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Advances in Beam Collimation at CERN

Stefano Redaelli, BE-ABP, on behalf of the collimation team

ARIES-APEC: “Mitigation Approaches for Storage Rings and Synchrotrons”
22nd June to 1st July, 2020 — Remote Event

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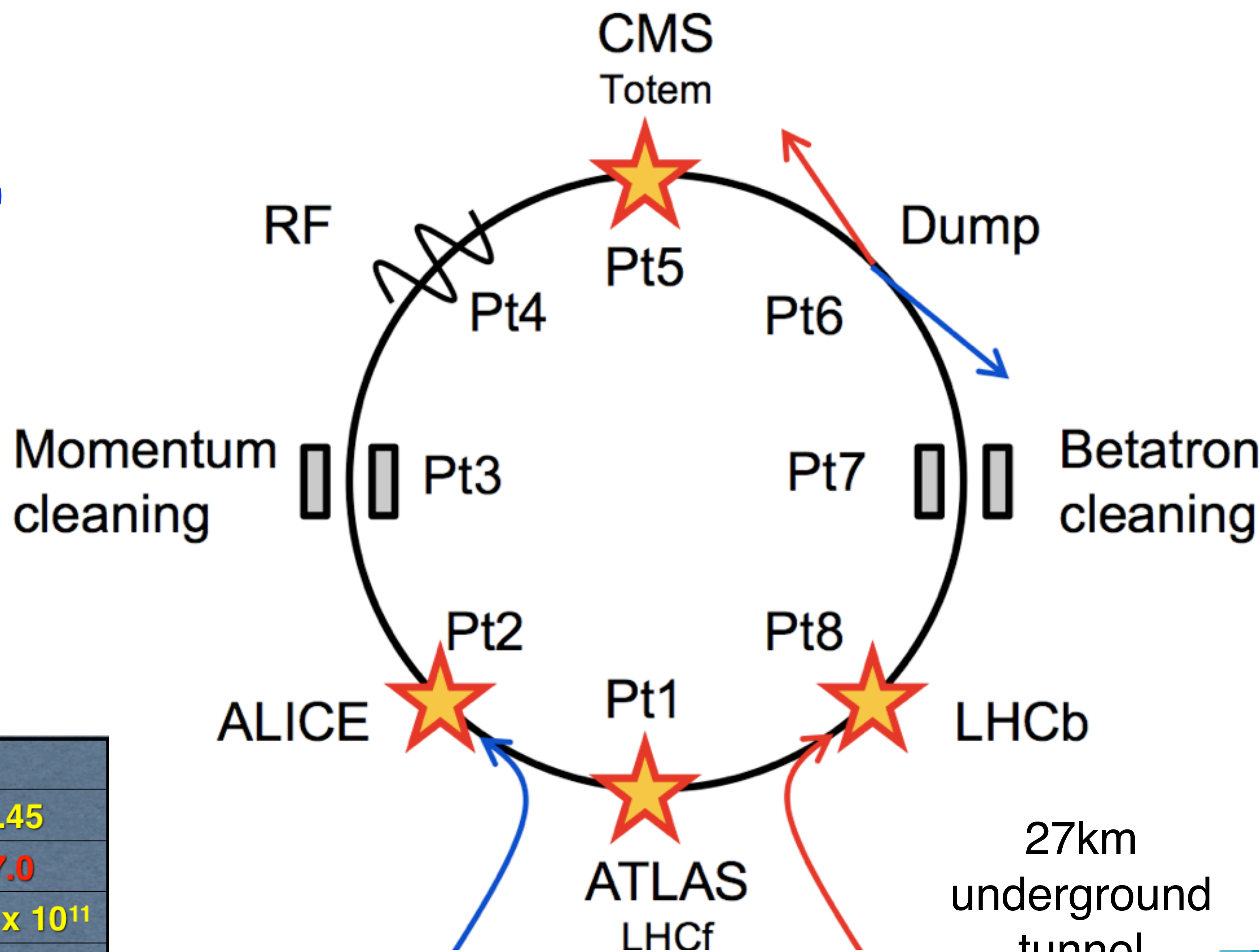
The Large Hadron Collider

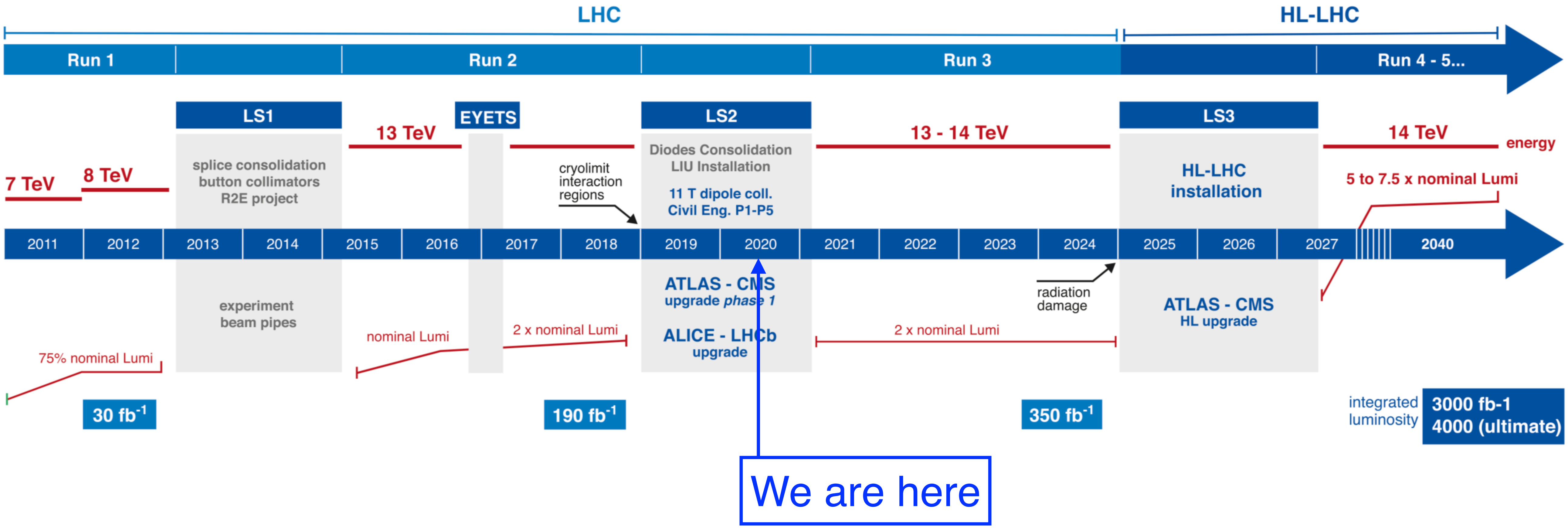
LHC Layout

- 8 arcs (~3 km)
- 8 straight sections (~700 m)
- Two-in-one magnet design
- 4 interaction points (IPs): IP1, IP2, IP5, IP8
- IP2/IP8: beam injection
- IP6: beam dump region
- IP4: RF (acceleration)
- IP3/IP7: **beam cleaning**



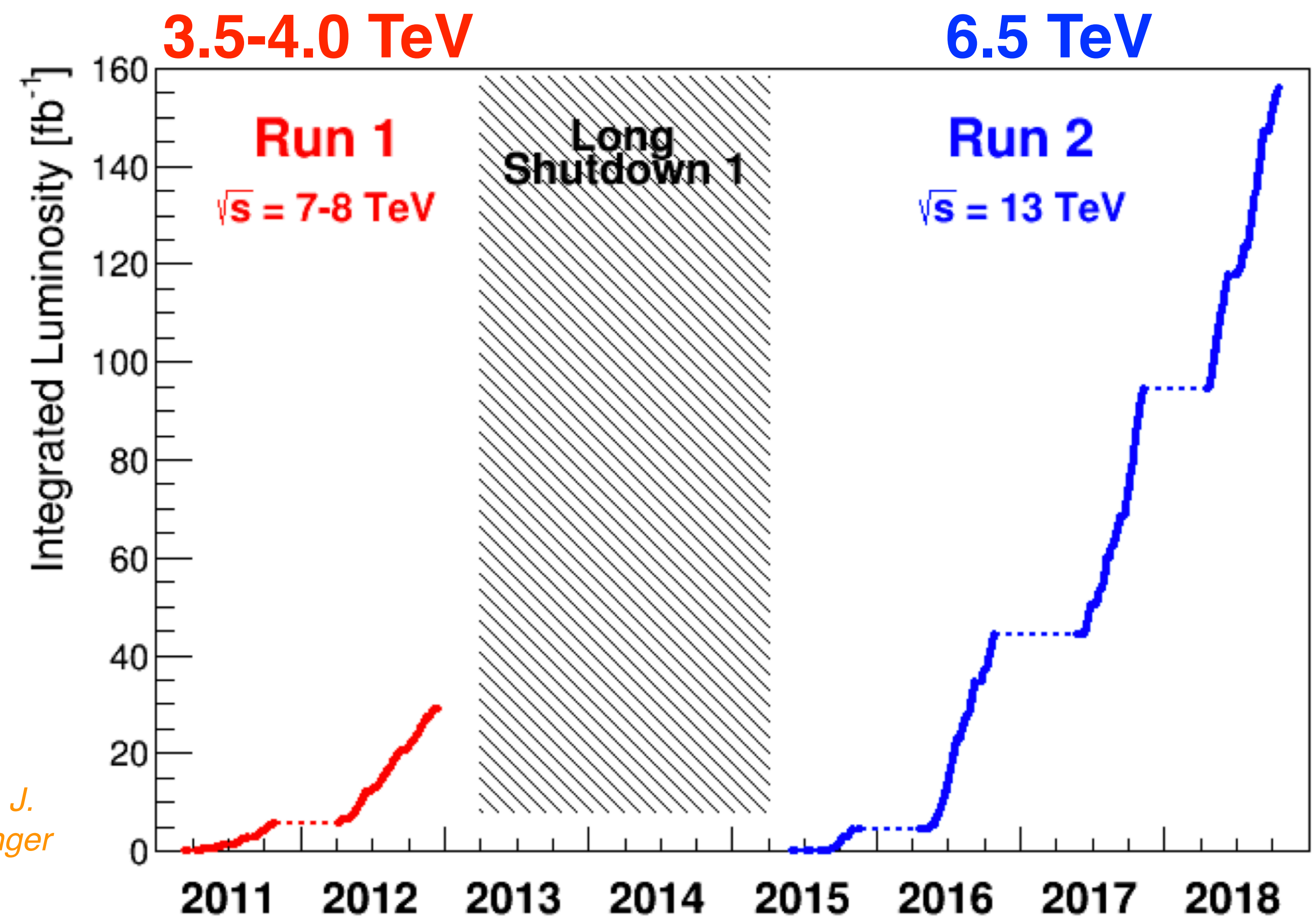
Nominal LHC parameters	
Beam injection energy (TeV)	0.45
Beam energy (TeV)	7.0
Number of particles per bunch	1.15×10^{11}
Number of bunches per beam	2808
Max stored beam energy (MJ)	362
Norm transverse emittance (μm rad)	3.75
Colliding beam size (μm)	16
Bunch length at 7 TeV (cm)	7.55

Timeline, and schedule as of 03/2020



"LS" = Long Shutdown
Run 1: 2010-2013 (3.5 TeV → 4.0TeV)
Run 2: 2015-2018 (6.5 TeV)
LIU: LHC Injector Upgrade, being deployed in LS2
HL-LHC: High-Luminosity LHC. Deployed in LS3, with important upgrades already taking place in LS2.

LHC performance in a nutshell



Court. J. Wenninger

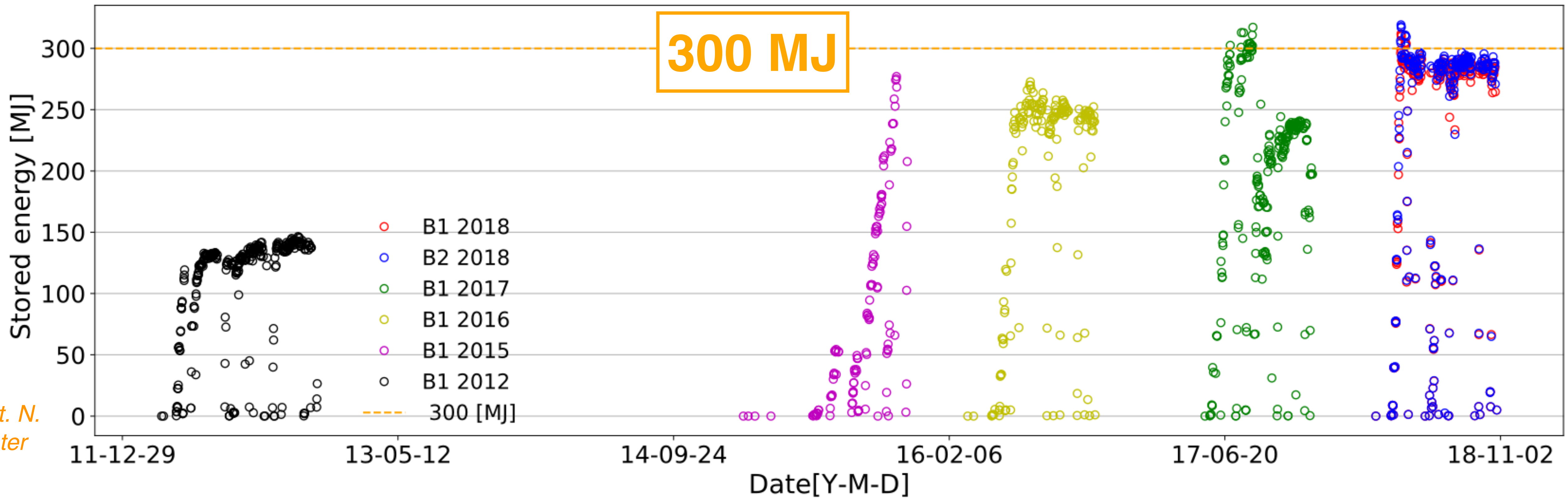
Period	Int. Luminosity [fb^{-1}]
Run 1	29.2
Run 2: 2015	4.2
Run 2: 2016	39.7
Run 2: 2017	50.2
Run 2: 2018	66
Total Run 1+ 2	**189.3**

Parameter	Design	2018
Bunch population N_b [10^{11} p]	1.15	**~1.2 (→ 1.4)**
No. bunches per train	288	**144**
No. bunches	2808	**2556**
Emittance ε [mm mrad]	3.75	**~2.2**
Full crossing angle [μrad]	285	**300 → 260**
β^* [cm]	55	**30 → 27.5 → 25**
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	**~2**

Key aspects related to beam collimation: handling high intensities, safe operation with very small β*, operational efficiency.

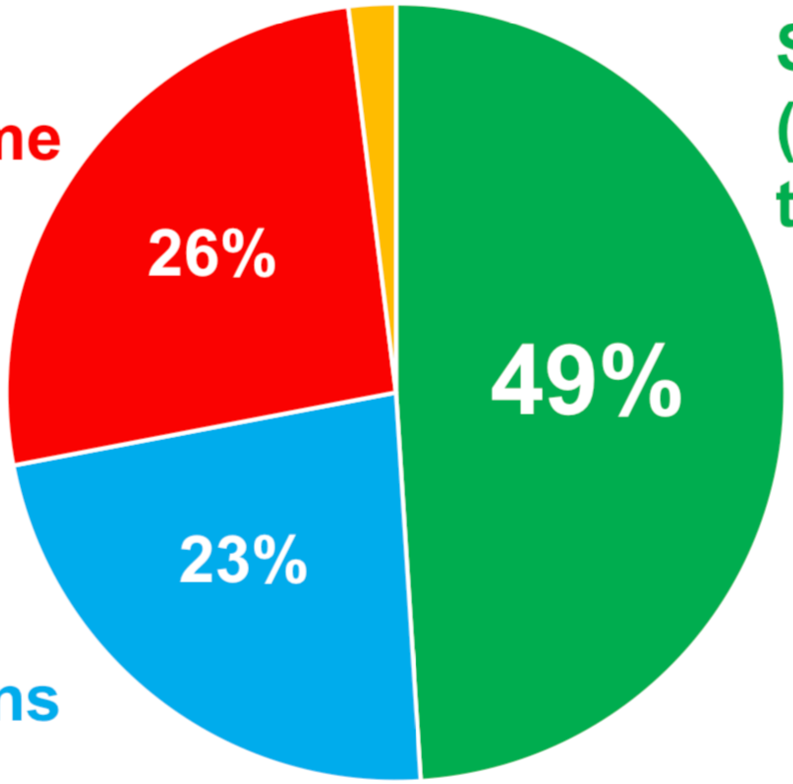
Crossing angle & β^* levelling in IP1/5

Beam stored energy at the LHC



Court. N. Fuster

So far, <u>no quenches</u> from “collimation losses”, throughout the operational cycle (injection, ramp, combined ramp&squeeze, squeeze at flat top, luminosity levelling). Very good control of losses.



Court. LHC OP team

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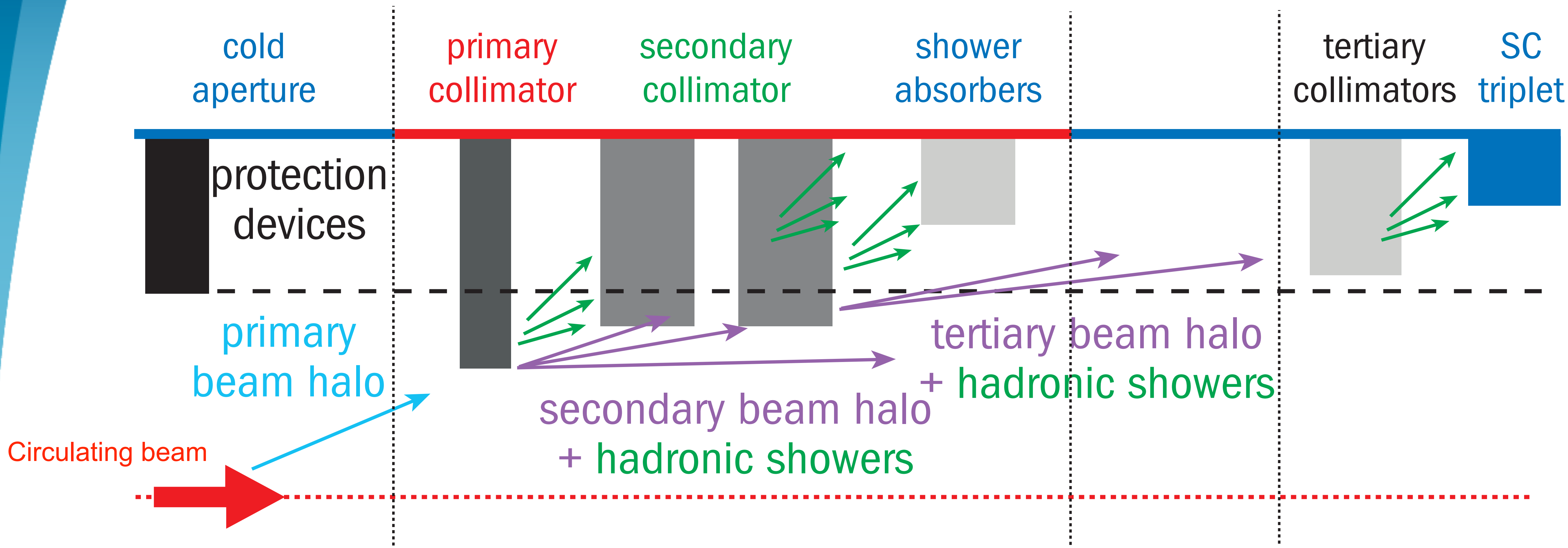
LHC multi-stage collimation



Three-stage cleaning in warm **cleaning 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

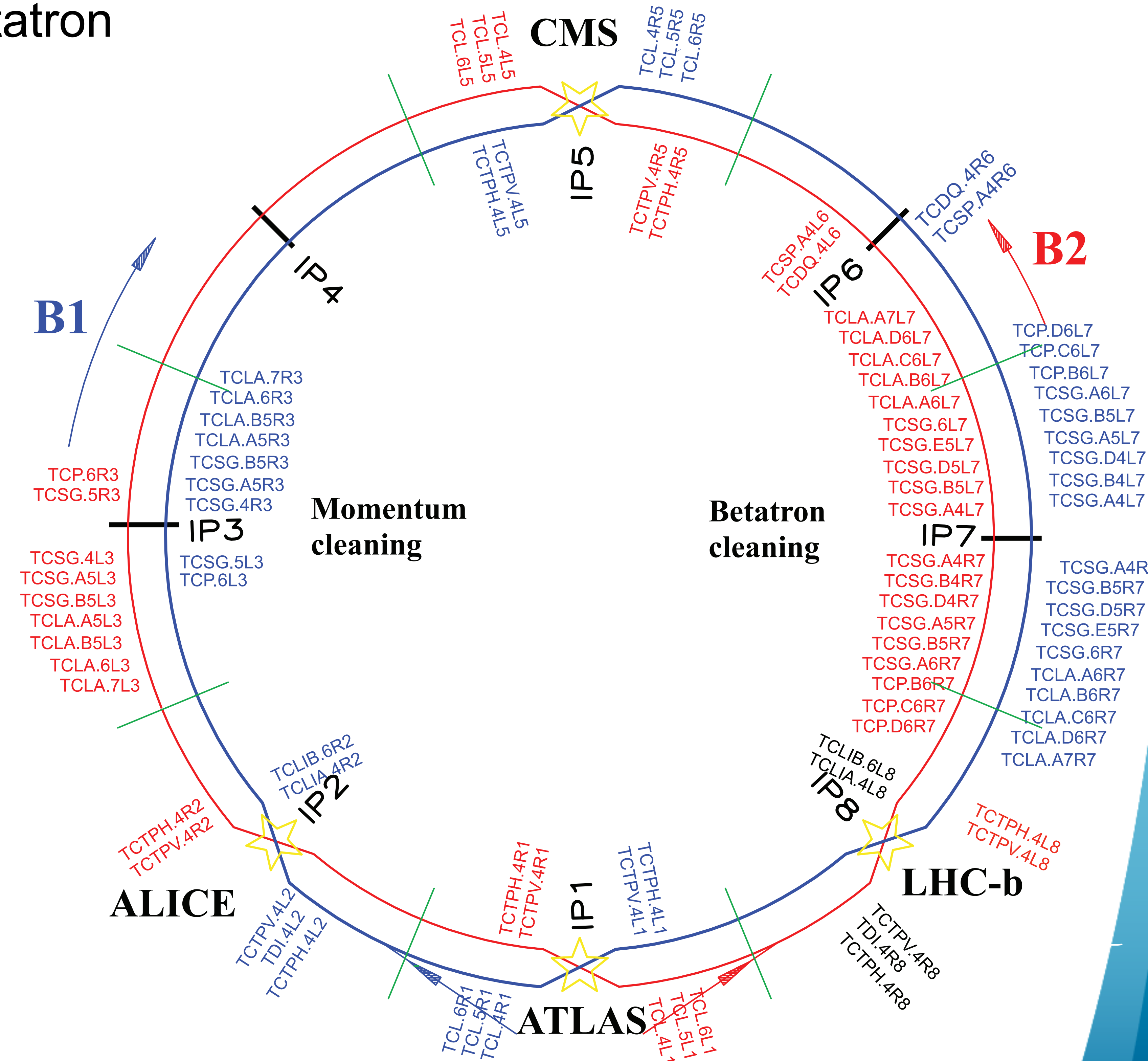
Distributed losses over many collimators to dispose safely of total losses.

LHC collimation layouts

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.



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

LHC collimation layouts

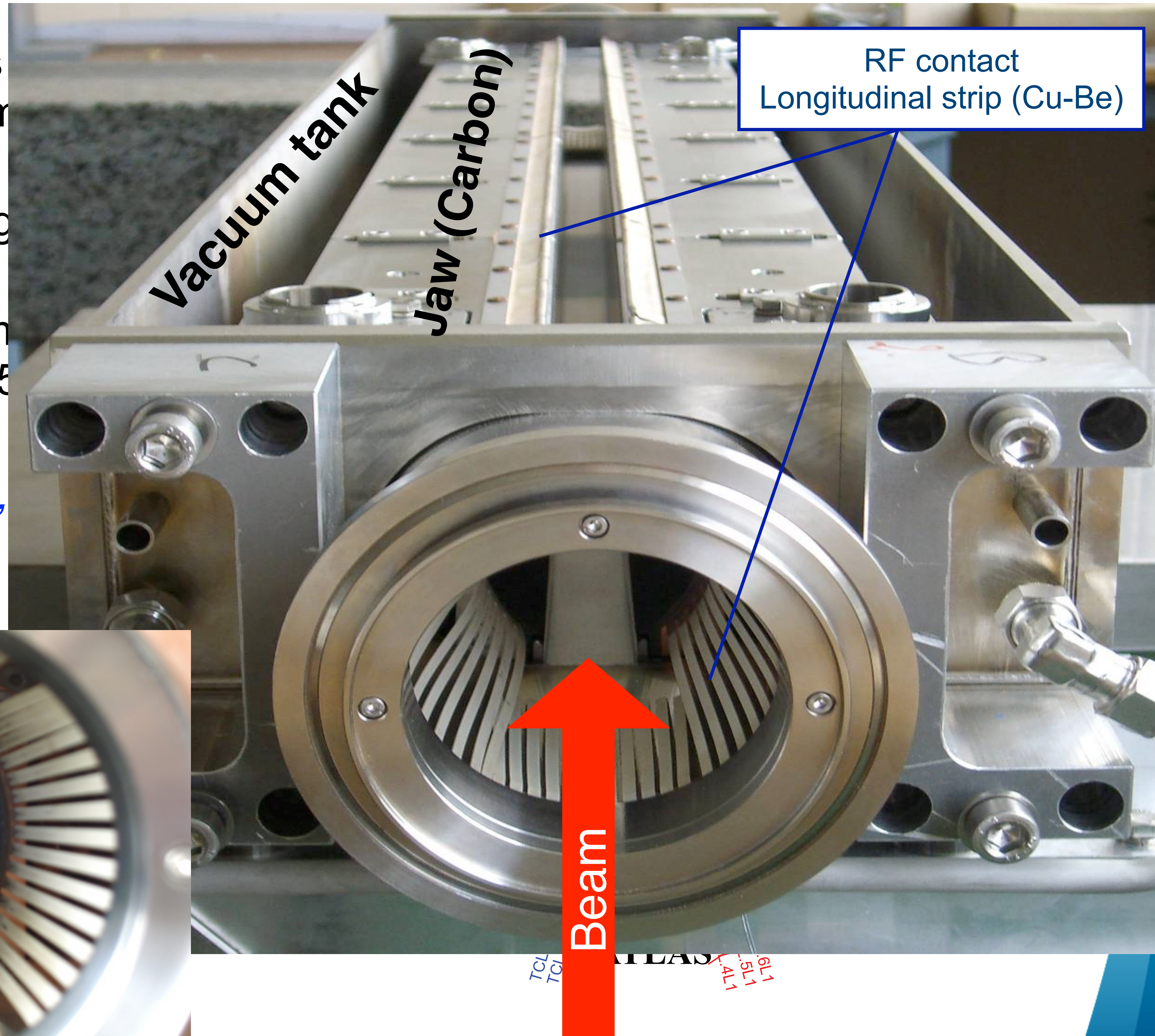
Dedicated insertions (IR7) and momentum cleaning systems.

