Internal Machine Protection Review
Collimation

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Internal Machine Protection Review, CERN

… for the LHC Collimation Project

Thanks to R. Bruce, D. Wollmann, S. Redaelli, …

Outline

- Introduction
- Hardware and Machine Protection Tests
- Interlock Thresholds and Damage Thresholds
- Setup Accuracy, Passive Protection and Cleaning Efficiency
- Beam Tests for Verification
- Beam Loss Events and Machine Stability
- Operational Issues
- Summary of Concerns

Introduction

- Here, focus on concerns (that we have ourselves or that others brought forward).
- Safety and robustness against beam failures has been the primary design goal of the collimation system since 2001!
- A lot of thoughts, many FTE of work and millions of CHF have gone into it!
- System is highly optimized, complex and not easy to see all the facets if you have not followed the work in the collimation WG over the years.
- Happy to explain whatever requires explanation.

Hardware and Machine Protection Tests

- List of tests formally defined: gap, position, temperature, RBAC, piquet, … interlocking.
- All interlocks tested and documented in MTF. All accessible through web page: http://www.cern.ch/lhc-collimation-project/mp-tests.htm
- A lot of effort and manpower invested.
- No feedback from MPP ➔ assume all is satisfactory.
- Automatic tools developed and allow redoing MP tests regularly. Redo after major stops (> 4 weeks).
- Not a single case of interlock failure so far (missing or fake interlocks).

MPP Tests (Pos/Gap)

Collimator Slot	MPP test results: EDMS Doc. No.		MTF
	2009	2010	
TCDD-4L2		https://edms.cern.ch/document/1062981/1	MTF
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		
TCDIV-20607	N/A	https://edms.cern.ch/document/1063705/1	
TCDIV-29012	https://edms.cern.ch/document/1052675/1		
TCDIV-29234	https://edms.cern.ch/document/1052531/1		
TCDIV-29509	https://edms.cern.ch/document/1052532/1		
TCDIV-87645	https://edms.cern.ch/document/1052533/1		
TCDIV-87804	https://edms.cern.ch/document/1052535/1		
TCDIV-88123	https://edms.cern.ch/document/1052536/1		
TCL-5L1-B2	https://edms.cern.ch/document/1052537/1		MTF
TCL-5L5-B2	https://edms.cern.ch/document/1052539/1	https://edms.cern.ch/document/1062991/1	MTF
TCL-5R1-B1	https://edms.cern.ch/document/1052540/1		MTF
TCL-5R5-B1	https://edms.cern.ch/document/1052541/1		MTF
TCLA-6L3-B2	https://edms.cern.ch/document/1052542/1	https://edms.cern.ch/document/1062992/1	MTF
TCLA-6R3-B1	https://edms.cern.ch/document/1052543/1	https://edms.cern.ch/document/1062993/1	MTF
TCLA-7L3-B2	https://edms.cern.ch/document/1052544/1		MTF
TCLA-7R3-B1	https://edms.cern.ch/document/1052546/1		MTF
TCLA-A5L3-B2	https://edms.cern.ch/document/1052547/1		MTF
TCLA-A5R3-B1	https://edms.cern.ch/document/1052548/1		MTF
TCLA-A6L7-B2	https://edms.cern.ch/document/1052549/1	https://edms.cern.ch/document/1062994/1	MTF
TCLA-A6R7-B1	https://edms.cern.ch/document/1052550/1		MTF
TCLA-A7L7-B2	https://edms.cern.ch/document/1052551/1		MTF
TCLA-A7R7-B1	https://edms.cern.ch/document/1052552/1		MTF
TCLA-B5L3-B2	https://edms.cern.ch/document/1052554/1		MTF

MPP Tests (Temp)

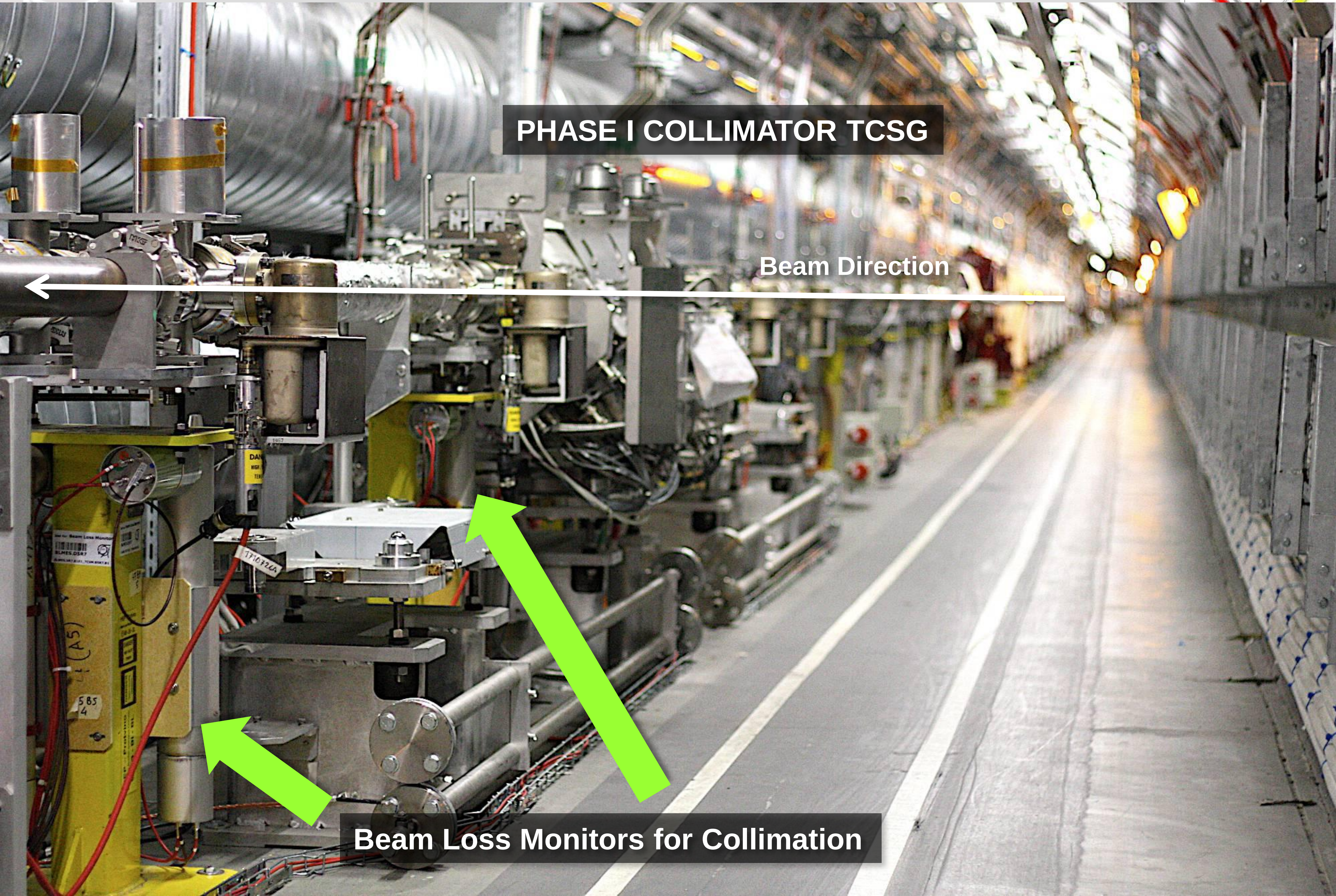
-------------------- analyzed ------------------------

Item	Alias	TStamp	Value	Status	StatusS	Threshold	BIC	tInit	End	Result
1	**TCTH_4L2_B1_TTLD**	2010.04.27 11:28:18.374	25.6	4	Auto Mode Status	50	CIB.UA23.L2.B1	1	0	OK
2	**TCTH_4L2_B1_TTRD**	2010.04.27 11:28:46.420	25.9	4	Auto Mode Status	50	CIB.UA23.L2.B1	1	0	OK
3	**TCTH_4L2_B1_TTLU**	2010.04.27 11:28:32.382	25.9	4	Auto Mode Status	50	CIB.UA23.L2.B1	1	0	OK
4	**TCTH_4L2_B1_TTRU**	2010.04.27 11:29:00.549	25.7	4	Auto Mode Status	50	CIB.UA23.L2.B1	1	0	OK
5	**TCTH_4L2_B1_TTW**	2010.04.27 11:41:02.577	25.4	4	Auto Mode Status	35	CIB.UA23.L2.B1	1	0	OK
6	**TCTVB_4L2_TTLD**	2010.04.27 11:31:09.070	25.3	4	Auto Mode Status	50	CIB.UA23.L2.B1,CIB.UA23.L2.B2	1/1/	0/0/	OK/OK/
7	**TCTVB_4L2_TTRU**	2010.04.27 11:32:13.496	25.4	4	Auto Mode Status	50	CIB.UA23.L2.B1,CIB.UA23.L2.B2	1/1/	0/0/	OK/OK/
8	**TCTVB_4L2_TTLU**	2010.04.27 11:31:41.267	25.3	4	Auto Mode Status	50	CIB.UA23.L2.B1,CIB.UA23.L2.B2	1/1/	0/0/	OK/OK/
9	**TCTVB_4L2_TTW**	2010.04.27 11:32:45.786	25.4	4	Auto Mode Status	35	CIB.UA23.L2.B1,CIB.UA23.L2.B2	1/1/	0/0/	OK/OK/
10	**TCDIV_29012_TTRU**	2010.04.27 11:26:11.812	24.8	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
11	**TCDIV_29012_TTLU**	2010.04.27 11:25:43.720	24.9	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
12	**TCDIV_29012_TTRD**	2010.04.27 11:25:57.705	24.5	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
13	**TCDIV_29012_TTLD**	2010.04.27 11:25:29.601	24.7	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
14	**TCDIH_29050_TTLU**	2010.04.27 11:22:55.025	25.6	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
15	**TCDIH_29050_TTRU**	2010.04.27 11:23:23.094	25.8	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
16	**TCDIH_29050_TTLD**	2010.04.27 11:22:40.941	25.3	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
17	**TCDIH_29050_TTRD**	2010.04.27 11:23:08.997	25.5	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
18	**TCDIH_29205_TTRD**	2010.04.27 11:24:05.256	25.3	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
19	**TCDIH_29205_TTLD**	2010.04.27 11:23:37.134	25.4	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
20	**TCDIH_29205_TTRU**	2010.04.27 11:24:19.369	25.4	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
21	**TCDIH_29205_TTLU**	2010.04.27 11:23:51.157	25.5	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
22	**TCDIV_29234_TTRU**	2010.04.27 11:27:08.059	24	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
23	**TCDIV_29234_TTLU**	2010.04.27 11:26:39.919	24	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
24	**TCDIV_29234_TTRD**	2010.04.27 11:26:53.962	24	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
25	**TCDIV_29234_TTLD**	2010.04.27 11:26:25.863	24.1	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
26	**TCDIH_29465_TTRD**	2010.04.27 11:25:01.480	25.4	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
27	**TCDIH_29465_TTLD**	2010.04.27 11:24:33.397	25.2	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
28	**TCDIH_29465_TTRU**	2010.04.27 11:25:15.566	25.6	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
29	**TCDIH_29465_TTLU**	2010.04.27 11:24:47.417	25.5	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
30	**TCDIV_29509_TTRD**	2010.04.27 11:27:50.220	23.4	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
31	**TCDIV_29509_TTLD**	2010.04.27 11:27:22.133	23.7	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK
32	**TCDIV_29509_TTRU**	2010.04.27 11:28:04.291	23.3	4	Auto Mode Status	50	CIB.SR2.INJ1.1	1	0	OK

Interlock Thresholds and Damage Thresholds

- Several kinds of thresholds to guarantee that collimators are in correct position and at normal temperature:
  - Jaw positions: ±0.5 mm (adjustable by experts)
  - Gap errors: ±0.5 mm (adjustable by experts)
  - Temperature: 50 deg C (changeable)
- In addition we have specified BLM thresholds:
  - Each collimator has two downstream BLM's assigned.
  - Thresholds specified for guaranteeing normal operation (in impacting power load, without contribution for cross-talk from showers):
    - Primary collimators: 430 – 1,100 kW
    - Secondary collimators: 43 – 110 kW
    - Tungsten collimators (TCT, TCLA): 0.2 – 0.6 kW
  - The BLM team has translated these specifications into BLM thresholds.

Beam Loss Monitors for Monitoring Losses at Collimators



BLM Threshold Specification Cleaning Insertions

Table 1: Estimated settings of "damage" interlock limits for various collimator types in the cleaning insertions. Power refers to nominal intensity.

Device	Location	Energy	Condition 1	Condition 2	Condition 3
TCP	IR3	450 GeV	dN/dt > 1.2e12 p/s for T > 10 s (87 kW)	dN/dt > 6e12 p/s for 1 s < T < 10 s (430 kW)	dN/dt > 1.5e13 p/s for T < 1 s (1.1 MW)
TCP	IR7	450 GeV	dN/dt > 1.2e12 p/s for T > 10 s (87 kW)	dN/dt > 6e12 p/s for T < 10 s (430 kW)	
TCP	IR3, IR7	7 TeV	dN/dt > 0.8e11 p/s for T > 10 s (90 kW)	dN/dt > 4e11 p/s for T < 10 s (449 kW)	
TCSG	IR3	450 GeV	dN/dt > 1.2e11 p/s for T > 10 s (9 kW)	dN/dt > 6e11 p/s for 1 s < T < 10 s (43 kW)	dN/dt > 1.5e12 p/s for T < 1 s (110 kW)
TCSG	IR7	450 GeV	dN/dt > 1.2e11 p/s for T > 10 s (9 kW)	dN/dt > 6e11 p/s for T < 10 s (43 kW)	
TCSG	IR3, IR7	7 TeV	dN/dt > 0.8e10 p/s for T > 10 s (9 kW)	dN/dt > 4e10 p/s for T < 10 s (45 kW)	
TCLA	IR3	450 GeV	dN/dt > 6e8 p/s for T > 10 s (45 W)	dN/dt > 3e9 p/s for 1 s < T < 10 s (215 W)	dN/dt > 7.5e9 p/s for T < 1 s (550 W)
TCLA	IR7	450 GeV	dN/dt > 6e8 p/s for T > 10 s (45 W)	dN/dt > 3e9 p/s for T < 10 s (215 W)	
TCLA	IR3, IR7	7 TeV	dN/dt > 4e7 p/s for T > 10 s (45 W)	dN/dt > 2e8 p/s for T < 10 s (225 W)	

BLM Threshold Specification Experimental Insertions

Table 2: Estimated settings of "damage" interlock limits for various collimator types outside of cleaning insertions. Power refers to nominal intensity.

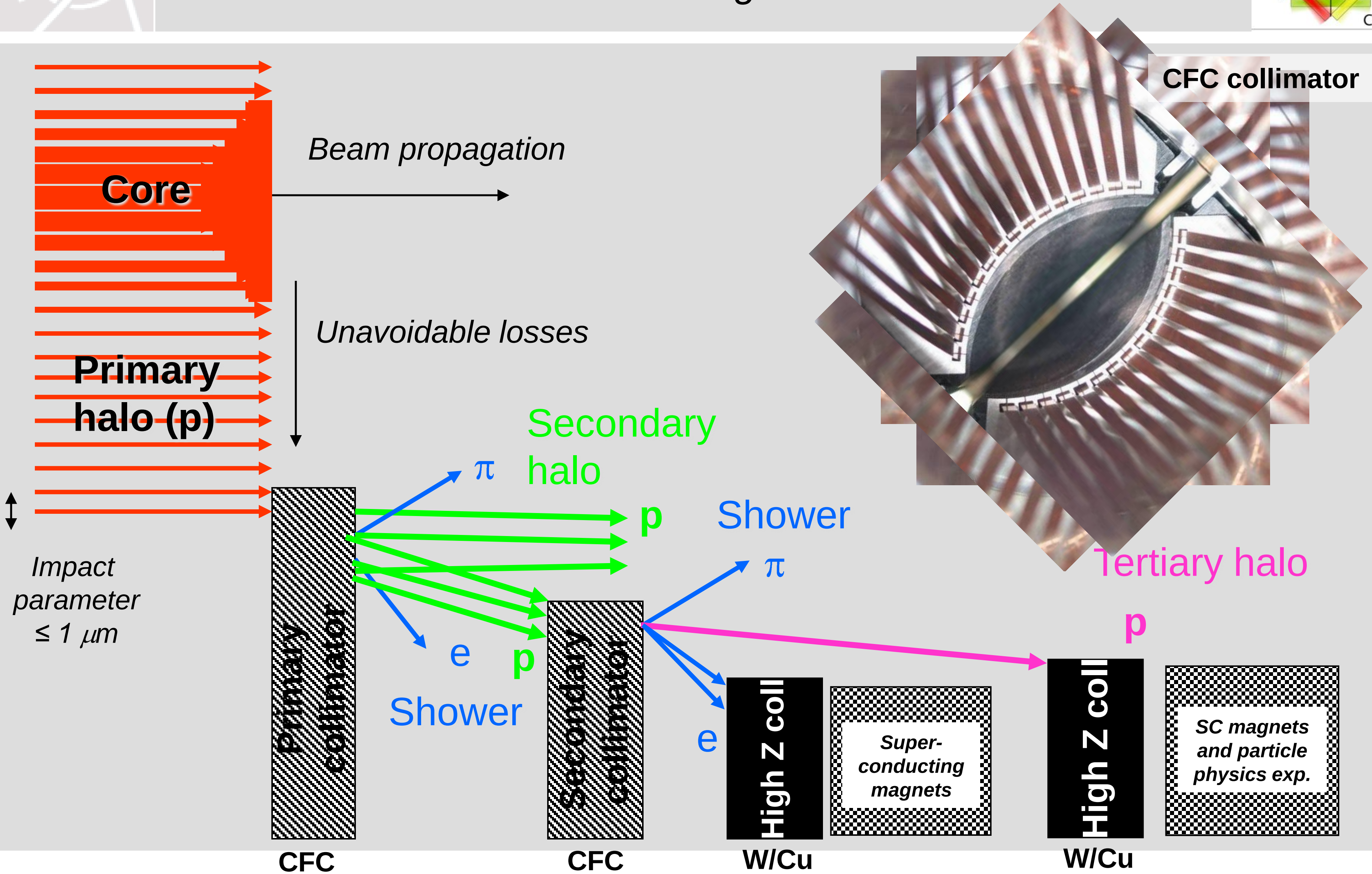
Device	Location	Energy	Condition 1	Condition 2	Condition 3
TCTH, TCTVA, TCTVB	IR1, IR2, IR5, IR8	450 GeV	dN/dt > 6e8 p/s for T > 10 s (45 W)	dN/dt > 3e9 p/s for T < 10 s (215 W)	
TCTH, TCTVA, TCTVB	IR1, IR2, IR5, IR8	7 TeV	dN/dt > 4e7 p/s for T > 10 s (45 W)	dN/dt > 2e8 p/s for T < 10 s (225 W)	
TCL, TCLP	IR1, IR5	450 GeV	dN/dt > 6e9 p/s for T > 10 s (450 W)	dN/dt > 3e10 p/s for T < 10 s (2.2 kW)	
TCL, TCLP	IR1, IR5	7 TeV	dN/dt > 4e8 p/s for T > 10 s (450 W)	dN/dt > 2e9 p/s for T < 10 s (2.2 kW)	
TCLIA, TCLIB, TCSG	IR2, IR6, IR8	450 GeV	dN/dt > 1.2e11 p/s for T > 10 s (9 kW)	dN/dt > 6e11 p/s for T < 10 s (43 kW)	
TCLIA, TCLIB, TCSG	IR2, IR6, IR8	7 TeV	dN/dt > 0.8e10 p/s for T > 10 s (9 kW)	dN/dt > 4e10 p/s for T < 10 s (45 kW)	

What are We Protecting Against?

