High Intensity Beam Dynamics Challenges for HL-LHC

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HB'23, CERN, Geneva, Switzerland – 10/10/2023

High Intensity Beam Dynamics Challenges for HL-LHC

- HL-LHC goals
- The electron cloud challenge
- Transverse impedance and stability
- Additional considerations

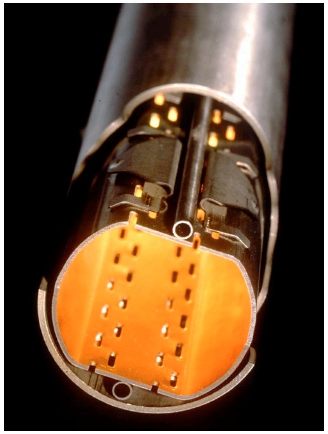
HL-LHC goals

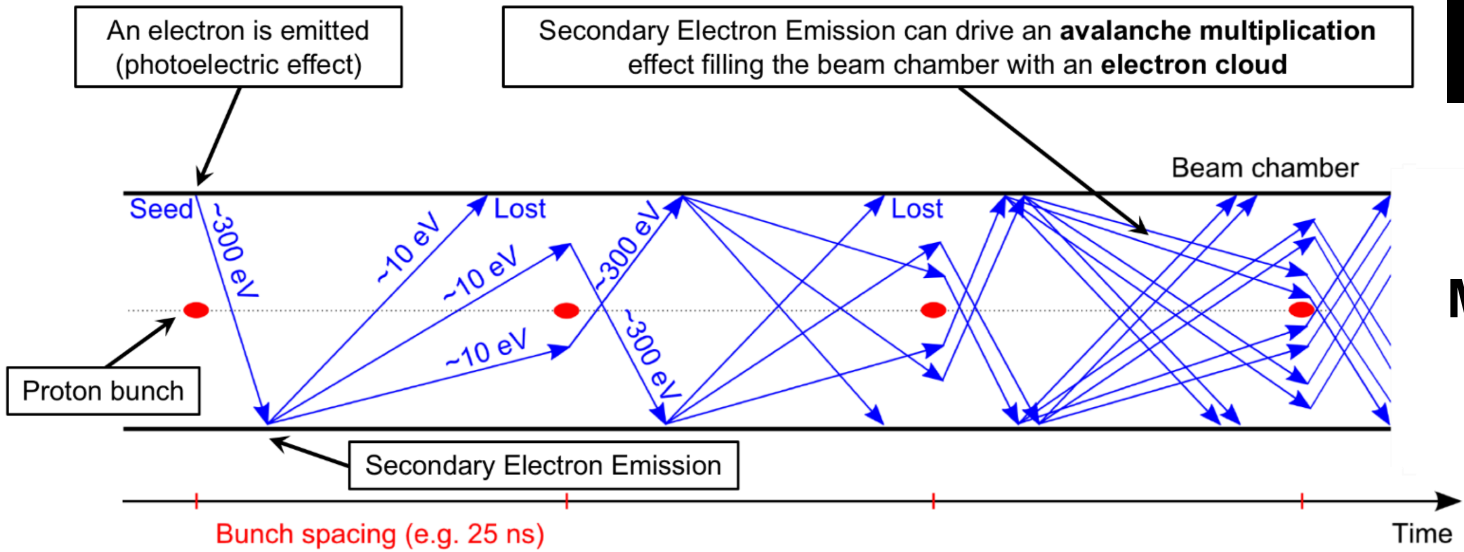
- Upgrade of the LHC to reach, in interaction points (IP) 1 & 5:
  - levelled luminosity 5×10^{34} cm^{-2} s^{-1},
  - integrated luminosity 250 fb^{-1} per year.
- This will be possible thanks to hardware upgrades, among which
  - LHC injector upgrade (LIU) – already performed and final goals within reach (2.2×10^{11}p+/b within 2 µm achieved) – see plenary talk by ***G. Rumolo*,** HB’23, 9/10/2023
  - Triplets exchange (and in general upgrade of insertion regions – IR – around IP 1 & 5)
  - New crab cavities
  - Collimation system upgrade
- An important ingredient is the increased brightness, from
  - Increased intensity: $N = 2.3 \times 10^{11}$protons/bunch
  - … within a similar normalized emittance: $\varepsilon_n = 2.5$ µm at the start of collisions (20% blow up in the LHC assumed)

⟶ What will limit the HL-LHC total intensity?

