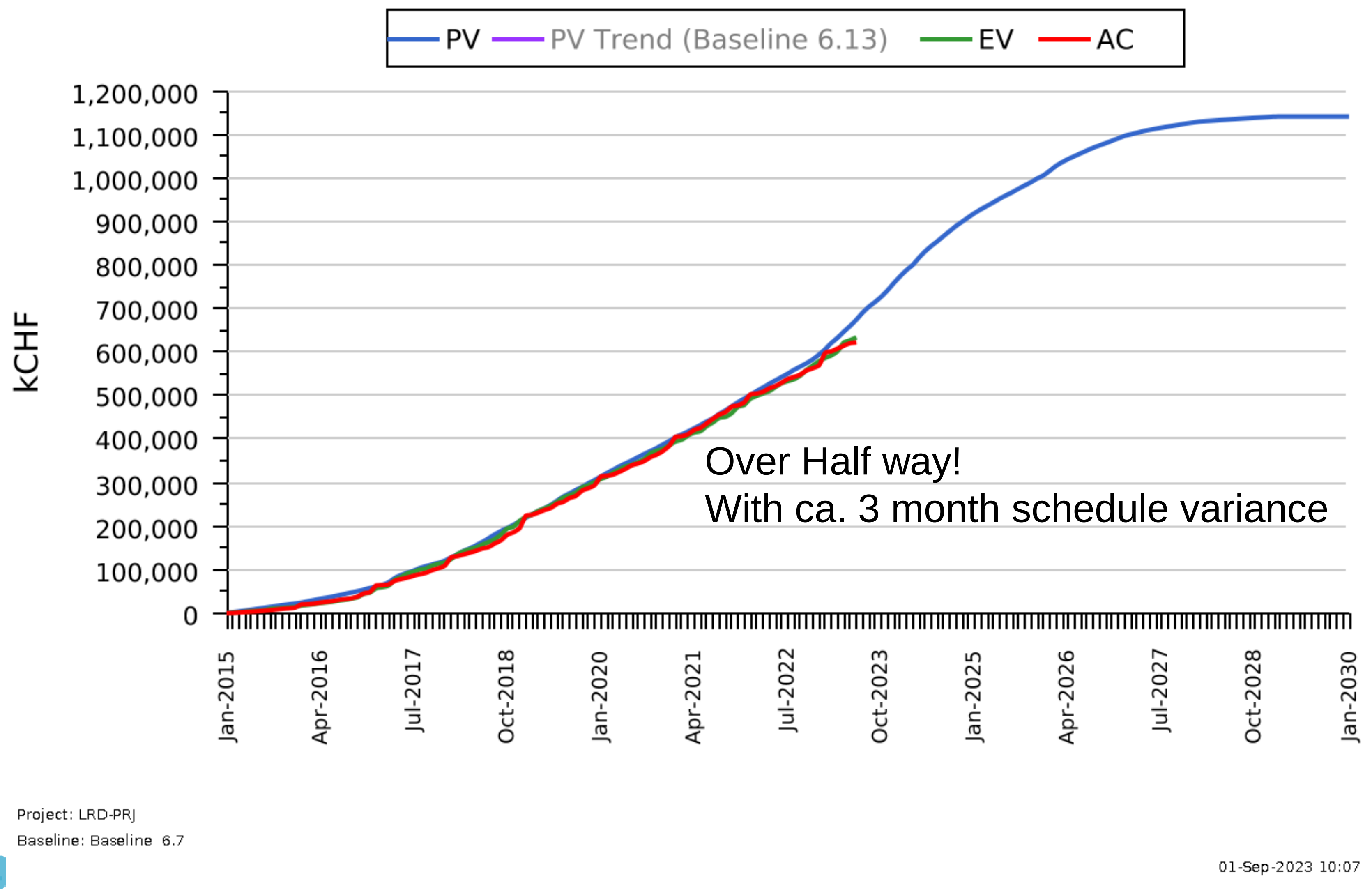
HL-LHC project Status

Y. Papaphilippou, CERN
On behalf of the HL-LHC project
Particular thanks to O. Brunning and R. Tomas for the material

Corfu2024 Workshop on Future Accelerators – 25/05/2024

Reminder of the HL-LHC Goals

From FP7 HiLumi LHC Design Study application in 2010



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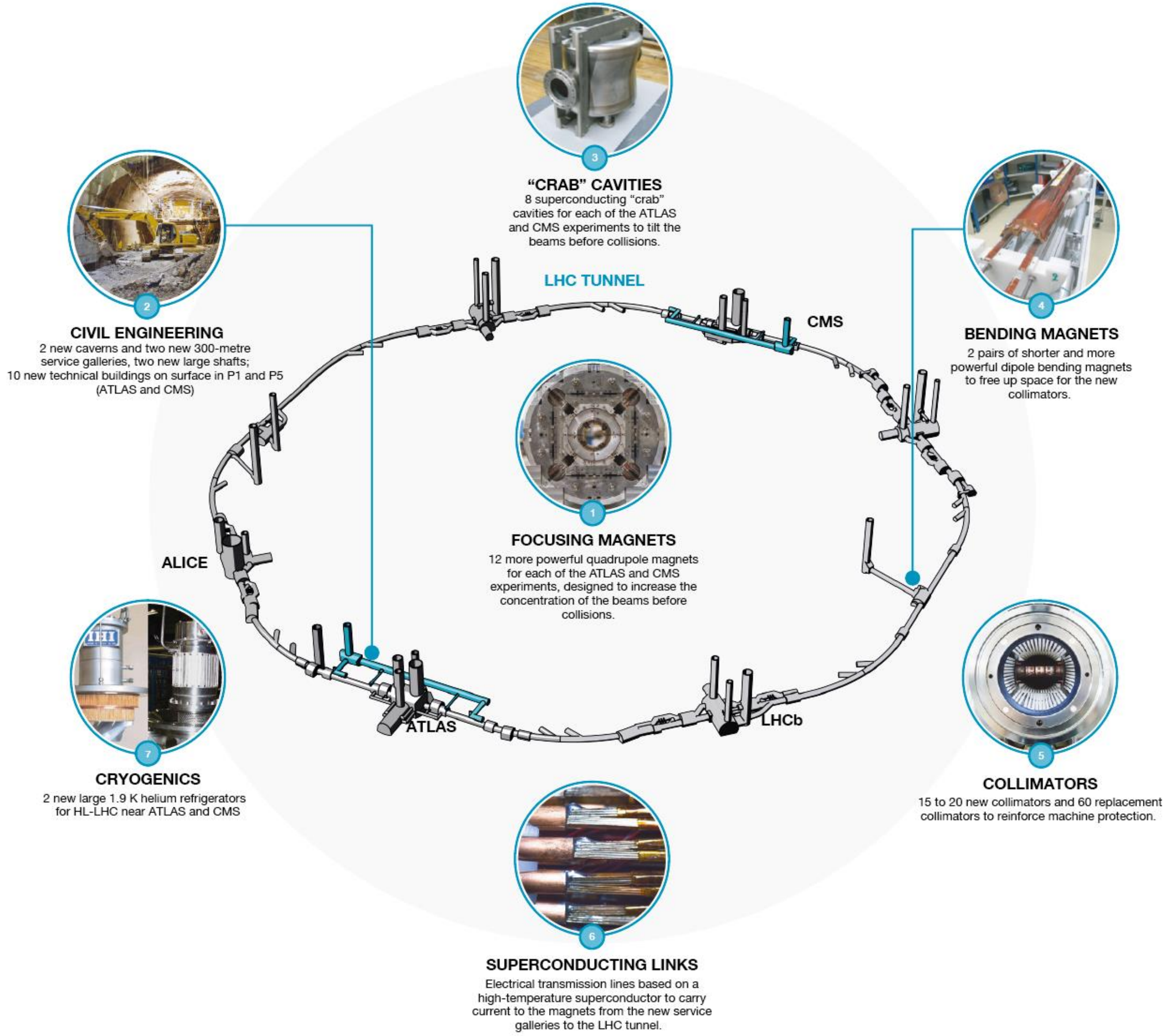
HiLumi LHC landmarks: a project for Physics and Technology jump



HiLumi HL-LHC PROJECT

LHC upgrade goals: Performance optimisation

Luminosity recipe (round beams):

$$L = \frac{n_b \times N_1 \times N_2 \times \gamma \times f_{rev}}{4\pi \times \beta^* \times \varepsilon_n} \times F(\phi, \beta^*, \varepsilon, \sigma_s)$$

➔1) maximize bunch intensities ➔Injector complex

➔2) minimize the beam emittance Upgrade LIU

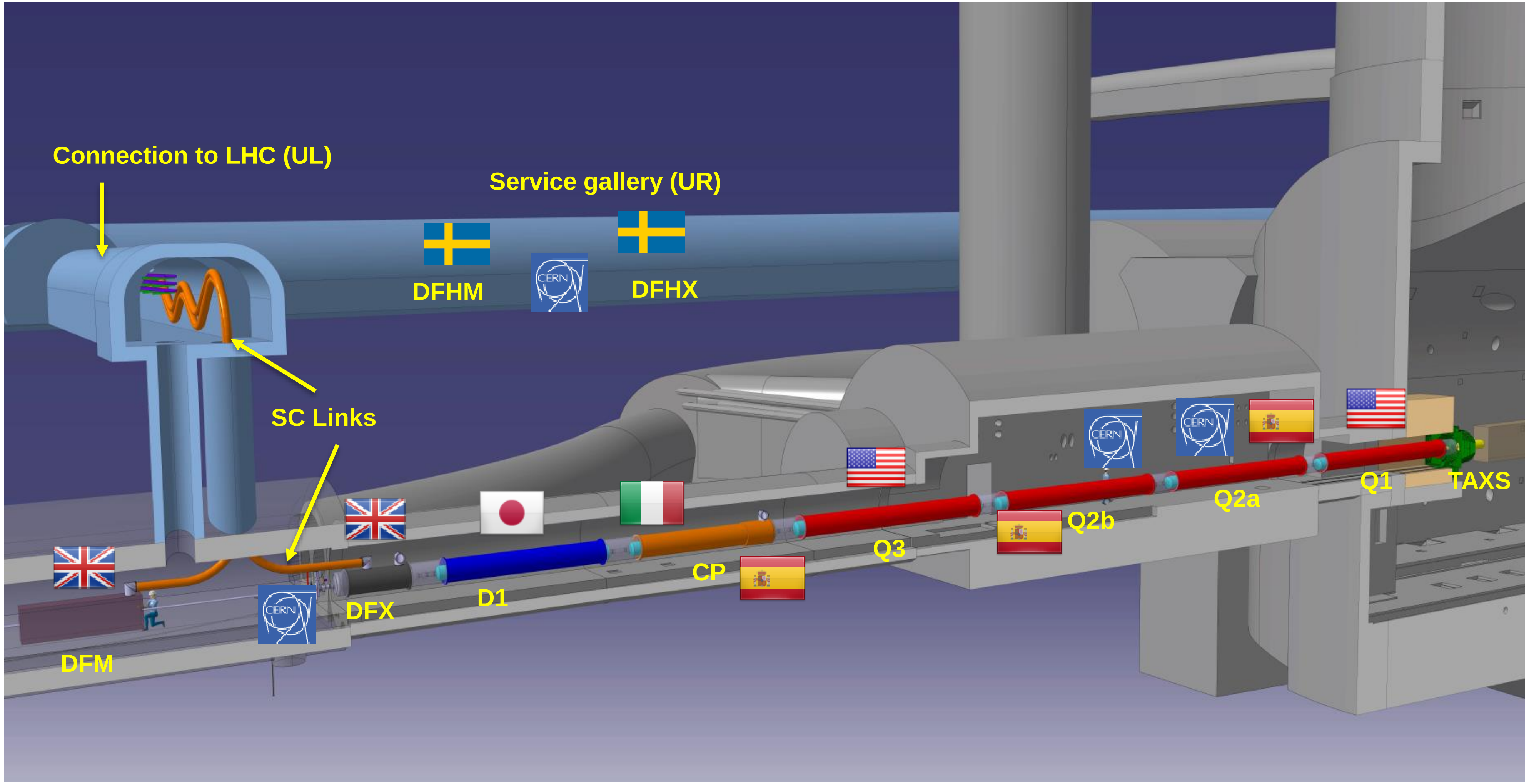
➔3) minimize beam size (constant beam power); ➔triplet aperture

➔4) maximize number of bunches (beam power); ➔25ns

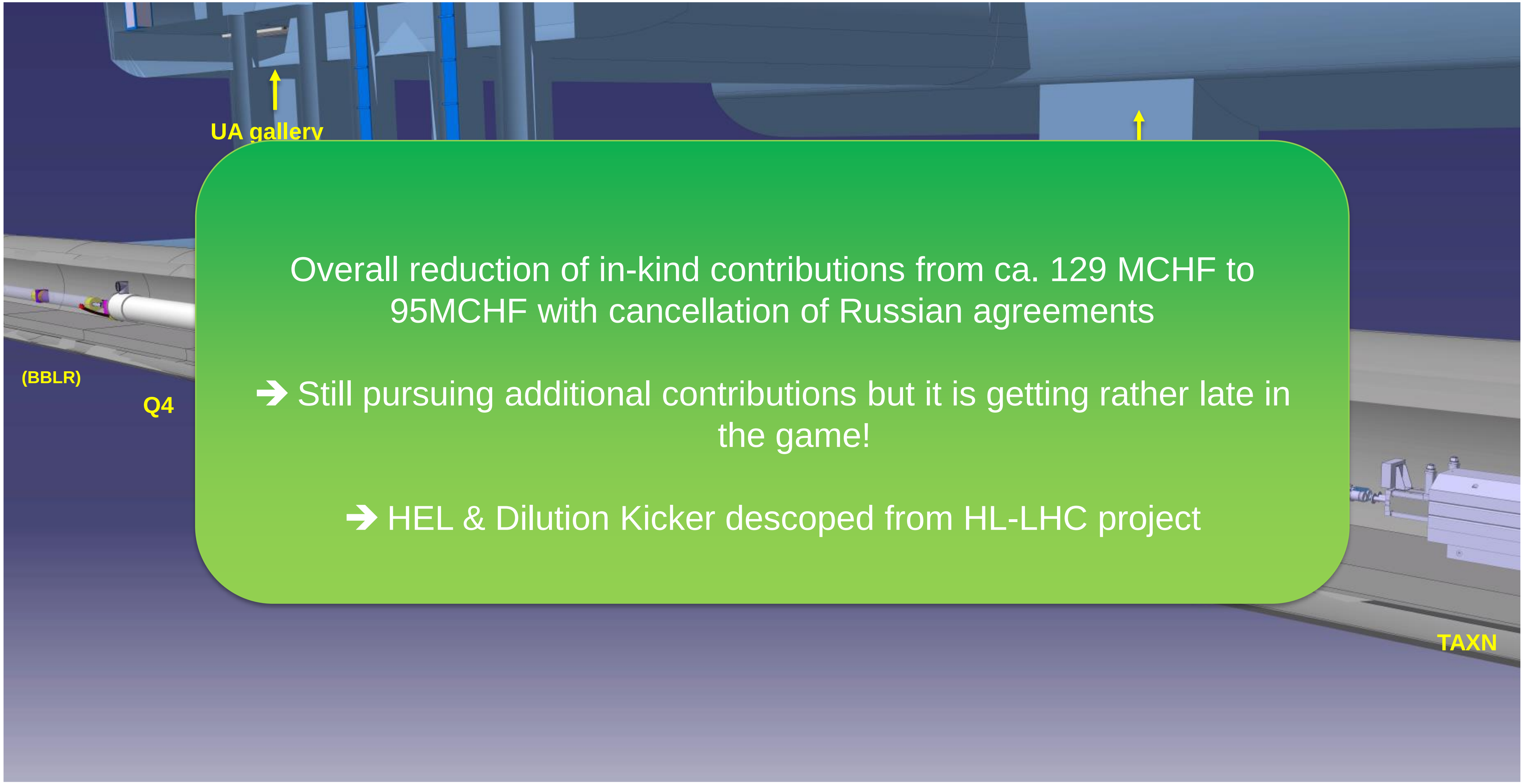
➔5) compensate for 'F'; ➔Crab Cavities

➔6) Improve machine 'Efficiency' ➔minimize number of unscheduled beam aborts

International Collaboration



The MS region with in-kind contributions

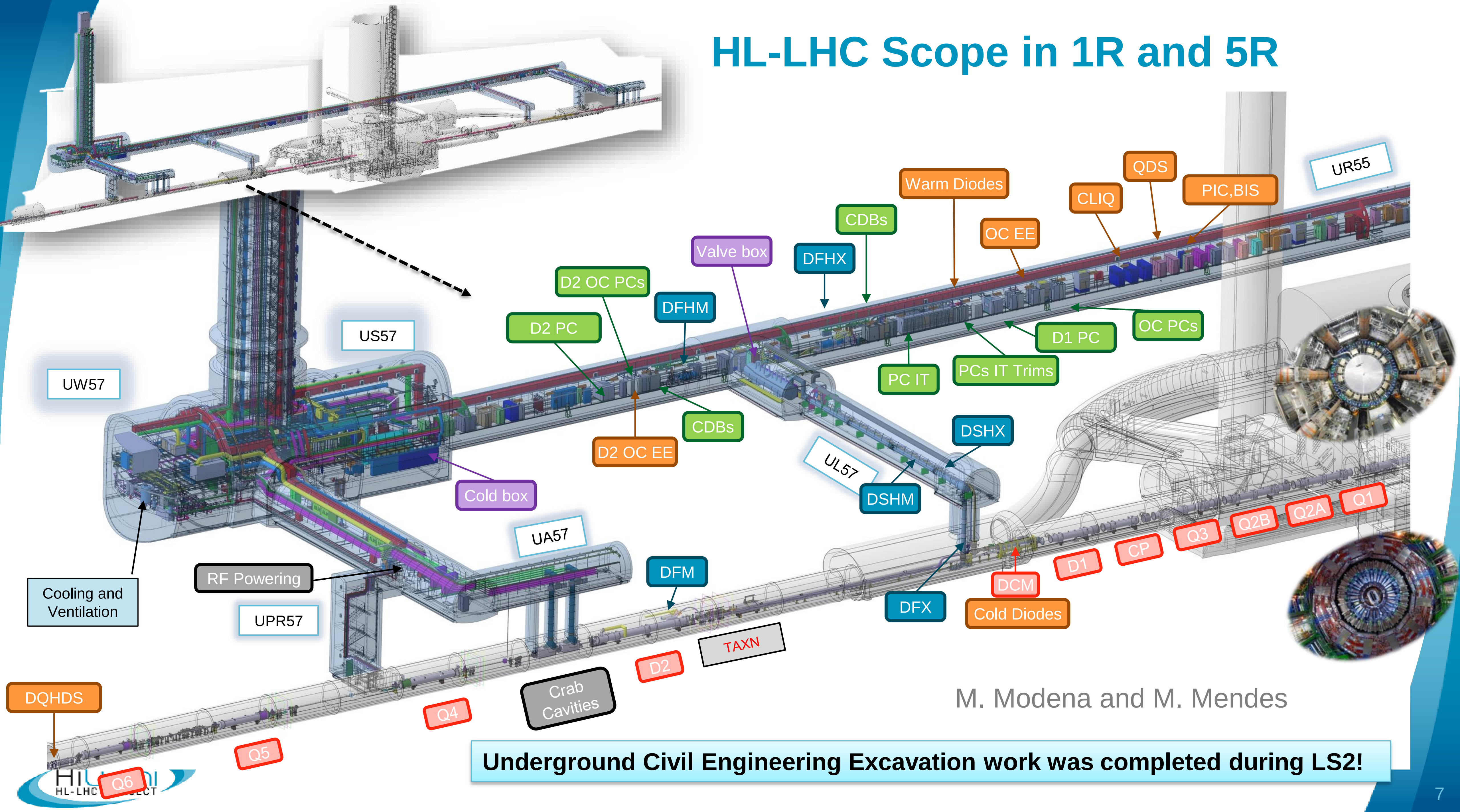


Overall reduction of in-kind contributions from ca. 129 MCHF to 95MCHF with cancellation of Russian agreements

➔ Still pursuing additional contributions but it is getting rather late in the game!