- Single-turn failures, e.g. asynchronous dump:
  - No way to protect against this with BLM's.
  - Rely on correct hierarchy and robustness of collimators for such an event.
  - For setup we must expose non-robust collimators for short periods: accept very small risk of minor collimator damage for asynchronous dump during setup. Lower risk than Tevatron every day!
- Slower failures:
  - Beam loss measurements should follow normal hierarchy.
  - BLM thresholds specified to enforce the hierarchy: Highest losses at primary collimators, lowest at tungsten collimators.
  - For this normal hierarchy, the integrity of the machine has been verified in years of studies in the collimation WG (heating to magnets, flanges, vacuum chambers, …).
  - BLM threshold do not give collimator damage thresholds!

Multi-Stage Cleaning & Protection

3-4 Stages



Example: Damage to Tungsten Collimators

- Conventional work horse in collimation systems (HERA, Tevatron, …).
- Used because of very high melting point (4420 deg C), excellent absorption and brittleness (no risk of catastrophic material rupture).
- Used in LHC for tertiary and quartiary collimation with heavy cooling capacity (~ 7 kW per collimator). Also, in-situ spare surface concept.
- These are very robust collimators for slower losses but watch out:
  - Single-turn shock impact: damage limit at 3.5 TeV is **1e9 – 3e9 protons lost in single turn** (deformation). Melting limit about factor 20 higher.
  - Multi-turn impacts: tungsten collimators can take ~50 times higher loads for long times than what we specified for the correct hierarchy (10 kW for 10s)!
- Collimation setup:
  - Need to move tungsten collimators to primary beam halo for 1e11 protons.
  - **Allow cut of 0.5% for 20 μm movement over 10 ms (100 turns): loss of 5e8 p! In 1 s scale this corresponds to 280 W. ZERO risk!**

Some Details for TCT/TCLA

To follow up on the recent questions about damage limits for tungsten collimators, we summarize the damage limits we established in the past for your information (thanks to Adriana, Alessandro Dalocchio, Alessandro Bertarelli, Francesco Cerruti):

Assumptions:

1. Instant deposition (< 1us)
2. Cp at 20 degrees (134 J/kg/K): to melt 450 kJ/kg with melting point T = 3400 degrees. This is 8.7 kJ/cm3.
3. Stress provoked by thermal shock (assuming 25 kJ/kg for plasticity limit): for plastic deformation 480 J/cm3
4. An independent estimate on maximum energy deposition for plastic deformation on Tungsten gave 300 J/cm3, with an instantaneous temperature rise of 130 degrees.
5. Let's assume as damage limit an average of 400 J/cm3.

Folding with energy deposition results:

1. 7 TeV: Damage limit for 0.5 mm beam size at TCT is **1.3e9 p** (depends on local beam size = squeeze, emittance). Tighter at TCLA collimators (0.2 mm beam size): **5e8 p**
2. 3.5 TeV: To play it safe use factor 2 relaxed damage limits (scale linear with energy): **~3e9 p** for TCT squeezed **1e9 p** for TCLA
3. Damage limits for melting are about a factor 20 higher than the quoted values. You can see that we will damage (deform) tungsten collimators much before melting them.

Estimates are conservative, as plastic deformation is mostly a problem from shock impact. Tolerances become less severe after some turns. It is clear that heat will dissipate if losses are distributed with time and the strong collimator cooling will further relax things.

MP Configuration Issue

- Collimation interlock thresholds are set up to guarantee maximum safety during regular operation. Detected several conditions of irregular conditions. Examples:
  - Starting ramp without collimators loaded for ramp.
  - Ramping up beam energy at 3.5 TeV with beam (pre-cycle combo).
  - Fast beam losses at collimators (0.5 MW threshold triggered).
  - Secondary and tertiary collimators acting as primary collimators.
  - Movement of collimators to outside of allowed limits.
  - Not compatible with requirements during collimation setup!
- No false interlocks so far.
- Collimation interlock thresholds are not set to allow setup of collimators during standard operation! If we would do this then protection would be overall relaxed (not desirable).

Collimators are designed for being hit by beam!

Collimators are much more robust than most other components in the ring! This includes tungsten collimators (except for single-turn failures).

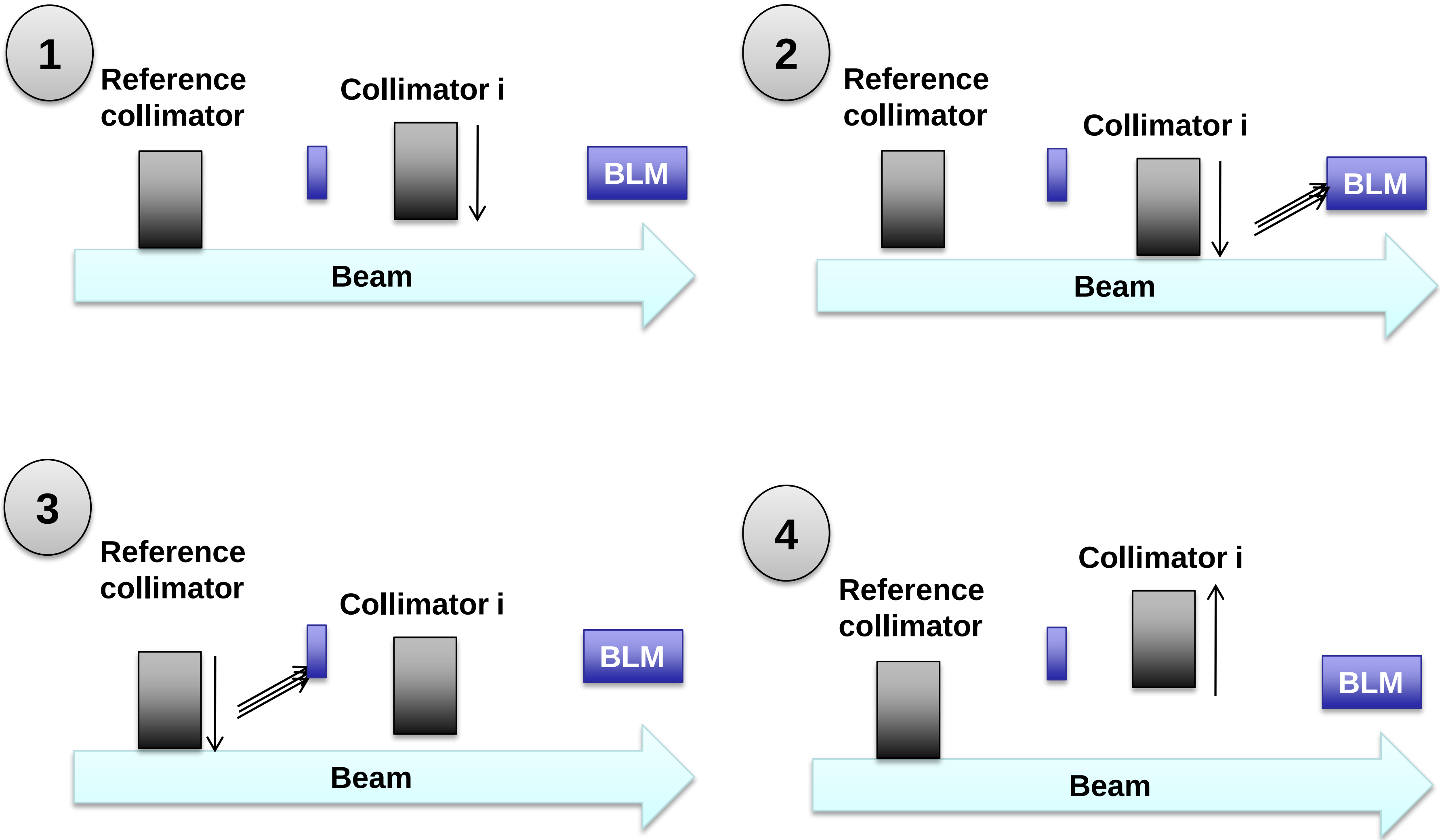
Usually collimators are frozen in for protection reasons! Need to violate this for setup!

Some flexibility is required in machine protection!

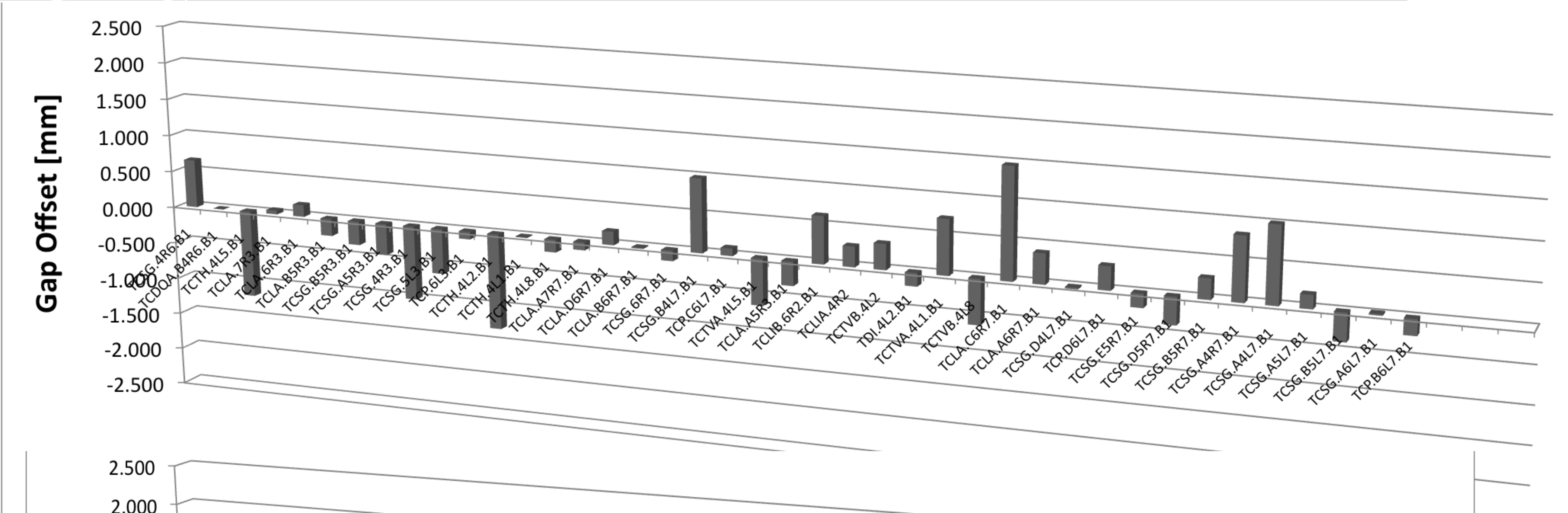
Setup Accuracy, Passive Protection and Cleaning Efficiency

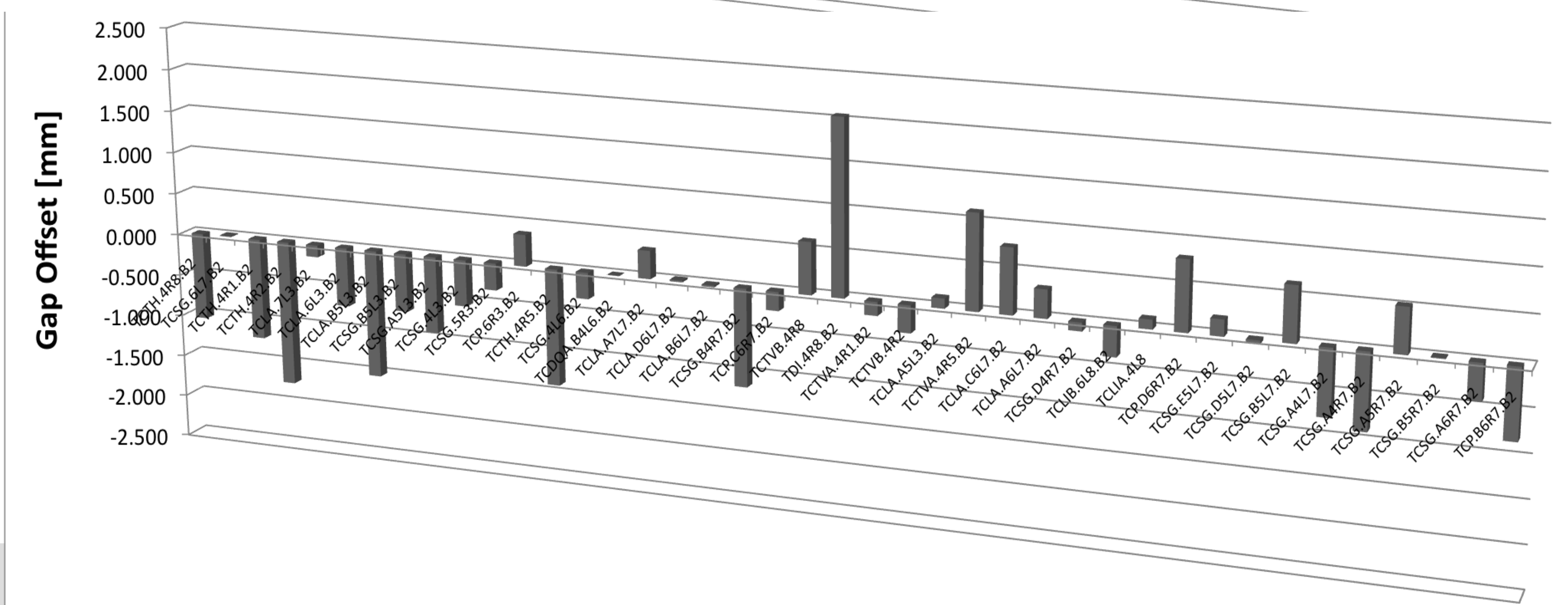
- At the LHC we set up collimation once and keep it for months!
- Very different for Tevatron and RHIC where collimators are set up for each new fill.
- LHC setup is affected by systematic issues! Will explain them.
- LHC collimator setup:
  - About 15 min per collimator.
  - Reliable gap center information.
  - Efficient detection of problematic cases.
  - Calibrated beam size dominated by systematic errors ➔ not possible presently to determine accurately the actual beam size.
- Stability cannot be judged yet: no stable setup and no regular monitoring of performance scheduled!