The electron cloud challenge

- Electron cloud has been a source of issues for LHC operation since 2010.
- It is mainly present in the LHC beam screens (covering >85% of LHC):

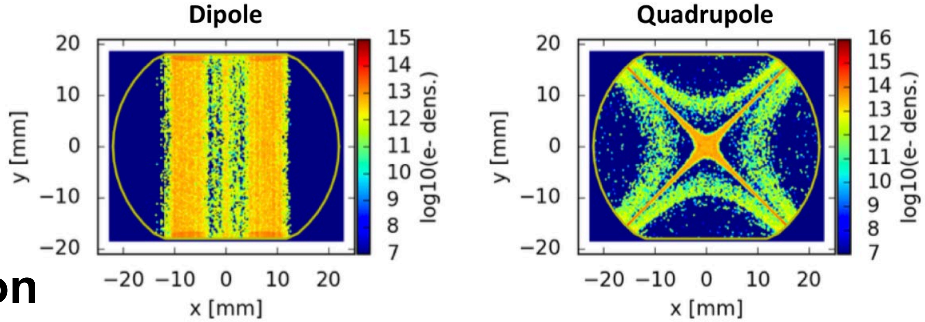




Multipacting

Courtesy **G. Iadarola** & **G. Rumolo**, *Proc. ICFA Mini-Workshop in Benevento, Italy, 18-22 Sept. 2017*

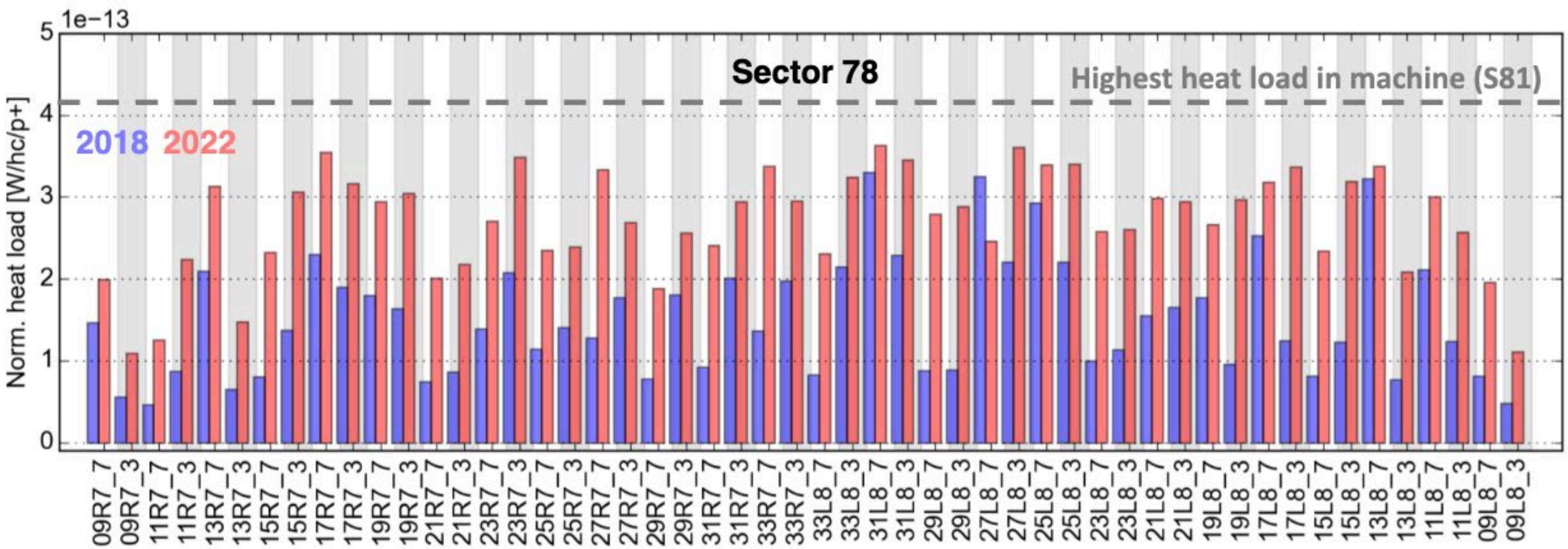
e-cloud distribution



The e-cloud situation in the LHC

- The situation has degraded during LS2 (2019-2021):

  Increase of heat load from e-cloud, in particular in sector 78
  ⟶ limits the intensity reach.