➔ HEL & Dilution Kicker descoped from HL-LHC project

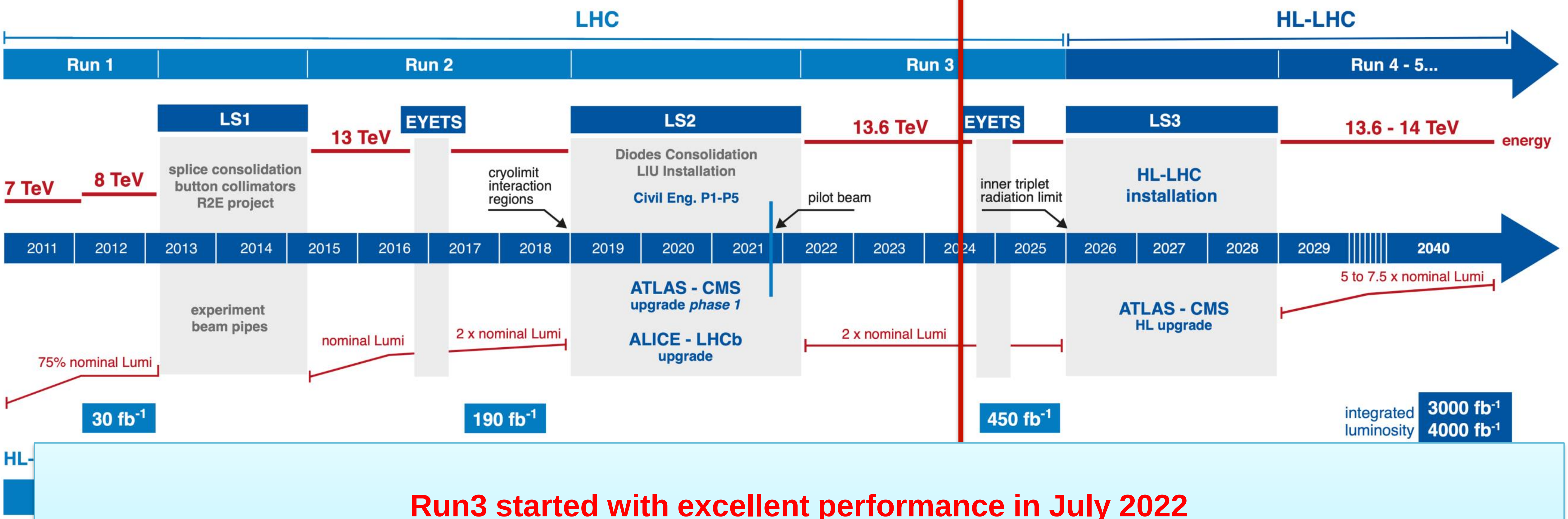
HL-LHC Scope in 1R and 5R



M. Modena and M. Mendes

Underground Civil Engineering Excavation work was completed during LS2!

LHC / HL-LHC Plan



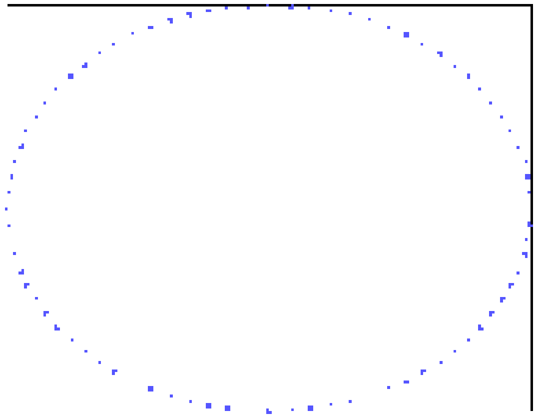
Run3 started with excellent performance in July 2022

Second Year of Run3 cut short due to leak in Pt8 Triplet magnet bellow

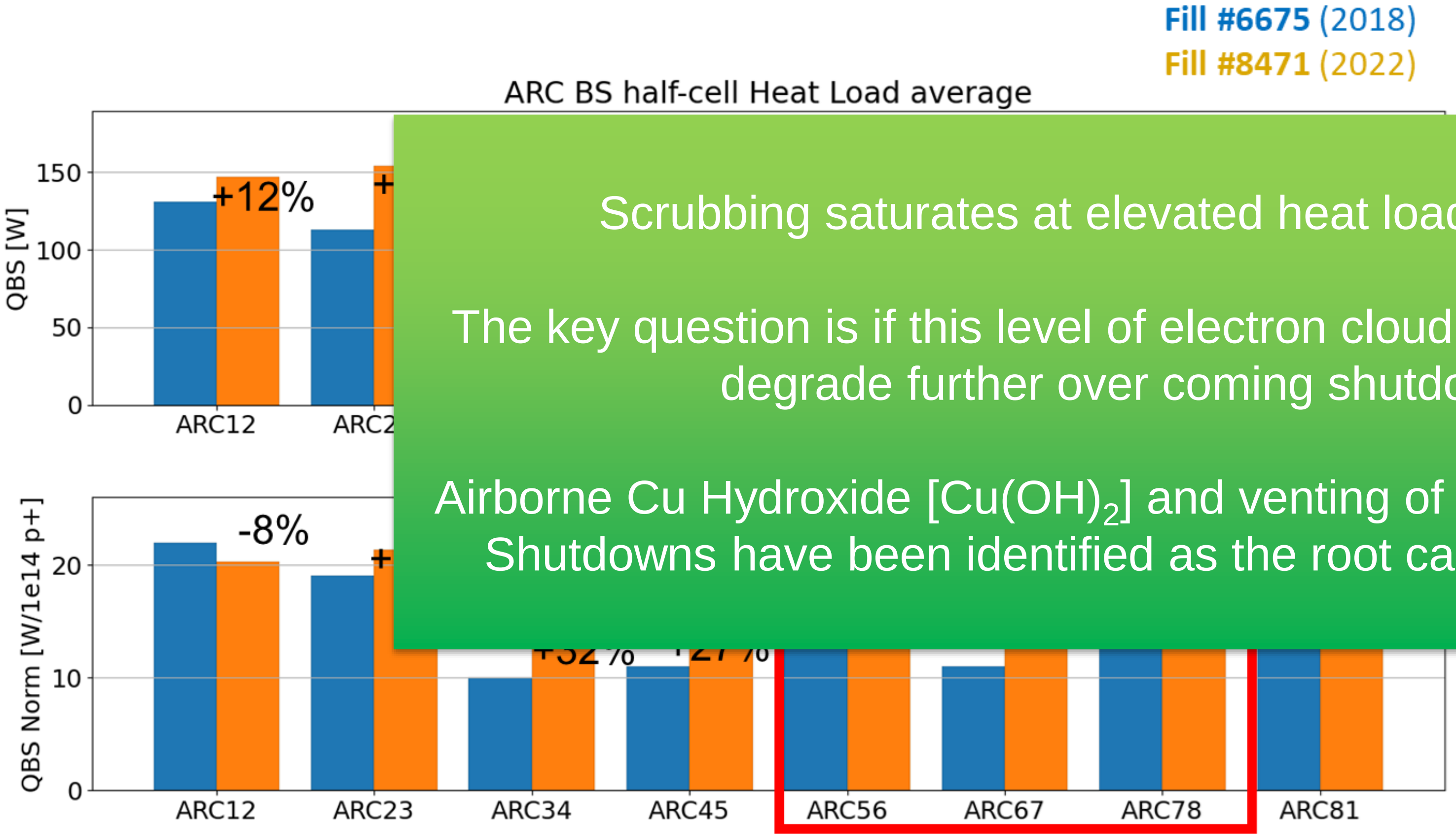
2024 run has started with new partial RP optics (triplet irradiation mitigation)

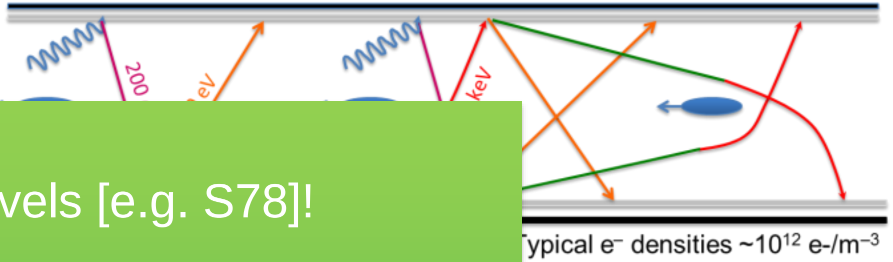
E-cloud still major limitation for allowing maximum number of bunches (cryo capacity)

Electron Cloud: Persisting into HL-LHC period



- Dealing with electron cloud
  - Sector 7-8 emerged degraded from LS2, determining heat load limitation of LHC





Scrubbing saturates at elevated heat load levels [e.g. S78]!

The key question is if this level of electron cloud remains stable or if it will degrade further over coming shutdown period?!

Airborne Cu Hydroxide [$Cu(OH)_2$] and venting of the apertures during Long Shutdowns have been identified as the root cause for this degradation

13-2015)

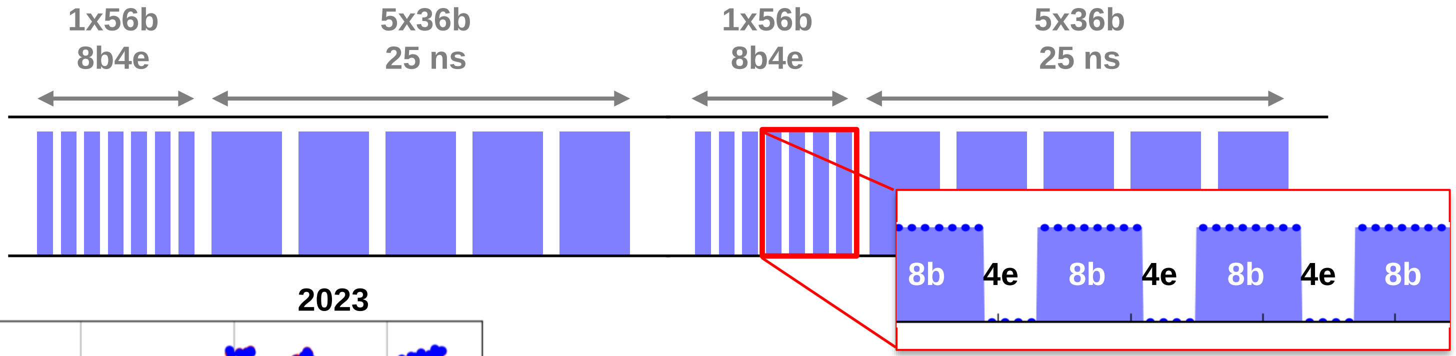
degradation of ... S23 & S78 & S81

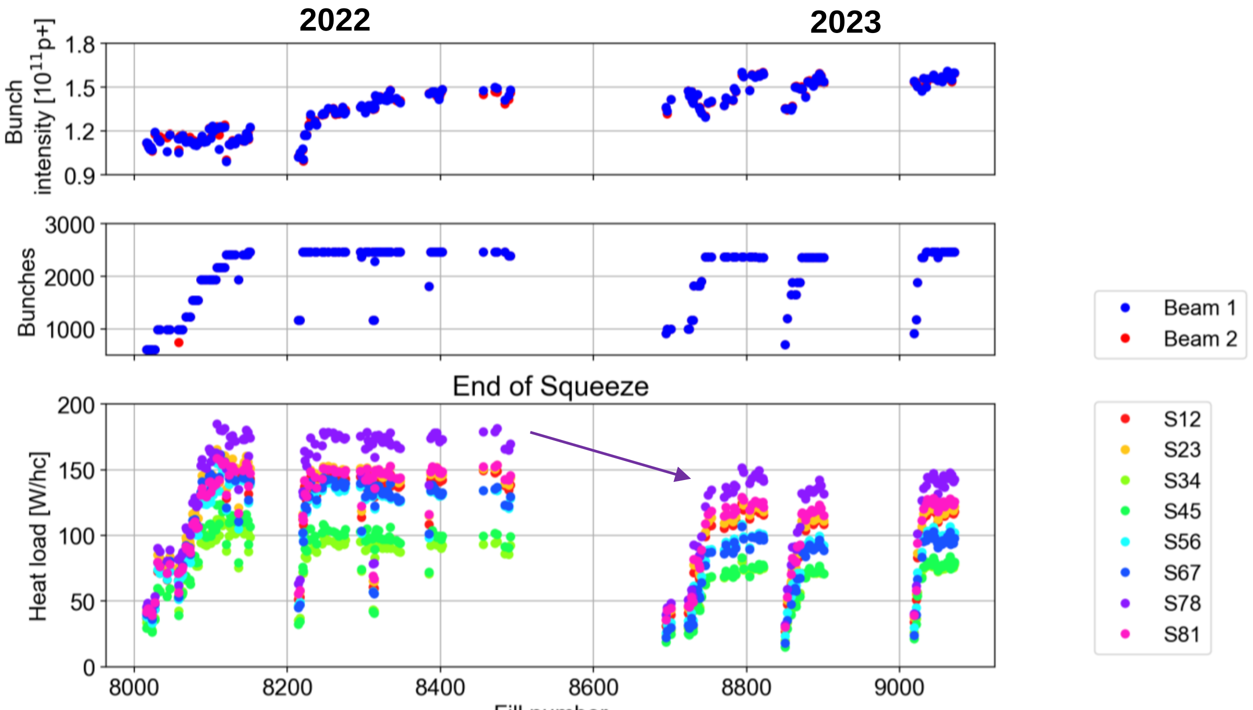
19-2022)

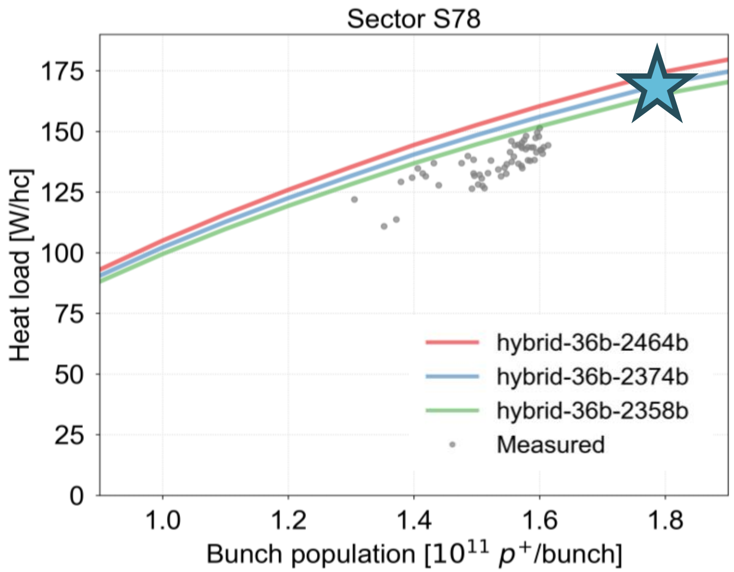
- Provoked significant degradation of heat loads in S56 & S67 & S78

Heat load reduction in LHC with hybrid scheme

- Hybrid filling scheme for e-cloud suppression for proton physics in 2023 (first time!). Reduced number of 25 ns bunches in 2024
  - Total intensity vs heat load optimised with trains mixing 8b4e and 25 ns (5x36b)
  - ~20% reduction in heat load per bunch allowed smooth operation with up to 1.6e11 p/b
  - Sufficient margin in heat load for increasing intensity to 1.8e11 p/b, as foreseen in 2023



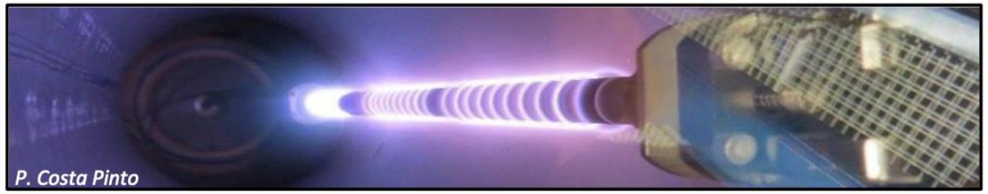




e-cloud: Mitigation Options for HL-LHC

- Beam stability is also degraded

  ⟶ one needs to address the root cause and not only the heat load with e.g. cryogenics upgrade.
- Ideal cure: in situ surface treatment (see *V. Petit*, *LHC Chamonix workshop, 23/01/2023)*
  - Plasma-assisted CuO reduction and carbon recovery (PE-CVD)
  - Carbon coating (10-20 nm) by sputtering (PVD)



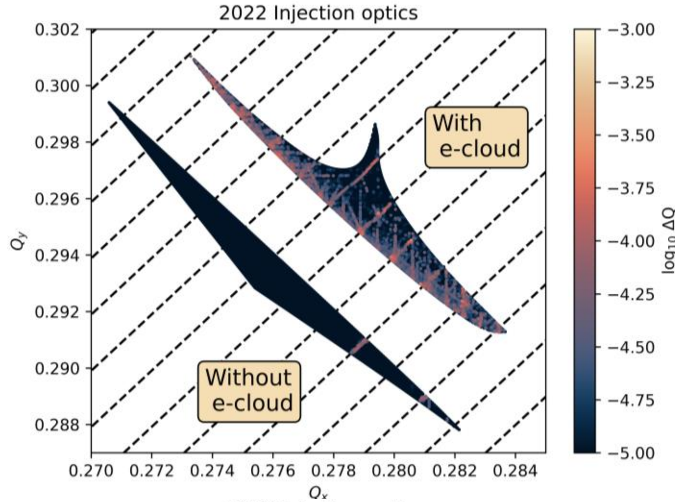
P. Costa Pinto

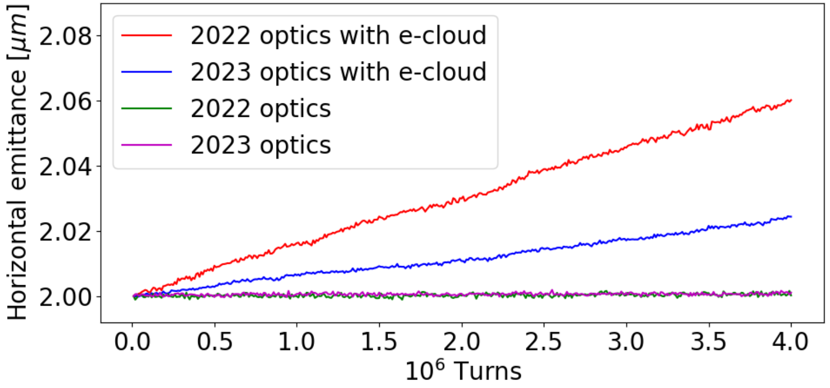
In-situ treatment tool testing and personnel training on mockup

