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57th ICFA Advanced Beam Dynamics Workshop on
High-Intensity and High-Brightness Hadron Beams
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LHC Collimation for Run II and beyond

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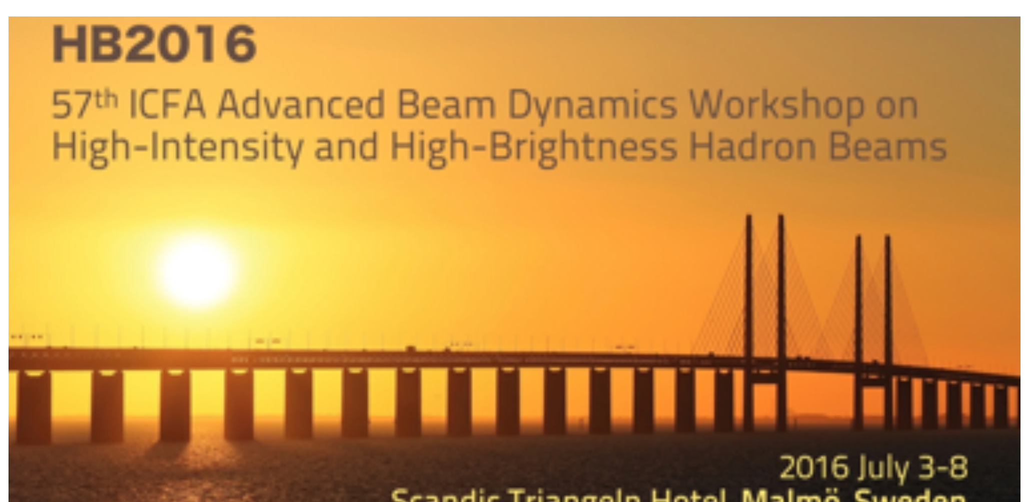
A. Mereghetti, D. Mirarchi, A. Rossi, R. Rossi, E. Quaranta,
B. Salvachua, G. Valentino, A. Valloni, J. Wagner



Acknowledgements

"Core" team in the LHC accelerator physics group:
R. Bruce, M. Fiascaris, H. Garcia[+], P. Hermes, R. Kwee[+], A. Mereghetti, D. Mirarchi, S.Redaelli, A. Rossi, R. Rossi, E. Quaranta, B. Salvachua, G. Valentino, A. Valloni, J. Wagner
- **— Responsibility of settings definition and operational performance**
- **— Accelerator physics simulations, code development**
- **— Specifications/definition of system limitations and future upgrades**

{+: Royal Holloway University}

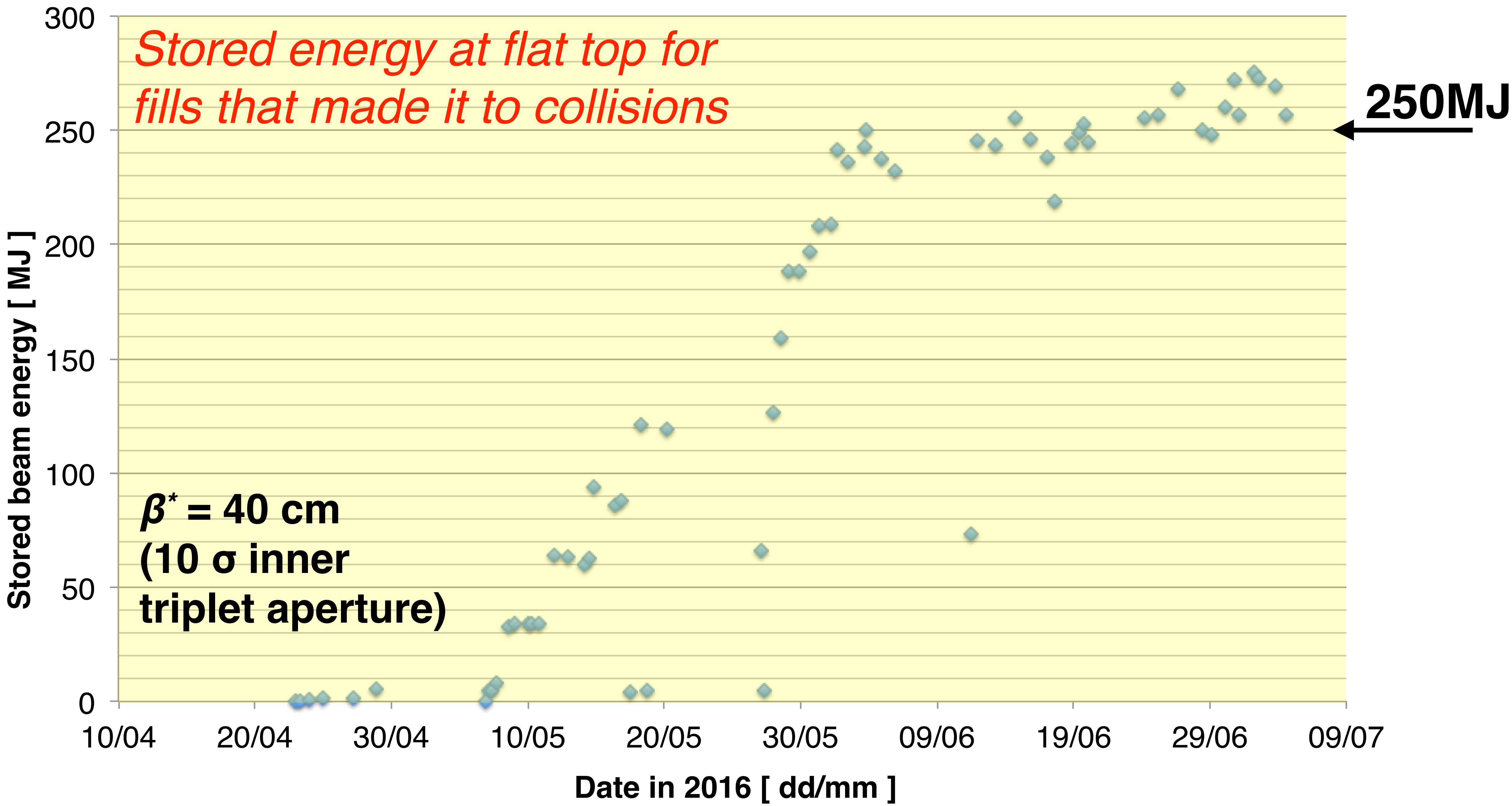
Strong synergy with and support from **other teams at CERN**:
- — **EN/STI** (energy deposition studies; collimator controls; collimation productions in industry)
- — **EN/MME** (engineering: design and materials; in-house productions)
- — **BE/BI** (beam diagnostics: BPM collimators)
- — **BE/OP** (operations) and BE/RF (loss maps, controlled blow-up)
- — **TE/VSC** (vacuum)
- — Machine protection, Injection & dump, Optics, impedance, operation, beam and HW commissioning, planning, survey and transport teams, etc.

O. Aberle, A. Bertarelli, F. Carra, F. Cerutti, M. Donze, J. Lendaro, A. Lechner, R. Losito, A. Masi, C. Mitifiot, S. Roesler, D. Jacquet, J. Wenninger, S. Gilardoni. G. Baud, A. Danisi, J. F. Fuchs, M. Gasior, D. Missiaen, J. Olexa, D. Valuch, W. Höfle, C. Boccard, J. Coupard, V. Vlachoudis. An many other people...

Many **international collaborations**: EuCARD 1+2, US-LARP, FNAL, SLAC, FP7-HiLumi, UNIMAN, Malta, BNL, Kurchatov...

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

LHC beam stored energy at 6.5 TeV



So far: no quenches from circulating beam losses!

{"UFO" quenches are an exception: cannot be cured by collimation}

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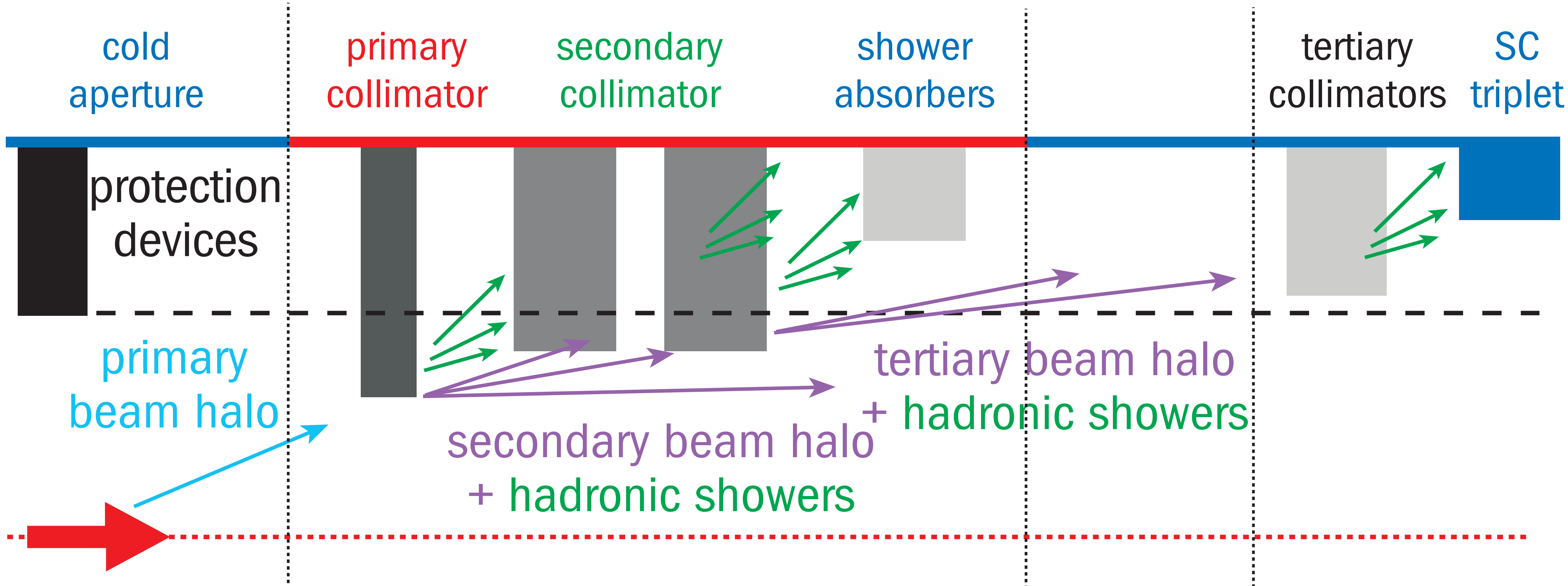
Roles of LHC collimation system

- **Halo cleaning** versus quench limits (super-conducting machines)
- Passive **machine protection**
  First line of defence in case of accidental failures.
- **Concentration of losses/activation** in controlled areas
  Ease maintenance by avoiding many distributed high-radiation areas.
- **Reduction total doses** on accelerator equipment
  Provide local protection to equipment exposed to high doses (like the warm magnets in cleaning insertions)
- **Cleaning of physics debris** (physics products, in colliders)
  Avoid magnet quenches close to the high-luminosity experiments
- Optimize **background** in the experiments
  Minimize the impact of halo losses on quality of detector's data
- Beam tail/halo **scraping**, **halo diagnostics**
  Control and probe the transverse or longitudinal shape of the beam

Multi-stage cleaning



Three-stage cleaning in two warm insertions: betatron (IR7) and off-momentum (IR3); local "tertiary" collimators at inner triplet.

Well-defined *collimation hierarchy* that integrates injection and dump protection collimators (as well as Roman pots). **Five stages**!

Machine aperture sets the scale for collimation hierarchy
→ present settings: **10 σ aperture** requires 5.5 σ primary cut.

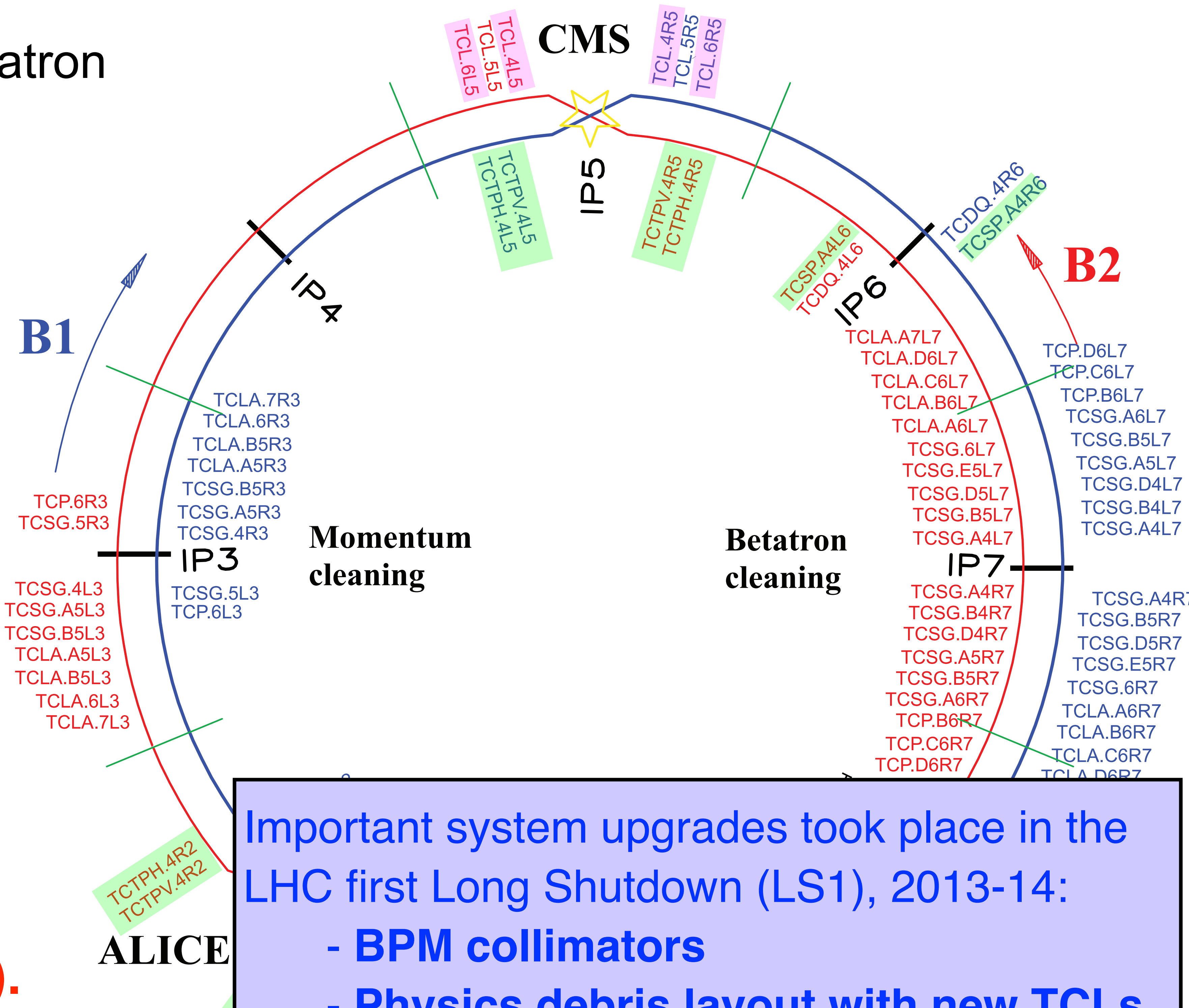
Tedious beam-based alignment to determine local orbit and beam size.

