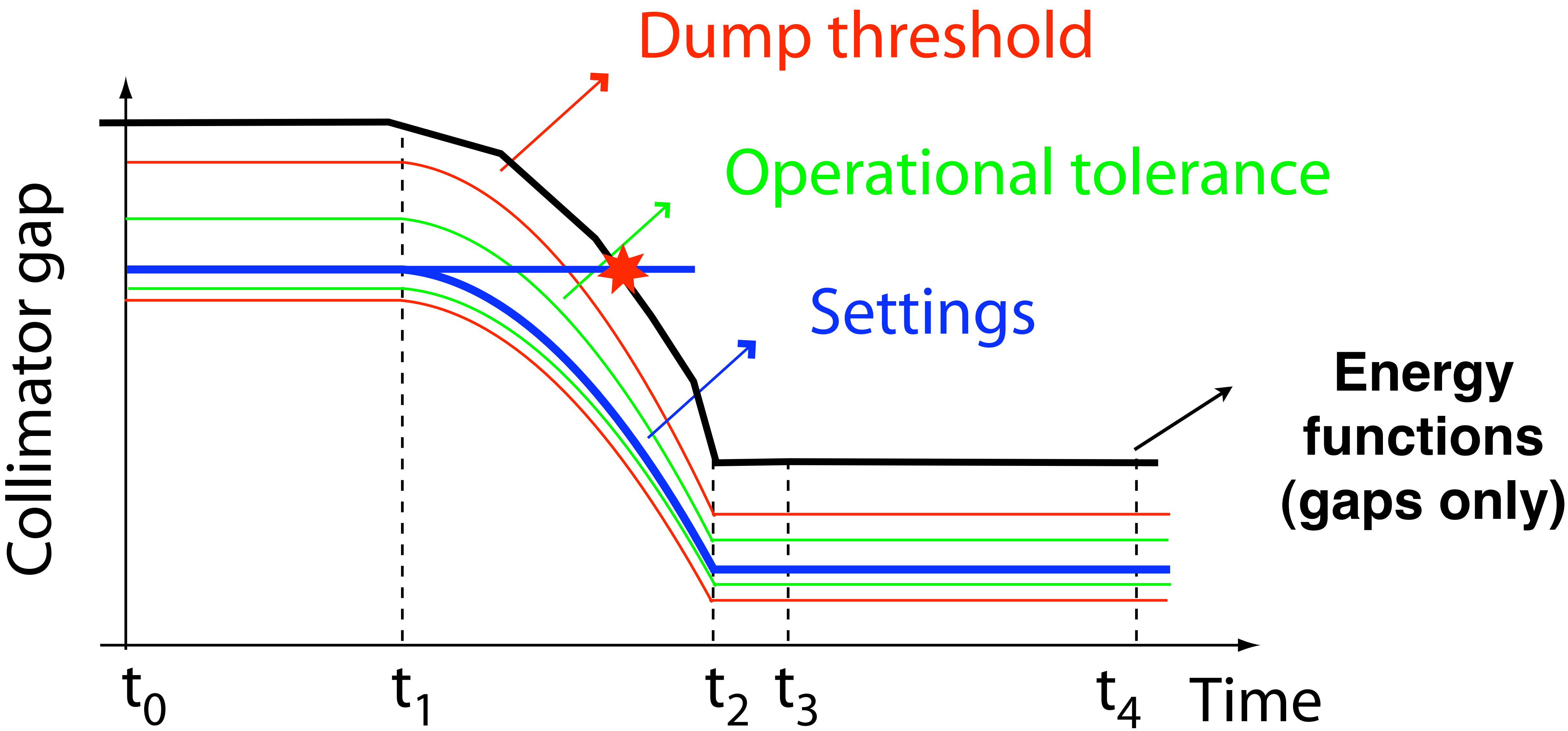


<u>Settings:</u> **4 stepping motors** for jaw corners - 1 motor for tank position.