***L. Mether**, [LHC Chamonix workshop](), 23/01/2023*

e-cloud: LHC news

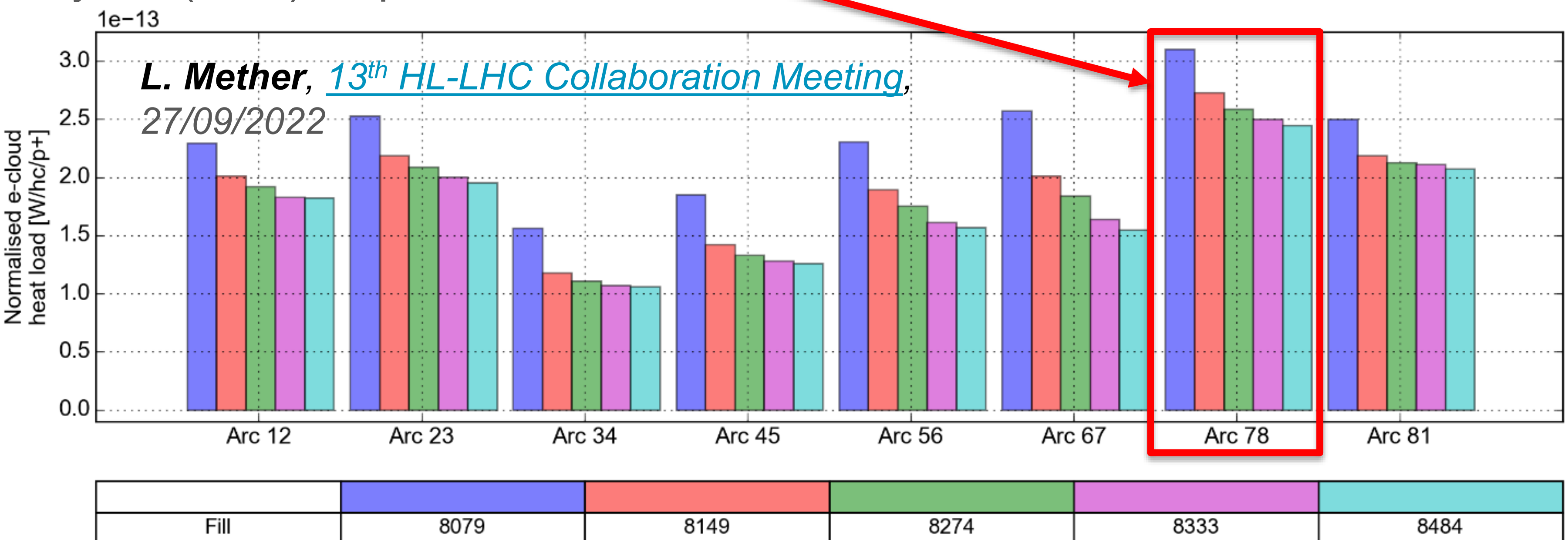
- The situation has degraded during LS2 (2019-2021):

  Increase of heat load from e-cloud, in particular in sector 78 ⟶ limits the intensity reach.

- **Scrubbing is levelling off in all sectors**

  ⟶ not expecting much further decrease of secondary emission yield (SEY), in particular for S78.