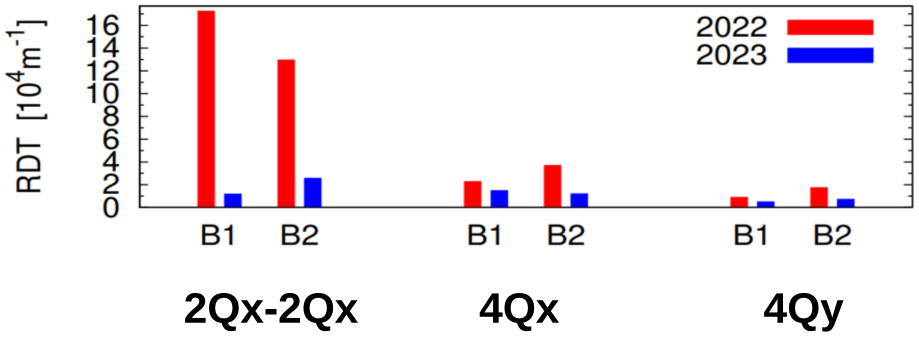
Consolidation Project proposed
(see ***M. Lamont***, *LHC "Chamonix" workshop summary, 25/03/2023)*

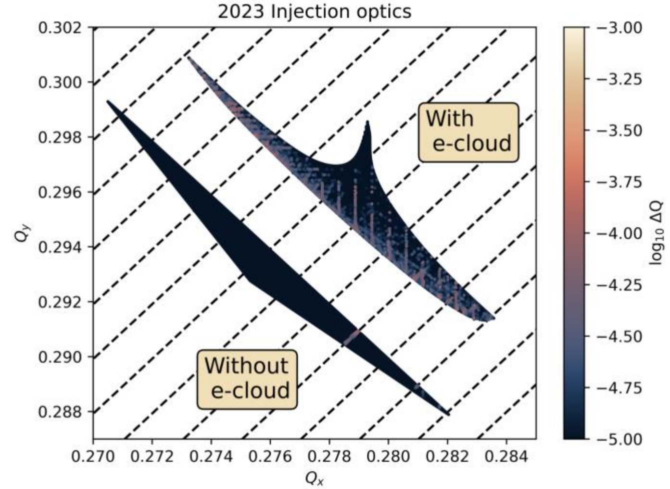
LHC optics corrections for incoherent e-cloud effects

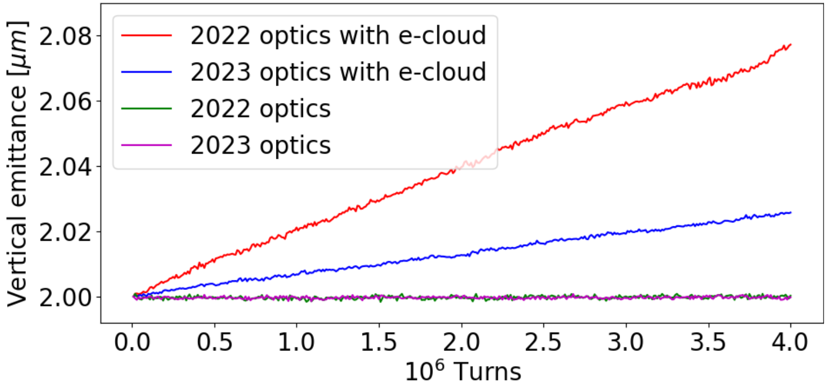
- LHC 2023 Injection optics modified to suppress synchro-betatron resonances excited by arc octupoles and e-cloud in quadrupoles – improving beam lifetime!

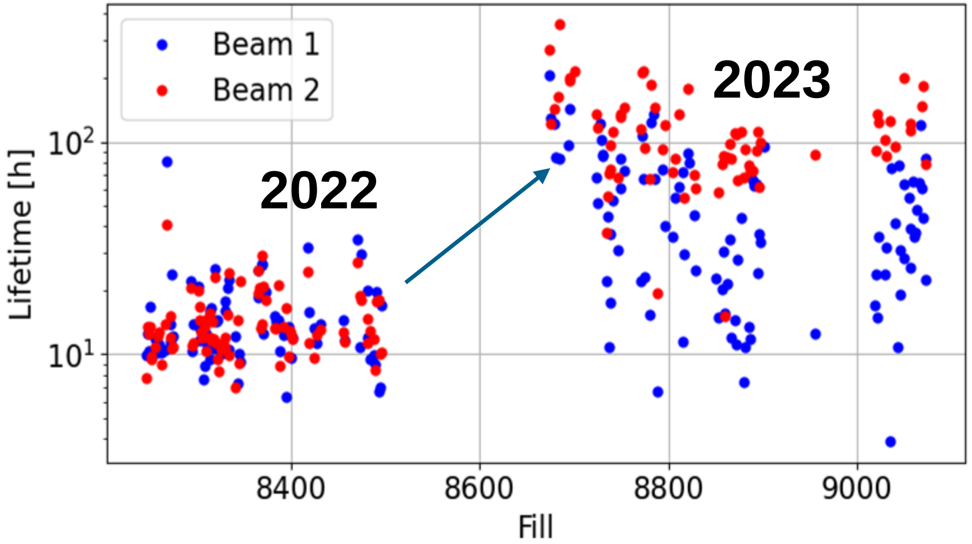




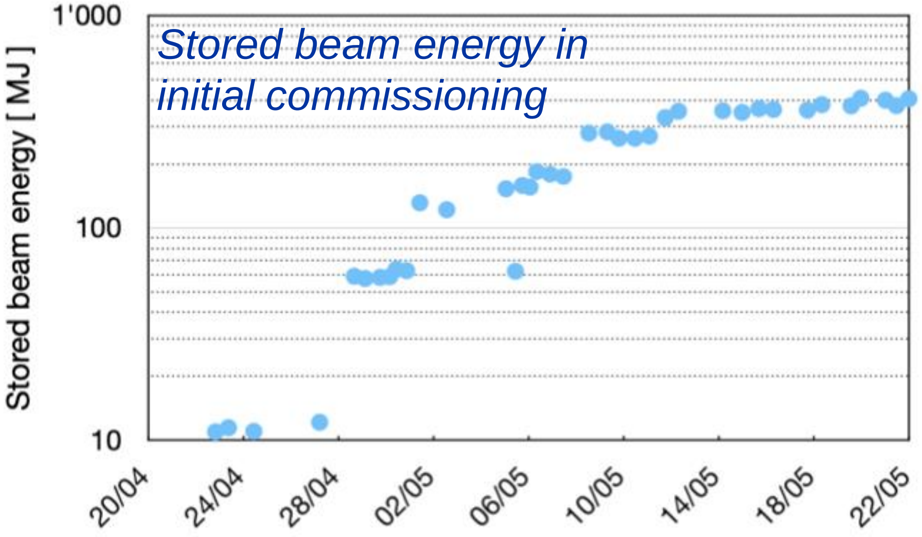


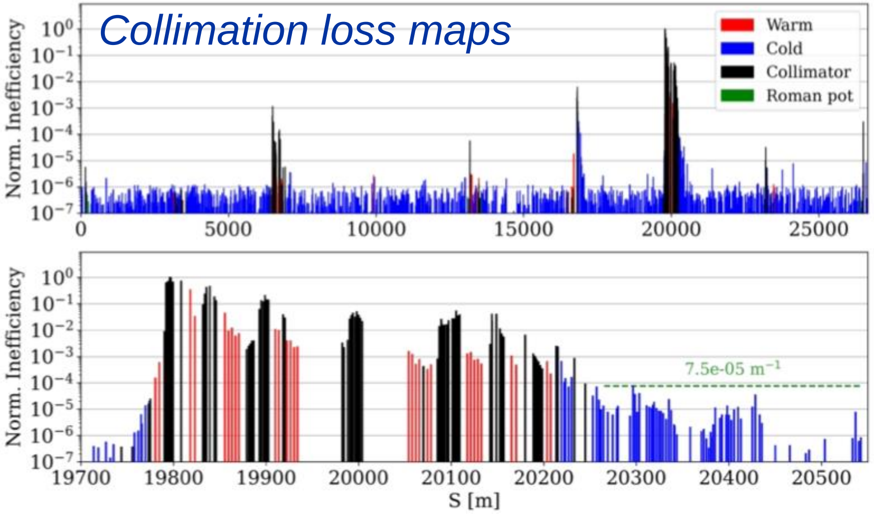




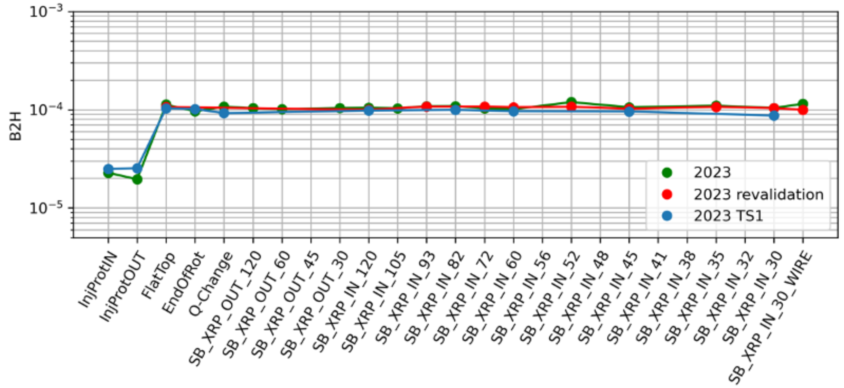


LHC proton Run 2023: collimation performance





- LHC stored beam energy in 2023 exceed **400MJ** at 6.8 TeV – new **record!**
- Excellent performance of collimation cleaning systems
  - Ensured safe operation and high availability in all operational phases
  - In particular, during **complex 2023 β* levelling scheme**!
  - **Cleaning inefficienc**ies often below the 10^{-4} level
- **New HL-LHC collimators** fully deployed in operation: low-impedance collimators, TCLD dispersion suppressor collimators (ions), crystal collimation scheme for high- β* run, …
- **Big effort** to ensure system commissioning, including all special runs, and to validate/monitor performance.

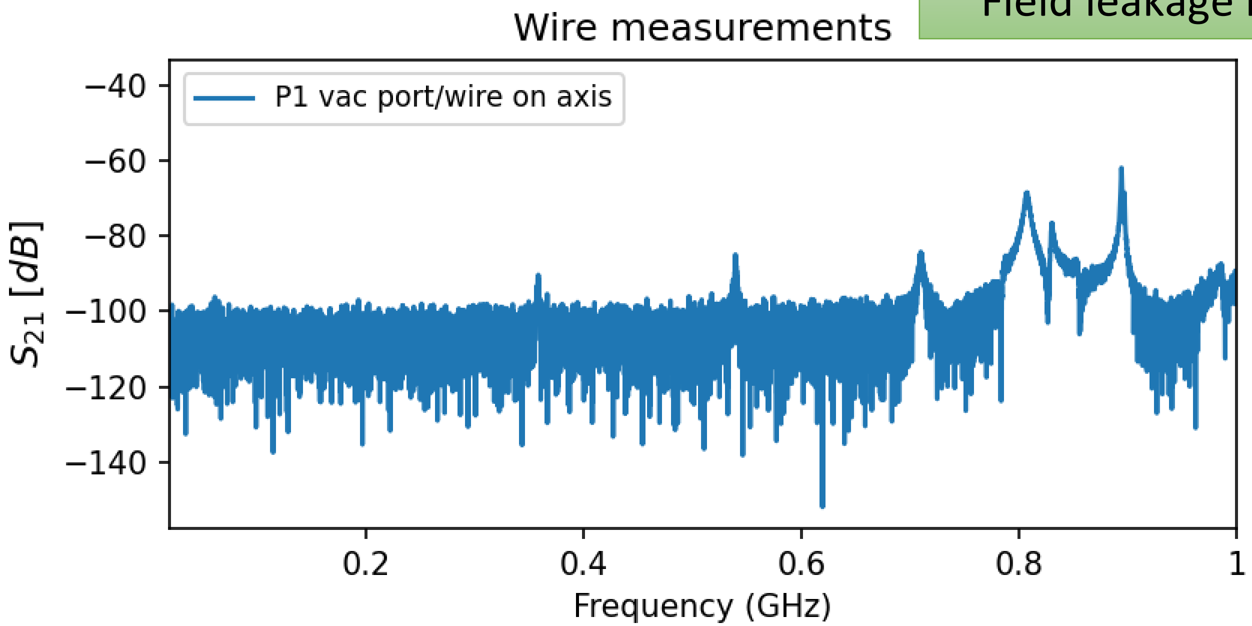


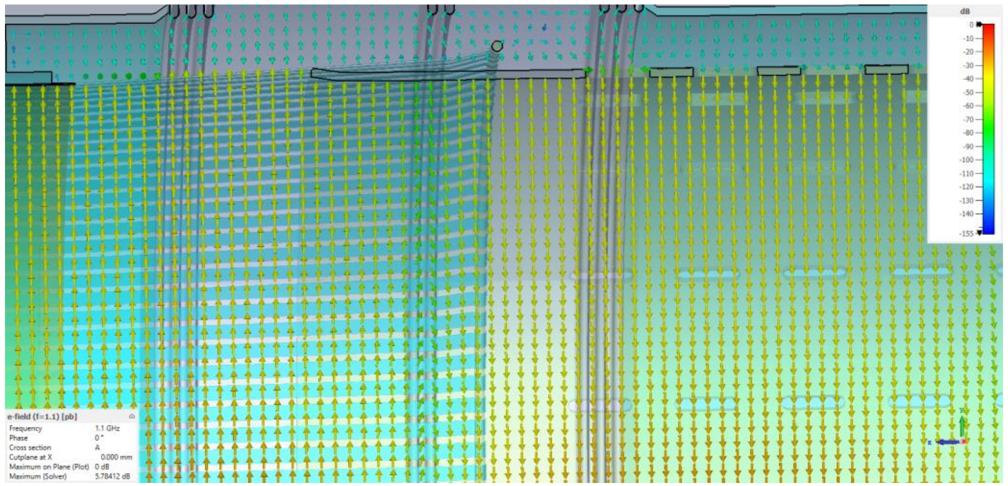
Example: B2H cleaning performance along the cycle

Studies on LHC RF fingers

Identification of the possible mechanism of failure: beam impedance induced heating due to field leakage from RF fingers

Field leakage measured and confirmed by simulations





More critical situation for larger module diameter, the (resonances driven at lower frequencies and induce higher power loss)

Simulations also suggest that beam offset and defects in RF finger production can magnify leaked modes

RP optics

The IT lifetime does not only depend on integrated performance, but also on

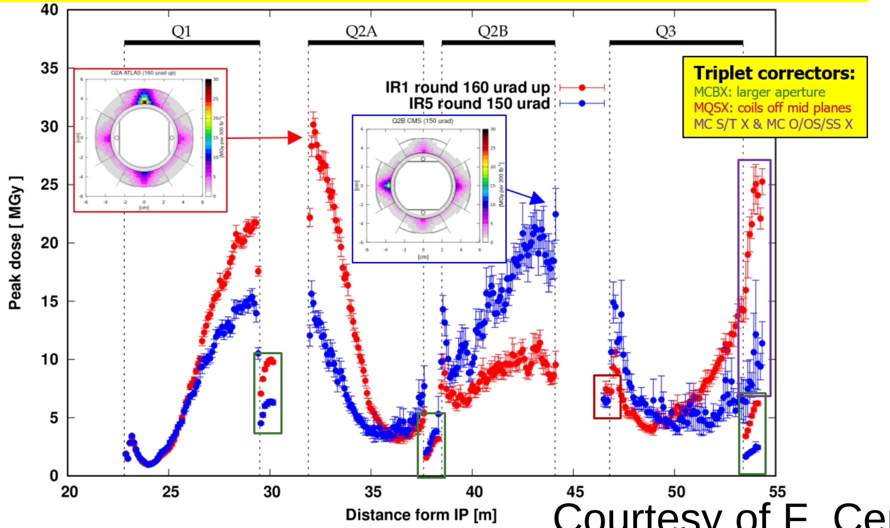
(i) X-angle plane and polarity (& magnitude)
→peak dose at 0º, 90º, 180º or 270º

(ii) Beam-screen orientation
→H & V planes “shielded” differently

(iii) IT polarity since most debris positively charged
→exported onto H or V plane

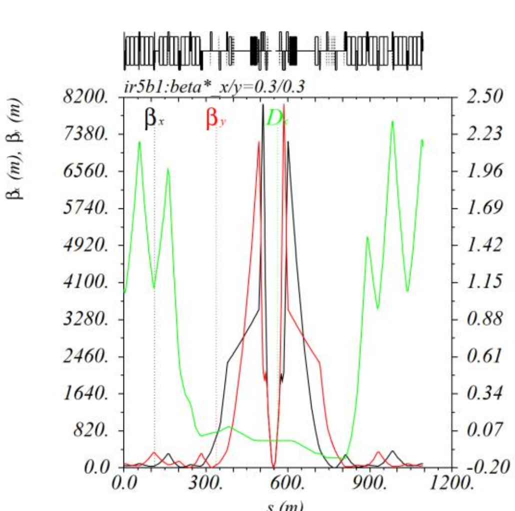
Optics with Reversed Polarity (RP) of the triplet do exist, e.g. with Q4 switched off, and nominal quad polarity restored as of Q5
→Enabling an increase of triplet longevity by 25%

Peak dose after 300 fb^{-1}
(ATLAS X-angle polarity reversal not included).