The Run II collimation system

Dedicated insertions for betatron (IR7) and momentum (IR3) cleaning systems.

Cleaning of incoming beam in all experiments.

Physics debris collimation in the high-lumi IR1/5.



Important system upgrades took place in the LHC first Long Shutdown (LS1), 2013-14:

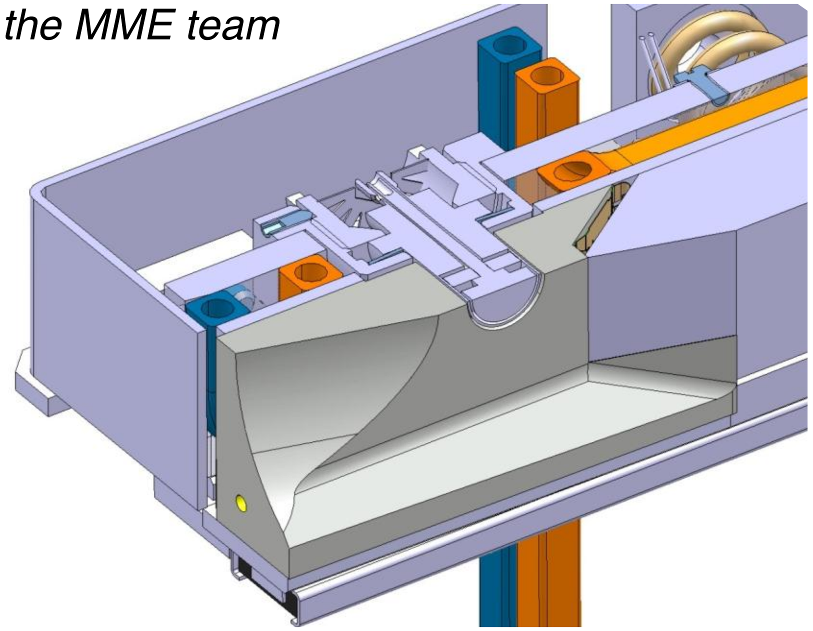
- **BPM collimators**
- **Physics debris layout with new TCLs**
- Improved protection of warm quadruples

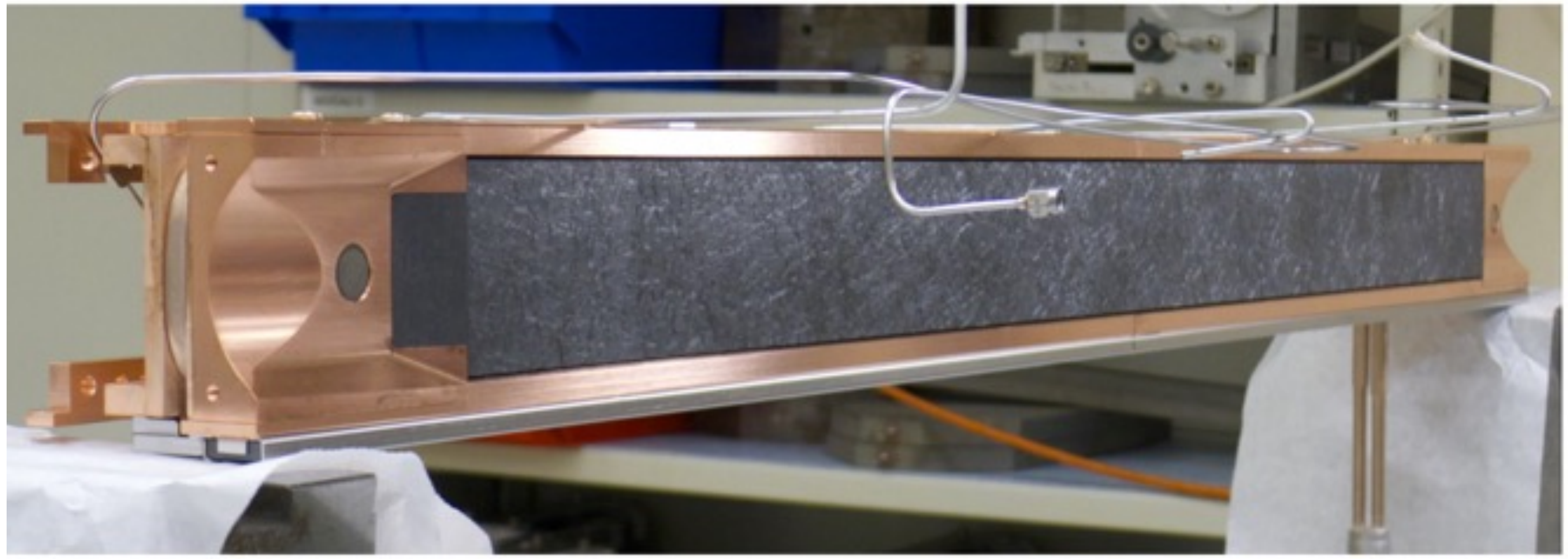
Crystal collimation setup in IR7.

Total of 118 [was 108 in Run I] **collimators (108** [was 100] **movable).**

BPM collimators

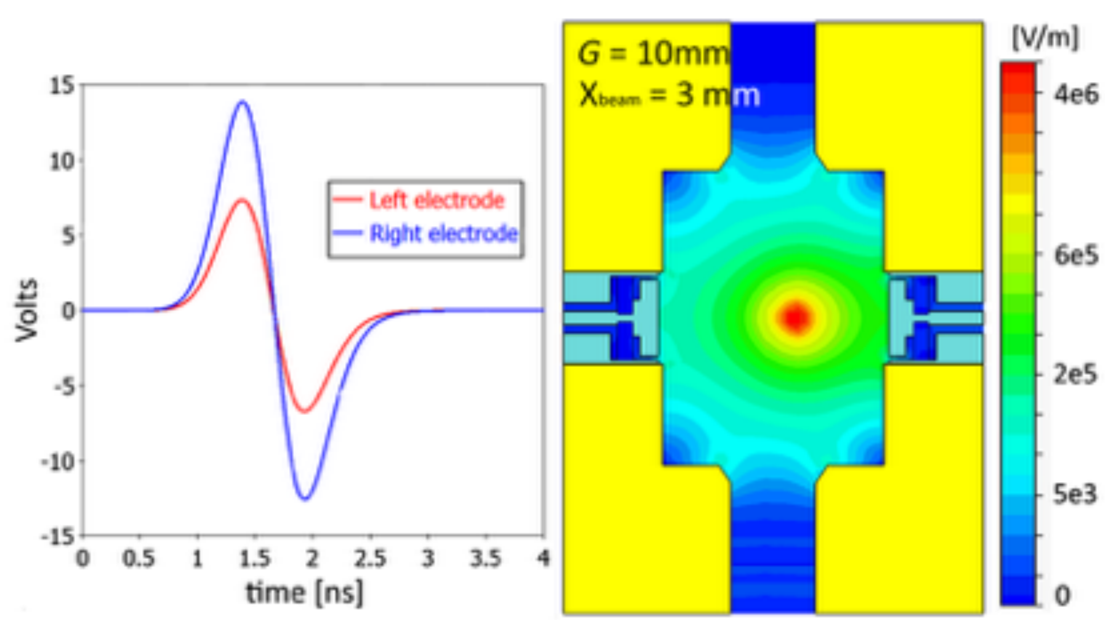
Courtesy of A. Dallocchio for the MME team

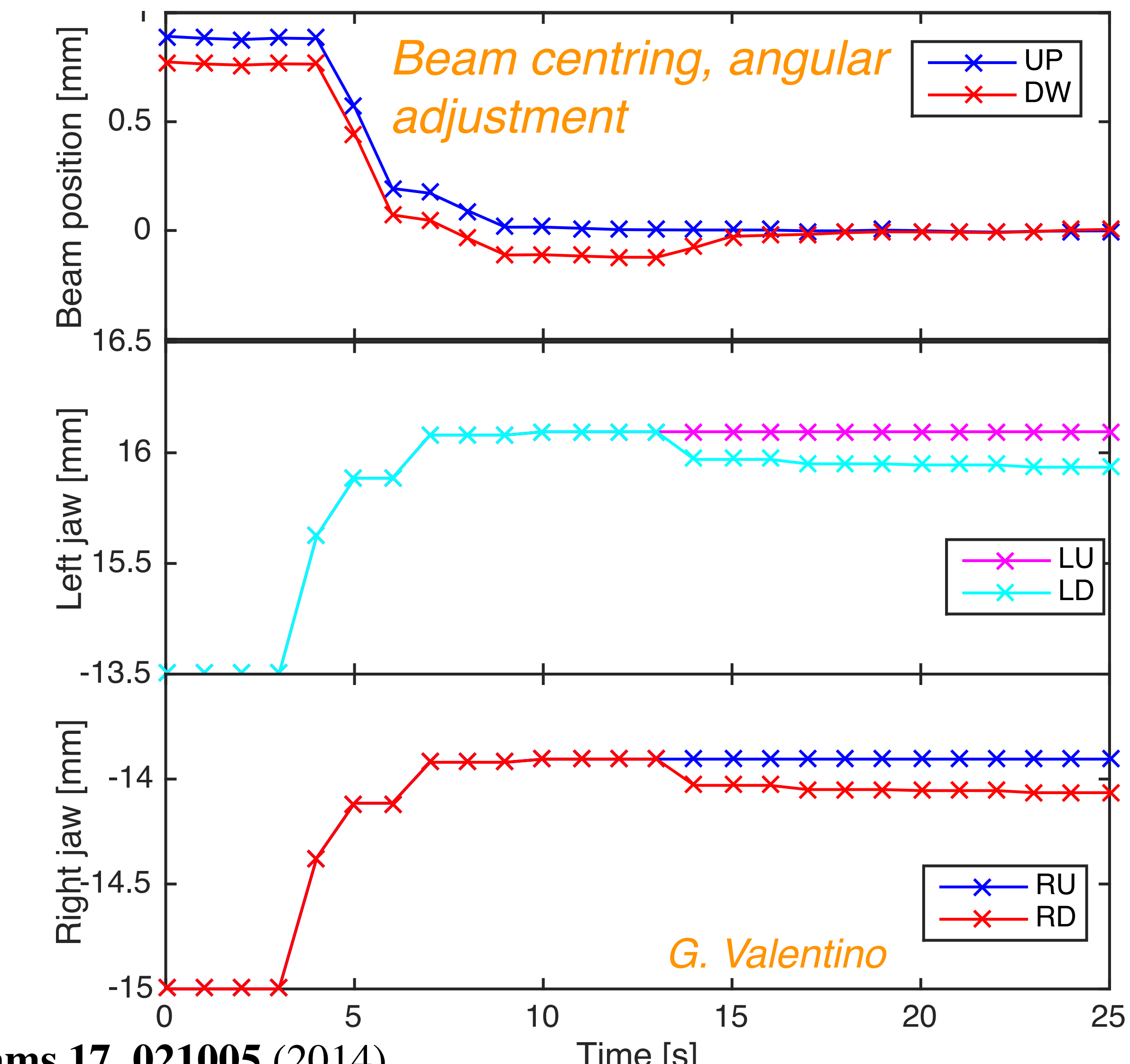




18 new BPM collimators installed in experiment and dump regions.

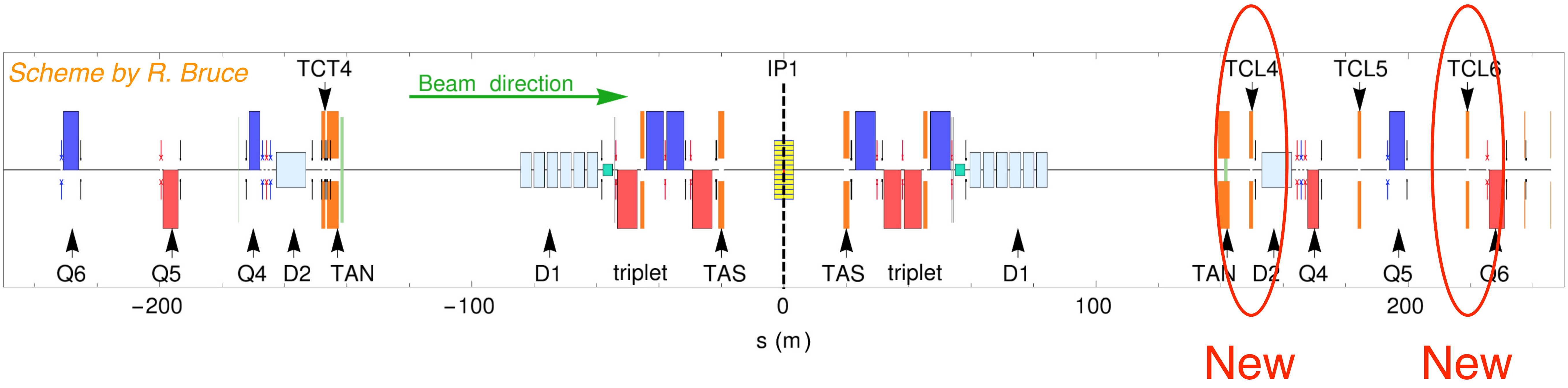
Aims: faster precise alignment; continuous orbit monitoring.