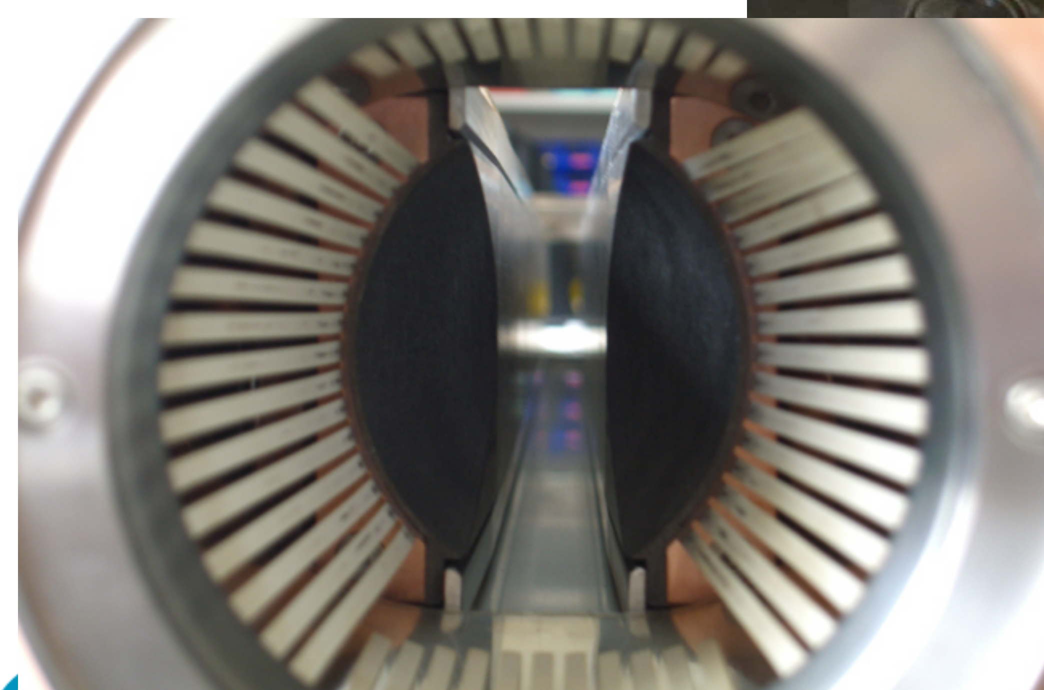
Cleaning of incoming in all experiments.

Physics debris collim in the high-lumi IR1/5

Materials: Carbon fibre (CFC), Tungsten, Copper

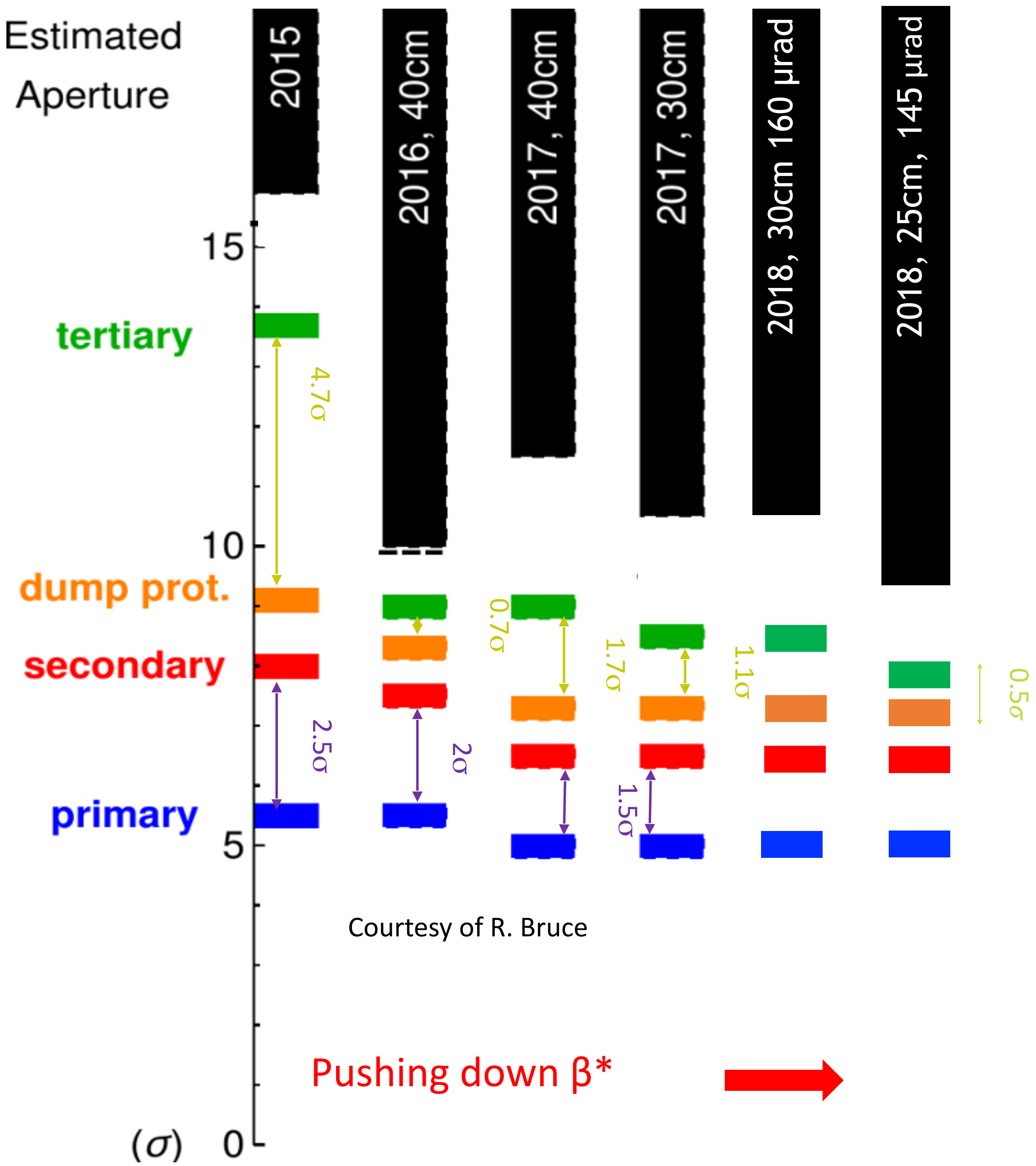
What the beam sees!



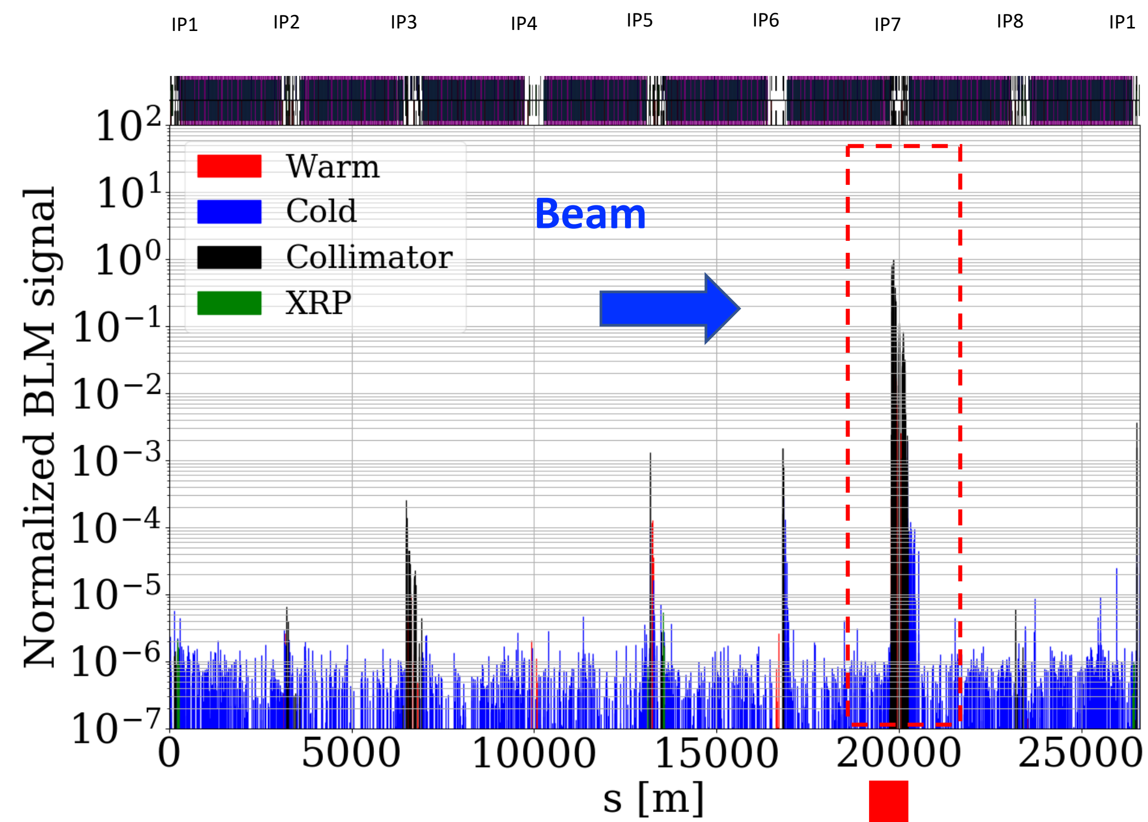


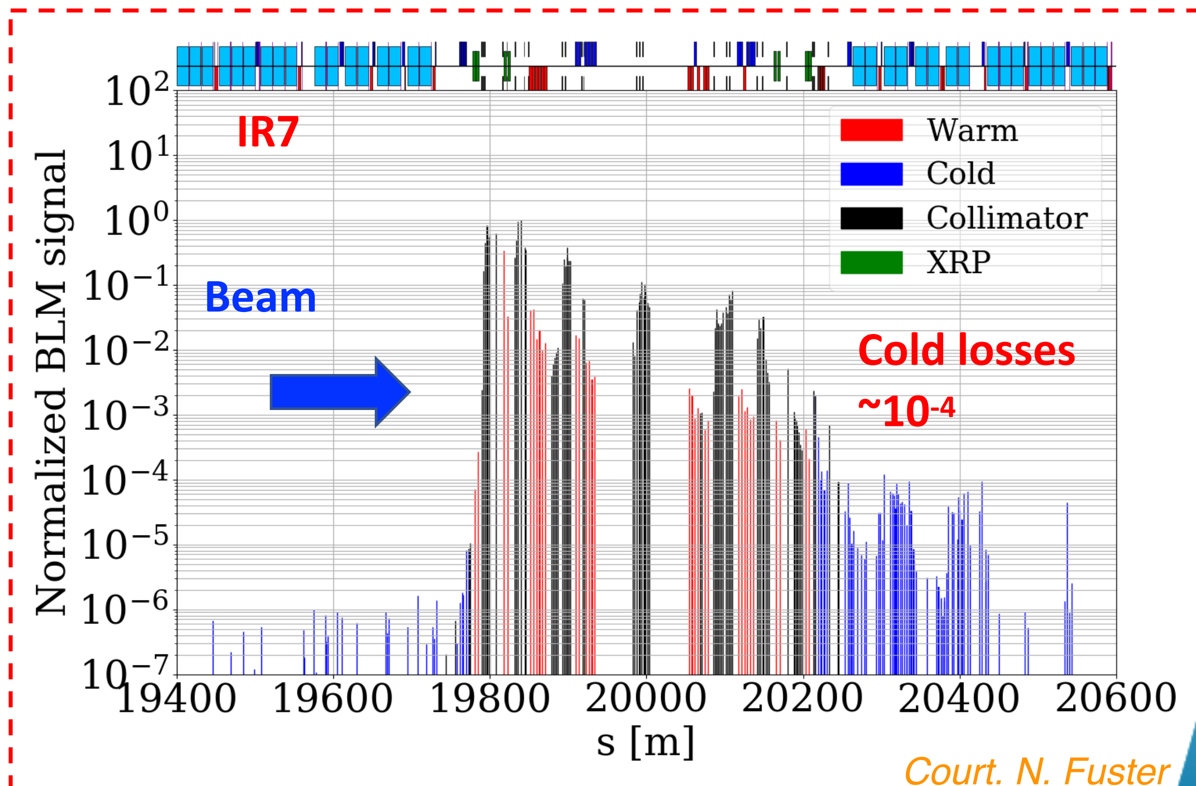
Collimator hierarchy and cleaning

LHC Collimation Project CERN



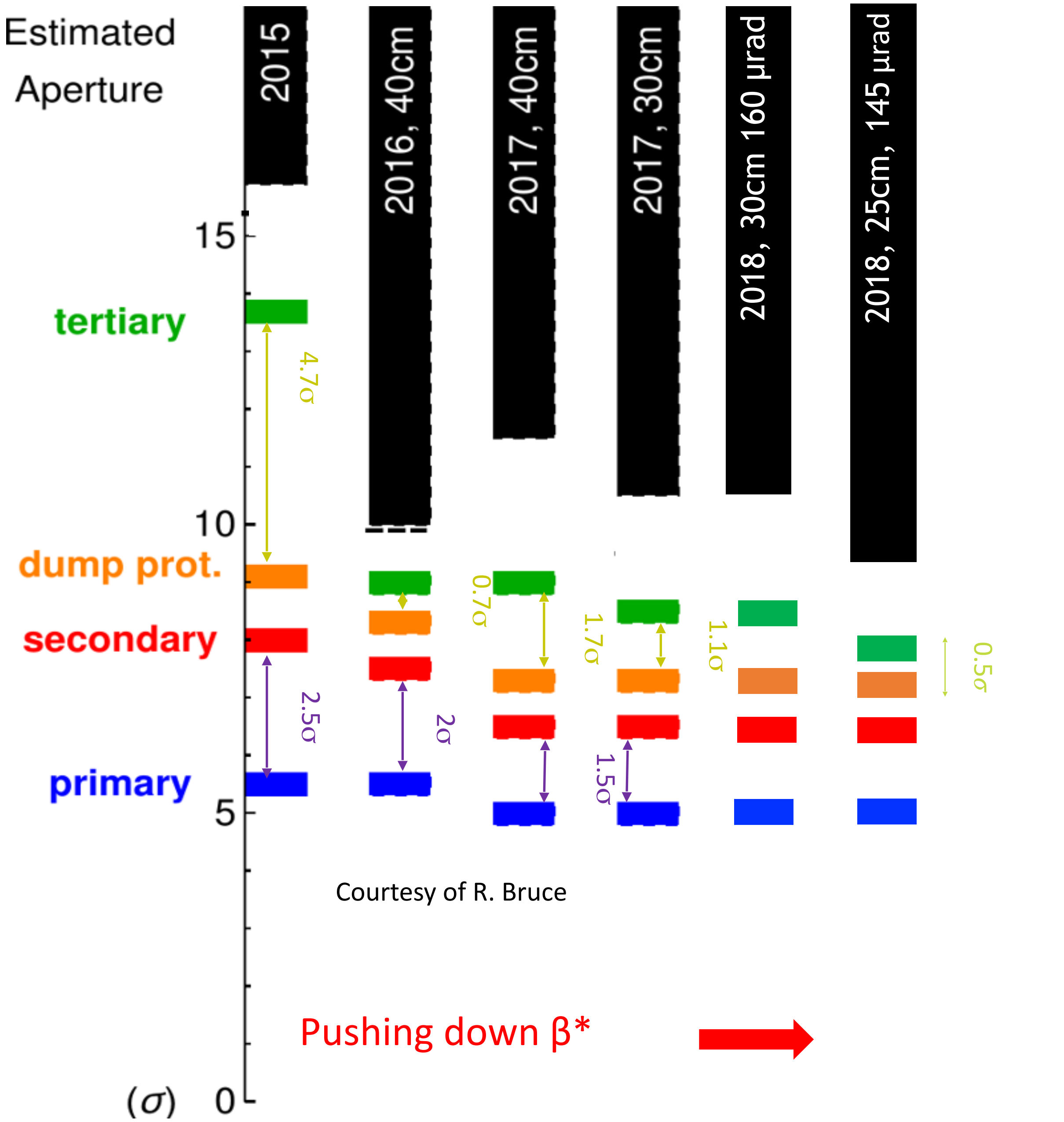
Tightening the collimation hierarchy is necessary to push β^*: allows protecting smaller triplet apertures.

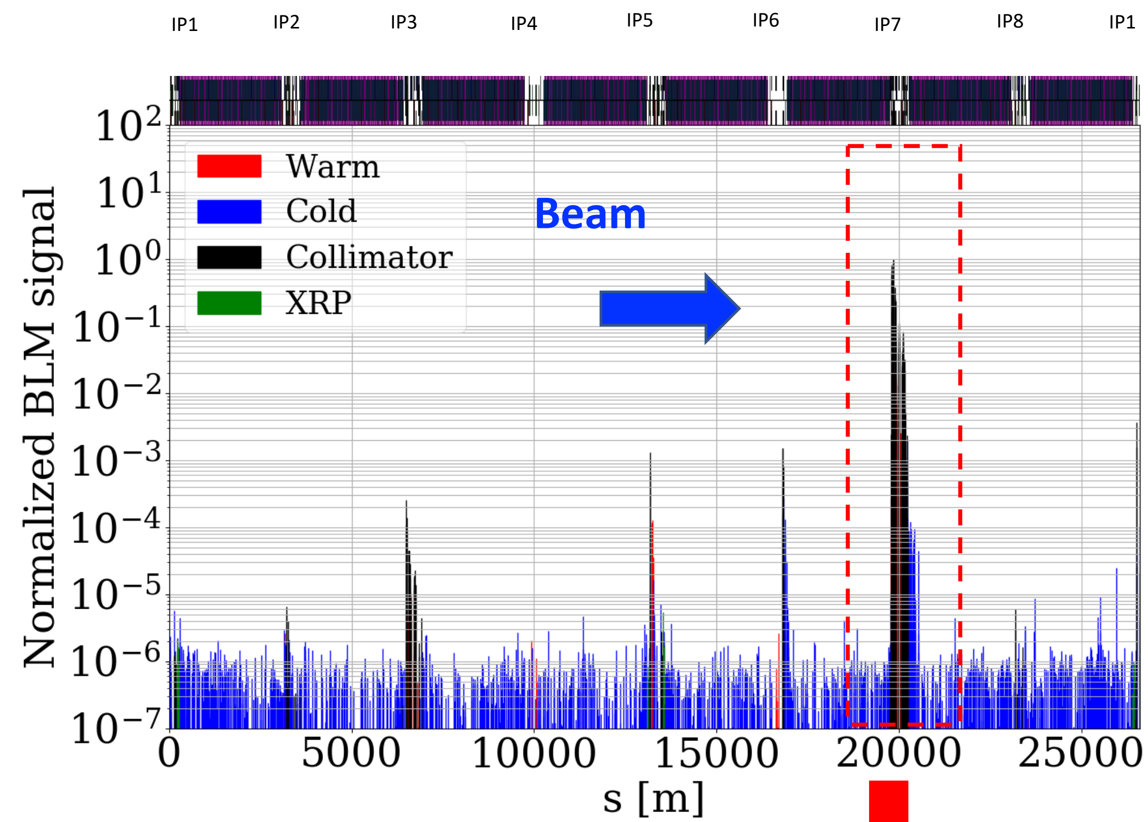


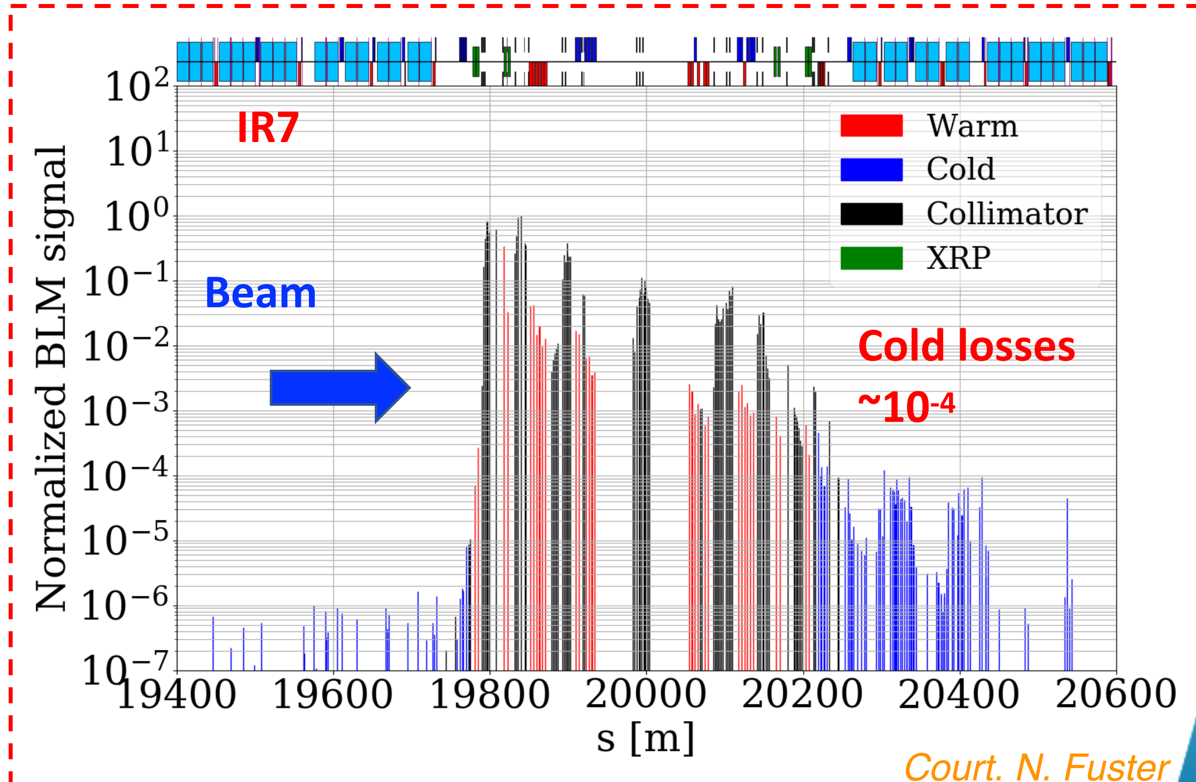


HiLumi HL-LHC PROJECT CERN

Collimator hierarchy and cleaning



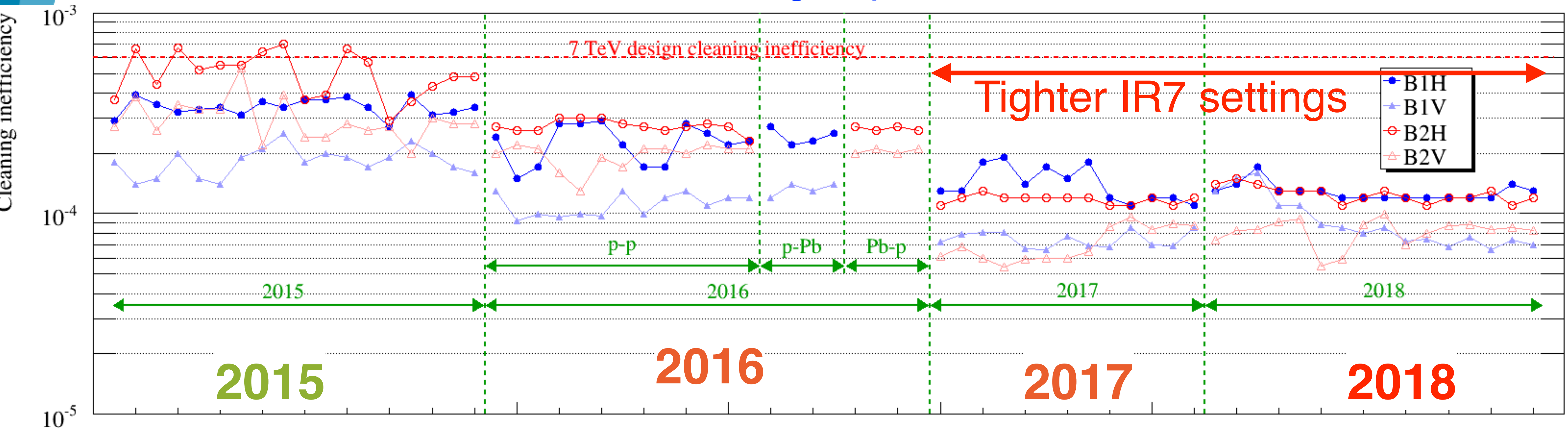




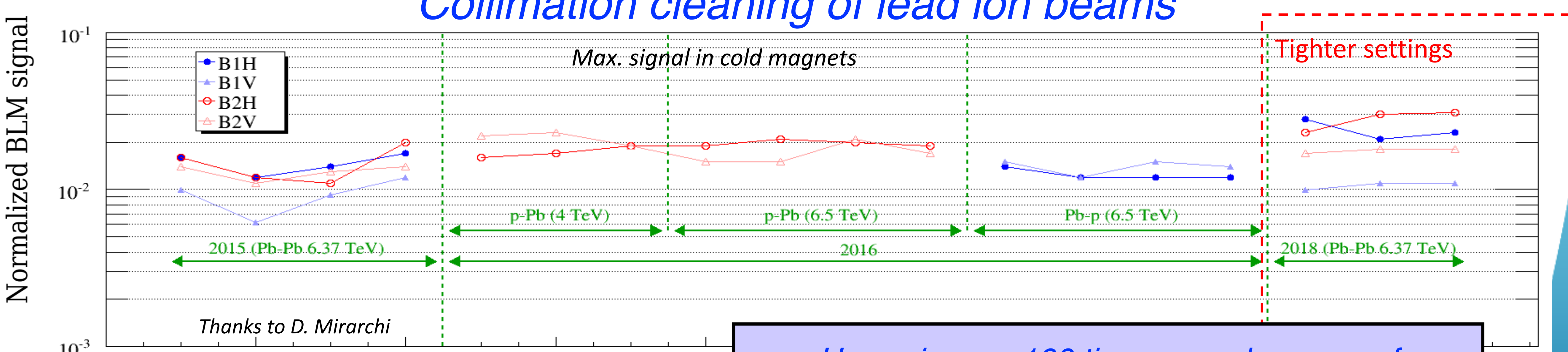
Excellent overall performance, with only 1 beam-based alignment per year!

