MP Issues from Collimation and Impact from Upgrades

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06/09/2010

Machine Protection Review, CERN

… for the LHC Collimation Project

Thanks to R. Bruce, D. Wollmann, S. Redaelli, T. Baer, M. Cauchi, A. Rossi, G. Valentino, F. Burkart, … (BE ABP/OP, design & control room work)

Design & prototyping: EN/MME (A. Bertarelli, A. Dallocchio, R. Perret, …)
Installation & low level controls: EN/STI (O. Aberle, R. Losito, A. Masi, …)

… plus many groups in BE, EN, TE, Safety, …

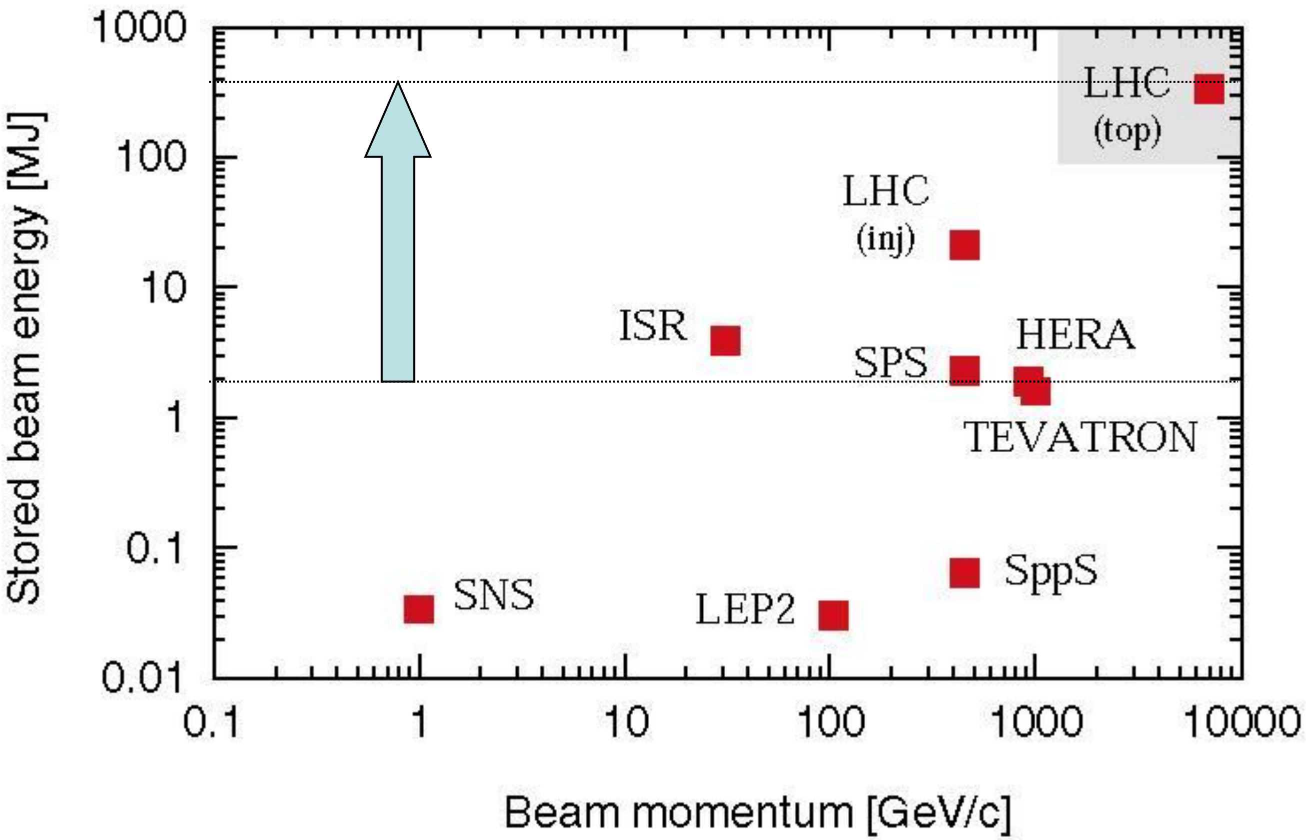
LHC Collimation System

- The LHC collimation system is the most elaborate collimation system built for any accelerator: 88 movable collimators with two jaws, absorbers, 2 warm cleaning insertions, experimental collimation, radiation handling, material robustness, …
- Involves a necessary complex control of ~400 DOF with several settings through the LHC operational cycle.
- It is studied and optimized since 2001 in the beam cleaning / collimation WG and the LHC collimation project.
- The previous talks explained its functioning and the results obtained with beam in detail.
- The system is designed as a cleaning system (determines location of collimators) but also offers passive protection (not ideal phase coverage).
- Here focus on MP issues of this complex system…

… celebration after 6.5 years of hard work in BE, EN, TE, RP, …

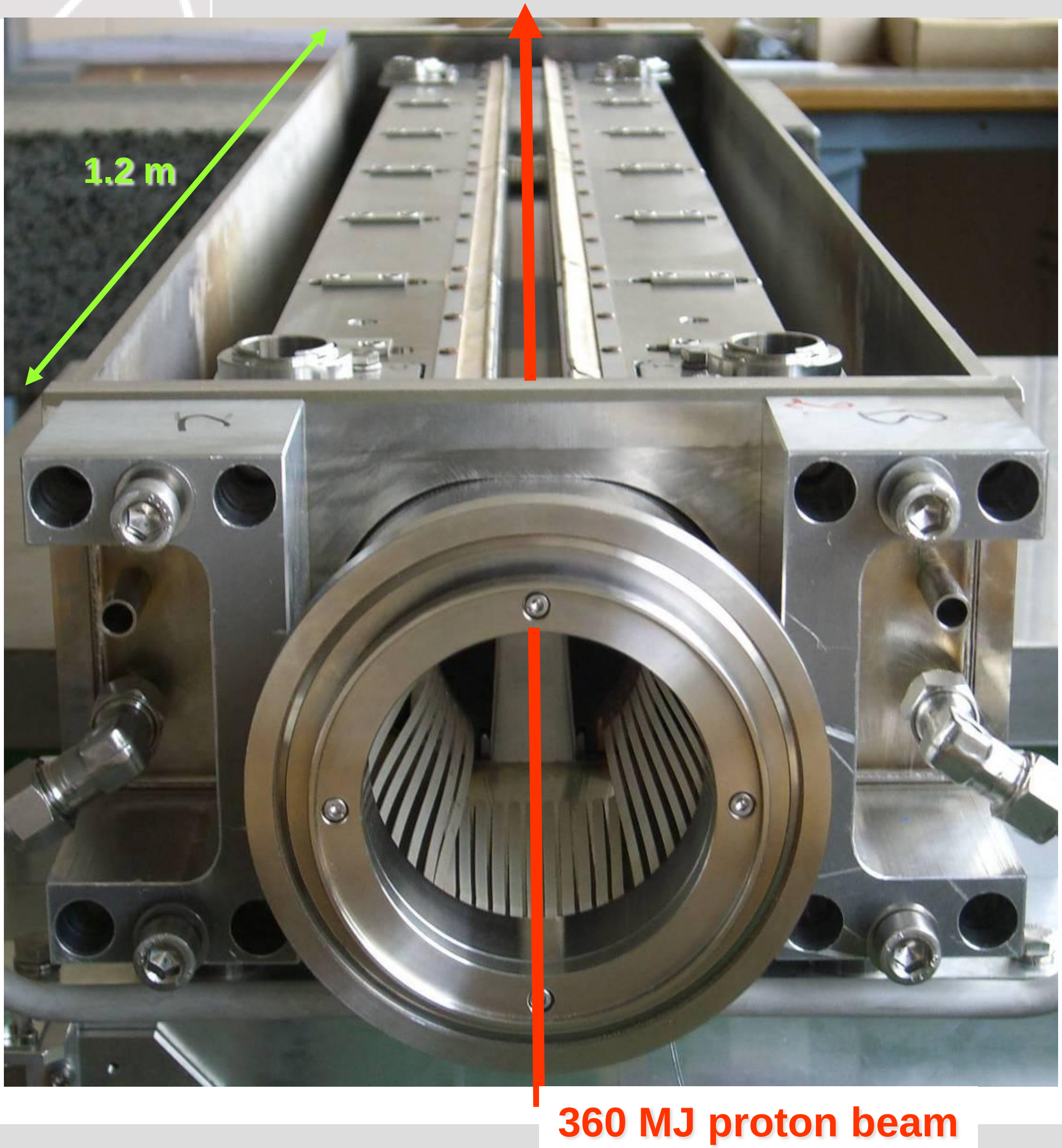
Stored Energy

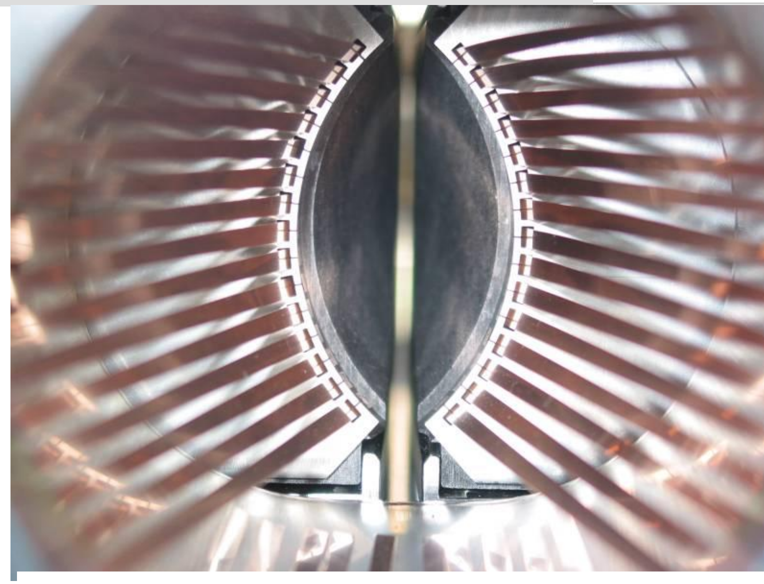
Nominal LHC design: 3 × 10[14] protons accelerated to 7 TeV/c circulating at 11 kHz in a SC ring

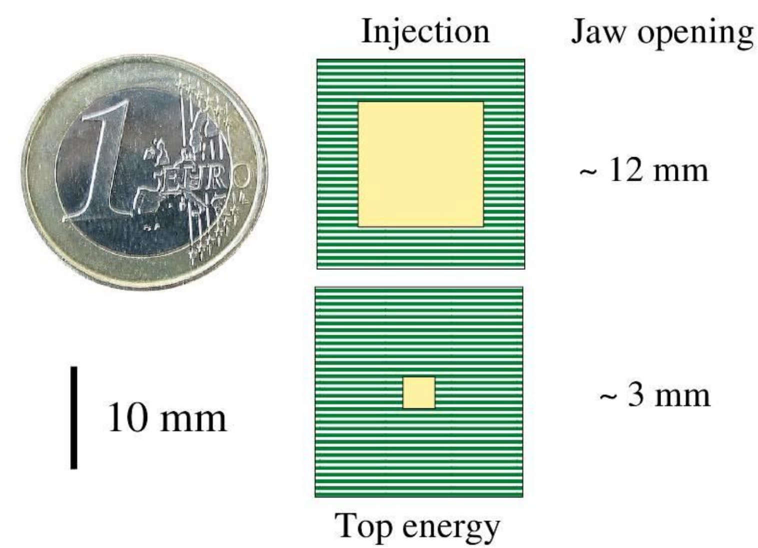


At less than 1% of nominal intensity LHC enters new territory. Collimators must survive expected beam loss…

The LHC Collimator
(Phase 1 MainDesign)