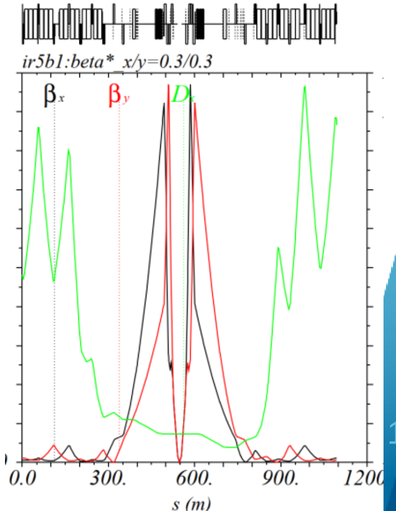


Courtesy of F. Cerutti

Nominal 30 cm
(FDF triplet +Q4 ON)



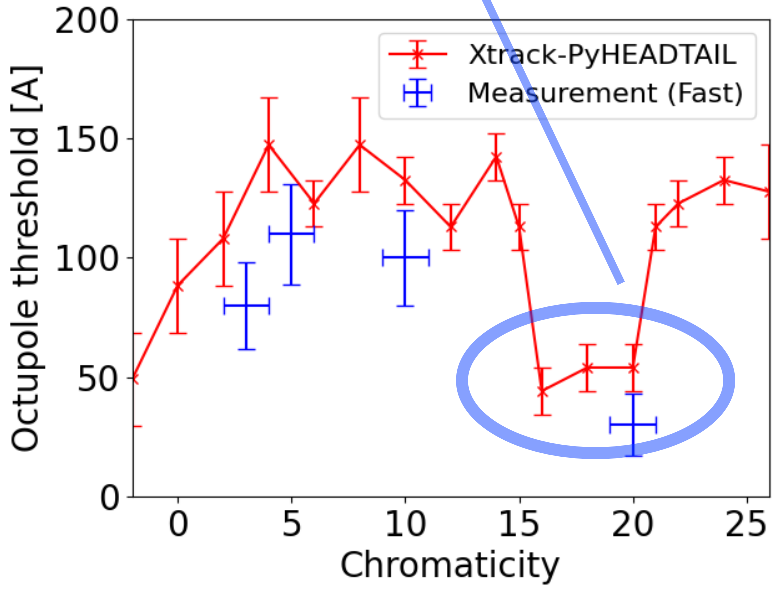
RP 30 cm
(DFD triplet+Q4 OFF)

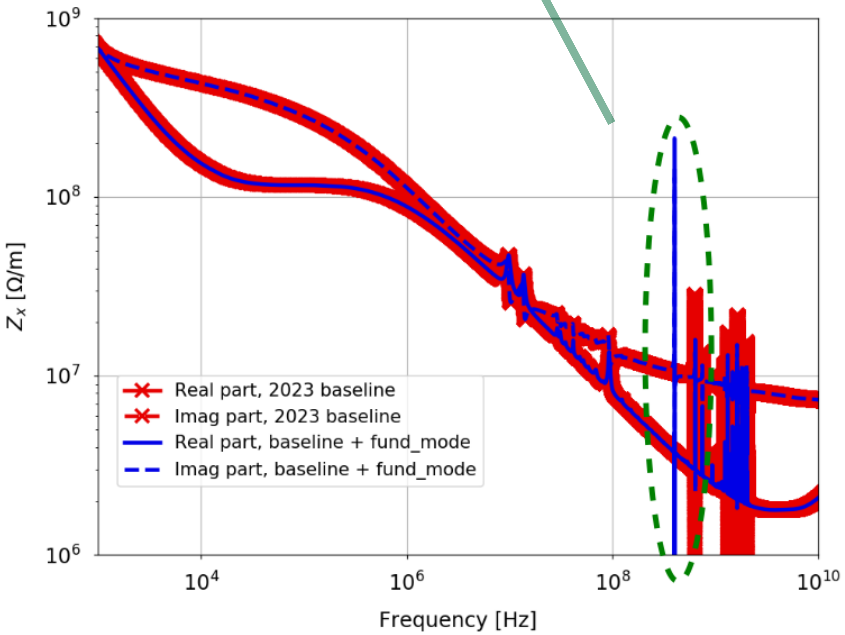


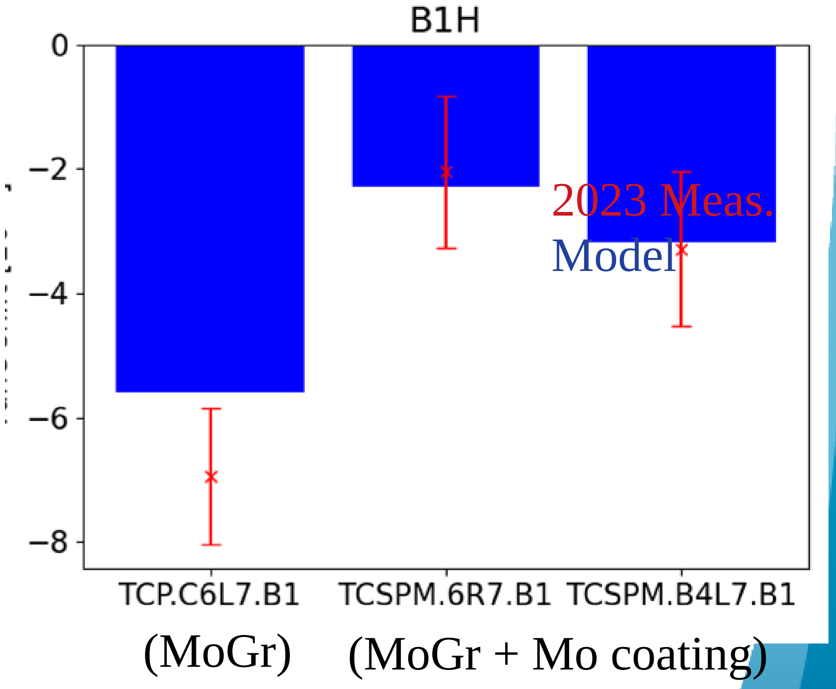
(HL-)LHC impedance & instabilities

- Few mitigation strategies under study for the instability driven by crab cavity fundamental mode:
  - RF feedback with comb filter
  - Flat optics
  - New IR7/IR3 optics
  - Chromaticity

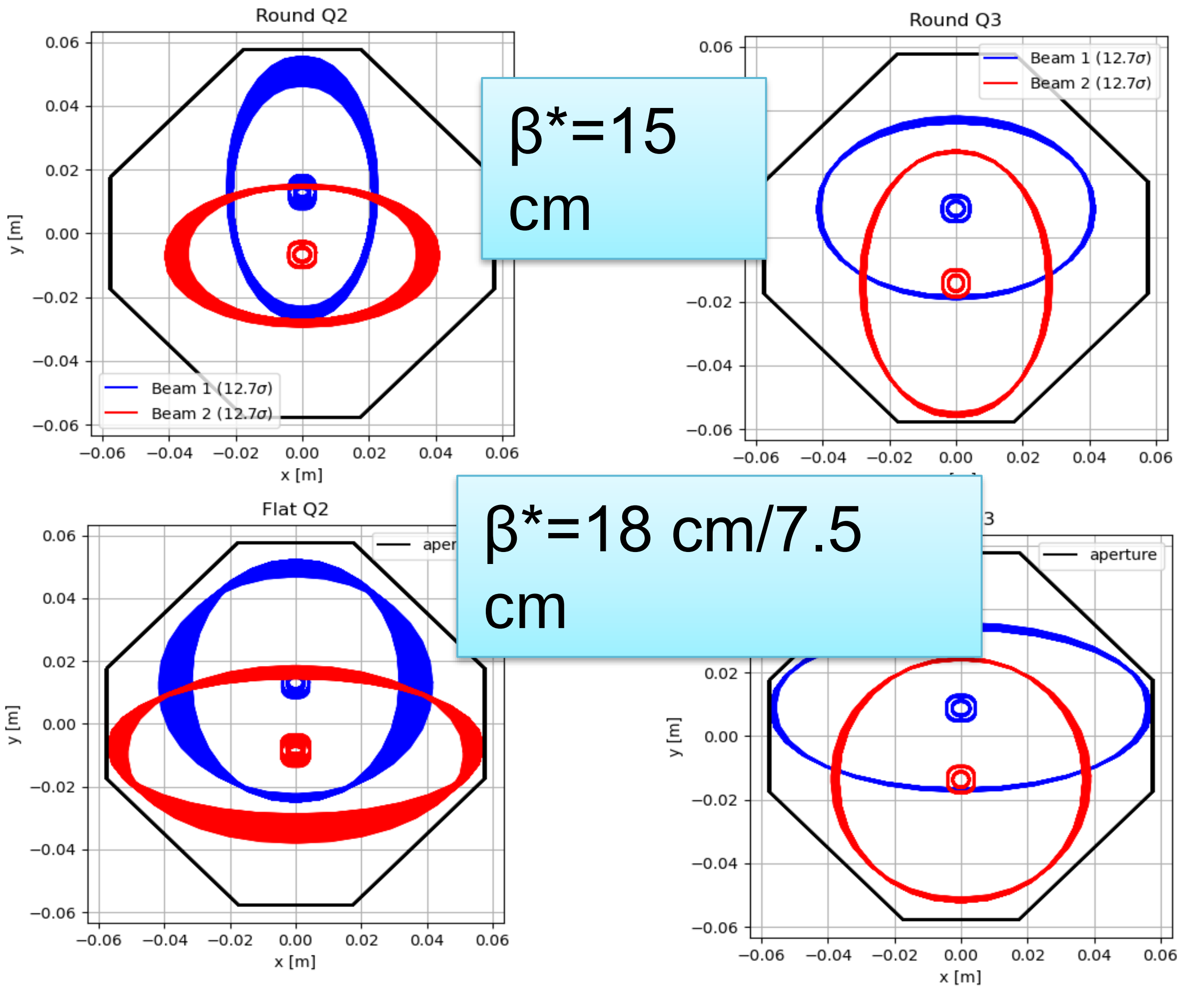
- No degradation of new low impedance collimator after one year of high intensity operation







HL-LHC flat optics



β*=15 cm

β*=18 cm/7.5 cm

$L_{lev.}$= **5×10^{34}cm^{-2}/s**

# of bunches	β*x,y [cm]	L_{int} [fb^{-1}] (Δ [%])	ppb$_{end\ Leveling}$ ppb$_{end}$ [10^{11}]	Pile-up	Fill length [h]
2748	15, 15	250	1.30-1.10	131	7.9
2748	18, 7.5	259 (+3.6)	1.10-0.96	131	8.7
2748	18, 9	257 (+2.8)	1.15-1.0	131	8.4

$L_{lev.}$= **7.5×10^{34}cm^{-2}/s**

# of bunches	β*x,y [cm]	L_{int} [fb^{-1}] (Δ [%])	ppb$_{end\ Leveling}$ ppb$_{end}$ [10^{11}]	Pile-up	Fill length [h]
2748	15, 15	303	1.60-1.2	197	5.2
2748	18,7.5	323 (+6.6)	1.40-1.11	197	5.5
2748	18, 9	318 (+4.9)	1.40-1.13	197	5.4

HiLumi HL-LHC PROJECT

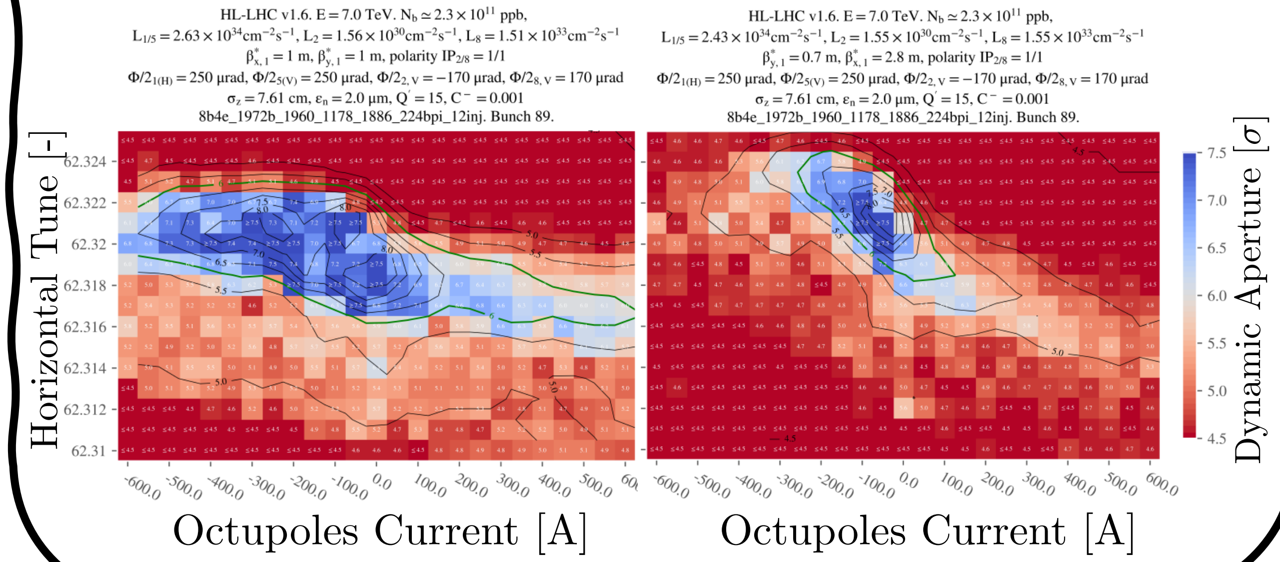
Beam-beam studies for LHC and HL

More on [HL-LHC Satellite Meeting,Vancouver, 2023]

Gain of flexibility helps to optimize involved configurations:

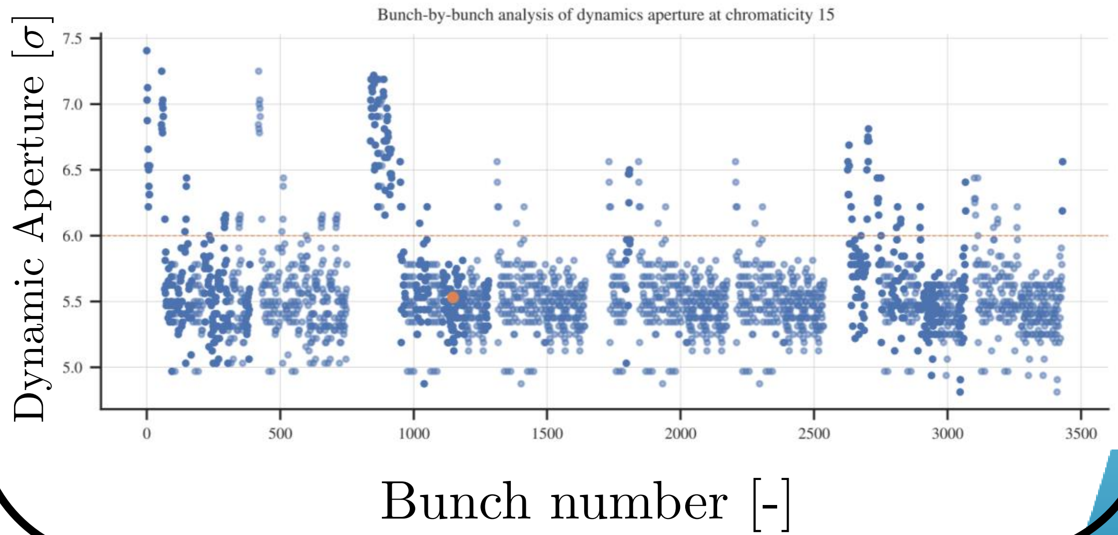
e.g. comparing round/flat optics DA octupoles vs. tune in HL-LHC in ADJUST with 8b4e filling scheme

ROUND OPTICS **FLAT OPTICS**



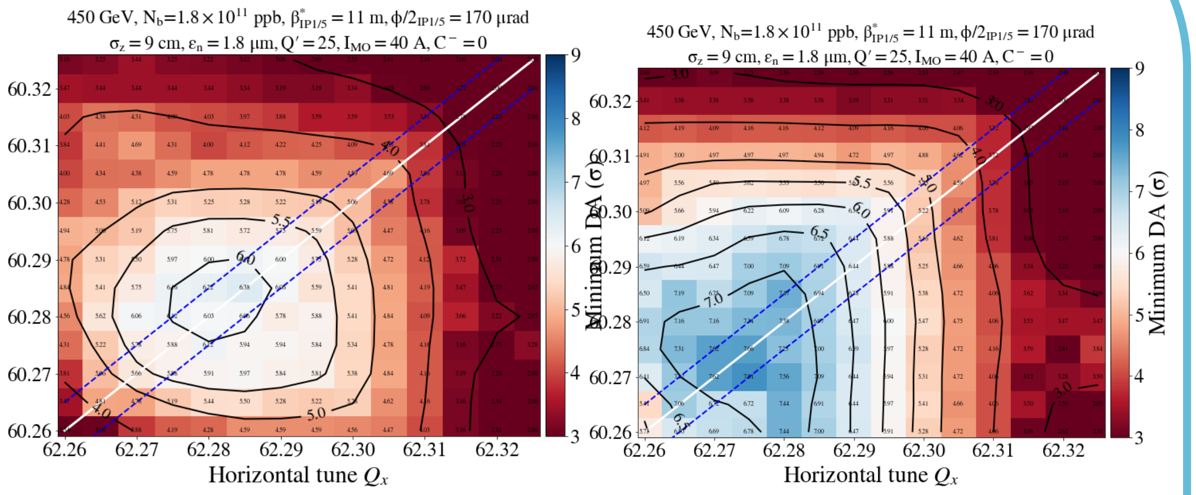
Improving toolbox with more advanced predictions:

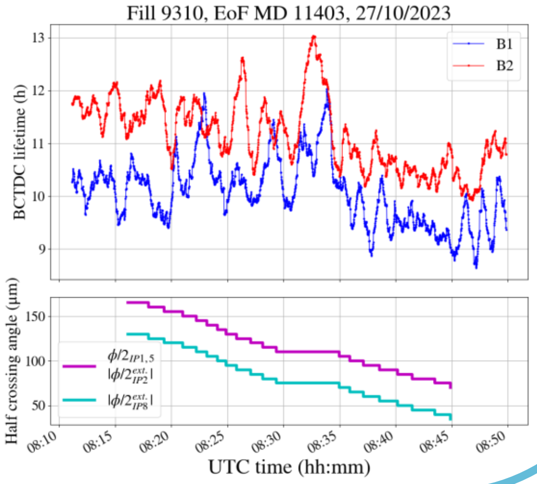
e.g. studies of bunch-by-bunch DA
→ important for hybrid filling schemes