Beam collimation performance at 6.5TeV

Collimation cleaning of proton beams



Collimation cleaning of lead ion beams



Heavy ions: ~ 100 time worse because of fragmentation / dissociation at primary collimators.

New challenges for HL-LHC

- Increased beam stored energy: 362MJ → 700MJ at 7 TeV

  Collimation cleaning *versus quench limits of superconducting magnets.*
  Machine protection constraints from ***beam tail*** *population.*

- Larger bunch intensity ($I_b = 2.3\text{x}10^{11}$p) in smaller emittance (2.0 μm)

  Collimation impedance *versus beam stability.*
  Collimator robustness *against regular and abnormal beam losses.*

- Larger p-p luminosity (1.0 x $10^{34}\text{cm}^{-2}\text{s}^{-1}$ → 5.0-7.5 x $10^{34}\text{cm}^{-2}\text{s}^{-1}$)

  Need to improve the ***collimation*** *of* ***physics debris****.*

  Overall upgrade of the ***collimation layouts*** *in the insertion regions.*

- Smaller β^* in the collision points (target = 15 cm)

  Cleaning and protection of high-luminosity insertions and physics background.

- Operational efficiency is a must for HL-LHC!

  Reliability of high precision devices in high radiation environment; alignment.

- Upgraded ion performance (6 x $10^{27}\text{cm}^{-2}\text{s}^{-1}$, i.e. 6 x nominal)

  Higher peak luminosity and nearly double Pb beam intensities.

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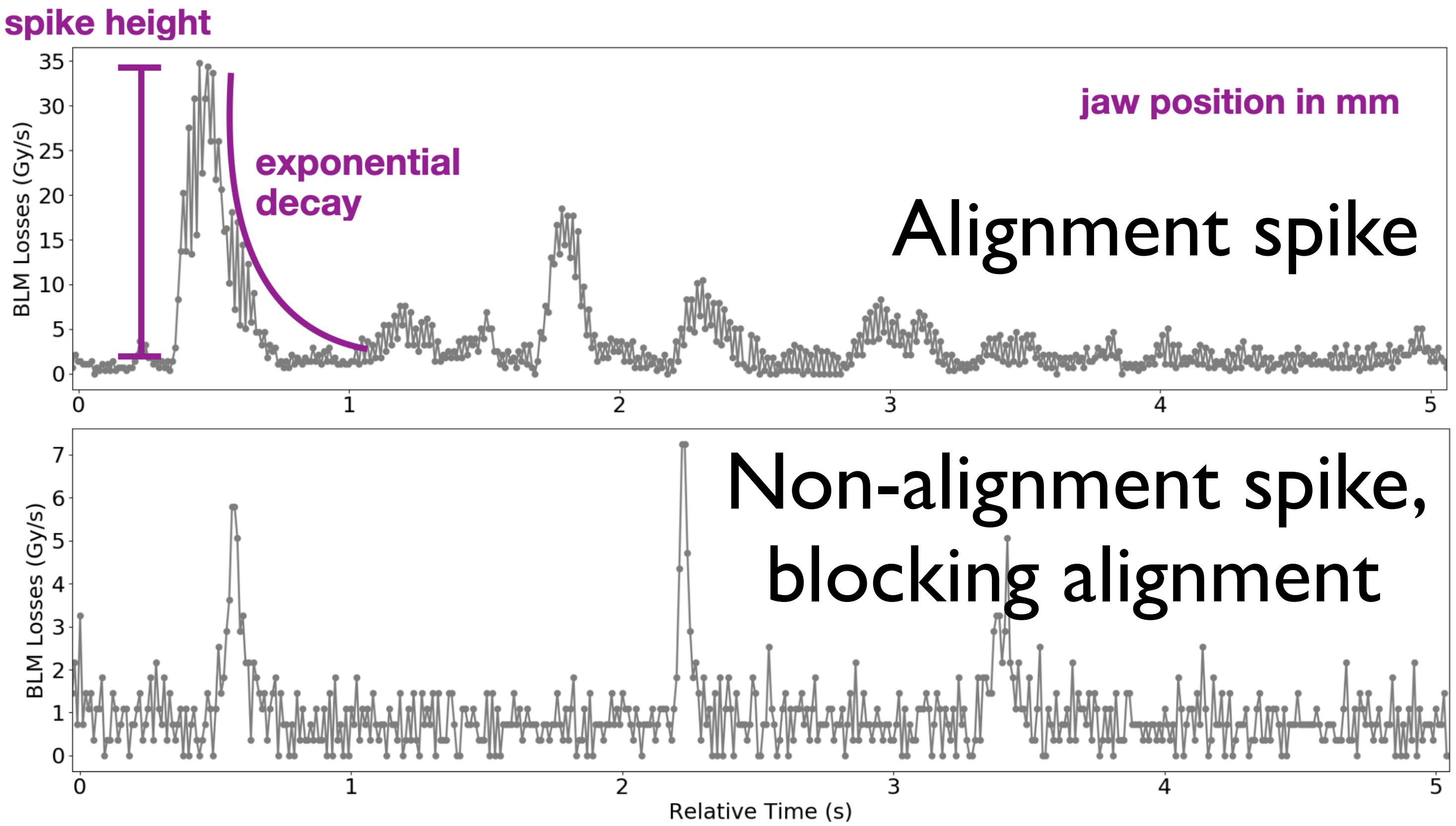
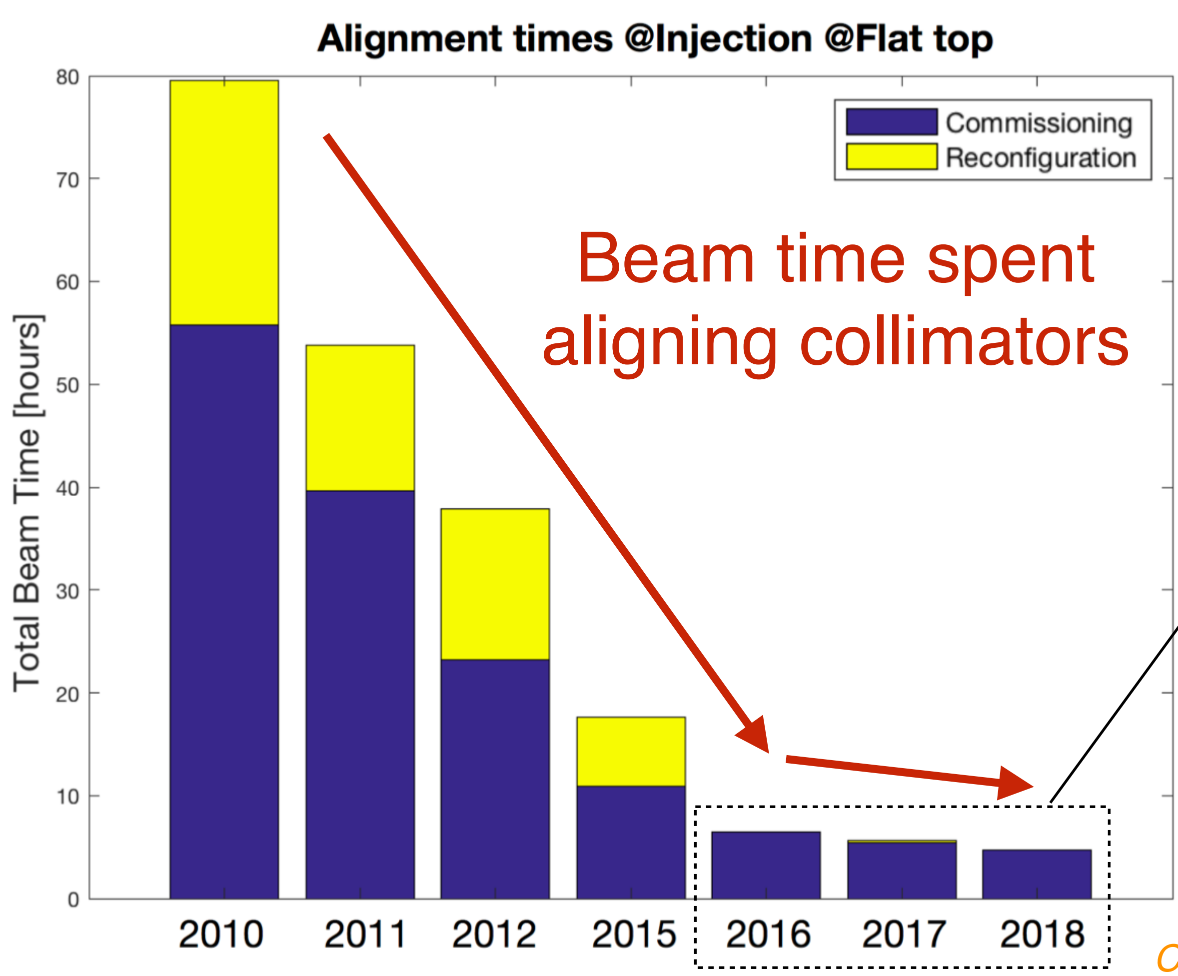
  - Main achievements in LHC Run 1 / 2
- **Mitigations and upgrades**
  - **Successful new features of Run 2**
  - **Planned upgrades**
  - **Hollow electron lenses**
  - **Crystal collimation of ion beams**
- Conclusions

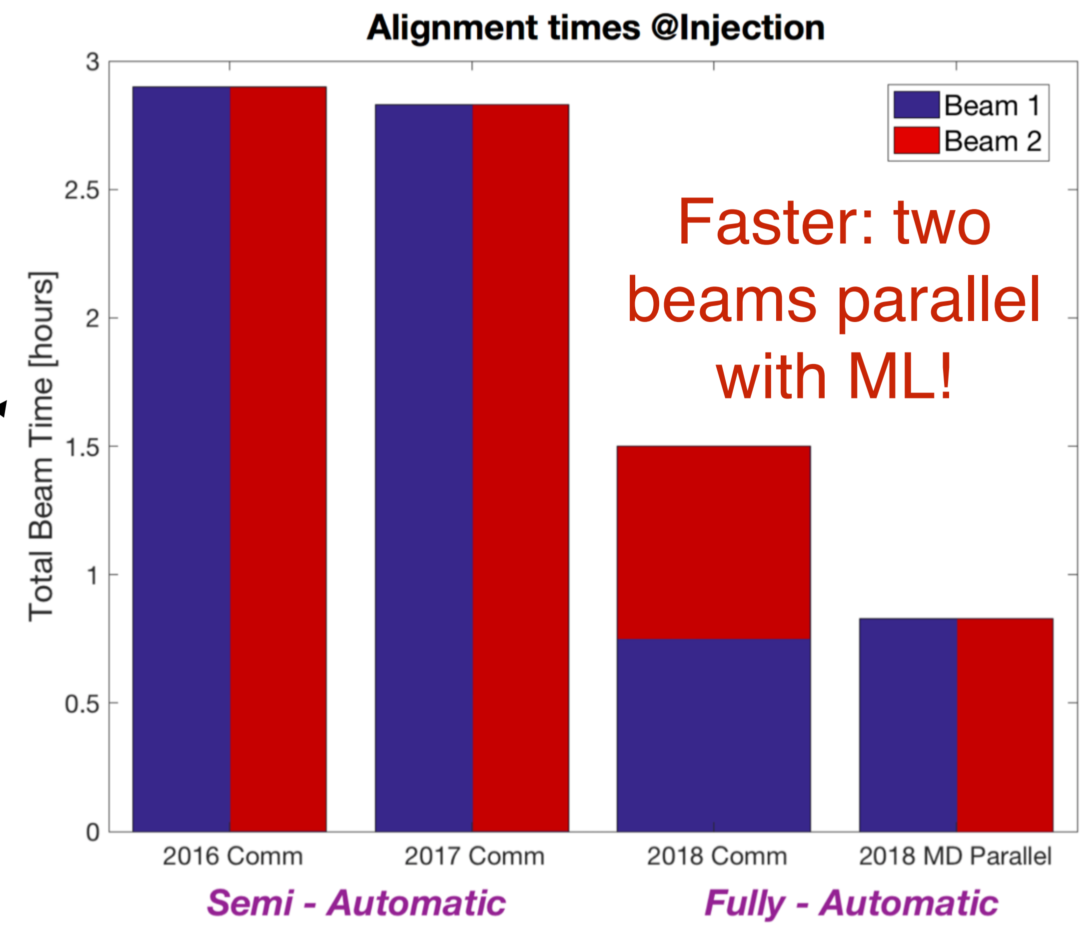
Improving operations: machine learning



Beam-based collimator alignment uses **machine learning**: faster and automated!

- Dataset of 1652 samples
- 5 features extracted
- 6 supervised machine learning models compared
- > 96% spike detection accuracy

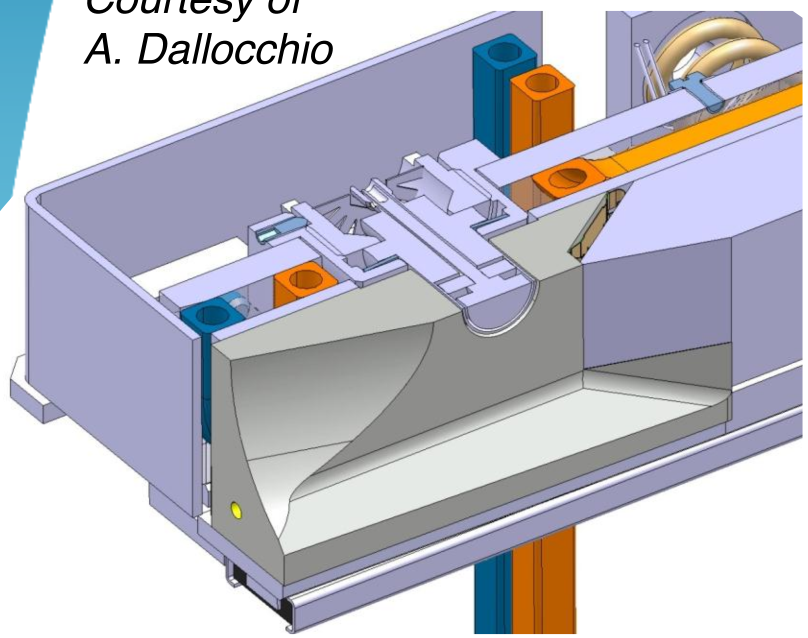


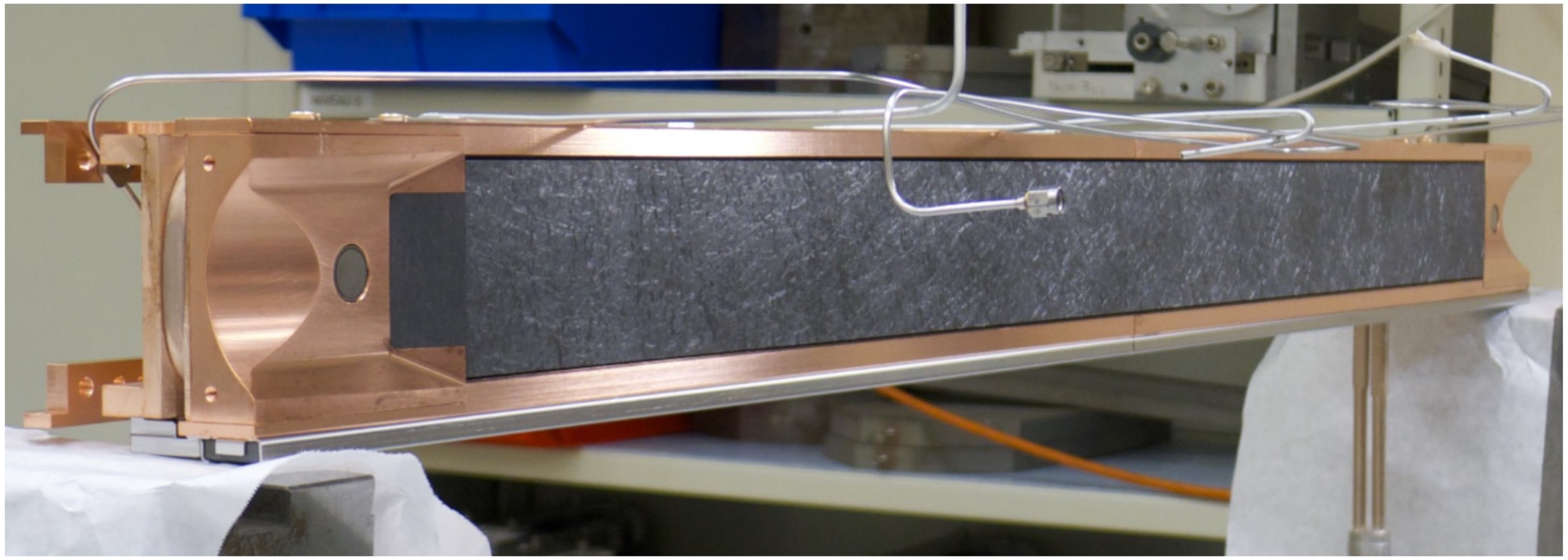


Court. G. Azzopardi

Improving operations: BPM collimators

Courtesy of A. Dallocchio

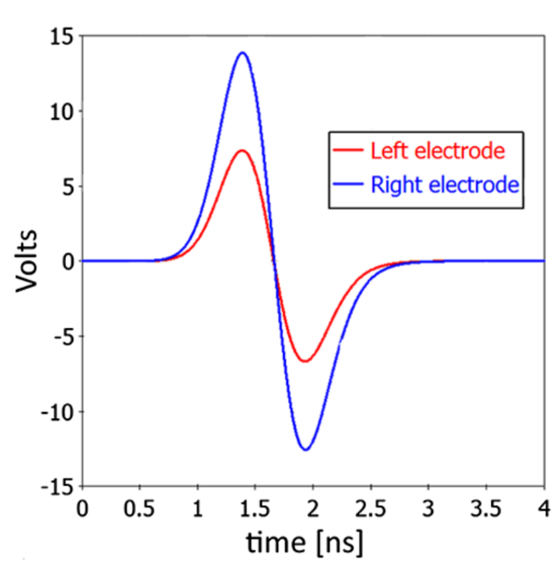


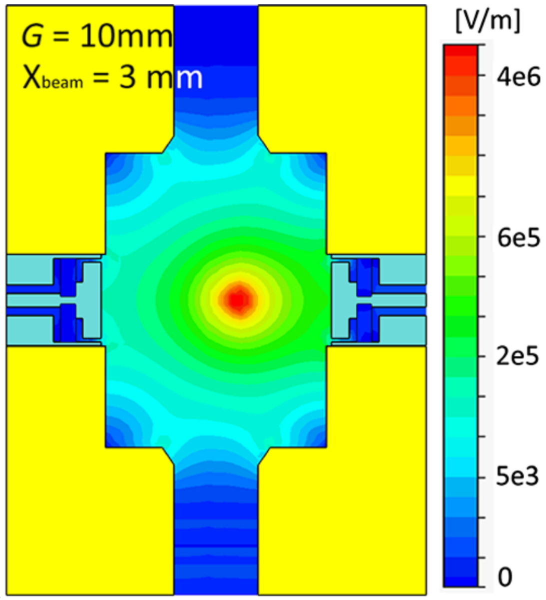


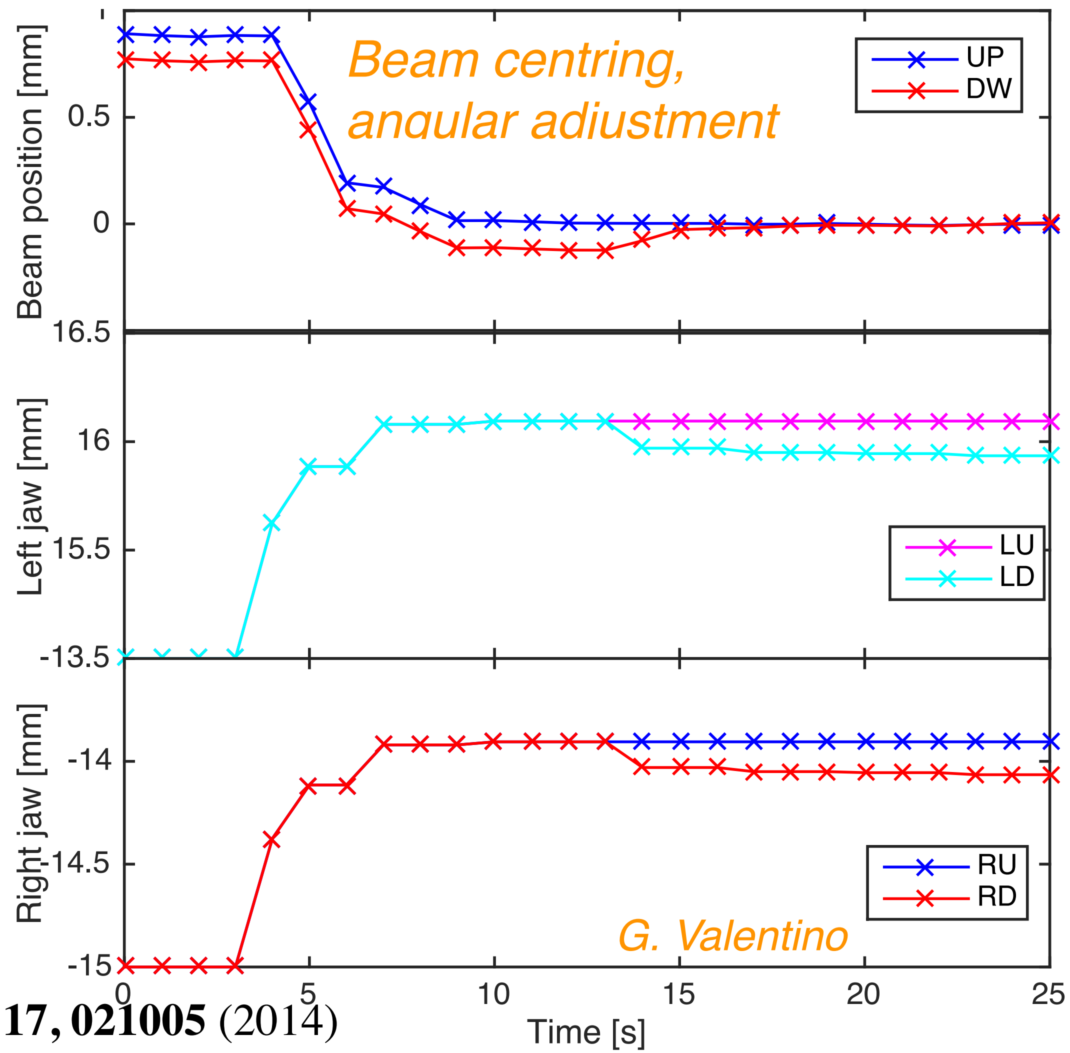
Aims: faster precise alignment; continuous orbit monitoring.

18 new BPM collimators installed in experiment and dump regions in LS1.

16 more in LS2. All future designs !







