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Present and future beam collimation: challenges and solutions for HL-LHC and future projects

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On behalf of the HL-LHC WP5 (Collimation Upgrade) and LHC collimation teams

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- Collimation in the LHC Run 3
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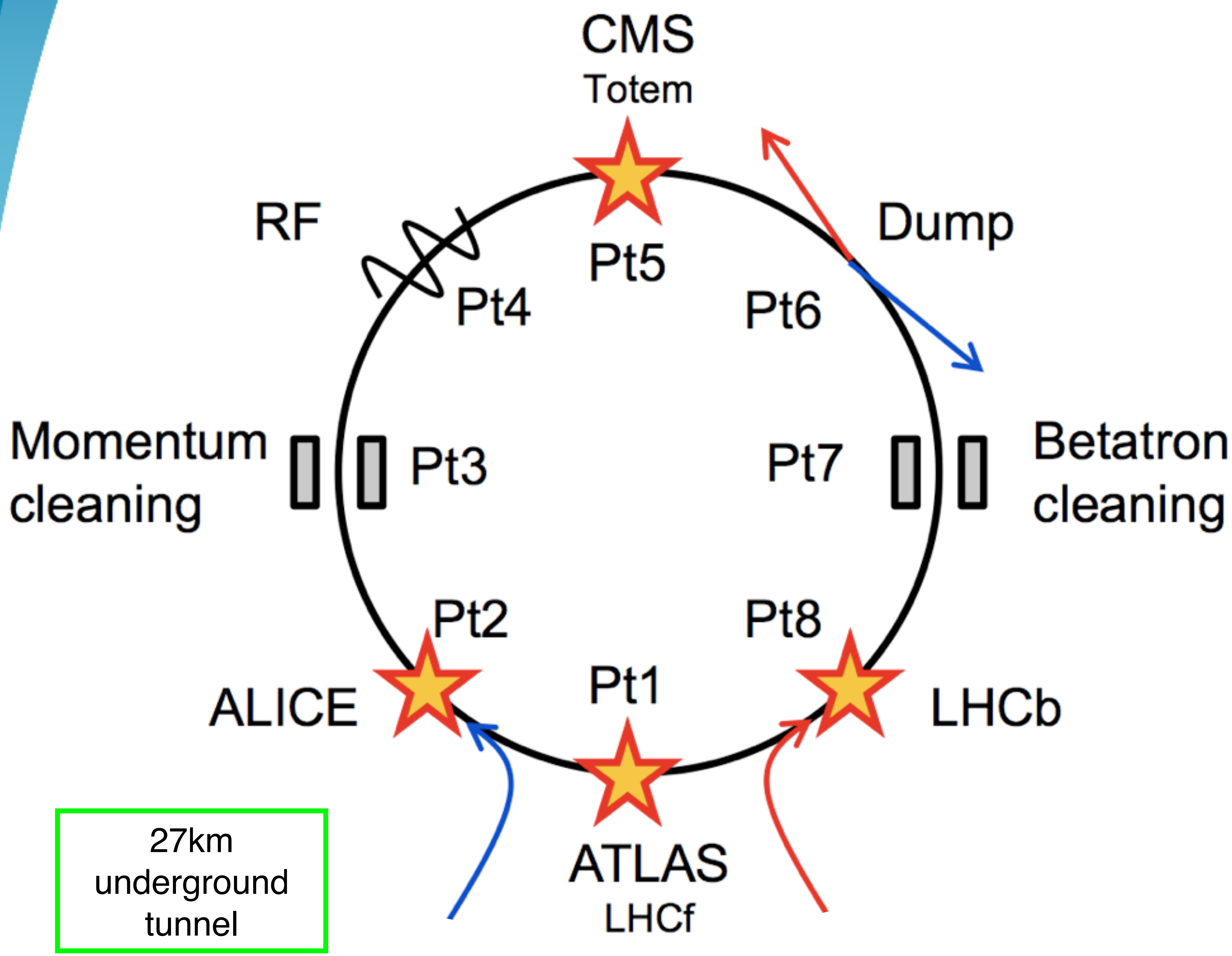
The Large Hadron Collider (LHC)

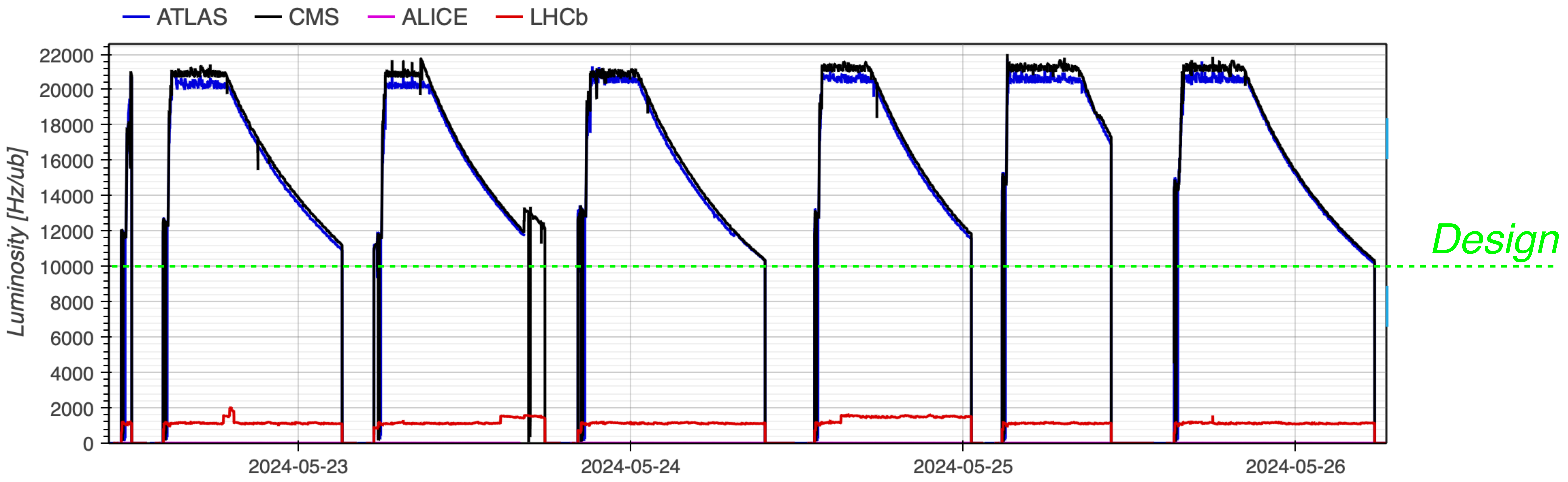


27km underground tunnel

- 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 systems

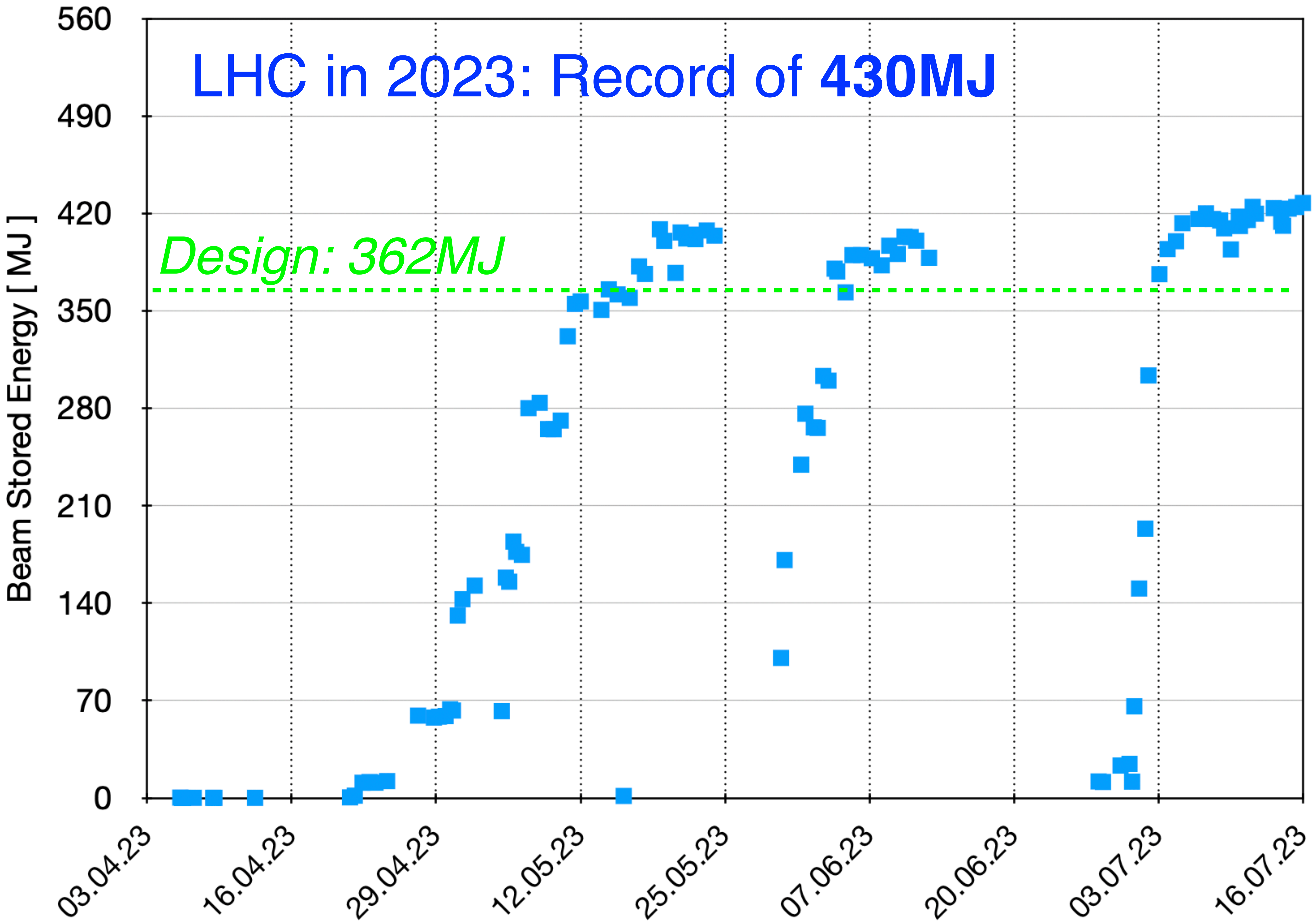
Nominal and achieved key LHC parameters			
	Design	2018	2024
Injection energy (TeV)	0.45	0.45	0.45
Top energy (TeV)	7	6.5	6.8
Particles per bunch, I_b (10^{11})	1.15	1.2	1.6
Number of bunches per beam	2808	2560	2352
Stored beam energy, E_b (MJ)	362	300	410
Beam current (A)	0.58	0.48	0.74
Transverse emittance (μm)	3.75	2.1	1.8
Colliding beta function, β^* (m)	0.55	0.25	0.30

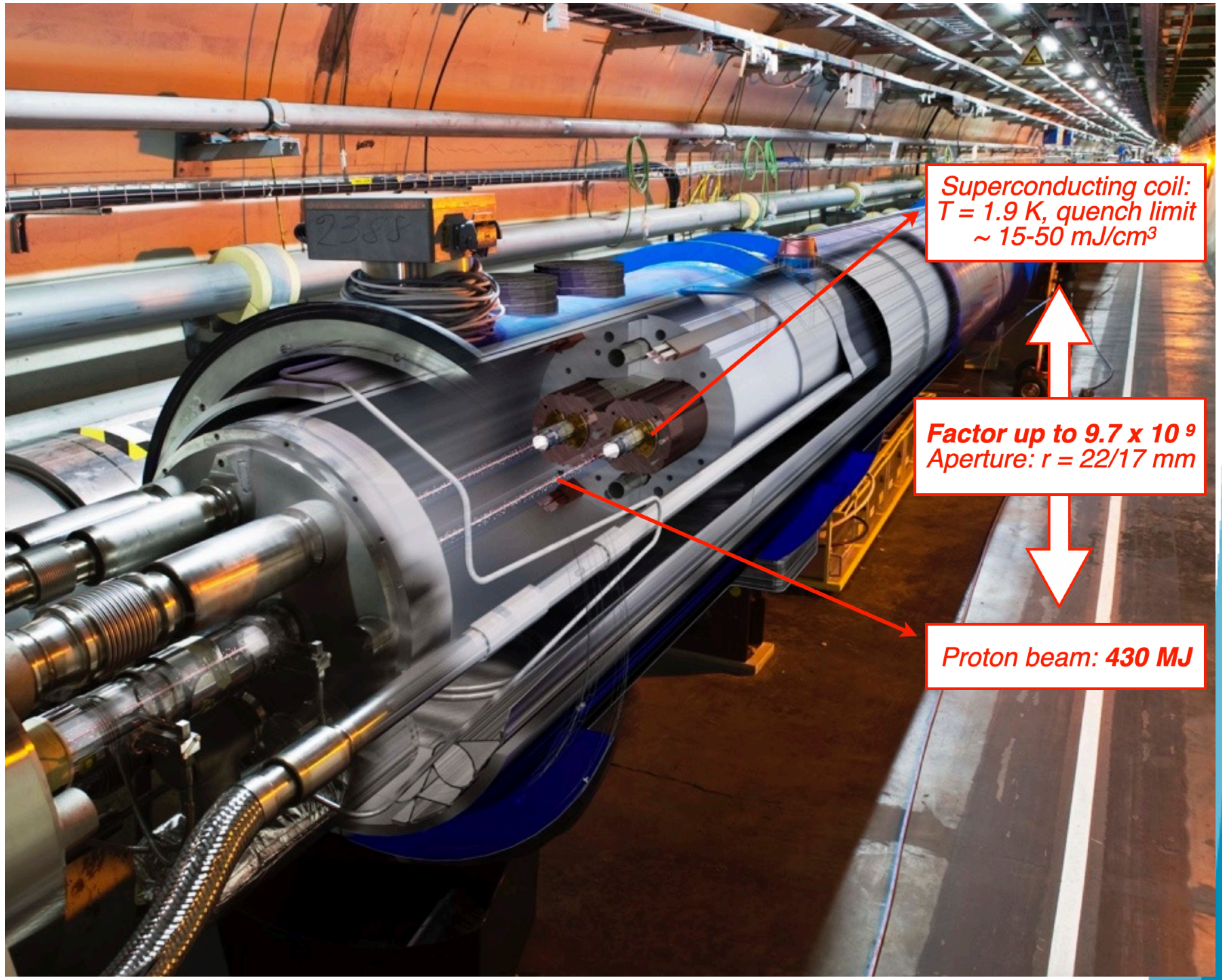
Present performance at 6.8 TeV



- Levelled **luminosity** at 2.1 x $10^{34}cm^{-2}s^{-1}$ ("limited" by cryogenics at triplets) Levelled on experiments pile-up around 60. **x 2.1**
- **Bunch current** 1.6 x 10^{11}p, limited to minimise risks of RF finger damage **x 1.4**
- **Beam stored energy** at 6.8TeV: ~430MJ (2023). **x 1.2**
- **Emittance** typically below 2μm in all planes **x 1.9**

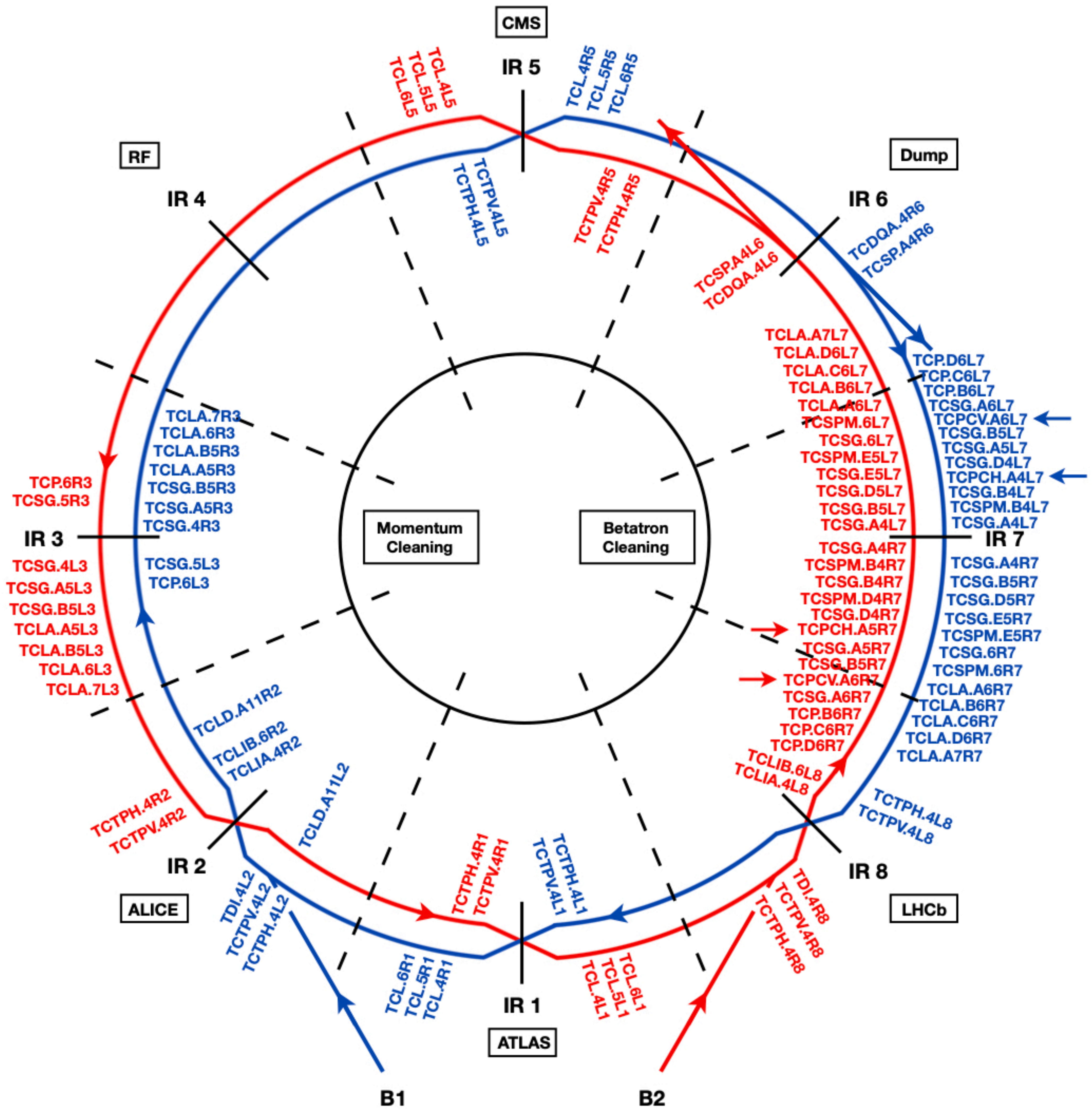
The LHC record stored beam energy

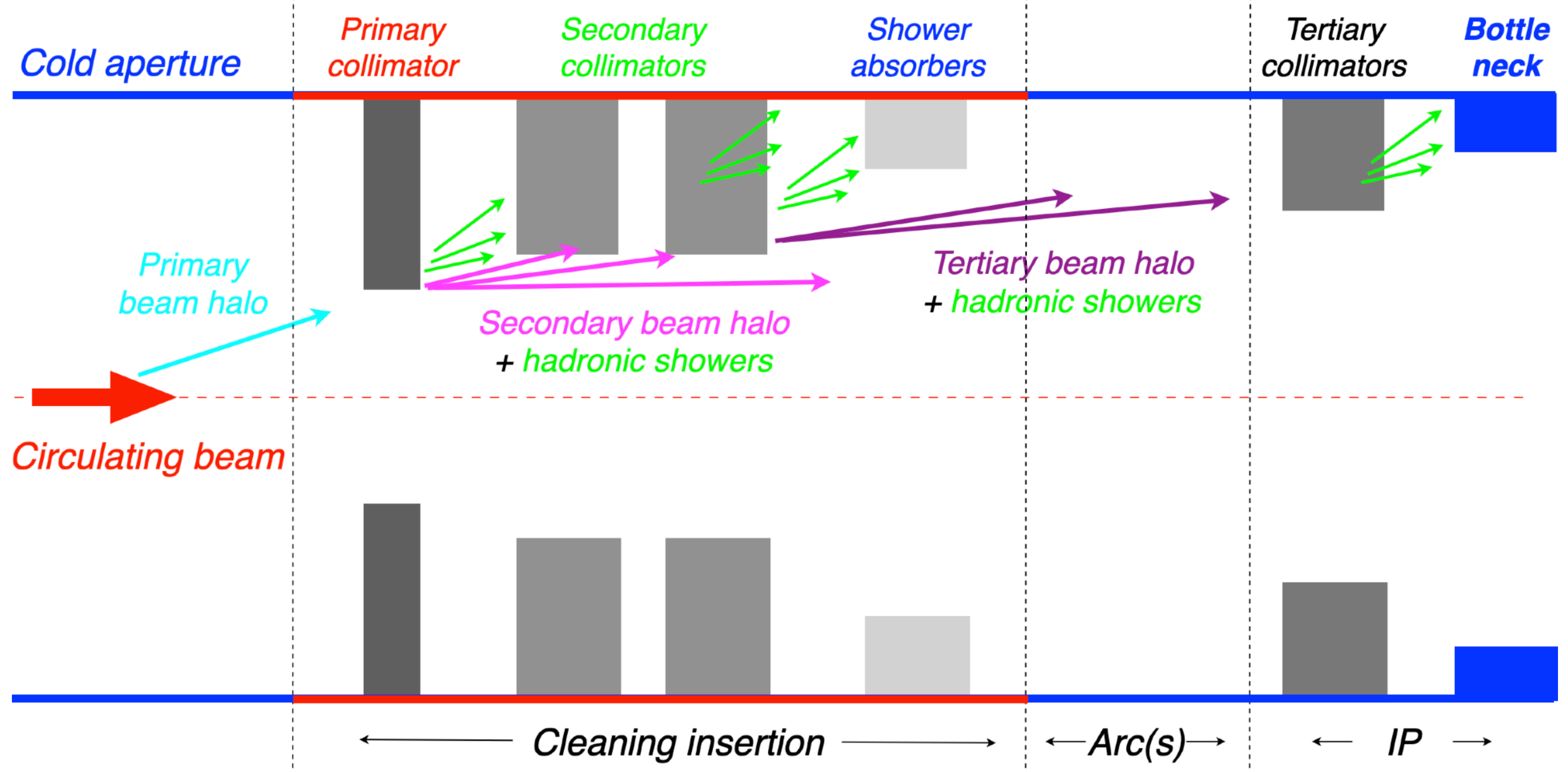




*Record in 2024: **~ 410MJ**: operation at reduced number of bunches because of e-cloud (see L. Mether talk)*

