LHC Collimation Review 2013

May 30th-31st, 2013

CERN, Geneva, Switzerland

Introduction to dispersion suppressor collimation

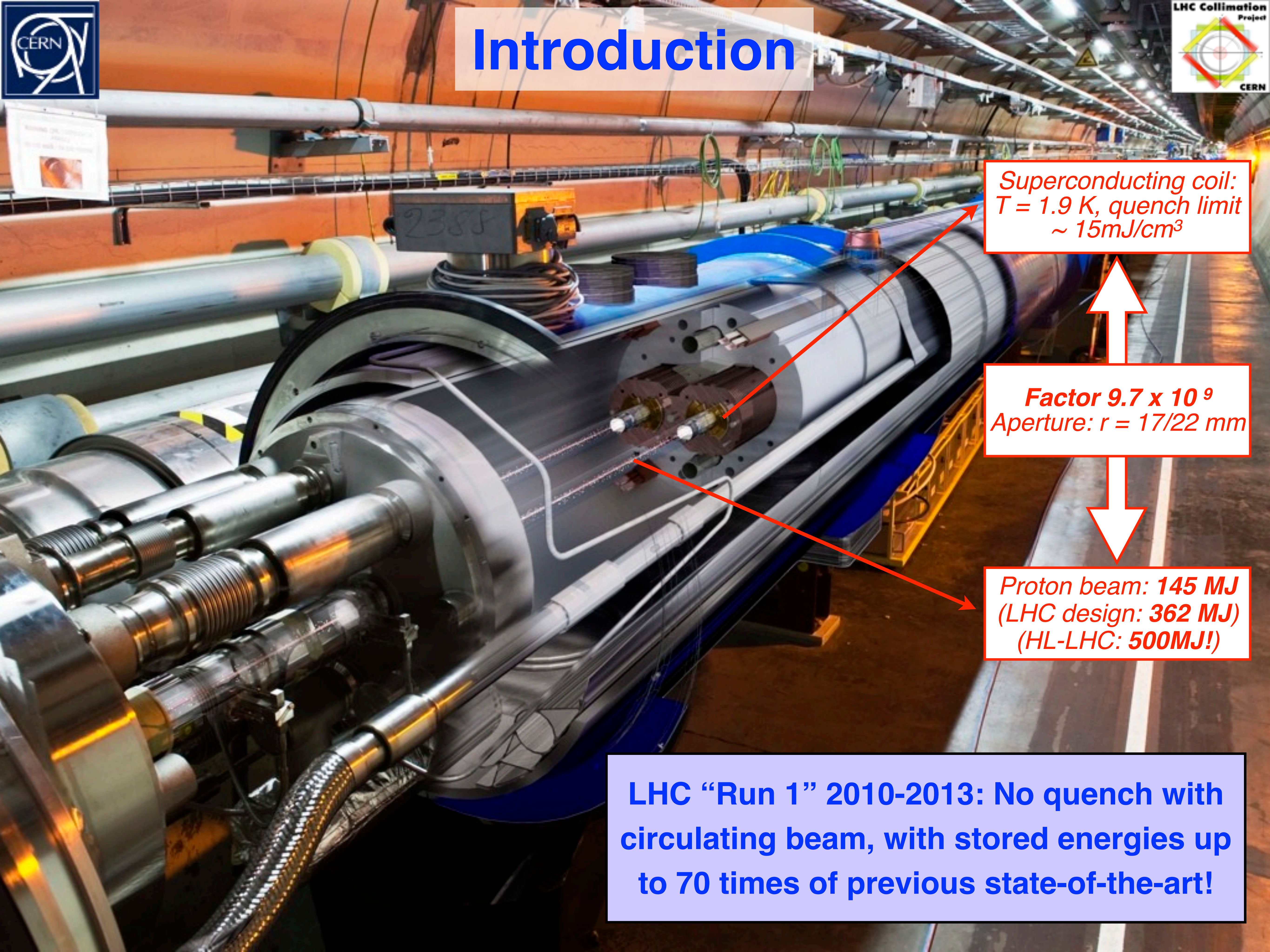
Stefano Redaelli for the collimation team

Inputs from: G. Arduini, R. Bruce, O. Brüning, F. Cerutti, J. Jowett, B. Salvachua, A. Verweij, and many other people.

Outline

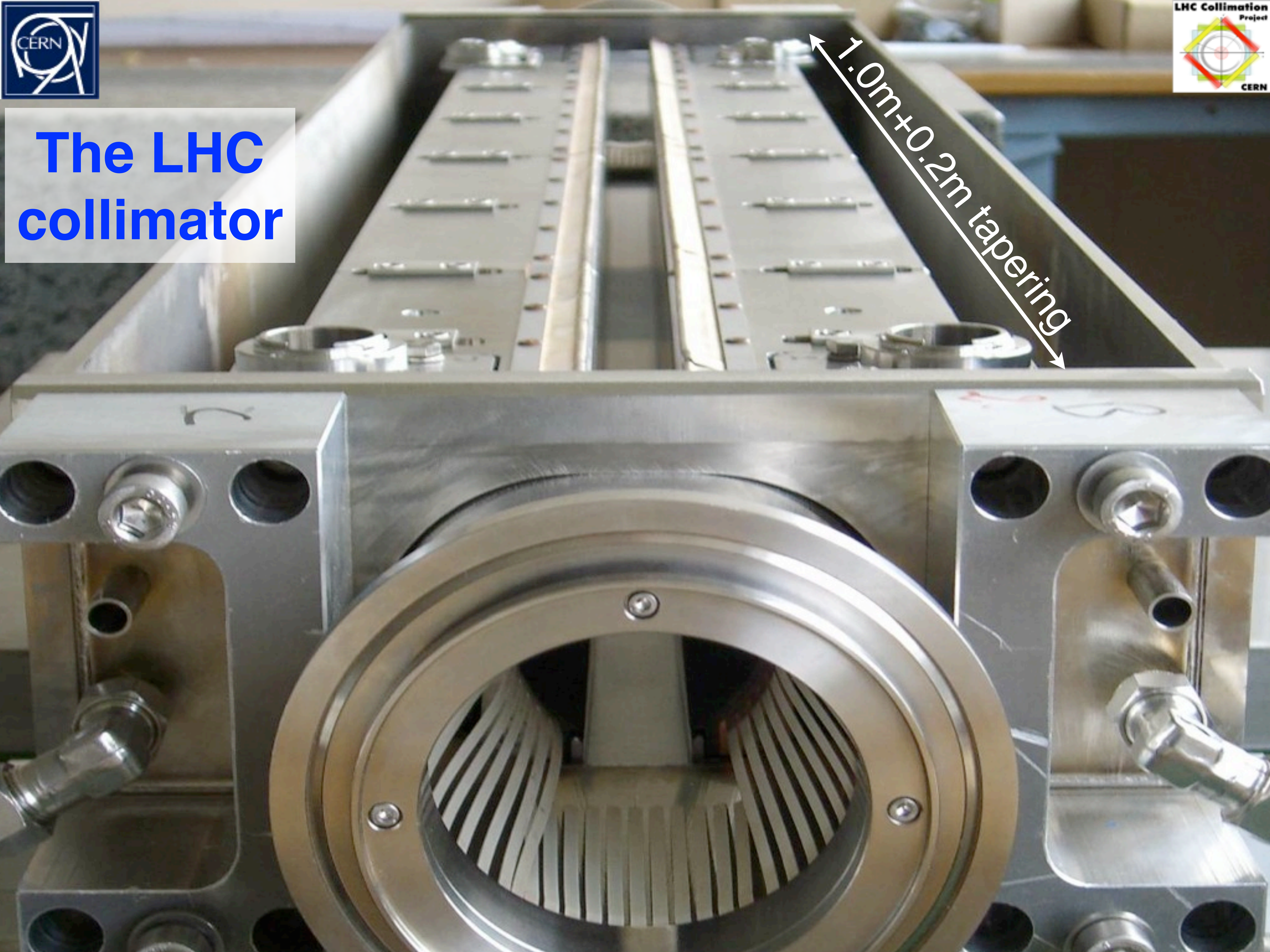
- Introduction
- Present LHC collimation
- DS collimation concept
- Scope of this review
- Ongoing LS1 upgrades
- Conclusions

Introduction



LHC "Run 1" 2010-2013: No quench with circulating beam, with stored energies up to 70 times of previous state-of-the-art!

The LHC collimator



Requirements to handle ~~360 MJ~~ 500MJ

Main **collimation challenges**:

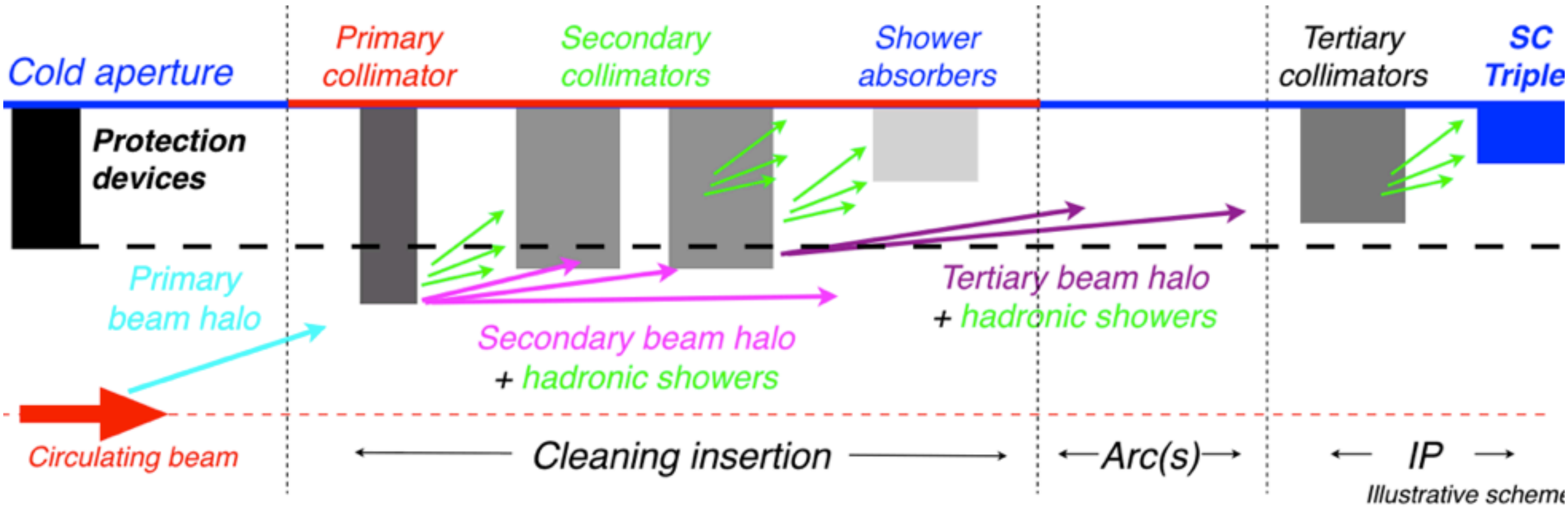
- **High stored energy**: Collimators needed in **all phases** *(inj., ramp, squeeze, physics);* Function-driven controls of jaw positions mandatory; **Robustness** and **cleaning efficiency**; Big and **distributed** system (100 collimators).
- **Small gaps**: Mechanical **precision**, **reproducibility**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

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

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

R. Assmann et al. (2003)

Multi-stage cleaning at the LHC



- Based on “bulk” amorphous jaws. Different materials: CFC, W, Cu, graphite.
- The **multi-stage collimation** keeps leakage to sensitive equipment at safe levels.
- Define of local collimation **cleaning inefficiency**: $\eta_c = \Delta N_{lost} / N_{abs} * 1 / \Delta s$

  Approximated in measurements by ratio of BLM signals to losses at primaries.
- Cold magnets: must stay below their quench limit.

  Cold losses, $\eta_c * N_{tot} / \tau_b$, in case of bad beam lifetime (τ_b) must be below quench limit R_q
- Other important role of the collimation system: minimize radiation doses to equipment.
- Minimize radiation doses on warm magnets in IR3/7 [*not discusses in this review*].
- Robust system providing excellent passive protection in case of failures.

Present LHC collimation layout

Two warm cleaning insertions, 3 collimation planes

- **IR3: Momentum cleaning**
  - **1 primary (H)**
  - **4 secondary (H)**
  - **4 shower abs. (H,V)**
- **IR7: Betatron cleaning**
  - **3 primary (H,V,S)**
  - **11 secondary (H,V,S)**
  - **5 shower abs. (H,V)**

Local cleaning at triplets

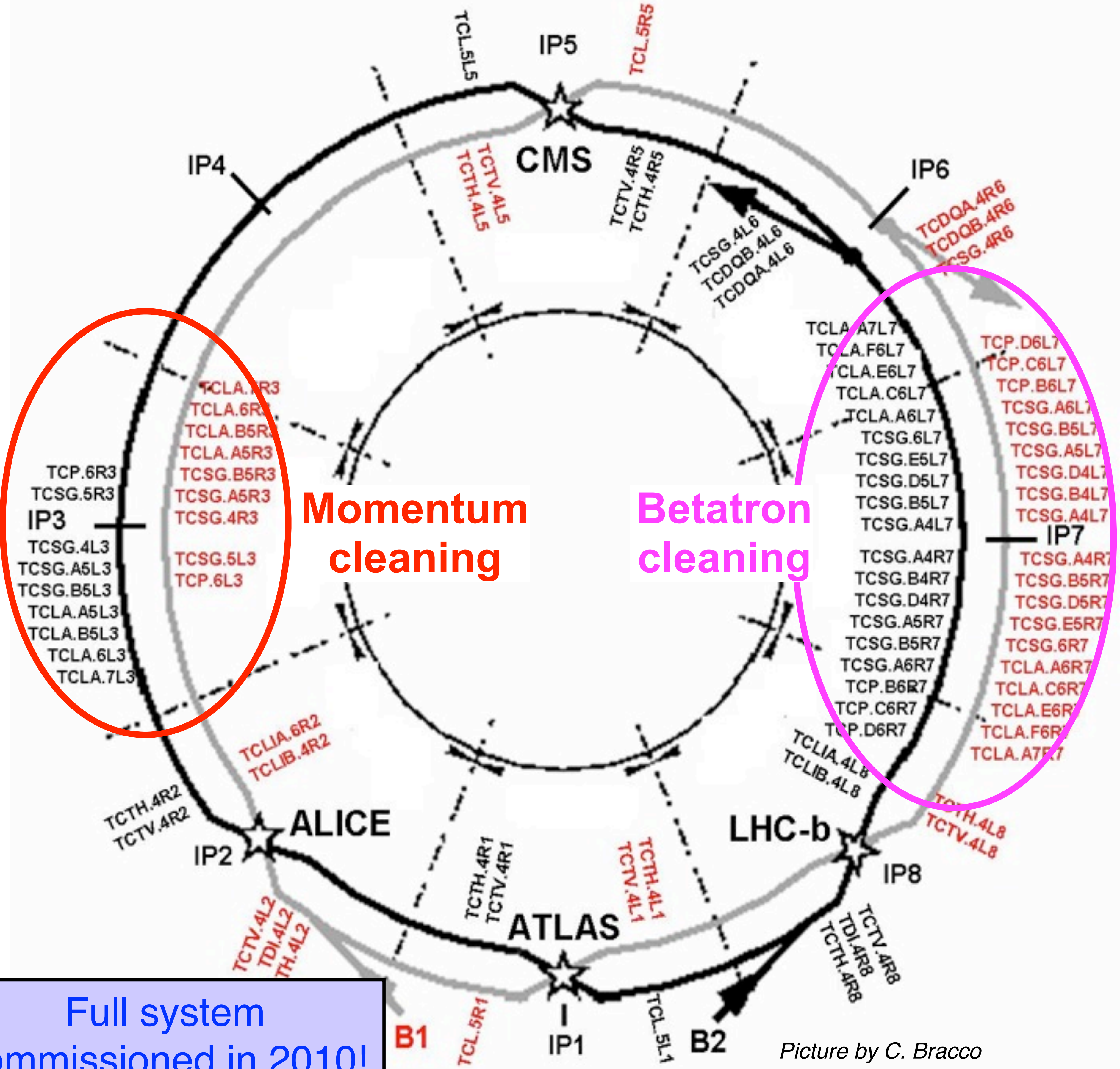
- **8 tertiary (2 per IP)**

Passive absorbers for warm magnets

Physics debris absorbers

Transfer lines (13 collimators)
Injection and dump protection (10)

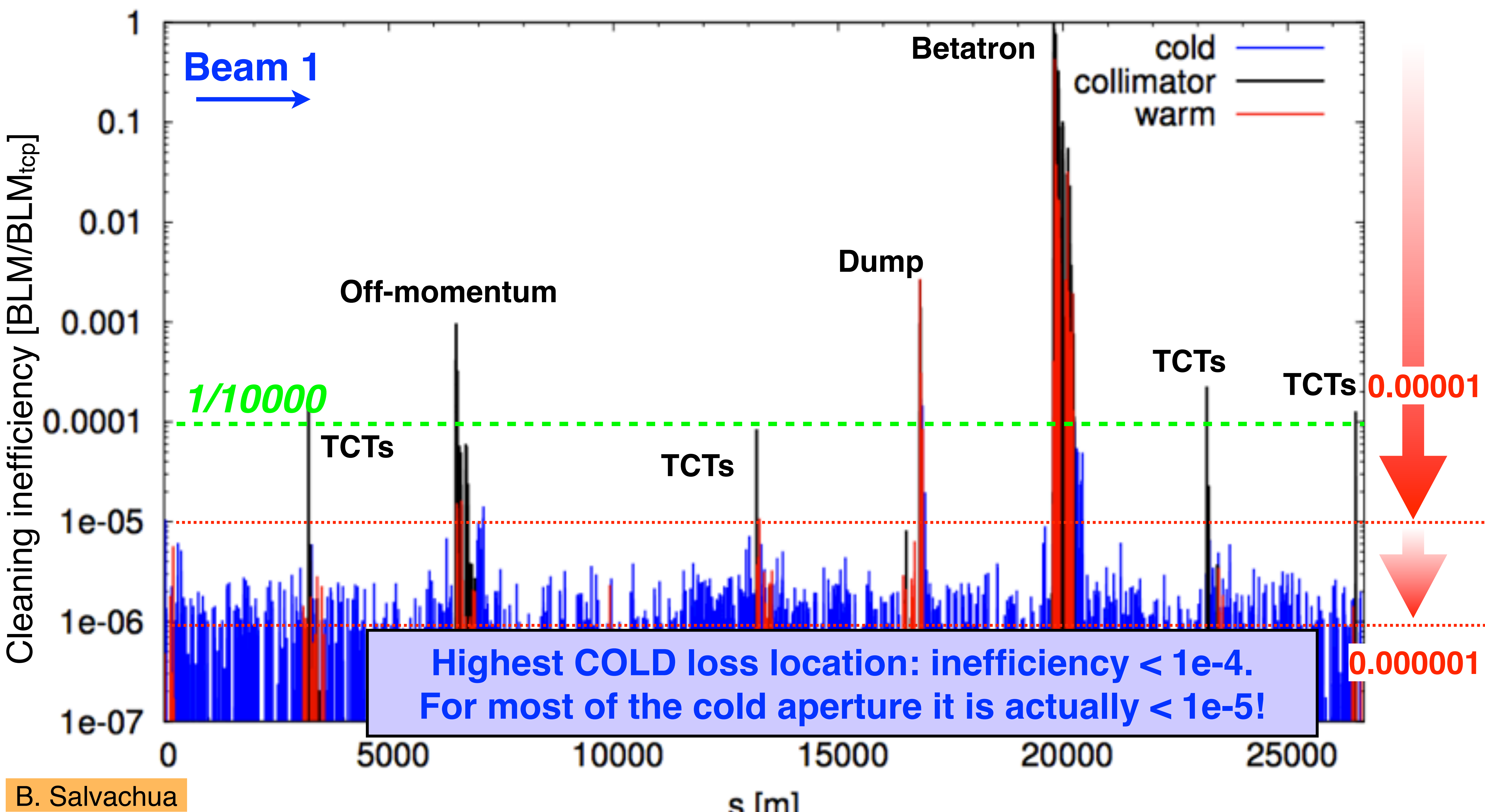
Total of 108 collimators (100 movable). Two jaws (4 motors) per collimator!