Improved Setup Agorithm

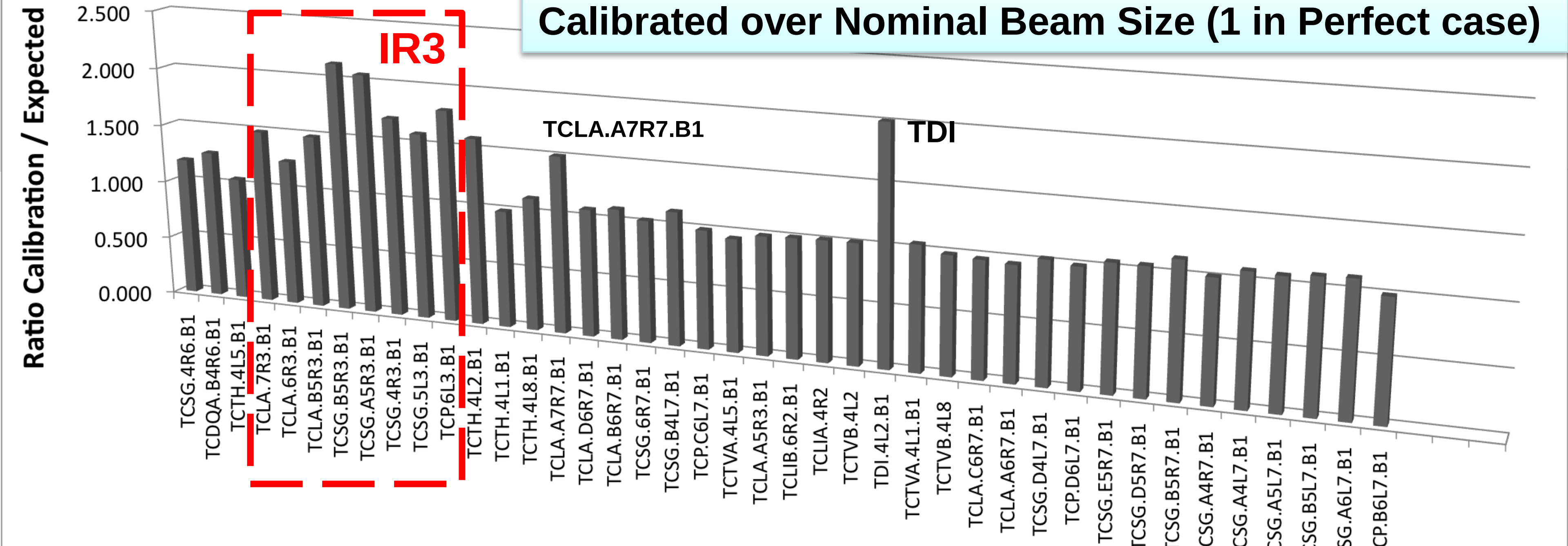


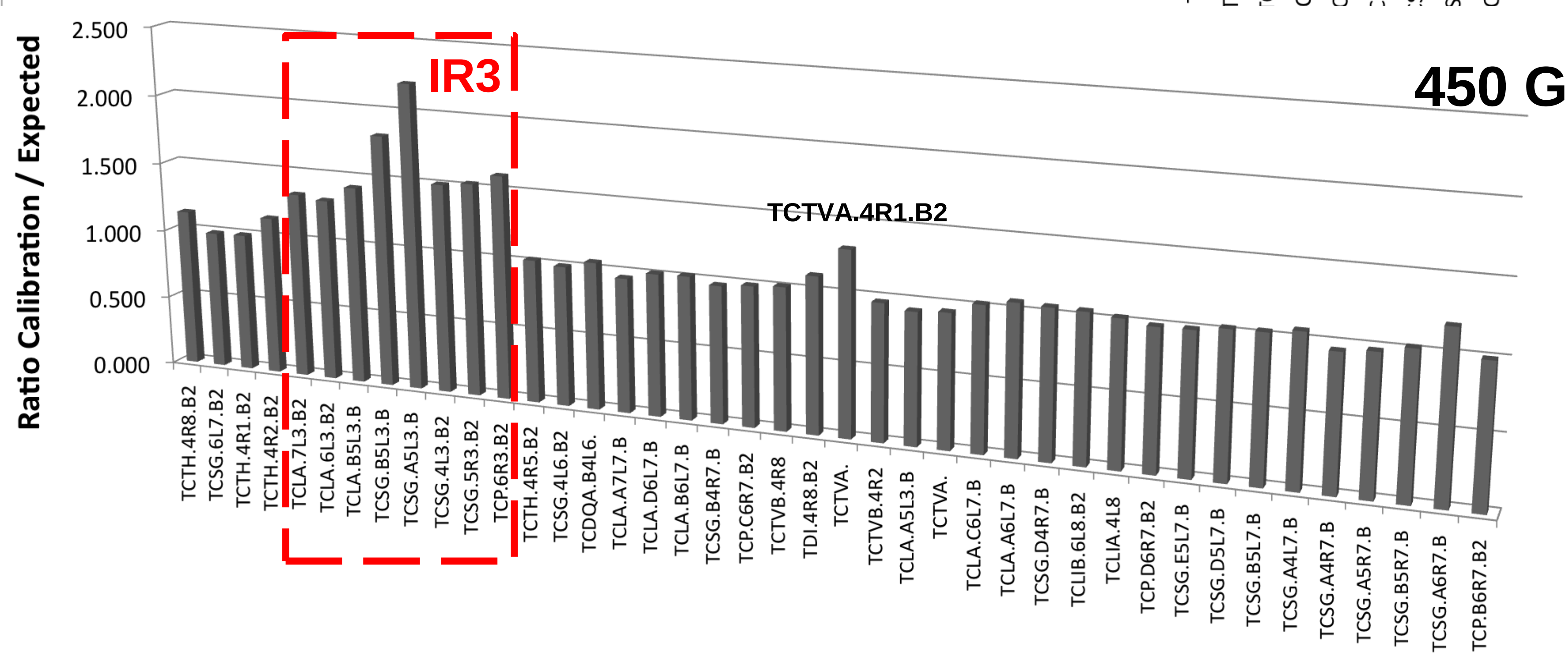
Results on Gap Centers





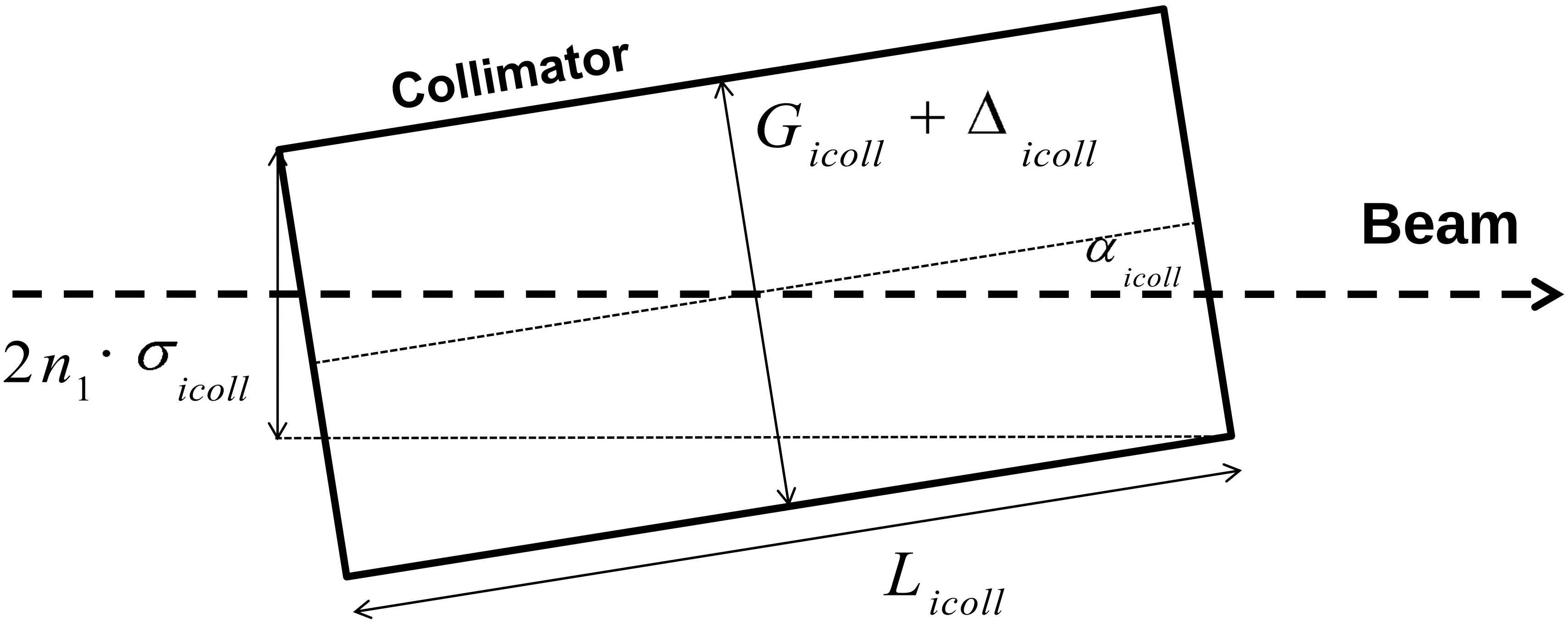
Calibrated over Nominal Beam Size (1 in Perfect case)





450 GeV

What Gap Do We Measure?



Measured Gap

$$G_{icoll} \approx 2n_1 \cdot \sigma_{icoll} + \Delta_{icoll} + \alpha_{icoll} \cdot L_{icoll}$$

Δ_{icoll} = Error on measured gap

together with B. Goddard

A Few Formulae

$$G_{TCP} \approx 2n_1 \cdot \sigma_{nom} + \Delta_{TCP} + \alpha_{icoll} \cdot L_{TCP}$$

$$n_1 = \frac{G_{TCP} - \Delta_{TCP} - \alpha_{icoll} \cdot L_{TCP}}{2\sigma_{nom}} \approx \frac{G_{TCP}}{2\sigma_{nom}}$$

$$G_{icoll} \approx 2n_1 \cdot \sigma_{icoll} + \Delta_{icoll} + \alpha_{icoll} \cdot L_{icoll}$$

$$\sigma_{icoll} = \frac{G_{icoll} - \Delta_{icoll} - \alpha_{icoll} \cdot L_{icoll}}{2n_1} \approx \frac{G_{icoll}}{2n_1}$$

Error (Perfect TCP)

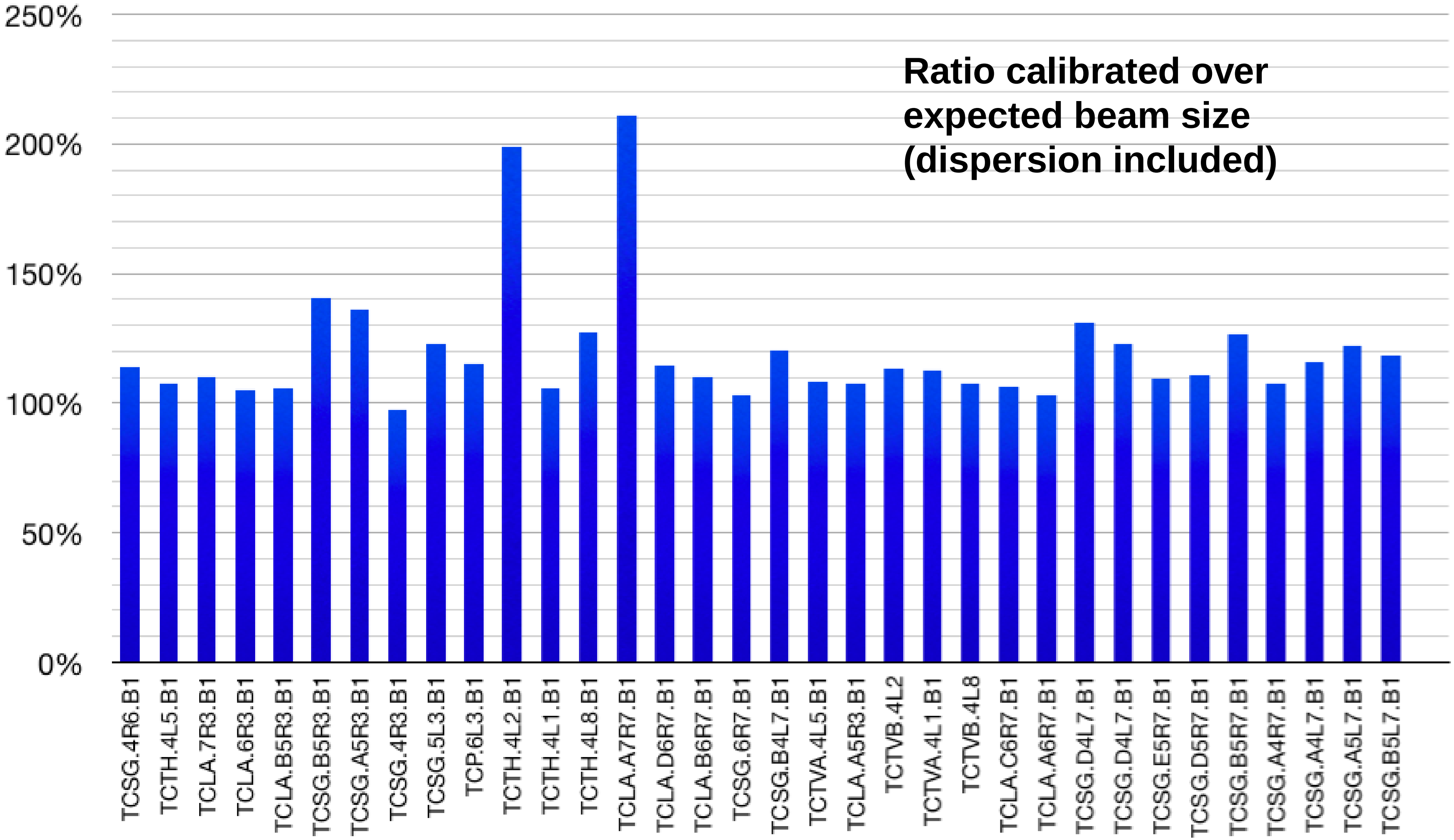
$$\Delta\sigma_{icoll} \approx \frac{\Delta_{icoll} + \alpha_{icoll} \cdot L_{icoll}}{2 n_1}$$

- Minimize error by working at maximum n1. Not much room, though, as primary collimators cannot be opened beyond 6 sigma at 3.5 TeV.
- Longer collimators and protection devices are more sensitive!
- Relative errors large for smaller nominal beam size (higher energy)
- Example: scale error 0.15 mm, angle error 0.15 mrad, length = 1 m