LHC multi-stage collimation system





It fulfils various critical roles

→ **betatron halo cleaning** (IR7)

→ off-momentum cleaning (IR3)

→ **Inner triplet and detector protection** (IR1/2/5/8)

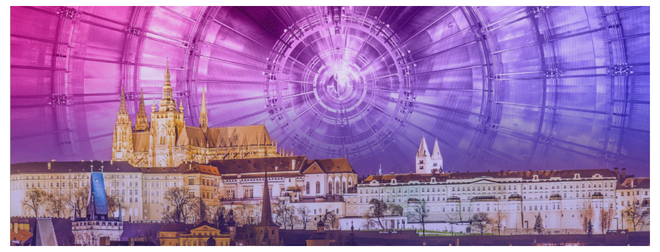
→ **Disposal of physics-debris products** (IR1/2/5)

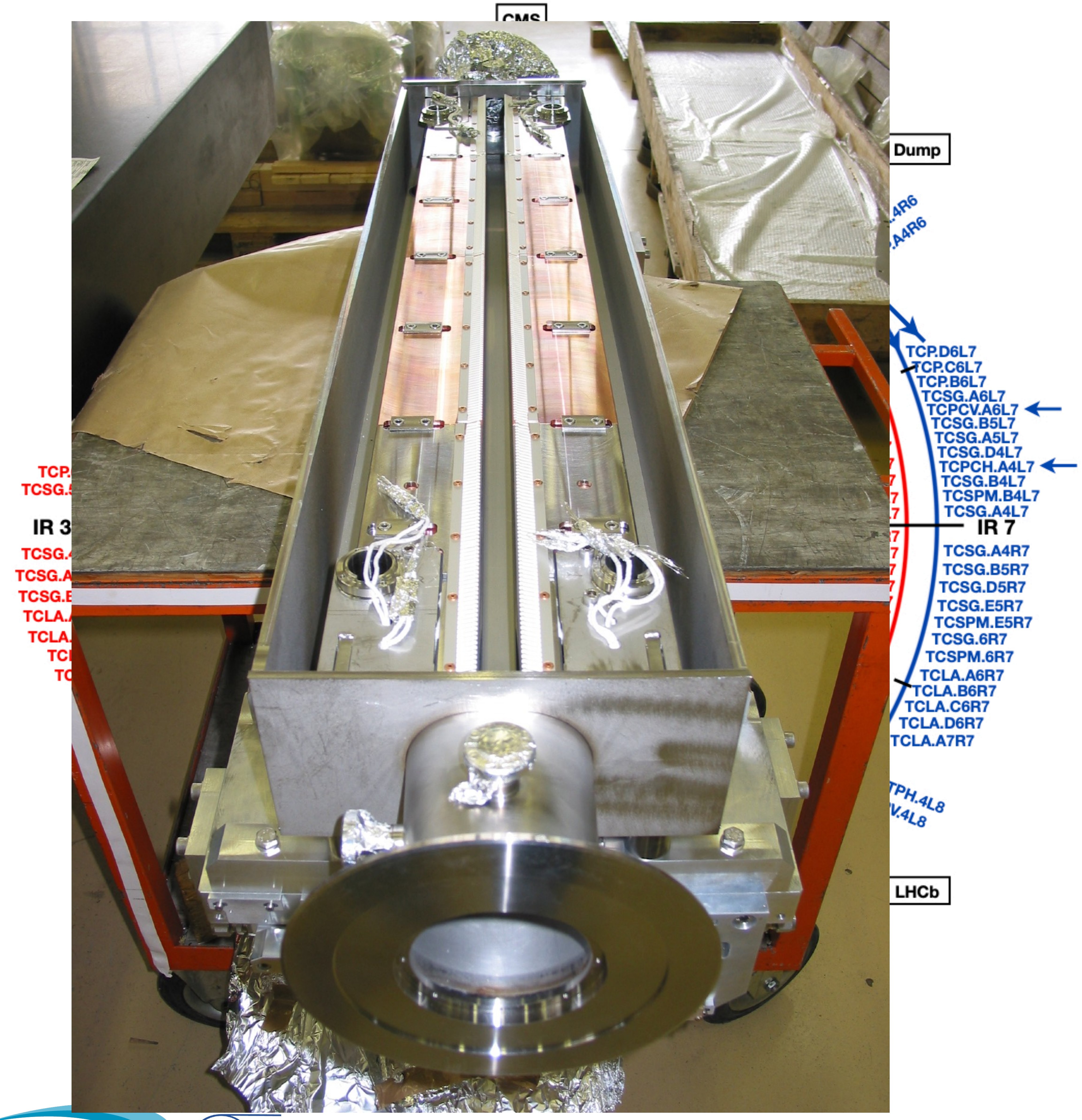
→ Injection protection (IR2/8)

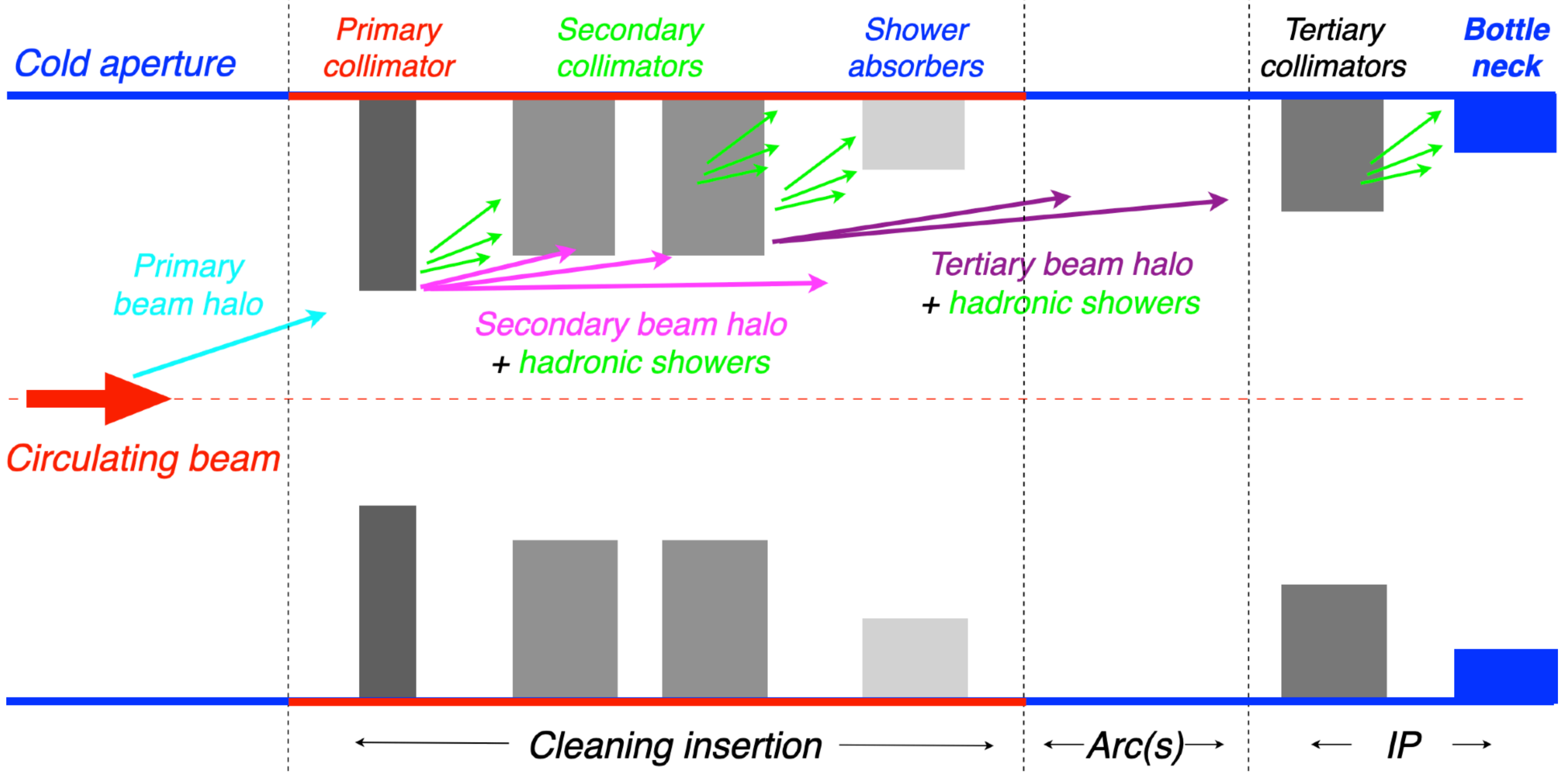
→ Beam-dump protection (IR6)

Run 3 system: more than 100 collimators!

LHC multi-stage collimation system







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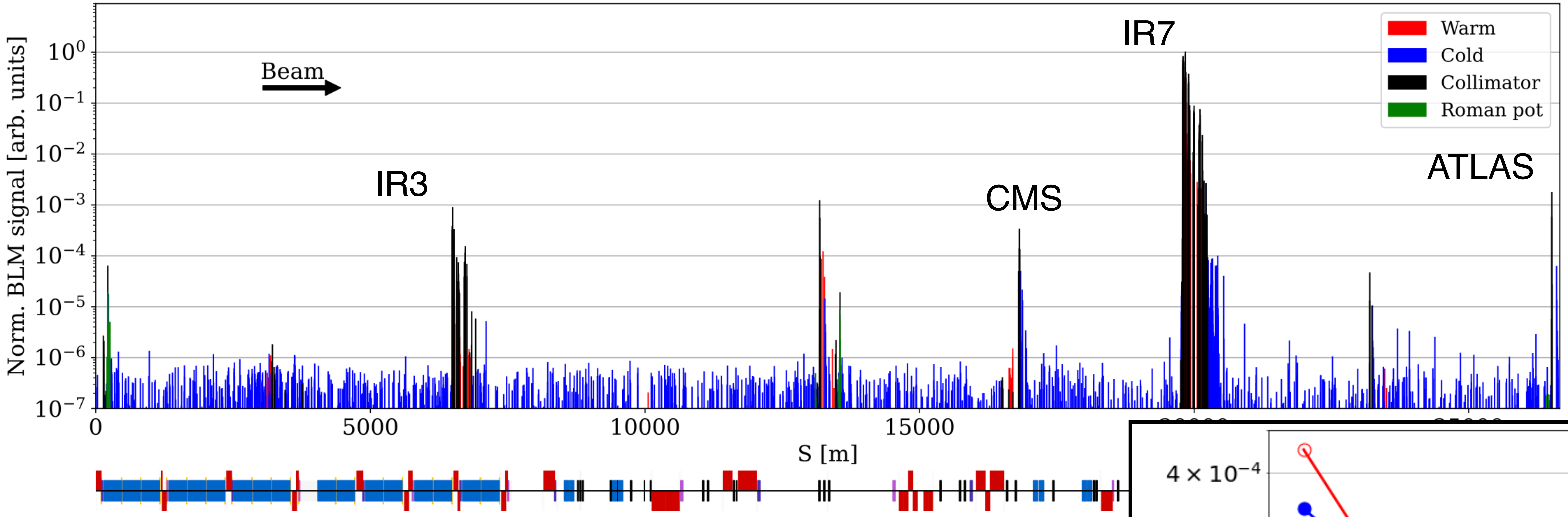
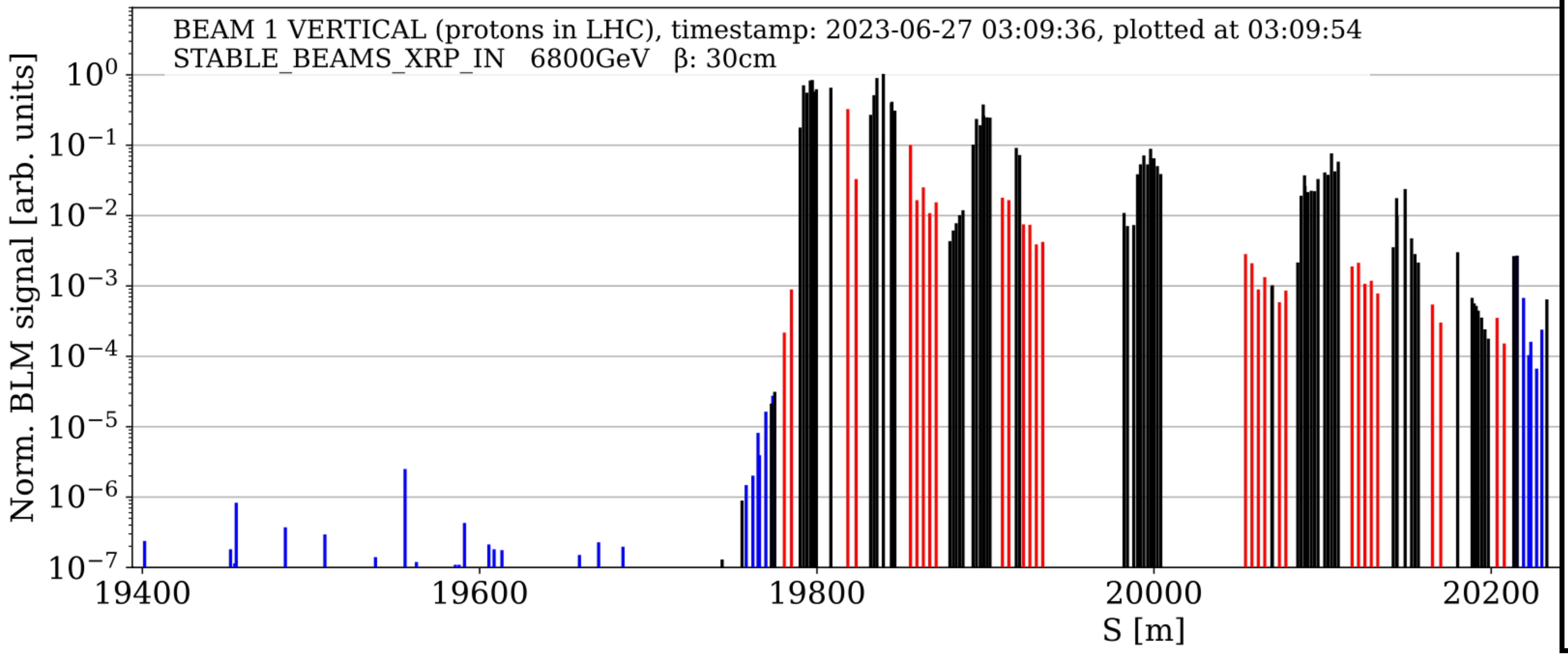
Run 3 system: more than 100 collimators!

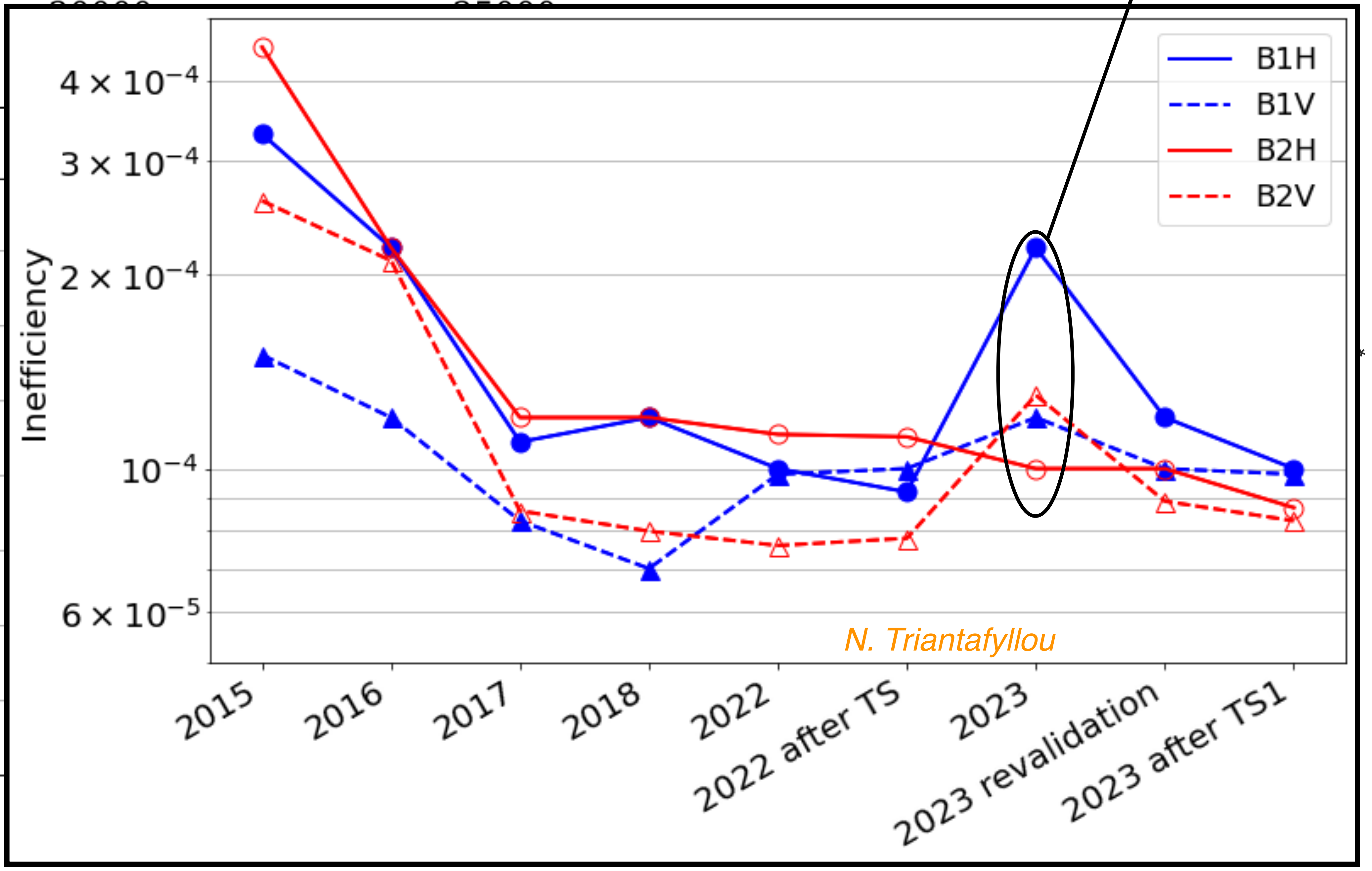
Collimation cleaning performance at 6.8 TeV





Excellent performance: we expect no limitations for protons!