Picture by C. Bracco

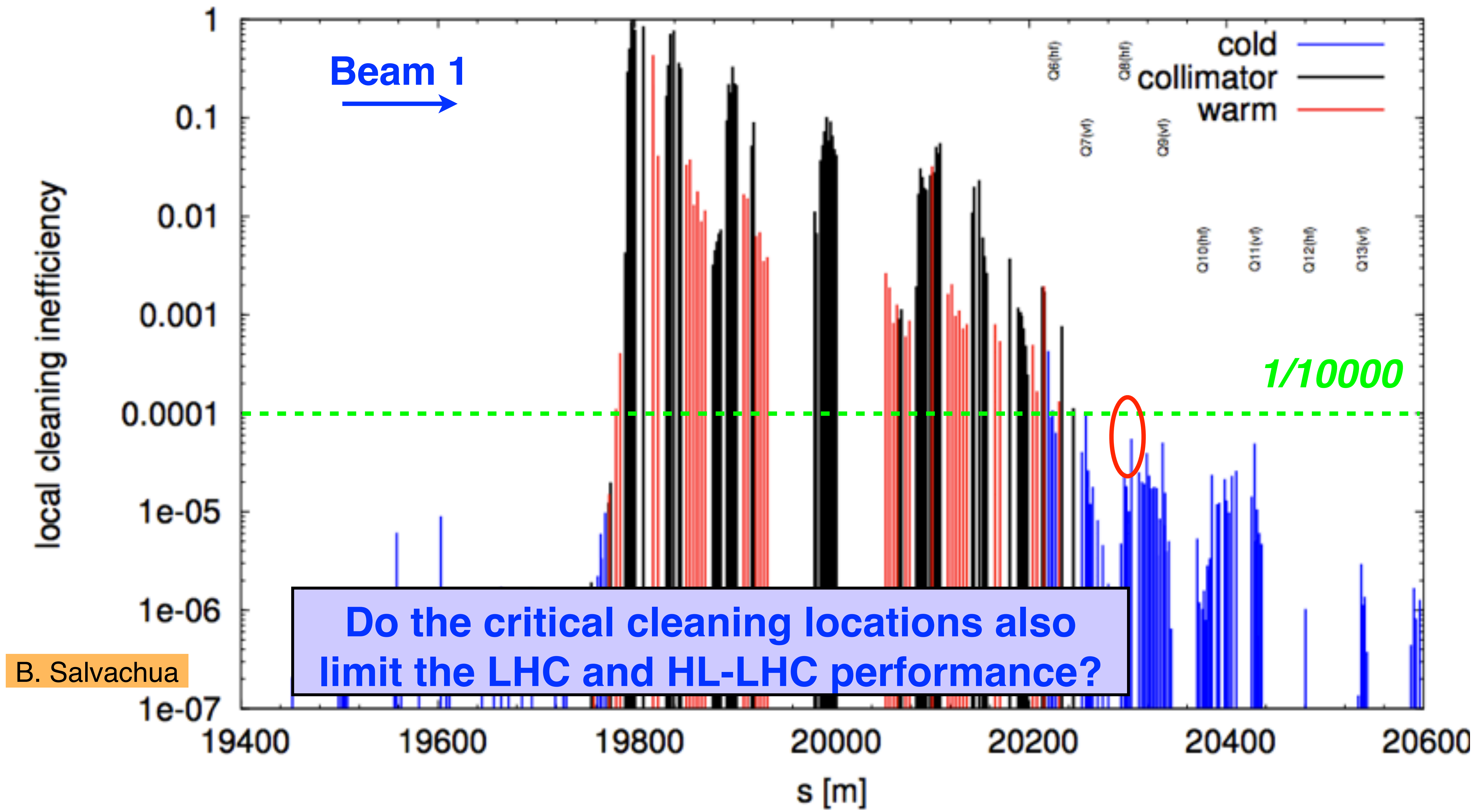
Full system commissioned in 2010!

Collimation cleaning at 4 TeV (β^*=60cm)



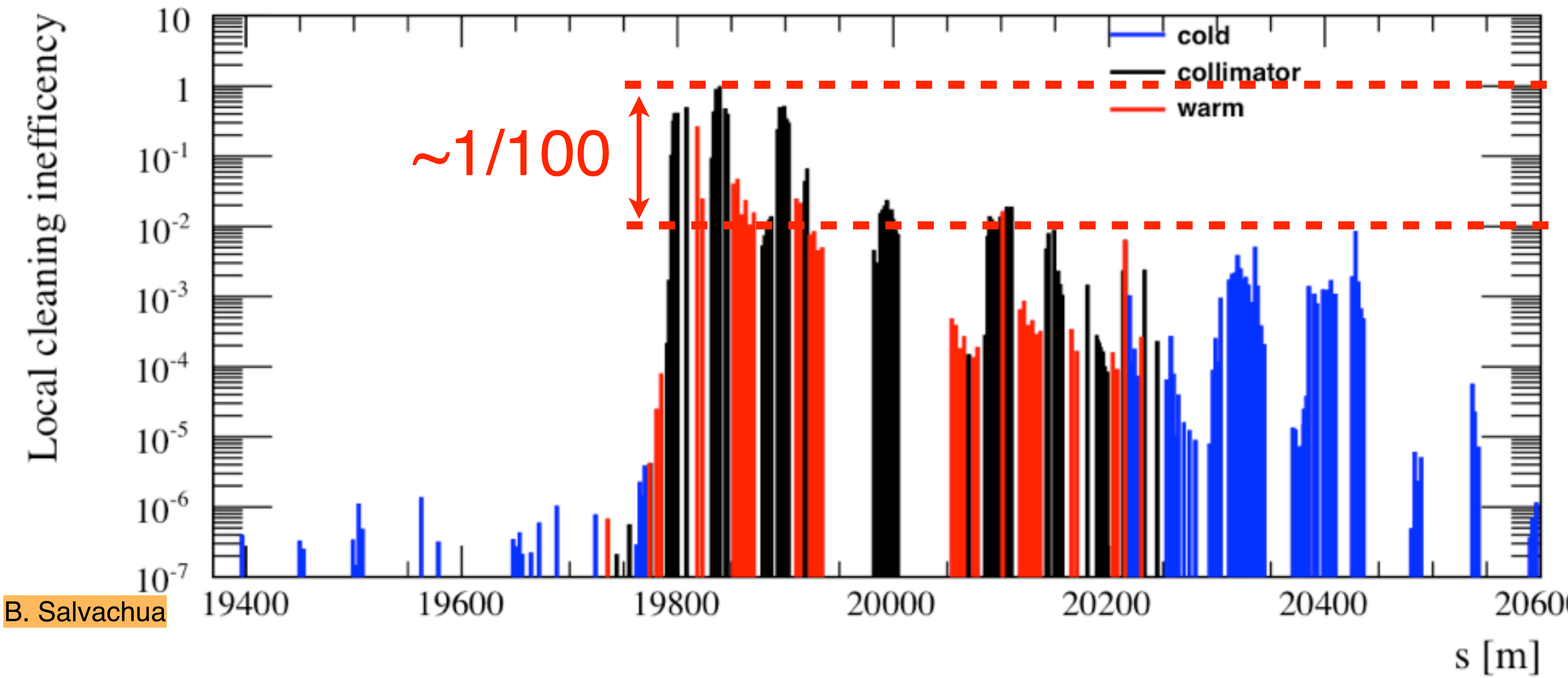
2012-13: "tight" collimator settings (TCP gaps as at 7 TeV) for higher beta*!
60 cm for protons, 80cm for ions.

Loss maps in IR7



Critical location (both beams): losses in the dispersion suppressor (highest at the Q8) from single diffractive interactions with the primary collimators. No other significant limitation have been observed so far from collimation cleaning.

Betatron cleaning with Lead ions



B. Salvachua

Experience at 4 TeV with Pb-p beams confirmed the results at 3.5 TeV:
IR7 cleaning in the order of **a few percents** for ion beams!

Present collimation not optimized for ions!

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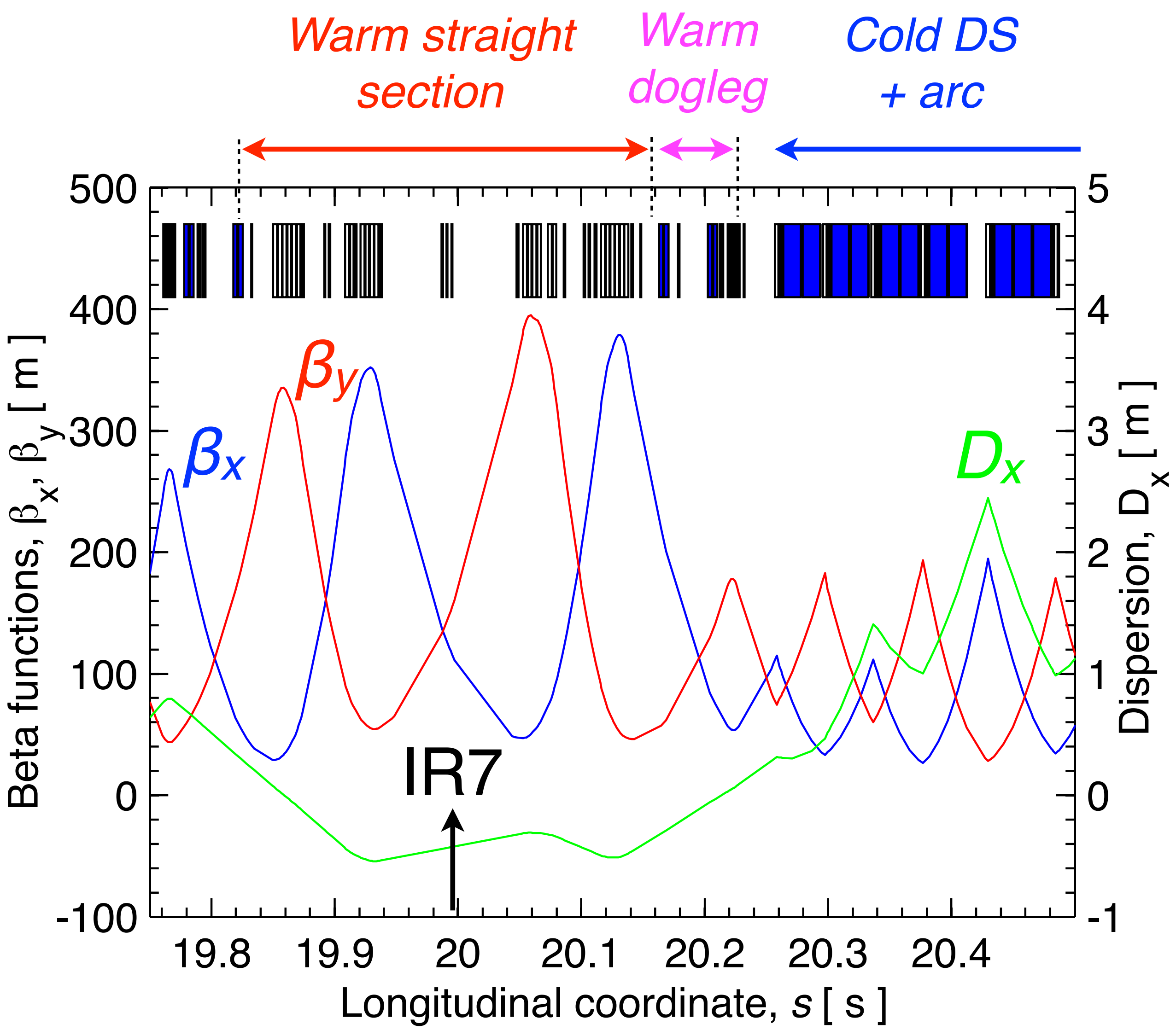
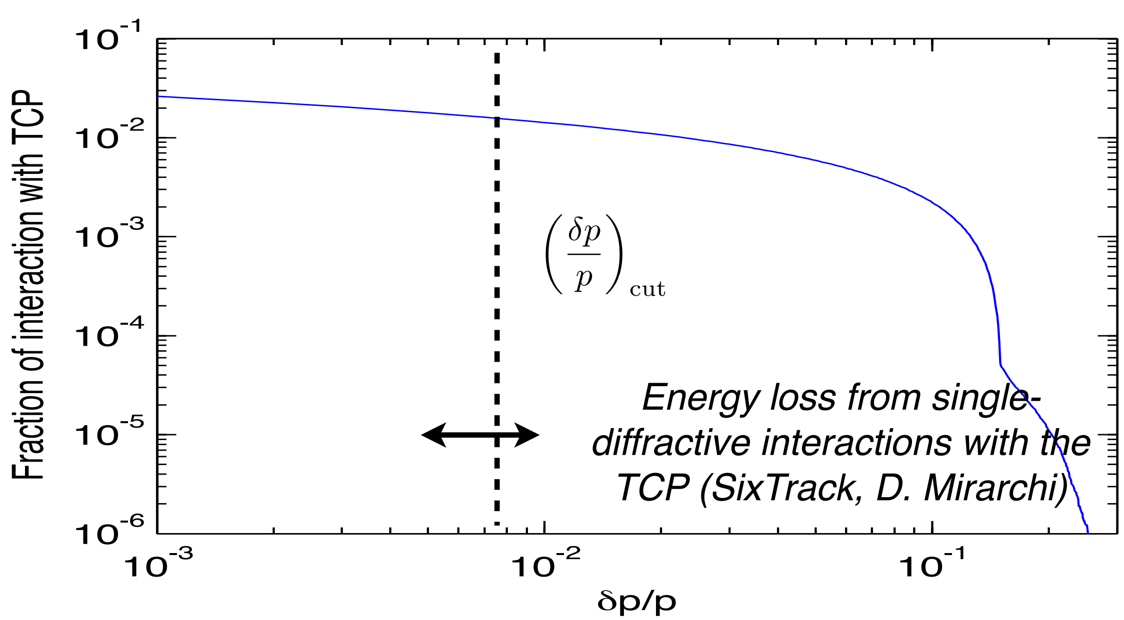
Dispersion suppressor losses



- Particles that **change rigidity** (e.g. lose energy) in a straight insertion are lost in the **dispersion suppressor** (DS): this is the first location with **high dispersion**.
- Cleaning insertions (IR3/7): proton mainly lose energy due to single-diffractive interactions with the primaries†.
- Experimental regions (IR1/2/5/8): protons lose energy in the collision process.
- Different **physics** for **ions**: similar qualitative behaviour due to rigidity change.
- Collimators are in the straight section: first dipoles in the DS act as **spectrometers**.
- No local protection available in the DS.



The present LHC collimation system cannot protect efficiently the DS!

This limitation predicted by simulations is confirmed by the operational experience (DS's are the highest cold loss locations).

