

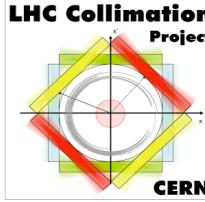
Operational Experience with the LHC Collimation System

Stefano Redaelli - AB Department, Operation Group

R. Assmann and A. Masi - AB Department

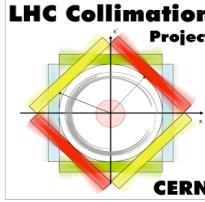
*with O. Aberle, C. Bracco, R. Chamizo, M. Donze, P. Gander, Y. Kadi,
M. Lamont, J. Lendaro, R. Losito, V. Previtali, T. Weiler, ...*





Acknowledgments

- Results of the work of many people presented
 - Control team
 - LHC Software Application (LSA) team: M. Lamont, G. Kruk, ...
 - LHC logging team: R. Billen, C. Roderick
 - Top-level implementations: E. Veyrunes, D. Jacquet, ...
 - Temperature acquisition system: E. Blanco, J. Brahy, M. Jonker
 - Operation / beam tests
 - M. Lamont, R. Bailey, G. Arduini, J. Wenninger
 - LHC operation shift crew
 - LHC Injection & Dump teams: E. Carlier, C. Boucly, B. Boddard, V. Kain
 - LHC beam interlock team (B. Puccio, J. Wenninger, R. Schmidt, ...)



Outline

Introduction

Requirements

The 2008 system

Operation aspects

Commissioning without beam

Synchronized energy ramps

Accuracy / Reproducibility

Interlock commissioning

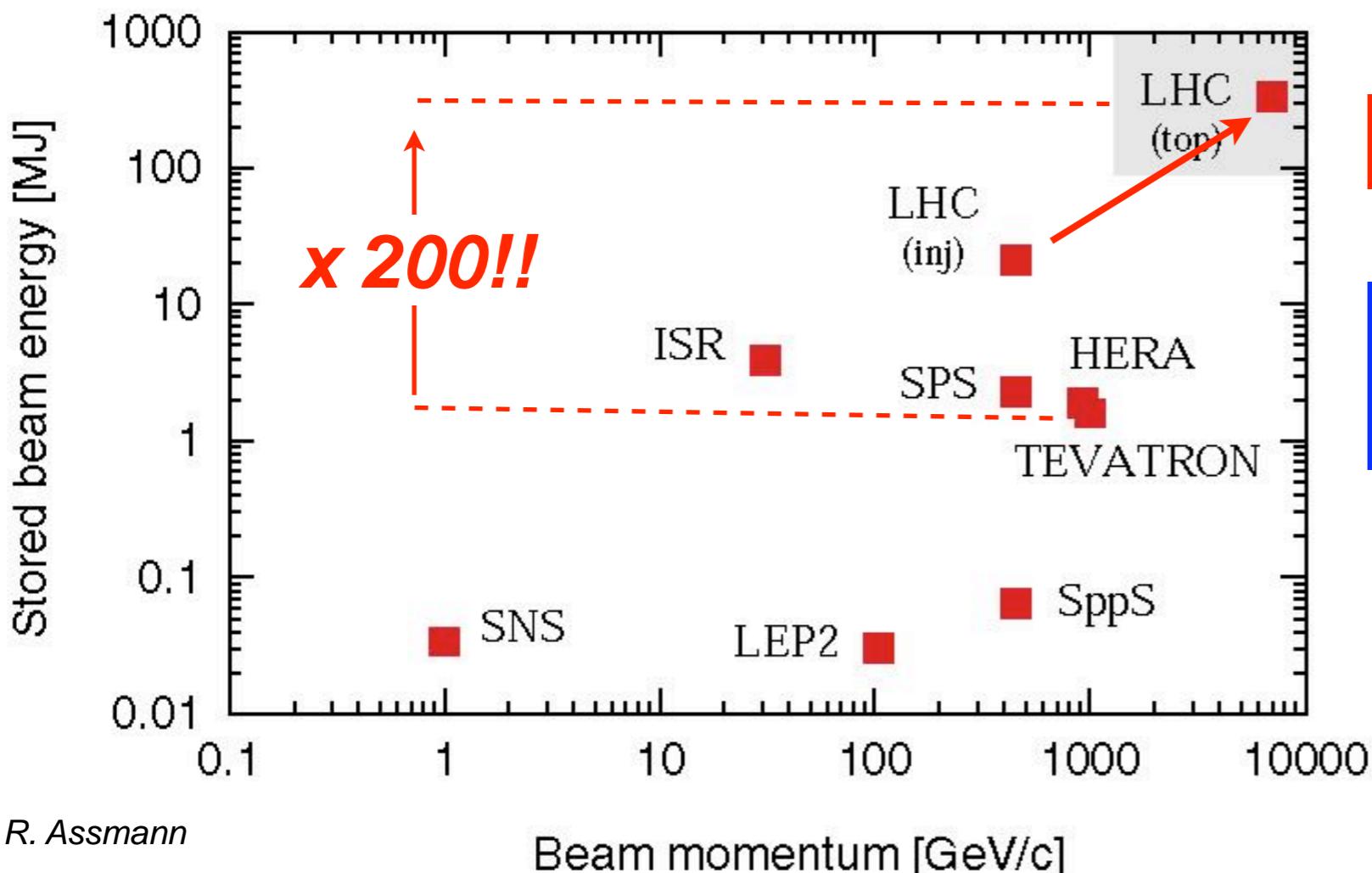
Experience with beam

Transfer line commissioning

Operation of ring collimators

Conclusions

Introduction



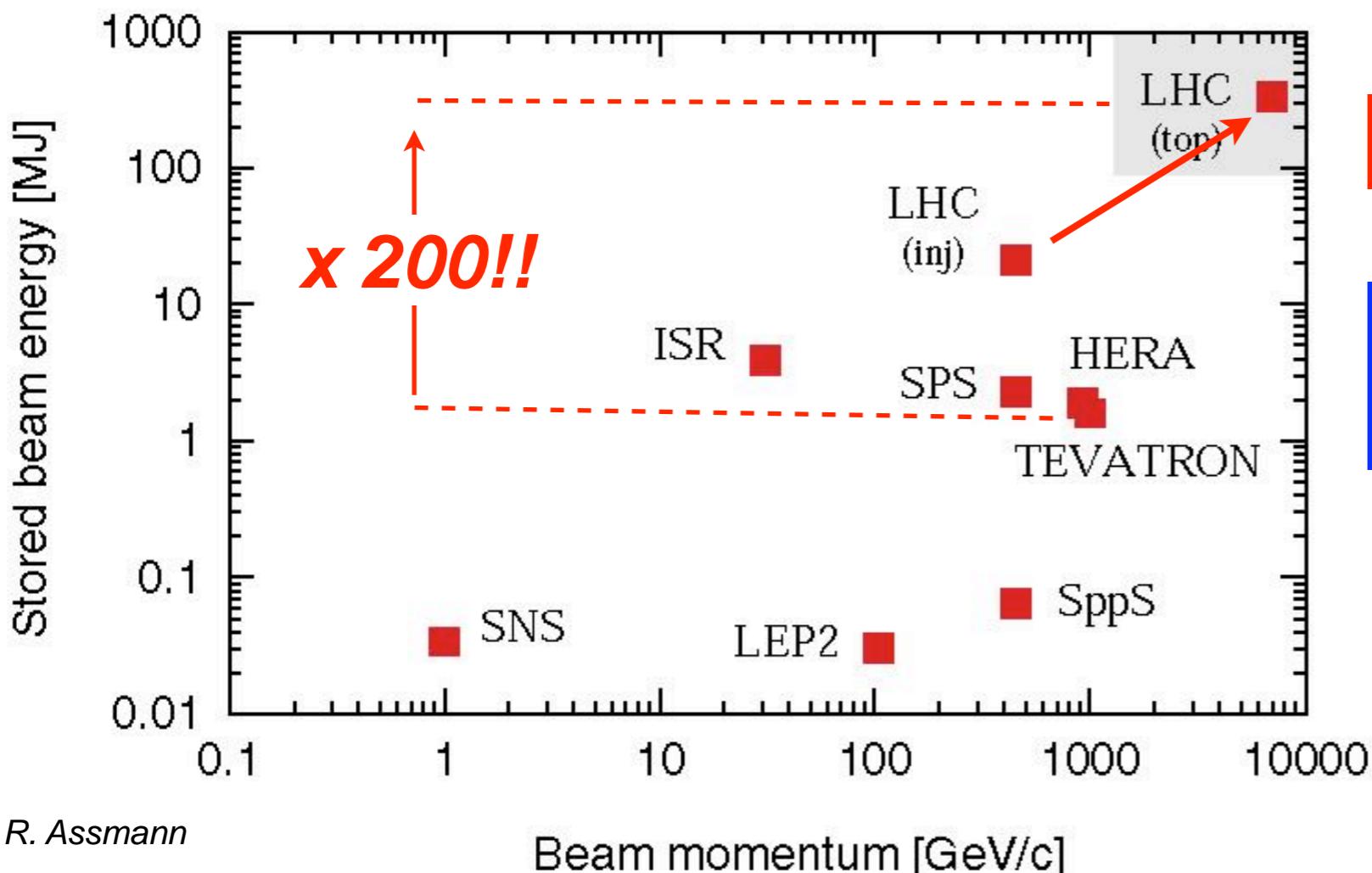
$$E_b = 0.45 \rightarrow 7 \text{ TeV}; I_b = 3.4 \times 10^{14}$$

Stored energy	362 MJ (7 TeV)
	23 MJ (450 GeV)
Quench limit	$\sim 10 \text{ mJ / cm}^3$
Damage (metal)	$\sim 50 \text{ kJ / mm}^2$



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

Introduction



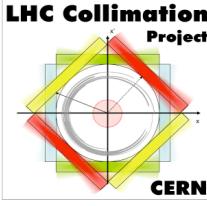
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- Control losses ***1000 times*** better than the state-of-the-art!
- Important role in ***machine protection***
- Need collimation in ***all machine states***: injection, ramp, squeeze, physics



System requirements



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Mechanical control

$b = 250 \mu\text{m}$ at 7 TeV

40 μm surface flatness over $L=1\text{m}$
20 μm positioning reproducibility
20 ms synchronization around ring
Function-driven movements



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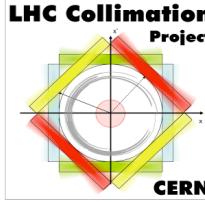
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Up to **30 kW** at top energy

Keep T < 50 °C



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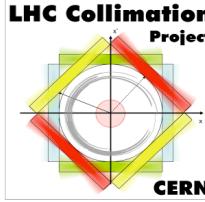
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Interlock positions (functions)

Interlock temperatures

Redundancy

Energy-based limits functions



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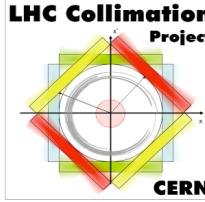
High radiation environment

$\sim 10^{16}$ protons per years!

Radiation hardness of components

Stepping motors: **~10-15 MGy**

Position sensors: **~ 30 MGy**



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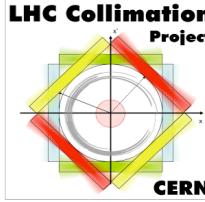
Failure scenarios [Robustness!]

Full **injection** batch

8 nominal bunches at **7 TeV/c**

→ 288 bunches $\approx 2 \text{ MJ}$ (**7.2 μsec**)

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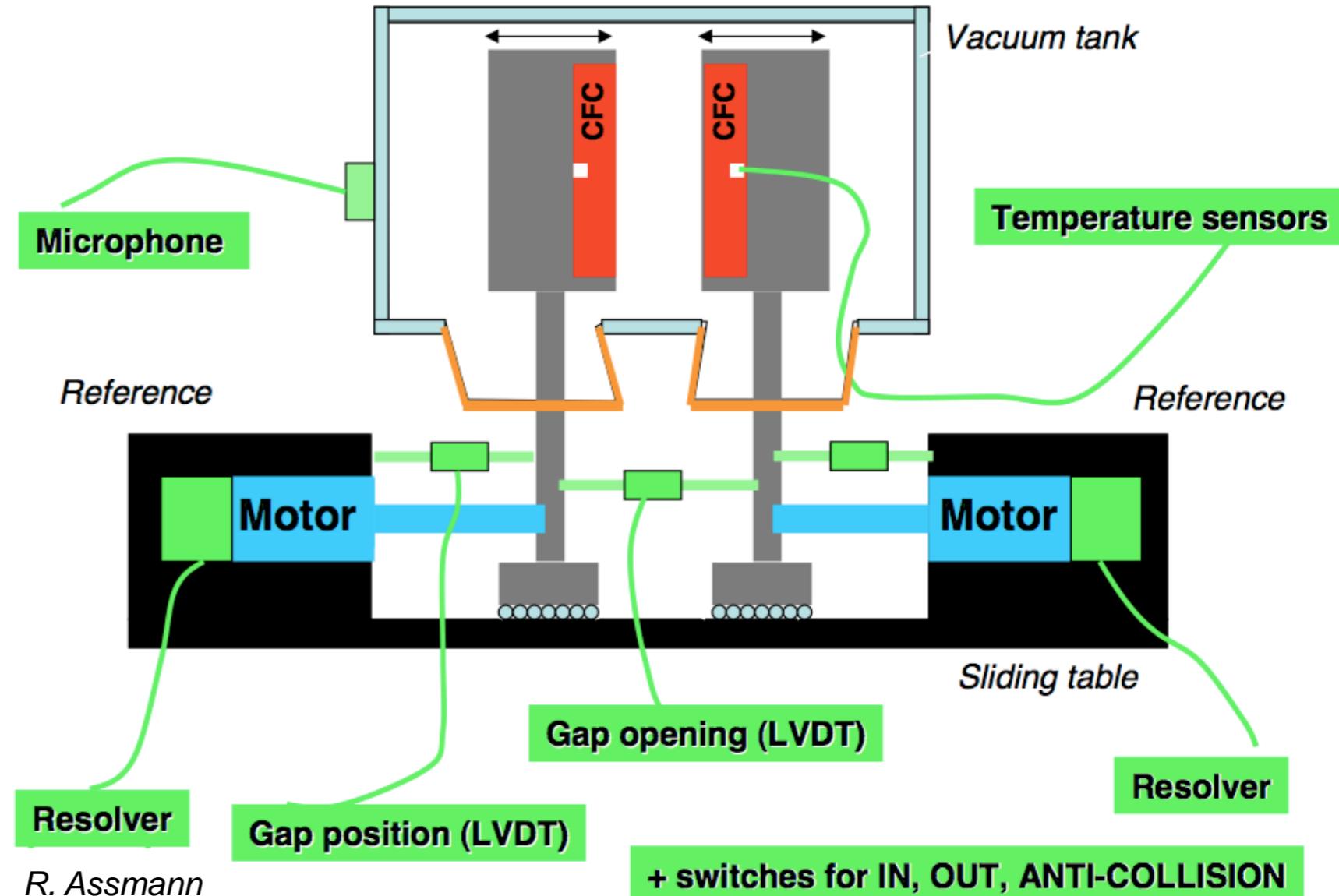
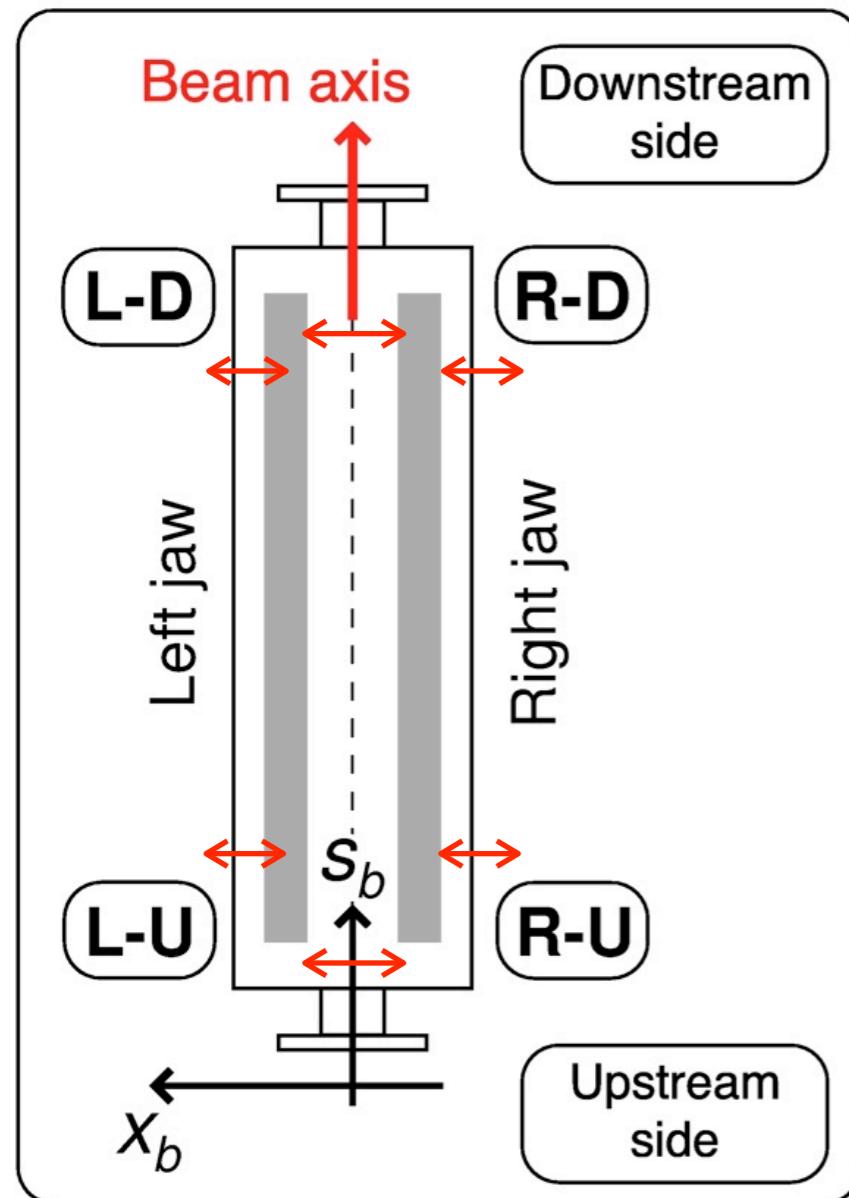
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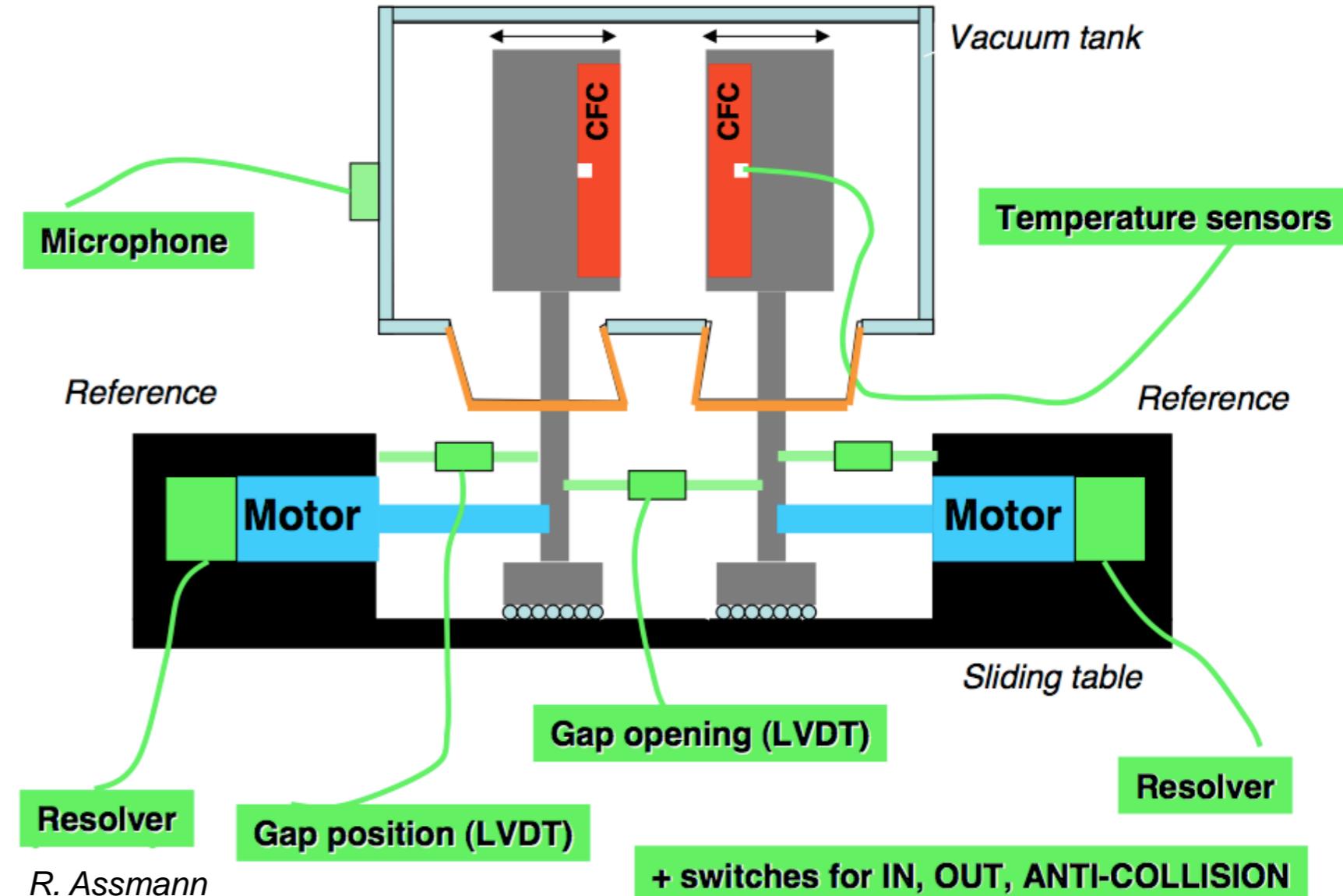
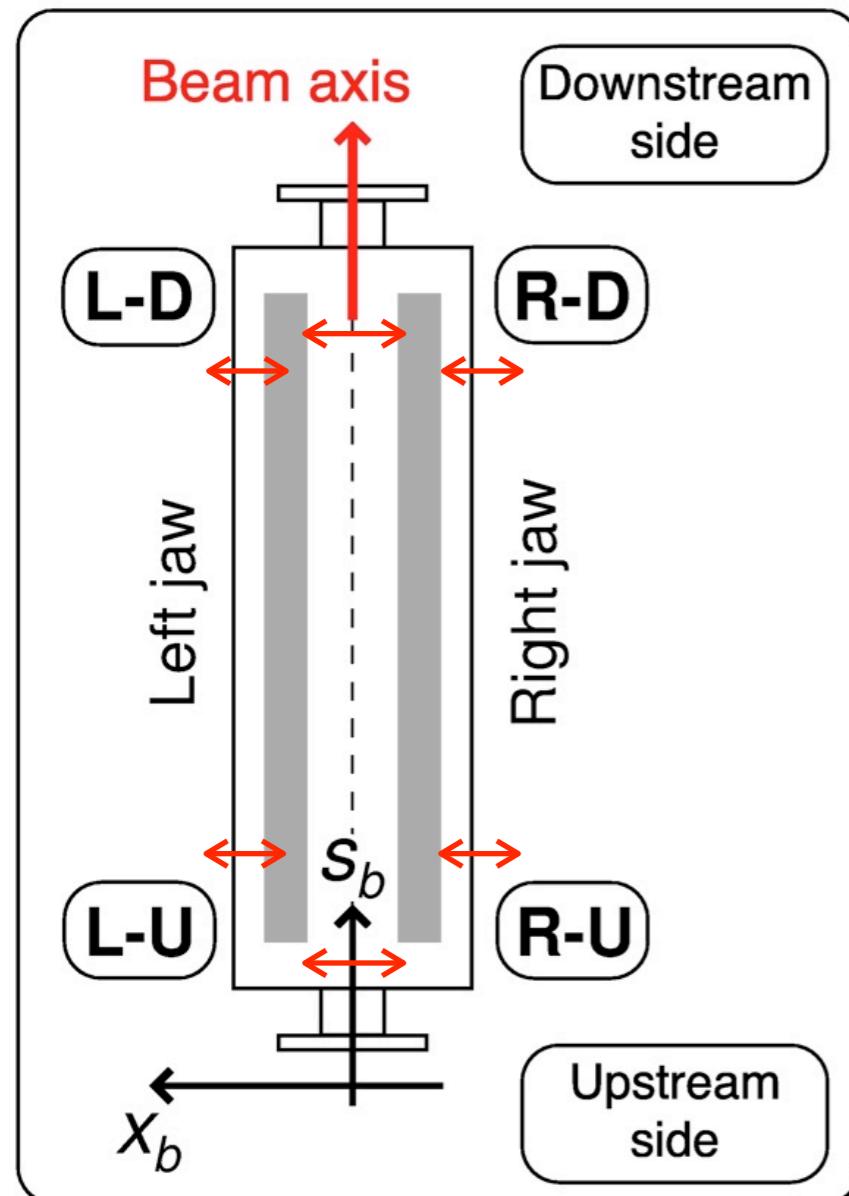
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Operational aspects: positioning



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

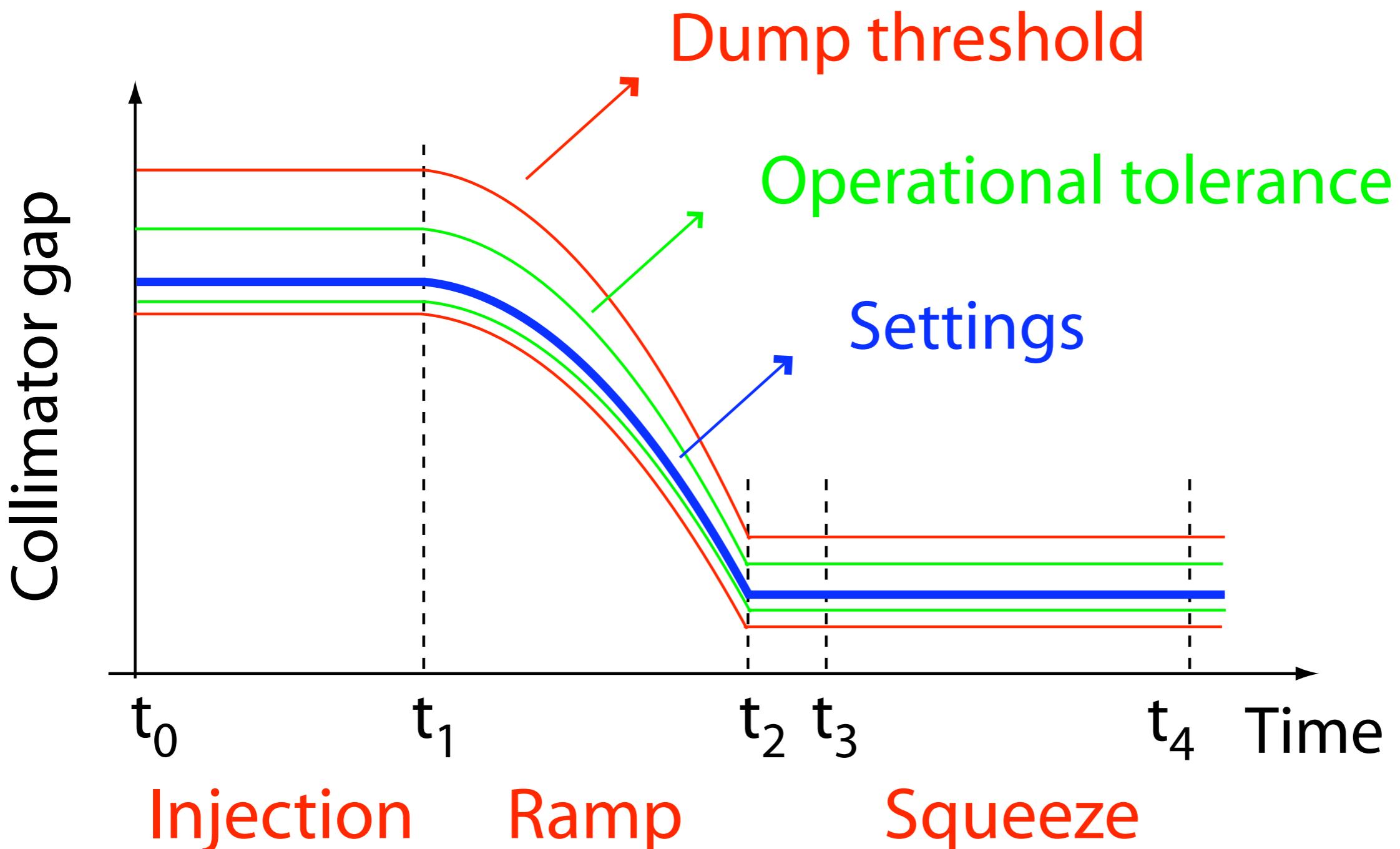
Survey: 7 direct measurements: **4 corners + 2 gaps + tank**

4 resolvers that count motor steps

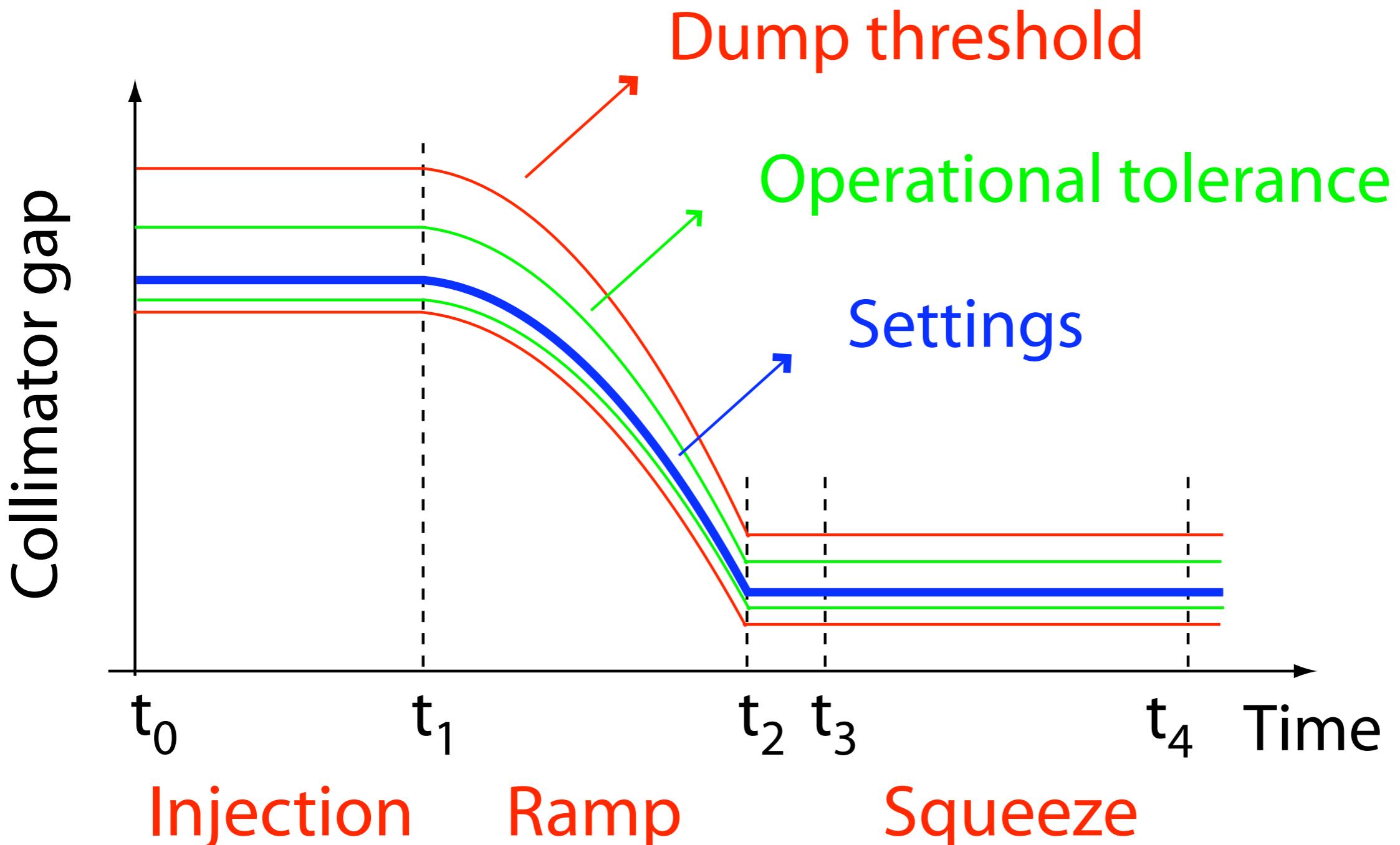
10 switch statuses (full-in, full-out, anti-collision)

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

Function driven settings and limits

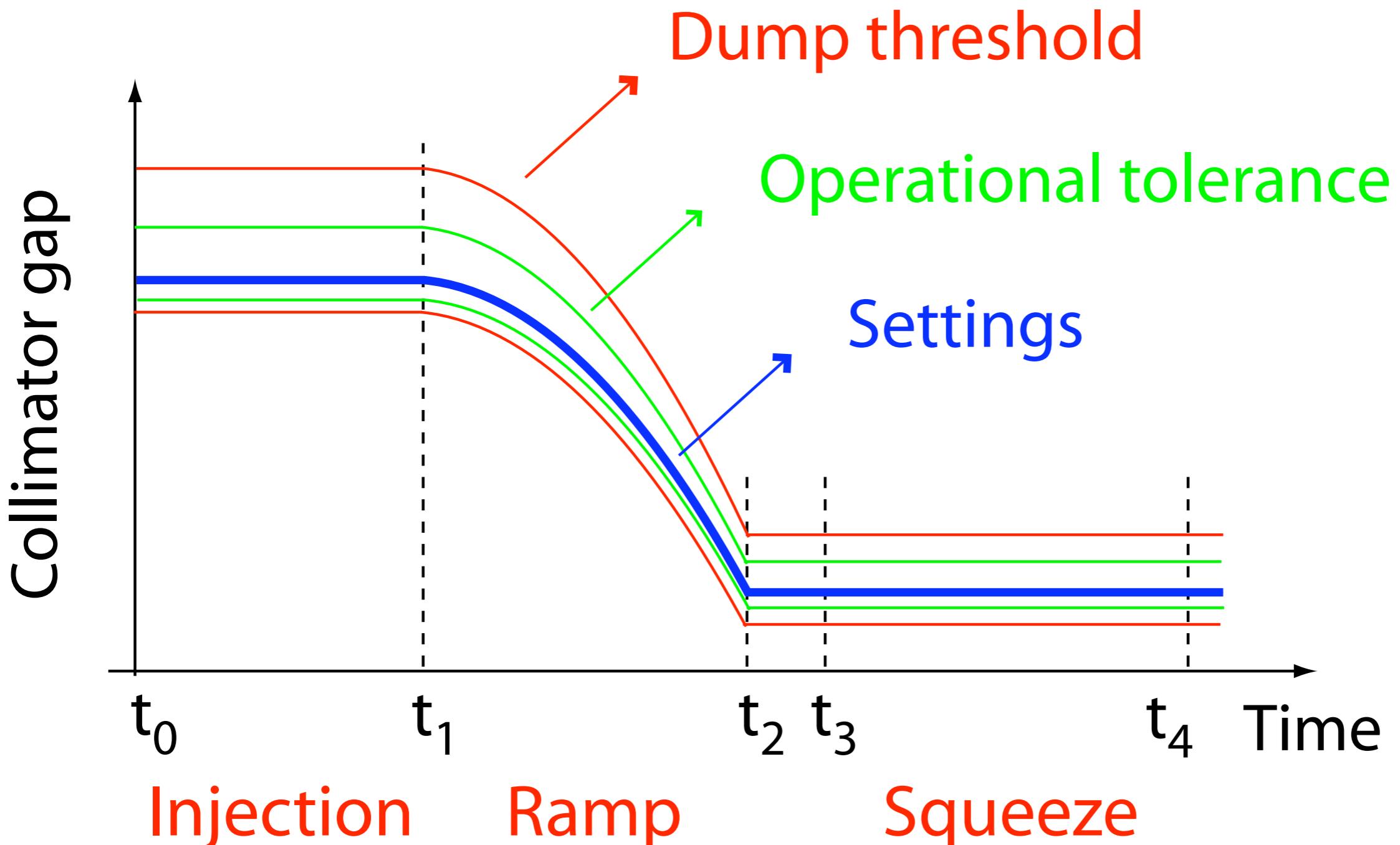


Function driven settings and limits



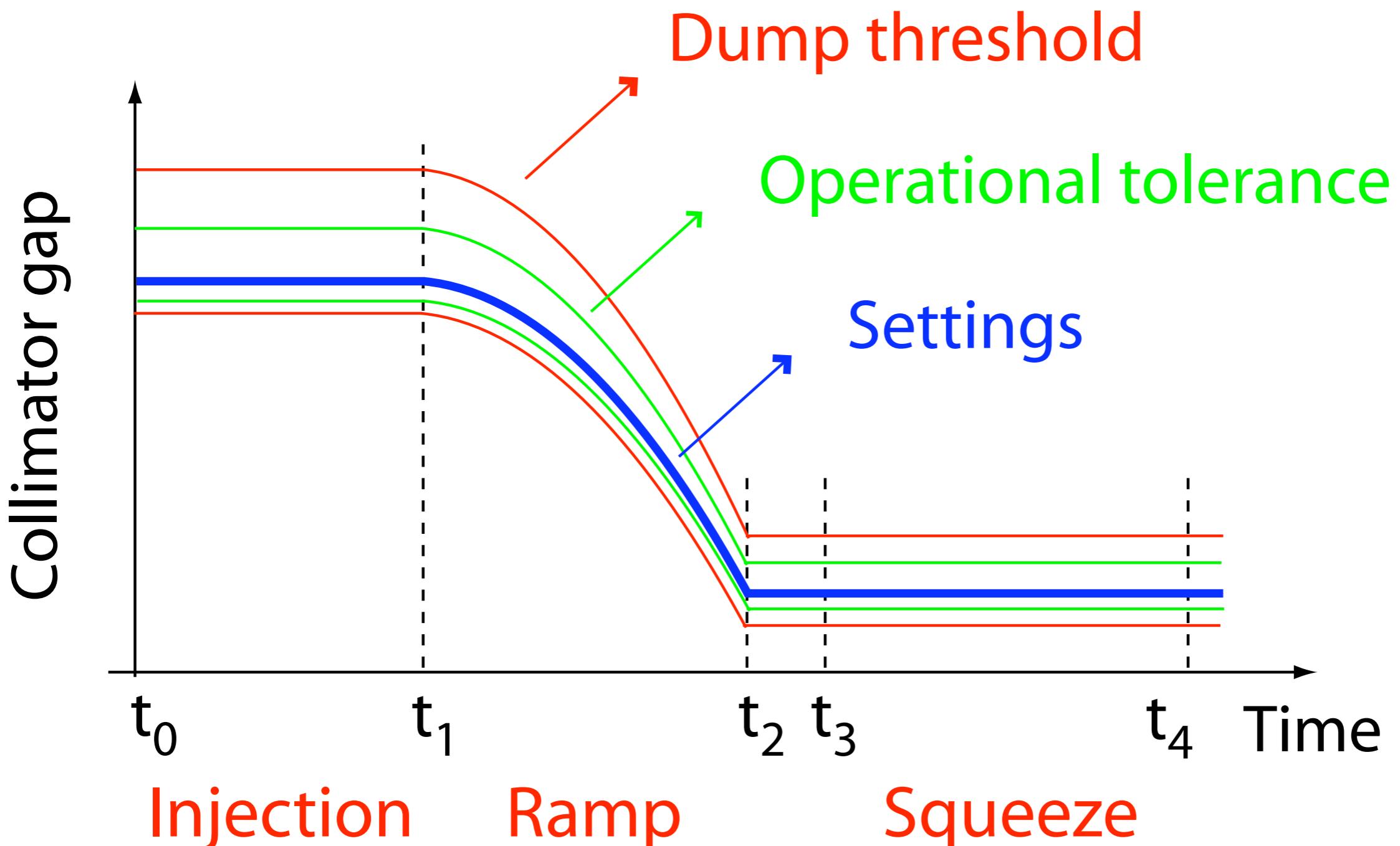
Time-functions for settings in all machine states

Function driven settings and limits



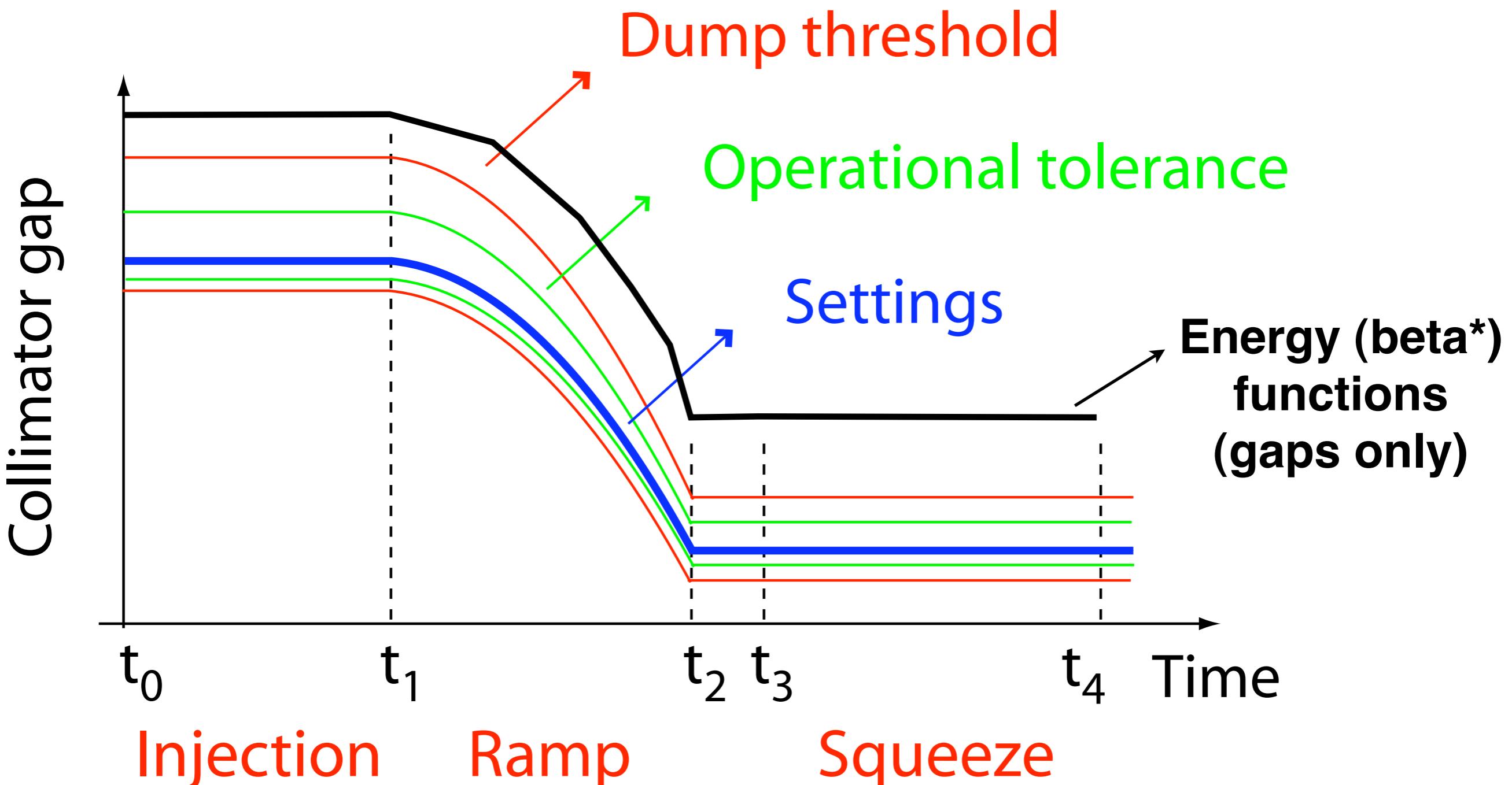
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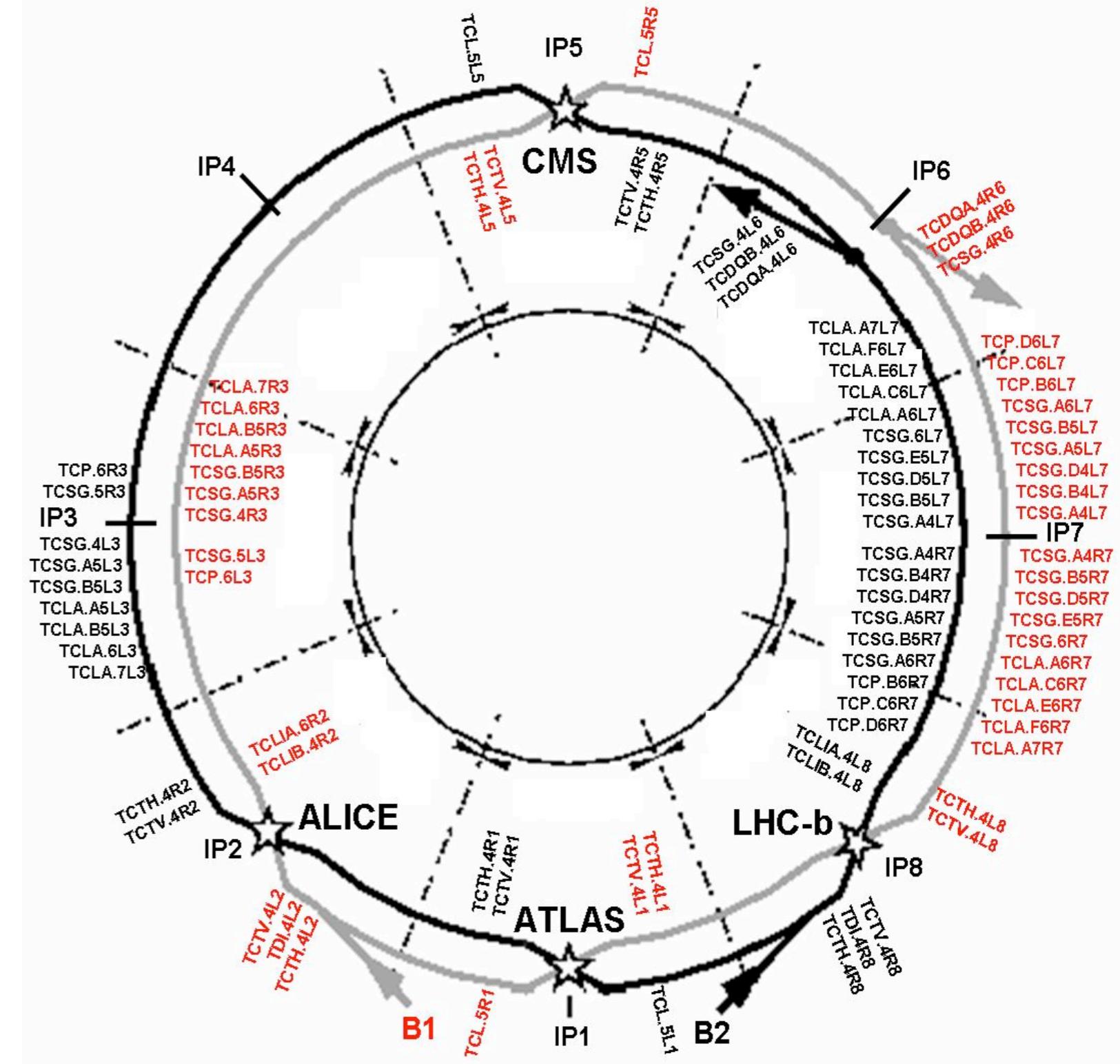
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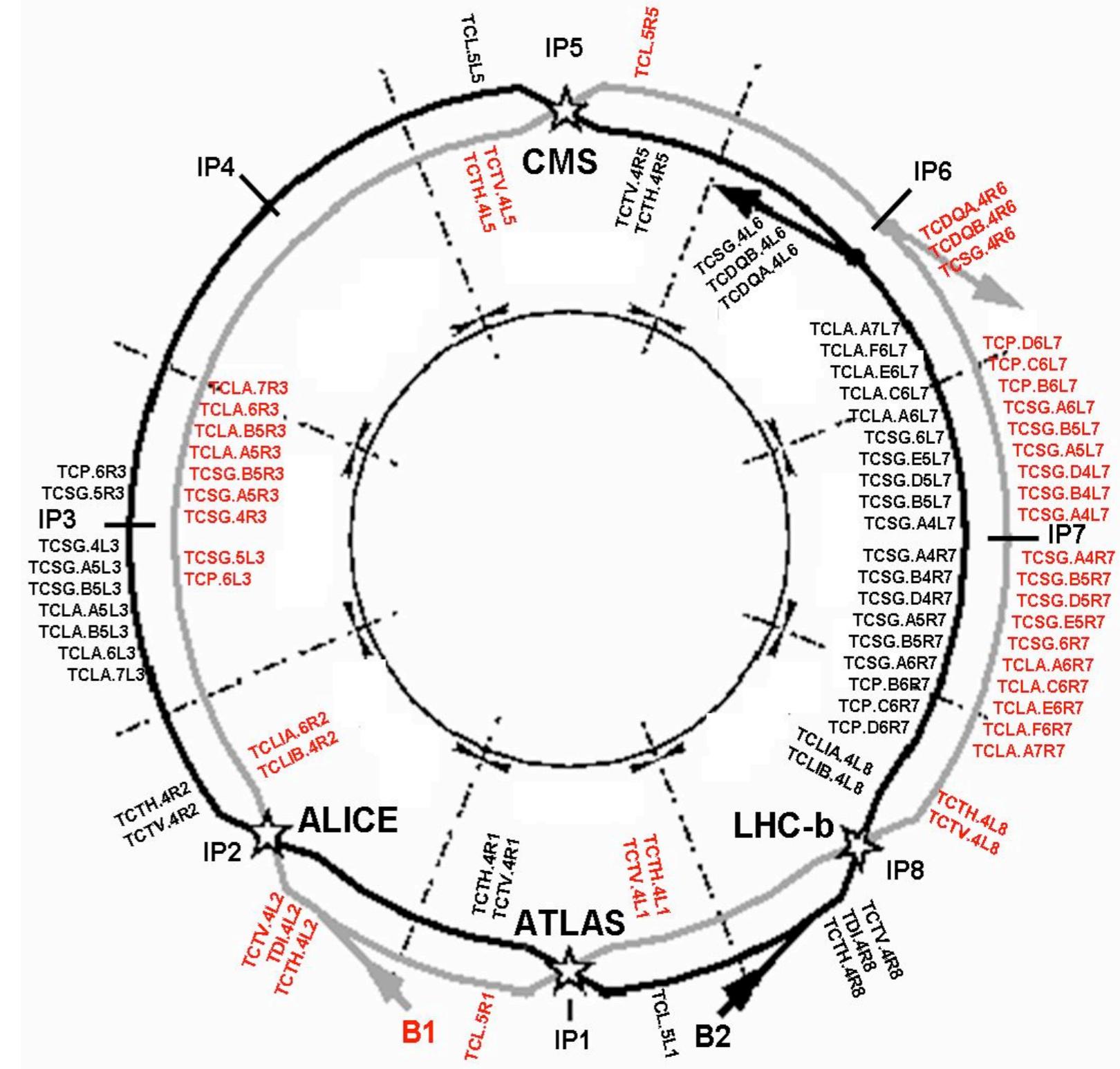
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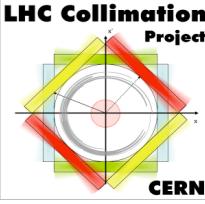
The 2008 collimation system



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Ring collimators:

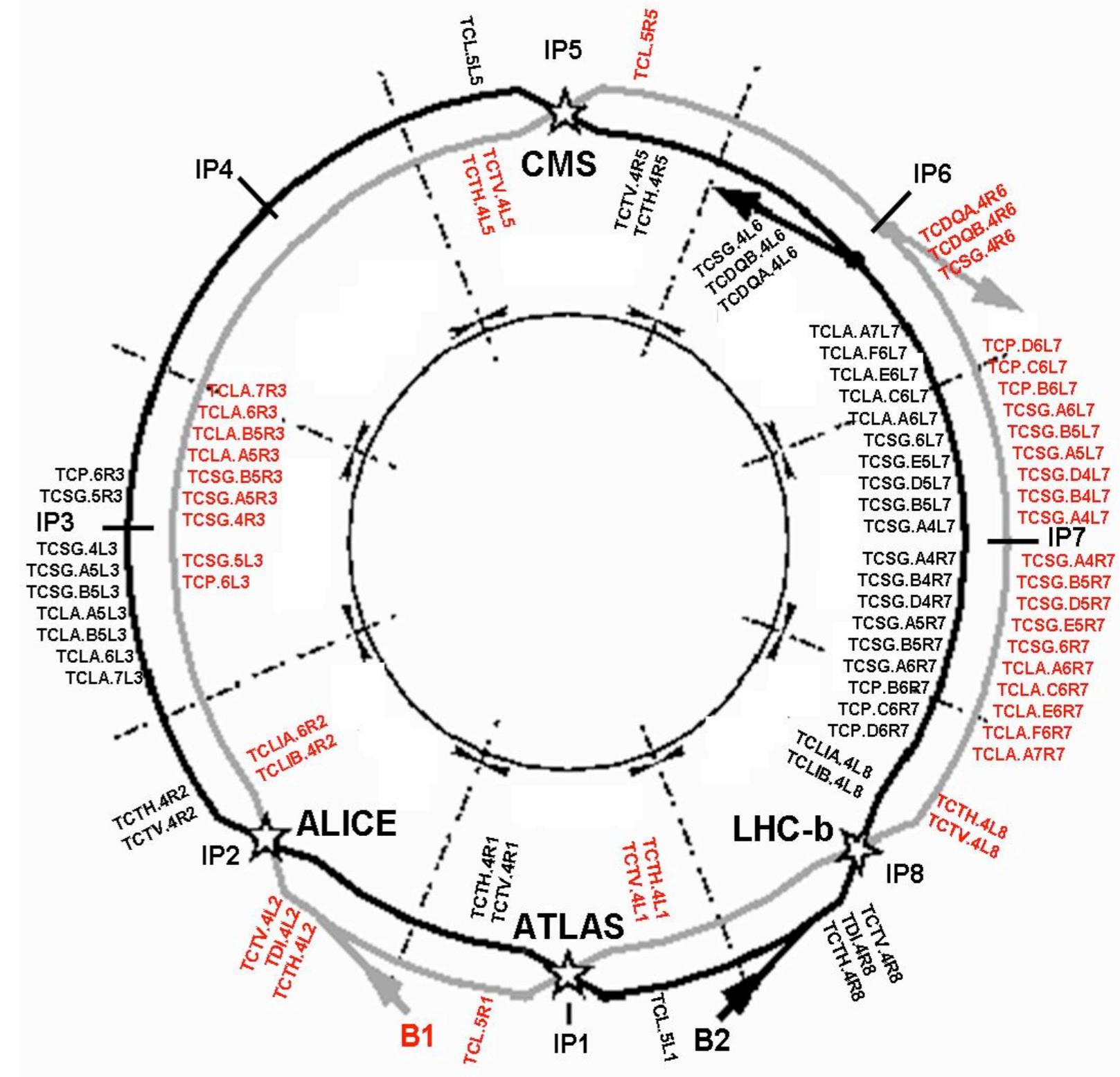




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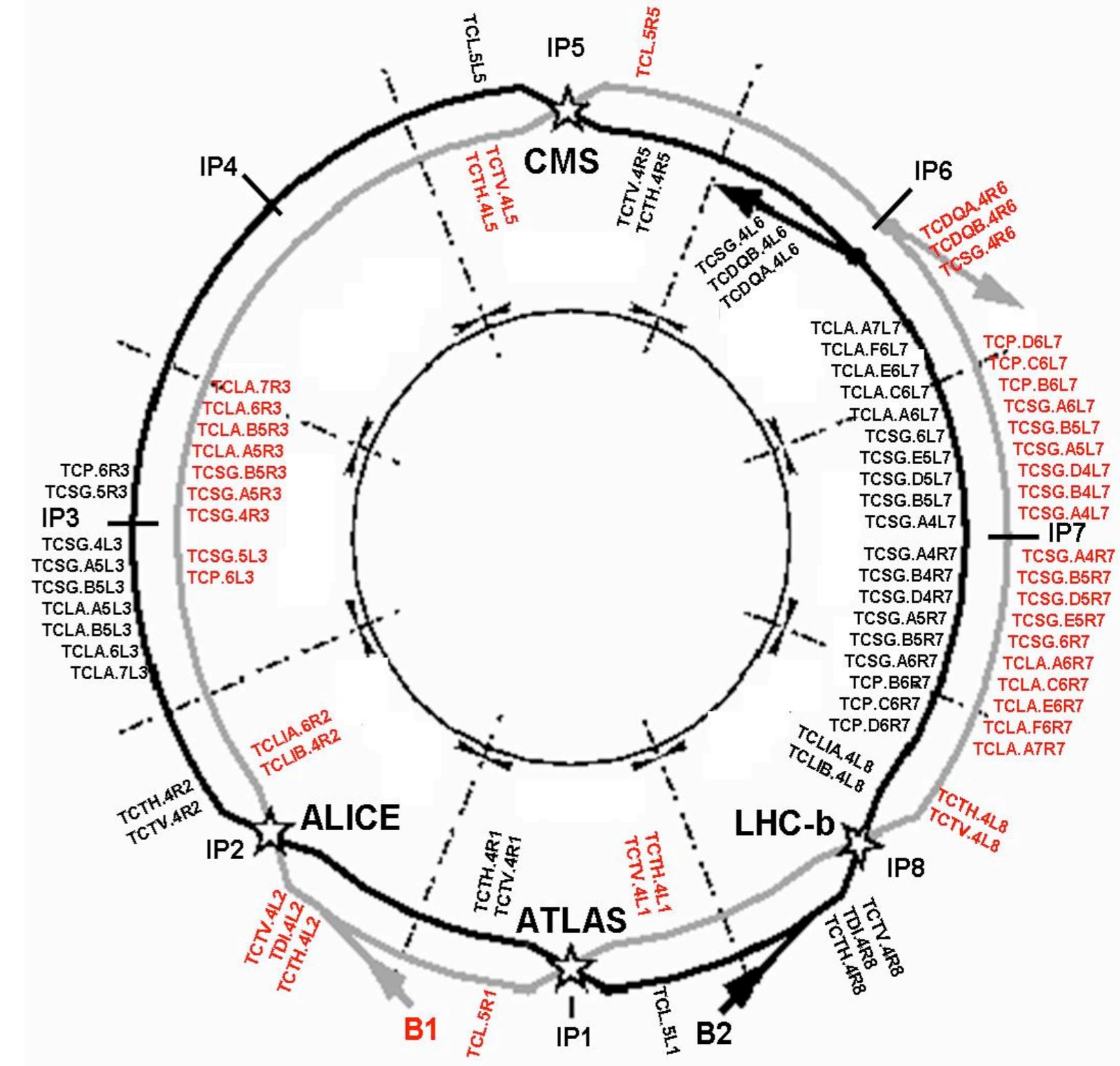
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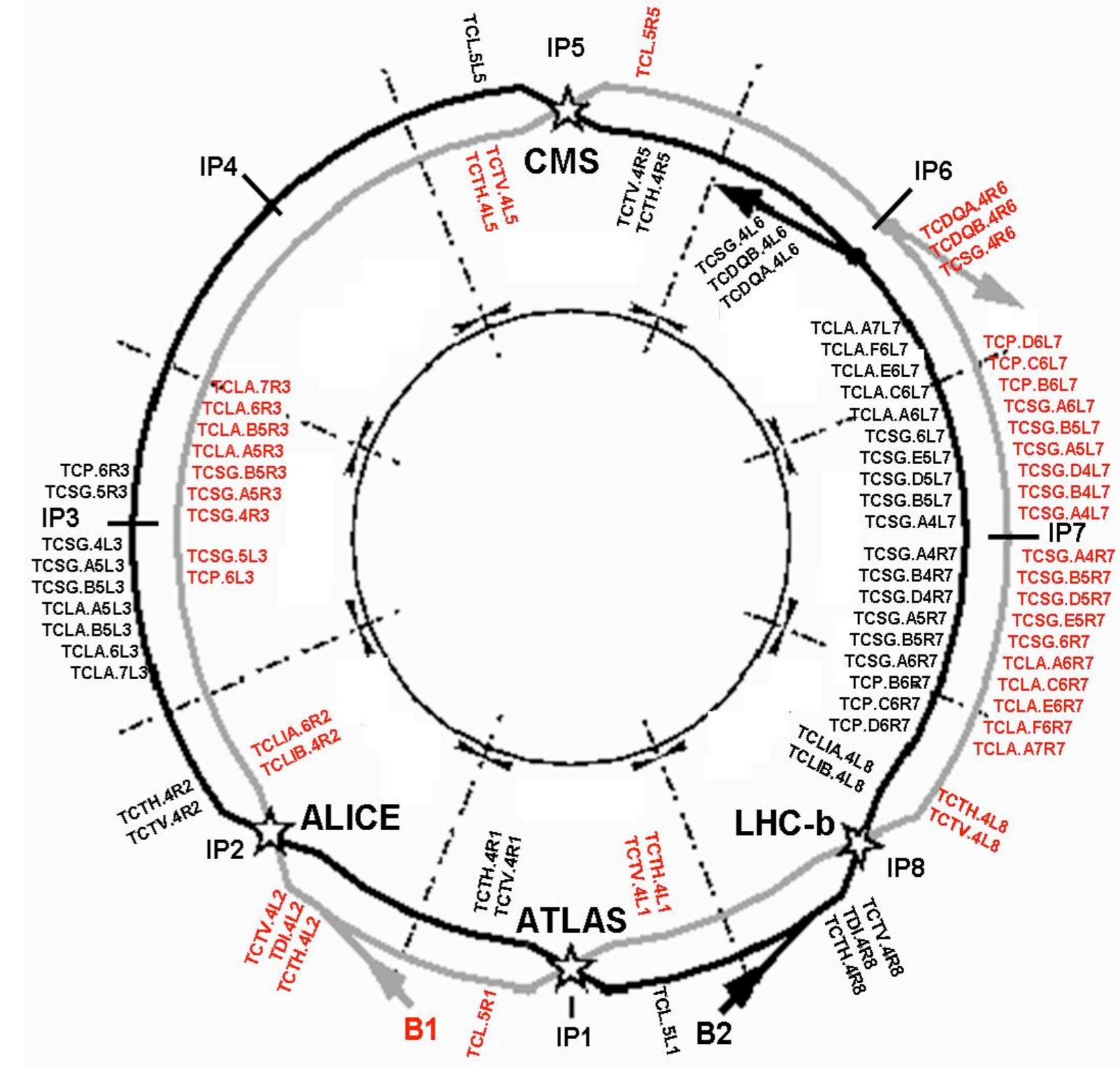
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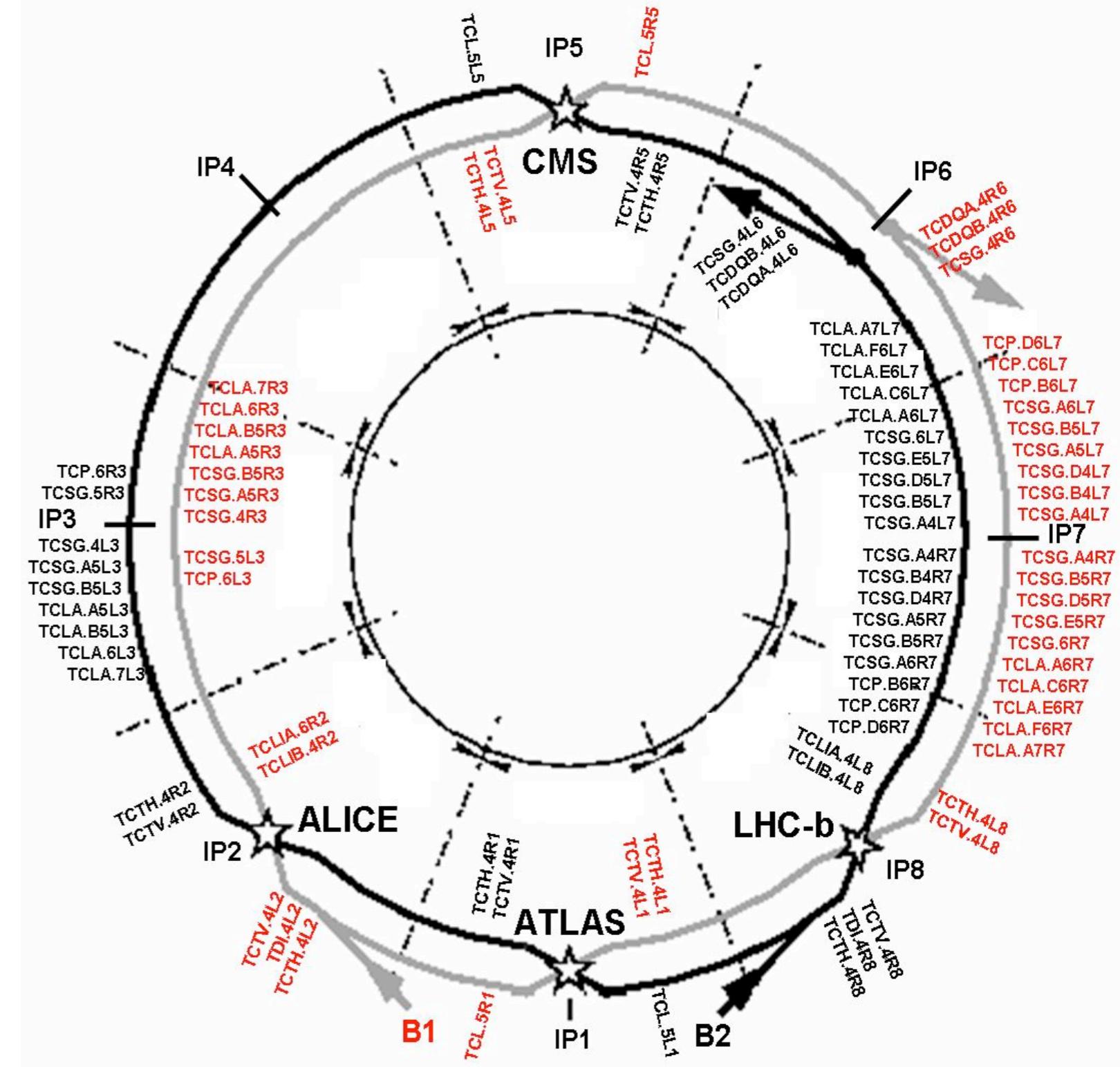