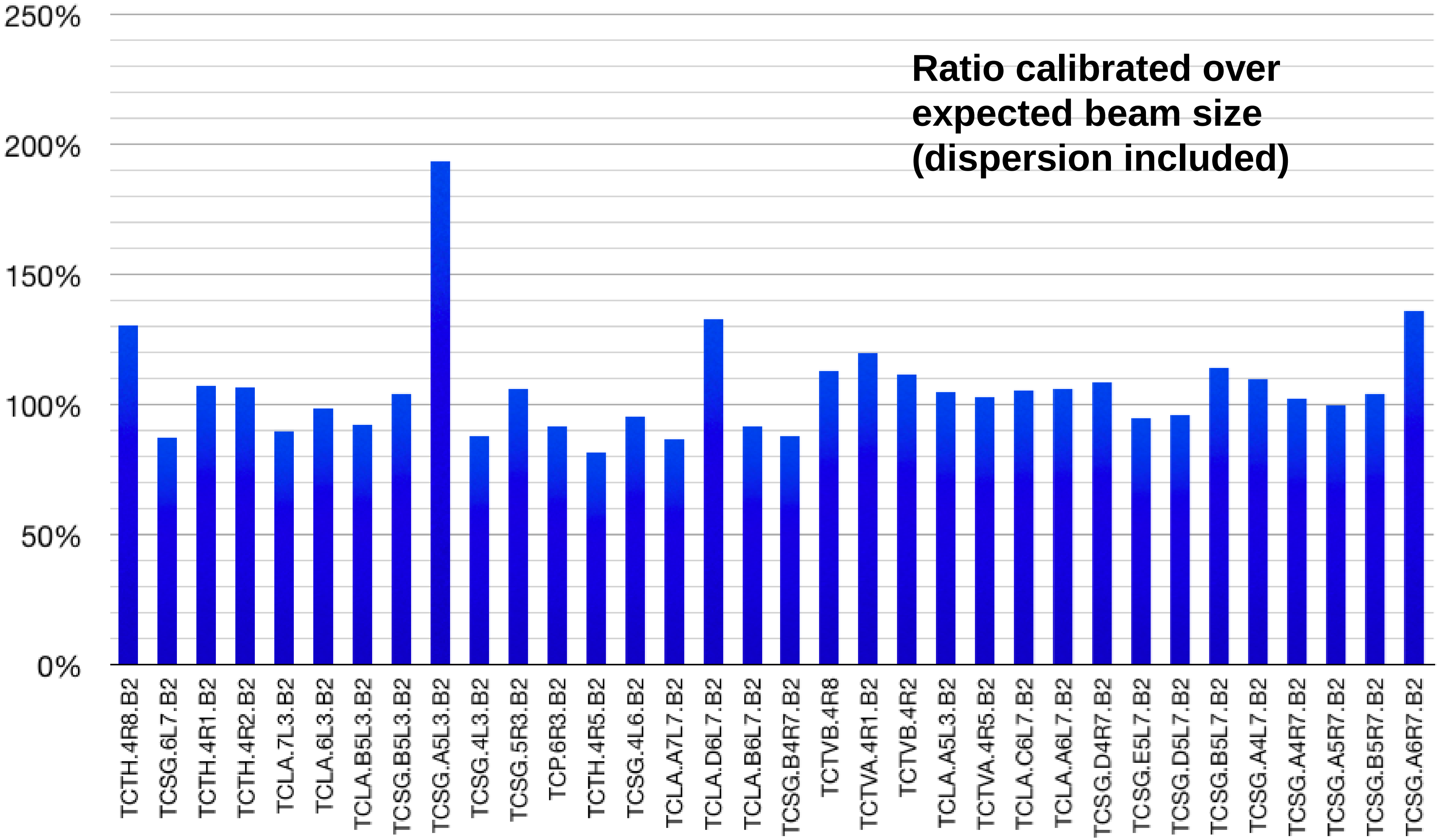
Beam size error: 0.15 mm / n1

For n1 = 3: 0.05 mm error
Spot sizes around 0.3 mm: ~15% error

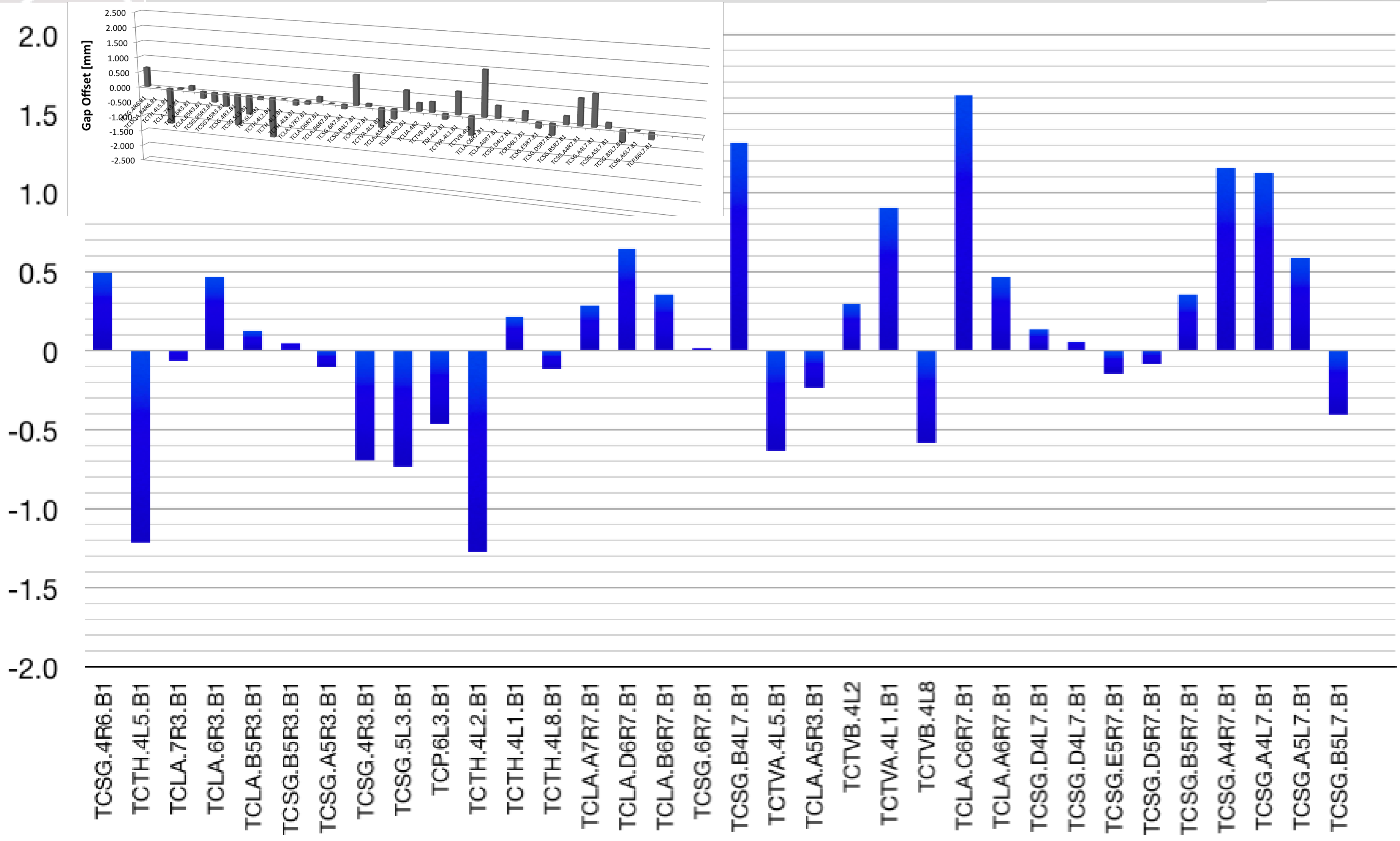
Beam 1 Setup Results 3.5 TeV Beam Size



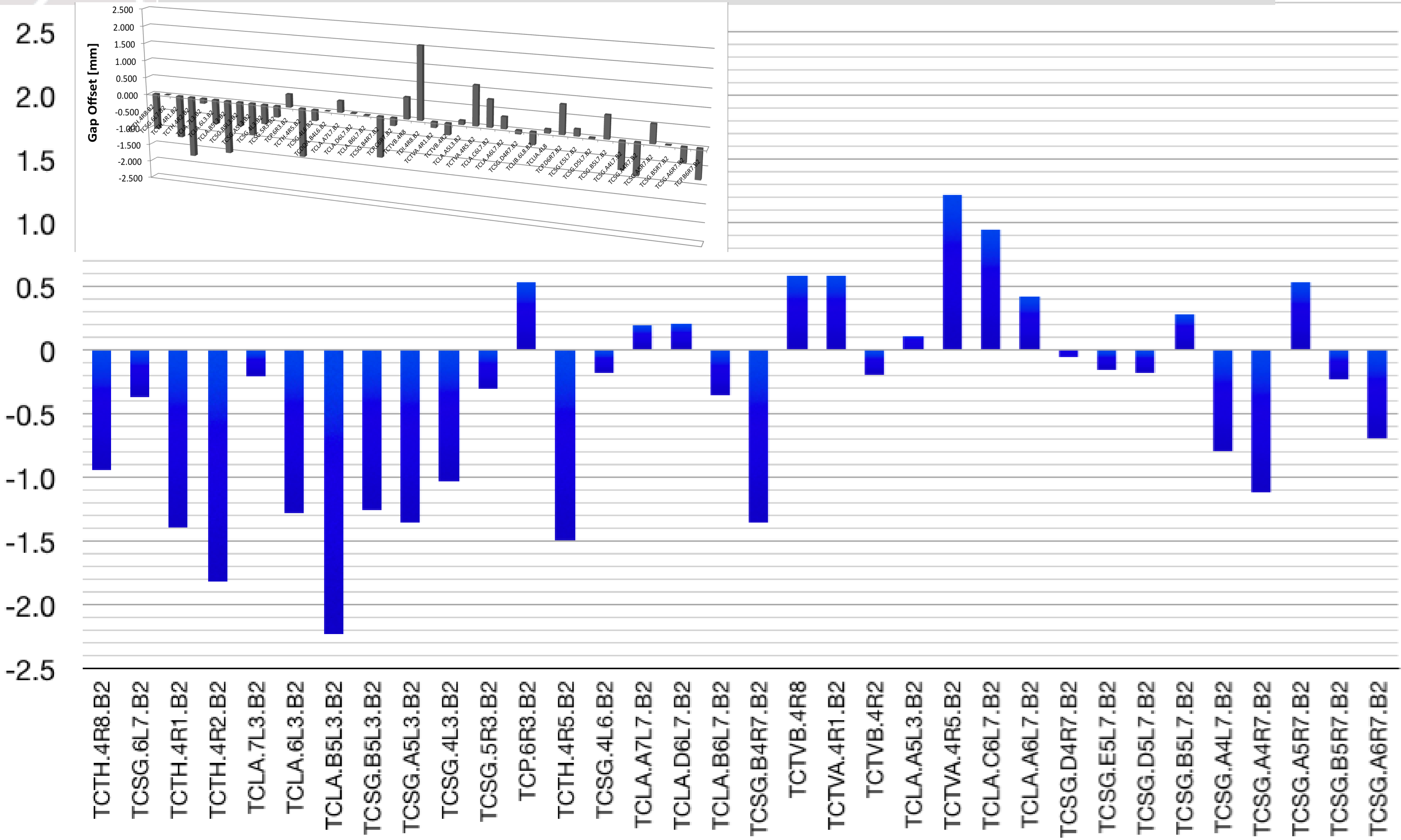
Beam 2 Setup Results 3.5 TeV
Beam Size



Gap Offsets (B1)



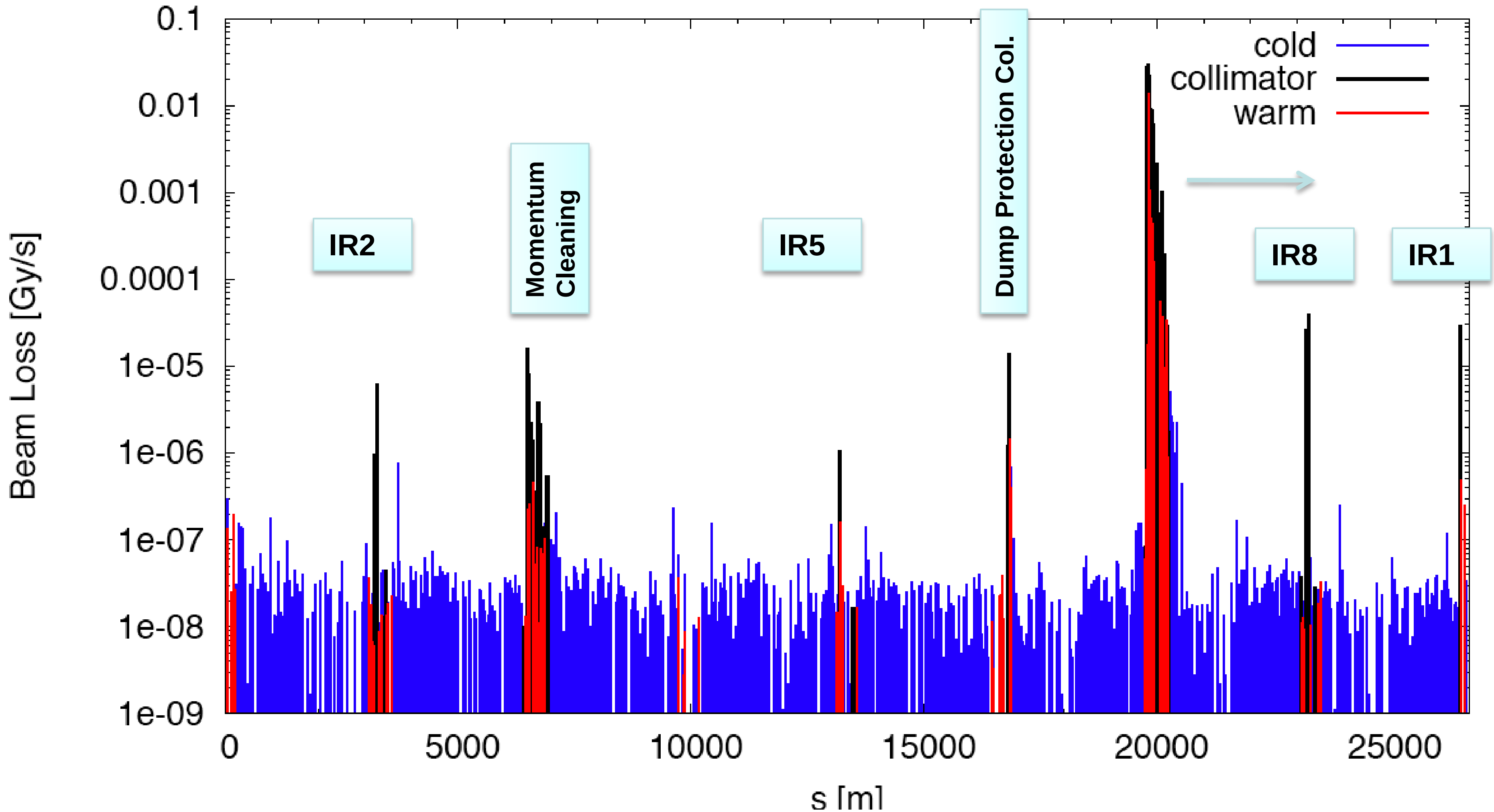
Gap Offsets (B2)



Beam Tests for Verification

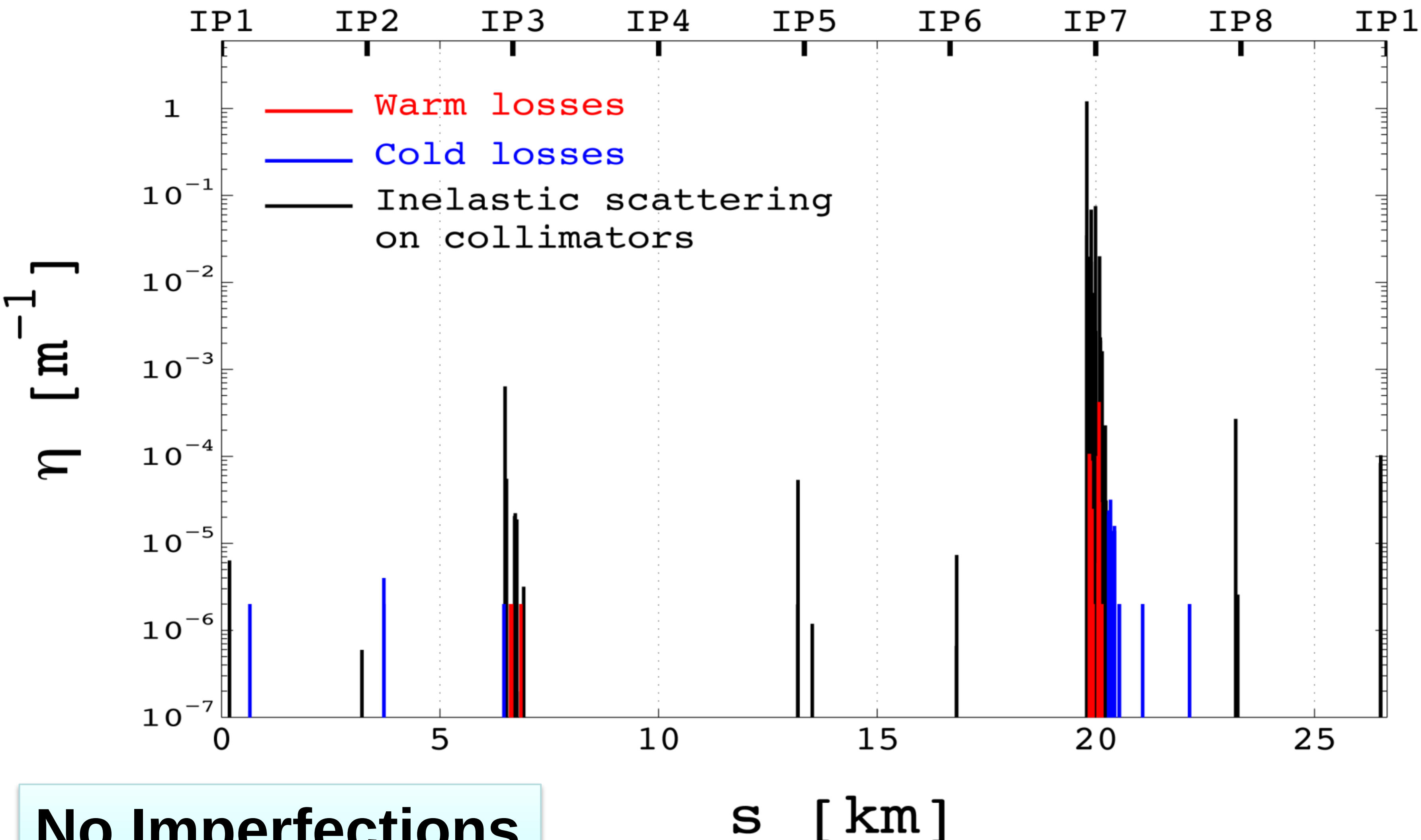
- **Verification is essential in view of possible errors in collimation setup!**
- Should be **repeated at least once a week** at end of fills to monitor performance and drifts.
- Only way to detect possible drifts and problems before the situation becomes unsafe!

Measured Cleaning at 3.5 TeV
(beam1, vertical beam loss, intermediate settings)



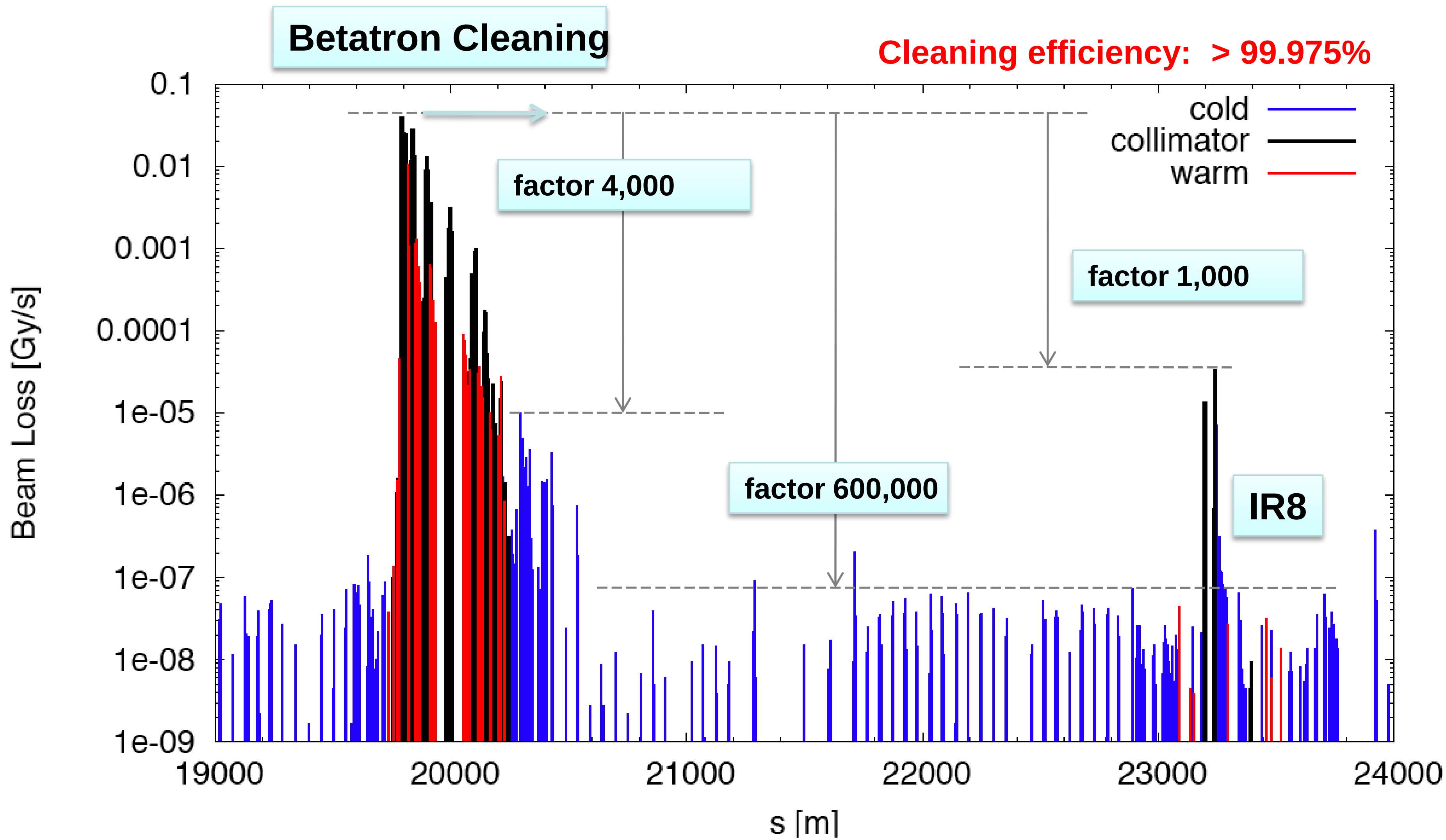
2m optics exposes IR's as expected! Protected by tertiary collimators.