† IR3: dispersion not zero but optimized to have TCP's as bottleneck -> same problem

DS limitation (1): halo cleaning

Minimum (assumed) beam lifetime

Quench limit of SC magnets

LHC total intensity reach from collimation

$$\boxed{N_{\rm tot} = \frac{\tau R_q}{\tilde{\eta}_c}}$$

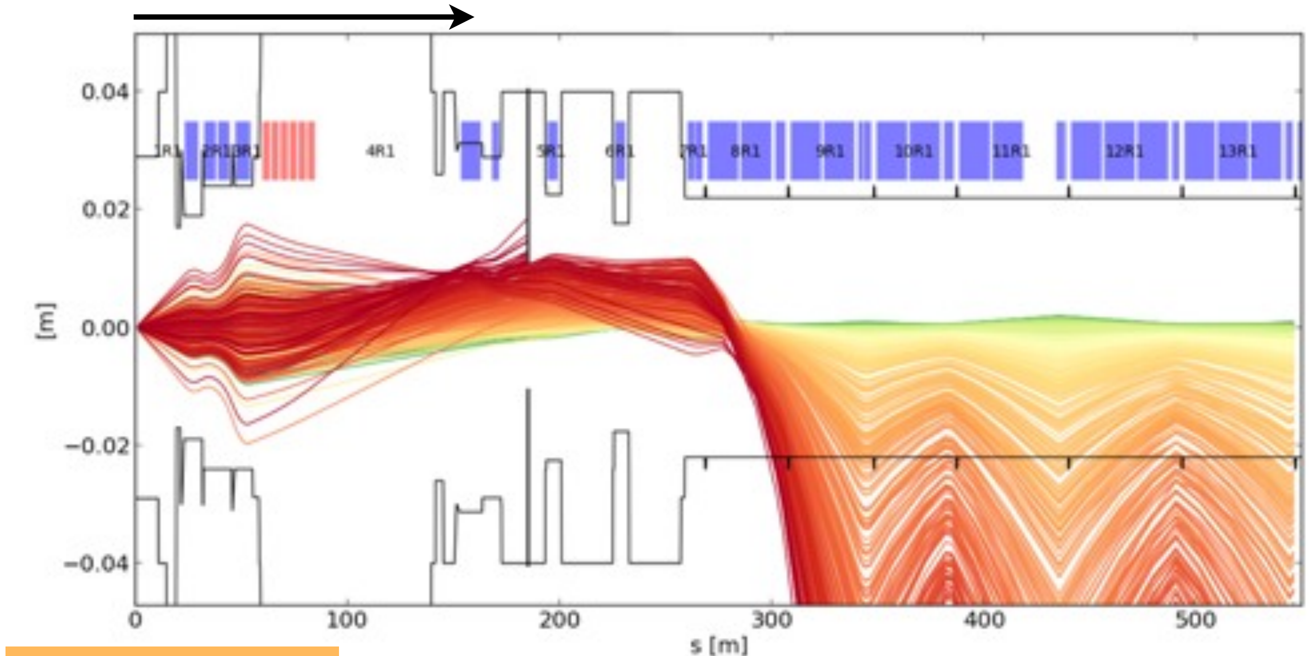
Collimation cleaning at limiting cold location

- 7 TeV extrapolations are scaled from **measurements** of achieved losses in dedicated quench tests and **measured and simulated** collimation cleaning.
  - *- Important: uncertainty on beam lifetime at higher energies.*
- **7 TeV** intensity reach: **<u>9.9 x 10^{14} p</u> for minimum lifetime of 0.2h**
  - *- This is about **3 times nominal** (1.15e11/bunch); **1.5 times HL-LHC** (2.2e11/b)*
  - *- Assumes tight settings and "pessimistic" lifetime from observations in 2012*
  - *- More realistic lifetime assumptions: 0.5-1.0 h (best beam) give more margin!*
  - *- Next talks: quench limits, lifetime, interplay stability/beta*/**number of dumps***
- **No new inputs for ion operation:** a quench tests could not be performed!
  - *- See talk by J. Jowett.*
- With the given **uncertainties,** it is important to keep the option to assess these assumptions with **operational experience** at energies close to 7 TeV.

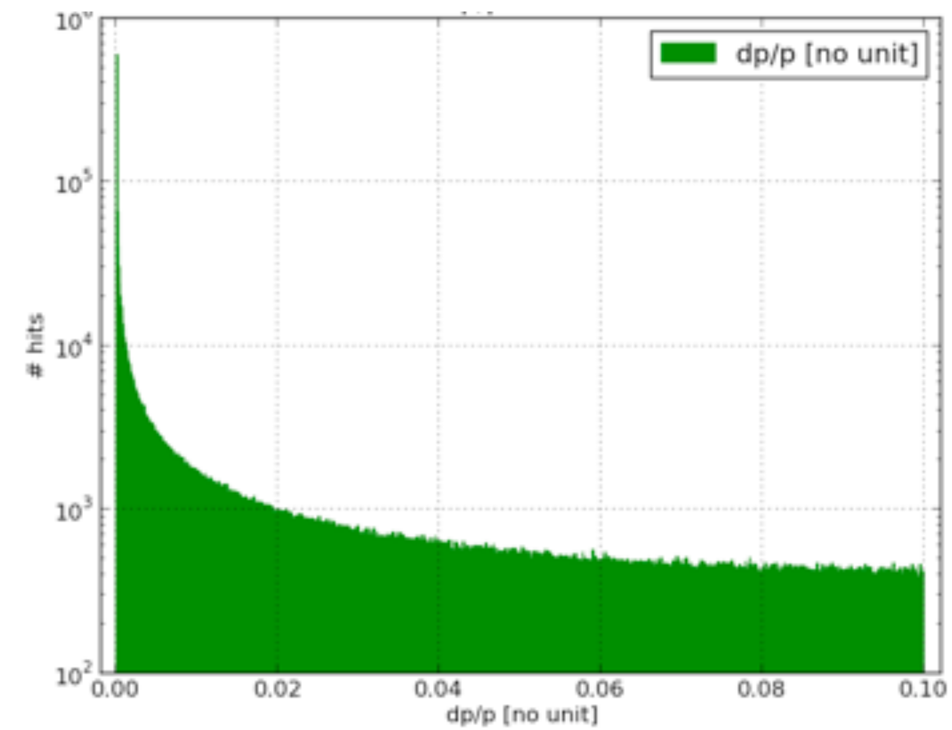
Need feedback from the review:
Safety factors appropriate?
Correct assumptions on lifetime?

DS limitation (2): physics debris

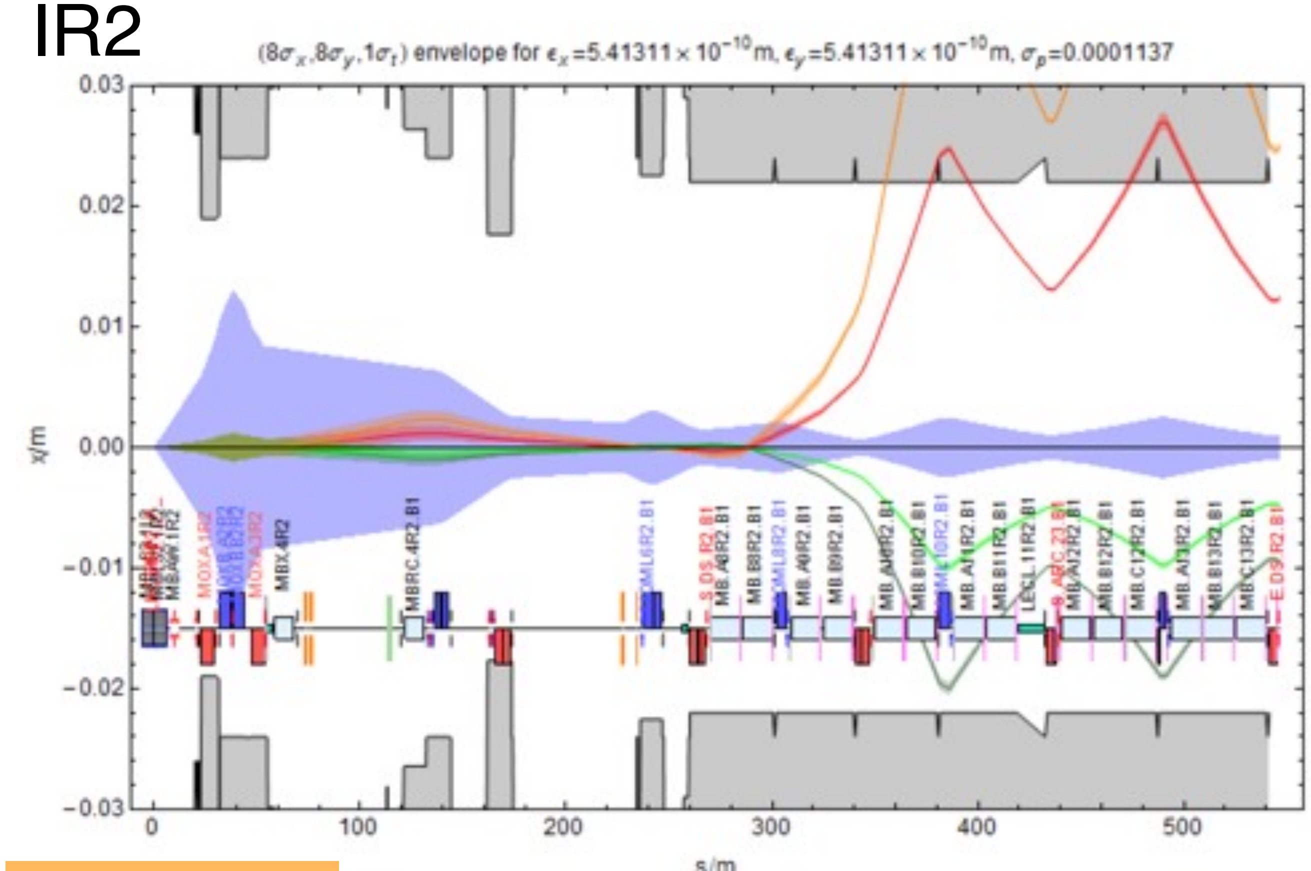
IR1



Talk A. Marsili



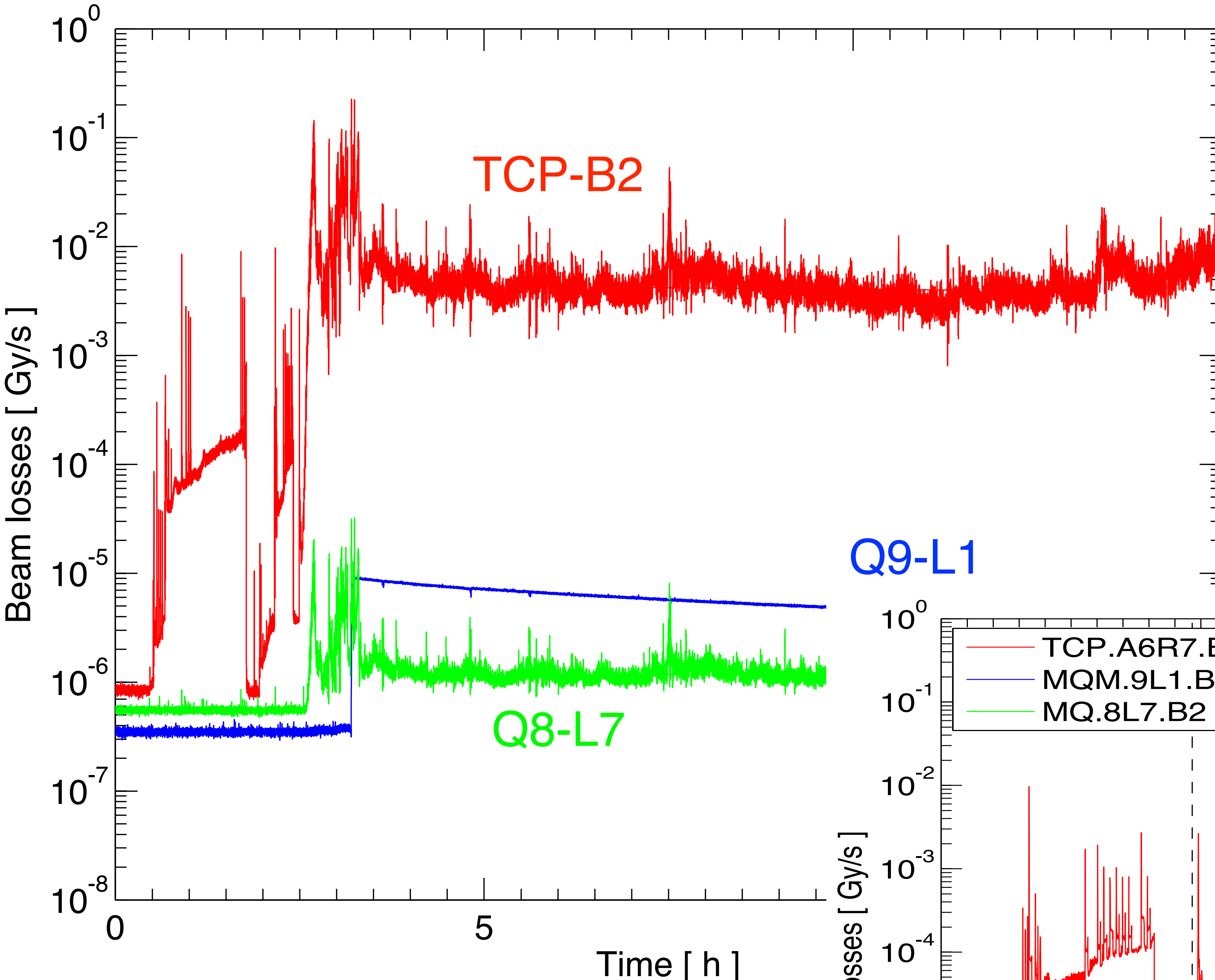
IR2



Talk J. Jowett

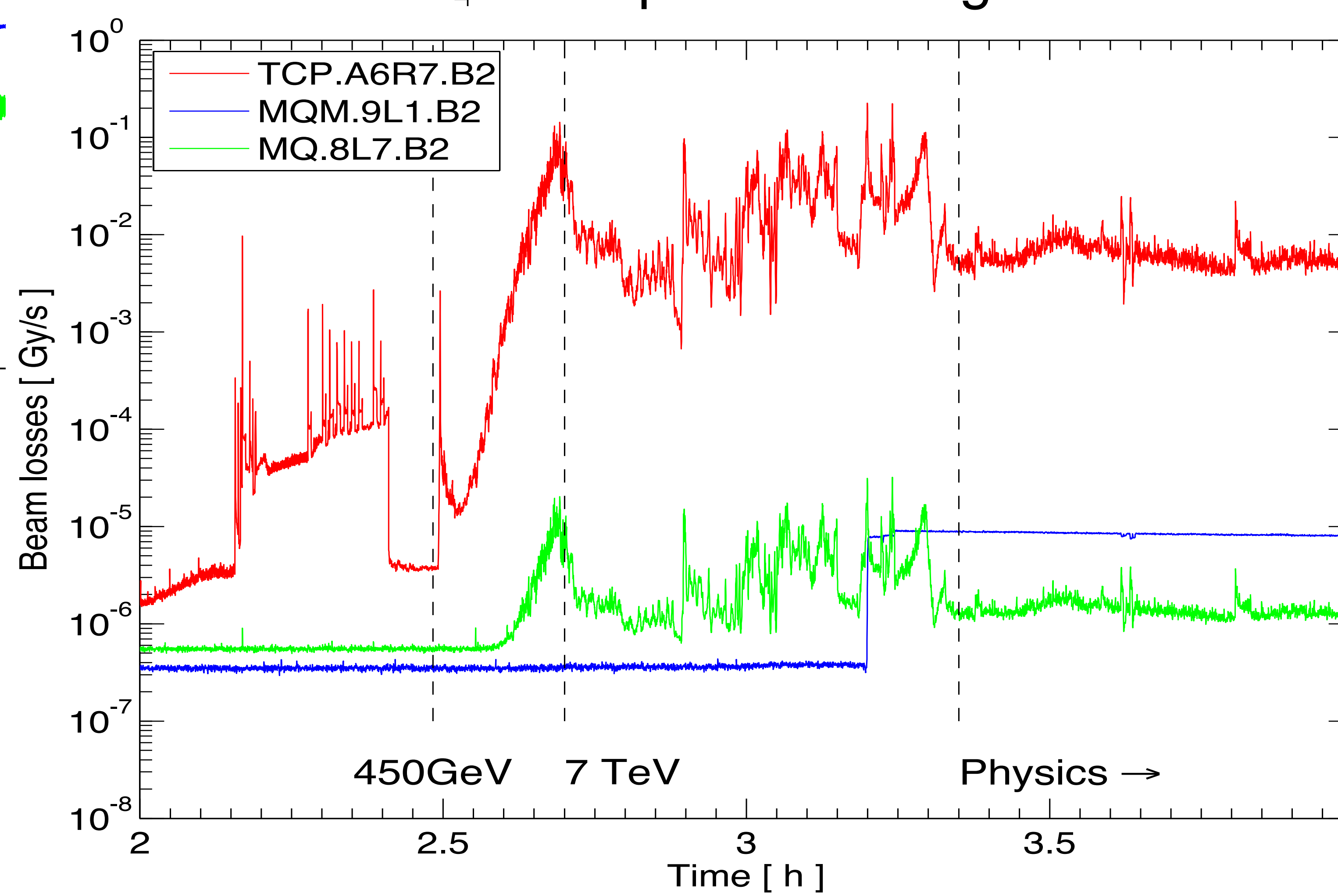
- Losses seen in the whole experimental insertion and DS from collision products.
- IR1/5 (high luminosity): concerns for matching quadrupoles, Q5 in particular.
- Possible concerns: **peak DS losses** when establishing collisions as well as **total doses** due to long physics runs.
- Different pattern for proton and ions - details in talks by A. Marsili and J. Jowett.

Comment on losses during the cycle



Our present understanding:

- Quenches in the cleaning insertions (e.g., IR7 DS) depends on total beam intensity;
- Quenches in the experimental regions' DSs depend on peak luminosity;
- Radiation doses in all IRs depend on integrated luminosity.