Issue with one IR7 collimator requiring a setting update



TS: technical stop

Continued improvements of cleaning performance (hardware + settings)

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See talk by H. Garcia for detail on upgrade scope

HL-LHC target parameters

Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)
Beam energy in collision [TeV]	7	7
N_b	1,15E+11	2,2E+11
n_b [12]	2808	2760
N_{tot}	3,2E+14	6,1E+14
Beam current [A]	0,58	1,1
Half Crossing angle [μrad]	142,5	250
Minimum β^* [m]	0,55	0,15
ε_n [μm]	3,75	2,50
ε_L [eVs]	2,5	3,03
Piwinski parameter	0,65	2,66
Peak Luminosity without crab-cavity [$cm^{-2} s^{-1}$]	1,00E+34	8,1E+34
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2} s^{-1}$]	-	1,70E+35
Events / crossing without levelling and without crab-cavity	27	212
Levelled Luminosity [$cm^{-2} s^{-1}$]	-	5,0E+34 [4]
Events / crossing (with leveling and crab-cavities for HL-LHC) [7]	27	131
Leveling time [h] (assuming no emittance growth) [7]	-	7,2
n_b / injection	288	288
ε_n at SPS extraction [μm] [3]	3,5	2,1

LHC Magnet system
LHC injector complex;
HL-LHC new collimation

HL-LHC triplet magnets

HL-LHC crab cavities
HL-LHC new collimation

Machine operation & availability

LHC injector complex

Lead ion beams (Run 3)

I_b [10^8 Pb] : 0.7 → 1.8

N_b : 592 → 1240

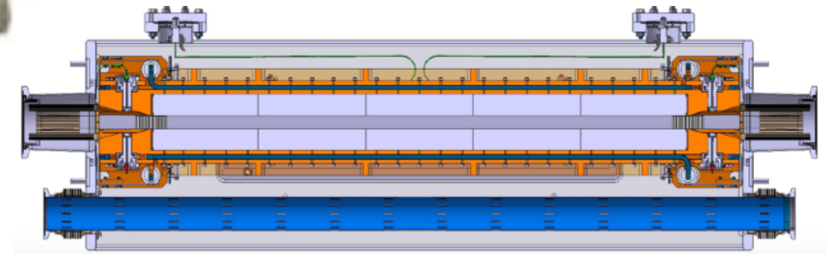
E_b [MJ] : 3.8 → **20.5**

Collimation upgrade pillars: (1) **better cleaning efficiency**; (2) **impedance reduction**; (3) cleaning **collisional debris** at higher luminosity. Both **protons** and **ions**!

HL-LHC collimation upgrade

LHC Collimation Project

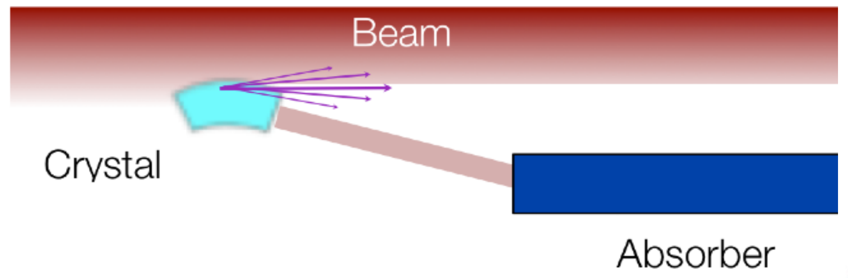
LS3



IR collimation: Completely new layouts and collimator designs: IR1+IR5: incoming and outgoing. Full remote alignment system (FRAS)

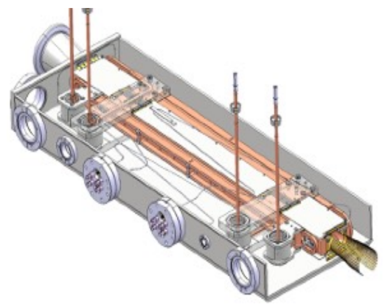
LS2

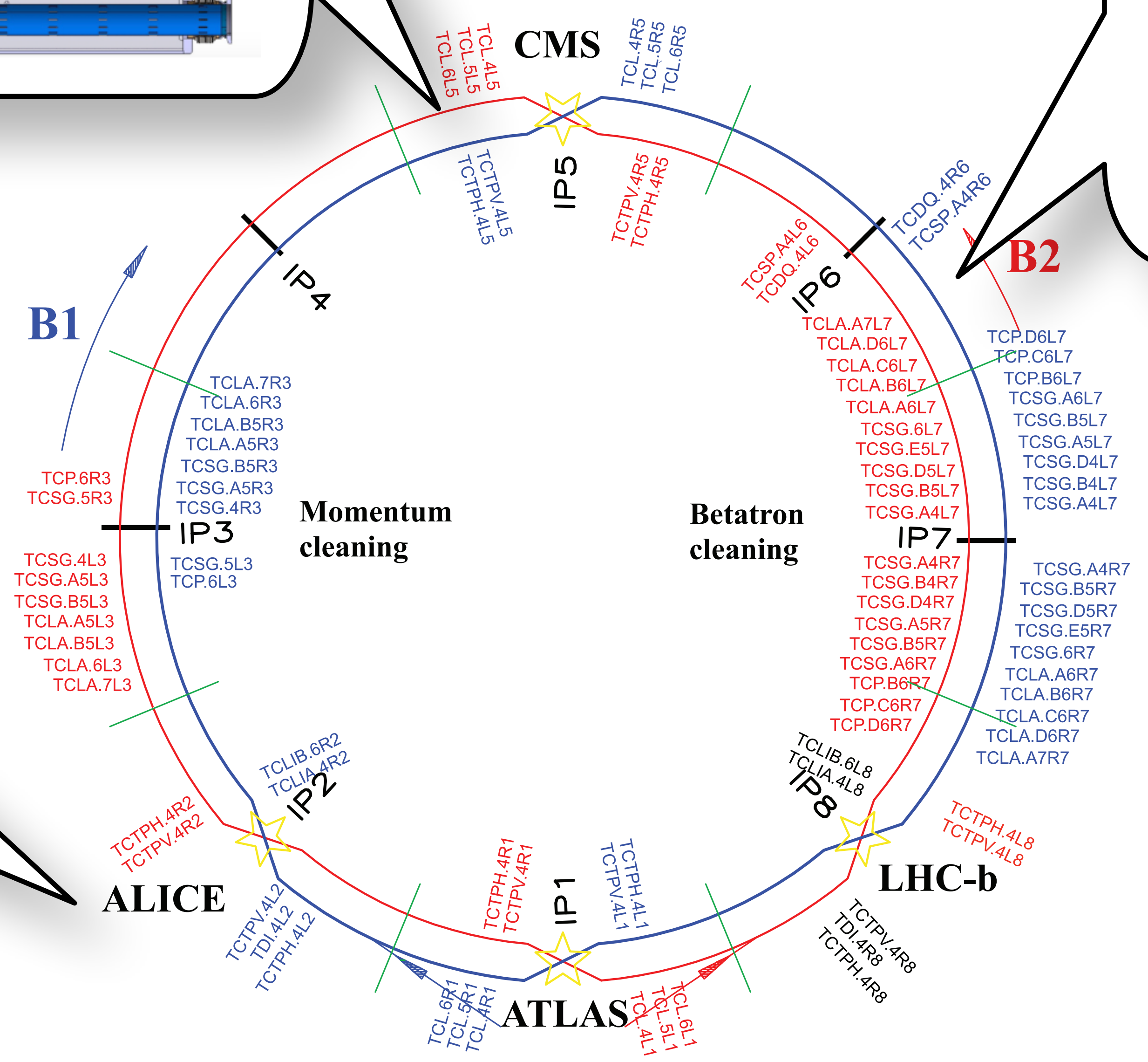
Crystal-assisted collimation (Pb ions)
4-8 bent crystals, 50 µrad bending
IP7 (betatron cleaning)



LS2

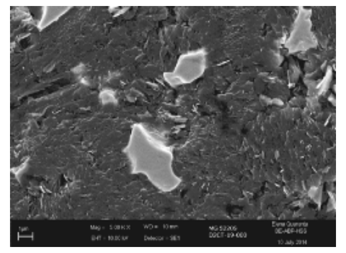
Dispersion suppressor collimation: Secondary beams from ion physics

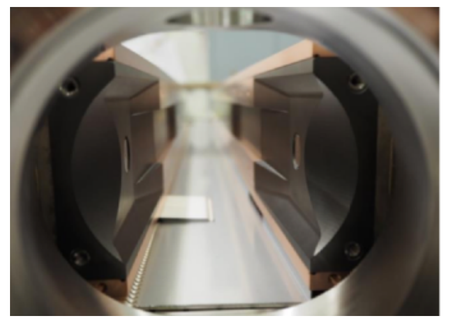


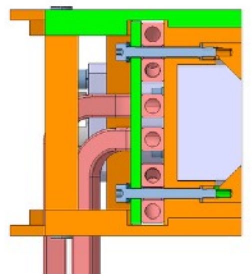


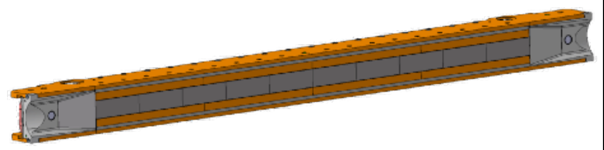
Impedance reduction: low-impedance, high robustness secondary collimators: coated MoGr and coated Gr
Un-coated MoGr primary collimators.

LS2+LS3









LS: Long Shutdown
LS2: 2019-2021
LS3: 2026-2029

LS2+LS3

Consolidation (not HL): low-impedance primaries (material from WP5), renew controls, maintain / replace rest of system

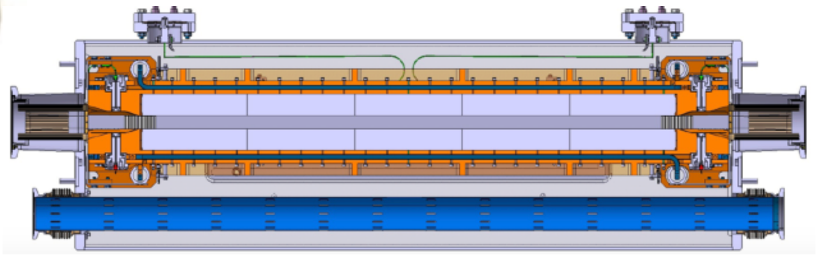
WP5 devices to be installed:
LS2: 14 movable collimators
LS3: 30 new collimators
+ 12 fixed masks (IR1/5)

HiLumi HL-LHC PROJECT CERN

HL-LHC collimation upgrade

LS3

IR collimation: Completely new layouts and collimator designs: IR1+IR5: incoming and outgoing. Full remote alignment system (FRAS)



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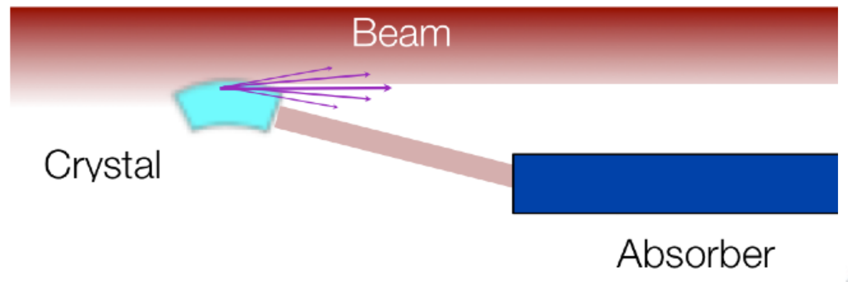

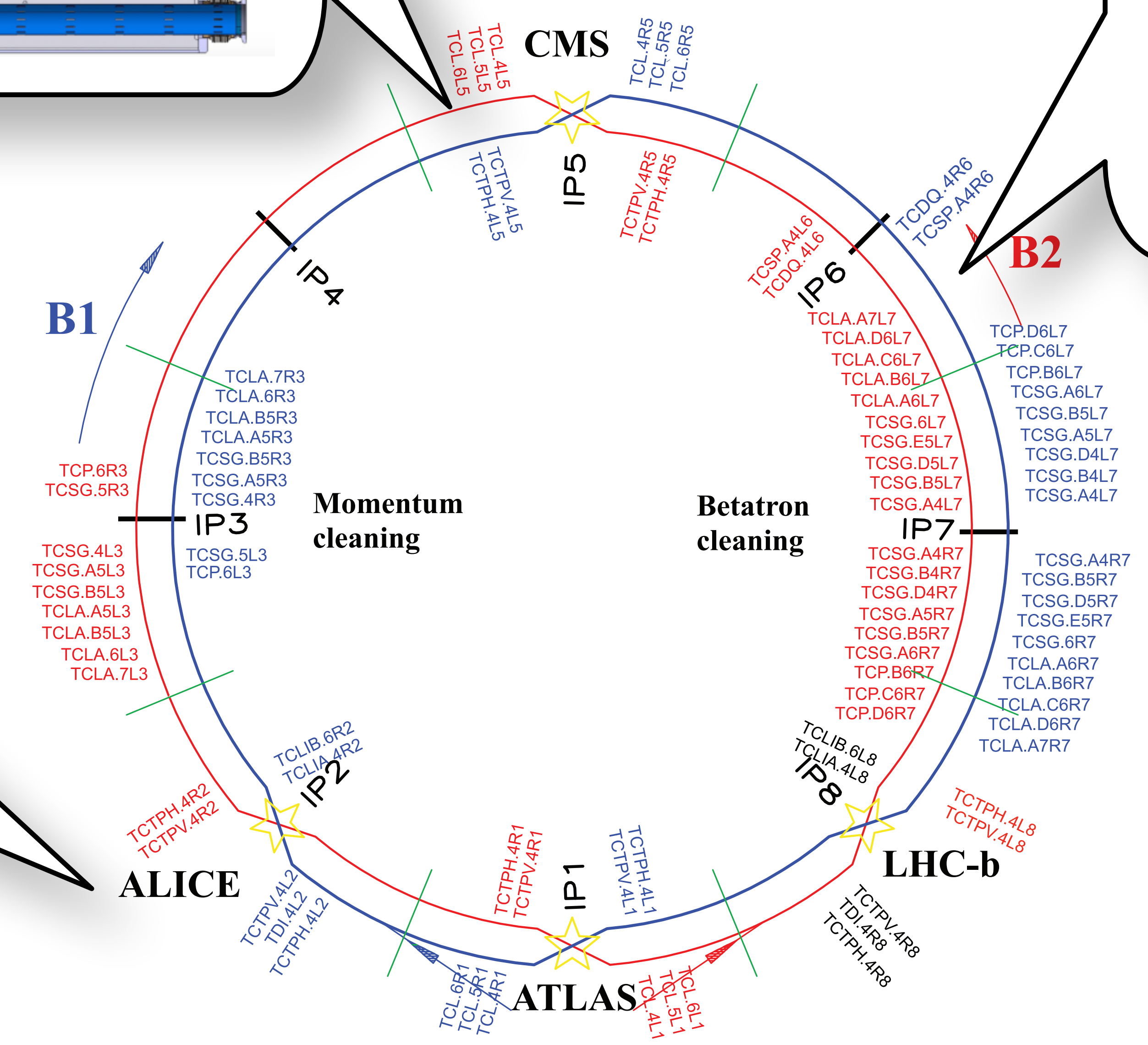

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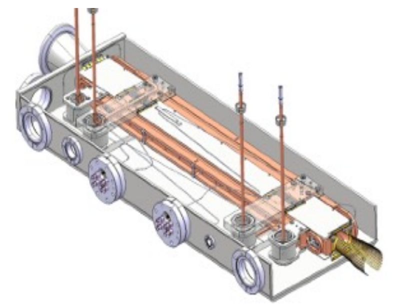

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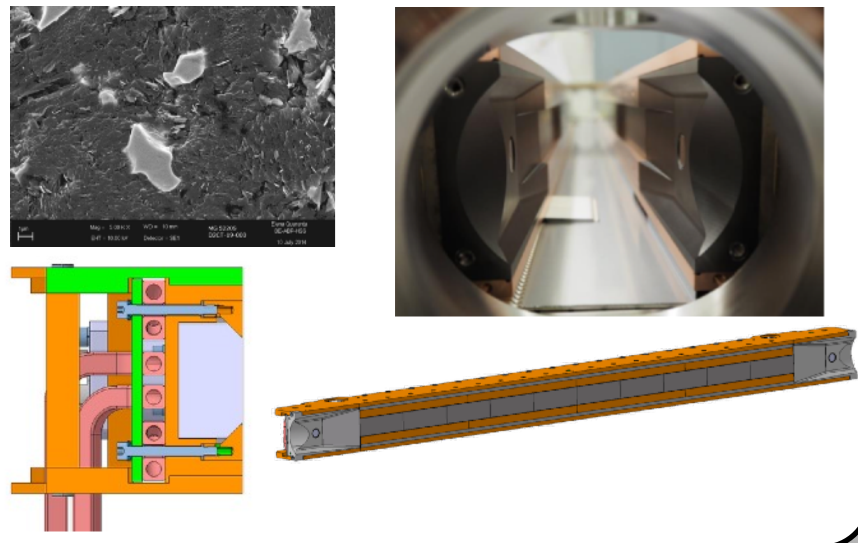

LS2+LS3

Crucial upgrades took place in LS2: LHC Run 3 operation already profiting!