Simulated Cleaning at 3.5 TeV
(beam1, vertical beam loss, intermediate settings)

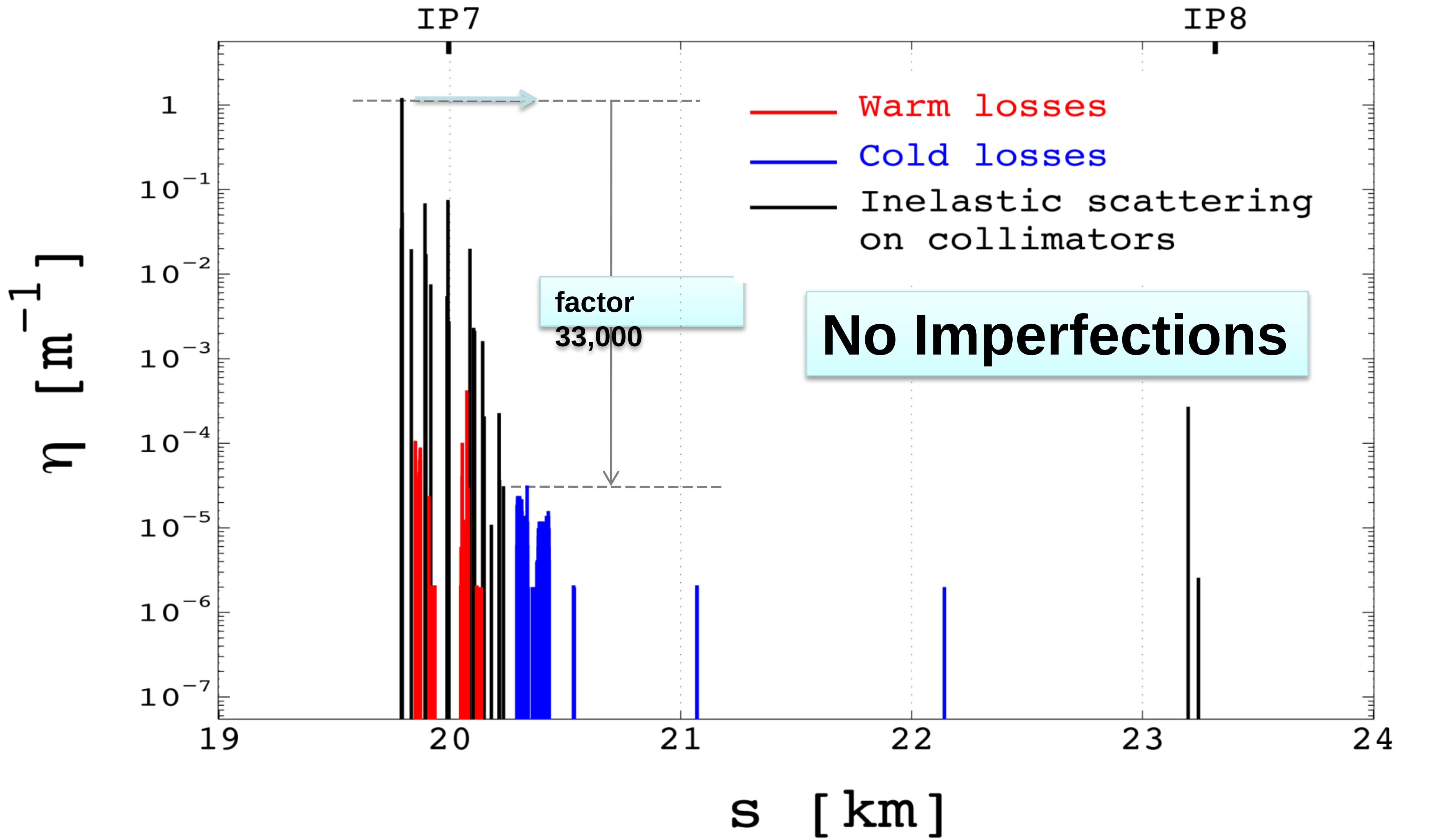


No Imperfections

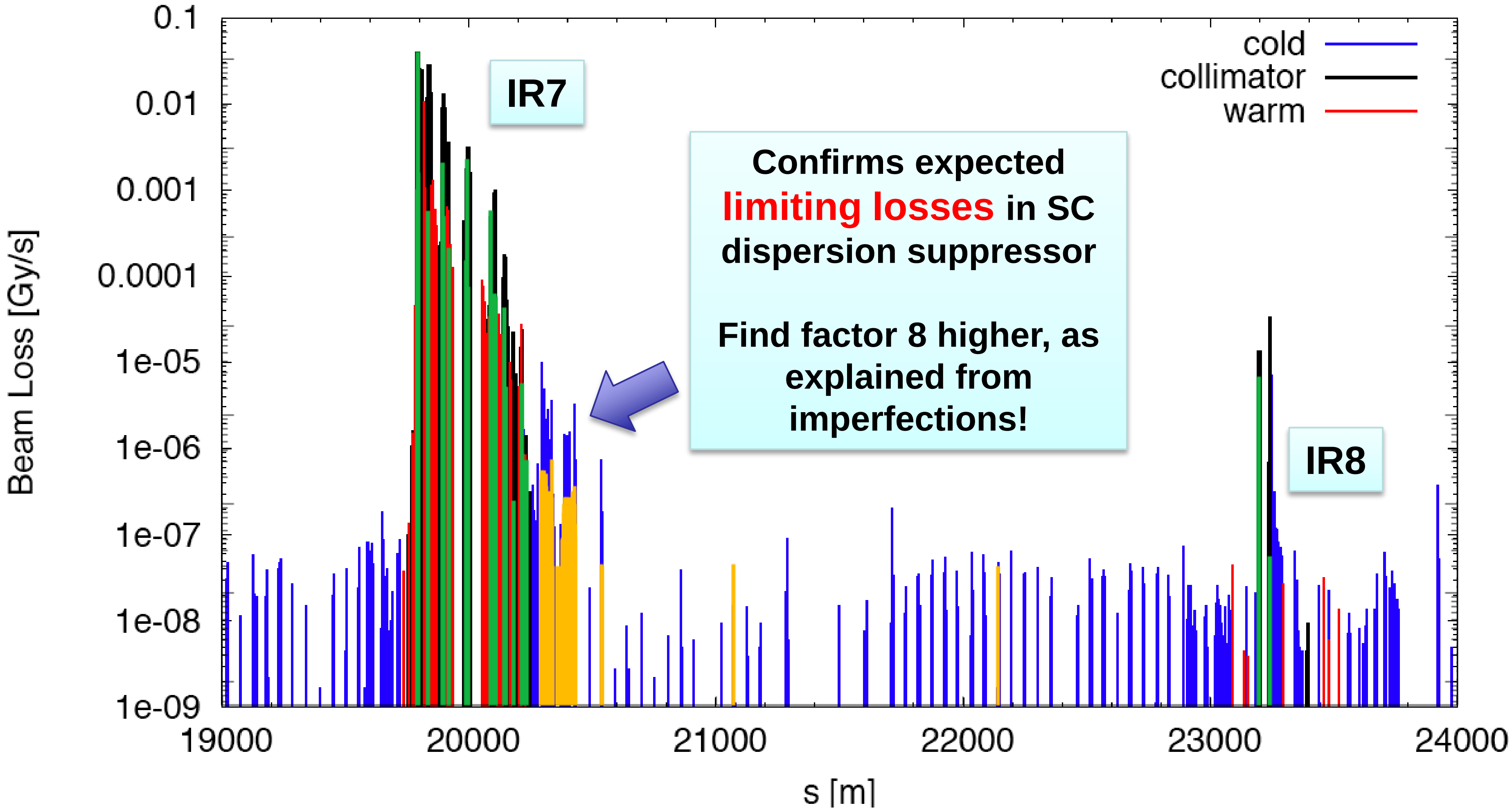
Measured Cleaning at 3.5 TeV
(beam1, vertical beam loss, intermediate settings)



Simulated Cleaning at 3.5 TeV
(beam1, vertical beam loss, intermediate settings)



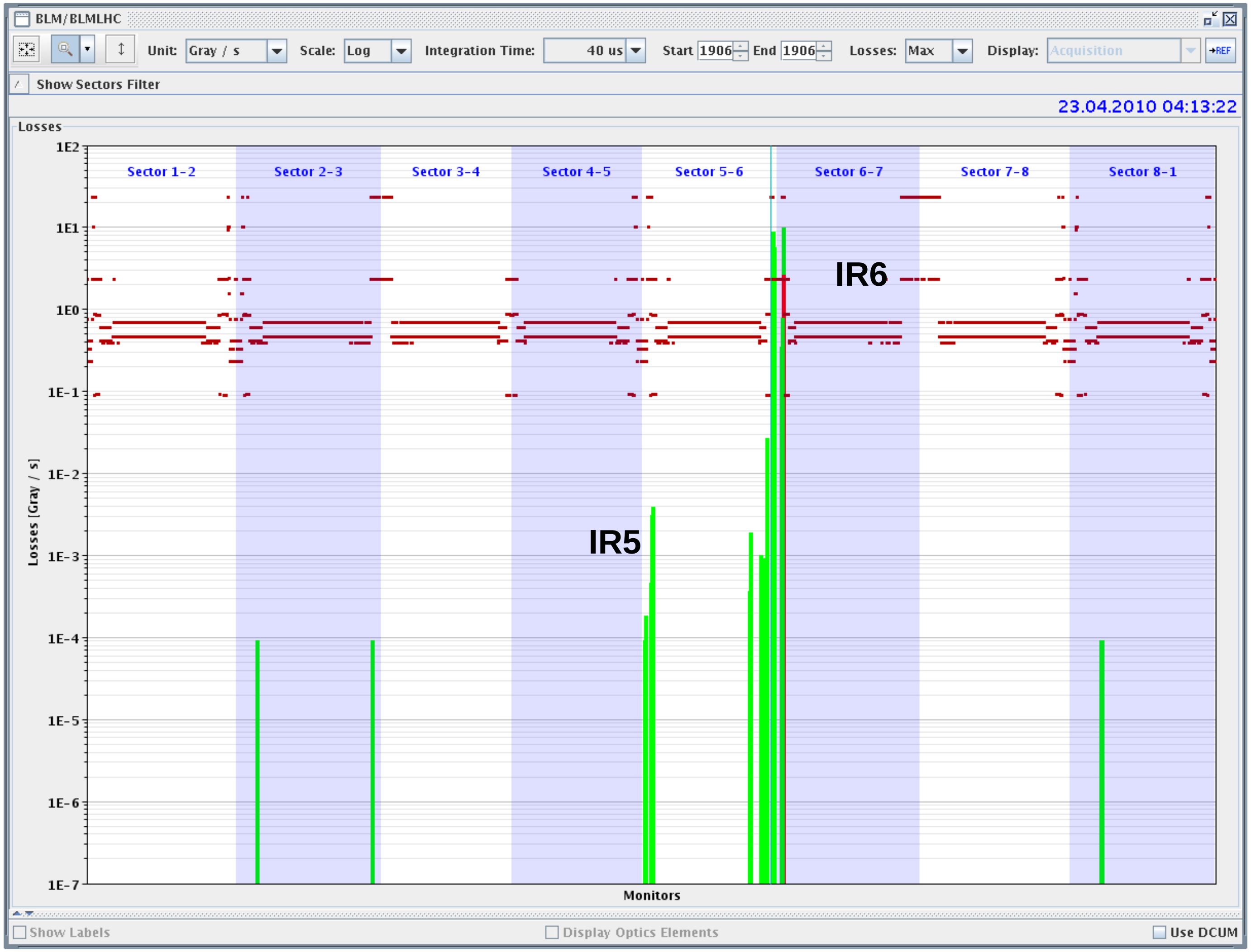
Meas. & Sim. Cleaning at 3.5 TeV
(beam1, vertical beam loss, intermediate settings)



Confirms expected **limiting losses** in SC dispersion suppressor

Find factor 8 higher, as explained from imperfections!

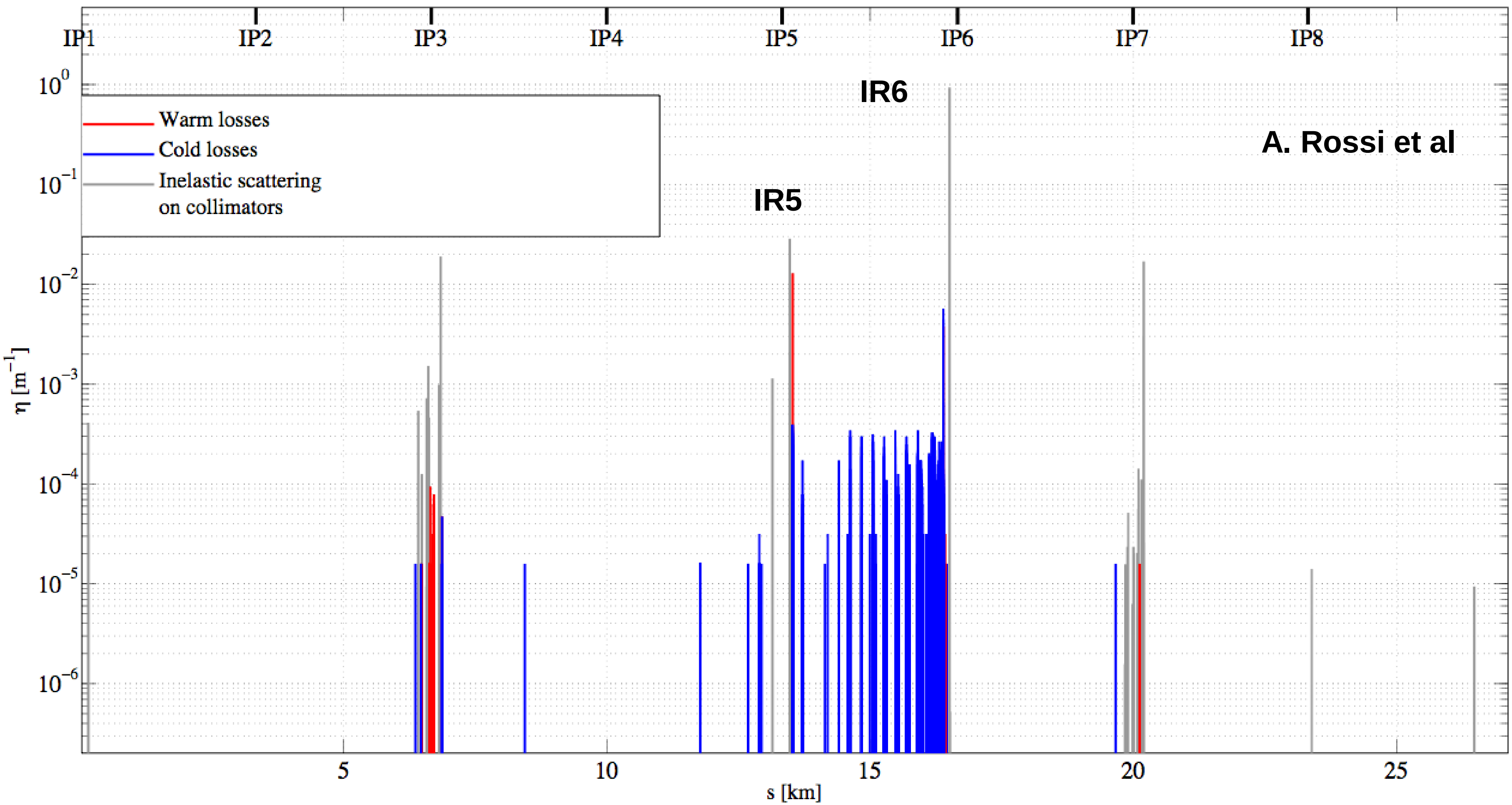
Leakage from IR6 Dumps



Brennan Goddard et al

Simulation

Case: Full Bunch Hitting TCSG@IR6, TCDQ out



Leakage of 2% with 1.5 cm rms beam size ➔ not worried for the TCT if below this!