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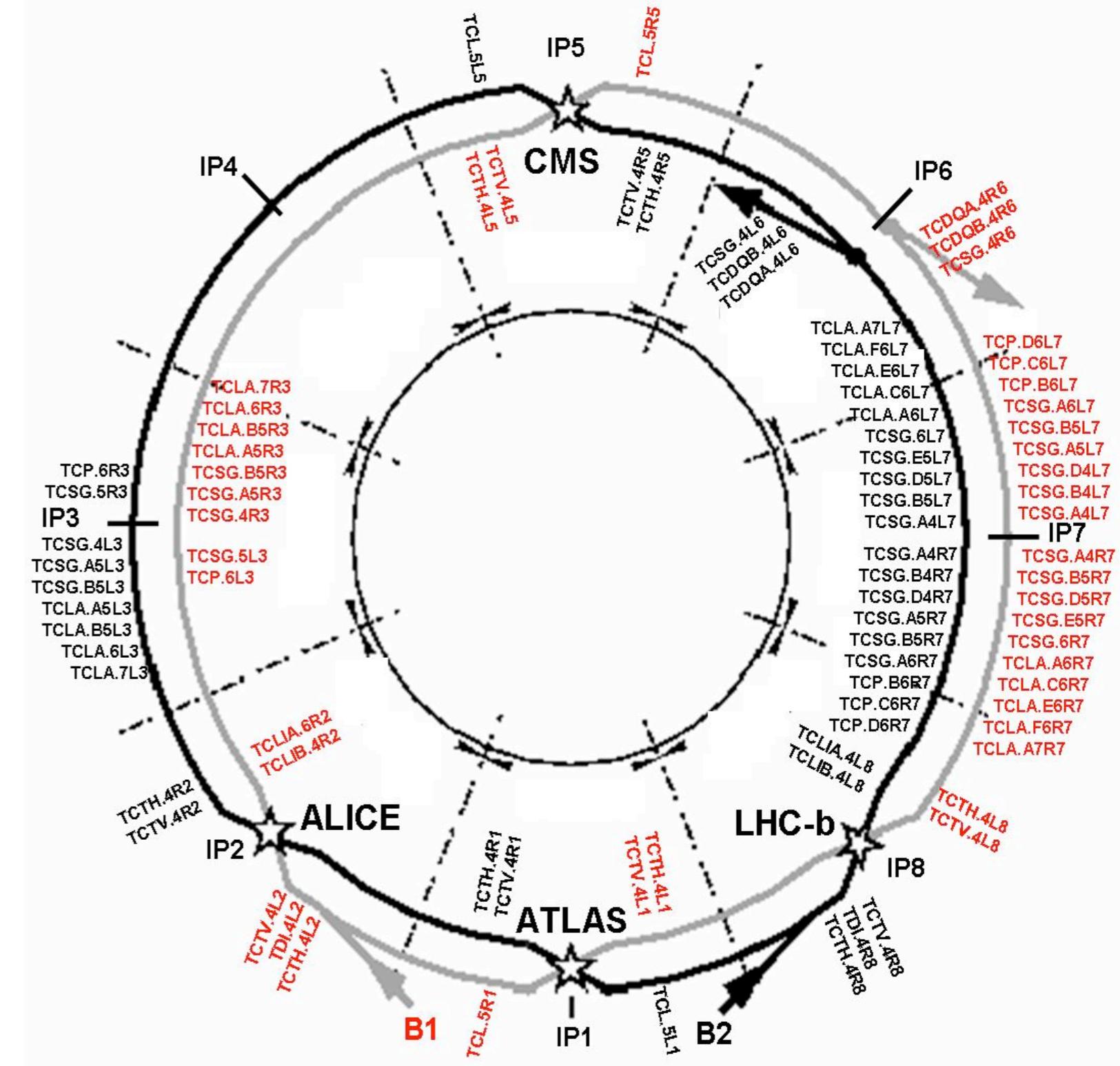
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Transfer lines:

- 13 TCDI's



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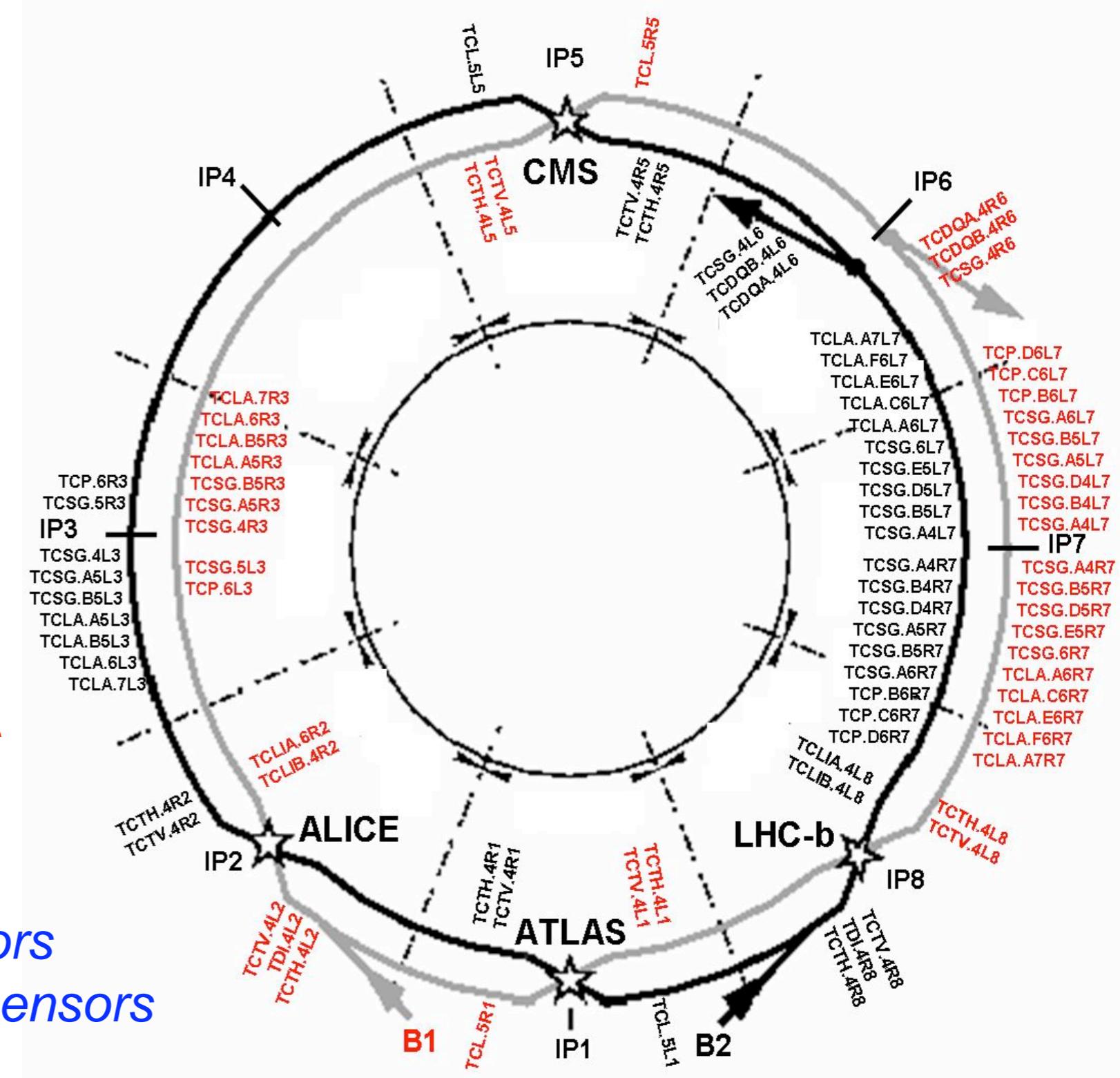
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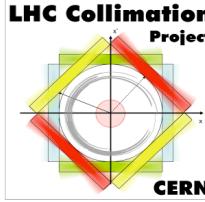
- 13 TCDI's

80 movable LHC collimators

for the 2008 system:

- 316 stepping motors
- 468 interlocked position sensors
- 403 interlocked temperature sensors
- 160 beam loss monitors for beam-based set-up





Outline

Introduction

Design/operational requirements

Recap. of collimator design

The 2008 system

Commissioning without beam

Synchronized energy ramps

Accuracy / reproducibility

Interlock commissioning

Experience with beam

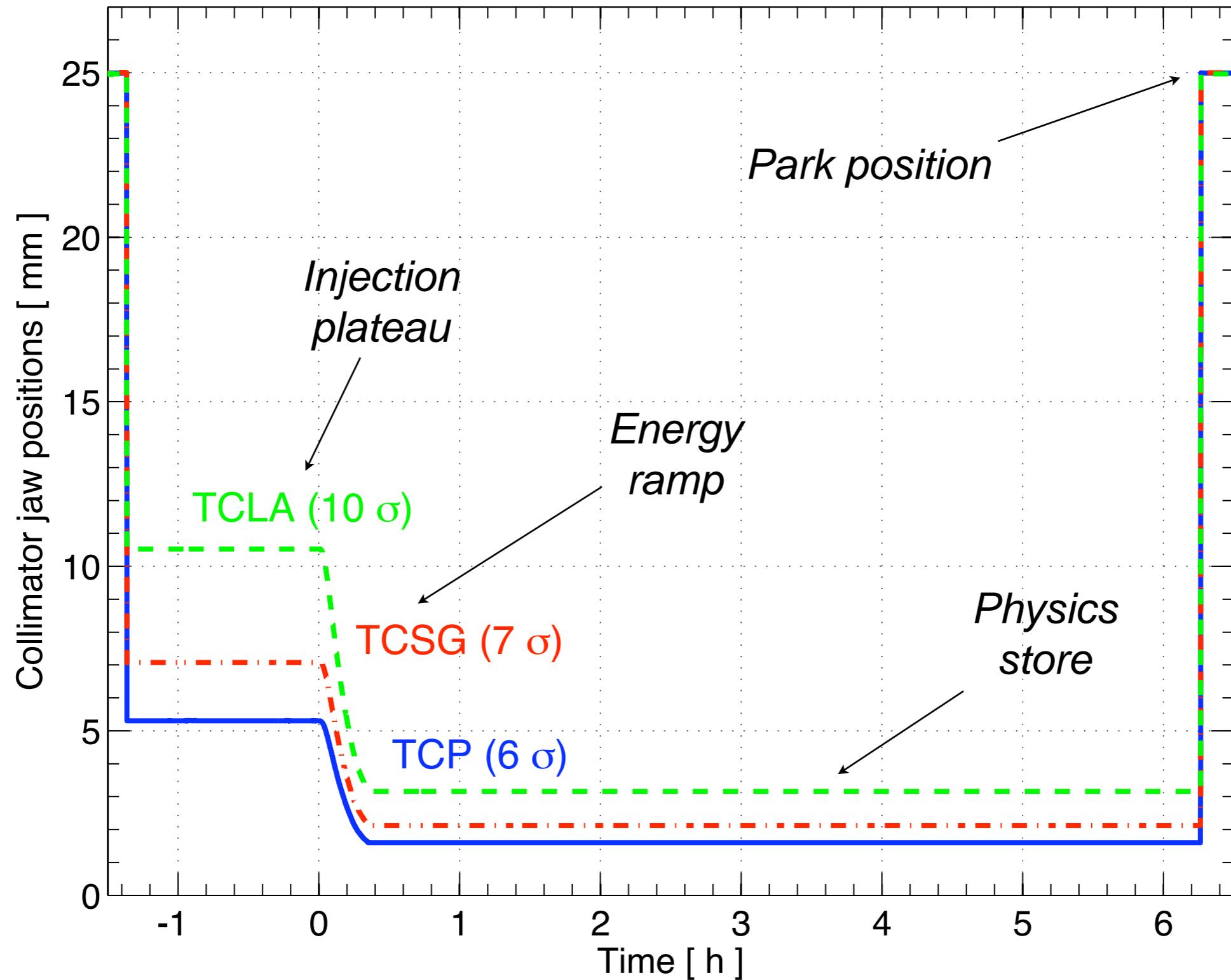
Transfer line commissioning

Operation of ring collimators

Conclusions

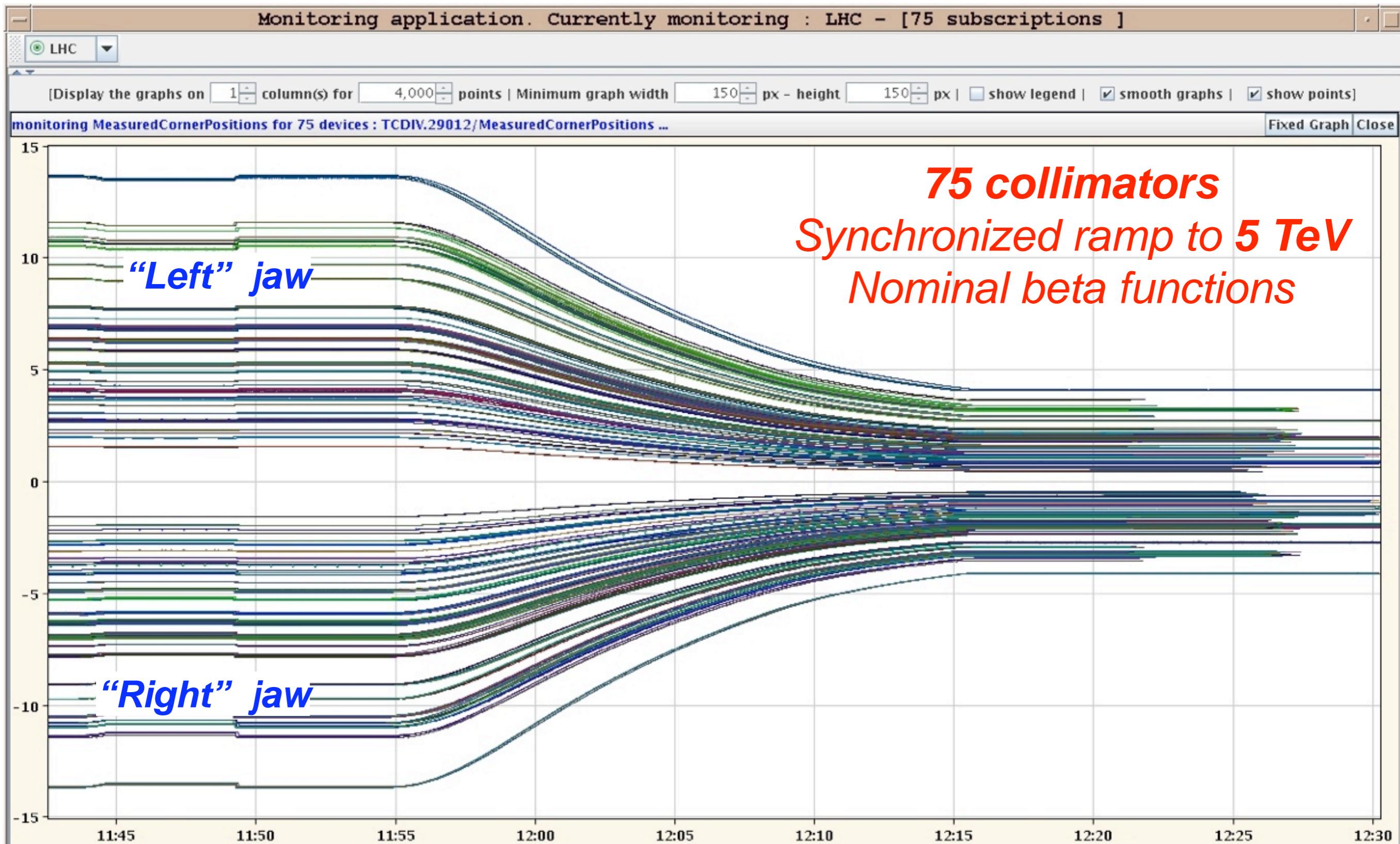
Collimator operational cycle

Measure jaw position (half gap) for three collimators in IP7



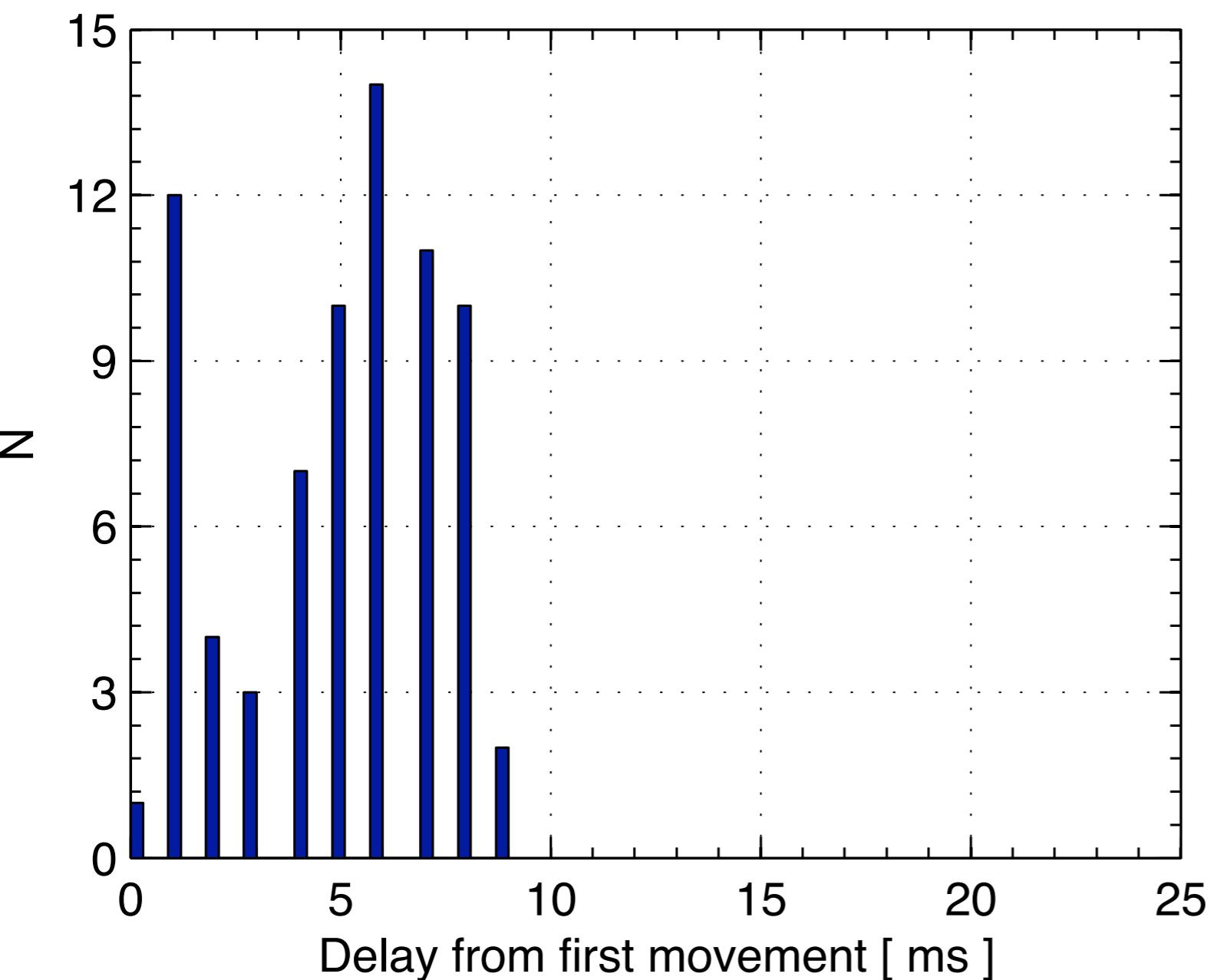
Synchronized ramp tests

Measured collimator jaw positions versus time



Synchronization of motion

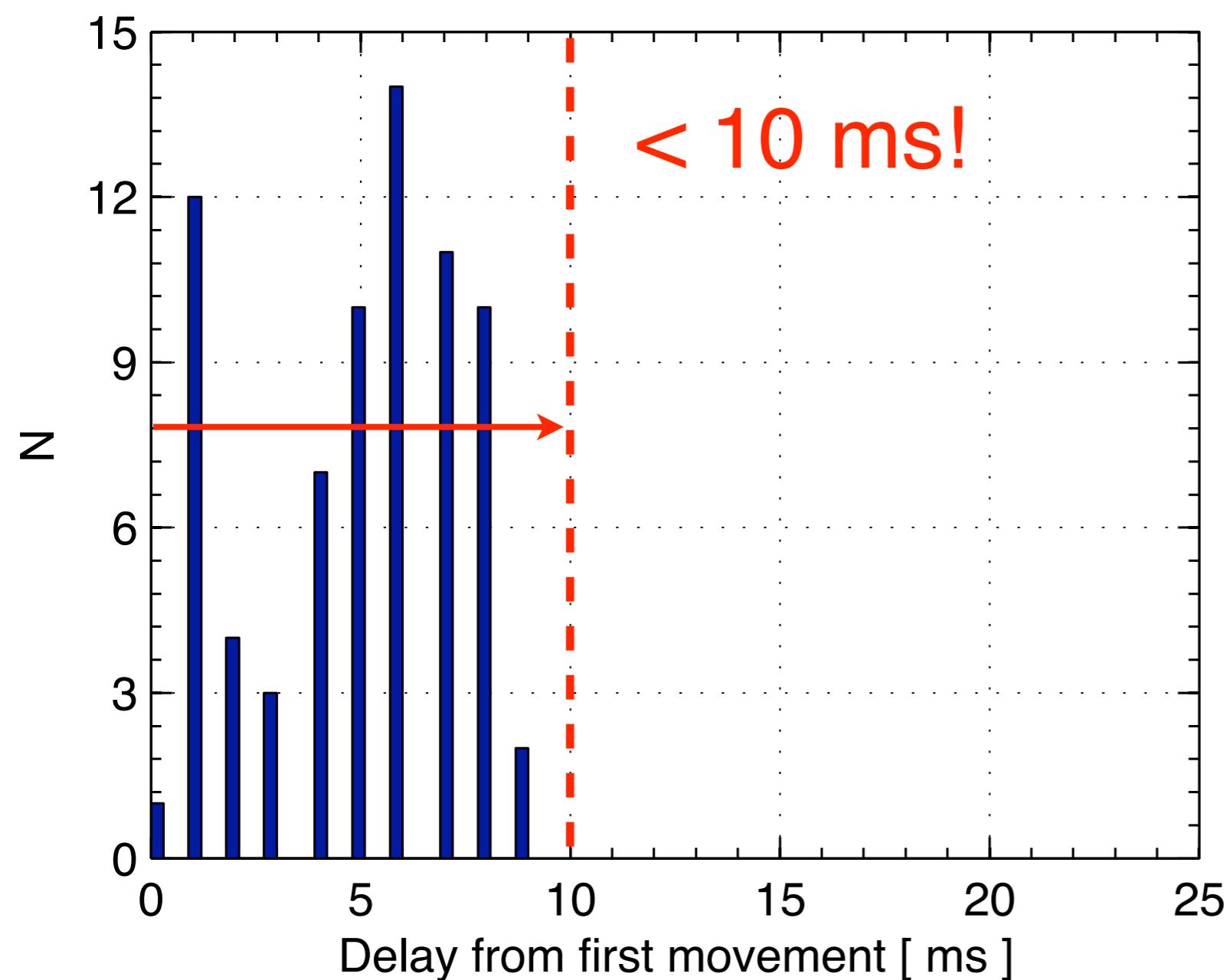
Distribution of starting times



74 collimators armed with ramp functions. Start of movements triggered by **hardware timing event**, distributed along the 27 km tunnel. Look at maximum **delay** after the first collimator starts moving.

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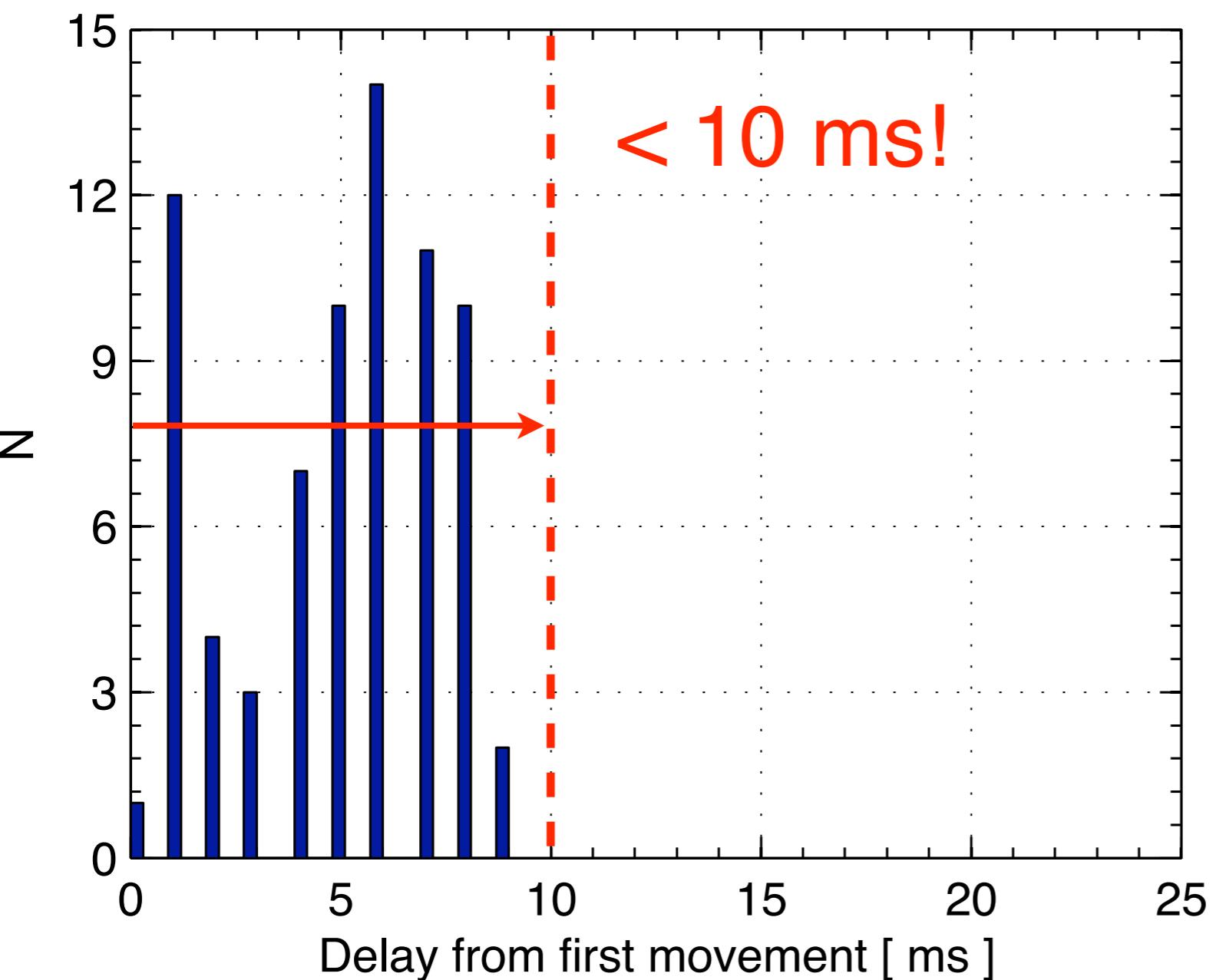
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74 **collimators** armed with ramp functions. Start of movements triggered by **hardware timing event**, distributed along the 27 km tunnel. Look at maximum **delay** after the first collimator starts moving.

Beam requirements: **< 20 ms**

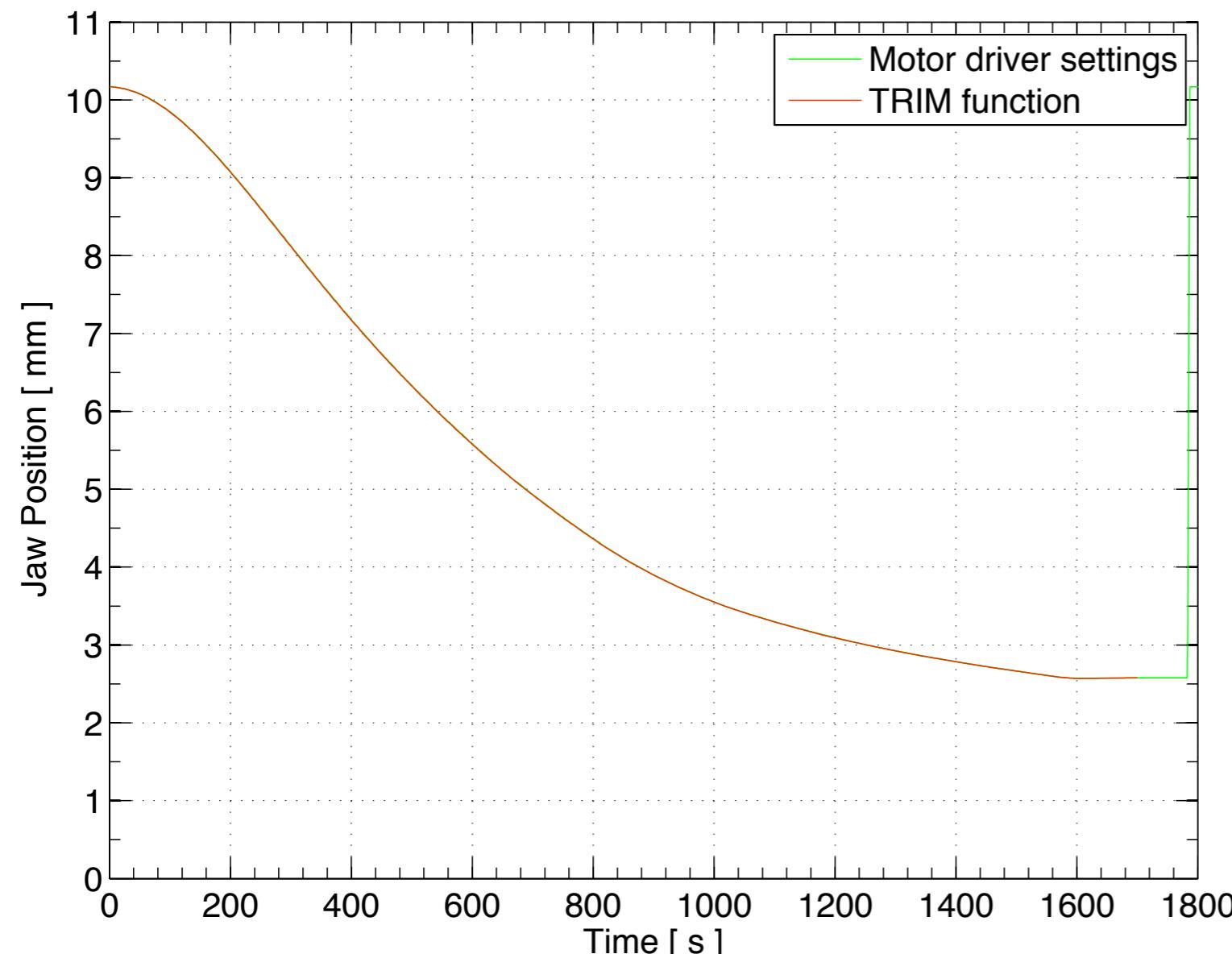
Achieved < 10 ms!

HW can do 100 times better (<1 ms), observed delays are determined by the read-back form the middle-ware.

Ongoing: synchronization with other accelerator systems (e.g., power converters, RF). No issue expected.

Accuracy of function execution

Requested/executed settings vs. time

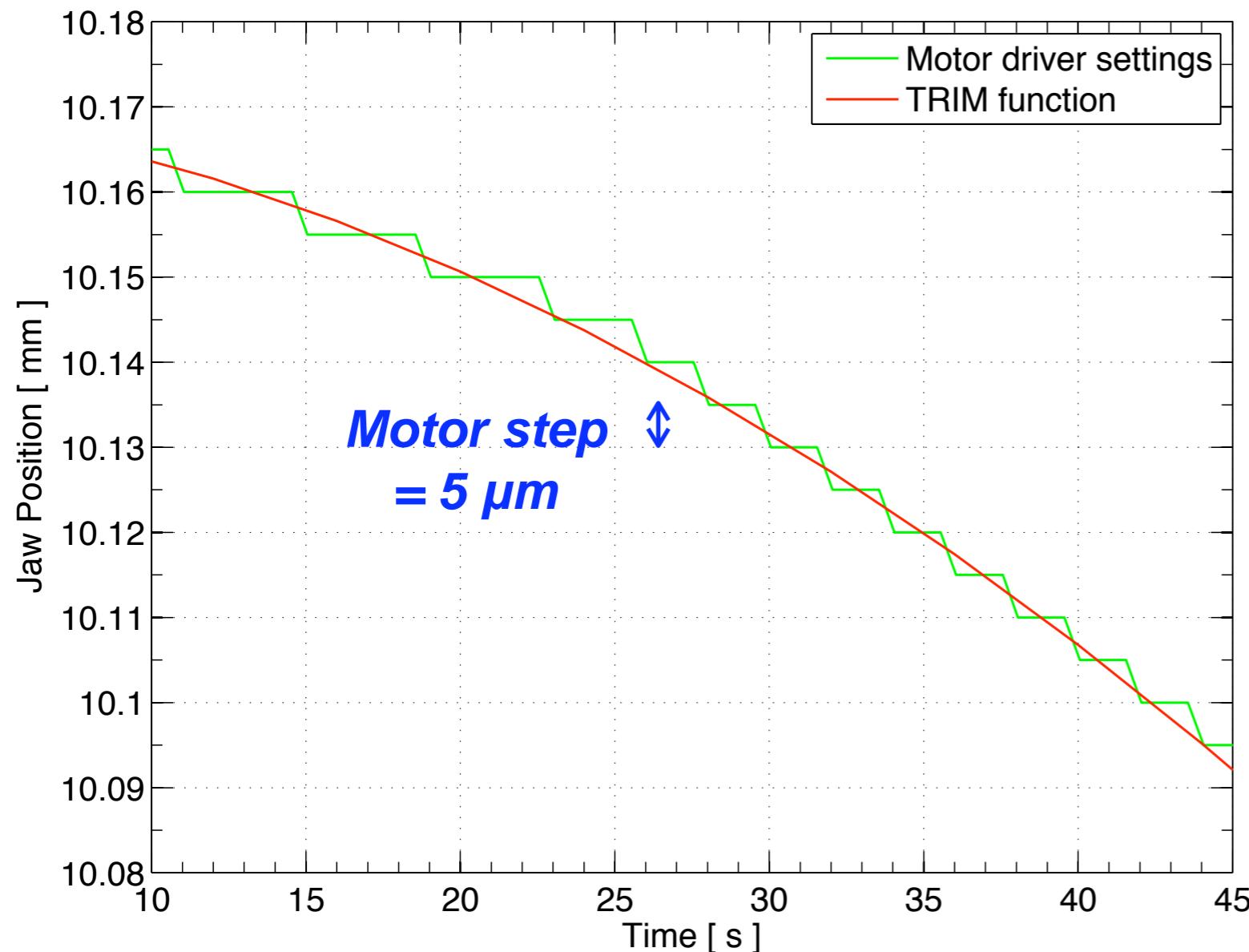


- Motor step = **5 μm**
- Operational motor speed = **2 mm/s**
- “Slow” functions are interpolated with the appropriate rate of step execution

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

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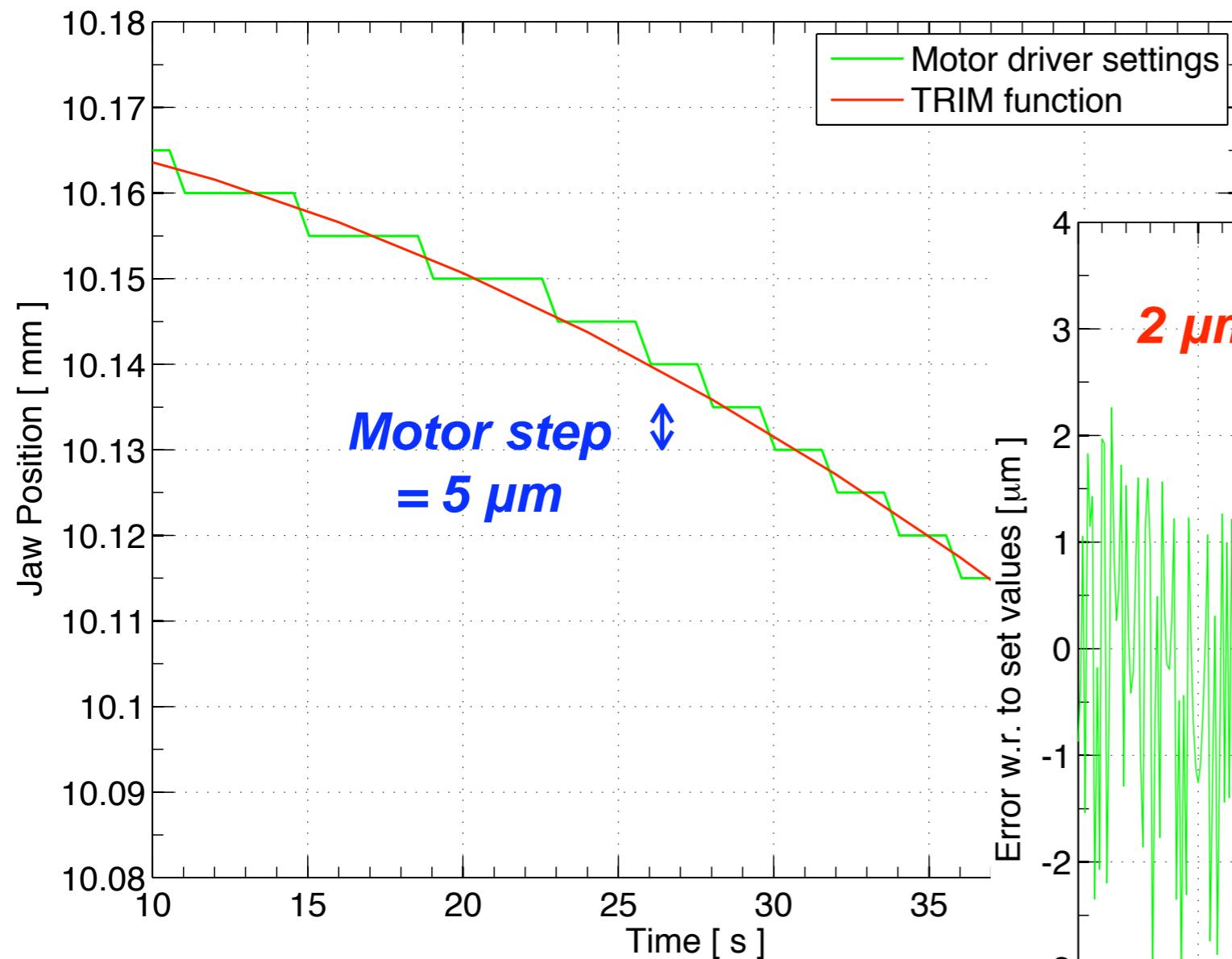


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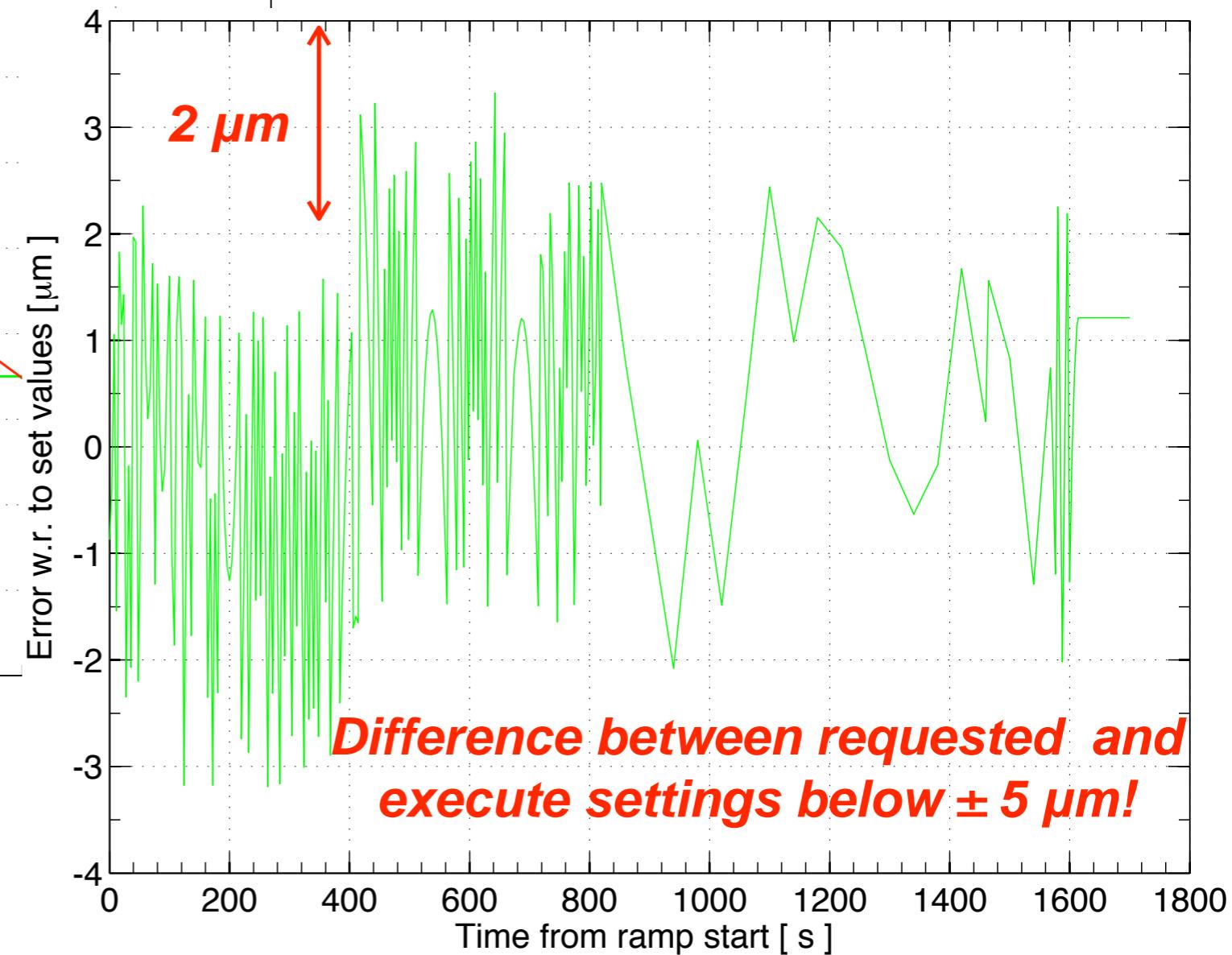
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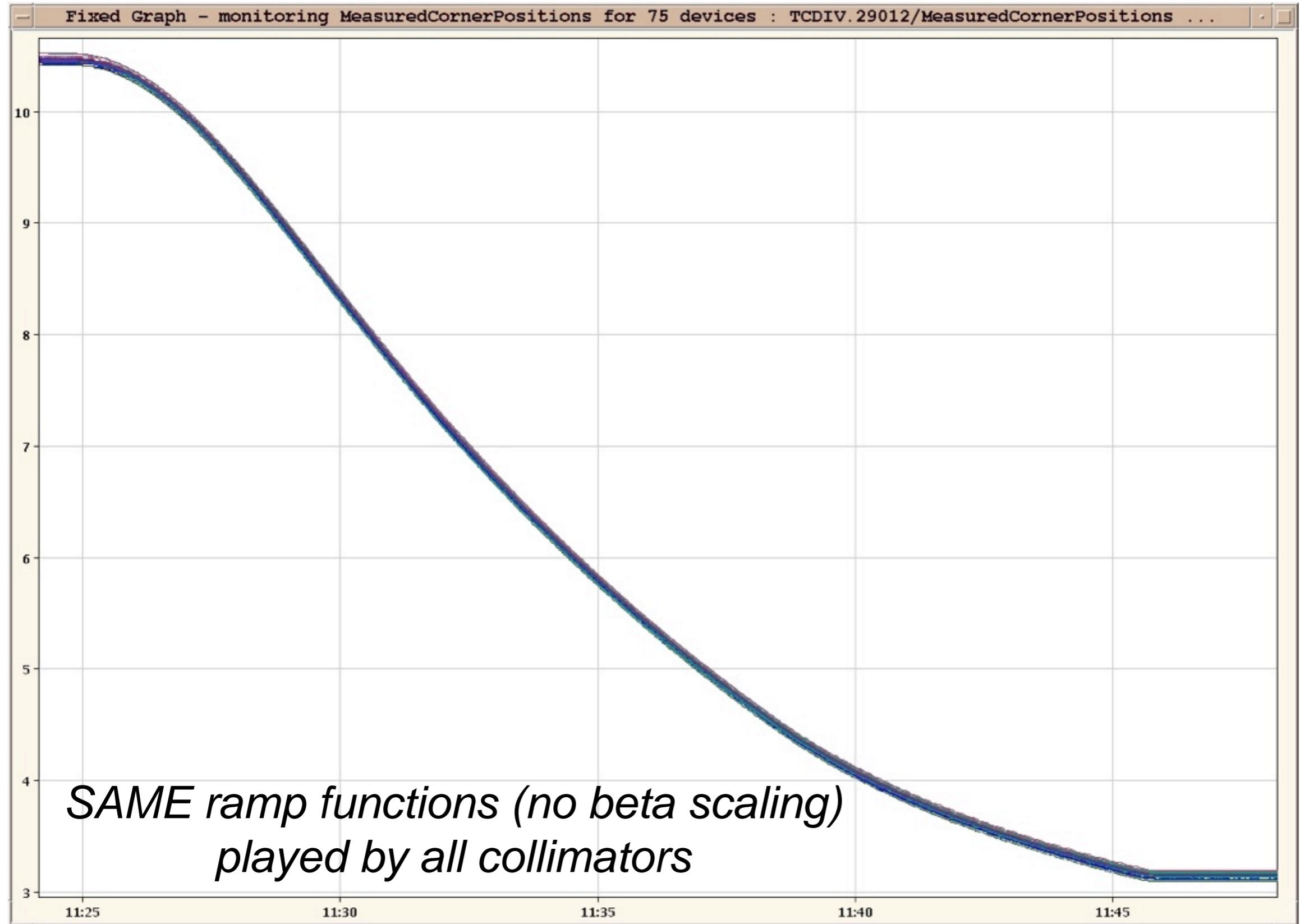
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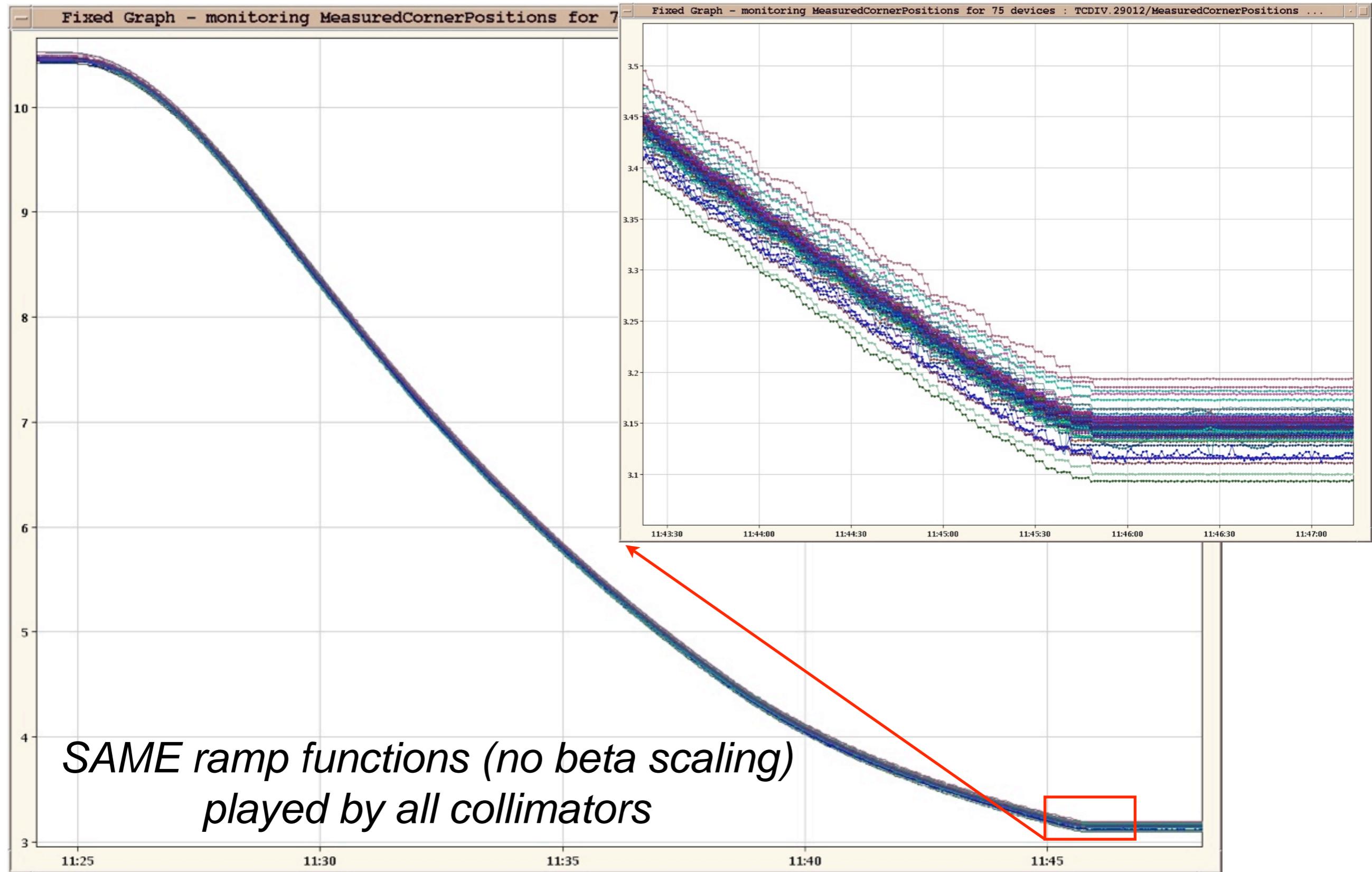
Synchronized ramp tests

Position of one collimator axis versus time



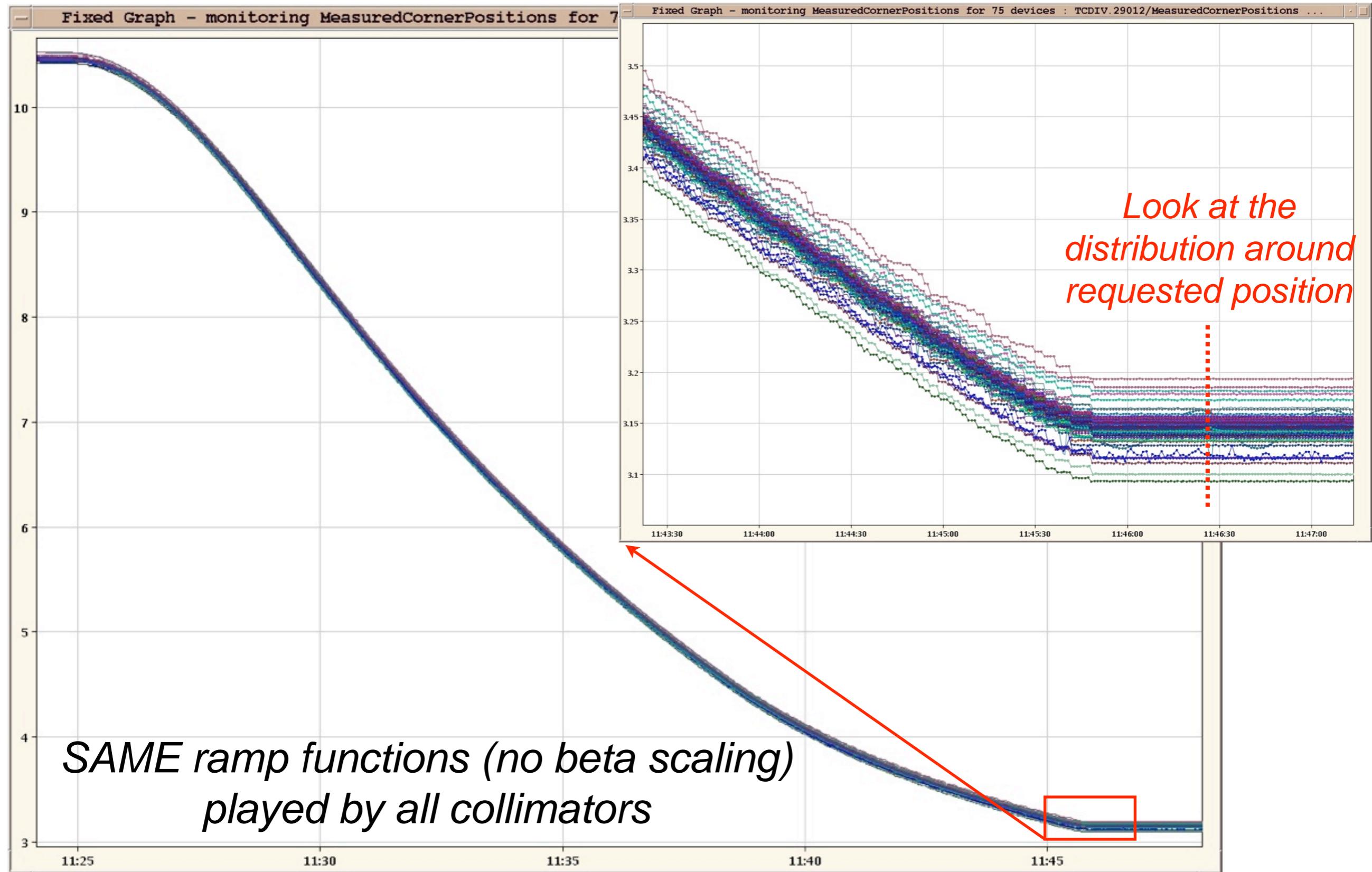
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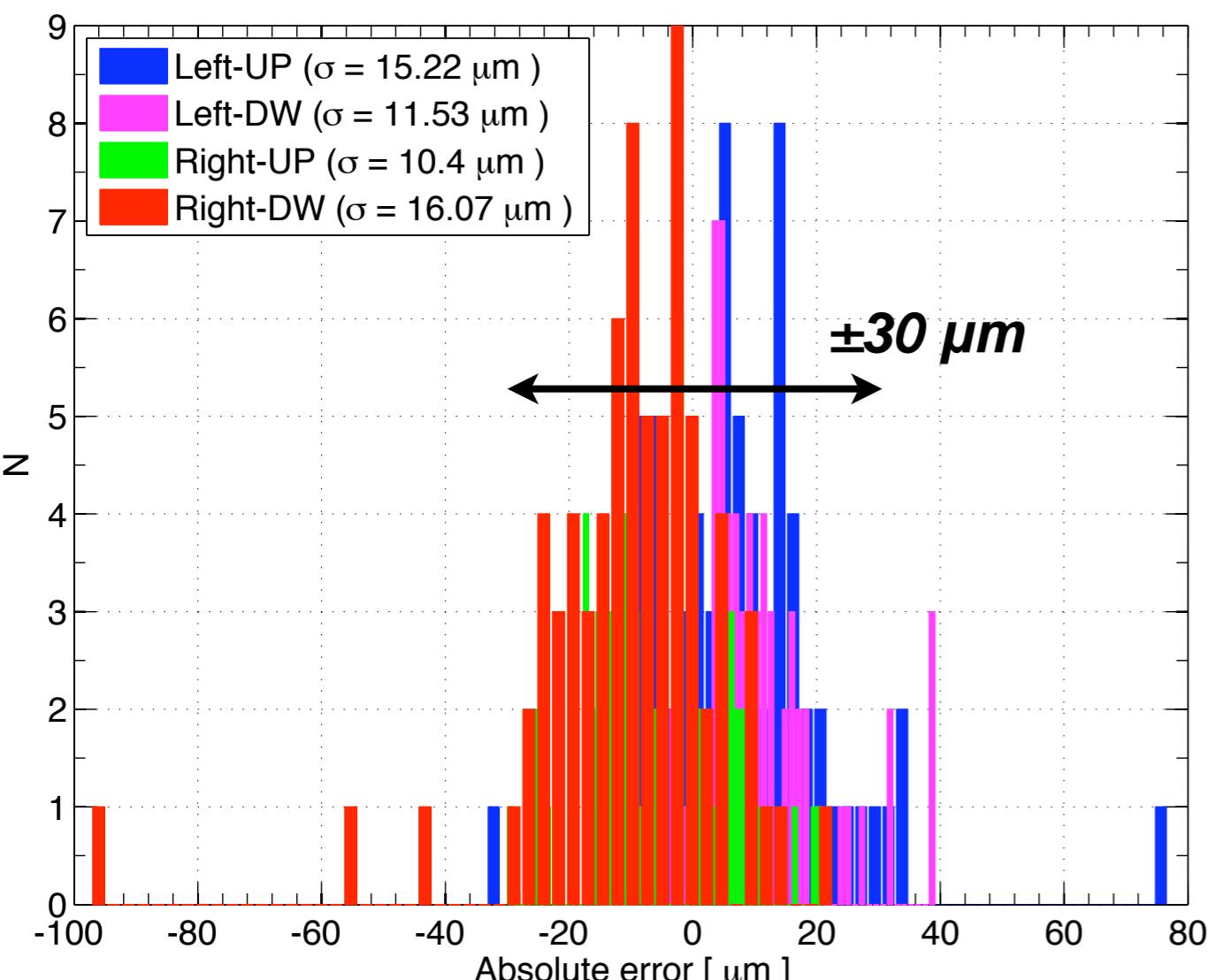
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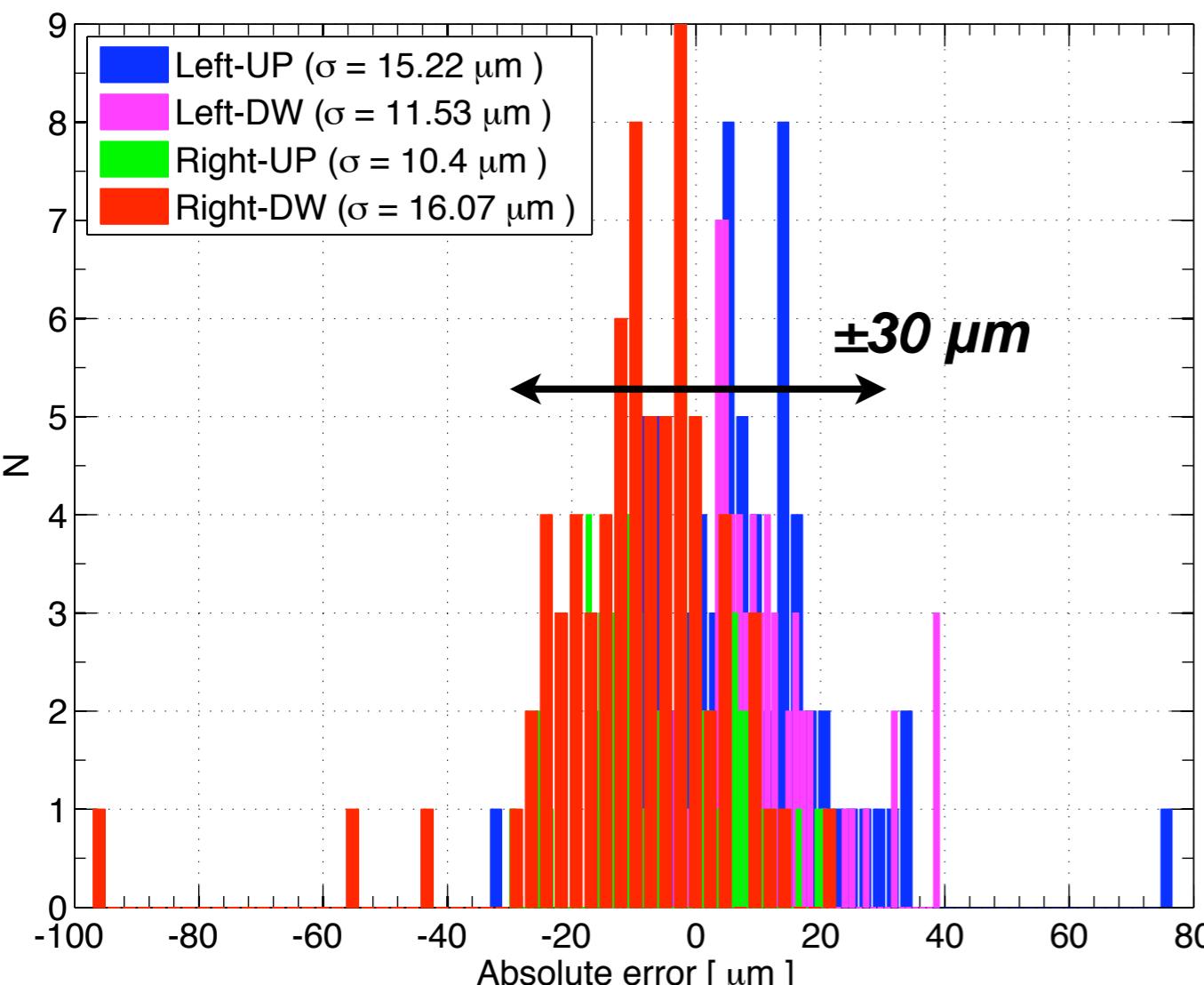
Distribution of errors (end of ramp)

Motor axes (300 sensors)

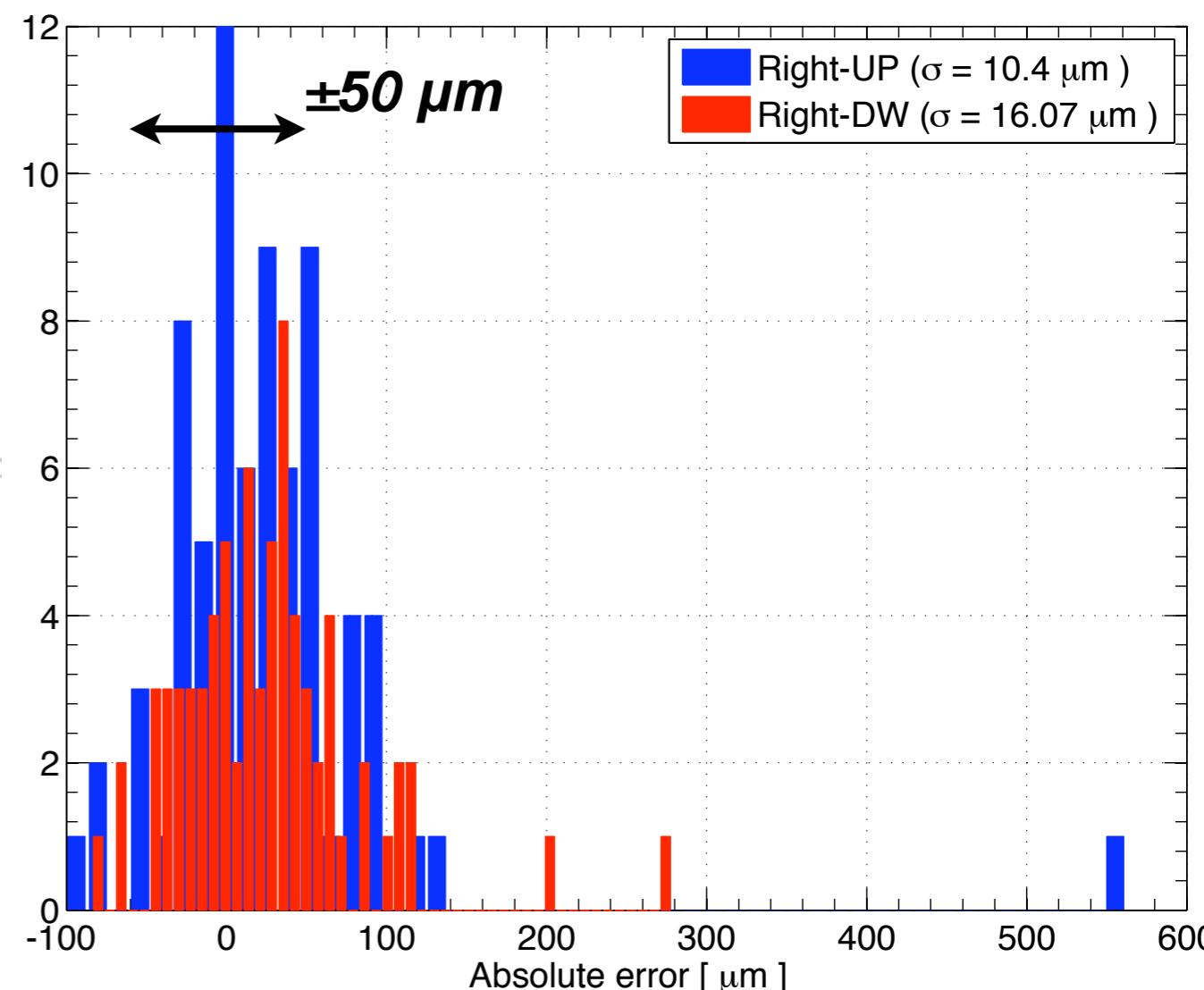


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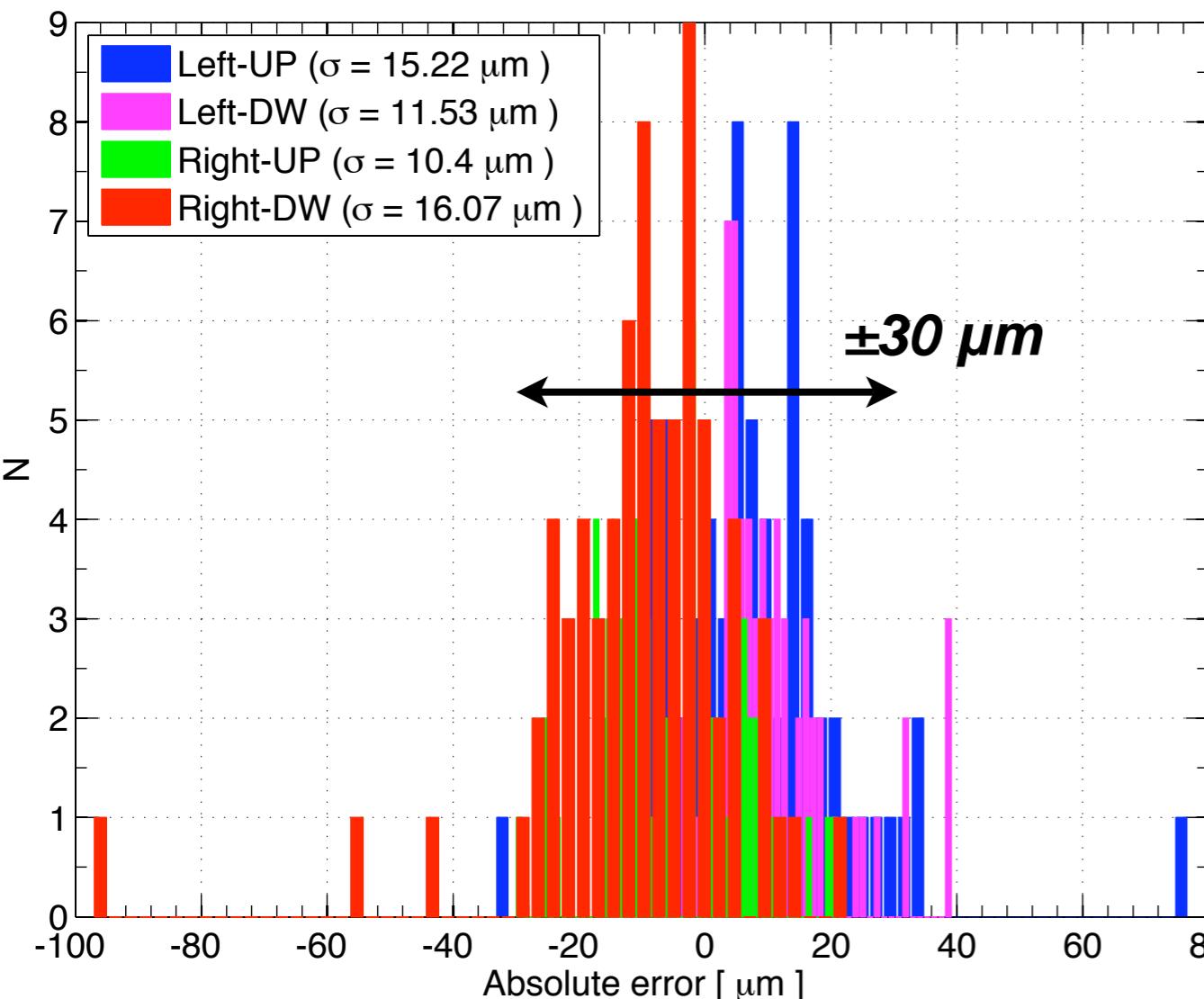