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

Improving operations: BPM collimators

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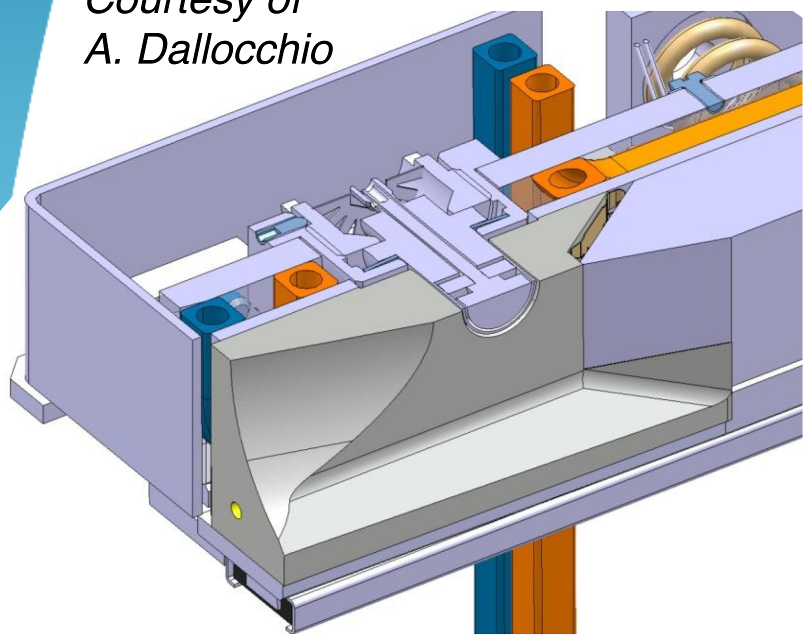

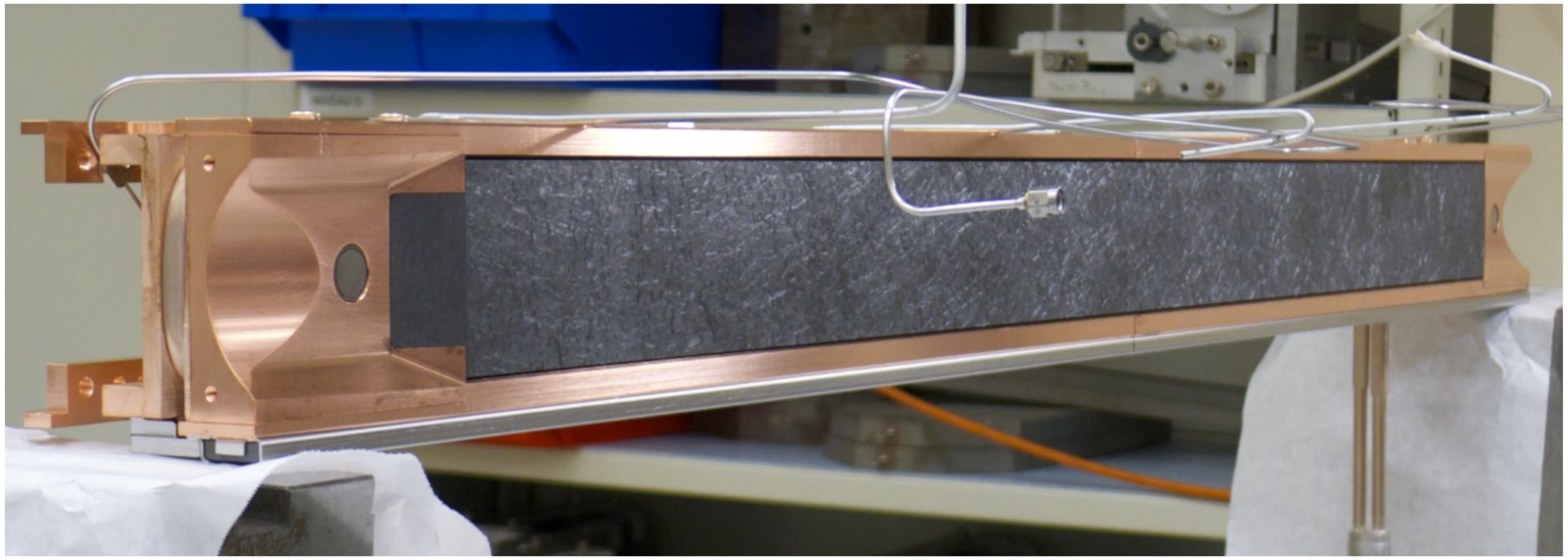

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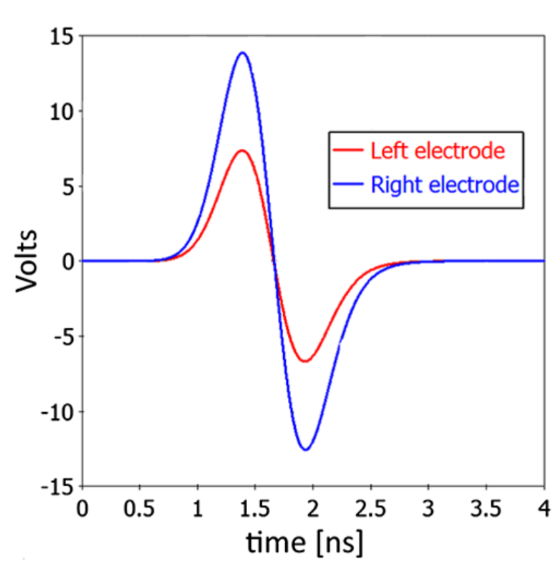
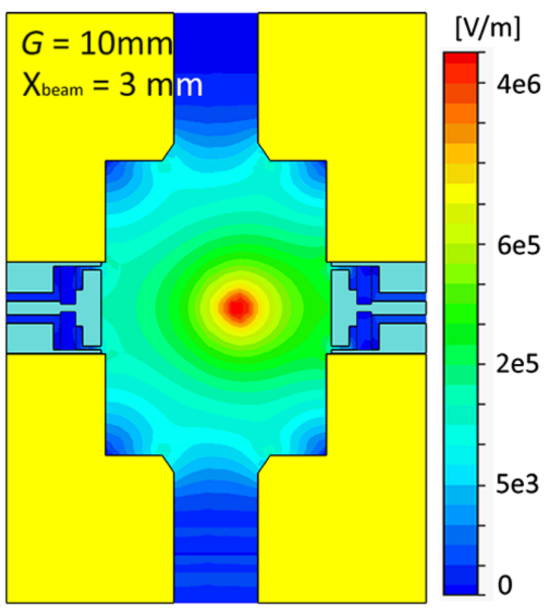
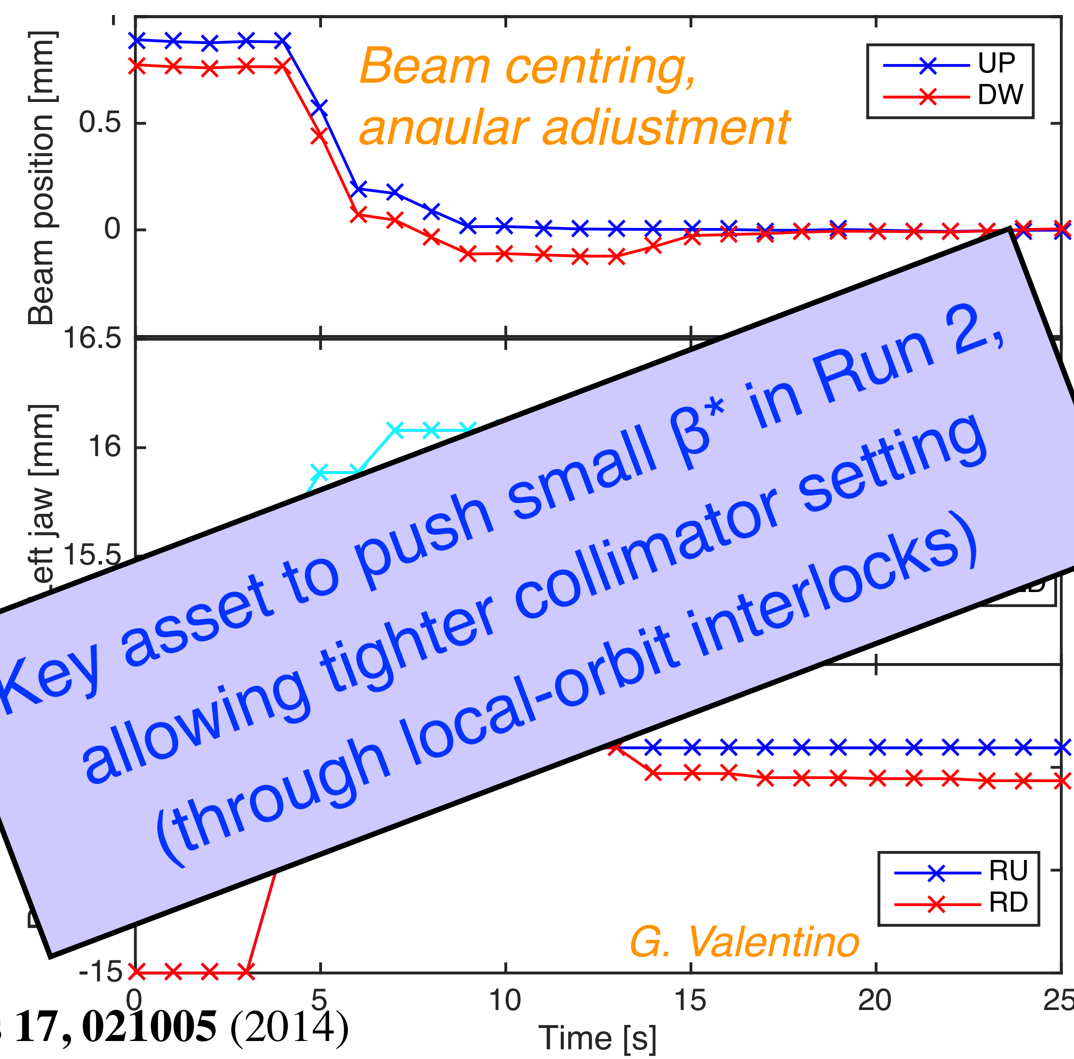




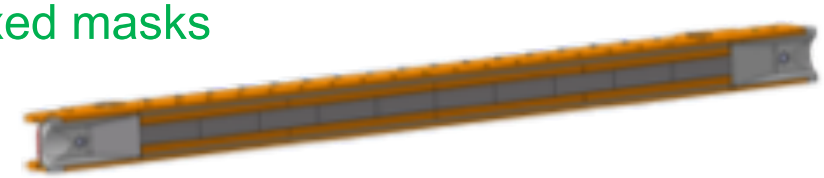


Key asset to push small β* in Run 2, allowing tighter collimator setting (through local-orbit interlocks)

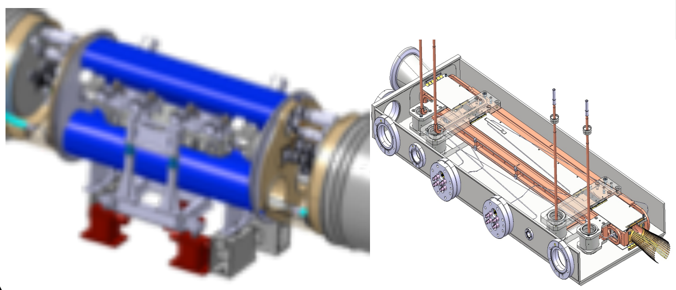
Phys. Rev. ST Accel. Beams 17, 021005 (2014)

Collimation upgrade plans — i

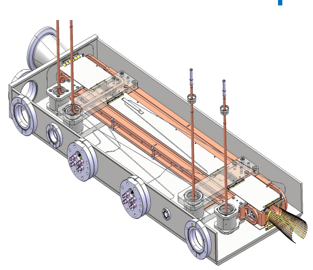
IR collimation:
Re-design layouts of in-coming and out-going collimation for the new IR1/5
Tertiary collimators, active absorbers, fixed masks

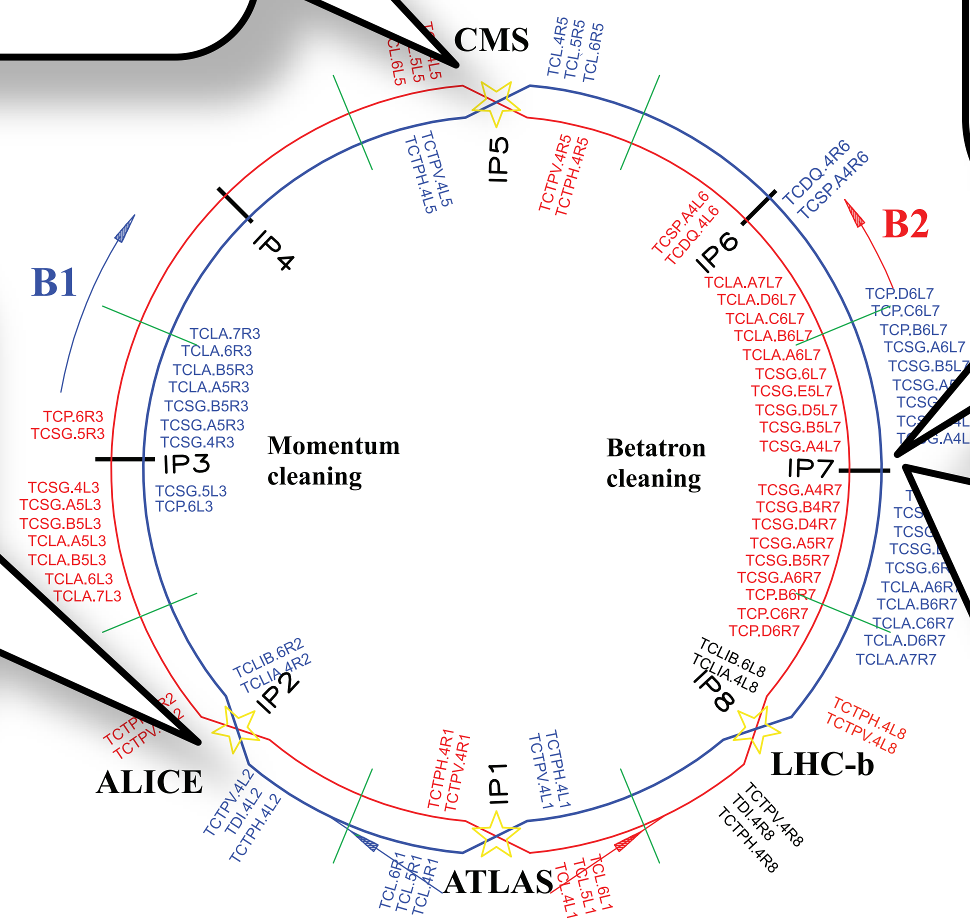


Dispersion suppressor collimation:
Betatron halo cleaning, DS collimators between 11T magnets

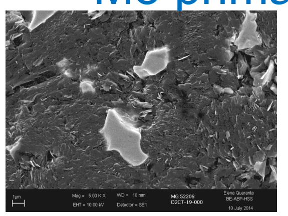


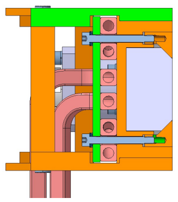
Dispersion suppressor collimation: Secondary beams from ion physics



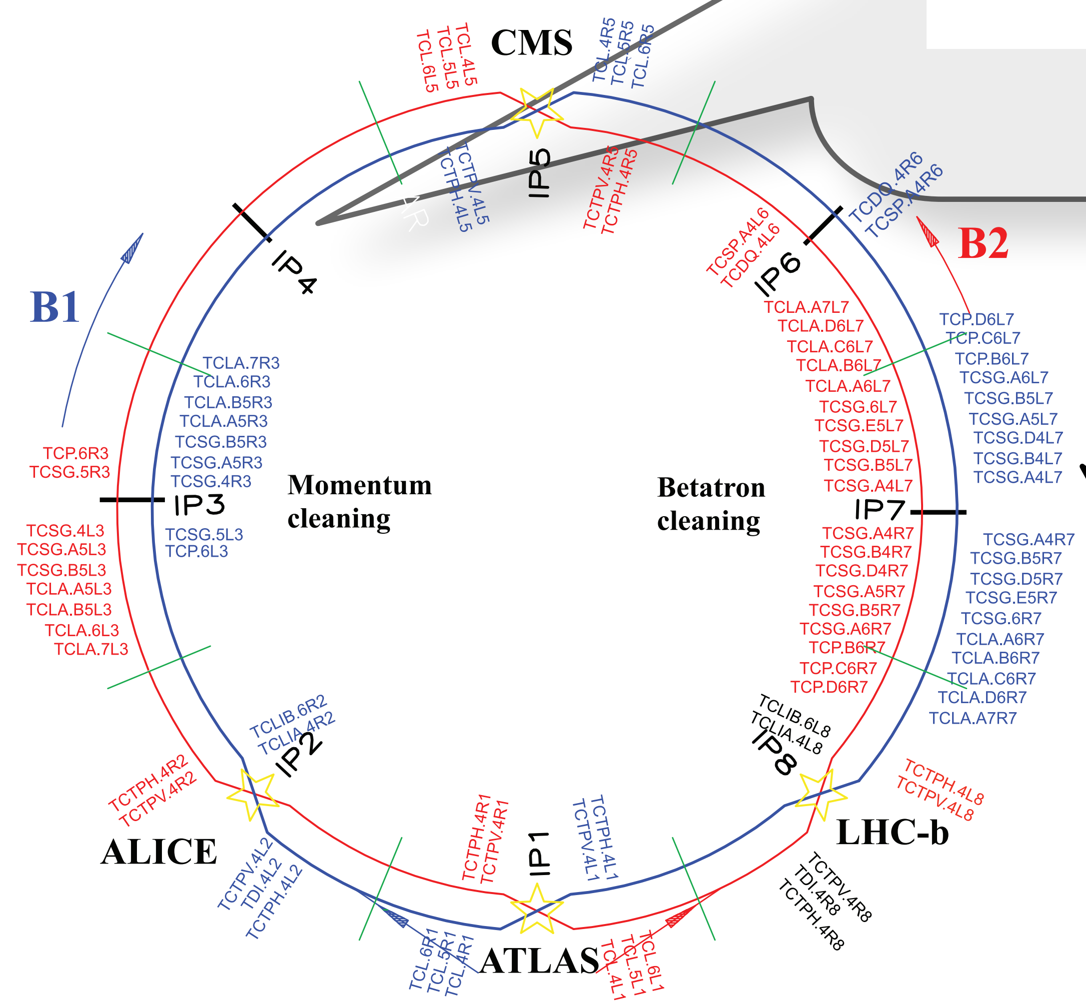


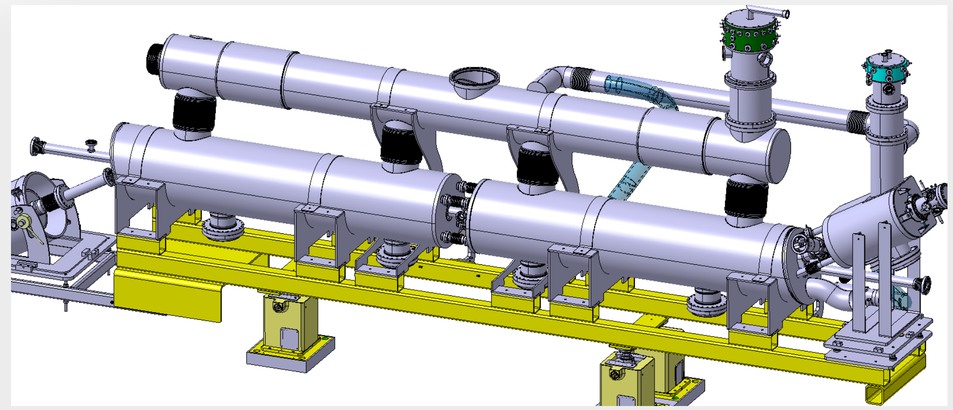
Impedance reduction: low-impedance, high robustness secondary collimators; coated MoGr
Mo primary collimators





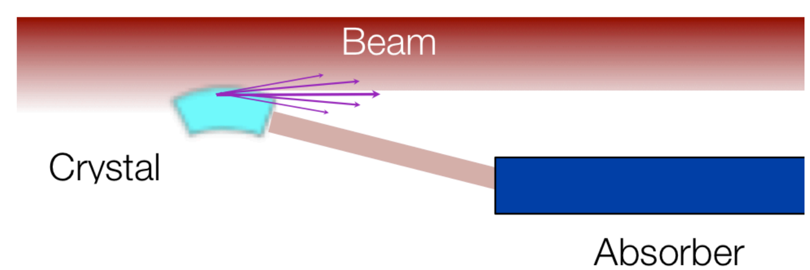
Collimation upgrade plans — ii

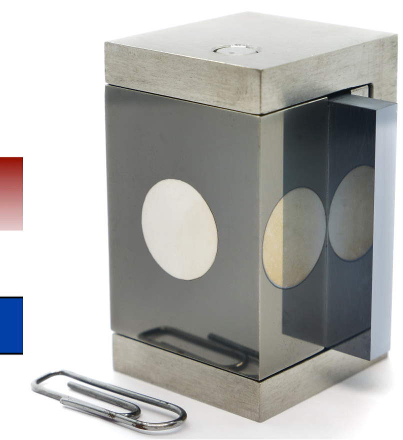




Hollow electron beam: 2 lenses
I_e = 5 A; l = 3 m; En = 10-15KeV; **IP4**

Crystal-assisted collimation (Pb ions)
4-8 bent crystals, 50 μrad bending
IP7 (betatron cleaning)



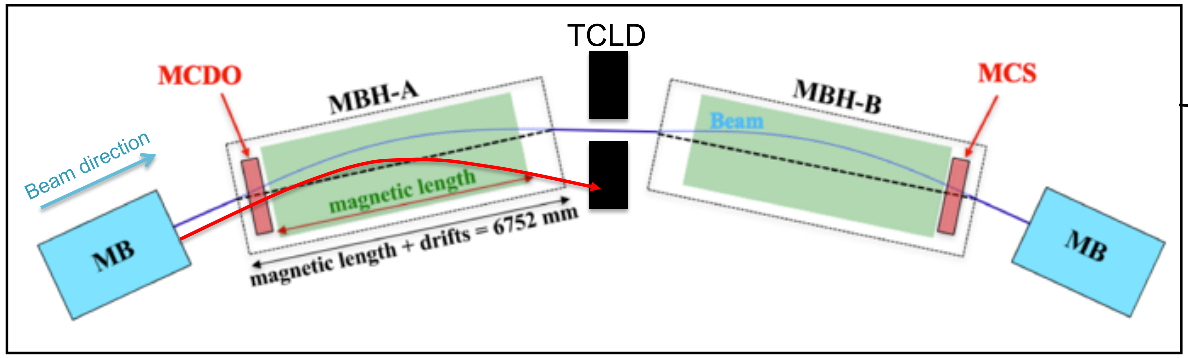


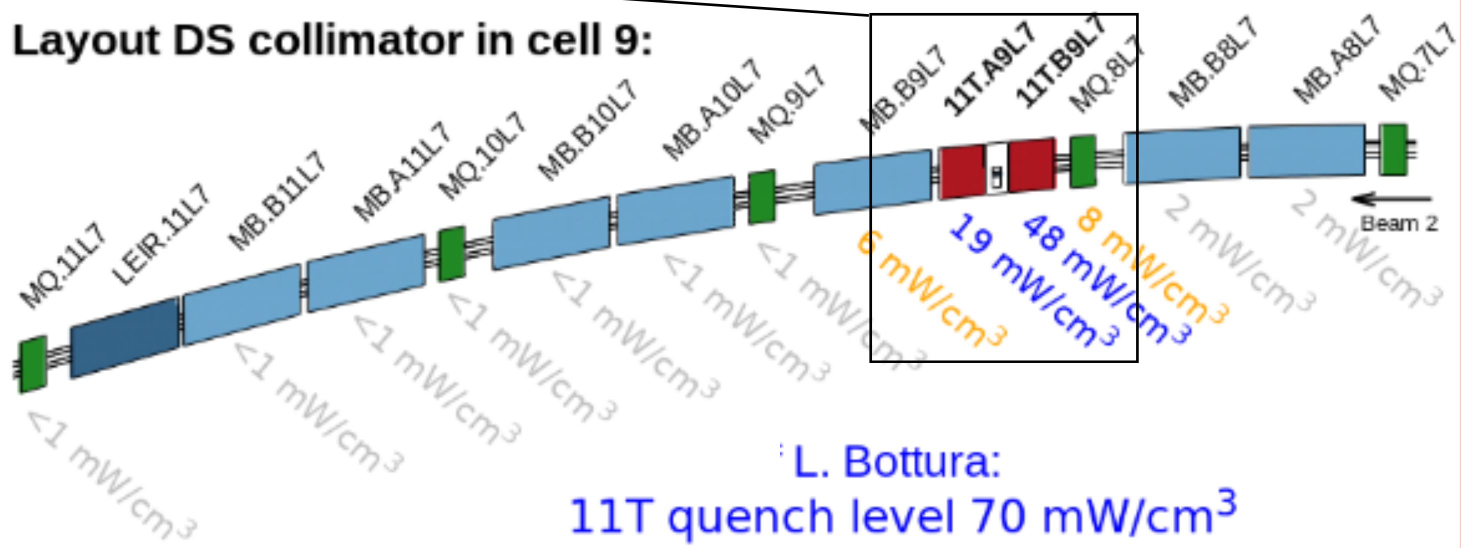
Part of our upgrade baseline since Dec. 2019

Dispersion suppressor collimation

Limiting locations for collimation cleaning are found in the dispersion suppressors (DSs). Need a local (warm) collimator in the cold regions:

- IR7 (betatron cleaning): proton and ion beams, with new 11T dipoles.
- IR2 (ALICE): losses from luminosity following ALICE upgrade in LS2.