Beam-beam studies for LHC and HL

DA improved with new injection phase

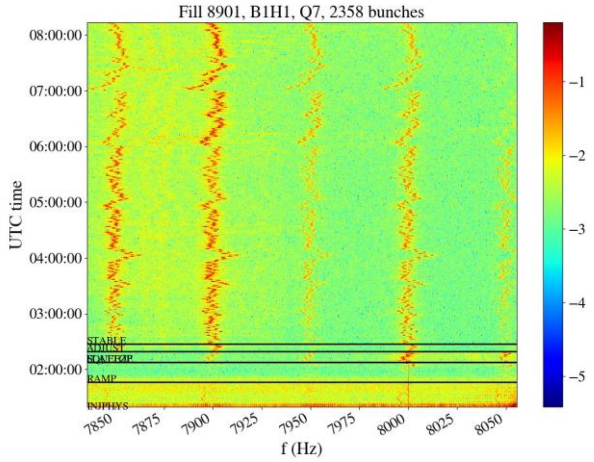


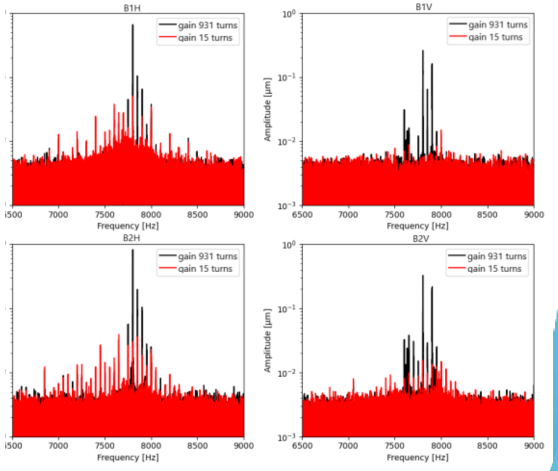


Identifying beam-beam limit during ion operation

Noise studies

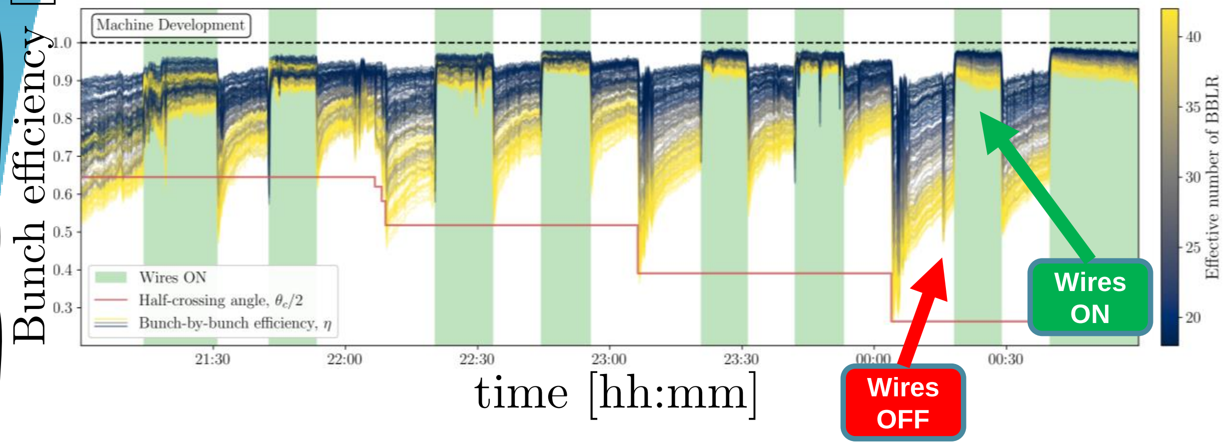
Systematic follow-up of 8 kHz cluster and 8 kHz MD



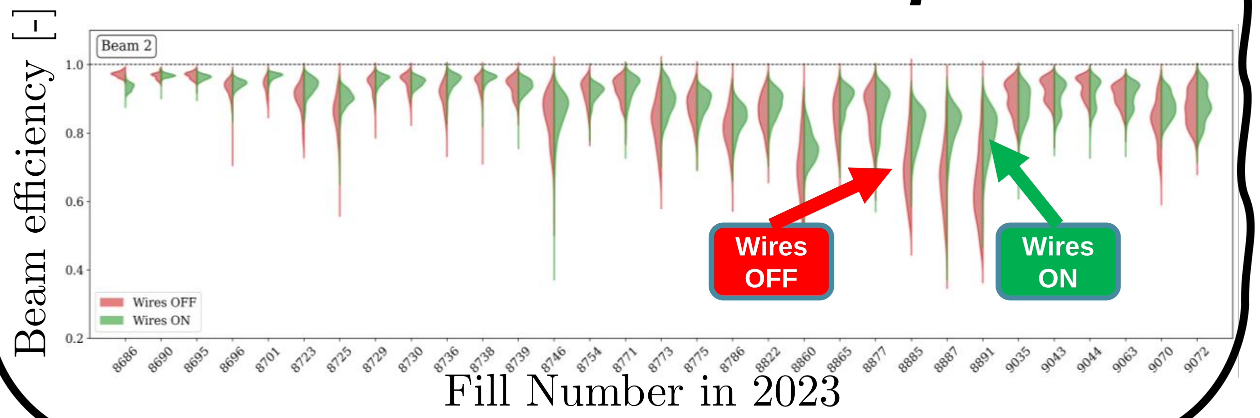


Beam-beam compensation using DC wires

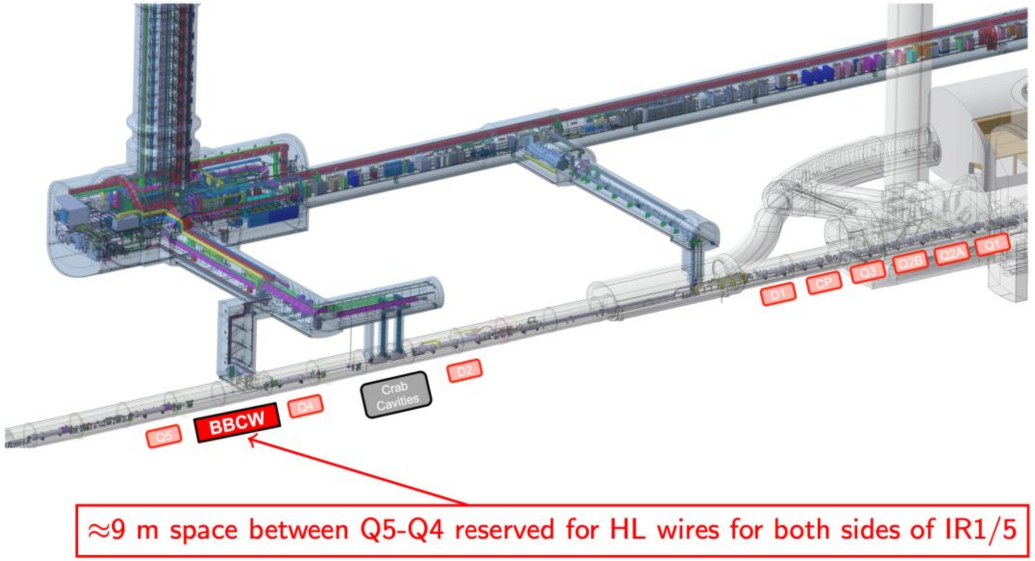
From MD…

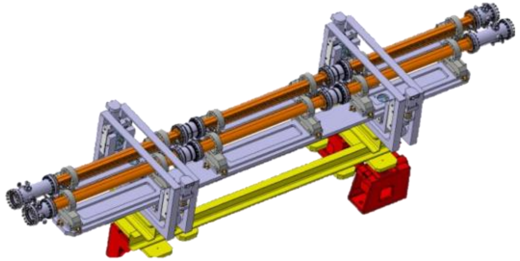


…to 2023 operation



From Run 3 to Run 4

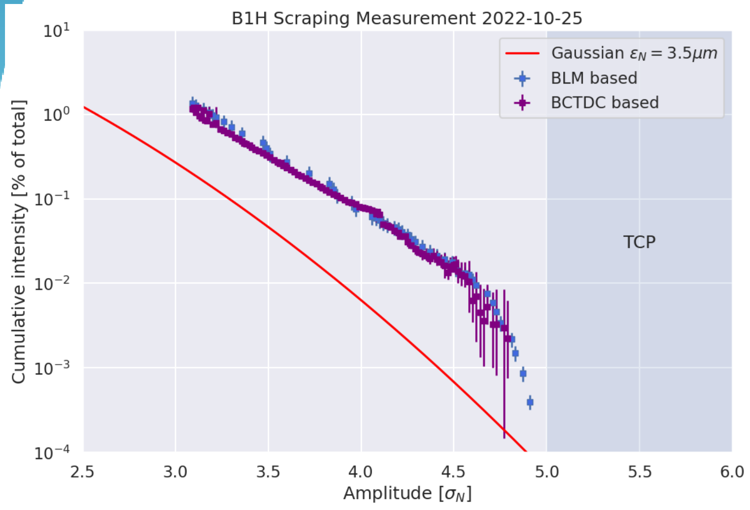




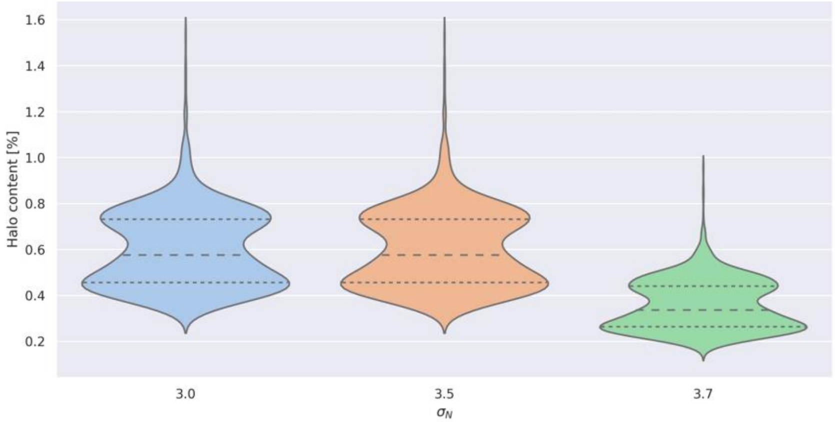
First Run 4 Design

More on [HL-LHC Satellite Meeting,Vancouver, 2023]

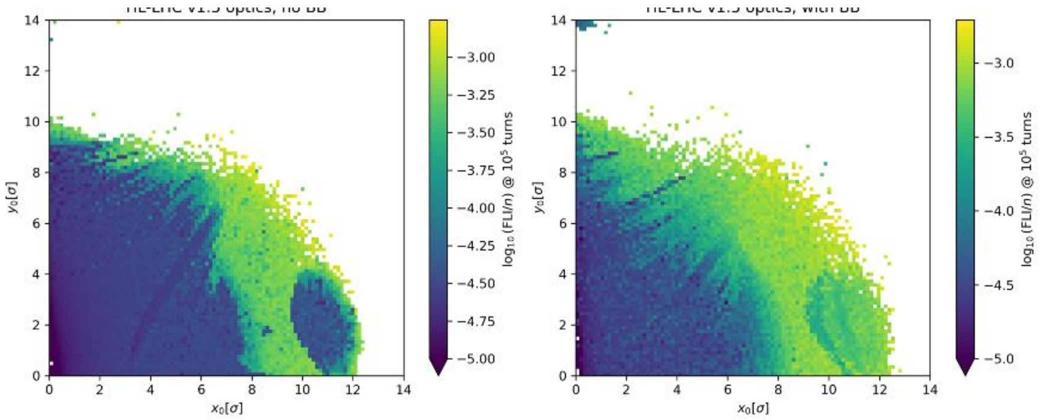
Advanced beam dynamics studies: halos in LHC

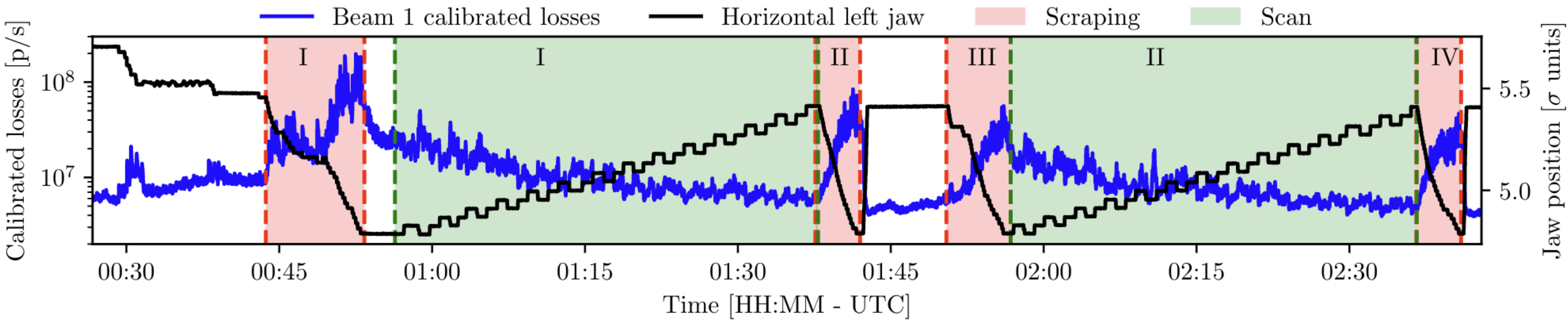


Spread of halo content across bunches



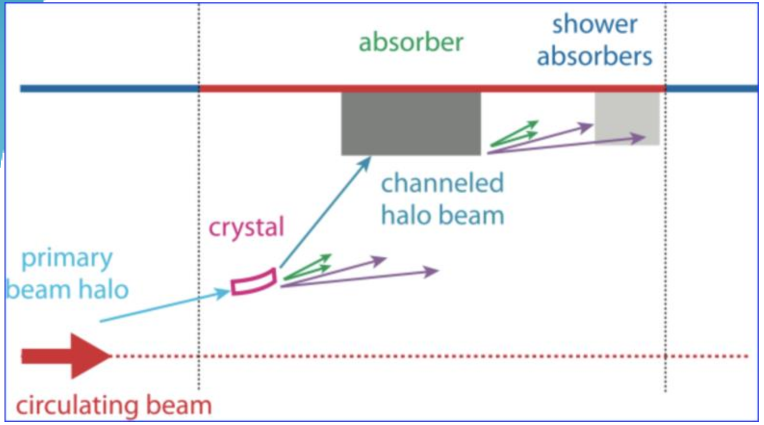
- Continued effort to understand potential halo limitations to LHC and HL-LHC performance
  - In 2023, severely jeopardized by MD available time with proton beam.
- **Characterization bunch-by-bunch could be achieved**
- Improved understanding of the effect from long-range wires
- Investigation on novel chaos indicators tools for accelerator physics
  - Initial GPU studies for Xsuite



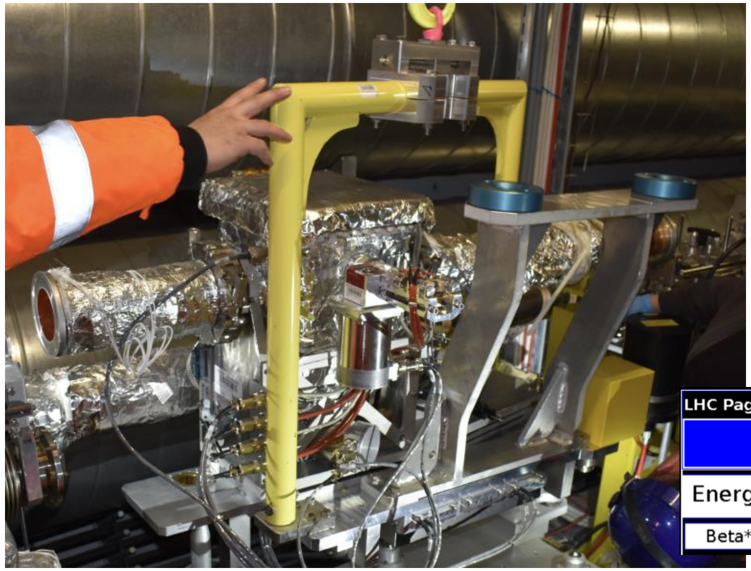


First deployment of crystal collimation

Crystal collimation scheme (illustrative)

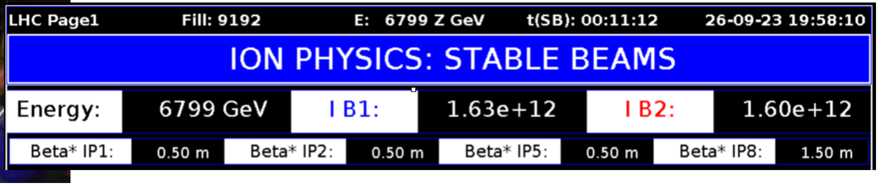


Built as a part of the HL-LHC upgrade (WP5) and installed in LS2 + YETS2022

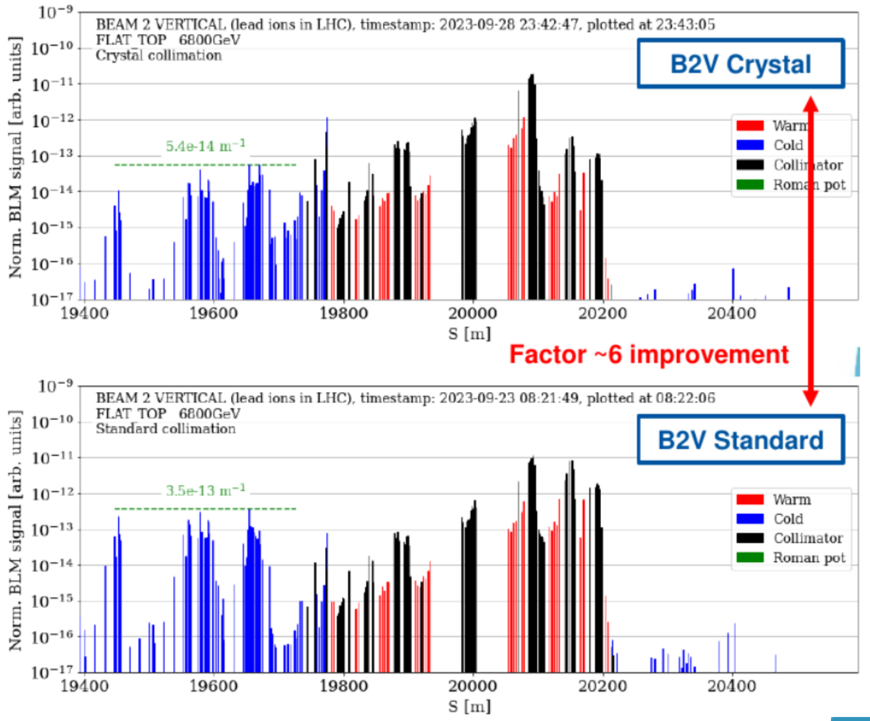


4mm-long LHC crystal

First ion beams with crystals on Sep. 23rd.