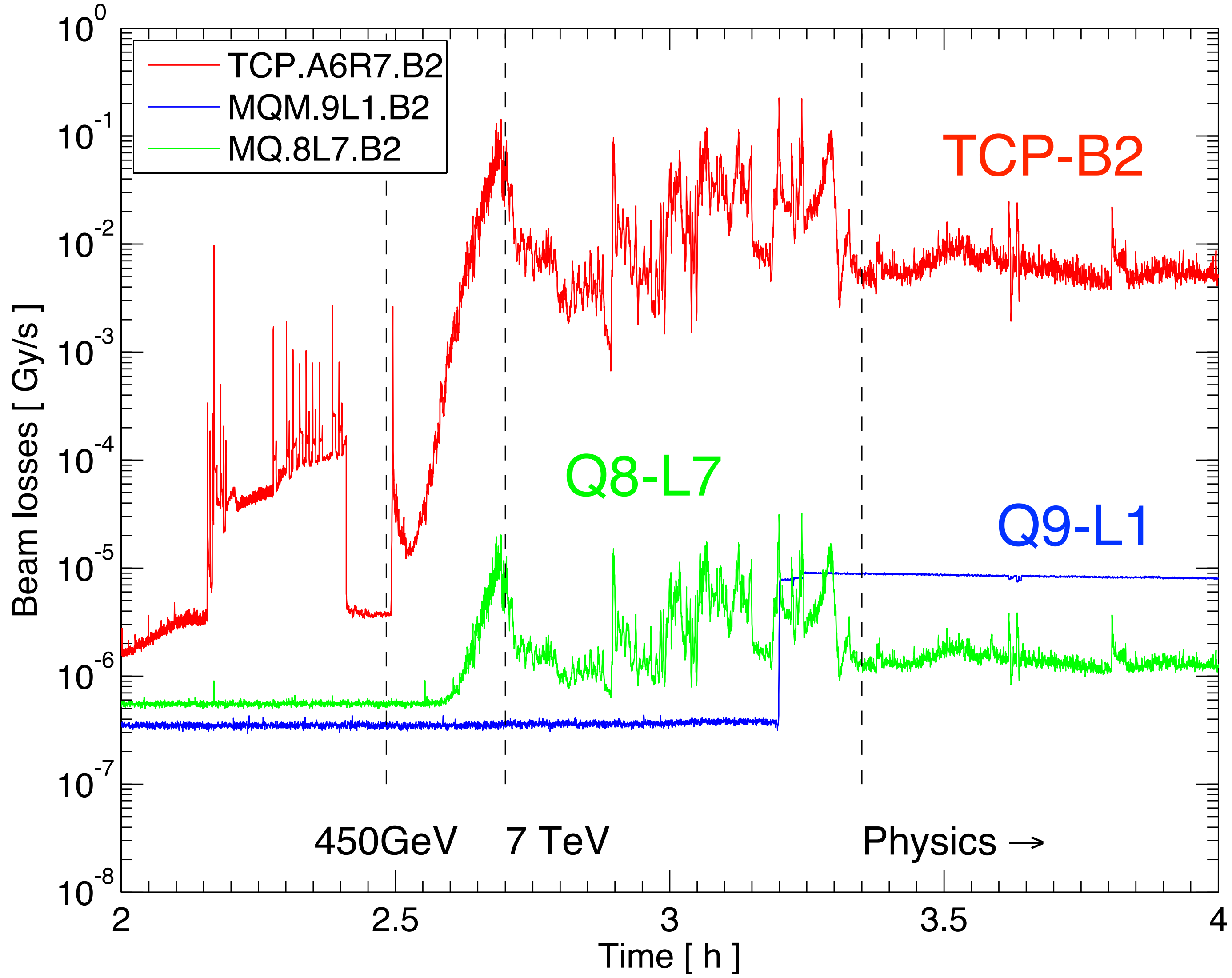


See losses in a typical cycle (F3202, L=7e^{33}cm^{-2}s^{-1}, I~2.2e^{14}p): loss spikes during setup (injection, ramp, squeeze, collision setup).

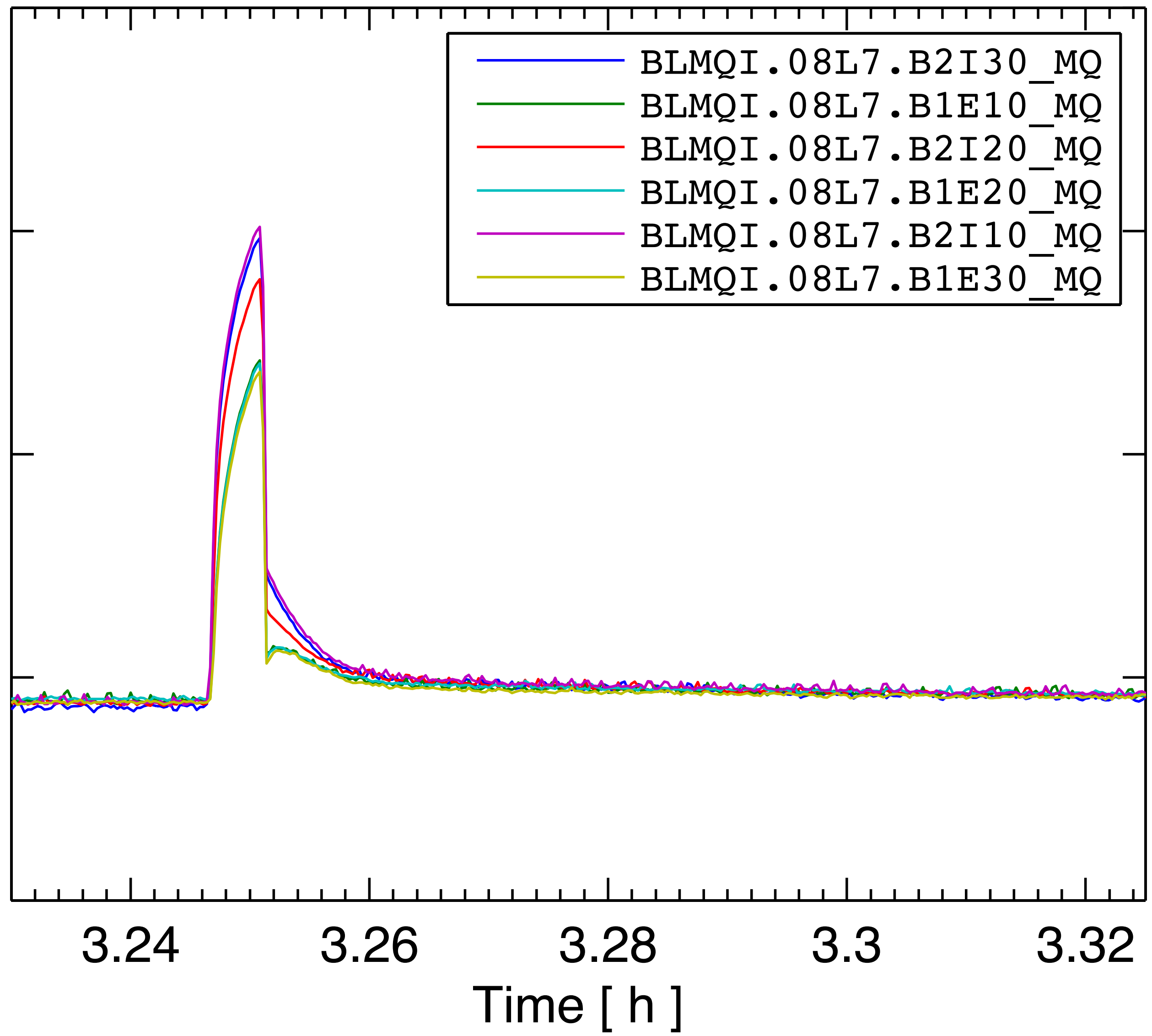
Loss at a TCP and at two limiting cold locations in IR7 and IR1.

Comparison to peak losses during 4 TeV quench tests (without quench)

Losses in a typical cycle



Achieved losses in Q8-L7 during quench test!



Summary of DS collimation needs

Scope of this review!

"Dynamic" table that might evolve during this review...		**Until HL-LHC** (before LS3) [$L=2.5\times10^{34}cm^{-2}s^{-1}$, $I_{tot}=3.2\times10^{14}p$]		**HL-LHC era** (after LS3) ($L=5\times10^{34}cm^{-2}s^{-1}$, $I_{tot}=6.2\times10^{14}p$)	
		Protons	Ions	Protons	Ions
IR7	Betatron cleaning	**Needed?**	**Needed?**	Needed? with or w/out ATS	Needed?
IR3	Momentum cleaning	Not needed	Not needed	Not needed	Not needed
IR1/5	ATLAS/CMS	Not needed	**Needed**	Needed? Updated layout	Needed?
IR2	ALICE	Not needed	**Needed**	Not needed	Needed?
IR8	LHCb	Not needed	Not operating	Not needed	Not operating

Complex parameter space that will be presented in the next talks.

Goal for the collimation project at this stage: we want to have solution available to address possible issues revealed by the operational experience at ~7 TeV. Decide then on which IR the priority should be put on.

Larger uncertainties for HL-LHC era, but more time to freeze layouts.

Do we have alternatives?

DS collimation solution poses important **technological challenges** but otherwise is a robust solution that provides the required cleaning (several talks on that). Local cleaning in DS works both for cleaning and experimental insertions!

Other possibilities exist on paper. Can they be ready for implementation in LS2?

Note that the **option to move magnets** (see later) **remains on the table**!

		Beam scraping / halo control	**Crystal collimation**
IR7	Betatron cleaning	Potentially yes.	Yes, on paper.
IR3	Momentum cleaning	Potentially yes.	Yes, on paper.
IR1/5	ATLAS/CMS	No	No
IR2			
IR8			

*These alternatives require **conceptual studies** and **beam tests** before being considered as a valuable alternative for LS2.*
*In additional, there is **no obvious cure** for the **experimental regions**.*
These ongoing studies are therefore not part on the review mandate.
Studies/beam test program ongoing for HL-LHC.

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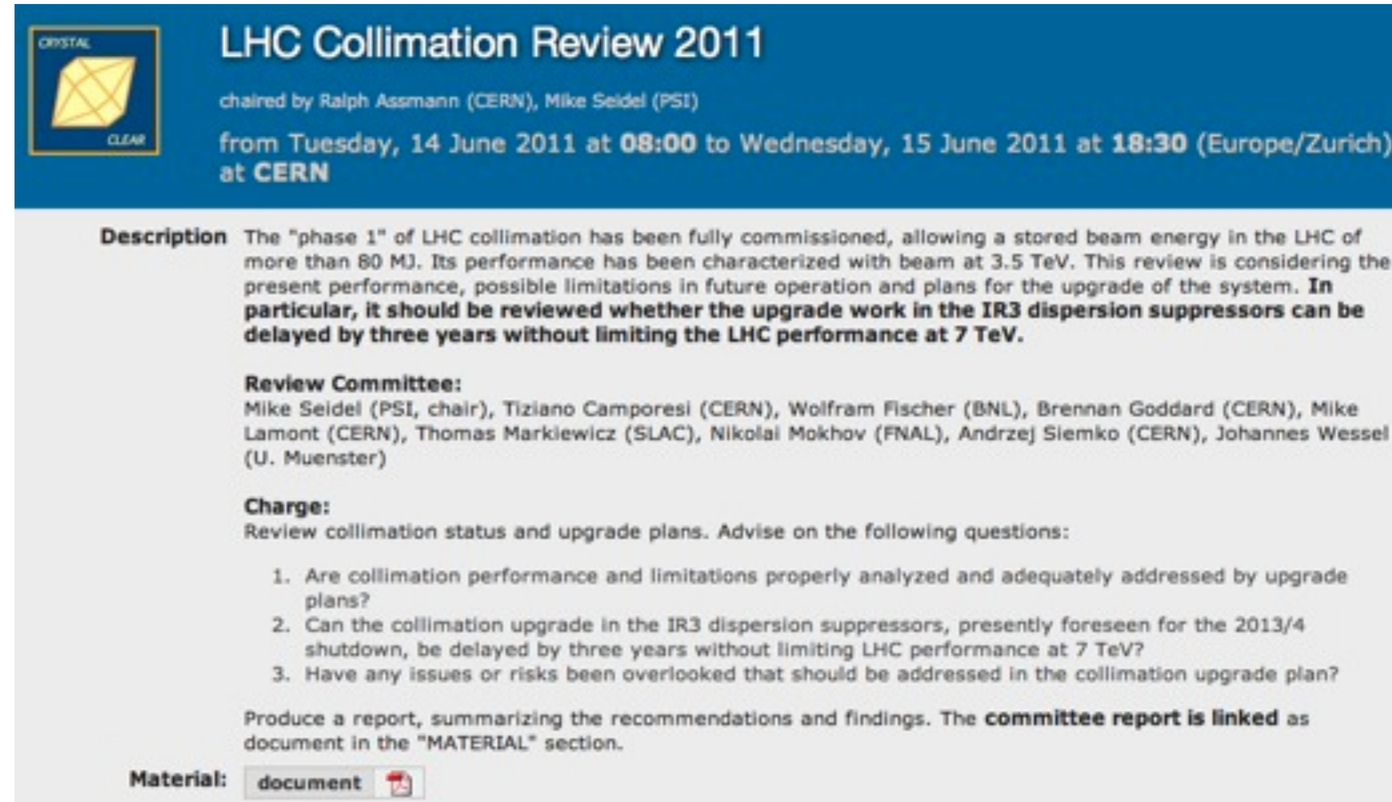
Baseline for DS collimation until 2011

- Concept of IR3 "combined cleaning":
  - 2 DS collimators in IR3
  - Add vertical secondaries to achieve betatron and momentum cleaning
- Cleaning not ideal but sufficient until LS2, IR7 upgrade would come later.
- Involved moving magnets between Q7 and Q11 at either side of IR3.
- Motivation: IR3 more radiation tolerant and DS easier to modify.


LHC Collimation Review 2011

chaired by Ralph Assmann (CERN), Mike Seidel (PSI)

from Tuesday, 14 June 2011 at **08:00** to Wednesday, 15 June 2011 at **18:30** (Europe/Zurich) at **CERN**

Description The "phase 1" of LHC collimation has been fully commissioned, allowing a stored beam energy in the LHC of more than 80 MJ. Its performance has been characterized with beam at 3.5 TeV. This review is considering the present performance, possible limitations in future operation and plans for the upgrade of the system. **In particular, it should be reviewed whether the upgrade work in the IR3 dispersion suppressors can be delayed by three years without limiting the LHC performance at 7 TeV.**

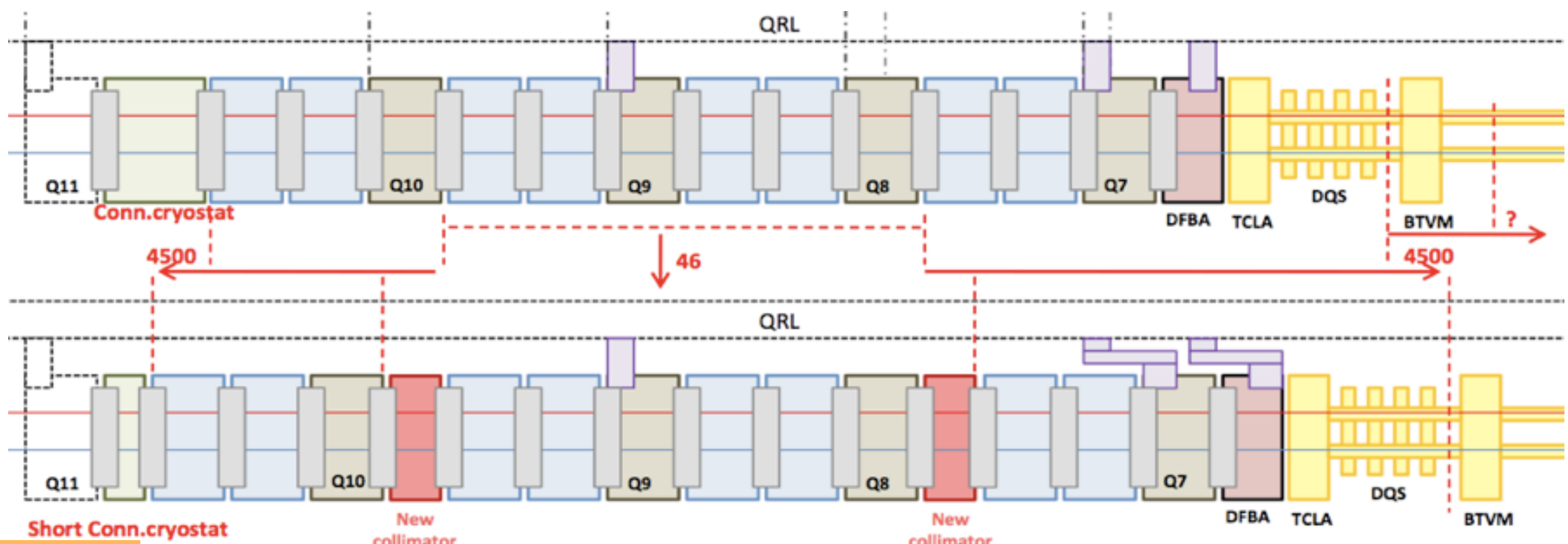
Review Committee:
Mike Seidel (PSI, chair), Tiziano Camporesi (CERN), Wolfram Fischer (BNL), Brennan Goddard (CERN), Mike Lamont (CERN), Thomas Markiewicz (SLAC), Nikolai Mokhov (FNAL), Andrzej Siemko (CERN), Johannes Wessel (U. Muenster)

Charge:
Review collimation status and upgrade plans. Advise on the following questions:

1. Are collimation performance and limitations properly analyzed and adequately addressed by upgrade plans?
2. Can the collimation upgrade in the IR3 dispersion suppressors, presently foreseen for the 2013/4 shutdown, be delayed by three years without limiting LHC performance at 7 TeV?
3. Have any issues or risks been overlooked that should be addressed in the collimation upgrade plan?

Produce a report, summarizing the recommendations and findings. The **committee report is linked** as document in the "MATERIAL" section.