Precision Requirements

closest to beam: primary (TCP) and secondary (TCS) collimators

Gaps: **± 6/7 σ**

2-3 mm

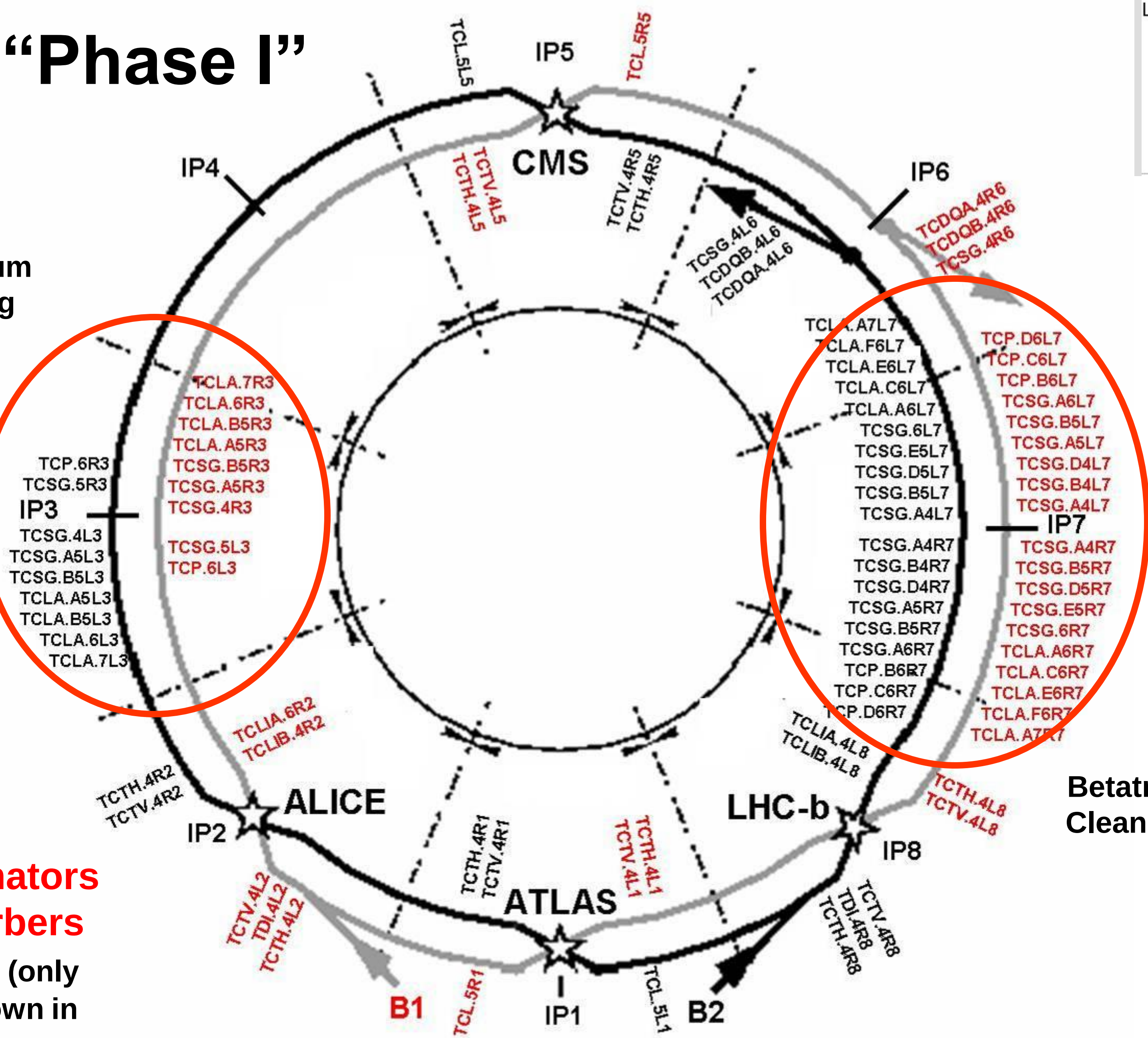
Parameter	Unit	Specification
Jaw material		CFC
Jaw length TCS TCP	cm cm	100 60
Jaw tapering	cm	10 + 10
Jaw cross section	mm^2	65 × 25
Jaw resistivity	μΩm	≤ 10
Surface roughness	μm	≤ 1.6
Jaw flatness error	**μm**	**≤ 40**
Heat load	kW	≤ 7
Jaw temperature	°C	≤ 50
Bake-out temp.	°C	250
Minimal gap	**mm**	**≤ 0.5**
Maximal gap	mm	≥ 58
Jaw position control	μm	≤ 10
Jaw angle control	μrad	≤ 15
Reproducibility	**μm**	**≤ 20**

2003 Specification

LHC collimators must work as precision devices!

"Phase I"

Momentum Cleaning

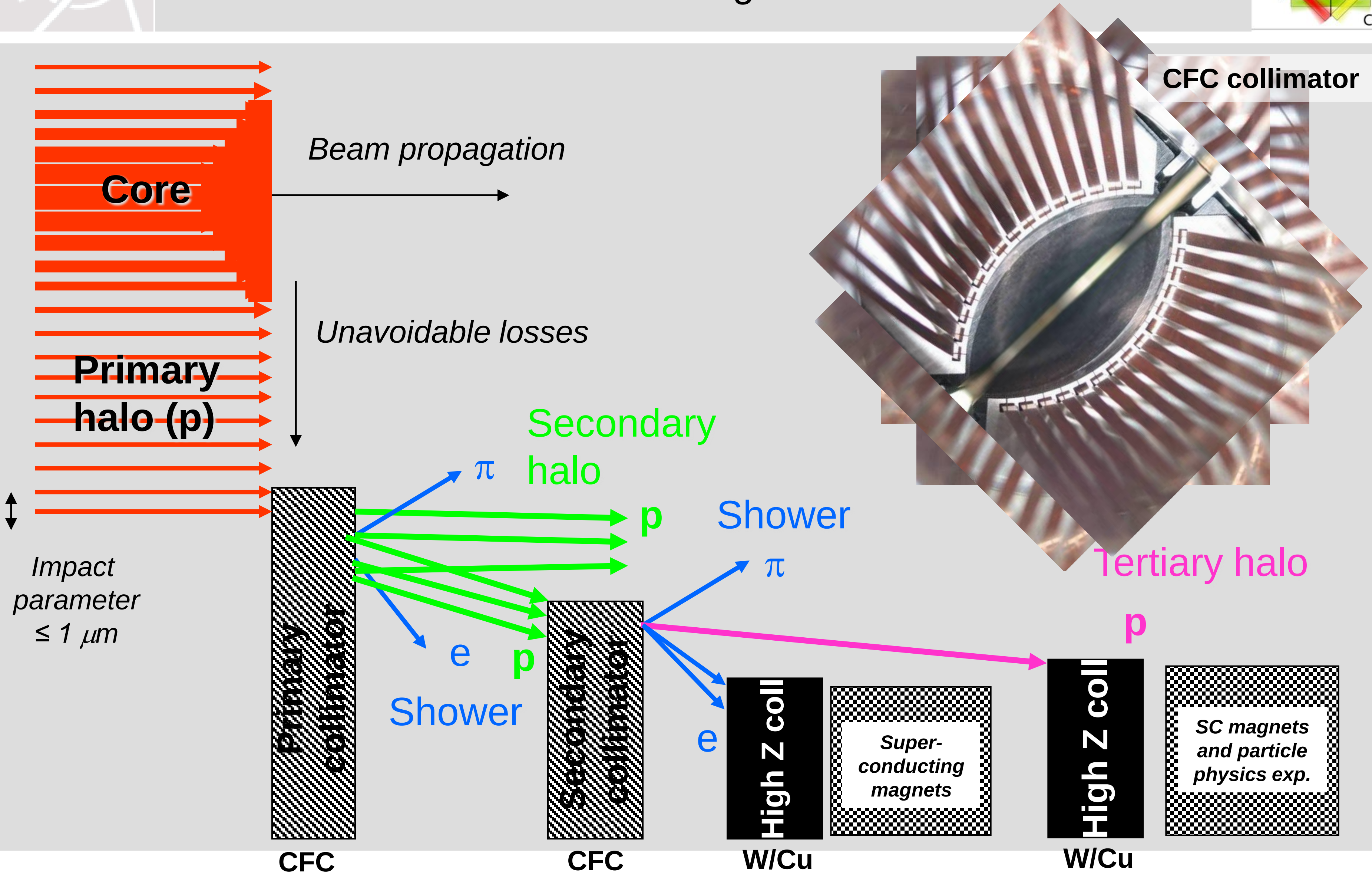


Betatron Cleaning

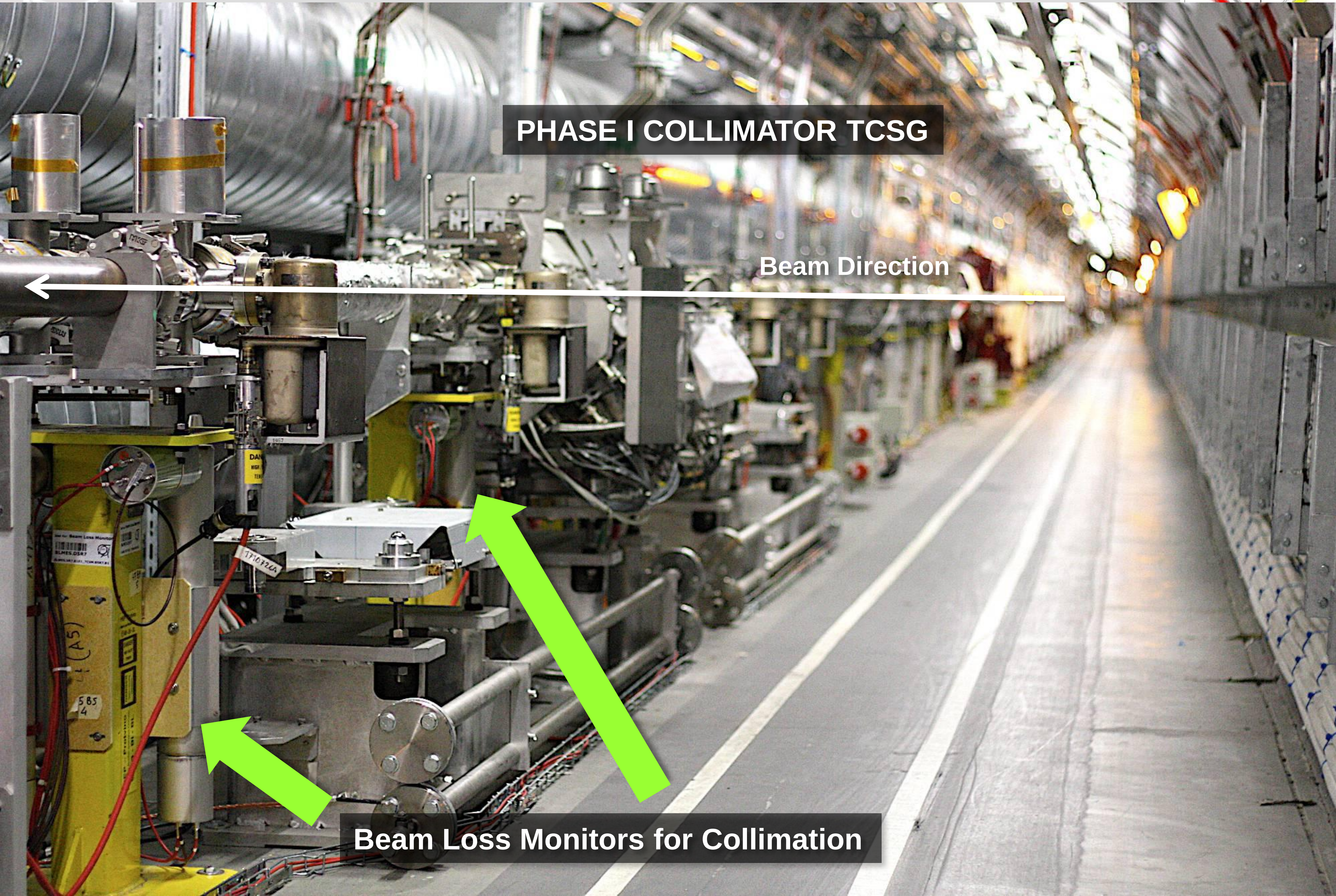
108 collimators and absorbers in phase I **(only movable shown in sketch)**

Multi-Stage Cleaning & Protection

3-4 Stages



Beam Loss Monitors for Monitoring Losses at Collimators



MP Role of Collimation

- Correct setup of collimation ensures highly efficient beam cleaning:
  - Tolerance for allowable LHC beam losses is maximized.
  - Risk of quenches is minimized.
  - Operational efficiency and integrated luminosity is maximized.
- **Correct setup of collimation ensures also several safety functions:**
  - Protection of accelerator against fast losses, e.g. erroneous dumps, wrong injection kicks, trips of fast magnets, RF trips, … → losses appear at collimators within given phase space coverage.
  - Protection of accelerator against long-term losses: radiation at foreseen locations, effectiveness of absorbers, survival of magnets, …
  - Correct environmental impact with losses at foreseen locations.
  - Robustness of collimation system against failures: collimators only damaged with multiple errors (e.g. asynchronous dump + dump protection out).

Collimation Condition

Good settings for given machine state!

for 2010: setup with relaxed 3.5 TeV tolerances (x 2.8) and limit on β* (> 2.5 m) → intermediate collimator settings!

Collimation Setting Calculation

- The collimator settings are calculated to:
  - Provide good efficiency.
  - Provide the correct collimator hierarchy (slow primary losses at primary collimators).
  - Protect the accelerator against the specified design errors.
  - Provide continuous cleaning and protection during all stages of beam operation: injection, prepare ramp, ramp, squeeze, collision, physics.
  - Provide maximum tolerances to beam and various collimator families.
  - Provide warning thresholds on all collimator axis positions versus time.
  - Provide interlock thresholds on all collimator axis positions versus time.
  - Provide interlock thresholds on all collimator gaps versus beam energy.
- Complex problem with some 100,000 numbers to control the system.
- Redundant calculation: time-dependent (ABP), energy-dependent (OP)

Required Flexibility

- **The LHC collider is not a static accelerator!**
- As a consequence the **collimation system cannot be a static system either!**
- Several settings for various stages with ramp functions in between.
- Interlock thresholds change as a function of operational stage.
- Only energy-dependent interlock thresholds remain unchanged.
- **All collimation tasks in operational sequence → operator has to execute the sequence tasks completely and in correct order.**
- Initially some problems (private sequences) but now works reliably. Sequence check tasks process implemented to enforce correct execution.