Gap measurements (150 sensors)

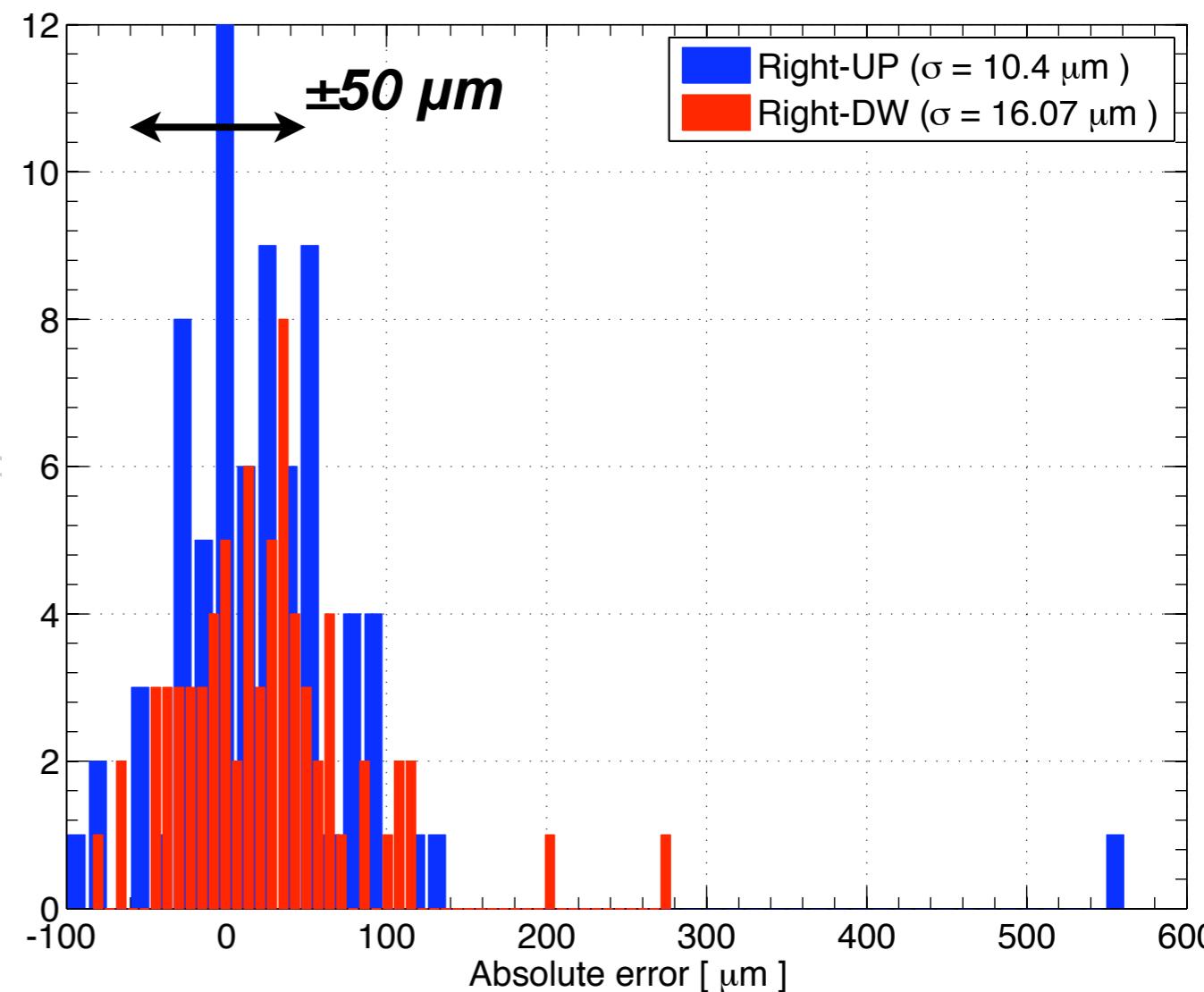


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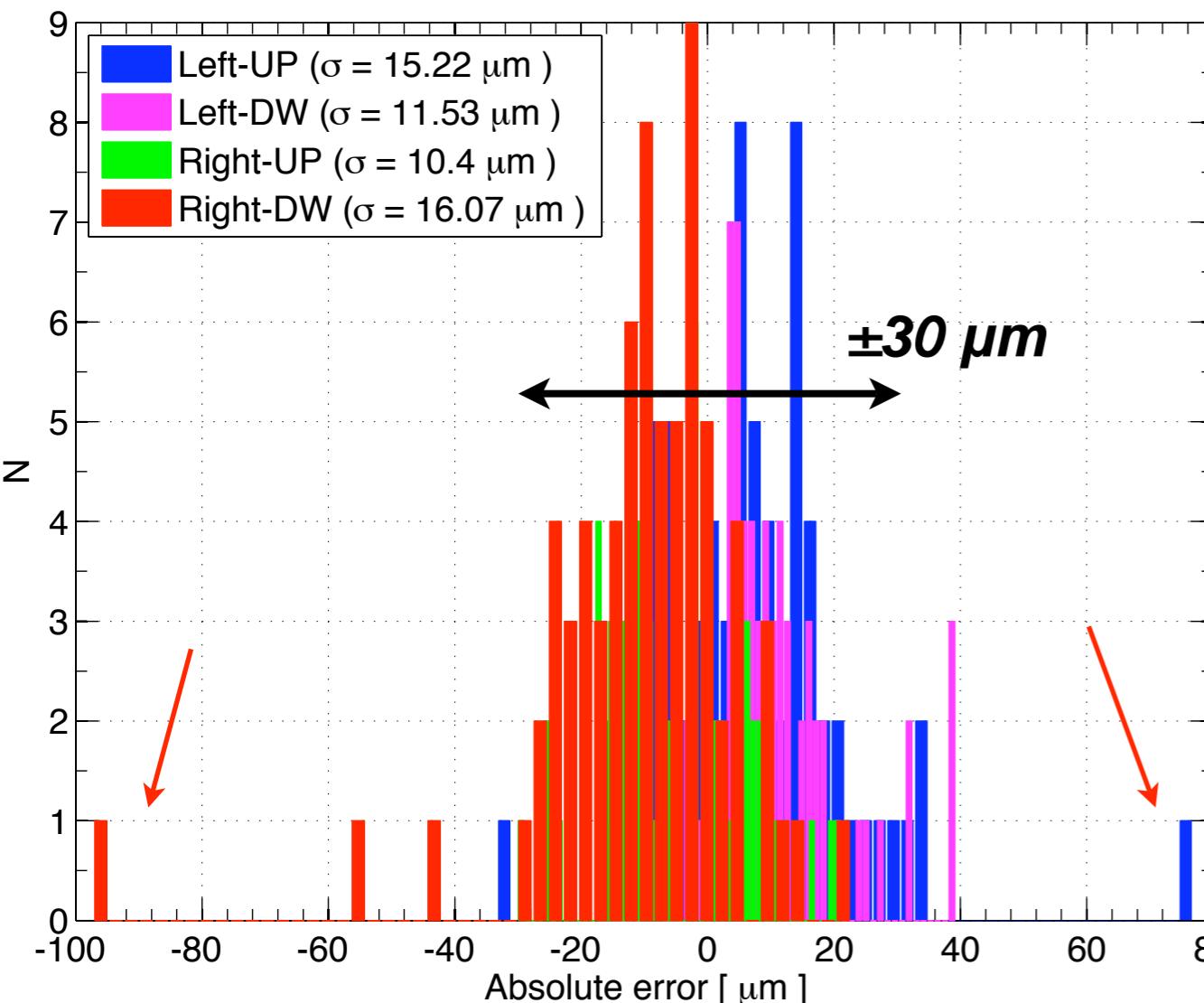
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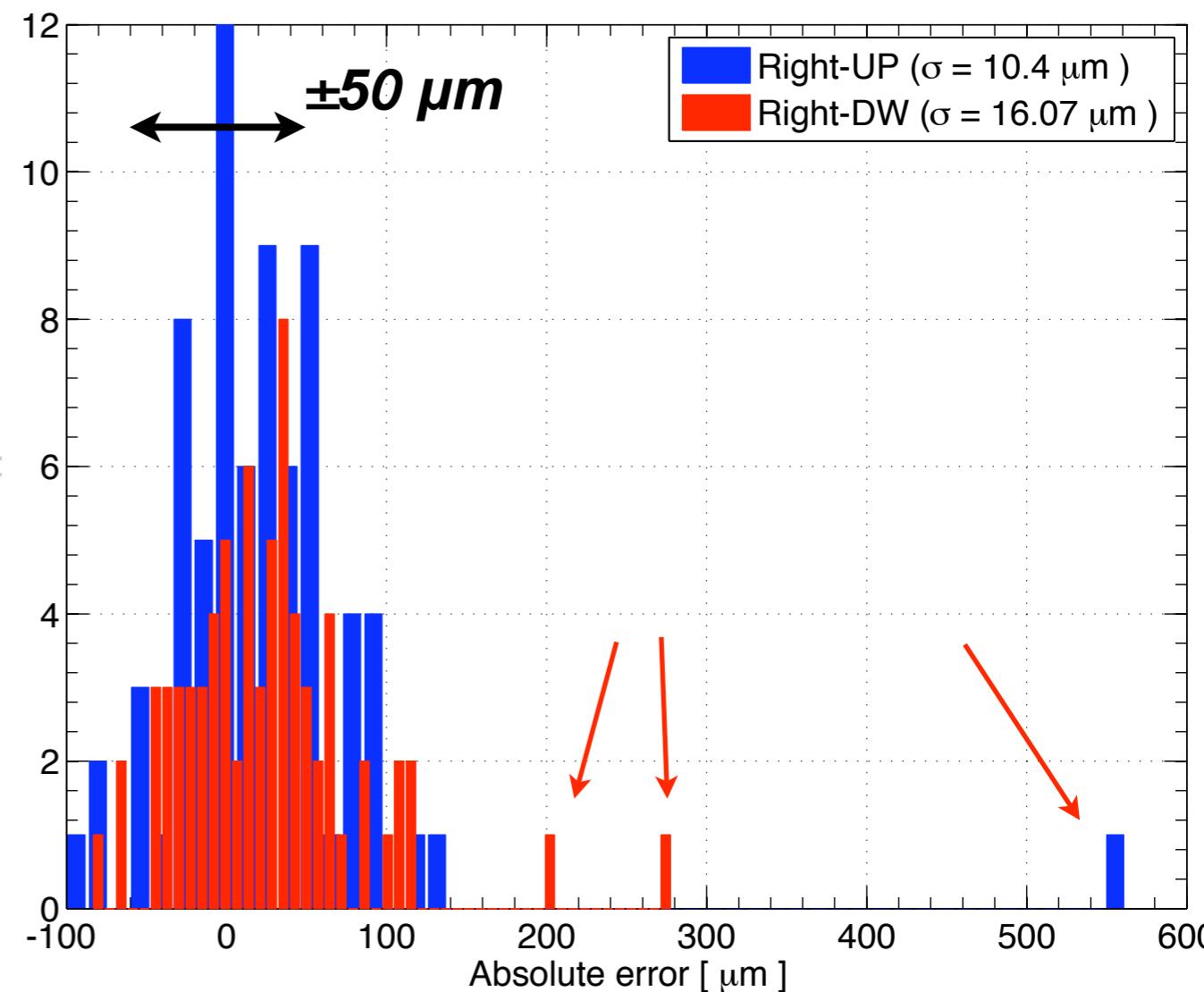
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- A few “bad guys” that need re-calibration (or possibly replacement)
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- Errors stay mainly CONSTANT during function execution: **REPRODUCIBILITY** will determine the system performance!

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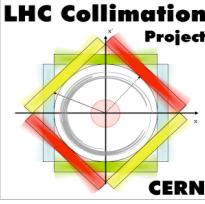
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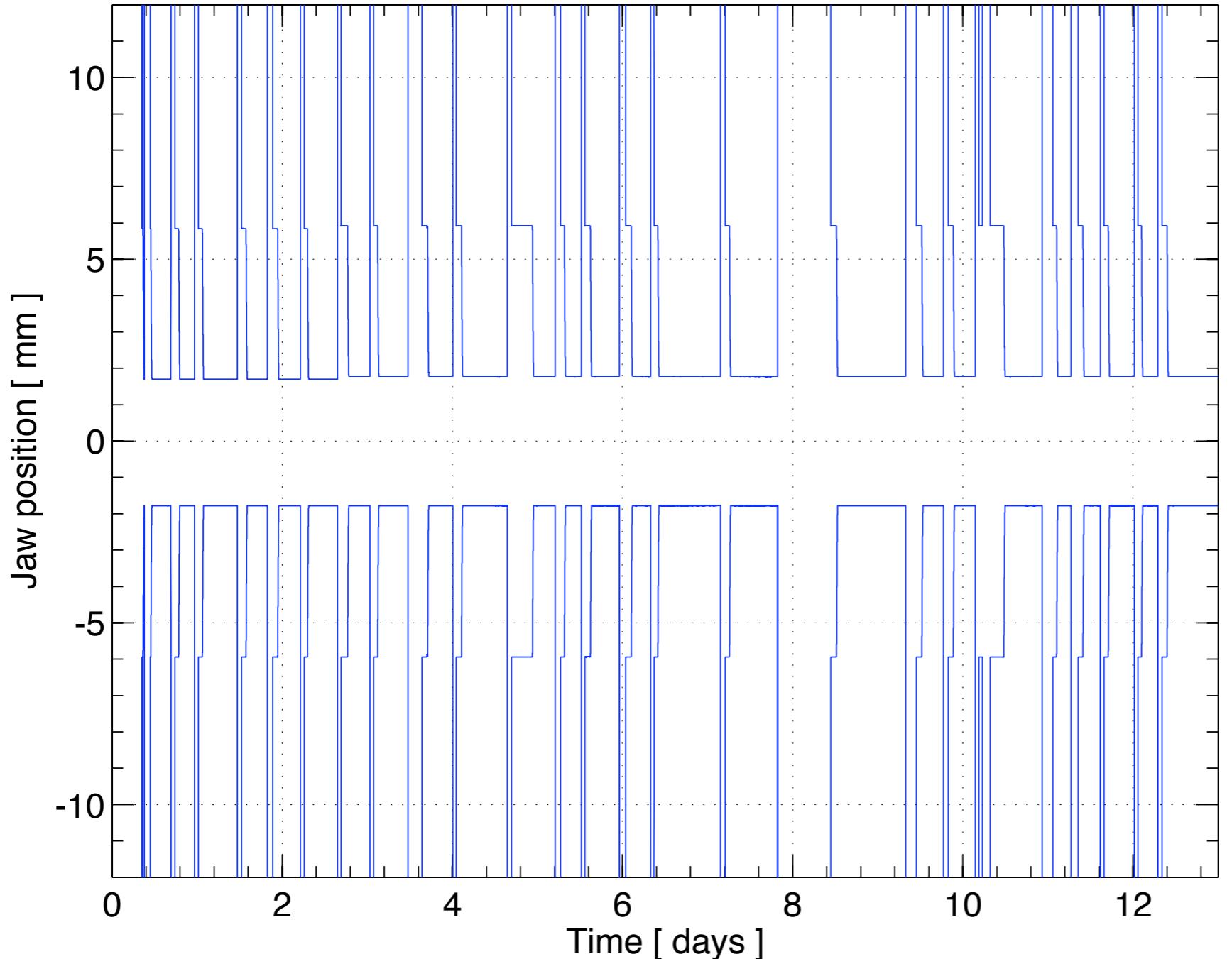
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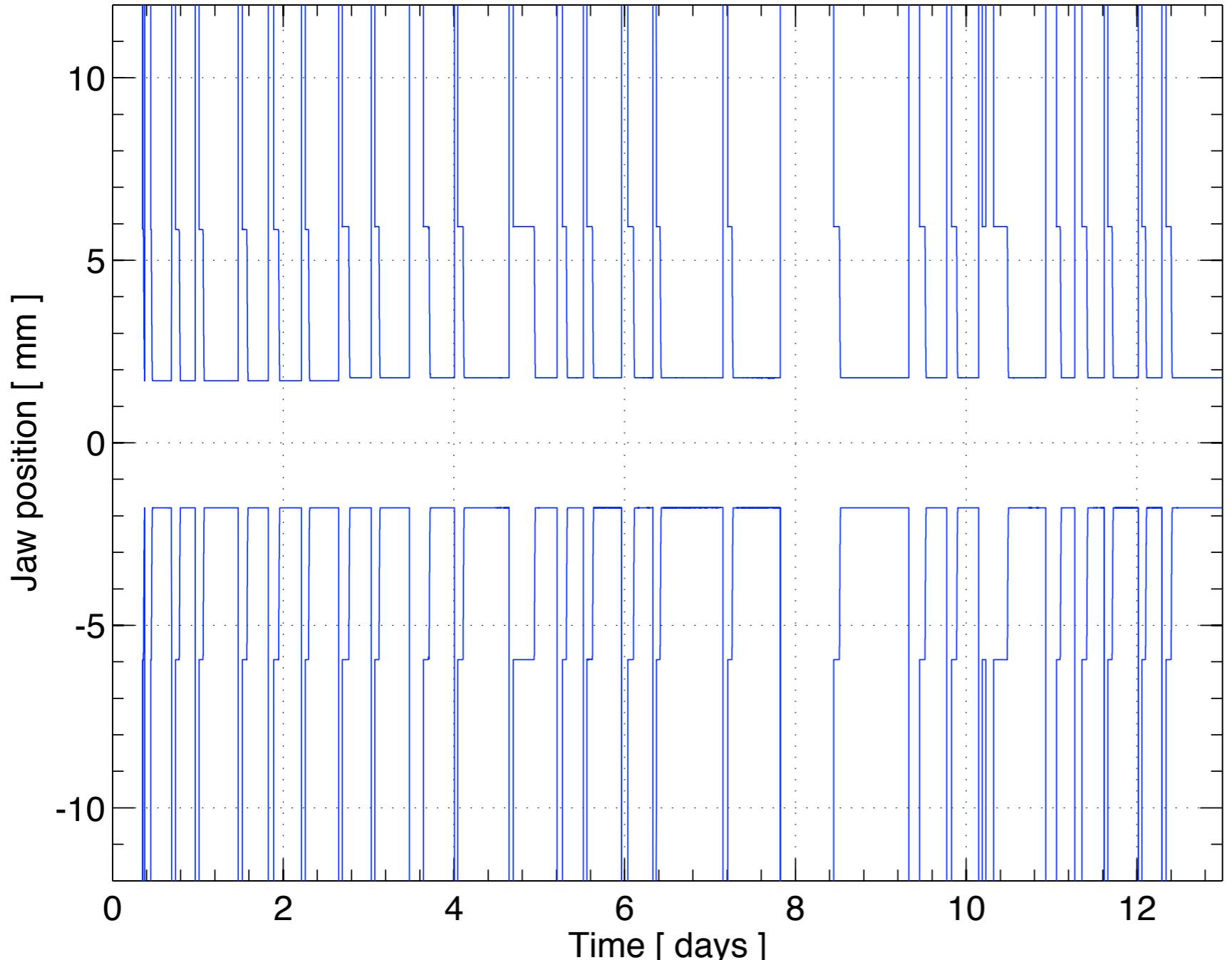
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Reproducibility tests

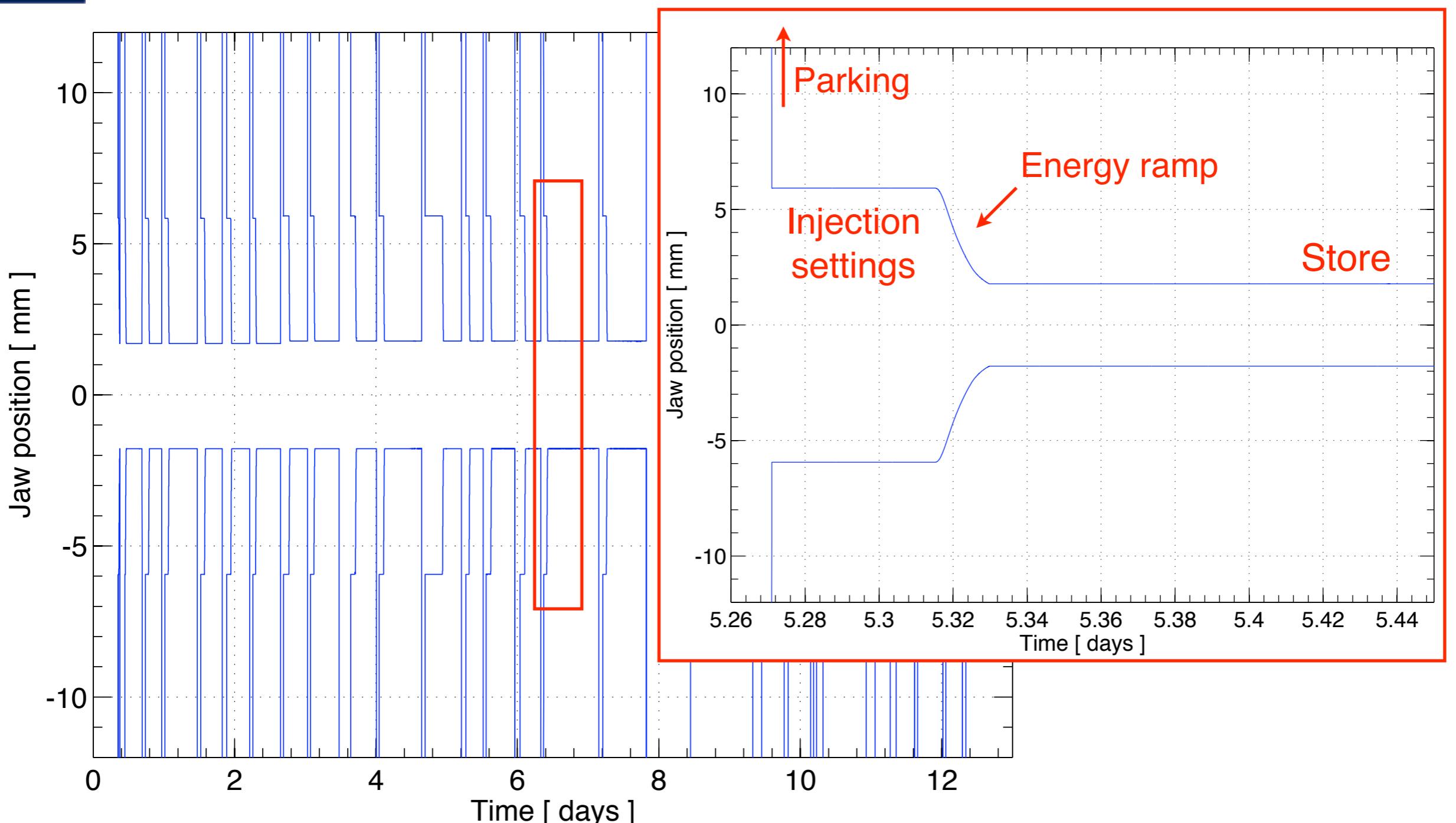


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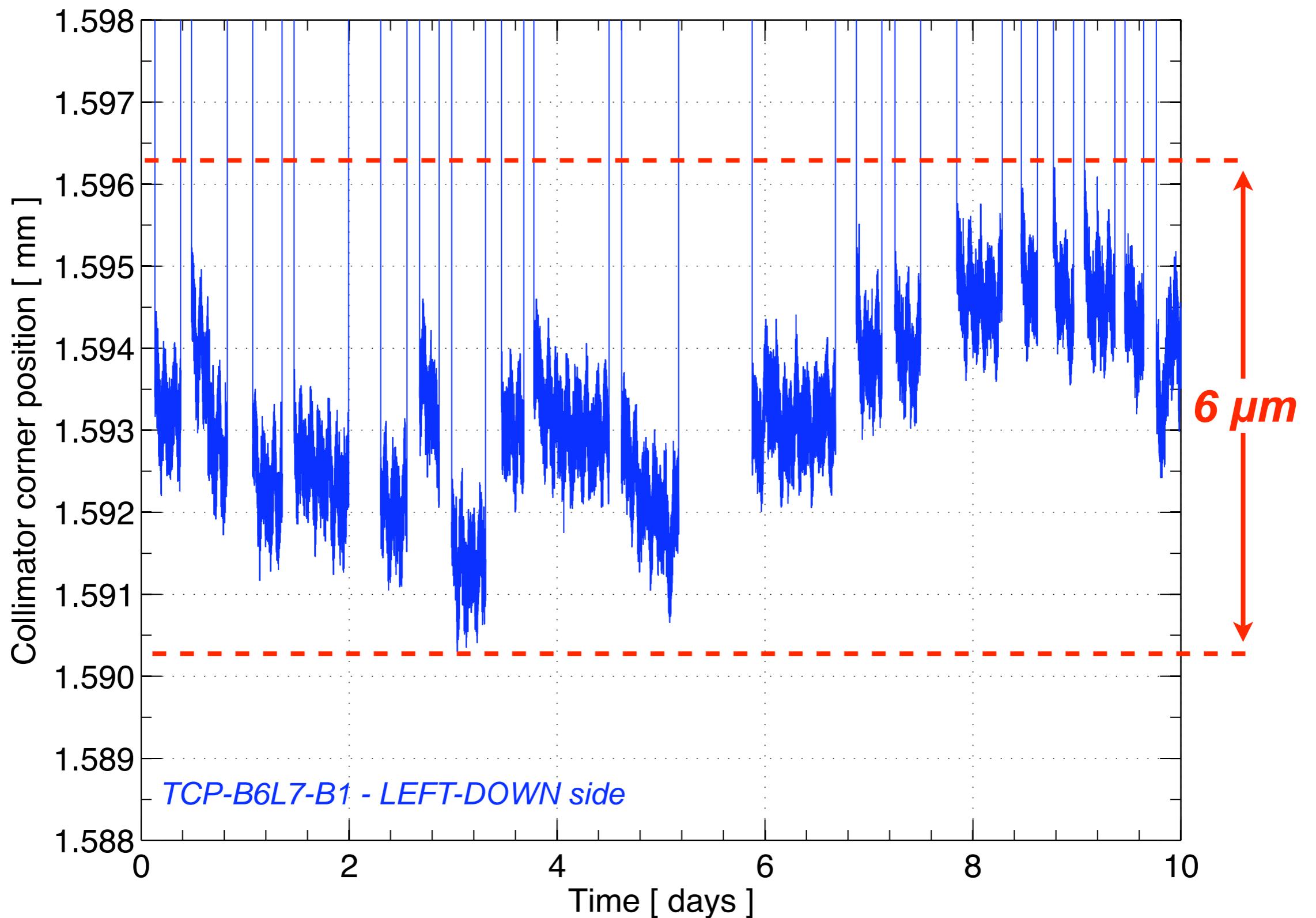
- Reproducibility tests: nominal operational cycles on **all 28 collimators in IP7**
- ~30 full cycles repeated during 10 days
- Real ramp functions to 5 TeV, nominal optics (different for each collimator)
- “Handed over” to operation crew (*special thanks to the LHC OP team*)

Reproducibility tests



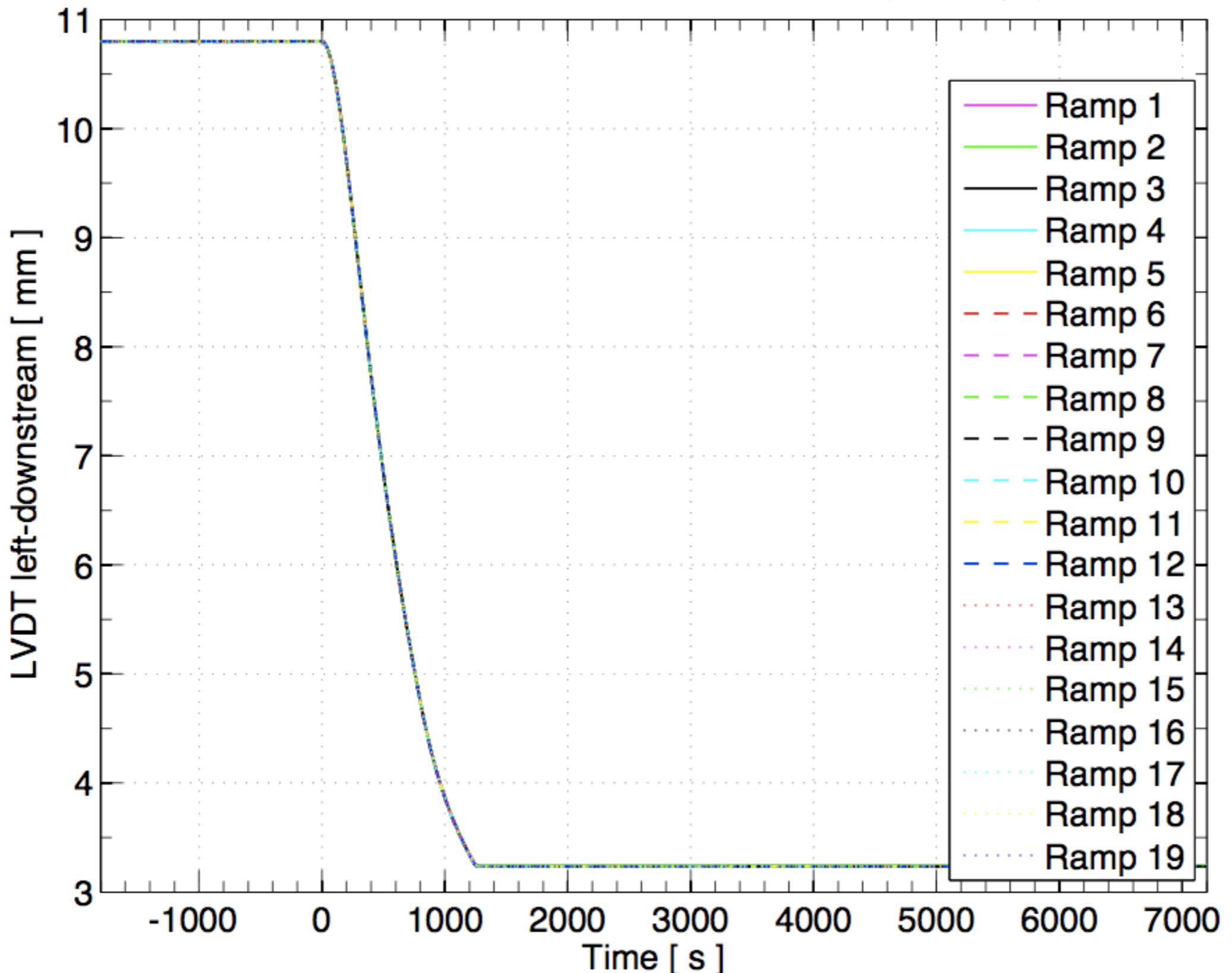
- Reproducibility tests: nominal operational cycles on **all 28 collimators in IP7**
- ~30 full cycles repeated during 10 days
- Real ramp functions to 5 TeV, nominal optics (different for each collimator)
- “Handed over” to operation crew (*special thanks to the LHC OP team*)

Reproducibility of physics settings



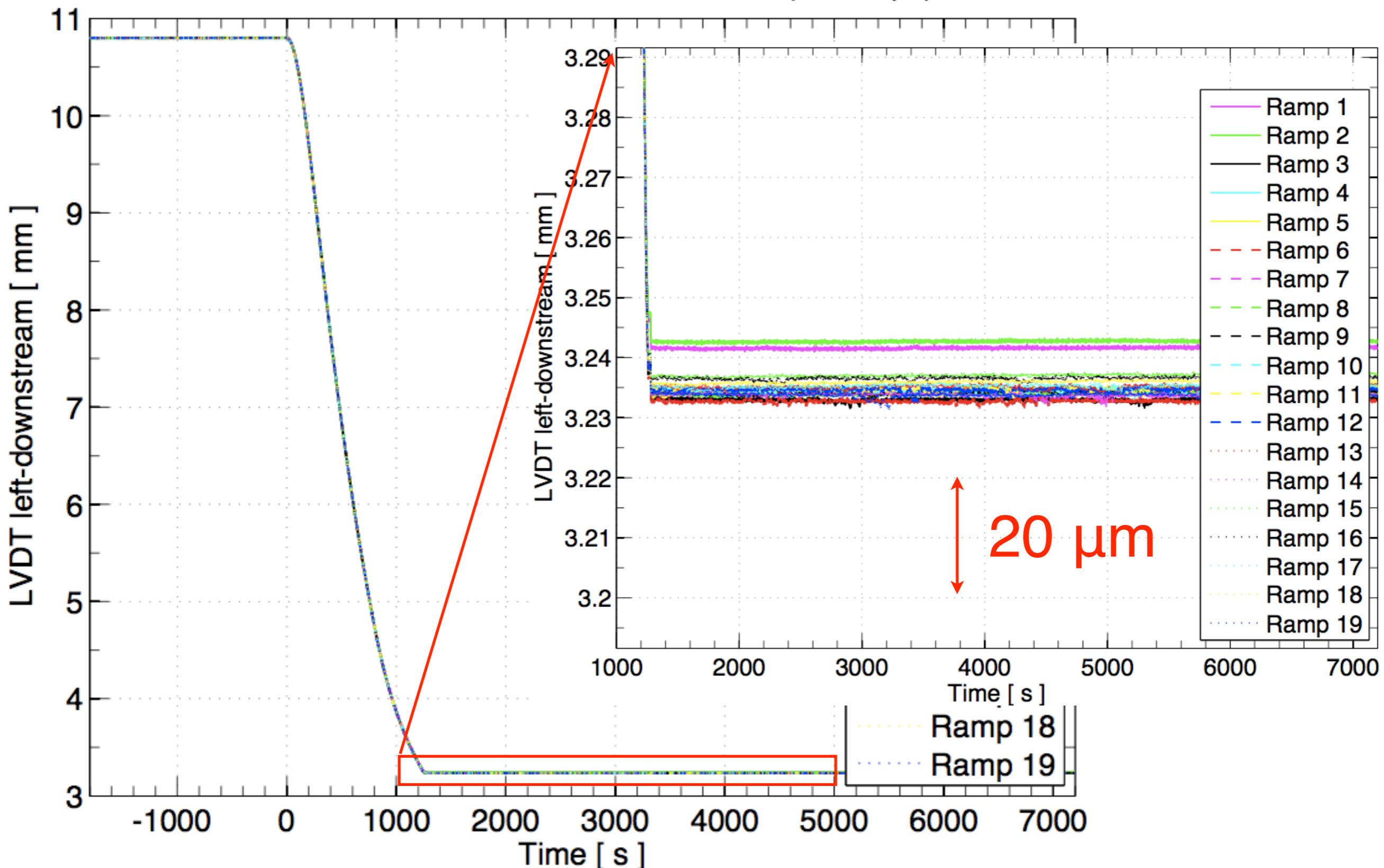
A few examples

TCLA-B6L7-B2 / LVDT left-downstream (19 ramps)



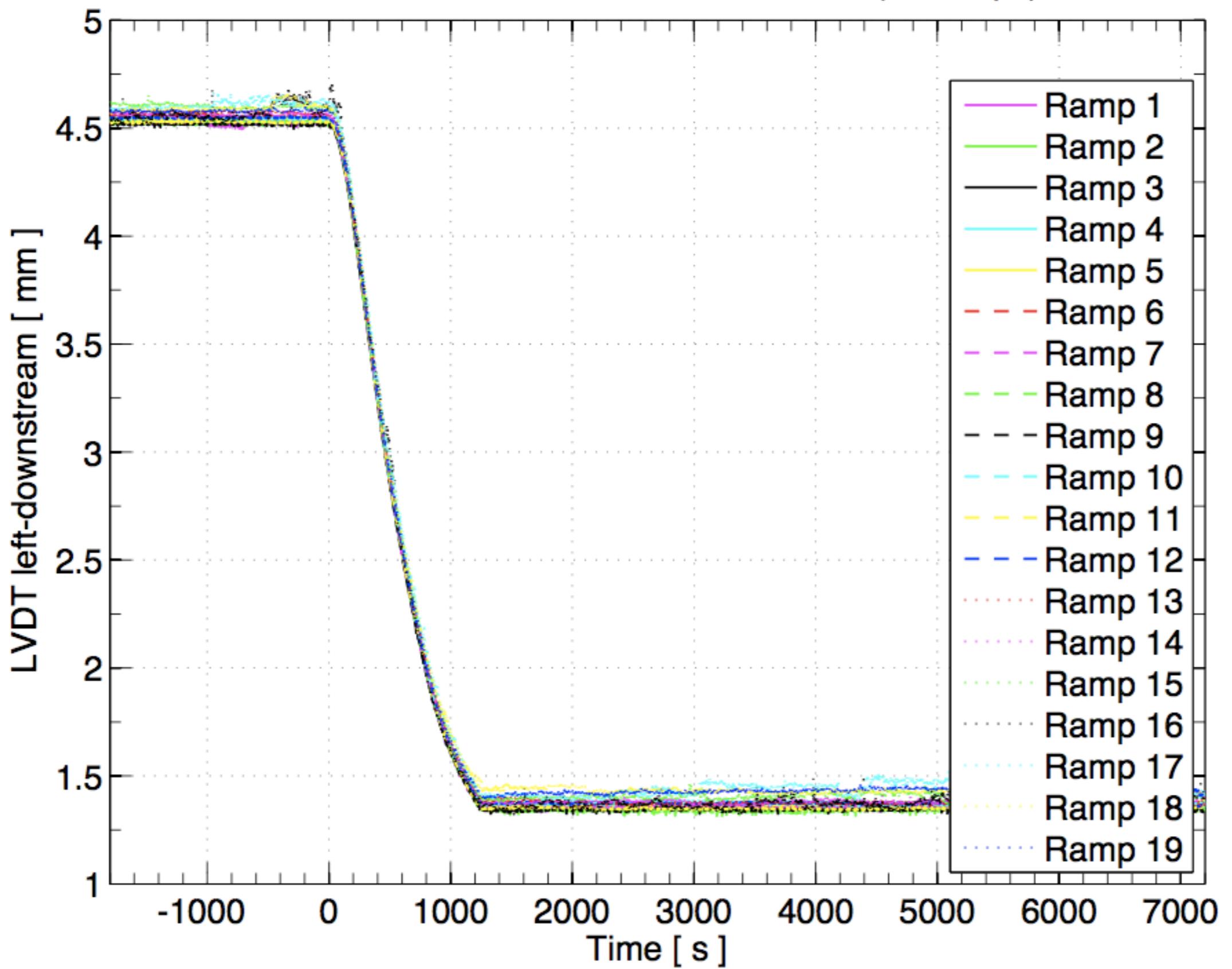
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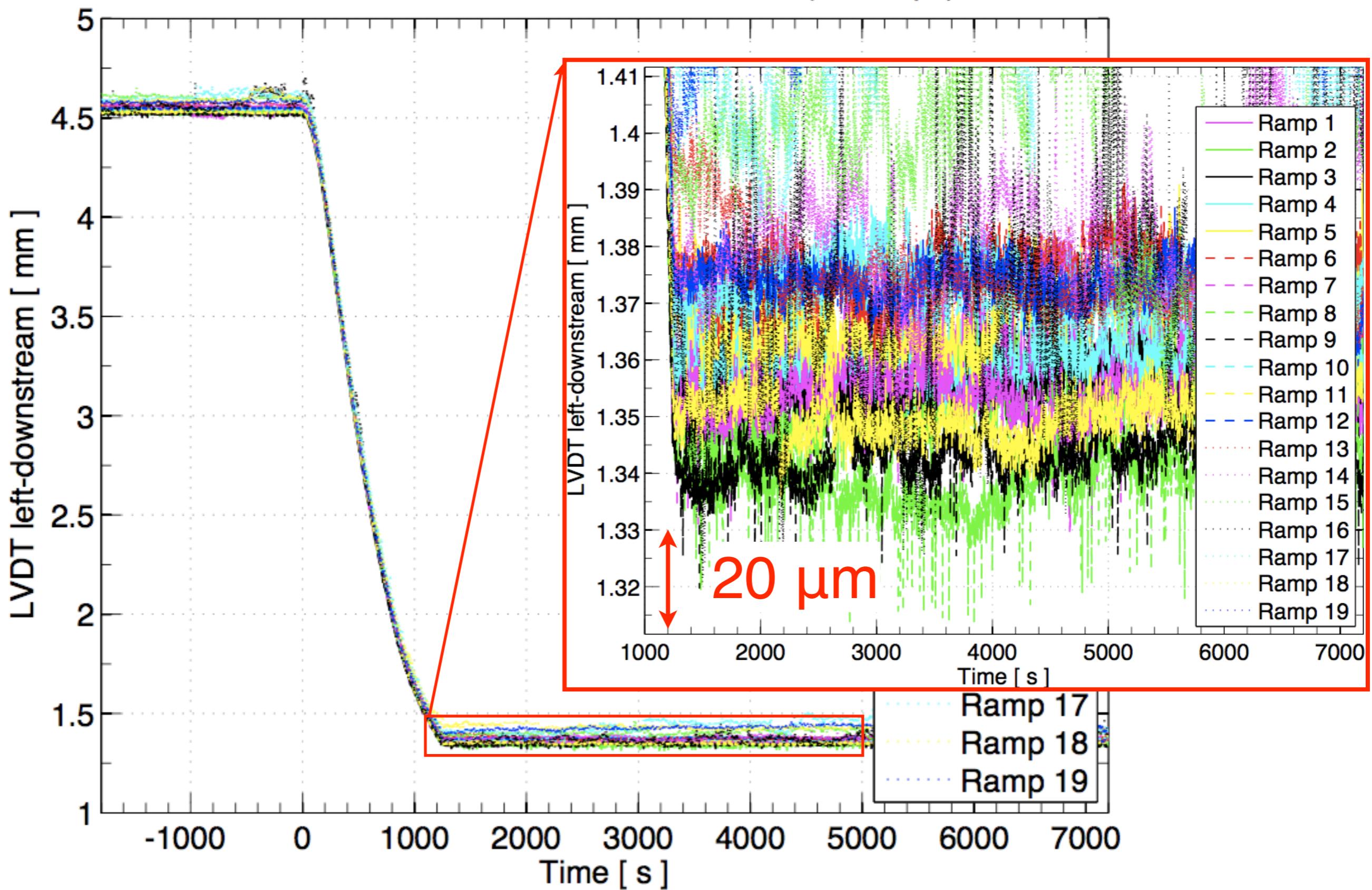
The worst case

TCP-D6L7-B1 / LVDT left-downstream (19 ramps)



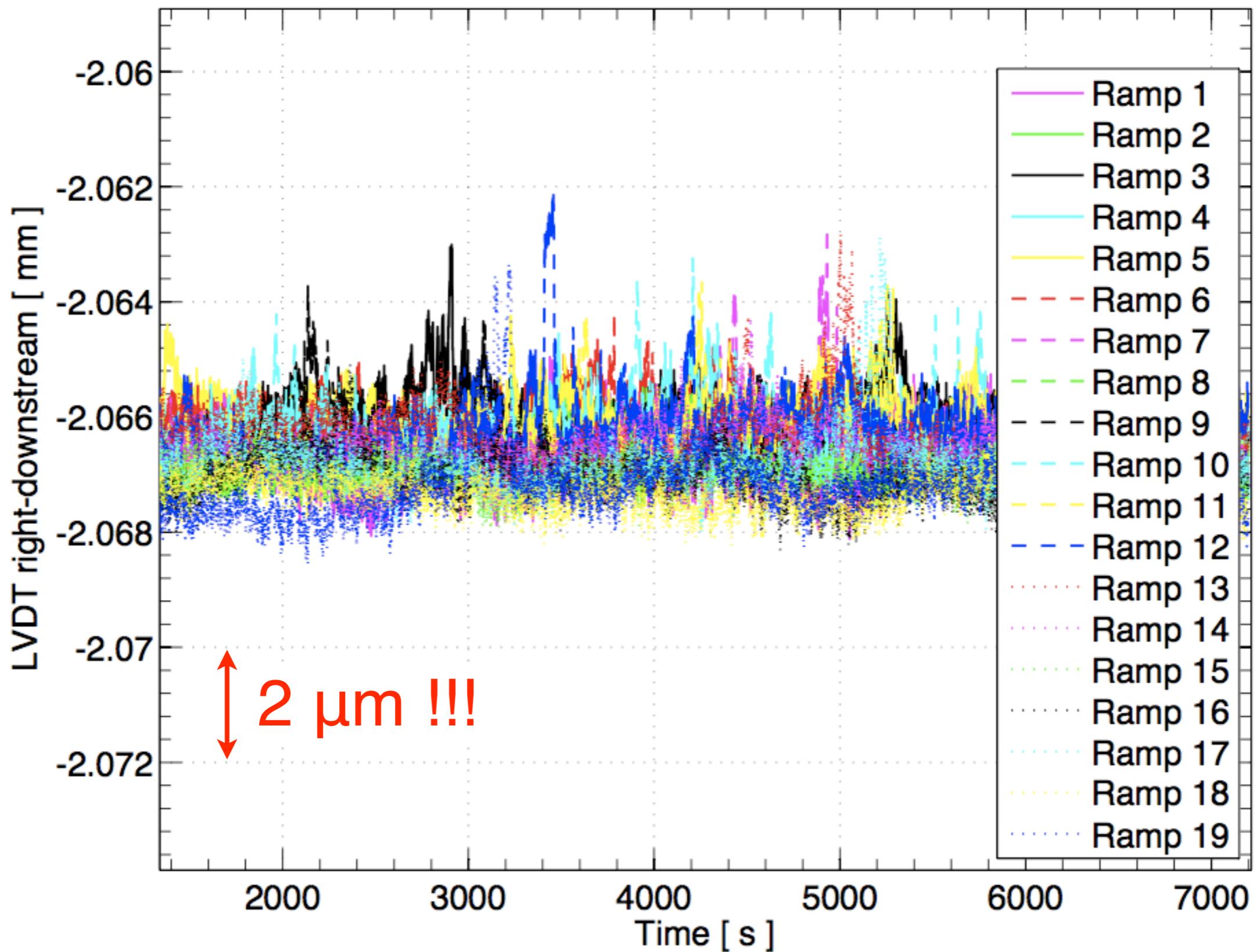
The worst case

TCP-D6L7-B1 / LVDT left-downstream (19 ramps)

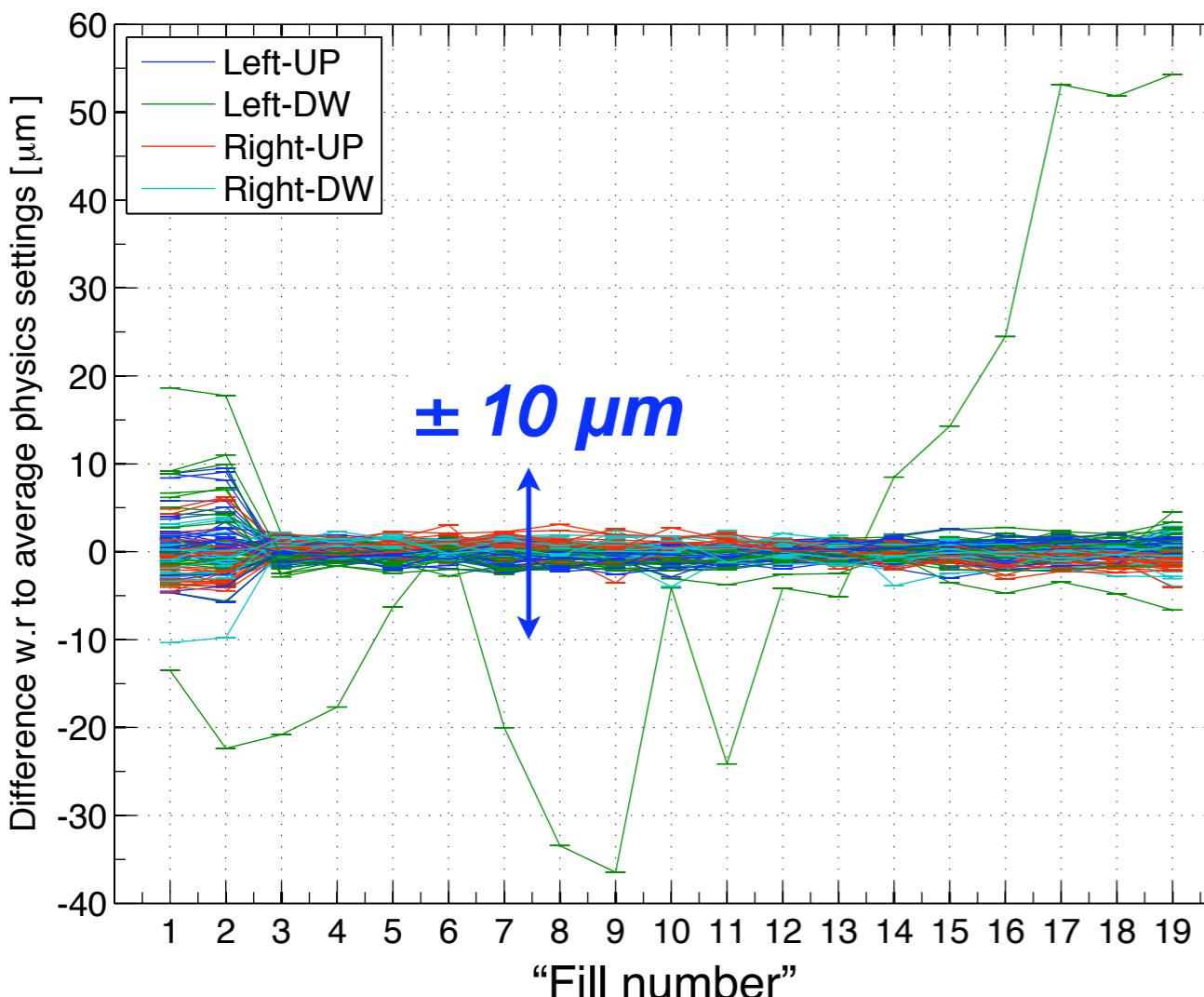


The best case

TCLA-D6R7-B1 / LVDT right-downstream (19 ramps)

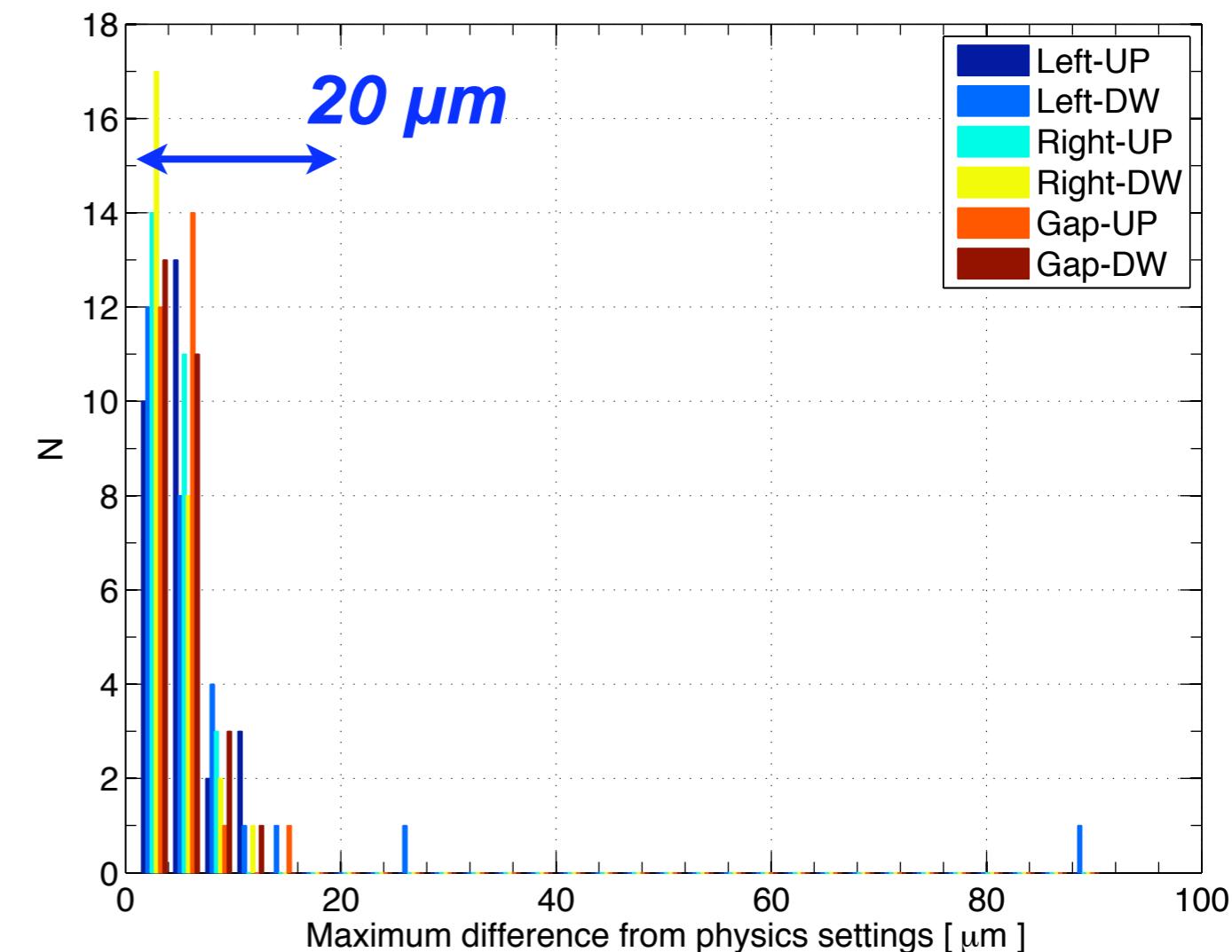
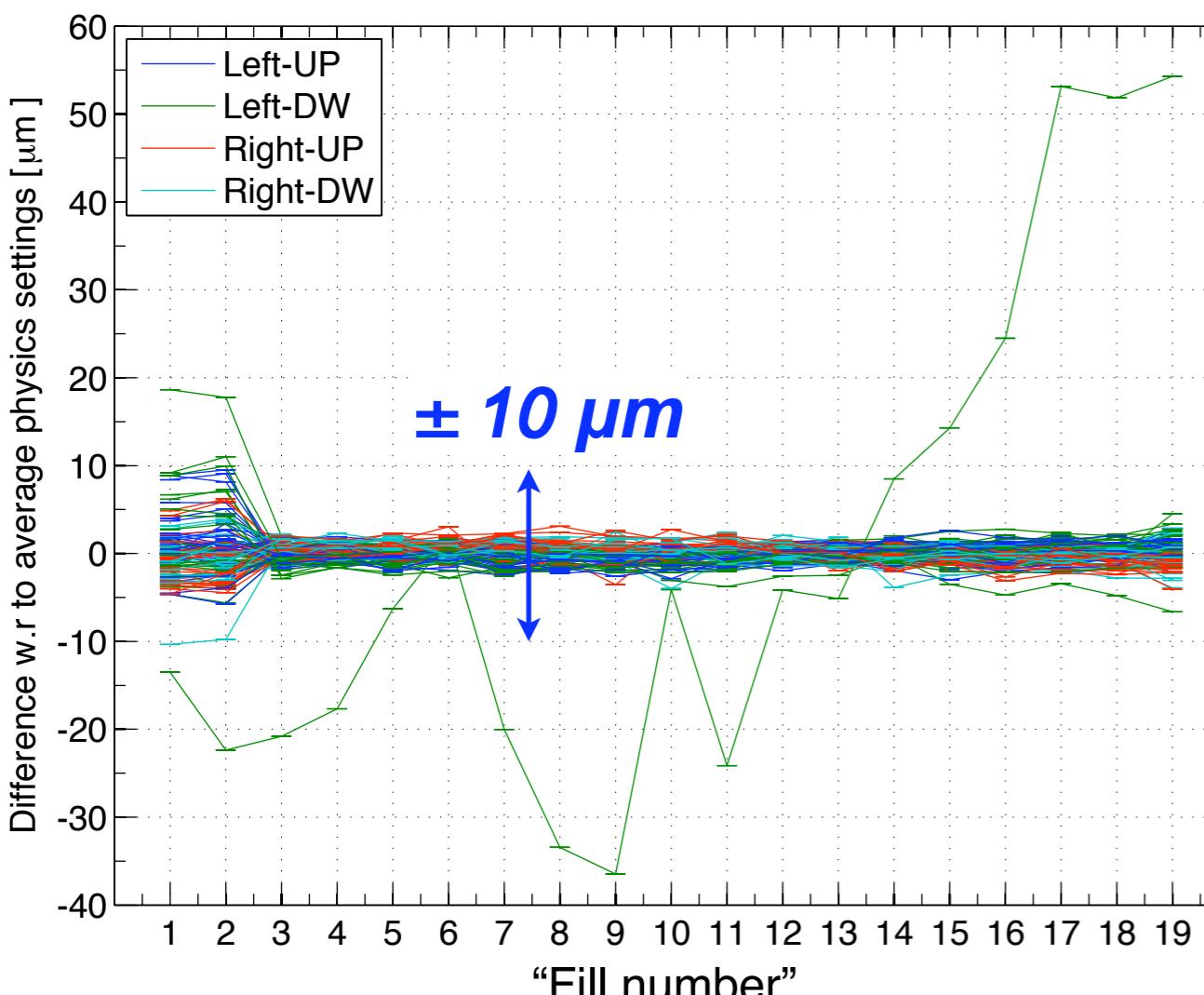


Summary of reproducibility results



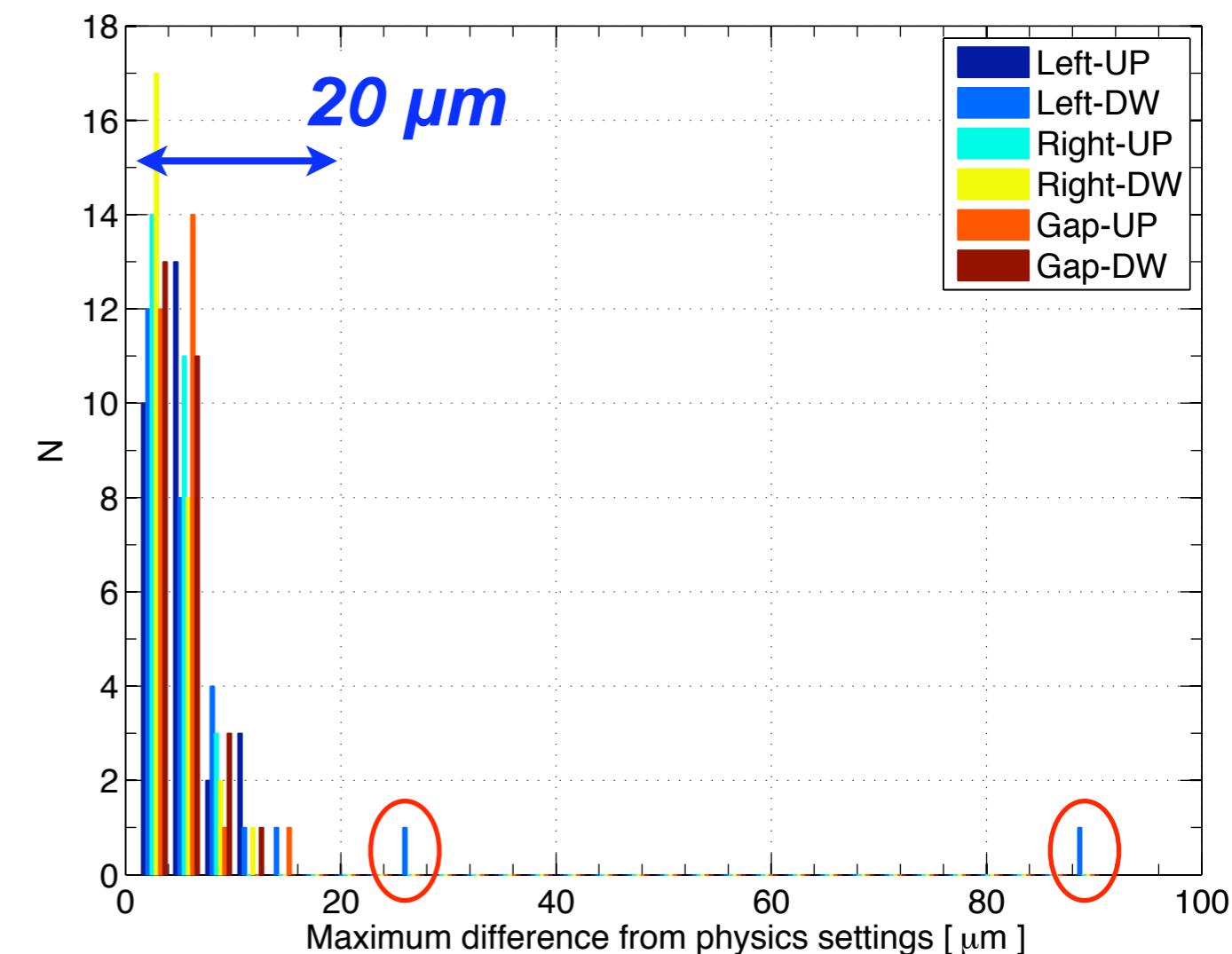
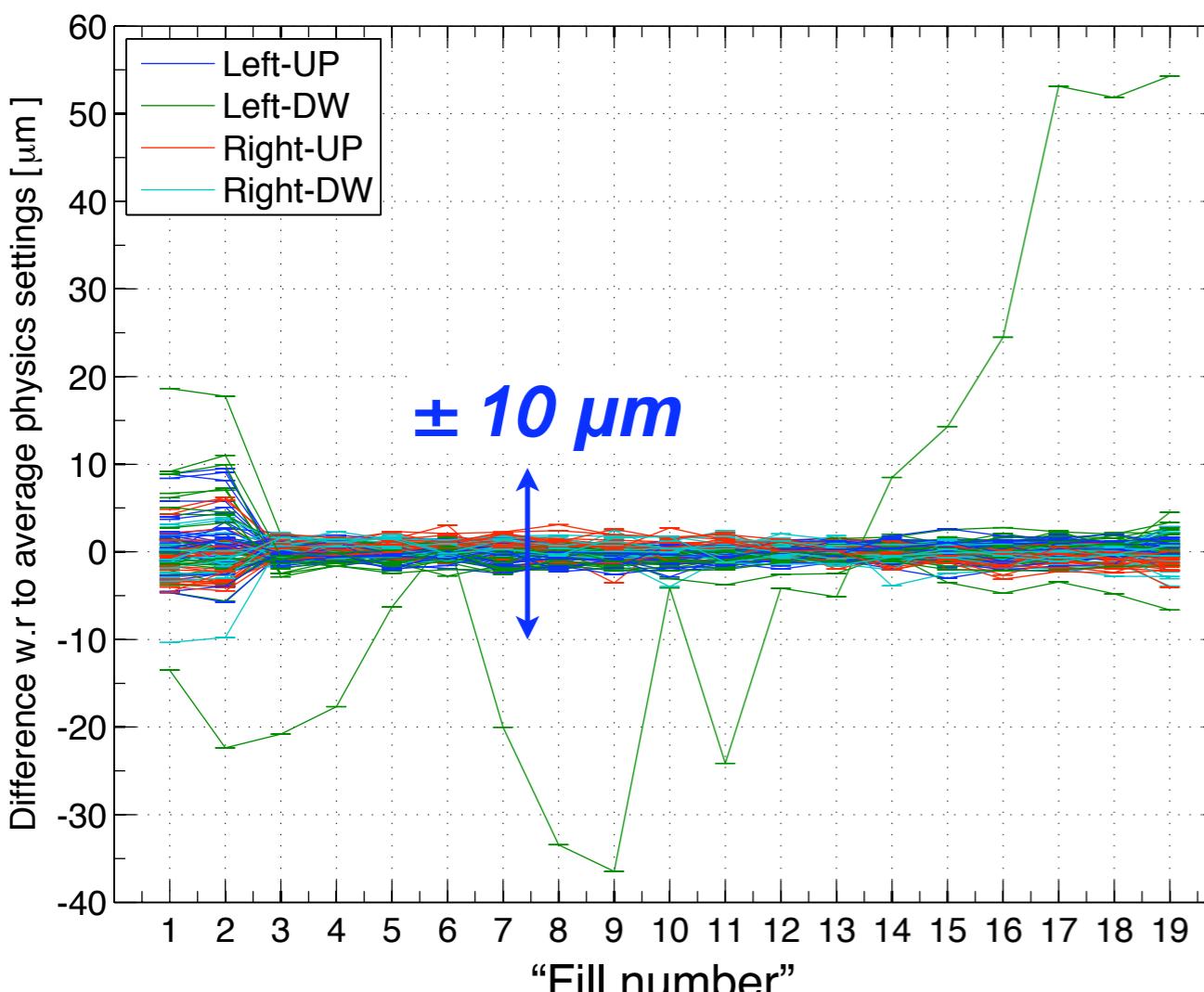
- 28 collimators (both beams of IR7)
- 112 stepping motors
- 168 position sensors (LVDT's)
- 19 consecutive nominal ramps over 10 days