Readiness for Higher Intensities from Collimation

LHC Collimation Project CERN

- If things are set up and the machine is kept within tolerances:

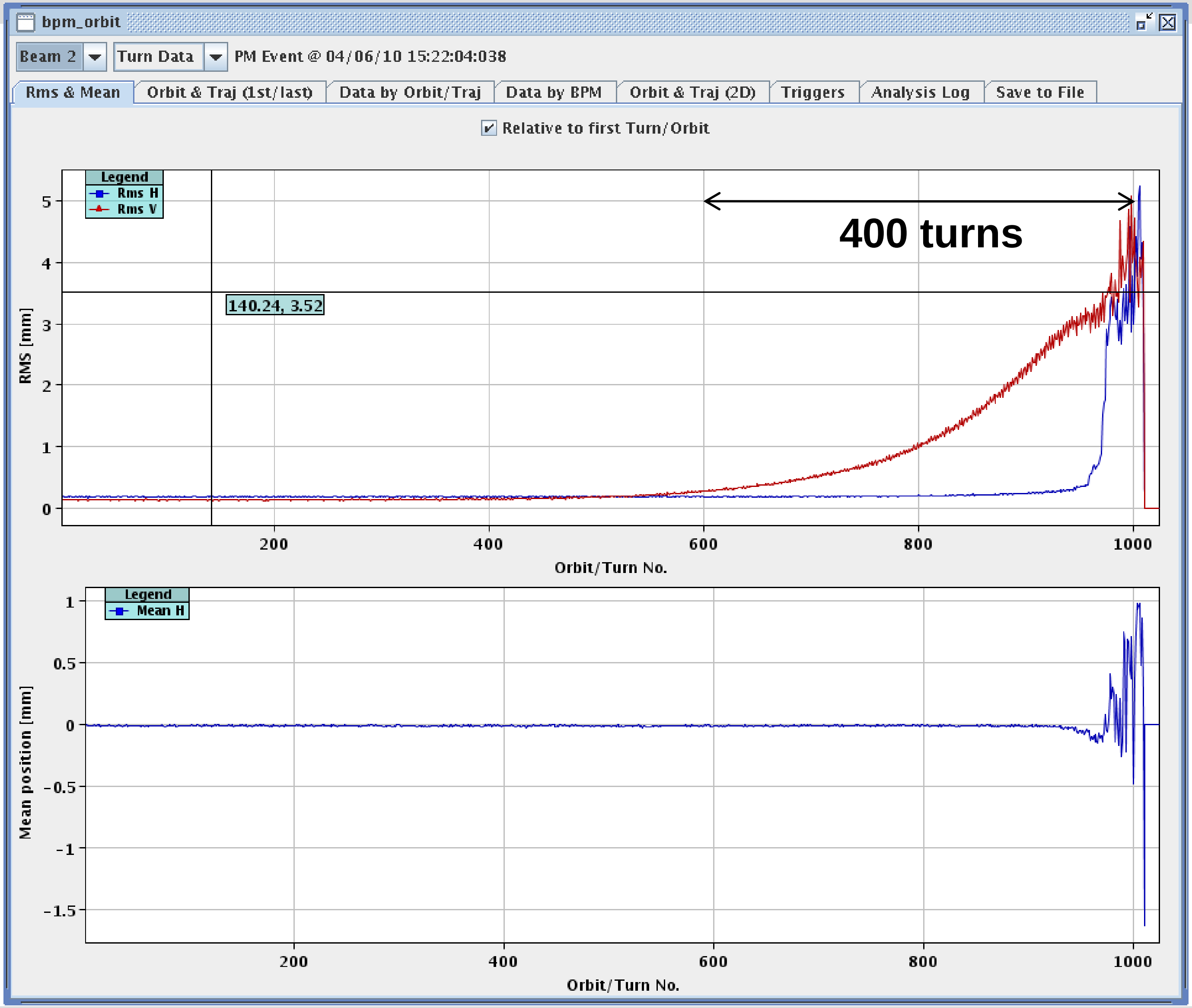
  Collimation is good for MJ regime, if set up for the right bunch intensity!

- Tolerances are now in the range of 200 μm for total operational budget (orbit stability and change in beta beat)!
- This is the agreed 0.2 σ budget for injection, kept constant in mm with energy due to intermediate collimation settings.
- Potential damage cannot be excluded if we are beyond ~400 μm with highest risk at IR3.
- However, at present very low intensities the damage risk is very low! Later it will be more dangerous!

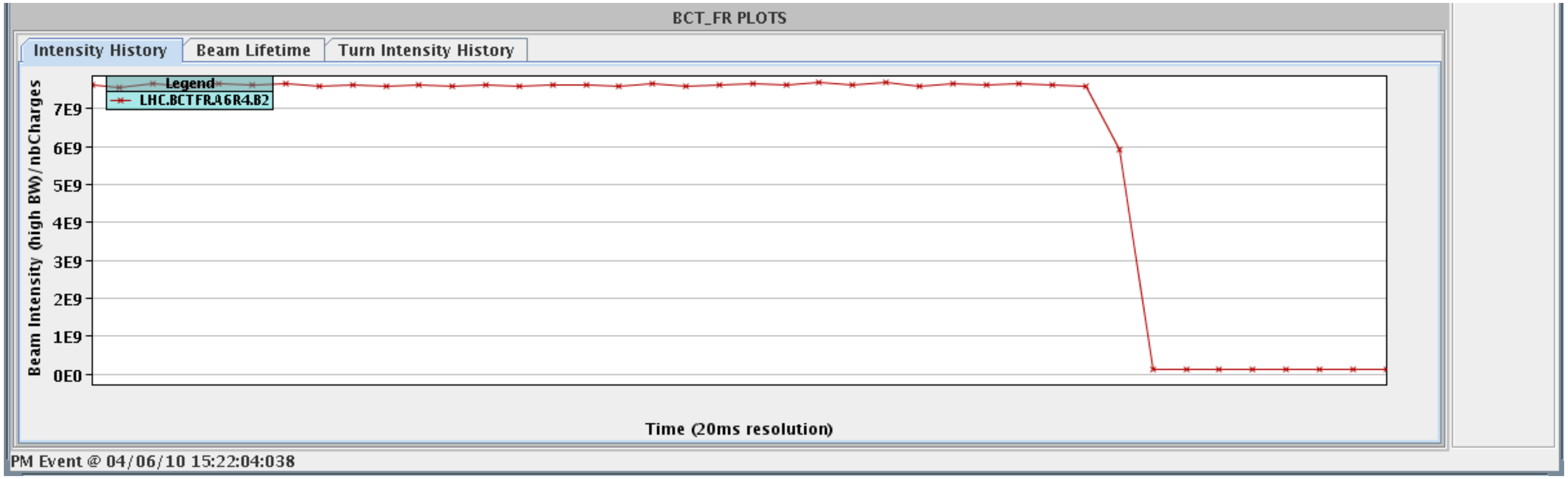
Beam Loss Events and Machine Stability

- Situation is very good if we keep the machine inside tolerances!
- Tolerances for LHC are very demanding, even when presently very much relaxed at 3.5 TeV and intermediate collimation settings.
- How do we do with this?
- This is just a collection of worrying observations over the last three weeks! Not a complete overview!

Very Fast Losses (Unexpected?)

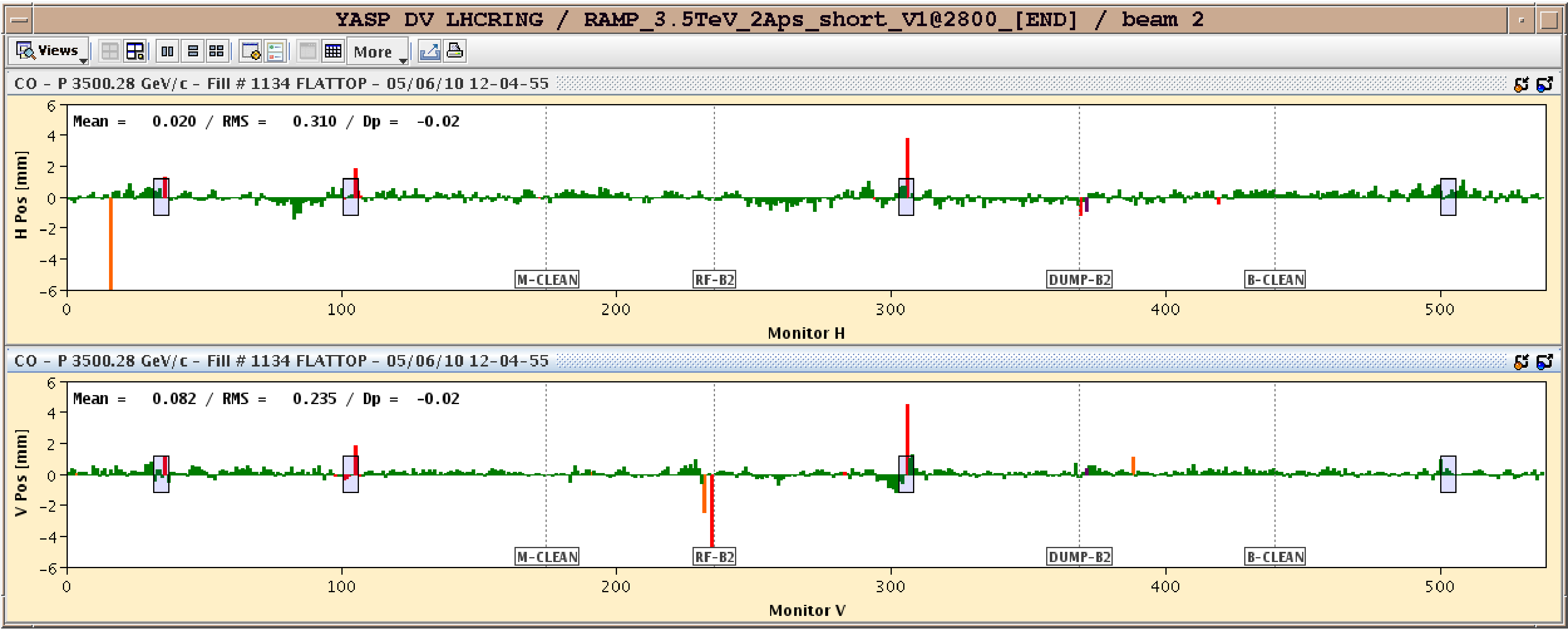


Very Fast Losses (Unexpected?)



- ➔ No stop of operation.
- ➔ No immediate analysis of impact and consequences.
- ➔ Kept working with high intensity!

3e11 p, Bump in IR5



➔ More than 5 times above specified tolerance!

➔ Kept working with high intensity, trying to correct it!

Working with Highly Non-Conform Orbit

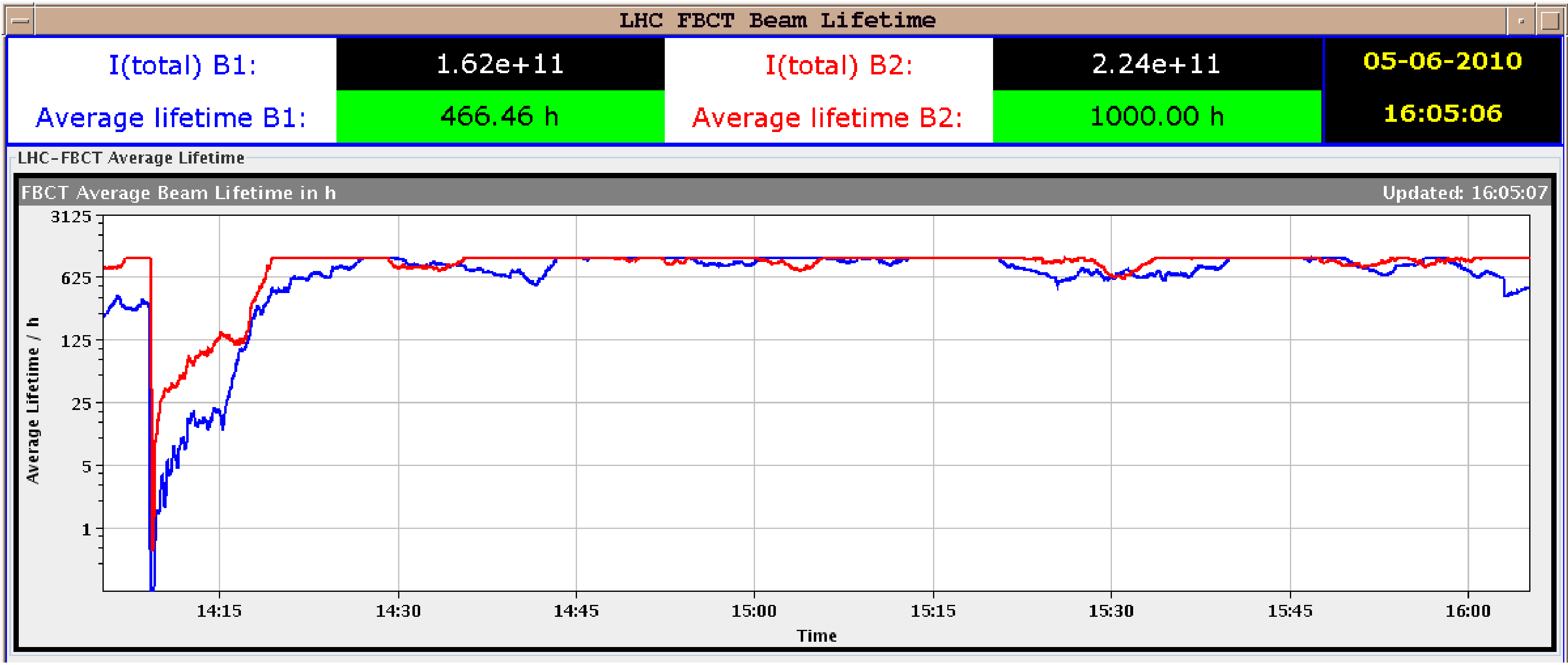
- ➔ Far out of tolerance!
- ➔ Kept working with high intensity, trying to correct it!

Excellent Lifetime, Isn't It?

LHC FBCT Beam Lifetime

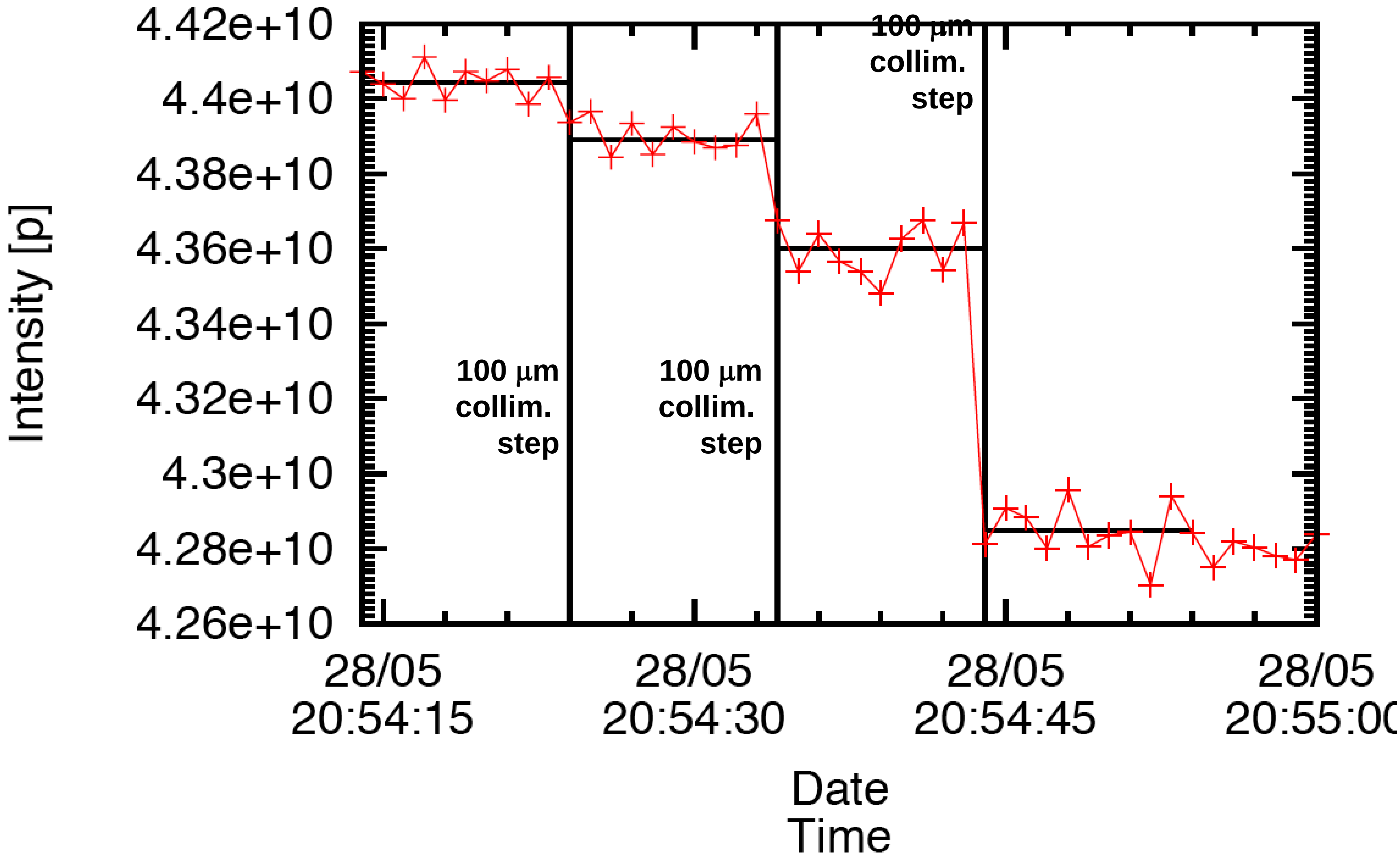
I(total) B1:	1.62e+11	I(total) B2:	2.24e+11	05-06-2010
Average lifetime B1:	466.46 h	Average lifetime B2:	1000.00 h	16:05:06

Excellent Lifetime, Isn't It?