Collimation Setting Overview

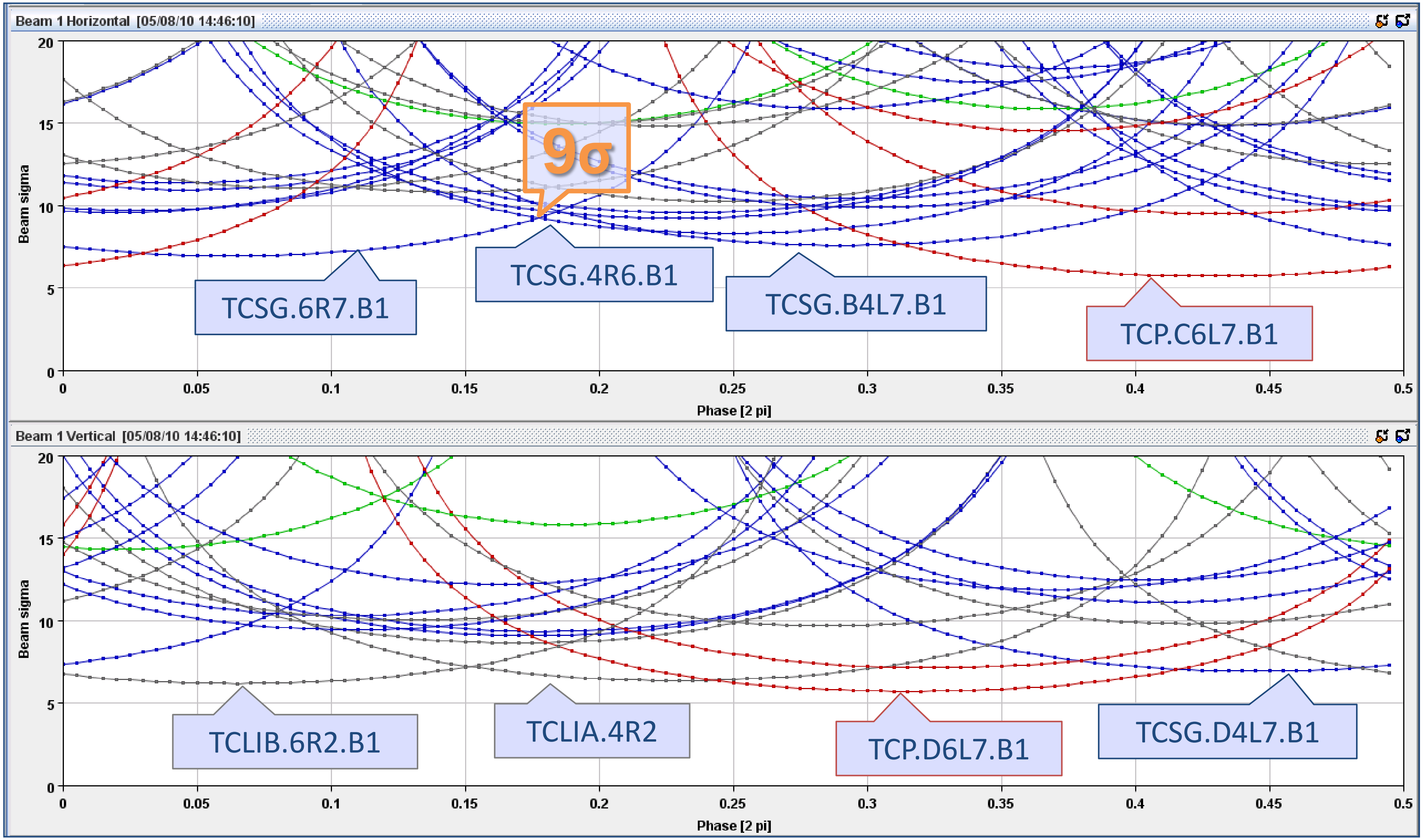
(in terms of β beam size, valid 12.6. – 30.8.2010)

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

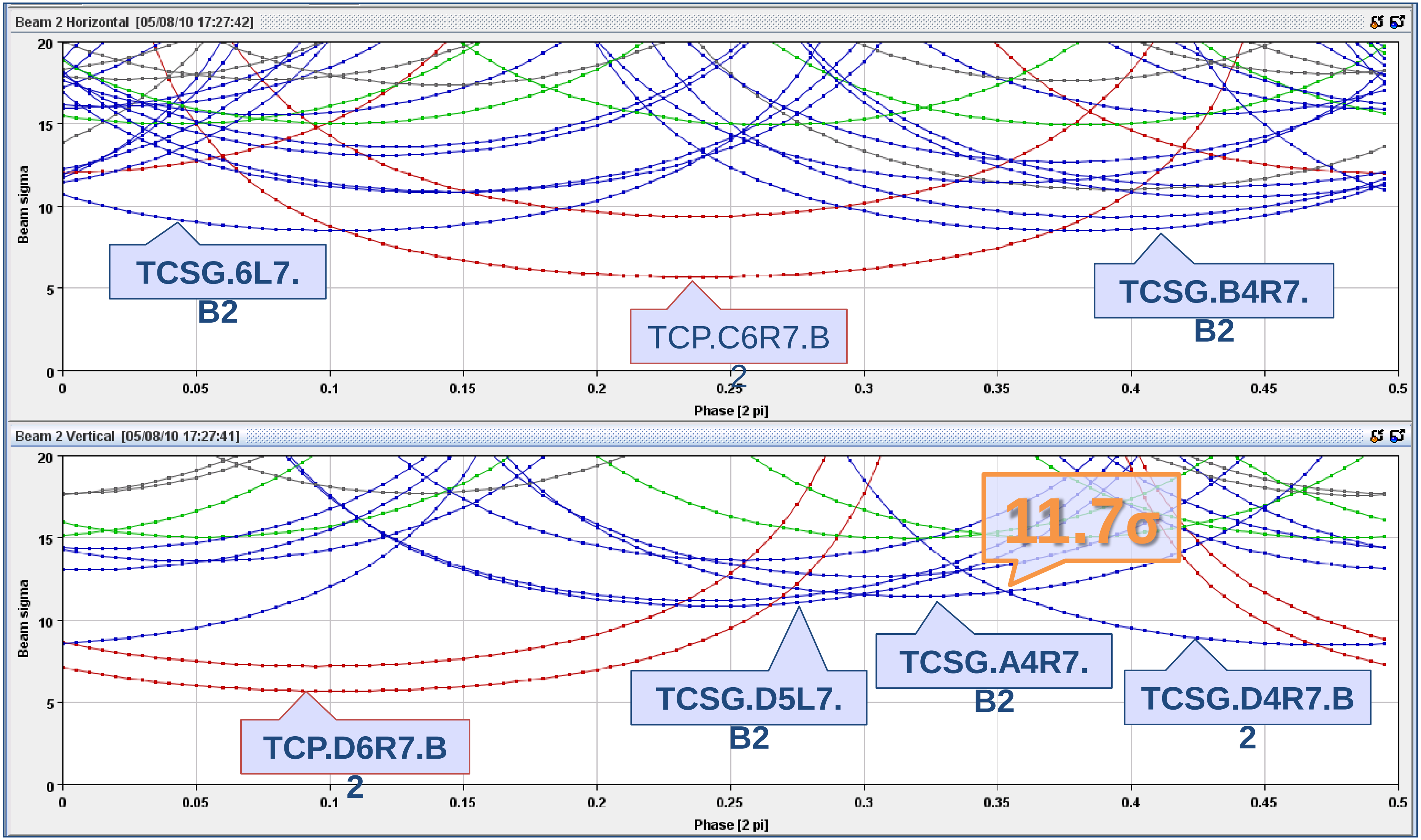
Ramp functions move smoothly from set 1 to set 2 during energy ramp!

3.5 TeV setup took ~30 h of beam time with single bunch of 1e11 p. Time distributed over 10 days with ~1 collimation shift per day.

Phase Space Coverage: Injection B1



Phase Space Coverage: 3.5 TeV, β*=3.5 m B2



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.

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.

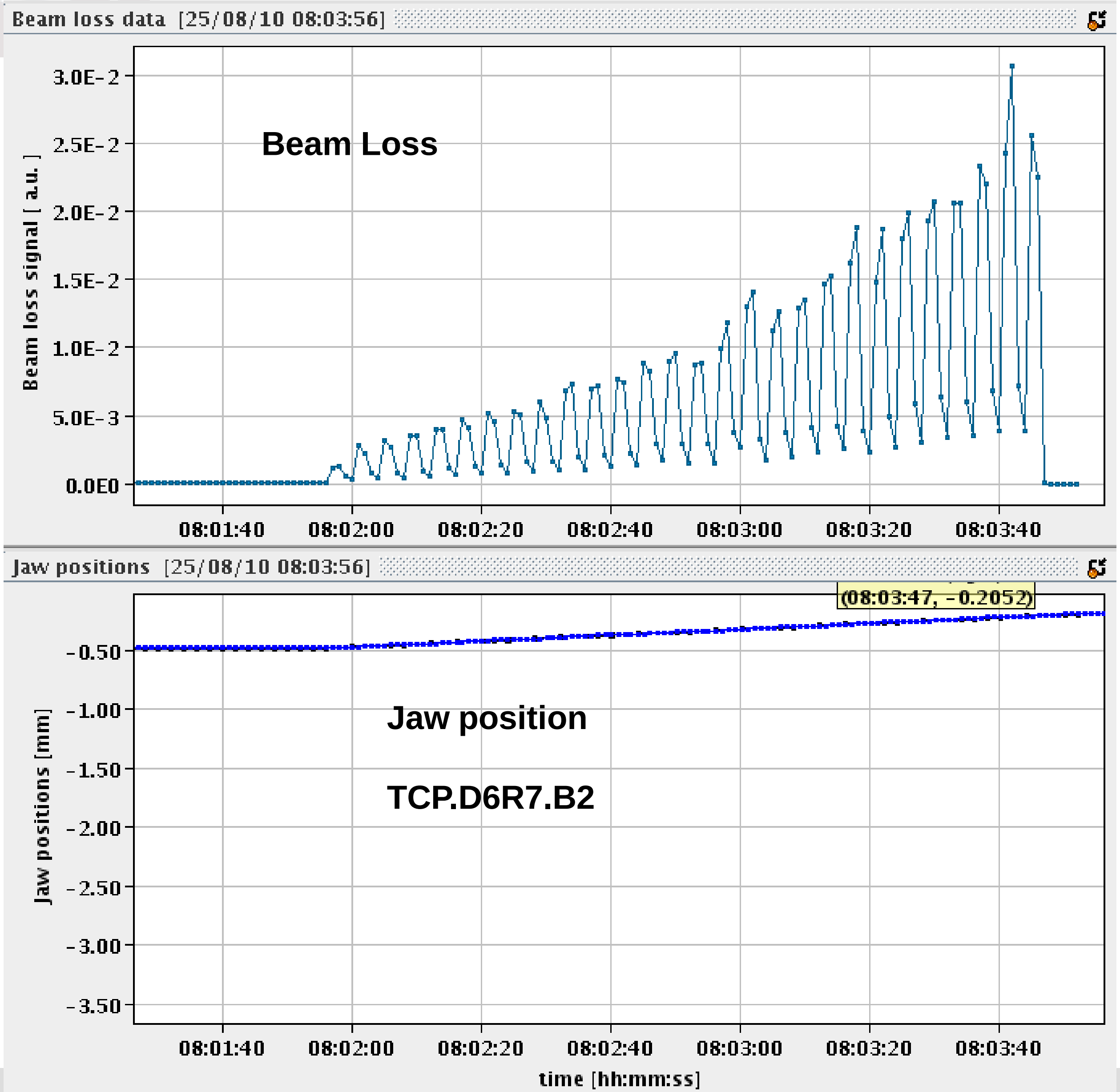
Device	Location	Energy	Condition 1	Condition 2	Condition 3
TCP	IR3	450 GeV	dN/dt > 1.2e12 p/s for T > 10 s (87 kW)	dN/dt > 6e12 p/s for 1 s < T < 10 s (430 kW)	dN/dt > 1.5e13 p/s for T < 1 s (1.1 MW)
TCP	IR7	450 GeV	dN/dt > 1.2e12 p/s for T > 10 s (87 kW)	dN/dt > 6e12 p/s for T < 10 s (430 kW)	
TCP	IR3, 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.

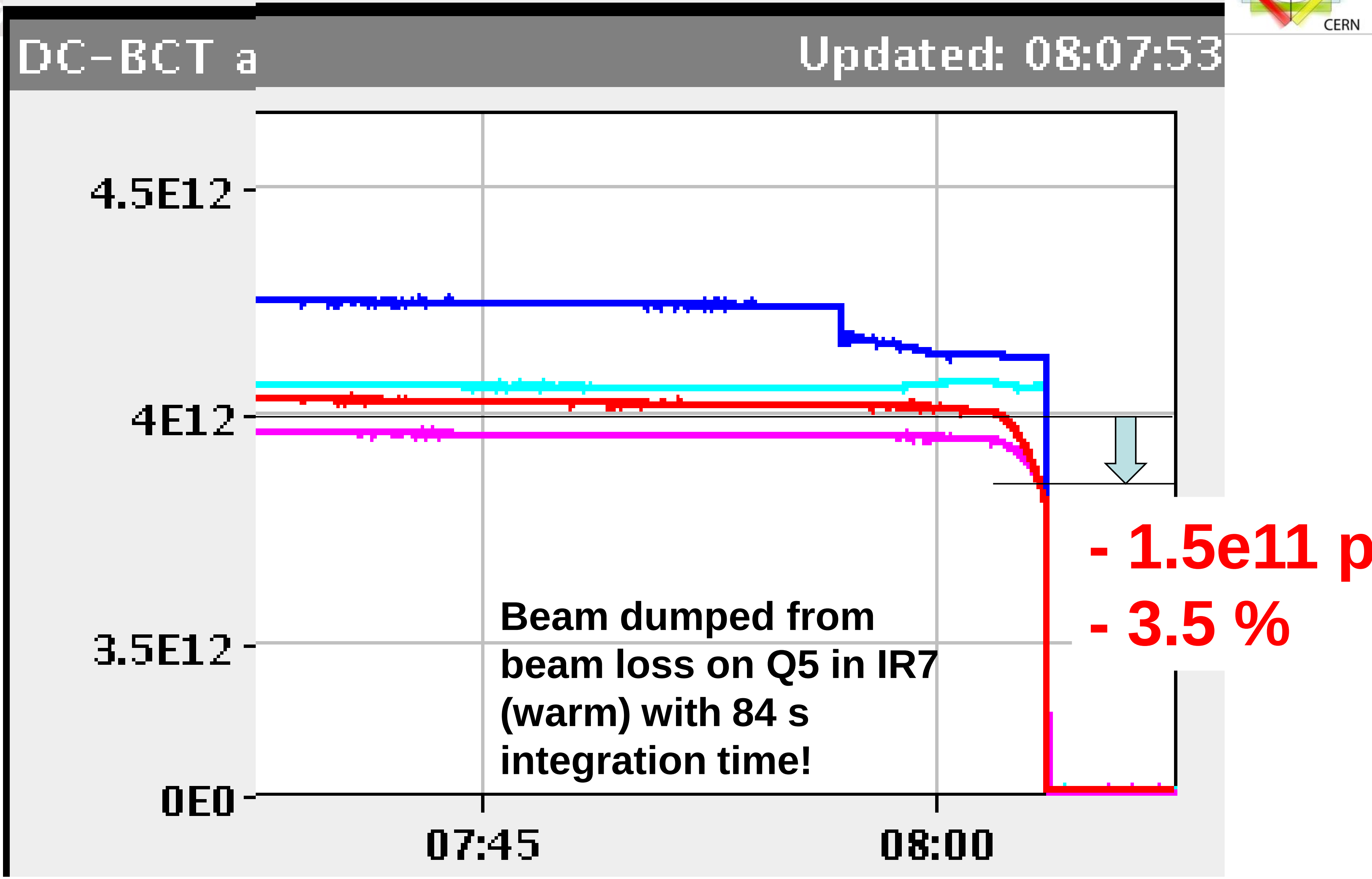
Device	Location	Energy	Condition 1	Condition 2	Condition 3
TCTH, TCTVA, TCTVB	IR1, IR2, IR5, IR8	450 GeV	dN/dt > 6e8 p/s for T > 10 s (45 W)	dN/dt > 3e9 p/s for T < 10 s (215 W)	
TCTH, TCTVA, TCTVB	IR1, IR2, IR5, IR8	7 TeV	dN/dt > 4e7 p/s for T > 10 s (45 W)	dN/dt > 2e8 p/s for T < 10 s (225 W)	
TCL, 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)	

