52nd ICFA Advanced Beam Dynamics Workshop
on High-Intensity and High-Brightness Hadron Beams, HB2012
Beijing, China, September 17th-21th, 2012

Collimation Experience at the Large Hadron Collider

Stefano Redaelli
on behalf of the LHC Collimation Project

Outline

- ☑ **Introduction**
- ☑ **LHC collimation system**
  - Requirements
  - Design, layout and settings
- ☑ **Collimation performance**
  - Cleaning and alignment
  - LHC β^* reach
  - Lead ions
  - Operational experience
- ☑ **Collimation in 2015**
- ☑ **Conclusions**

Not covered here:
Simulations vs measurements
Limitations and upgrade scenarios > LS2
Advanced collimator concepts/materials

Collimation people and references

O. Aberle, R. Assmann, J.P. Bacher, V. Baglin, G. Bellodi, A. Bertarelli, V. Boccone, A.P. Bouzoud, C. Bracco, H. Braun, R. Bruce, F. Burkart, M. Cauchi, F. Cerutti, M. Donze, N. Hilleret, E.B. Holzer, D. Jacquet, J.B. Jeanneret, J.M. Jimenez, K. Kershaw, G. Kruk, M. Lamont, L. Lari, J. Lendaro, A. Lechner, J. Lettry, R. Losito, A. Marsili, A. Masi, M. Mayer, E. Métral, C. Mitifiot, R. Perret, S. Perrolaz, V. Previtali, C. Rathjen, S. Redaelli, G. Robert-Demolaize, C. Roderick, S. Roesler, A. Rossi, F. Ruggiero, B. Salvachua, M. Santana, R. Schmidt, P. Sievers, K. Tsoulou, G. Valentino, E. Veyrunes, H. Vincke, V. Vlachoudis, T. Weiler, J. Wenninger, D. Wollmann.
An many other people...

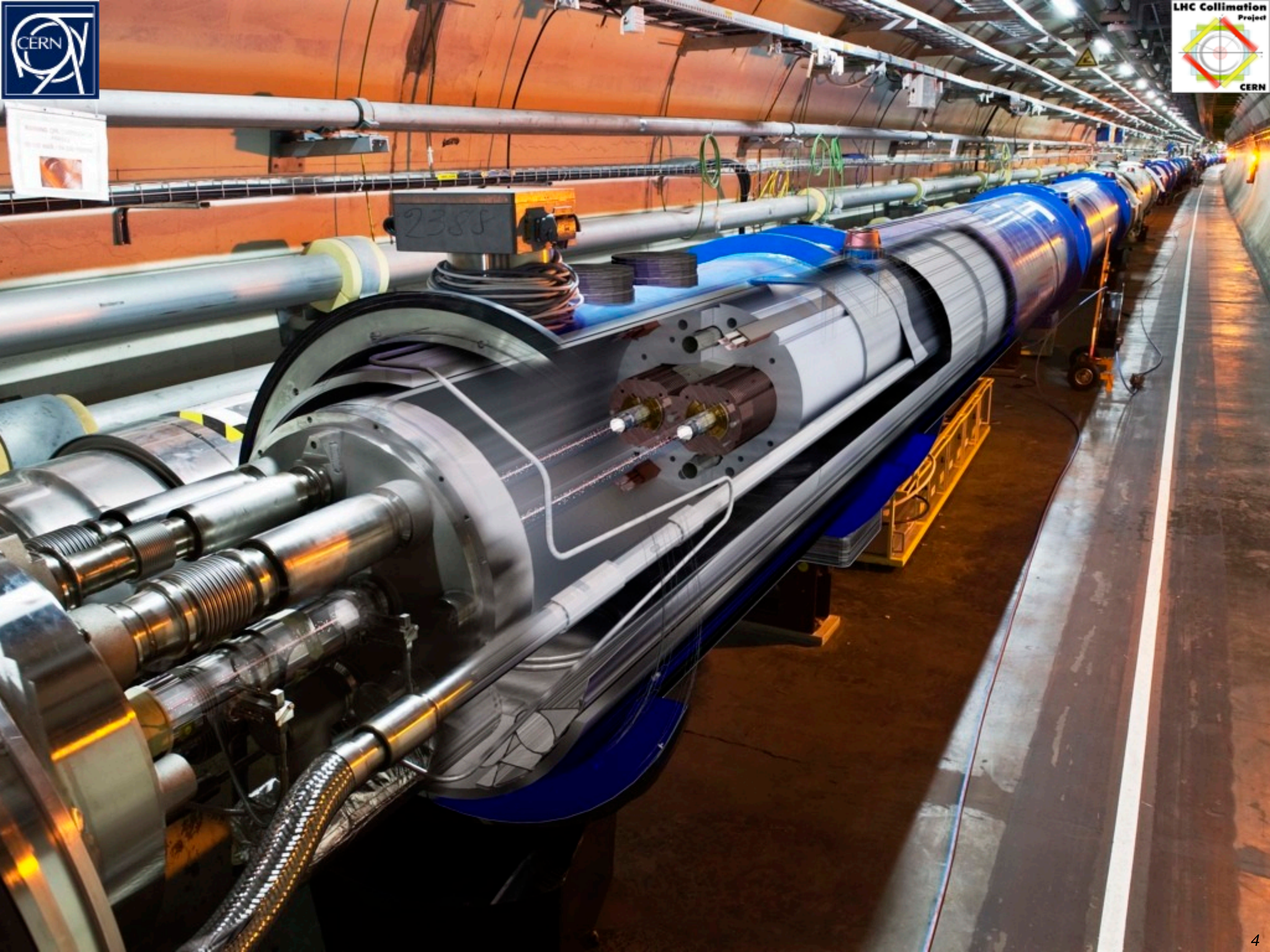
"Core" team in the LHC accelerator physics group:
R. Bruce, M. Cauchi, D. Deboy, L. Lari, M. Salvachua, A. Rossi, A. Marsili
Recent former members: R. Assmann, F. Burkart, D. Wollmann

Strong synergy with **other teams at CERN**: Machine protection, Injection & dump, Optics, impedance, operation, beam instrumentation, beam and HW commissioning, ...

Many **international collaborations**: EuCARD, US-LARP, FNAL, SLAC, TRIUMF, IHEP, BNL, Kurchatov...

Reference to talks/papers related to the LHC collimation at this workshop:

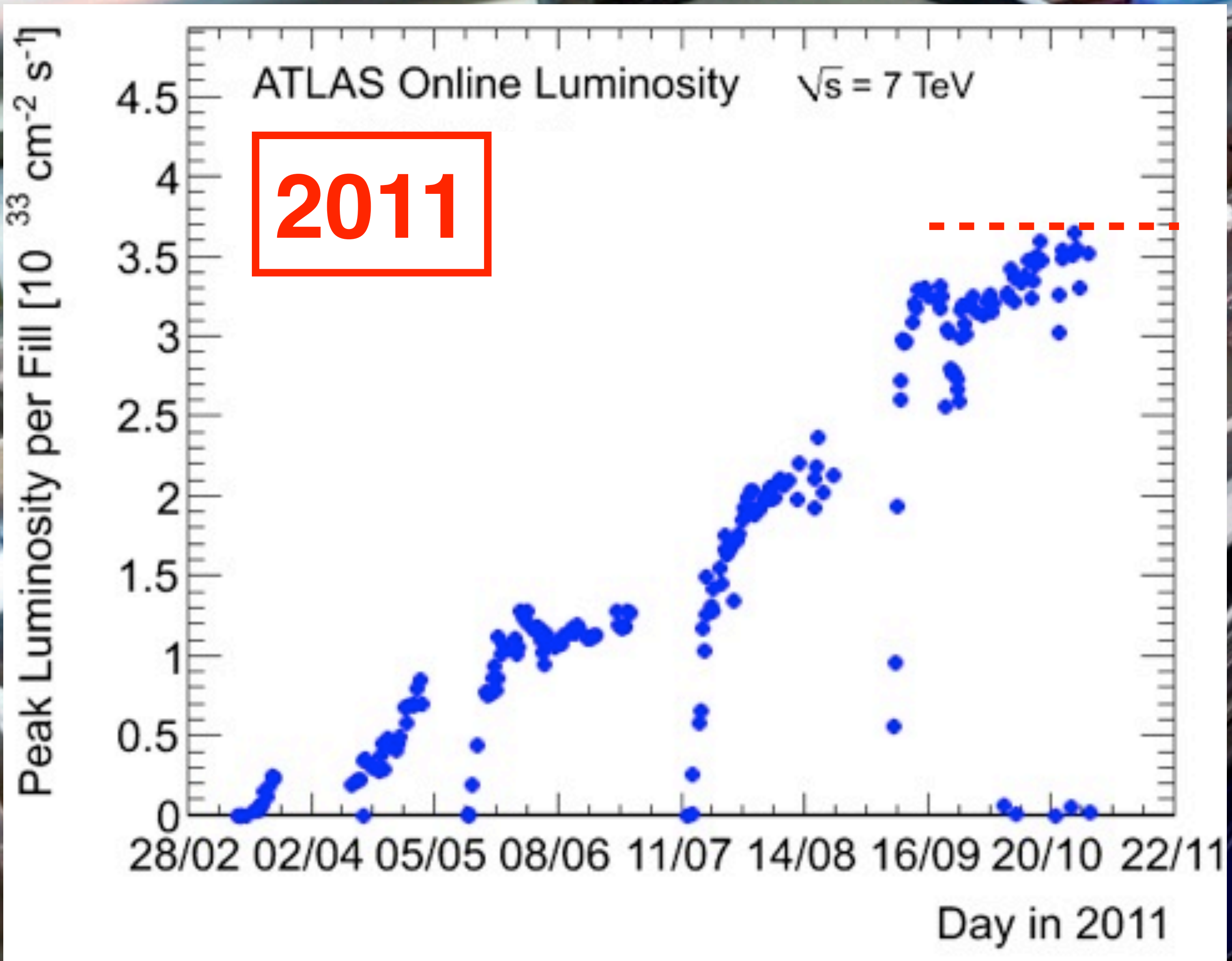
- **MOP242**: D. Wollmann *et al.*: SPS beam measurements with BPM-embedded collimators
- **MPO245**: S. Redaelli *et al.*: Collimator quench tests for proton and ion beams at 3.5 Z TeV
- **MPO246**: G. Valentino *et al.*: BPM-interpolated orbit to speed up collimator alignment
- **MOP240**: A. Bertarelli *et al.*: Collimator material tests at HiRadMat
- **WEO3C03**: : G. Stancari *et al.*: Beam halo dynamics and diffusion models
- **TUO3A02**: S. Montesano *et al.*: Crystal collimation
- **MOI1A01**: R. Schmidt, LHC machine protection
- **TU03C01**: L. Ponce, Beam losses at the LHC
- **WEO1A02**: B. Salvant, LHC impedance models

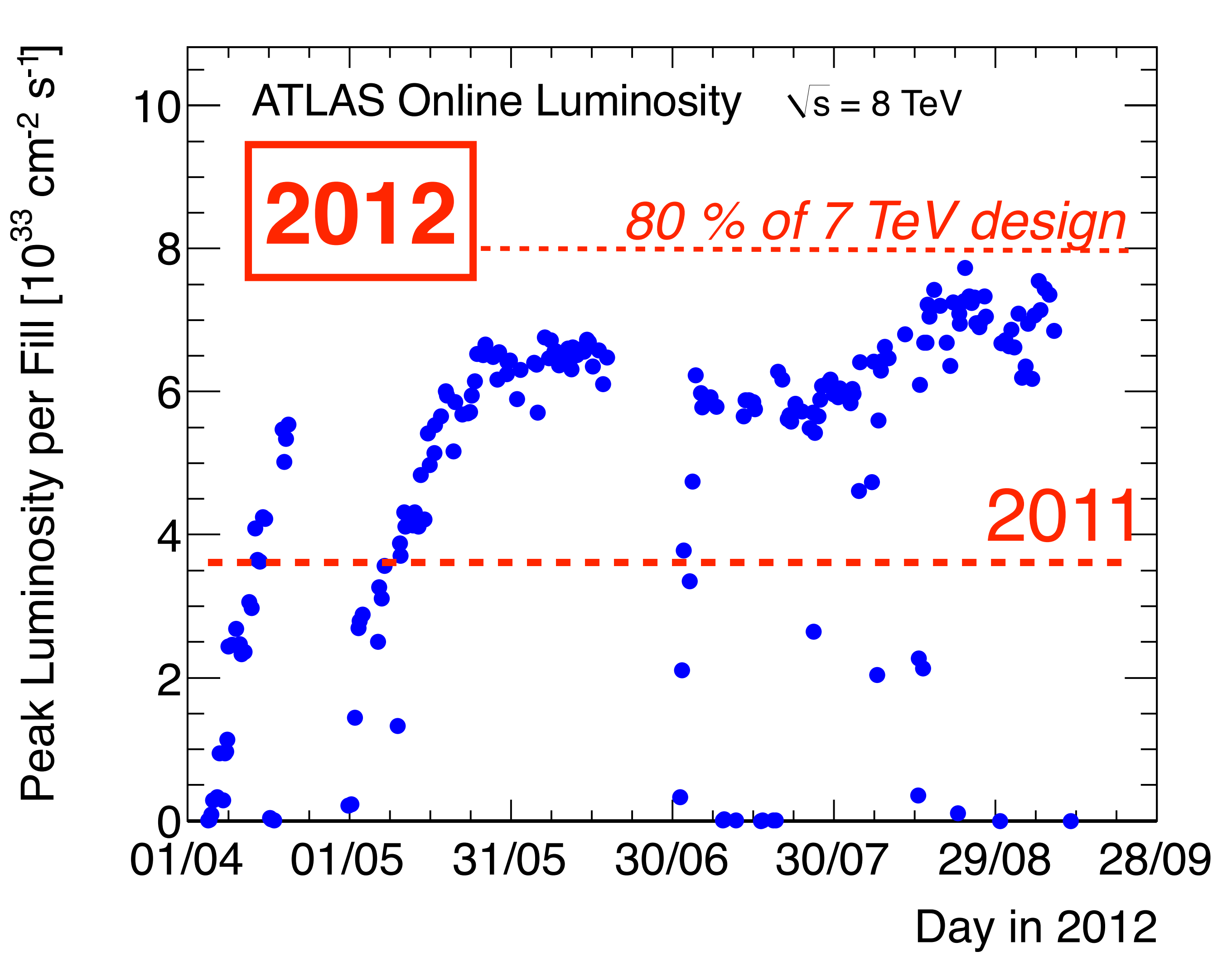


LHC performance

2011 : 3.5 TeV, β* = 1.0 m, ~110 MJ (1380 bunches at 50 ns)