Safety margin of ~3 for 11T dipole losses: 25mW/cm³ vs 70mW/cm³

Specific implementation for the LHC. Future accelerators (e.g., FCChh) will plan the DS design taking local collimation needs into account

Dispersion suppressor collimation

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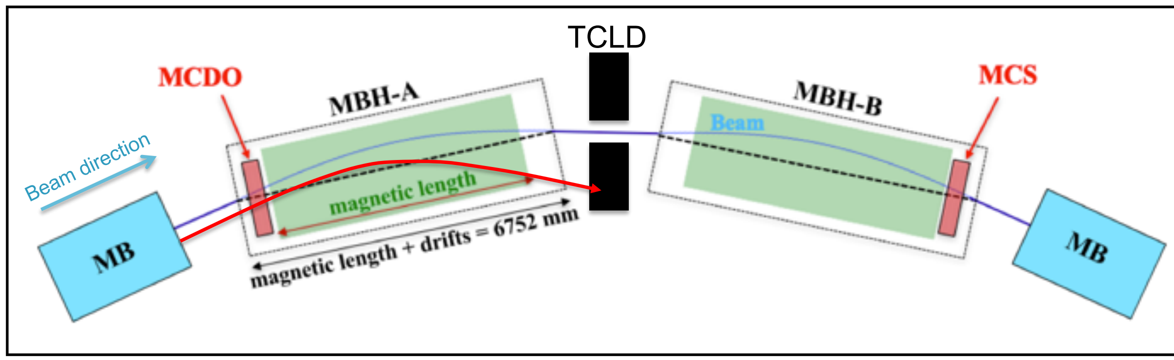

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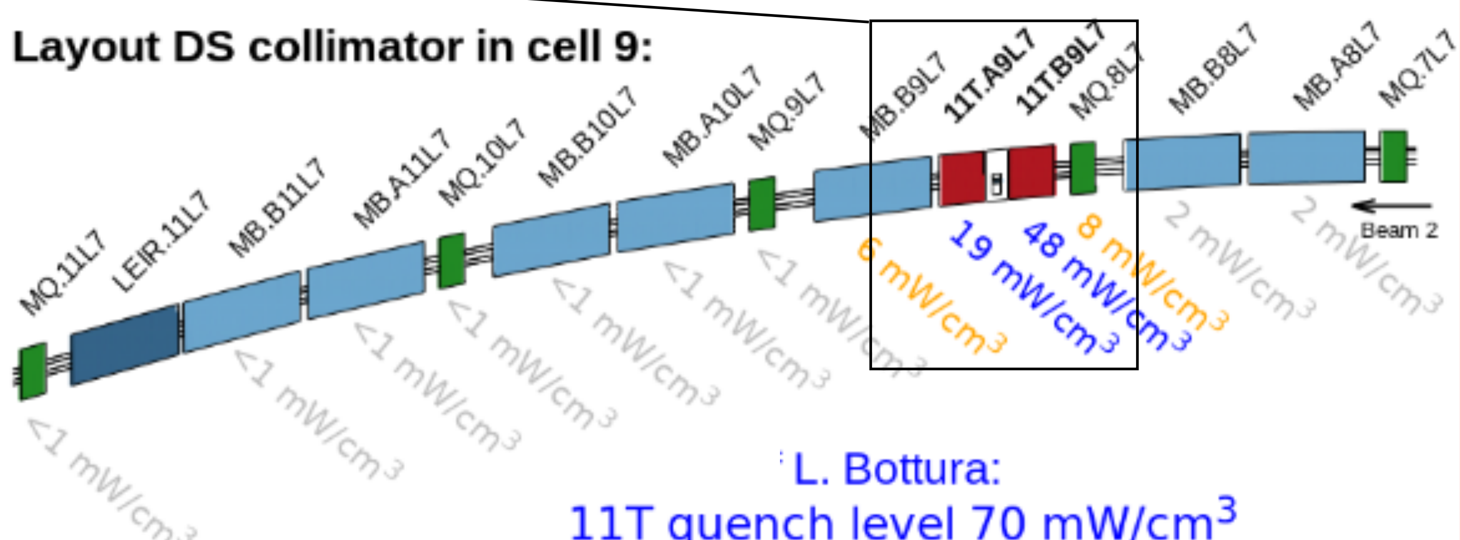
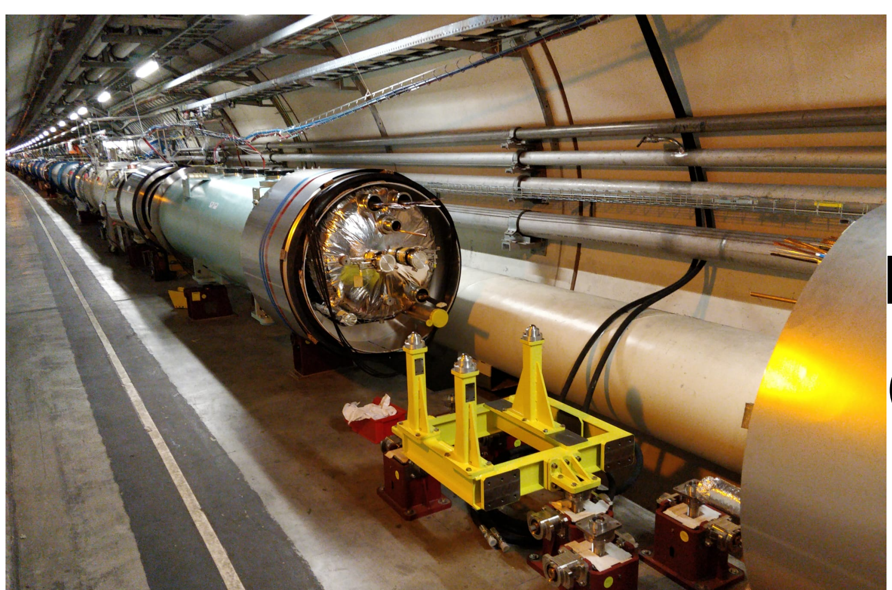
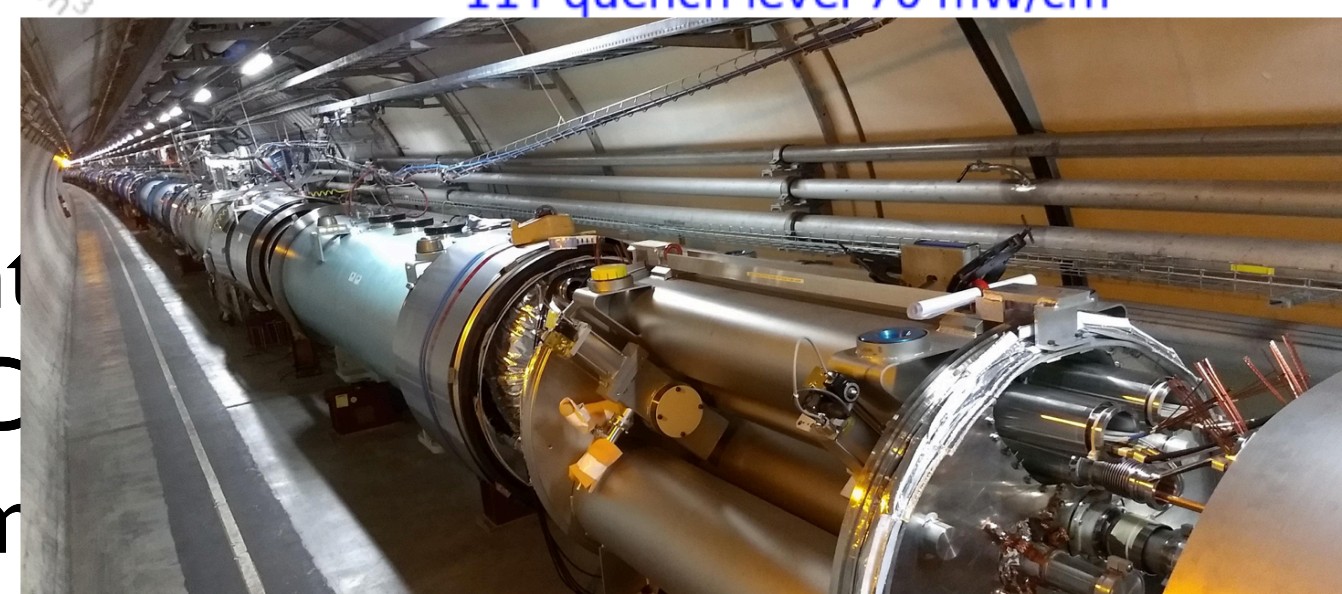


L. Bottura:
11T quench level 70 mW/cm^3

4 TCLDs planned in LS2, in each DS of IR7 and IR2

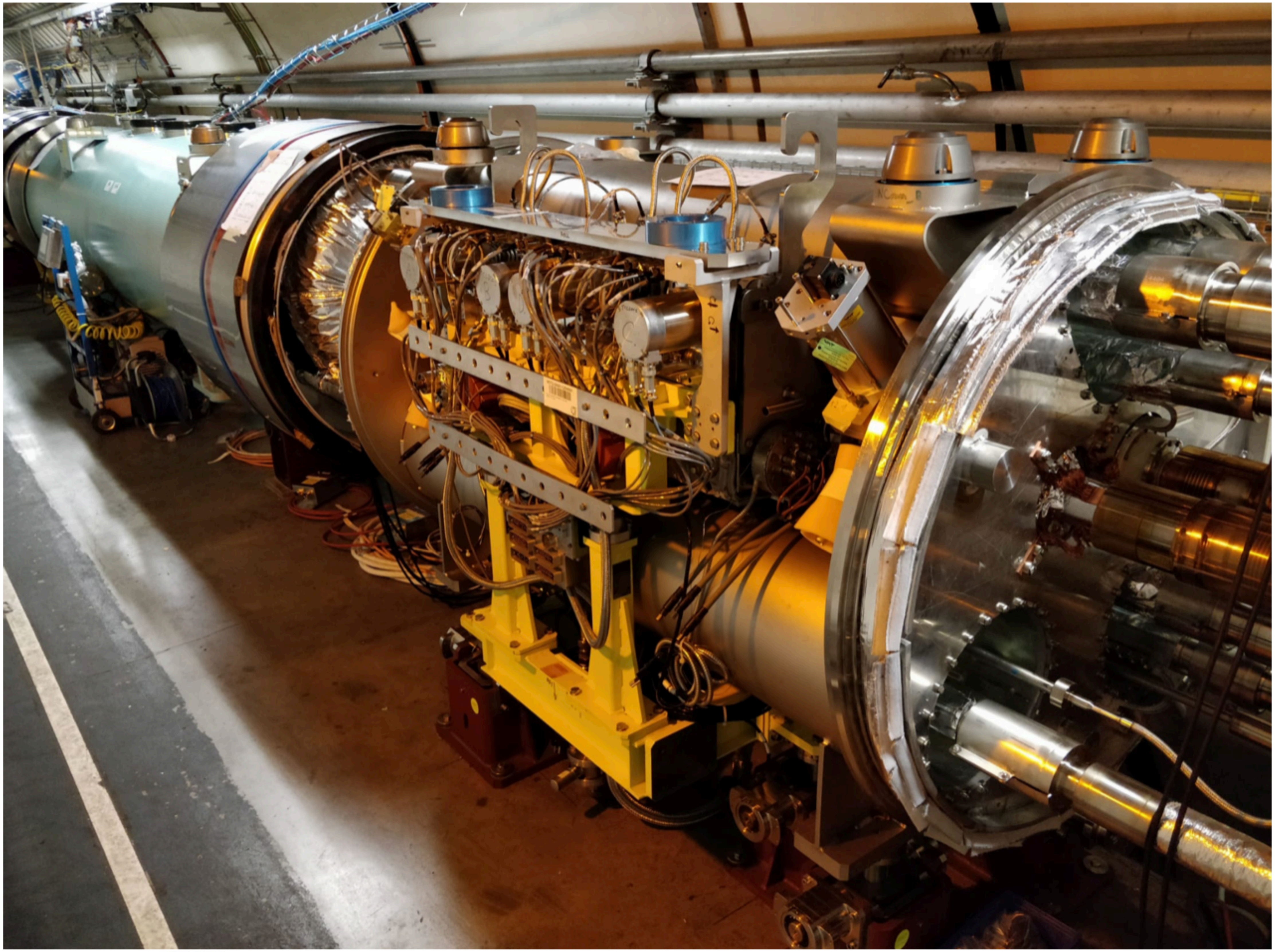


Collimator support



Courtesy WP11: cryo by-pass at the connection cryostat to house the TCLD

Dispersion suppressor collimation



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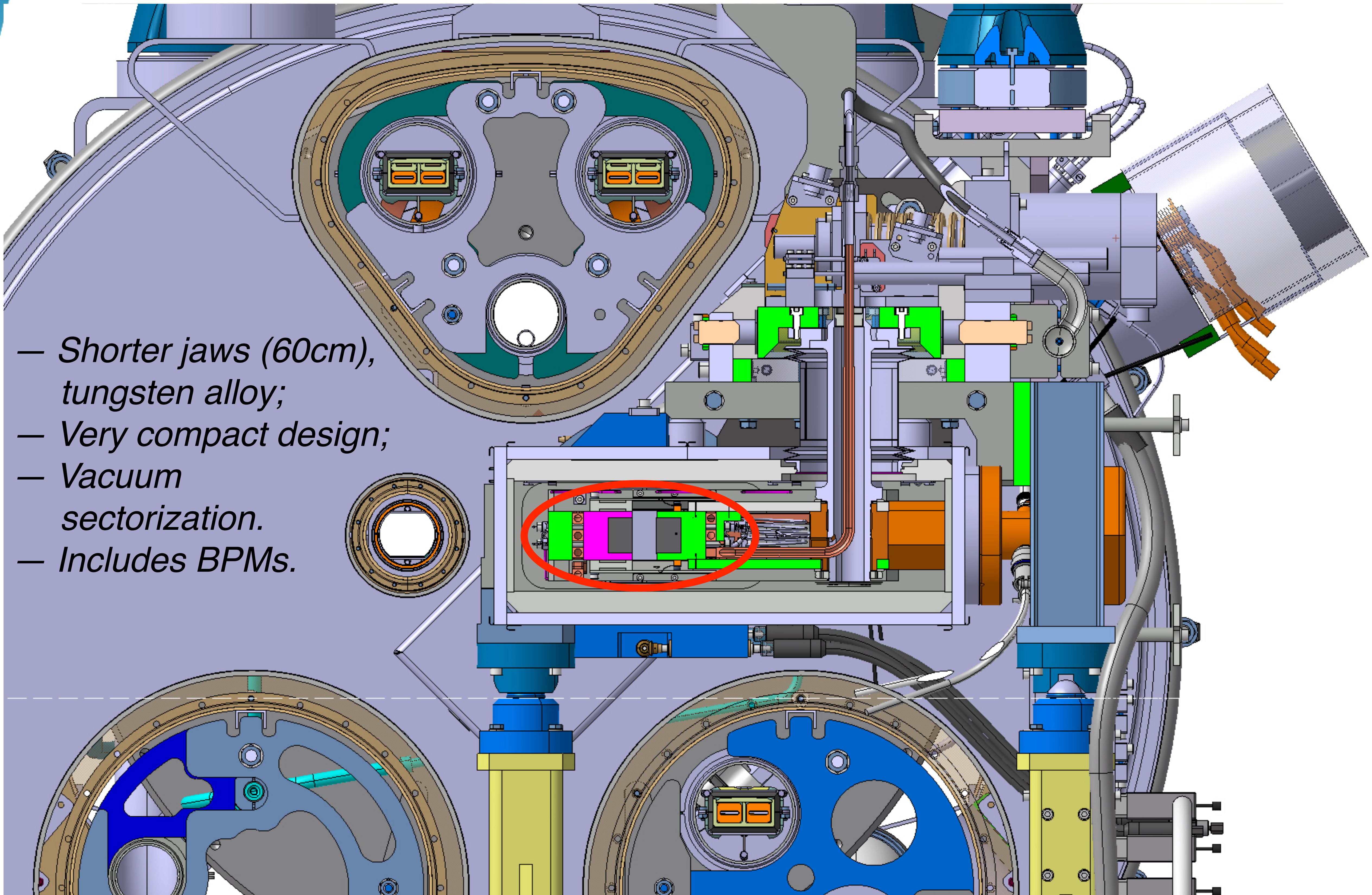
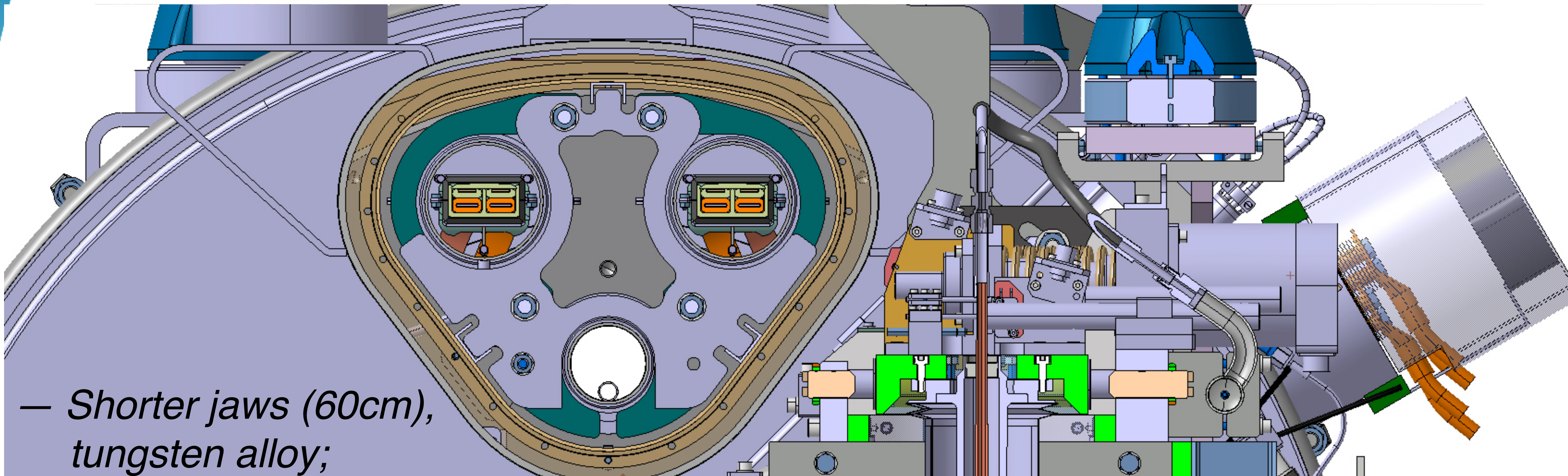


- *Shorter jaws (60cm), tungsten alloy;*
- *Very compact design;*
- *Vacuum sectorization.*
- *Includes BPMs.*

Dispersion suppressor collimation



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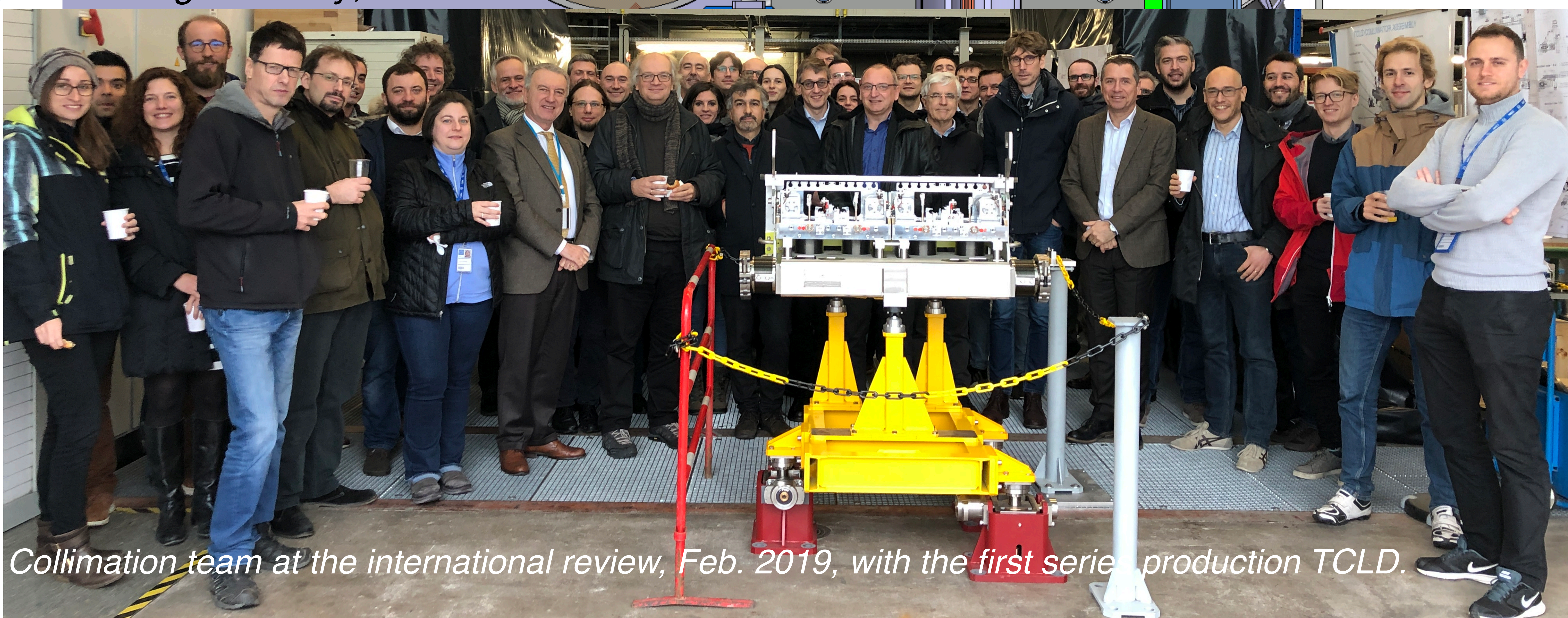
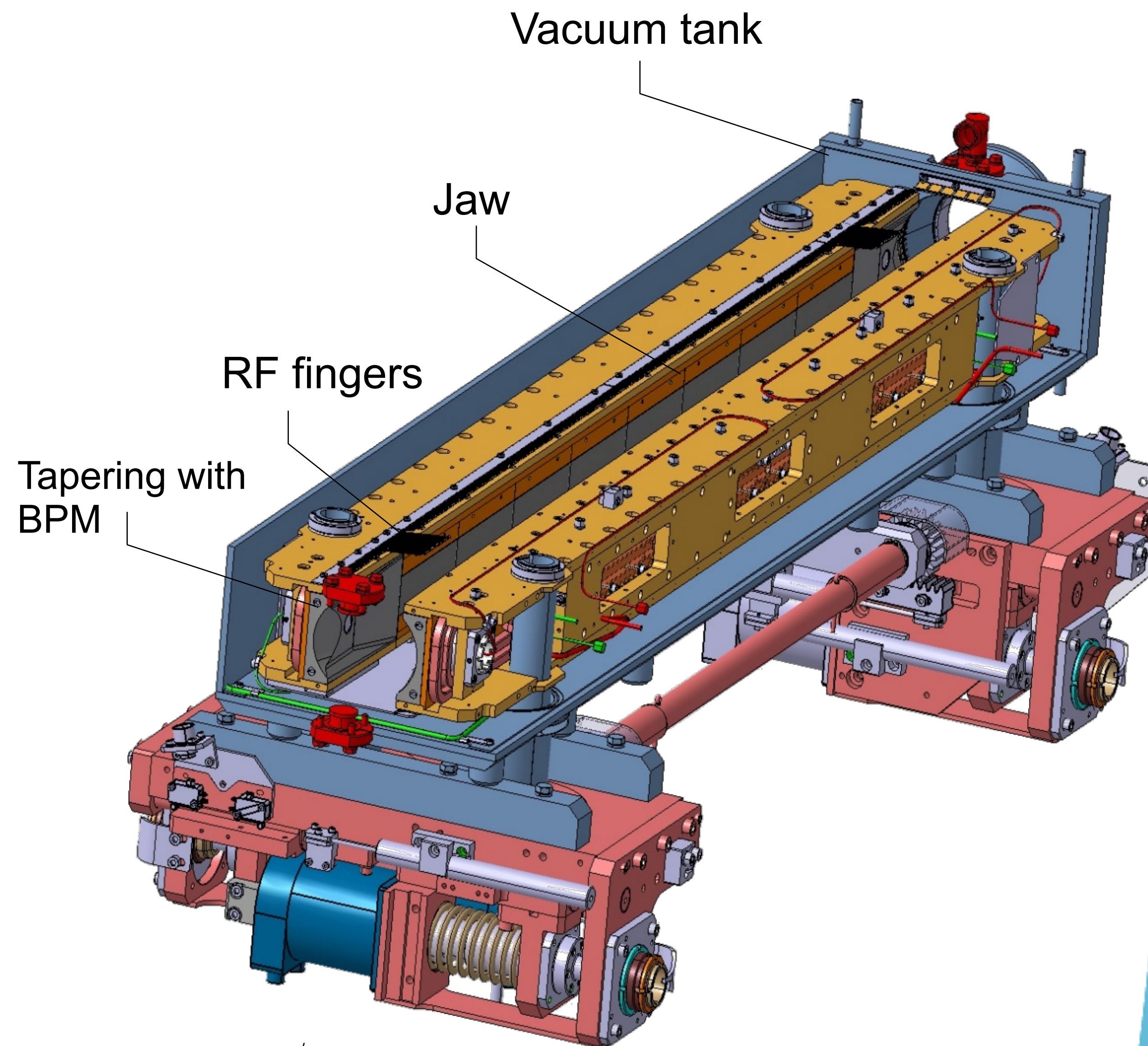


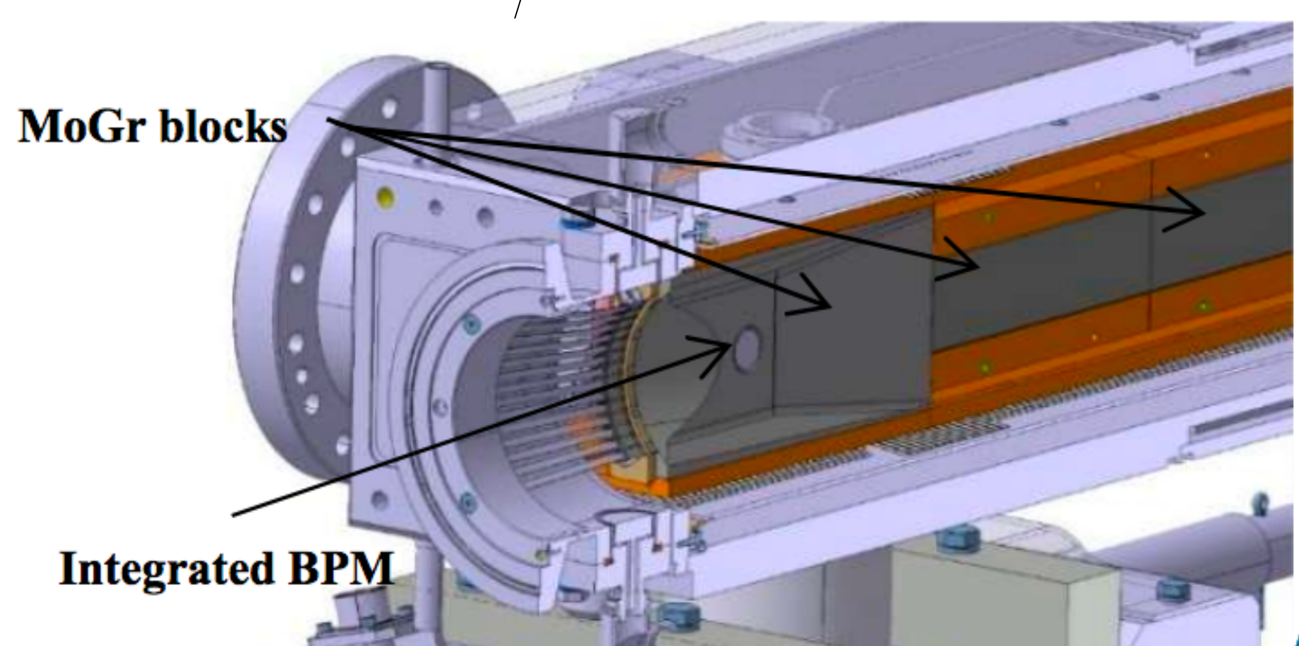
Collimation team at the international review, Feb. 2019, with the first series production TCLD.