- First operational deployment of crystal collimation scheme
  - Completed upgrade of IR7 system, 4 new crystals (after some hiccups)
  - Special run at high-β* also profited for low backgrounds at β* = 3km / 6km!
- **Excellent cleaning performance achieved with lead beams at 6.8 Z TeV !**
  - Standard collimation **improved by more than a factor 5**
- Some issues with **stability of the optimal angular position** to be addressed for future lead ion runs

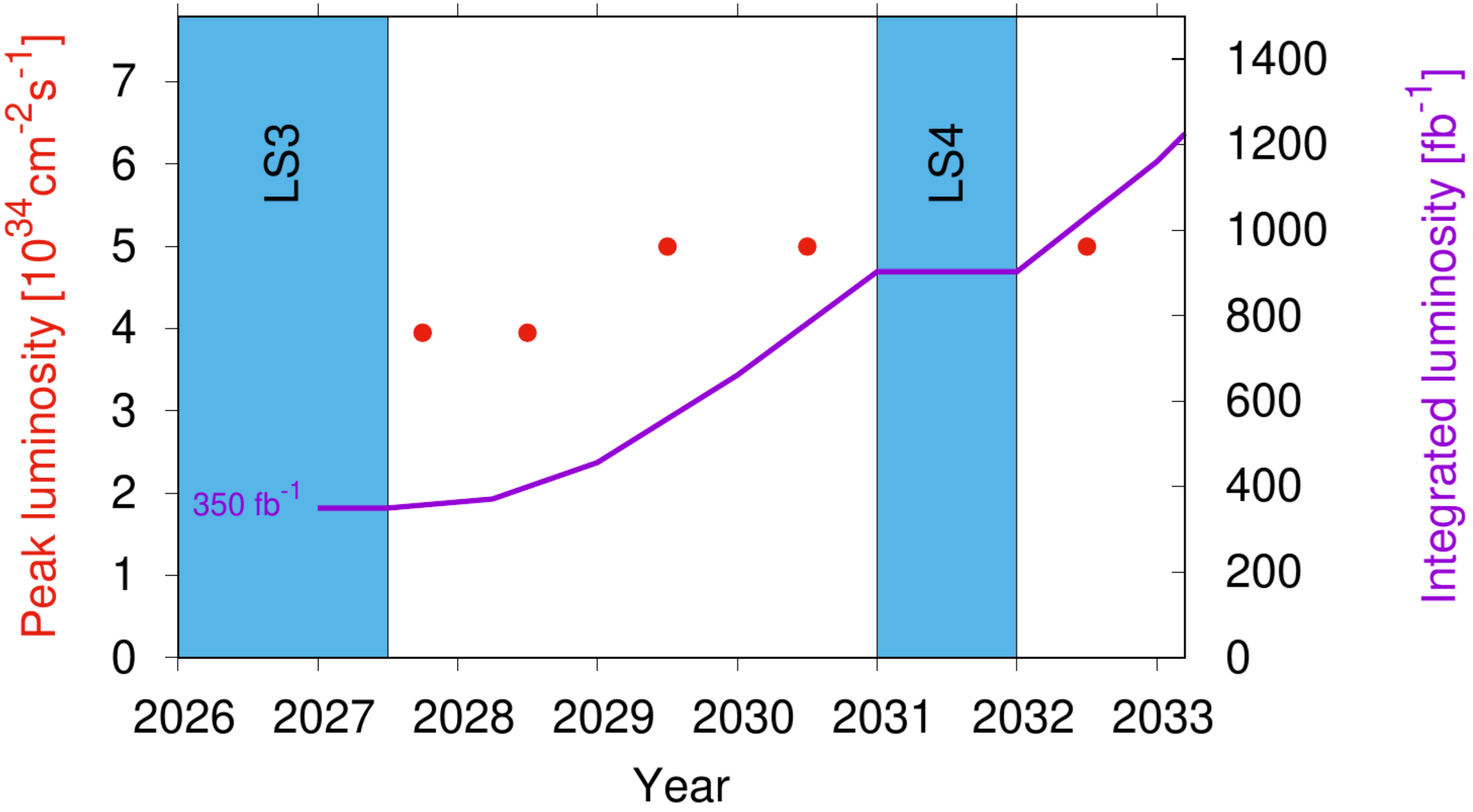


LIU beams arrived in 2023!!!! *(almost)*

See H. Bartosik’s slides in 216th HL WP2 meeting

year	Intensity at FT [p/b]	# of bunches	Batch spacing [ns]	Bunch length [ns]	Beam type	Date
2023	2.2e11	4 x 72	200	1.6	Standard	13.06.
2023	2.0e11	2 x 56	250	1.6	8b4e	05.04.
2023	1.8e11	56 + 5 x 36	200	1.6	hybrid	19.05.

Latest Run 4 baseline   CERN-ACC-2022-0001



Run length of 3.5 years, β^*=20 cm, with HEL, no MS10, primary coll. at 8.5σ, integrated luminosity: 550 fb^{-1} = **21 + 85 + 205 + 242 fb^{-1}** (3% below HL target: 250)

Optics options end of leveling, Nominal scenario

For all cases: $L_{lev.}$= **5×10^{34} cm^{-2}/s**, crossing angle = 500 μm, crab cavity noise without feedback, Cryo step at 2.5×10^{34}cm^{-2}/s for 10min and linear ramp*, IBS emittance growth and SR damping, 160 days and 50% efficiency.

# of bunches	$\beta^*_{x,y}$ [cm]	L_{int} [fb^{-1}] (Δ [%])	ppb_{endLev} ppb_{end} [10^{11}]	Pile-up	Fill length [h]
2748	15, 15	250	1.30-1.10	131	7.9
2748	18, 7.5	259 (+3.6)	1.10-0.96	131	8.7
2748	18, 9	257 (+2.8)	1.15-1.0	131	8.4

Flat optics improves the performance of the nominal scenario by **2.8%** or **3.6%** for β^*=18,9cm and β^*=18,7.5cm respectively.

*Cryo step (lumi & length) is under review

Optics options end of leveling, Ultimate

For all cases: $L_{lev.}$= **7.5×10^{34}cm^{-2}/s** (+same points as in previous slide)

# of bunches	**$\beta^*_{x,y}$ [cm]**	**L_{int} [fb^{-1}] (Δ [%])**	**ppb_{endLev} ppb_{end} [10^{11}]**	**Pile-up**	**Fill length [h]**
2748	15, 15	303	1.60-1.2	197	5.2
2748	18,7.5	323 (+6.6)	1.40-1.11	197	5.5
2748	18, 9	318 (+4.9)	1.40-1.13	197	5.4

Flat optics improves the performance of the Ultimate scenario by **4.9%** or **6.6%** for β^*=18,9cm and β^*=18,7.5cm, respectively.

Towards an update of Run 4 scenario (protons)

- e-cloud is likely to limit the number of bunches in Run 4 ⟶ 8b+4e or hybrid scheme needed, plus flat optics (~ +5% luminosity, and help with crab cavity impedance):

# of bunches	PU	Integrated Lumi [1/fb] (Δ[%])	Feasibility from		
			e-cloud	Beam Dynamics	Experiments
2748 (25ns)	132	257 (0%)	No	Yes	Yes
	200	318 (+23%)	No	To be studied	Yes
2200 (hybrid)	140	217 (-16%)	Maybe	Yes	Yes
	200	257 (0%)	Maybe	Studies ongoing	Yes
1972 (8b+4e)	140	194 (-24%)	Yes	Yes	Yes
	200	230 (-10%)	Yes	Yes for DA	Yes
1972 2.5×10^{11}	200	253 (-1%)	Exceeding LIU and HL-LHC goals, but worth investigating if possible		

Assumptions:
$\beta^*_{x,y}$ = 18, 9 cm
Half crossing angle = 250 μrad
160 days,
eff.=50%

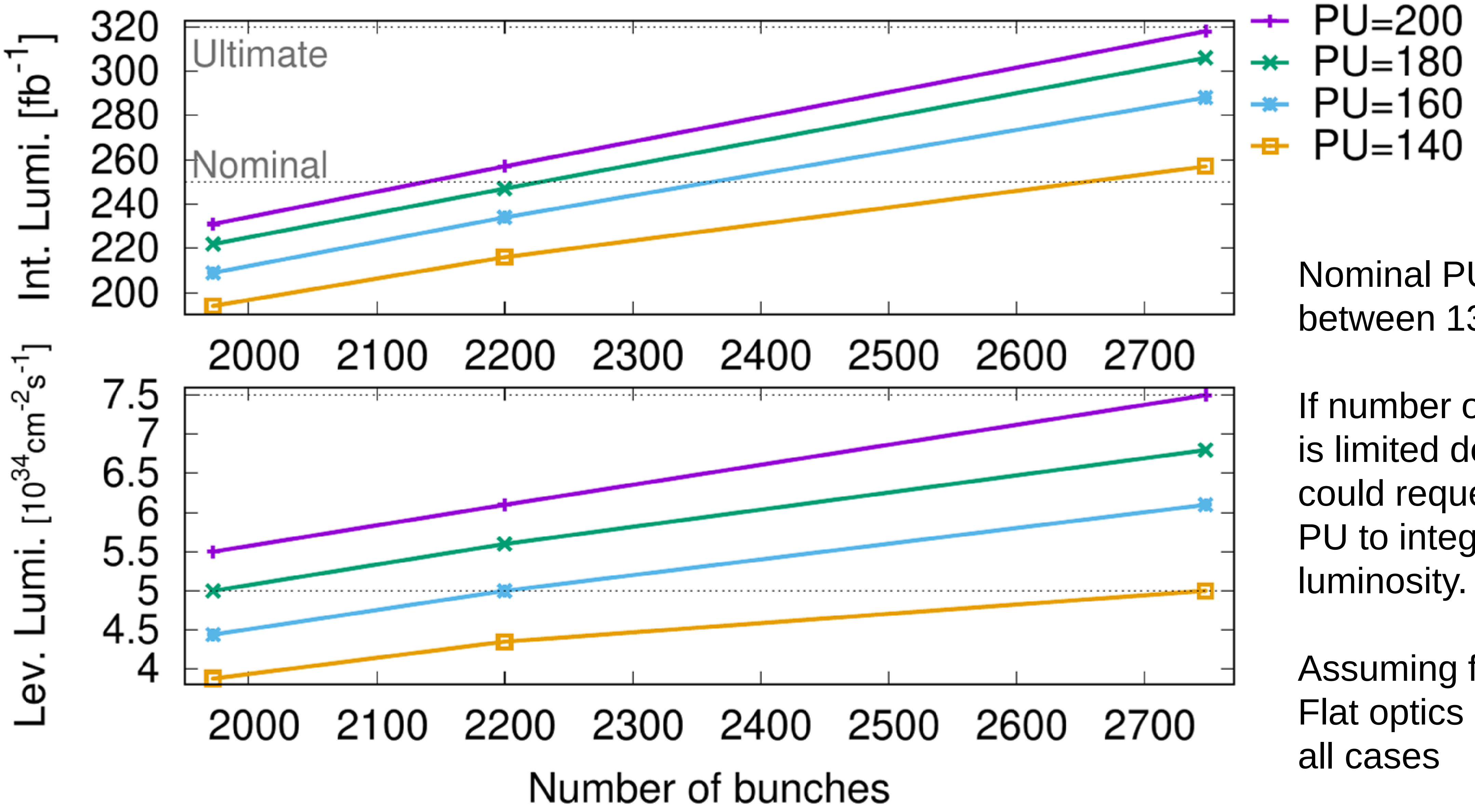
Preliminary input from various teams rather positive, but many studies still needed.

***R. De Maria**, LHC Chamonix workshop, 24/01/2023 (+ input from experiments & WP2)*

Filling schemes for Run 4 under consideration

1. **2760 bunches**: Nominal, but not fully guaranteed even by fixing 100 half cells
2. **2X00 bunches**: Alternative in case of further degradation of SEY (under study).
3. **1972 bunches**: Pure 8b4e, very robust.

Integrated and leveled luminosity versus # of bunches & PU

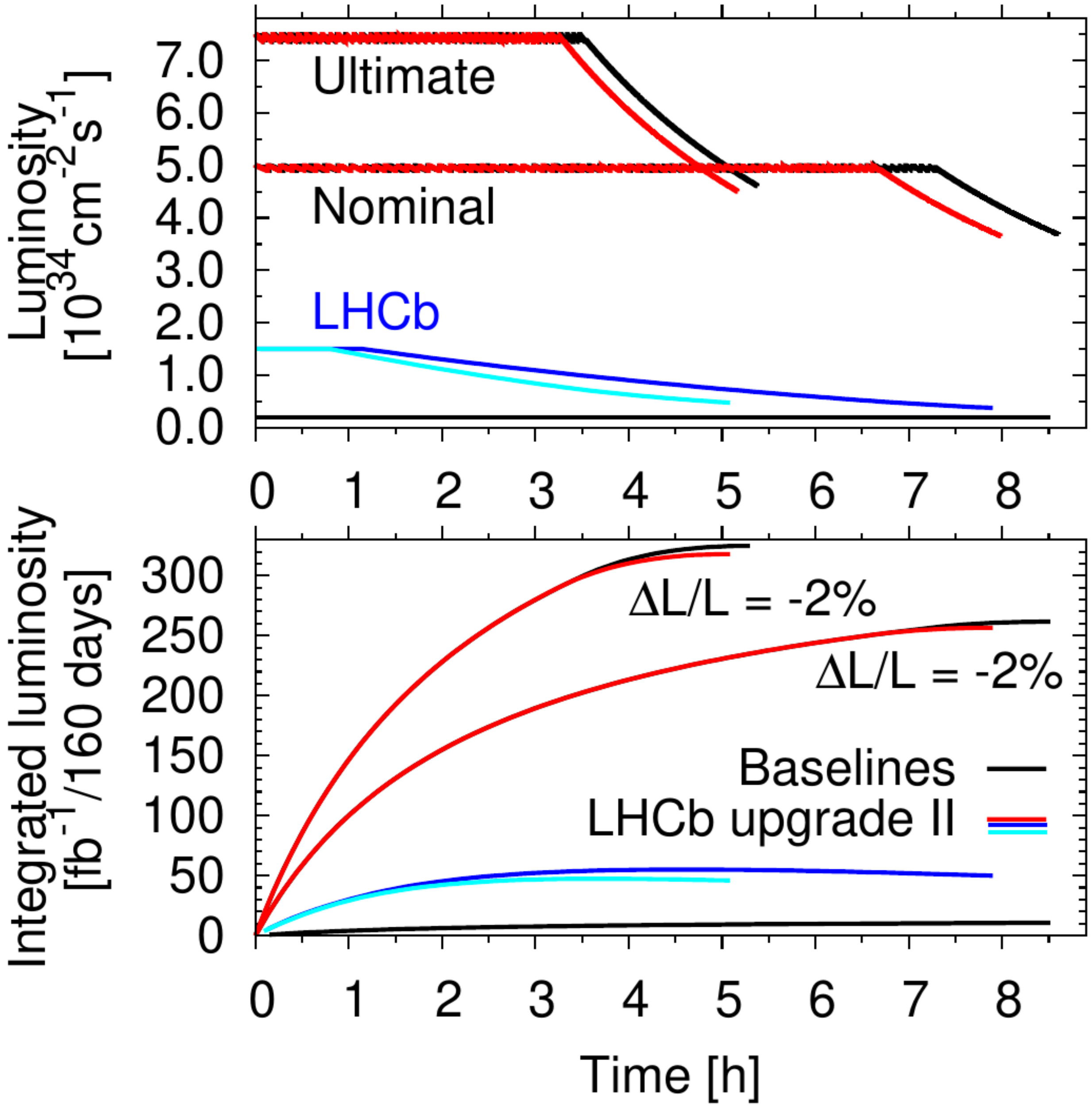


Nominal PU is between 131-140.

If number of bunches is limited detectors could request larger PU to integrate more luminosity.

Assuming for now Flat optics 18,9cm for all cases

LHCb upgrade II (in Run 5)



LHCb upgrade II, L lev = 1.5×10^{34} cm^{-2} s^{-1} would reduce ATLAS/CMS integrated lu-minosity by 2% for both Nominal and Ultimate

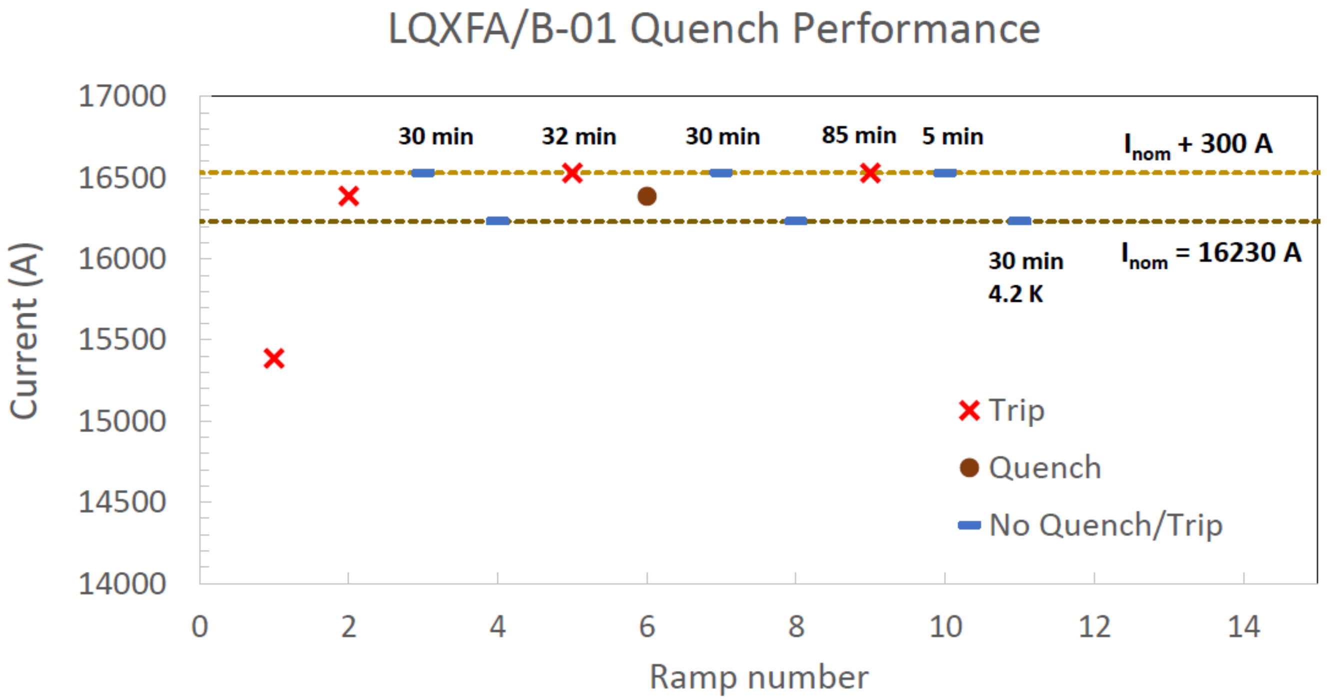
Reduced lifetime from increased beam-beam not included here

→**Need to develop a fully new operational scenario with LHCb II.**

Increased burn-off in IP8 casues bunch-by-bunch variations, under study.