Summary of reproducibility results



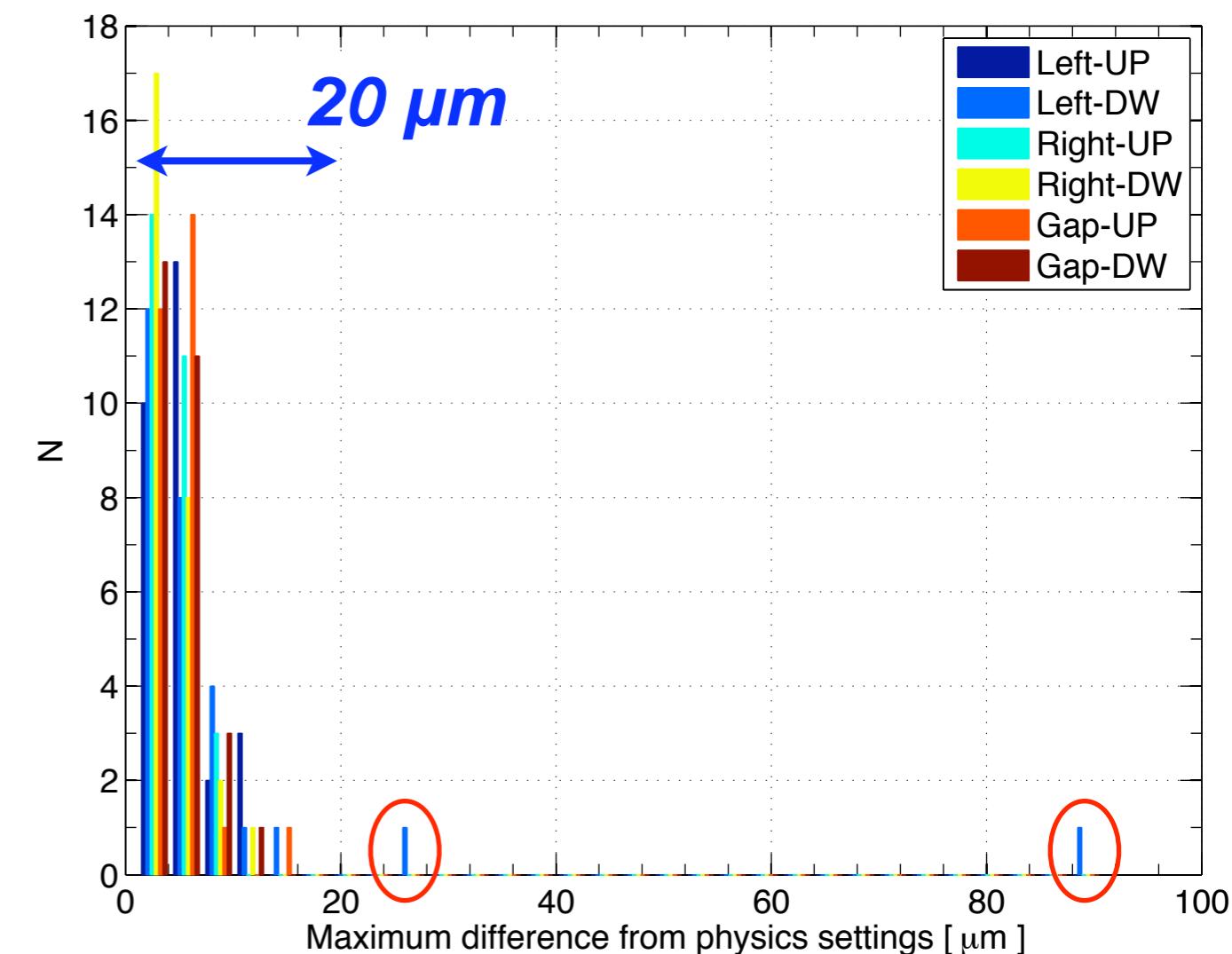
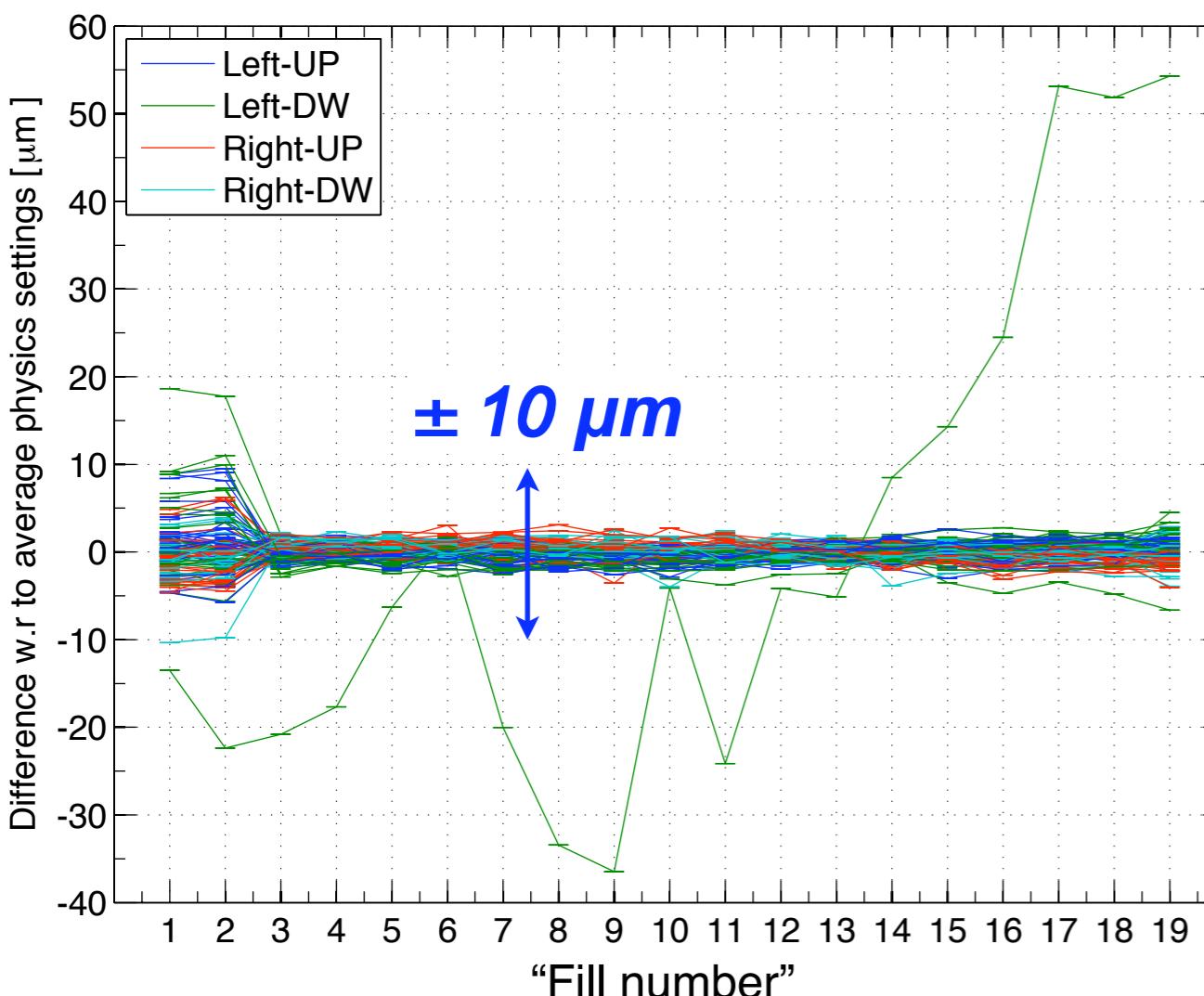
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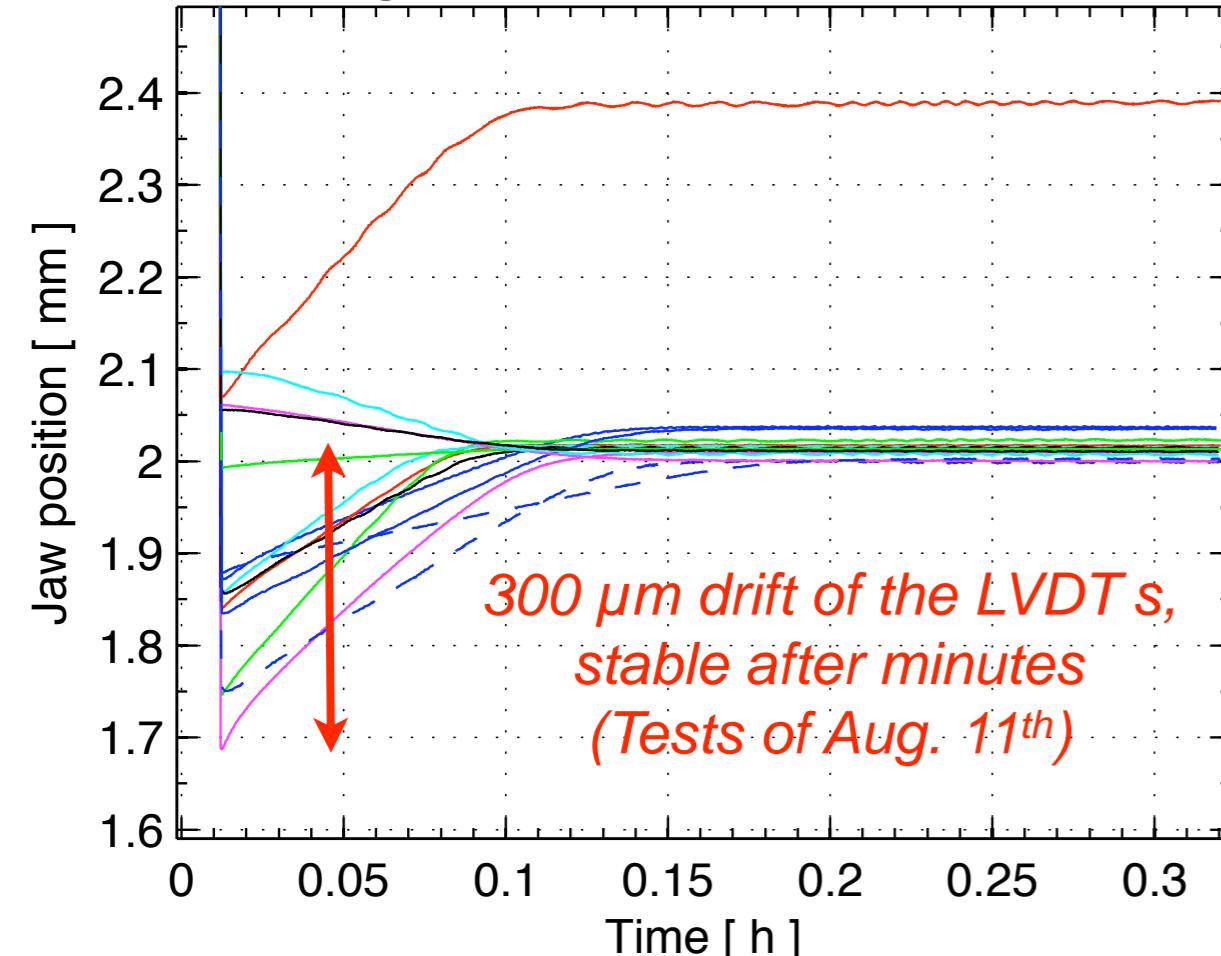
Specs on reproducibility of settings are achieved:
measured **BELLOW $20 \mu\text{m}$!!**



Isolated problems encountered

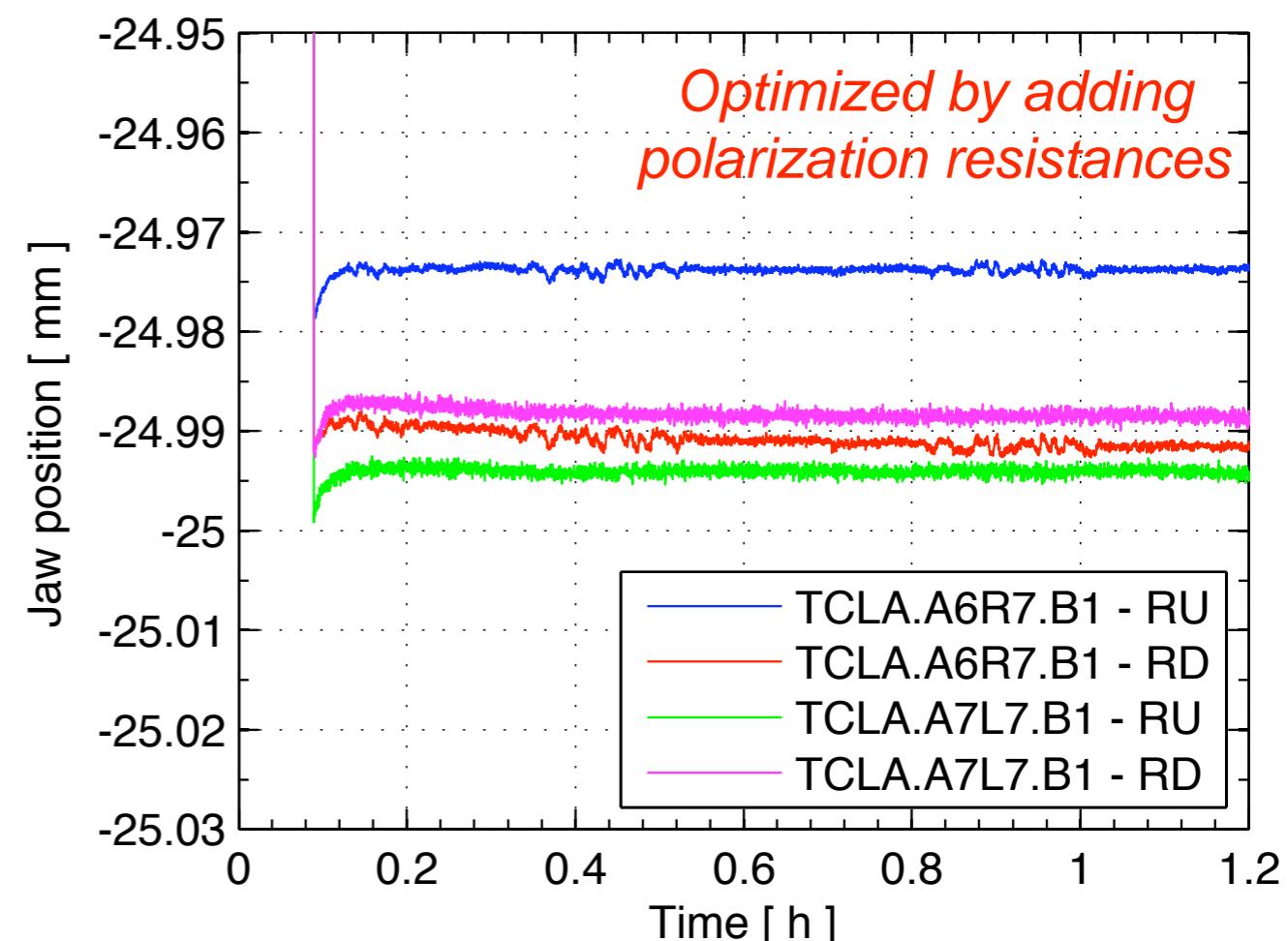
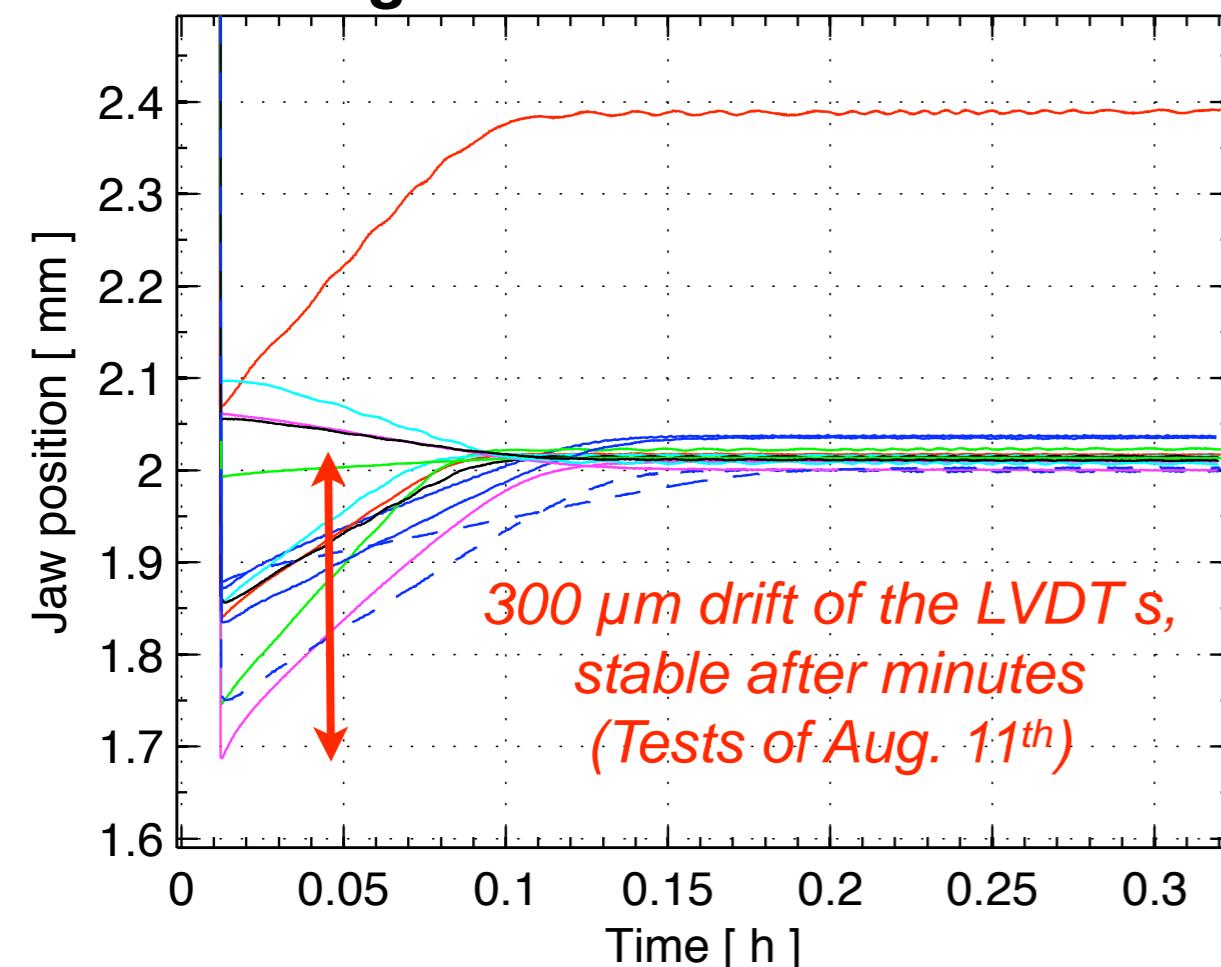
Isolated problems encountered

Signal drift of LVDT sensors



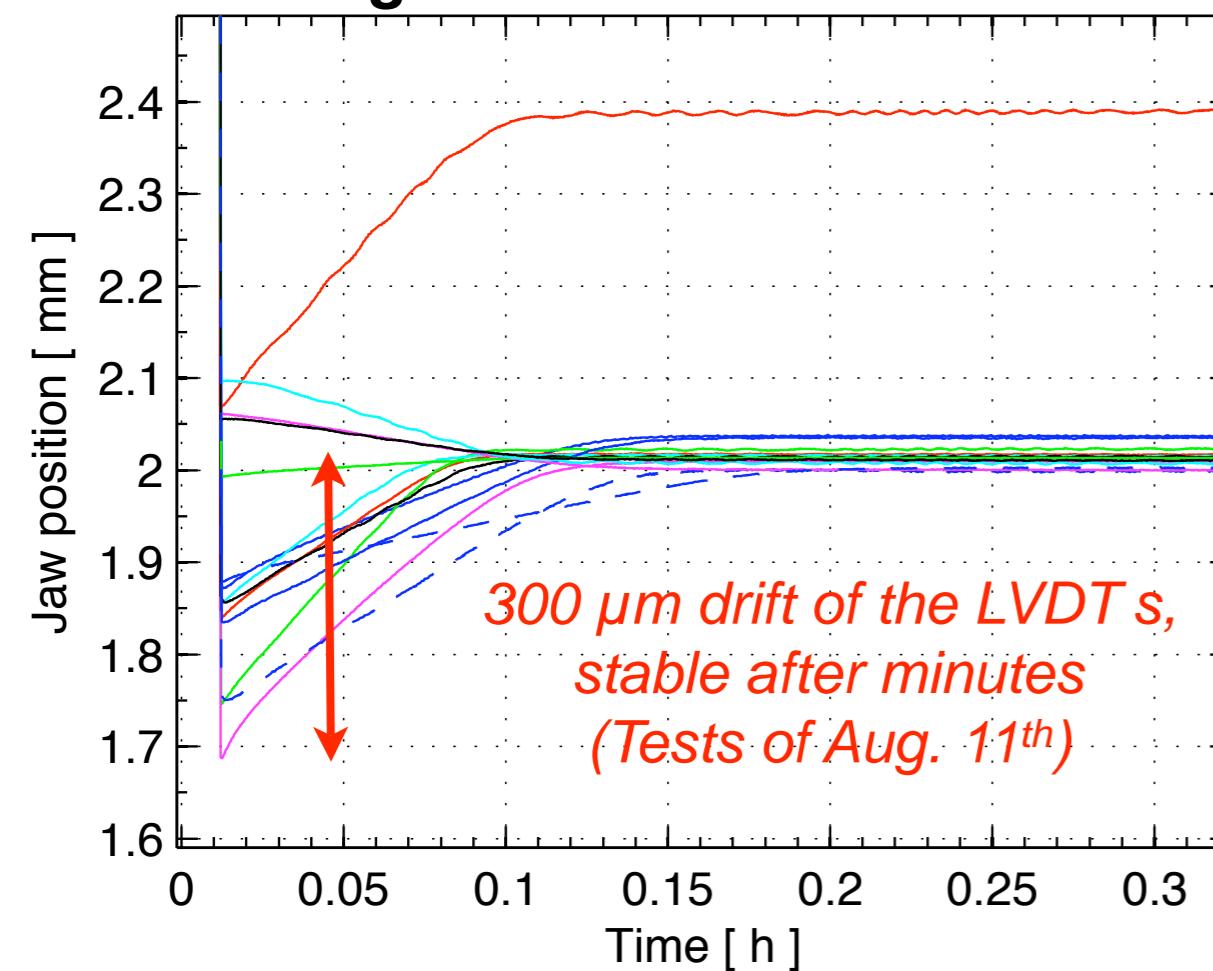
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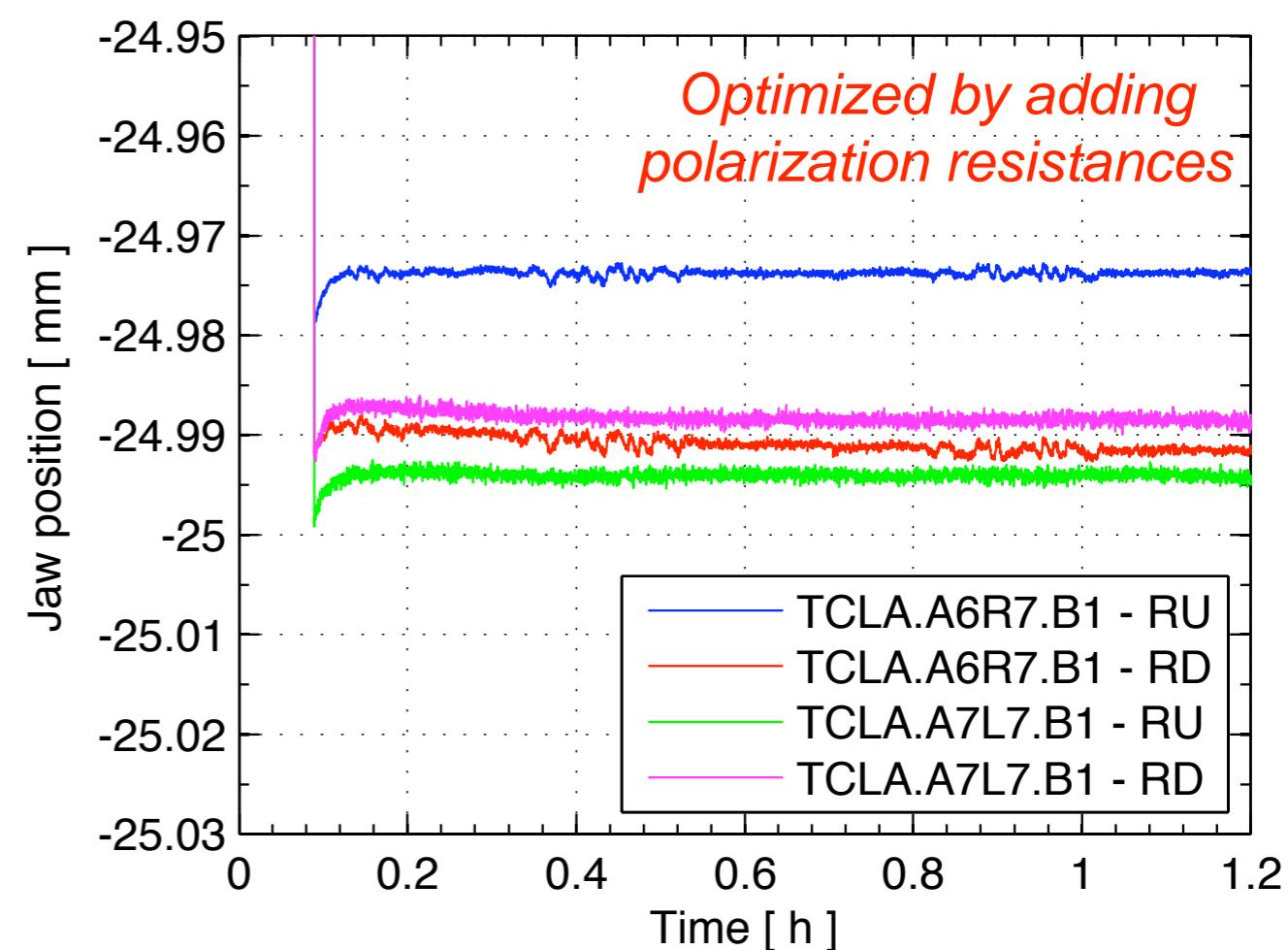
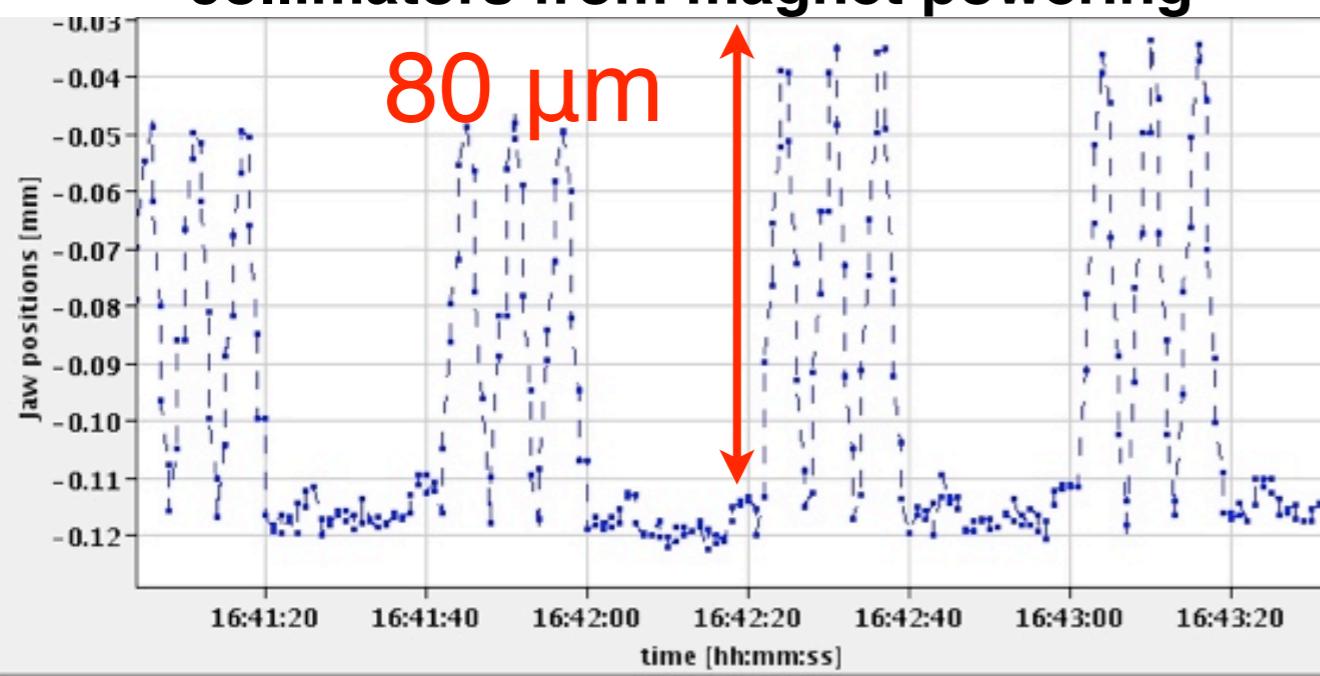


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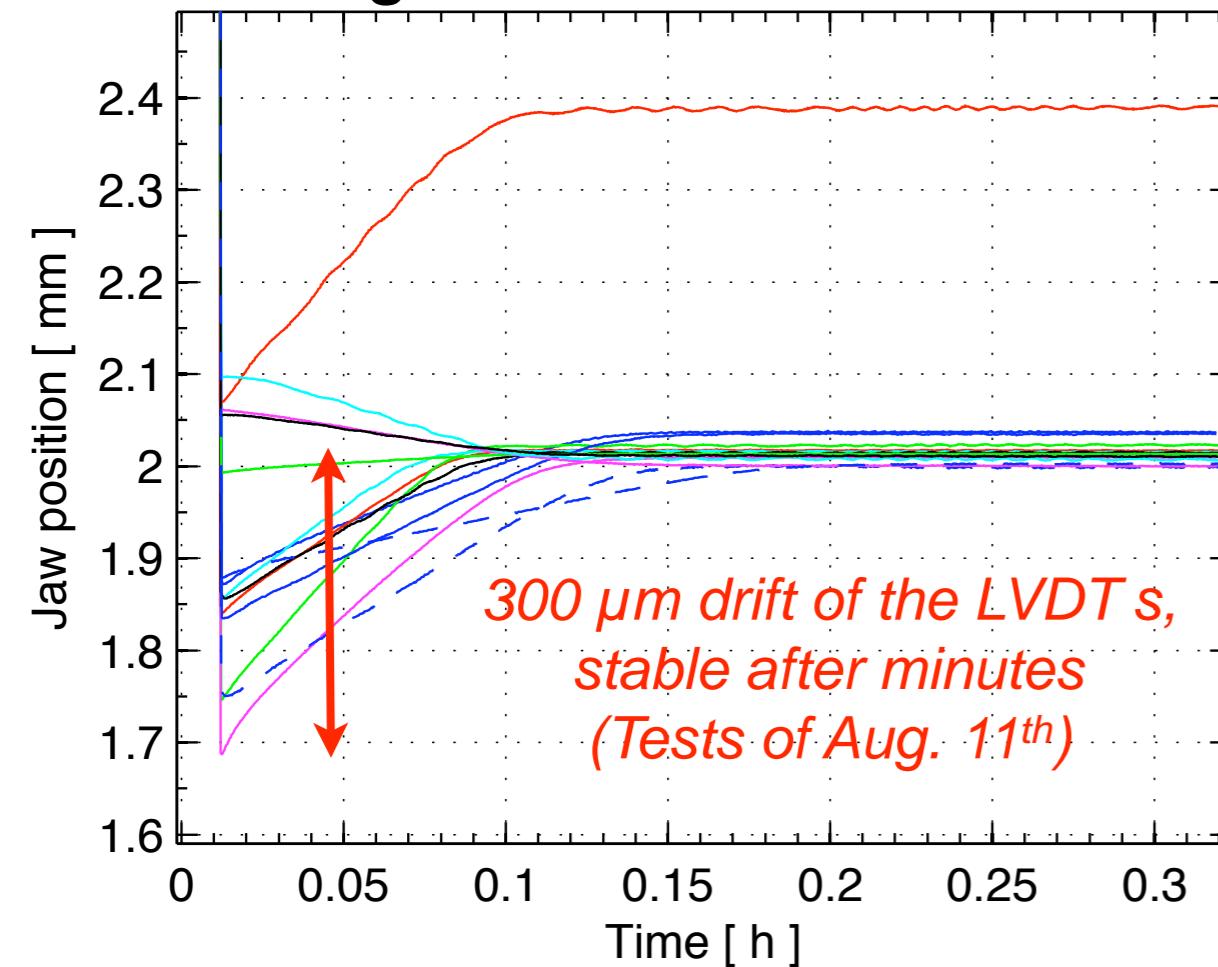
EM interference with the transfer line collimators from magnet powering



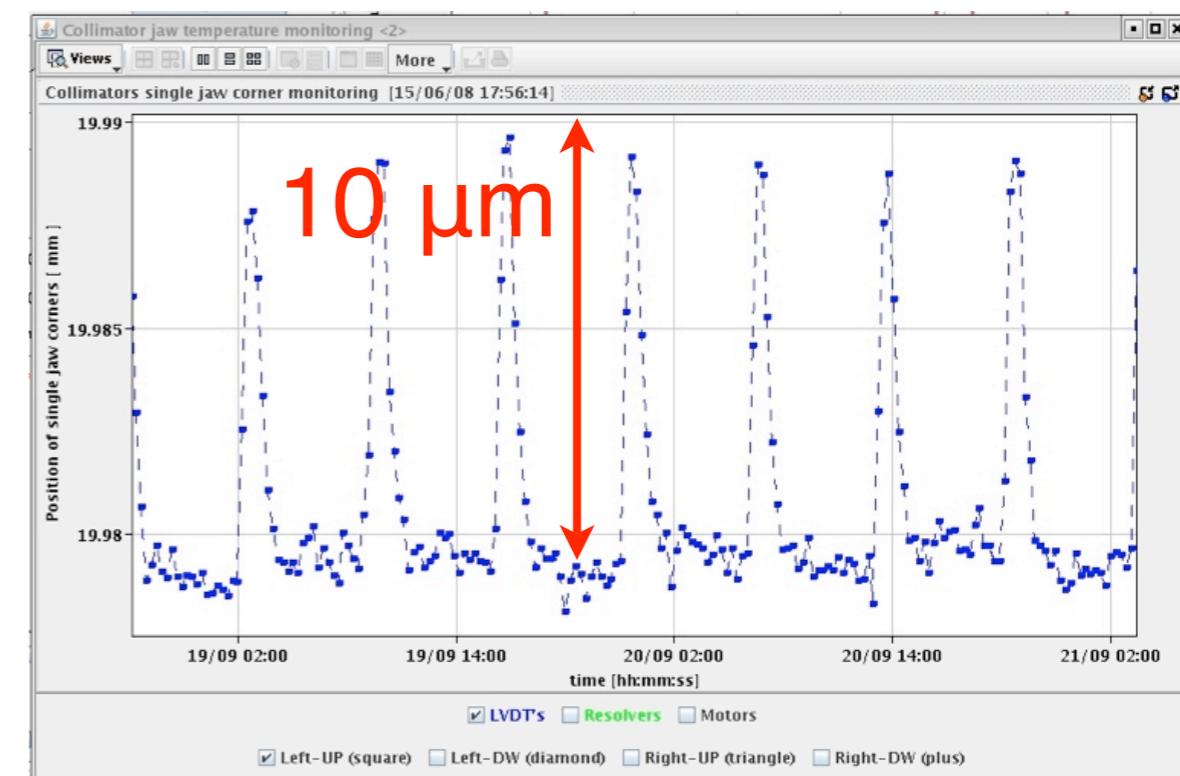
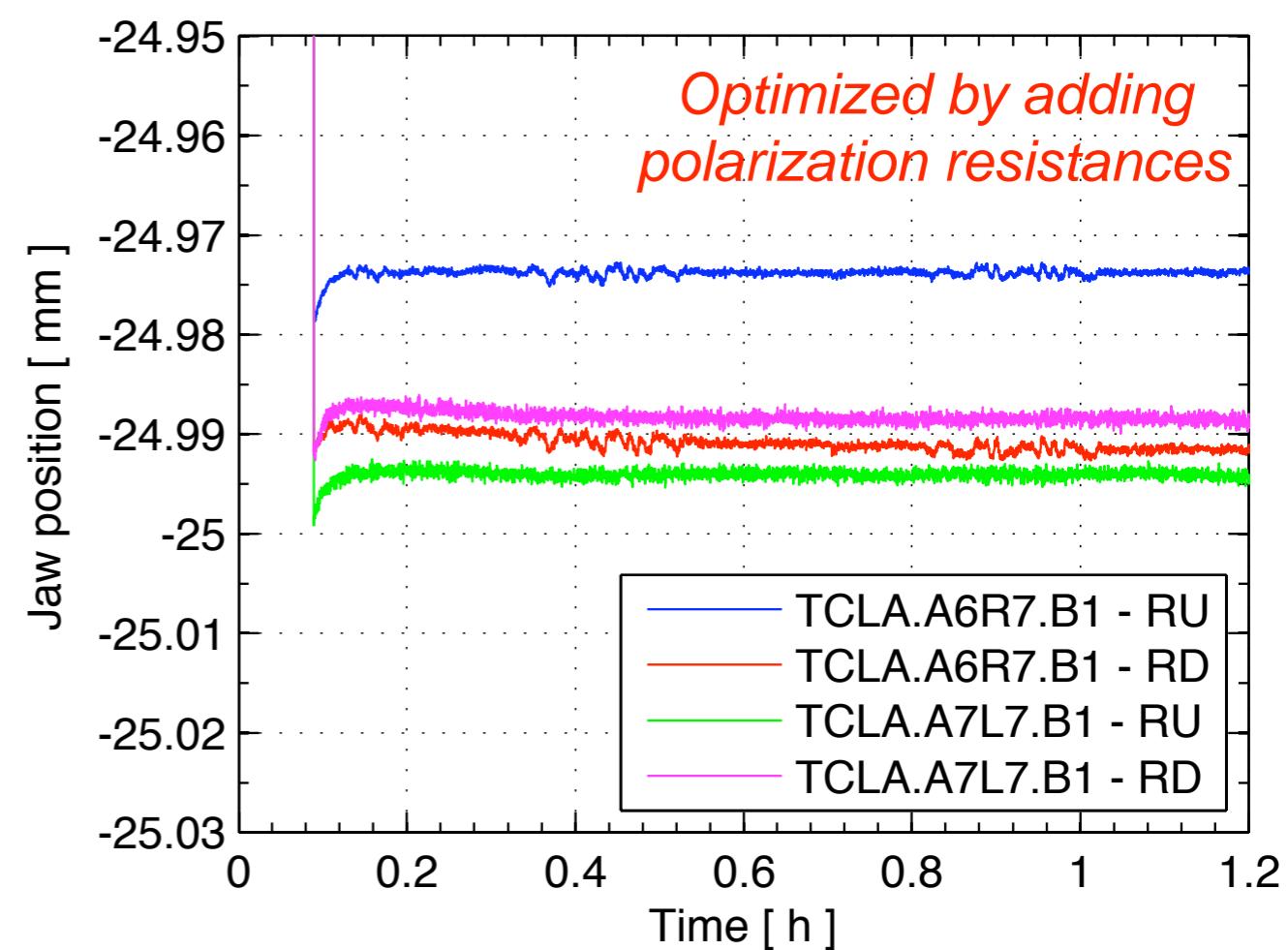
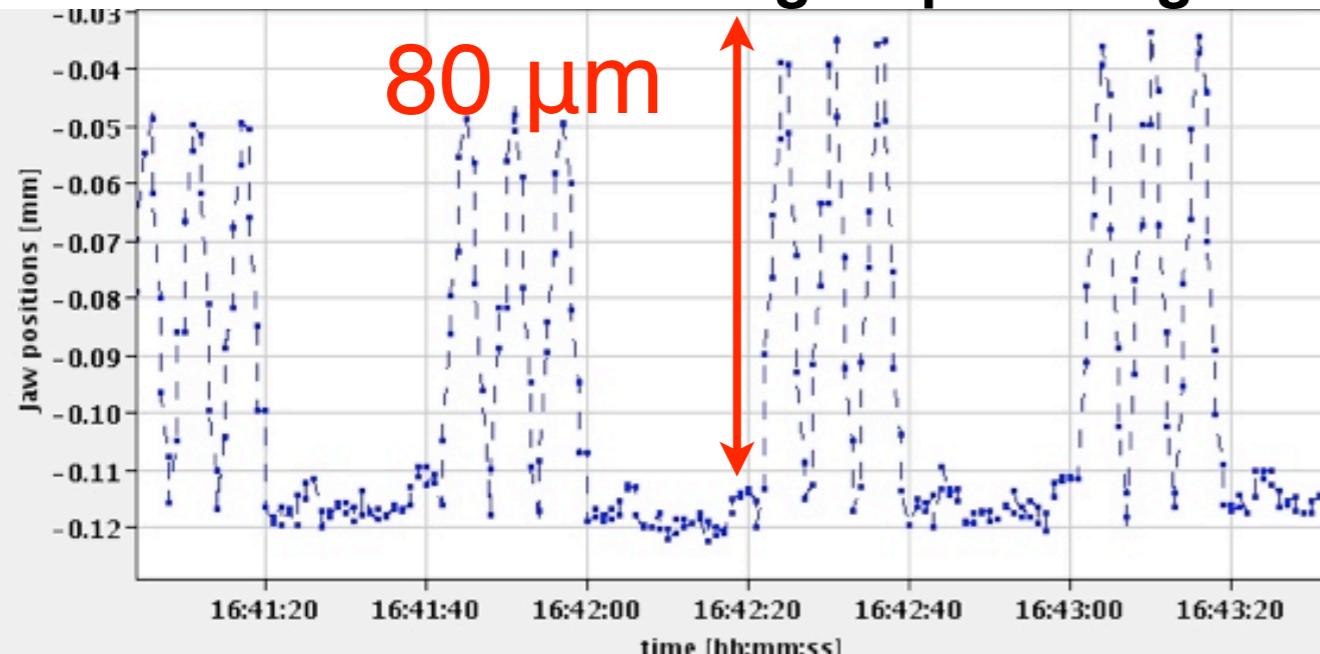


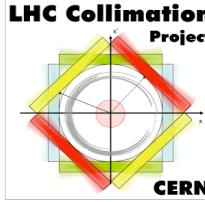
Isolated problems encountered

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Interlock commissioning

4 motor axes and 2 gap: **4 limit functions**
each (dump/warn IN and OUT)

24 limit functions per collimator

In addition, **2 energy limits** for the gaps

Violation of tolerance: (1) stop the
movement, (2) system internal fault and
(3) activation of the **beam interlock**.

As a part of the system cold-check out,
ALL the degrees of freedom were verified
with the final interlock chain
~ 30 s per axis, 5 min per collimator!

Interlock commissioning

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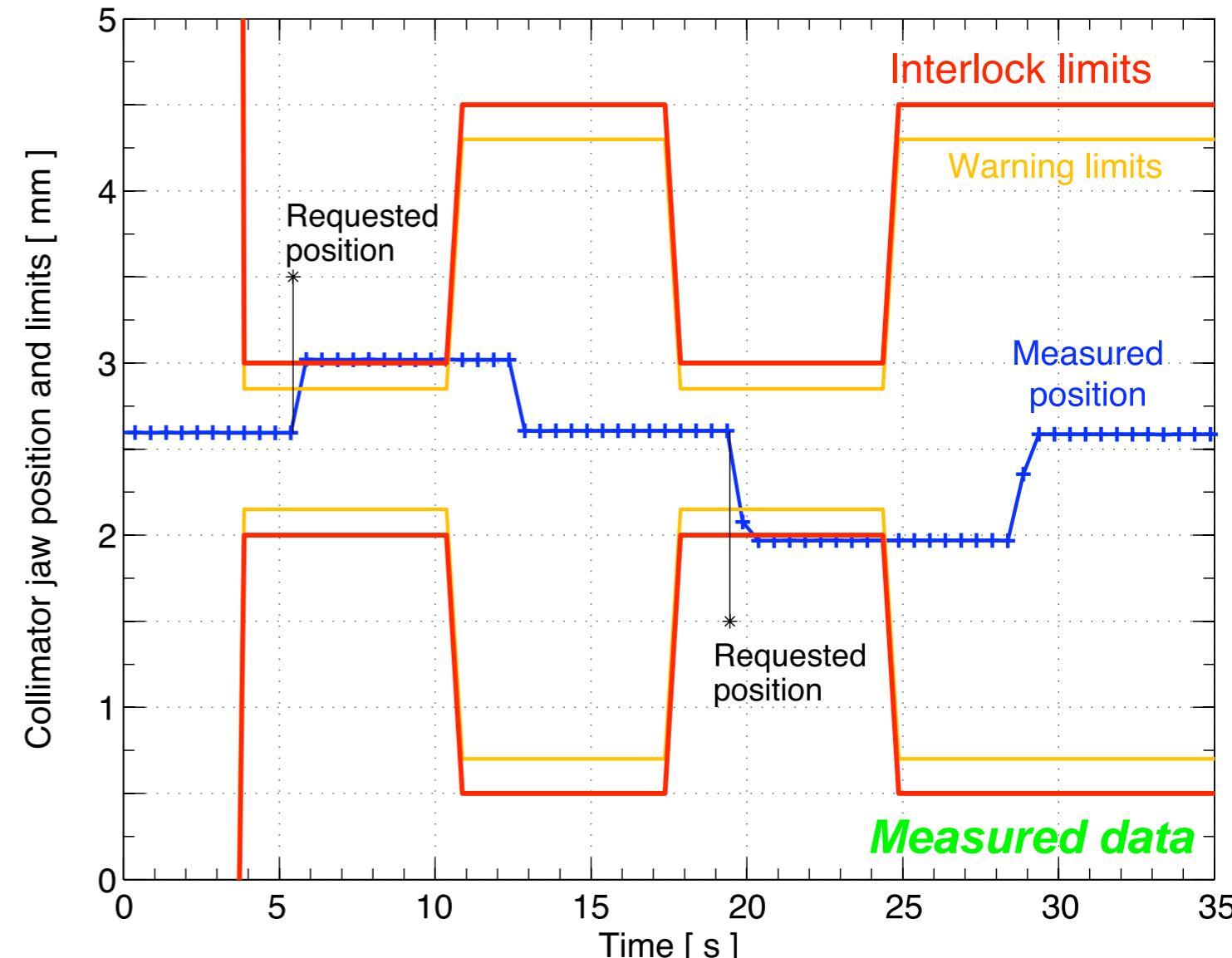
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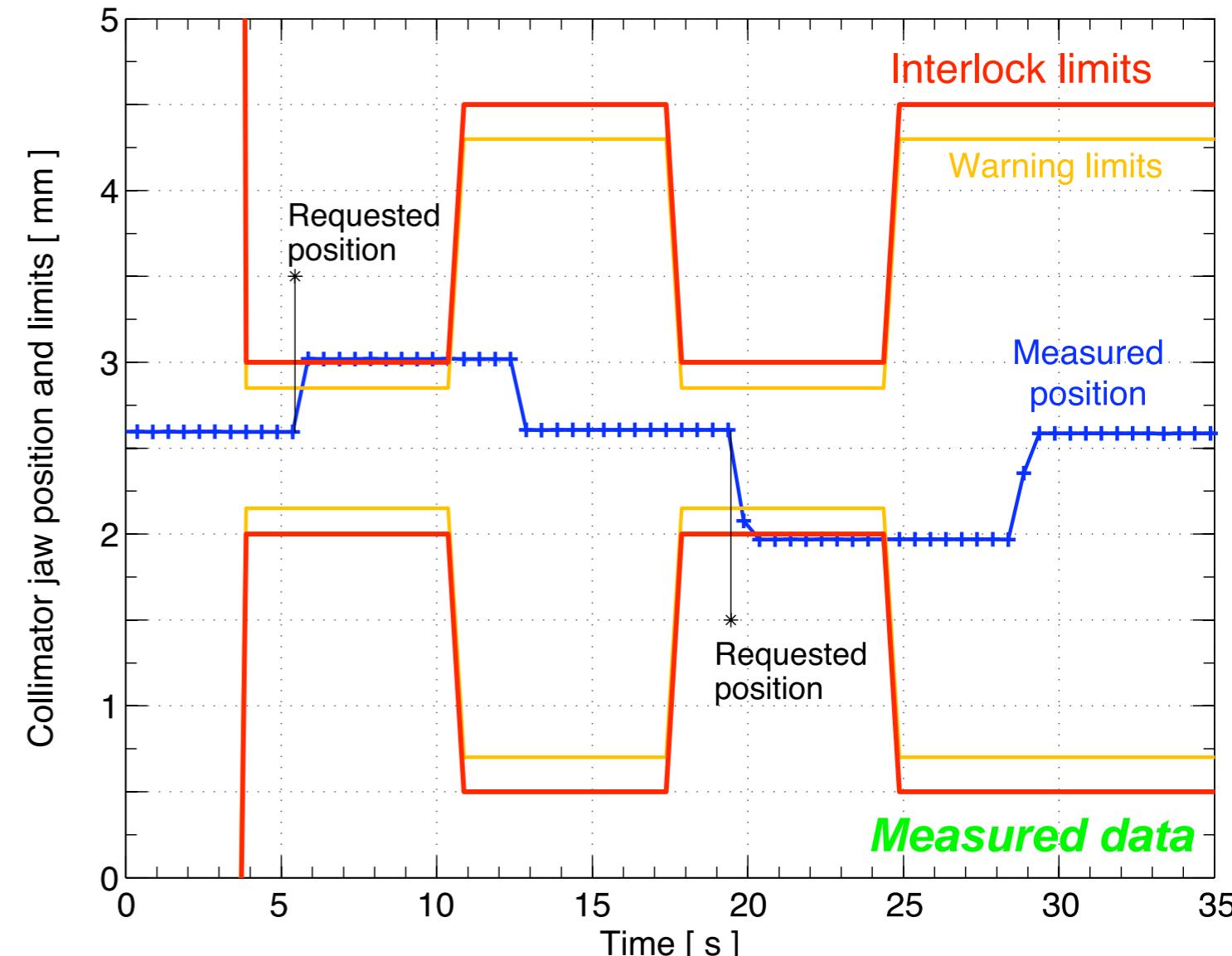
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Sequence **automatized** and **implemented** in the collimator application software

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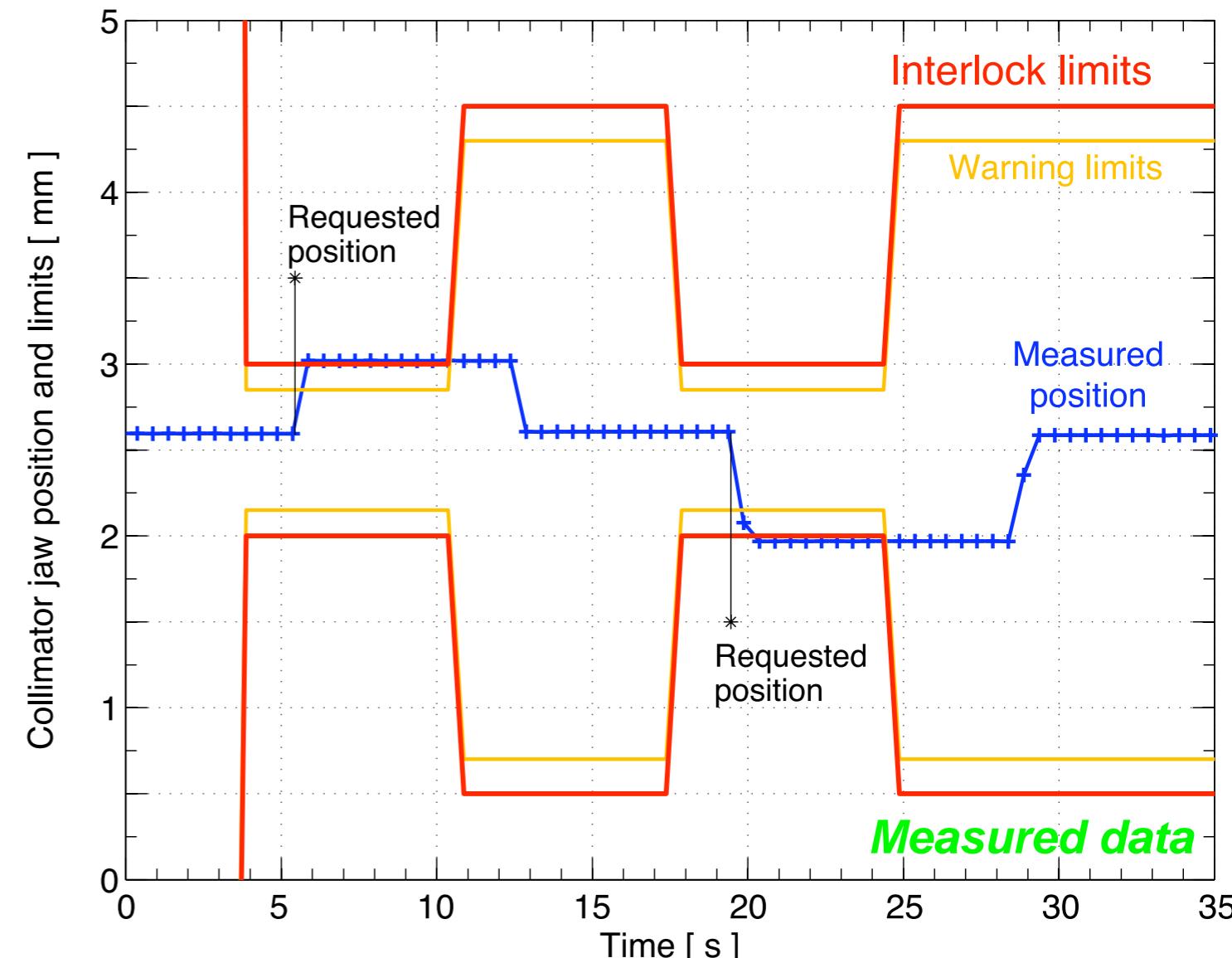
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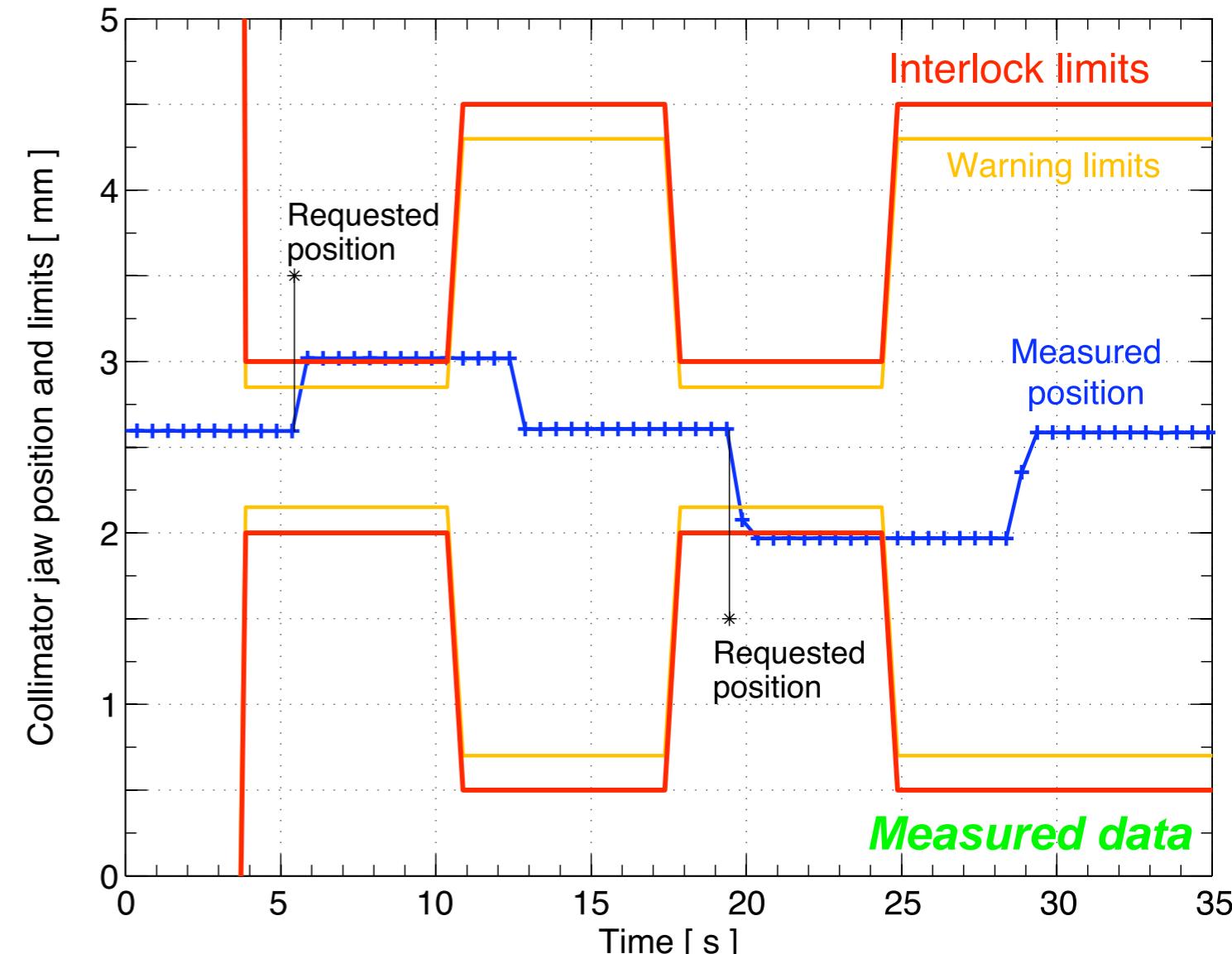
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Similarly, all the interlocks for the **403 temperature sensors** were also verified

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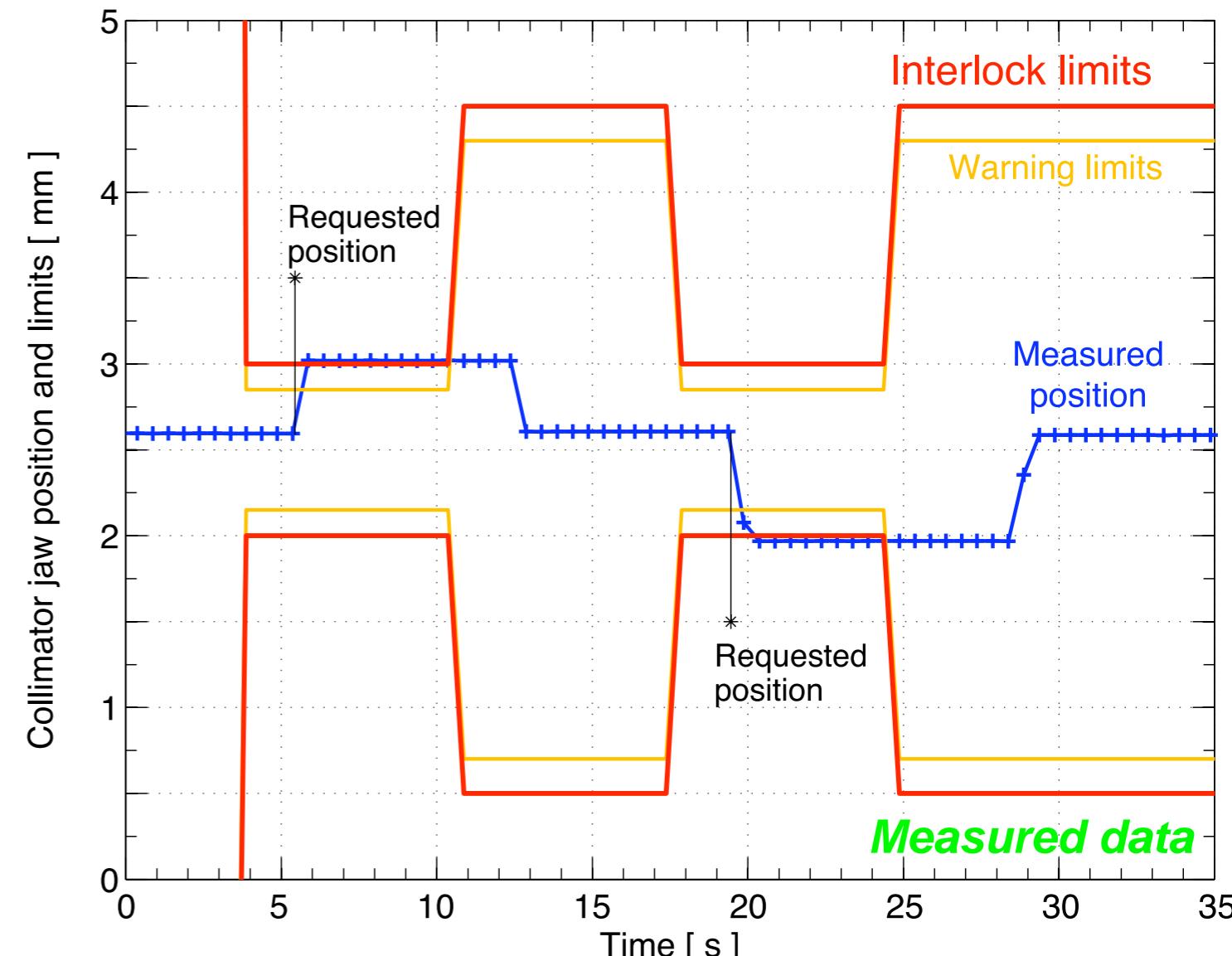
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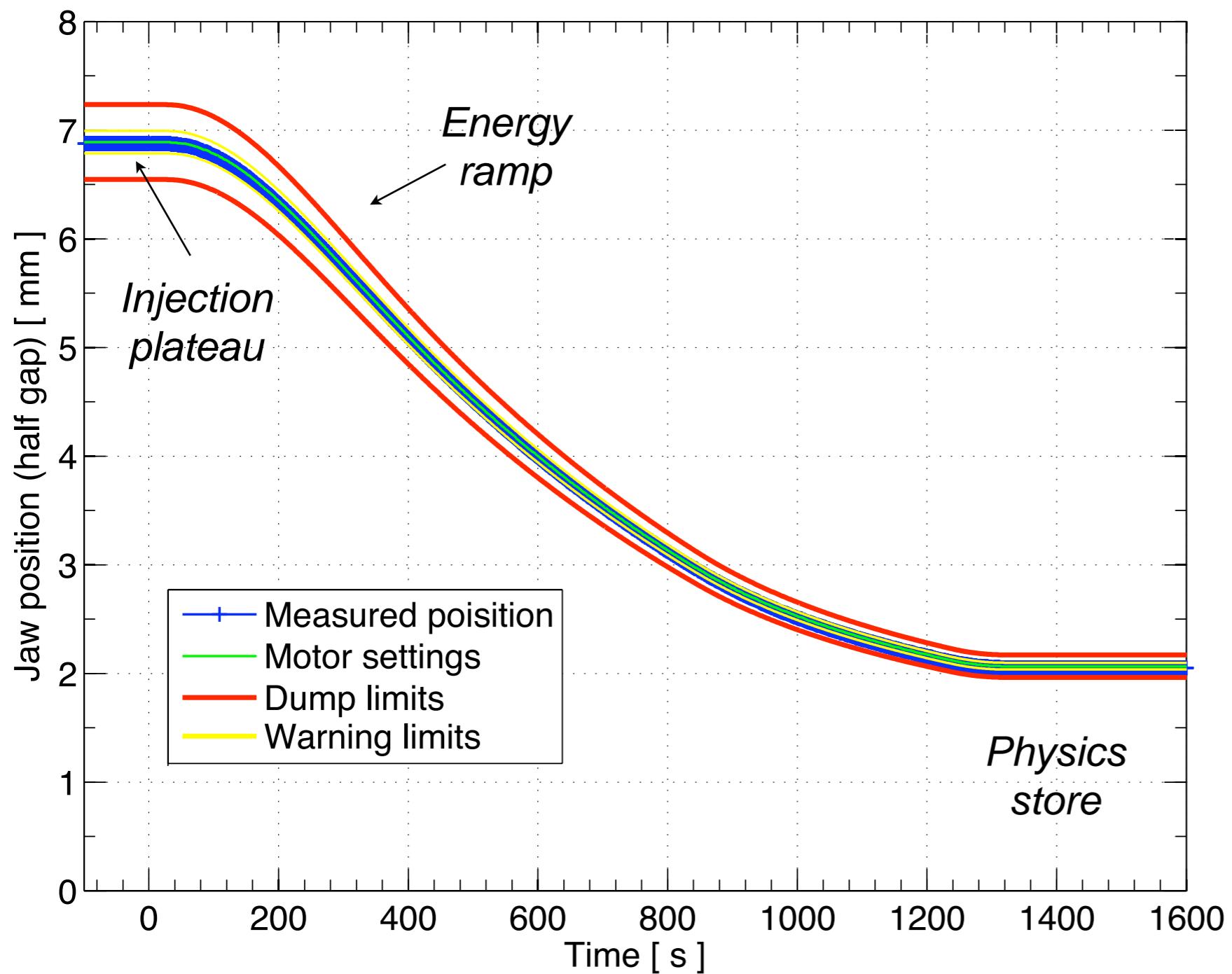
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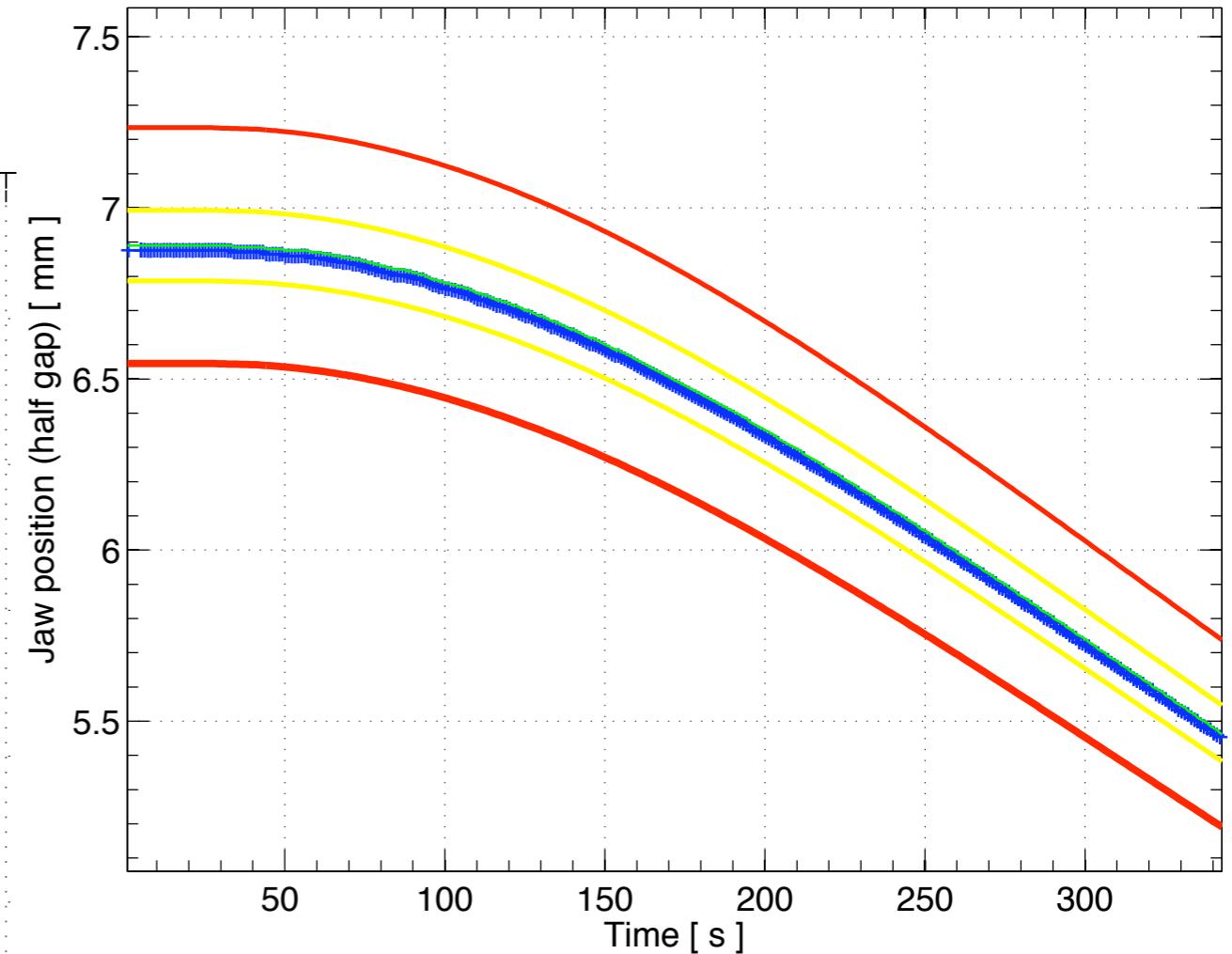
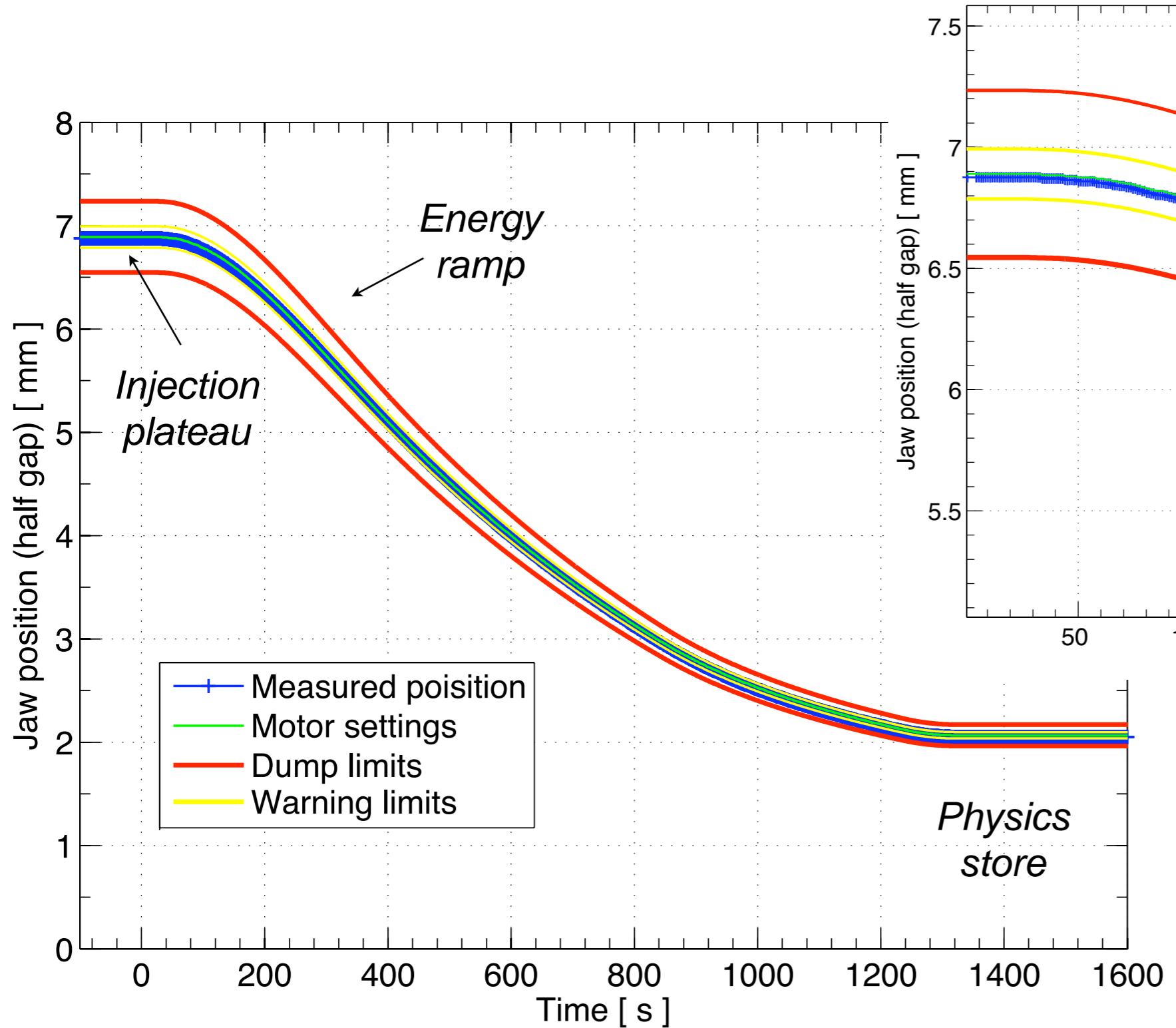
Outcome: A few problems encountered and solved.