Material: document



V. Parma *et al.*

Baseline for DS collimation until 2011

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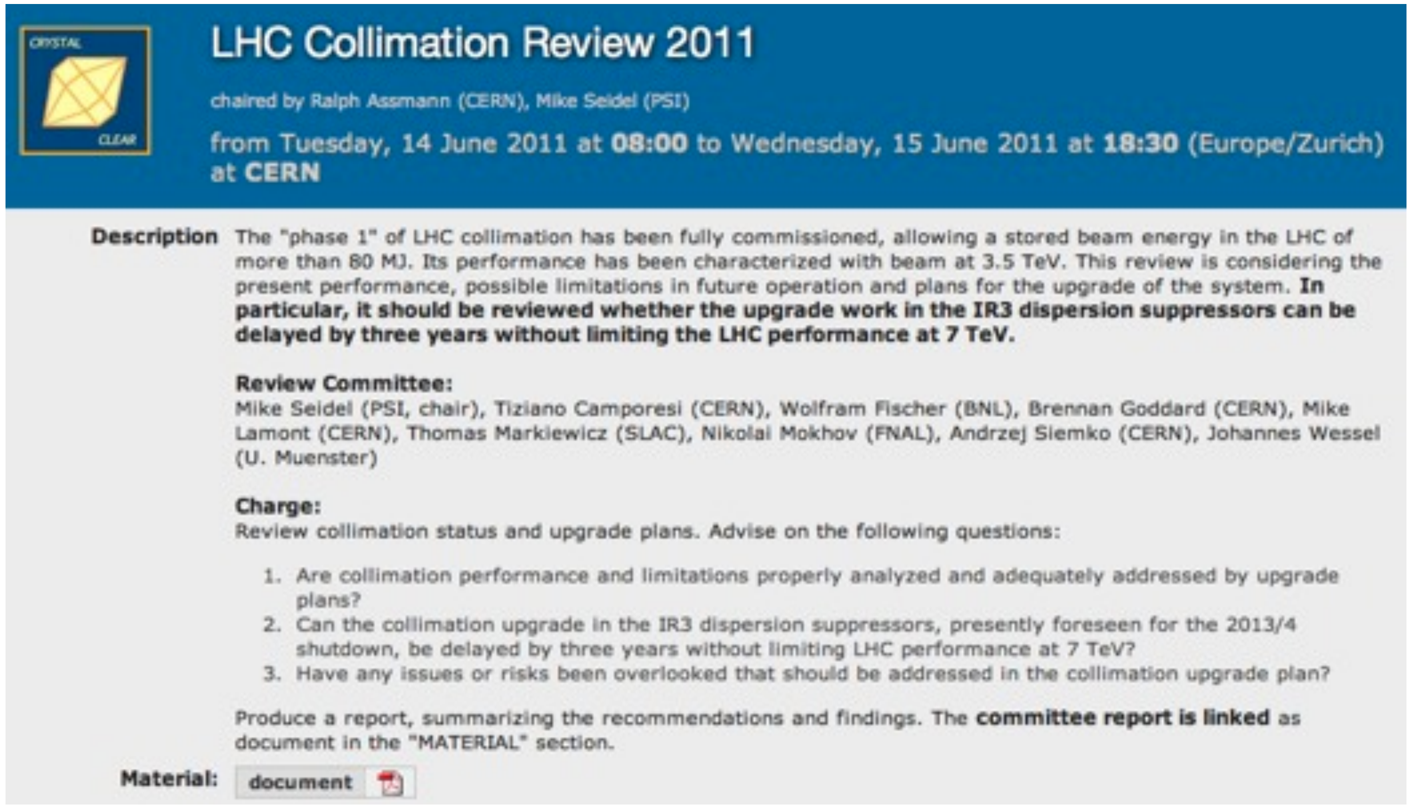
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- In 2011, following also the recommendation of the review, it was decided to postpone the important works for the IR3 combined system:
  Acceptably small risk of seeing performance limited between LS1 and LS2 compared to risk taken in changing layout
  Significant manpower involved for moving magnets
- Encouraged to prepare for implementation in LS2+, profiting of 11T dipole research
- Why another review now?

What has changed?

(only aspects relevant for DS collimation)

- More operational **experience**: could handle **140MJ** beams!
- Confirmed the collimation performance with “tight” settings, understand better the **hierarchy setting limits**.
  - *- More insight on the* ***interplay*** *between* ***β* reach*** *and* ***impedance limits***
- **New quench tests**: we raised the lower quench limit estimate
  - *- Still no quench with losses 3-10 times larger than 2011!*
- BUT: we experienced a **worsening of beam lifetime** for smaller β^* operation with tight collimator settings.
  - *- Lost more than a factor 20 compared to 2011;*
  - *- Now losses during whole cycle and not only when bringing beam in collision*
- The option of the temporary IR3 combined cleaning is dismissed. We consider instead one single solution for HL-LHC.
  - *- 11T dipoles would ease the implementation in IR7, if needed.*
  - *- IR7 will be more radiation tolerant thanks to electronic relocation - No talk scheduled on that unless requested by review panel!*
- Important experience on **IR debris cleaning** for protons
  - *- New TCL collimator layout proposed!*
- Decision on **warm** vs cold DS collimator made for LS2 timeline
- Planned **ALICE upgrade** for $6 \times 10^{27} cm^{-2} s^{-1}$

Scope and mandate

- ☑ I think that major decisions on the DS modification for high intensity proton operation should be taken after some **experience at 6.5-7 TeV**
- ☑ Can we decide now about implementation for **ion operation**?
- ☑ *What do we need to do in the next ~2 years in order to make sure that in 2015 we will have all the technical background to decide on the DS collimation, if needed?*
- ☑ Are there viable alternatives to the scheme based on the 11T dipoles?

LHC Collimation Review 2013

chaired by Mike Seidel (PSI)

from Thursday, 30 May 2013 at **08:30** to Friday, 31 May 2013 at **18:00** (Europe/Zurich)
at **CERN (30-7-018 - Kjell Johnsen Auditorium)**

Description

Introduction:
In the frame of the LHC upgrades towards the High Luminosity LHC (HL-LHC), the improvement of the LHC collimation system is a critical aspect. The review has the main scope of assessing the needs of new collimators in the LHC cold dispersion suppressors for the operation beyond LS2.

Charge of the review panel:
The committee should look into the various aspects of the presented upgrade baseline and advise in particular on the need to pursue R&D on 11T dipoles for a possible installation in the LHC for LS2.

- Are the assumptions for performance reach estimates appropriate and adequately addressed?
- Is the present upgrade strategy appropriate in view of being able to take a decision in 2015?
- Is there any aspect that has been overlooked?

A final report should be produced and delivered to Steve Myers and Stefano Redaelli.

Review panel:
Mike Seidel (PSI, Chair), Giorgio Apollinari (FNAL), Wolfram Fischer (BNL), Marzio Nessi (ATLAS), Rudiger Schmidt (CERN/ESS), Carsten Omet (GSI).

Material: notes

A look at the program

Three main sessions:

S1. Introduction and review scope

The HL-LHC timeline - L. Rossi
Introduction to DS collimation - S. Redaelli
Present LHC collimator - R. Losito

S2. Estimated performance reach at > 6.5 TeV

Cleaning performance - B. Salvachua
Setting limits and beta reach - R. Bruce*
Impedance - N. Mounet
Collimation cleaning with ATS optics for HL-LHC - A. Marsili
DS collimation for heavy-ion operation - J. Jowett
Energy deposition simulations for quench tests - E. Skordis
Quench limits: extrapolation of quench tests to 7 TeV - A. Verweij
Overview of quench limits for faster time ranges - M. Sapinski

S4. Status of DS collimation implementation

What do we need to decide now to have Nb3Sn dipo
Status of 11T dipole program - M. Karppinen
Cryogenics design choices and integration issues - V
Status of the TCLD collimator design - A. Bertarelli
Heat load scenarios and protection levels for ions - G

- ☑ Outlook of HL-LHC collimation studies in one single talk in S4
- ☑ "Social" program: Visit of collimation workshops on Wed. and review dinner on Thu.

Many thanks to Julia D. for the help in the organization! Feel free to contact her, Lucio or myself in case of any issue!

Many thanks to all speakers!

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Collimation operational experience

- **Very good performance** of the collimation system so far (up to 140MJ):
  - *- Validated all critical design choices (HW, SW, interlocking, ...);*
  - *- Cleaning close to simulations and ok for operation after LS1;*
  - *- We learned that we can rely on the machine stability!*
  - *- Established and improved semi-automatic alignment tools;*
  - *- Performance estimates based on 2011 quench tests - to be reviewed at the end of 2012.*
- The present LHC collimation **cannot protect** the cold dispersion suppressors.
  - *- Critical locations with present layout: IR7, IR1/5, IR2 (ions).*
  - *- Investigations ongoing on limitations from quench and magnet lifetime.*
- The collimators determine the **LHC impedance**
  - *- Rich program on "dream" materials and new collimator concepts.*

LS1

- Collimation alignments and validation of new setting are **time-consuming**.
- The **operation flexibility** in the experimental regions (VdM scans, spectrometer polarity changes, β* leveling, ...) is affected by collimation constraints.
- The **β^* reach** is determined by collimation constraints: retraction between beam dump and horizontal TCTs which are not robust.
- Collimator handling in **radiation environment** will be challenging.

LHC collimation after LS1

- The 16 Tungsten TCTs (industrial production) in all IRs and the 2 Carbon TCSGs in IR6 (in-house production) will be replaced by new collimators with integrated BPMs.

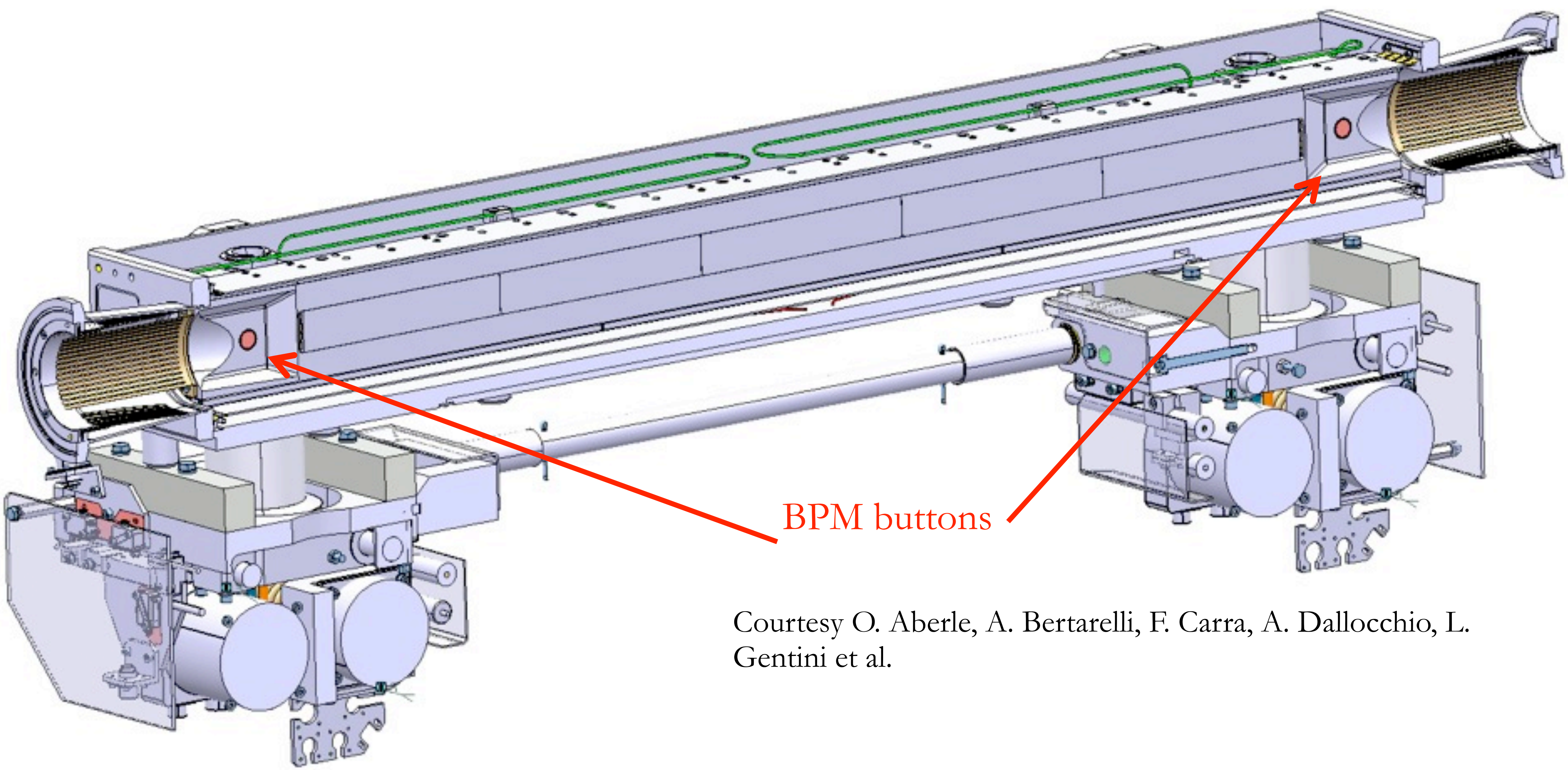
  Tests in the SPS with mock-up collimator very successful

  Gain: can re-align dynamically during standard fills. No need for special low-intensity fills

  → Drastically reduced setup time (gain of a factor ~100) => more flexibility in IR configurations

  → Improved monitoring of TCT centres in the IRs (reduce validation time)!

  → Reduced orbit margins in cleaning hierarchy => more room to squeeze β^* *(see R. Bruce's talk)*



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

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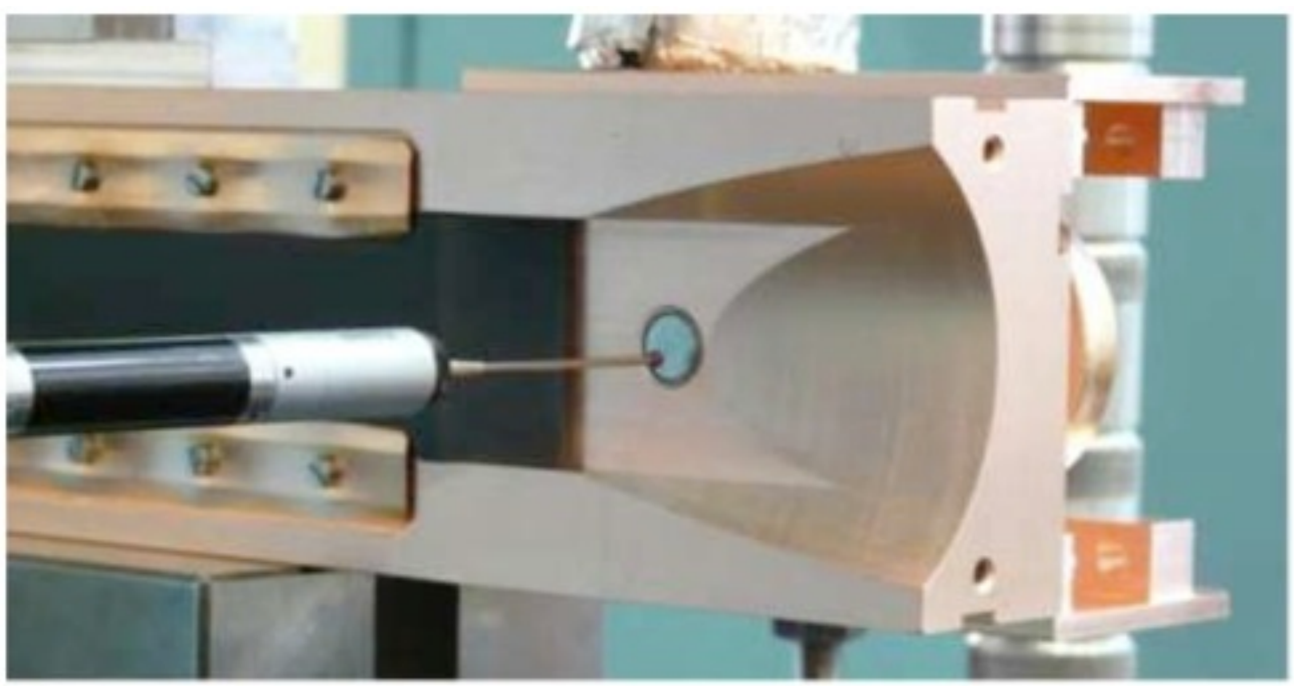
  → Reduced orbit margins in cleaning hierarchy => more room to squeeze *β* (see R. Bruce's talk)*

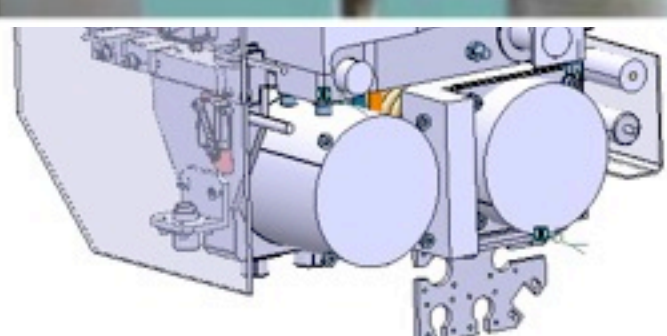
- Other system improvements ongoing:

  → Improved layout in IR8 (better impedance);

  → Additional passive absorbers in IR3 to increase the warm magnet lifetime;

  → Improved **TCL layouts in IR1/5** for better absorption of physics debris.