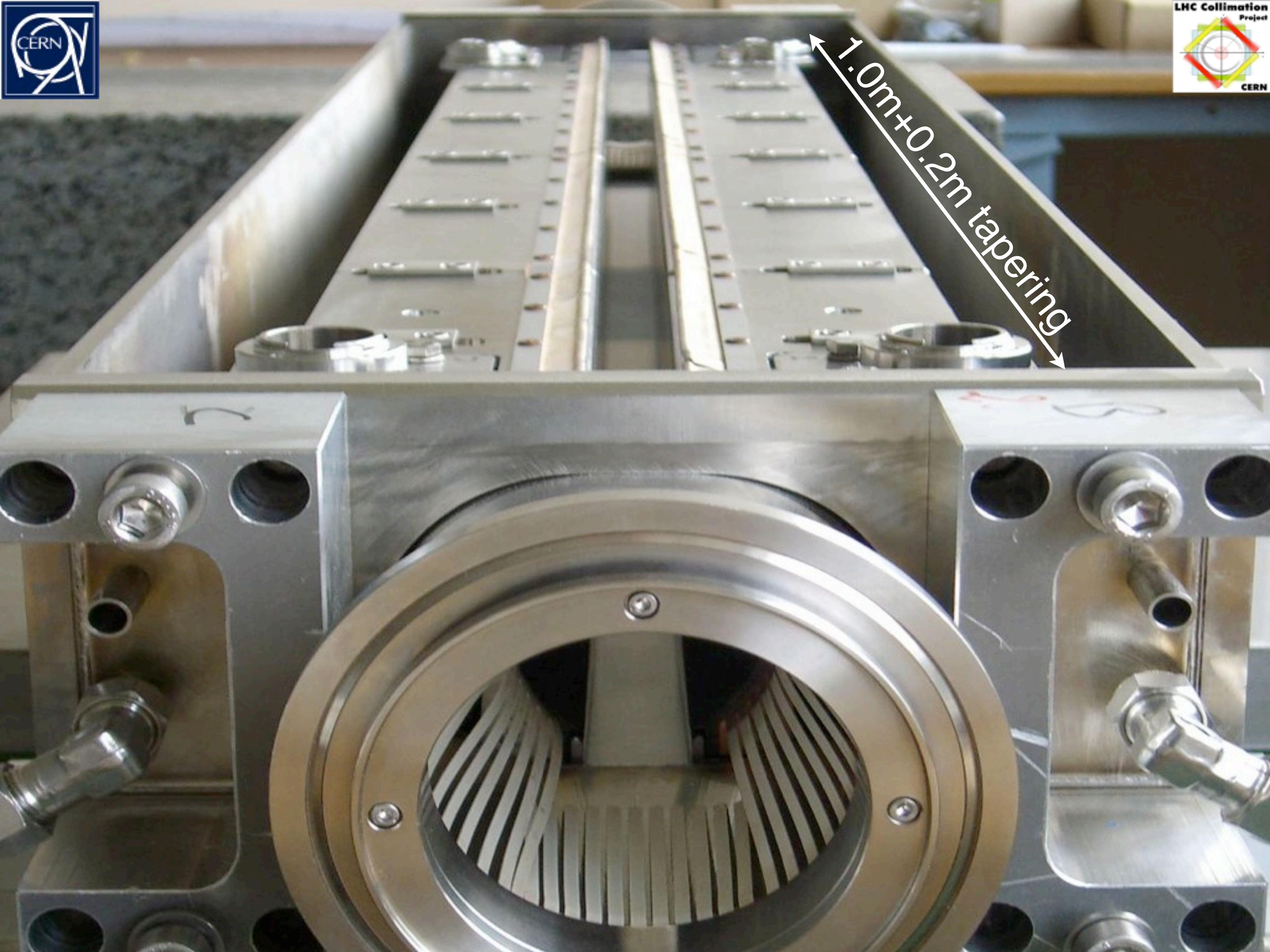
2012 : 4.0 TeV, β* = 0.6 m, ~140 MJ (1380 bunches at 50 ns)





No quench with circulating beam, with stored energies up to 70 times of previous state-of-the-art!

The collimator system performance is a crucial ingredient in this achievement!


1.0m+0.2m tapering

Requirements to handle 360 MJ

Requirements to handle 360 MJ

Main **collimation challenges**:

- **High stored energy**: Collimators needed in **all phases** *(inj., ramp, squeeze, physics);* Function-driven controls of jaw positions mandatory; **Robustness** and **cleaning efficiency**; Big and **distributed** system (100 collimators).
- **Small gaps**: Mechanical **precision**, **reproducibility** (< 20 microns); Constraints on orbit/optics **reproducibility**; Machine **impedance** and beam instabilities.
- **Collimator hierarchy**: Collimators determine the LHC $\boldsymbol{\beta^*}$ **reach**.
- **Machine protection**: Redundant **interlocks** of collimator jaw positions and gaps.
- **High-radiation environ.**: **Radiation**-hard components (HW + SW); Challenging remote **handling**, design for quick installation.

Parameter		Unit	Specification
Jaw material			CFC
Jaw length	TCS	cm	100
	TCP	cm	60
Jaw tapering		cm	10 + 10
Jaw cross section		mm²	65 × 25
Jaw resistivity		μΩm	≤ 10
Surface roughness		μm	≤ 1.6
Jaw flatness error		**μm**	**≤ 40**

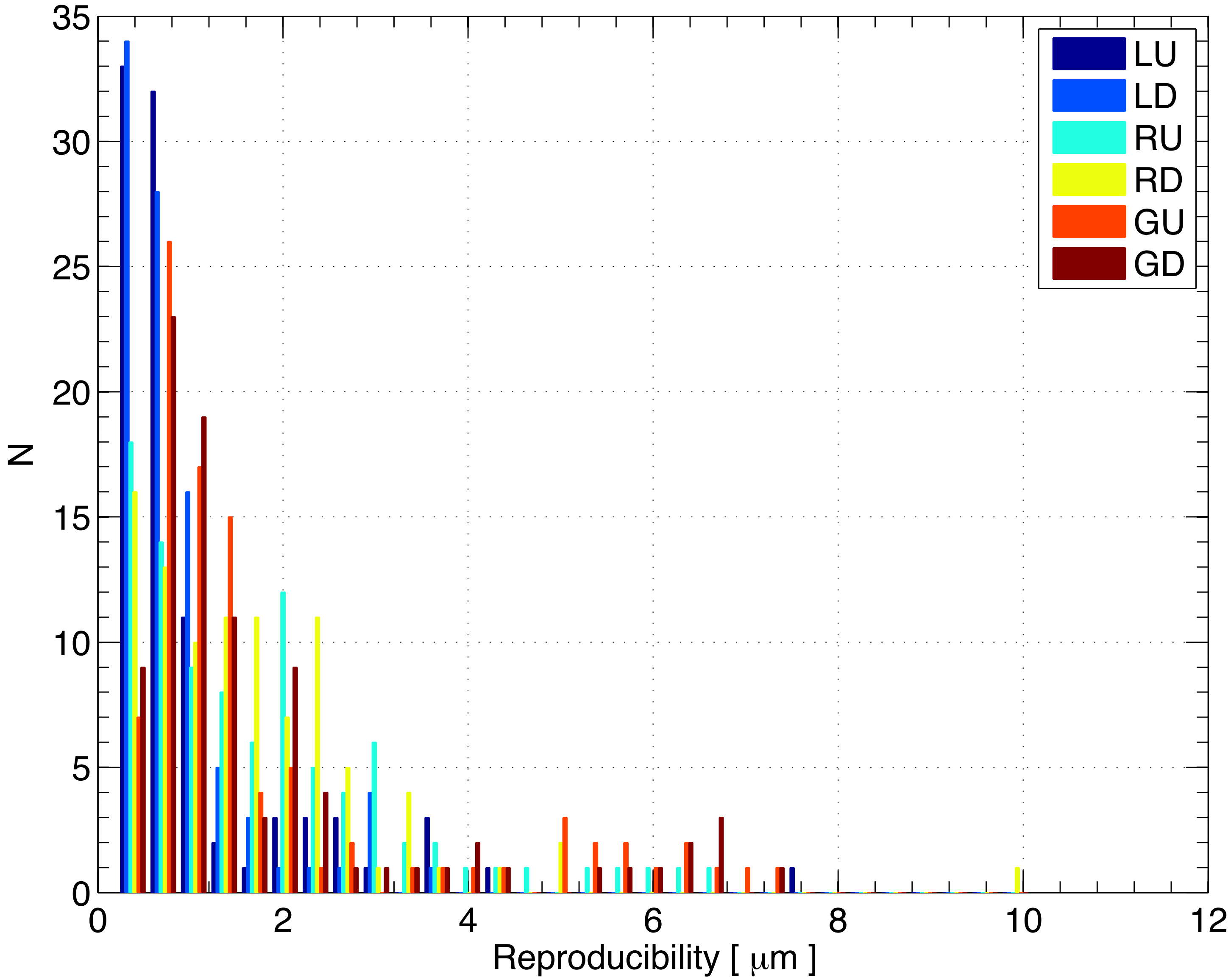
Heat load	kW	≤ 7
Jaw temperature	°C	≤ 50
Bake-out temp.	°C	250
Minimal gap	**mm**	**≤ 0.5**
Maximal gap	mm	≥ 58
Jaw position control	μm	≤ 10
Jaw angle control	μrad	≤ 15
Reproducibility	**μm**	**≤ 20**

R. Assmann et al. (2003)

A "staged" approach was adopted to cope with conflicting requirements

Example: settings reproducibility

Reproducibility of measured jaw positions during remote commissioning: simulated 30 “ramp” executions and compared final positions (small gaps)



Example: settings reproducibility

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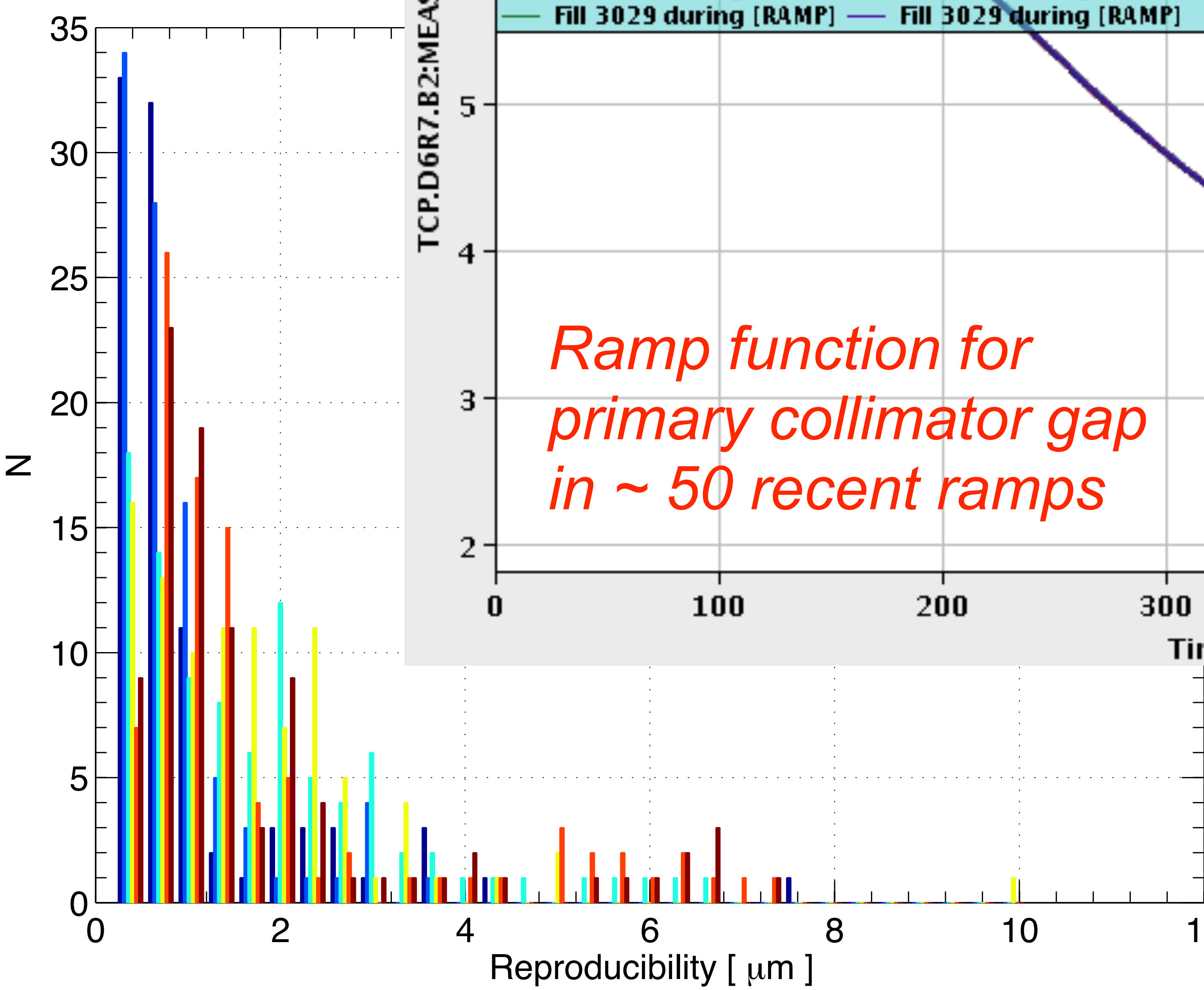
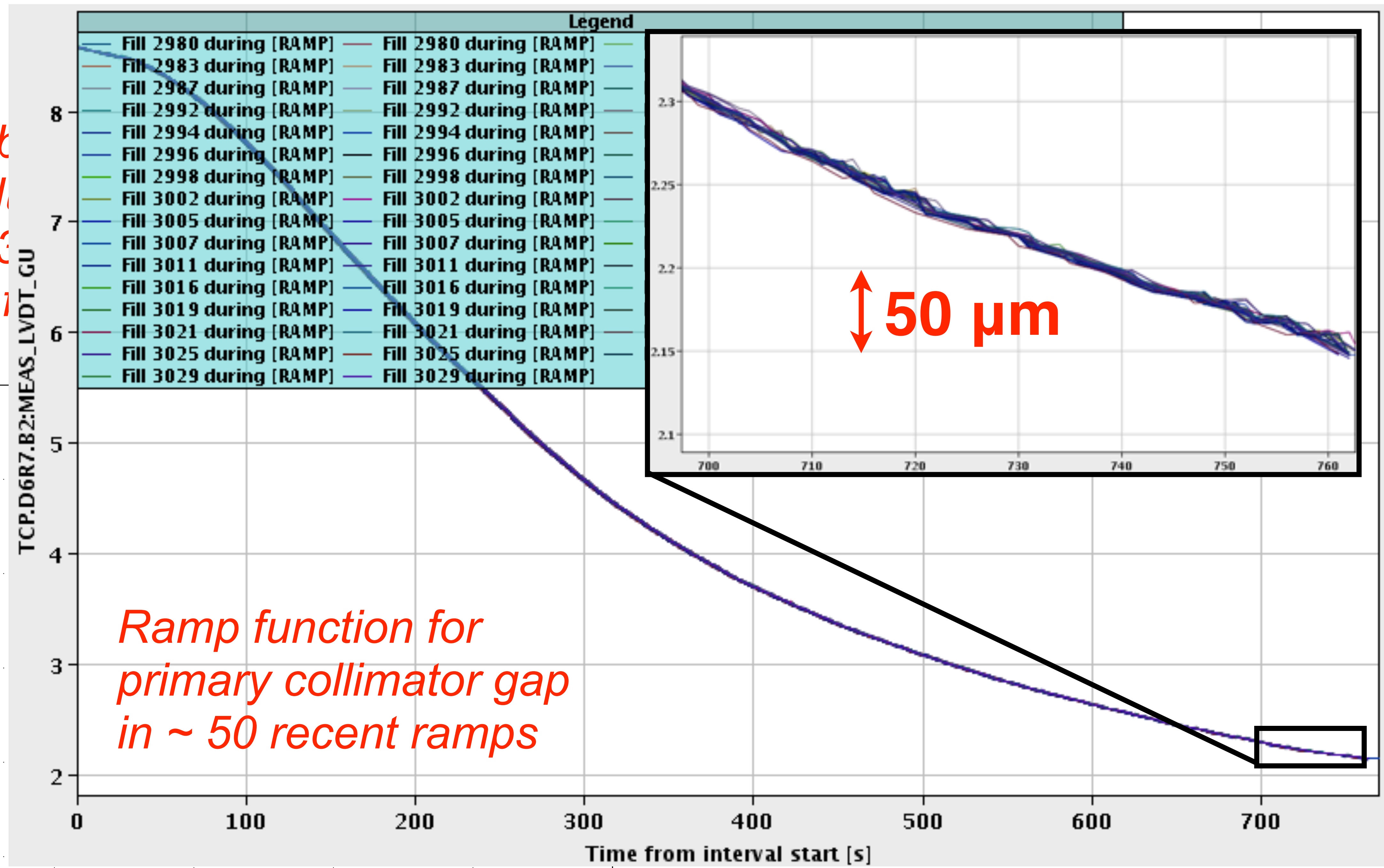