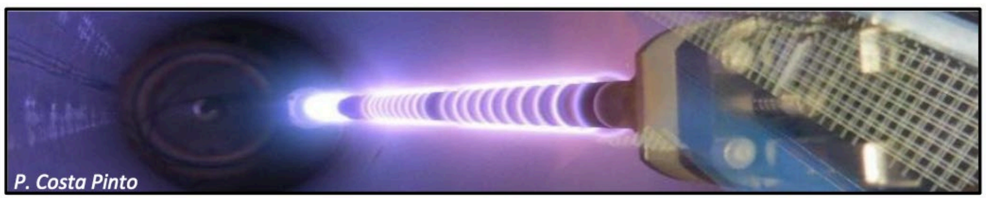
L. Mether, _13th HL-LHC Collaboration Meeting_, _27/09/2022_



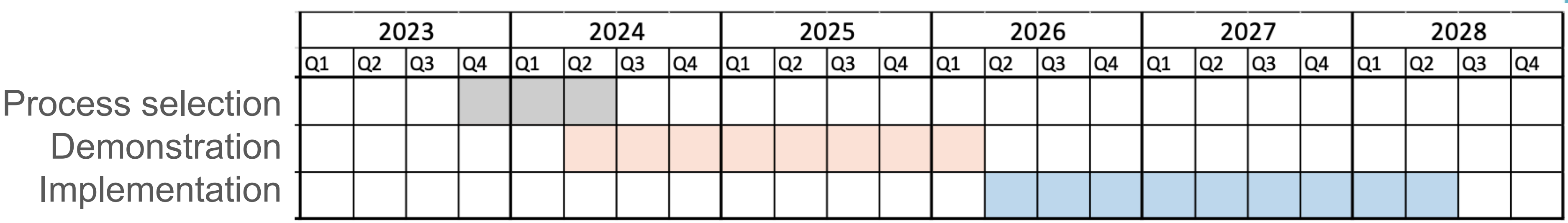
*See also **L. Mether's poster**, THBP31, HB'23*

e-cloud: mitigations

- 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)

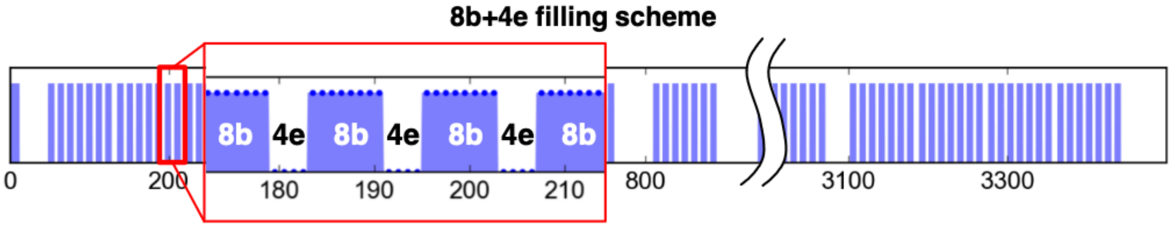


⟹ **Project proposed** (see ***M. Lamont***, *LHC "Chamonix" workshop summary, 25/03/2023, and **V. Baglin**, 13th HL-LHC Collaboration Meeting, 26/09/2023)*



e-cloud: filling scheme mitigation

- Standard filling scheme will be achievable only with surface treatment.
- 8b4e very effective to reduce heat load (>55%) and removes any stability issue but limits the bunches to <2000



G. Iadarola et al in Proc. 6th LHC Operations Evian Workshop, 2015, pp. 101–110

- Hybrid schemes (mix 25 ns with 8b+4e) are a good compromise (& tunable).