LS2+LS3

Consolidation (not HL): low-impedance primaries (material from WP5), renew controls, maintain / replace rest of system

WP5 devices to be installed:
LS2: 14 movable collimators
LS3: 30 new collimators
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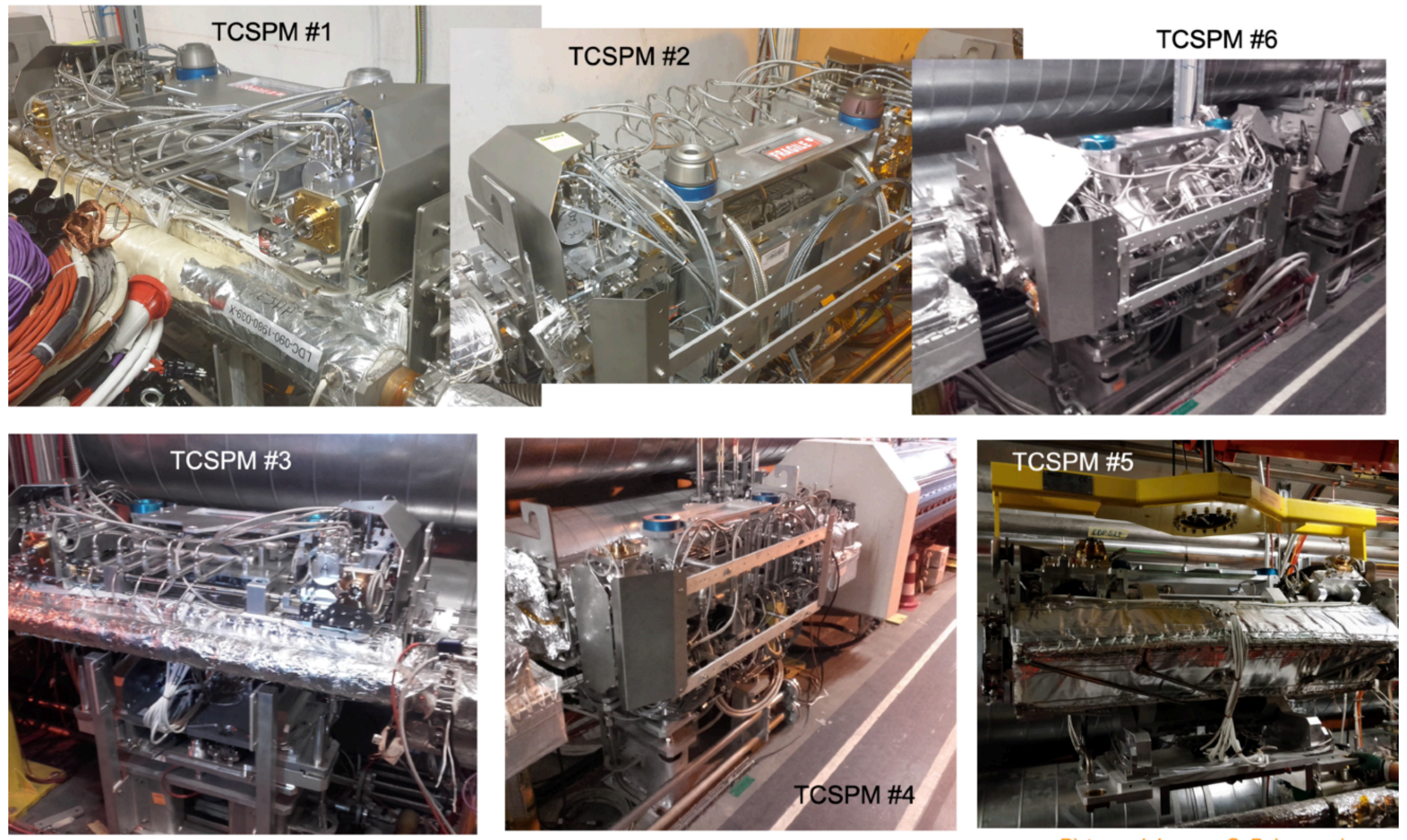
LS2 collimation installations for HL-LHC

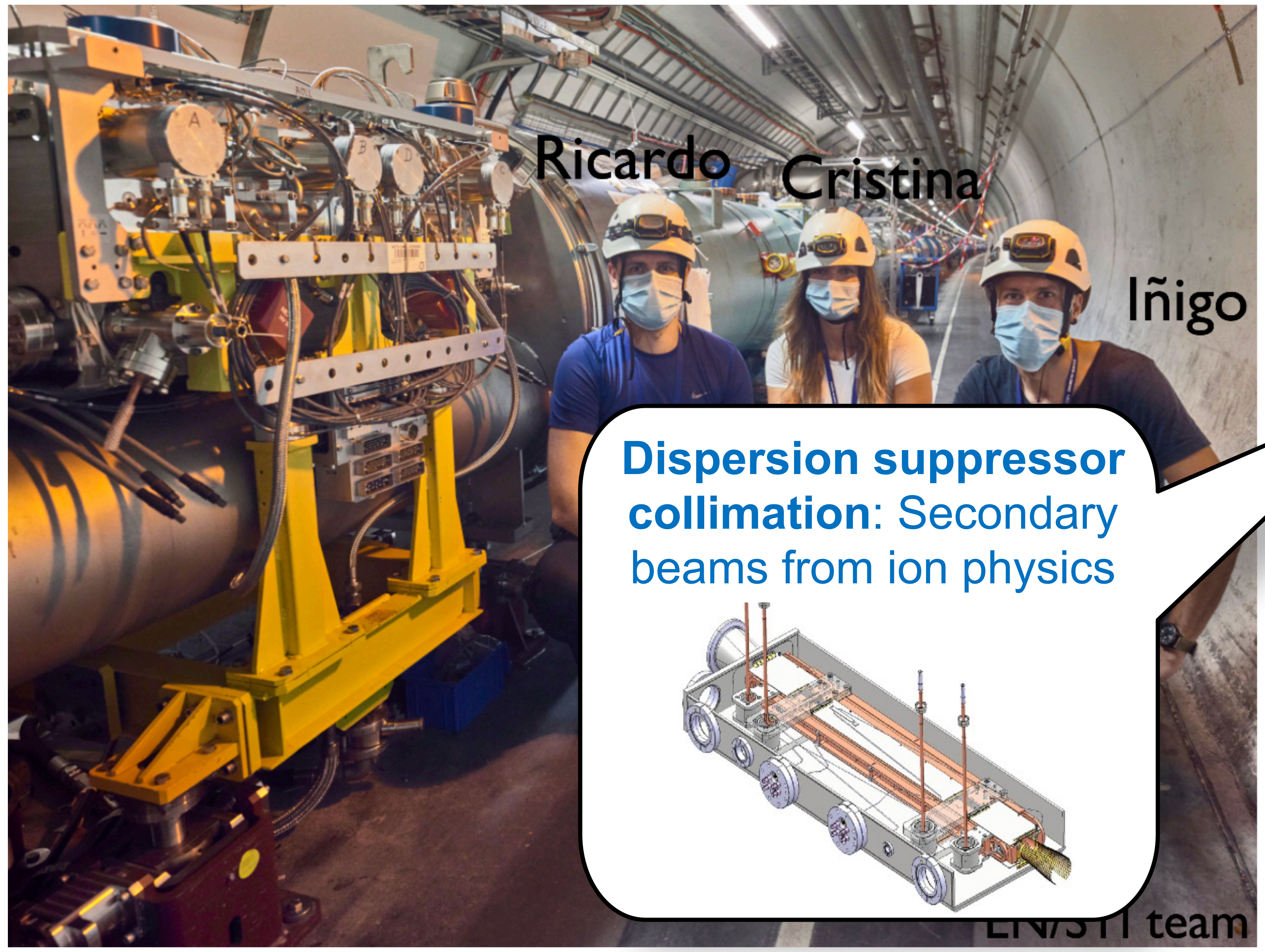
Upgrades that took place in LS2
- Dispersion suppressor collimators, IR2
- Low-impedance secondaries (coated), IR7
- Low-impedance primaries, IR7
- Passive absorbers for IR7
- Crystal primary collimators in IR7 (2022-2023)

22 collimators built, 18 for installation (4 spares)
6 crystal collimators (spares)

Coated secondary collimators: 8 installed IR7



Pictures: I. Lamas, C. Bahamonde



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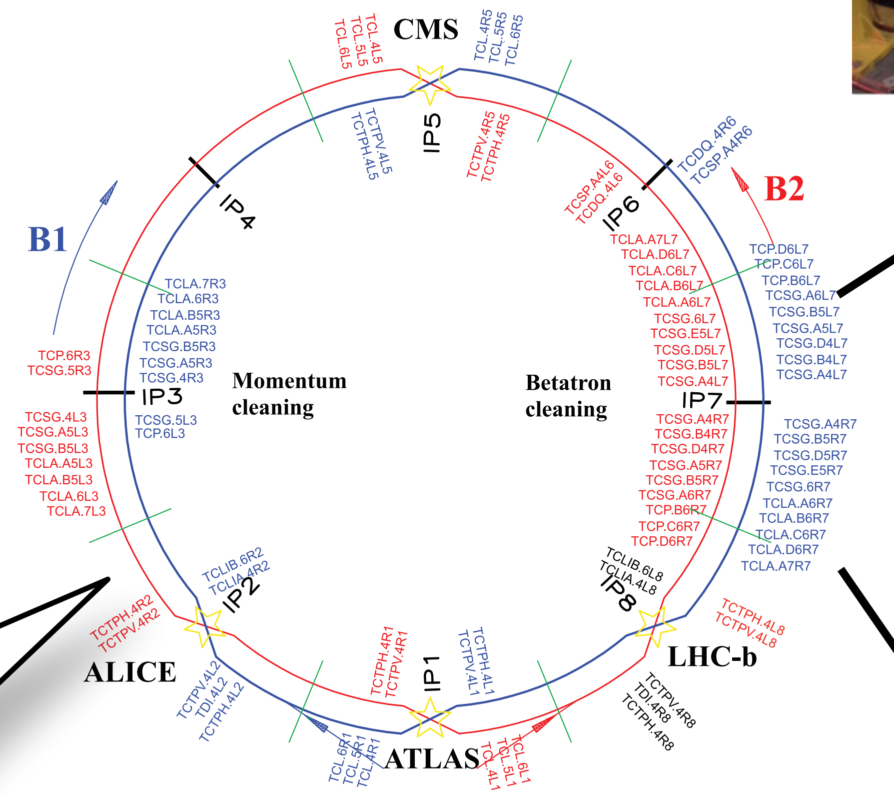

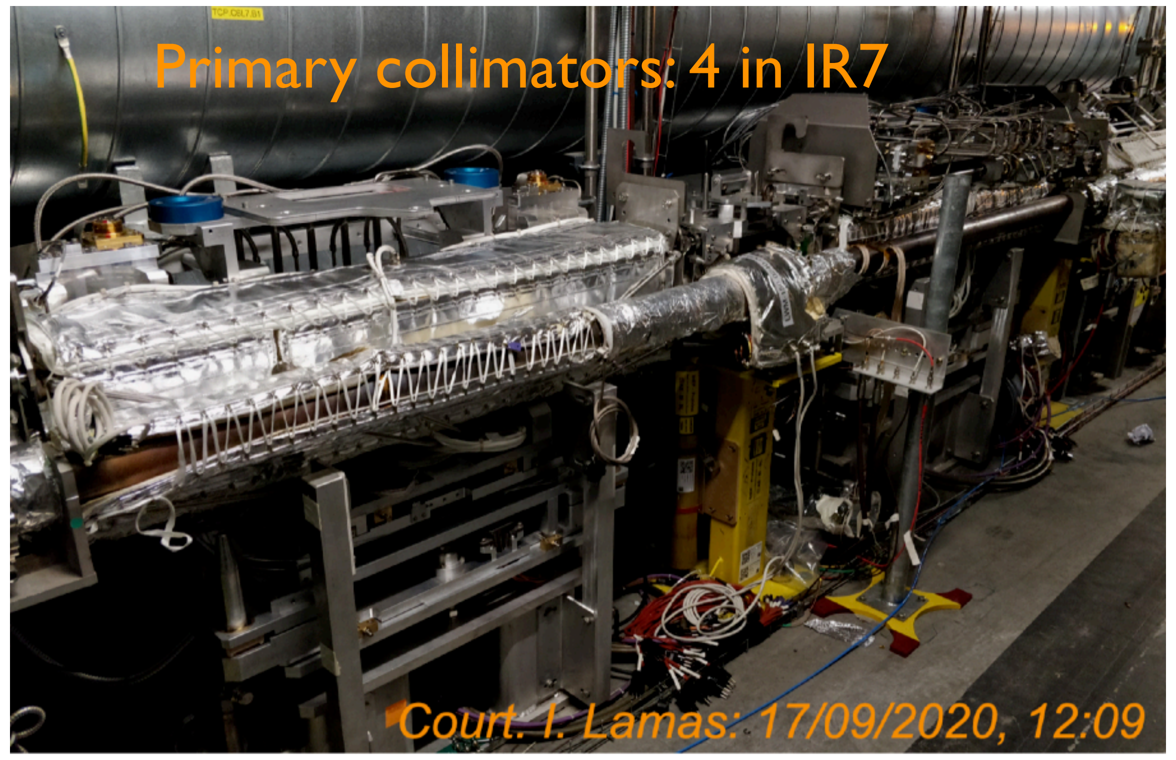

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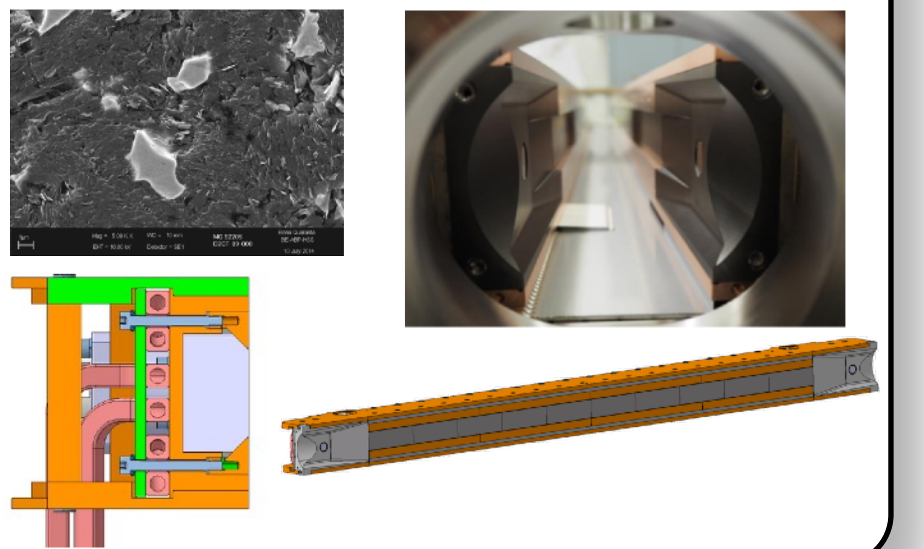


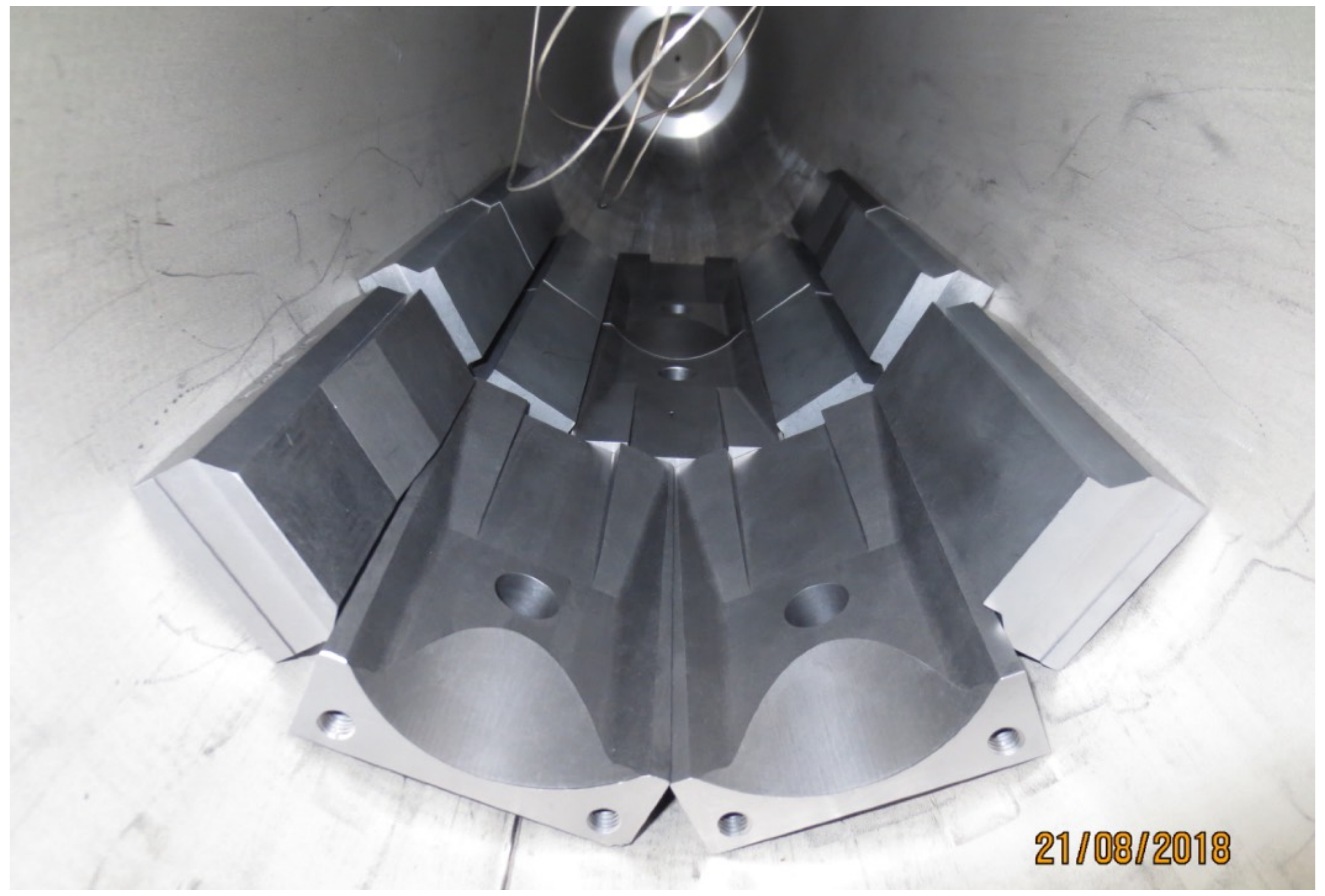
Very successful collaboration across several groups in the ATS sector!

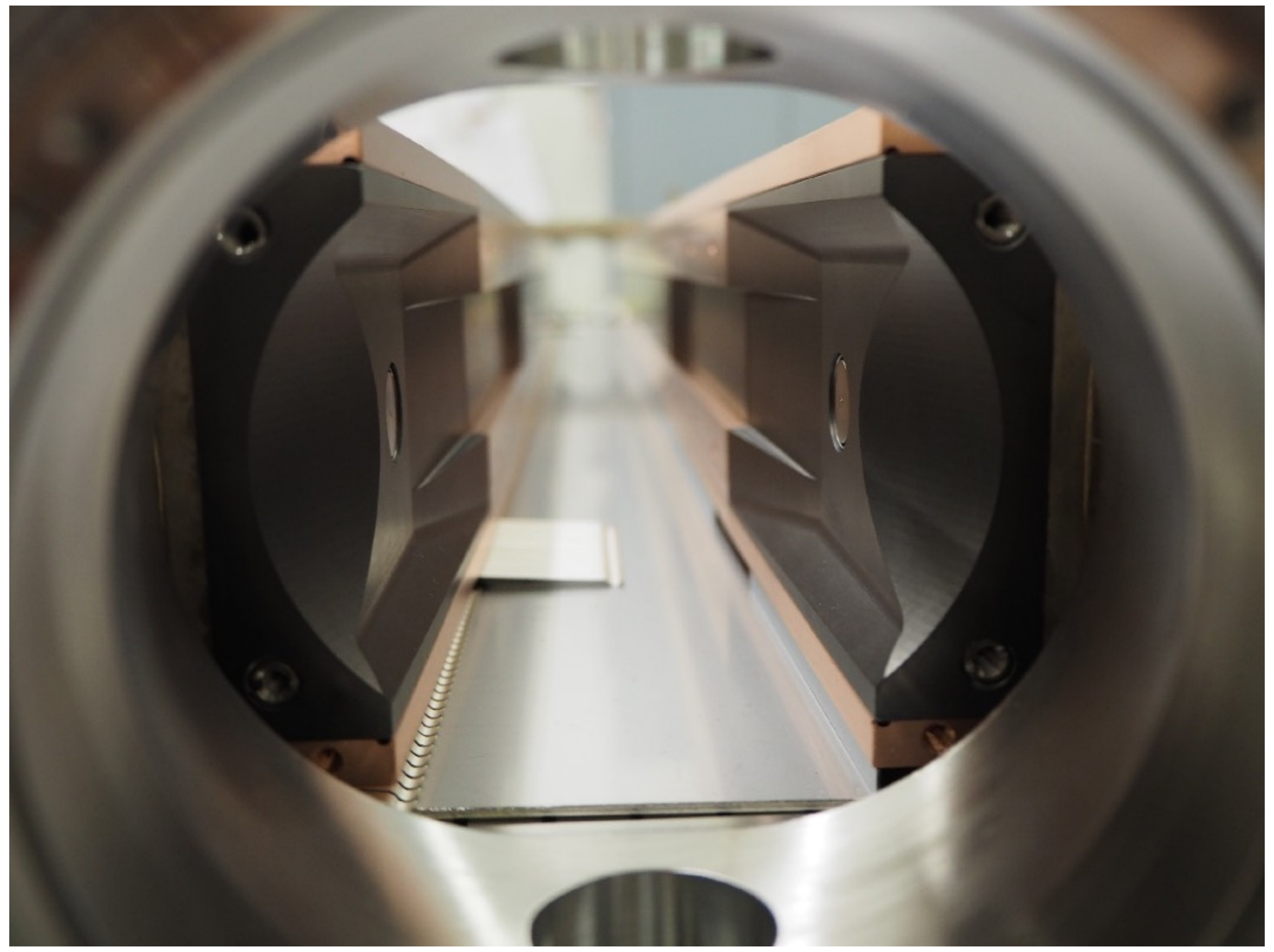
$$\mathcal{L} = \frac{N_1 N_2 k_b f \gamma}{4\pi\epsilon_n \beta^*} F$$