Measuring Tails (10 min end-of-fill)

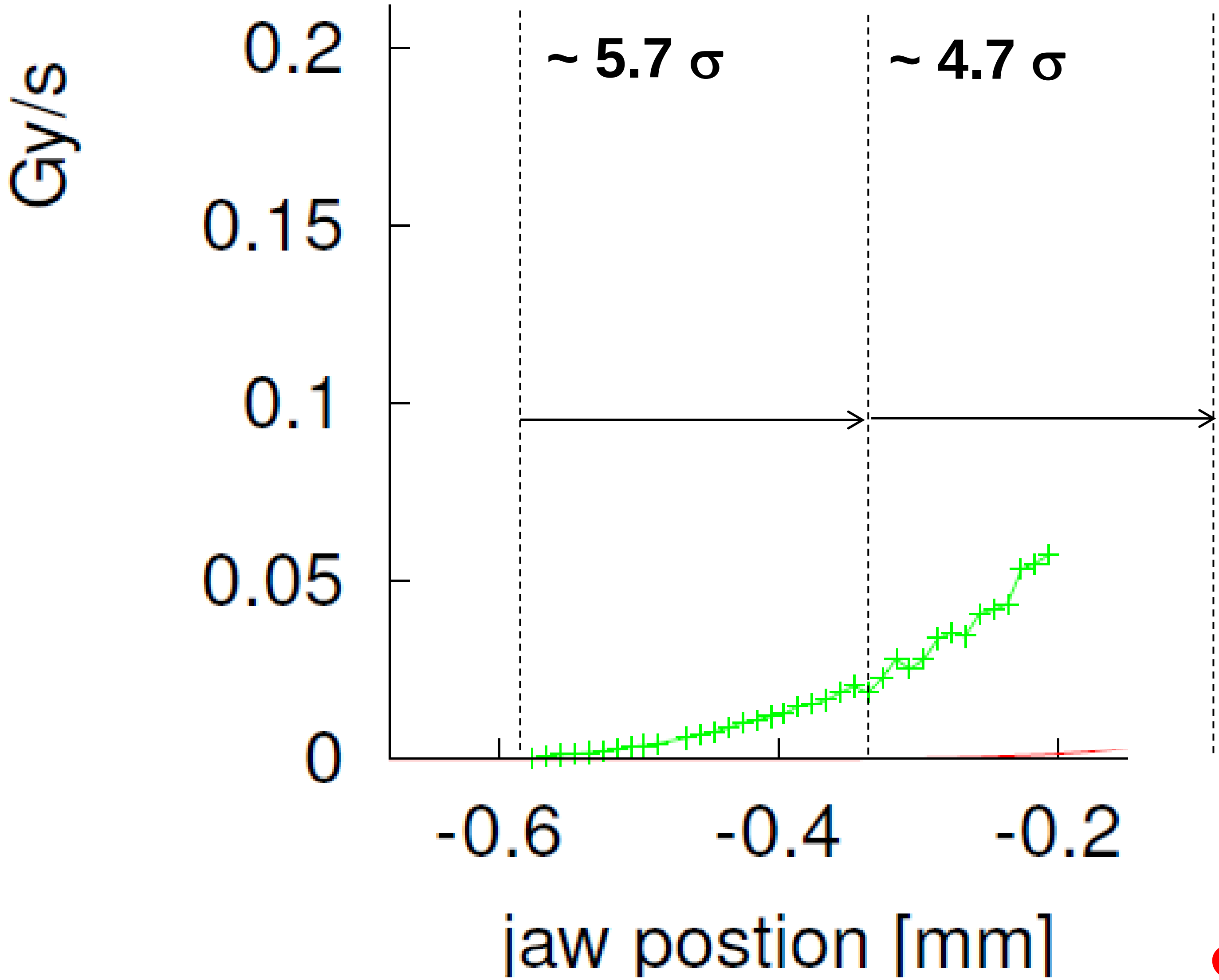


Jaw towards beam

Beam Intensity



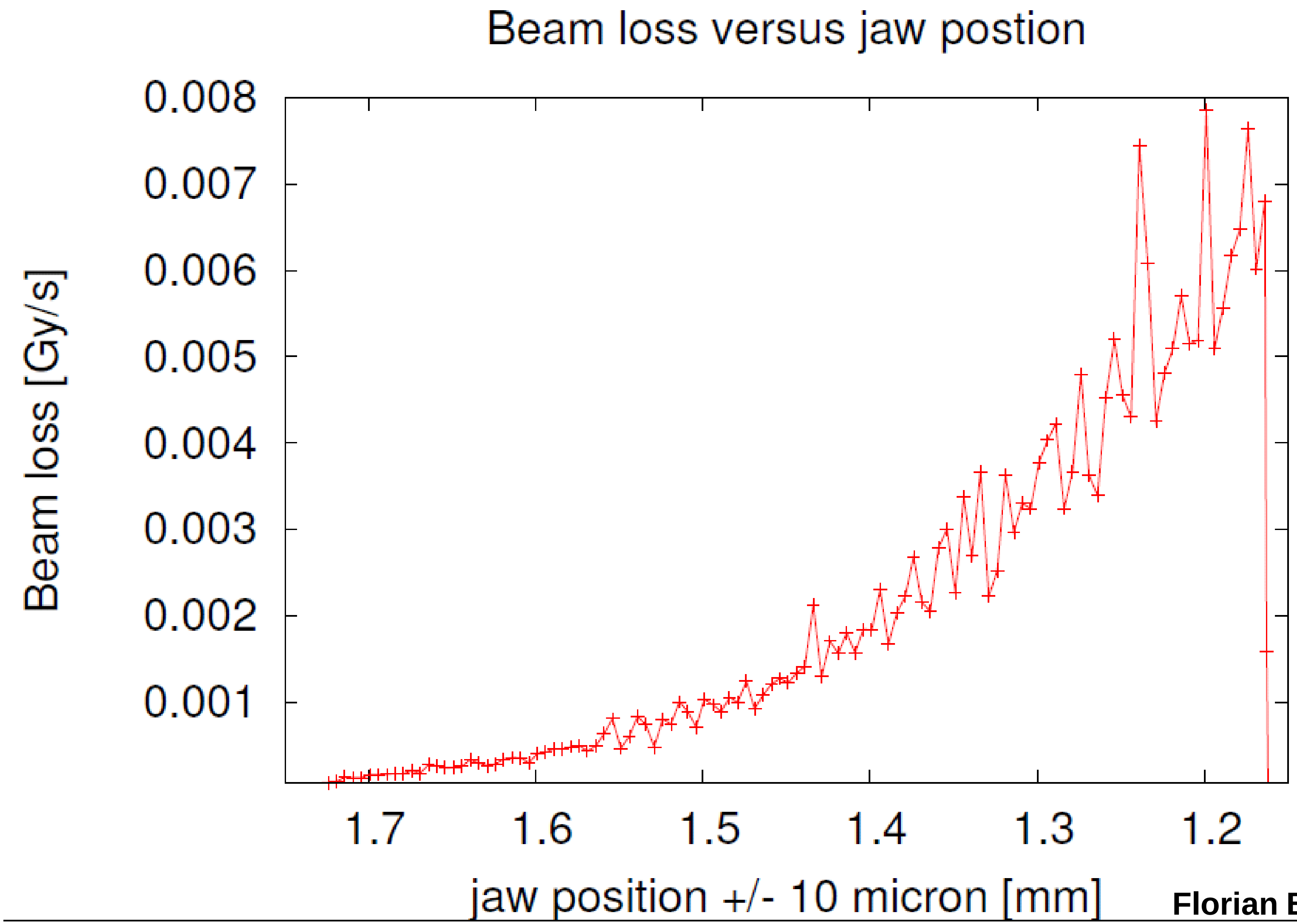
Beam Distribution: Beam 2 Tail V after 13h of Physics



3.5% of beam within 1.5 σ

σ_y = 0.27 mm

Beam 2 H Tail after 3h30 of Physics



Florian Burkart et al

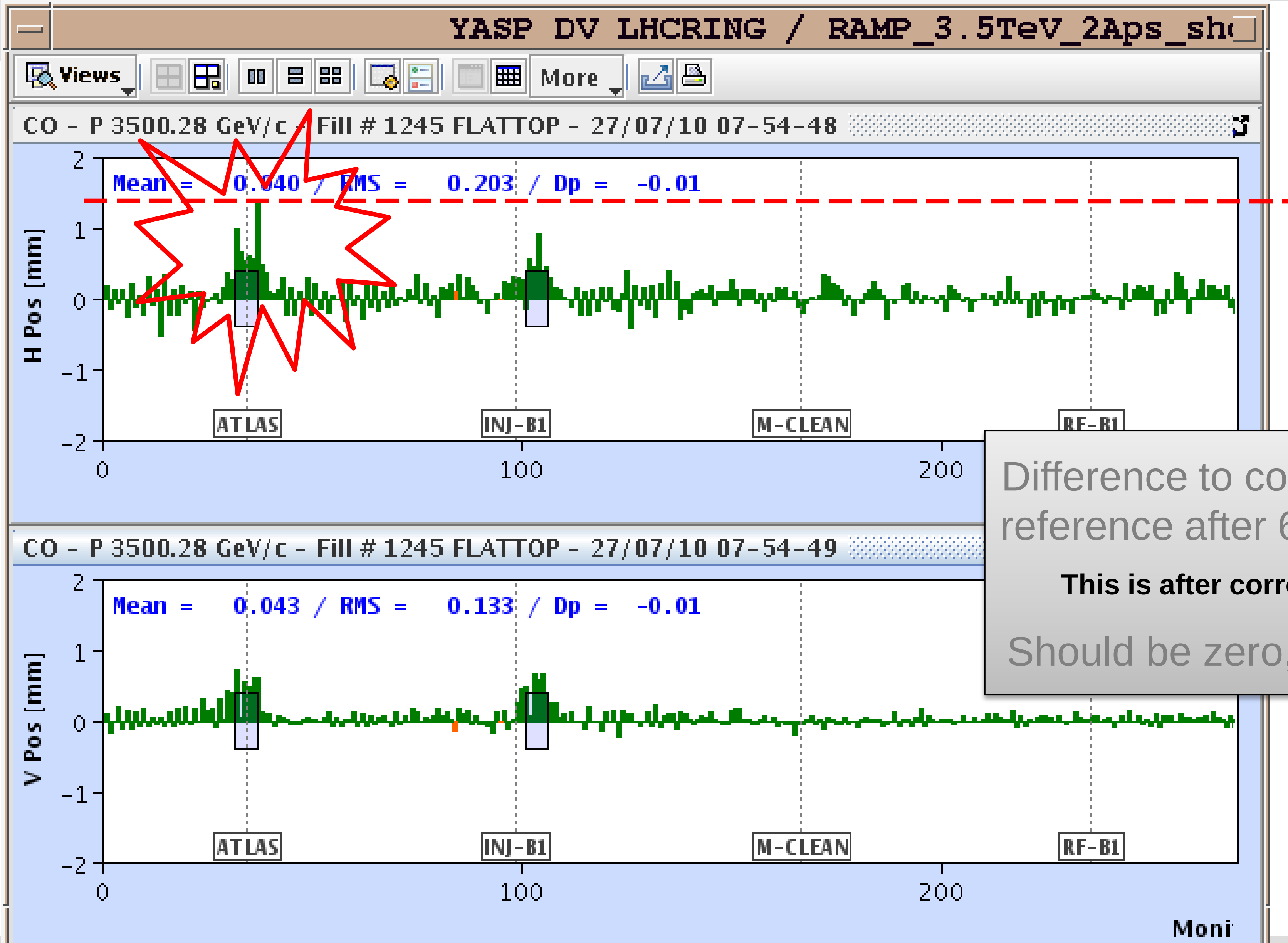
Previous talks …

- … have hopefully convinced you that:
  - **We can calculate safe settings for the overall system**
  - **We know how to set up the system and drive it through the full cycle**
  - **We tightly control that collimator jaw positions are correct**
  - **We redundantly control that collimation gaps are correct and exclude operational errors (e.g. EIC forgets loading of ramp functions)**
  - **We achieve the expected performance level**
  - **We can detect cases with wrong collimator hierarchy**
  - **We can monitor collimator hierarchy and performance with time**
  - **We have a very reliable system (required for radiation)**
- As a consequence: no damage and no quench so far
- **What are issues?**

Collimation MP Issues

- Tail population once we have much higher intensity (steepness of losses).
- Orbit effect on validity of collimation setup:
  - Validity depends on orbit stability and reproducibility.
  - Orbit changes are factor ~10 above collimation specification (0.3 σ). Even at 3.5 TeV with relaxed collimator setup, we are still factor 3-4 above requirements.
  - Orbit interlocks are at values which are far beyond the tolerances and can therefore not protect against wrong orbit.
- Non-specified losses at collimators:
  - Several massive losses seen up to July. Coherent instabilities.
  - Seems OK since we stabilize this with transverse feedback.
  - Spontaneous trims of RF frequency, orbit correctors, …
  - Some problems were fixed and came back (RF trims).
  - Seems OK since August.