News materials: low-impedance

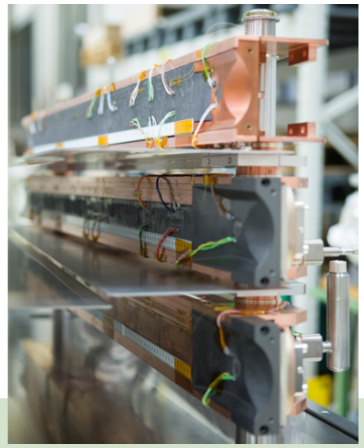
- Updated design for the primary and secondary collimators; includes BPMs.
- Based on a newly developed material: ***Molybdenum-Graphite***, *with or without Mo-coating;*
- *Change 9 out of 11 secondary, and 2 out of 3 primary collimators per beam.*
- *First phase of low-impedance reduction starts in LS2 with 6 new collimators per beam! Following beam tests on prototype.*

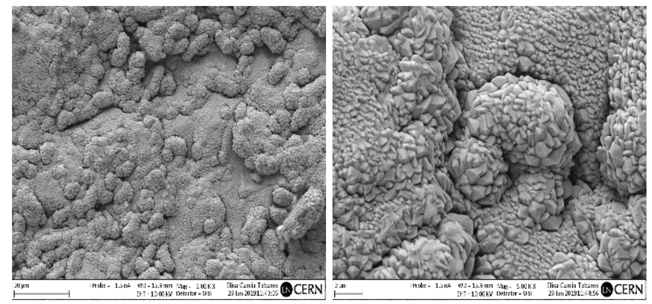


Key features: similar robustness against beam impact as then optimised CFC used in the LHC; ~5 times better electrical conductivity (x100 with Mo coating).Good adhesions of Mo coating.



MoGr development timeline





MoGr bulk R&D

2013/16: in collaboration with Italian SME (Brevetti Bizz)

MoGr bulk validation

2015: HiRadMat at CERN
2015: Ion irradiation at GSI
2016: proton irradiation at BNL

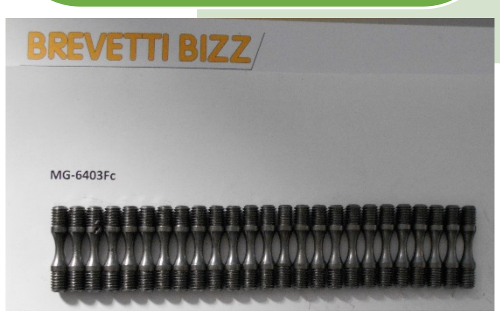
Mo coating R&D and validation

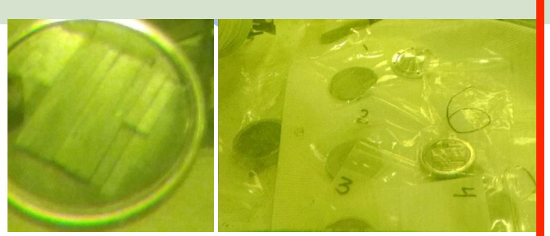
2016/17: magnetron sputtering at CERN
2018: proton irradiation at BNL
2019: ion irradiation at GSI

Series production

2018-20: bulk MoGr blocks produced at Nanoker (ES)
2019-20: coating by HIPIMS at DTI (DK)

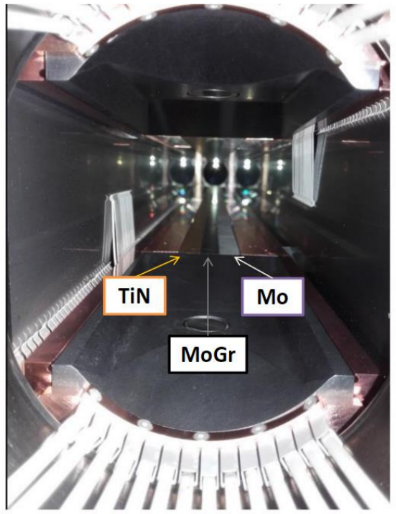
Mo-coated MoGr collimator installation



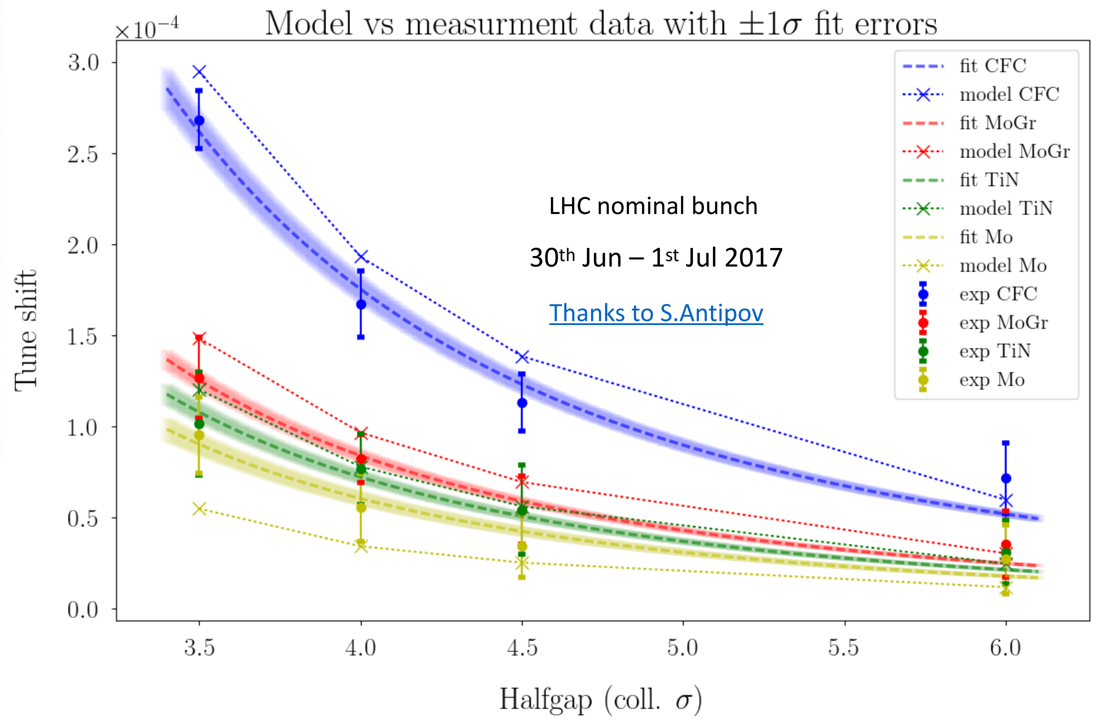


2017: full-size prototype installed in the LHC for beam tests

Status of low-impedance upgrade



(3-BPM design)

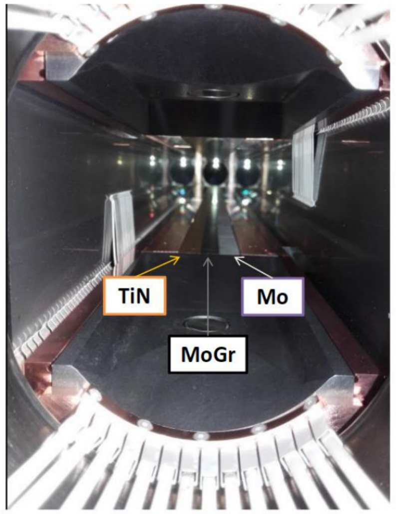


Full-scale prototype installed in the LHC in 2017 for beam tests: successfully demonstrating the impedance gains!

The reduction of the impedance is confirmed. The experience gained had been incorporated in the TCSPM design in terms of specifications on the coating layer.

Court. I. Lamas, F. Carra

Status of low-impedance upgrade



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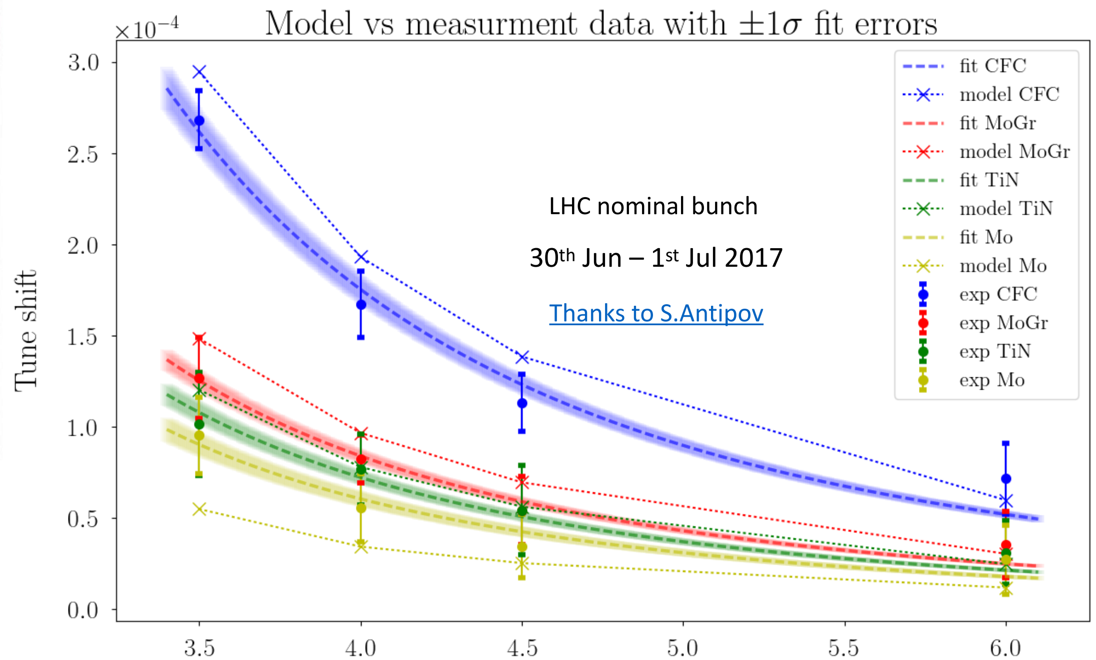

Full-scale prototype installed in the LHC in 2017 for beam tests: successfully demonstrating the impedance gains!

Ongoing industrial production: 7 new collimators received at CERN, being prepared for installation (2 already in the machine!).

Court. I. Lamas, F. Carra

Status of low-impedance upgrade

(3-BP

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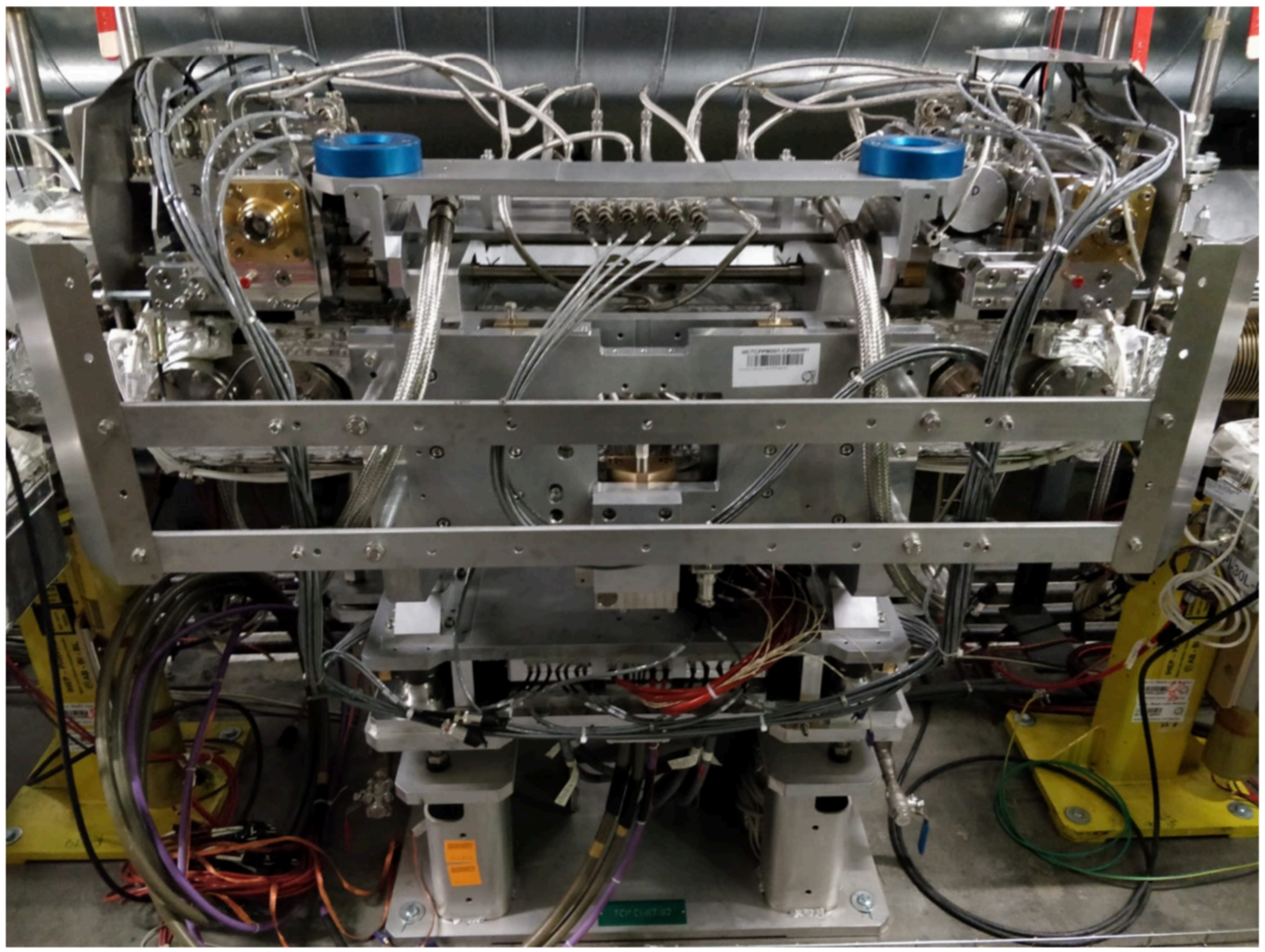

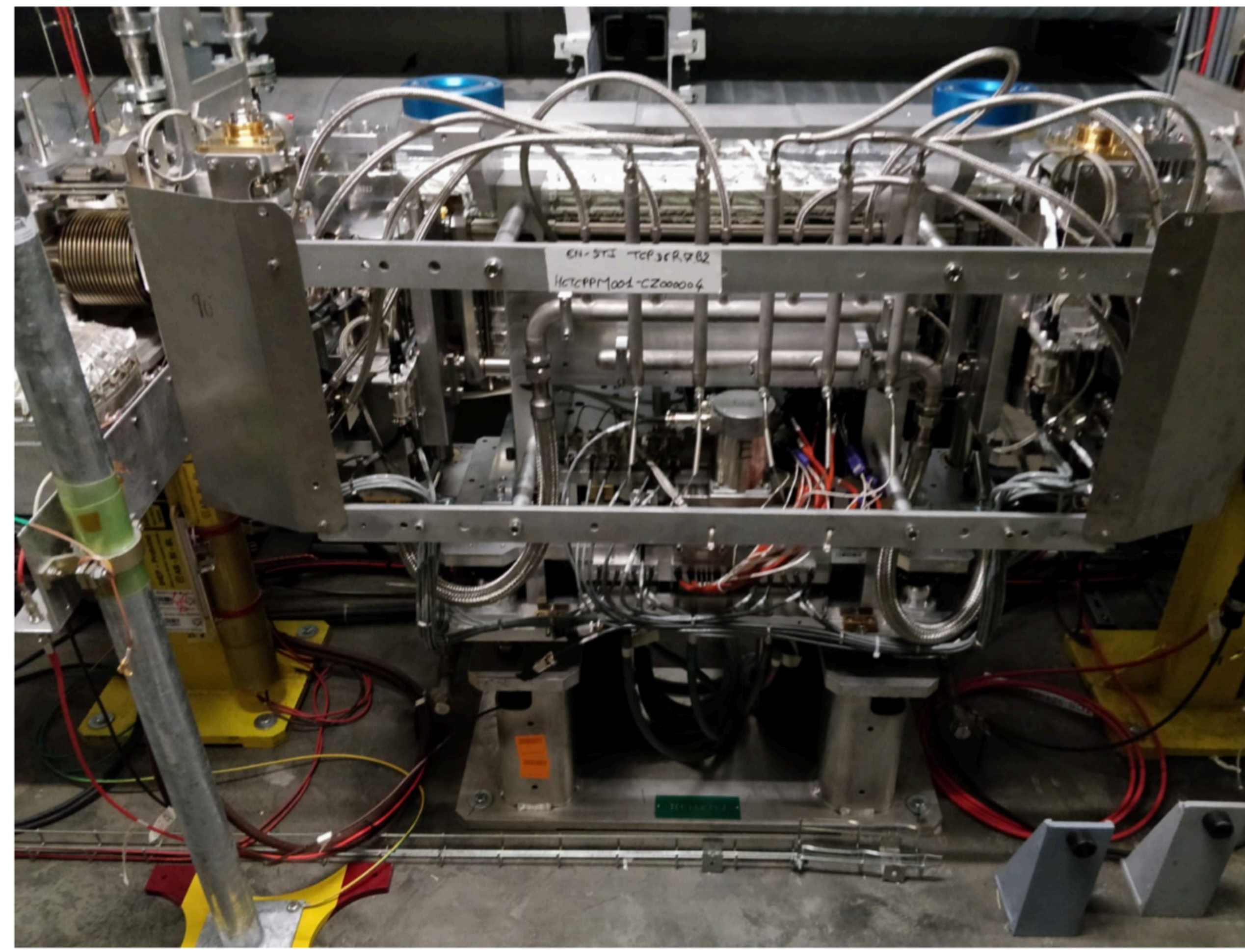

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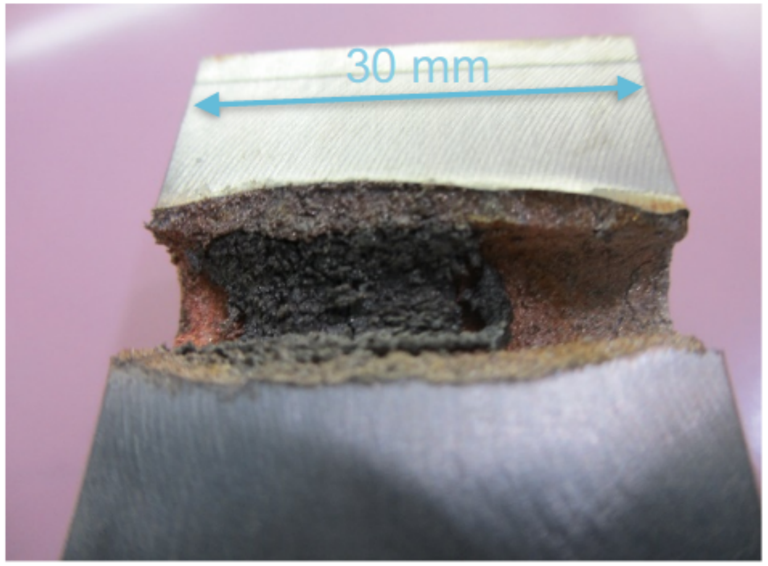
Court. I. Lamas, F. Carra

News materials: higher robustness

Controlled tests at on sample of material of the present tertiary collimators, at HiRadMat. Studies onset of damage and extent of damage for design beam failures.

Present

Inermet 180 (heavy tungsten alloy)



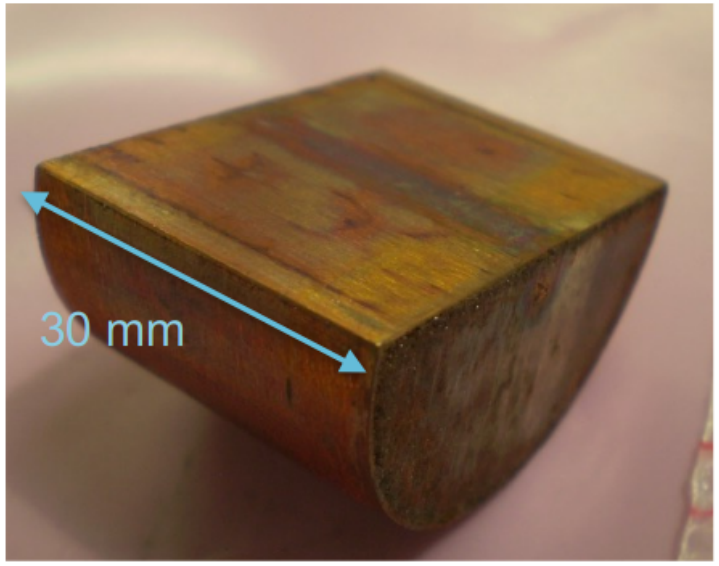
HiRadMat: 440GeV equivalent of 1.5 x 1 nominal HL-LHC bunch

Onset of plastic deformation ~ **5e9**

Fragment ejection ~ 2e10p!
(an LHC pilot bunch)

Future

Copper-diamond



HiRadMat: 440GeV equivalent of 3 x 1 nominal HL-LHC bunch

Onset of plastic deformation ~ **1.3e11**

Fragment ejection ~ 2.2e11p!
(not seen in HRM for bulk)

Developed a material that is adequate for triplet and experiment protection and is about 15 times more robust than the present tungsten alloy.

Active halo control — motivation

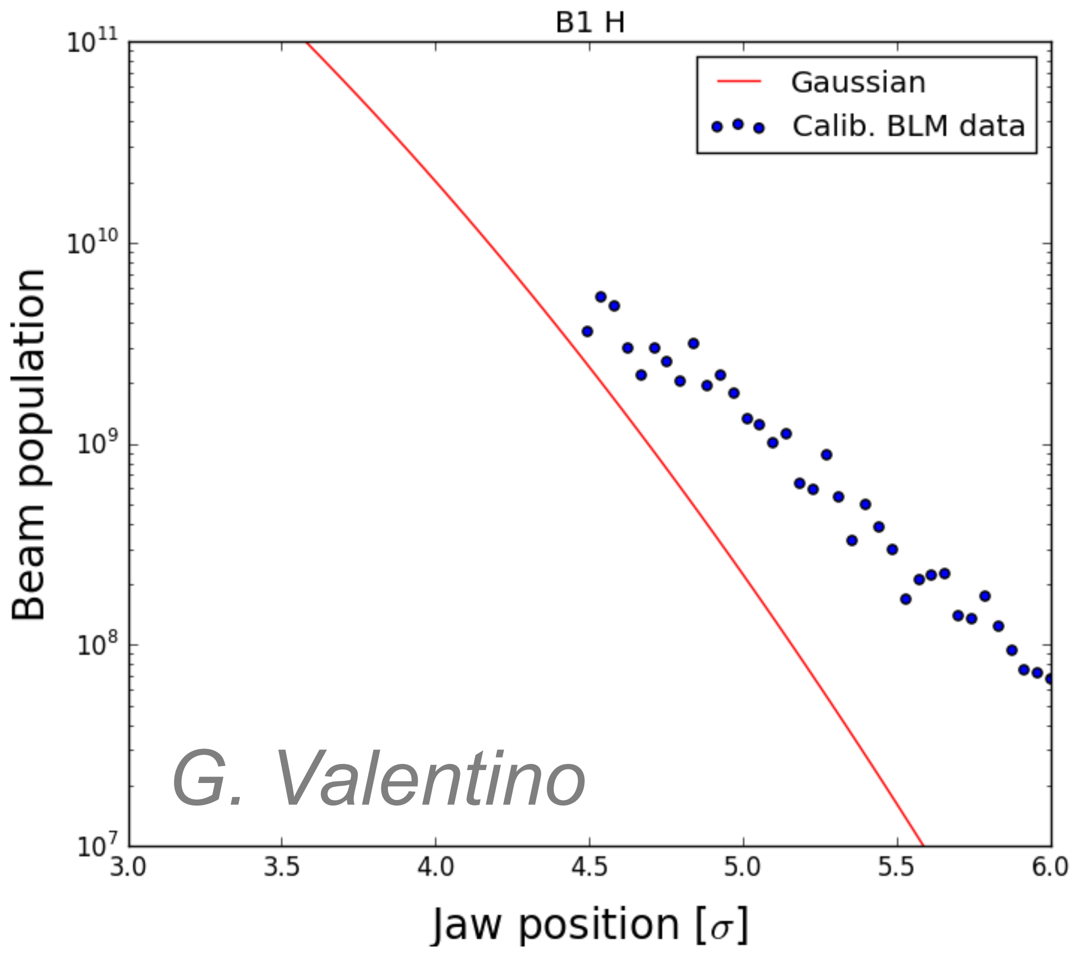
HL-LHC target 700 MJ stored beam energy (~ x2 LHC)