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

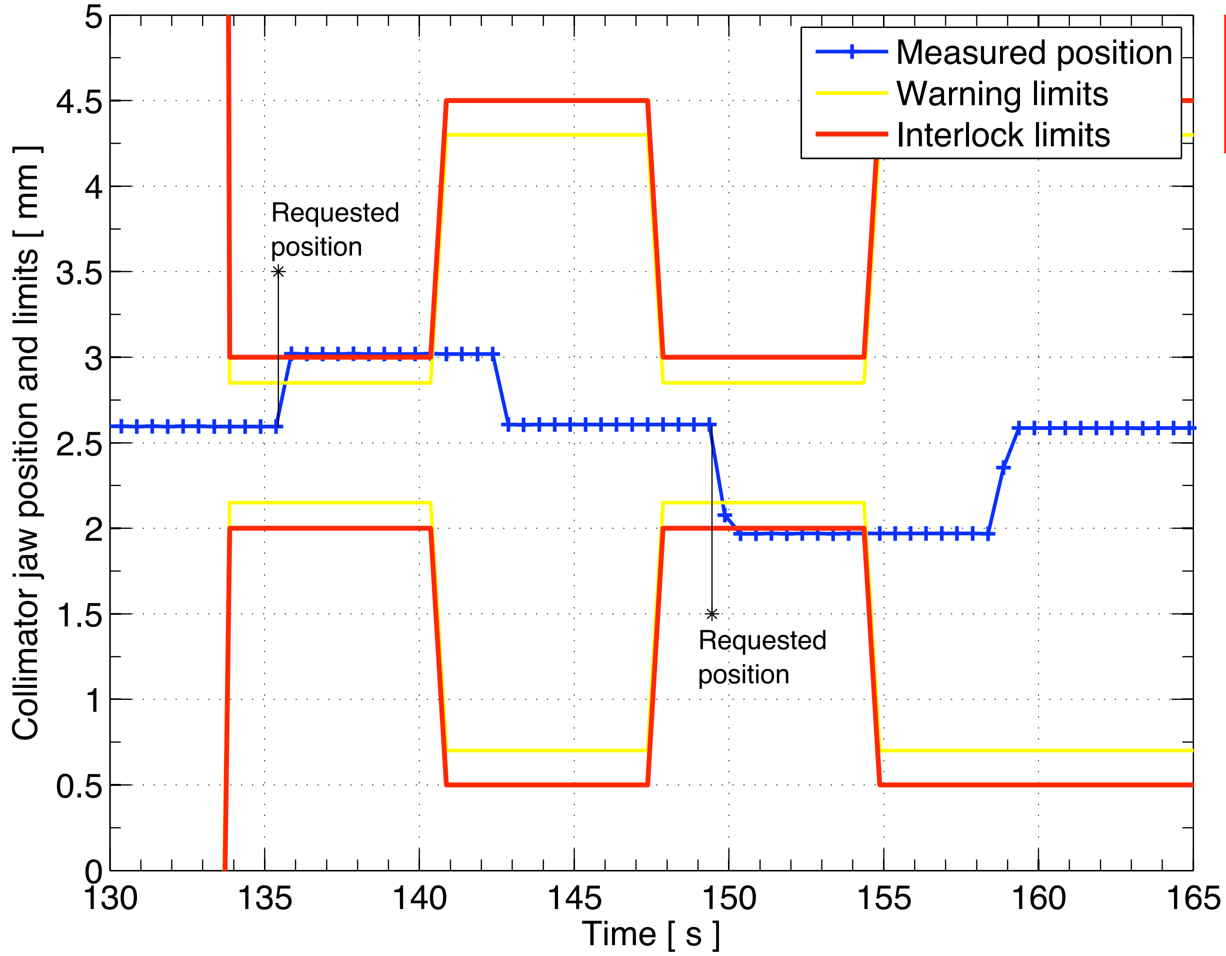
<u>Redundancy</u>: motors+resolvers+LVDT's (*Linear Variable Differential Transformer*) =
14 position measurements per collimator

Position and gap interlocks



- Two regimes: discrete ("actual") and time-functions *(internal clock at 100 Hz)*
- **Inner** and **outer thresholds** as a function of **time** for each motor **axis** and **gap** (<u>24 per collimator</u>). Triggered by timing event (e.g. start of ramp).
- "Double protection" → BIC loop broken AND jaw stopped
- <u>Redundancy</u>: **maximum allowed gap versus energy** (2 per collimator)
- Additional request to implement **beta-squeeze factor** for TCT interlocking.

Commissioning of MP without beam



Example: 1 degree of freedom

Summary for 14 limits

ollimator MP sequence for	TCLA.6R3.B1 / TCLA.IP3.B1.3.H
formation on monitoring	TCLA.6R3.B1/CollimatorStatus#prsErrors
	CIB.UJ33.U3.B1/ COLLPOS input (CH8)
equence start time :	29/10/2009 11:39:13

Sensor – Limit violated	BIC fault	BIC time	PRS fault	PRS time	Delay [ms]	Result
GAP DOWNSTREAM – ENERGY MAX	Ok	11:44:10:939	Ok	11:44:11:273	-334	Ok
GAP UPSTREAM – ENERGY MAX	Ok	11:43:52:789	Ok	11:43:53:093	-304	Ok
GAP DOWNSTREAM – IN	Ok	11:43:27:389	Ok	11:43:27:842	-453	Ok
GAP DOWNSTREAM – OUT	Ok	11:43:07:578	Ok	11:43:07:642	-64	Ok
GAP UPSTREAM – IN	Ok	11:42:44:648	Ok	11:42:45:421	-773	Ok
GAP UPSTREAM – OUT	Ok	11:42:24:838	Ok	11:42:25:221	-383	Ok
RIGHT DOWNSTREAM – IN	Ok	11:42:02:077	Ok	11:42:03:001	-924	Ok
RIGHT DOWNSTREAM – OUT	Ok	11:41:43:272	Ok	11:41:42:800	472	Ok
RIGHT UPSTREAM – IN	Ok	11:41:19:047	Ok	11:41:19:570	-523	Ok
RIGHT UPSTREAM – OUT	Ok	11:40:59:187	Ok	11:40:59:369	-182	Ok
LEFT DOWNSTREAM – IN	Ok	11:40:36:276	Ok	11:40:37:149	-873	Ok
LEFT DOWNSTREAM – OUT	Ok	11:40:16:216	Ok	11:40:16:949	-733	Ok
LEFT UPSTREAM – IN	Ok	11:39:53:286	Ok	11:39:53:718	-432	Ok
LEFT UPSTREAM – OUT	Ok	11:39:33:386	Ok	11:39:33:518	-132	Ok