Many Examples of IR Bumps – Here 27.7.



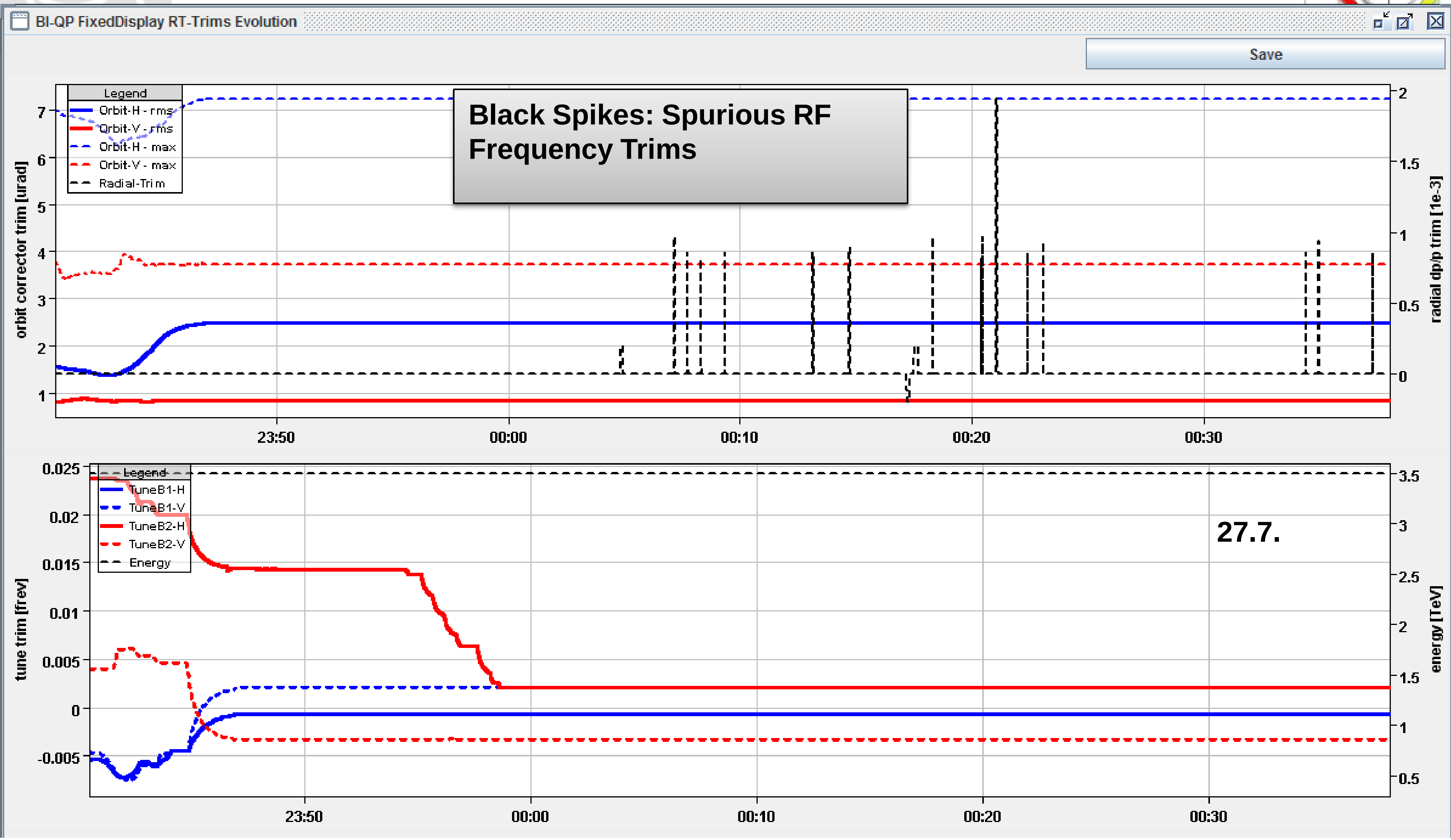
Difference to collimation reference after 6 weeks.

This is after correction!

Should be zero, ideally!

Orbit Feedback Sends Spurious RF Trims

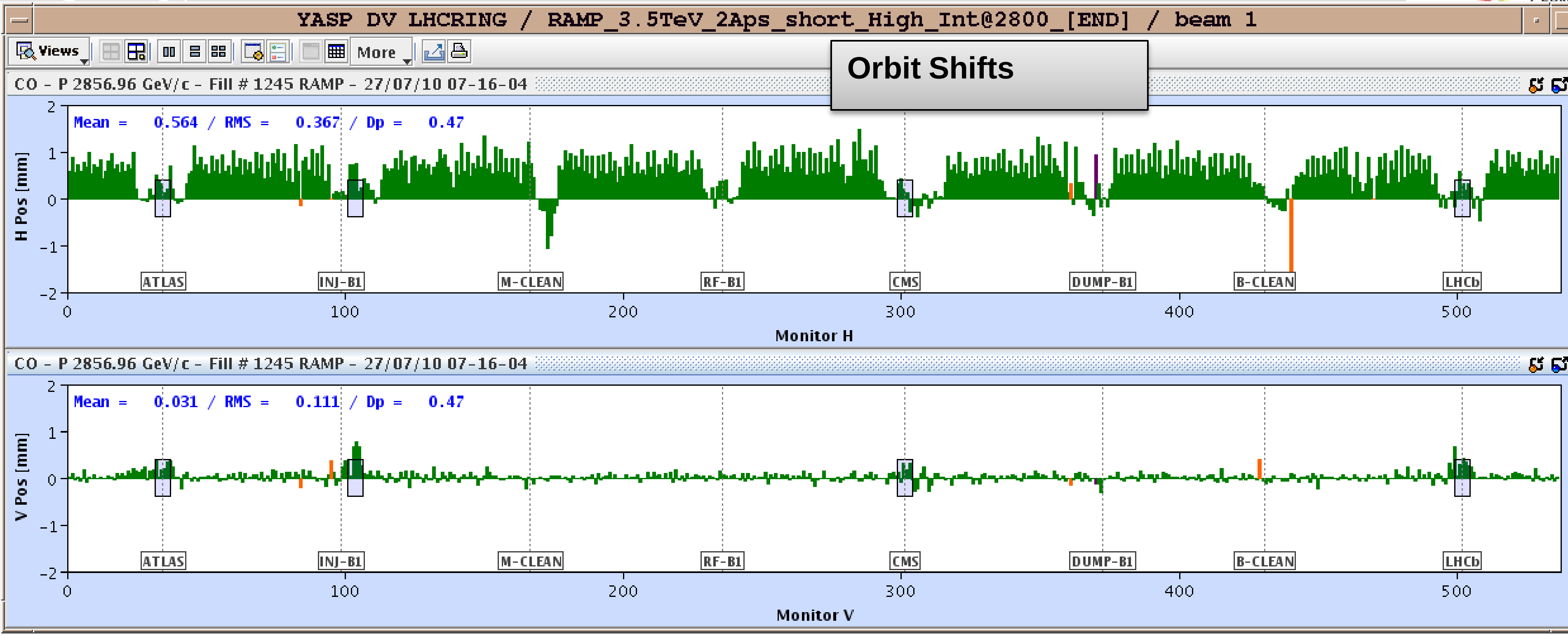
LHC Collimation Project



Black Spikes: Spurious RF Frequency Trims

Spurious Trims: Orbit Jumps

27.7.



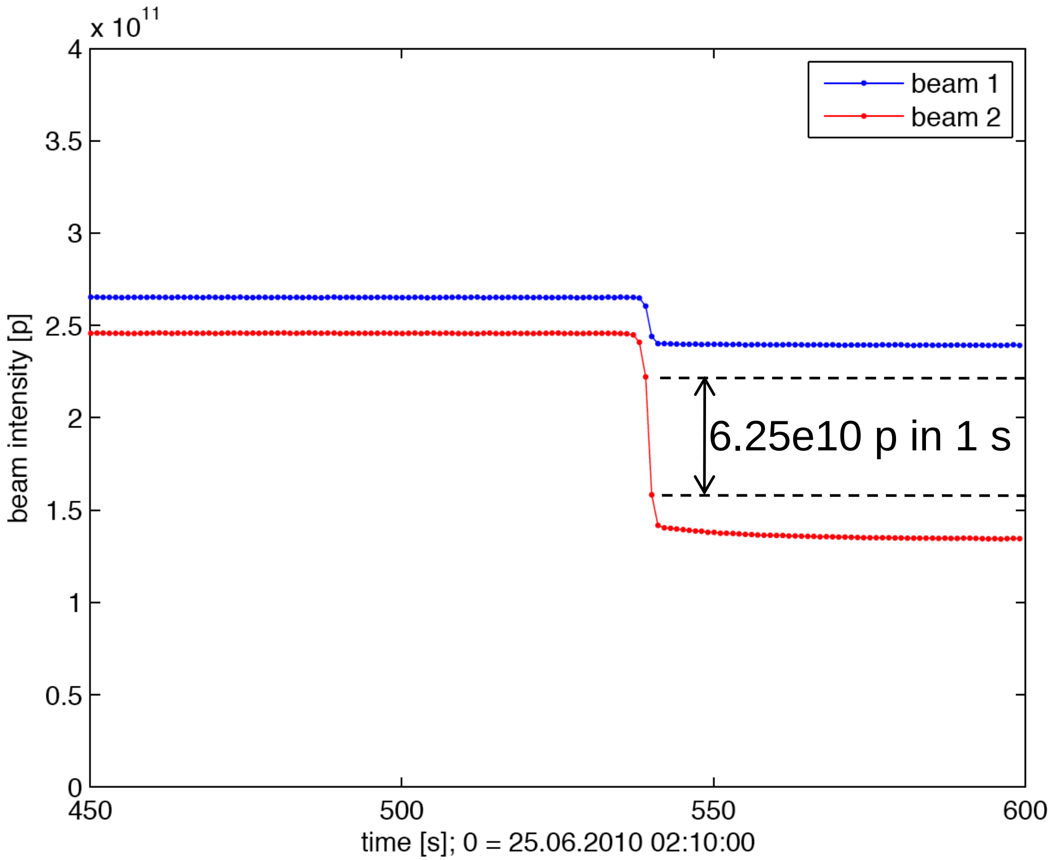
Orbit Shifts

→ See horizontal and vertical orbit changes!
→ IR bumps are dispersion bumps…

Loss in Stable Beams – Problem for Collimation? Solved for now…

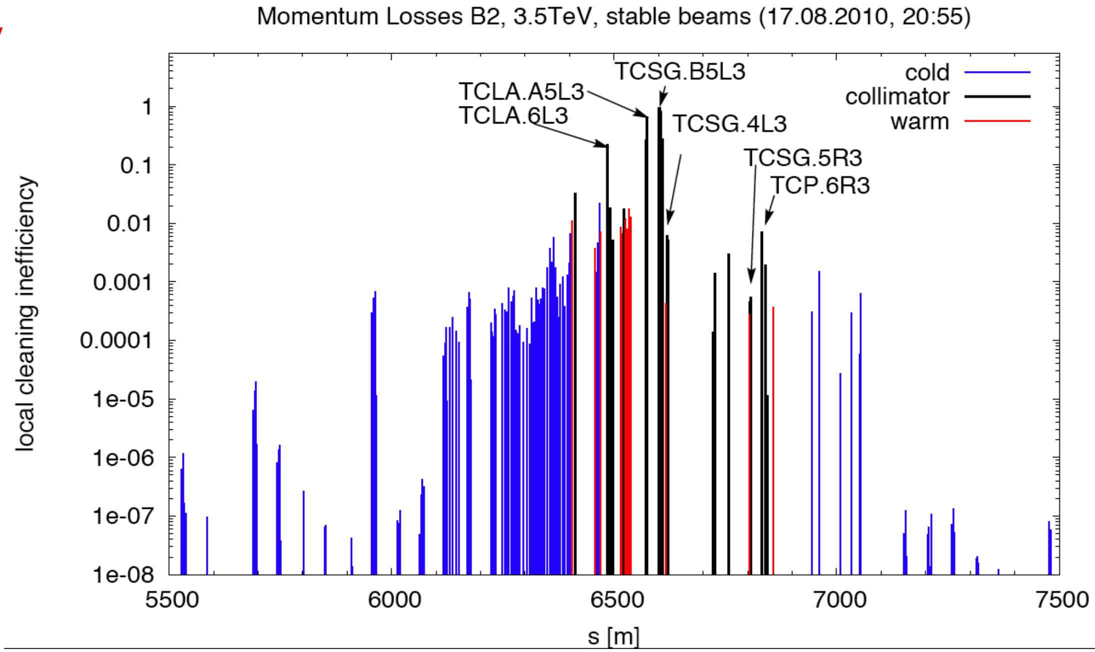
25.06.2010, 02:19

- Sudden beam loss during stable beams.
- Peak beam loss rate: 6.3e10 p/s for beam 2. Relative loss rate: 26 %/s
- Reminder: Specified peak beam loss rate at 7 TeV is 4e11 p/s!
- During this fill we reached with 0.1% of nominal intensity already 16% of nominal loss rate!
- Relative loss rate was 260 times beyond specification!
- Good case to analyze collimation performance.



How Well to Maintain It?

- E.g.: Found **wrong hierarchy in IR3 on 17.8.2010**.
- Only appears for positive momentum errors, beam 2.
- Exposes end of cleaning insertion to very high losses! Absorbers at start of insertion not effective.



- Can we run like this? YES, for many months without problems until something happens…
- Condition for damage: (1) positive energy error (had it but now protected with interlock), (2) wrong hierarchy, (3) BLM's not reacting or loss too fast for BLM reaction time. Overall UNLIKELY!