New low-impedance collimators (MoGr)

Molybdenum-graphite (MoGr), novel material developed:
- x5 better conductivity than carbon fibre composite (CFC)
- x100 with Mo coating

Un-coated MoGr for primary collimators, Mo-coating for secondary collimators



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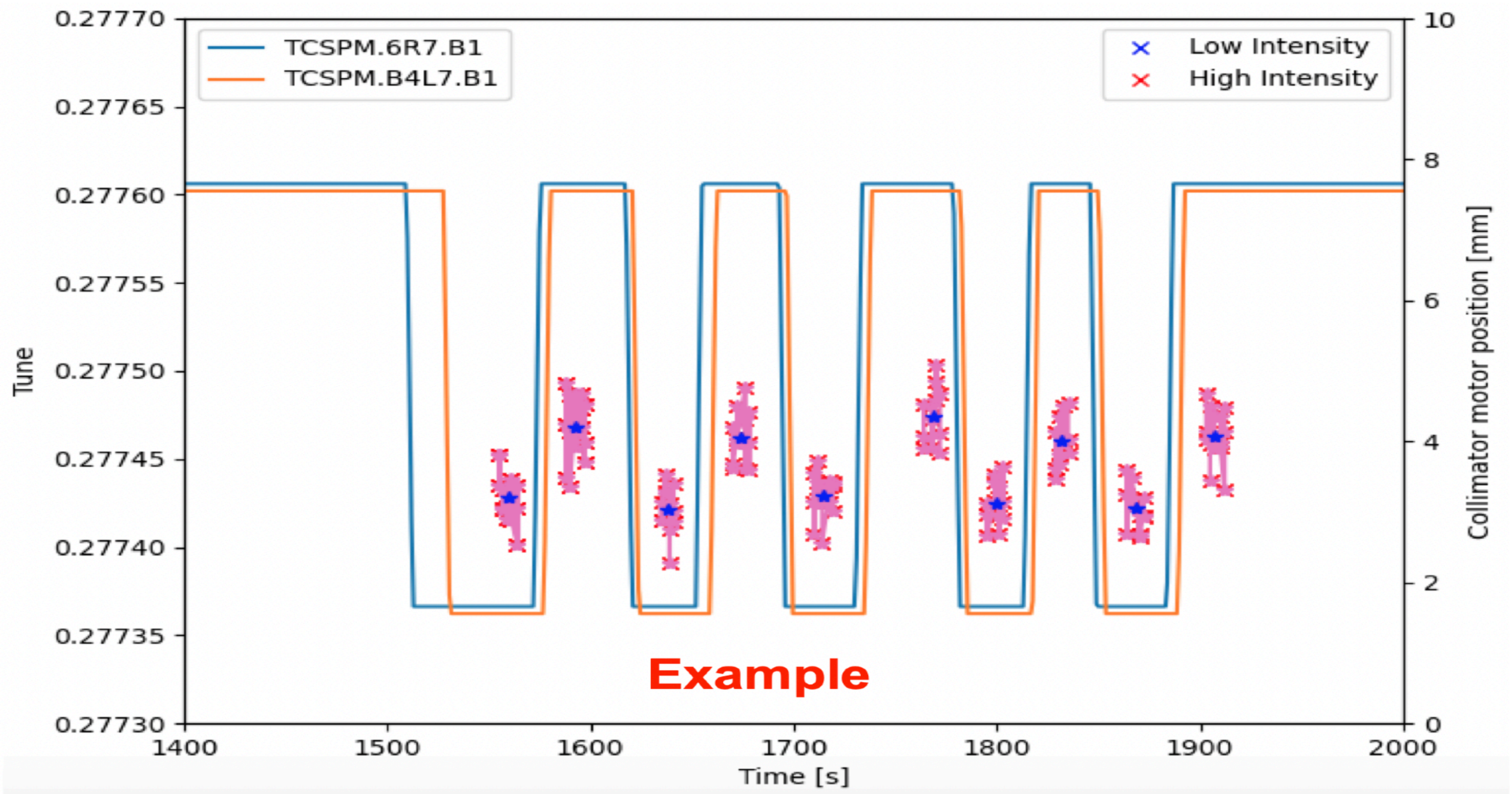
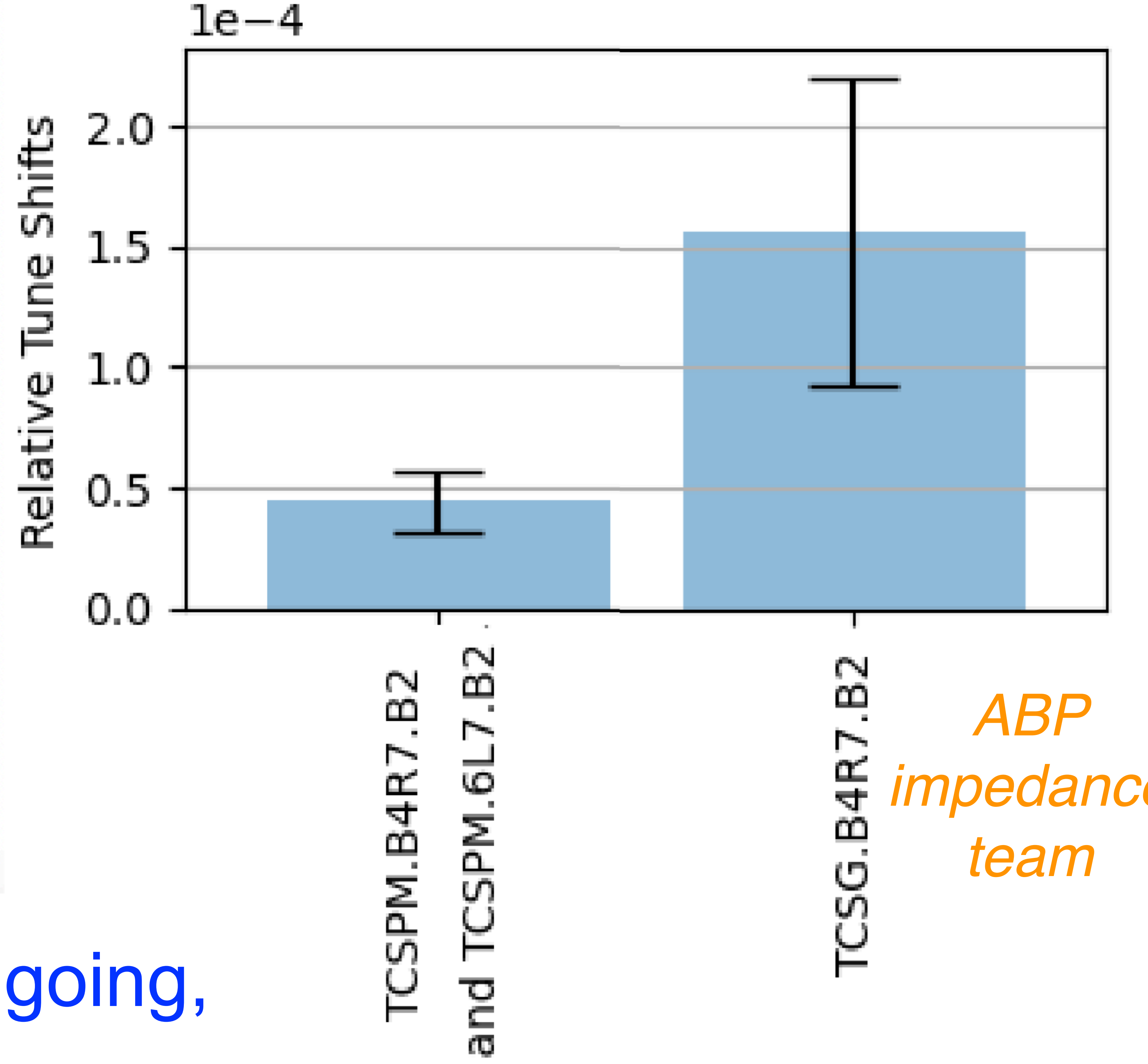
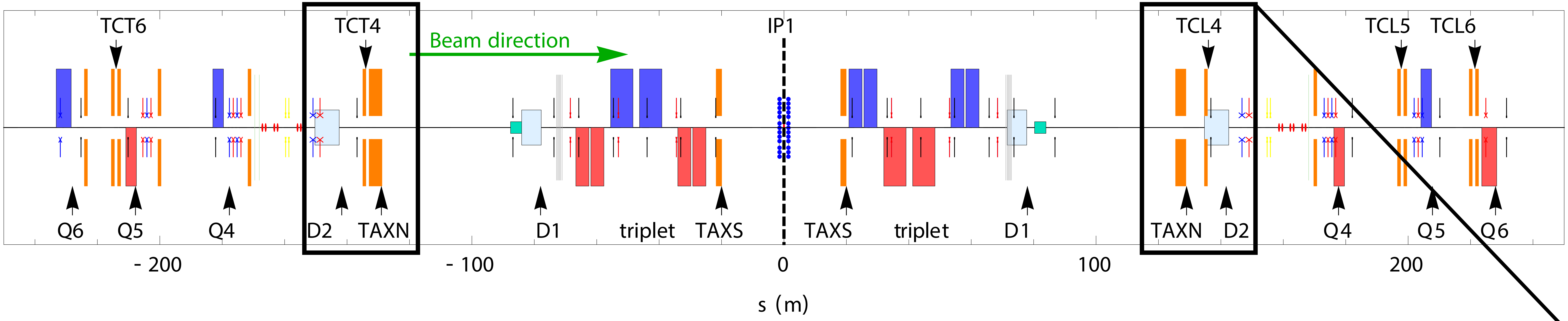




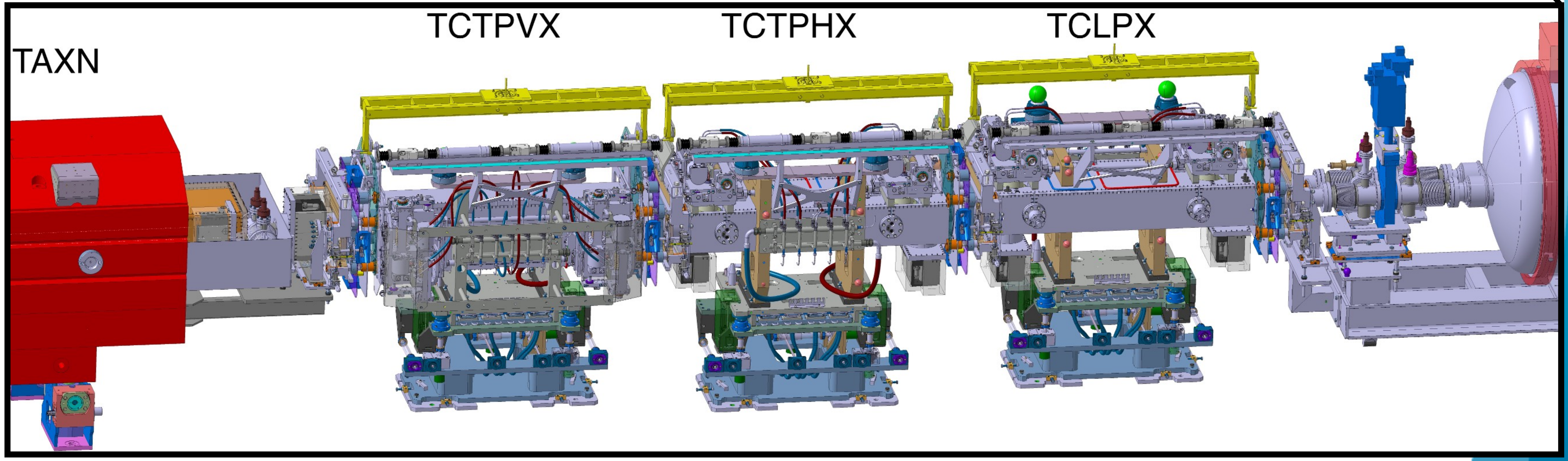
ABP impedance team

- Comparison ongoing with models ongoing, results in Run 3 are very promising!

New collimation system in interaction regions



- **Tertiary collimators** to protect against incoming beam losses + **physics debris collimators**
- **Two-in-one design** for H collimators to fit the tight space at the re-combination region between TAXN and D2.
- Other collimators in cell 5 and cell 6 use the more-conventional single-beam design



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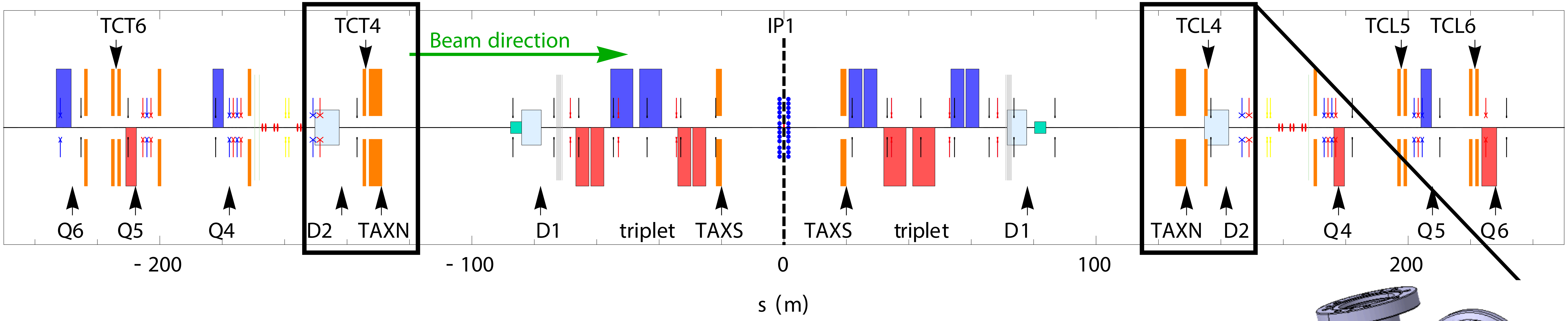