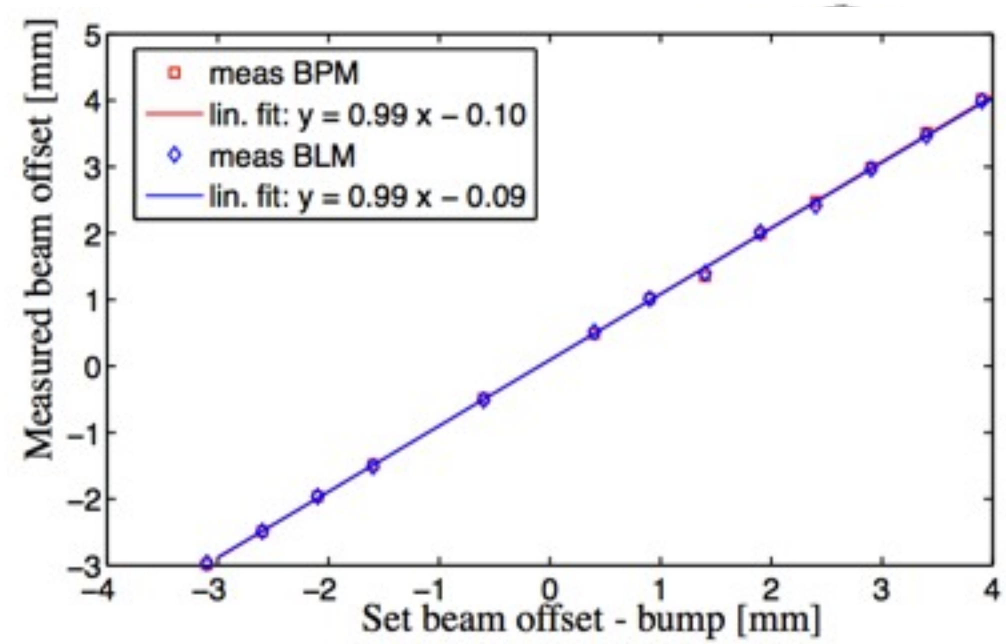
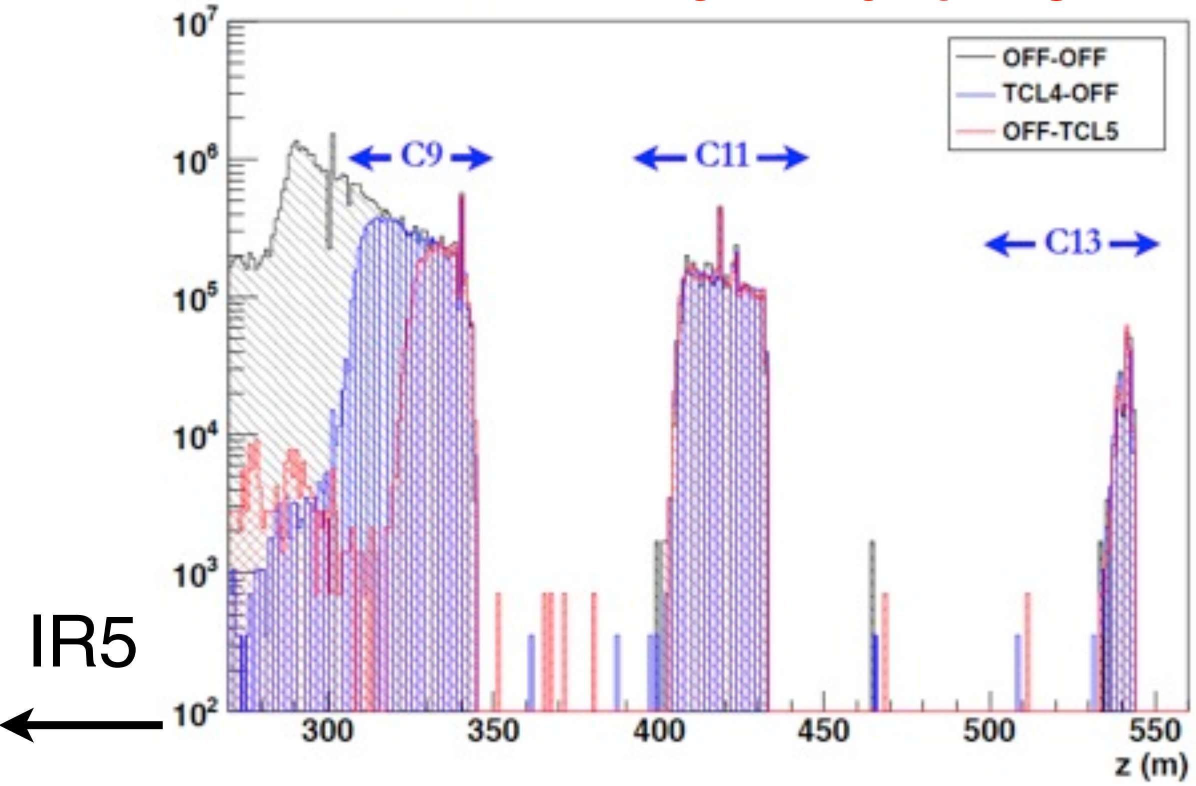


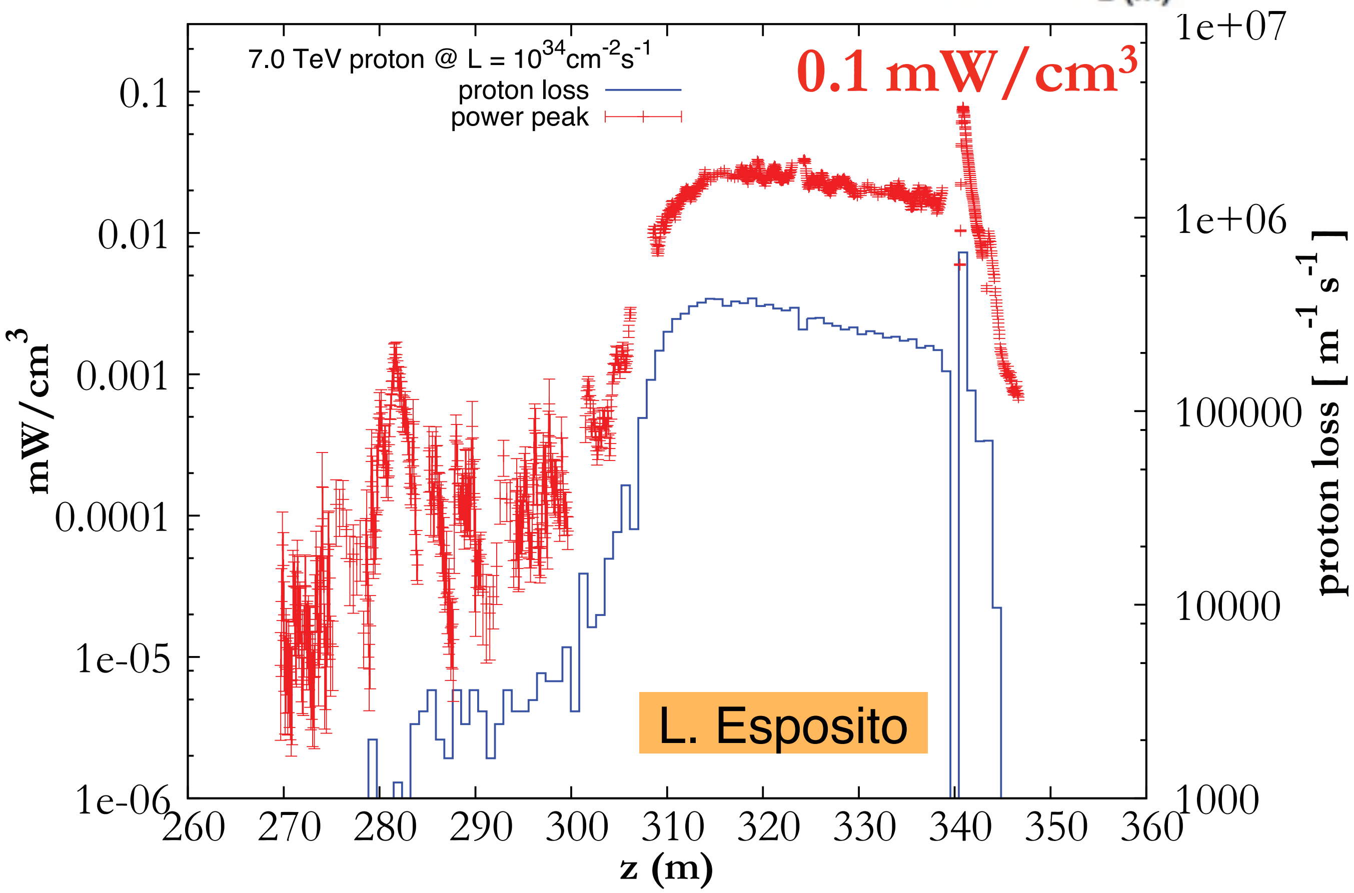
Figure 8: Correlation between measured beam centres (BPMs - red, BLM based method - blue) and the bump settings for the orbit offset at the collimator. The error in the bump settings was estimated to about 10% of the movement increment.

D. Wollmann *et al.*: HB2012

Solution of limitations in IR1/5

Losses in the IR5 DS
for $L=10^{34}cm^{-2}s^{-1}$





- Baseline layout to improve debris losses with "TCL" collimators proposed for implementation in LS1 alread
  - *S. Redaelli, LMC Nov. 7th, 2012.*
- Present layout: 1 TCL in cell 5 (**TCL-5**)
- New layout: add **TCL-4** and **TCL-6**
- With TCL-4, losses **below 1 mW/cm³**, i.e. **more than a factor 10** below quench limit!
- Sufficient margin for the operation until LS3 with peak luminosity below $3x10^{34}$!
- Further gain by factor > 50 with TCL-6 expected in DS.
- Caveats:
  - Ongoing comparison with 4 TeV measurements to improve understanding
  - Loss distributions with new TCLs need assessment against R2E requirements
  - Operationally, need to synchronize with need of **forward physics community**

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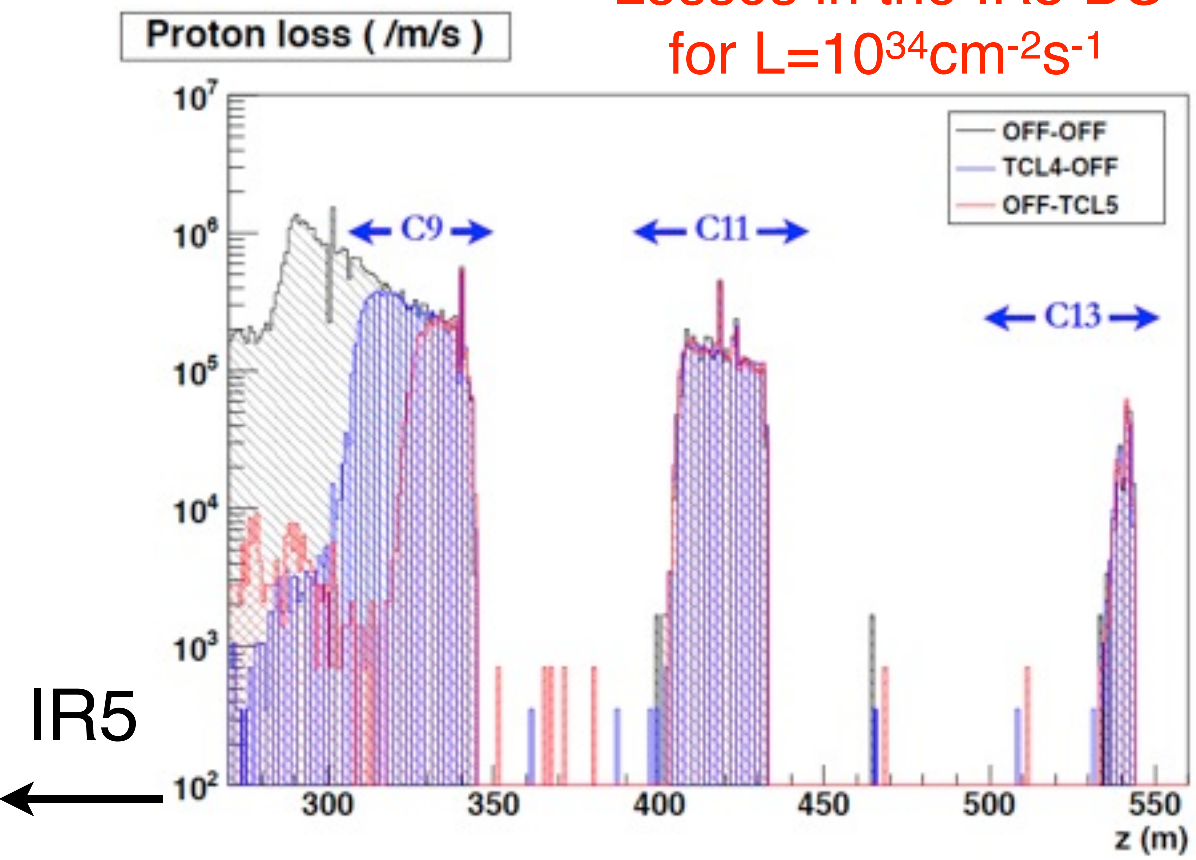

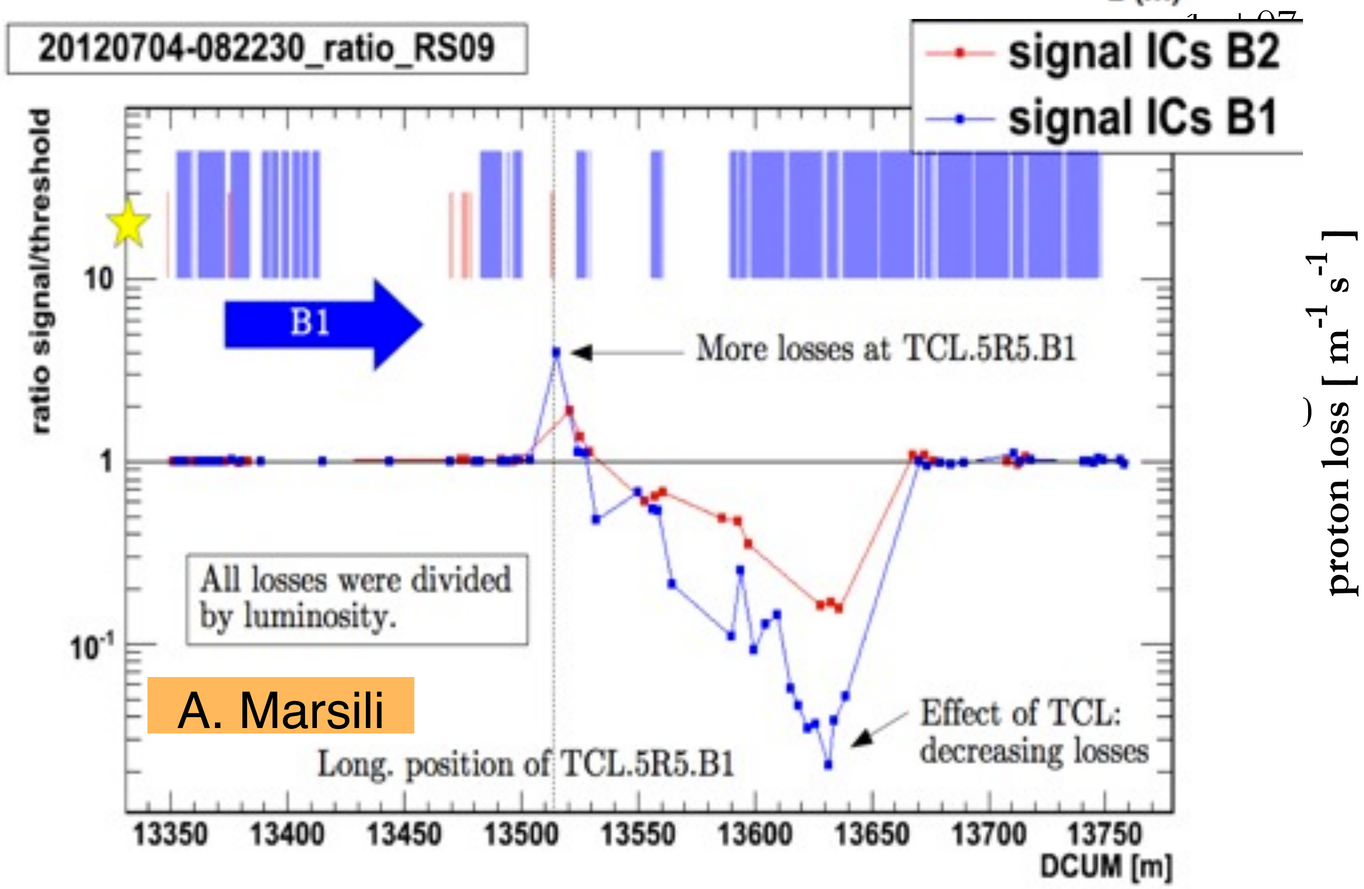

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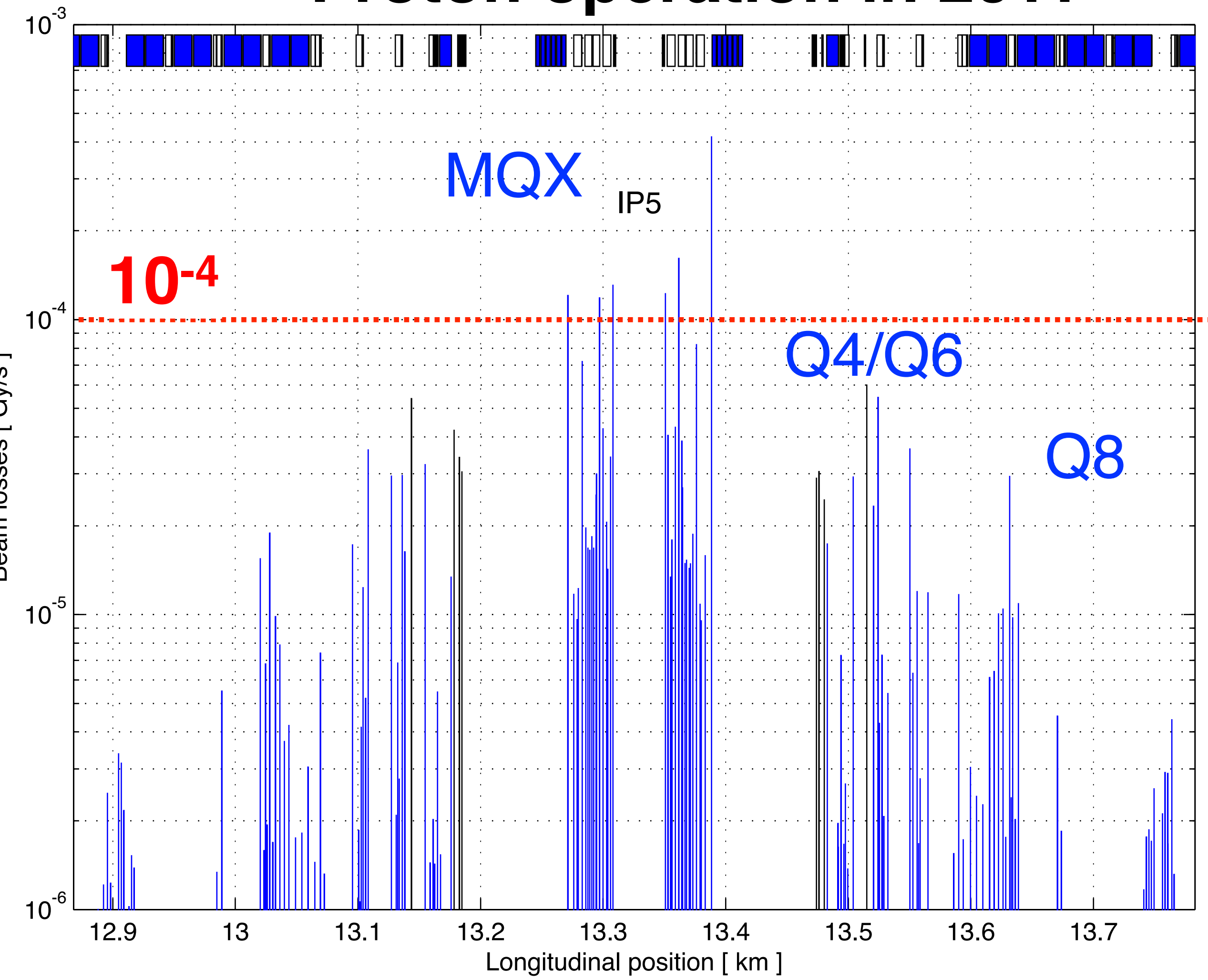
Conclusions