Design for the Unlikely

- Many collimation requirements just arise because we prepare for an unlikely and rare event.
- The LHC protection is too sophisticated to have a clear-cut failure mode (e.g. x% probability of failure within y weeks due to problem z).
- Any accident in the LHC will be a coincidence of several unlikely things happening at the same time (as in all complex machineries).
- I find it mandatory to maintain the collimation system in order to be prepared for an unlikely and rare event. Accepted by management.
- Need clear MP policy with respect to multiple failures. In some cases lot's of speculation with multiple failures, in other cases discarded.
- **How many of our protection layers are required for safe operation (all?).**

Example: TCT Collimator Damage with Multiple Failures

- TCT's are tungsten collimators (not robust) in experimental IR's with largest margins in whole system (protect triplets):
  - – Margin to primary collimators: 9.3 σ . Margin to dump protection: 4.4 – 5.7 σ
- Conditions for damage to TCT collimators:
  1) Asynchronous dump or single-module pre-fire
  2) One bunch deflected with right phase to hit TCT
  3a) Two independent dump protection collimators out and/or
  3b) Large orbit errors at TCT's and/or dump protection collimators
- Then possibility to hit Tungsten jaw of collimator with 1 bunch, close to surface… Most likely scratch surface. Water pipes qualified to 120b.
- Unlikely error, not observed so far (see monitoring of efficiency)
- Detailed study ongoing in any case for this multiple failure case! In any case, collimators are there for beam impact! No panic.

Intensity Increase

(Discussions Ongoing – Ruediger Proposed to Present This)

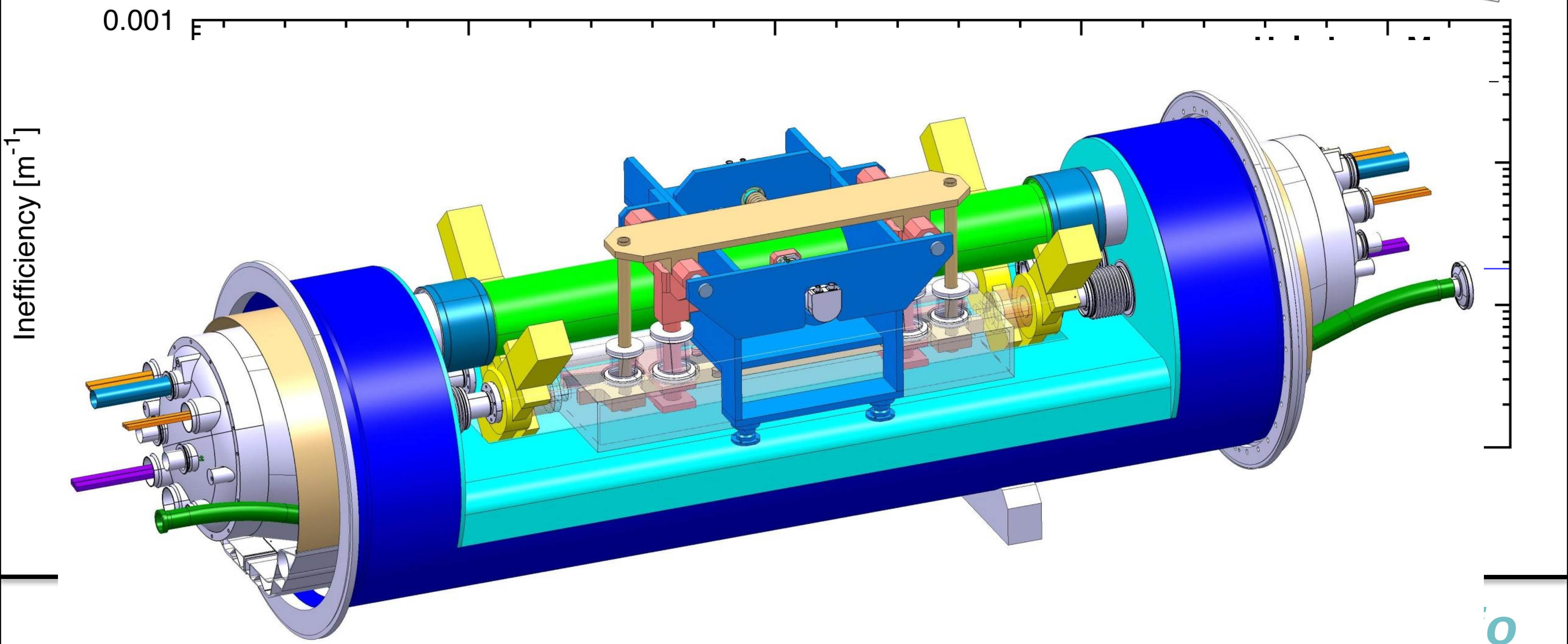
- MP policy recent months:
  - Setup in June for nominal bunch intensity. Assume stability of setup.
  - Exponential increase in number of bunches. Factor 2 per step up to 2.7 MJ.
  - Experience of 2 weeks per step.
- August period with stable conditions has given excellent results. Losses inside specification, collimation system performance stable, no quench.
- Proposed alternative approach:
  - Setup for bunch train. Qualify for fully conform systems. Take time to fix.
  - Rapidly increase intensity (e.g. 2.7 MJ per fill) after setup (best protection) until non-conformity is seen.
  - Invest time gained for performance monitoring and fixing issues when seen.
  - Assumption is that 2 week observation time is insufficient to see rare accidents anyway. Base increase on August experience.

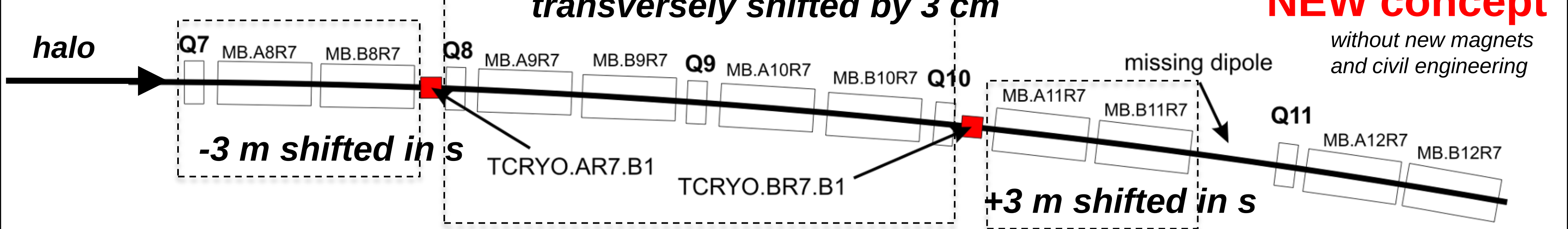
Outlook: Upgrades

- We plan upgrades on present system for 2011 (during christmas break):
  - Use of squeeze factor for interlocks during squeeze.
  - More automated setup: faster and less prone to human error (risk of wrong dump during collimator setup with broken hierarchy).
- Upgrades in 2012 shutdown:
  - Relocate all losses to IR3 (radiation to electronics) and catch losses in dispersion suppressors (DS collimators).
- Upgrades in 2016 shutdown:
  - Full collimation upgrade.
  - Collimators with in-jaw buttons: non-destructive centering and setup of collimators. 100 times faster setup. Can be done every fill. Precise interlock of orbit – collimator offsets. Tested in SPS successfully.

TCRYO

Downstream of IR7 β-cleaning

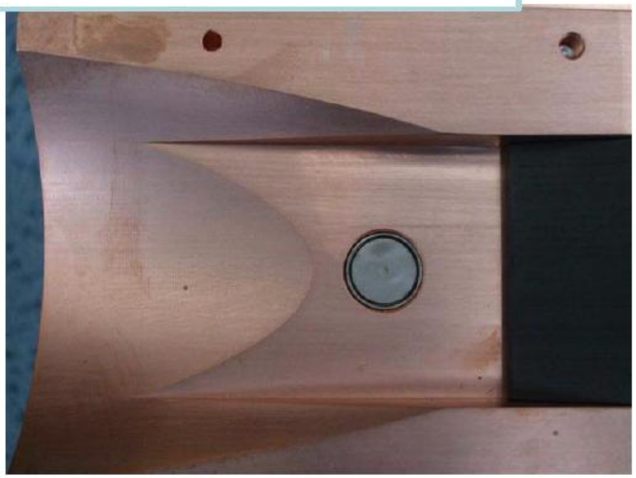




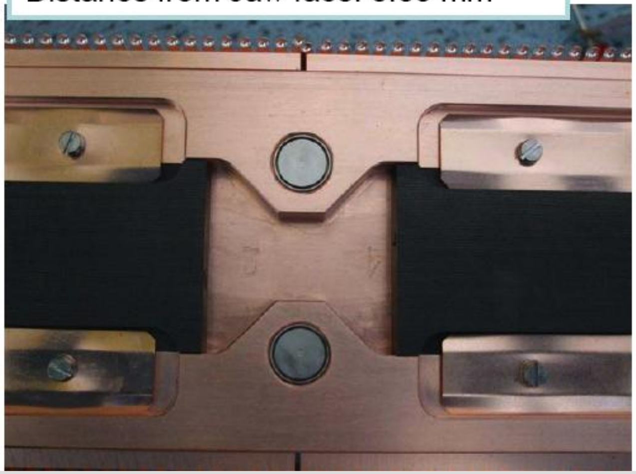
Installation of 1st Phase II Collimator

(CERN type, BPM's in jaws, into SPS for beam tests)

Button 1 at upstream port on D side
Distance from Jaw face: 10 mm

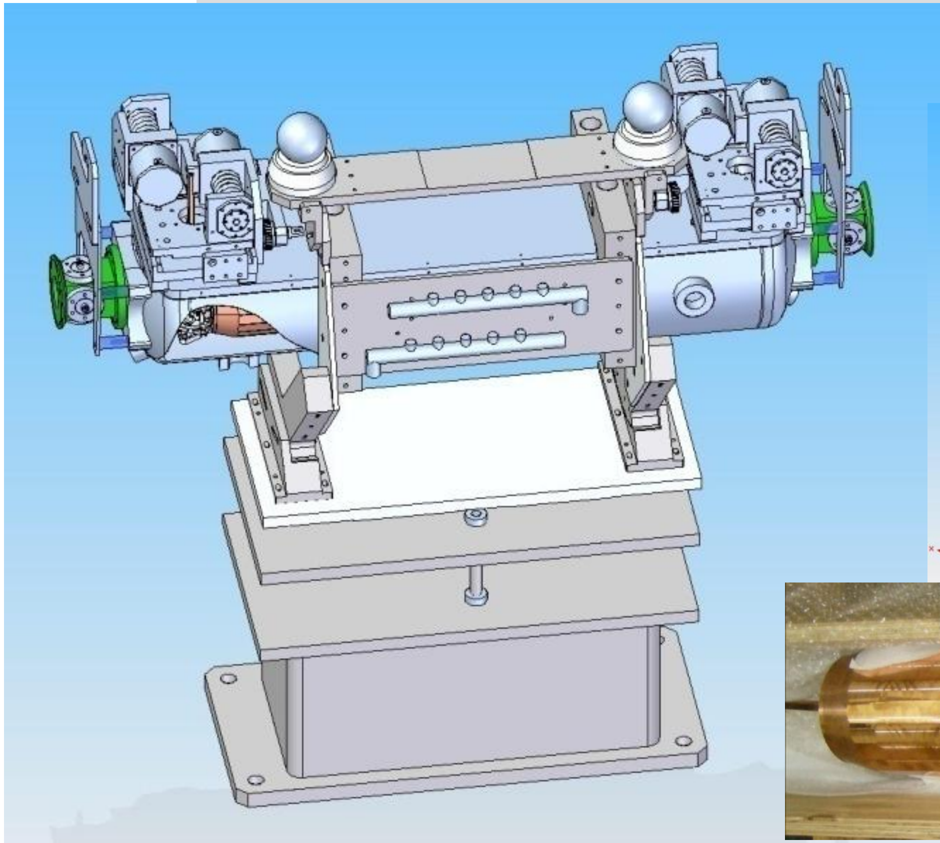


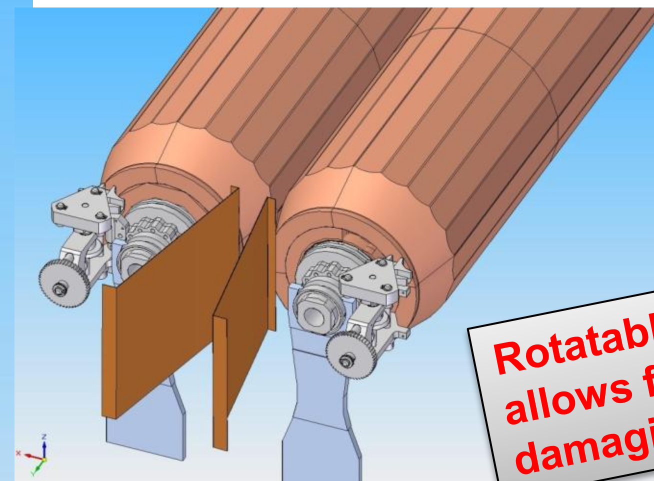
Button 10 at center of jaw on DB side
Distance from Jaw face: 0.05 mm



US Work on Phase II Design

(LARP funded, SLAC linear collider design to LHC)





Rotatable high Z jaw allows for multiple damaging beam hits!

First prototype to be delivered from SLAC to CERN in August 2010. Installation into SPS in 2010/11 shutdown. Beam tests in 2011.