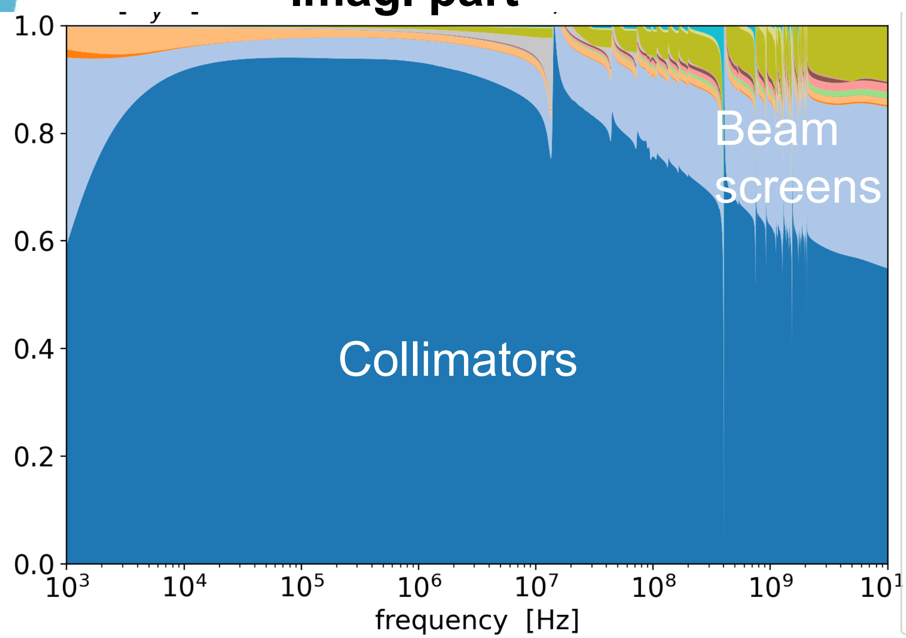
HL-LHC scheme	8b4e ratio	Number of bunches	Q'	Assumptions
Standard	0%	2748	>15	Surface treatment
Hybrid	47%	2320	>15	No further degradation
8b4e	100%	1972	-	Strong degradation

⟶ e-cloud will probably limit the number of bunches during the first HL-LHC run, and except with 8b4e, the chromaticity will have to be maintained high.

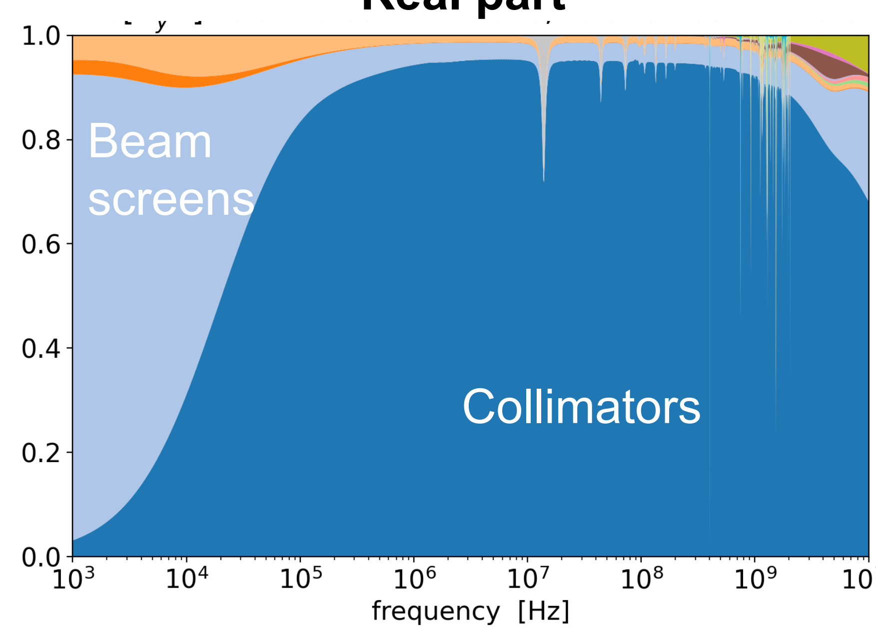
Transverse impedance & stability

- Breakdown of all vertical impedance contributions in most critical phase of cycle (flat top, i.e. after ramp & before collision process):

Imag. part



Real part



Here with relaxed collimator settings (see next slides)

Collimators

- Collimators are the main contributors to the LHC impedance, in particular from their resistive-wall impedance (initially made in poorly conductive in carbon-reinforced carbon).
- Several options for the collimator half-gaps (here defined in units of σ for a normalized emittance of 2.5 μm), leading to a different protected aperture:

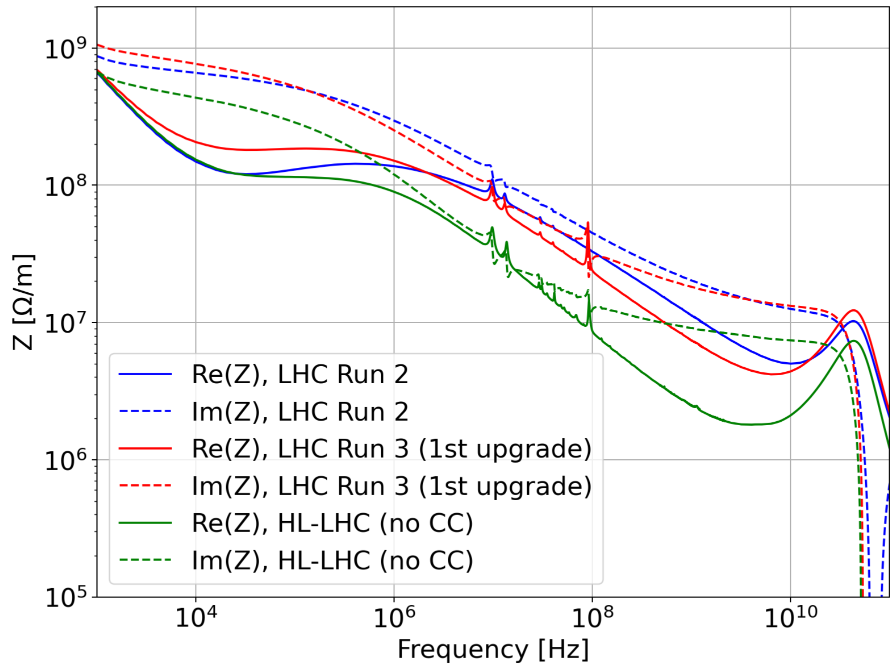
		Relaxed		Tight	
	IP1/5 β^* [cm]	15	20	15	20
(primaries)	TCP IR7	8.5		6.7	
(secondaries)	TCS IR7	10.1		9.1	
(absorbers)	TCLA IR7	13.7		12.7	
(dump prot.)	TCDQ/TCS IR6	11.1		10.1	
(tertiaries)	TCT 1/5	11.4	13.2	10.4	12.0
	Protected aperture 1/5	12.4	14.2	11.4	13.0
	Aperture bottleneck 1/5	13.1–16.6	15.2–19.2	13.1–16.6	15.2–19.2

Pending assessment of aperture at start of Run 4

Collimators upgrade

- Strong effort to decrease the machine impedance through upgrades of the collimation system (see ***S. Redaelli*** et al, CERN-ACC-NOTE-2019-0001, ***S. A. Antipov*** et al, PRST-AB, 23, p. 034403, 2020, ***C. Accettura*** et al., Proc. IPAC'23, pp. 2956–2959)
- Many primary and secondary collimators already replaced by higher conductivity ones (Mo-graphite, Mo-coated for secondaries)
- More secondaries to be replaced by Cu-coated graphite ones in the next shutdown.

Total horizontal, dipolar (driving) impedance (with relaxed settings for HL)

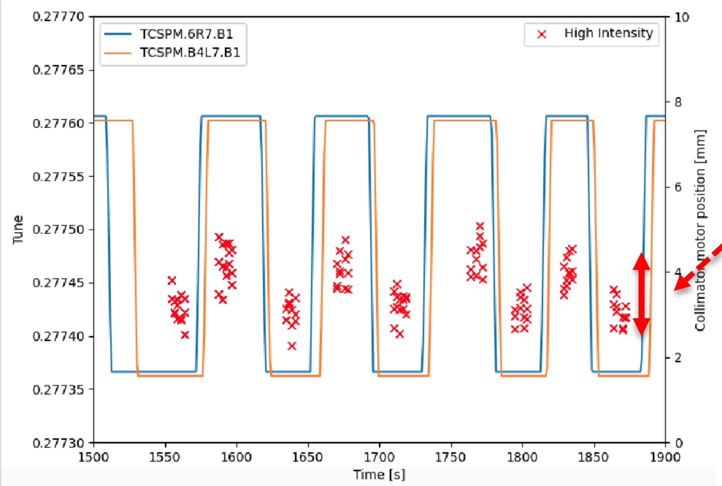


Studies ongoing to decrease even further impedance through optics optimisation (IR7 & 3) – see ***B. Lindström****'s* talk, *TUC4C2, HB'23* (Tuesday afternoon),