Sequence implemented in the collimator application software:

“Hit” 12 interlock limits (inner+outer for 6 LVDT’s);

“Hit” the 2 limits of maximum gap values ver

Monitor on-line: (1) collimator status and (2) statu

Result report automatically generated.

Each interlock tested individually, complete system operational in Oct. 2009 before start of beam commissioning!

Documentation

Specifications

MPS Commissioning Procedure

THE COMMISSIONING OF THE LHC MACHINE PROTECTION SYSTEM

MPS ASPECTS OF THE COLLIMATION SYSTEM COMMISSIONING

Abstract

This document describes the set of tests which will be carried-out to validate for operation the machine protection aspects of the **LHC collimation system.** The area concerned by these tests extends over 7 out of the 8 long straight sections.

These tests include the Hardware Commissioning, the machine check-out and the tests with beam, to the extent that they are relevant for the machine protection functionality of collimation.

Prepared by :	Checked by :	Approved by :
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Tracking web page on collimation project site

LHC Collimation Project

Home of the Project for the LHC Collimation System

Top	Project Team	Notes	Collimator List	Sounds/Movies	Meetings
Links	Papers	Talks (WG)	Layout IR3/7	Collimator DB	Pictures
MP Tests					

The LHC Collimation system is a system designed to provide beam cleaning and limited passive protection to the LHC. The precise control of the jaw positions versus time and beam position has important relevance for machine protection of the LHC. The system is **protected by various interlocks** against wrong positioning. These interlocks are subject to thourough testing as part of MP proecdures.

The results of machine protection (MP) tests for the LHC collimation system are documented in **EDMS reports and in the MTF database system** (also used for production and quality control of collimators). Here we provide easy links to the relevant documents for all installed collimators, which are treated through the LHC collimation project.

Quick jump to:

Test position interlock	Test energy-gap interlock	Test local mode interlock
Test power cut interlock	Test reboot interlock	Test temperature interlock
Test RBAC interlock	Test MCS-Collimation role	

http://lhc-collimation-project.web.cern.ch/lhc-collimation-project/mp-tests.htm

Collimator Slot	MPP test results: EDMS Doc. No. 2009	2010
TCDD-4L2		https://edms.cern.ch/document/
TCDIH-29012	https://edms.cern.ch/document/1052530/1	
TCDIH-29050	https://edms.cern.ch/document/1052525/1	
TCDIH-29205	https://edms.cern.ch/document/1052526/1	
TCDIH-29465	https://edms.cern.ch/document/1052522/1	
TCDIH-87441	https://edms.cern.ch/document/1052527/1	
TCDIH-87904	https://edms.cern.ch/document/1052528/1	
TCDIH-88121	https://edms.cern.ch/document/1052529/1	