- **The present collimation system was introduced**
- **The achieved collimation performance was reviewed and the concerns on dispersion suppressor (DS) losses introduced.**
    - *The LHC and the collimation system worked very well (140MJ; ~30fb^{-1})!*
    - *The present LHC collimation cannot protect efficiently the DS's*
    - *Is this going to induce a performance limitation for the LHC and HL-LHC?*
- **We ask advice to an external review panel on whether we are on good track to address potential performance limitations revealed by the LHC operation in 2015 at energies close to 7 TeV.**
    - *The overall performance is very encouraging, but we want to be sure that future performance limitations are excluded with appropriate margins*
    - *Our goal is to be ready for actions in LS2 if needed.*
- **If available in time, the 11 T dipoles would provide an elegant and "transparent" solution, "easily" applicable to several IR's**
    - *Can we have a solution bases on this technology for possible actions in LS2?*
- **Other upgrade studies will be presented at the end of this review!**

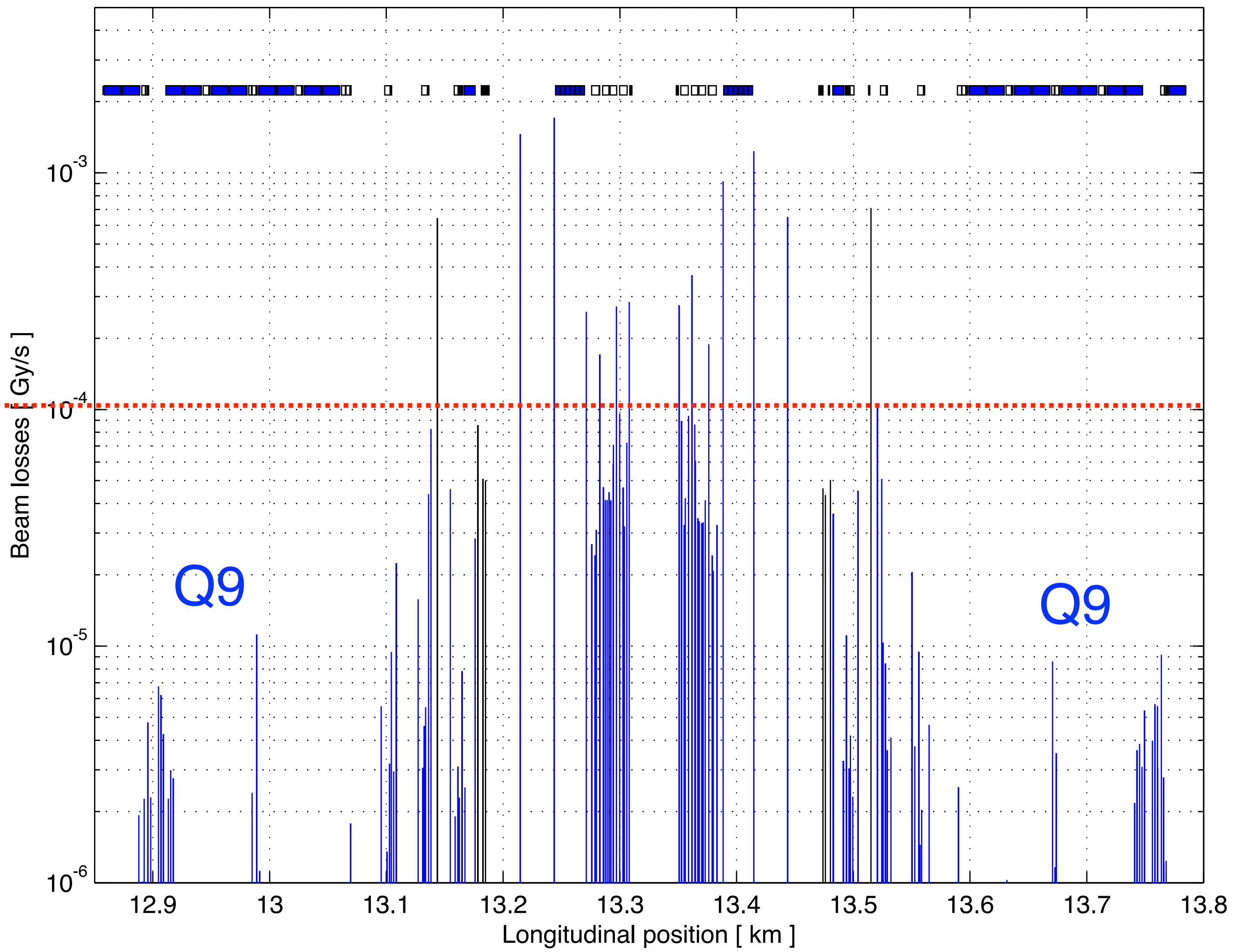
Reserve slides

Losses from luminosity debris

Proton operation in 2011

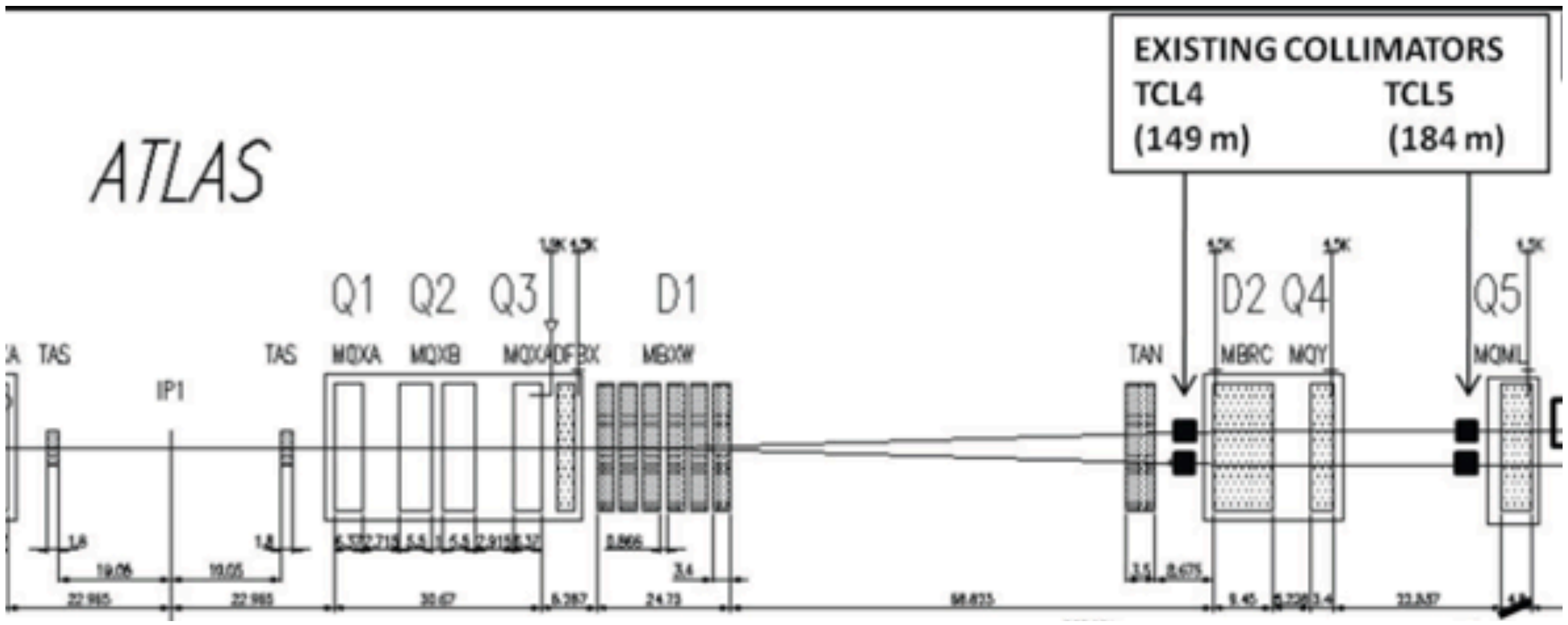


Proton operation in 2012

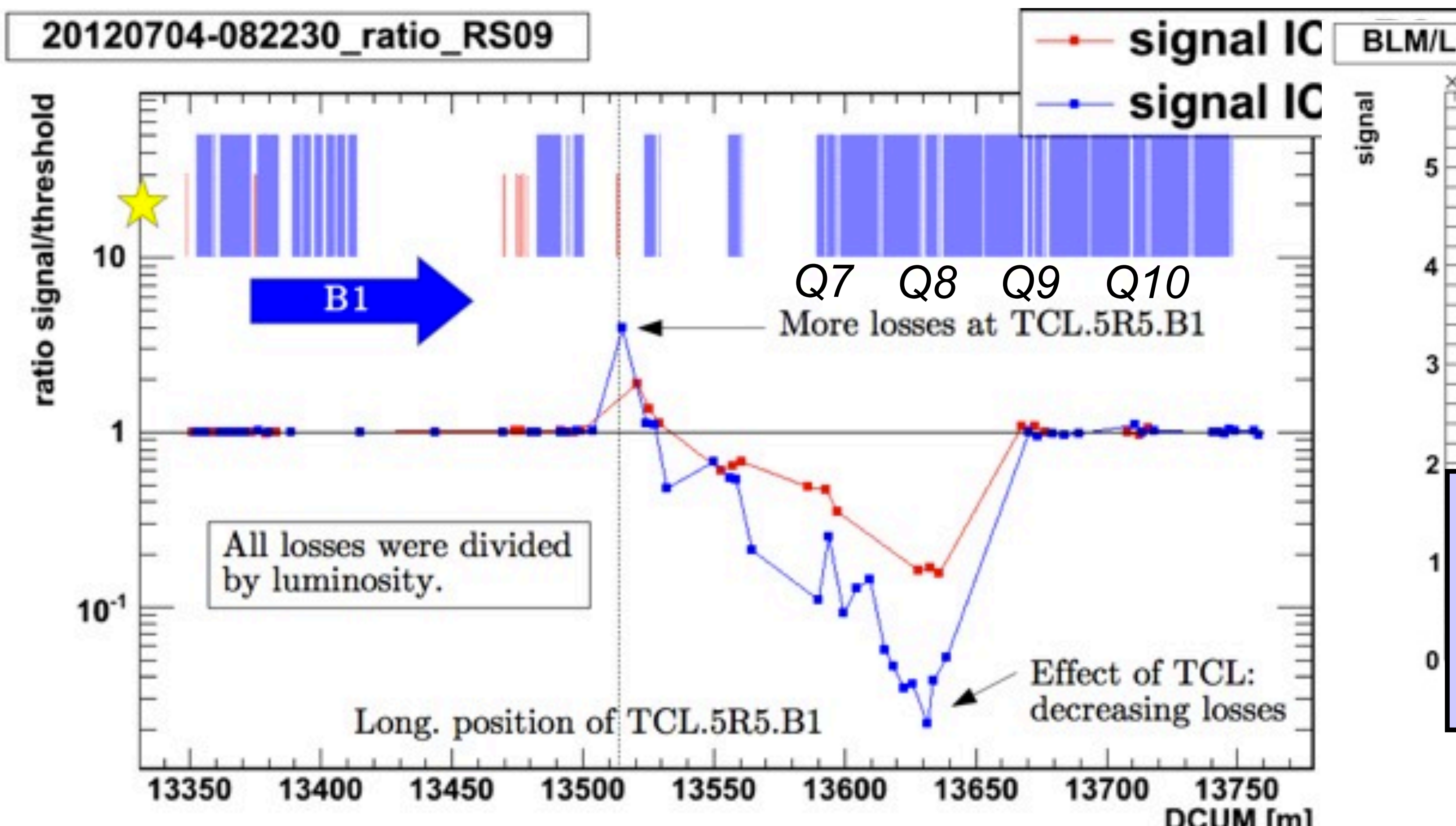


Ongoing program (beam measurements + tracking and energy deposition simulations) followed up by the ColUSM to understand the present losses from luminosity debris ➙ feedback on layout of experimental regions.

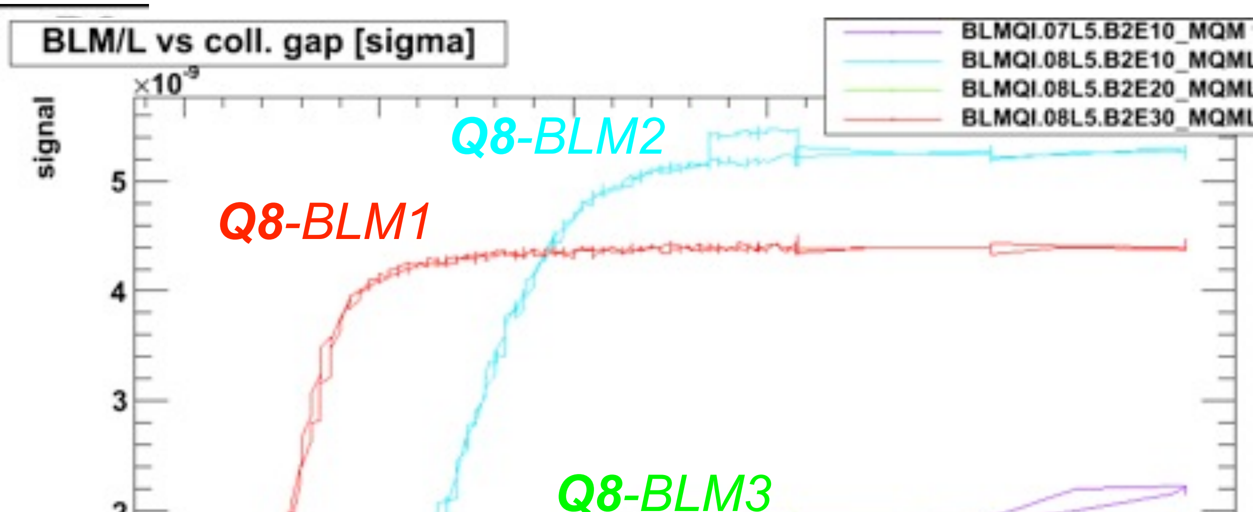
Measurements of TCL scans in IR1/5



Gap scans with the physics debris collimators (TCLs) in IR1/5: *direct measurements of loads in matching section and DS; simulation benchmark.*
Immediate interest: update of IR1/5 layout during LS1!



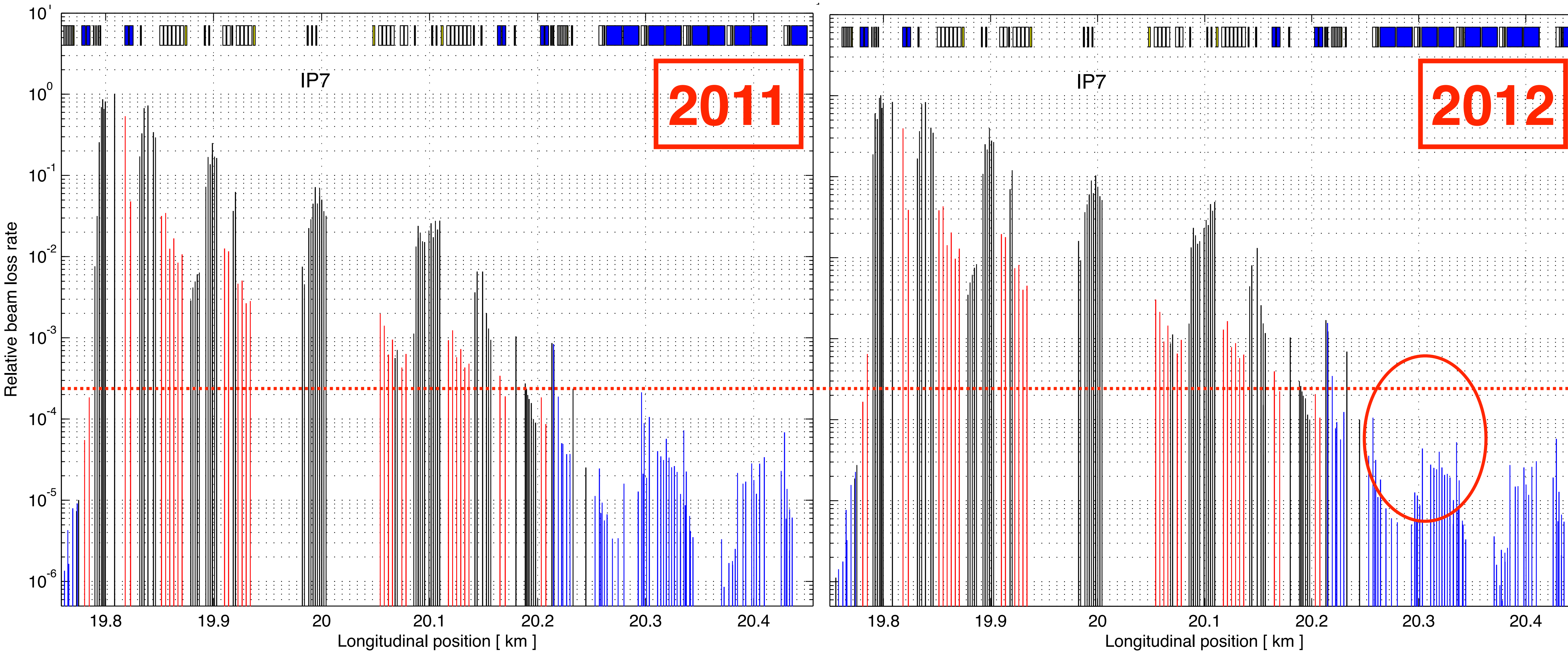
A. Marsili



Proposal to perform cryogenics measurements in standard physics fills in different conditions.