LHC tune shift measurements

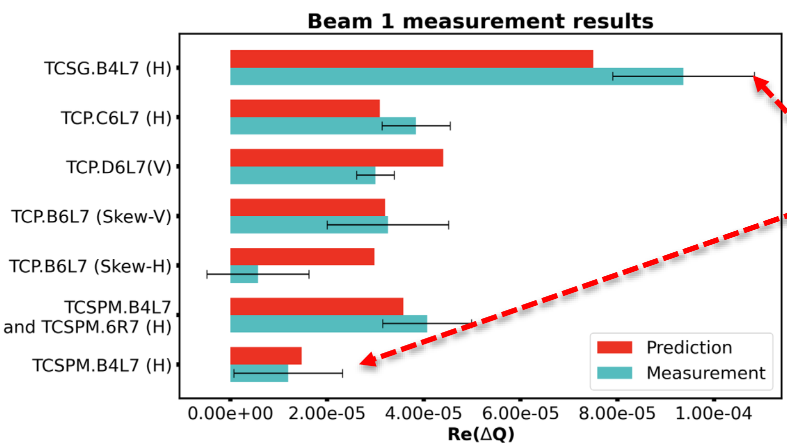
- Tune shift from collimators measured during LHC Run 3 ⟶ impedance reduction confirmed:

TCSPM.B4L7.B1 and TCSPM.6R7.B1 :

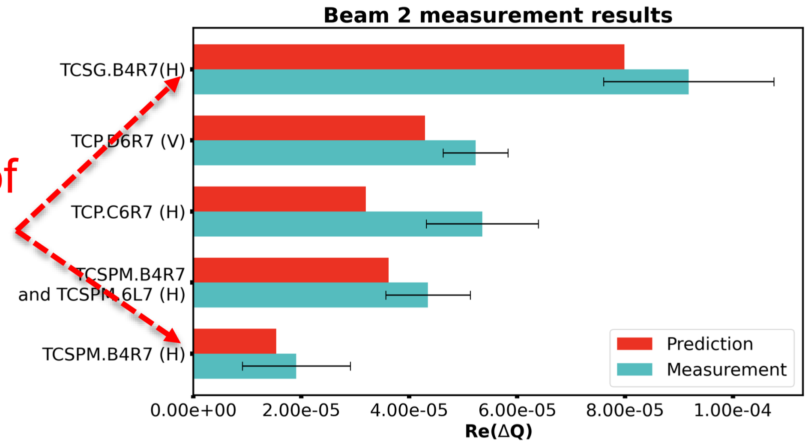


Back-and-forth motion of the jaws to check tune shift from impedance of single collimators

Adnan Kurtulus, [ABP-CEI meeting 15/12/2022]