Functionality FULLY validated. Ready for higher stored energies!

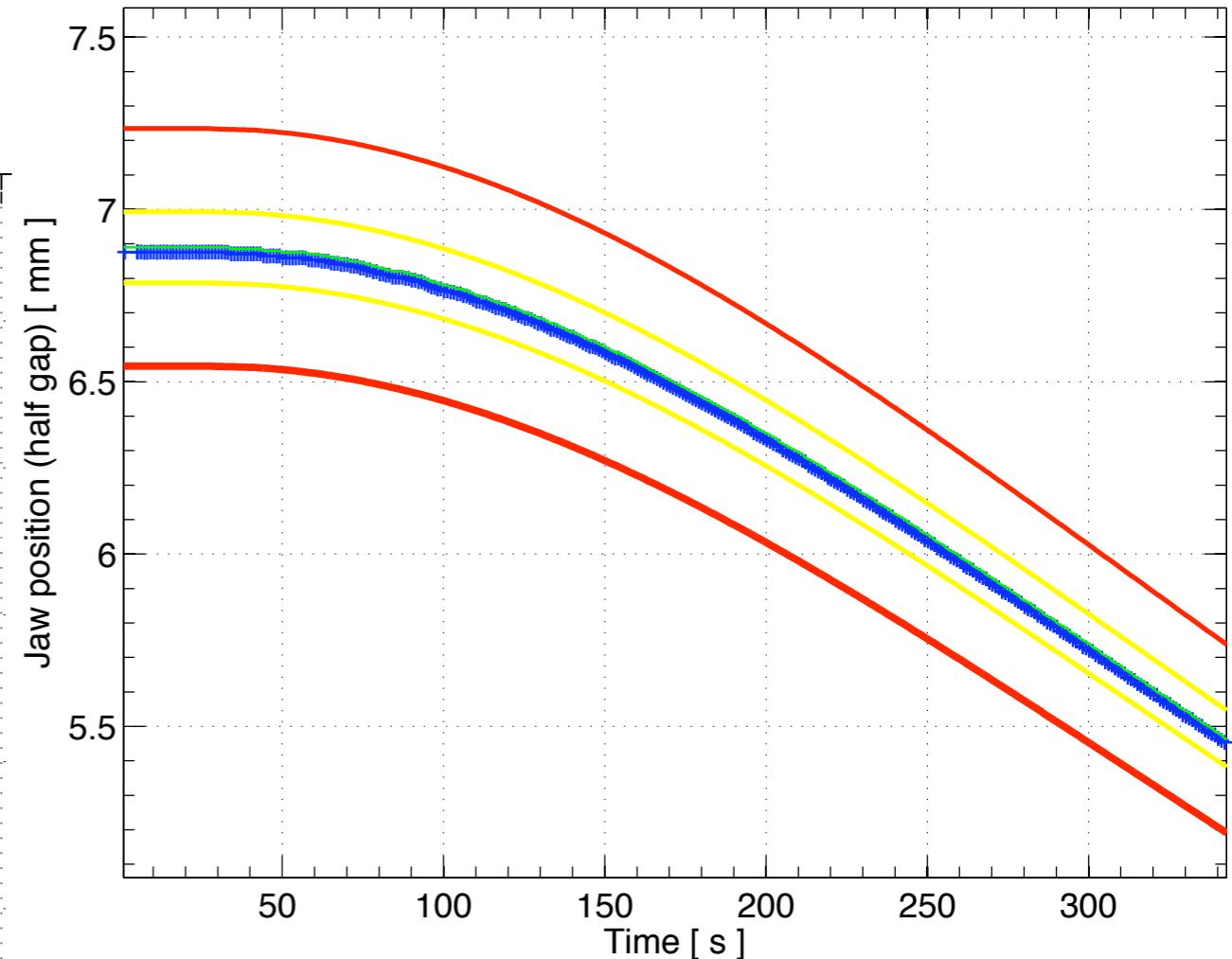
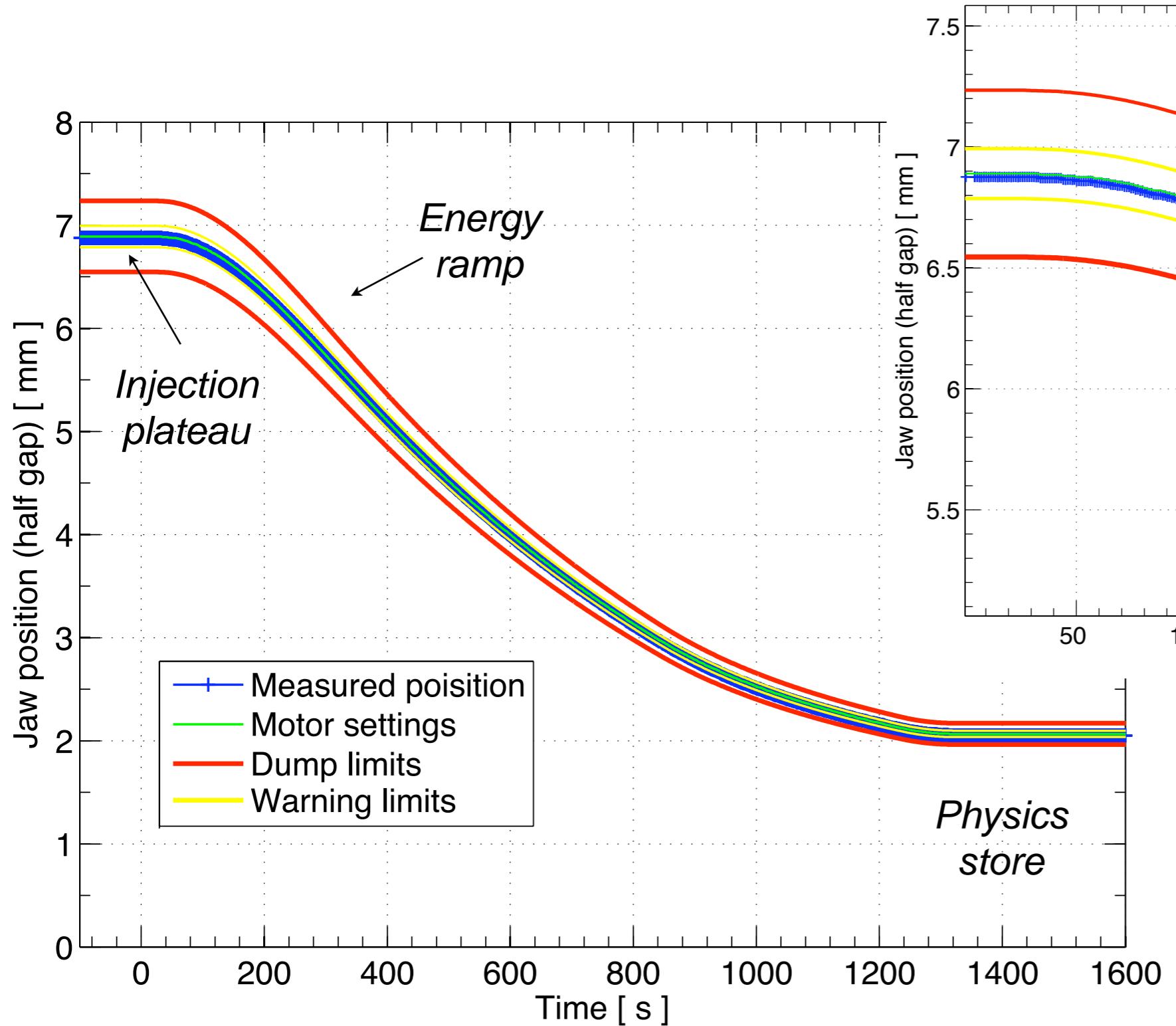
Function-driven limits



Function-driven limits

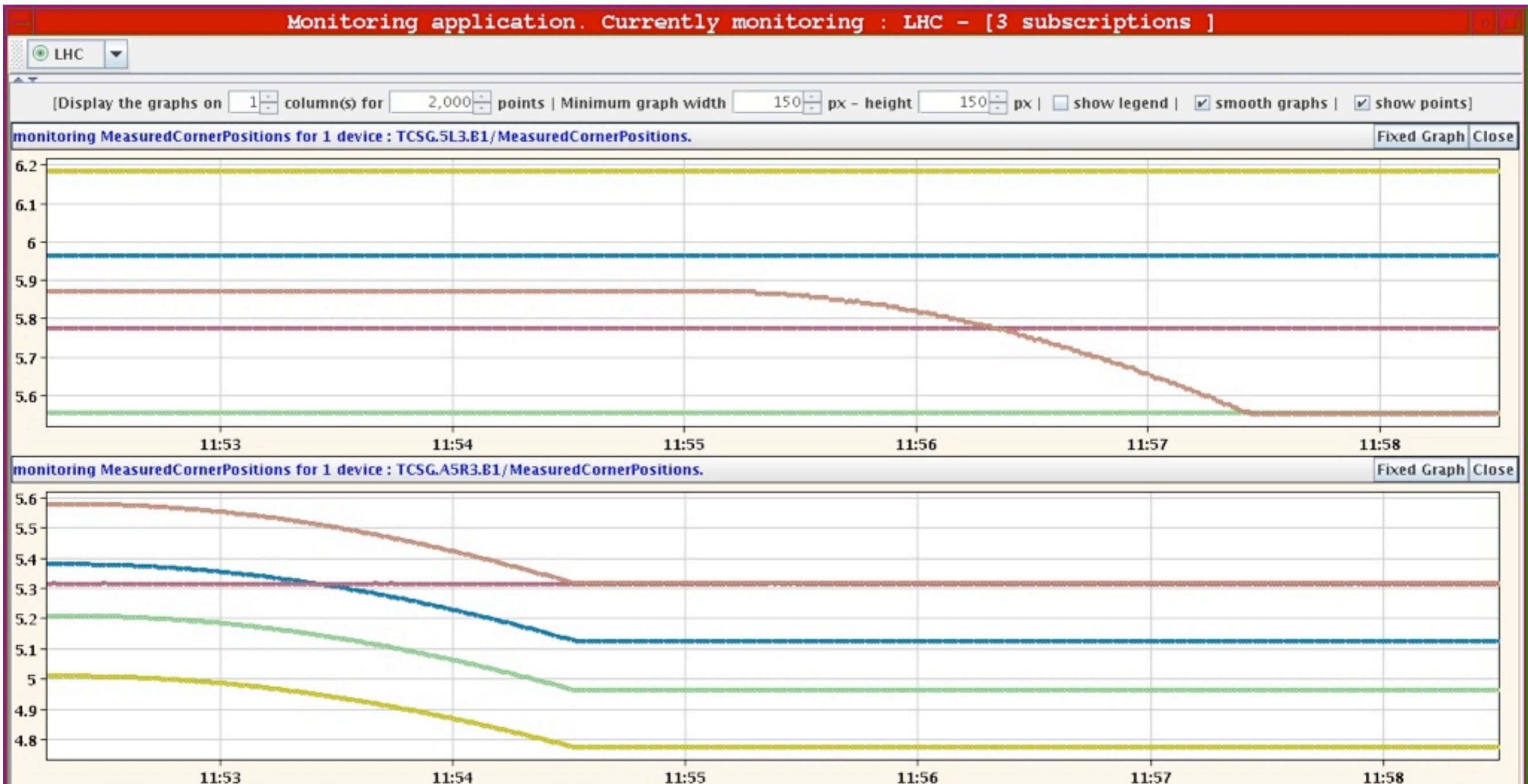


Function-driven limits



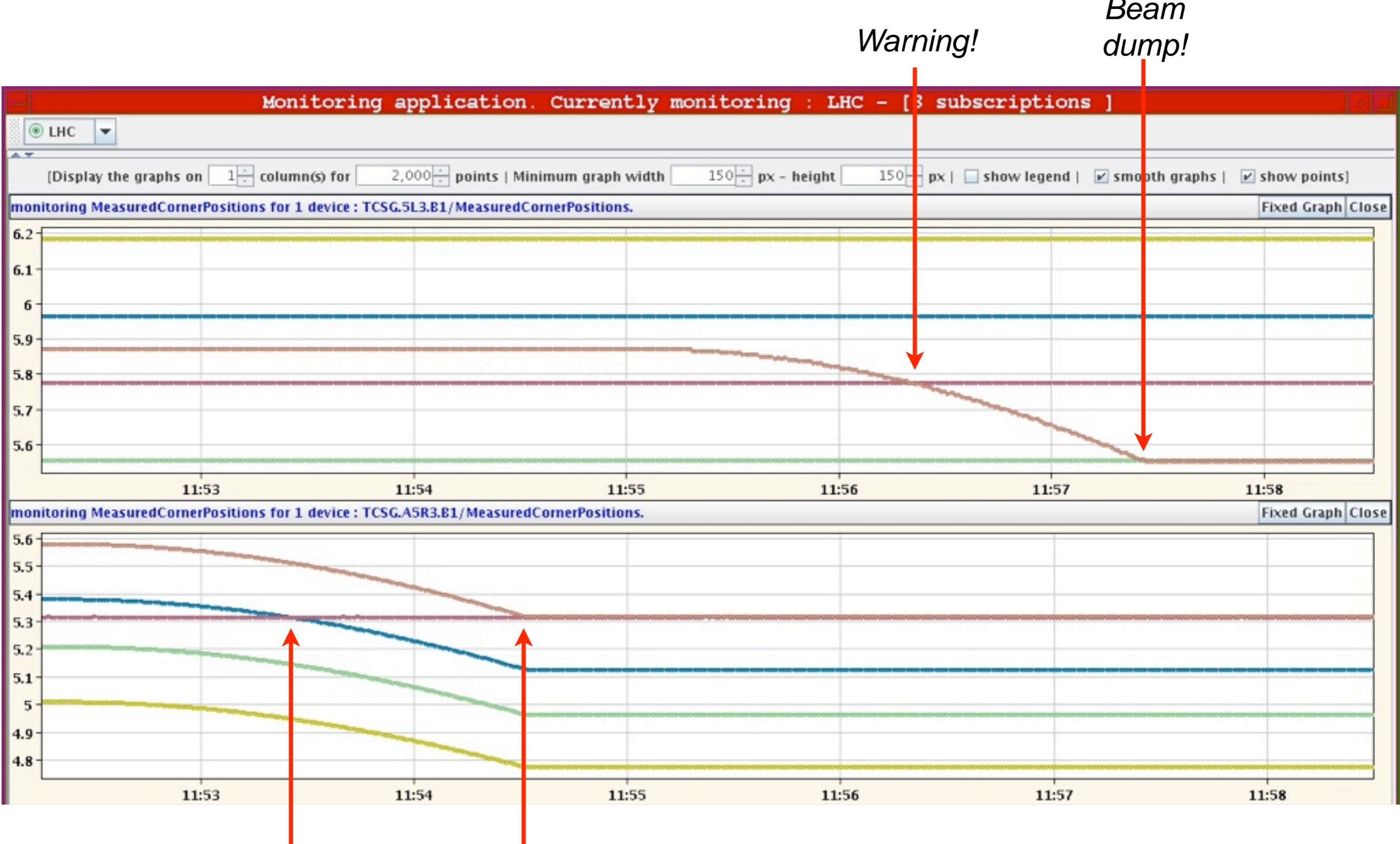
- Individual system tests performed with several collimators in the tunnel
- Synchronization with the LHC power converters
- Reproducibility studies will tell how tight can we set the operational window

Systematic checks of limit functions



Various case studies for failure cases: settings or limits do not start as expected...

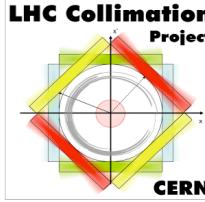
Systematic checks of limit functions



Warning!

Beam
dump!

Various case studies for failure cases: settings or limits do not start as expected...



Outline

Introduction

Operational requirements

Recap. of collimator design

The 2008 system

Commissioning without beam

Synchronized energy ramps

Accuracy / Reproducibility

Interlock commissioning

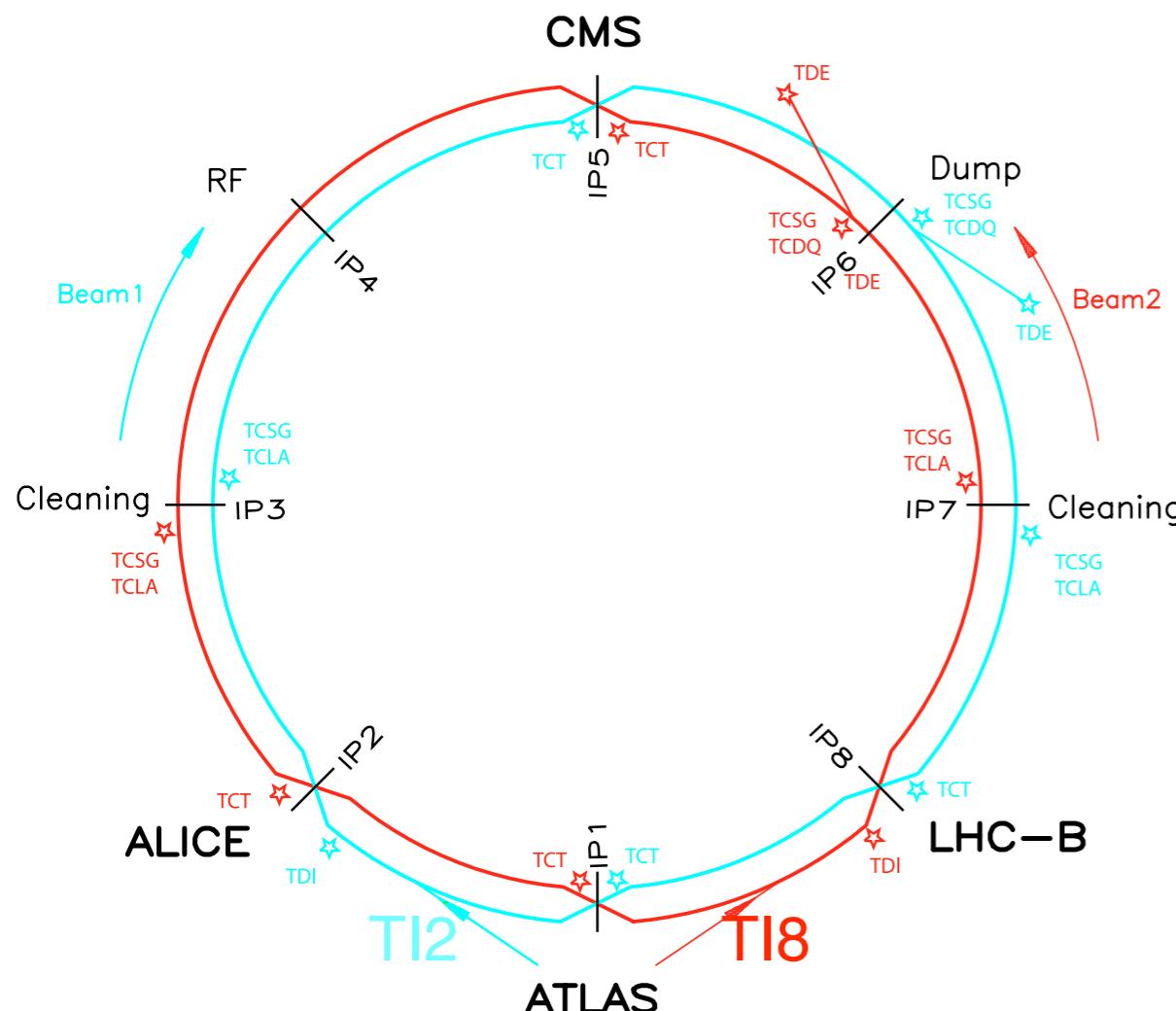
Experience with beam

Transfer line commissioning

Operation of ring collimators

Conclusions

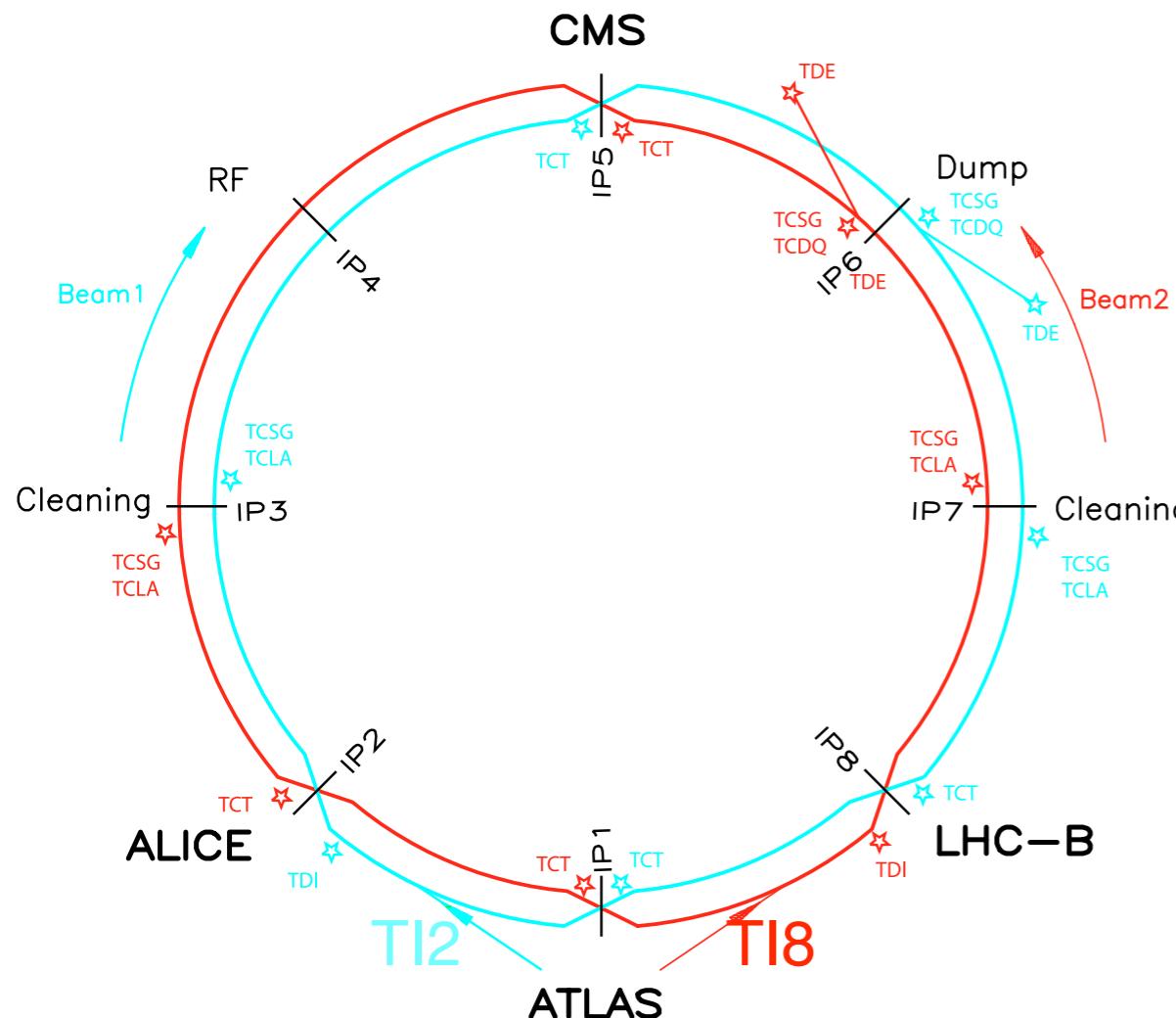
Overview of collimator beam tests



- 1) Beam commissioning of three transfer line collimators in TI2 (June 2008)
 - 2) Various “synchronization” and circulating beam tests in the LHC:
 - Collimators used to stop the beam during 4 synchronization tests (Aug./Sep.)
 - and in beam commissioning of Set. 10th
- Not possible to beam-commission the cleaning role with circulating beam.

Date	Test Outline
8-11 August	Beam 1 through sector 23
22-25 August	Beam 2 though sector 78, beam 1 through sector 23
5-8 September	Beam 2 through sectors 78,67, beam 1 through sectors 23, 34, 45
9 September	Preparation for 10 th September – beam 1 through sectors 23, 34, 45
10 September	Beam 1 and beam 2 around the whole circumference of the LHC

Overview of collimator beam tests



The LHC Injection Tests

I. Agapov, M. Aiba, M. Albert, R. Alemany Fernandez, G. Arduini, R. Assmann, R. Bailey, R. Billen, L. Bottura, O. Brüning, A. Butterworth, R. Calaga, E. Carlier, P. Collier, B. Dehning, L. Deniau, S. Fartoukh, F. Follin, D. Forkel-Wirth, K. Fuchsberger, R. Giachino, M. Giovannozzi, B. Goddard, J-J. Gras, E. Hatziangeli, P. Hagen, D. Jacquet, L. Jensen, R. Jones, V. Kain, I. Kozsar, T. Kramer, G. Kruk, M. Lamont, J. Lewis, A. Macpherson, M. Meddahi, V. Mertens, M. Misiowiec, S. Page, L. Ponce, B. Puccio, S. Redaelli, C. Roderick, S. Roesler, F. Roncarolo, M. Sapinski, F. Schmidt, R. Schmidt, W. Sliwinski, R. Steinhagen, M. Strzelczyk, Y. Sun, B. Todd, E. Todesco, R. Tomas Garcia, J. Uythoven, W. Venturini Delsolaro, Heinz Vincke, Helmut Vincke, E. Veyrunes, J. Wenninger, R. Wolf, C. Zamantzas, F. Zimmermann.

LHC Performance Note 1

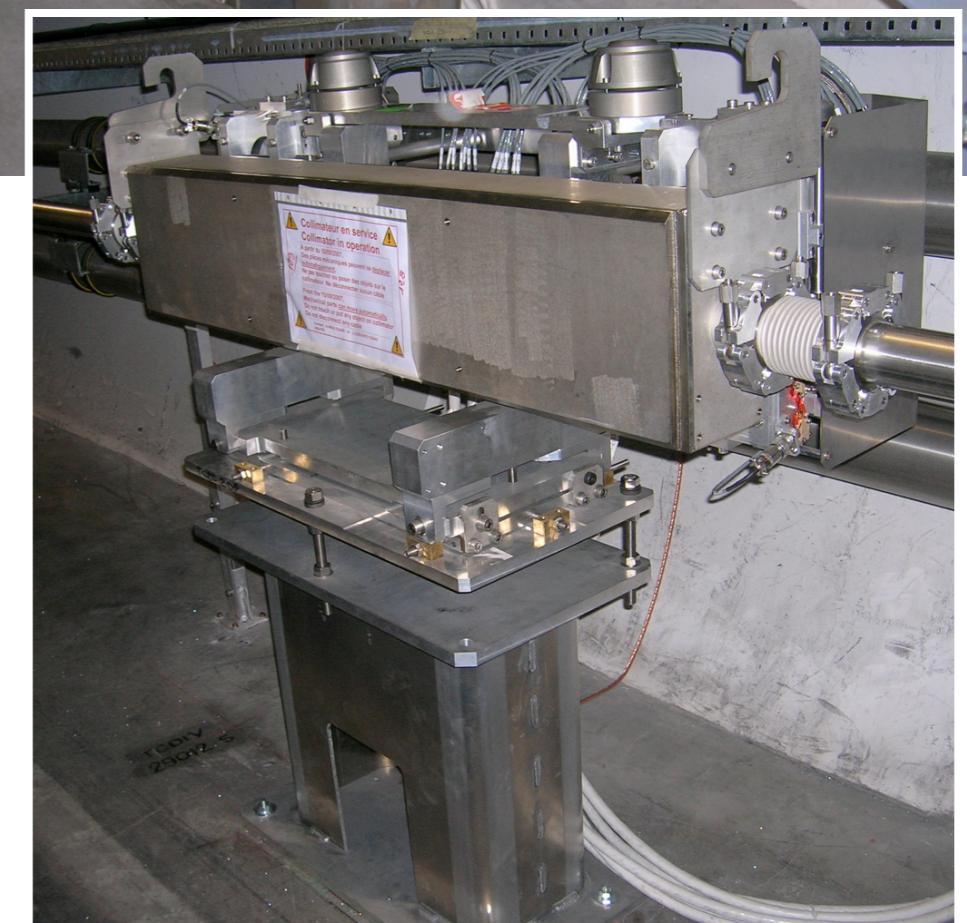
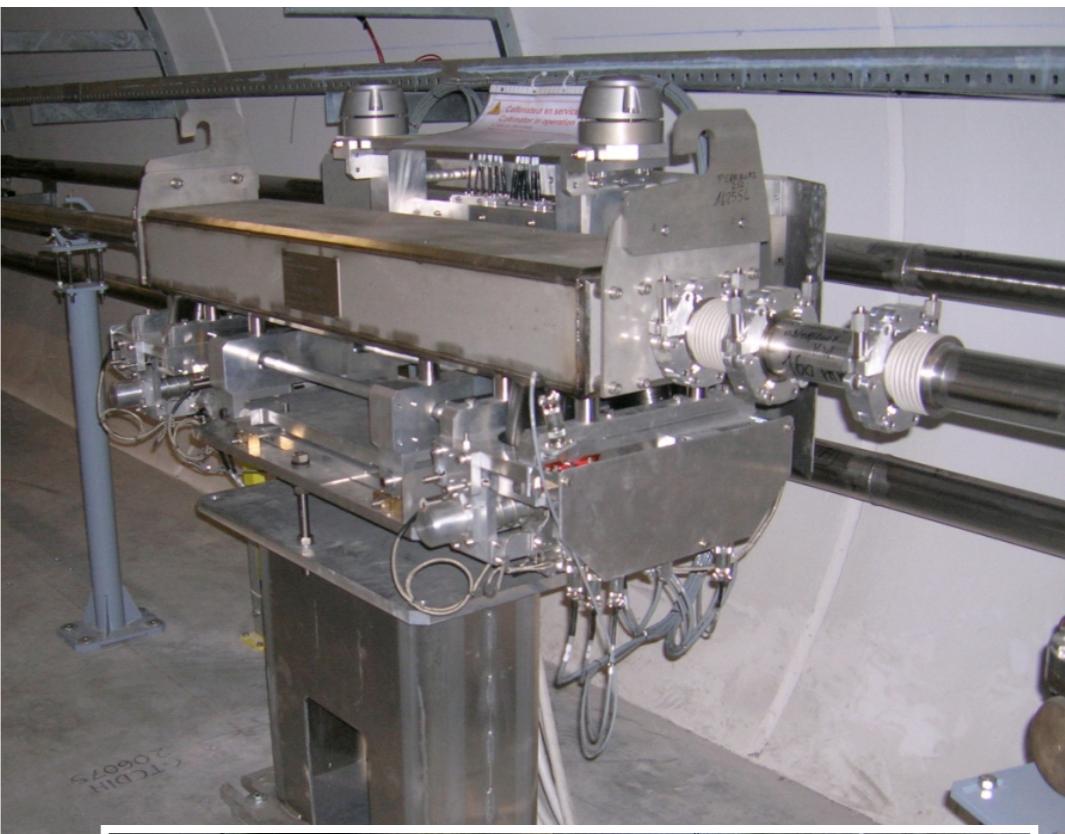
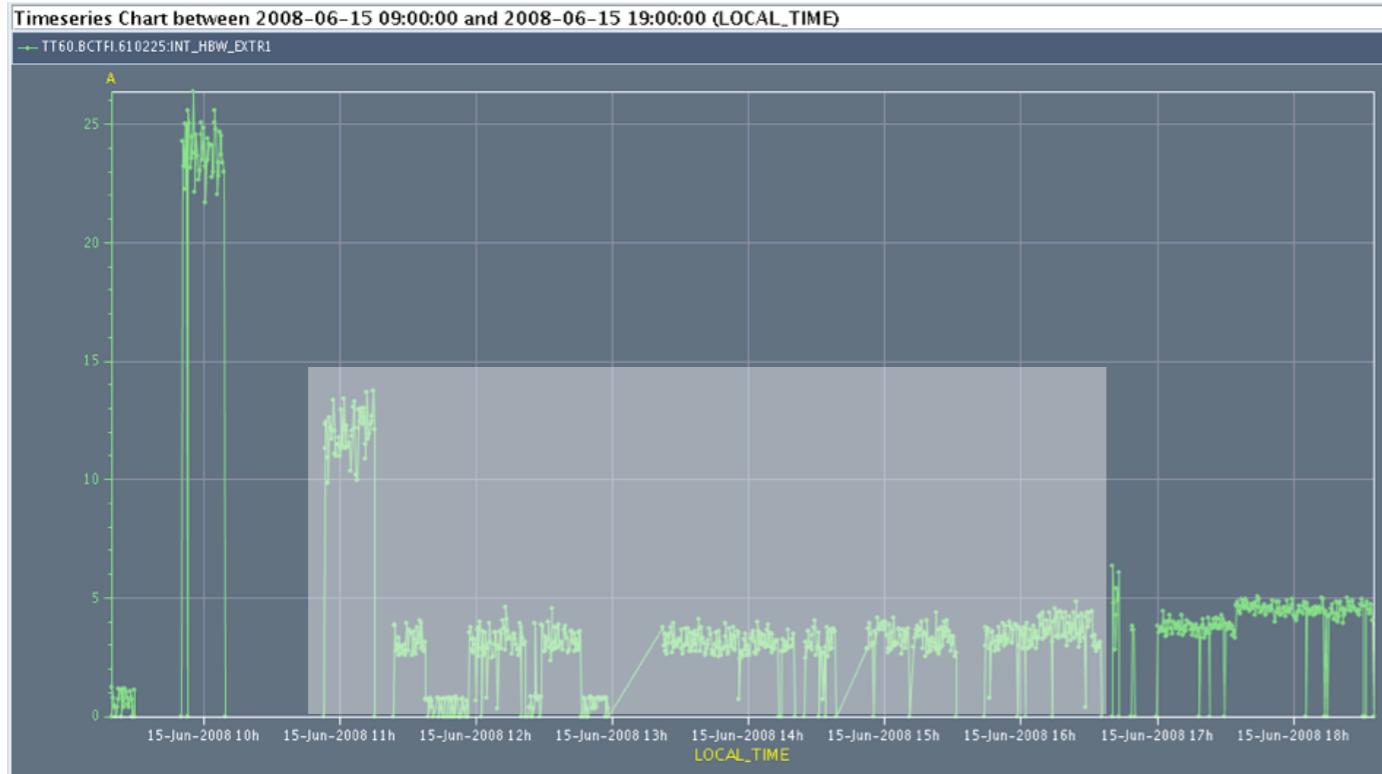
2008-10-21

Mike.Lamont@cern.ch

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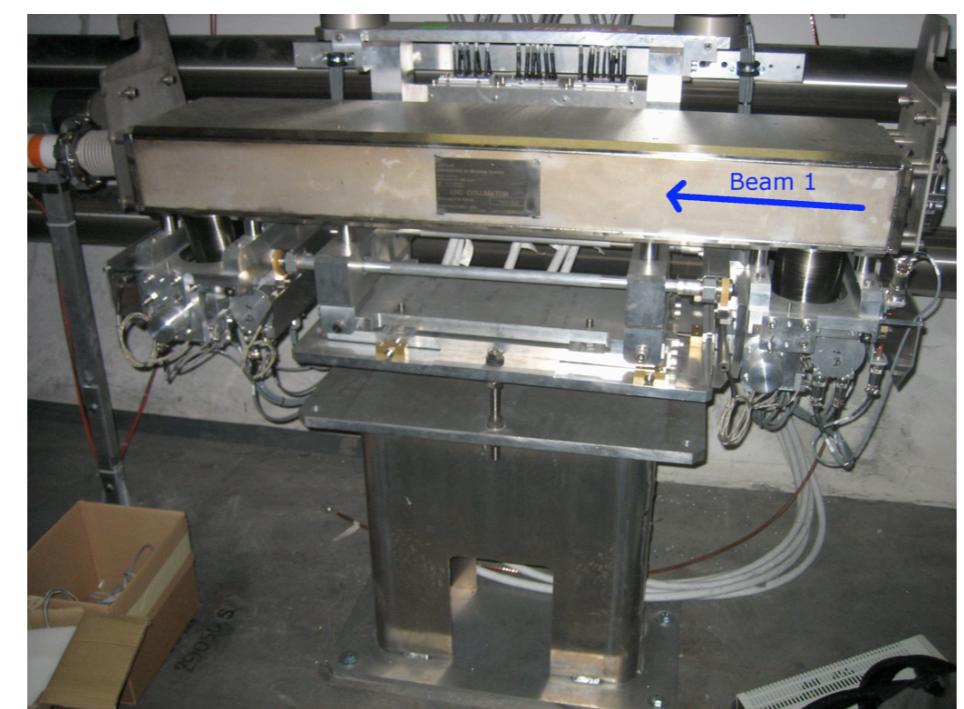
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Transfer line collimation tests



Beam commissioning
of **THREE TCDI**
collimators in TI2

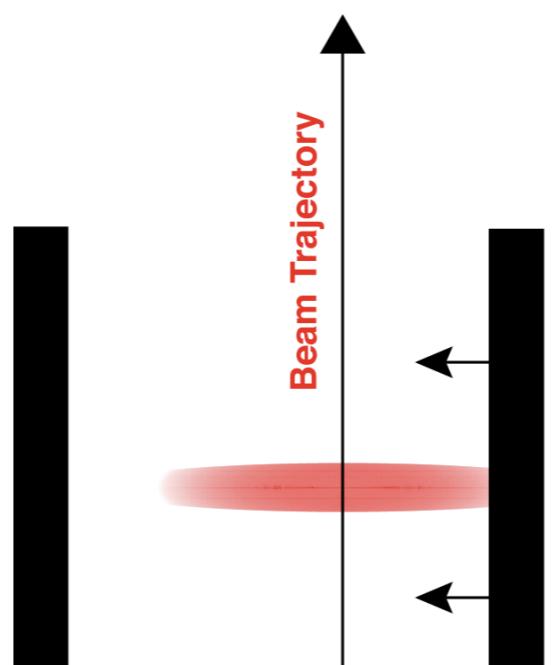
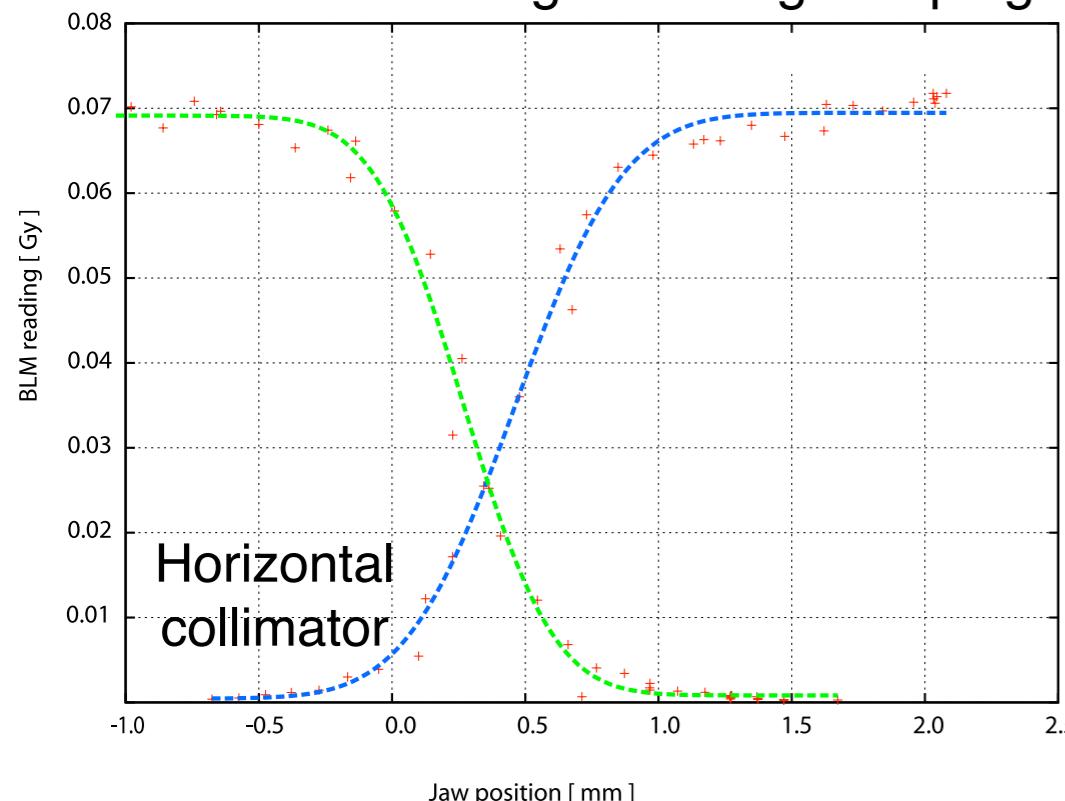
Beam conditions:
single and multi-
bunches,
 $\sim 5 \times 10^{10}$ p per bunch
Limited time available



O. Aberle, R. Assmann, M. Brugger,
V. Kain, A. Masi, V. Previtali,
S. Redaelli, T. Weiler, J. Uythoven

Beam-based alignment

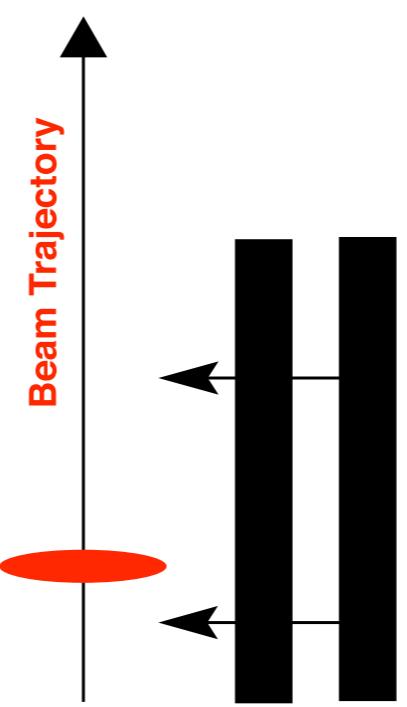
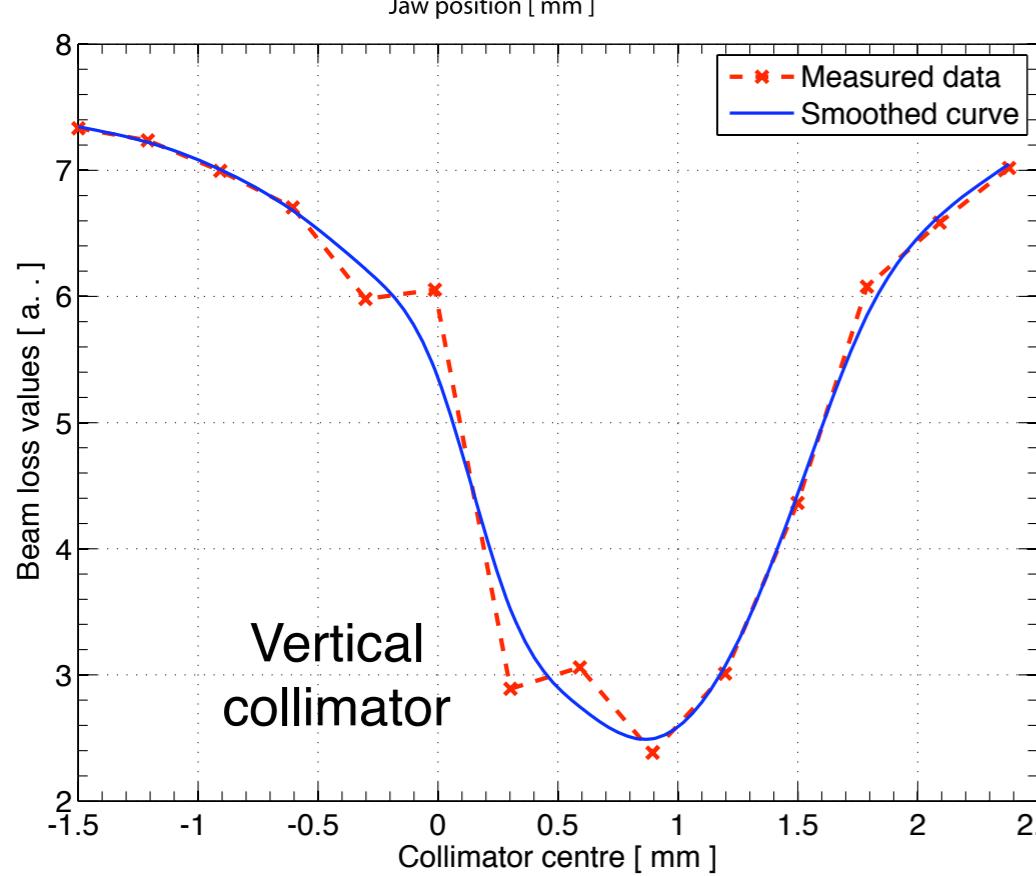
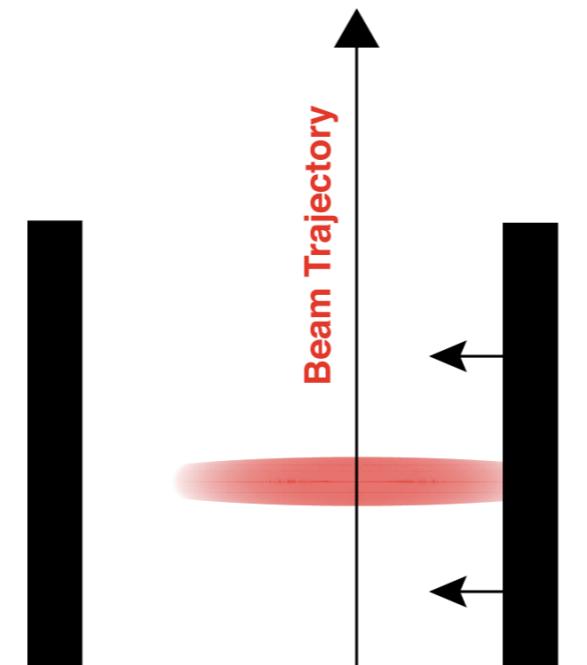
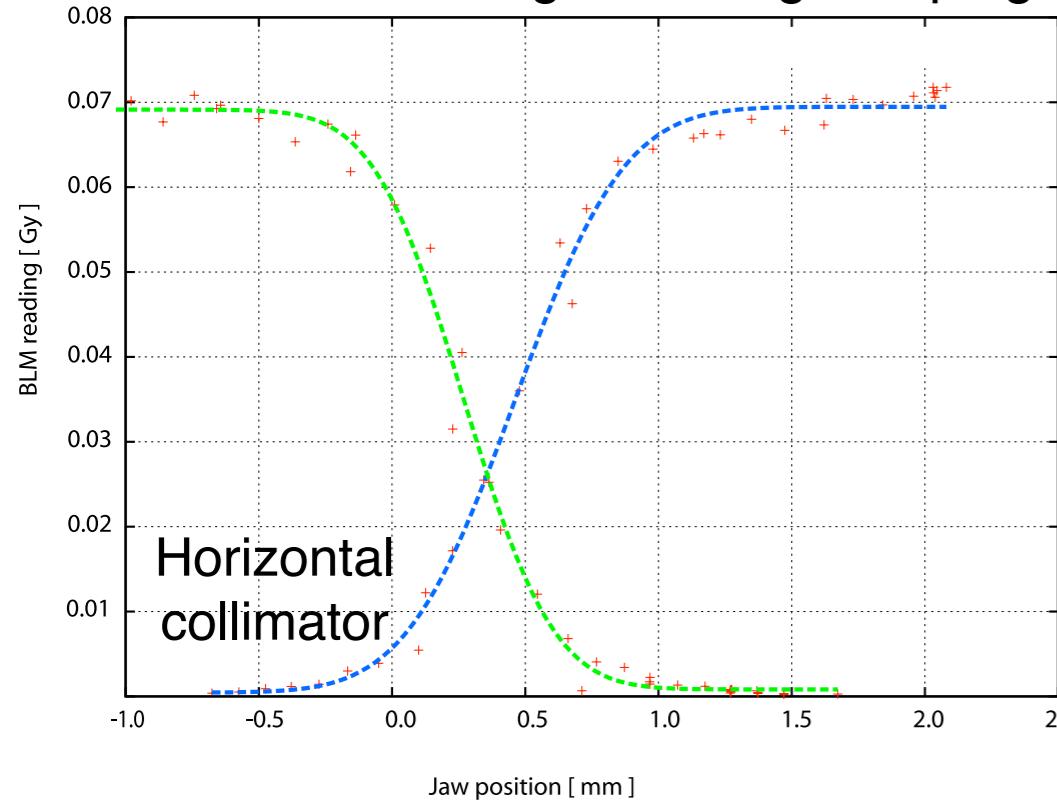
Beam loss signal during scraping



Vertical
collimator

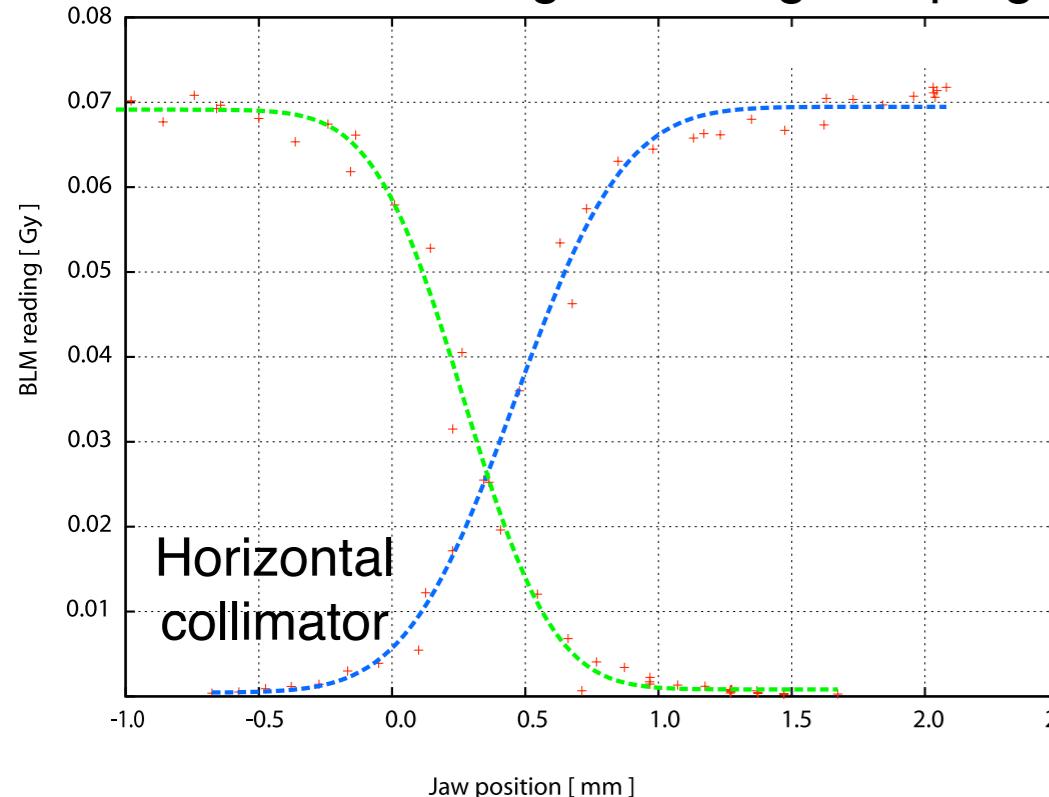
Beam-based alignment

Beam loss signal during scraping



Beam-based alignment

Beam loss signal during scraping



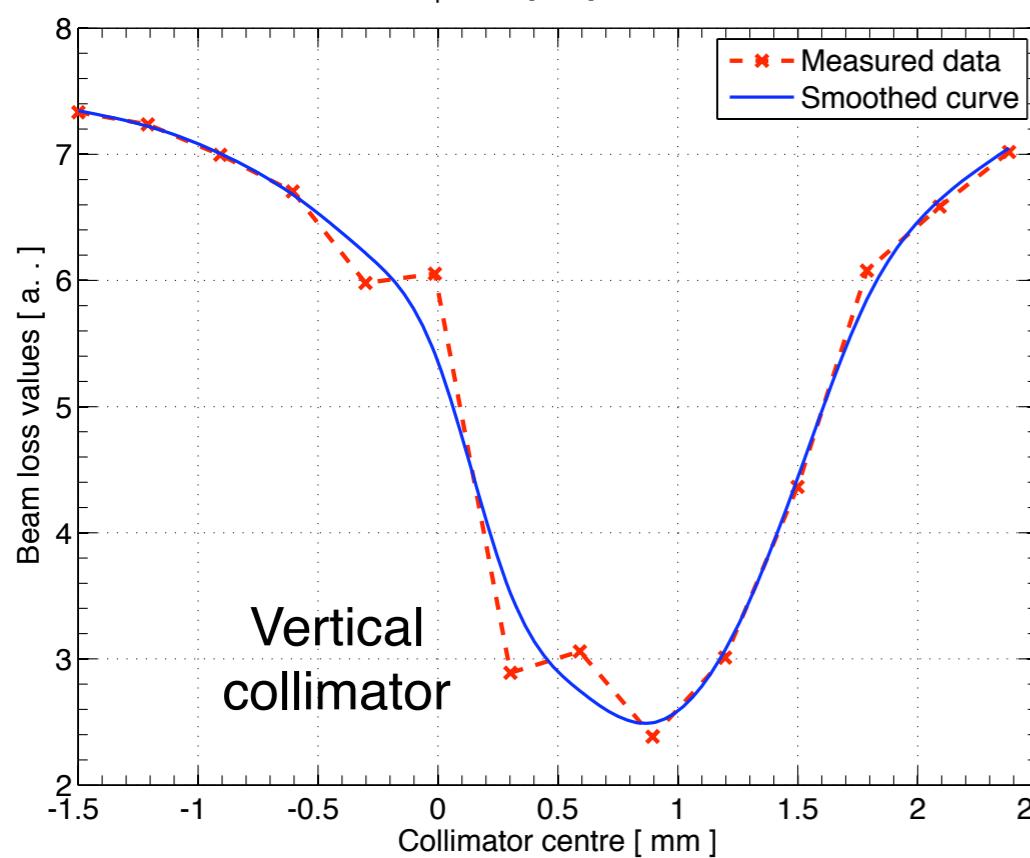
Horizontal collimator



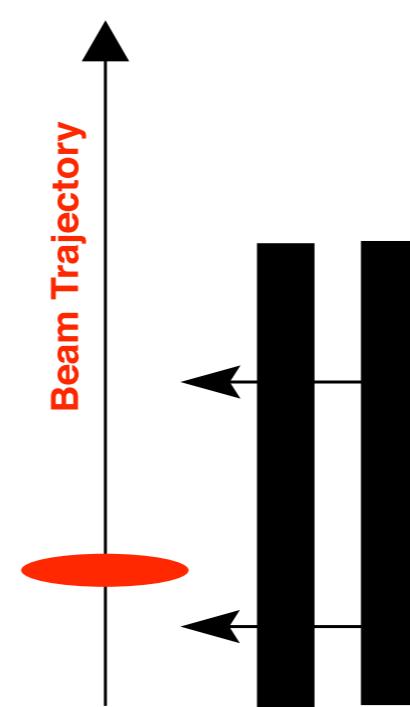
Beam scraping based on the reading of the beam loss monitors.

Beam centre and beam sizes at the collimator were measured.

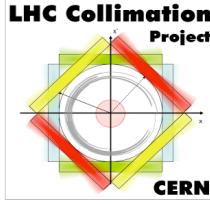
Accuracy below **50 µm**, results in agreement with other beam measurements (orbit, emittance, ...).