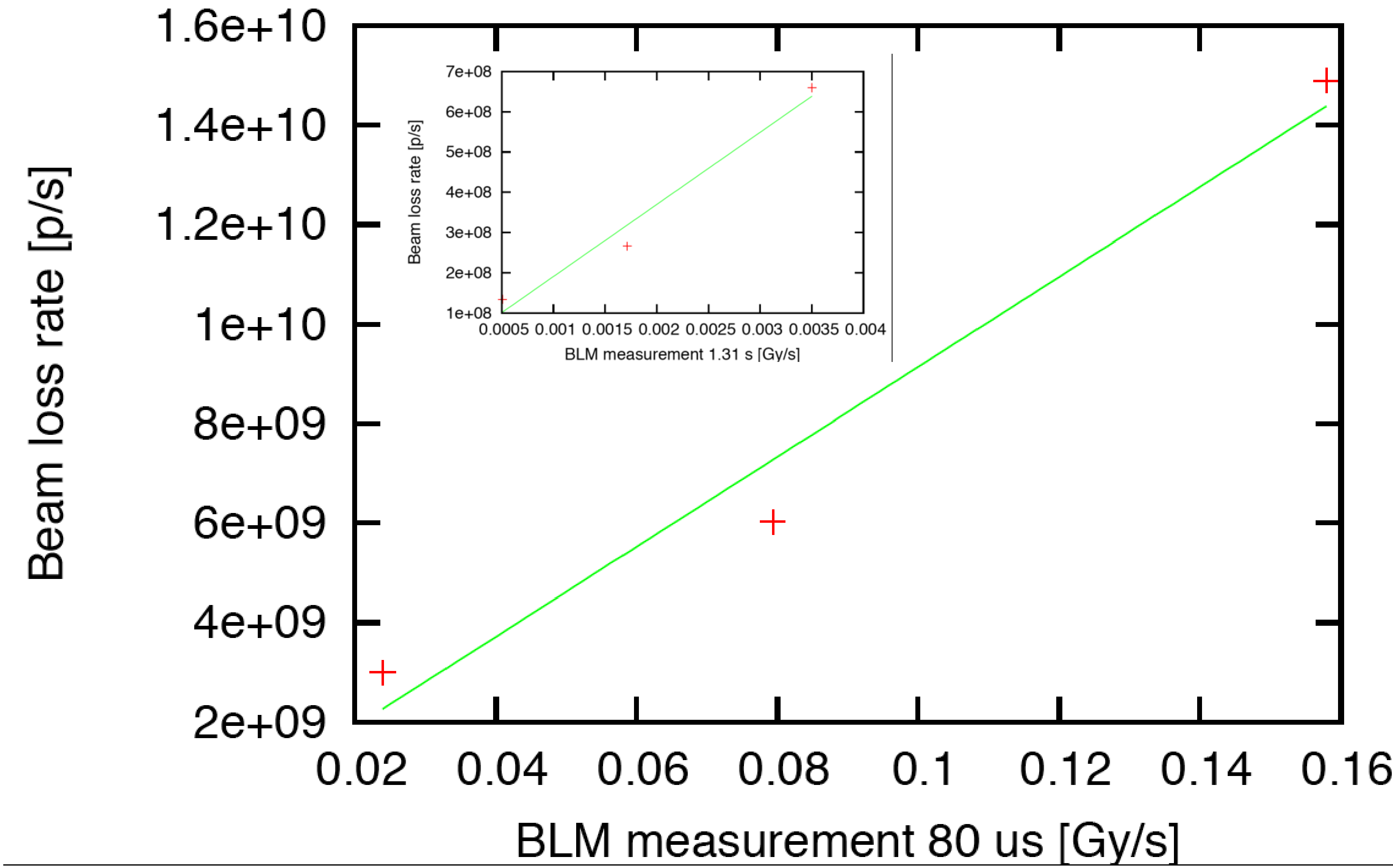


… only if you look at the right time!

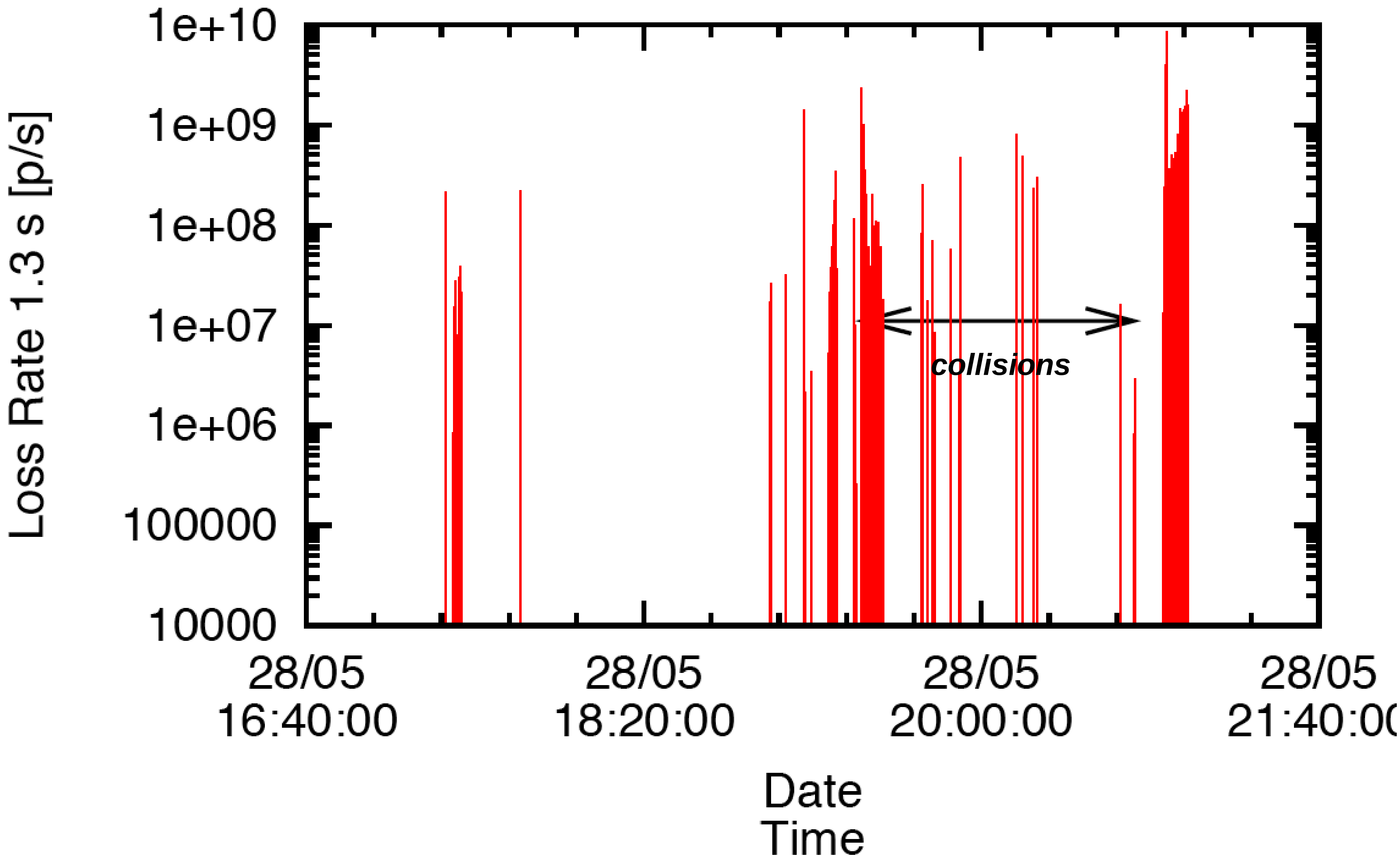
Scraping Test at the End with 1e11 p/bunch



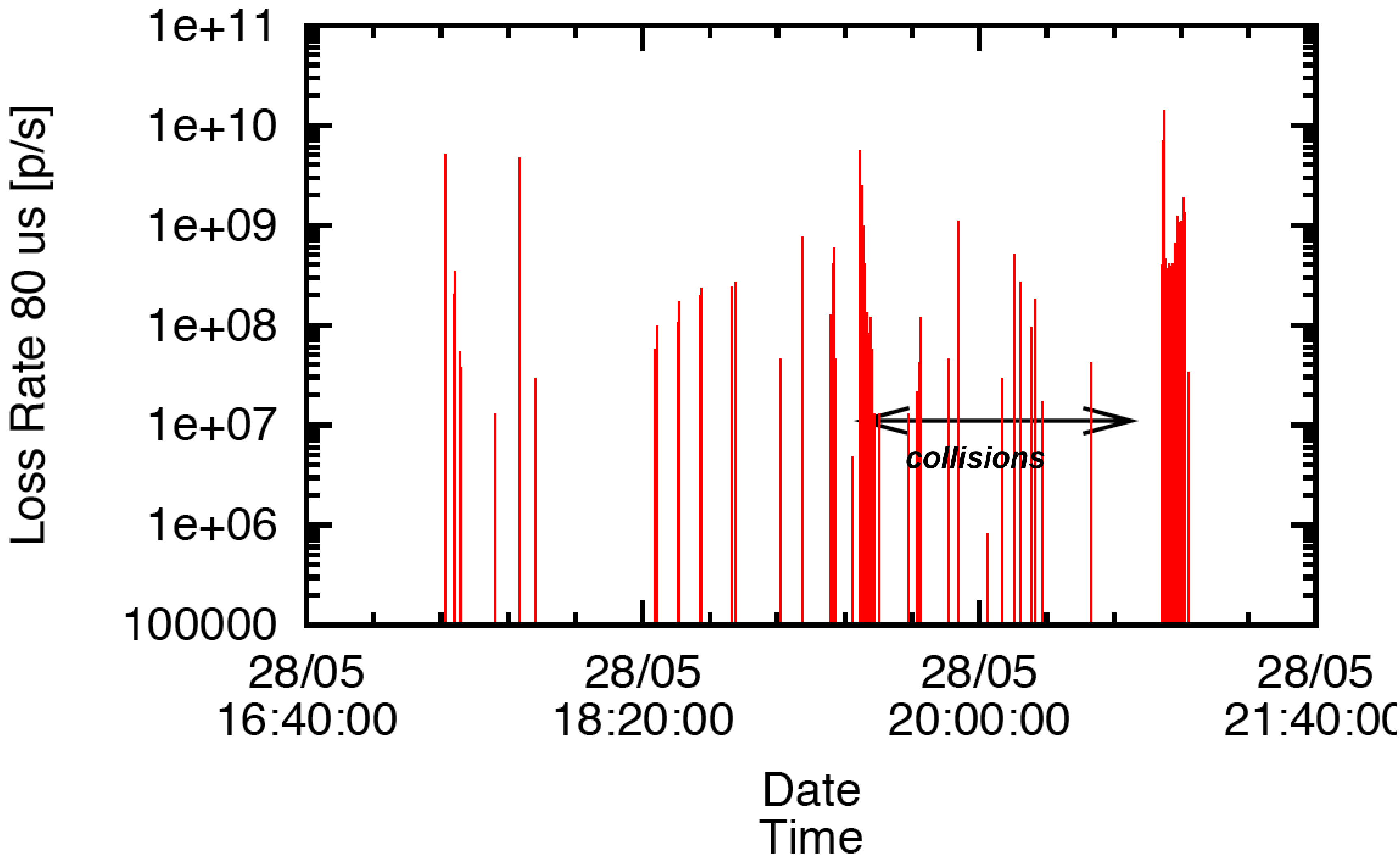
Allows Calibration of BLM at Primary Coll.



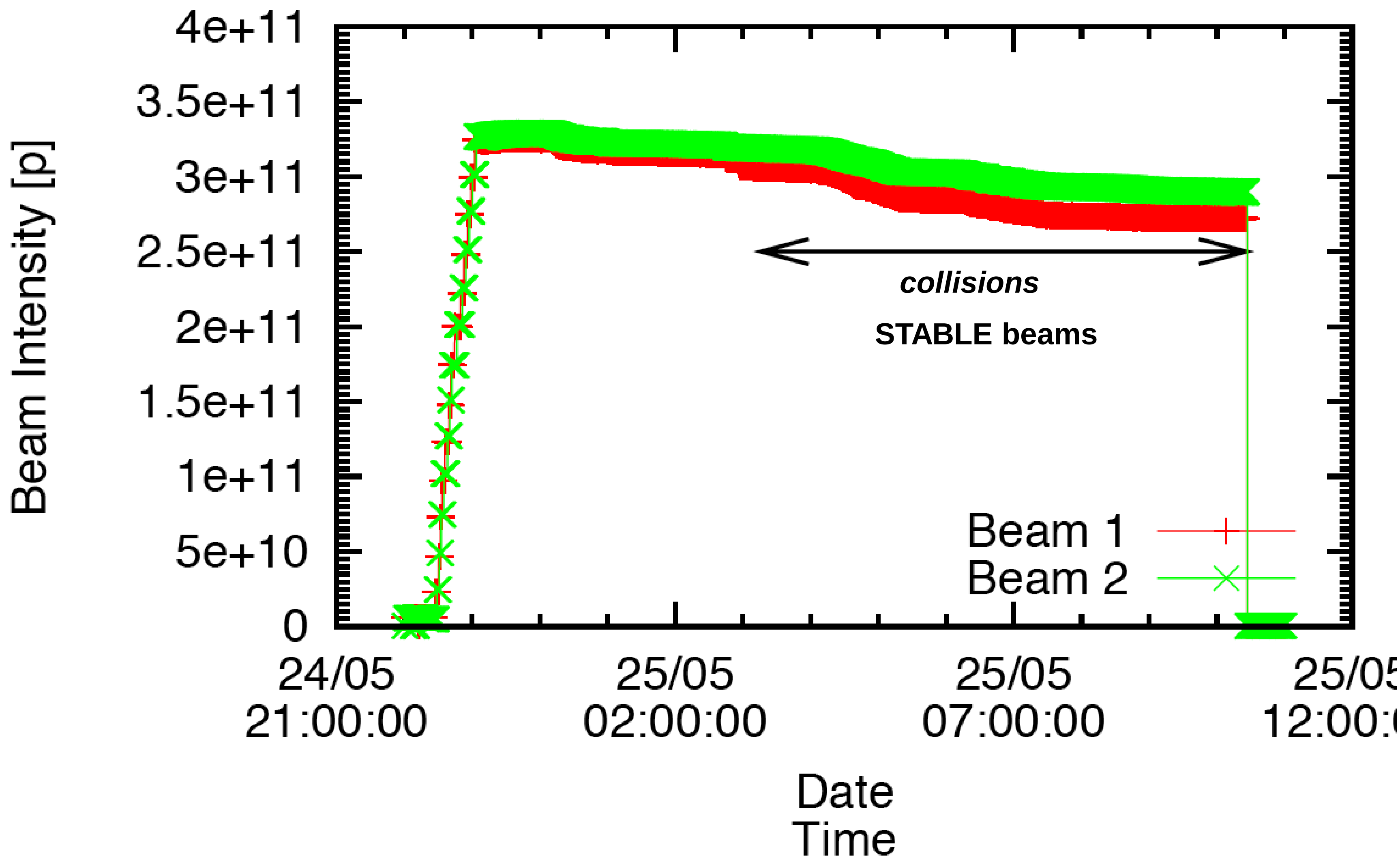
Integrated Loss Rate at 1.3 s (1e11 p)