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MP test – CERN - TCLA-6L3-B2
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Specification - Quality
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Description	Machine Protections tests on LHC Collimators
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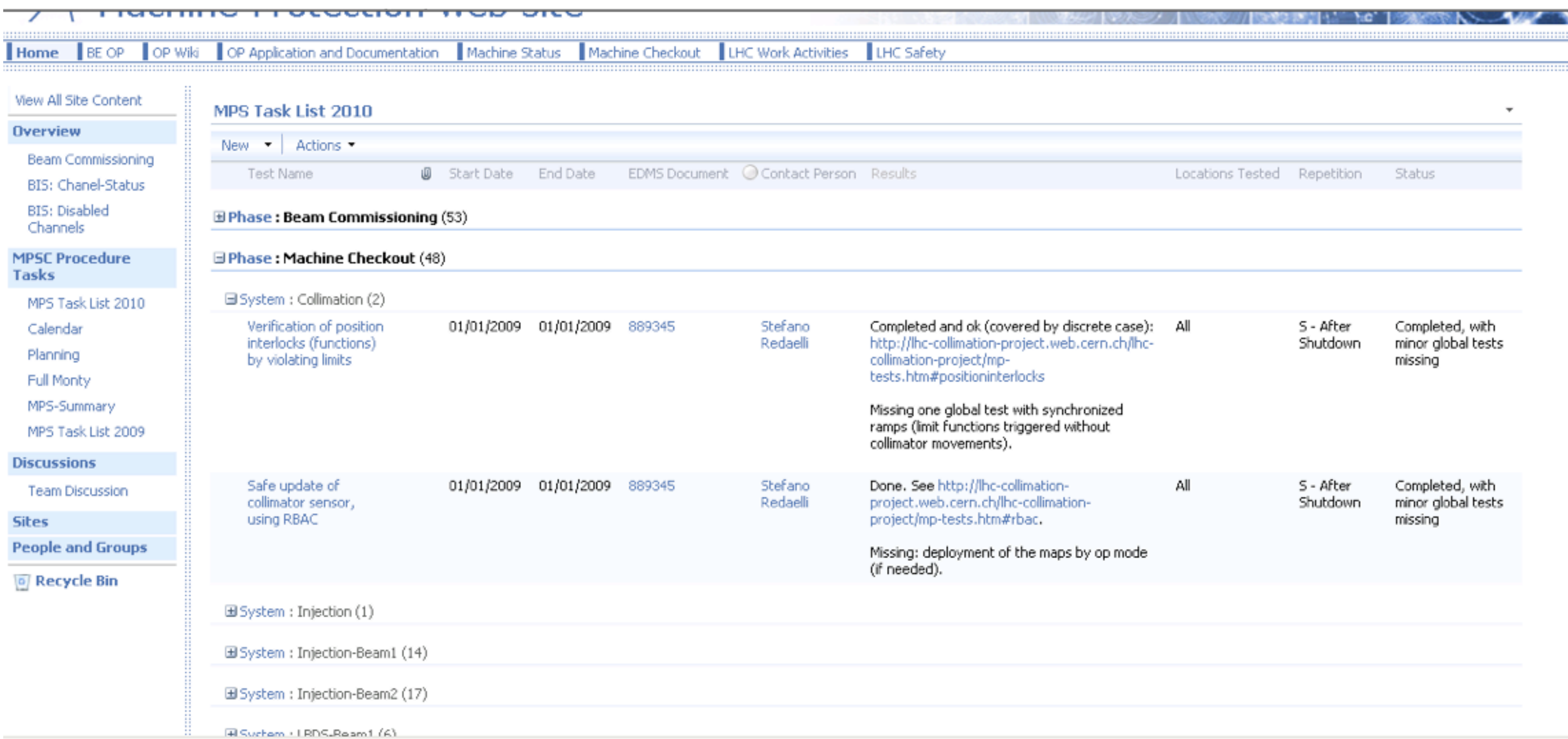
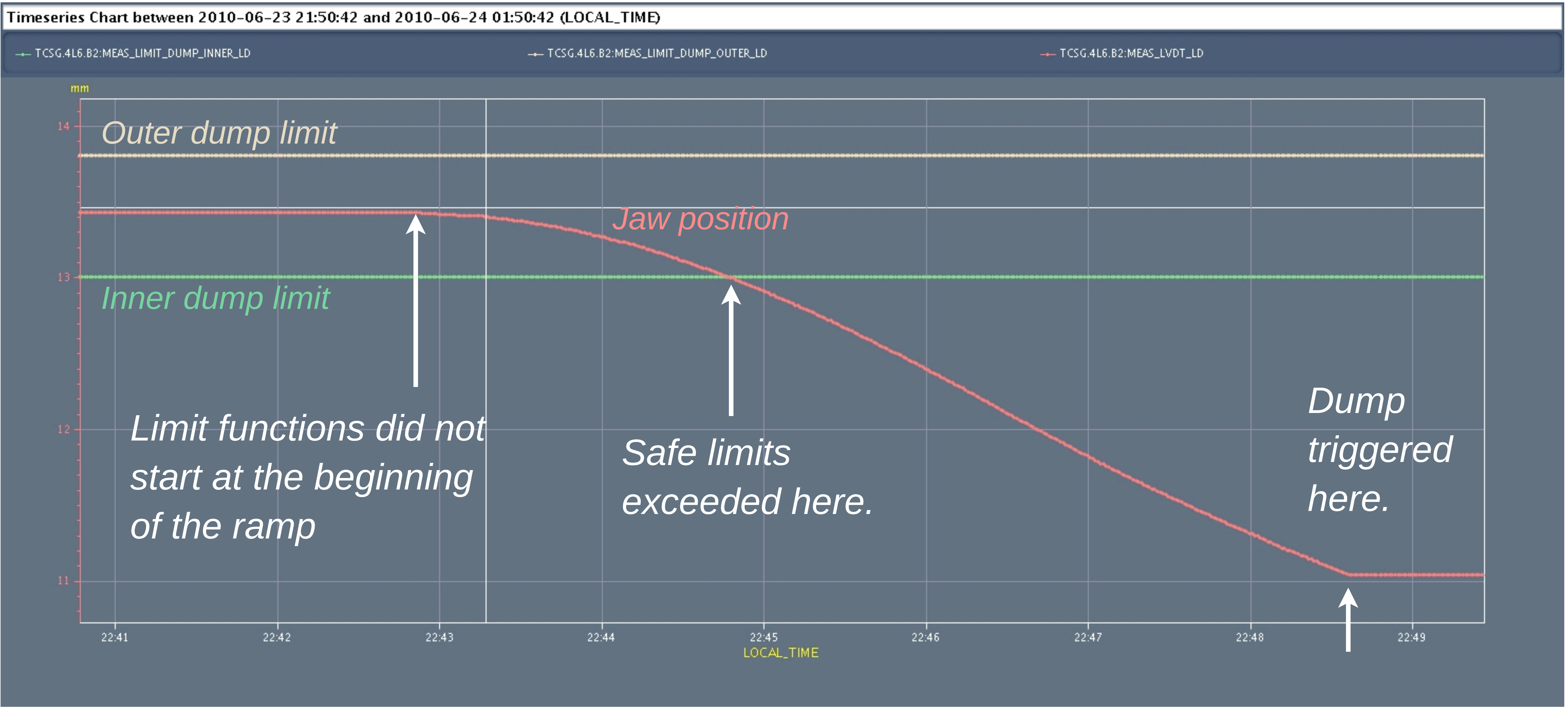
More on documentation