Vertical collimator



Beam-based parameters used on-line to generate nominal **protection settings!**



Generation of protection settings

X Trim Editor

Beams IPs Families Parameters Type Groups Parameters

B1	TI2	TCDIH	PHYSICS : COLL_JAW_TOLERANCE	TCDIH.20607/BBCentre
B2		TCDIV	PHYSICS : COLL_JAW	TCDIH.20607/BBParam#sigma_x
			PHYSICS : COLL_BBOptics	TCDIH.20607/BBParam#sigma_xp
			PHYSICS : COLL_NSIGMA	TCDIH.20607/BBParam#sigma_y
			PHYSICS : COLL_BBParam	TCDIH.20607/BBParam#sigma_yp
			PHYSICS : COLL_BBCentre	TCDIH.20607/NSIGMA
			PHYSICS : COLL_HalfGap_TOL	TCDIH.29050/BBCentre
			PHYSICS : COLL_HalfGap	TCDIH.29050/BBParam#sigma_z

Select All Select All Select All Select All Select All

Setting part: Value Target Correction Trim History Time base: SuperCycle Cycle/BeamProcess

Parameter	ramp_5TeV_ir5@0_[START]
TCDIH.20607/BBCentre	0.85
sigma_x	0.62
TCDIH.20607/NSIGMA	4.5

Trim

return

Beam Processes Beams IPs Families Parameters Type Groups Parameters

_NON_MULTIPLICATED_LHC	B1	TI2	TCDIH	PHYSICS : COLL_JAW	TCDIH.29465/RequiredAbsPositionFunct#left_downstream
DISCRETE_LHCRING_INJ_KICKER_V1			TCDIV	PHYSICS : COLL_BBOptics	TCDIH.29465/RequiredAbsPositionFunct#left_upstream
ramp_5TeV_ir5@0_[START]	B2			PHYSICS : COLL_NSIGMA	TCDIH.29465/RequiredAbsPositionFunct#right_downstream
Collimator_testV1.TRACKING-TEST-7TeV.BPO				PHYSICS : COLL_BBParam	TCDIH.29465/RequiredAbsPositionFunct#right_upstream
PRECYCLE-TEST-V2_MIKE-V1				PHYSICS : COLL_BBCentre	TCDIH.20607/RequiredAbsPositionFunct#left_downstream
RAMP-IR5-4.135TeV@0_[START]				PHYSICS : COLL_HalfGap_TOL	TCDIH.20607/RequiredAbsPositionFunct#left_upstream
RAMP-IR5-4.135TeV_V1				PHYSICS : COLL_HalfGap	TCDIH.20607/RequiredAbsPositionFunct#right_downstream
RAMP-IR5-4.2TeV_V1				PHYSICS : COLL_NSIGMA_TOL	TCDIH.20607/RequiredAbsPositionFunct#right_upstream
RAMP-IR5@0_[START]				HW SETTINGS : COLL_MOTOR_TOLERANCE	TCDIH.29050/RequiredAbsPositionFunct#left_downstream
RAMP_IR5V1_RAMP_IR5_PPO				HW SETTINGS : COLL_MOTOR_POSITION	TCDIH.29050/RequiredAbsPositionFunct#left_upstream

Show hidden Select All Select All Select All Select All Select All

Setting part: Value Target Correction Trim History Time base: SuperCycle Cycle/BeamProcess

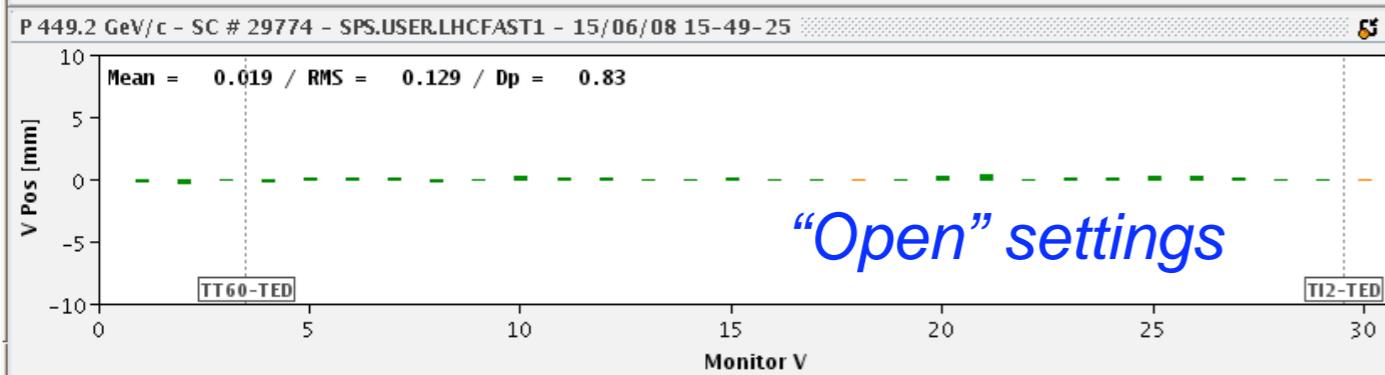
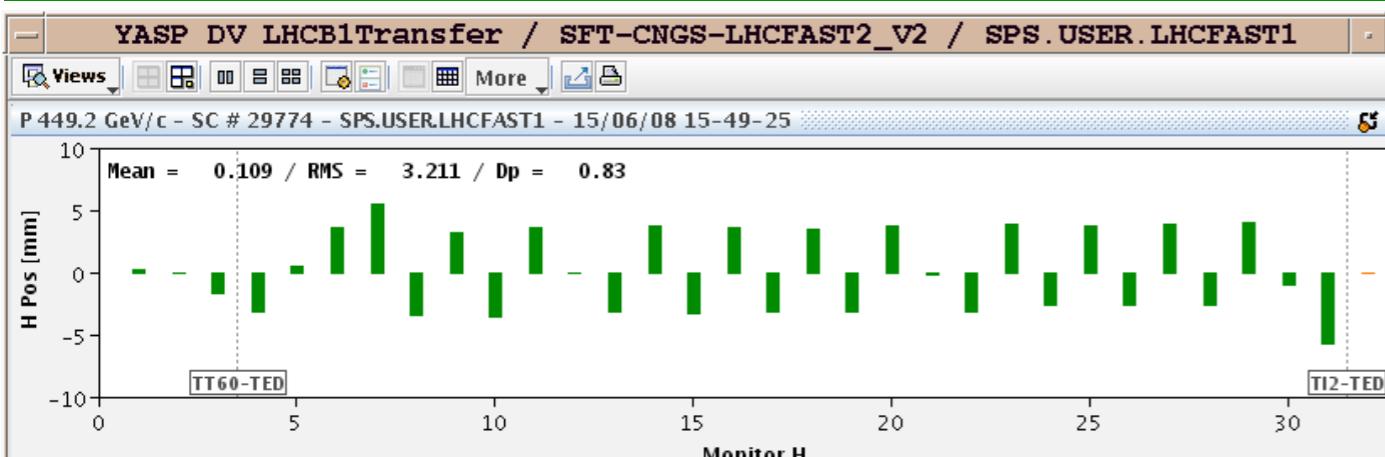
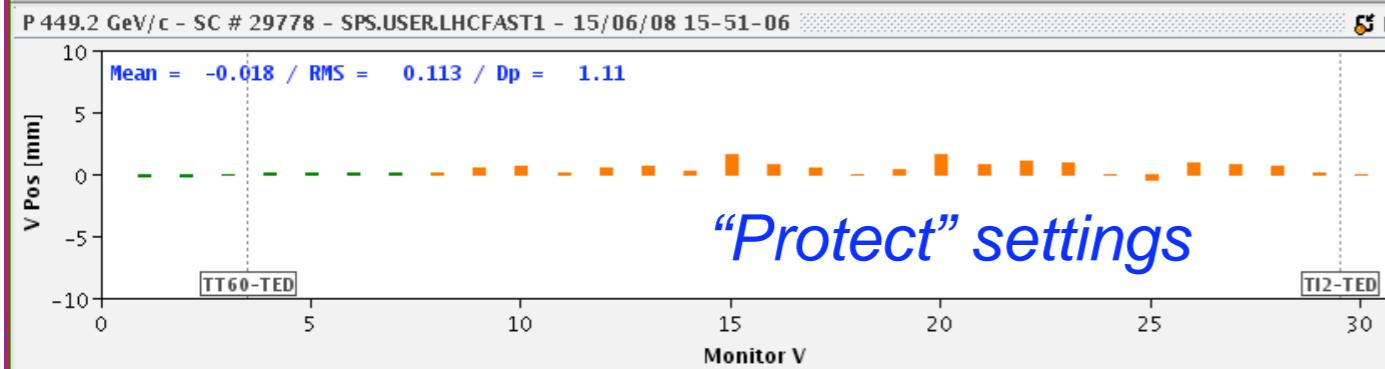
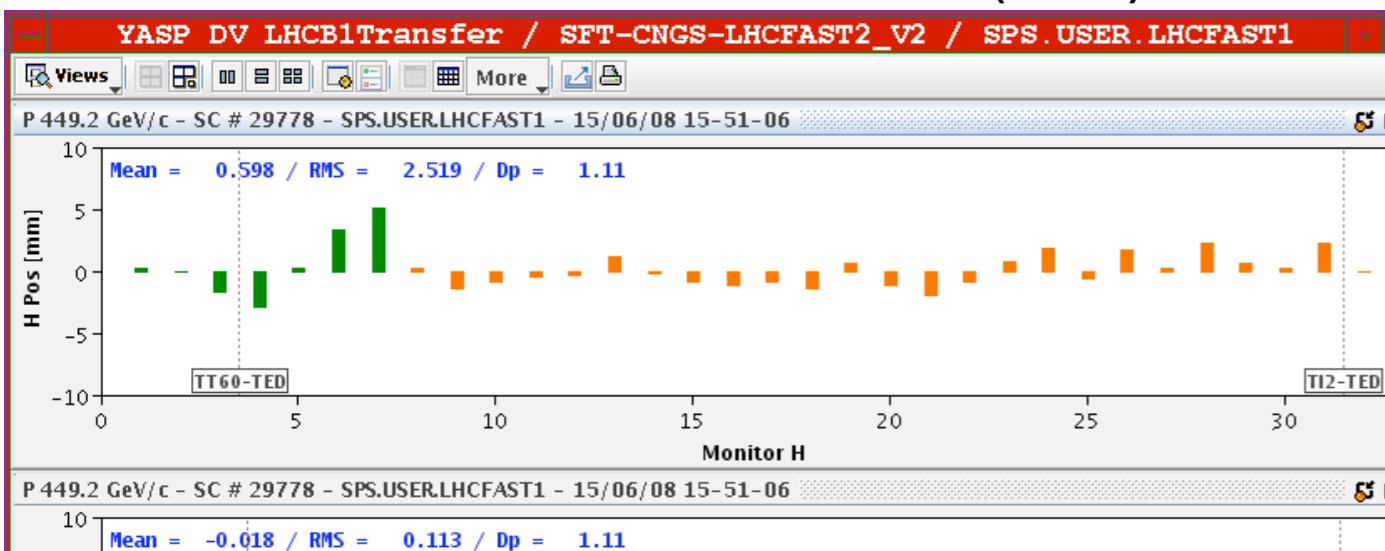
Parameter	ramp_5TeV_ir5@0_[START]
left_downstream	3.6399500556074607
left_upstream	3.6400499443925396
right_downstream	-1.9400499443925394
right_upstream	-1.9399500556074605

Trim



Beam verification of protection settings

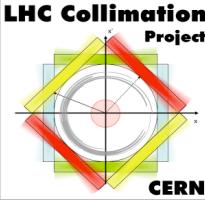
Measured beam orbit (H/V)



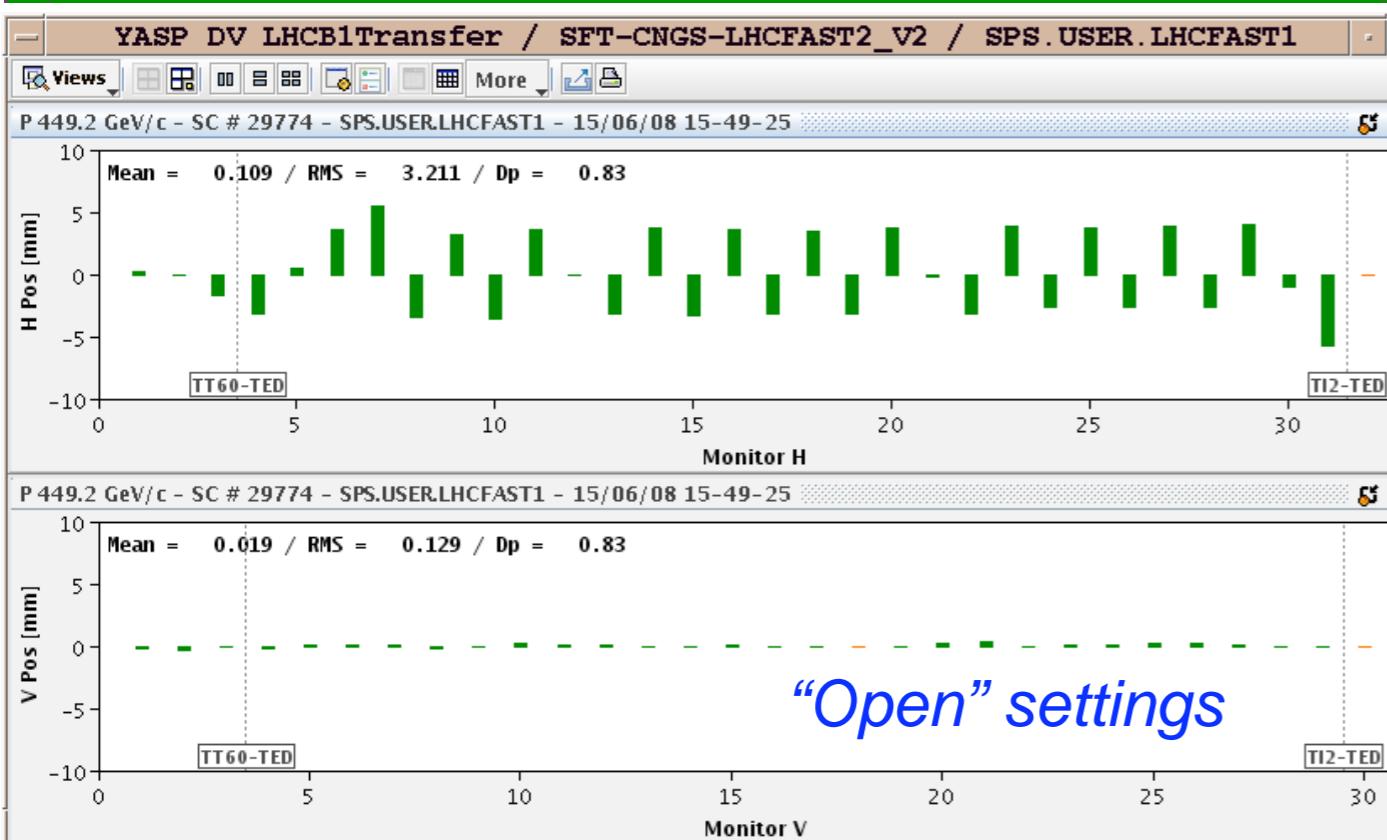
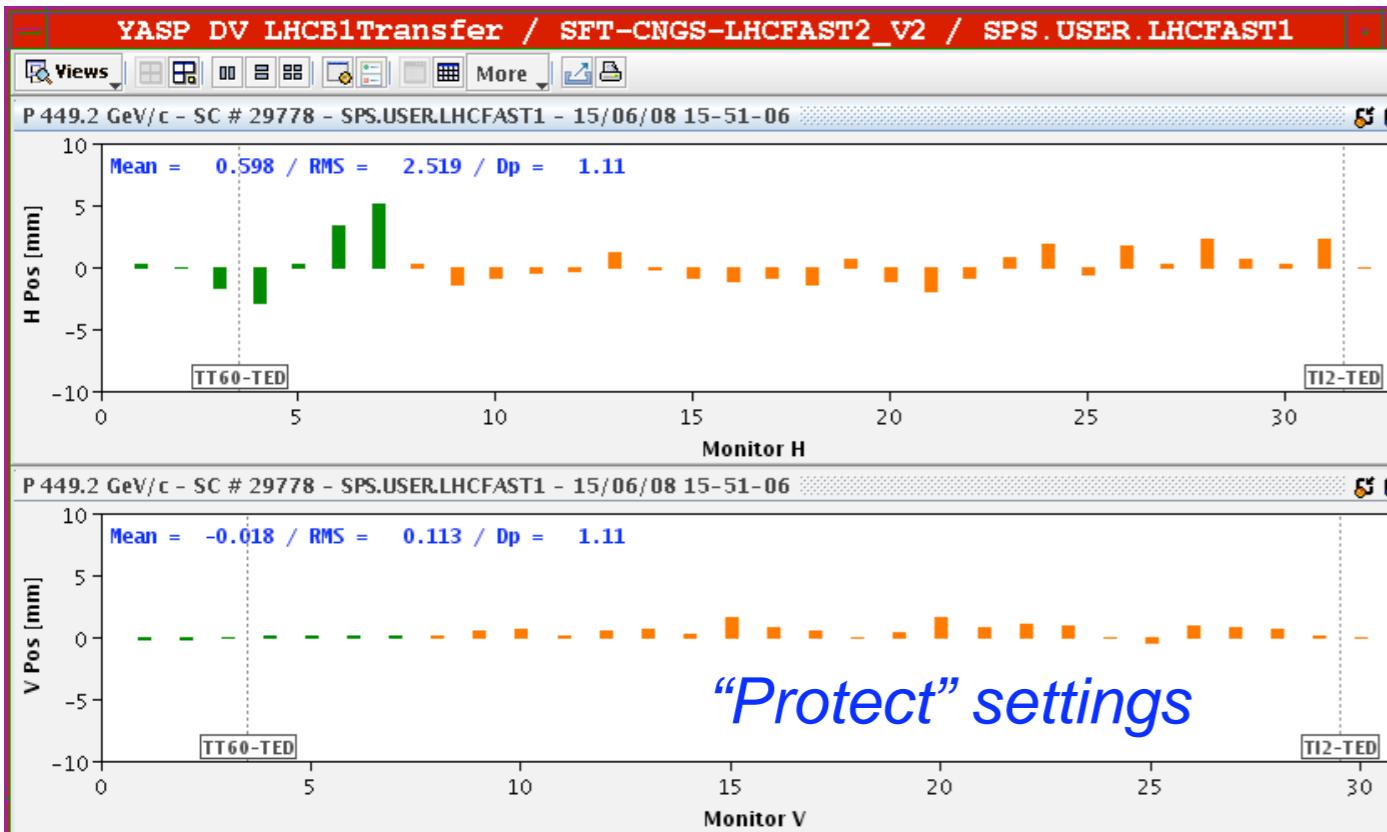
Tested systematically one collimator.



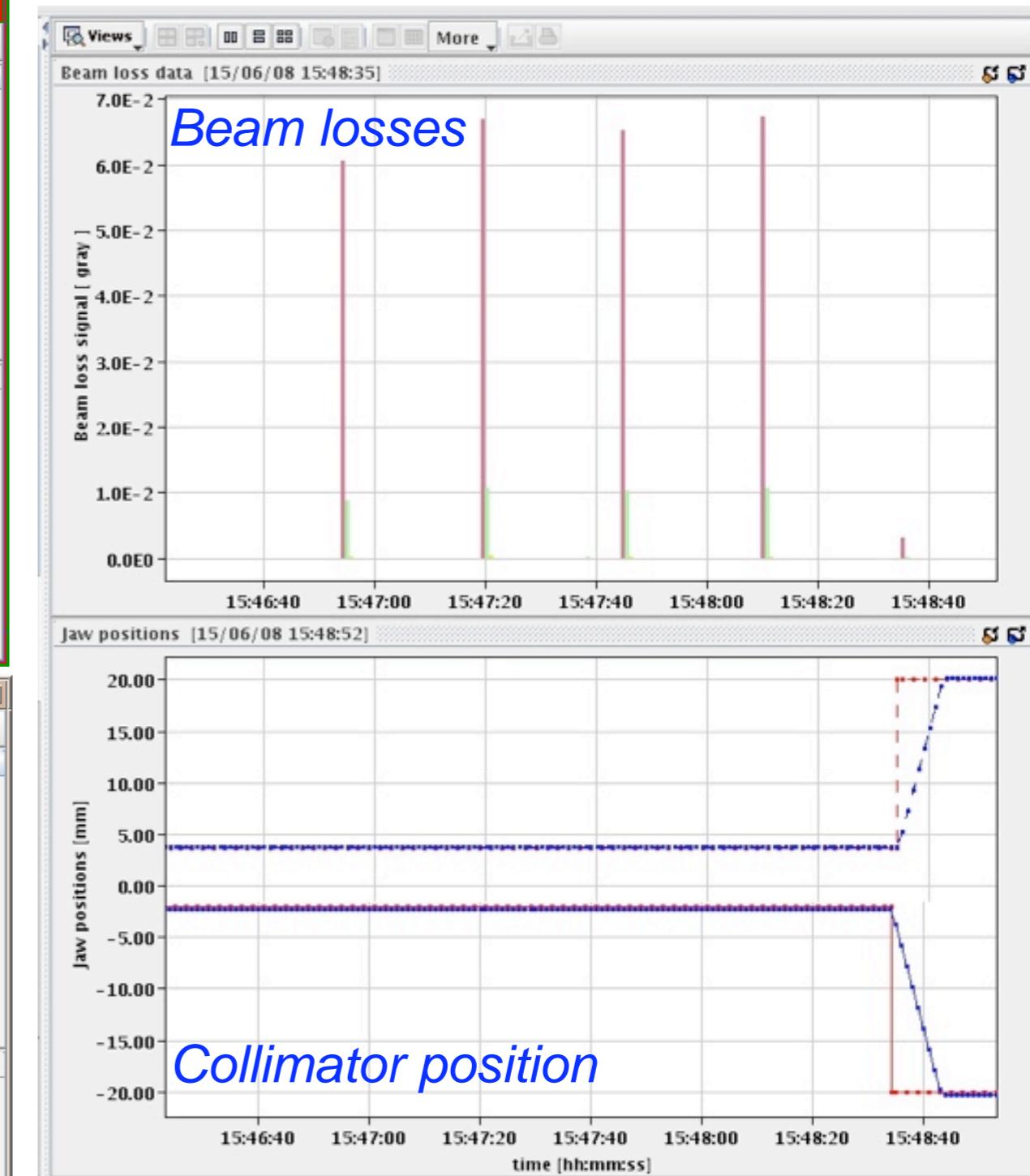
Beam verification of protection settings



Measured beam orbit (H/V)



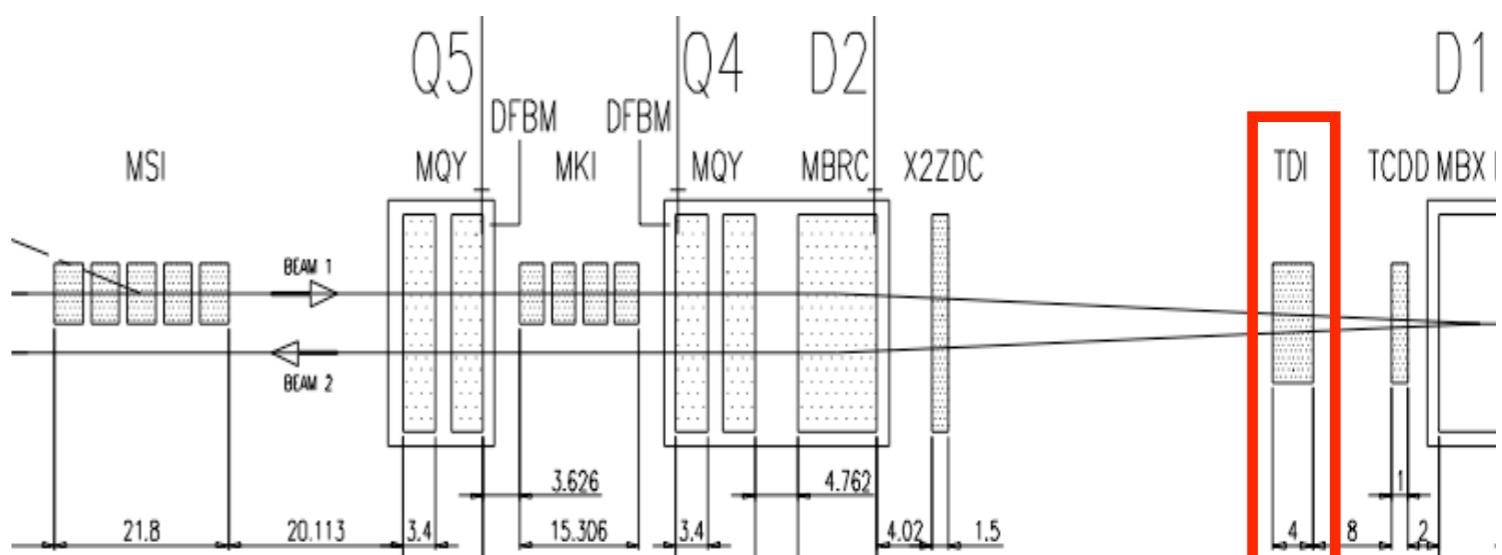
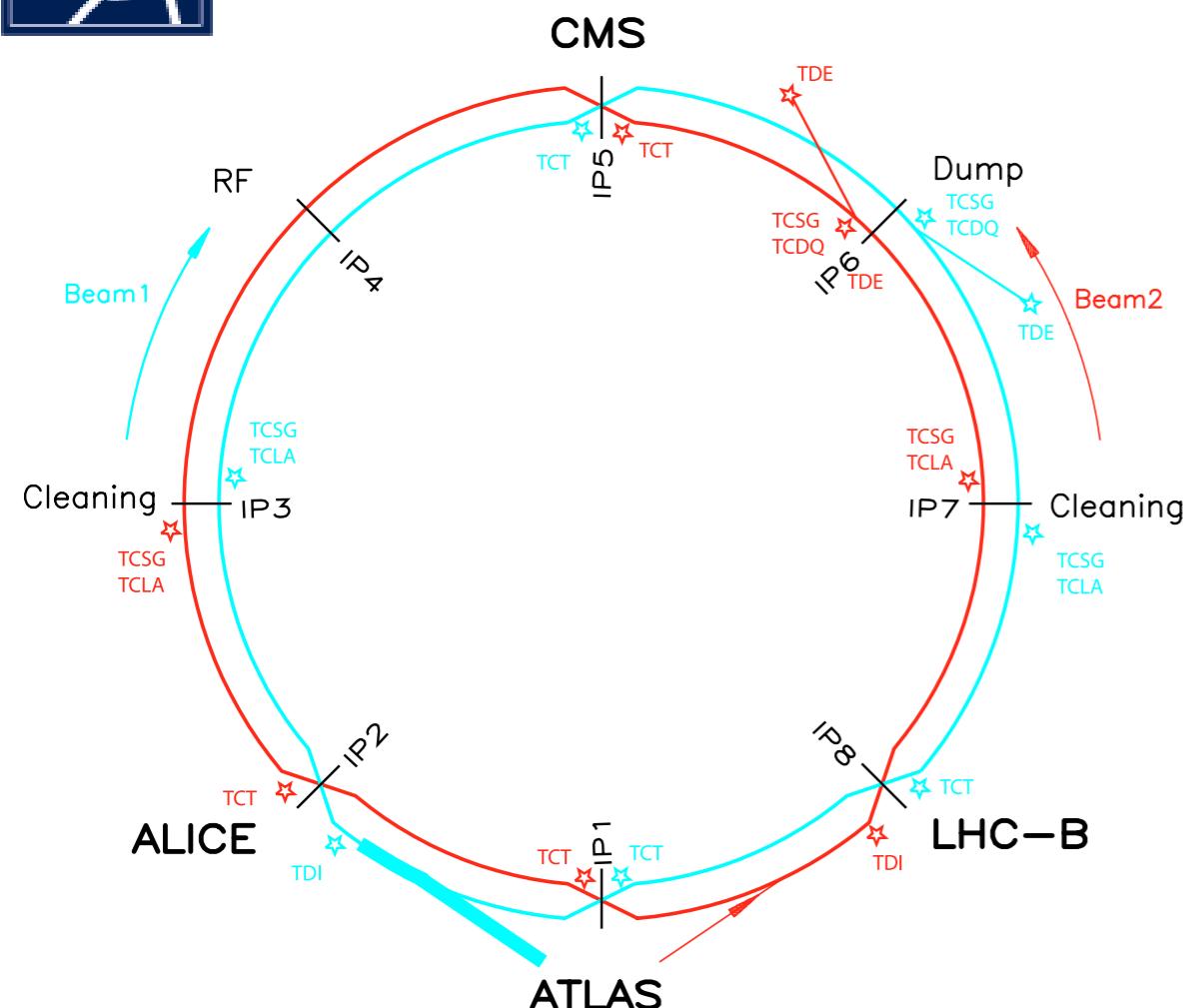
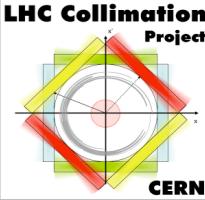
Beam losses at the collimator



Tested systematically one collimator.

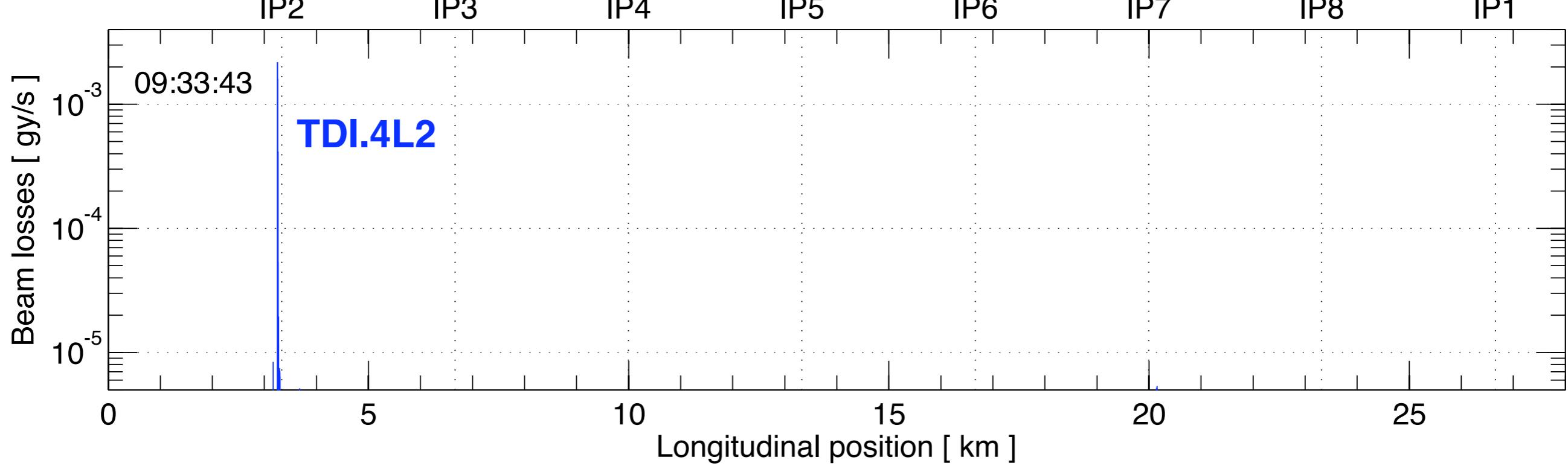
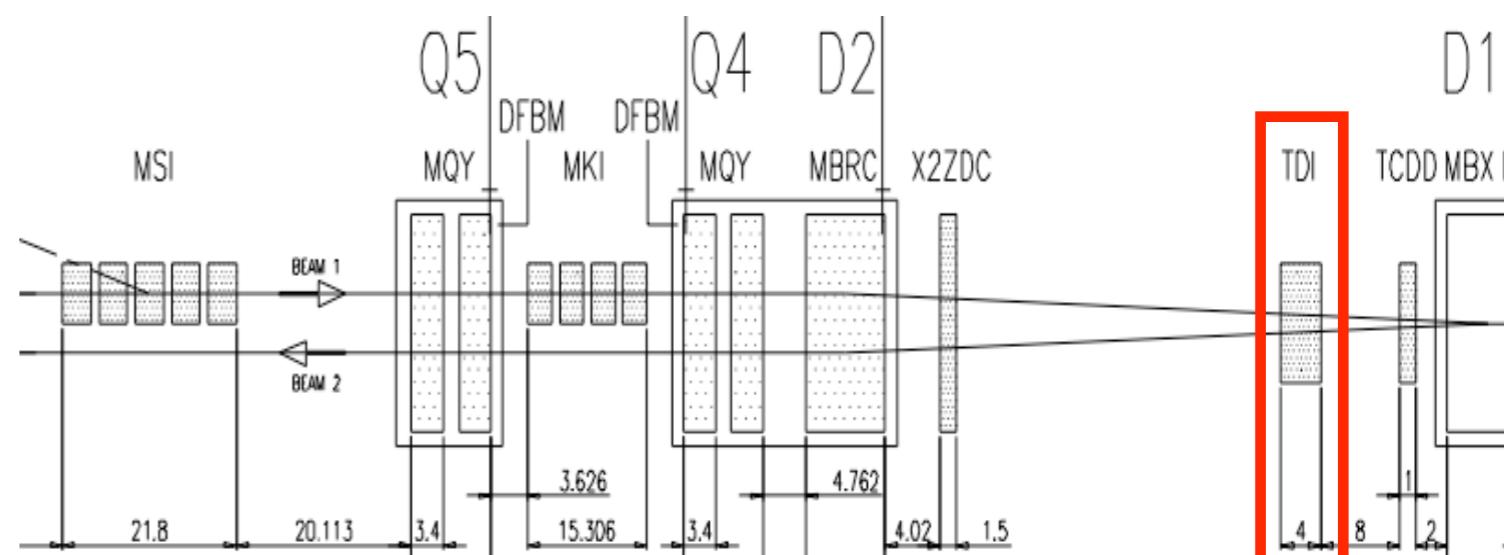
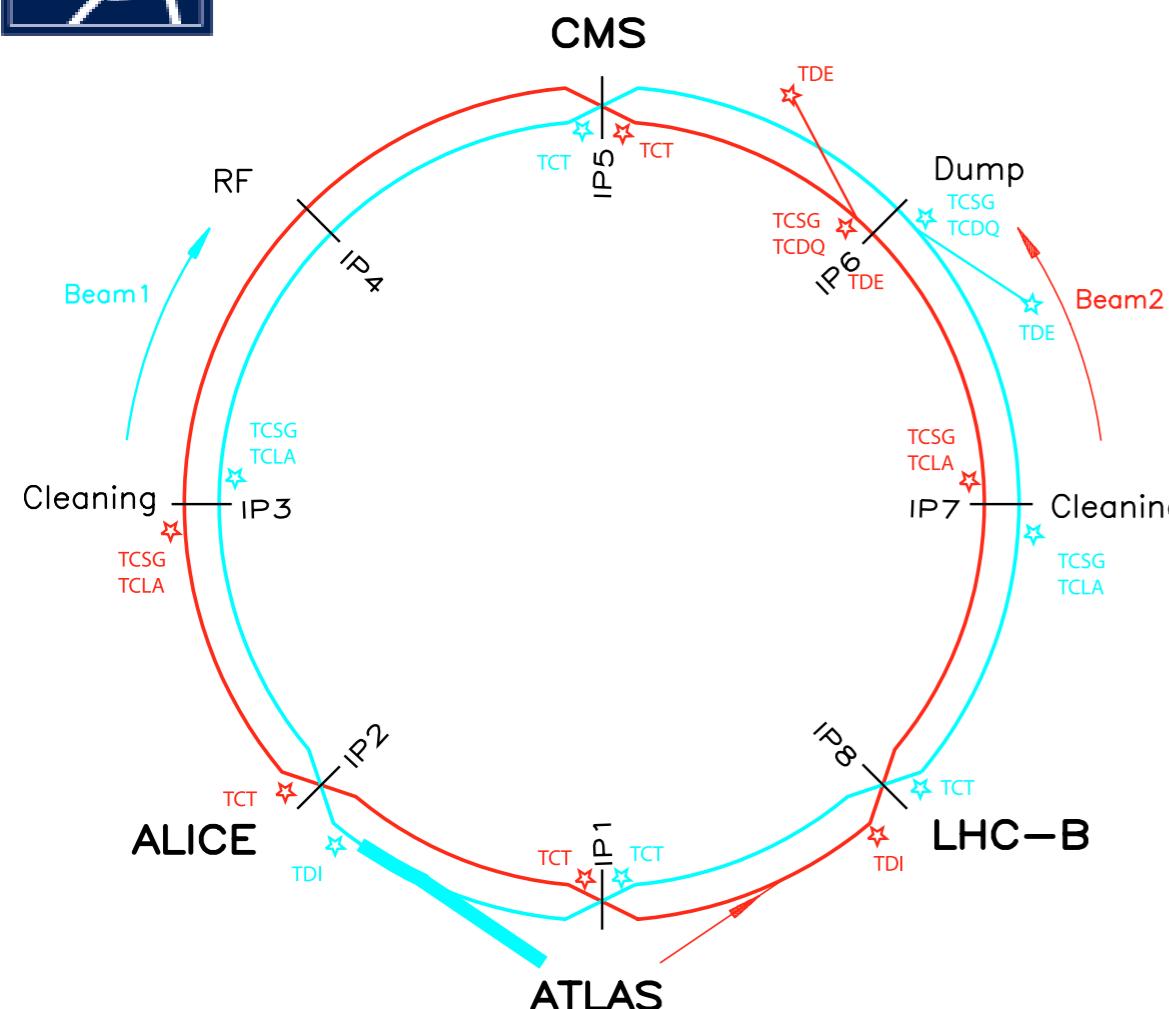
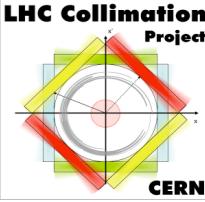


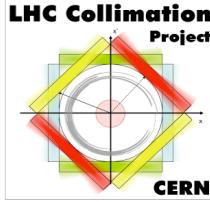
Beam on TDI



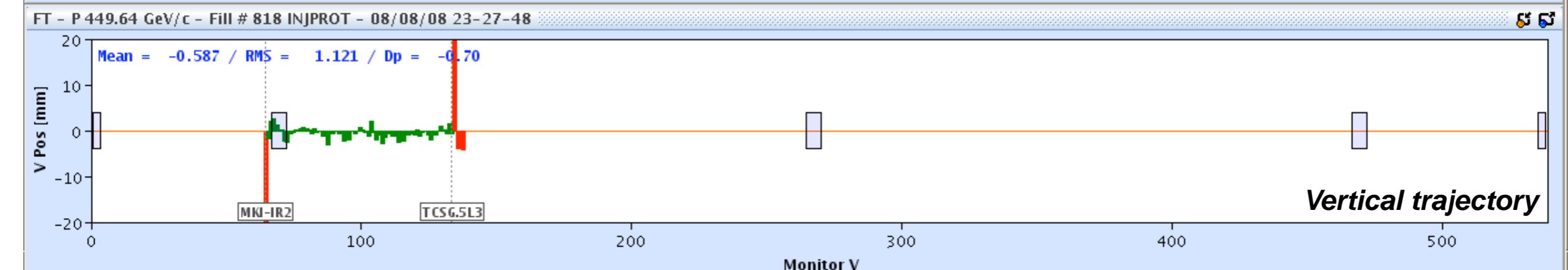
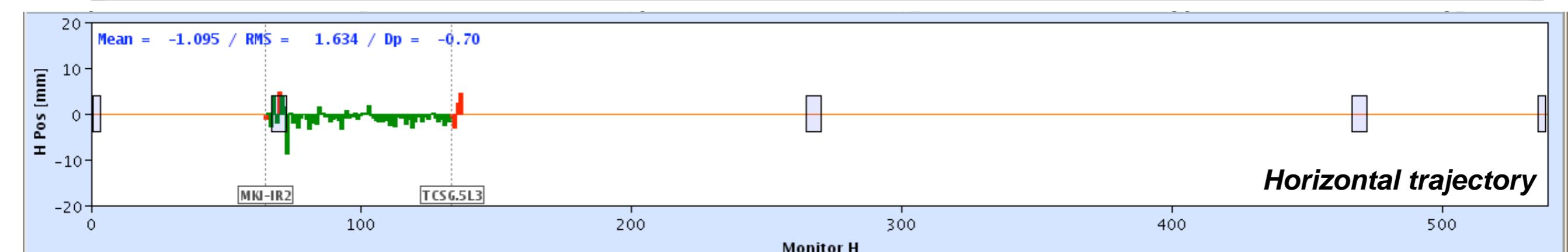
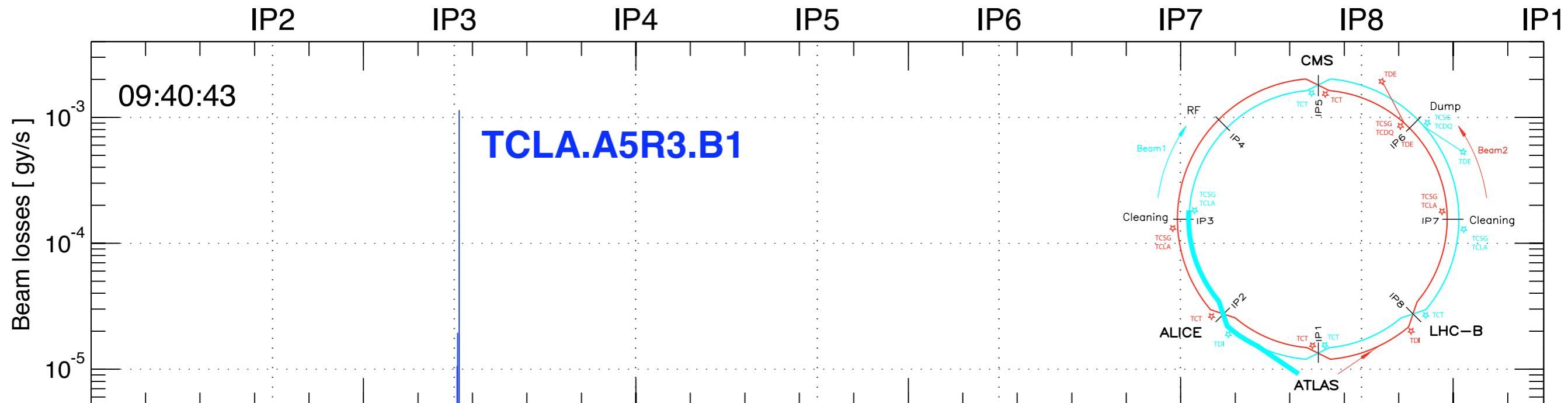


Beam on TDI



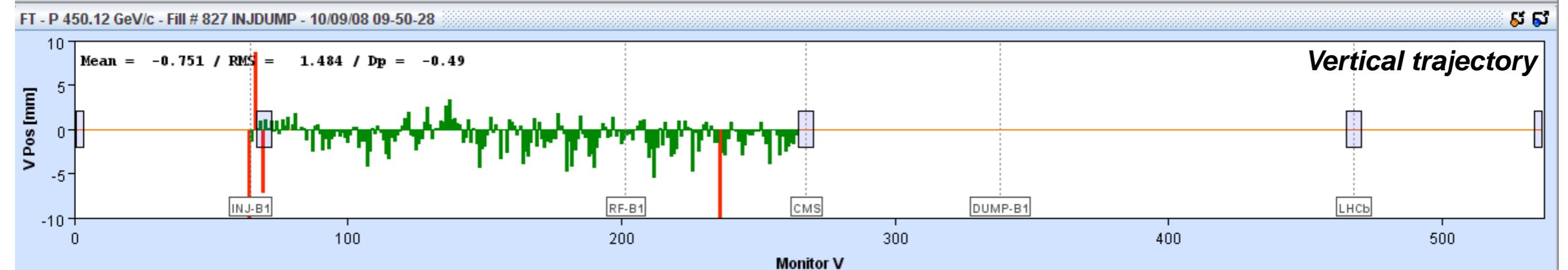
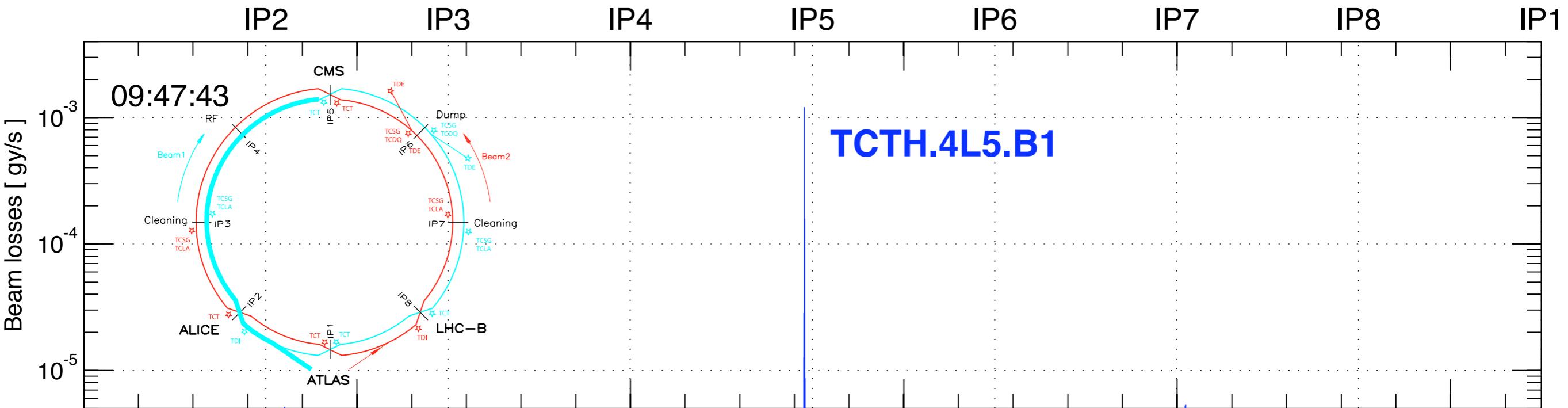
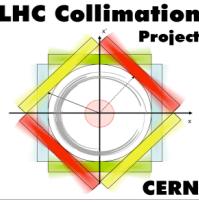


Beam to IP3



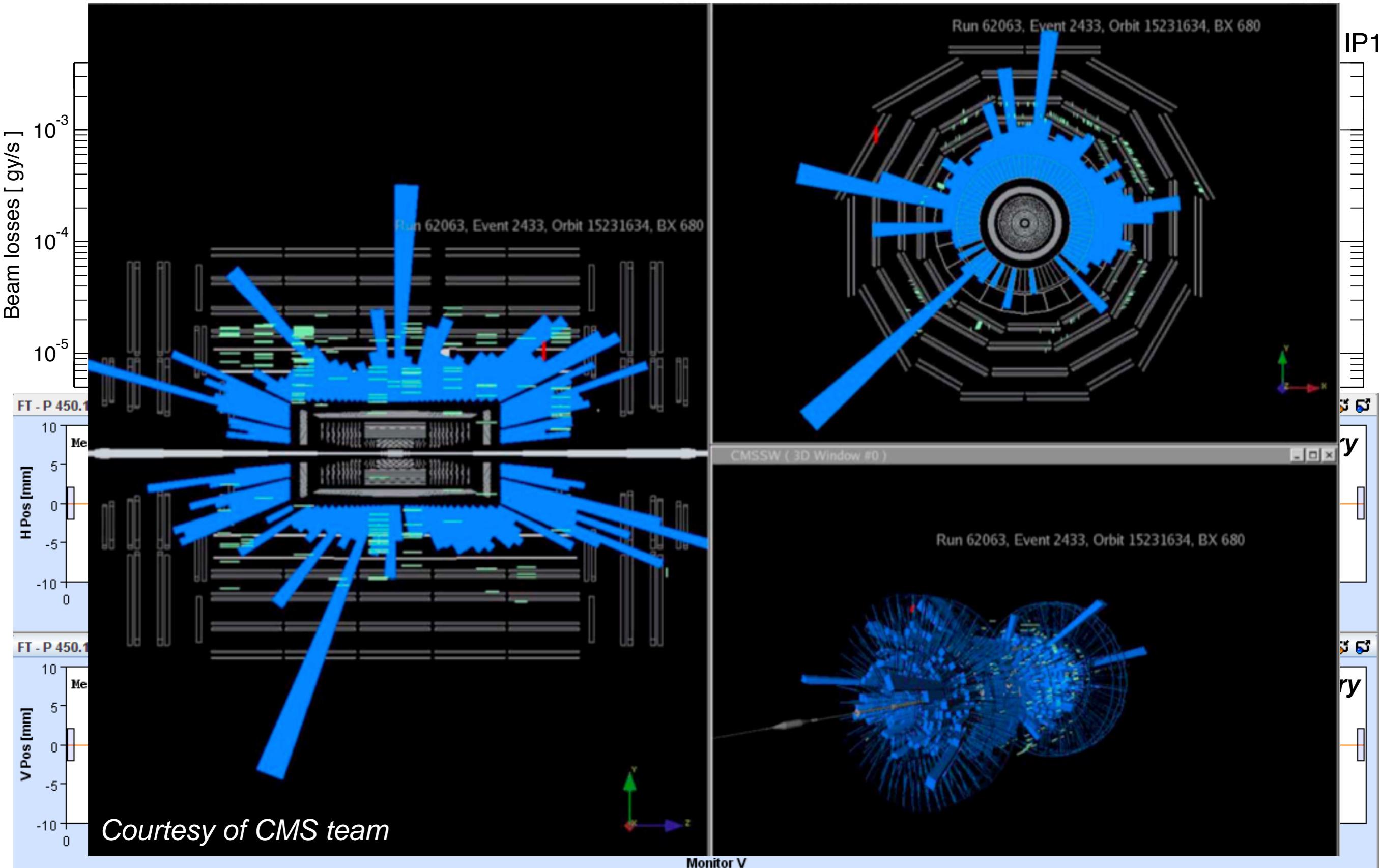
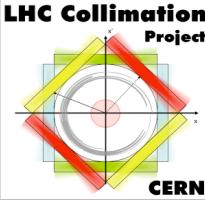


Beam to IP5



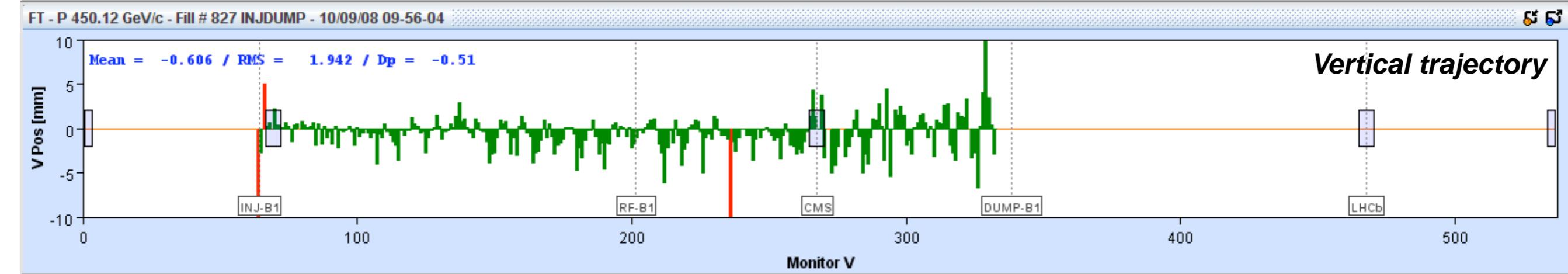
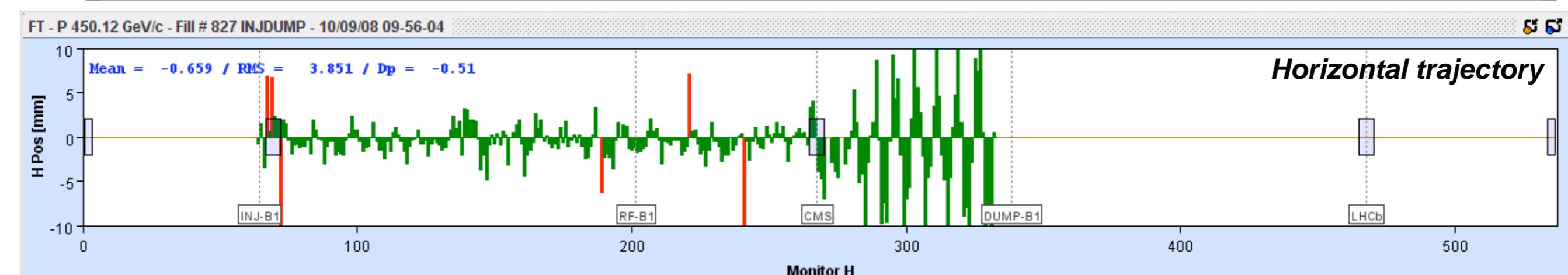
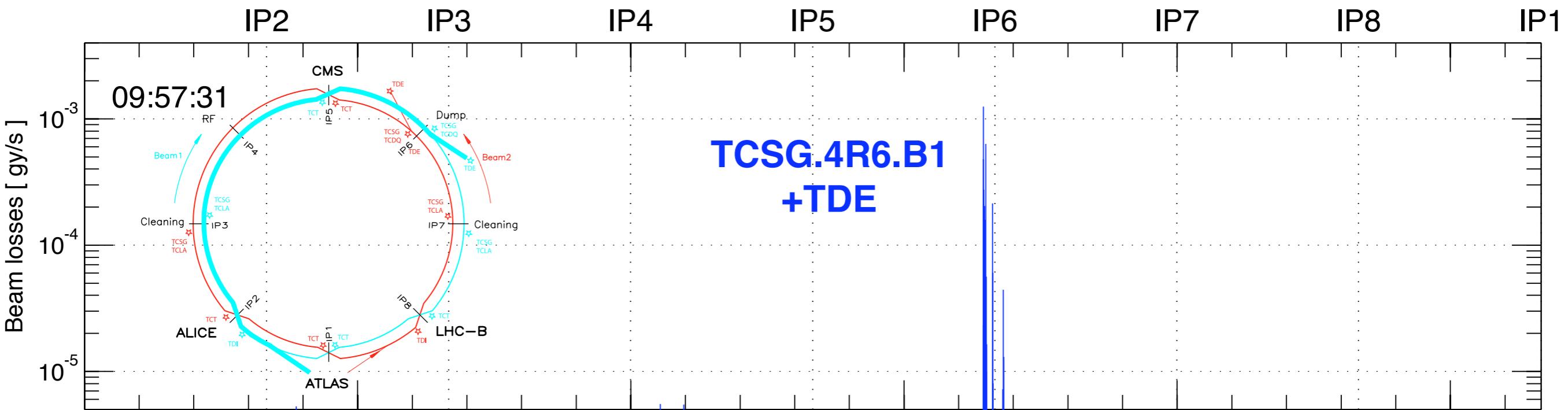


Beam to IP5



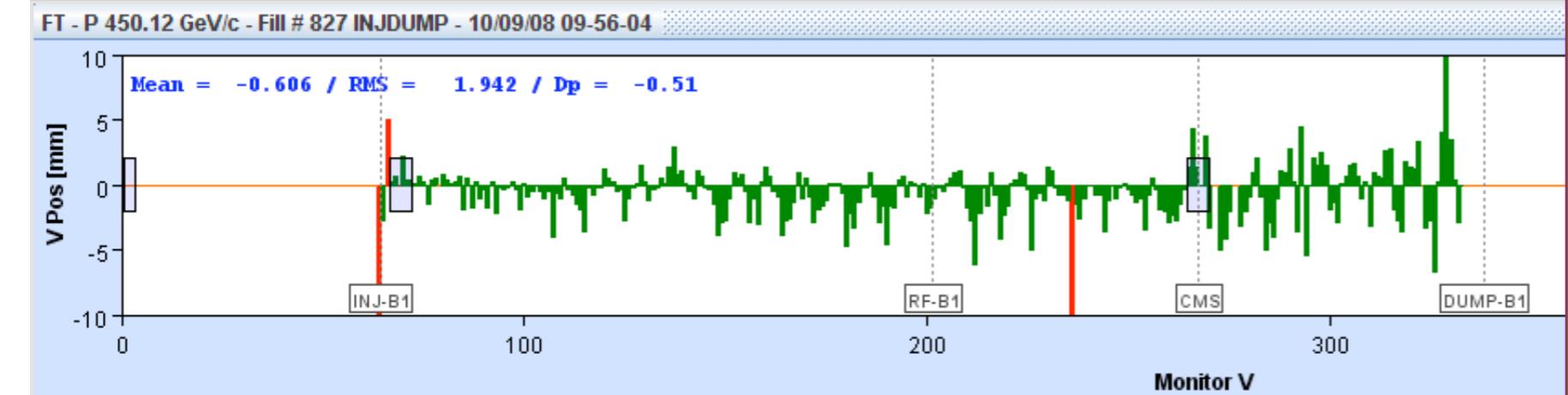
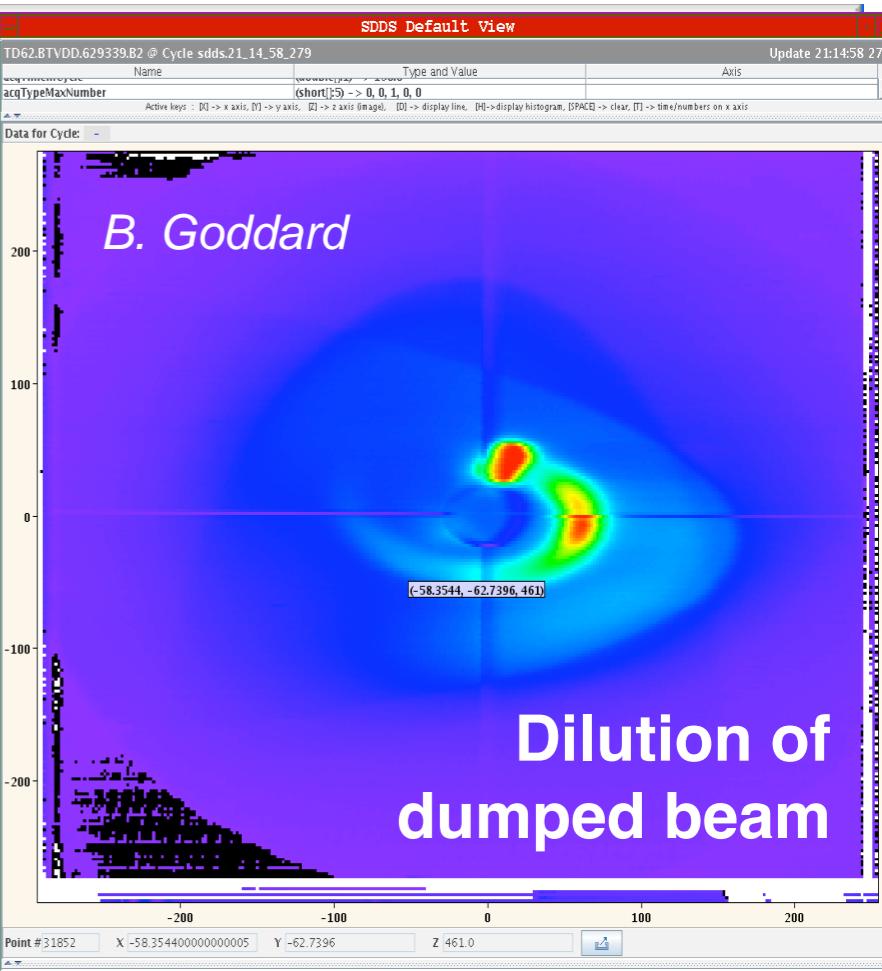
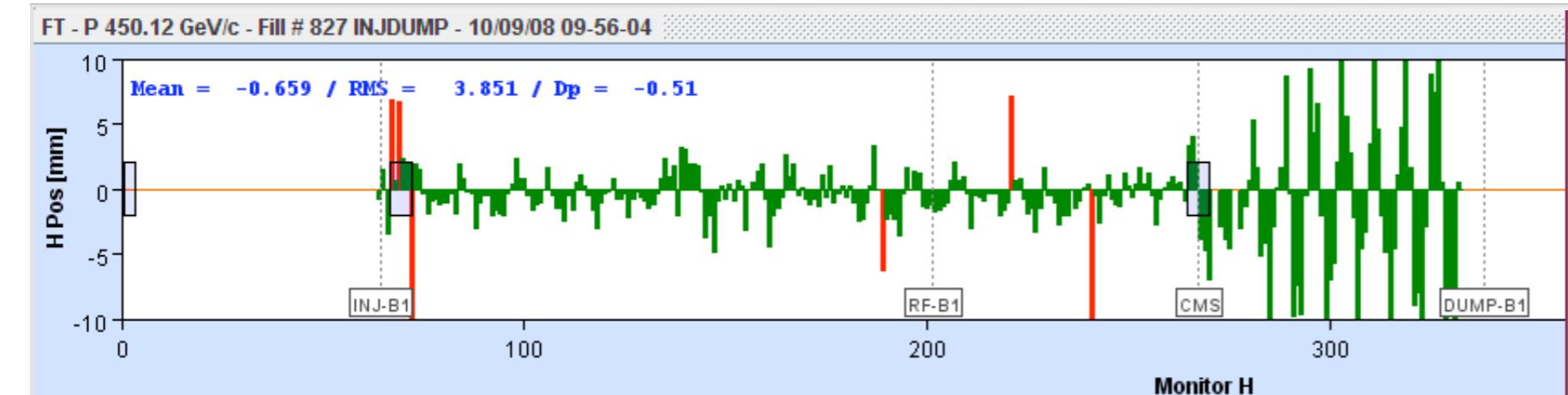
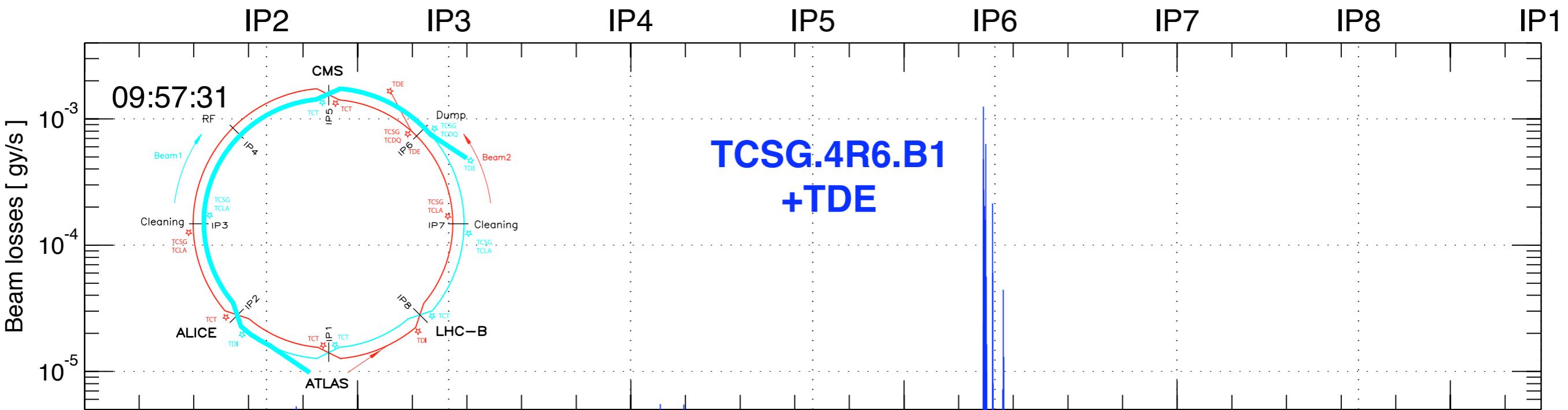


Beam to IP6



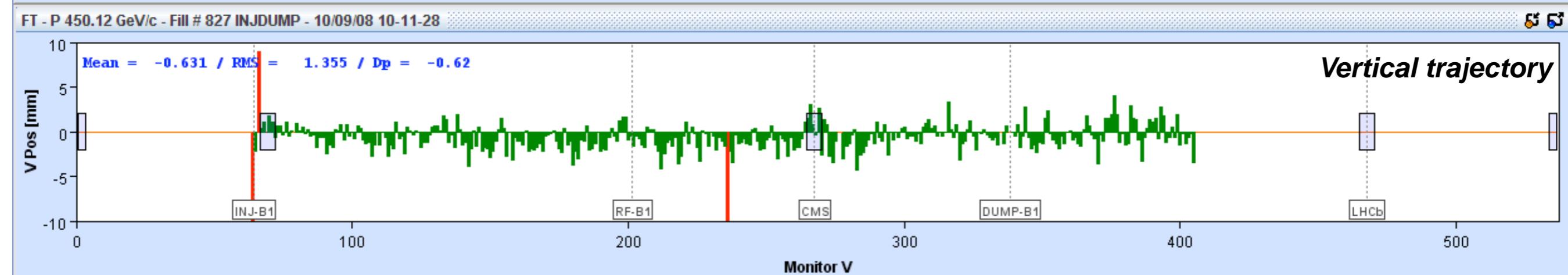
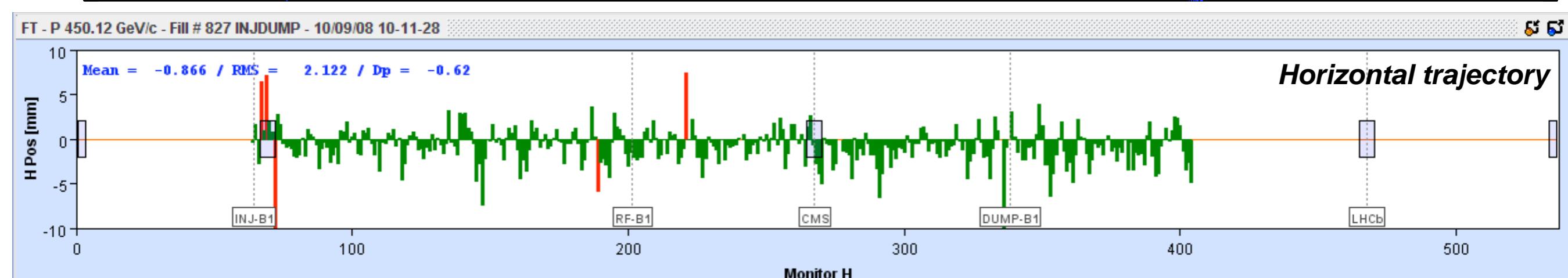
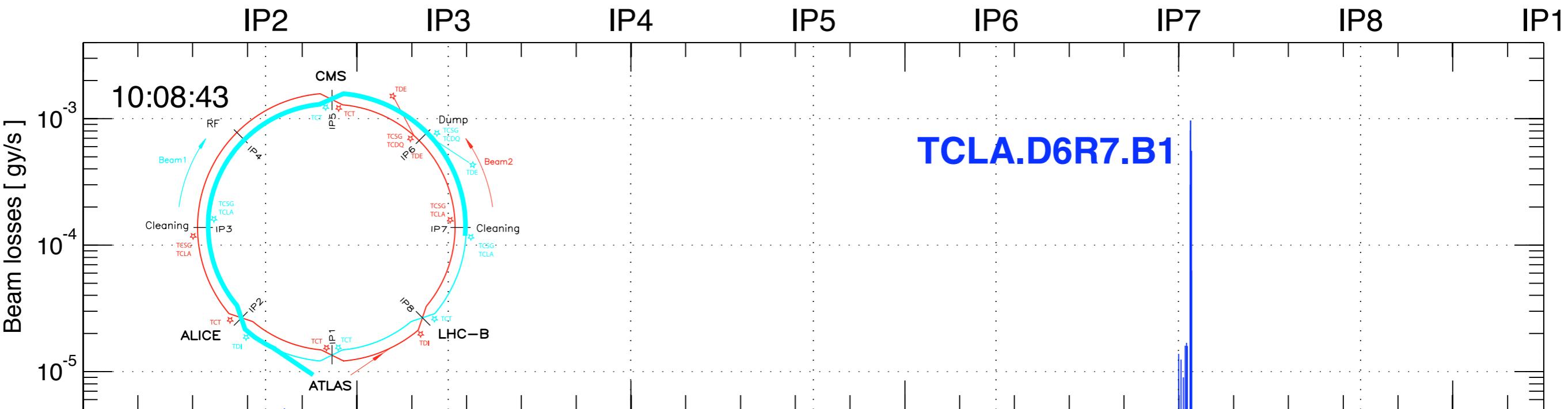


Beam to IP6



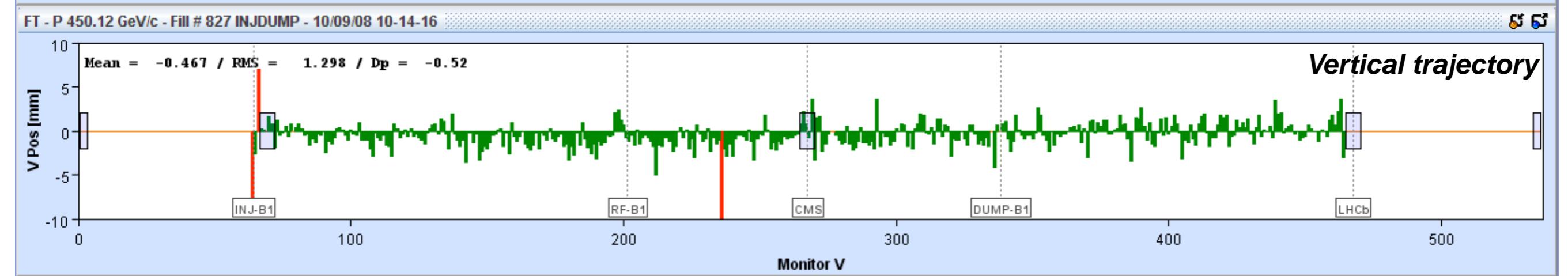
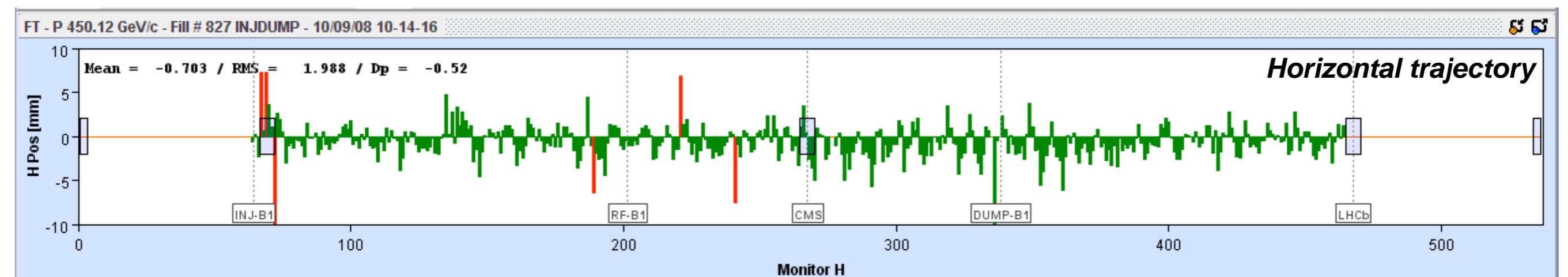
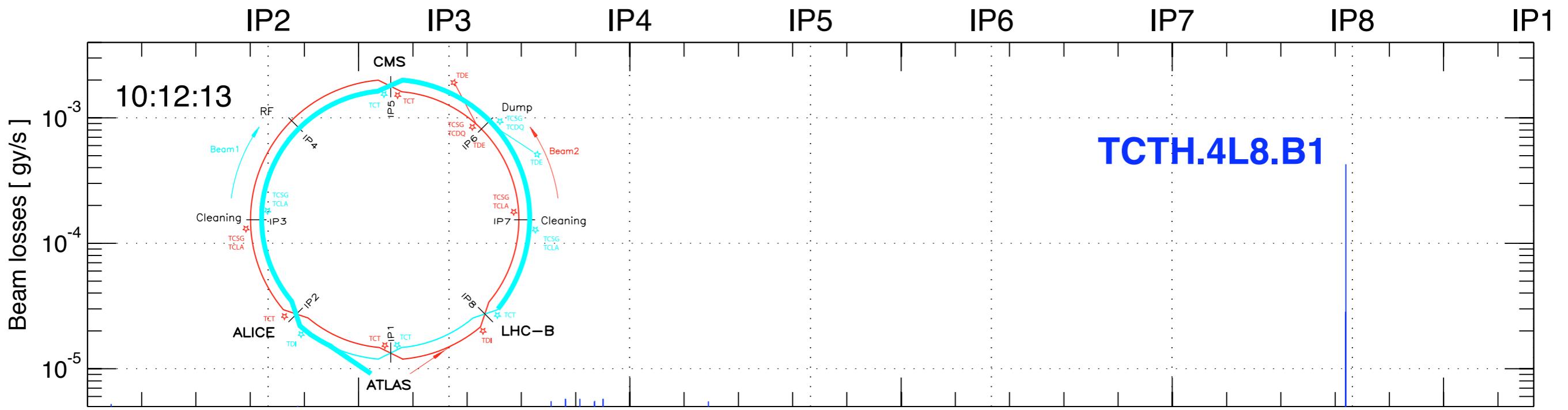