New collimation challenges, new failure scenarios

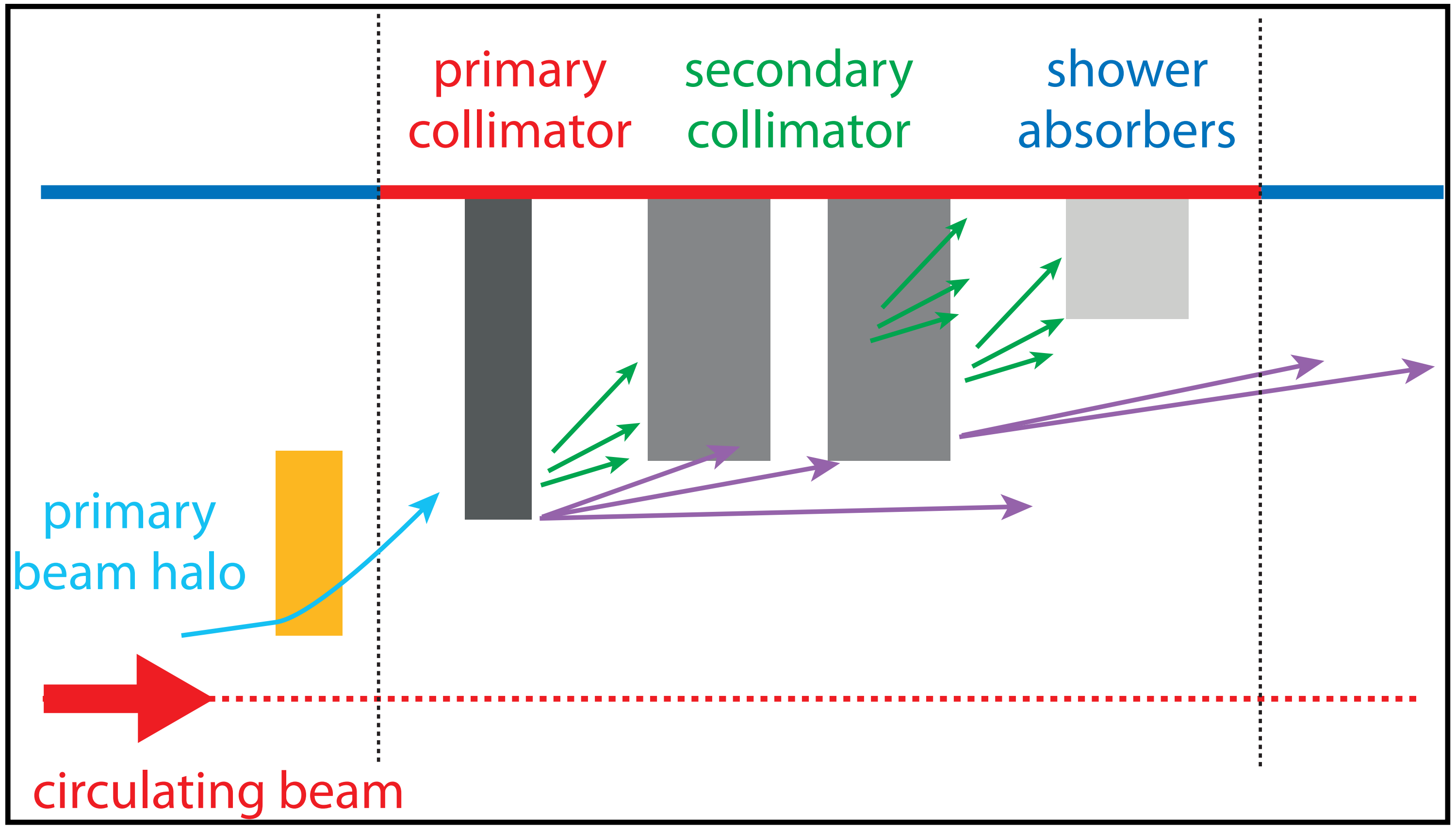
Consistent indications of over-populated tails in the LHC's Run I and Run II (collimator scan measurements)

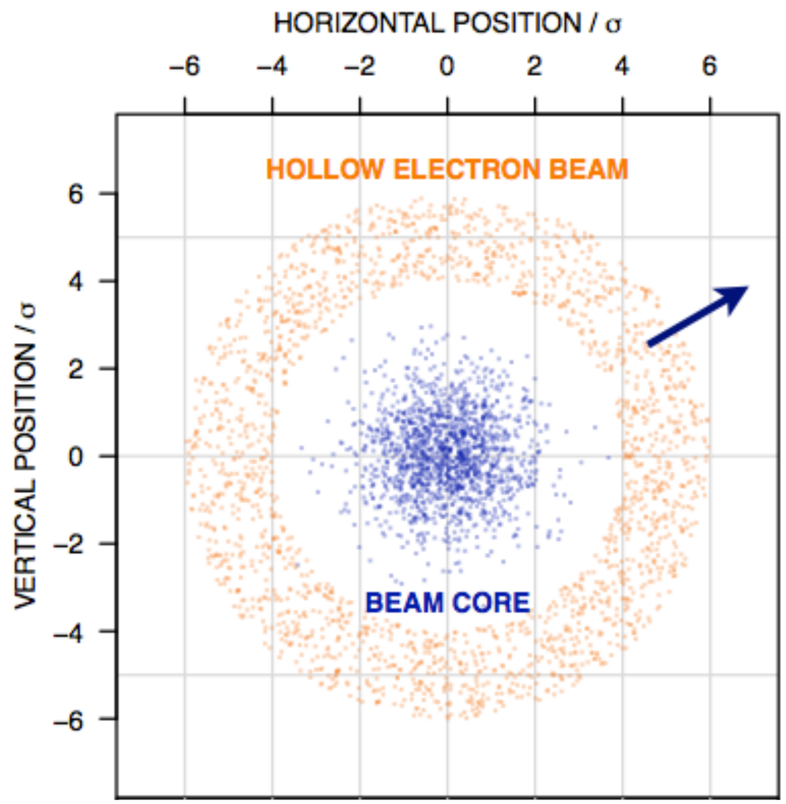
- Up to 5% of total beam current *statically* stored in the tails (35 MJ if the same was true for HL-LHC!)
- Obvious concerns for machine availability (dumps from loss spikes)
- High potential of damage

Need for an active tail control at the HL-LHC deemed necessary, assessed through different review panels.



Hollow electron lenses for HL-LHC





Active halo depletion: control diffusion speed, selective by amplitude.

— it is integrated into the hierarchy of the collimation system that remains responsible for the halo disposal.

— it allows distributing losses over a desired time interval.

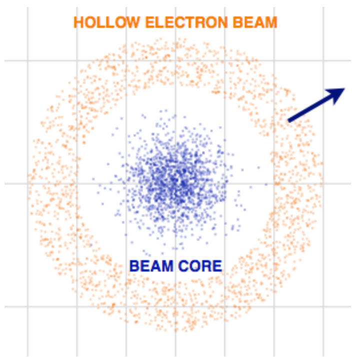
— it controls tail populations close to collimator jaws (deplete tails).

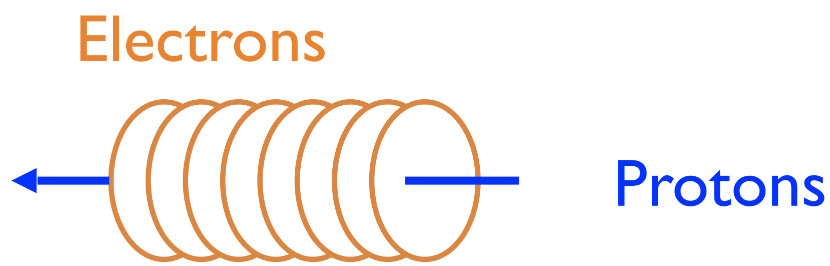
Hollow electron lenses:

"Non-material" scraper; small kick per turn → safe device

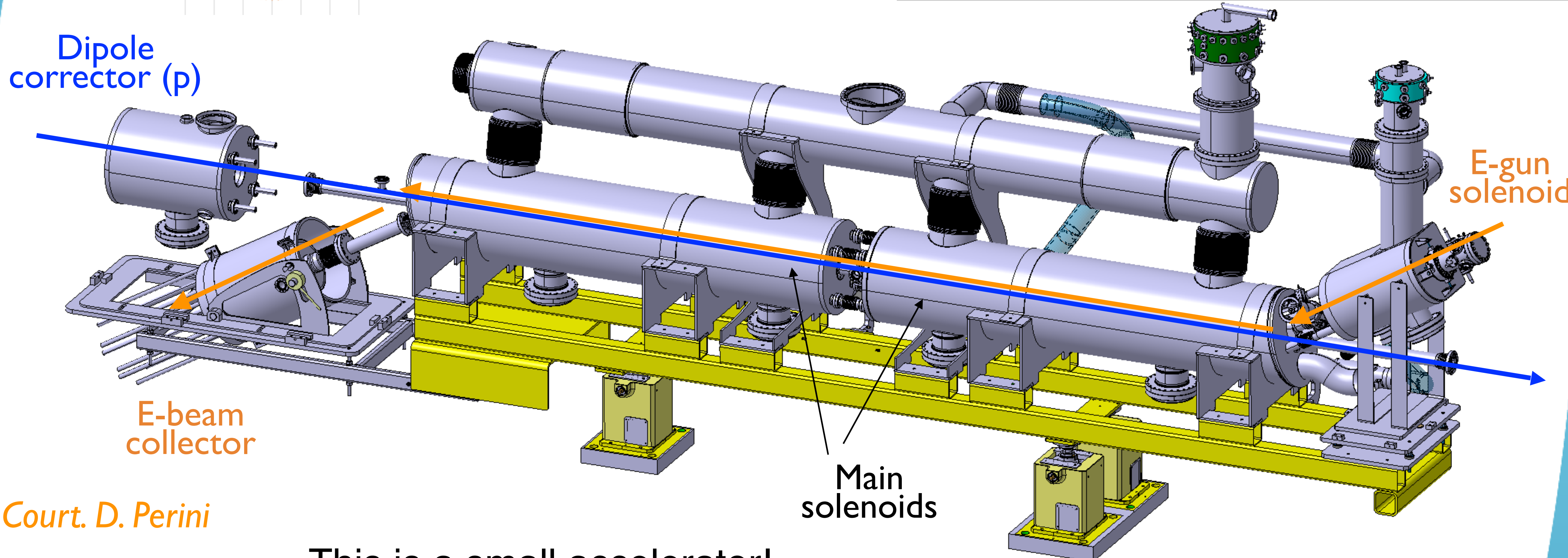
Can be installed in other points than IR7

Hollow electron lenses design





"S" shape to compensate effects on core from e-beam asymmetries.
Goal: 5A e-beam current; batch-by-batch excitation; various powering schemes.

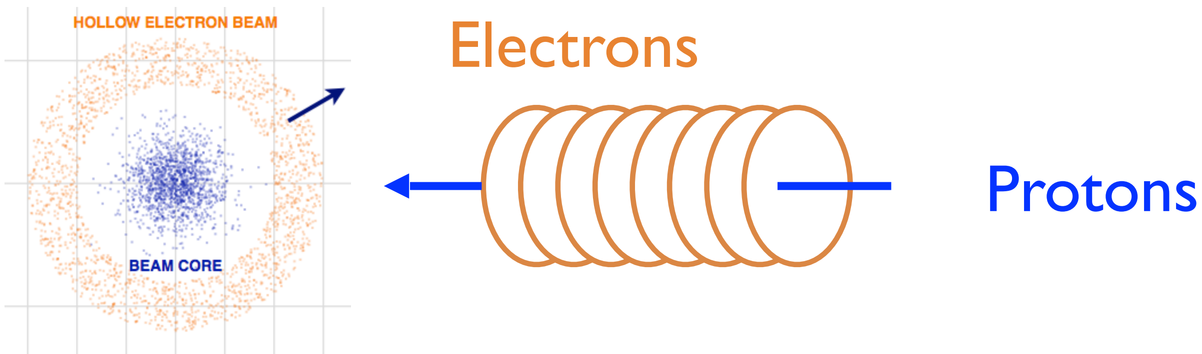


Court. D. Perini

This is a small accelerator!

- Cryogenics and magnetic system;
- Electron gun and collector;
- Electron and proton beam diagnostics;
- Vacuum system;
- Support and alignment systems.

Hollow electron lenses design



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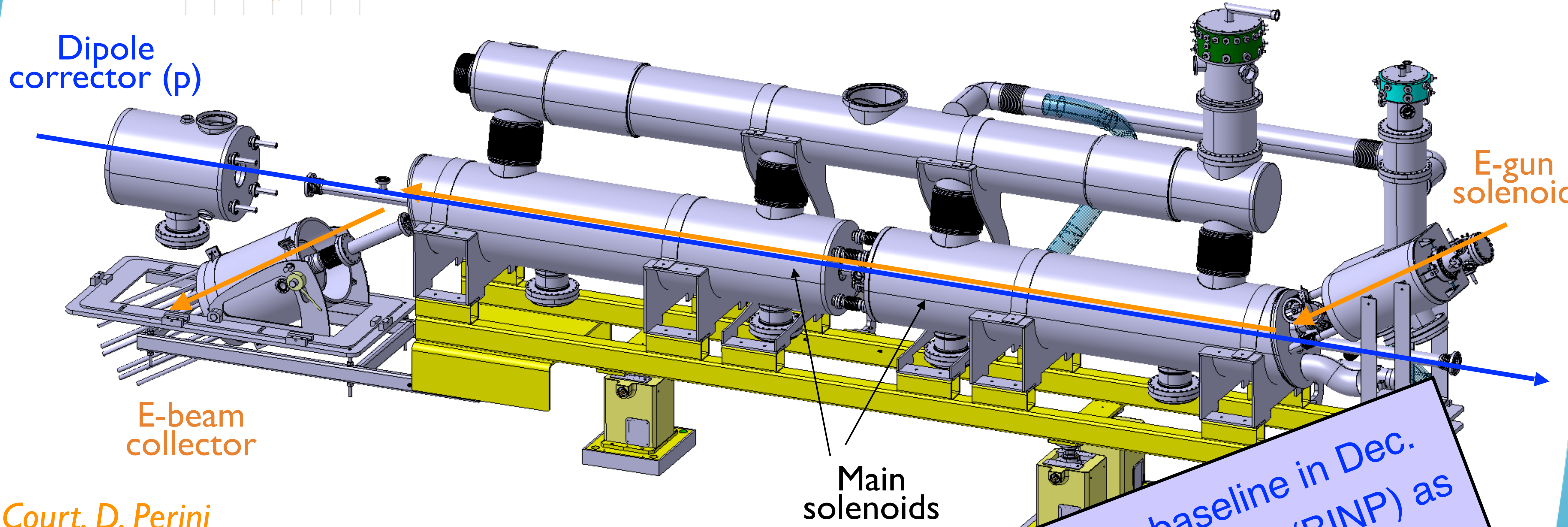

Court. D. Perini

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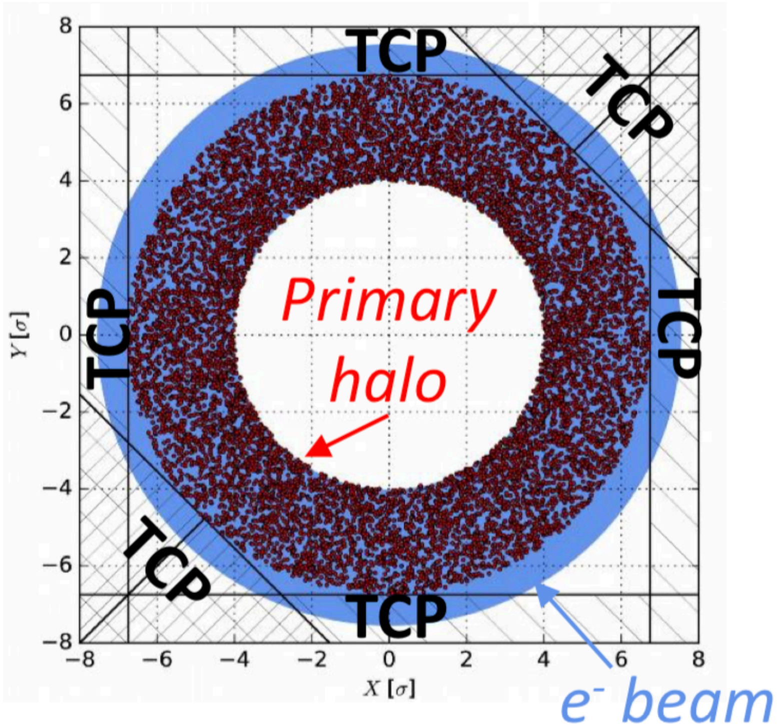
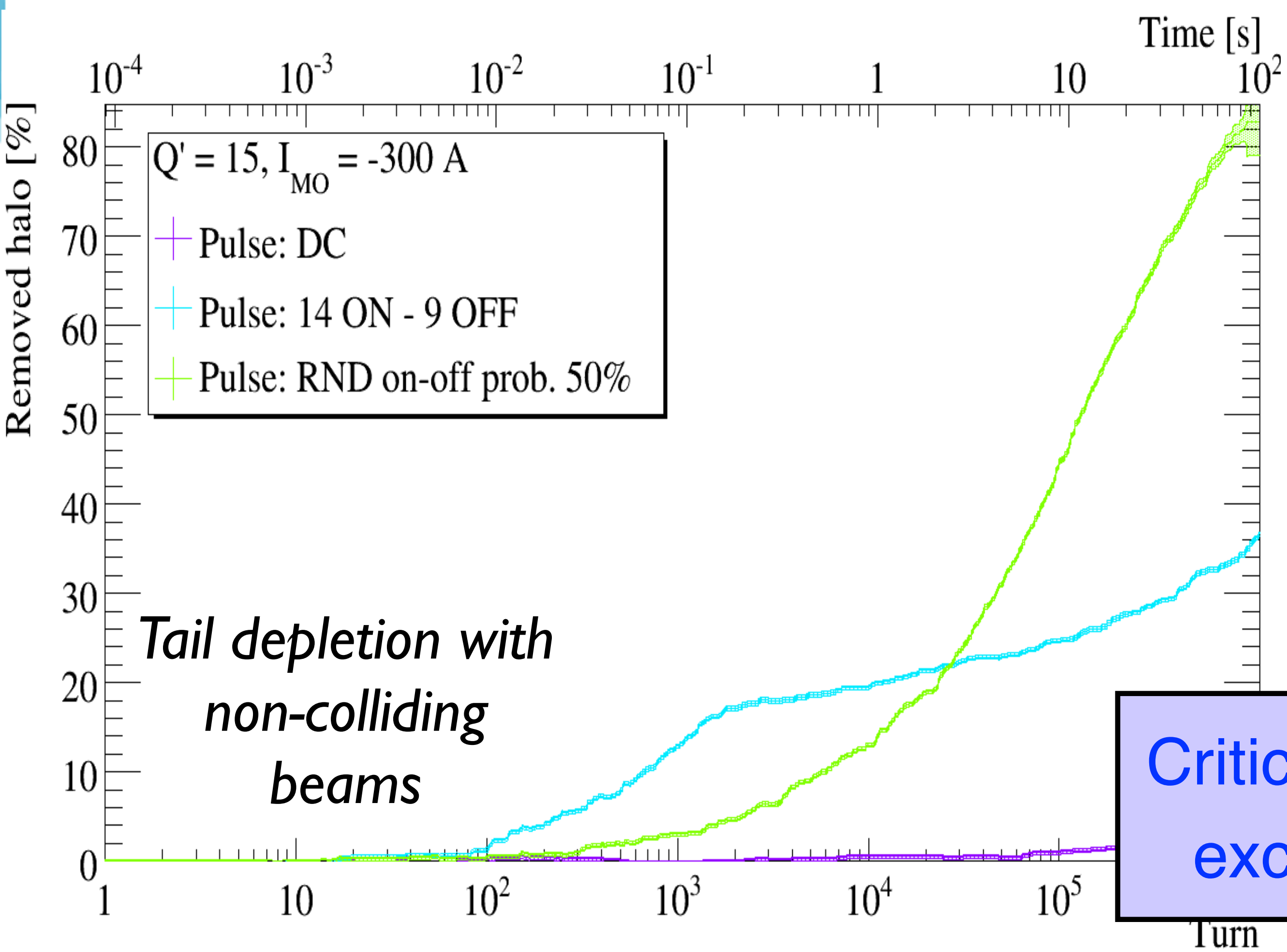
- Vacuum system;
- Support and alignment systems.

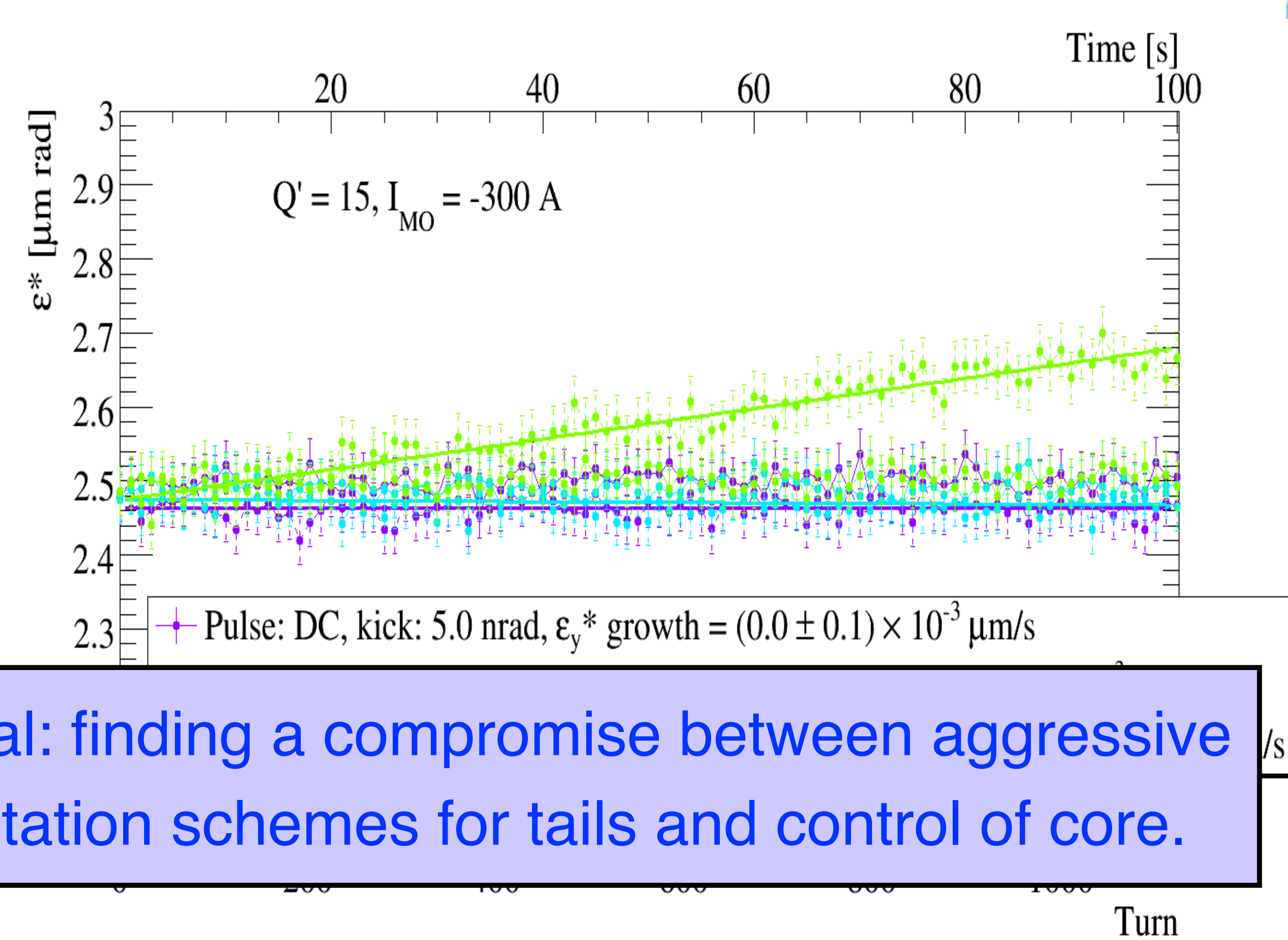
Added to upgrade baseline in Dec. 2019. To be built in Russia (BINP) as in-king contribution to HL-LHC.

Simulated performance (preliminary)



- HEL integrated as magnetic element in SixTrack (various models for e.m. fields, with imperfections)
- Simulation setup can include scattering with collimators
- Various excitation profiles being considered
- Ongoing: optimisation of pulsing pattern and tolerance studies



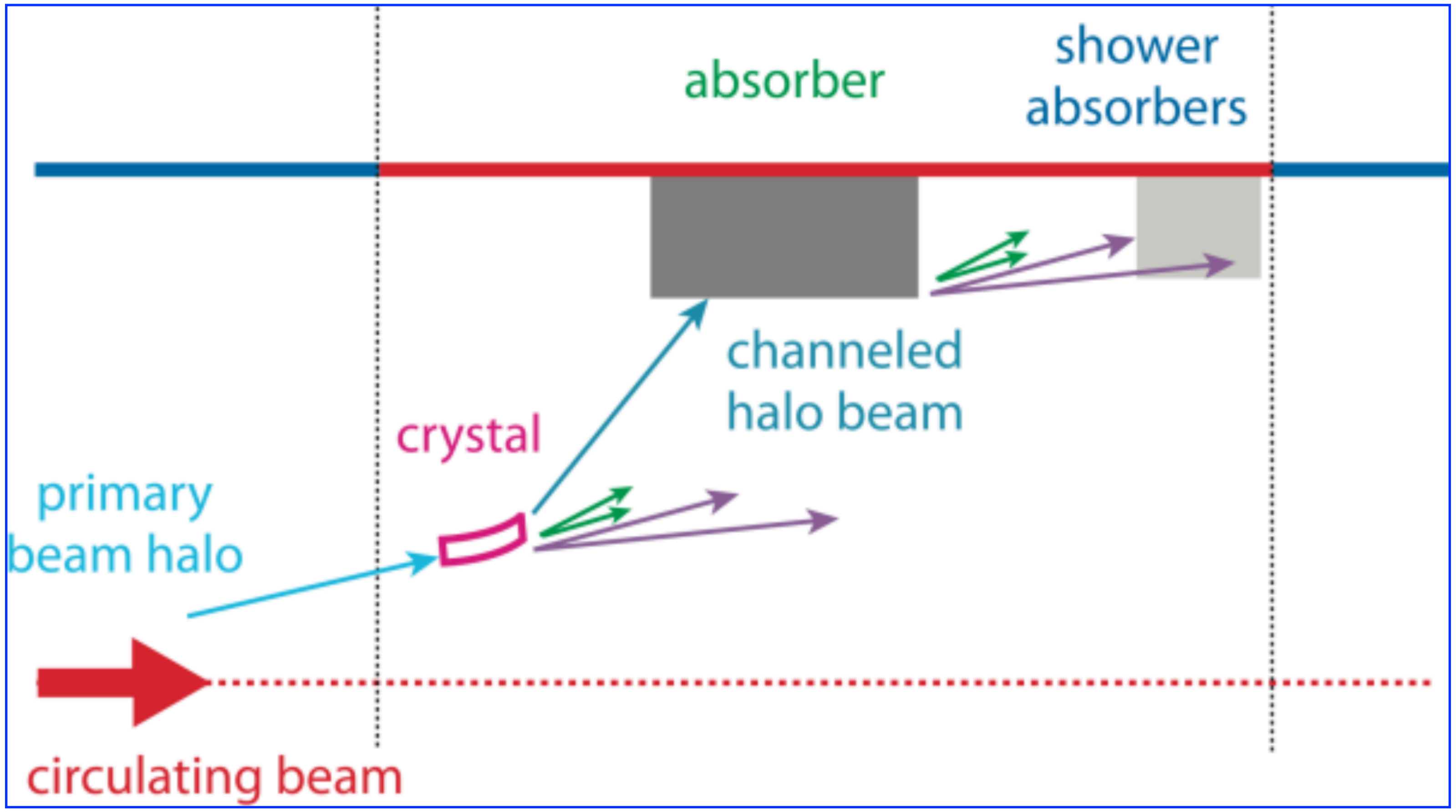


Critical: finding a compromise between aggressive excitation schemes for tails and control of core.