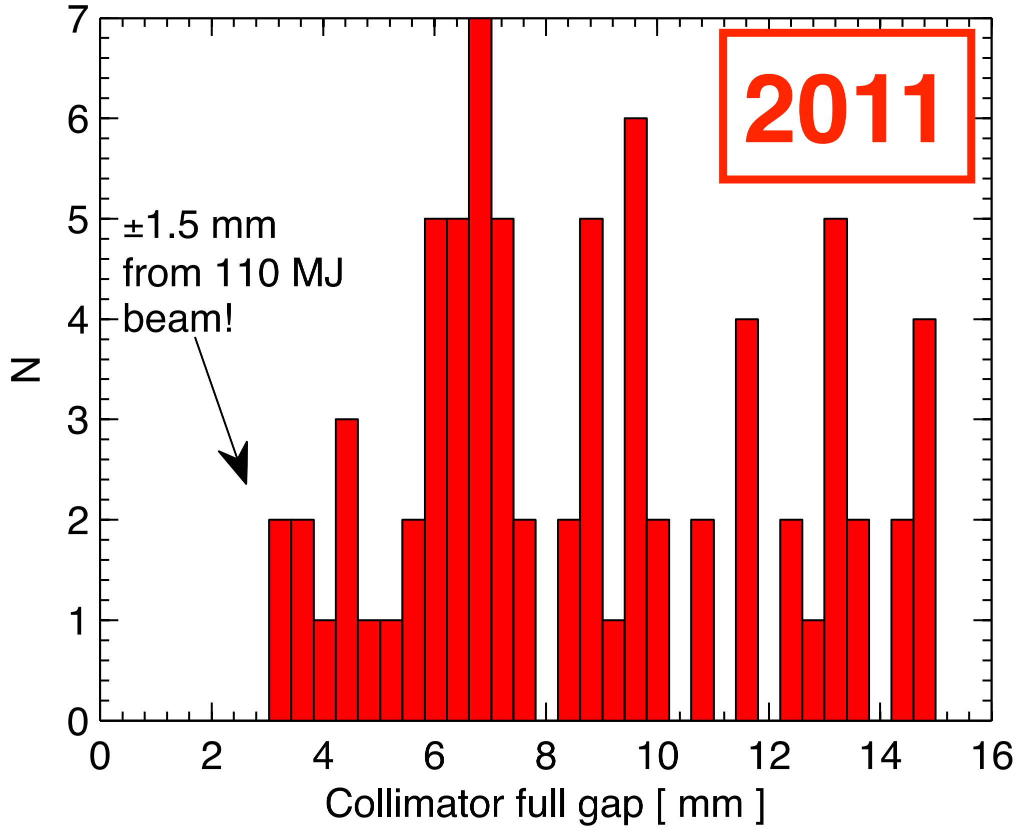
See also talk by F. Cerutti at the CWG, Aug. 2012.

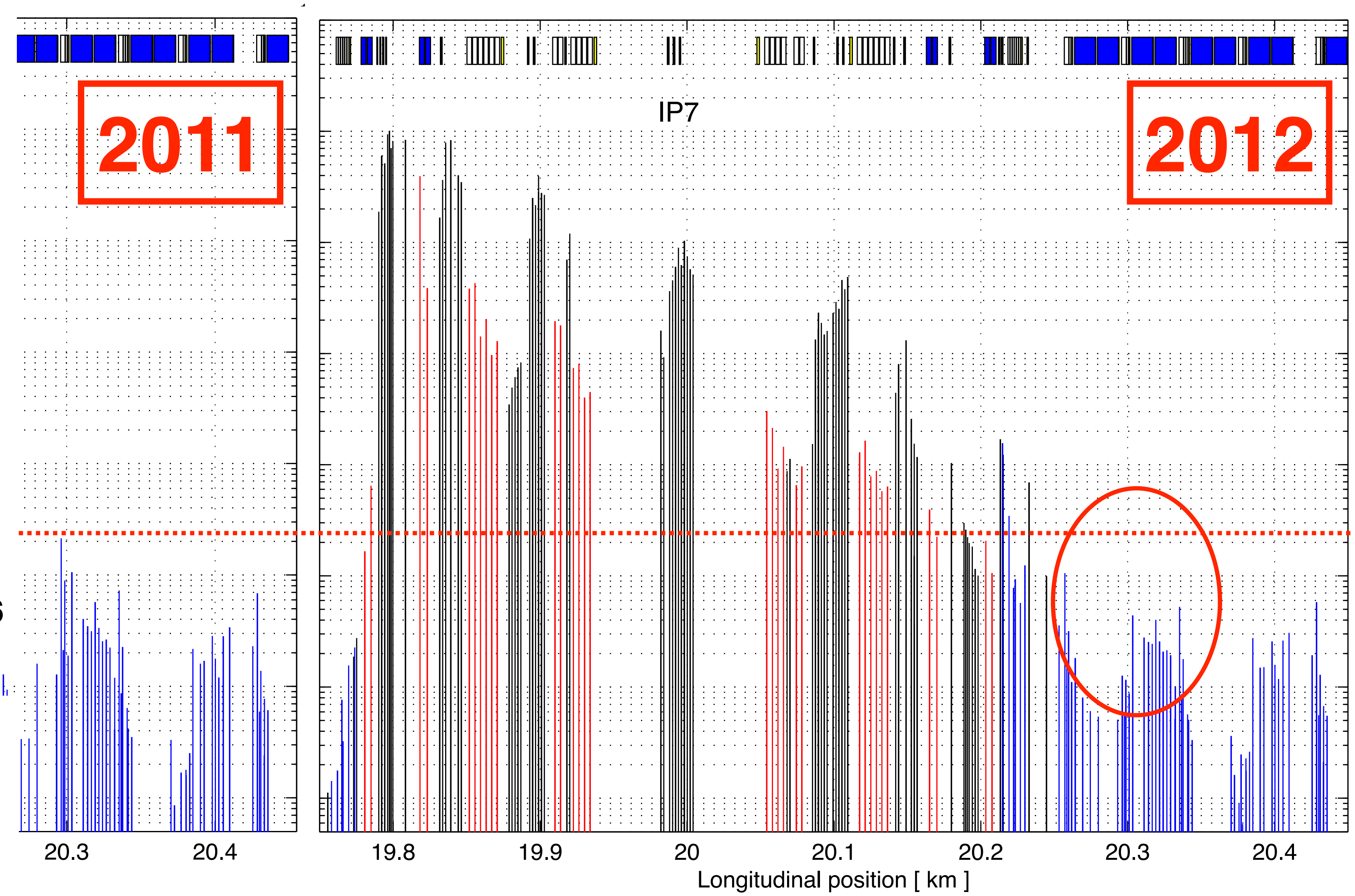
Comparison: 2011 vs 2012

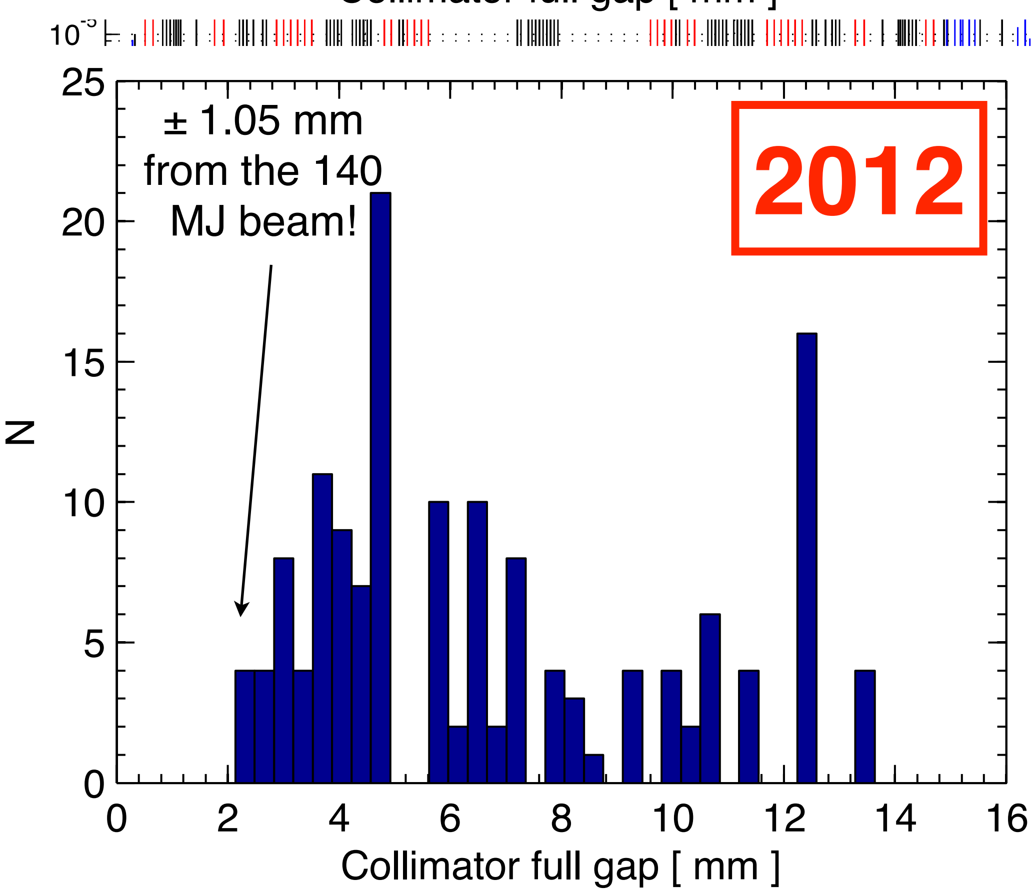


The local cleaning in the IR7 DS's was improved by a **factor ~5** compared to 2011.
Improvements from 2011 driven by the deployment of collimator **"tight" settings**.
(TCP settings equivalent to 7 TeV nominal gaps), studies in MDs in 2011.
Drawbacks: we are now dealing with **larger losses** in standard operation: **tail removal** during ramp and beam instabilities from **larger impedance**!

Comparison: 2011 vs 2012







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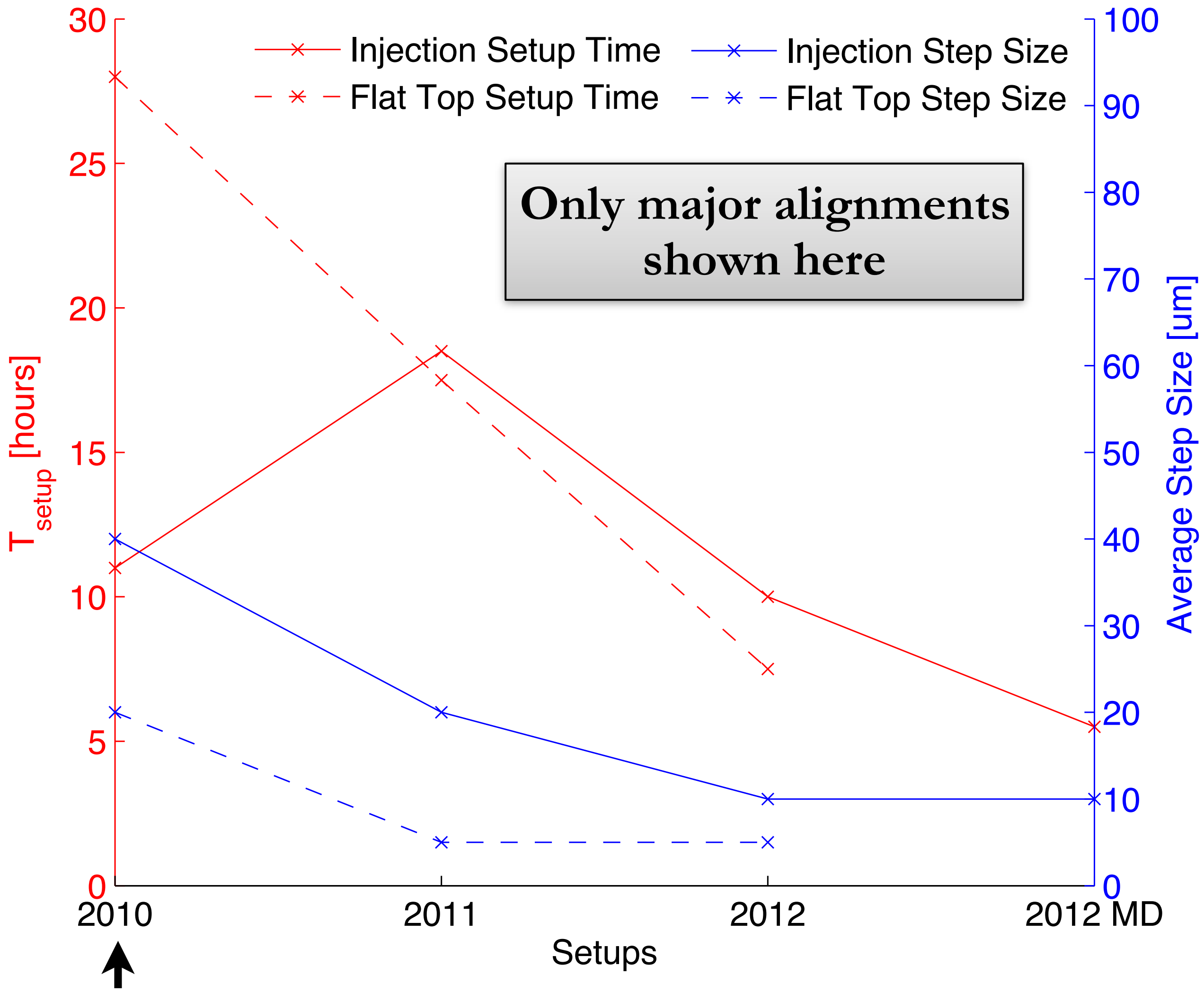
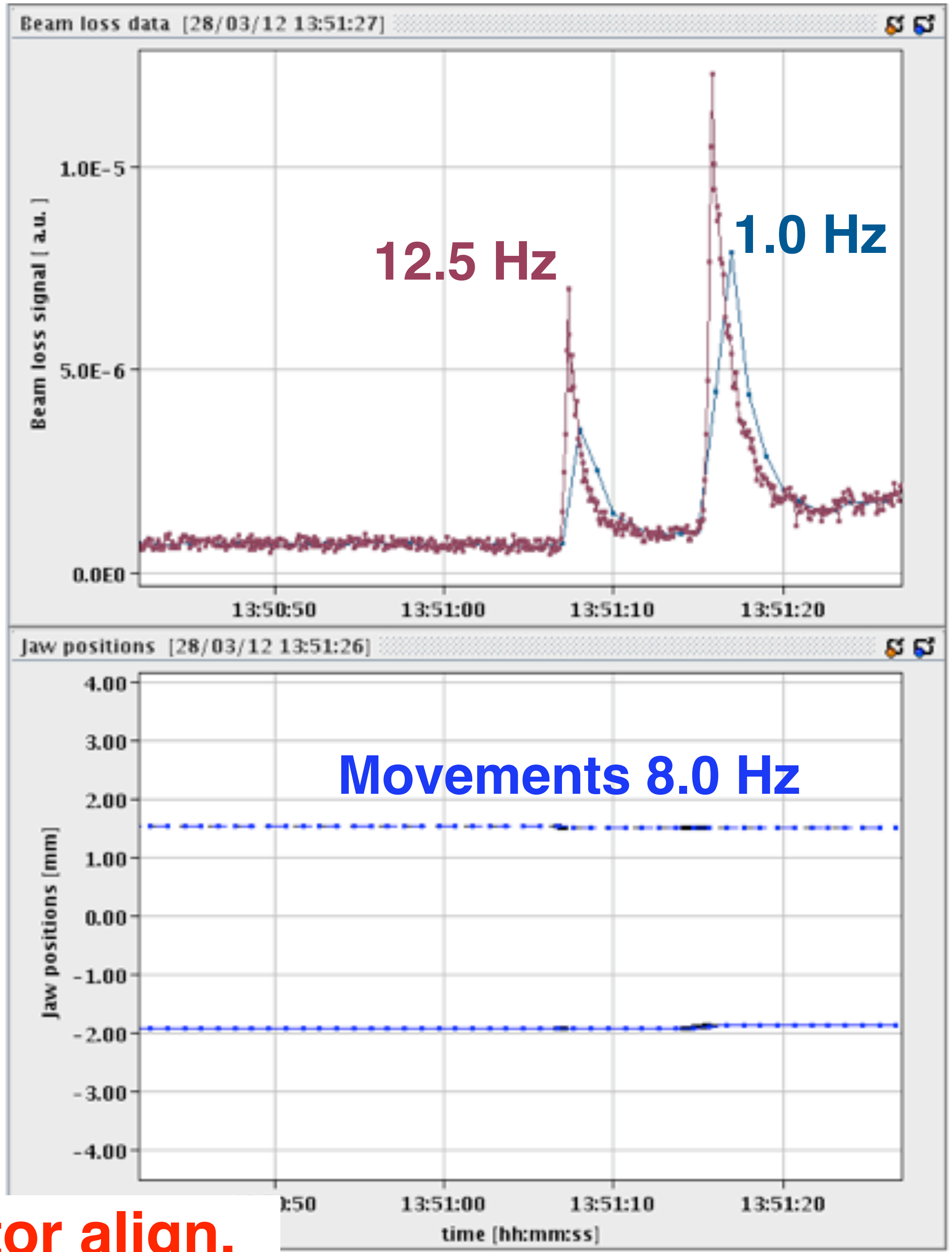
Collimator alignment

2012 commissioning: alignment campaigns

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





Number of dump triggered during collimator align.

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

Ph.D. work of G. Valentino
See a recent ICAP + HB2012 papers