Time to build 5 collimators: 1 year. If decision in 2012 then available in 2013…

Conclusion

- LHC collimation works with expected performance level and has shown an amazing stability over the last 2 months.
- Collimation interlocking has proven very effective, catching even non specified errors (e.g. ramp up of beam energy from 3.5 TeV with beam inside the machine).
- The achieved orbit tolerances are non-conform, especially in the IR's. So far no sign of increased losses in the IR's. So good enough for intermediate collimation settings at 3.5 TeV and $\beta^* = 3.5$ m.
- The collimation system should be kept well set up, to be prepared for rare and unlikely accident cases. 2 weeks running does not prove safety.
- Need consistent policy for multiple failures.
- This takes beam time for monitoring (~6h per week) and fixing issues.
- Once fully set up, we prefer a very fast increase in beam intensity with time for monitoring and addressing non-conform issues.

Reserve Slides

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.

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).

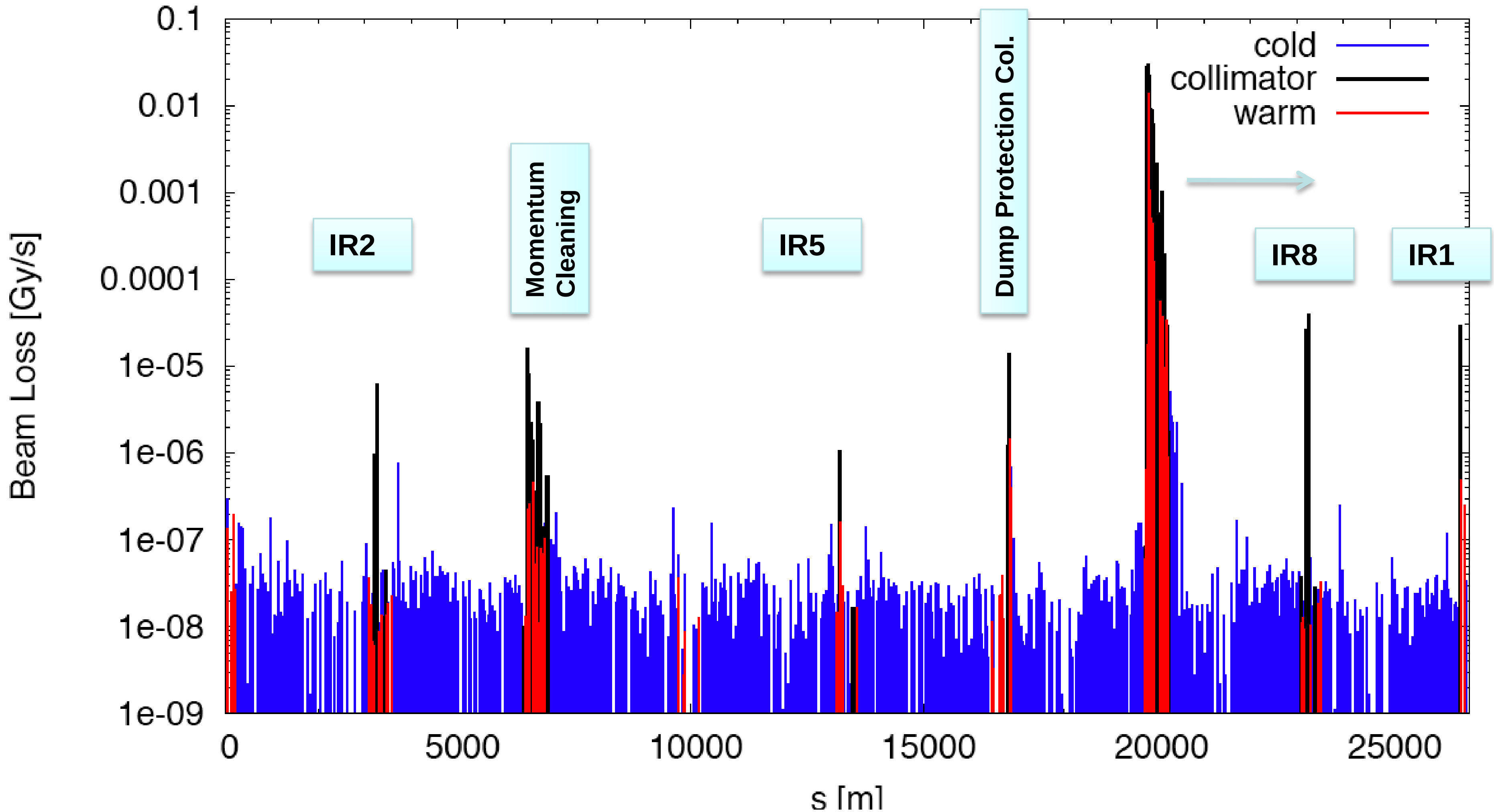
Usually collimators are frozen in for protection reasons! Need to violate this for setup!

Some flexibility is required in machine protection!

Beam Tests for Verification

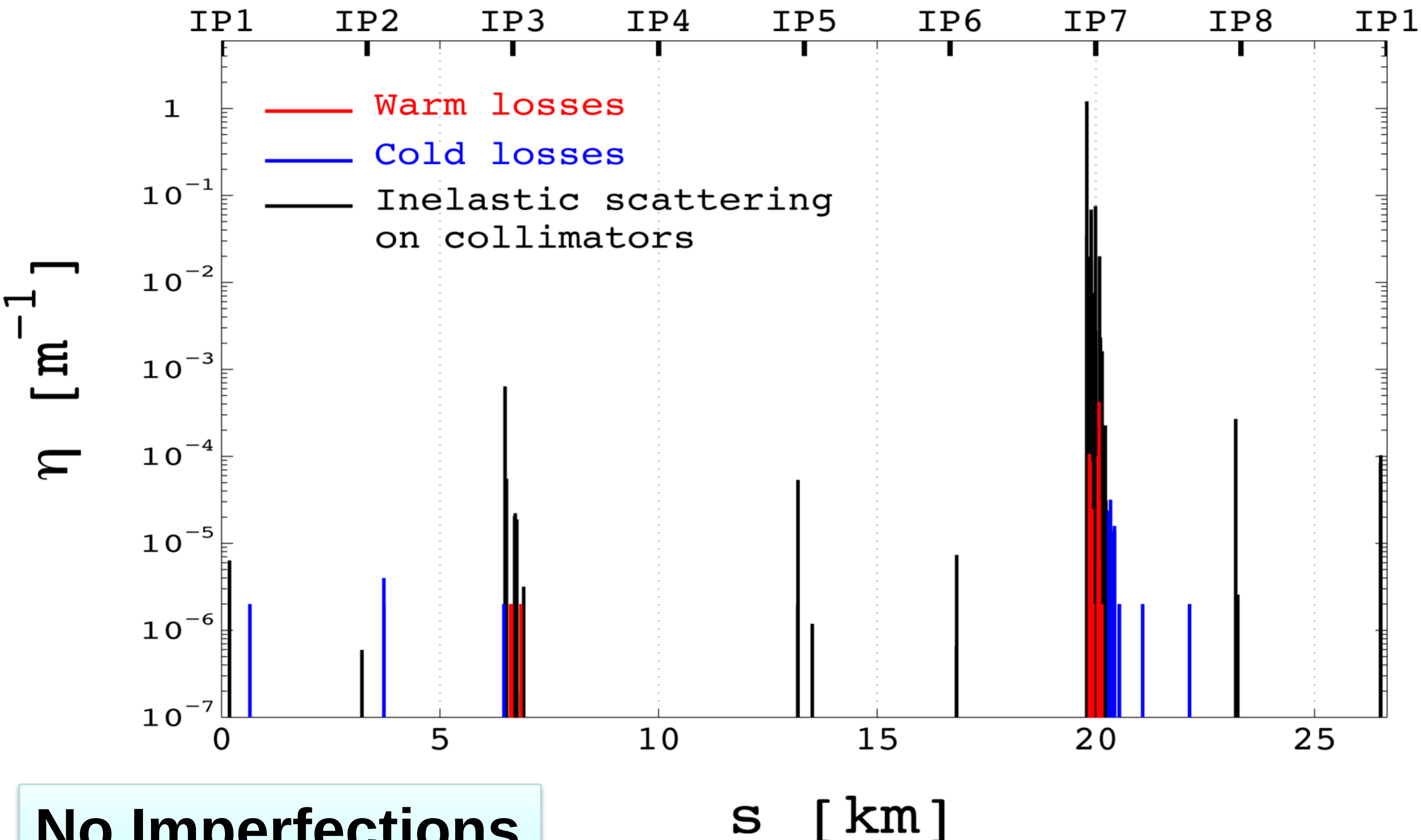
- **Verification is essential in view of possible errors in collimation setup!**
- Should be **repeated at least once a week** at end of fills to monitor performance and drifts.
- Only way to detect possible drifts and problems before the situation becomes unsafe!

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)