Court. D. Mirarchi

The crystal collimation concept

(replacing the 3-stage system for betatron cleaning)



The rest of the hierarchy (protection, inner triplet, etc…) remains needed!

Crystal-based betratron halo cleaning

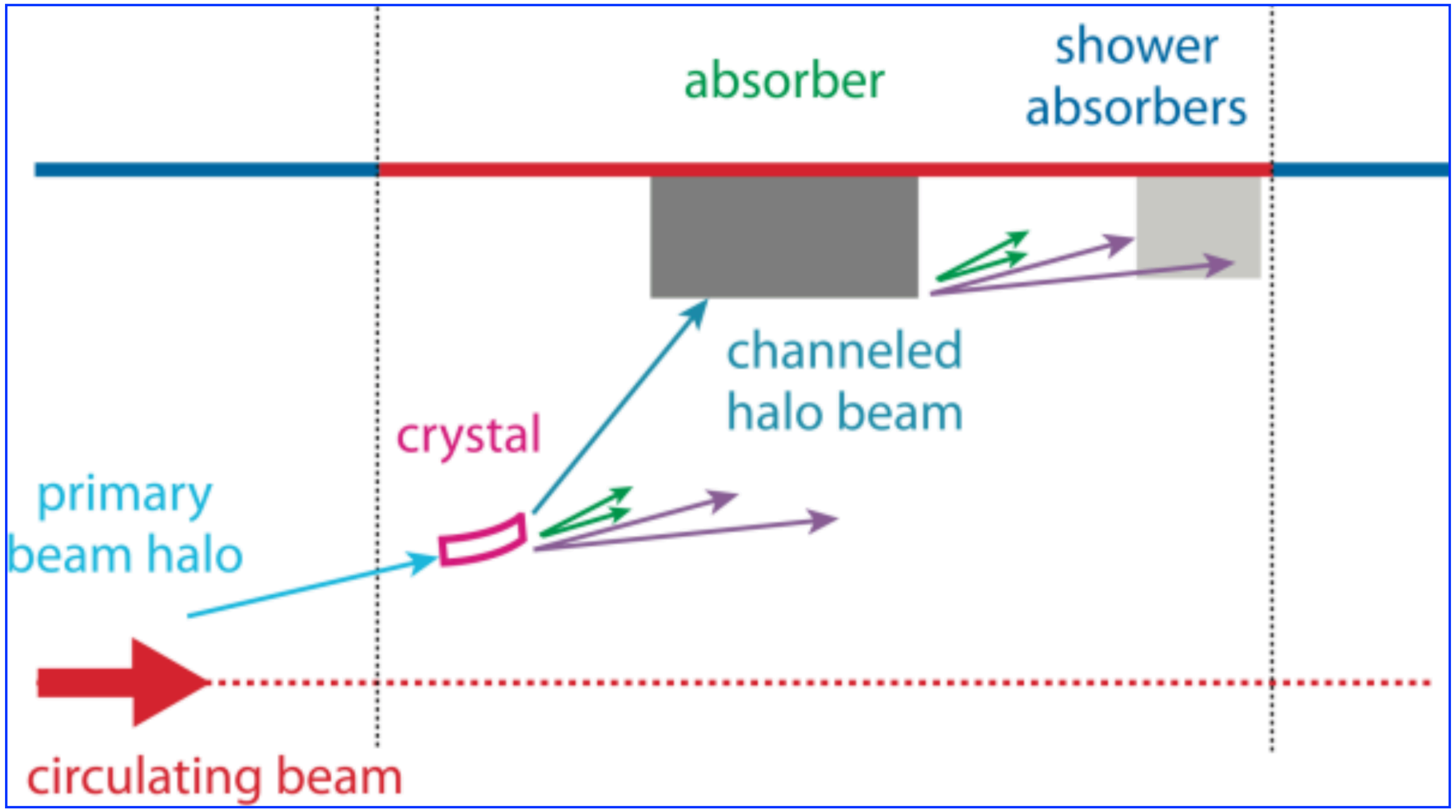
- Bent crystal replaces horizontal and vertical primary collimators
- A single massive absorber (per plane) intercepts the channeled halo
- Needs additional shower absorbers, but "cleaner" disposal of primary losses

Promises: Improvement of cleaning, with fewer collimators, in particular for heavy ion beams (suppress of fragmentation/dissociation!)

Challenges: Quality and performance of crystal assembly (new energy regime)
Angular control within sub-micro radiants
Safe and efficient disposal of channeled halo

The crystal collimation concept

(replacing the 3-stage system for betatron cleaning)



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Challenges: Quality

Angular

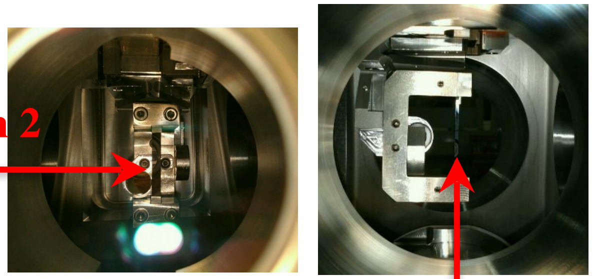
Safe and efficient disposal of channeled halo

Added as a part of the upgrade baseline in Dec. 2019 (through in-kind contribution) as mitigation for schedule issues with the 11T dipole, for lead ion collimation in Run 3.

LHC crystal collimation layouts

Four crystals installed in the LHC: two per beam, one per plane. Provided and validated by the UA9 collaboration. 2 producers: PNPI (3 crystals) and INFN-Fe (1).

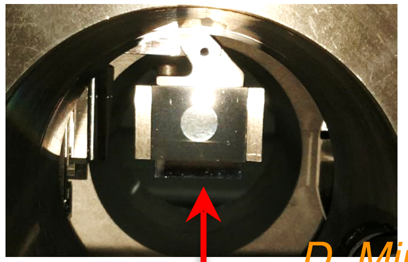
TCPCH.A5R7.B2



PNPI

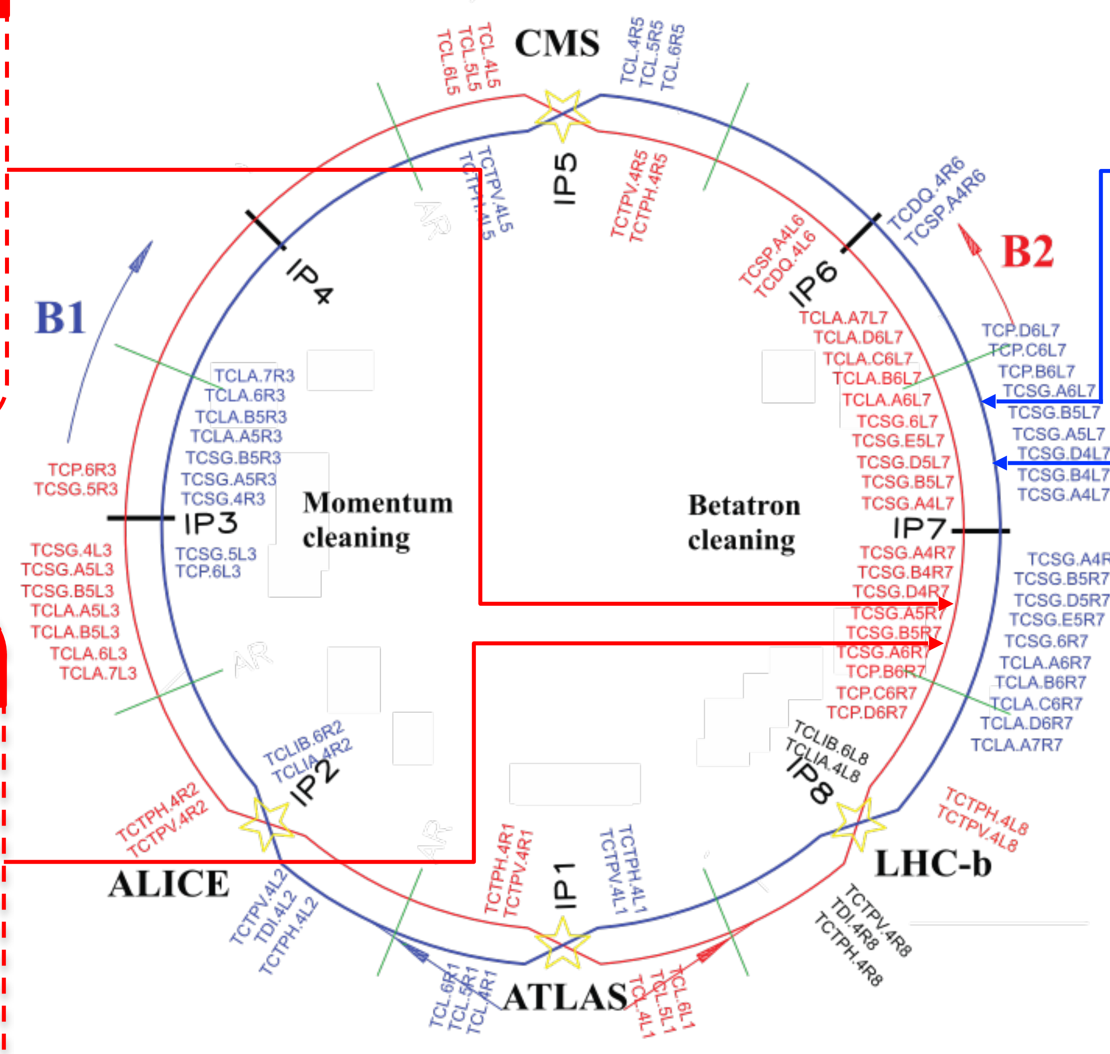
Pics. courtesy of Y. Gavrikov

TCPCV.A6R7.B2

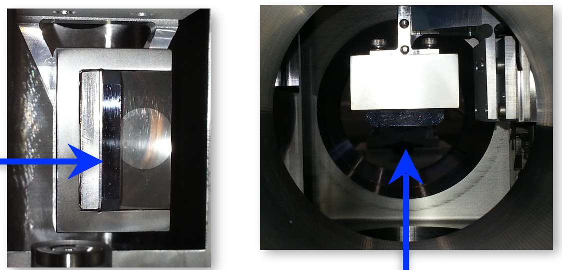


D. Mirarchi

PNPI

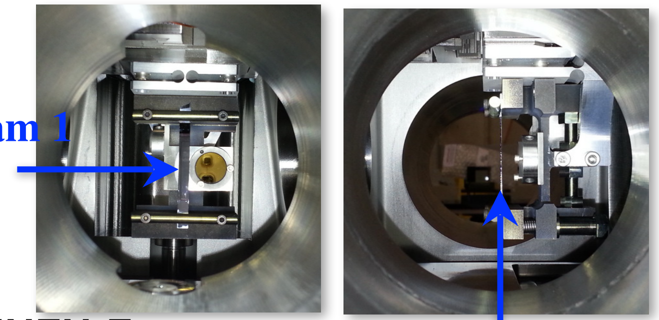


TCPCV.A6L7.B1



PNPI

TCPCH.A4L7.B1



INFN-Fe

Complete layout : both beams and planes — allow thorough investigations and **operational** tests

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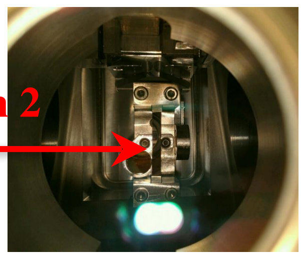
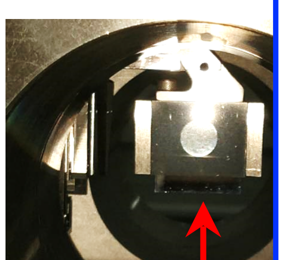


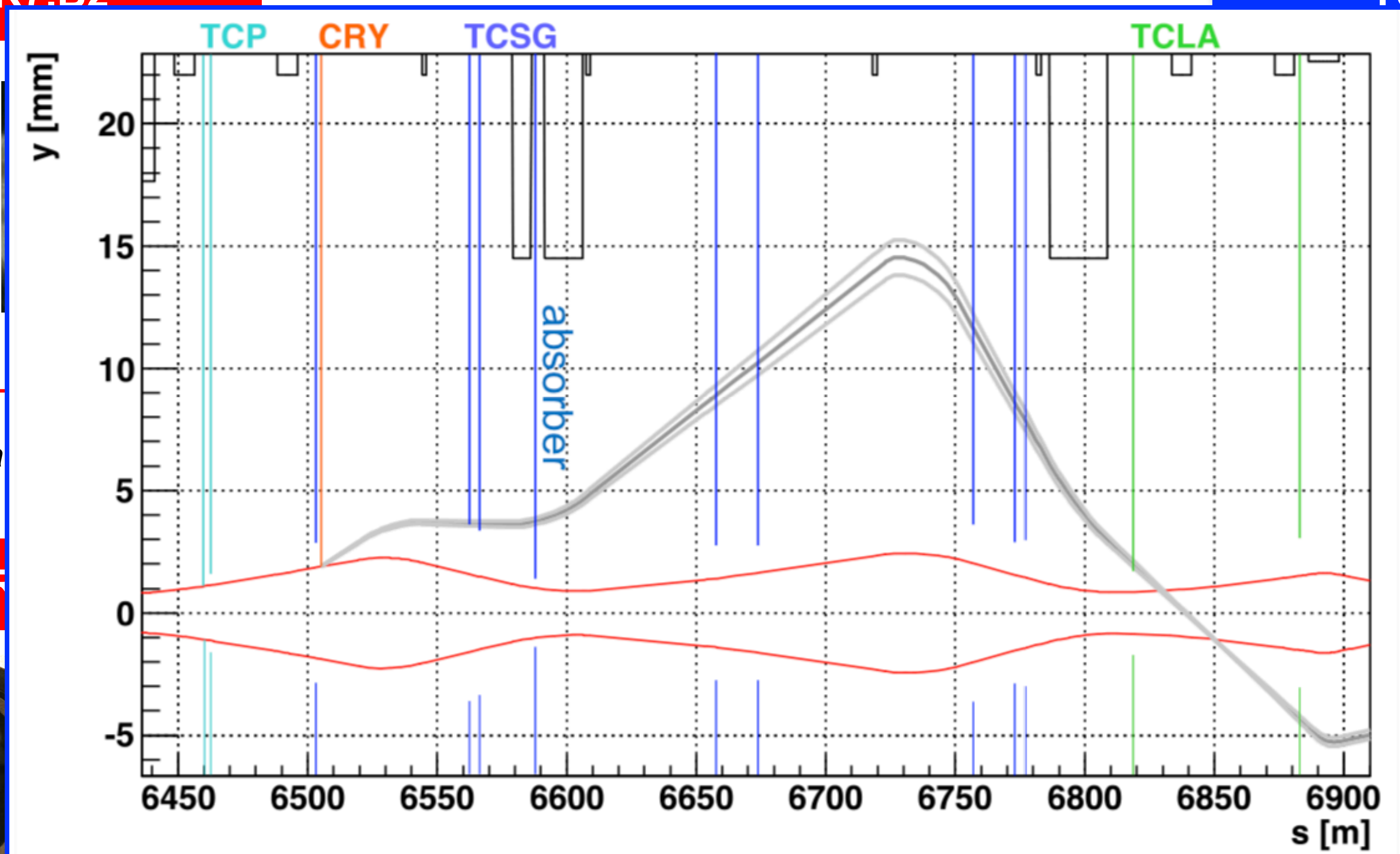
PNPI

Pics. courtesy of Y. Ga

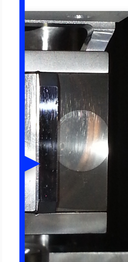
TCPCV.A6R

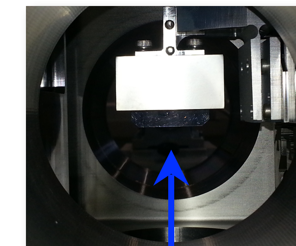


PNPI



TCPCV.A6L7.B1





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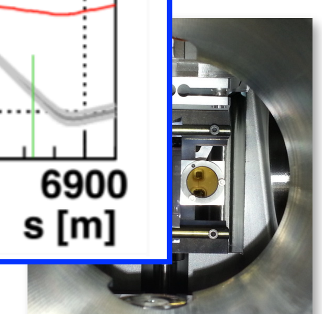
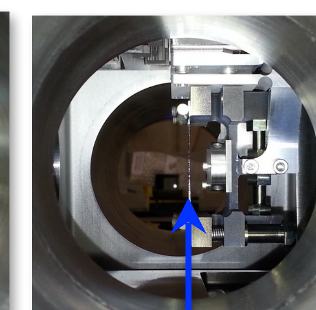


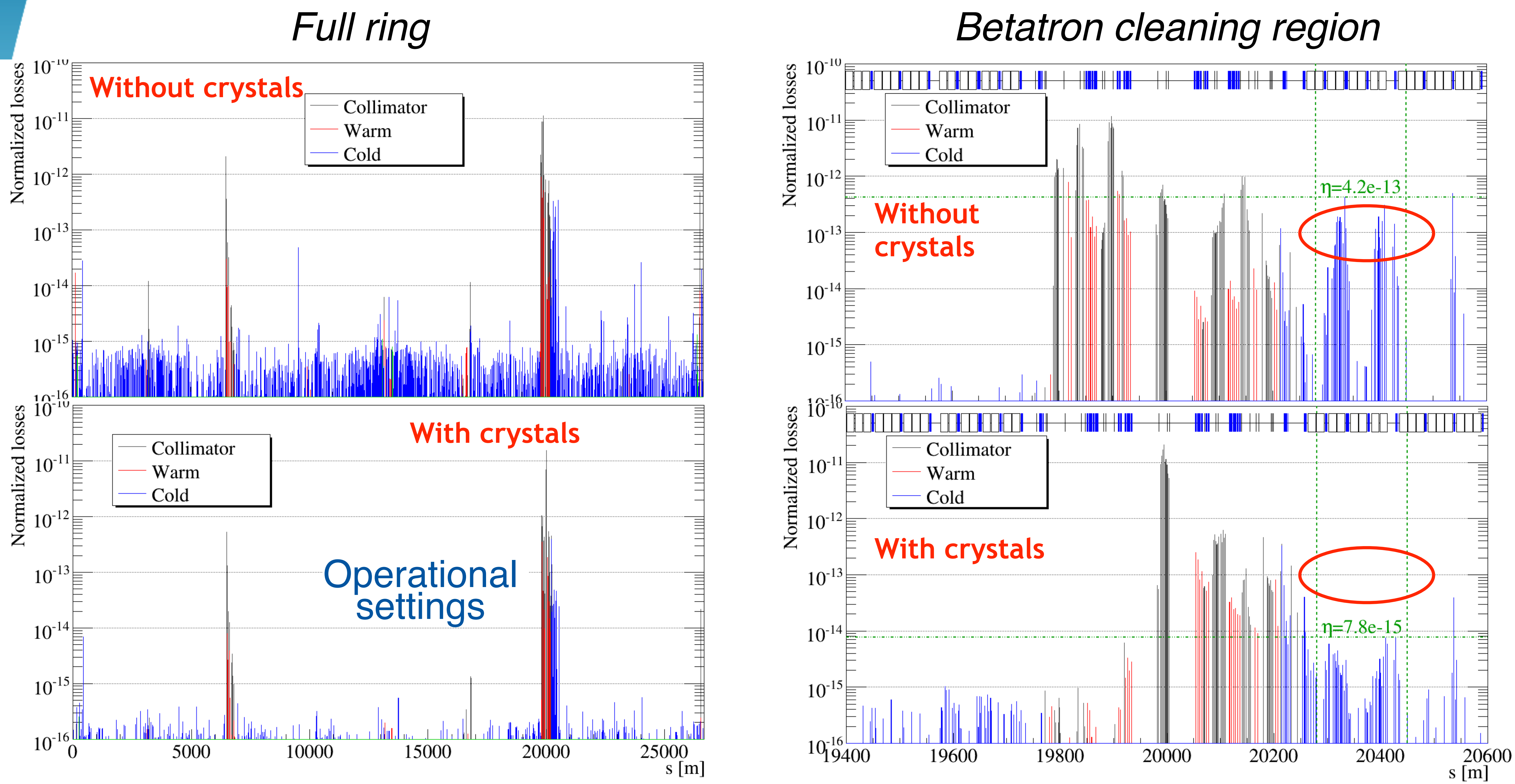


INFN-Fe

TCP = primary collimator
TCSG = secondary collimator
TCLA = shower absorber

Complete layout : both beams and planes — allow thorough investigations and **operational** tests

Collimation cleaning: 6.37 Z TeV Pb beams

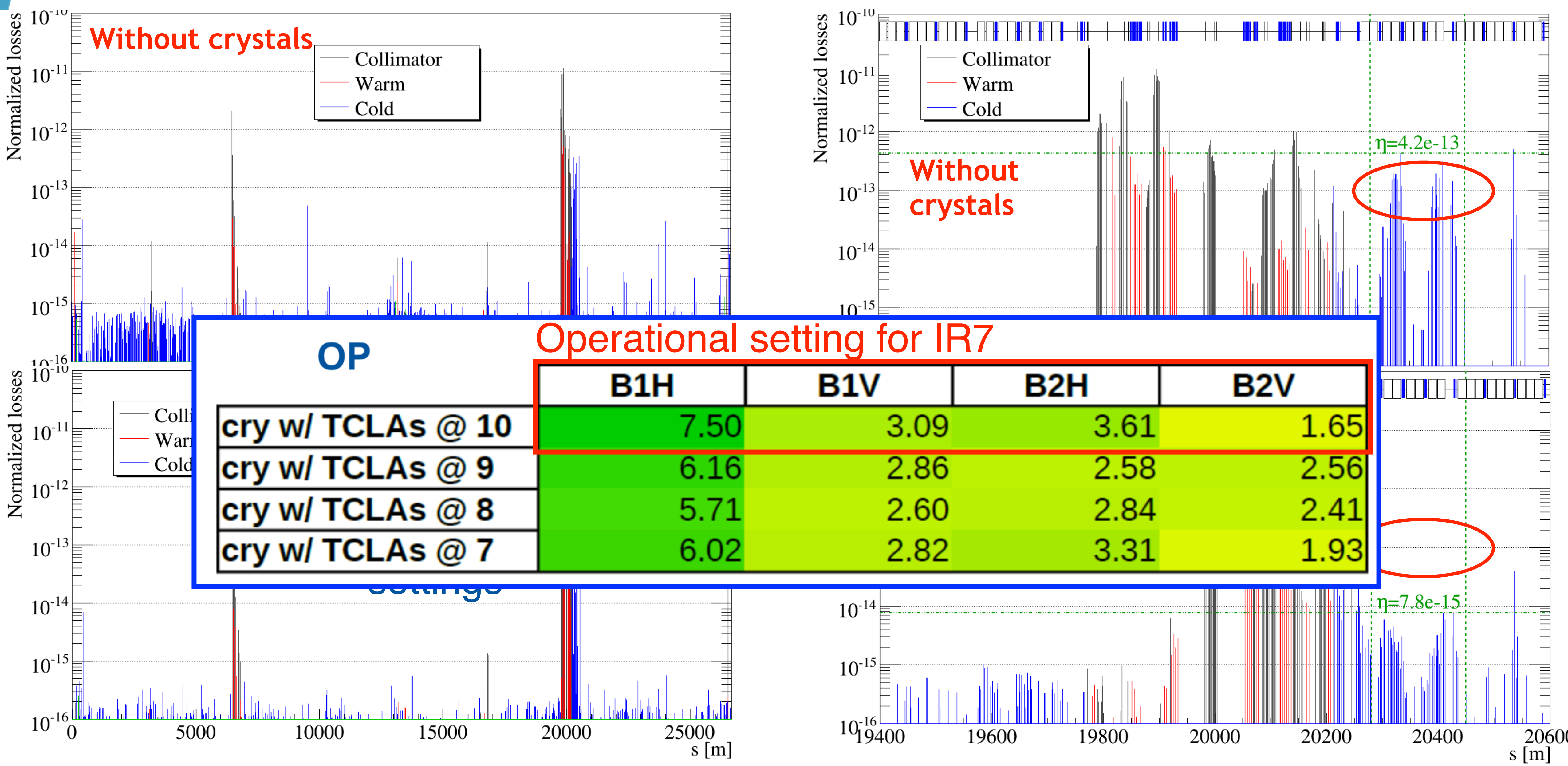


- Overall reduction of losses around the ring with crystal added to system.
- Tested with high ions intensities (~600 bunches)!
- Cleaning improvement up to a **factor 7** (more with optimised settings).
- Not the same improvement with all crystals — to be understood.

(measurements available for a broad variety of settings)

Collimation cleaning: 6.37 Z TeV Pb beams

Full ring | *Betatron cleaning region*



OP — Operational setting for IR7

	B1H	B1V	B2H	B2V
cry w/ TCLAs @ 10	7.50	3.09	3.61	1.65
cry w/ TCLAs @ 9	6.16	2.86	2.58	2.56
cry w/ TCLAs @ 8	5.71	2.60	2.84	2.41
cry w/ TCLAs @ 7	6.02	2.82	3.31	1.93

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(measurements available for a broad variety of settings)

Conclusions

- Beam collimation is an important ingredient for the performance of high-energy and high-intensity hadron colliders
- The collimation performance at the LHC is very satisfactory, and it needs further improvements for the future.
  - The understanding of LHC performance and limitations guided new developments
  - Imminent preparation of the HL-LHC: several upgrades are already ongoing!
  - Technologies and know-how also considered for future accelerators.
- Several items are planned in the upgrade baseline for HL-LHC
  - Low-impedance, high robustness, DS cleaning and new collimator designs
- Recent additions to the baseline (through in-kind contributions):
  - Hollow electron lenses as a way to actively control beam tails.
  - Crystal collimation of heavy-ion beams.
- Looking forward to testing with beam some key upgrades
  - First phase of impedance reduction (new materials), local DS cleaning with 11T dipoles, crystal collimation will be available in Run 3 already!