Results of collimator collimator machine protection commissioning linked to from the MPP we page.



One problem encountered with beam...



One bug found in the control system: limit functions were zeroed in some cases and did not play the correct ramp profiles. System still safe: beams dumped (but the bug caused a delay of ~3 min in the interlock trigger).

This happened twice before we could trace the bug and fix it.

Outline

- Introduction
- Layout and hierarchy
- Collimator interlocking
- **Collimation operation**
  - **- Present run scenario**
  - **- Performance**
- Conclusions

Collimator “relaxed” settings

	Unit	Plane	Set 1	Set 2	Set 3	Set 4
Condition			Injection optics	Injection optics	Collision optics, separated	Collision optics, colliding, crossing angle
Energy	[GeV]		450	3500	3500	3500
Primary cut IR7	[σ]	H. V, S	5.7	5.7	5.7	5.7
Secondary cut IR7	[σ]	H, V, S	6.7	8.5	8.5	8.5
Quartiary cut IR7	[σ]	H, V	10.0	17.7	17.7	17.7
Primary cut IR3	[σ]	H	8.0	12	12	12
Secondary cut IR3	[σ]	H	9.3	15.6	15.6	15.6
Quartiary cut IR3	[σ]	H, V	10.0	17.6	17.6	17.6
Tertiary cut experiments	[σ]	H, V	15-25	40-70	15	15
TCSG/TCDQ IR6	[σ]	H	7-8	9.3-10.6	9.3-10.6	9.3-10.6

Relaxed configuration are possible with **squeezed beams** because at 3.5 TeV the **triplet aperture is larger**: 17 sigmas instead than the nominal 8.5 sigmas → *RB’s talk*

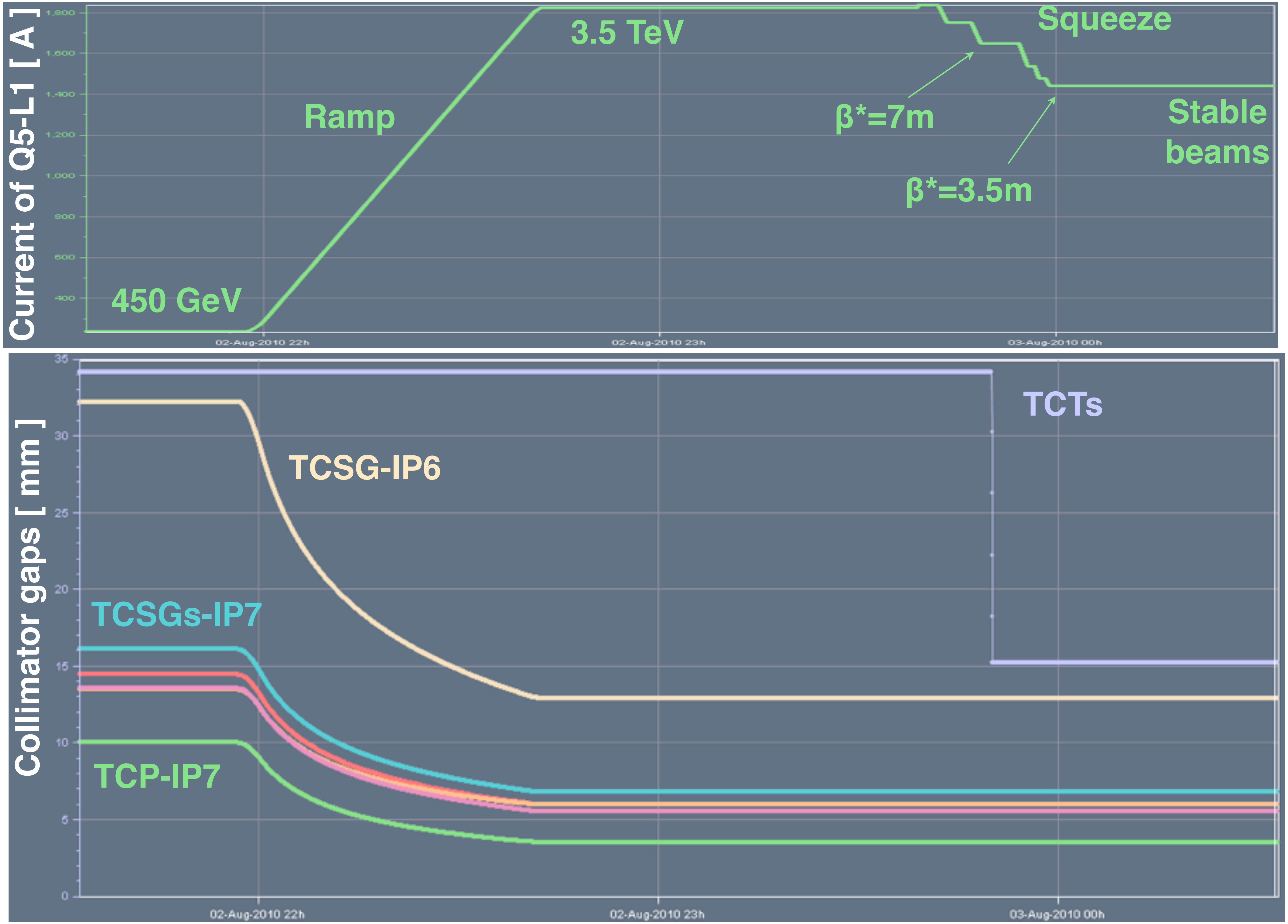
“**Relaxed settings**”: during **ramp**, only TCP gap scale like √(energy). Other collimators maintain a constant retraction in mm → allows more margins.
This gives more operational margin against the protection device retraction: ~ 5 sigmas!