Phys. Rev. ST Accel. Beams 17, 021005 (2014)

Collimation around experiments



In preparation for the **high-luminosity** operation at **6.5 TeV**, improved the **physics debris collimation** downstream of ATLAS an CMS:

- 12 "TCL" collimators in the matching sections of IR1/5.
  (as opposed to 4 only in Run I)

Motivations and advantages:

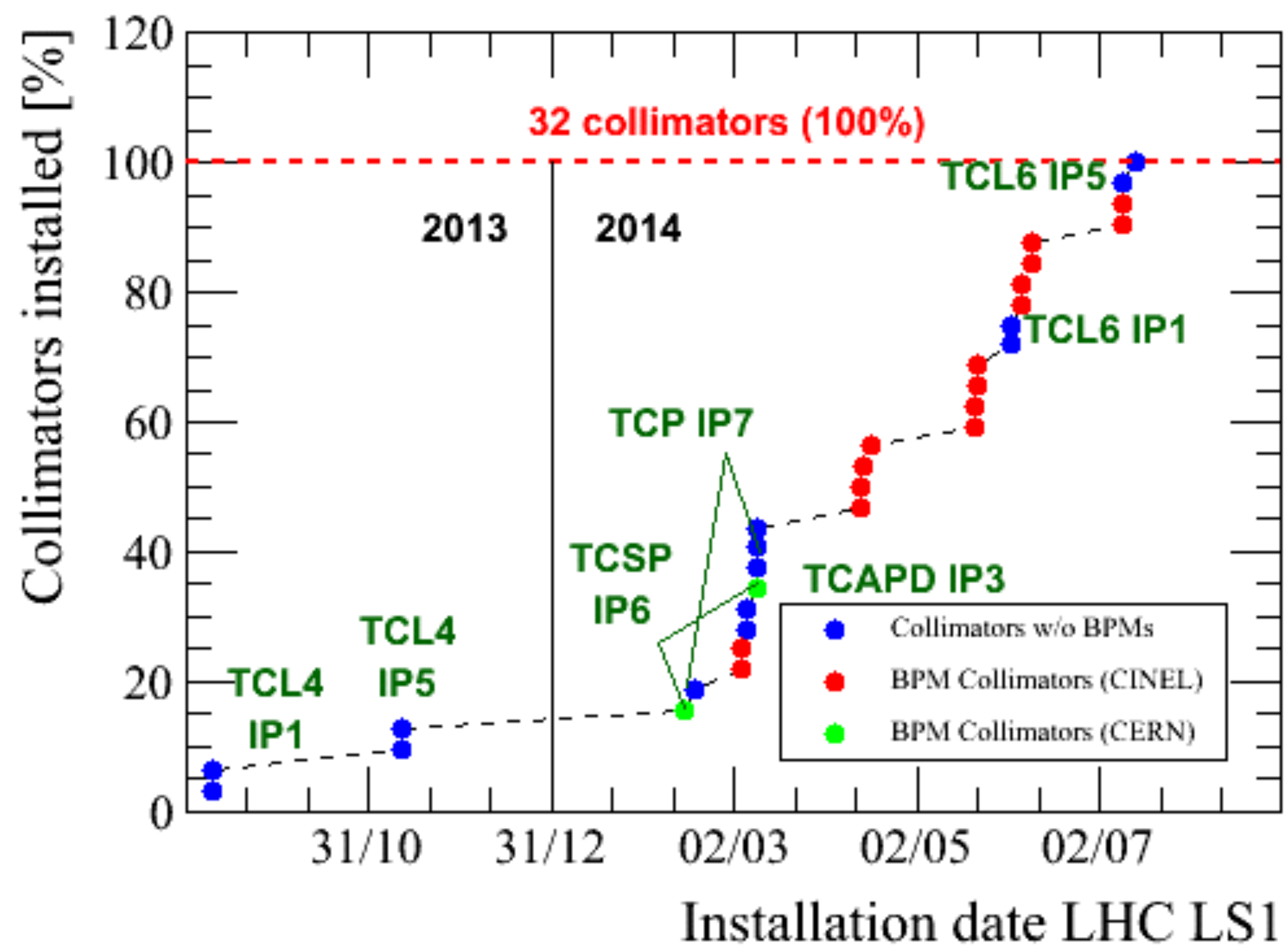
- Allow operation at design luminosity;
- Improved flexibility for forward physics experiments (Roman pots);
- Concentration of radiation hot spots.

Other improvements and "LS1" works

- 5-times better **passive absorption** of warm magnets in off-momentum insertion.
- **Improved collimator vacuum layouts** close to LHCb.
- **Improved reliability of collimator controls**: more redundancy against single-event upset, better availability

LS1: 32 collimators in the machine (new or "reshuffled"), i.e. 30% of the system!

O. Aberle, B. Salvachua, J. Coupard
Thanks to the CERN teams involved in production and installation!



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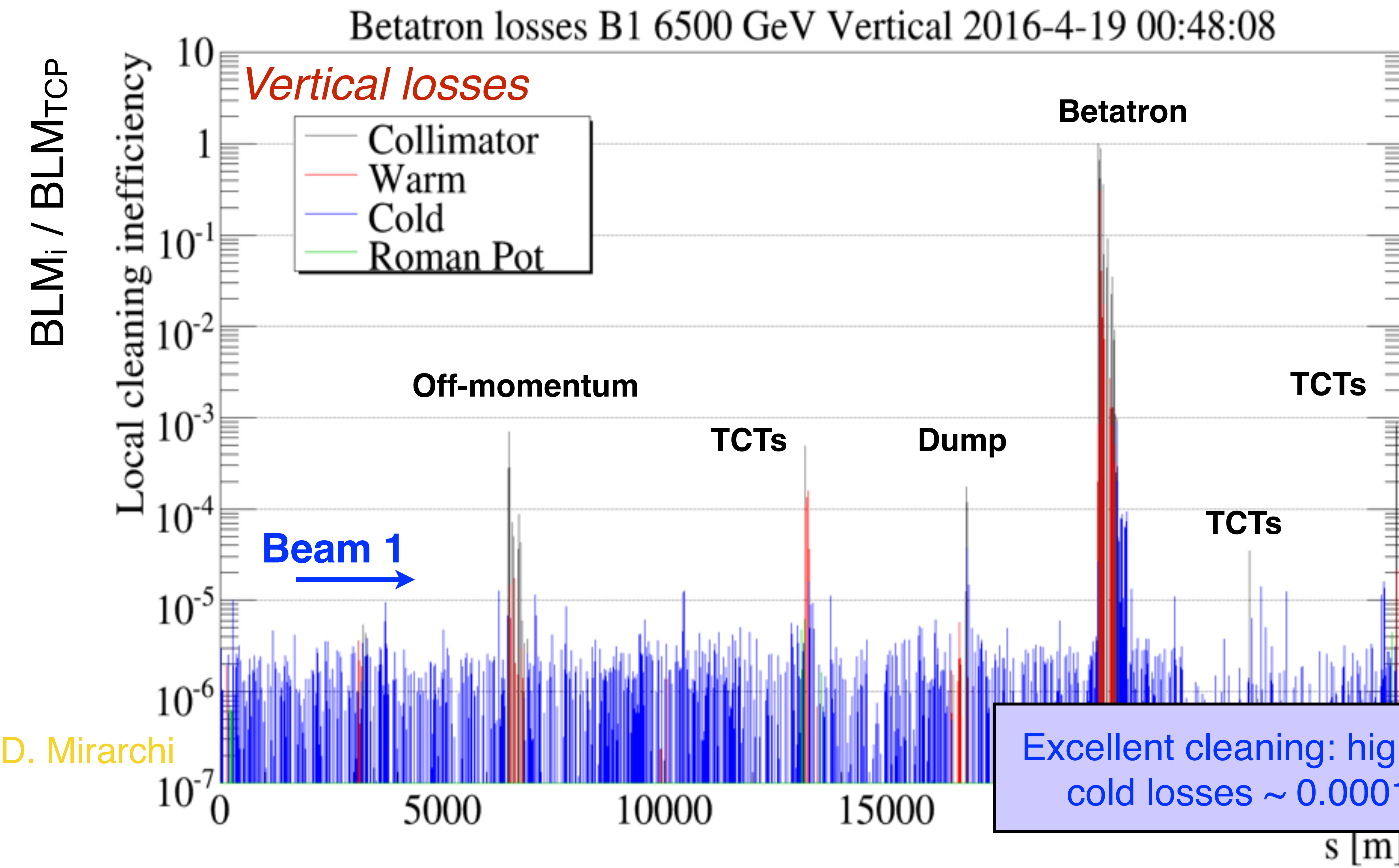
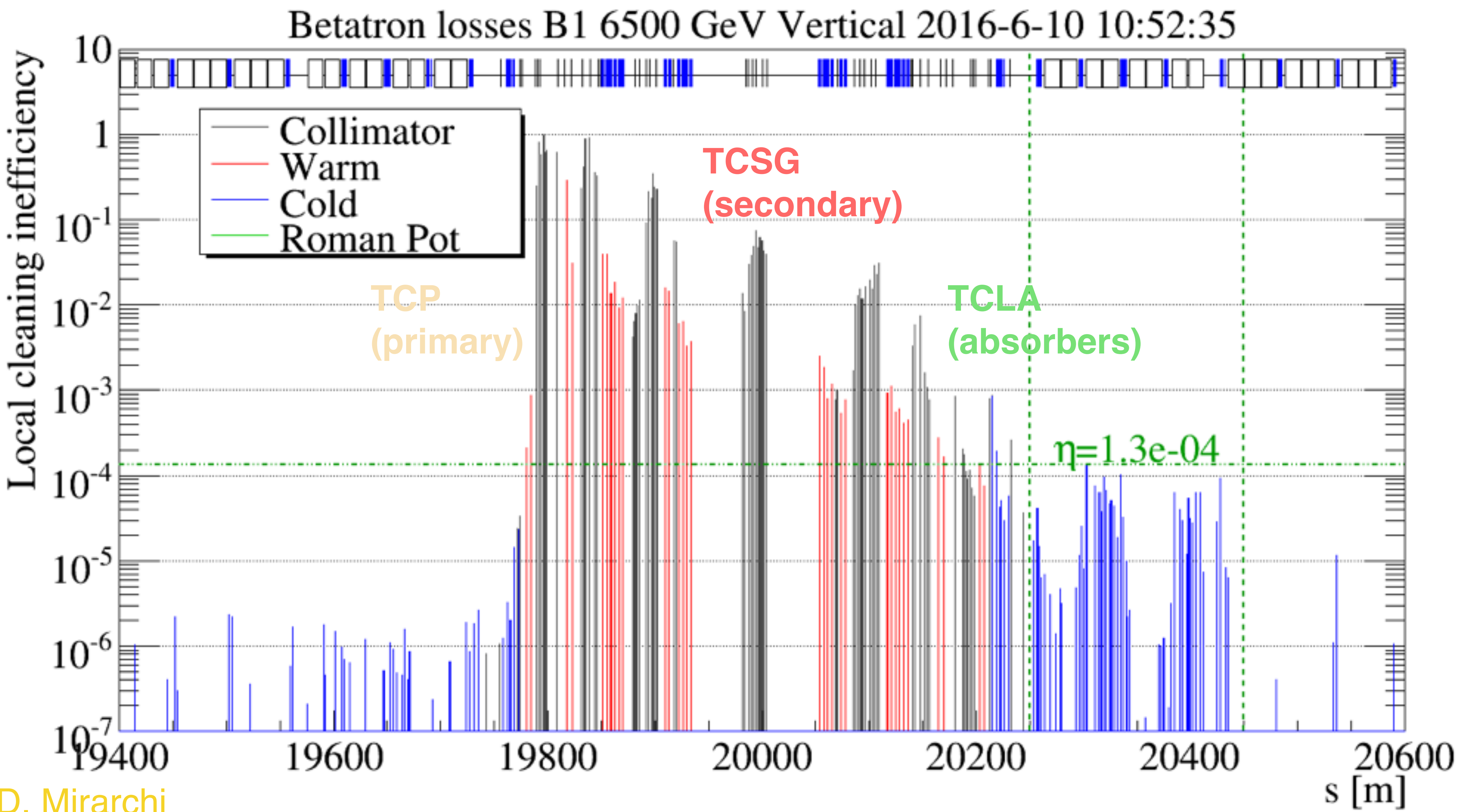
Collimation cleaning 6.5 TeV, β^*=40cm



Excellent cleaning: highest cold losses ~ 0.0001!

System validation through controlled excitations of transverse beam losses (triggered by transverse damper).

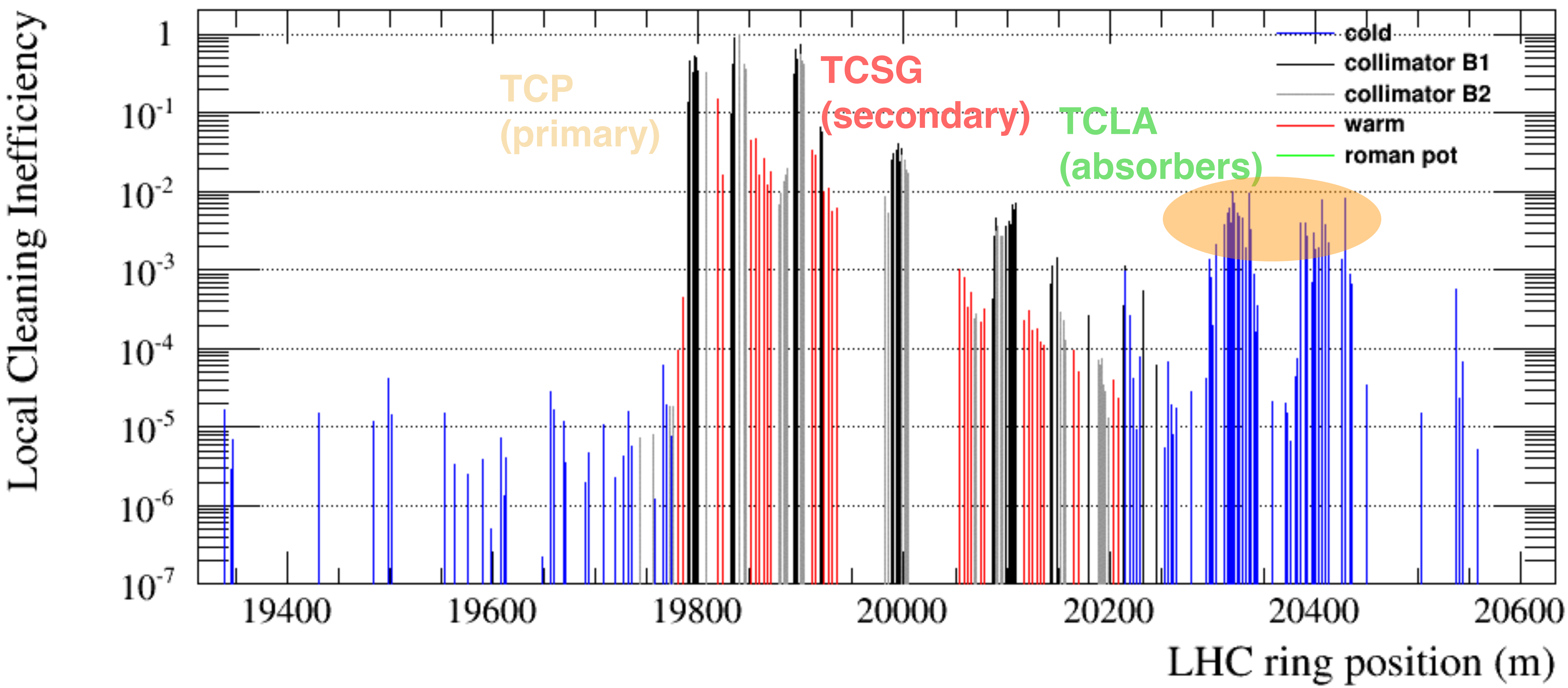
IR7 losses (betatron insertion)