Ramp function for primary collimator gap in ~ 50 recent ramps

Caveat:
System is somewhat affected by power cuts (e.g. from storms): errors go up to < 20-30μm

LHC collimation layout

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

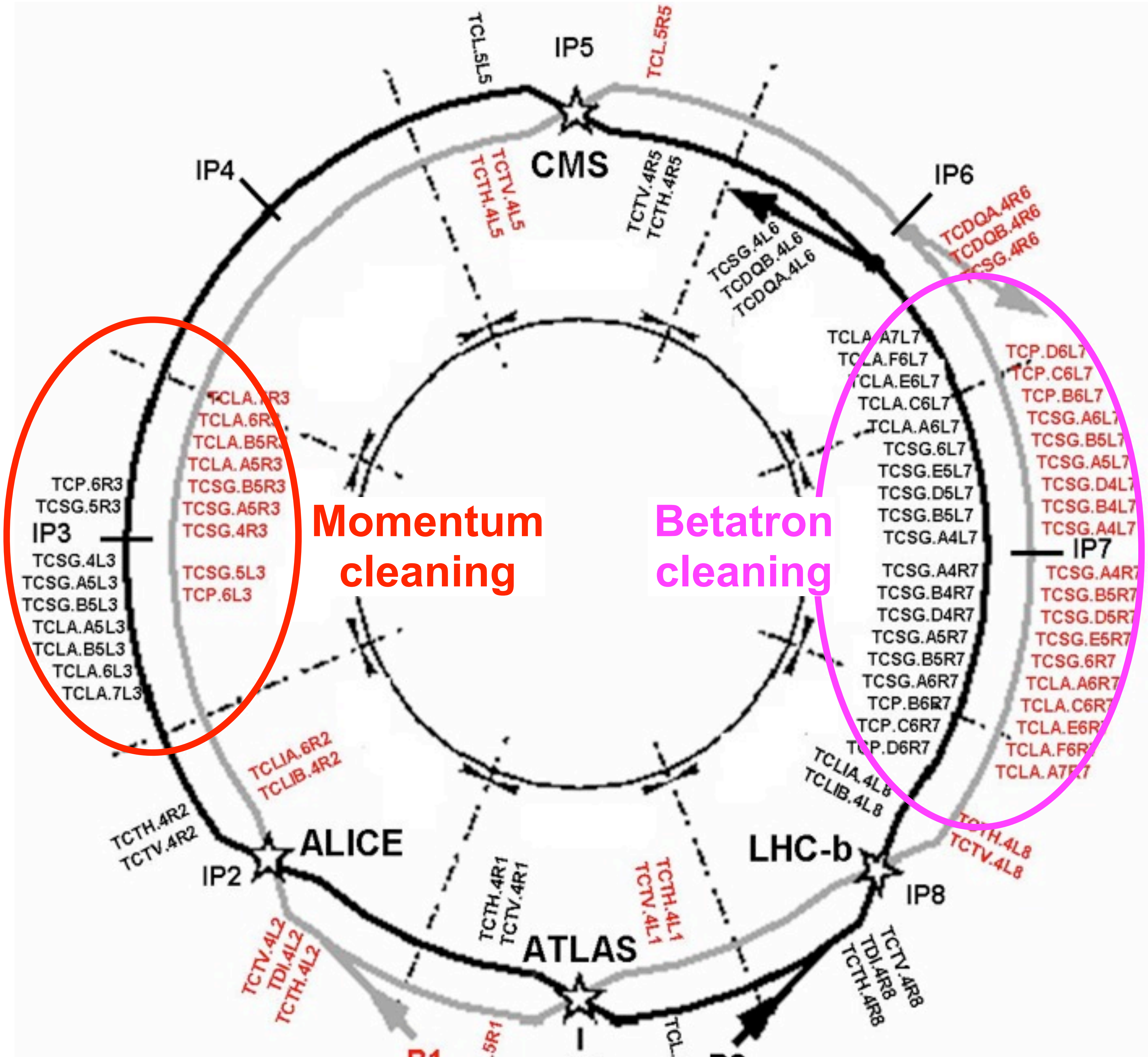
- **8 tertiary (2 per IP)**

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

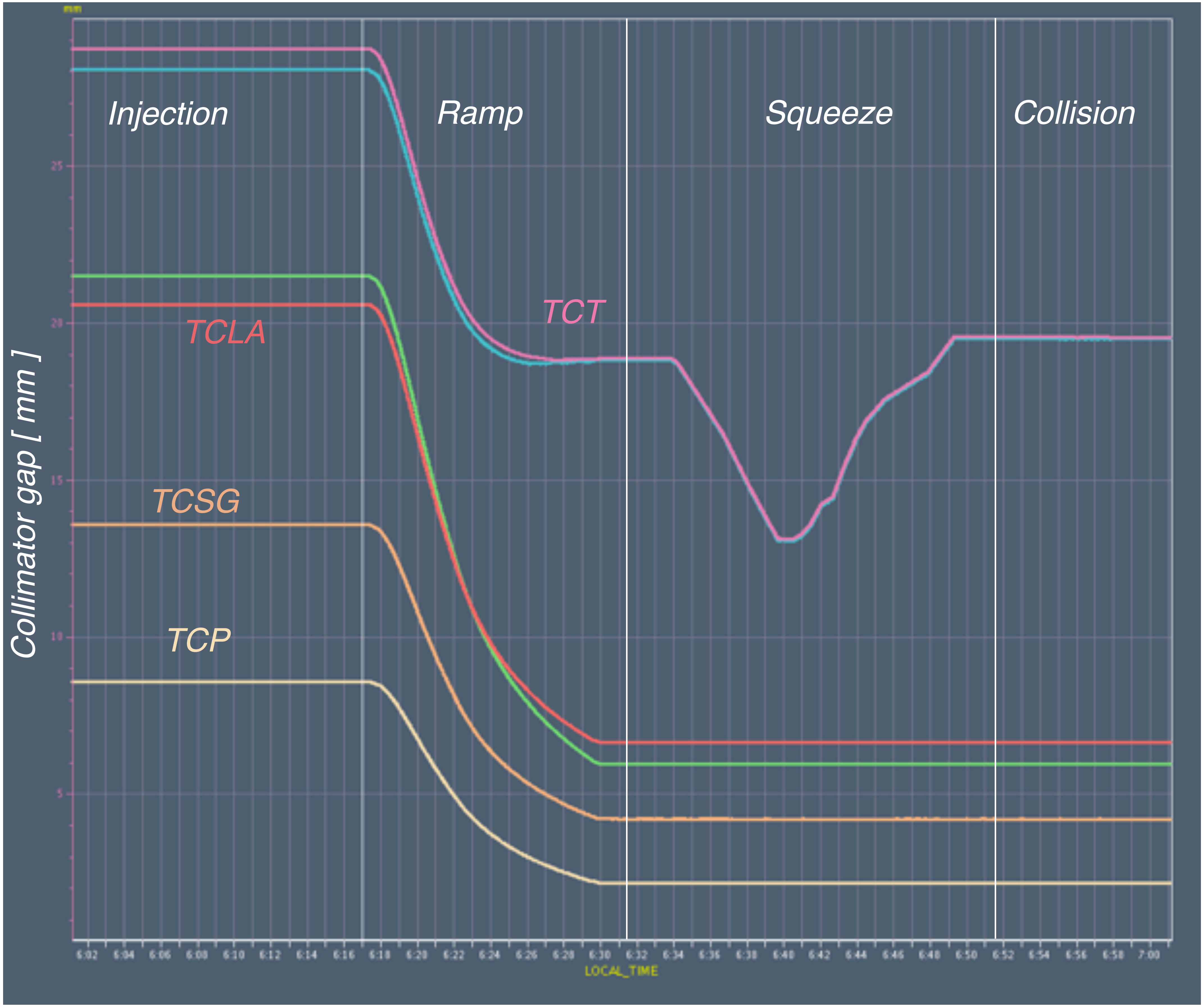
2012 collimator setting table

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 IR8	[μrad]	n.a.	n.a.	170	220 (H)	220 (H)	100 (V)
Crossing angle IR2	[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

4 sets of beam-based settings, smooth transition between different sets.

Each setting set must be validated by loss maps.