Beam-based settings last established in mid June - stable operation since then.

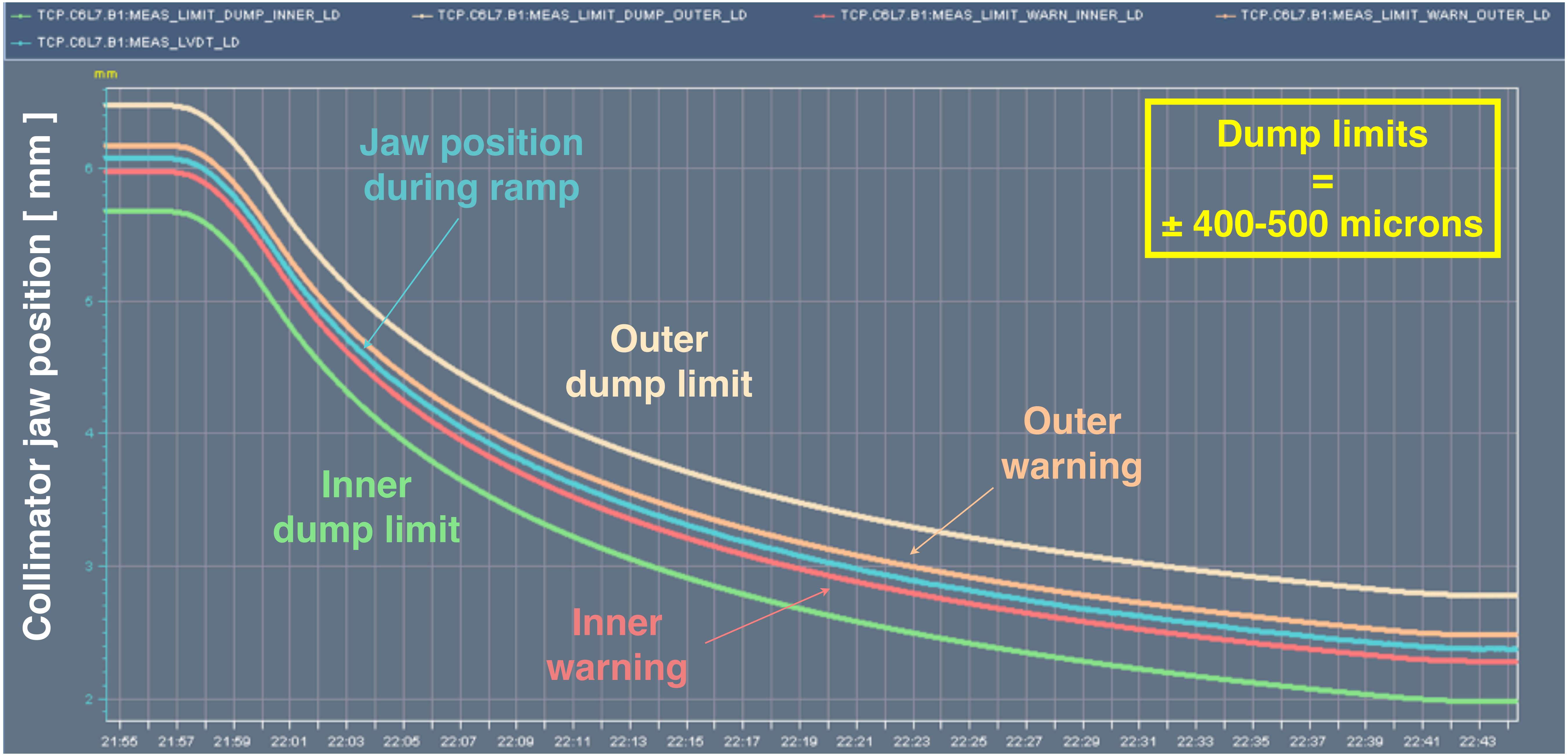
Limit thresholds associated to each set of settings.