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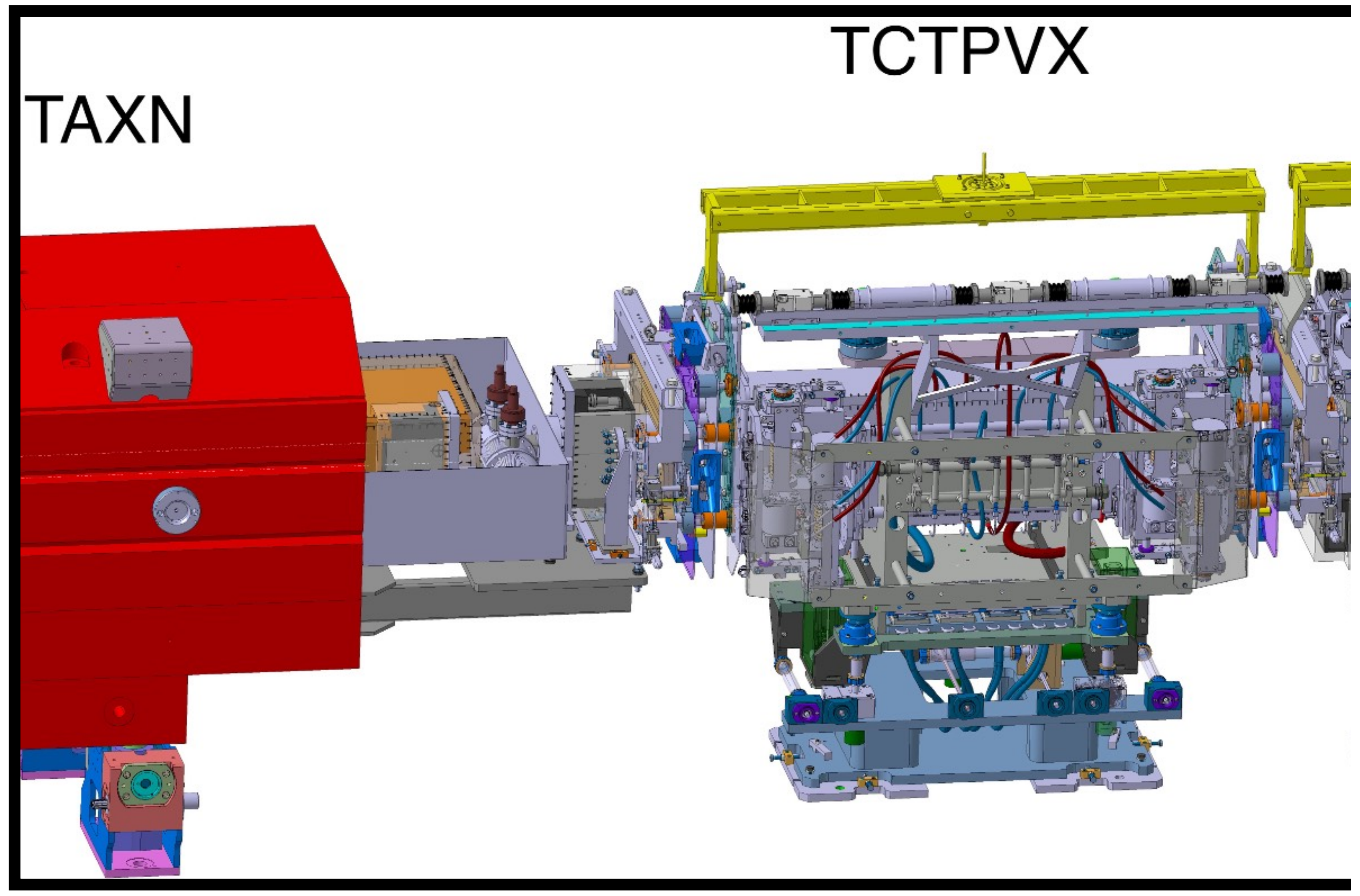
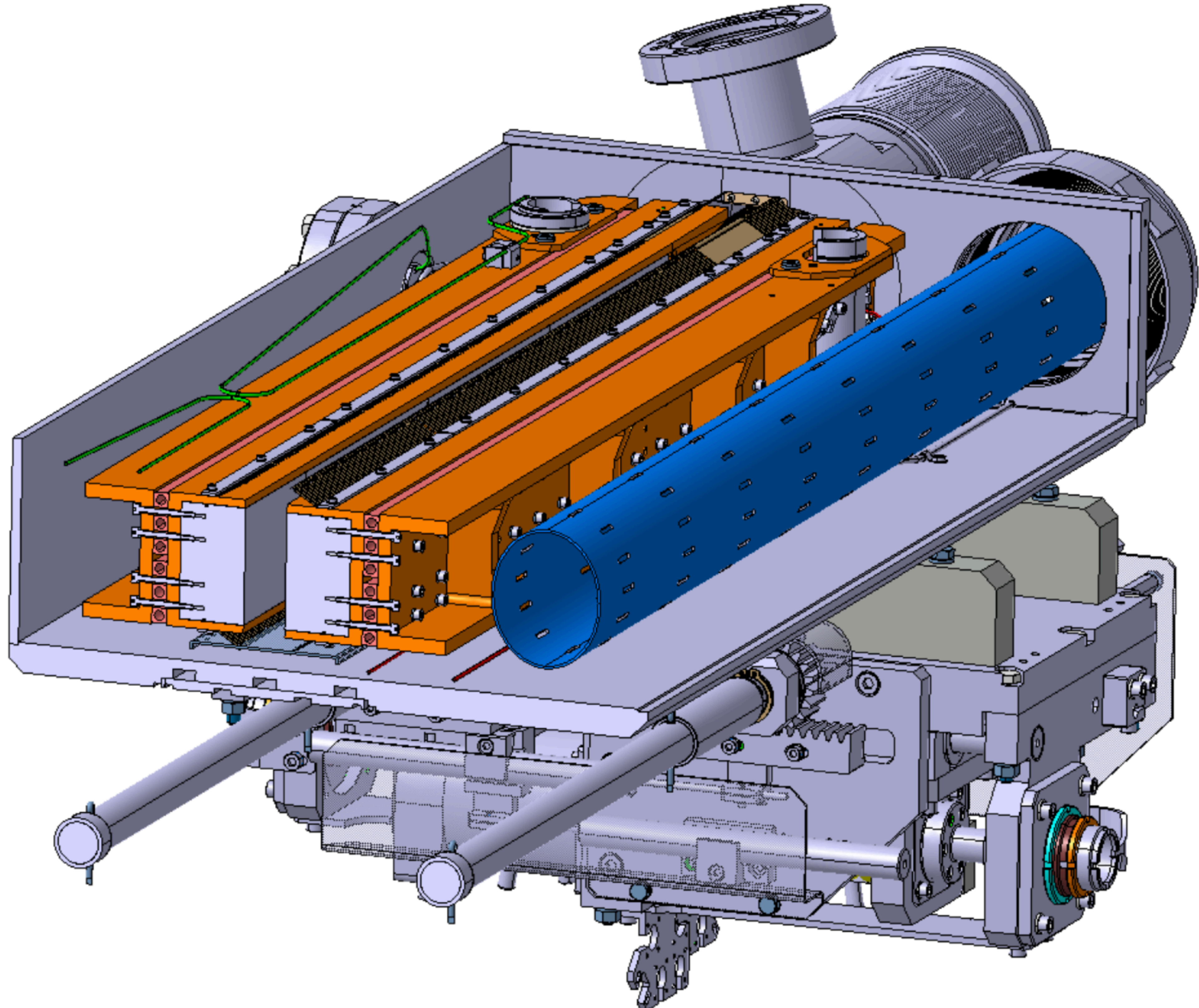
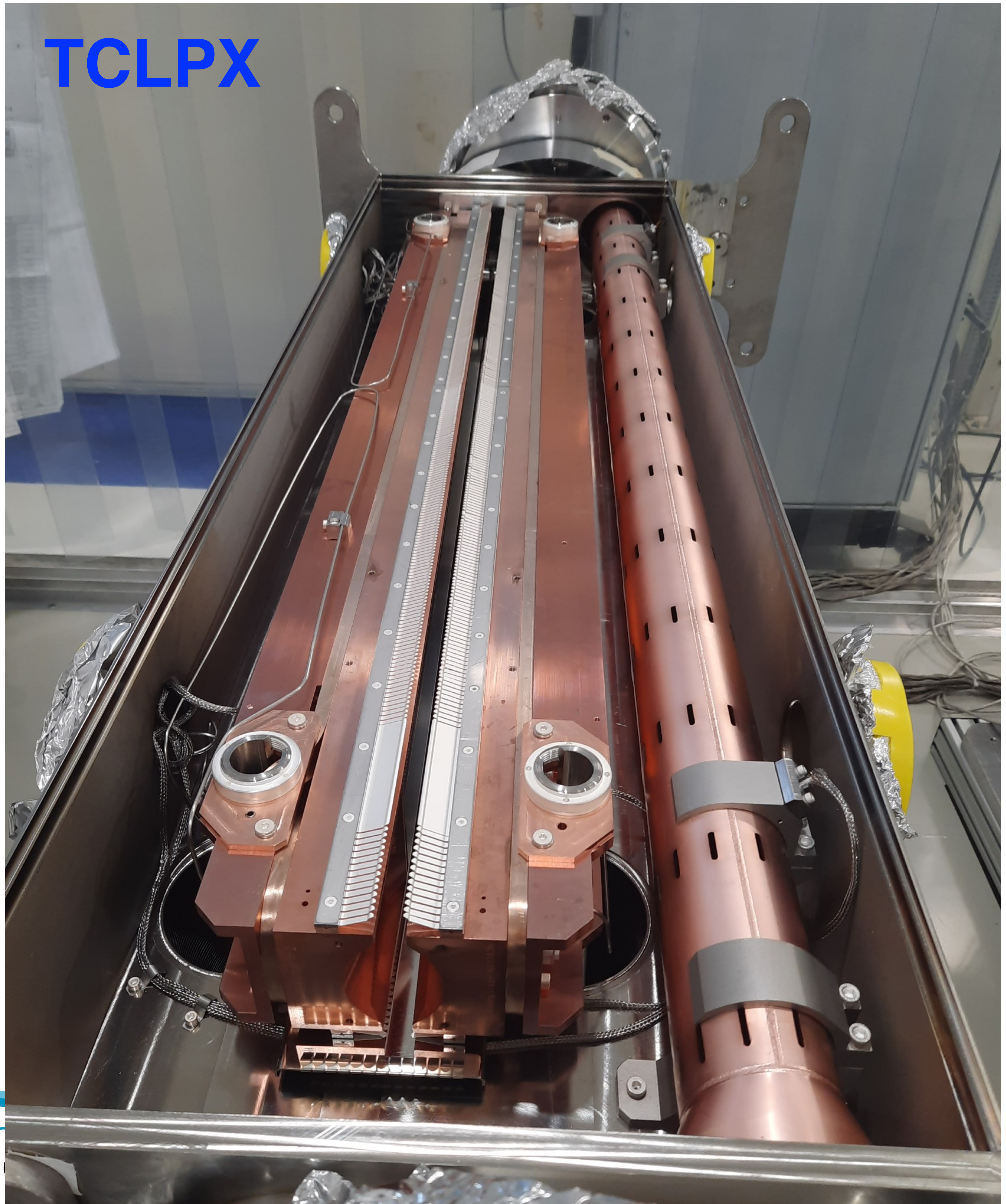
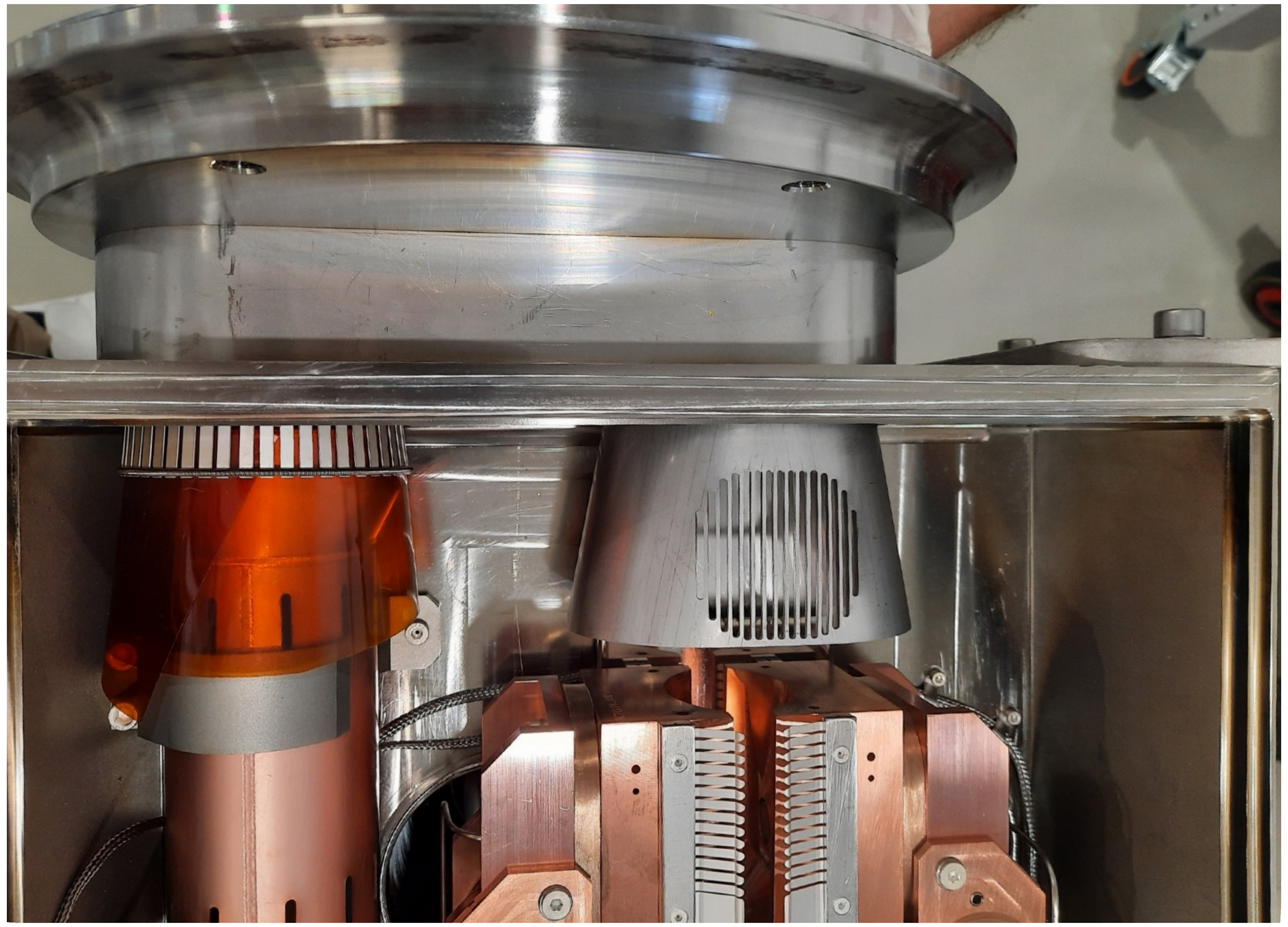




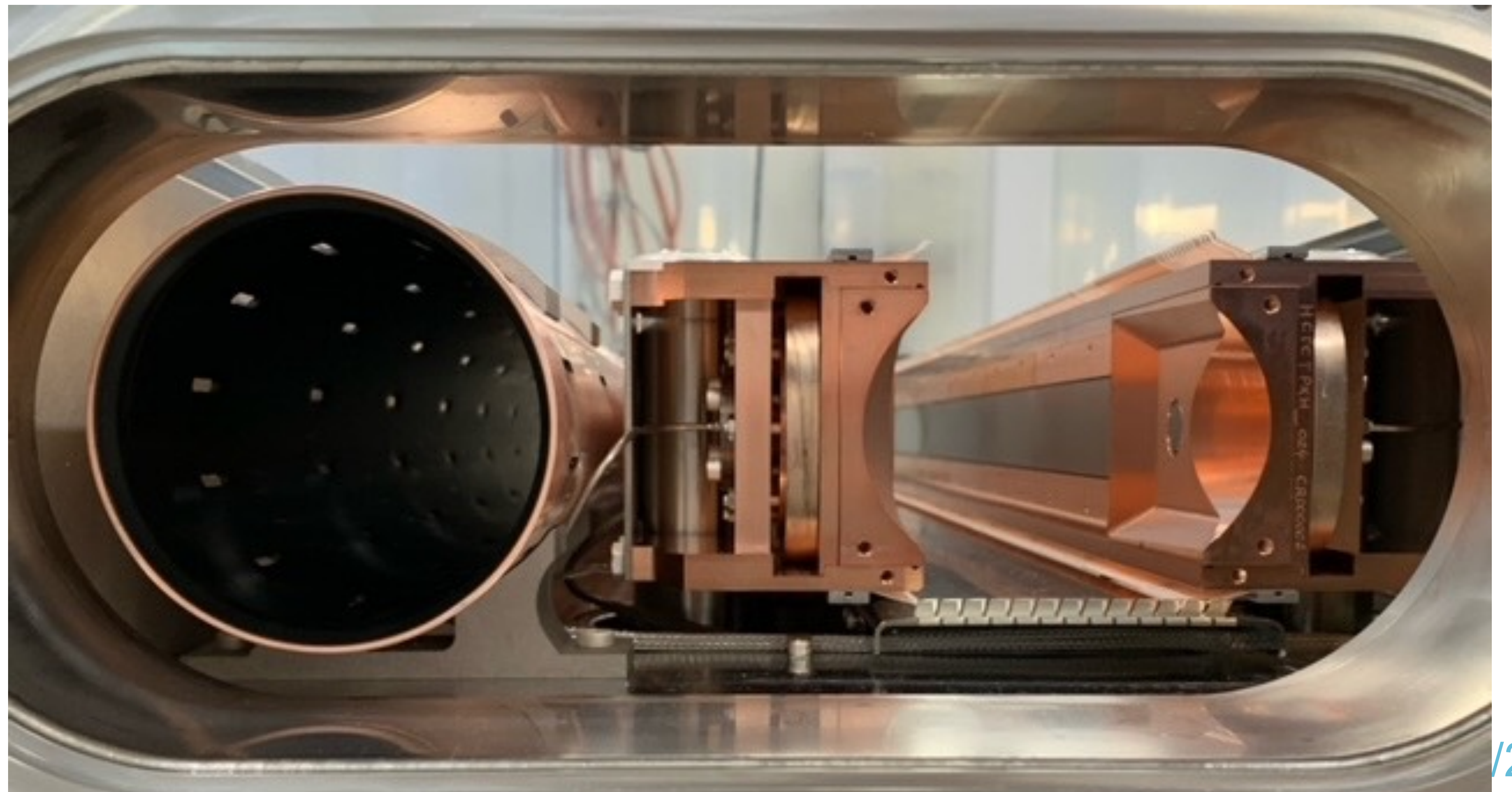
Prototypes of “X” collimators



TCLPX extremity, top view

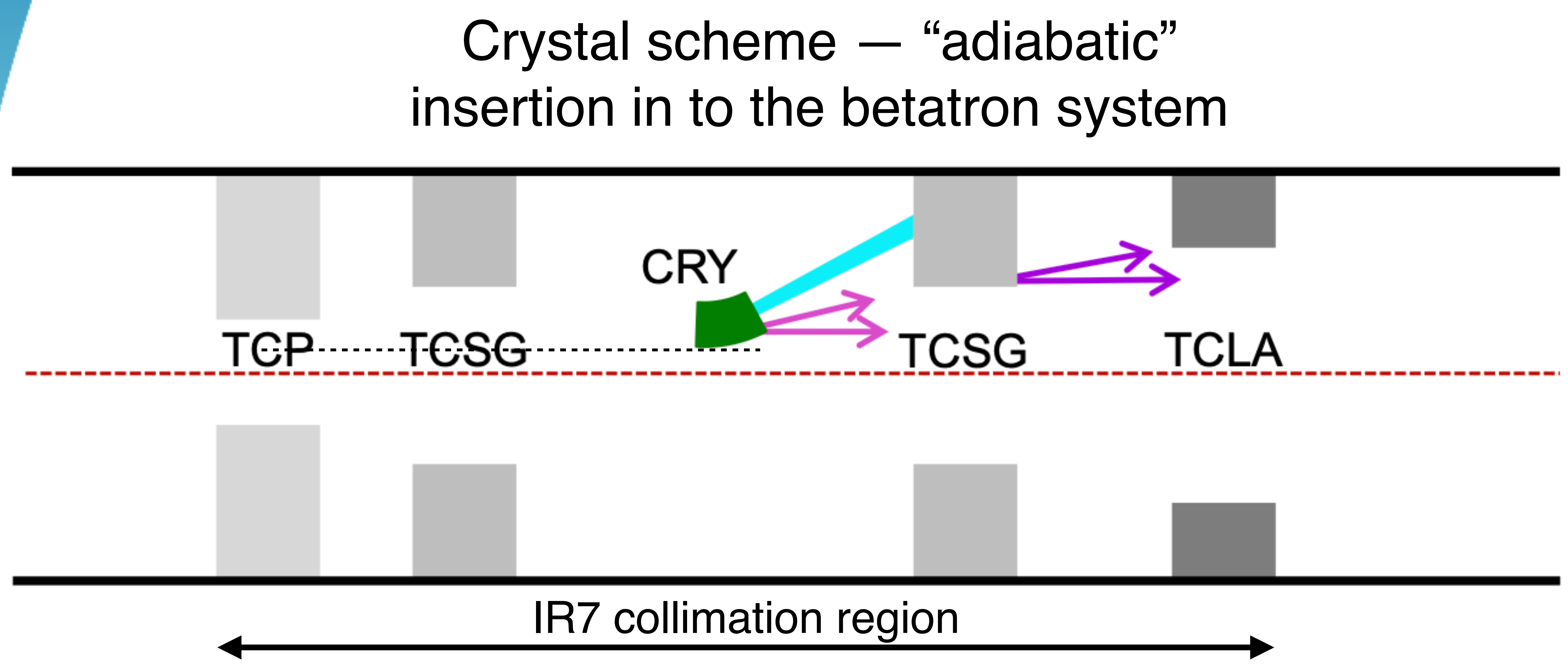


Front views of a TCTPXH

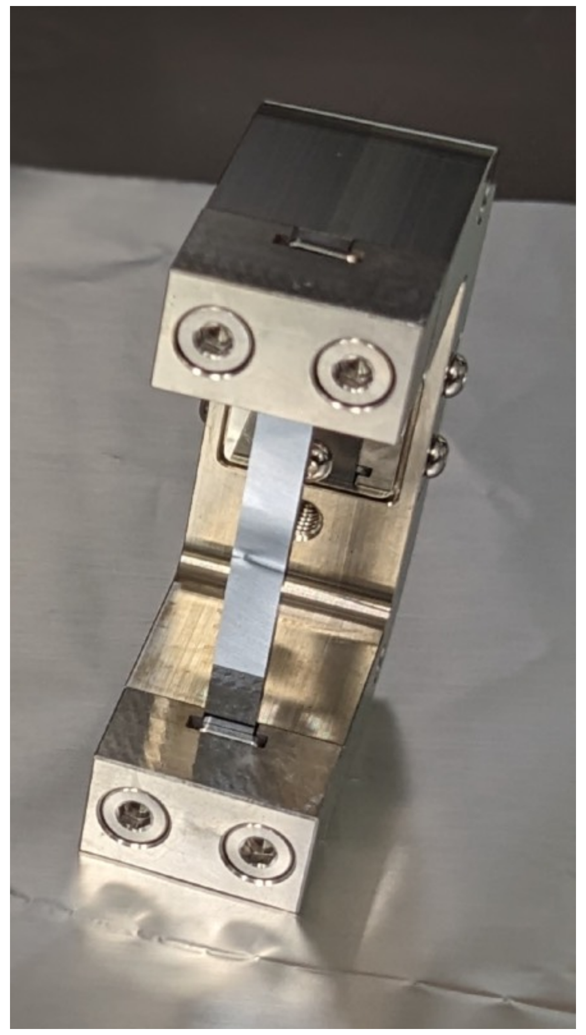


Courtesy F.X. Nuiry& D. Baillard

Operational configuration for Pb ion run



TCPC = crystal primary collimator
TCP = primary collimator
TCS = secondary collimator
TCLA = shower absorber
TCT = tertiary collimators (in experiments)



Si crystal (4mm) bent to 50μrad is equivalent to ~300T at 7TeV!