Collaborations: MQXFA - CA01

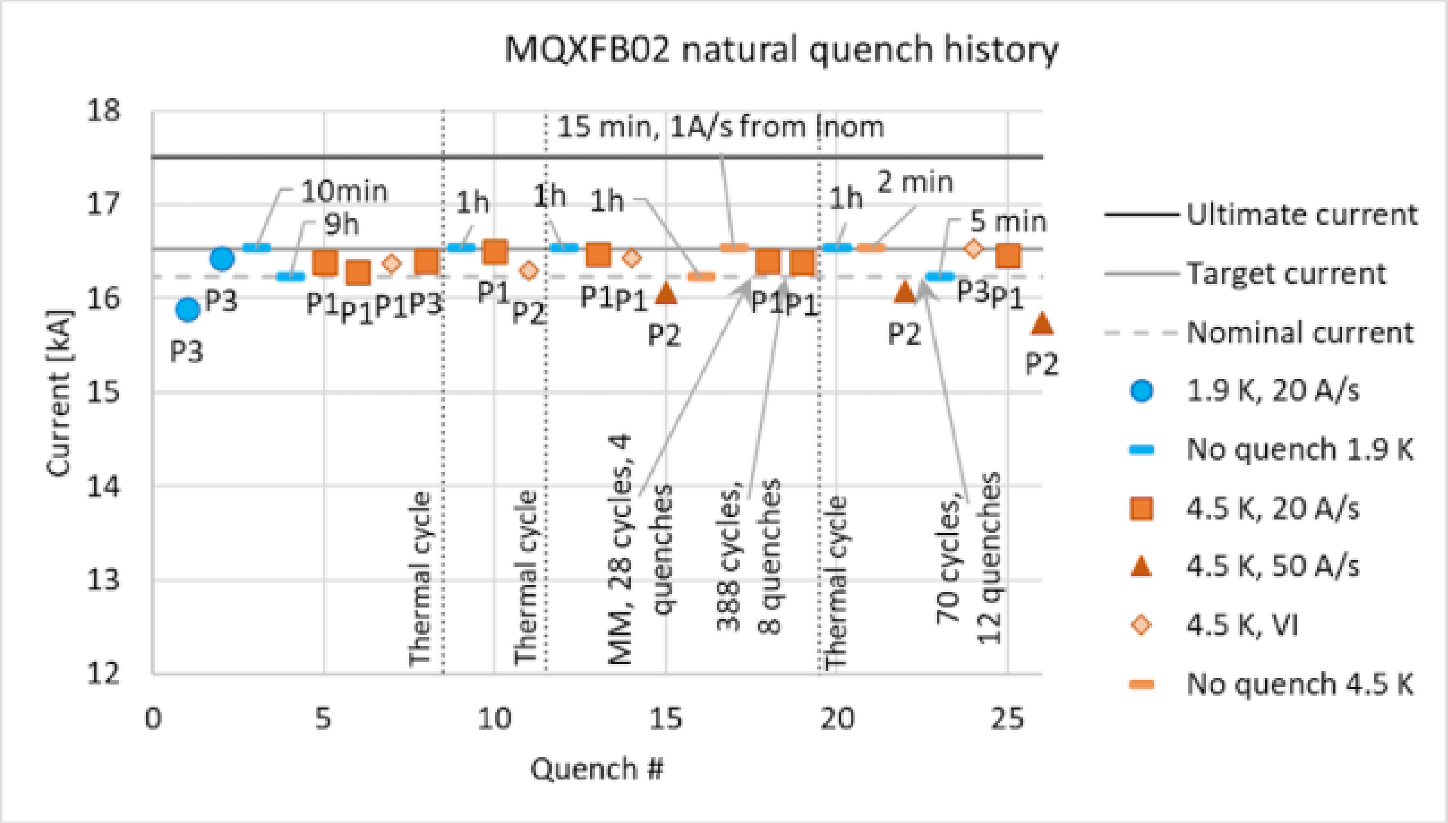
- First cold mass reaching performance – no retraining after thermal cycle (not shown in the plot)
- Welded before Welding Parameter Specification approval – derogation with CERN Safety Unit
- Issues (2) with QH and V-tap – acceptable for IT-string (EDMS 2769128) (EDMS 2883868) ➔ will require repair later
- Issue with leaks tightness test – Instrumentation (EDMS 2905753)



Quench performance of LQXFA01 (Test eng. B. Yahia, WPE: G. Ambrosio, S. Feher, et al.)

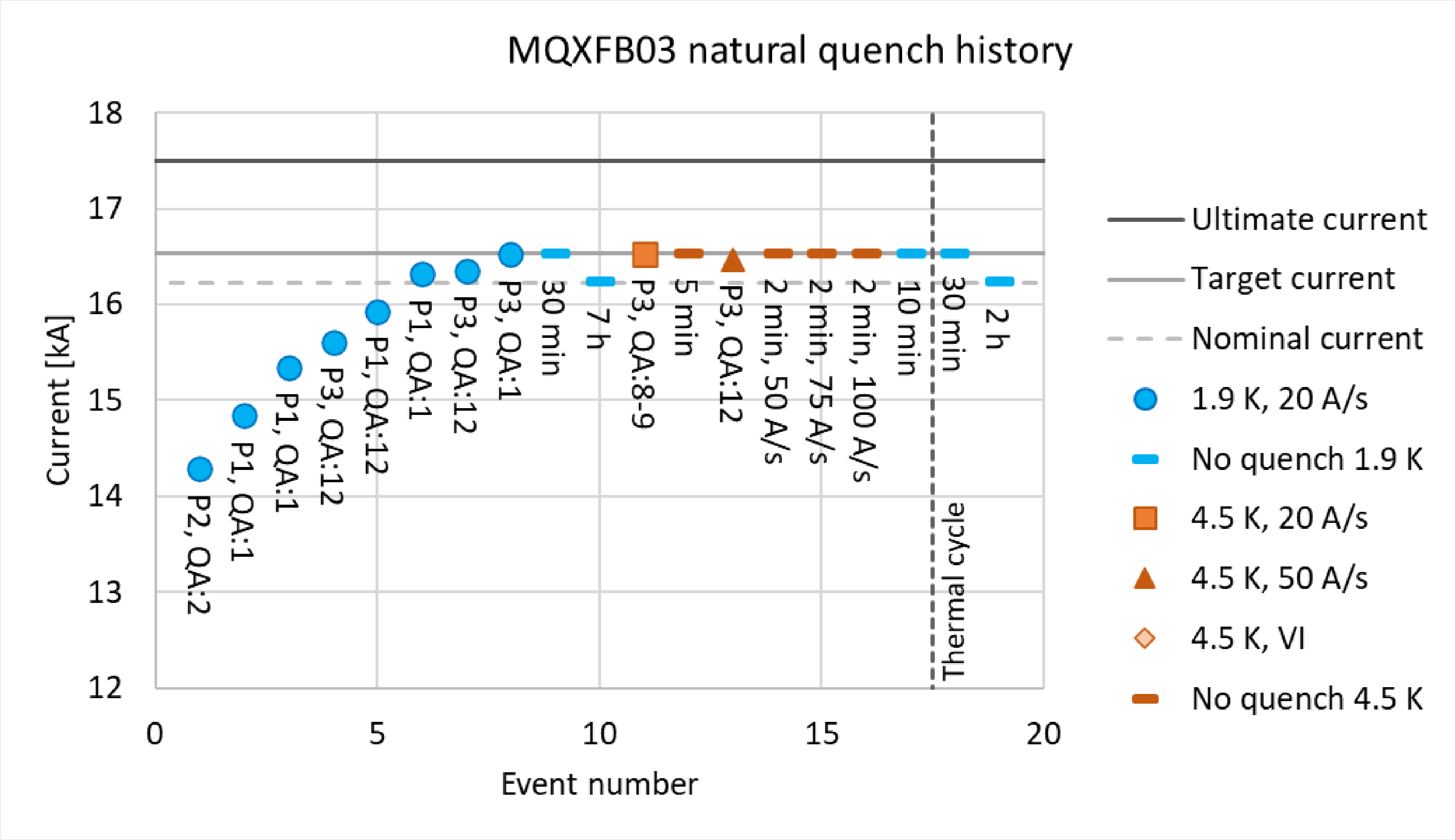
Recent Milestones

- MQXFB02 reached nominal + 300A @ 1.9K but limited @ 4.5K

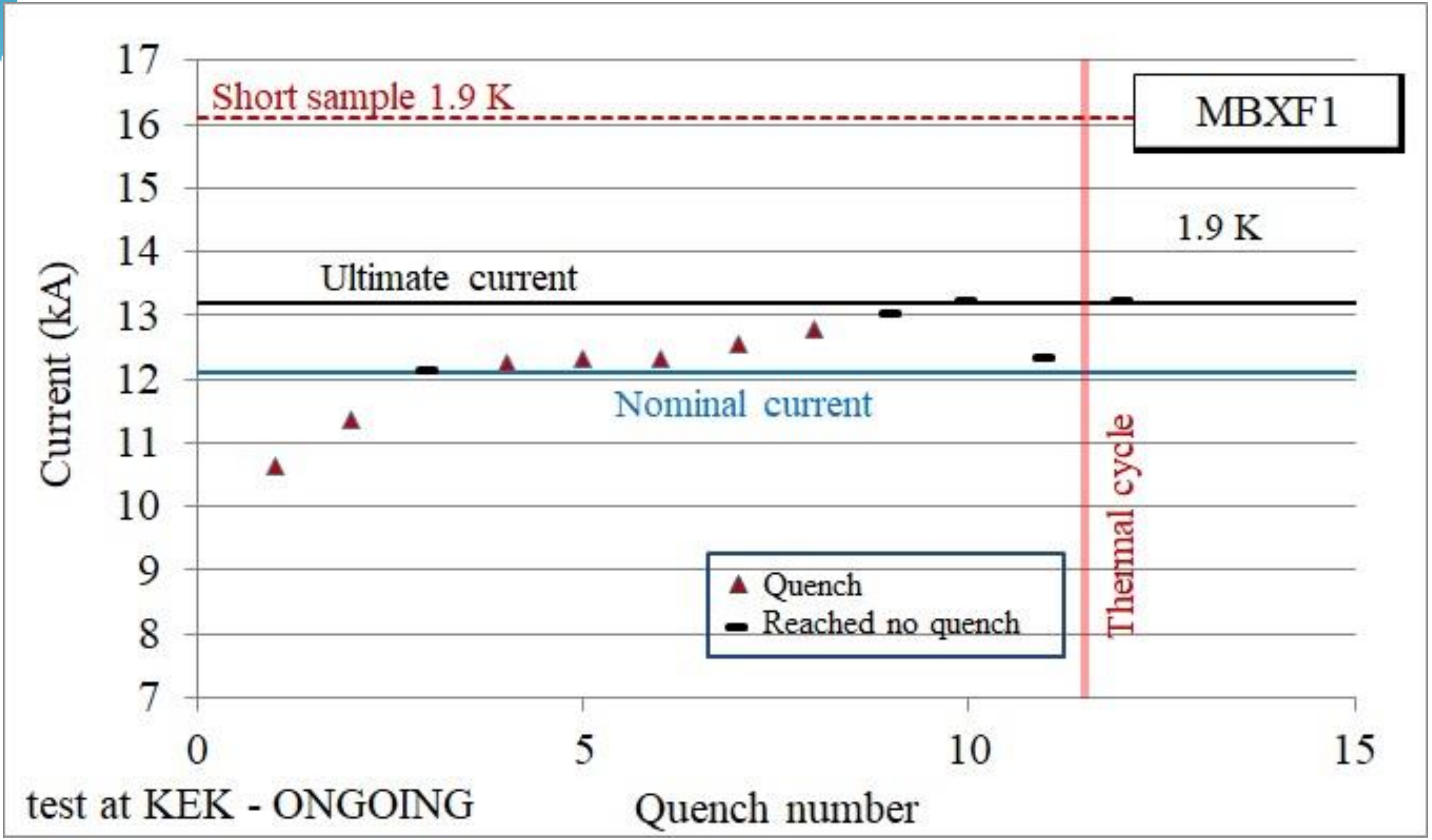


Status MQXFB – Q2: Cryo-Module Assembly at CERN - 03

- MQXFBP3 test at CERN
  - Nominal +300A @ 1.9K and TC ✓
- MQXFB02 test at CERN
  - nominal +300A @ 1.9K and
- Limitation @ 4.5K, but temp margins compatible with ulti operation energy @ 1.9K
- Both P3 and B02 went throu thermal cycles without degra
- MQXFB03 reached nominal 4.5K!
- On Track for Series Product Nb_3Sn HL-LHC Triplet Quac Magnets



D1 Series Production Validation @ KEK



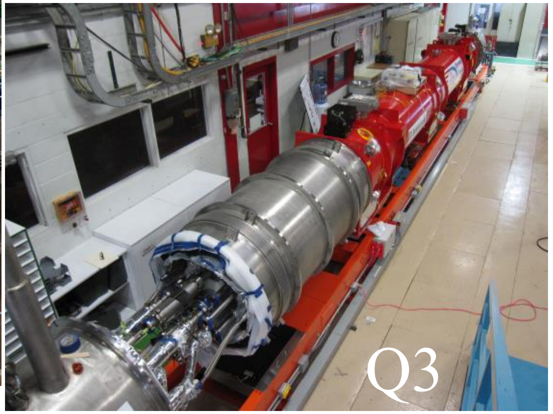
Successful upgrade of the KEK test station ✓

Production of MQXF5 Ongoing @ Hitachi

Half of the coil production Is completed

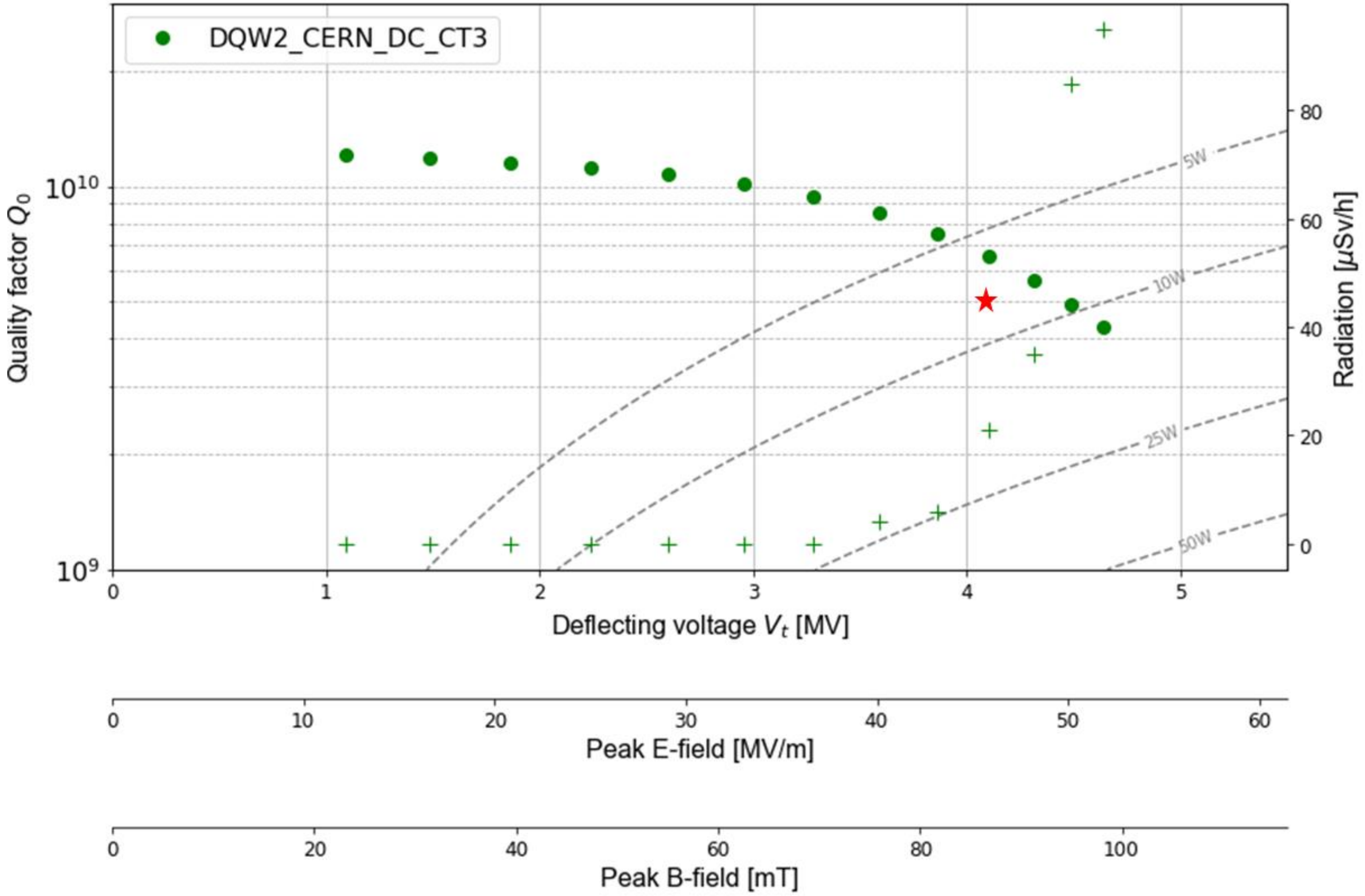
THE STRING INGREDIENTS ARE GETTING READY

- Dates given in schedule change request, [EDMS 2898265]
  - Q1: magnet cold mass being welded → Available in September 2024
  - Q2a: MQXFBP2b completed → On SM18 Testbench → Available April 2024
  - Q2b: MQXFBP3b completed → Available for Testbench Jan. → April 2024
  - Q3: magnet being prepared for shipment to CERN → Available July 2024
  - CP cryostating Phase II ongoing → Available August 2024
  - D1 cryostating completed → Available for Testbench → Available March 2024



Recent Milestones

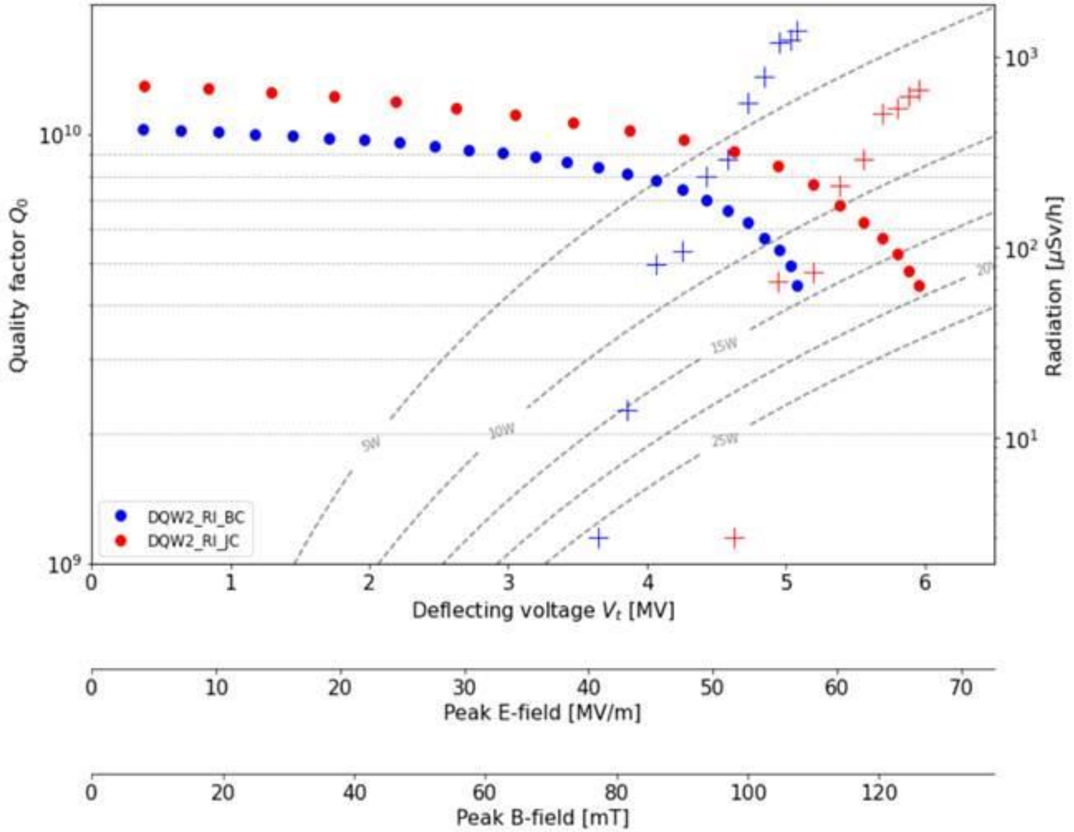
- February 2023: He Vessel welding for 1st Series DQW Crab Cavity