Smooth transition between different sets, all driven through collimator sequences.

Operation during inj, ramp & squeeze

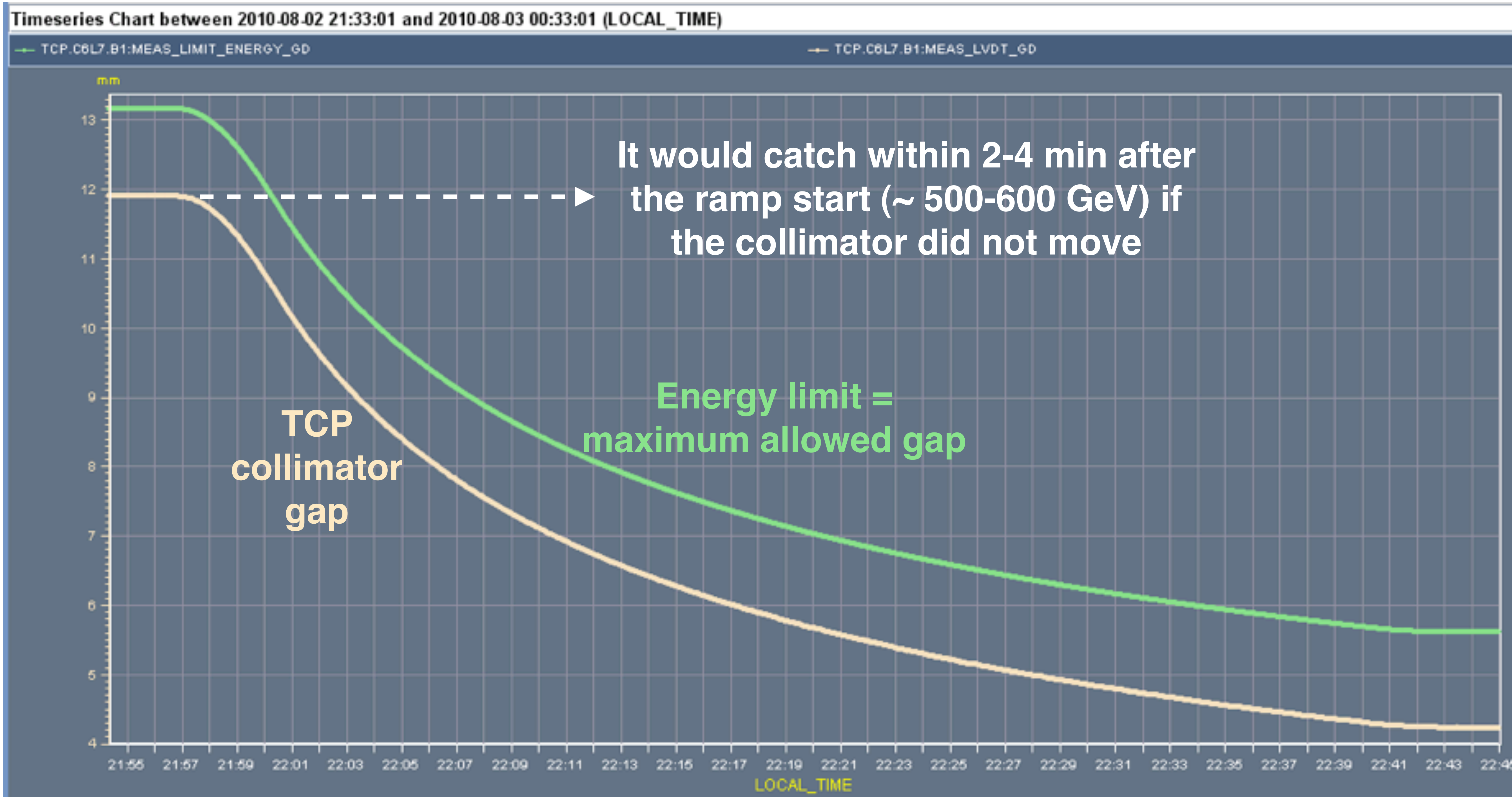


Time-dependent limit functions



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.