D. Mirarchi

Limiting locations for cleaning: dispersion suppressors around IR7

Pb ion cleaning (betatron insertion)



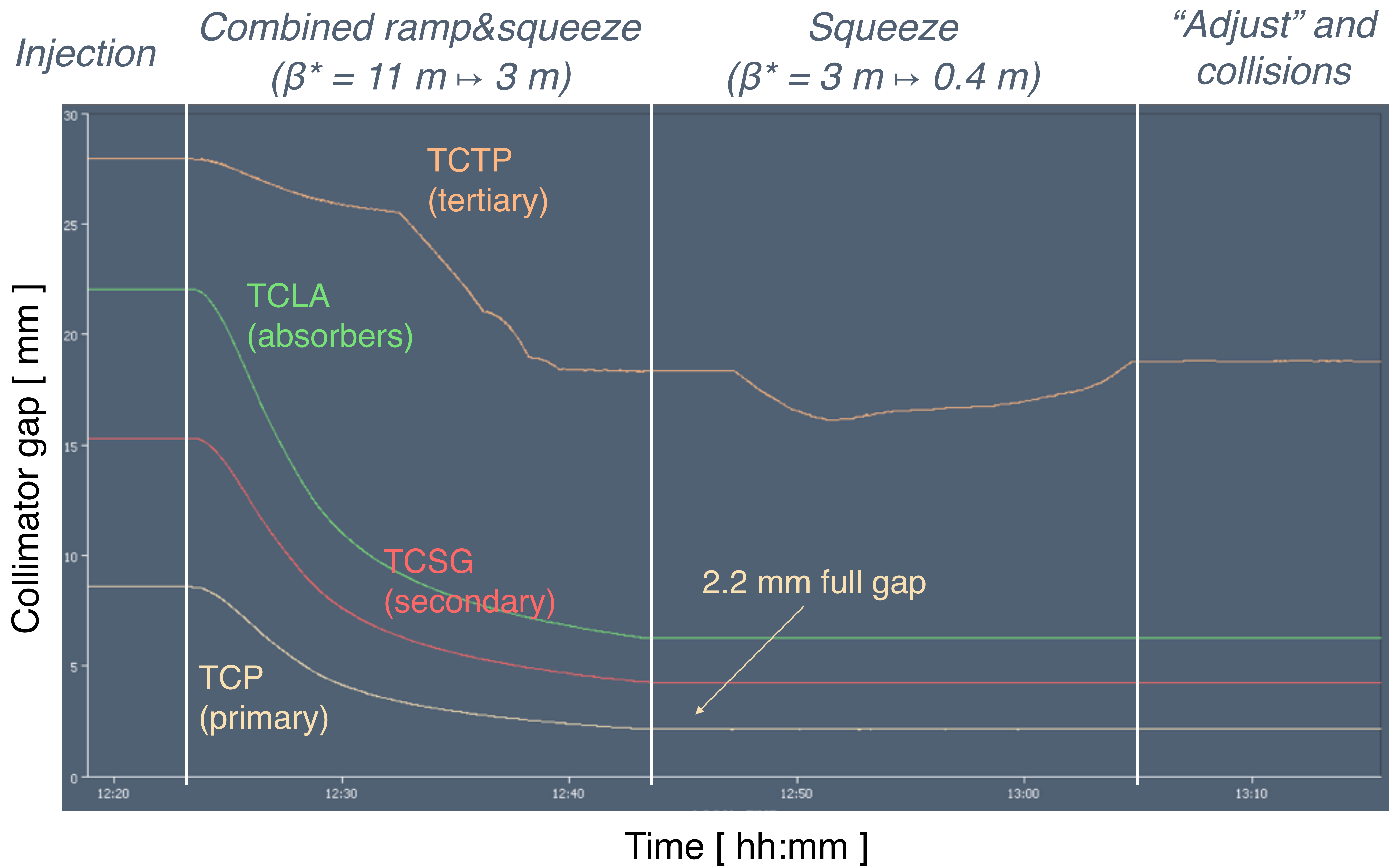
Betratron cleaning of ion beams limited by ion fragments:
a few 0.01, i.e. 100 times worst than for protons.

Summary table for collimator families

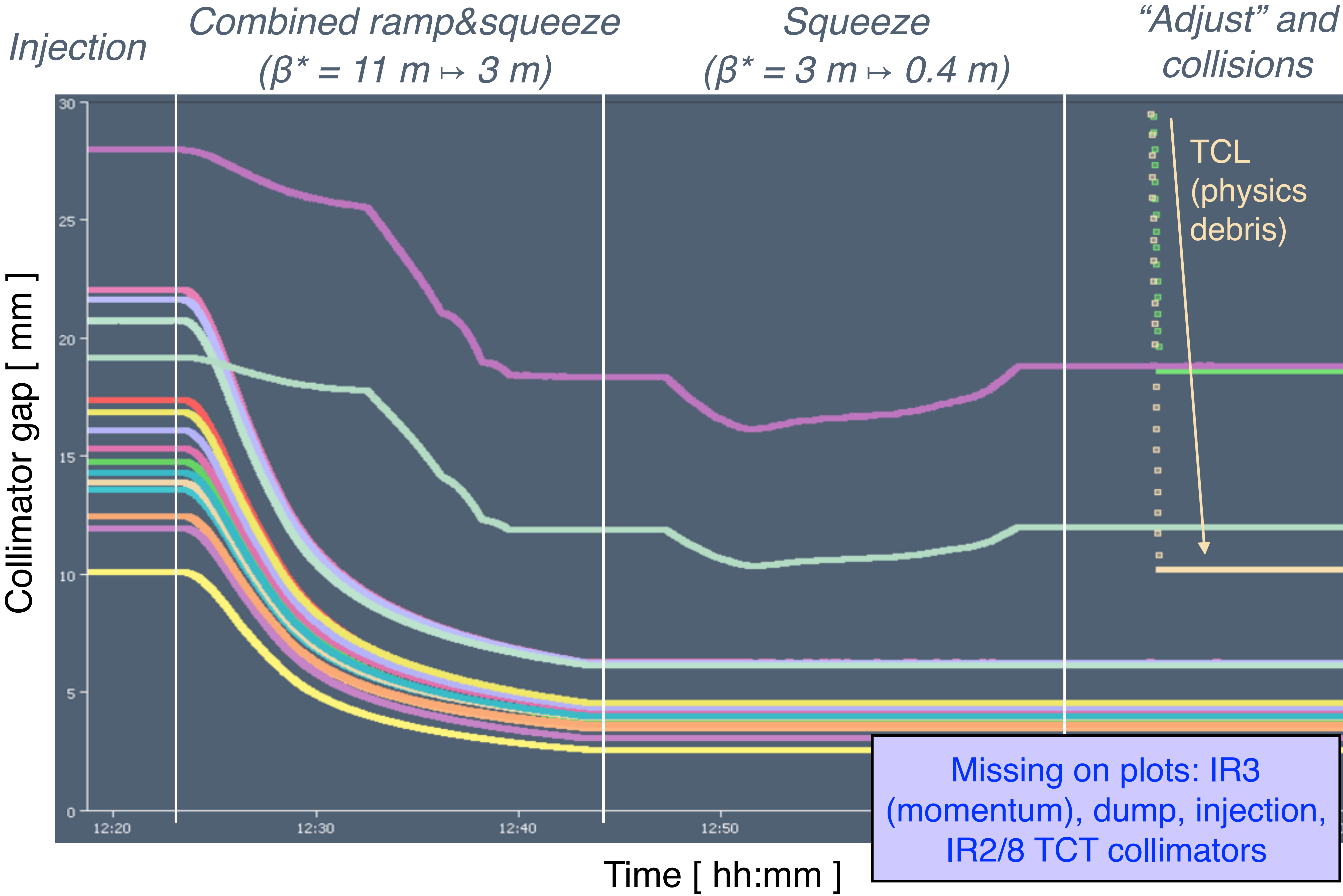
Collimator	Setting injection	Setting flat top (3m)	Setting collision
TCP IR7	5.7	5.5	5.5
TCSG IR7	6.7	7.5	7.5
TCLA IR7	10.0	11.0	11.0
TCP IR3	8.0	15.0	15.0
TCSG IR3	9.3	18.0	18.0
TCLA IR3	12.0	20.0	20.0
TCSG IR6	7.5	8.3	8.3
TCDQ IR6	8.0	8.3	8.3
TCT IR1/5	13.0	23.0	9.0
TCT IR2	13.0	37.0	37.0
TCT IR8	13.0	23.0	15.0
TCL 4/5/6, no Totem	out	out	15 / 15 / out
TCL 4/5/6, with Totem	out	out	15 / 35 / 20

Beam-based alignment carried out in each configuration, then smooth and continuous setting functions built to ensure optimum settings throughout the operational cycle.