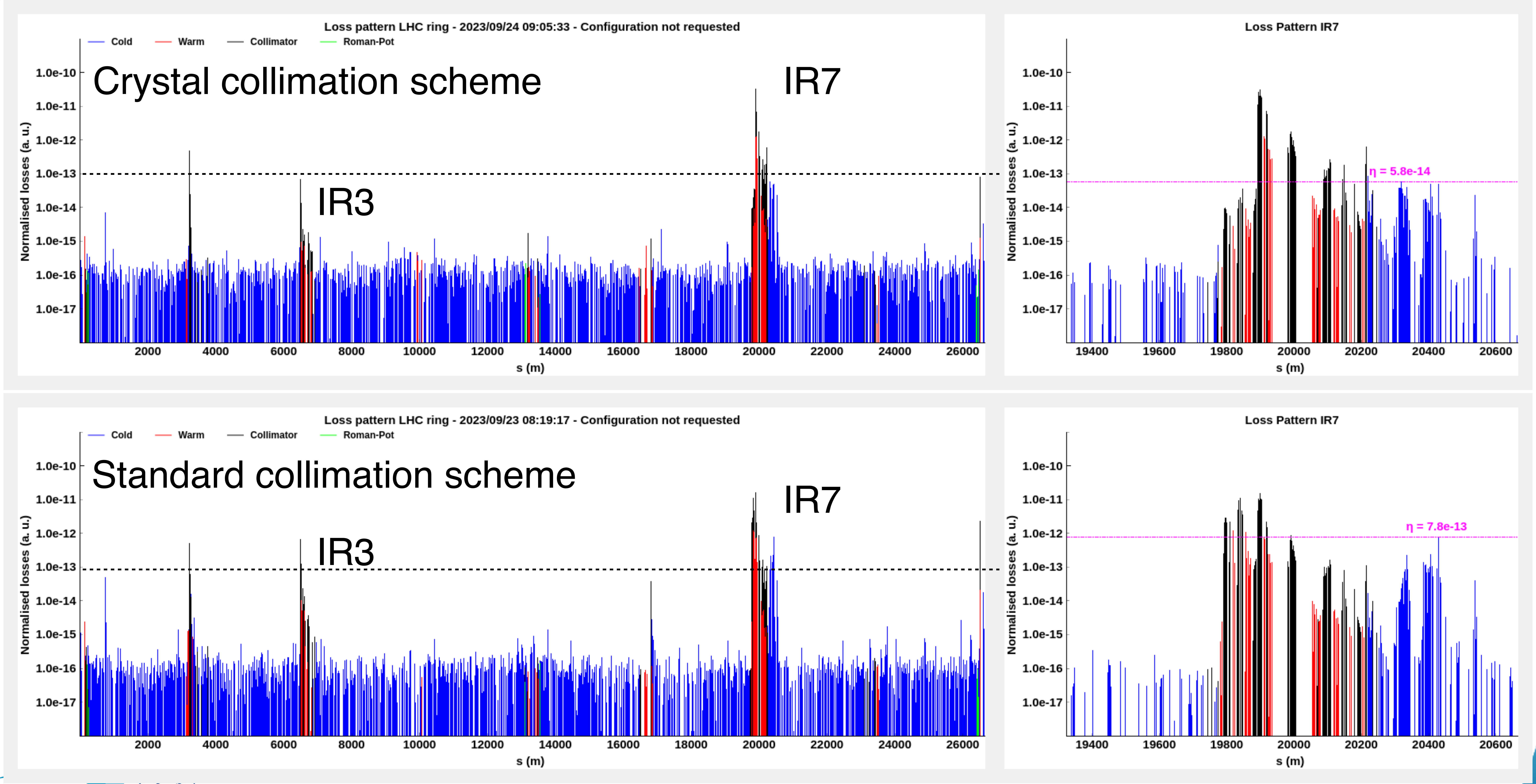
See talks by N. Canale for an introduction and by P. Hermes for other applications at the LHC

Scope: improve collimation cleaning for heavy ion beam

Technology tested extensively at the LHC energy during Run 2, before deploying a new system with 4 crystals in IR7.

Acknow.: Bent crystal for HL-LHC produced by INFN-Fe and PNPI

Measured crystal collimation cleaning



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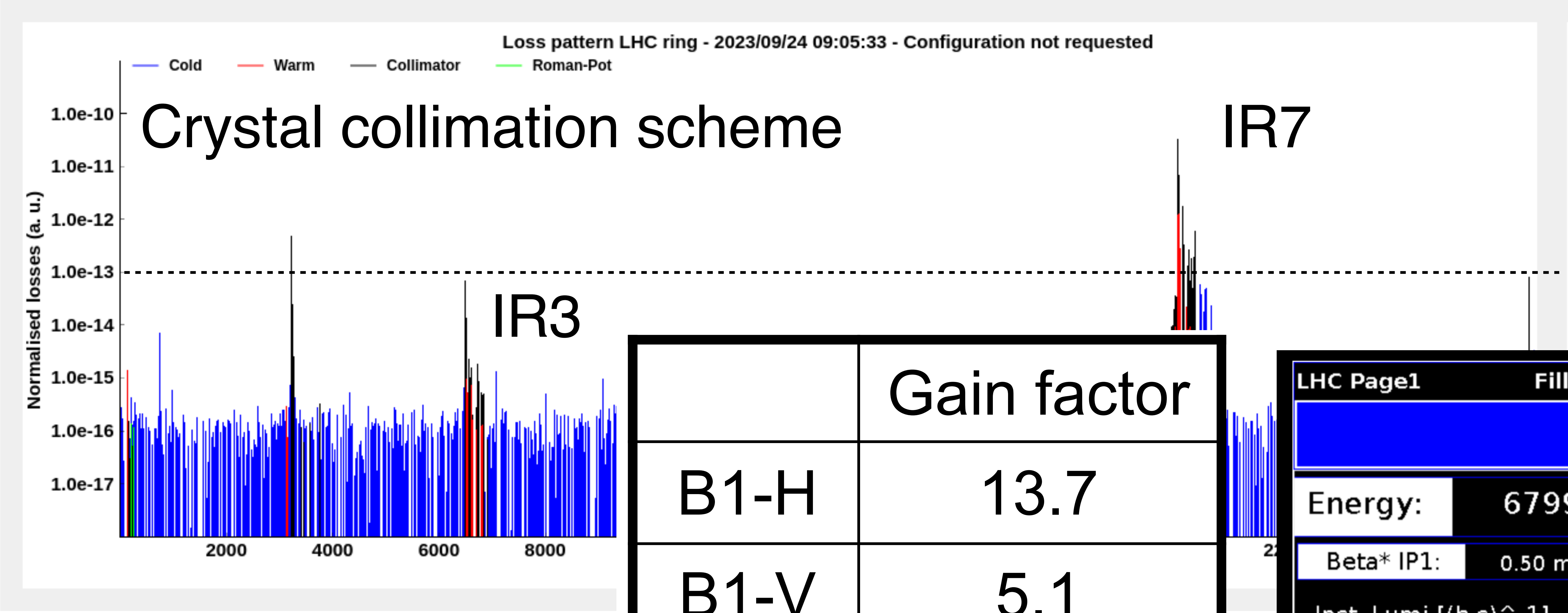
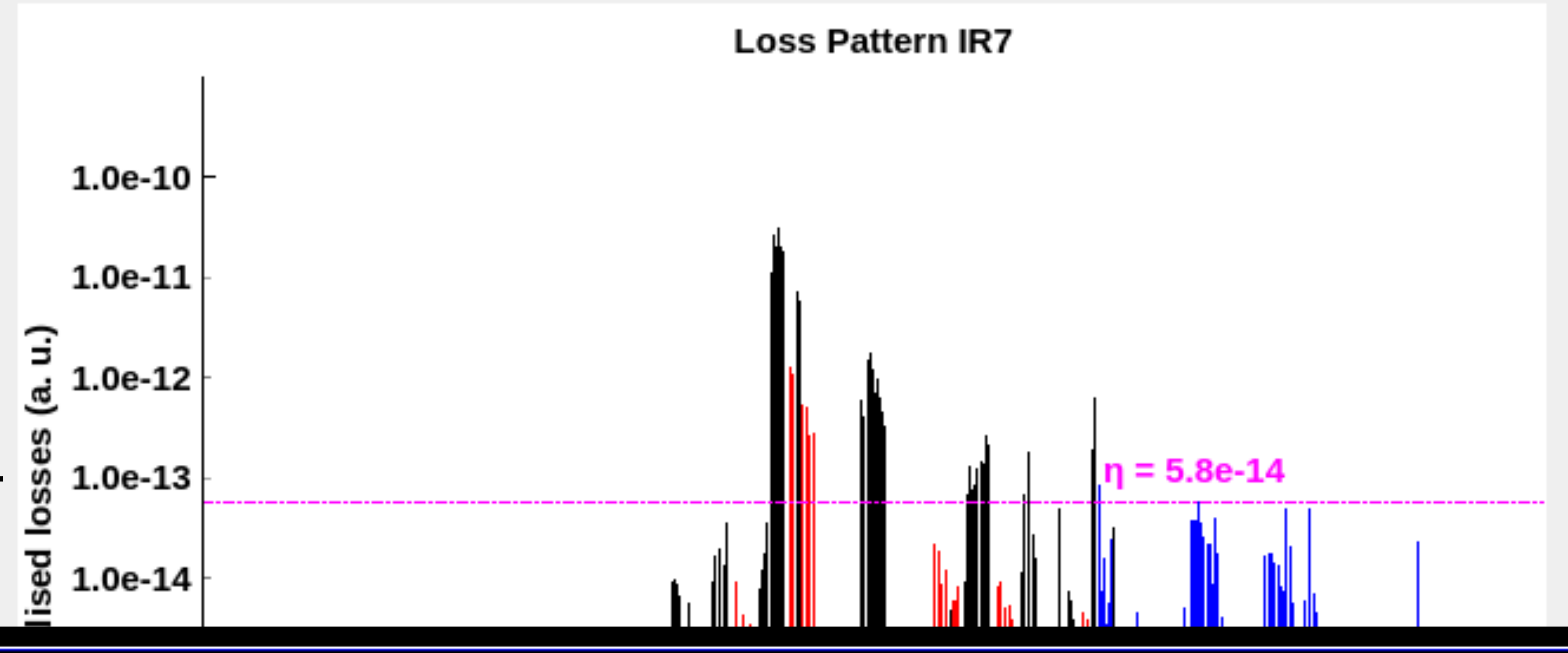
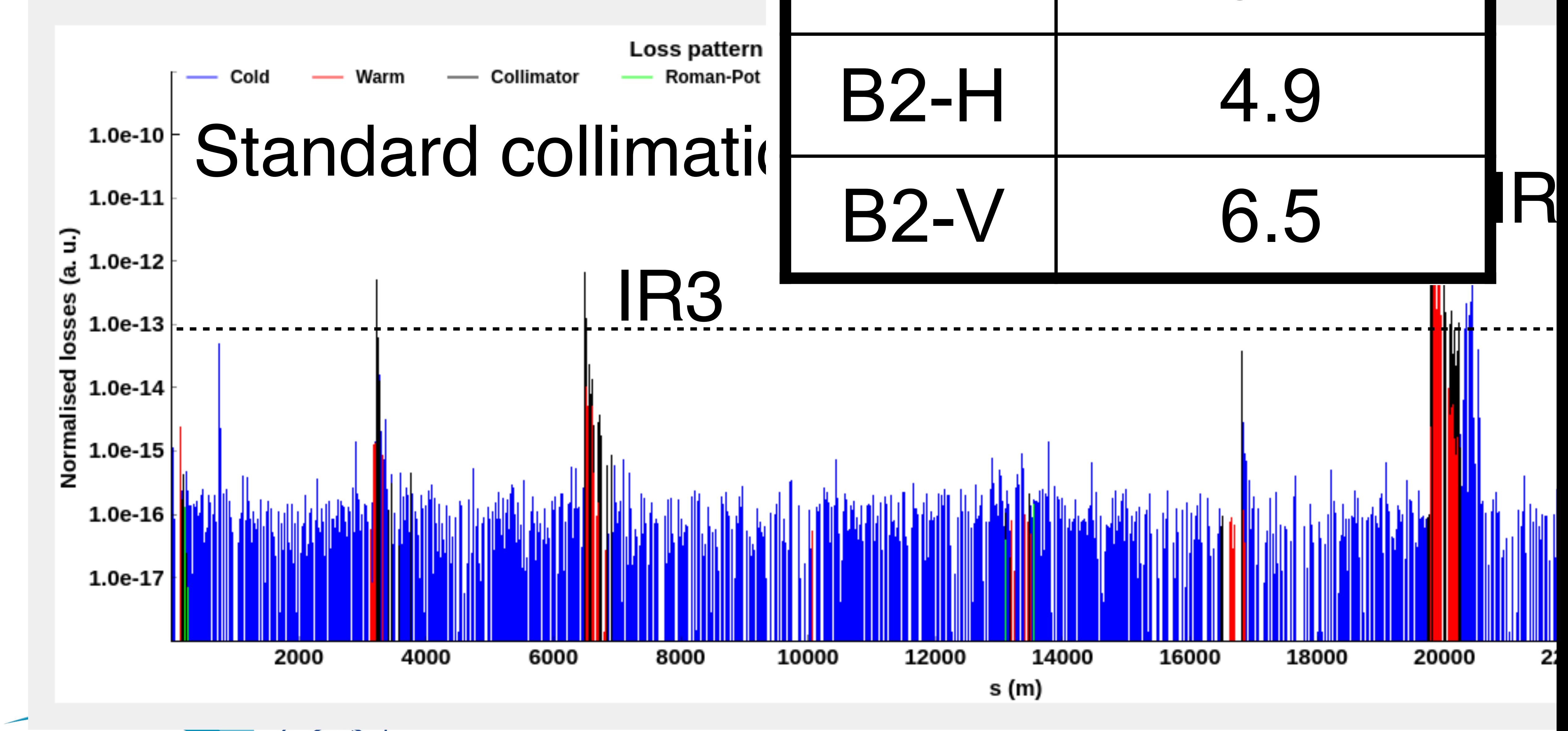
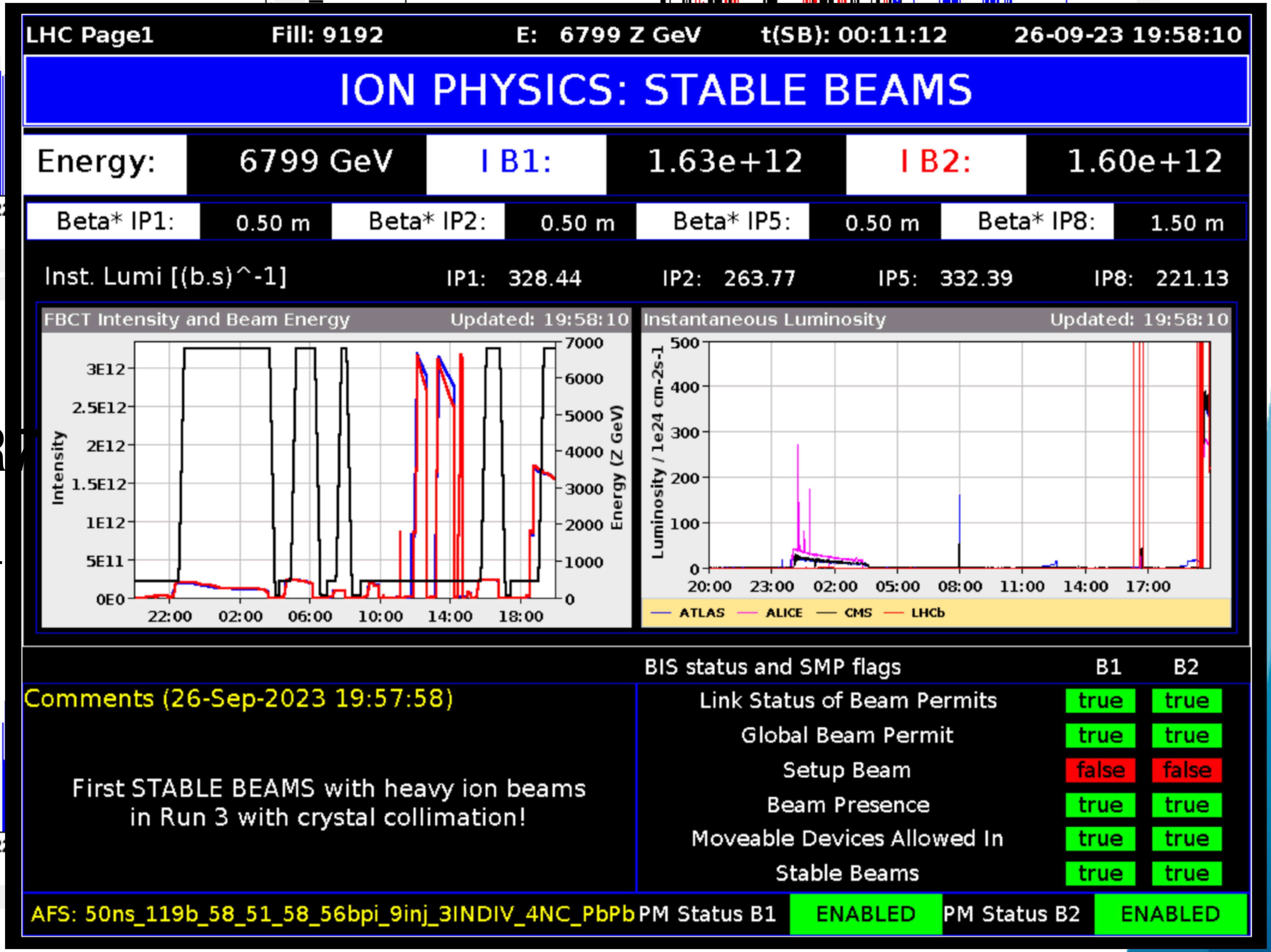






	Gain factor
B1-H	13.7
B1-V	5.1
B2-H	4.9
B2-V	6.5



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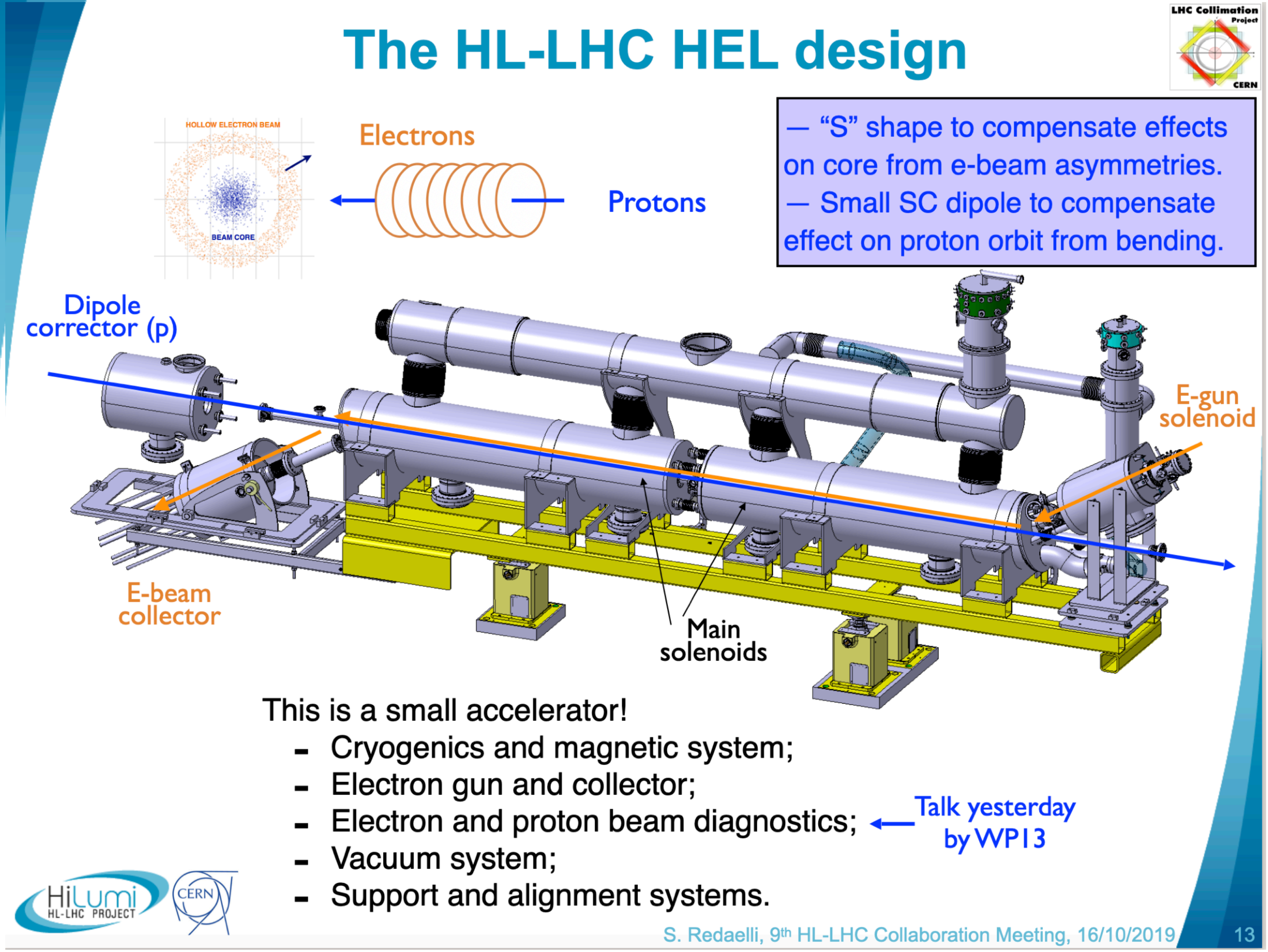
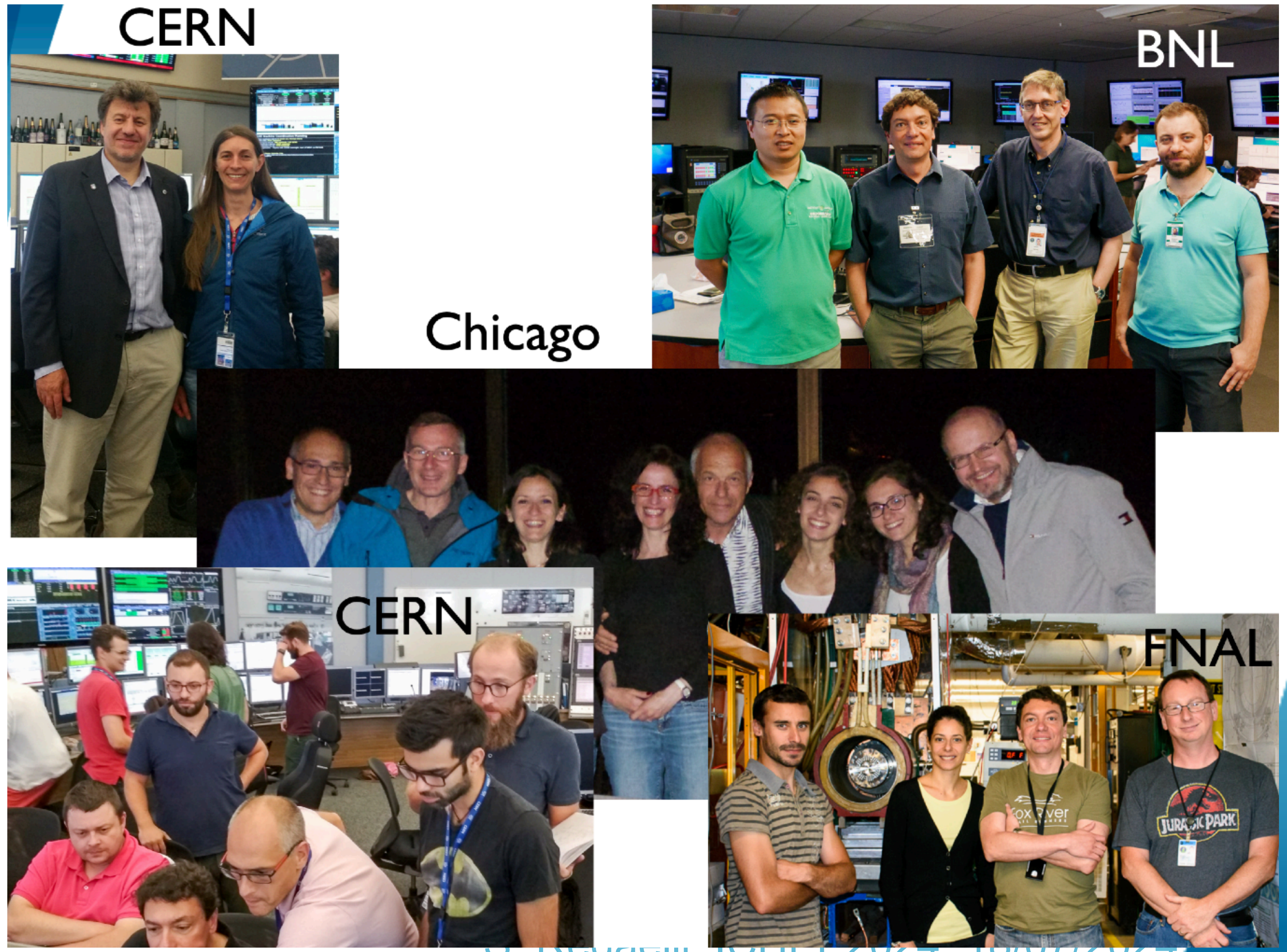
- Conclusions