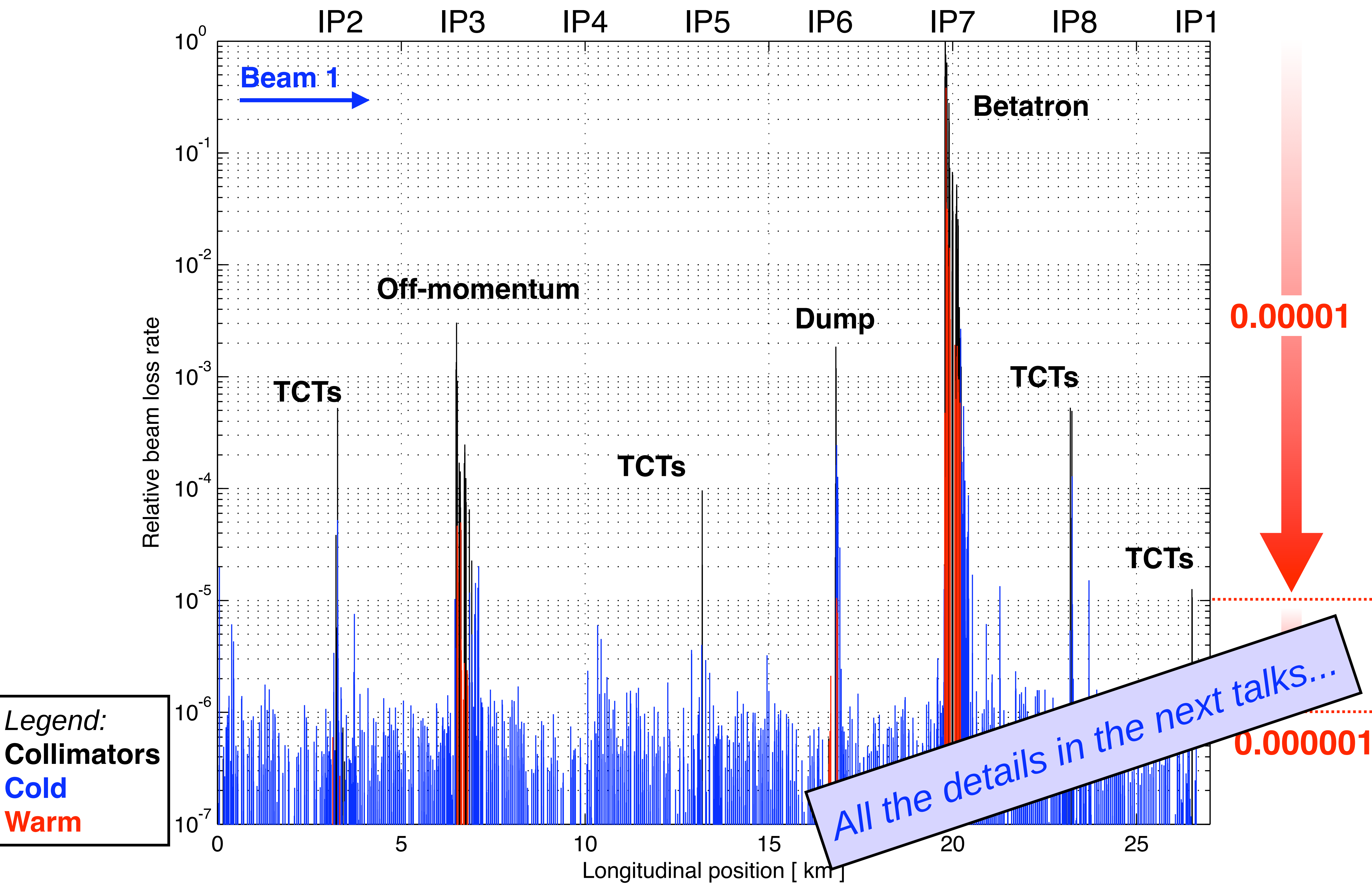
Gap energy limits



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).

Measured cleaning at 3.5 TeV, β*=3.5m



Conclusions

- **Introduced the key concepts of the LHC collimation system**
  Most complex build so far: 108 collimators, 400 degrees of freedom;
  Cleaning needed all the time → Collimators are “ramped” and “squeezed”;
  Two-jaw design → safer because beams cannot drift away.
- **Reviewed the implemented machine protection features.**
  Highly redundant positioning control.
  More than 2000 interlock thresholds ensure the correct positioning.
  More than 500 individually interlocked temperature sensors.
  All interlocks were tested individually: large amount of work before beam operation payed off to achieve a smooth and safe operation.
- **Reviewed the operation of the system.**
  Present modus operandi: infrequent system setup + reproducible machine.
  Outstanding performance: no quenches in operation with up to ~3MJ.
  Collimation hierarchy needs constant monitoring!
- **More details in the companion talks that follow...**
  Details of cleaning performance in the last months of operation;
  Closer look at the experiments regions (critical: TCT / triplet protection);
  Various machine protection aspects of the present operation.