Operational cycle — i

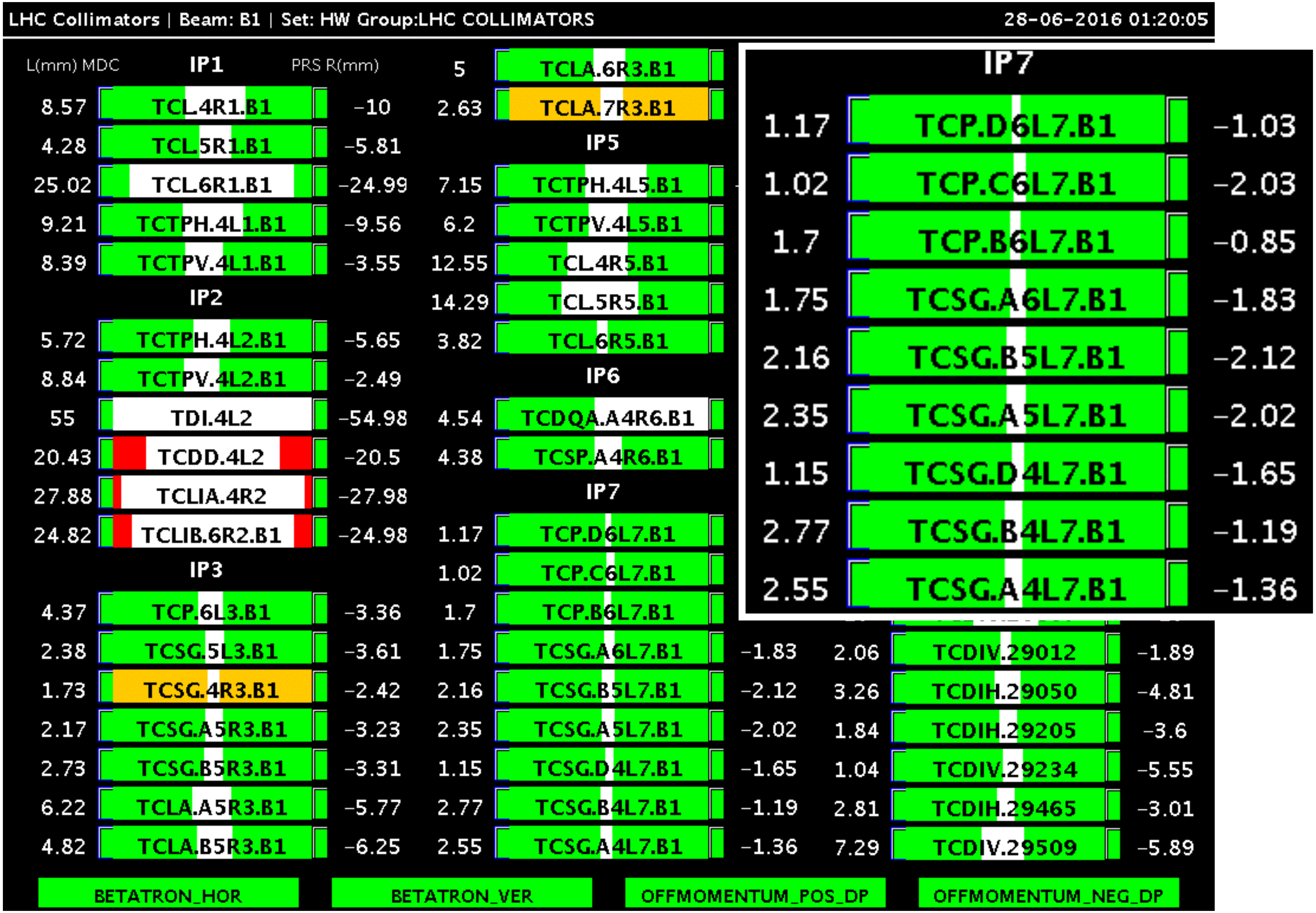


Operational cycle — ii

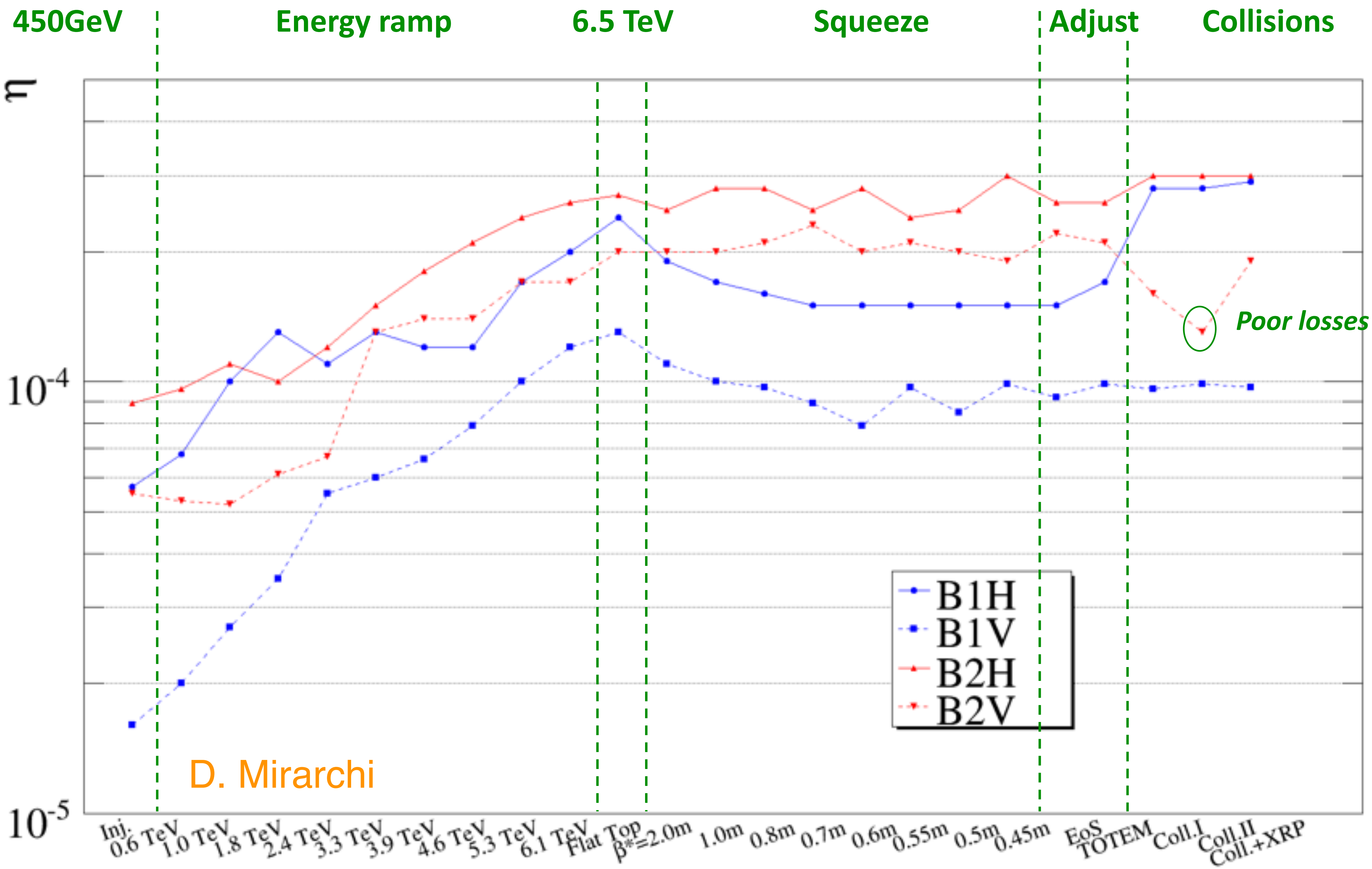


Missing on plots: IR3 (momentum), dump, injection, IR2/8 TCT collimators

Complete system, Beam 1

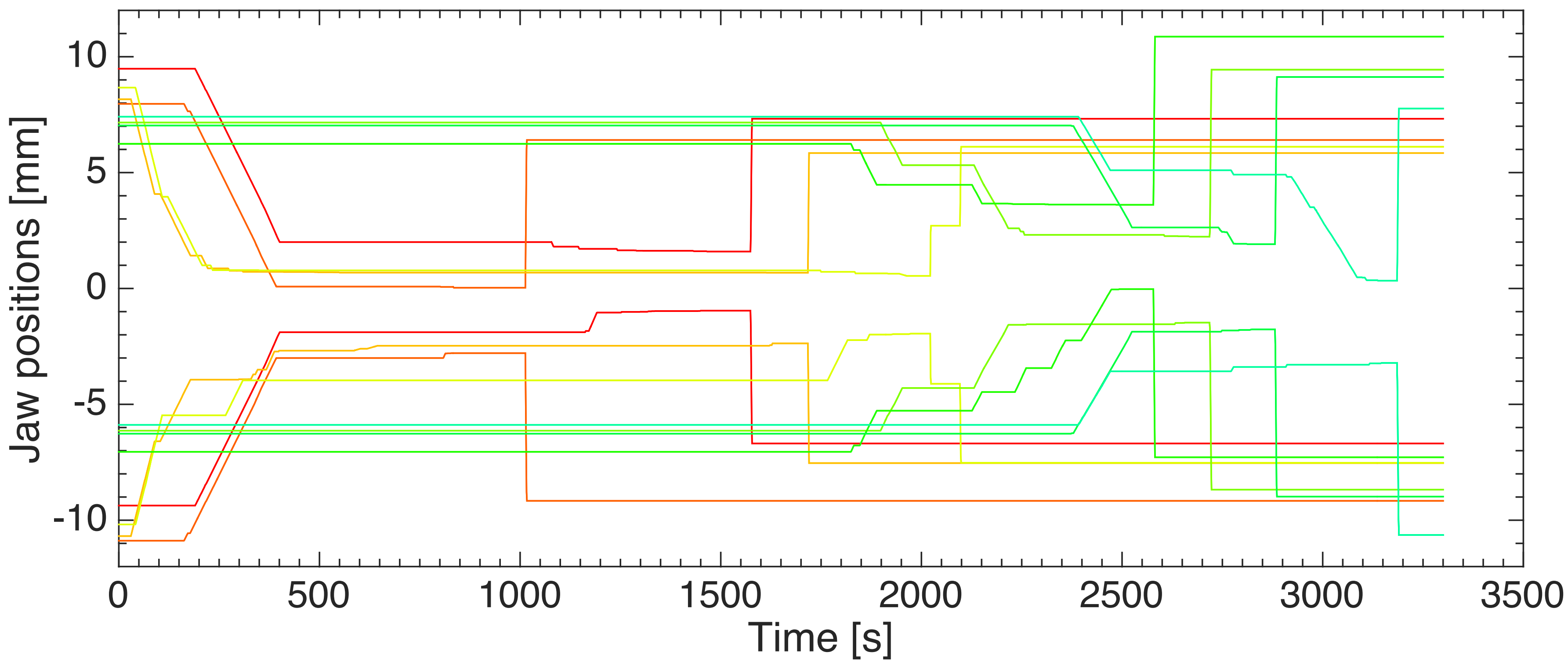


Cleaning throughout the cycle

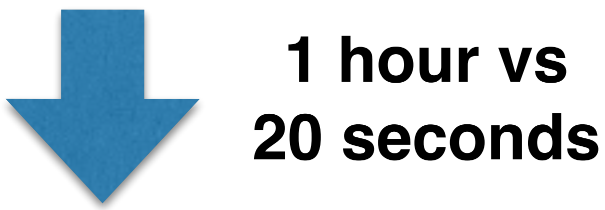


Excellent control of losses in all dynamics phases of the operational cycle!

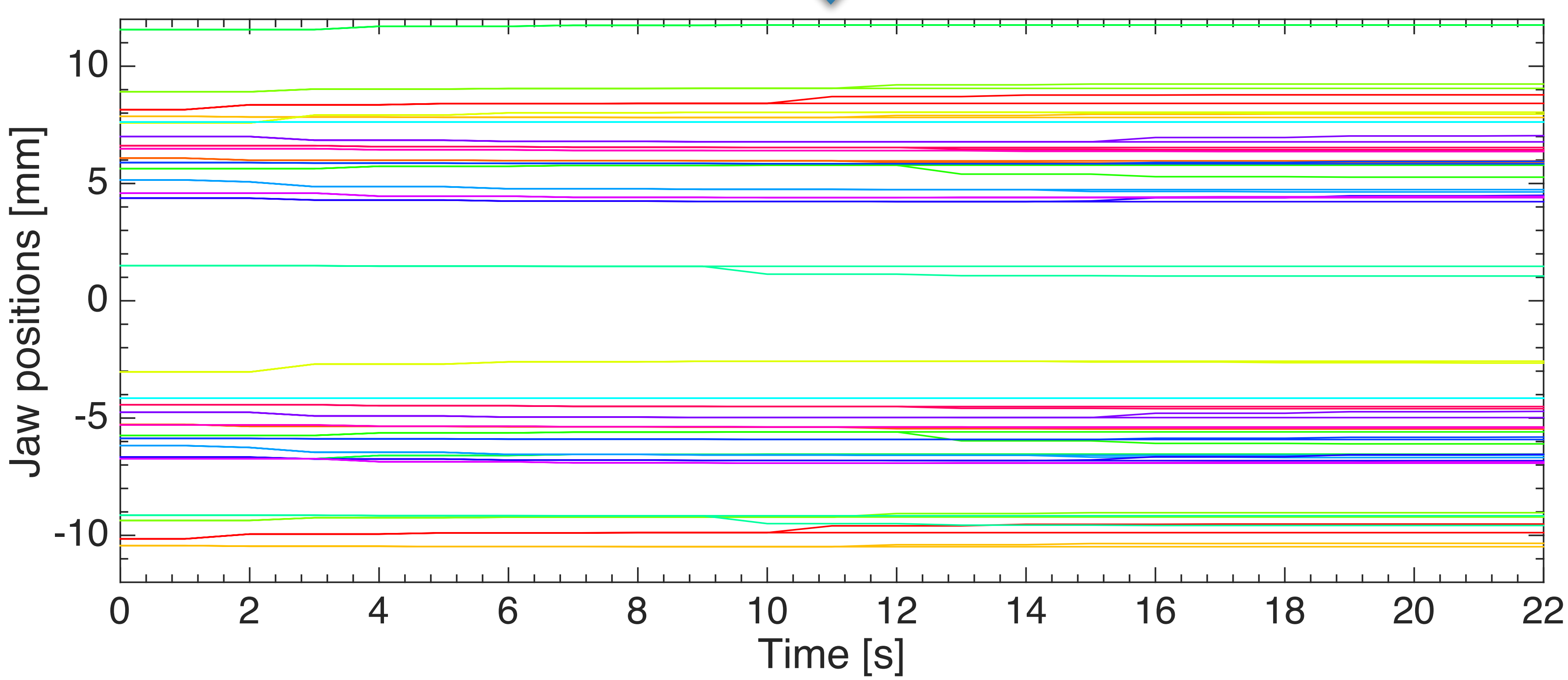
BPM collimators — alignment



Standard method: collimators closed until each jaw touches the beam halo. One collimator per beam at a time.