Collimator gaps during the OP cycle



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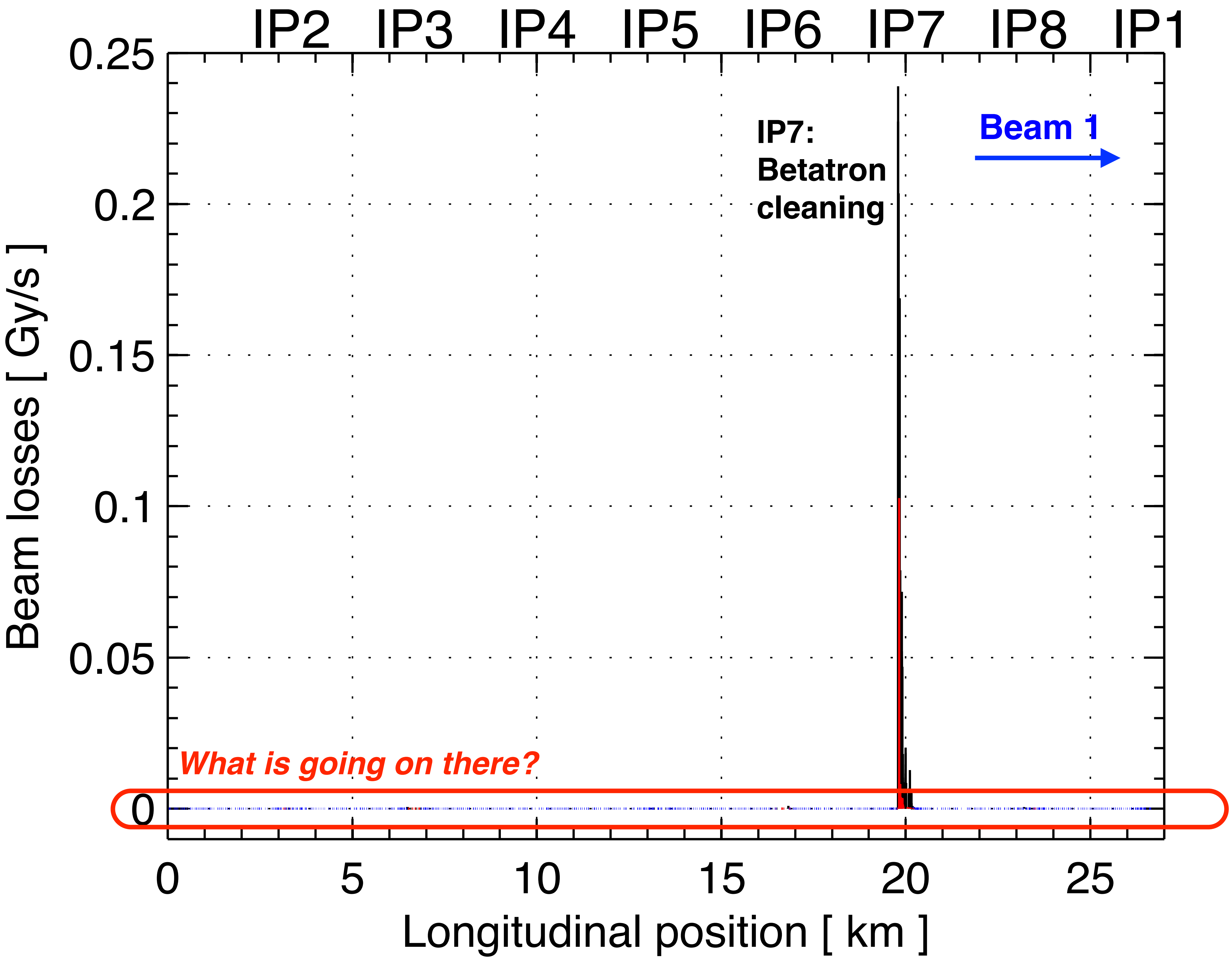
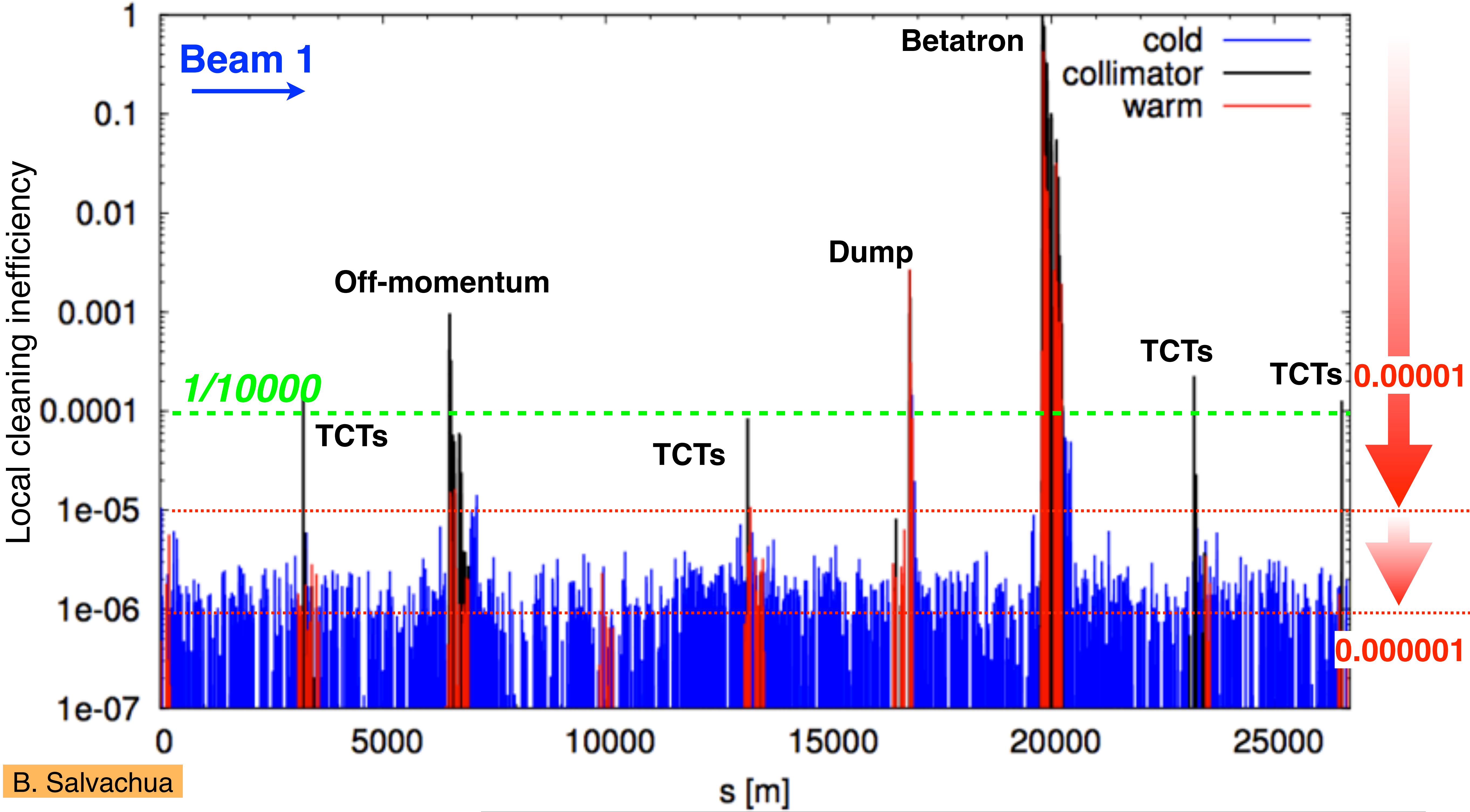
Collimation cleaning

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



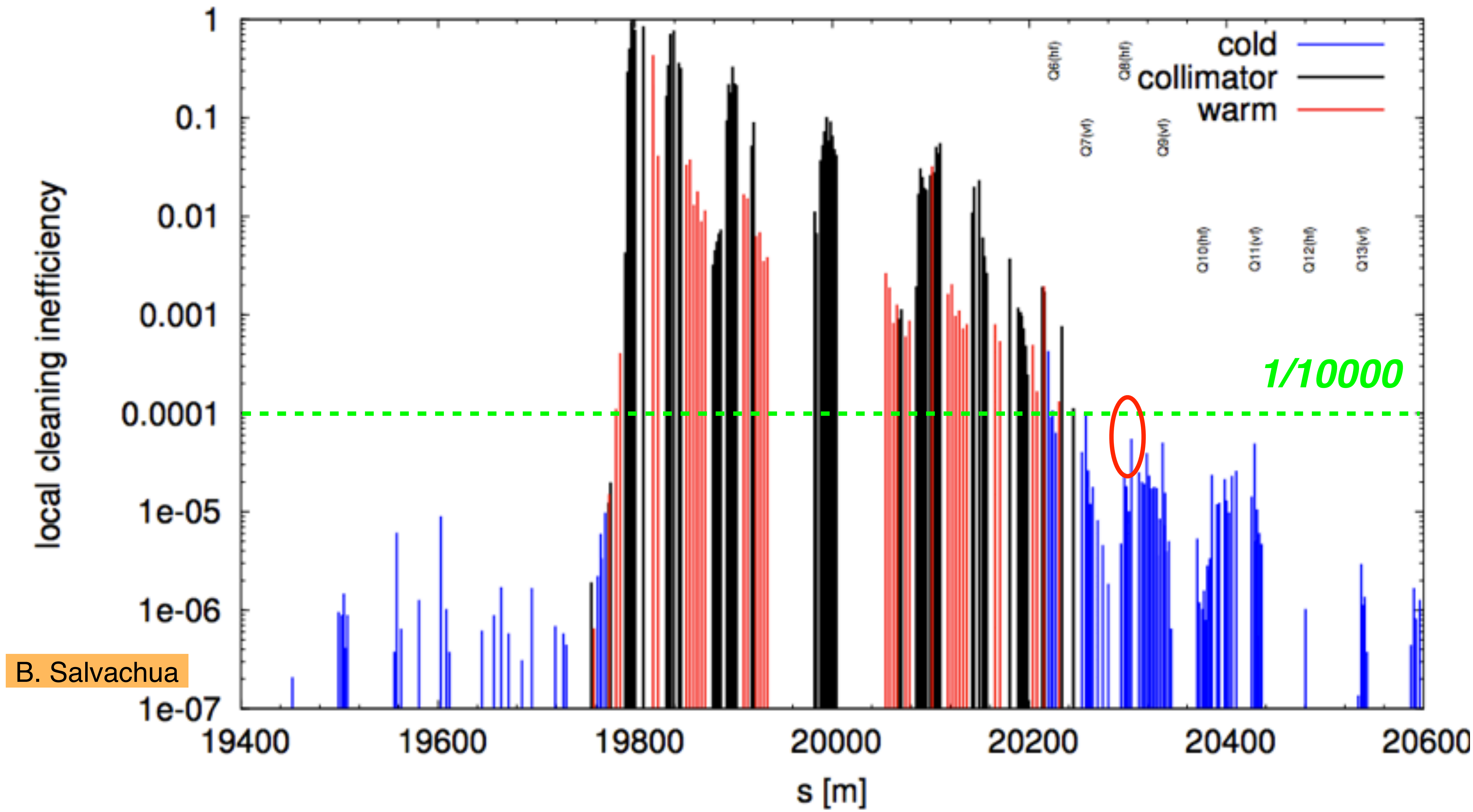
Collimation cleaning: 4.0 TeV, β^*=0.6 m



B. Salvachua

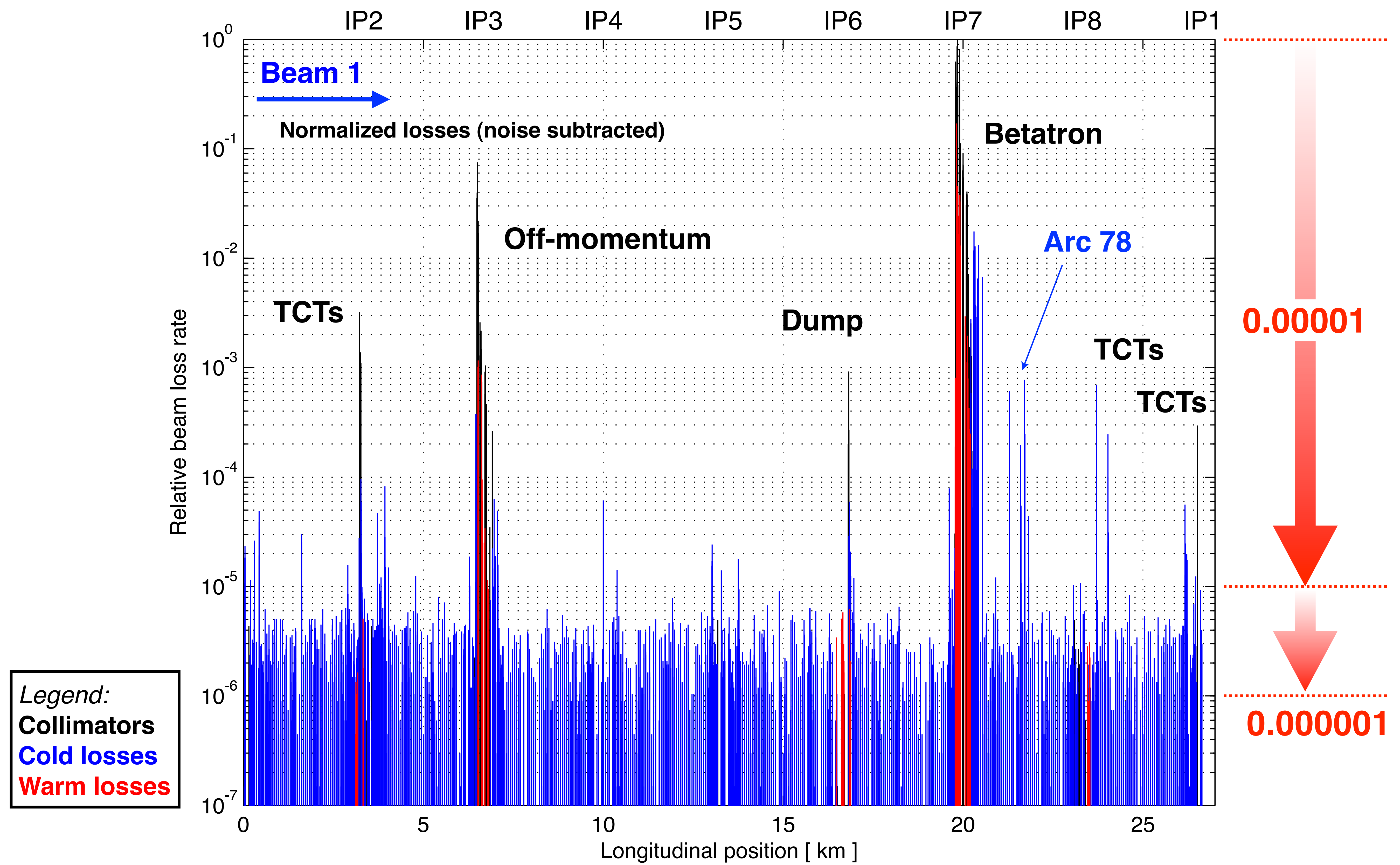
Highest COLD loss location: efficiency of > 99.99% !
Most of the ring actually > 99.999%