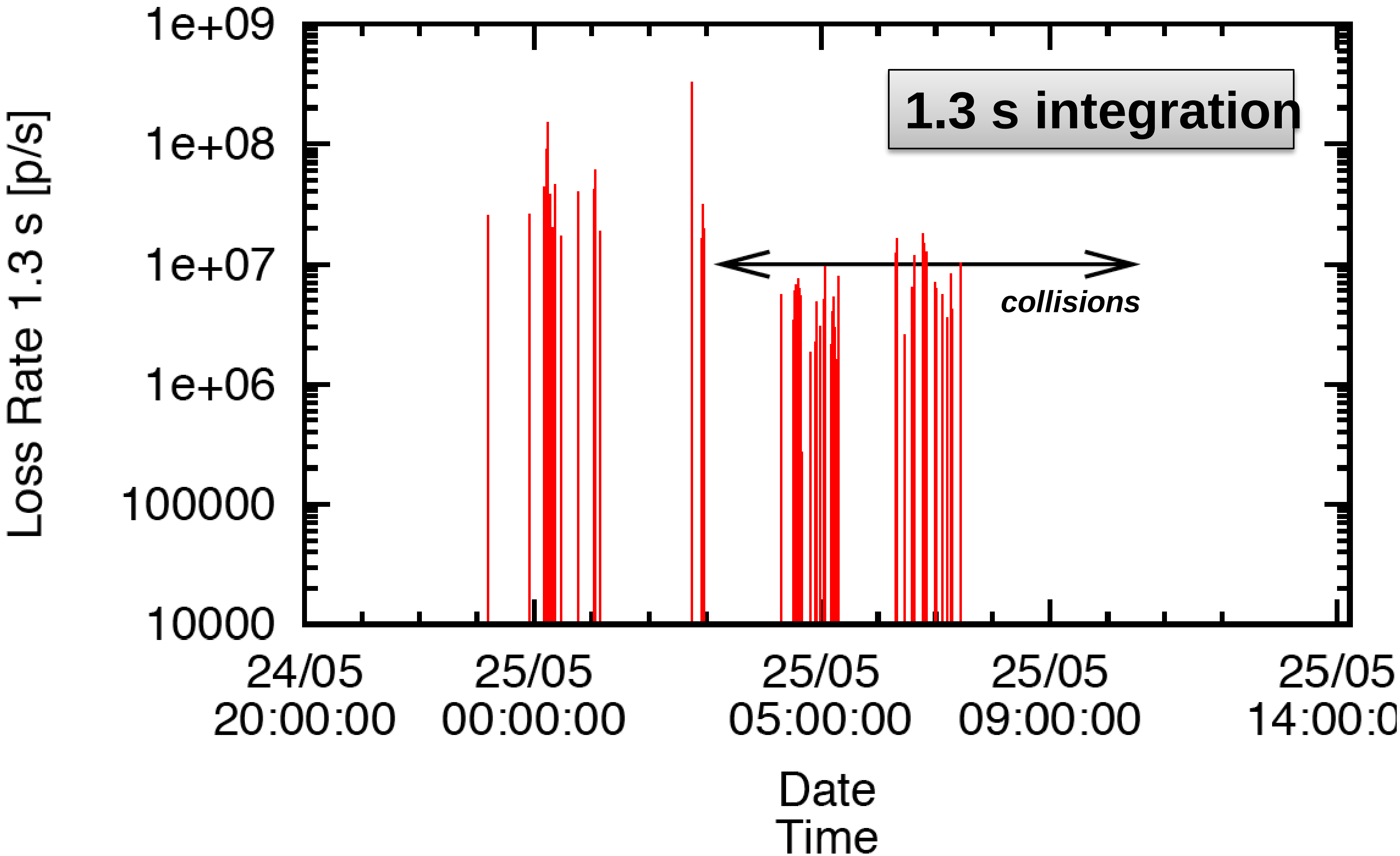
Peak Loss Rate at 80 us



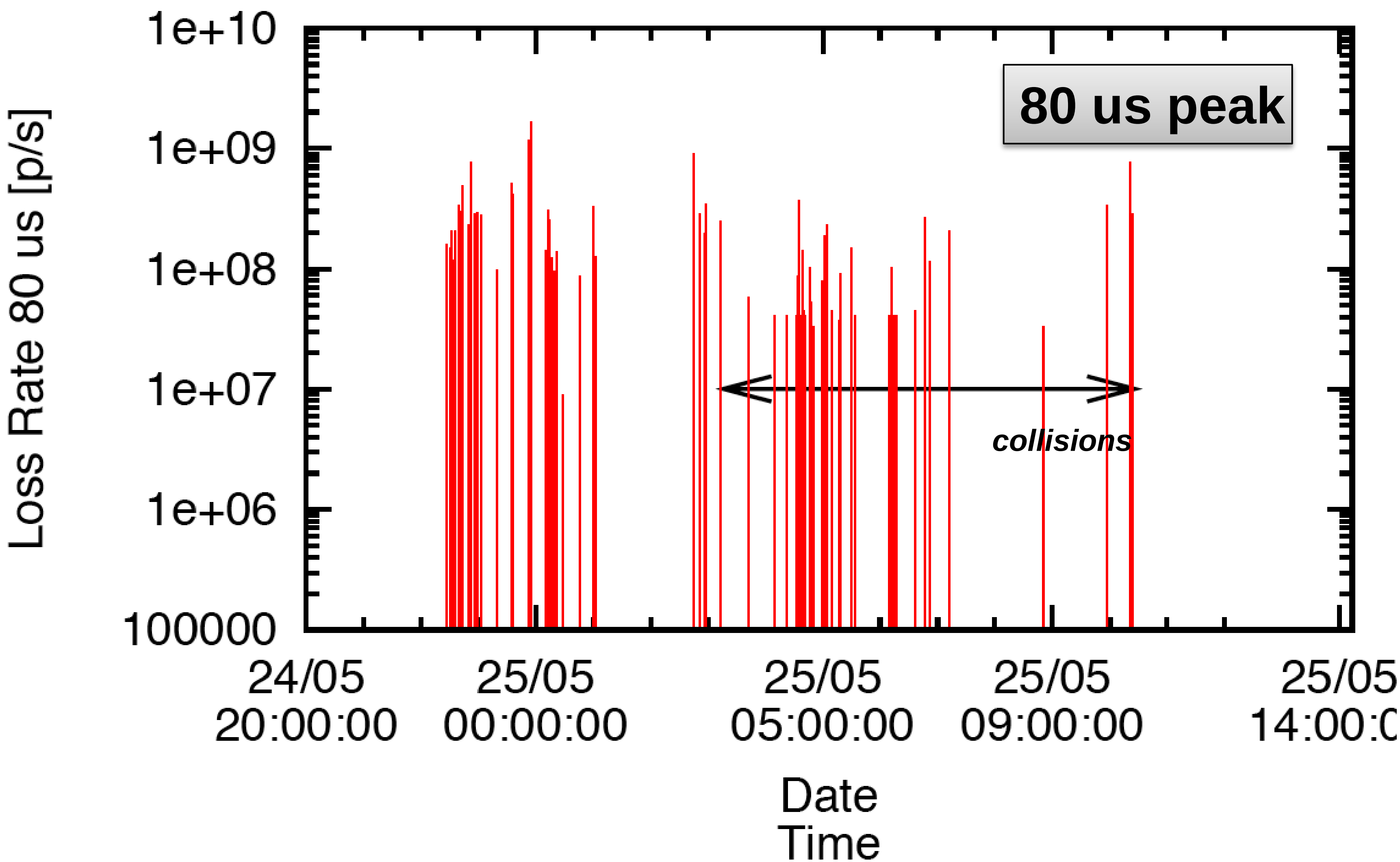
Beam Intensity: Intermittent Bursts of Losses



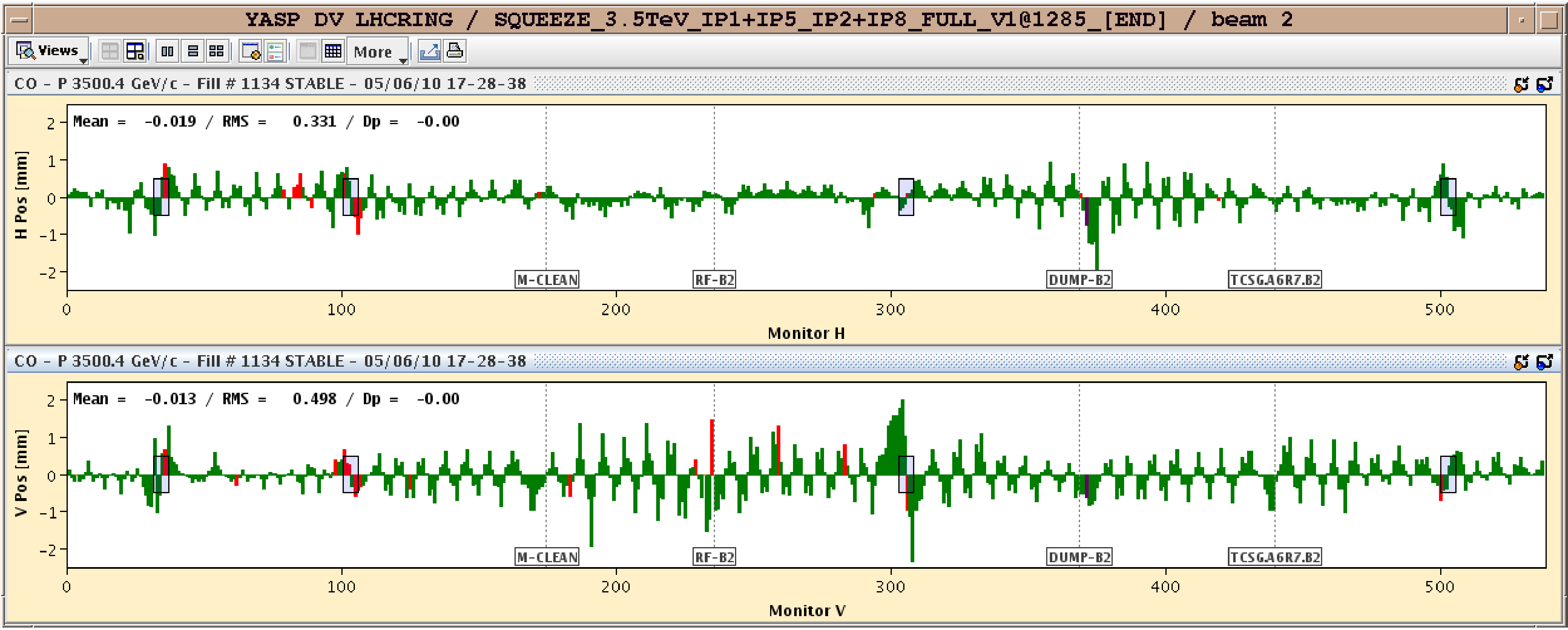
Losses at Primary Collimator TCPH



Losses at Primary Collimator TCPH

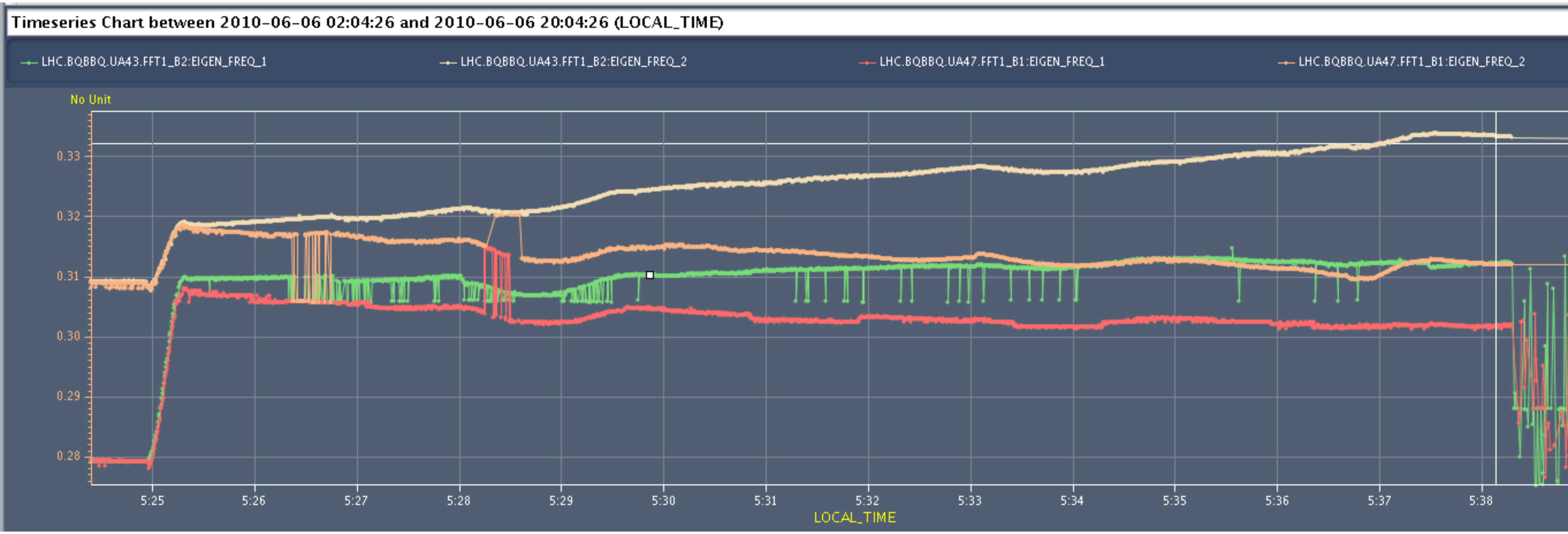


Nominal Peak Losses with 3e11 at 3.5 TeV, Peak Loss at TCSG

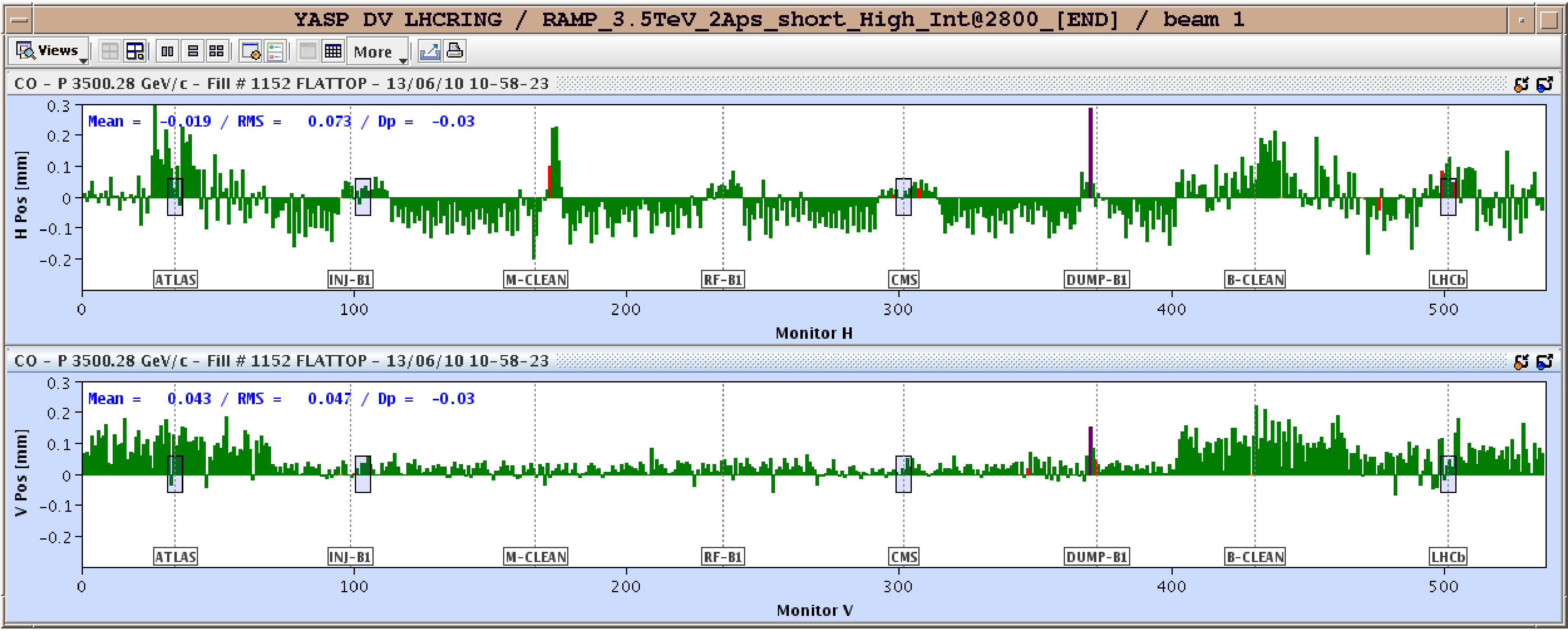


Dump from Magnet BLM
(chromaticity measurement)

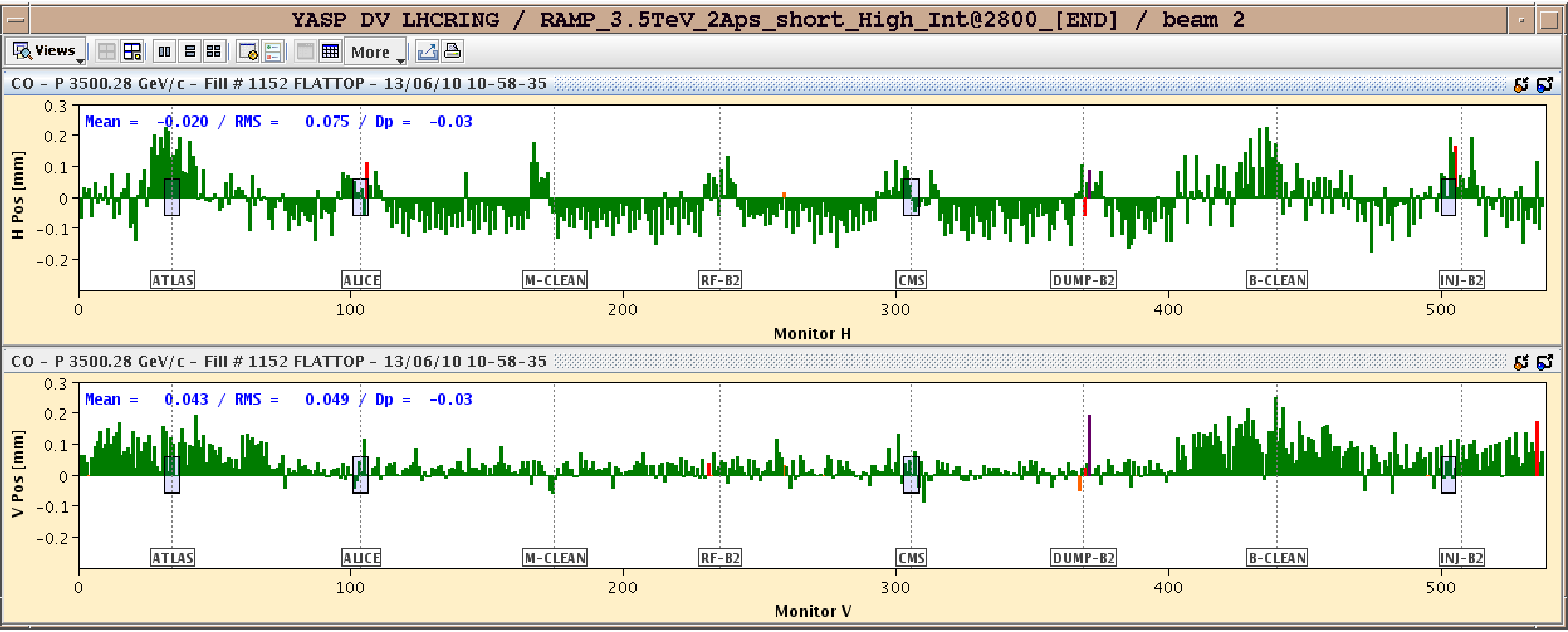
Squeeze: Crossing 1/3 Resonance – Beam Dump



Orbit Drift in 2h (B1)



Orbit Drift in 2h (B2)



What Does This Mean?

- LHC is an excellent machine. Progress is outstanding.
- However, we must realize that shit happens and that it is not difficult to find examples of highly non-conform events.
- Our reaction was not always as agreed beforehand. We were often pretty relaxed.
- Good news:
  - All the non-conform events were survived without any issue, not even a quench. Flawless protection!
  - Collimation very robust so far!
- Bad news:
  - It is worrisome that we reach nominal loss rates with 0.1% of intensity at the relaxed 3.5 TeV energy. Also in stable beams: Too high losses!
  - When running outside of agreed tolerances we run with increased risk and possible damage cannot be excluded!

Operational Issues

- Collimators are run by OP through the nominal sequence.
- The nominal sequence loads all collimator positions and interlock thresholds and executes them.
- Position interlock thresholds are updated versus time for different parts of operation. Relies on OP to execute sequence fully and in correct order.
- In addition a non-changeable, energy-dependent gap threshold verifies that collimator gaps close with energy. Impossible to ramp without collimators!
- Initially private sequences or jumping in sequences resulted in ramps with injection protection collimators not retracted. Recently fully OK. Want to close last hole by checking for gaps opening versus energy!
- Squeeze to low beta* will be a next challenge (change of energy-dependent gap threshold)!

Summary of Concerns

- Flexibility of MP is an issue. Too rigid right now: Increases risk as more time is spent in setup and as system tests with beam are compromised!
- Don't worry too much about collimator damage: Collimators are made for beam loss and much more robust than most other things!
- Collimator setup adequate for 3.5 TeV and 2m beta*. No quenches so far. However, important issues to be addressed for going beyond.
- Qualification is crucial in view of some problems seen! Monitoring…
- **OK for MJ regime afterwards, if agreed tolerances are kept.**
- At the moment, many examples for out of tolerance operation can be found. Surprisingly high losses for this very low intensity!
- Recommend to be much more stringent in following agreed operation! Minimize risk!
- Sequence-drive collimator operation OK right now. Quite safe but will try to enforce also retraction of injection protection devices! Discipline!