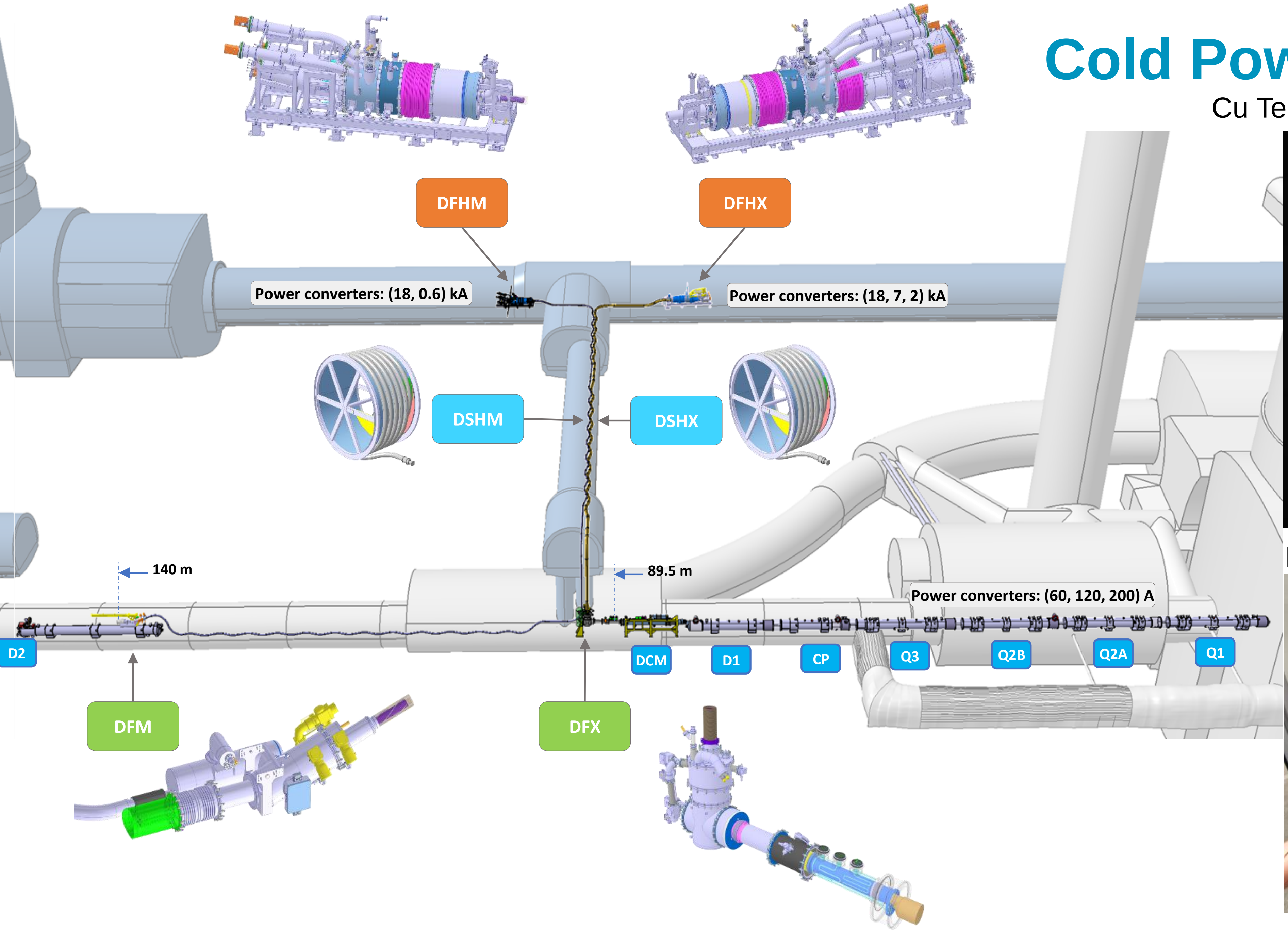
3rd test beyond the specification with 100 μm additional chemistry of HOMs & 120^{0}deg vacuum bake

Industrial DQW Series (RI)

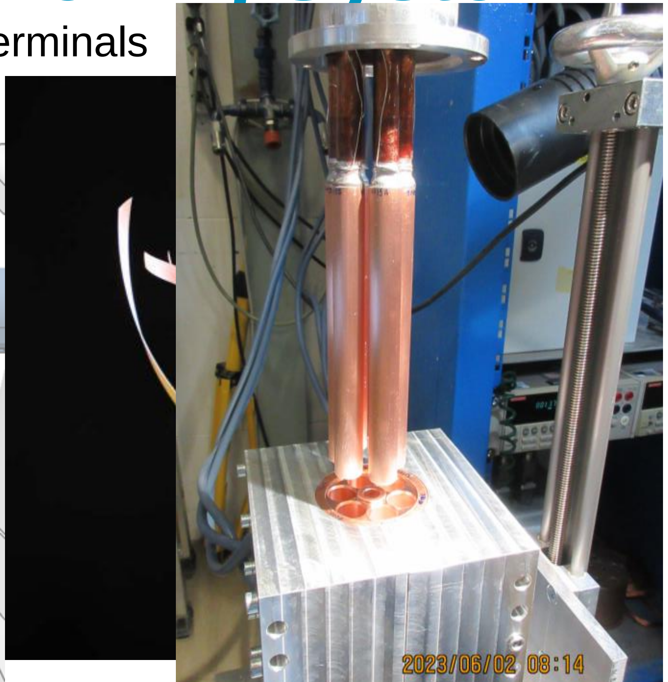
- 1st pre-series jacketed cavity with excellent results, metrology to be finalized before acceptance
- 2nd cavity in metrology and cold tests soon



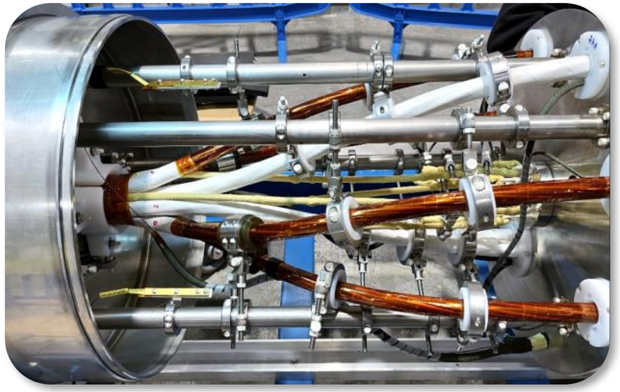
Cold Powering System

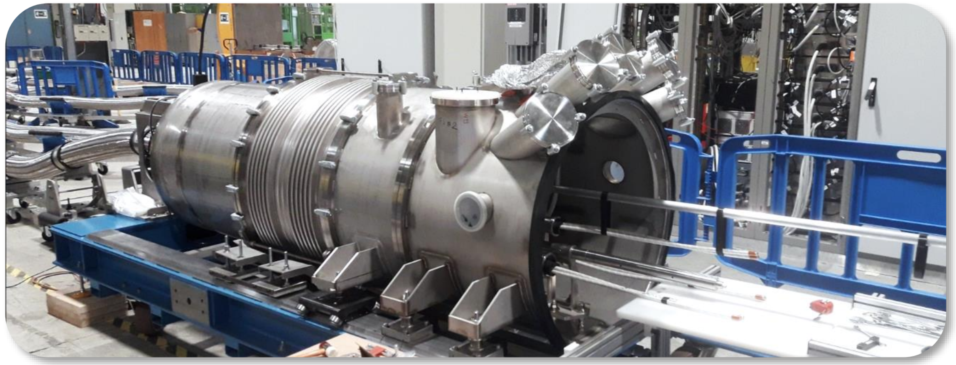


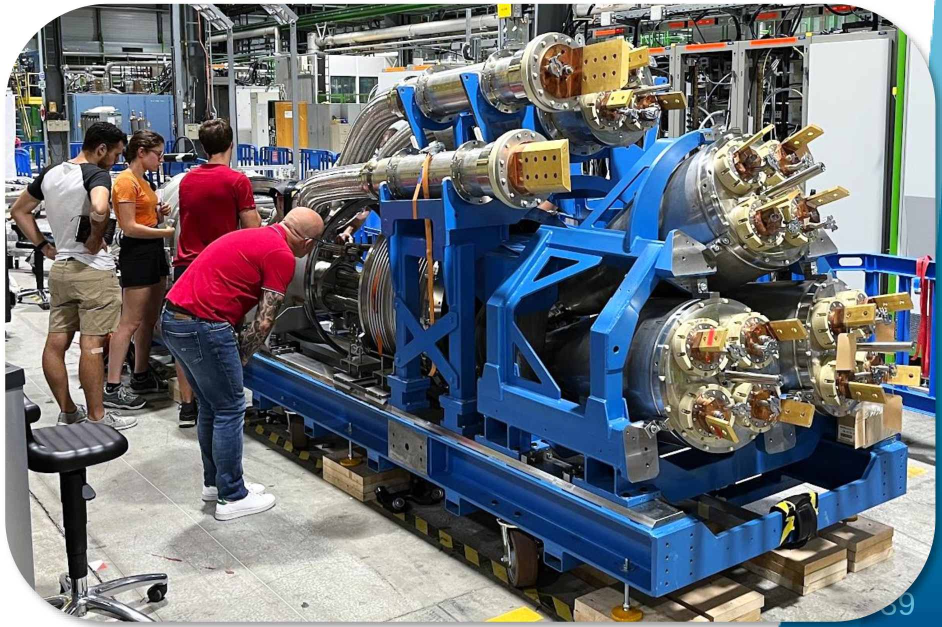
Cu Terminals



REBCO Cable



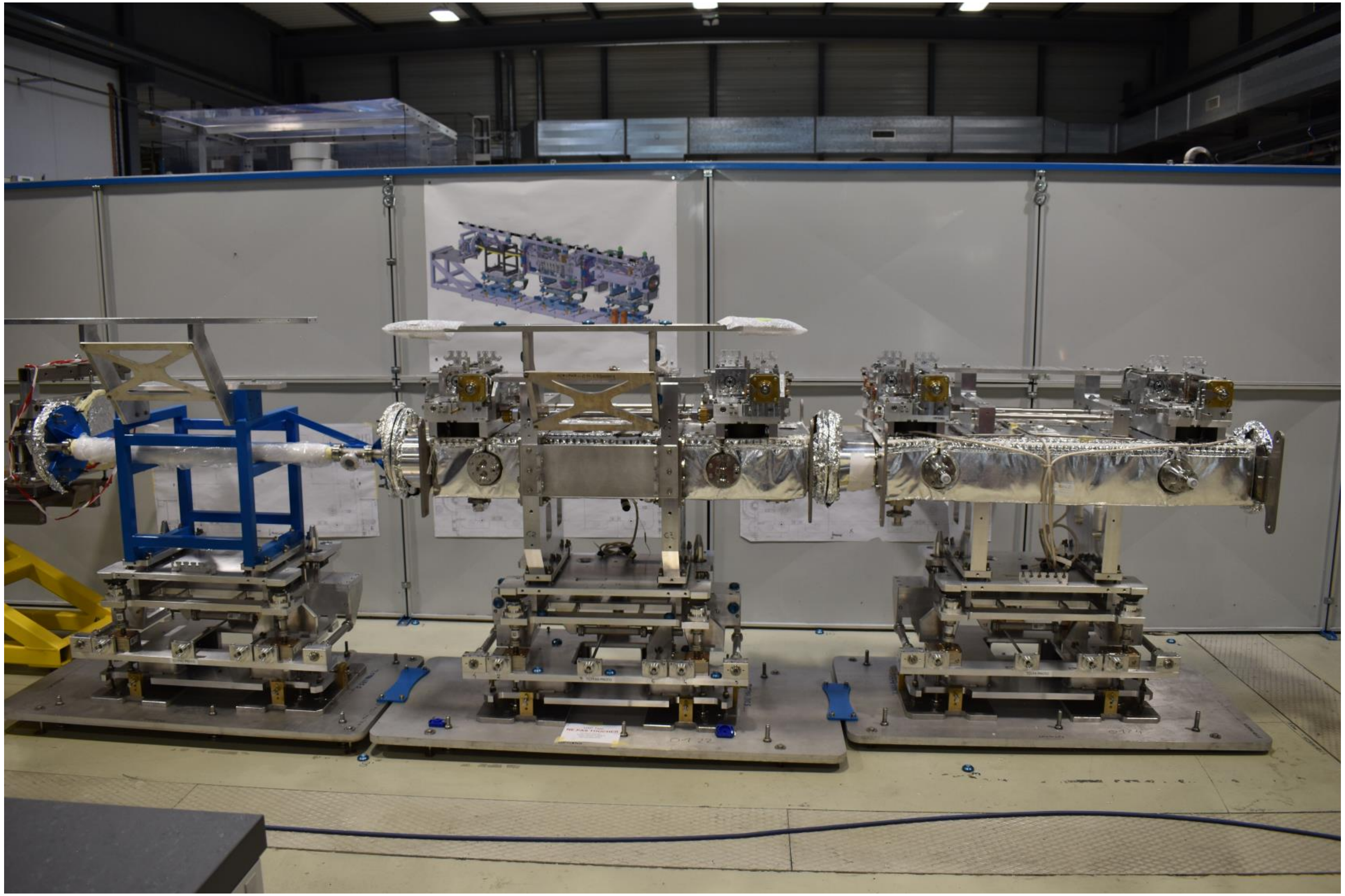




SC-Link-DFHX assembly in pictures

FRAS Test Stand and Validation

IR Collimators and String Assembly



IR1/5 underground civil engineering completed in 2022

Construction Finished End 2022

work was conducted during LS2 ➔ vibration impact

Completion of Surface buildings in 2023

Work Ended Spring 2023

20th January 2023
Celebration Ceremony: Point 5

in Pt1 and Pt5

ny CERN teams (EN-ACE, SCE, HSE WP17,...)

/02/2023

30/06/2023

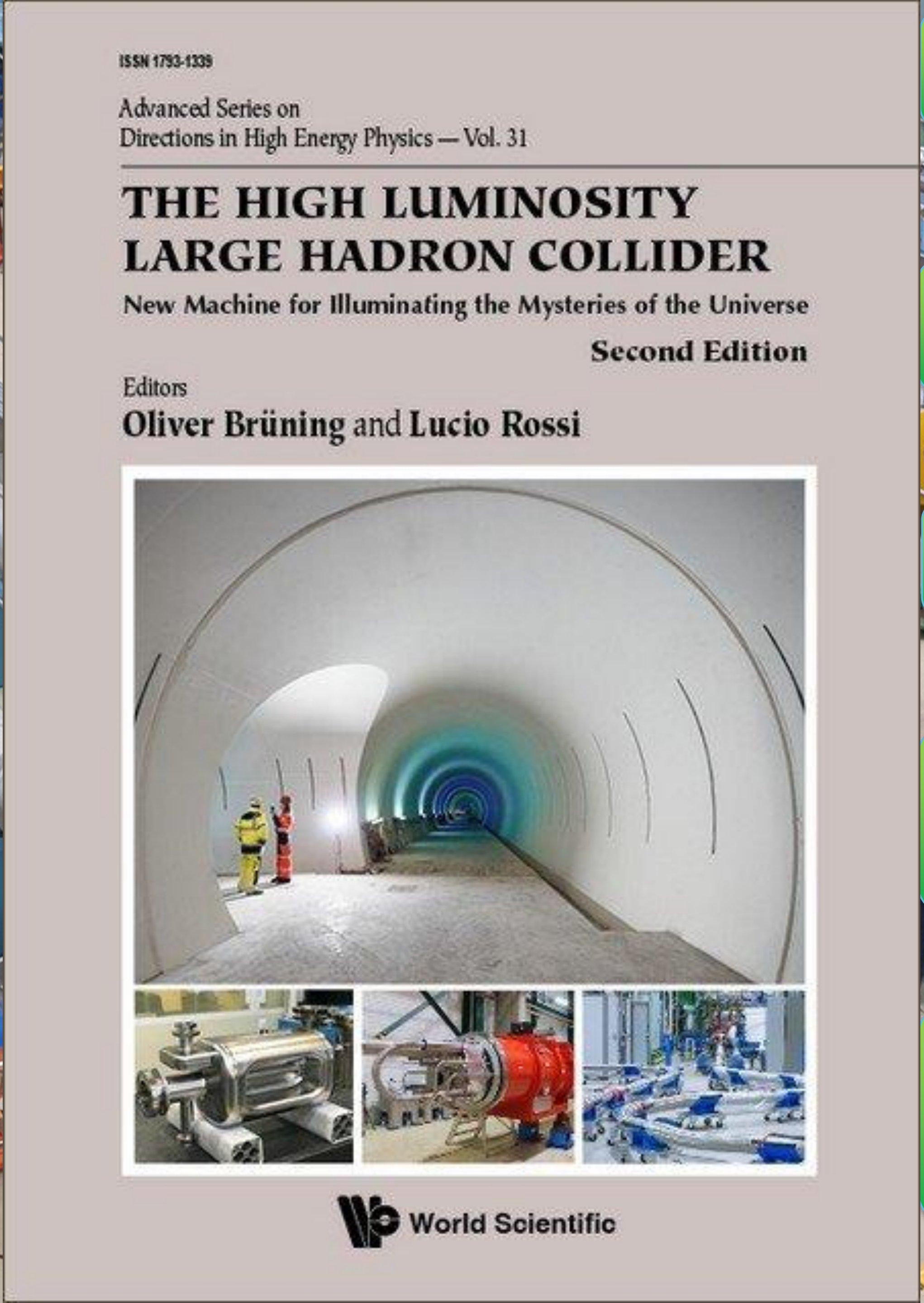
RFD CM : Latest Assembly

Lowering of Top plate to Cavity String successful !!

Since last PSM (Jul), important alignment issue between top plate and cavity string corrected with some non-conformities (not ideal but ok)

October deadline for installation in the SPS Test-facility!

Available beginning of 2024
Open Access Publication
https://doi.org/10.1142/13487
ISBN: 978-981-127-894-5



Civil Engineering Work Completed

All magnet productions on good track!

1st Part of Collimation Upgrade completed

The project is on Track for installation
during LS3 starting in 2026

Stay Tuned for completion of the IT-String installation in 2024 and operation as of 2025!

Thank you for your attention