Losses in IR7: 4.0 TeV, β^*=0.6 m

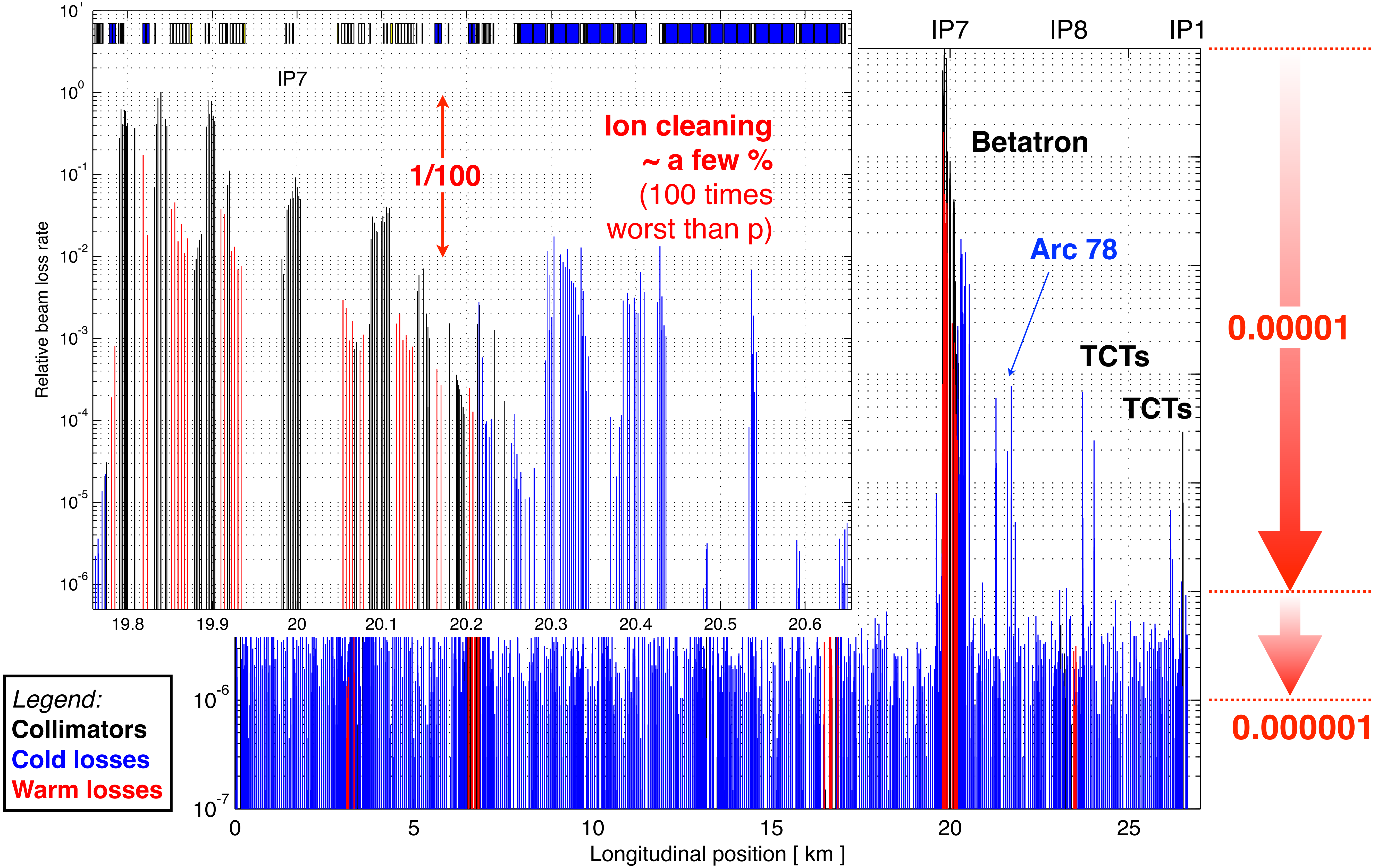


<u>Critical location</u> (both beams): losses in the dispersion suppressor (Q8) from <u>single diffractive</u> interactions with the primary collimators.
With squeezed beams: tertiary collimators (TCTs) protect locally the triplets.

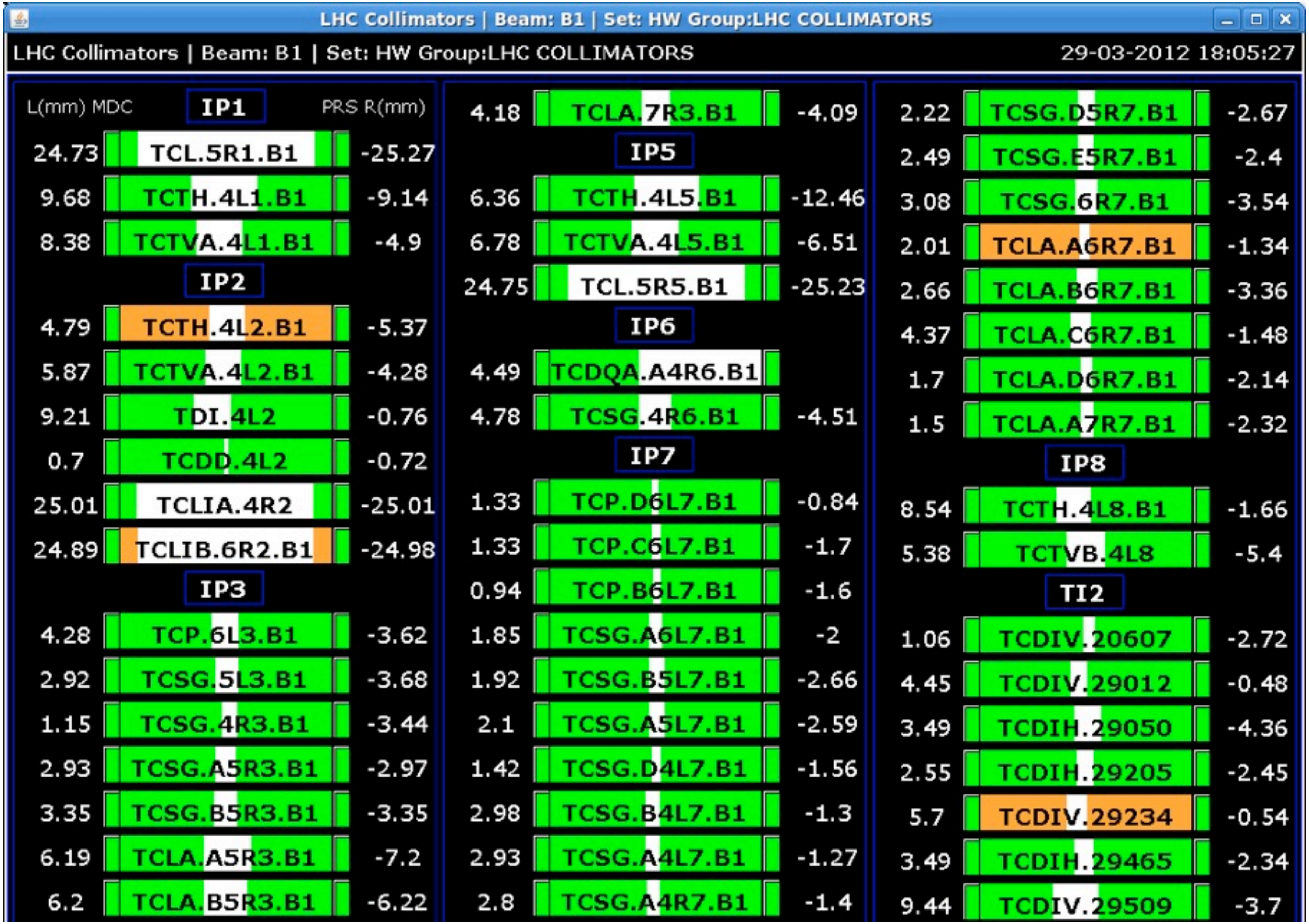
Lead ion beam at 3.5 TeV (2011)



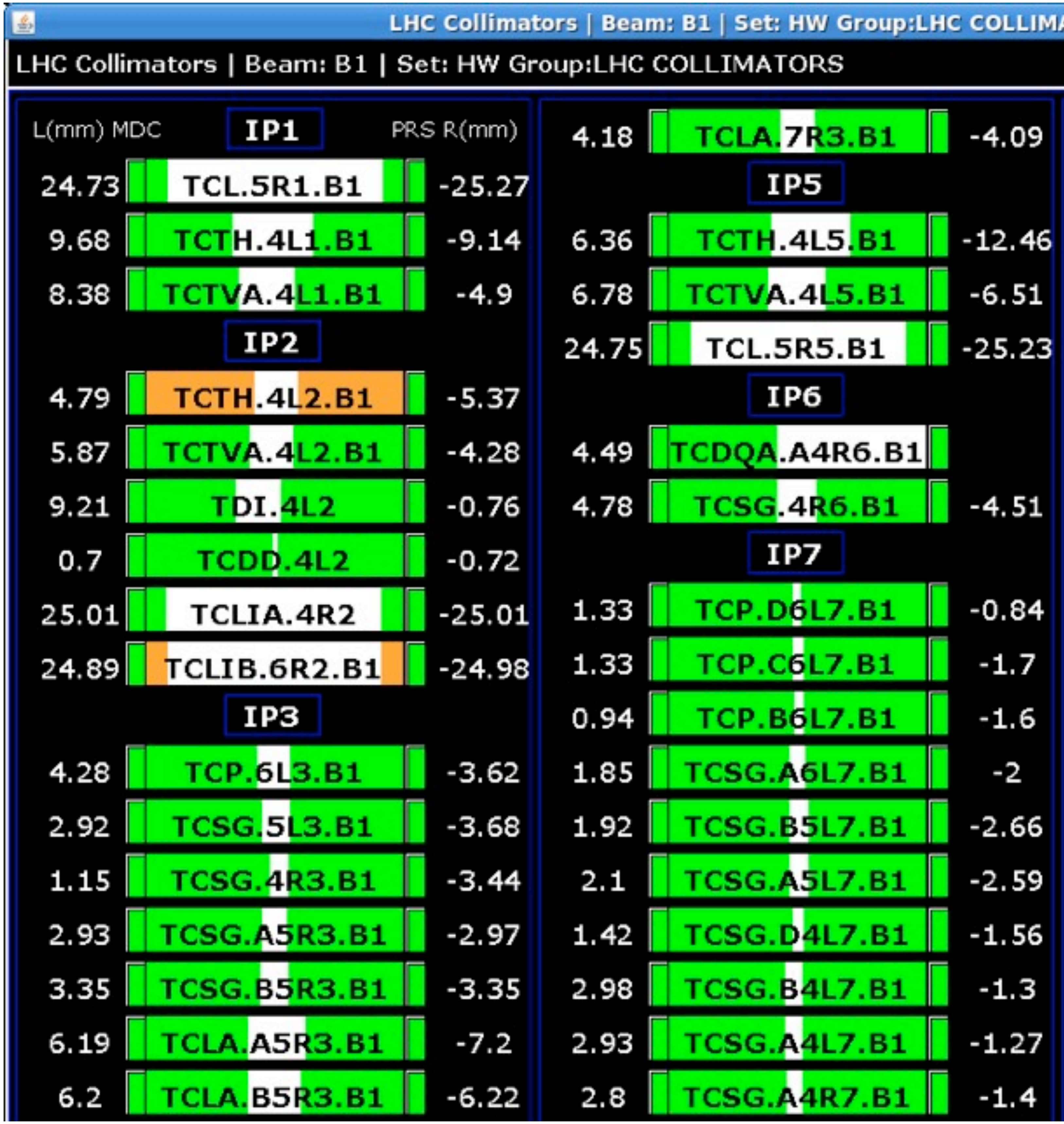
Lead ion beam at 3.5 TeV (2011)