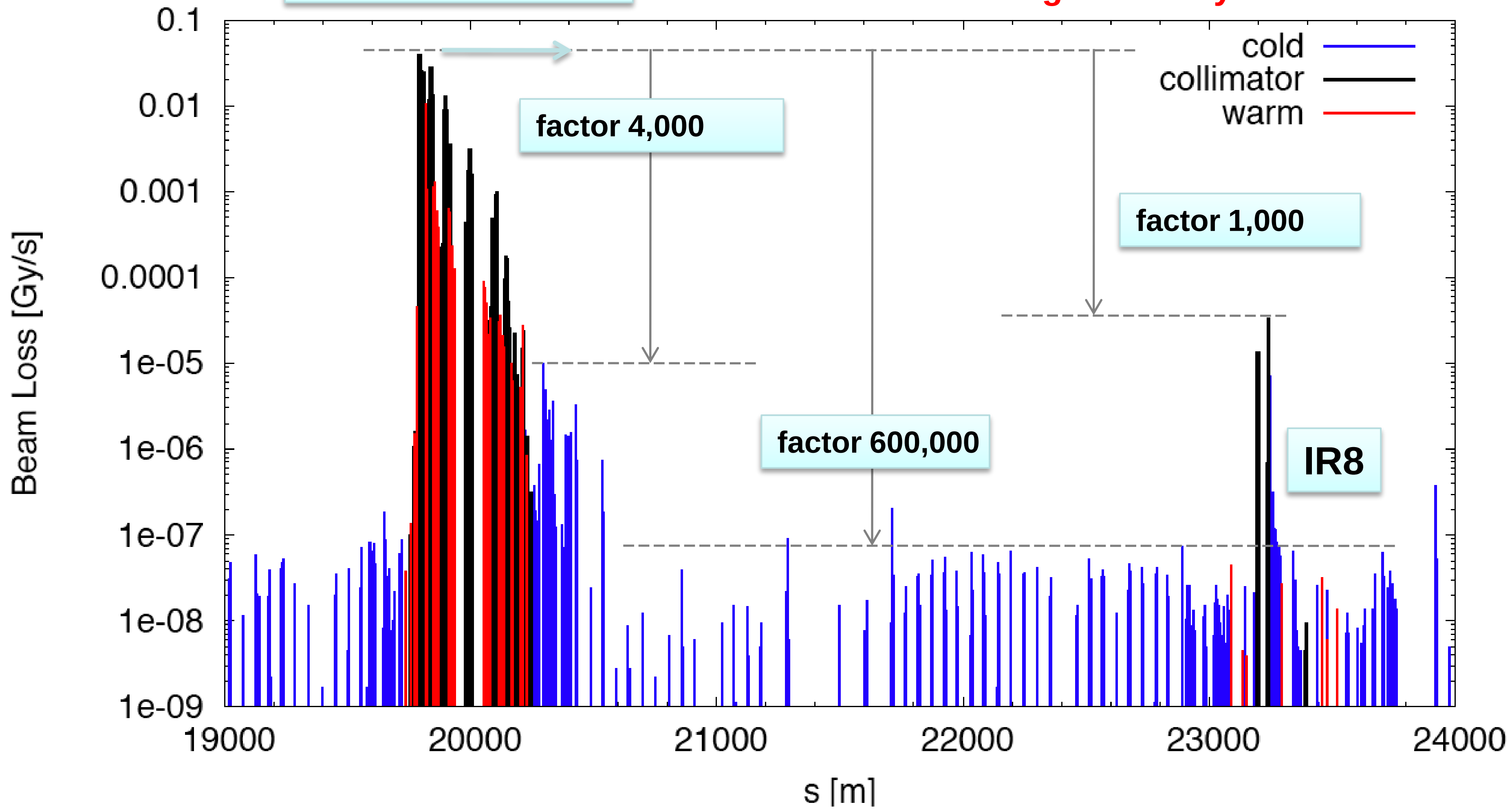


No Imperfections

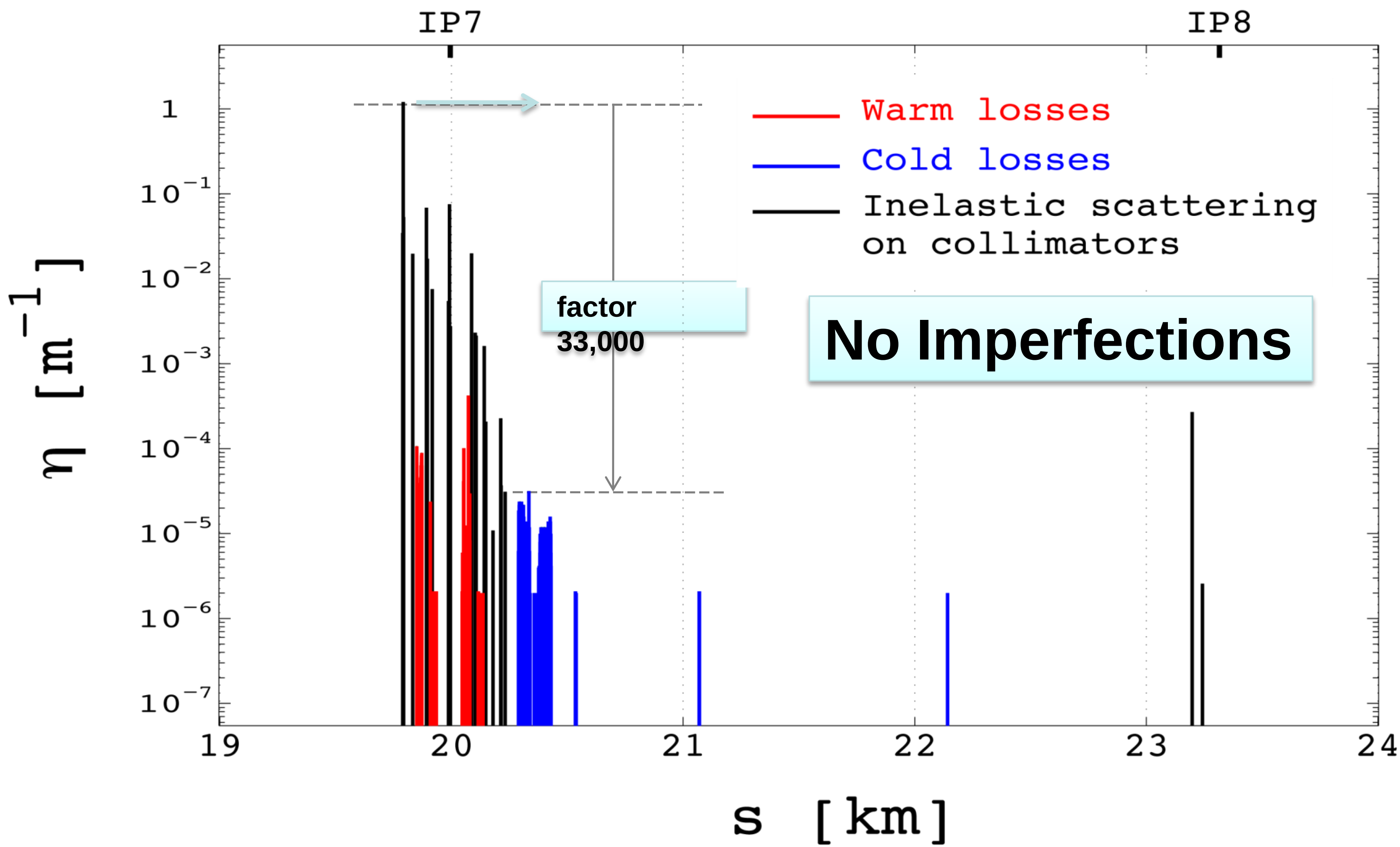
Measured Cleaning at 3.5 TeV
(beam1, vertical beam loss, intermediate settings)

Betatron Cleaning

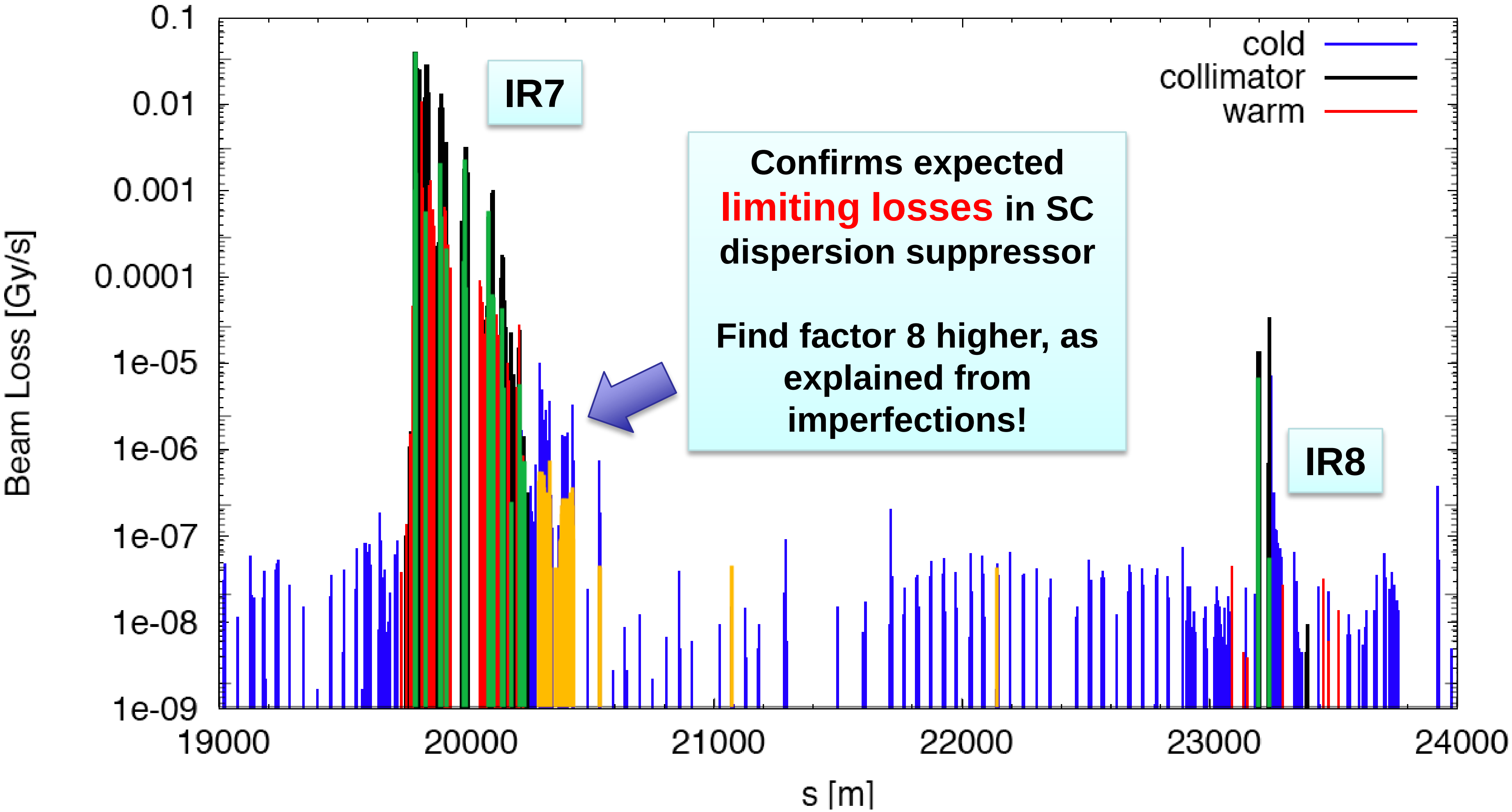
Cleaning efficiency: > 99.975%



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



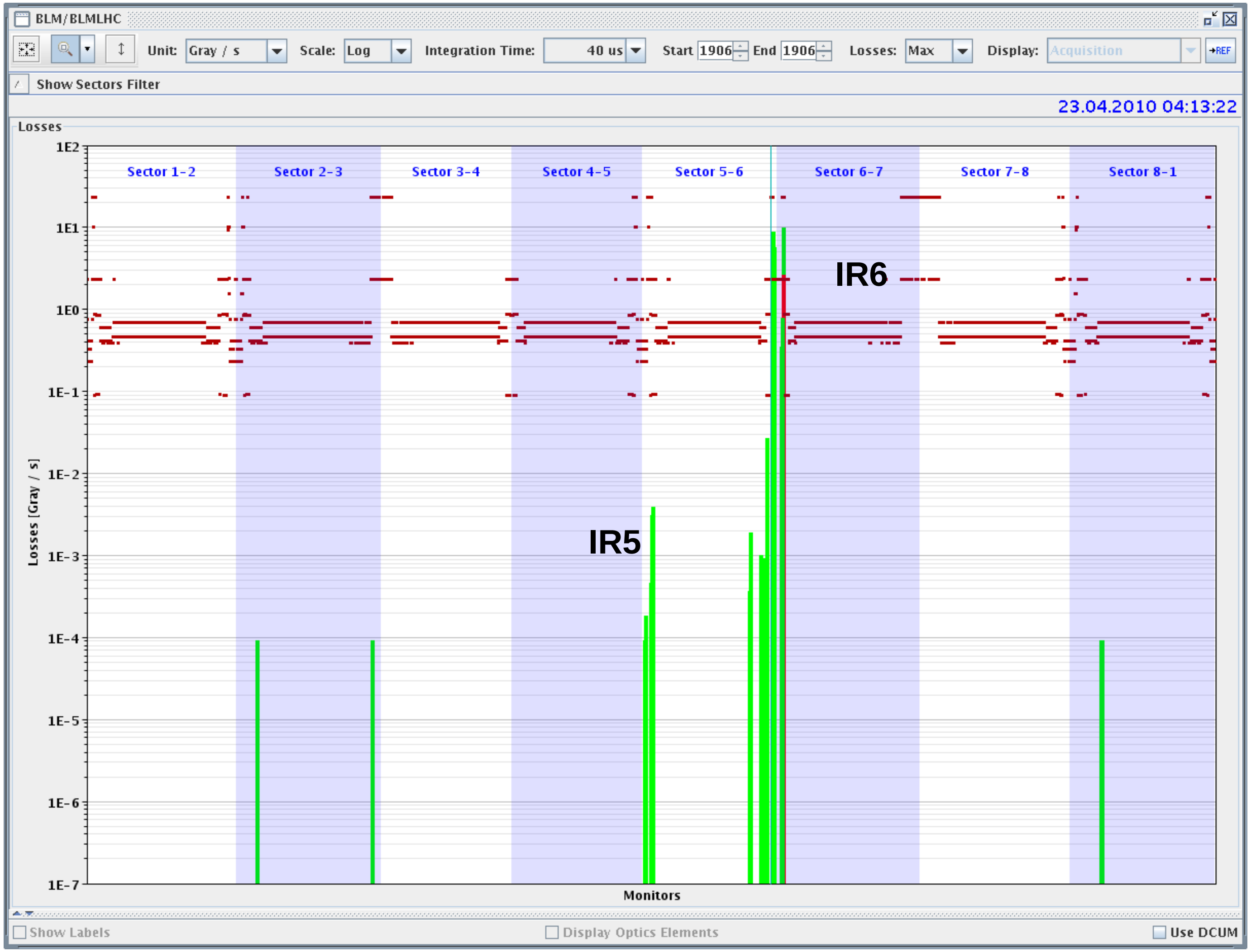
Meas. & Sim. Cleaning at 3.5 TeV
(beam1, vertical beam loss, intermediate settings)



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

Find factor 8 higher, as explained from imperfections!

Leakage from IR6 Dumps



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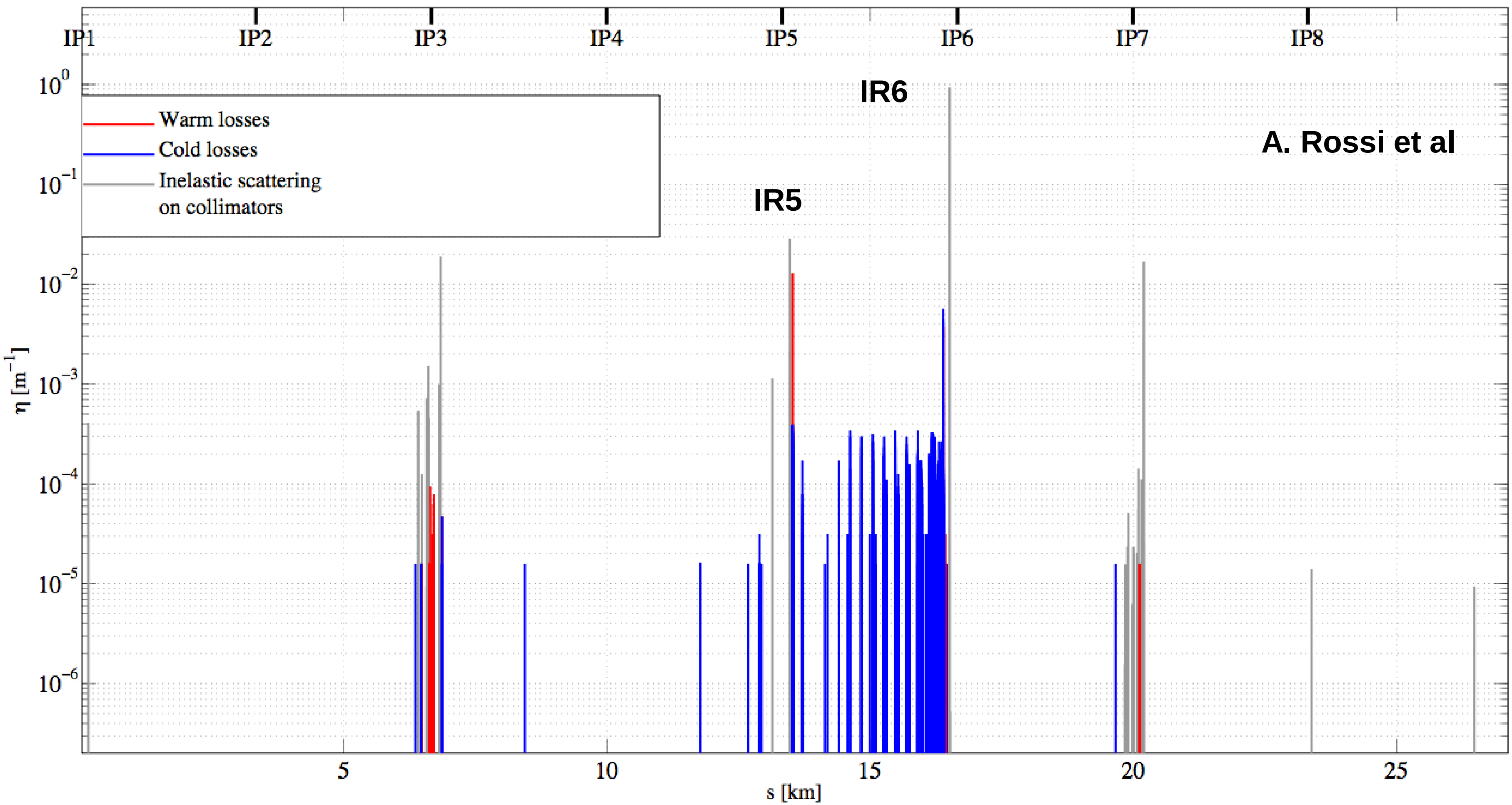
Simulation

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!

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)!