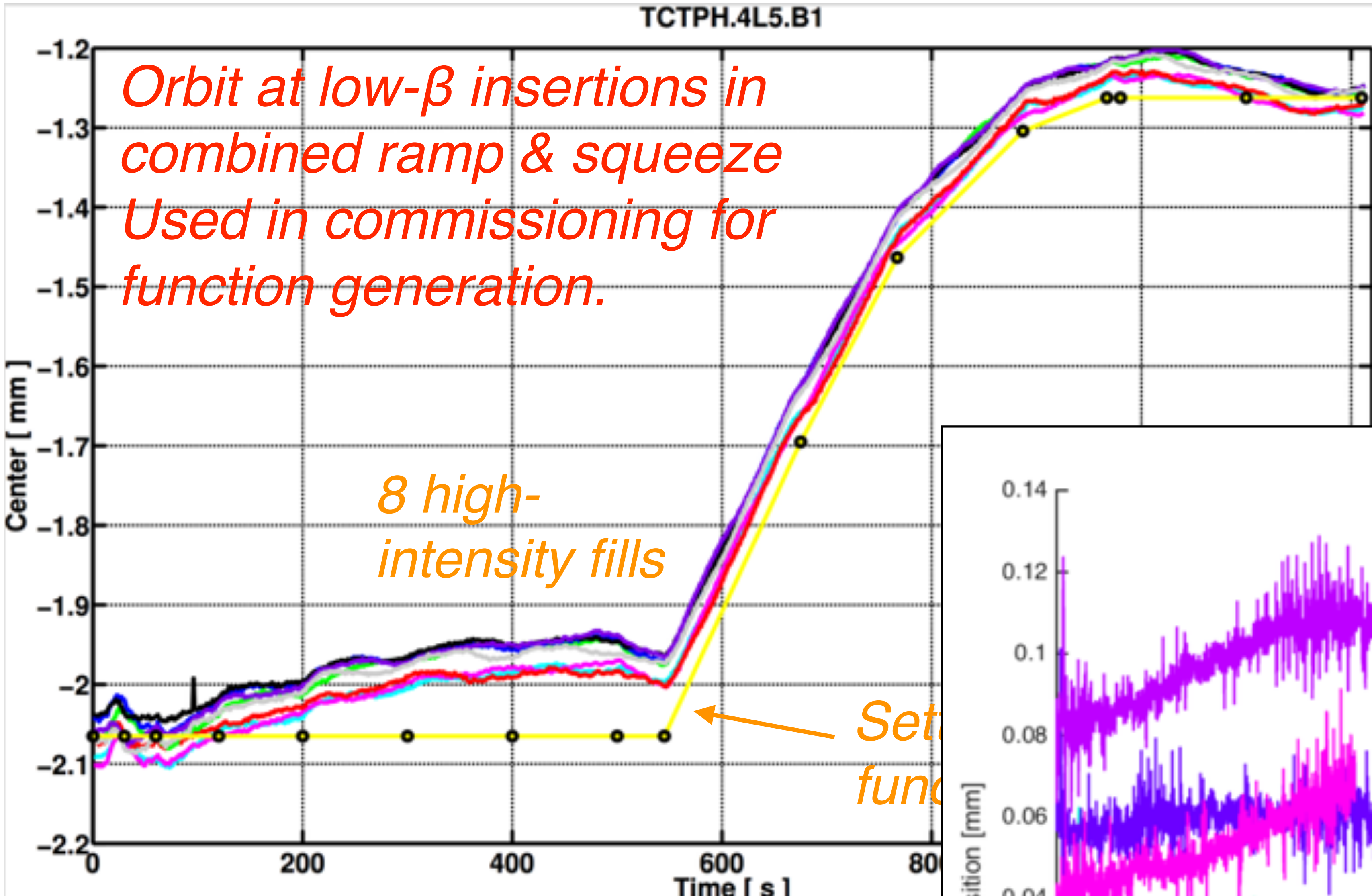


G. Valentino



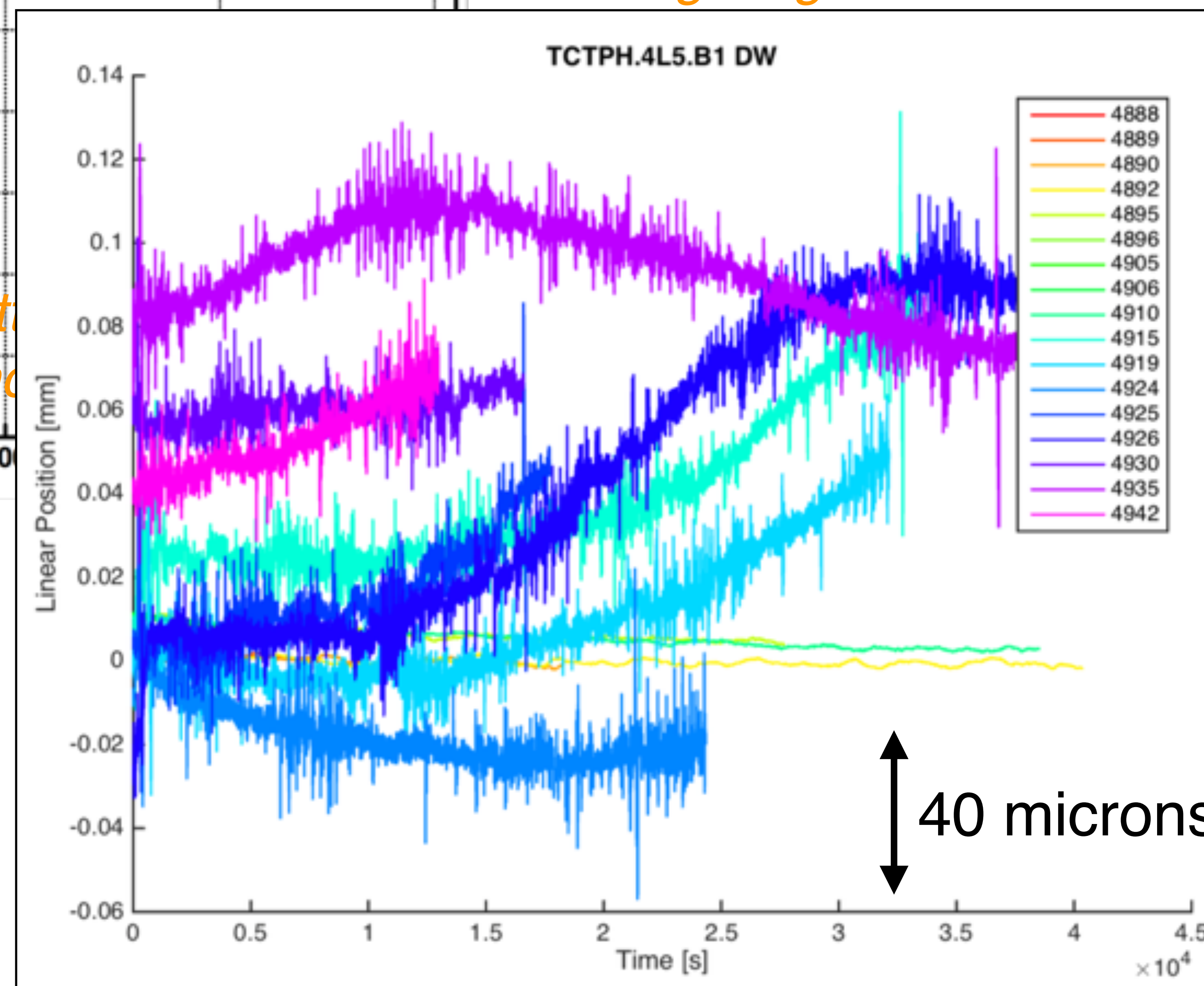
BPM alignment: done at large gaps, several collimators in parallel! Improved safety: jaws far from circulating beams. Can be done with any beam intensity.

BPM collimators — orbit monitoring



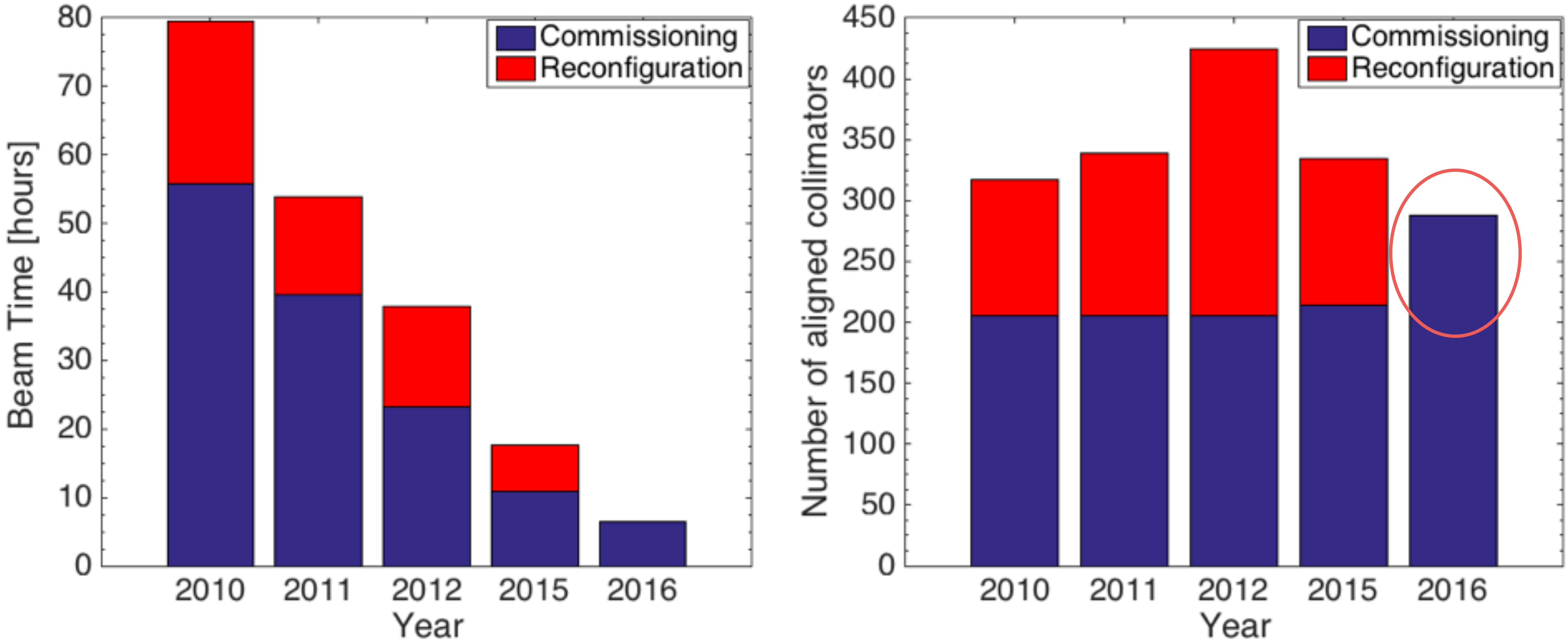
A. Mereghetti, A. Valloni

Monitoring of local orbit during long fills in collision.



We will exploit the possibility to set interlocks on orbit position to push forward the beta reach of the LHC!*

Overall alignment performance



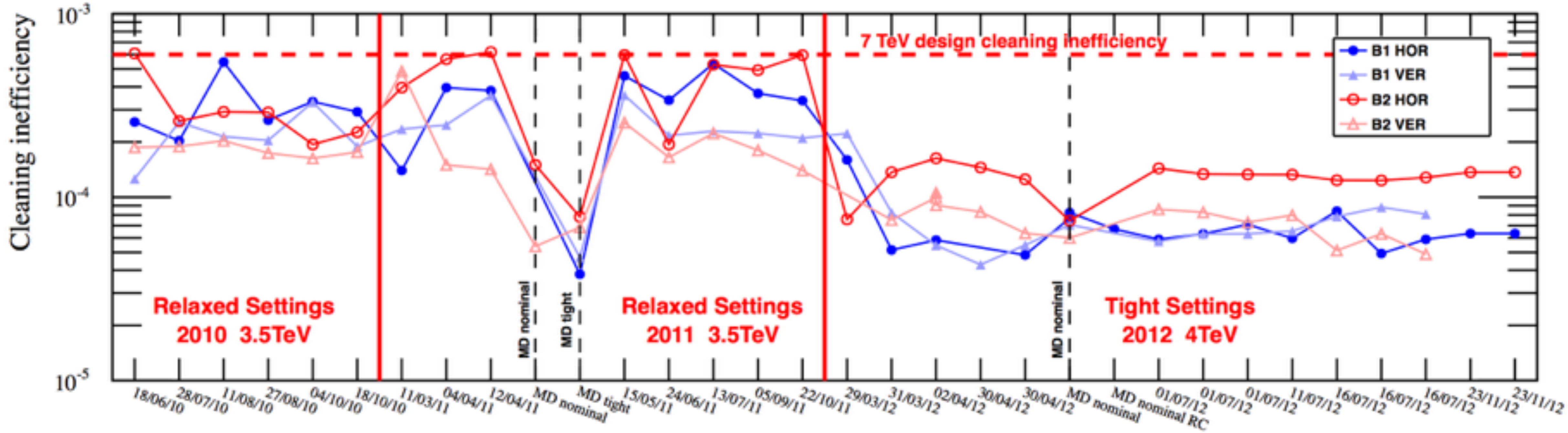
G. Valentino

Faster alignment = more flexibility for machine configuration changes.

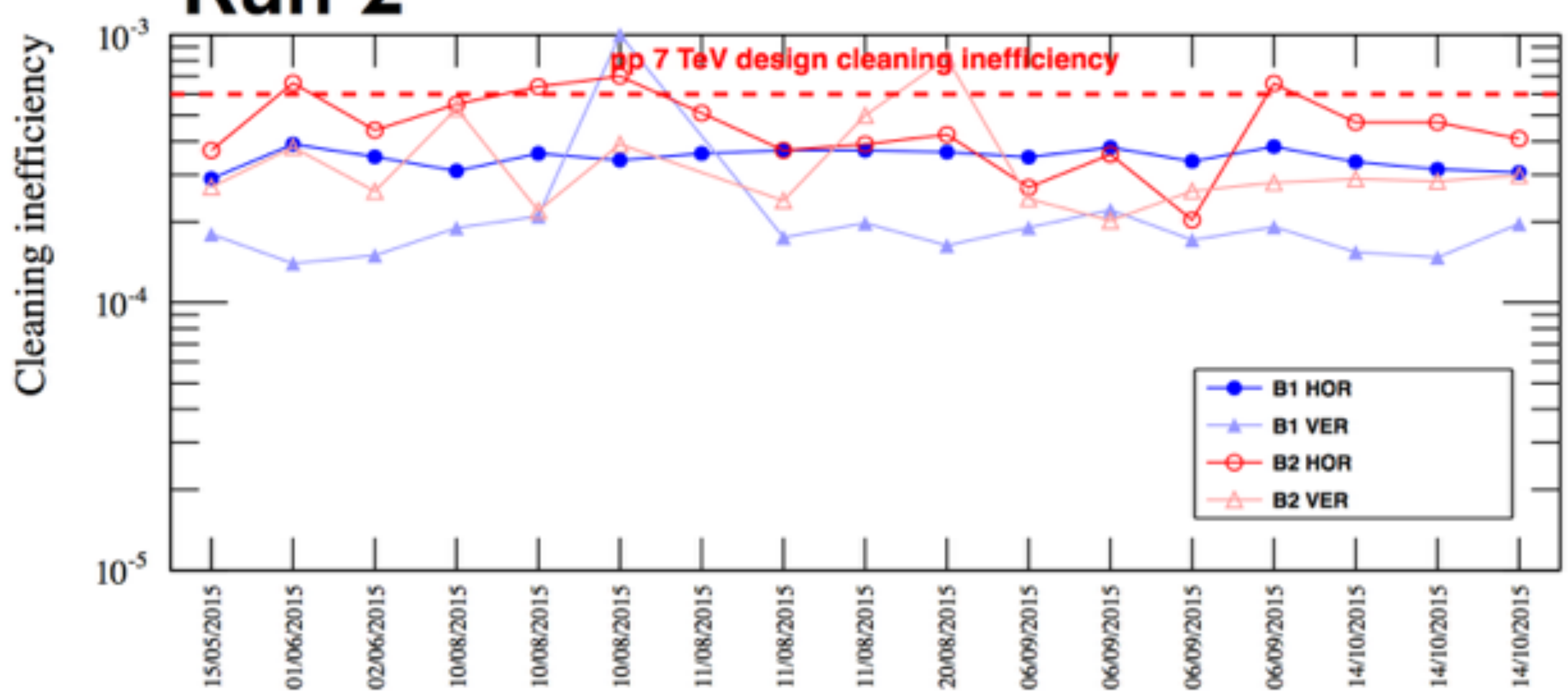
Recent improvements:
- BPM collimators;
- 100Hz BLM data used in closed loop;
- advanced algorithms for parallel alignment.

Stability of cleaning performance

Run I



Run 2



B. Salvachua

Excellent stability of performance achieved with **1 alignment per year**!