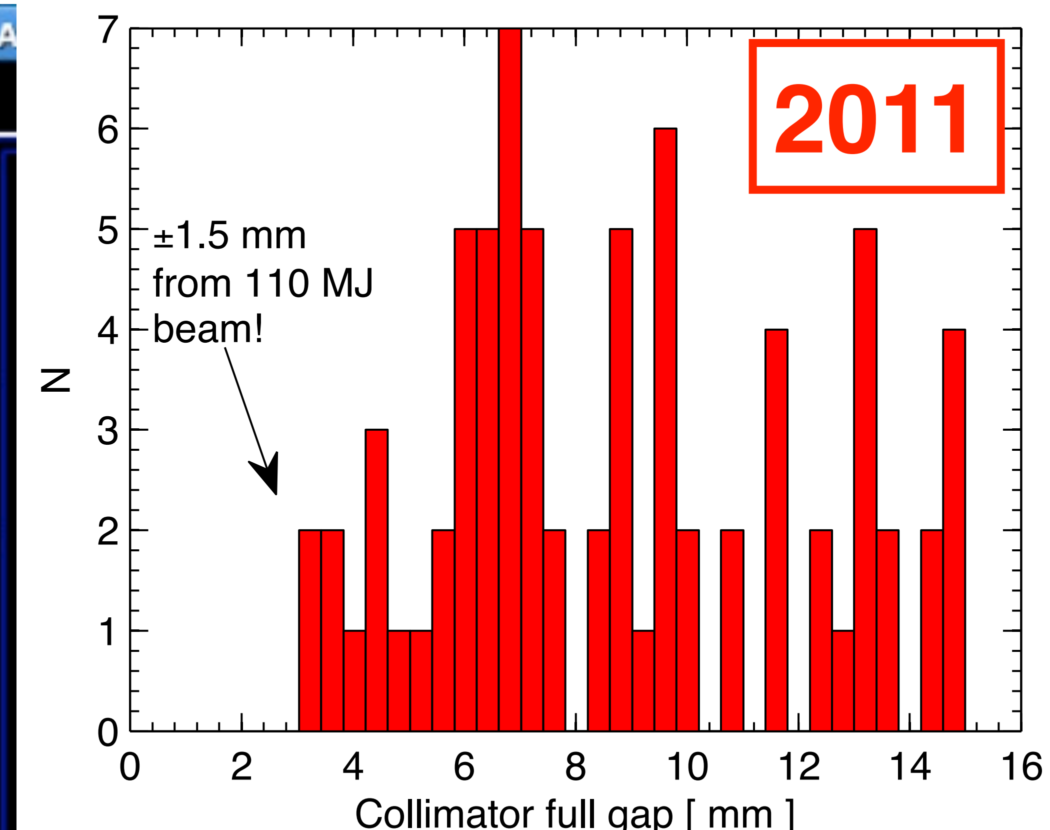
4 TeV physics settings in millimeters



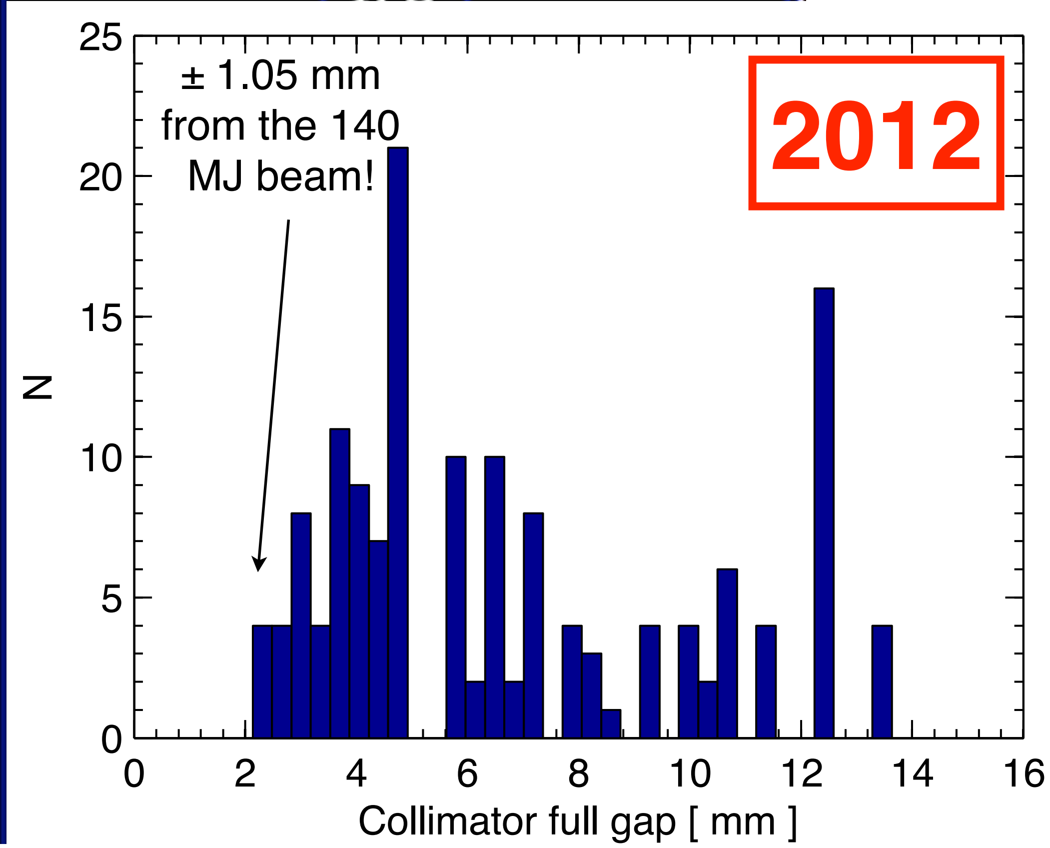
4 TeV physics settings in millimeters



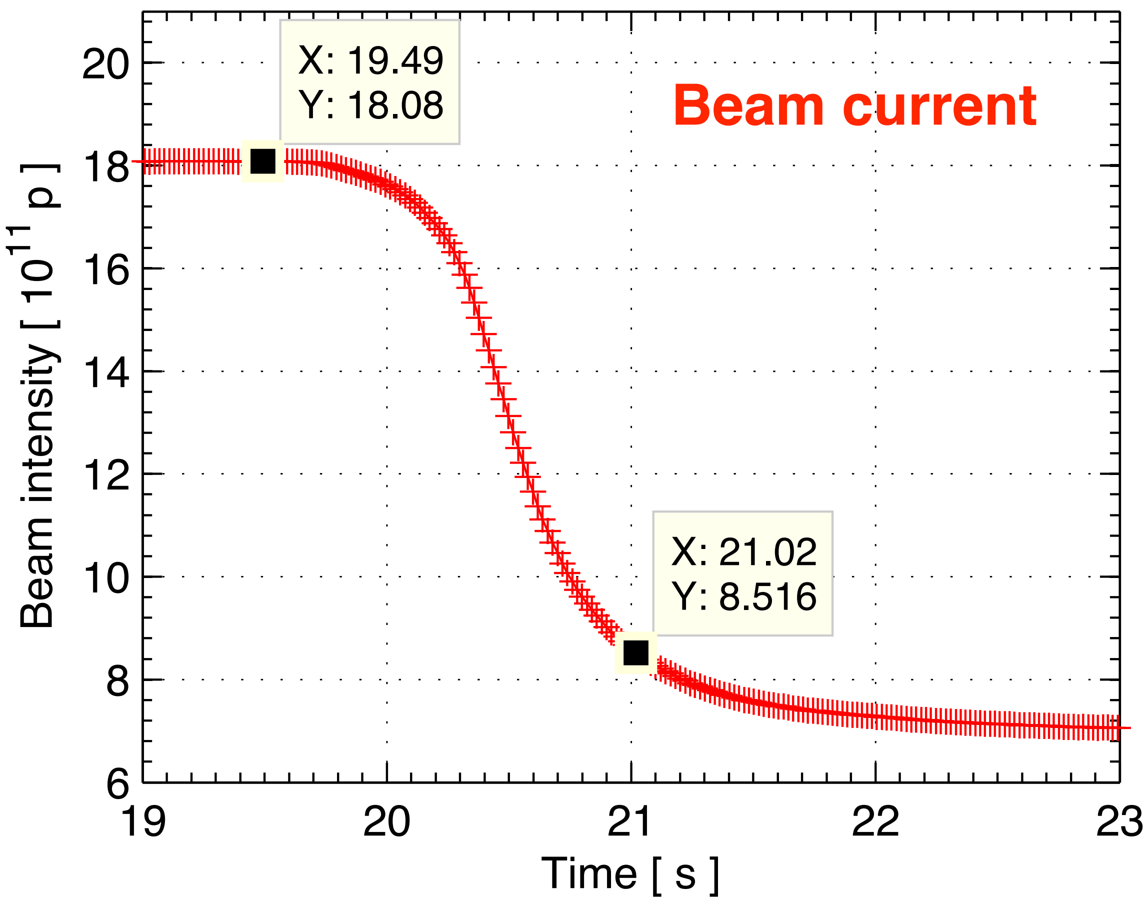
L(mm) MDC		PRS R(mm)
	IP1	
24.73	TCL.5R1.B1	-25.27
9.68	TCTH.4L1.B1	-9.14
8.38	TCTVA.4L1.B1	-4.9
	IP2	
4.79	TCTH.4L2.B1	-5.37
5.87	TCTVA.4L2.B1	-4.28
9.21	TDI.4L2	-0.76
0.7	TCDD.4L2	-0.72
25.01	TCLIA.4R2	-25.01
24.89	TCLIB.6R2.B1	-24.98
	IP3	
4.28	TCP.6L3.B1	-3.62
2.92	TCSG.5L3.B1	-3.68
1.15	TCSG.4R3.B1	-3.44
2.93	TCSG.A5R3.B1	-2.97
3.35	TCSG.B5R3.B1	-3.35
6.19	TCLA.A5R3.B1	-7.2
6.2	TCLA.B5R3.B1	-6.22
4.18	TCLA.7R3.B1	-4.09
	IP5	
6.36	TCTH.4L5.B1	-12.46
6.78	TCTVA.4L5.B1	-6.51
24.75	TCL.5R5.B1	-25.23
	IP6	
4.49	TCDQA.A4R6.B1	
4.78	TCSG.4R6.B1	-4.51
	IP7	
1.33	TCP.D6L7.B1	-0.84
1.33	TCP.C6L7.B1	-1.7
0.94	TCP.B6L7.B1	-1.6
1.85	TCSG.A6L7.B1	-2
1.92	TCSG.B5L7.B1	-2.66
2.1	TCSG.A5L7.B1	-2.59
1.42	TCSG.D4L7.B1	-1.56
2.98	TCSG.B4L7.B1	-1.3
2.93	TCSG.A4L7.B1	-1.27
2.8	TCSG.A4R7.B1	-1.4



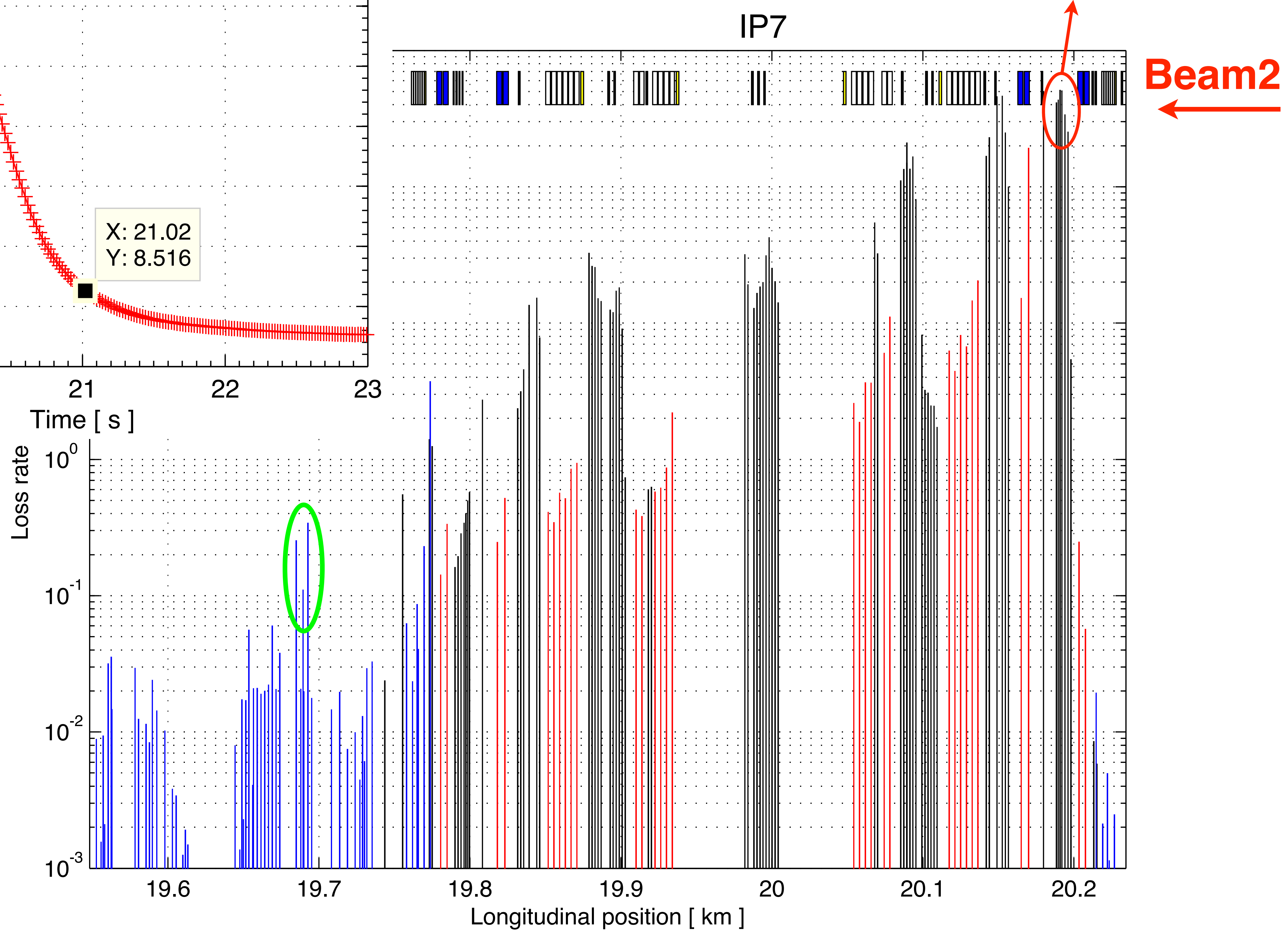
IP8



Handling large beam losses



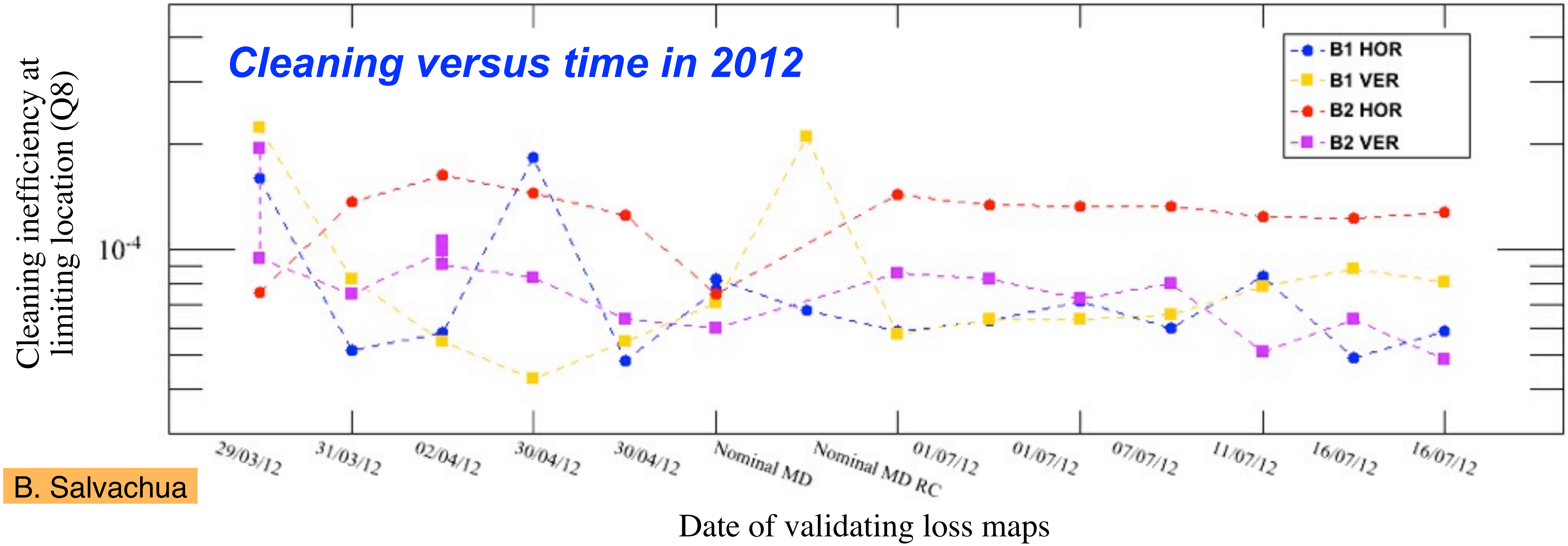
500 kW primary losses on the TCP at 3.5 TeV!