Hollow electron lenses (HELs)

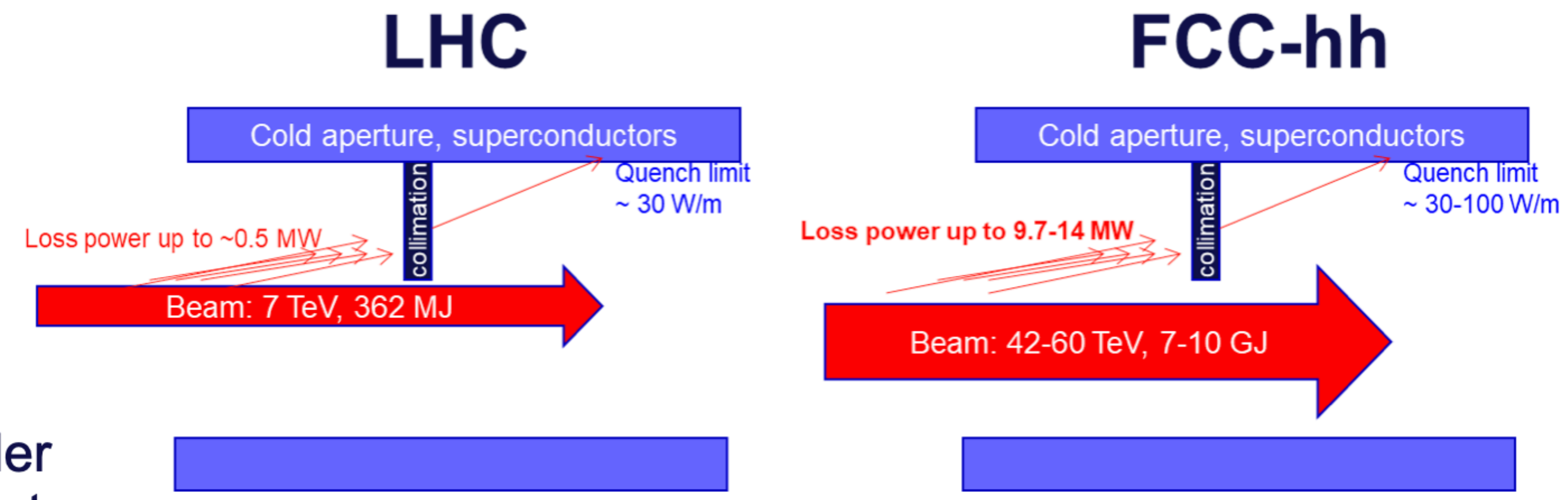


The HELs for beam collimation cannot materialise for LS3 given the situation in EU and the cancellation of Russian in-kind. **Earliest installation in LS4 → removed from the present scope of HL-LHC.** Actively pursuing halo limitation studies, and presently re-assessing the needs.



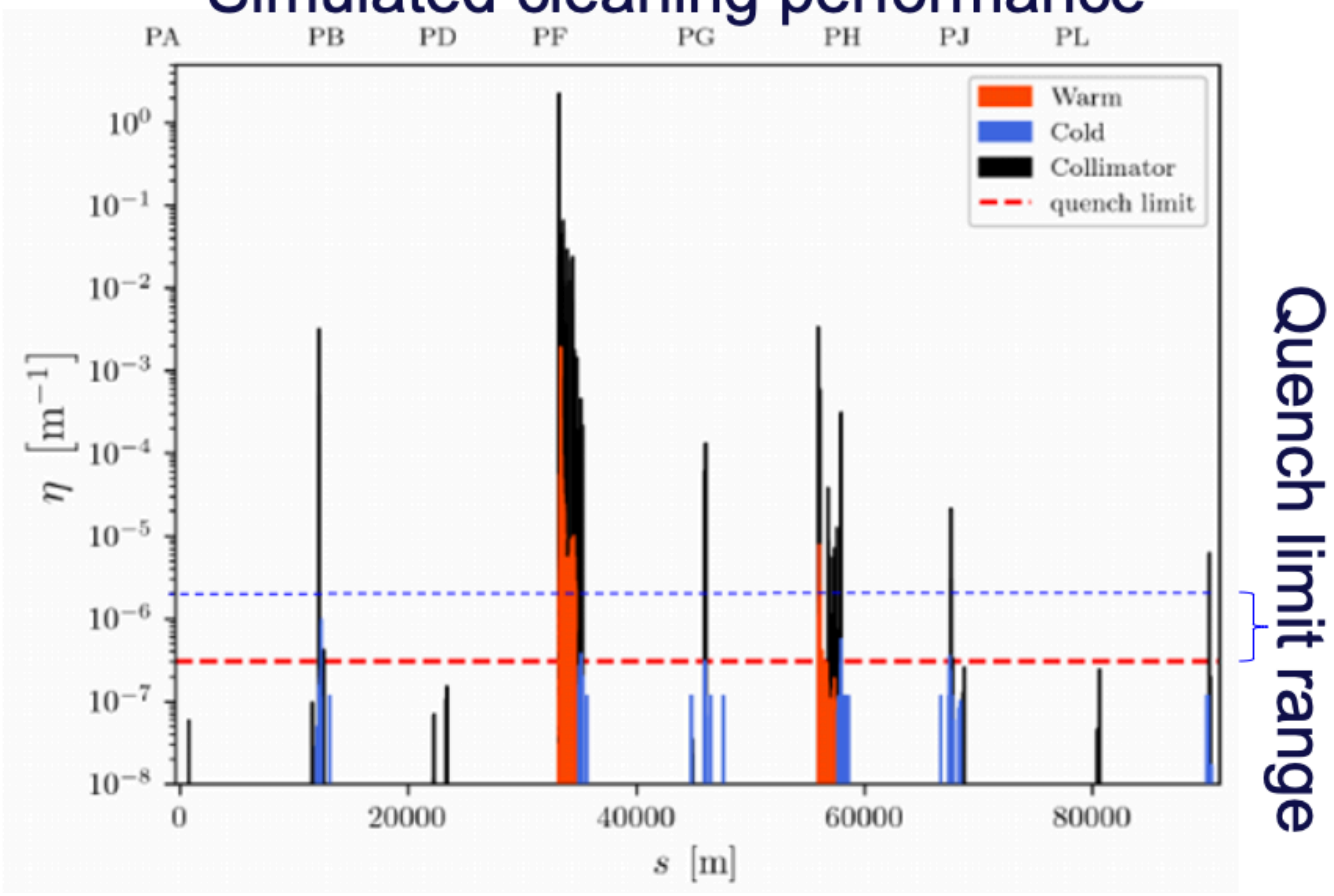
Hollow electron beams can control the halo diffusion and population, enhancing the collimation performance.

FCC-hh collimation



- In FCC-hh, factor ~30 higher stored beam energy than in LHC design → collimation extremely challenging!
- Also: higher energy → smaller gaps → impedance constraints
- Using multi-stage system as in LHC, with shorter primaries, additional absorbers and dispersion suppressor collimators
- Very challenging to achieved good cleaning performance → further optimization to be done
- Important with thermo-mechanical studies of impacted collimators to see that they survive

Simulated cleaning performance



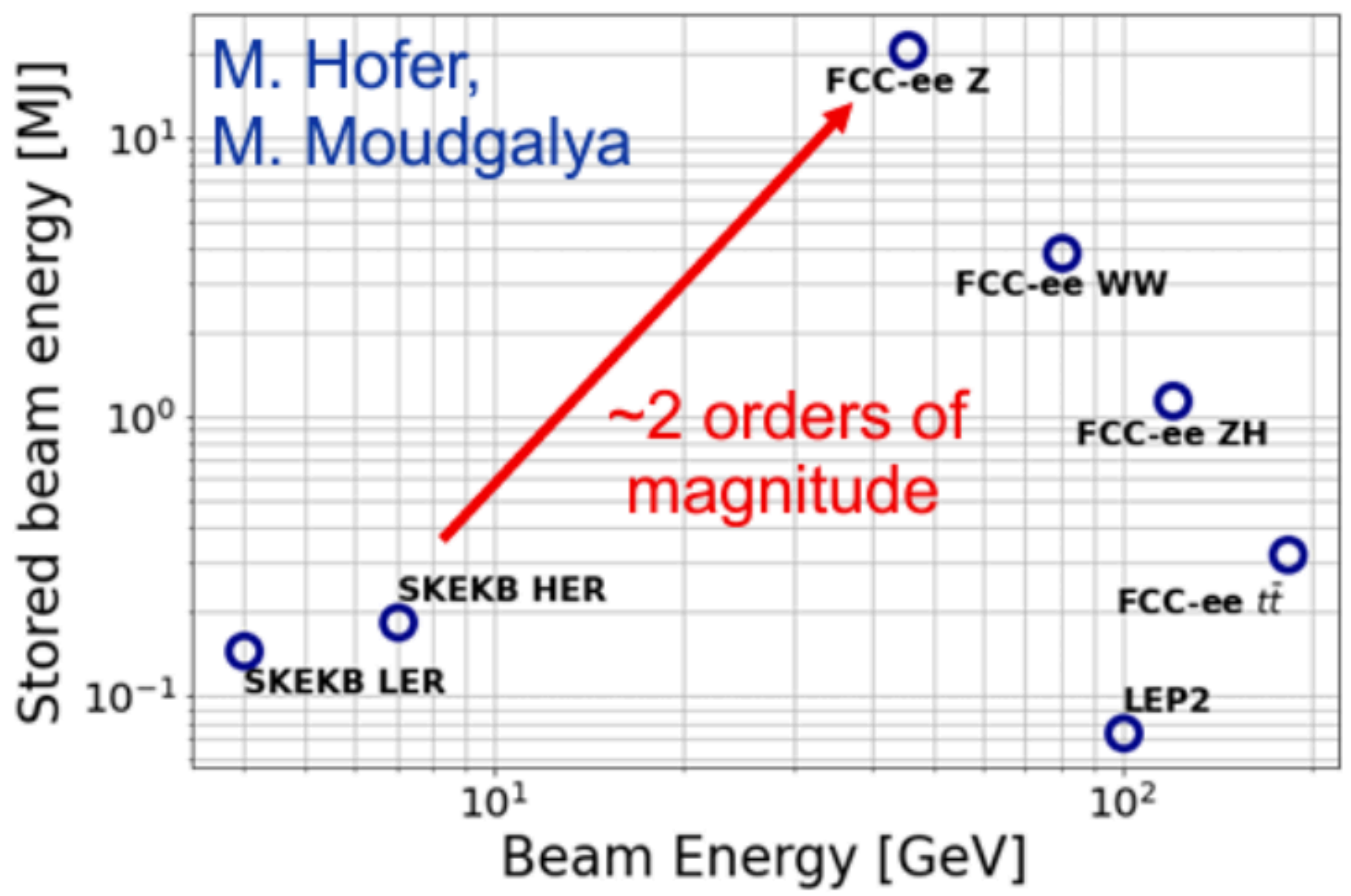
Courtesy R. Bruce

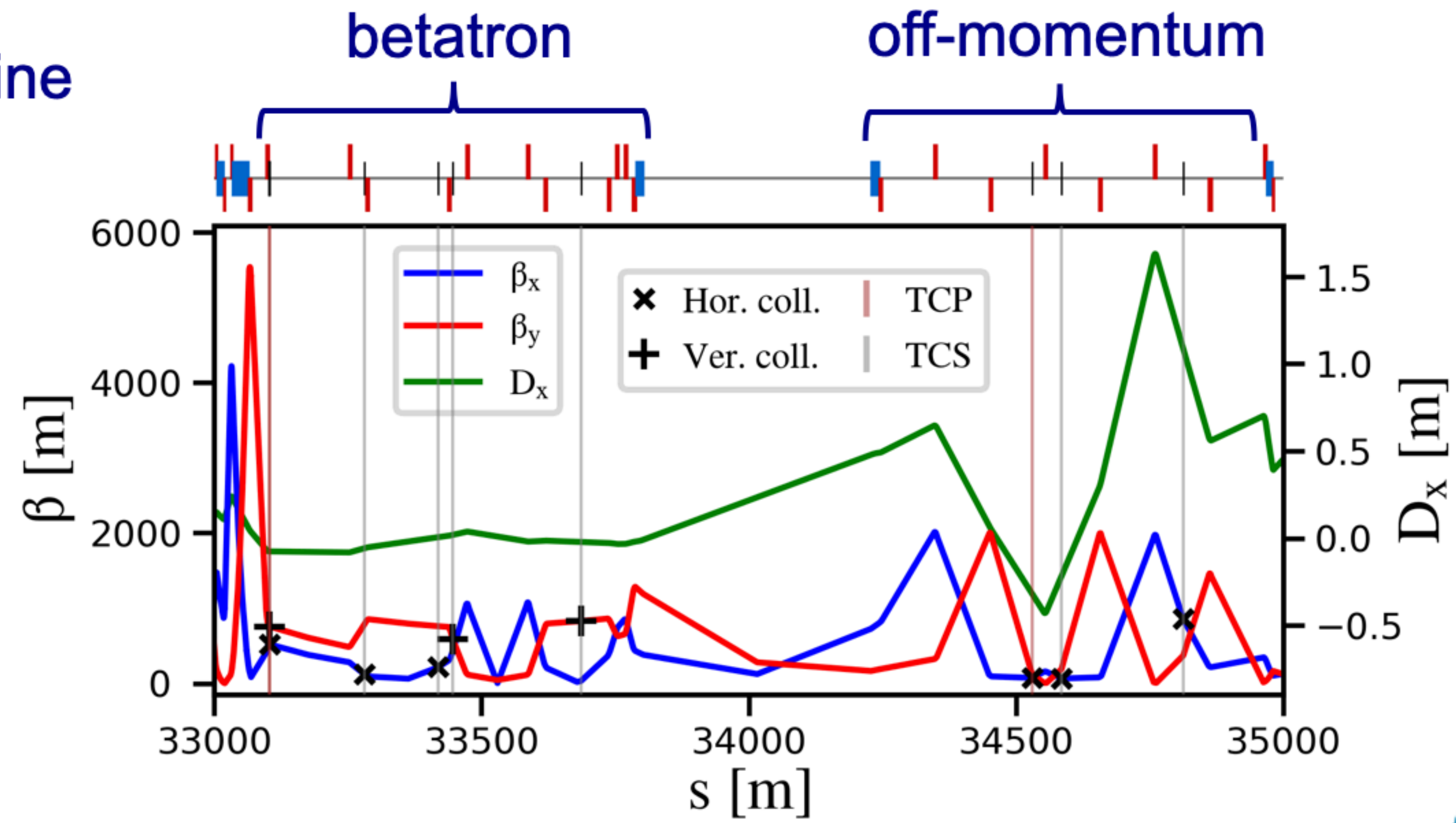
See G. Perez talk on FCC-hh design

Collimation at FCC-ee

- **FCC-ee is the FCC first stage e^+e^- collider**
  - ➢ 90.7 km circumference, tunnel compatible with FCC-hh
  - ➢ 4 beam operation modes, optimized for production of different particles: ***Z*** (45.6 GeV), ***W*** (80 GeV), ***H*** (120 GeV), ***ttbar*** (182.5 GeV)
- **FCC-ee presents unique challenges**
  - ➢ Unprecedented stored beam energy for a lepton collider: up to **17.5 MJ** in the ***Z*** operation mode (45.6 GeV)
  - ➢ Highly destructive beams
  - ➢ **Beam halo collimation** indispensable to protect the machine from unavoidable beam losses
- **Dedicated straight section for beam halo collimation**
  - ➢ Two-stage betatron and off-momentum collimation system in one insertion
  - ➢ Ensure protection of the aperture bottlenecks in different conditions

Comparison of lepton colliders





Courtesy G. Broggi

See K. Andre talk.

Conclusions

- Reviewed the LHC collimation needs and performance
  - Excellent performance, enabling LHC operation well beyond design parameters!
- The HL-LHC upgrade required an improved beam collimation on various fronts
  - New challenges mainly related to increased beam current and higher peak luminosity
  - Main pillars: lower impedance; better cleaning (ions); better detector protection and physics debris
  - Two-stage approach for collimation upgrade enable performance boost already in Run 3.
- New technologies and designs were developed and are already being tested
  - Novel materials for low-impedance collimation solutions, without and with coating
  - Crystal collimation of heavy-ion beams
  - New warm collimators in the cold dispersion suppressor region
  - Novel 2-in-1 design to address the challenges of the new HL-LHC experimental insertions
- This provides a solid base for collimation solutions for future projects
  - FCC-hh collimation well defined, profiting from key solutions for HL-LHC
  - FCC-ee collimation design actively being worked on