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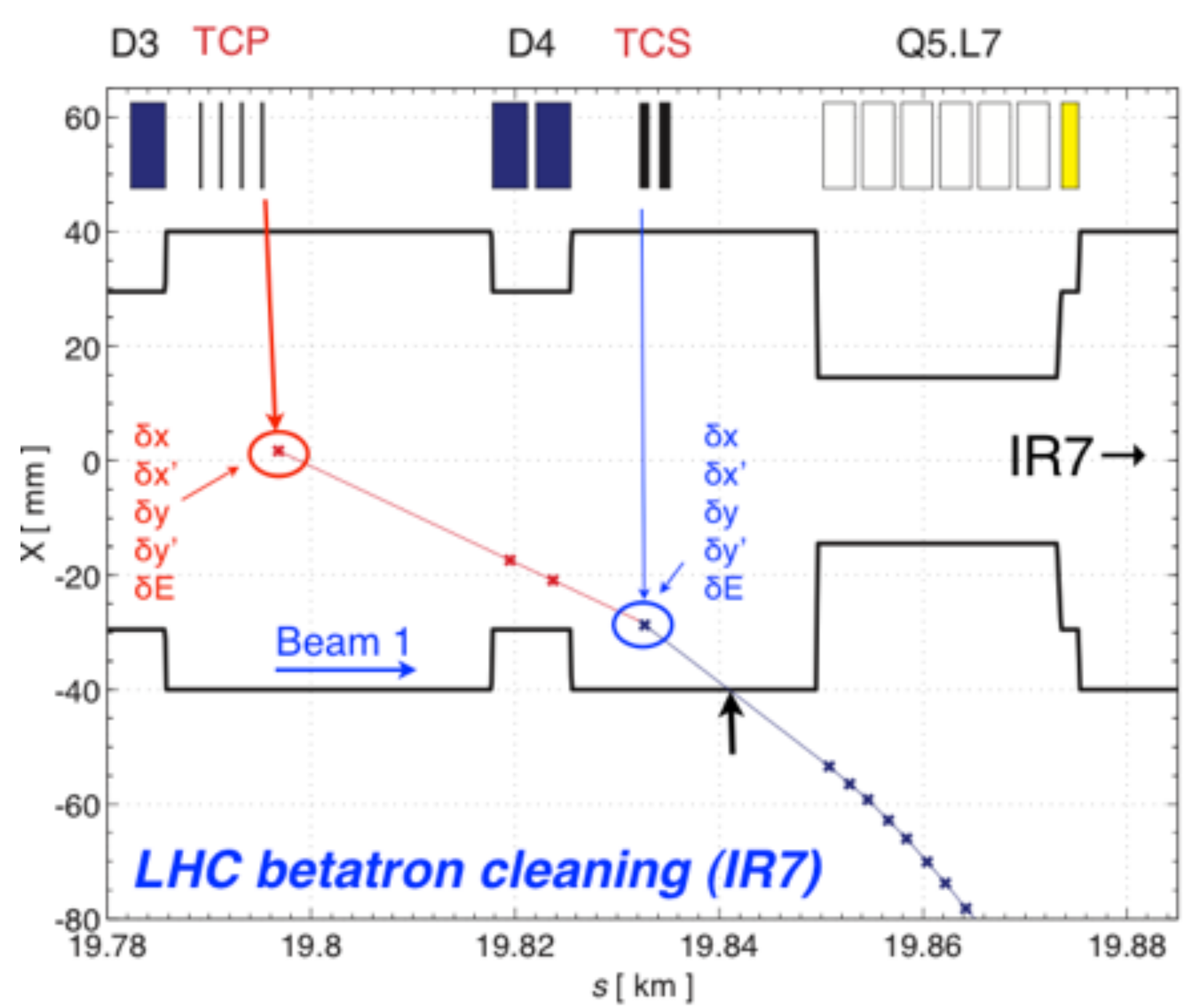
Simulation tools

Accurate tracking of halo particles 6D dynamics, chromatic effects, δp/p, high order field errors, ...	**SixTrack**
Detailed collimator geometry Implement all collimators and protection devices, treat any azimuthal angle, tilt/flatness errors	
Scattering routine Track protons inside collimator materials	**K2**
Detailed aperture model Precisely find the locations of losses	**BeamLossPattern**

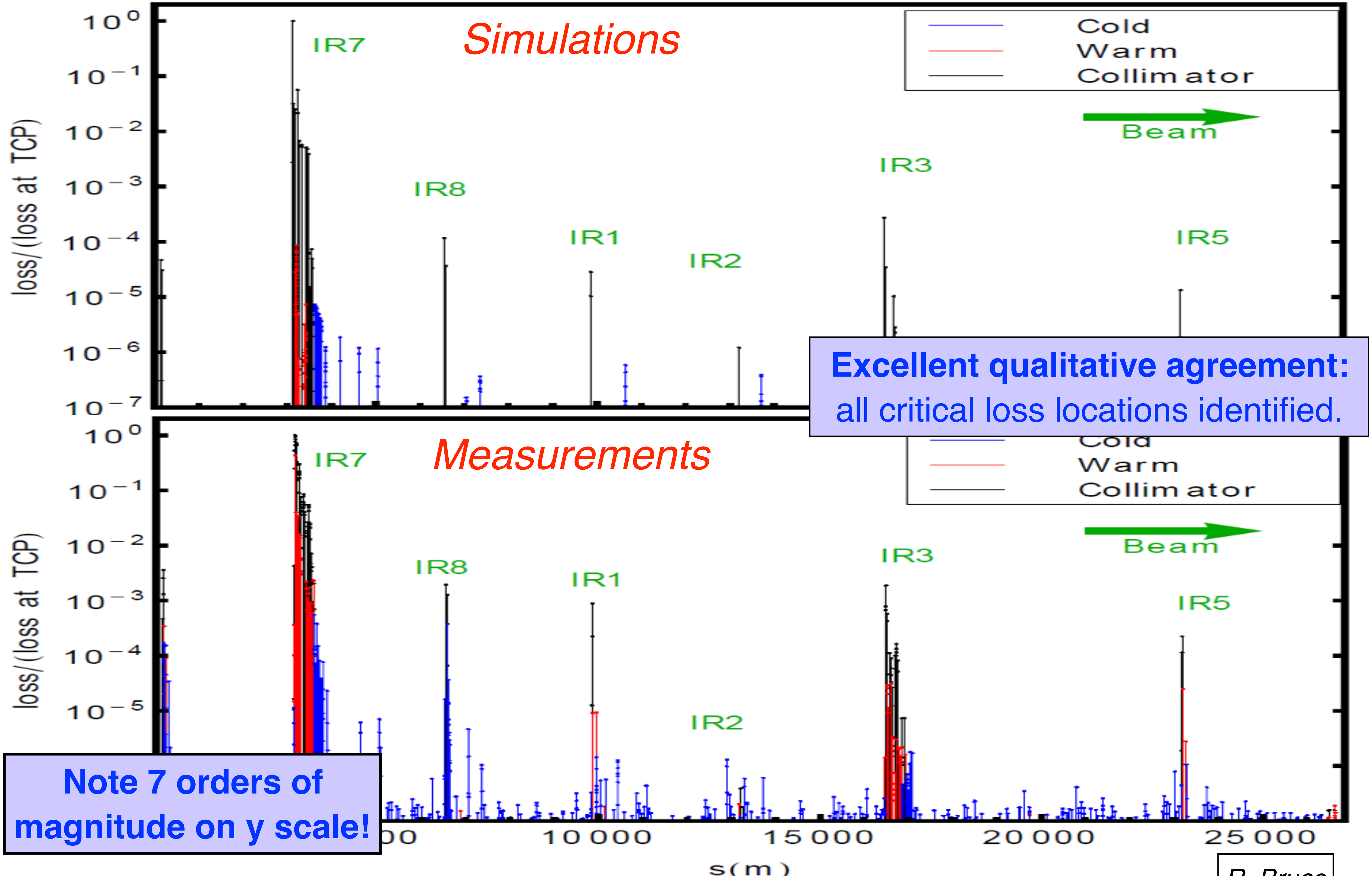
All combined in a simulation package for collimation cleaning studies: G. Robert-Demolaize, R. Assmann, S. Redaelli, F. Schmidt, **A new version of SixTrack with collimation and aperture interface**, PAC2005

Recent developments:

- New simulations for ion beams
- Crystal collimation implemented
- Coupling with FLUKA (EN/STI)
- Development of other tools (Merlin)
- Implementation on new materials
- …



Comparison — full ring at 3.5 TeV



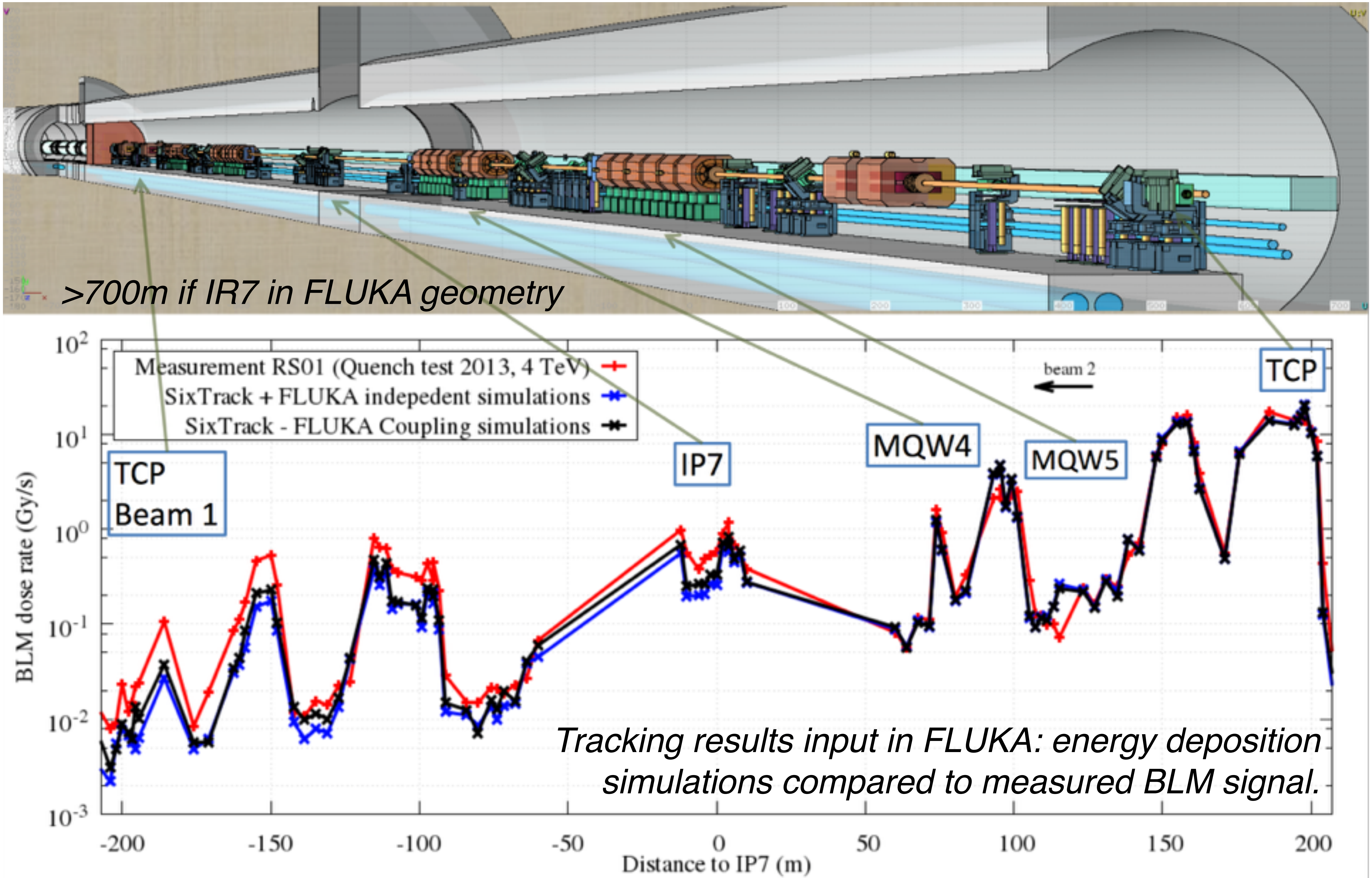
Excellent qualitative agreement:
all critical loss locations identified.

Note 7 orders of magnitude on y scale!

R. Bruce

Phys. Rev. ST Accel. Beams 17, 081004 (2014)

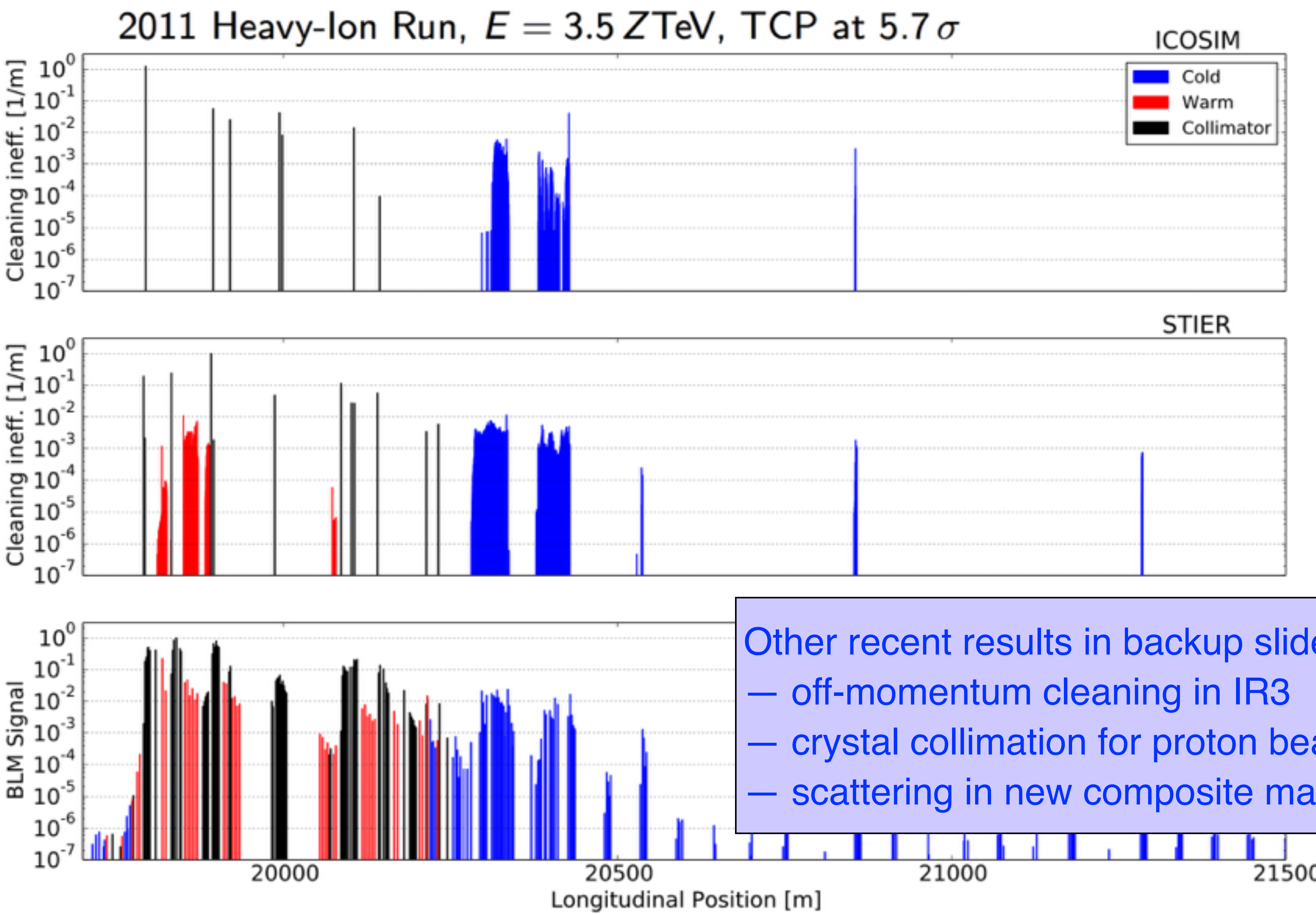
Complete simulations — energy deposition



E. Skordis for the CERN FLUKA team

Simulations of ion collimation

Nucl. Instrum. Meth. A819 (2016) 73-83



Other recent results in backup slides:

— off-momentum cleaning in IR3

— crystal collimation for proton beams

— scattering in new composite materials.

P. Hermes, PhD work

Results from energy deposition studies with hiSixtrack/FLUKA coupling in preparation.