LHC collimation system could handle 500 kW losses in a superconducting machine!

Poster MPO245

Stability of cleaning performance



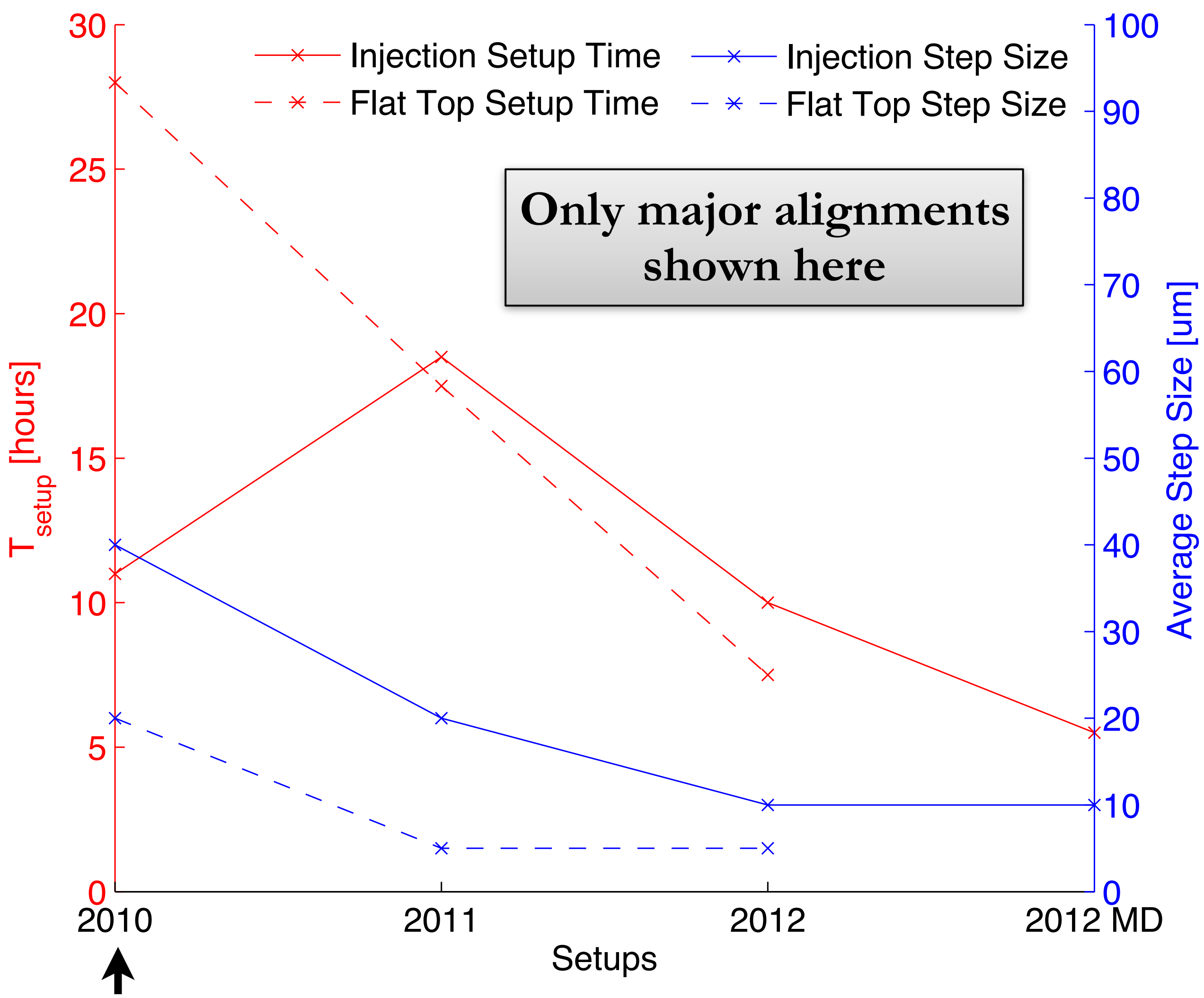
B. Salvachua

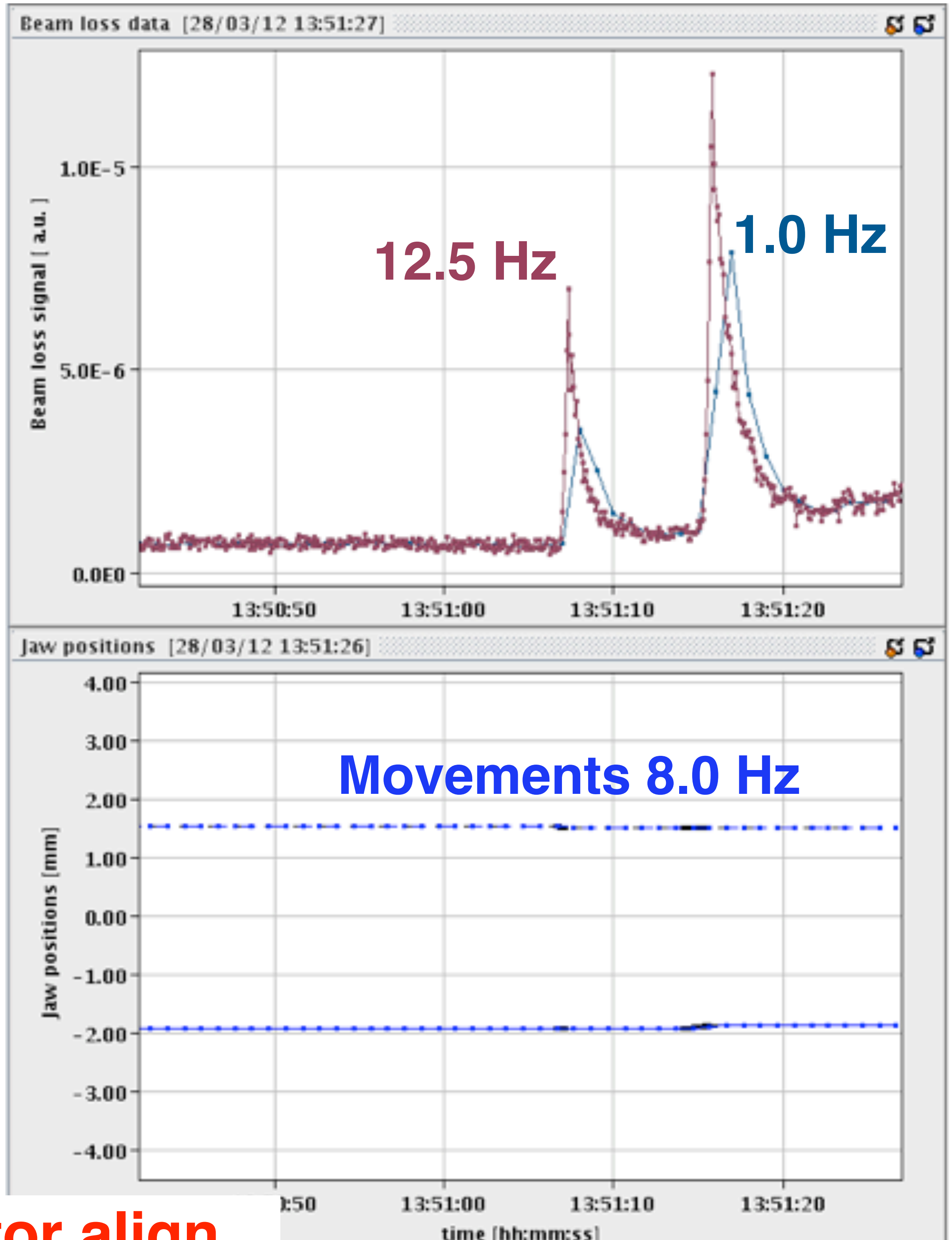
- **Excellent stability** of cleaning performance observed!
- Achieved with **only 1 alignment per year** in IR3/6/7 (2x30 collimators).
- Operational strategy: **Unfrequent alignments** and **regular validation campaigns** for the collimator cleaning and hierarchy (loss maps)
  - *Monitoring of standard physics fills + periodic dedicated loss maps*
- New alignments are needed for **new physics configurations**
  - *Changes optics or orbit, Van der Meer scans, spectrometer polarity, ...*

Collimator alignment

2012 commissioning: alignment campaigns

Setup Type	Injection	Flat Top	Squeezed	Colliding
Date	21/03	29/03	31/03	30/03
N. of coll.	86	80	16	20





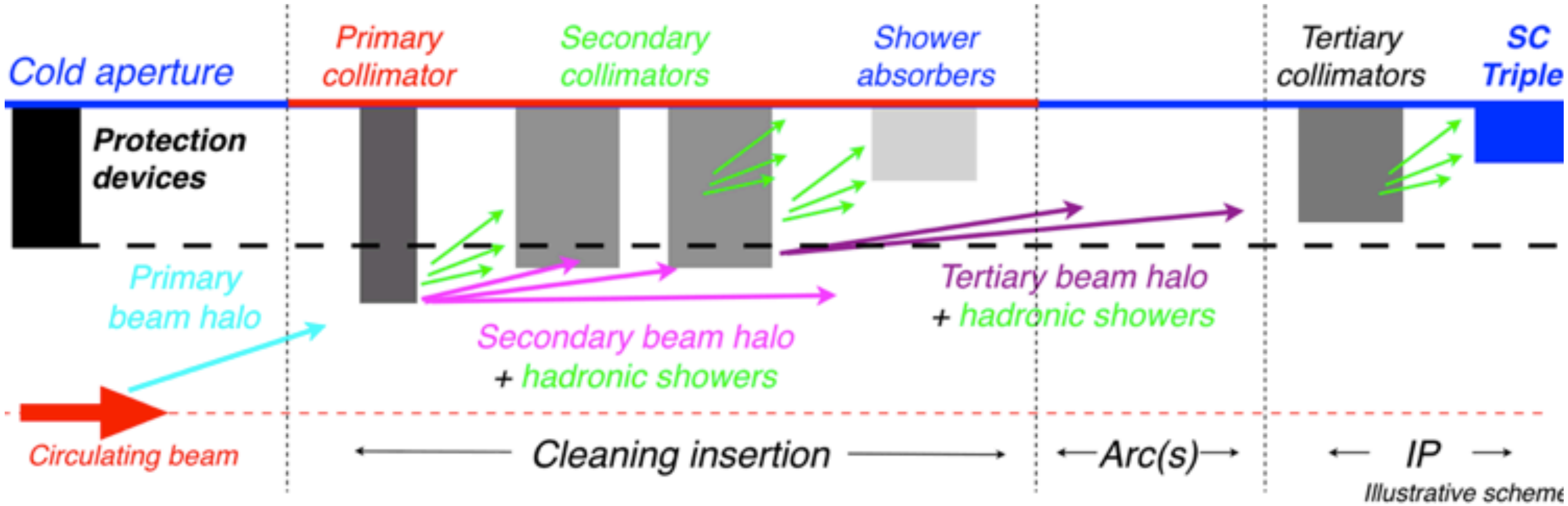
Number of dump triggered during collimator align.

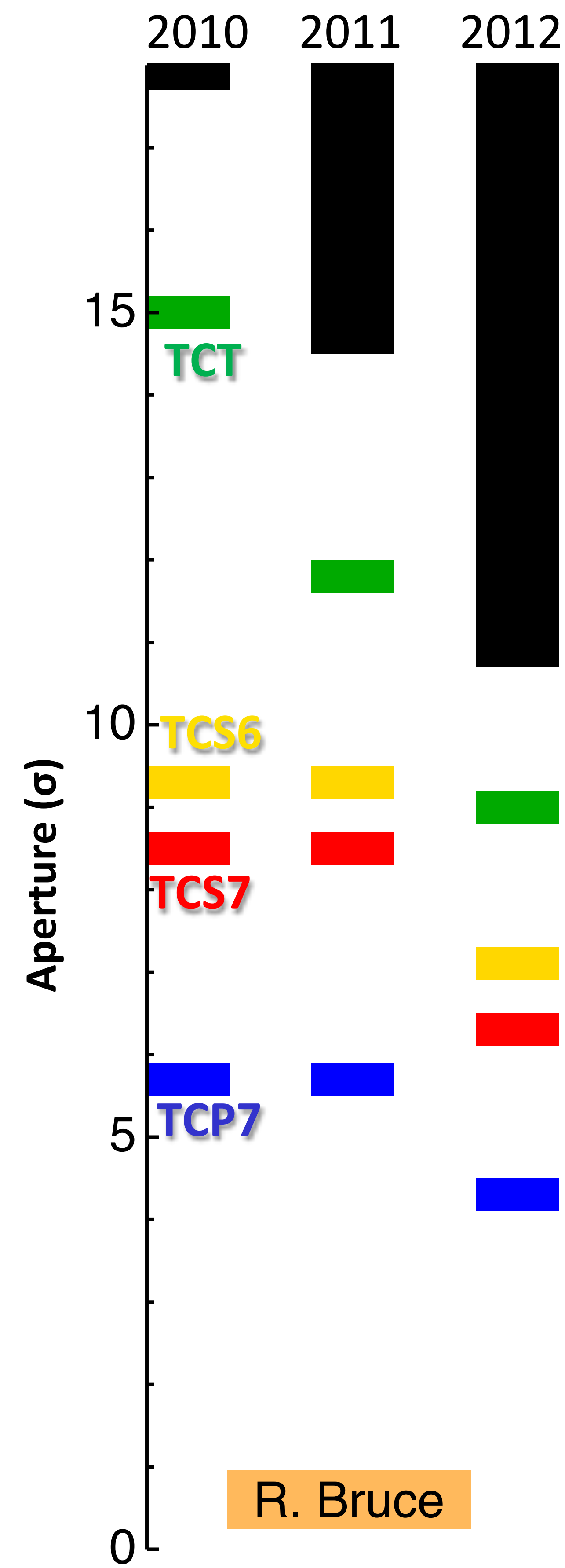
	2010 (Manual)	2011 (1 Hz)	2012 (8 Hz)
Num. of dumps	1 (inj) + 4 (3.5TeV)	2 + 0	0 + 0