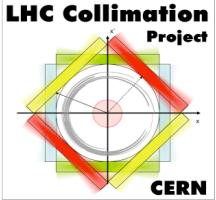
Beam to IP7



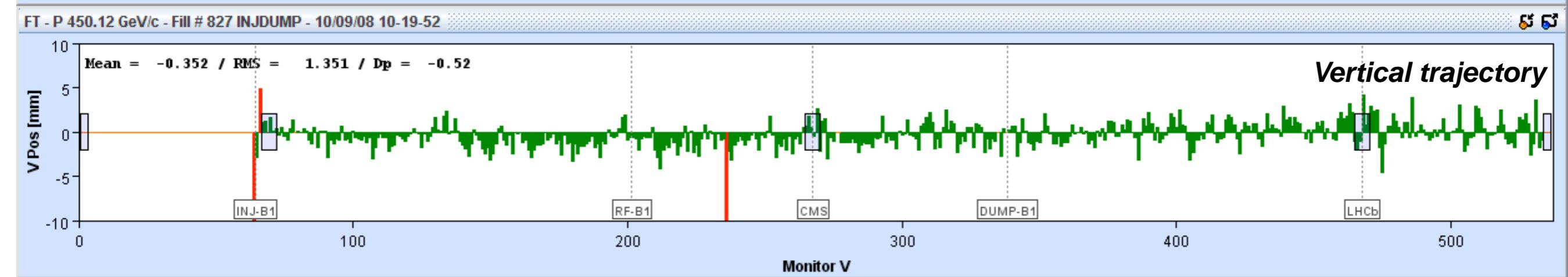
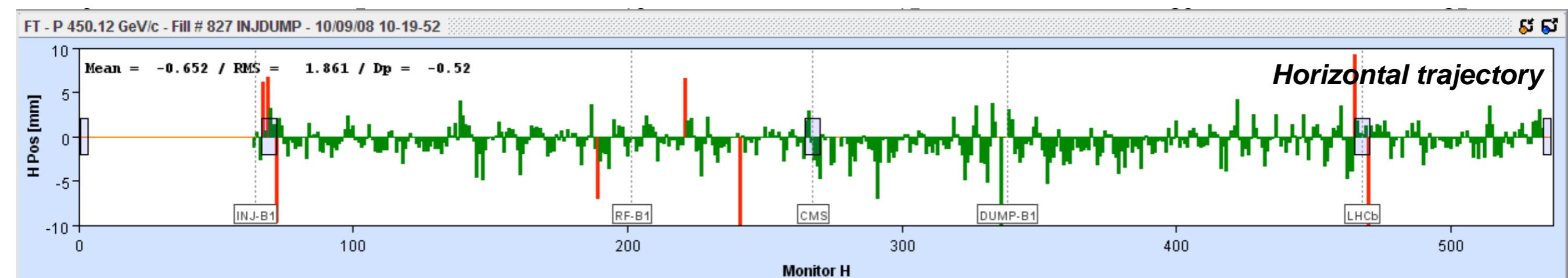
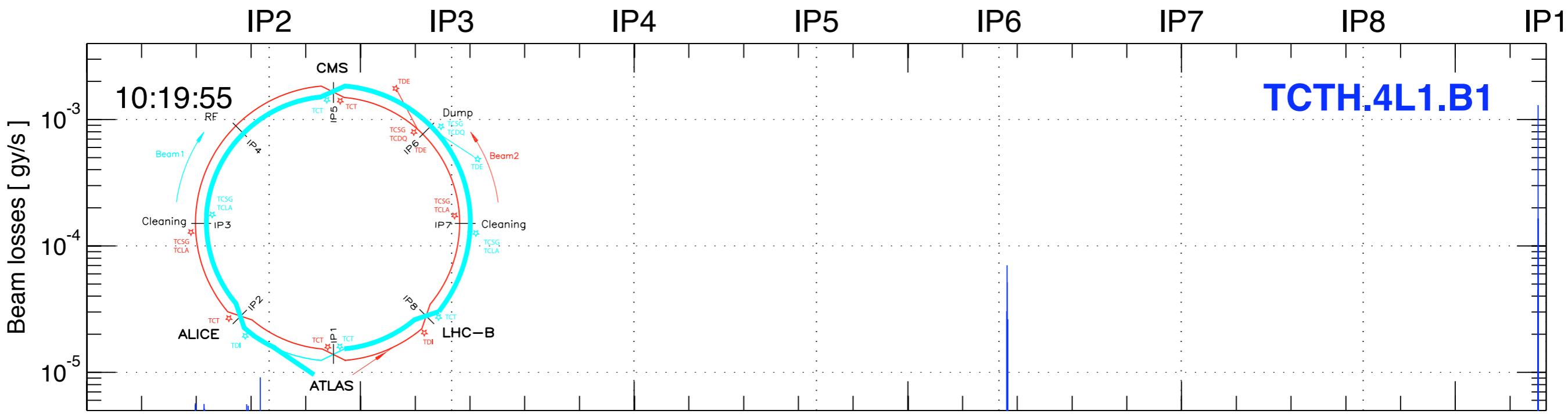


Beam to IP8



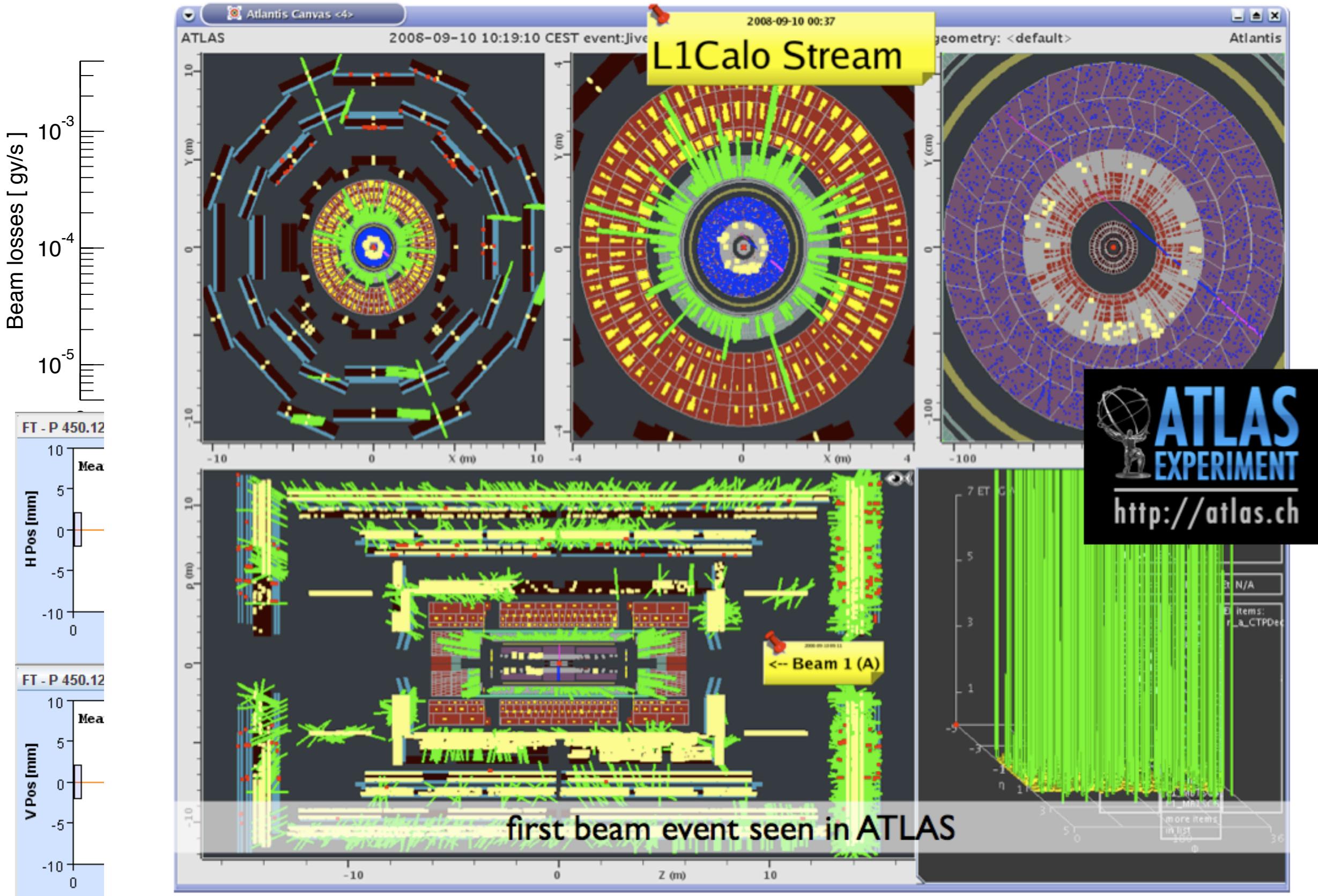
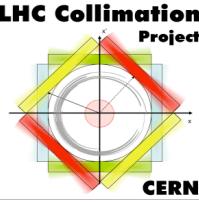


Beam to IP1





Beam to IP1



IP1

1

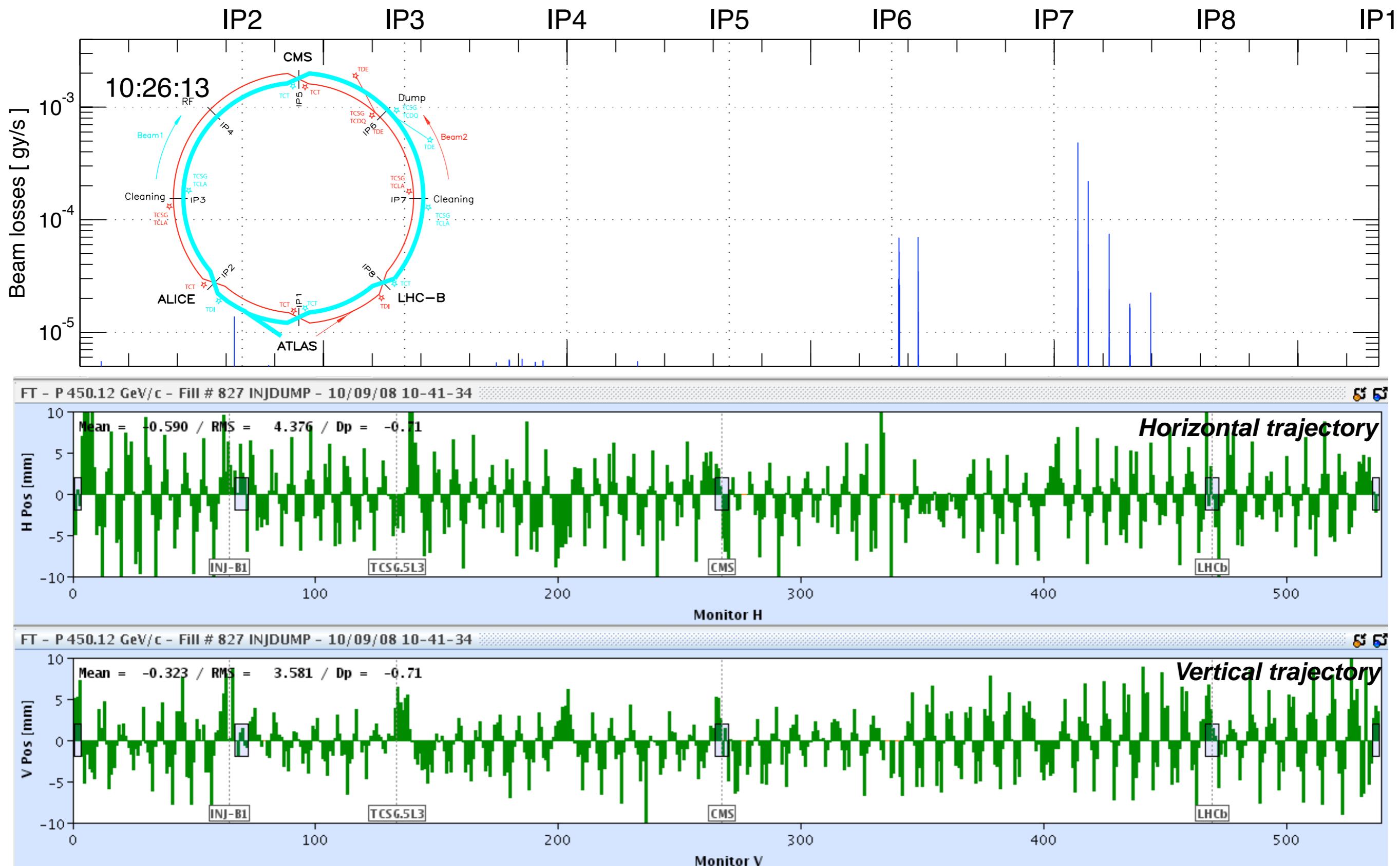
factory

factory

factory

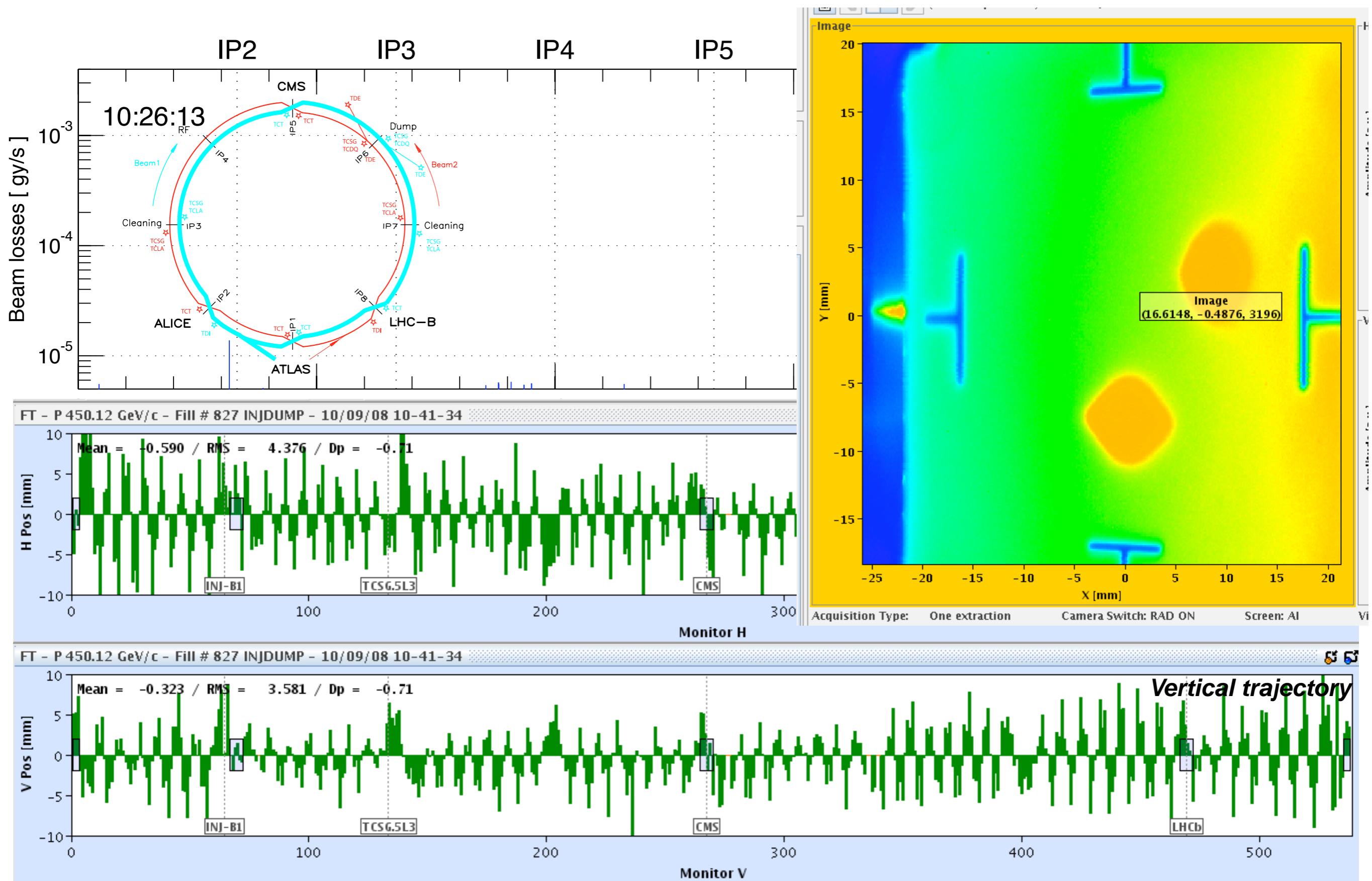
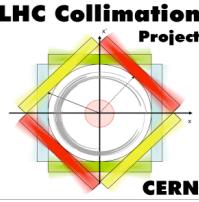


First turn!

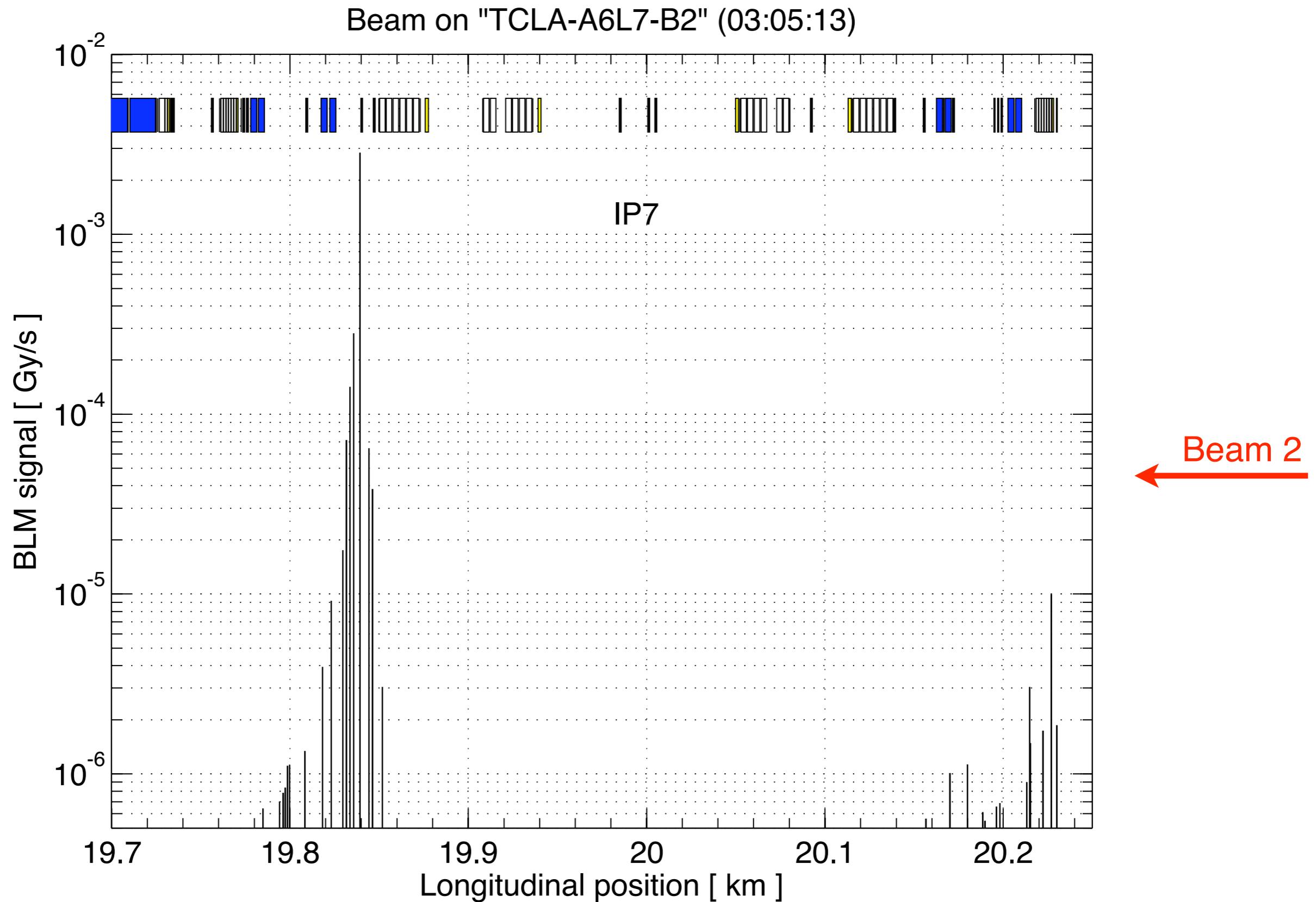


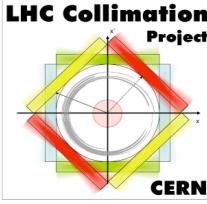


First turn!

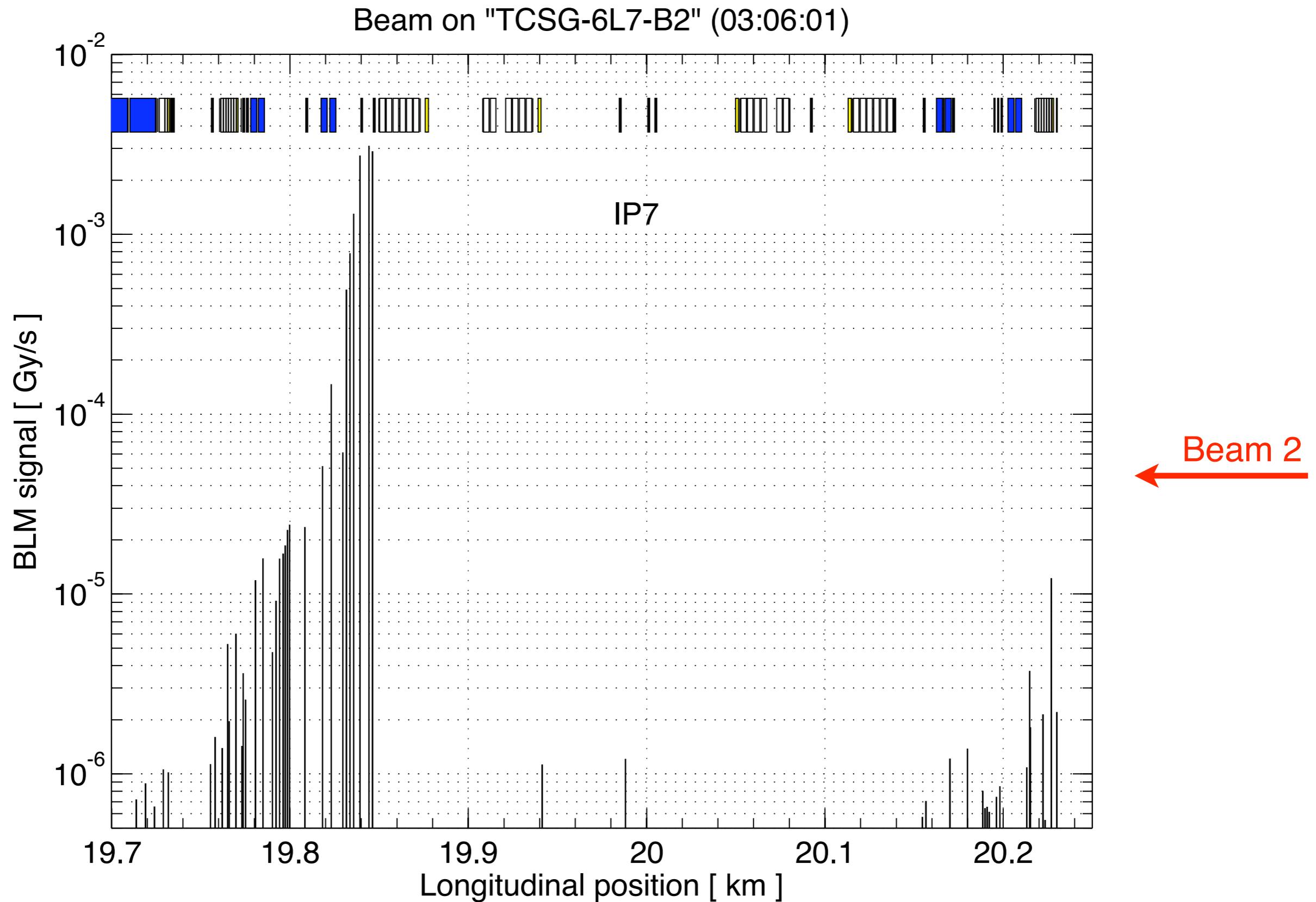


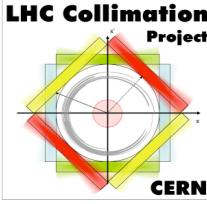
Detailed response studies in IP7



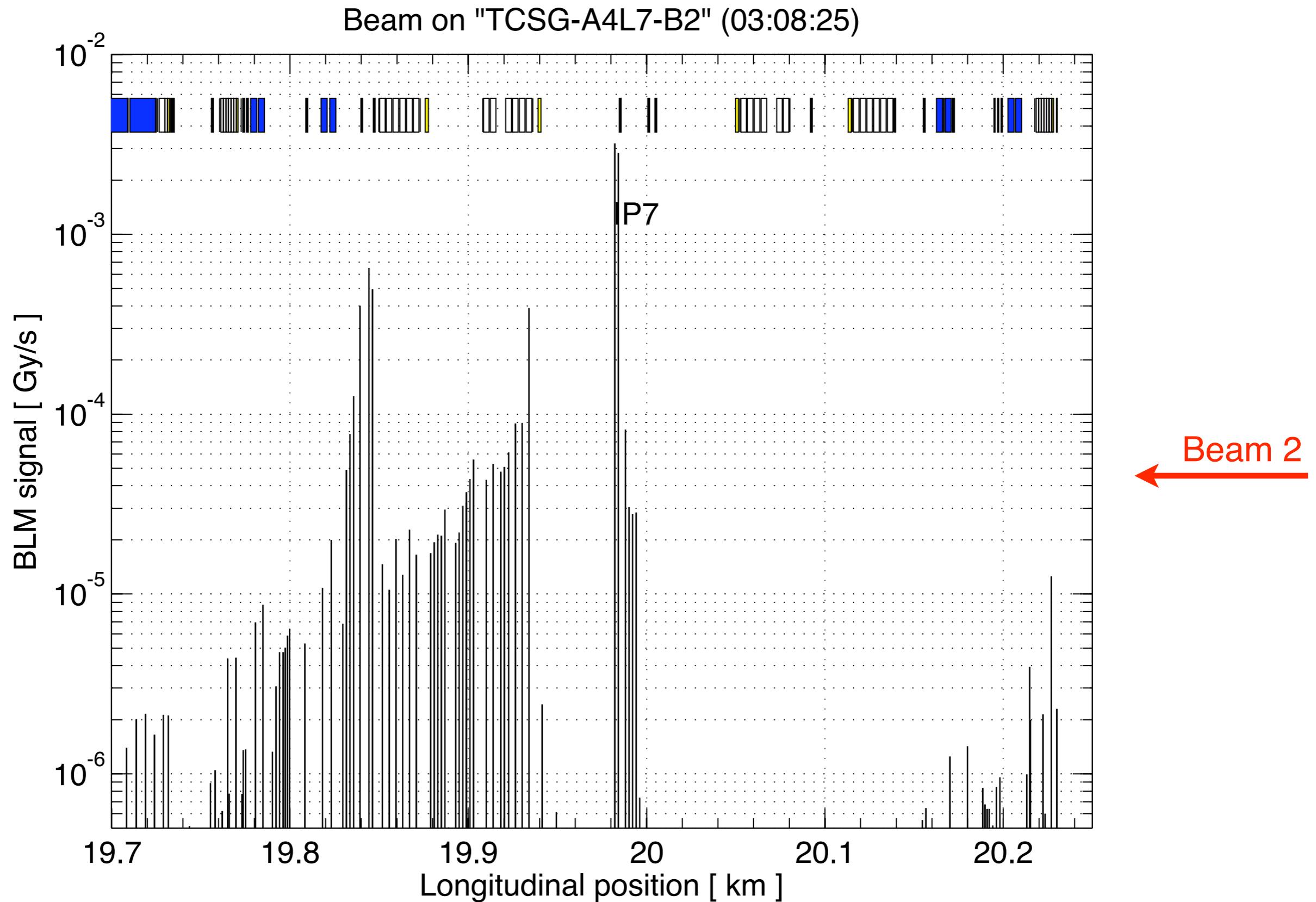


Detailed response studies in IP7

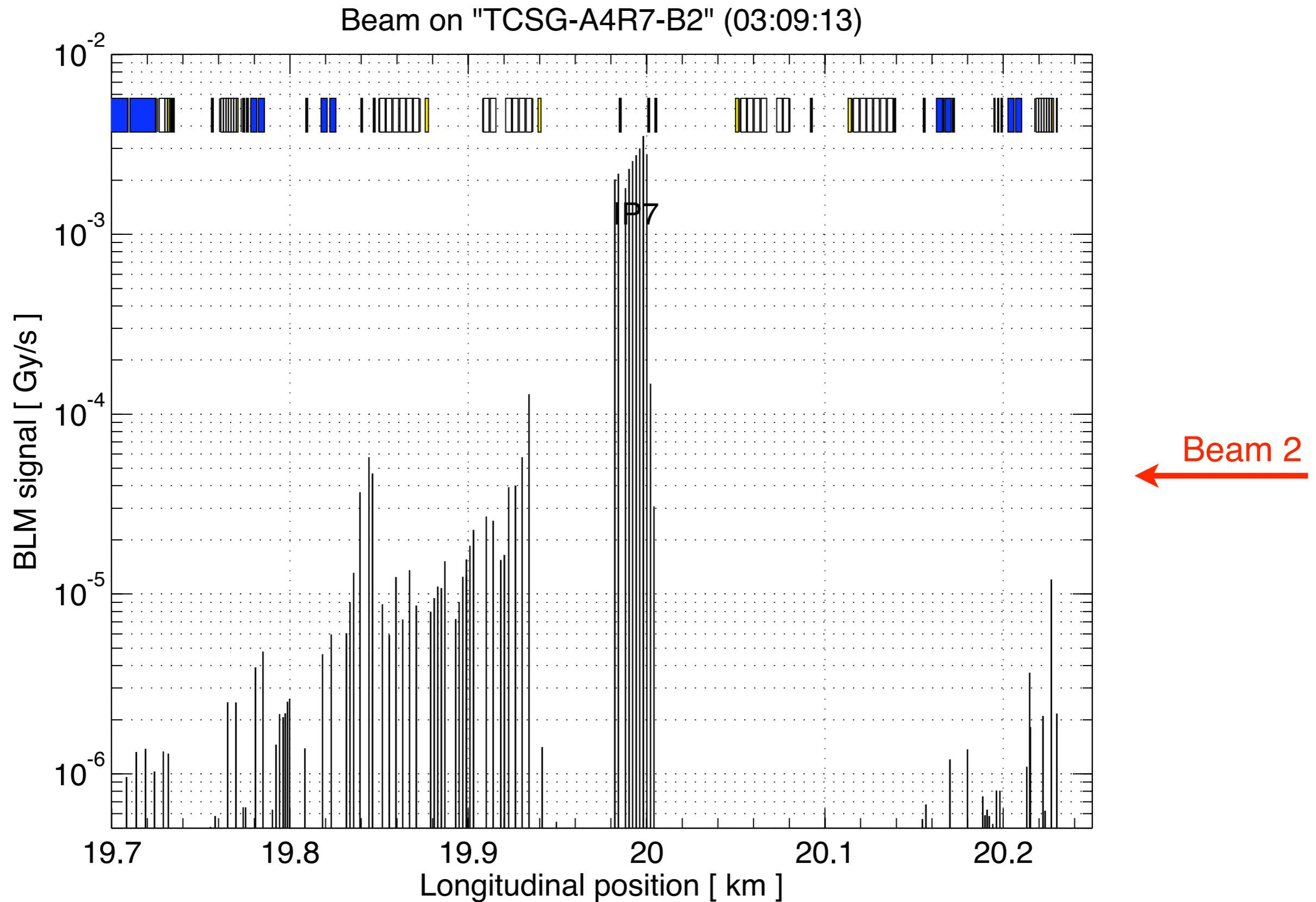




Detailed response studies in IP7

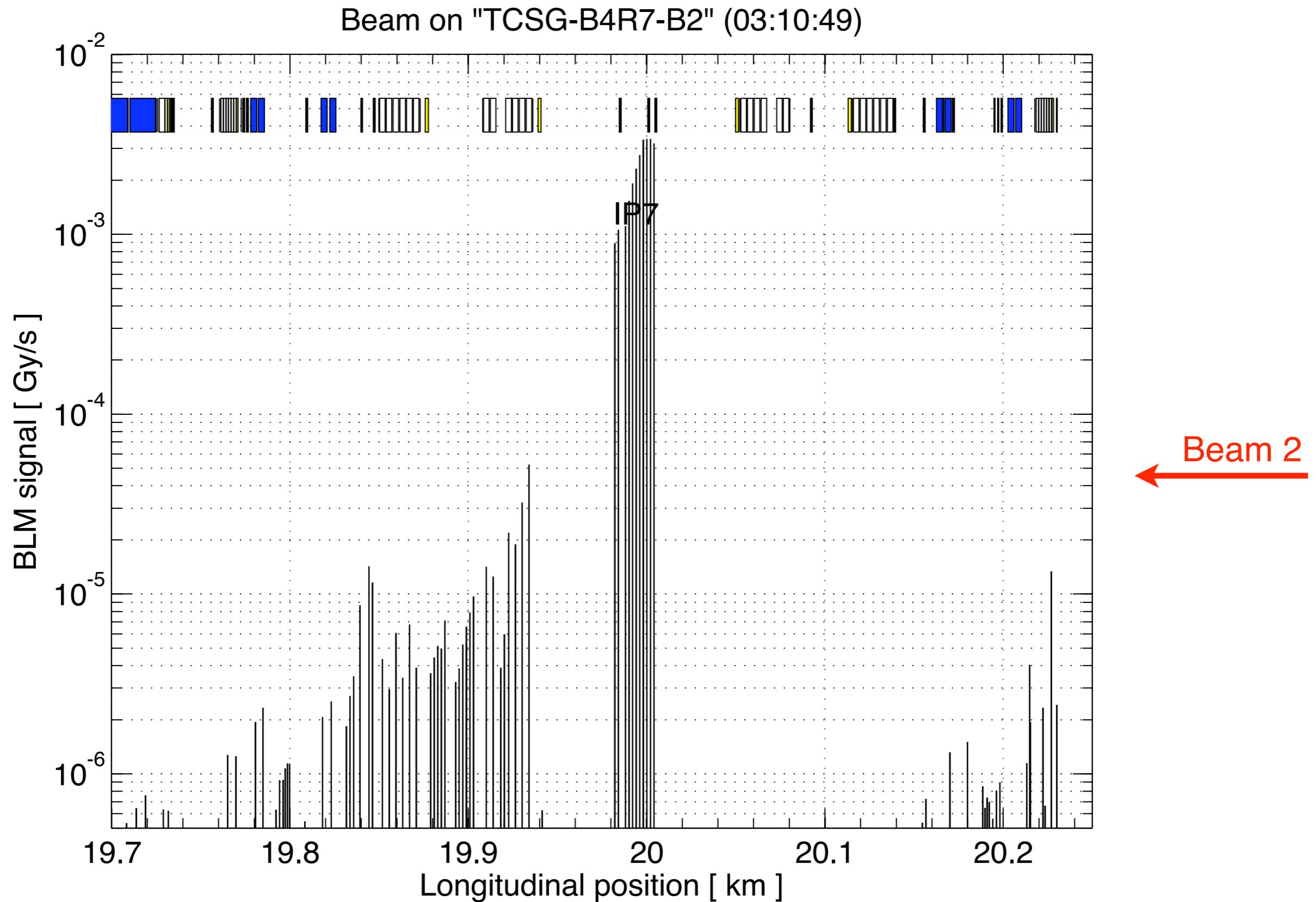


Detailed response studies in IP7



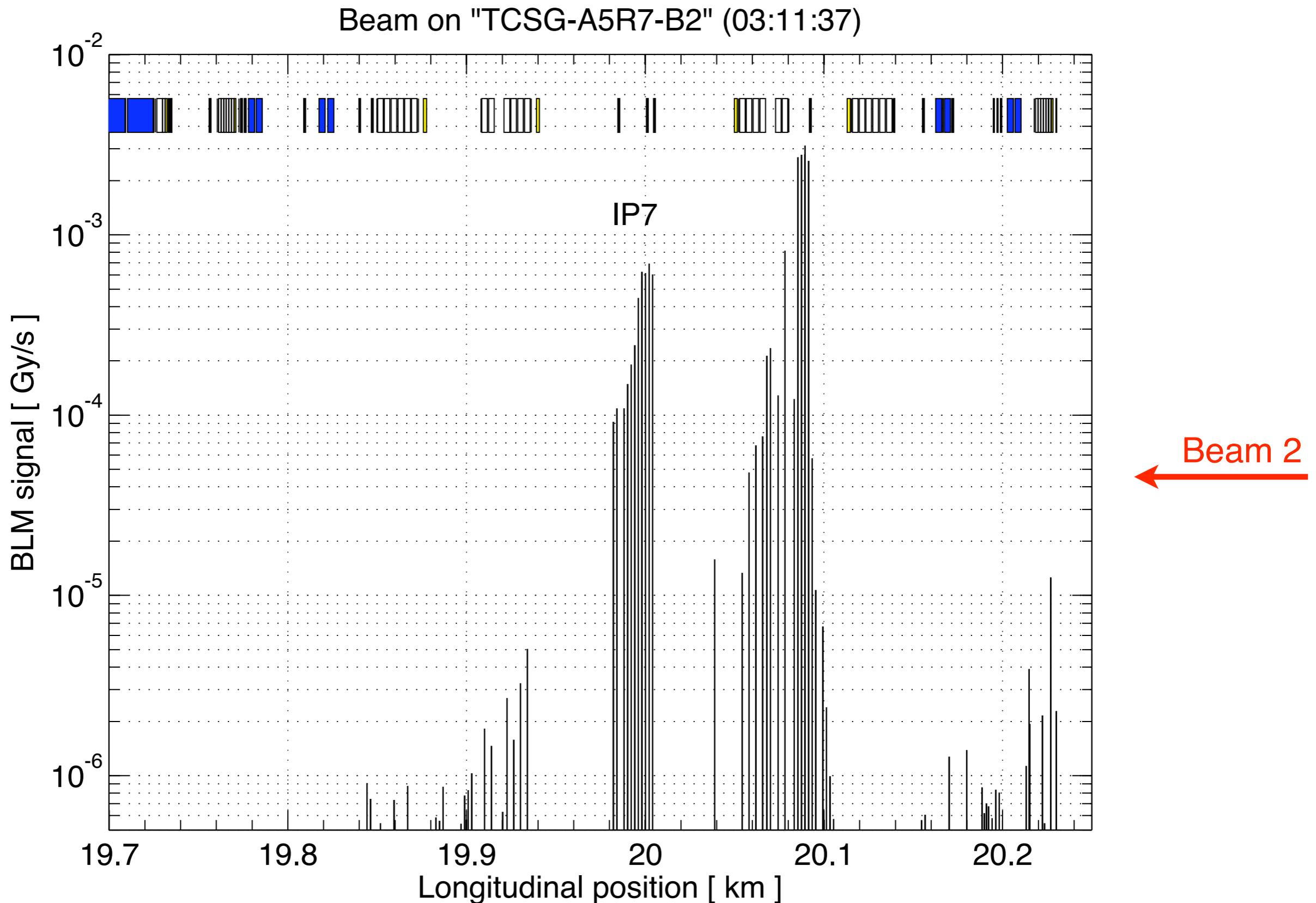


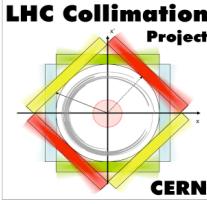
Detailed response studies in IP7



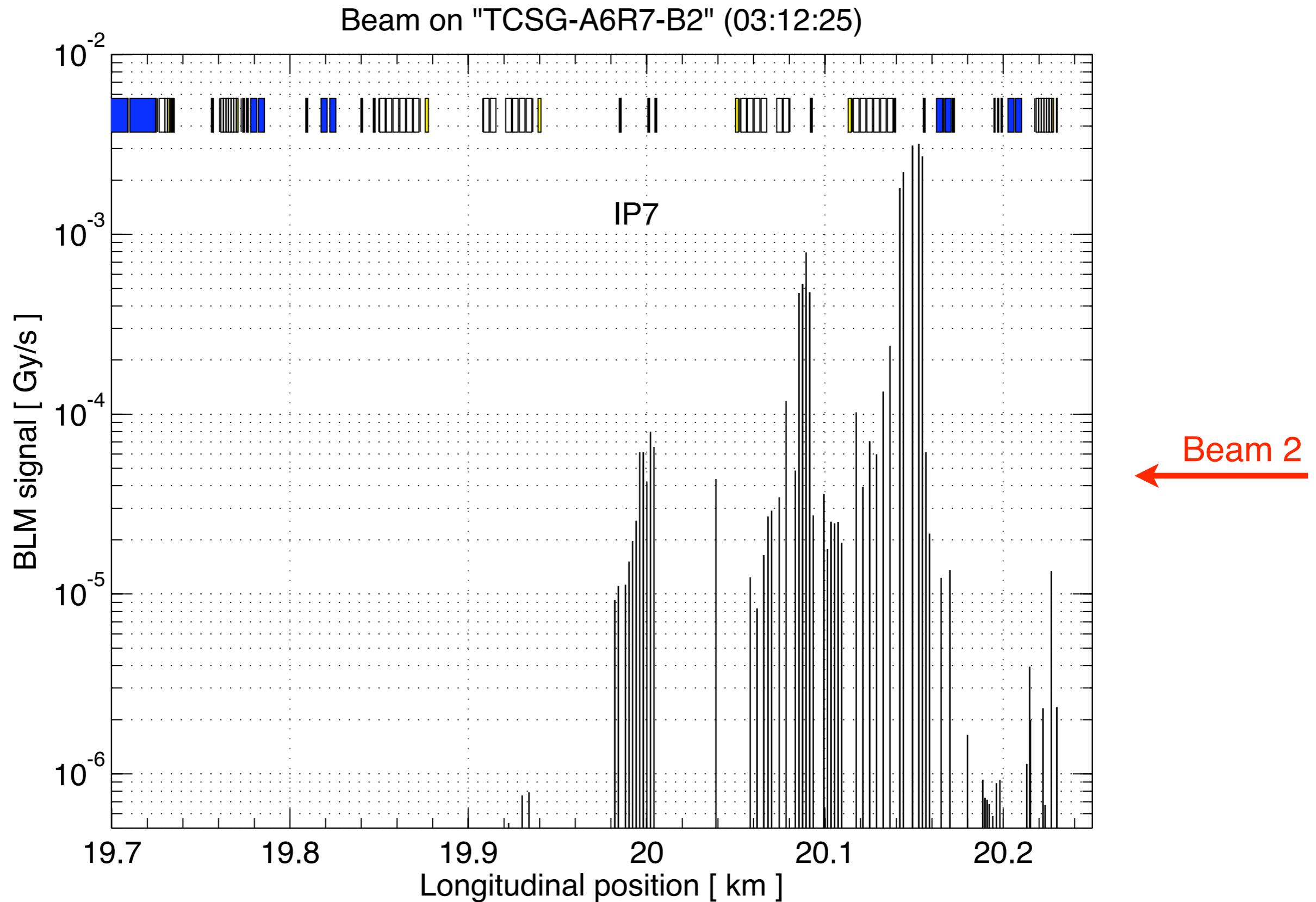


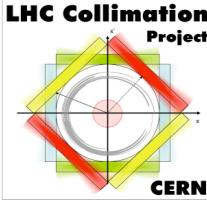
Detailed response studies in IP7



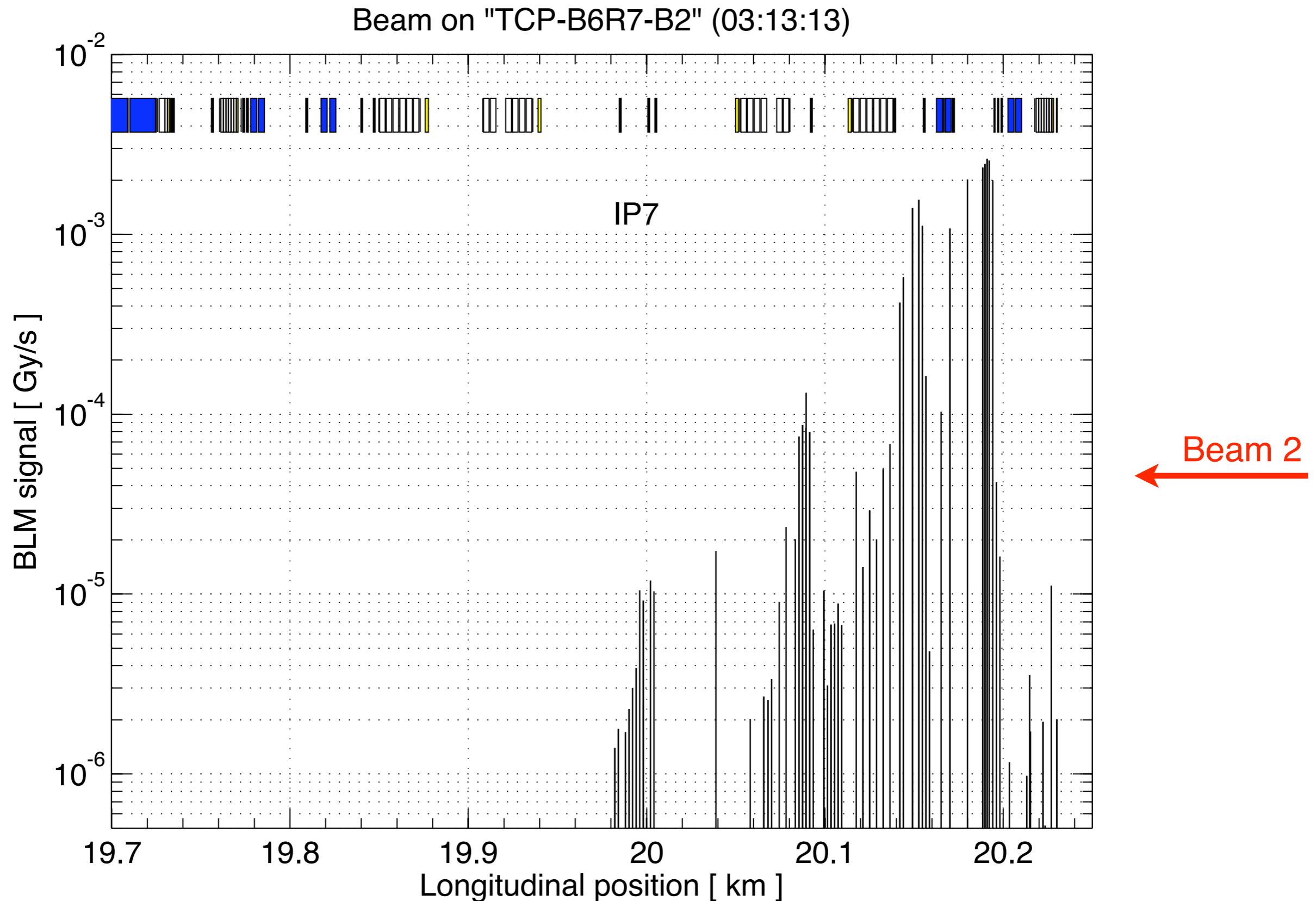


Detailed response studies in IP7



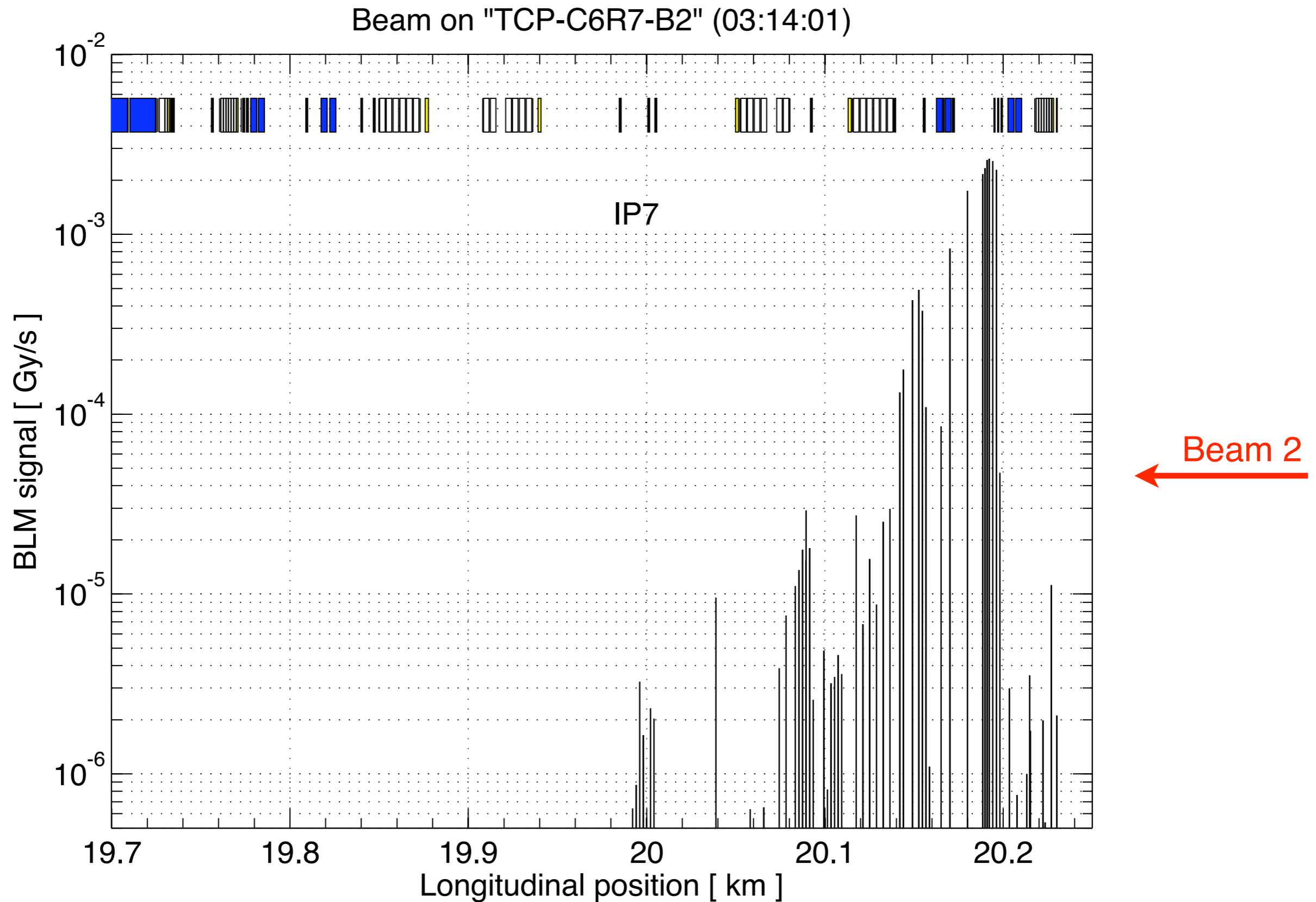


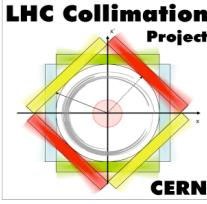
Detailed response studies in IP7



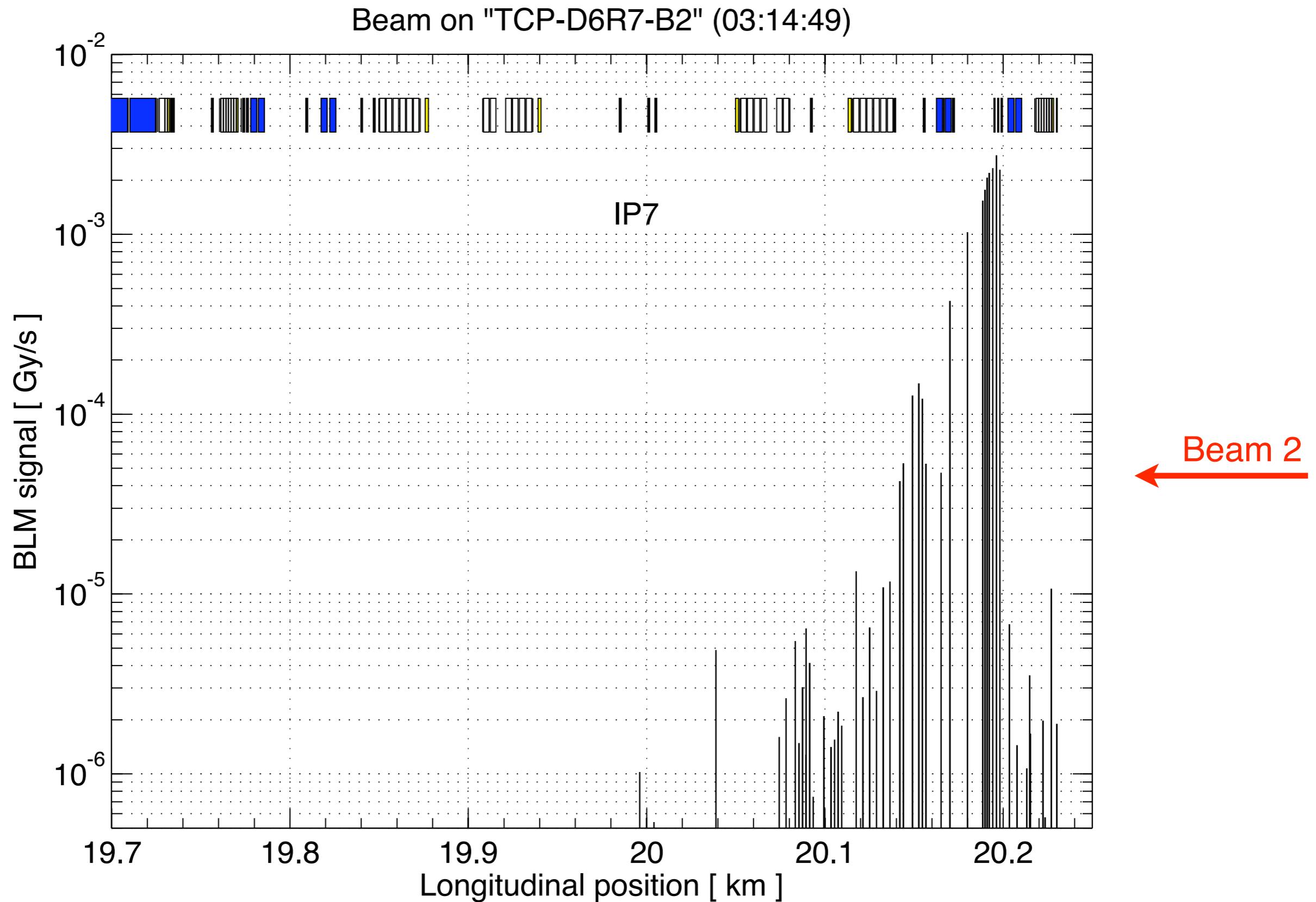


Detailed response studies in IP7



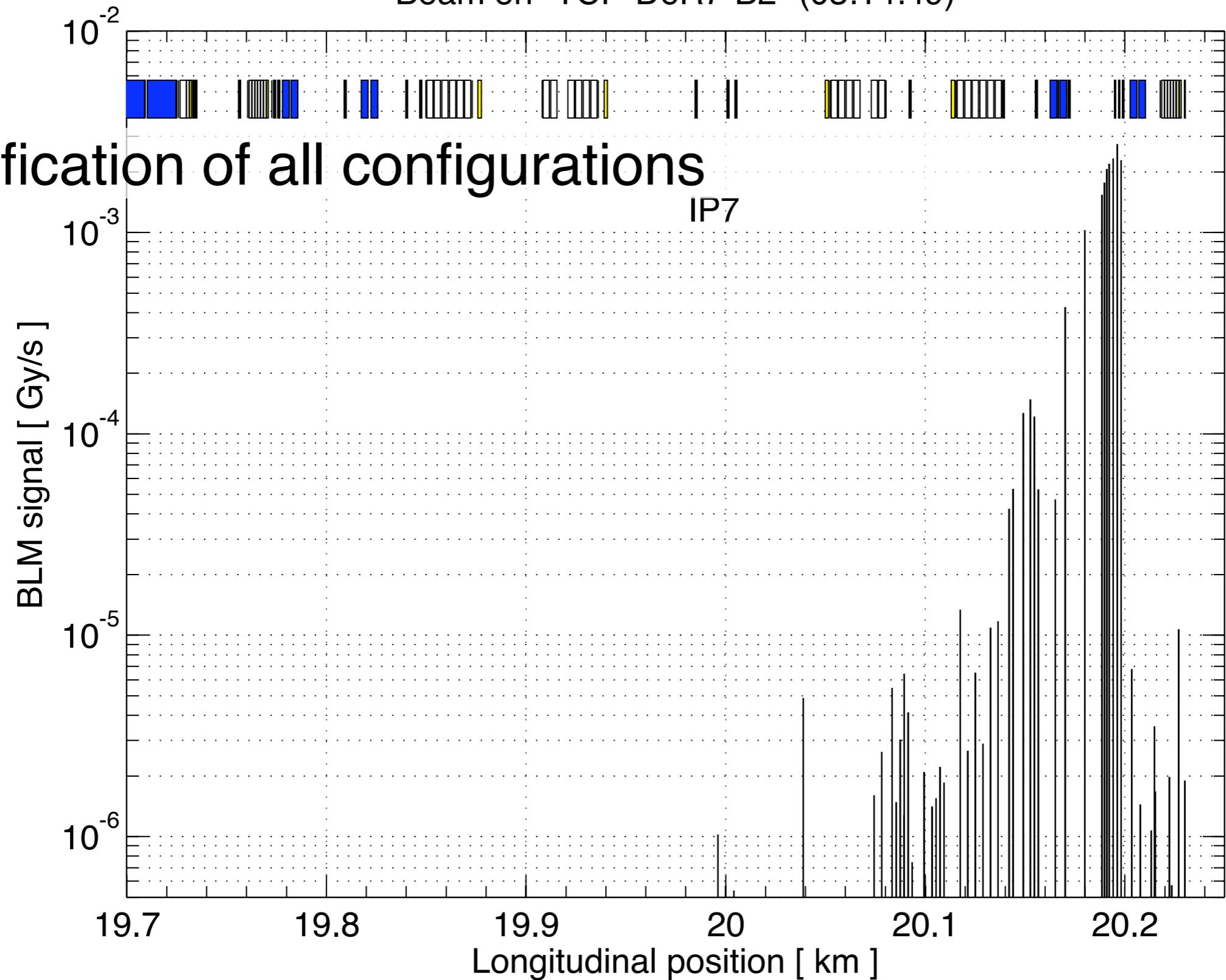


Detailed response studies in IP7



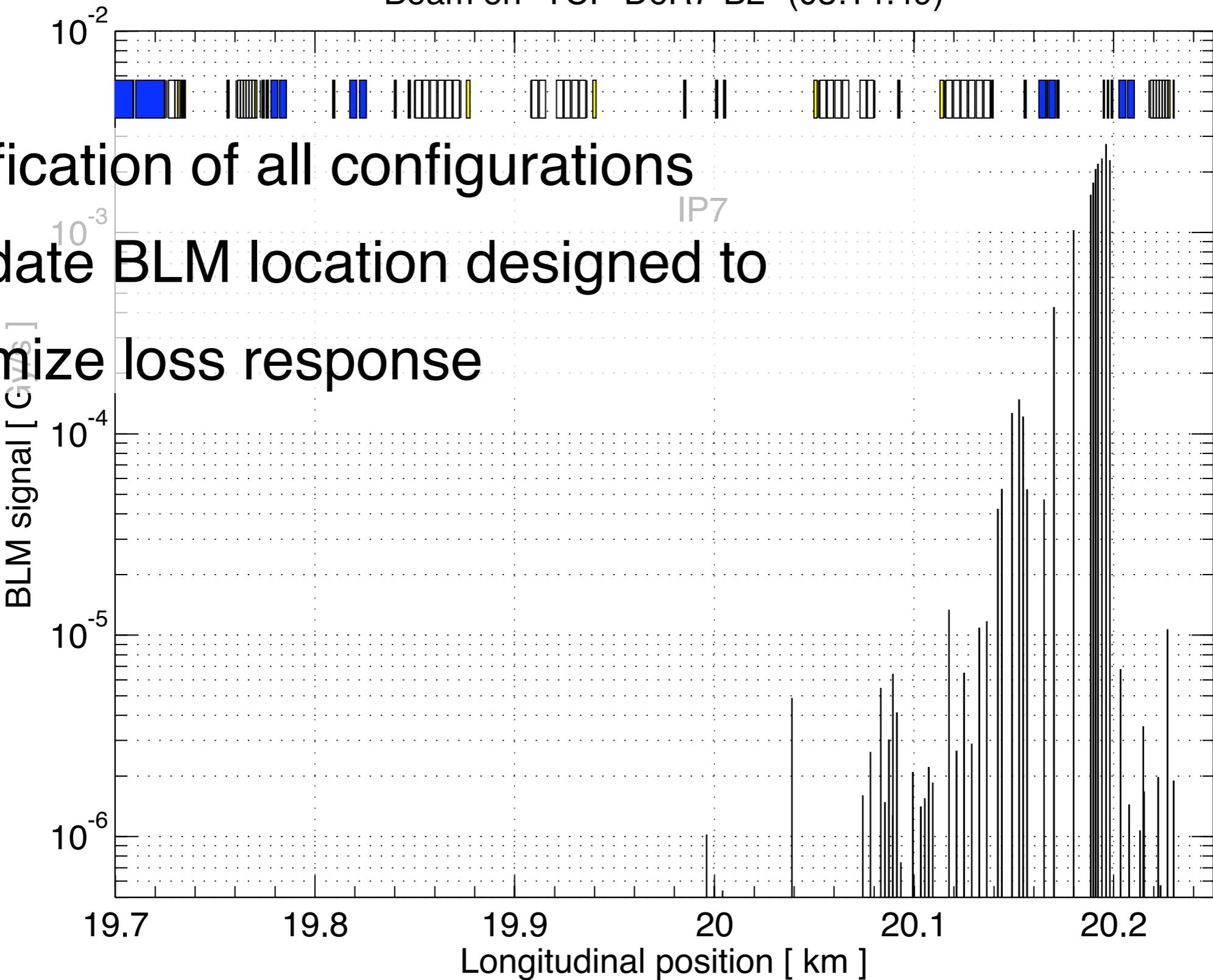
Detailed response studies in IP7

Beam on "TCP-D6R7-B2" (03:14:49)



Detailed response studies in IP7

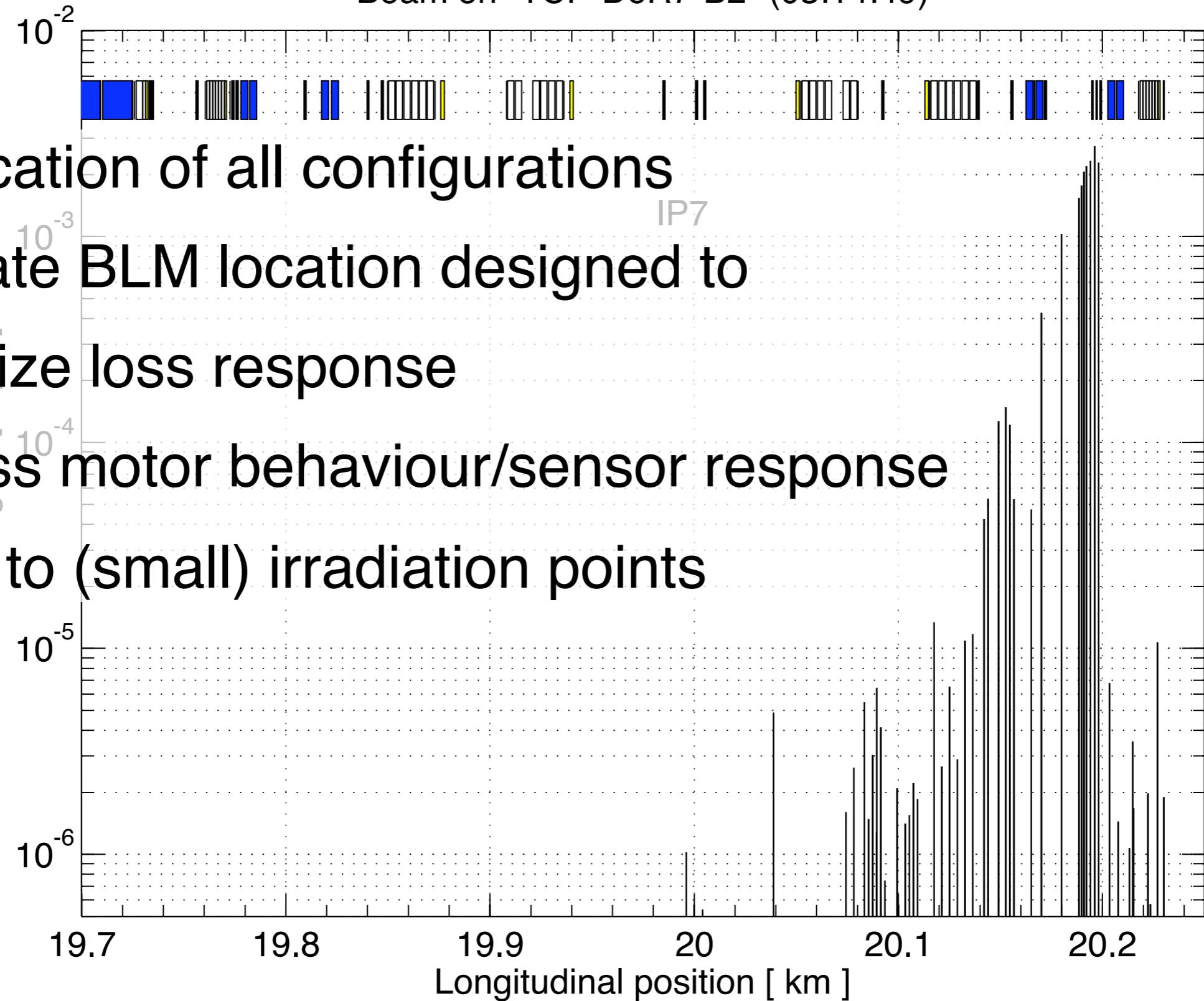
Beam on "TCP-D6R7-B2" (03:14:49)





Detailed response studies in IP7

Beam on "TCP-D6R7-B2" (03:14:49)



Verification of all configurations

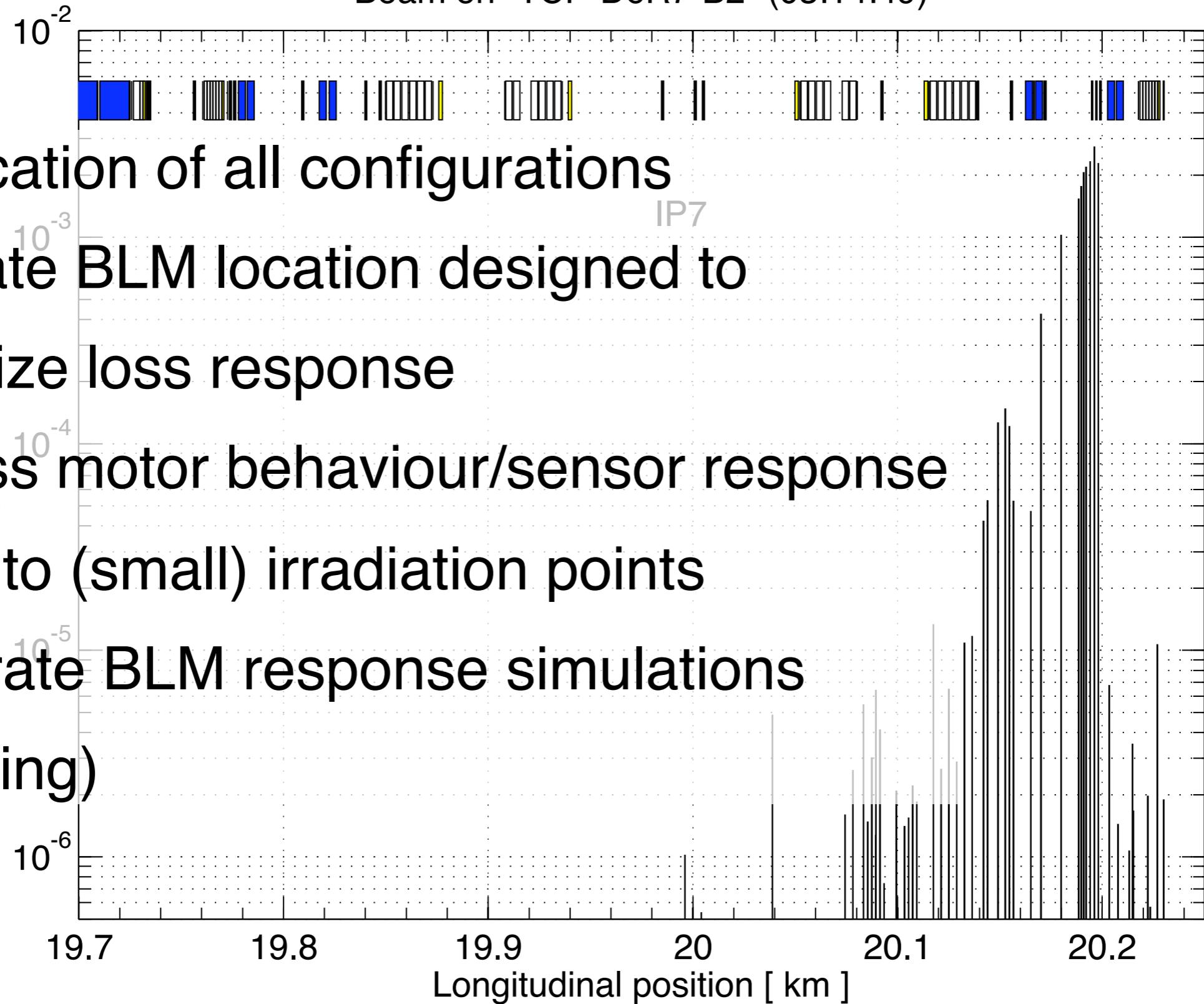
Validate BLM location designed to
optimize loss response