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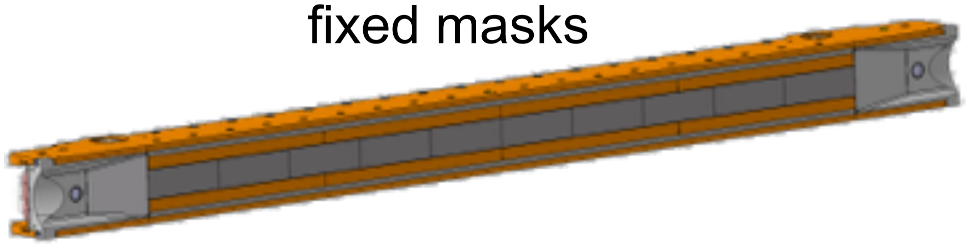
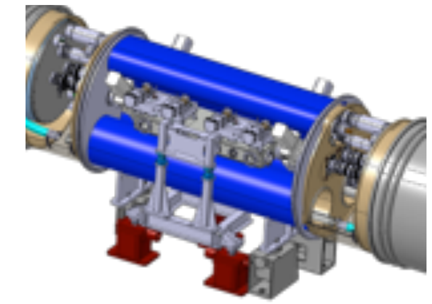
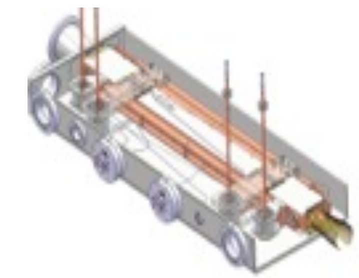
HL-LHC collimation upgrade

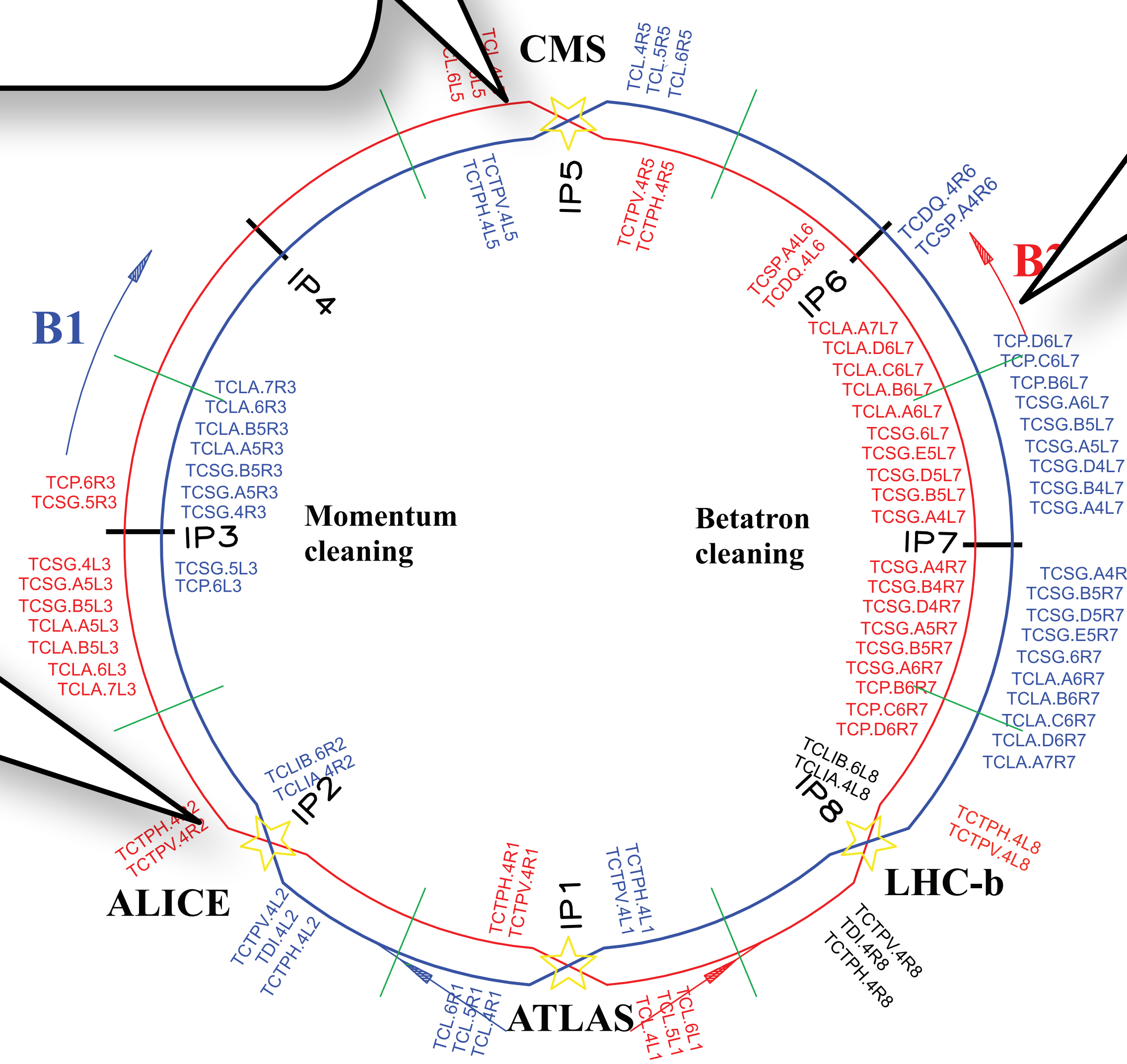
Completely new layouts
Novel materials: TCTs in CuCD
IR1+IR5, <u>per beam</u>:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks



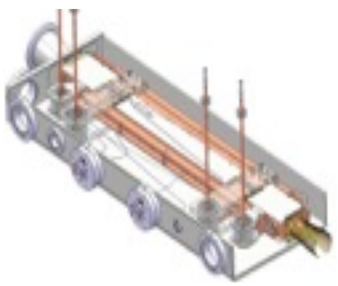
Cleaning: DS coll. + 11T dipoles, 2 units per beam



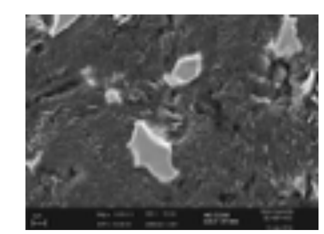


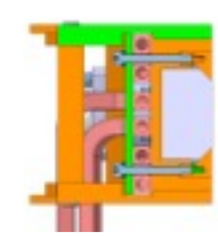


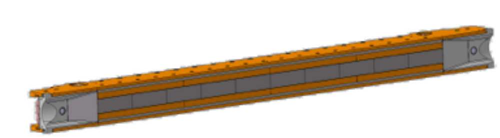
Ion physics debris: DS collimation



Low-impedance, high robustness secondary collimators: Mo coated MoGr

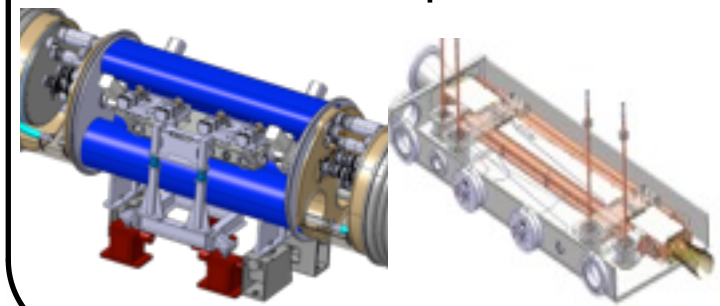




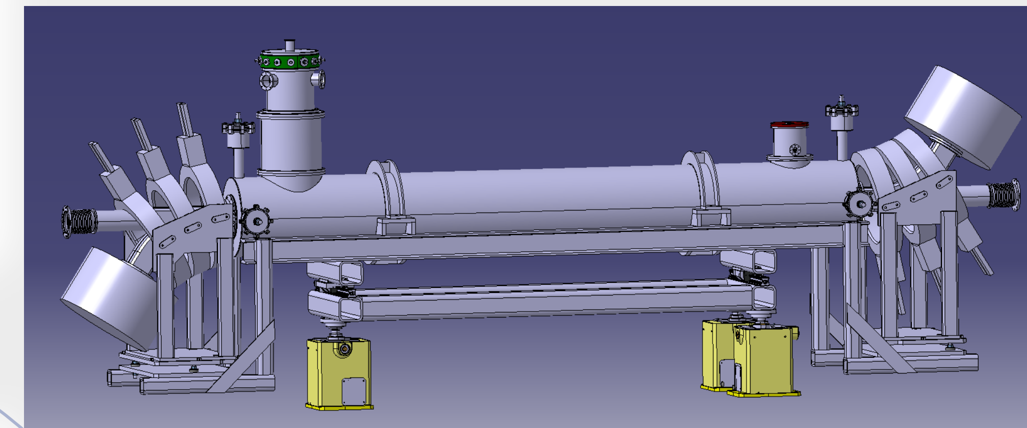


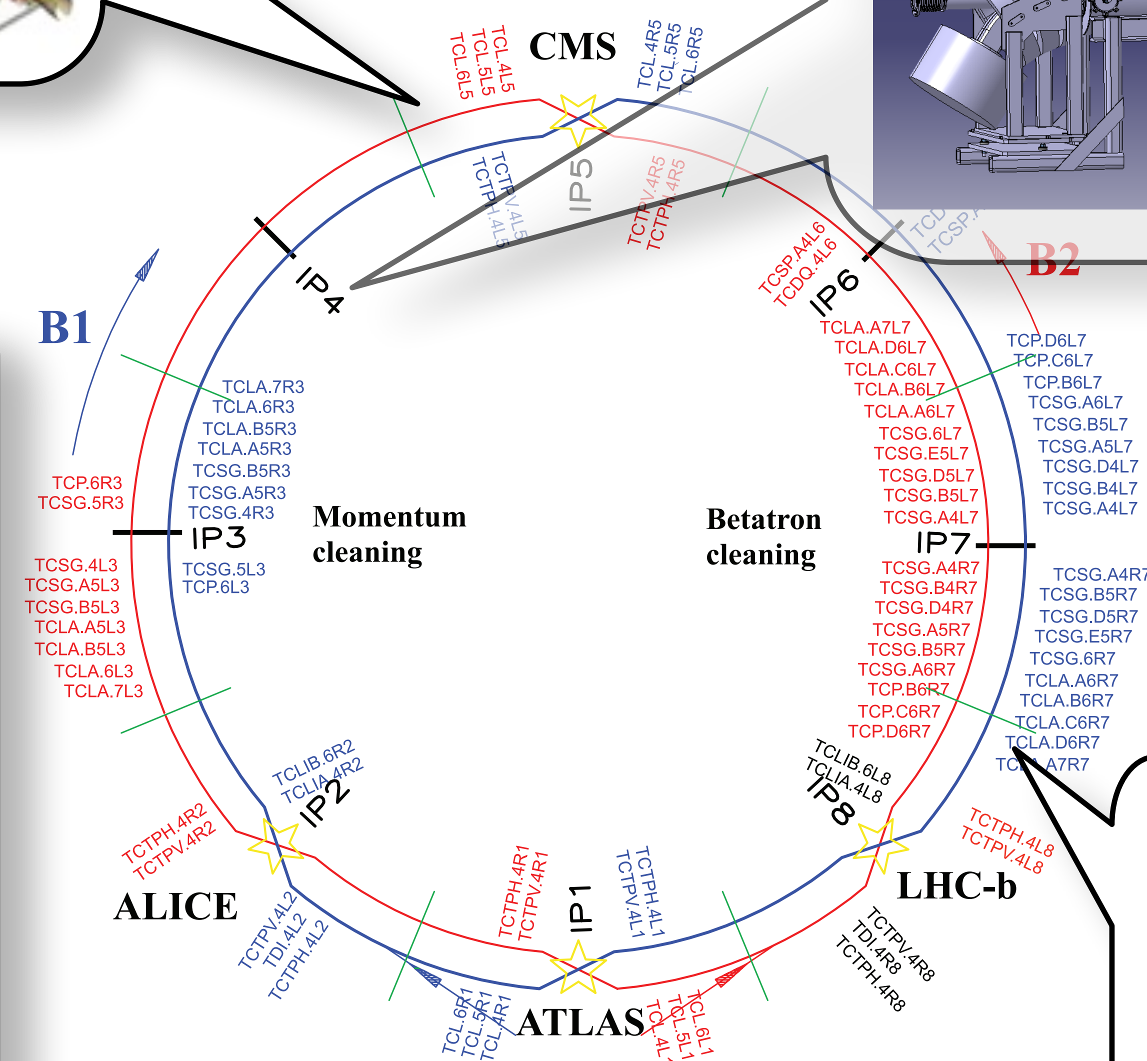
HL-LHC collimation studies

ATLAS/CMS physics debris:
DS coll. + 11T dipoles

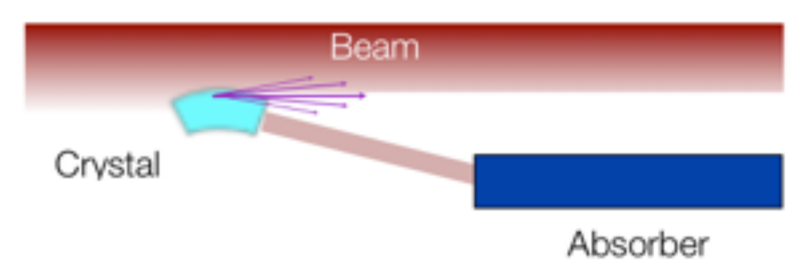


Hollow e-lenses for cleaning





Advanced materials in IR3:
low-impedance secondaries



Conclusions

- **Reviewed the collimation system for the LHC Run II (2015-18)**
  - *Important performance improvements following upgrades in the first long shutdown*
  - *New BPM collimators, better reliability and physics debris cleaning, fast alignment.*
- **The performance at 6.5TeV is very satisfactory**
  - *Cleaning efficiencies down to ~1e-4 ensured a quench-free operation with >250MJ*
  - *Continued improving duration and accuracy of collimator alignment campaigns.*
  - *Excellent machine and collimation stability.*
  - *Used the good performance to push the beta* to ~30% beyond nominal!*
- **Reported on recent results from continued effort to improve in simulations the understanding of collimation losses**
  - *Important improvements in the last years: integrated simulations.*
  - *Better modelling of heavy-ion loss mechanisms and patterns.*
- **Briefly recalled upgrade plans within HL-LHC project**
  - *Lower impedance, dispersion suppressor cleaning and new IR layouts are the keys to achieve a further factor 2 in stored beam energies at the HL-LHC*
  - *Exciting R&D program on hollow lenses and crystal collimation continues*