Ph.D. work of G. Valentino
See a recent ICAP paper + MPO246

Collimation hierarchy and β* reach

LHC multi-stage collimation





- **Tight settings** established in **2012** after thorough validation in 2011 *(monitoring of standard fills + dedicated MD)*
- Important **advantages**:
  - Improved β^* reach **60 cm**: 40-50% gain in luminosity reach!
  - Better cleaning!
  - Still "relaxed" orbit margins (1 alignment per year!)
  - Gain operational experience with small 7 TeV gaps (in mm)
- **Drawbacks**:
  - Larger losses in operation *(talks: R. Schmidt MOI1A01, and L. Ponce TU03C01)*
  - Increased **impedance** → instabilities *(See B. Salvant, WEO1A02)*

Collimation operational experience

- **Very good performance** of the collimation system so far (up to 140MJ):
  - *- Validated <u>all</u> critial design choices (HW, SW, interlocking, ...);*
  - *- Cleaning close to simulations and ok for 1.5 nominal intensity at 7 TeV;*
  - *- We learned that we can rely on the machine stability!*
  - *- Established and improved semi-automatic alignment tools;*
- **Performance estimates** indicate no limitations from cleaning at 6.5-7.0 TeV
  - *- Critical loss locations as predicted: dispersion suppressor magnets.*
  - *- Based on 2011 quench tests of dispersion suppressor magnets, at 3.5 TeV (MPO245);*
  - *- Estimated will be updated after new quench tests at 4 TeV (Feb. 2013).*
- The present LHC collimation **cannot protect** the cold dispersion suppressors.
  - *- No obvious limitation for quench, magnet lifetime is being addressed.*
  - *- Focus of present studies is moved to the experimental regions.*
- The collimators determine the **LHC impedance** → *see B. Salvant (WEO1A02)*
  - *- Rich program on "dream" materials and new collimator concepts.*
- Collimation alignments and validation of new setting are **time-consuming**.
- The **operation flexibility** in the experimental regions (VdM scans, spectrometer polarity, β* leveling, ...) is affected by collimation constraints.
- The ***β**** **reach** is determined by <u>collimation constraints</u>: retraction between beam dump and horizontal <u>TCTs</u> which are not robust.
- Collimator handling in **radiation environment** will be challenging.

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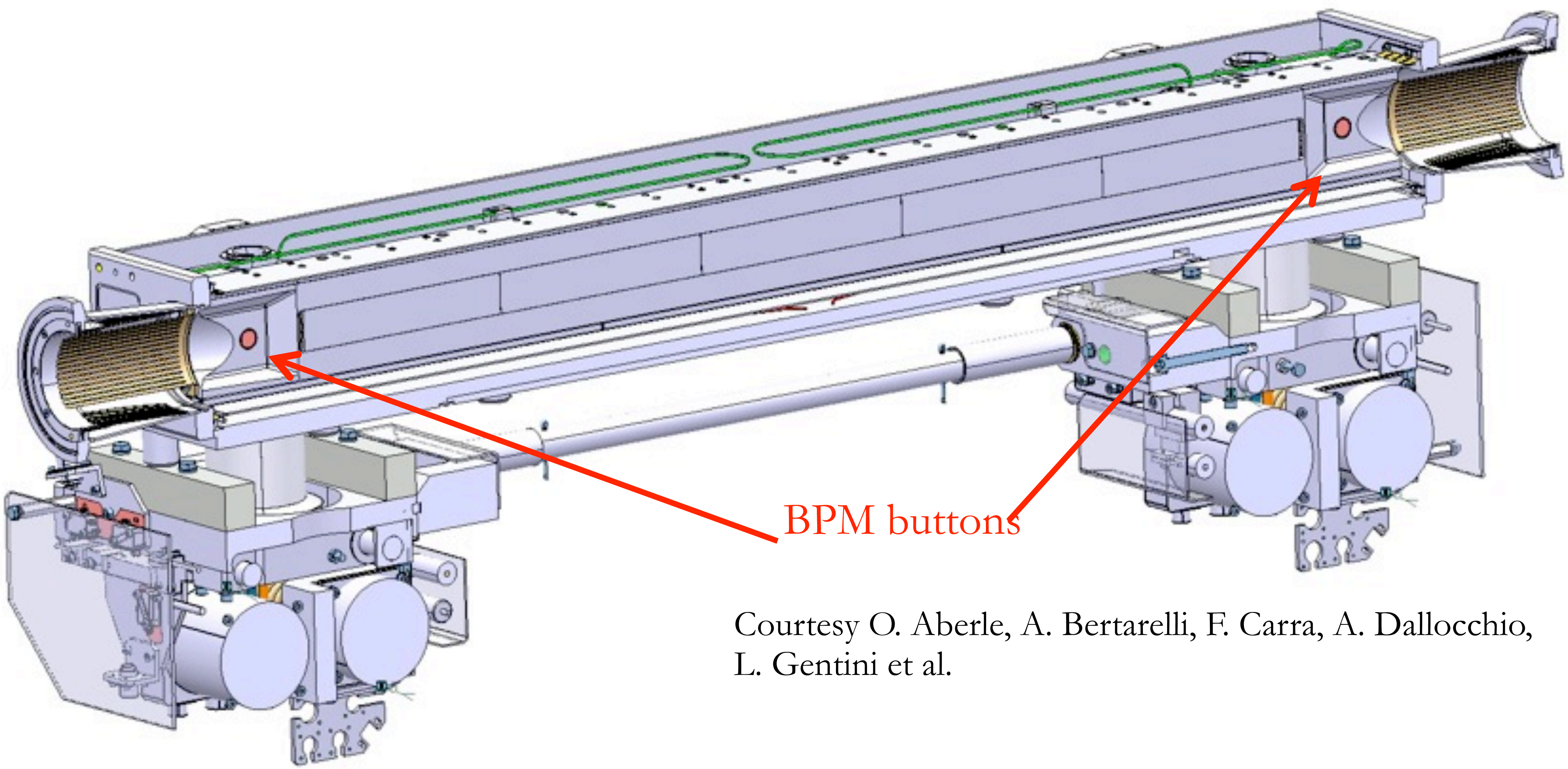
Collimator improvements for 2015

- The 16 Tungsten TCTs (industrial production) in all IRs and the 2 Carbon TCSGs in IR6 (in-house production) will be replaced by new collimators with integrated BPMs.
- Tests in the SPS with mock-up collimator very successful!
- **Gain**: can re-align dynamically during standard fills. No need for special low-intensity fills
  ➙ Drastically reduced setup time (gain of a factor ~100) => more flexibility in IR configurations
  ➙ Improved monitoring of TCT centres in the IRs (reduce validation time)!
  ➙ Reduced orbit margins in cleaning hierarchy => more room to squeeze β^*
- Other system improvements being prepared (additional absorbers, improved IR layouts, ..) - No treated here.



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

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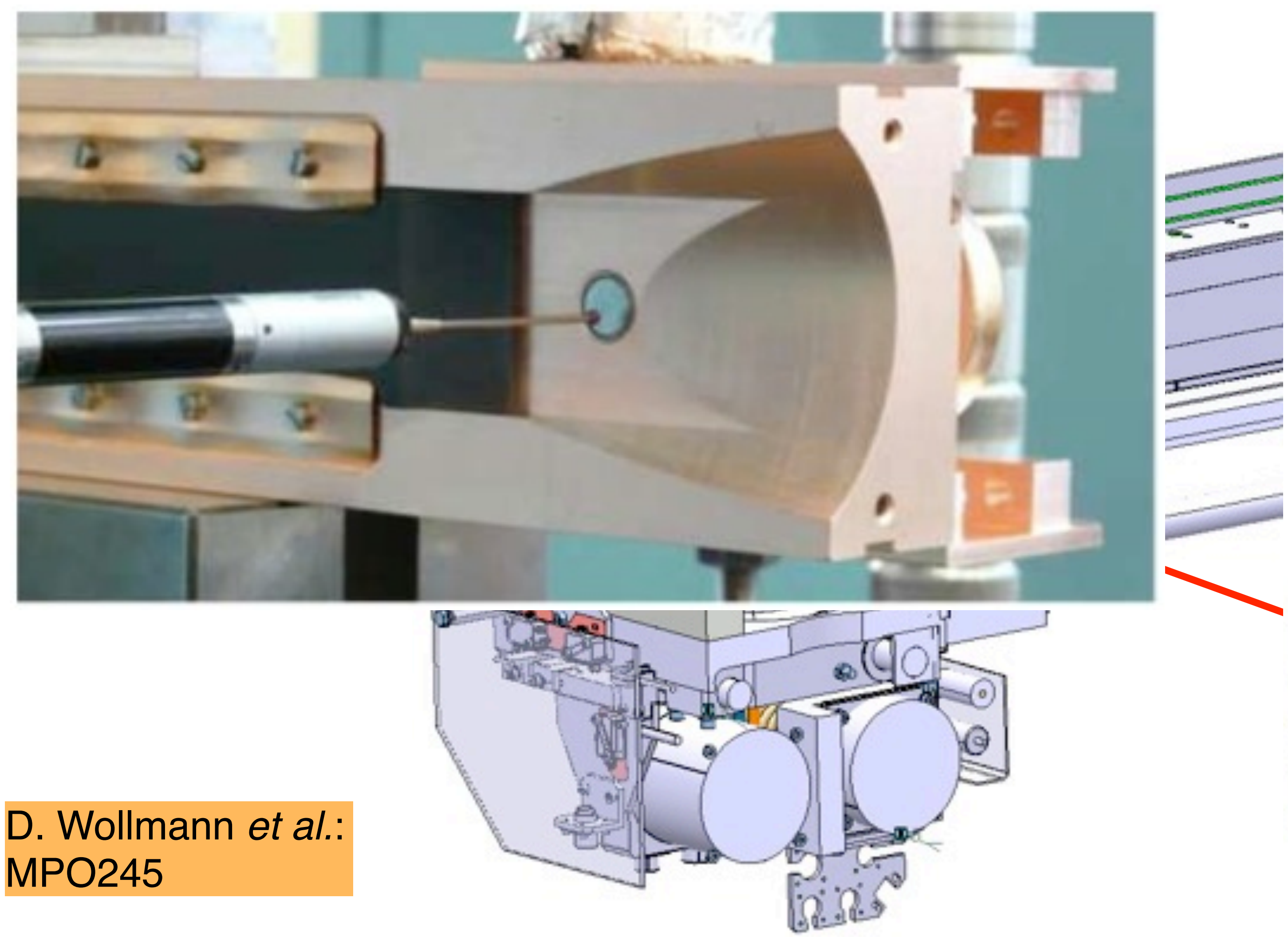

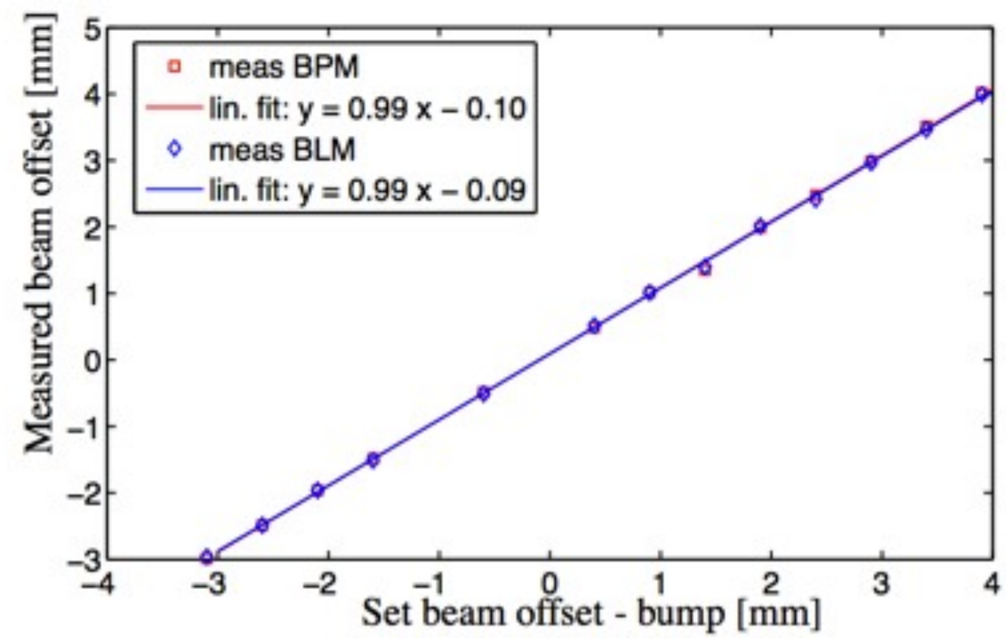

Figure 8: Correlation between measured beam centres (BPMs - red, BLM based method - blue) and the bump settings for the orbit offset at the collimator. The error in the bump settings was estimated to about 10% of the movement increment.

D. Wollmann *et al.*: MPO245

Conclusions

- ☑ The performance of the **LHC collimation system** was presented.
  - *- Considered runs of 2010/11/12, with focus on the 2012 operation at 7.7x10^{33} cm^{-2}s^{-1}.*
- ☑ The LHC and its collimation system **work well** (up to > 130 MJ)
  - *- Cleaning inefficiency below a few 0.0001, stable during one whole run.*
  - *- Improved semi-automatic alignment tools were deployed.*
  - *- Tighter collimator settings allowed a **β^*=60cm** (we are now at 77% of 7TeV design lumi).*
- ☑ No performance limitations are expected from collimation cleaning for the operation in 2015 at 6.5-7.0 TeV, if the LHC works as at 4 TeV.
- ☑ The **operational experience** with the present system was presented
  - *- Identified areas of improvement for pushing further the performance reach;*
  - *- System changes can only be addressed partially before the operation in 2015 (LS1): focus on what limited more the LHC operation.*
- ☑ Tertiary collimators in the IRs will be replaced with new collimators with integrated BPMs for a faster alignment and improved peak luminosity.
- ☑ The future for the High Luminosity LHC is being prepared!
  - *- System improvements for implementation in 2018 and 2021 (LS2 and LS3) will be finalized after first experience at ~7 TeV (2015).*