Assess motor behaviour/sensor response
close to (small) irradiation points



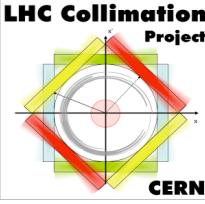
Detailed response studies in IP7

Beam on "TCP-D6R7-B2" (03:14:49)





Conclusions



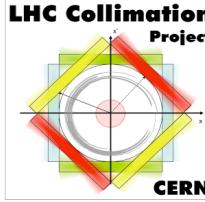


Conclusions

- Operational experience of the collimation system was reviewed**

Mainly “dry-runs” as a part of system HW commissioning

Missed the chance to perform circulating beam tests



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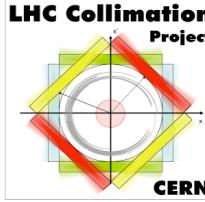
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The main design tolerance are basically achieved

Machine protection functionality validated

Controls at all levels fully deployed, very satisfactory performance



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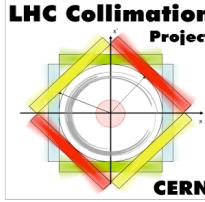
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First systematic commissioning in the transfer lines

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Unforeseen but entertaining use for physics events in IP1/5



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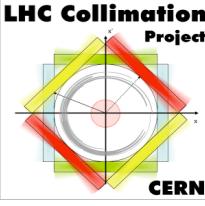
Unforeseen but entertaining use for physics events in IP1/5

Outlook:

Implementation of 2009 system

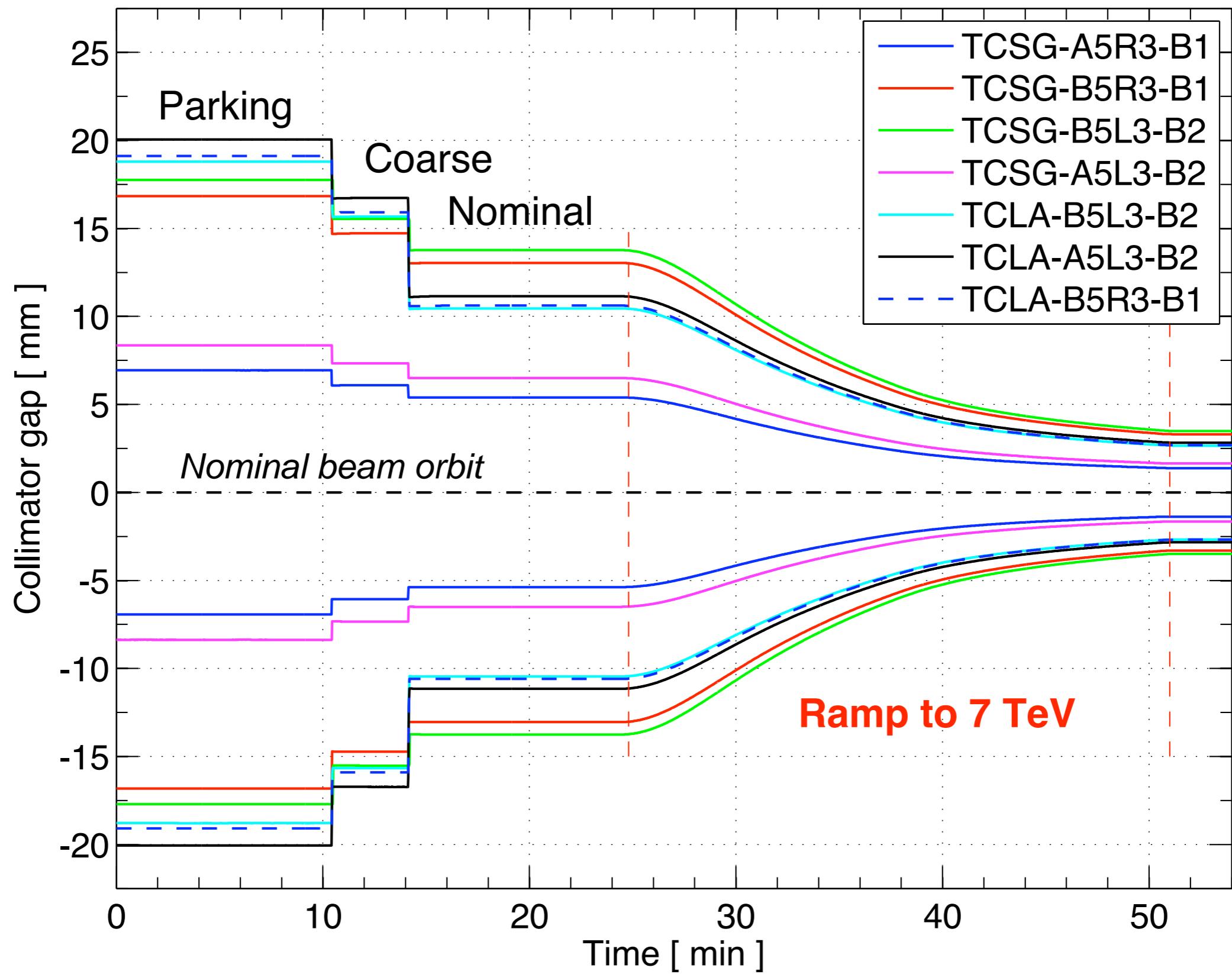
TODO list for improvements compiled, will be followed up

Further tests of reproducibility to optimized operational settings

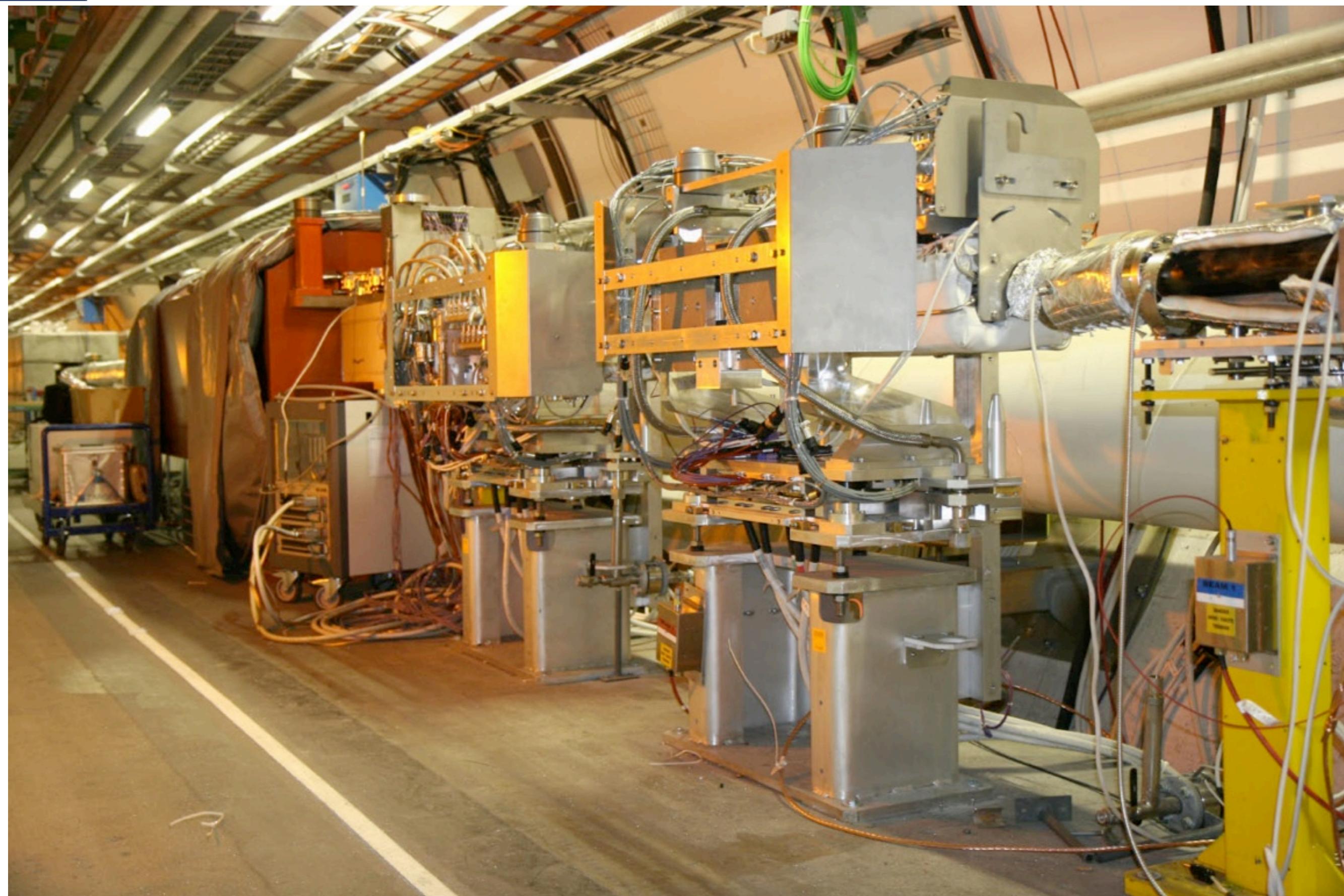


Reserve slides

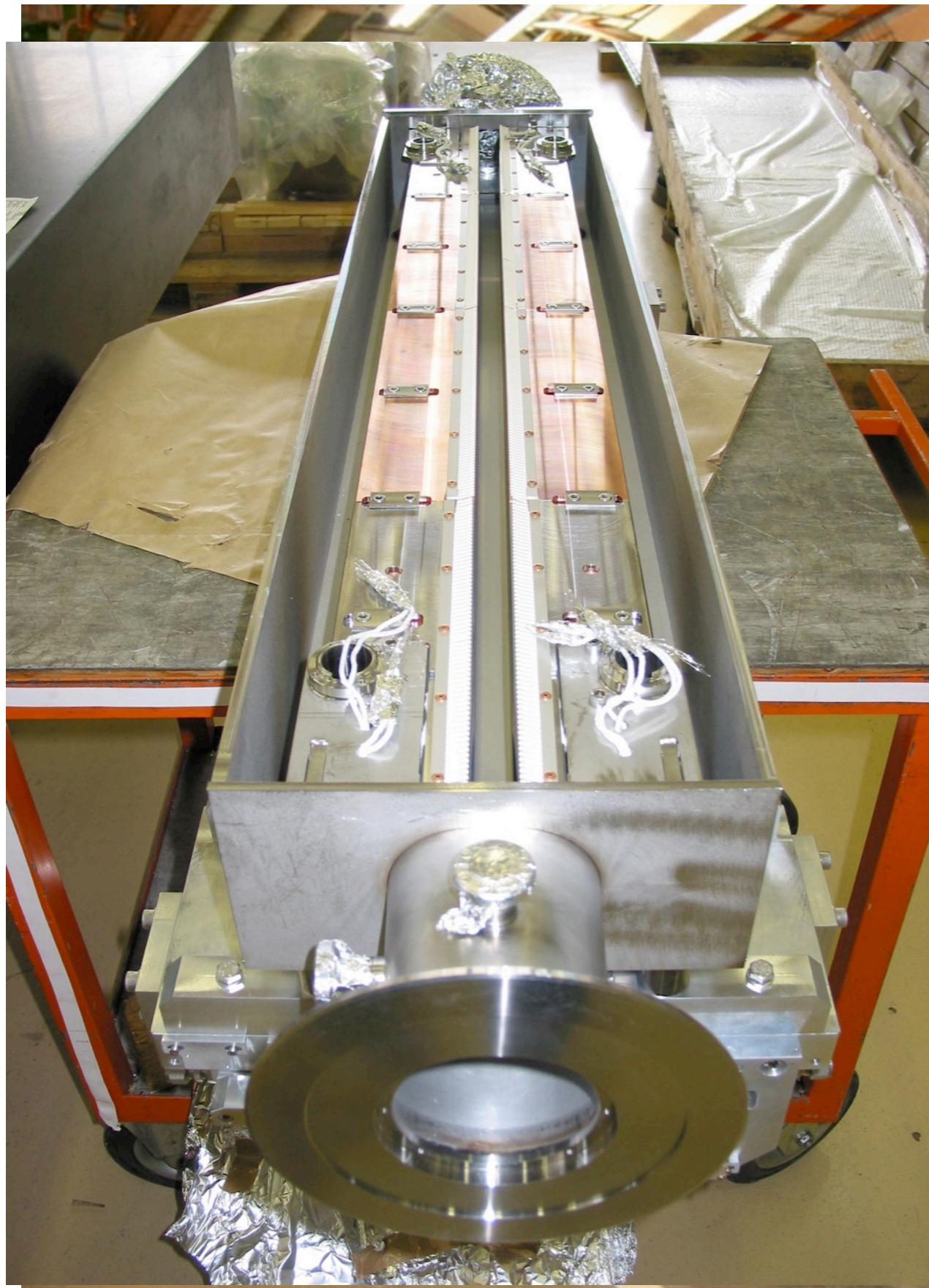
Nominal operational cycle



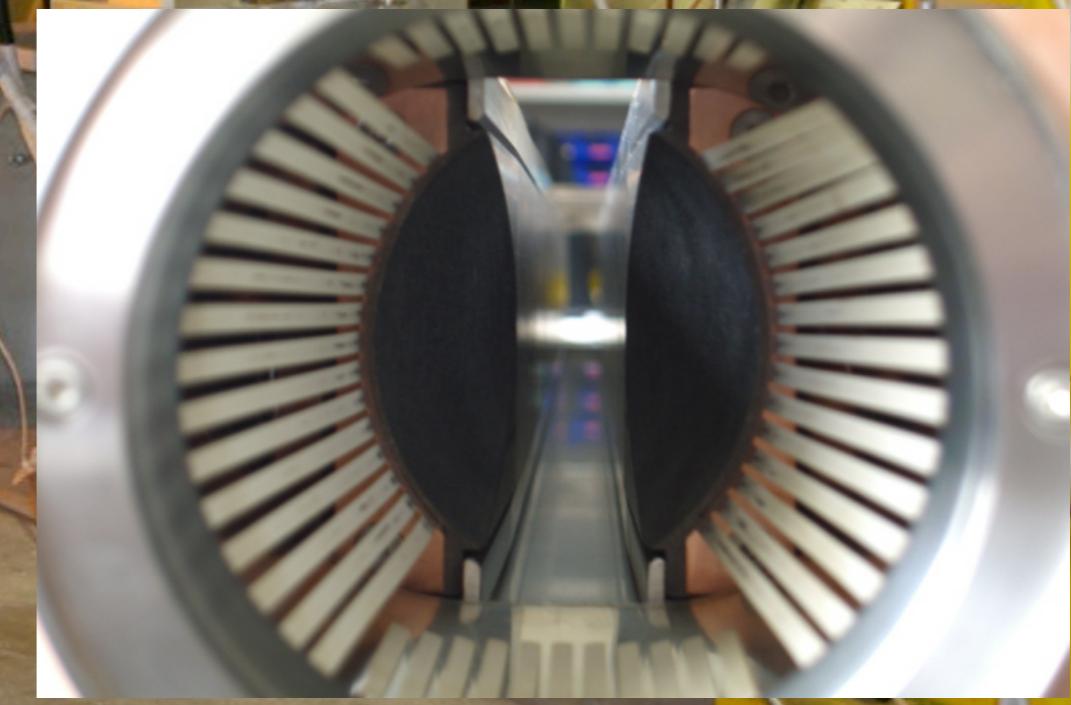
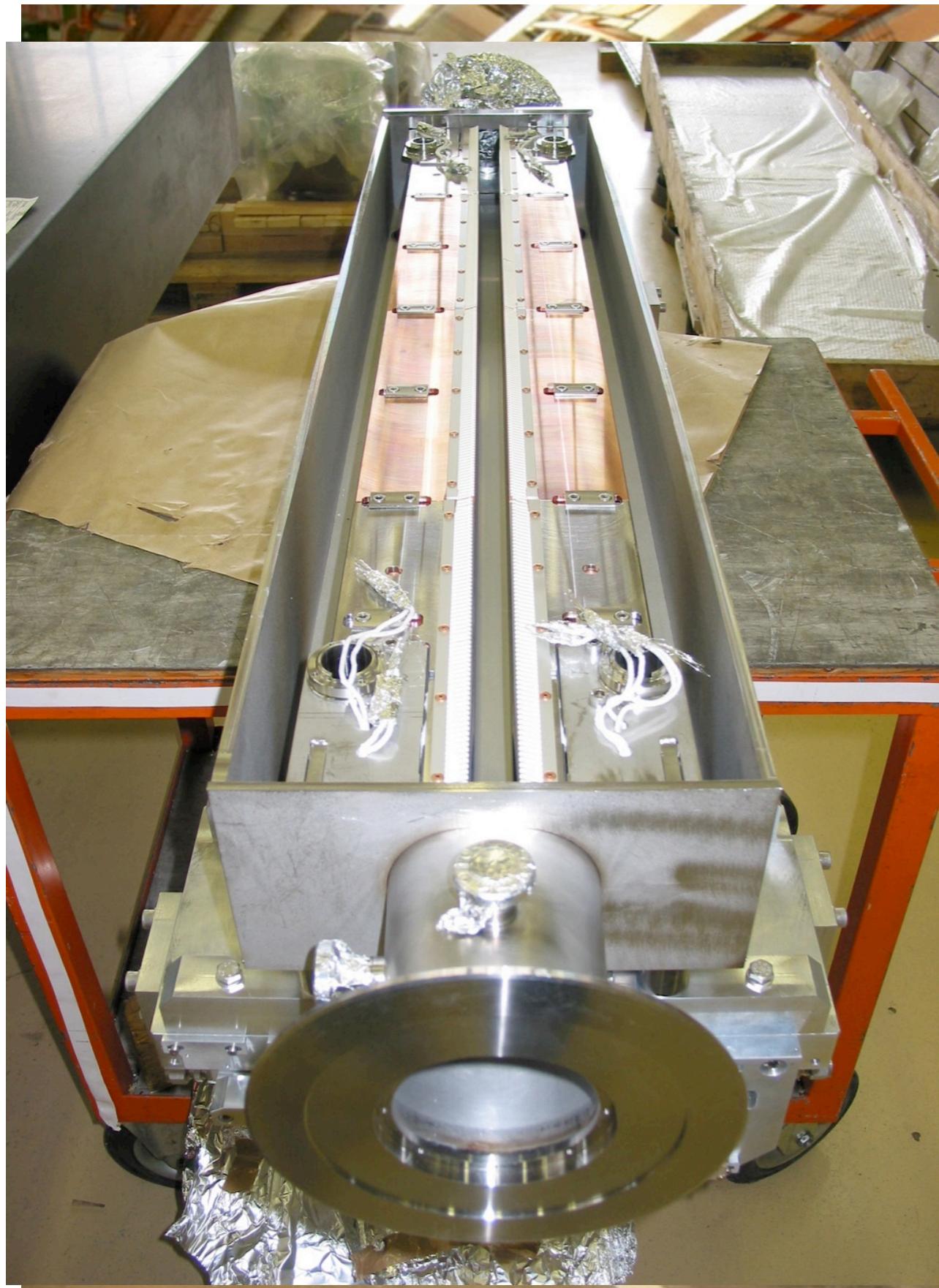
The LHC collimator



The LHC collimator



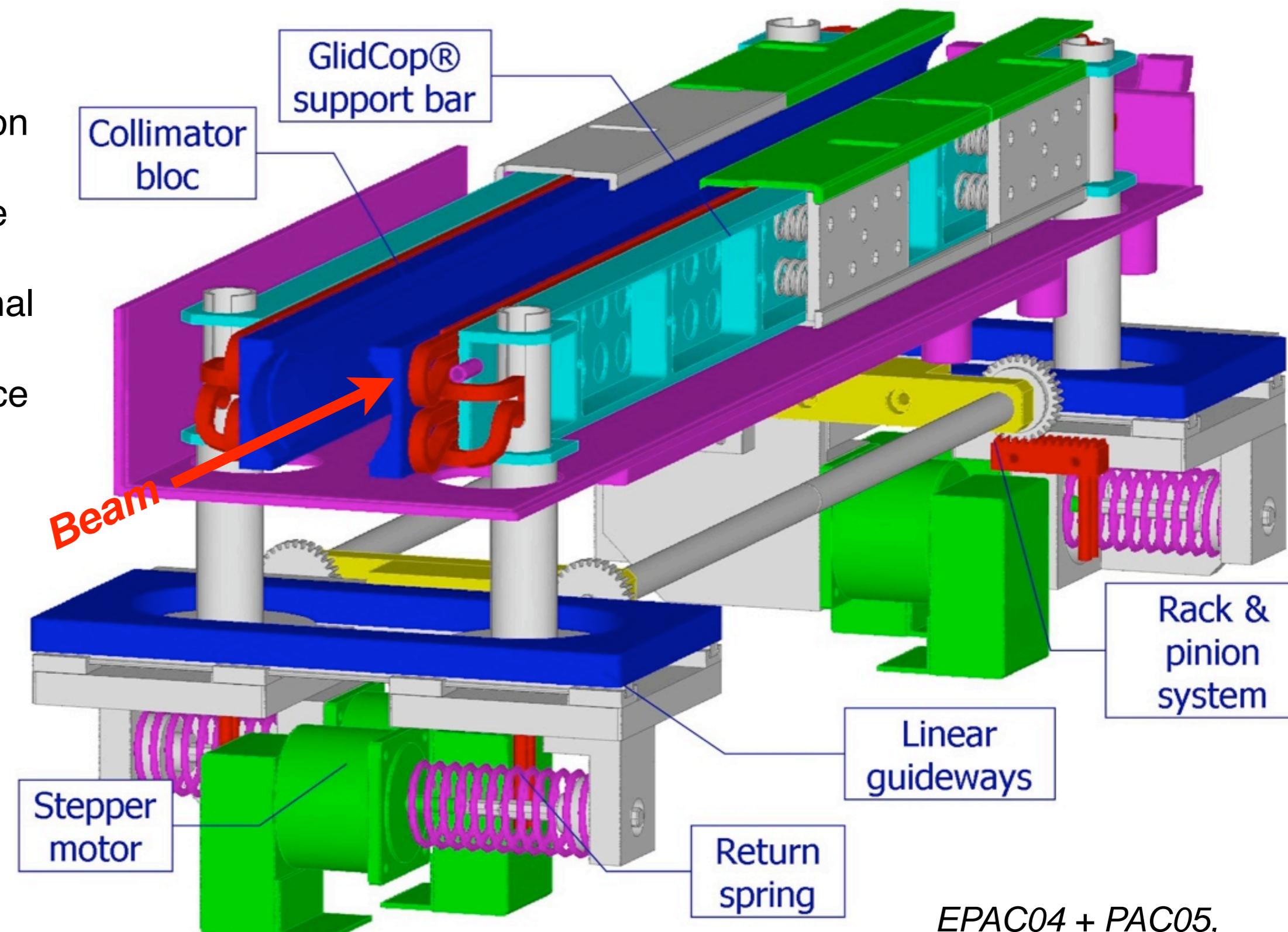
The LHC collimator



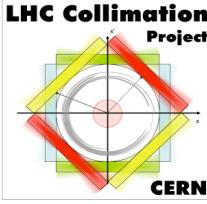
The collimator assembly

Main design features:

- Two jaws (position and angle)
- Concept of spare surface
- Different azimuthal angles (H,V,S)
- External reference of jaw position
- Auto-retraction
- RF fingers
- Jaw cooling



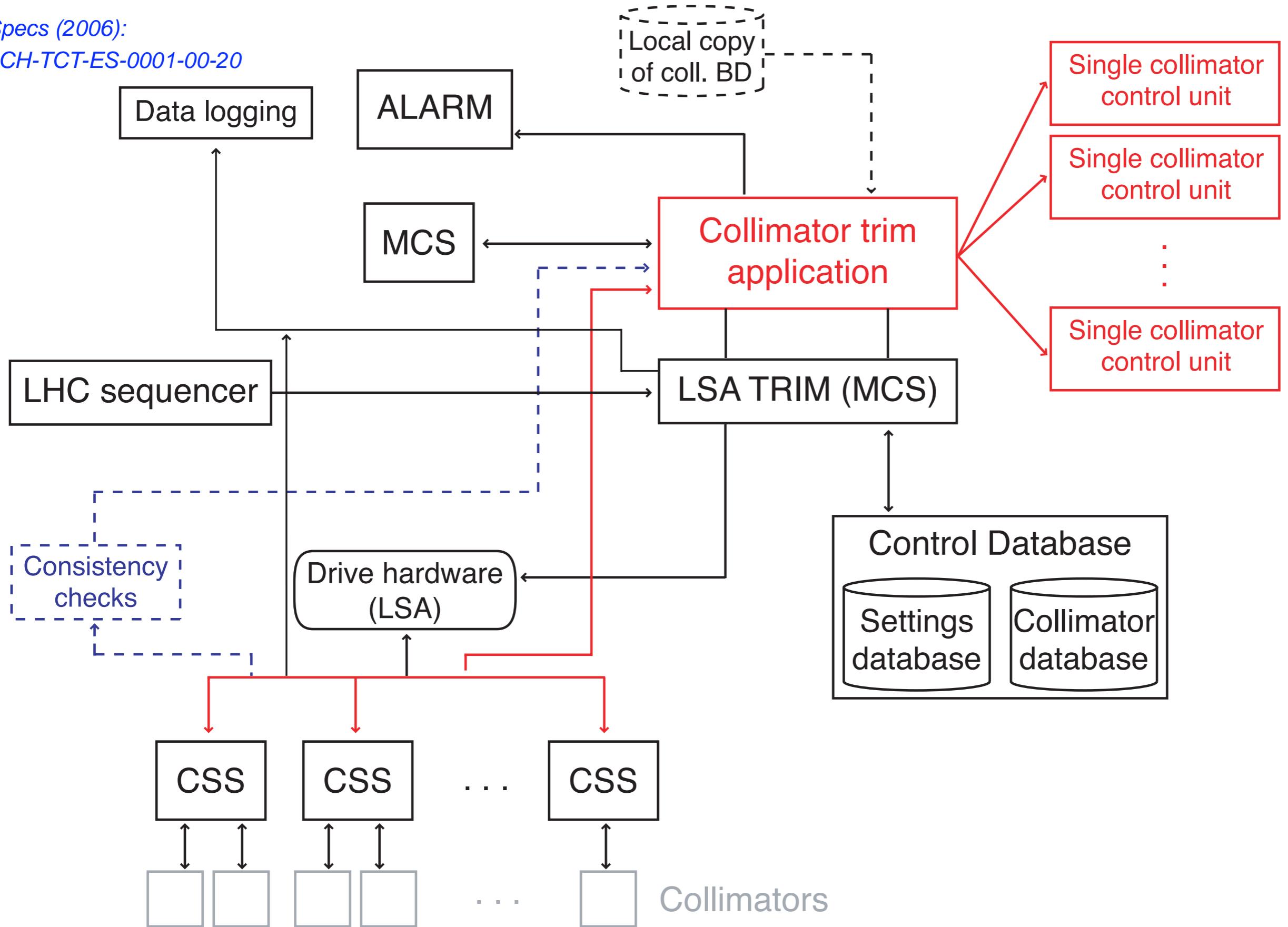
EPAC04 + PAC05,
A. Bertarelli et al.



Top-level controls architecture

Specs (2006):

LCH-TCT-ES-0001-00-20

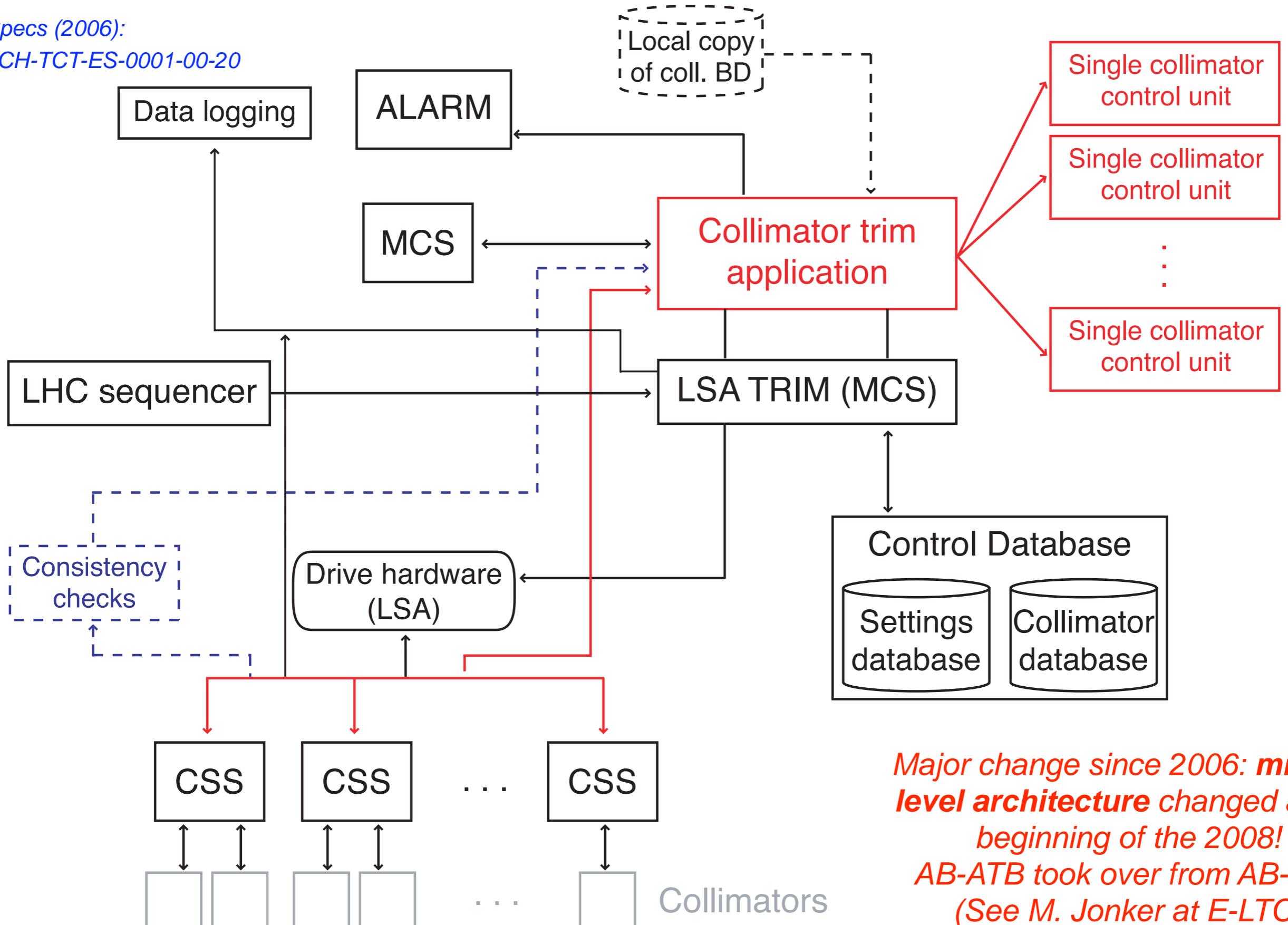




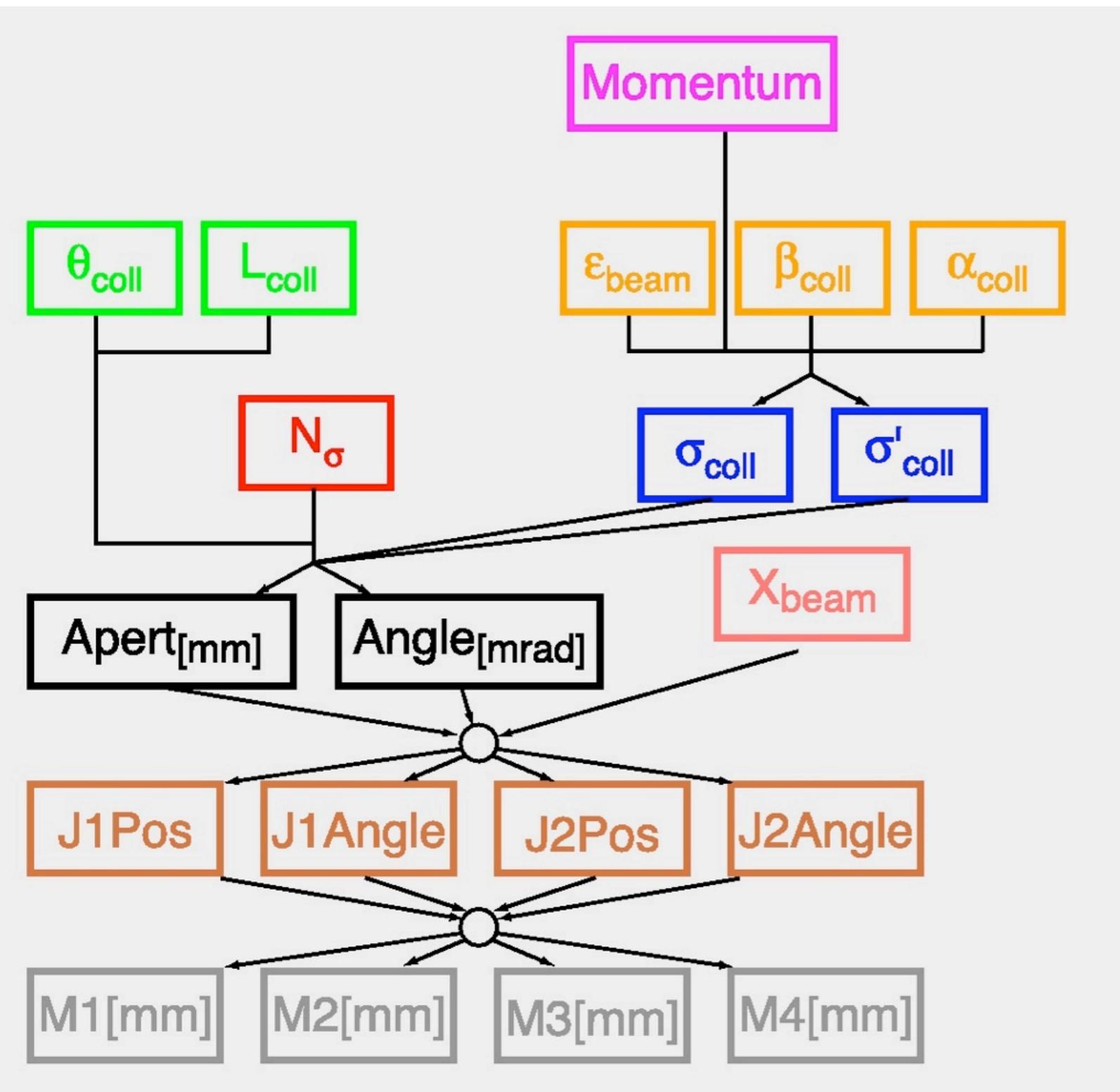
Top-level controls architecture

Specs (2006):

LCH-TCT-ES-0001-00-20



Settings in beam sigma units



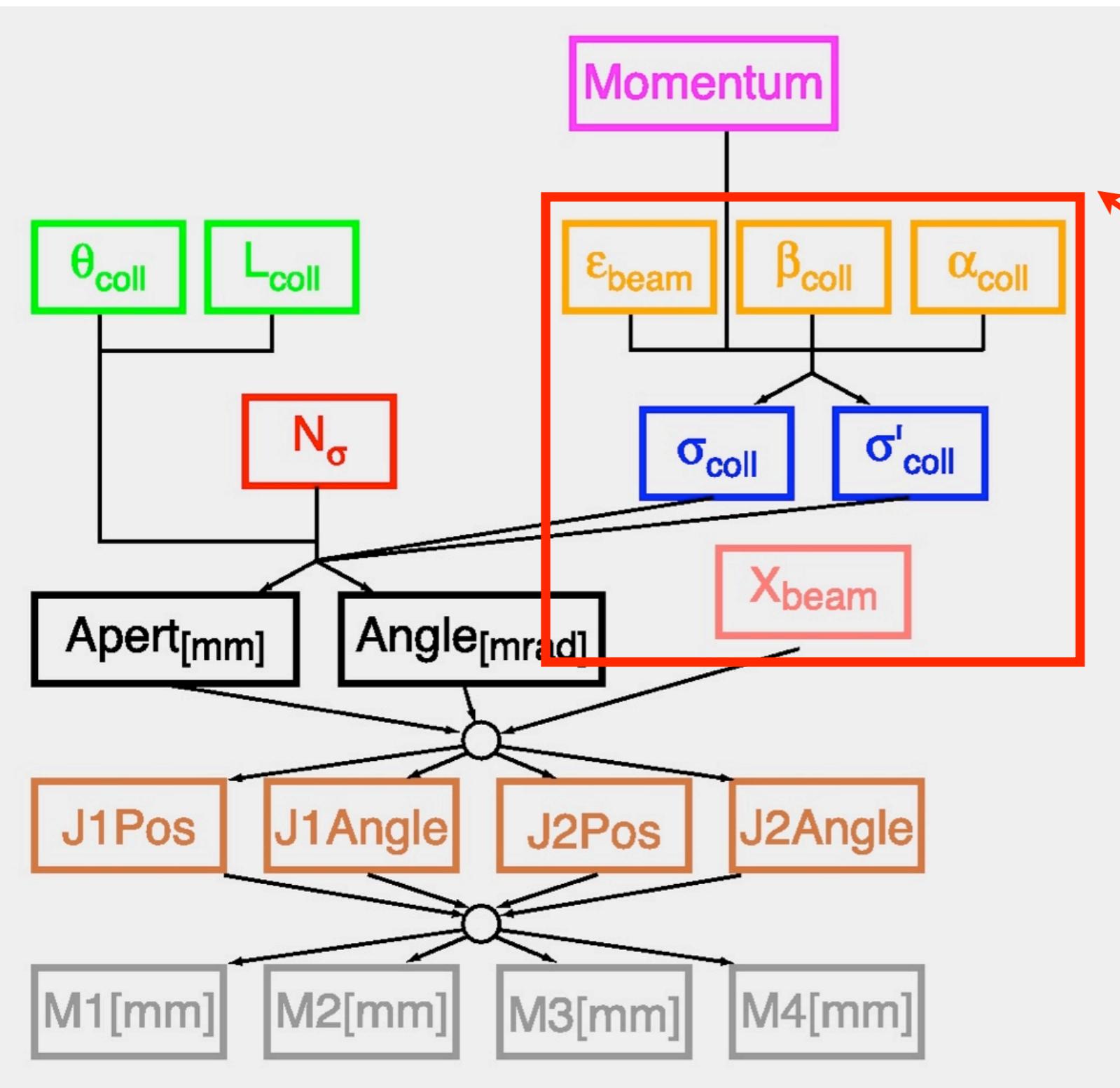
Parameter space for
settings in **units sigma!**
(trims at all levels possible!)

Canonical settings:

$TCP \rightarrow 6$
 $TCSG \rightarrow 7$
 $TCT \rightarrow 8.5$

Database definition of the parameter space and the associate makerules maintained by D. Jacquet, great support from LSA team!

Settings in beam sigma units



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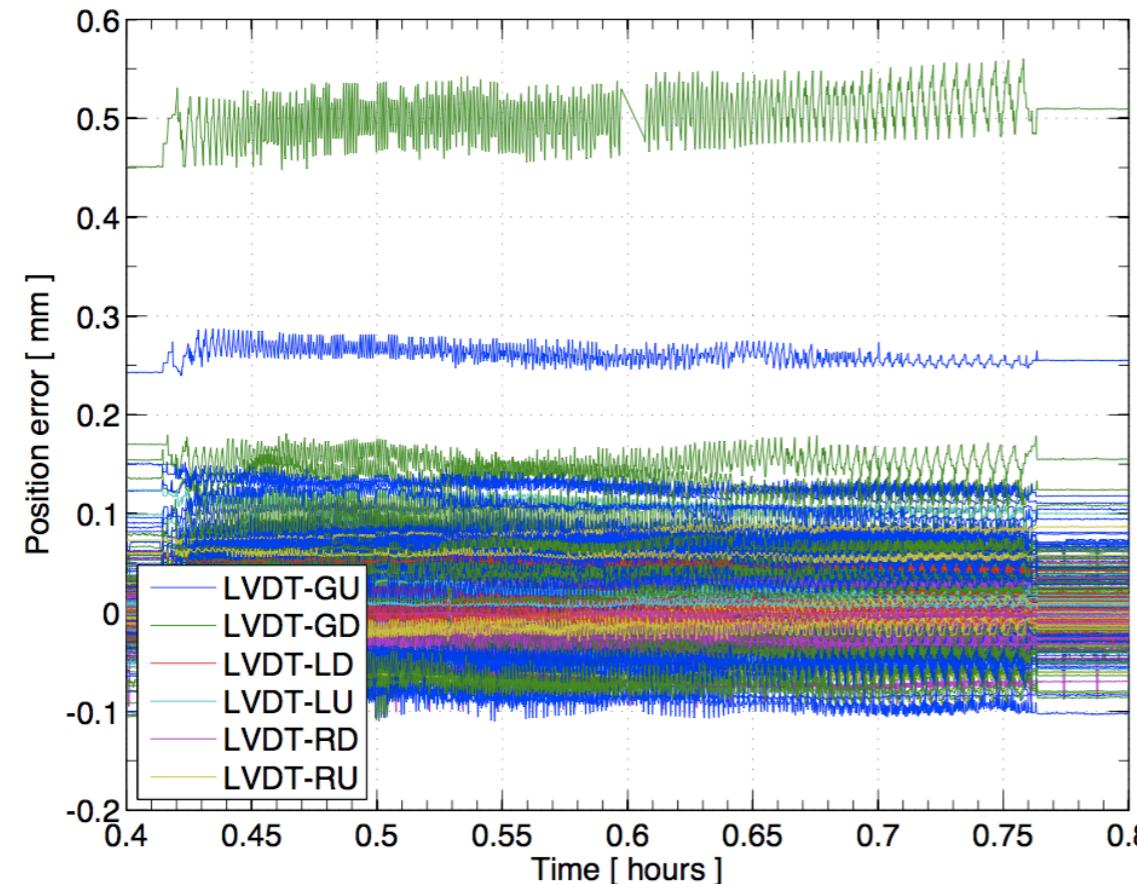
$TCP \rightarrow 6$
 $TCSG \rightarrow 7$
 $TCT \rightarrow 8.5$

Beam-based parameters
 will be determined for each collimator with beam and stored in the setting DB
(now: nominal values imported at the generation level)

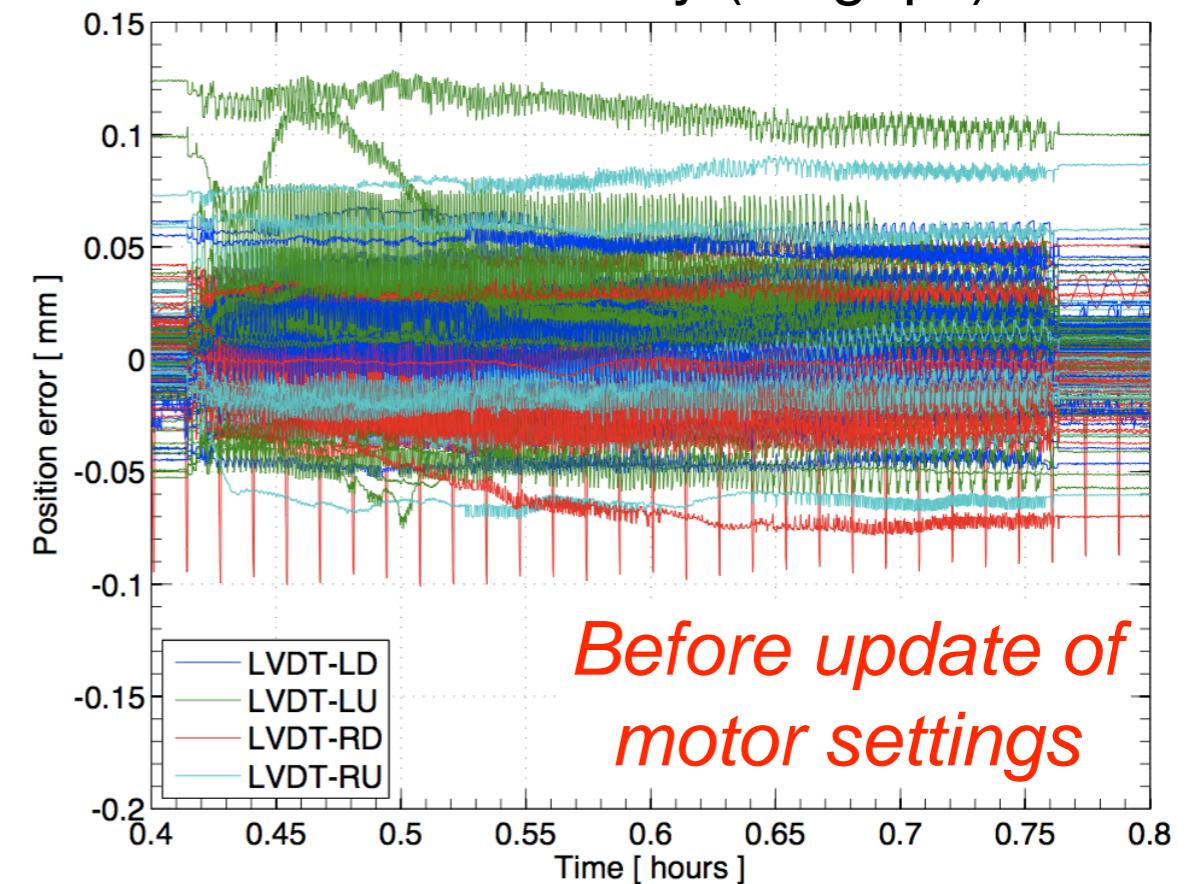
Database definition of the parameter space and the associate makerules maintained by D. Jacquet, great support from LSA team!

Distribution of setting / LVDT errors

All sensors

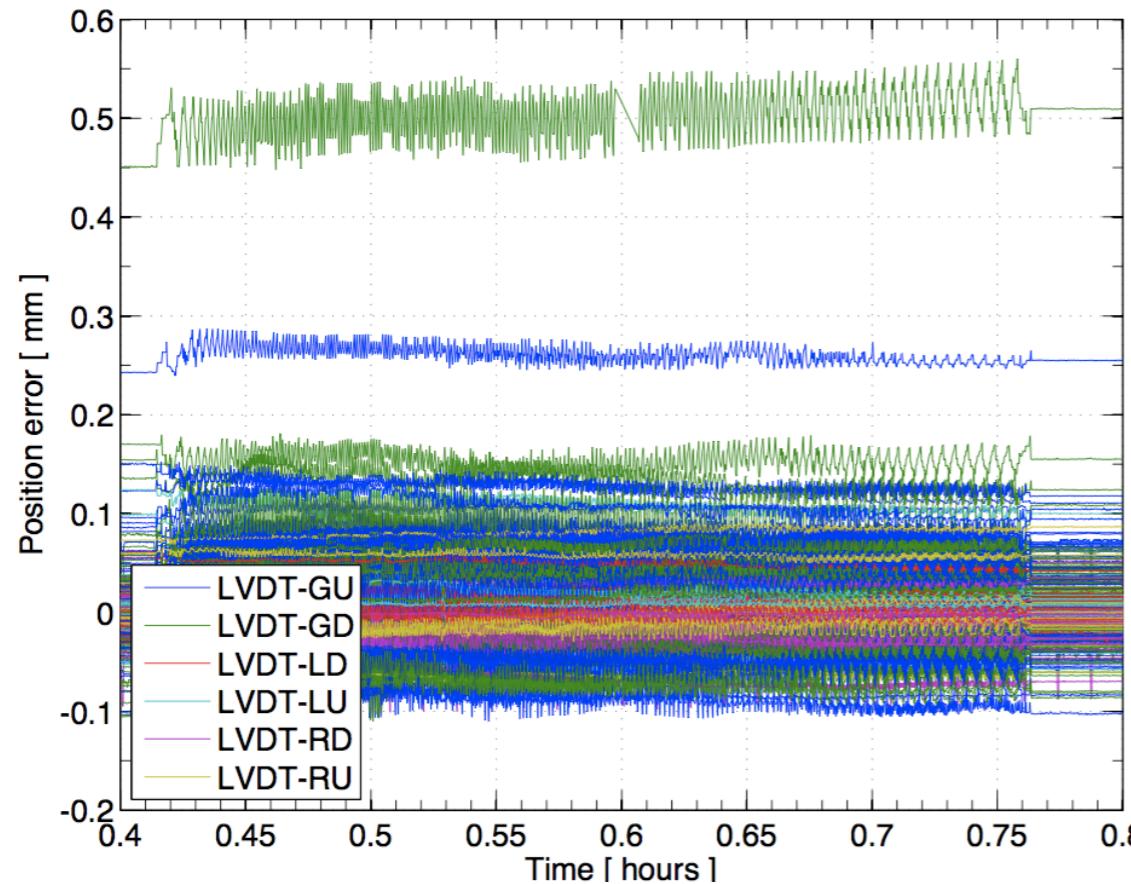


Corners only (no gaps)

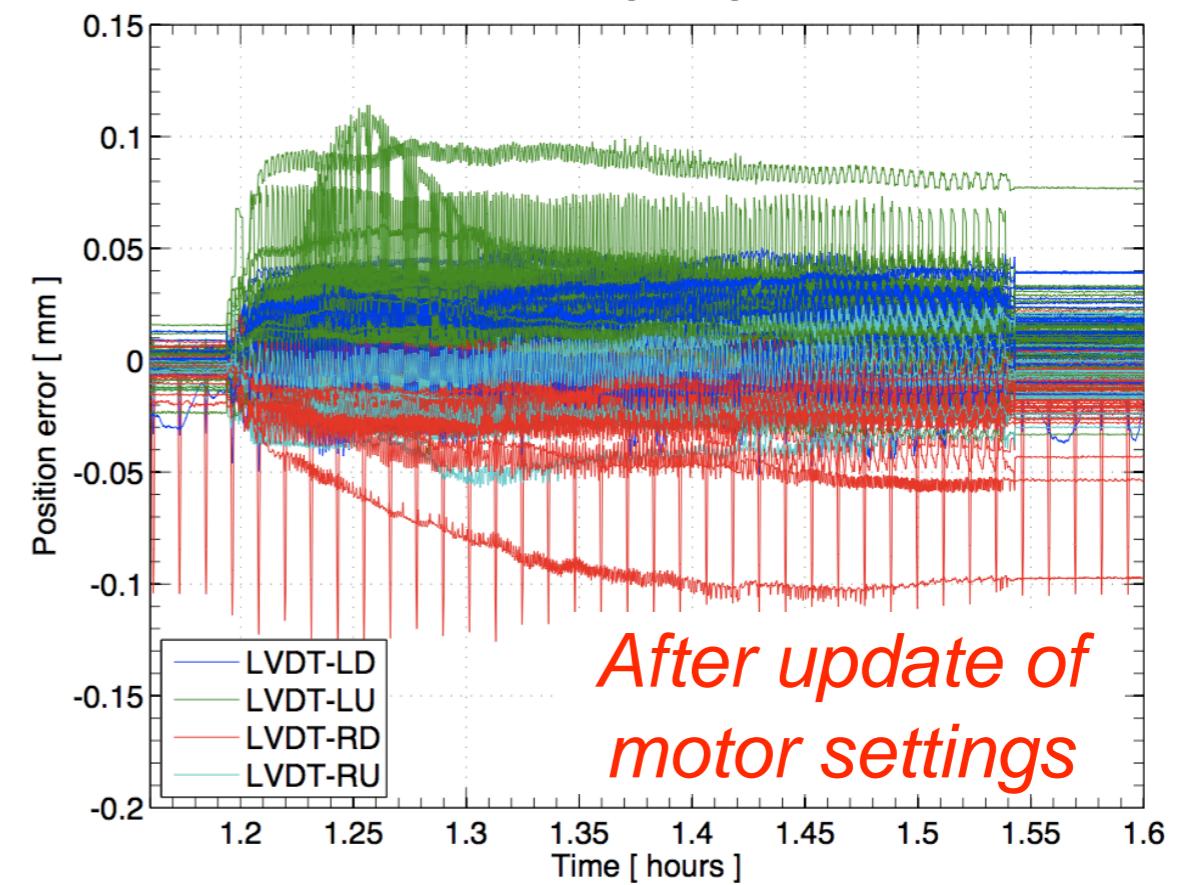
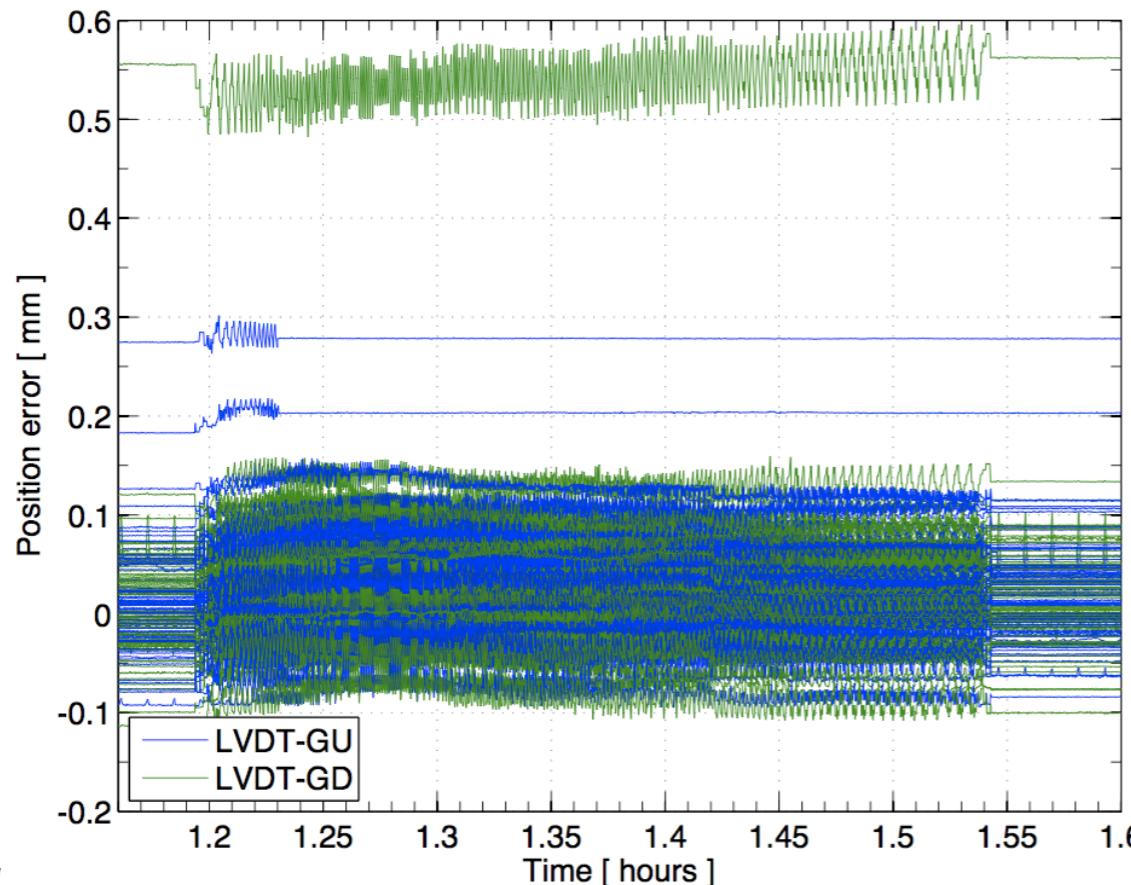
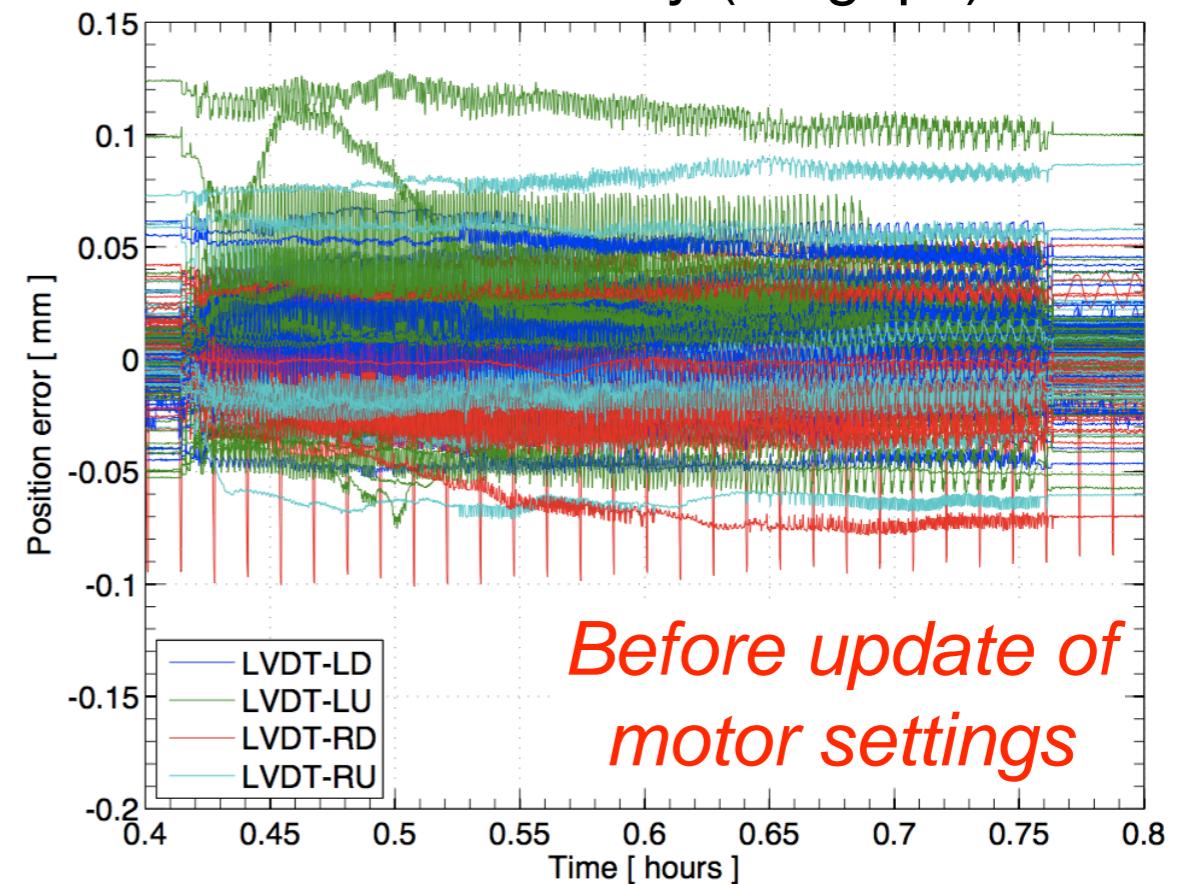


Distribution of setting / LVDT errors

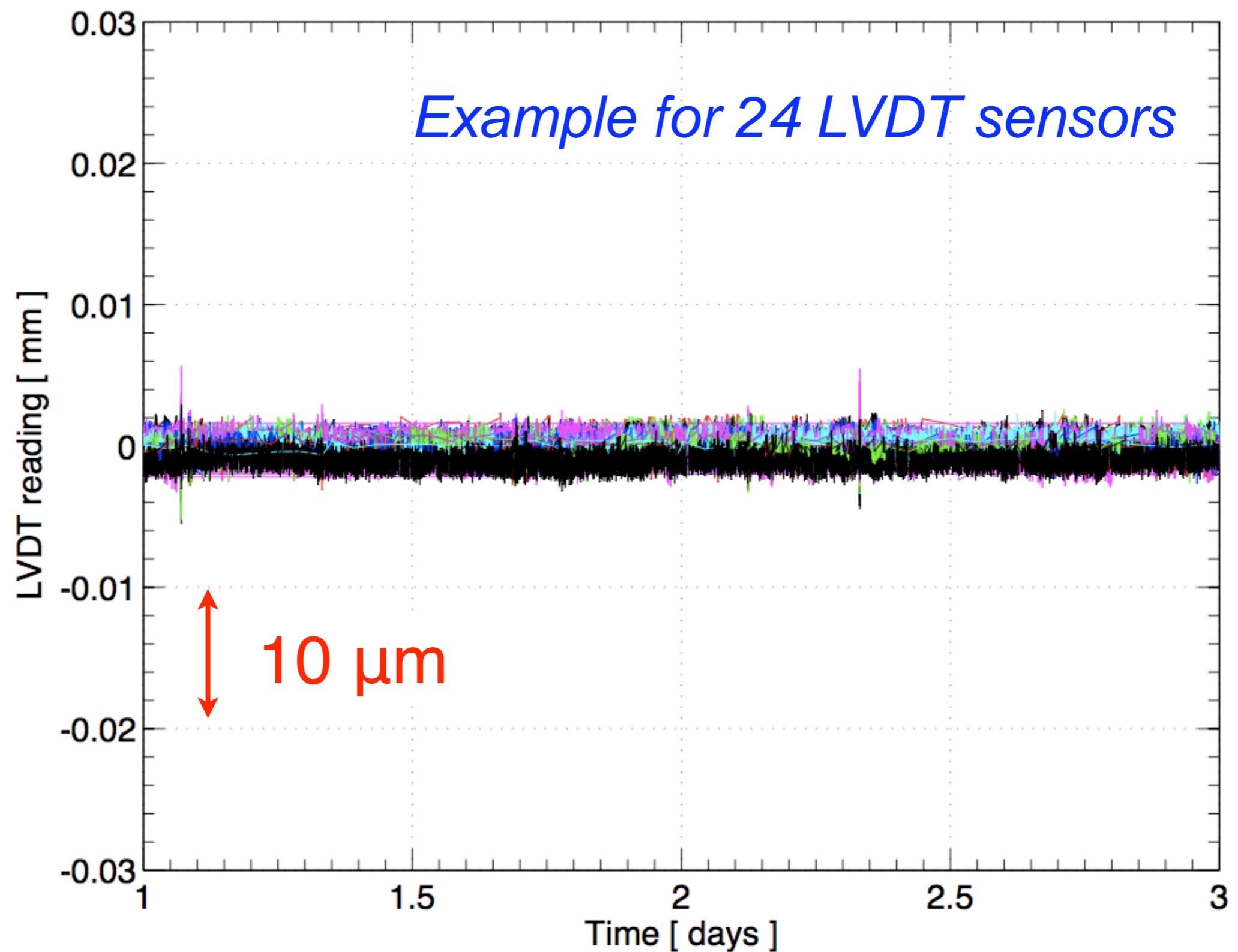
All sensors



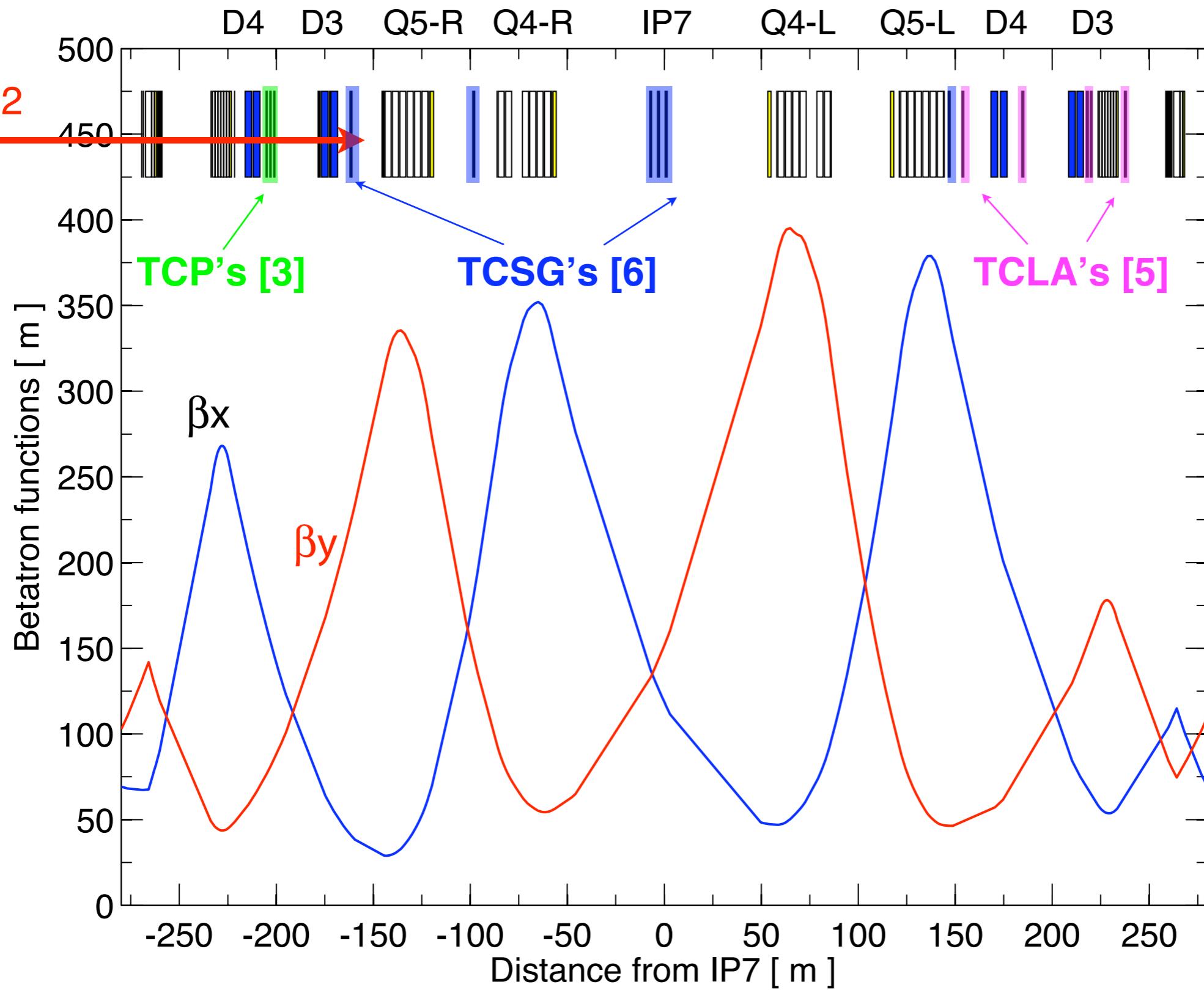
Corners only (no gaps)



Long term stability



Collimators gap during IR7 BLM response





Collimators gap during IR7 BLM response