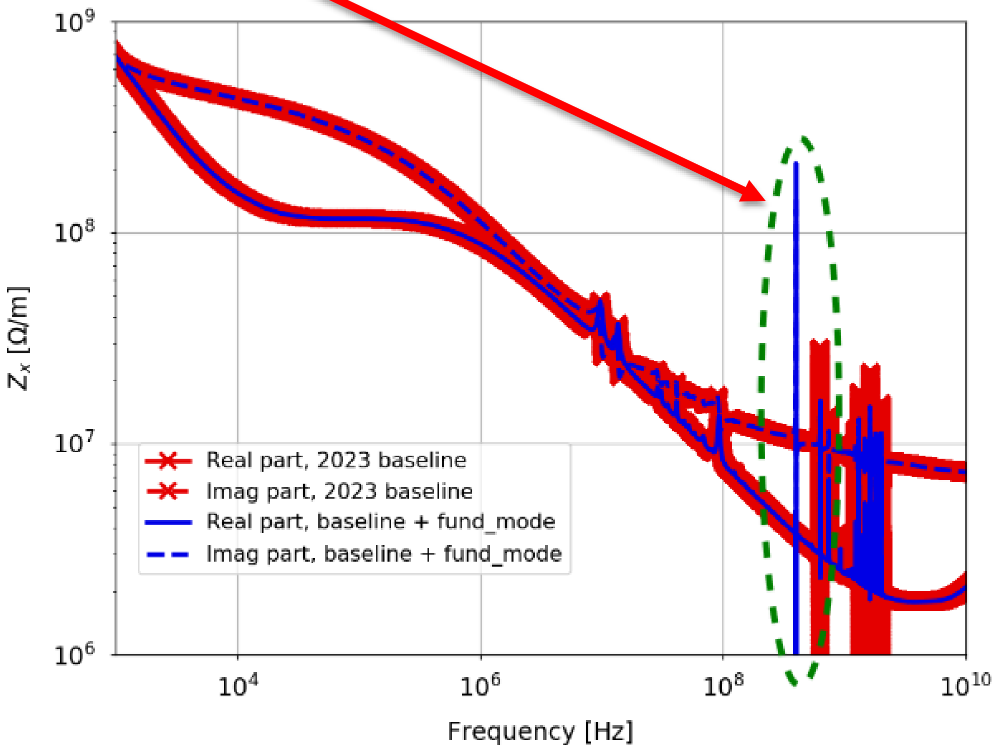


Impact of LS2 upgrade



Crab cavities (CC) impedance

- Crab cavities also have a strong impact on stability, from their fundamental mode:

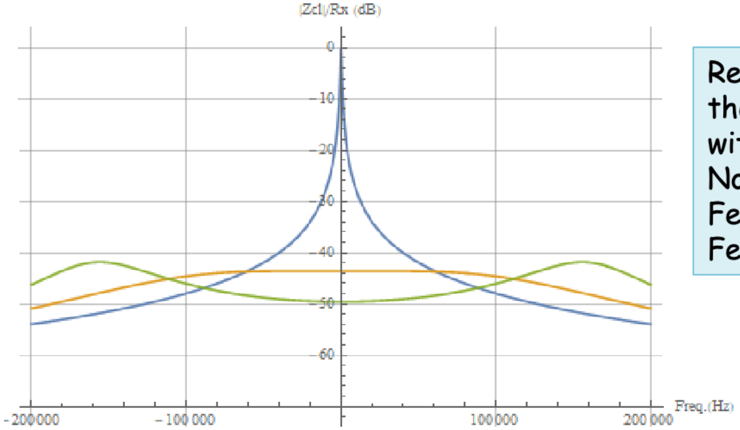


Total horizontal, dipolar (driving) impedance with CC fundamental mode

***L. Giacomel**, 211th WP2 meeting, 17/01/2023*

Crab cavities: impedance mitigation

- Gain of standard RF feedback cannot be increased further:



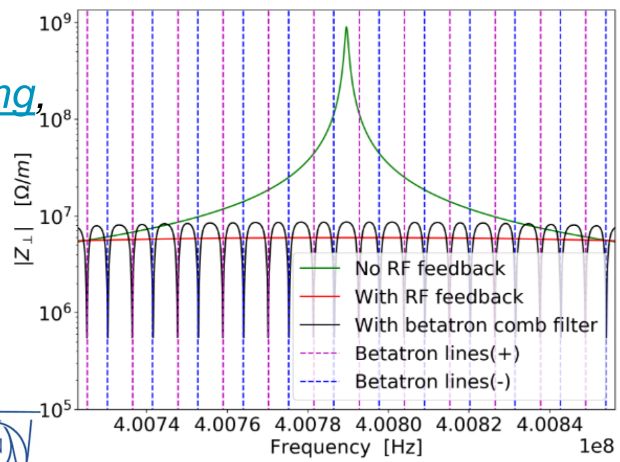
Reduction of the modulus of the transverse impedance with:
No feedback (blue)
Feedback gain=150 (orange)
Feedback gain=300 (green).

***P. Baudrenghien**, [WP2/WP4 meeting], 22/11/2022*

... but a **comb filter** can reduce impedance effects by acting at the right frequencies (betatron lines):

***L. Giacomel**, [WP2/WP4 meeting], 21/03/2023*

See also ***L. Giacomel's poster**, THBP40, HB'23*

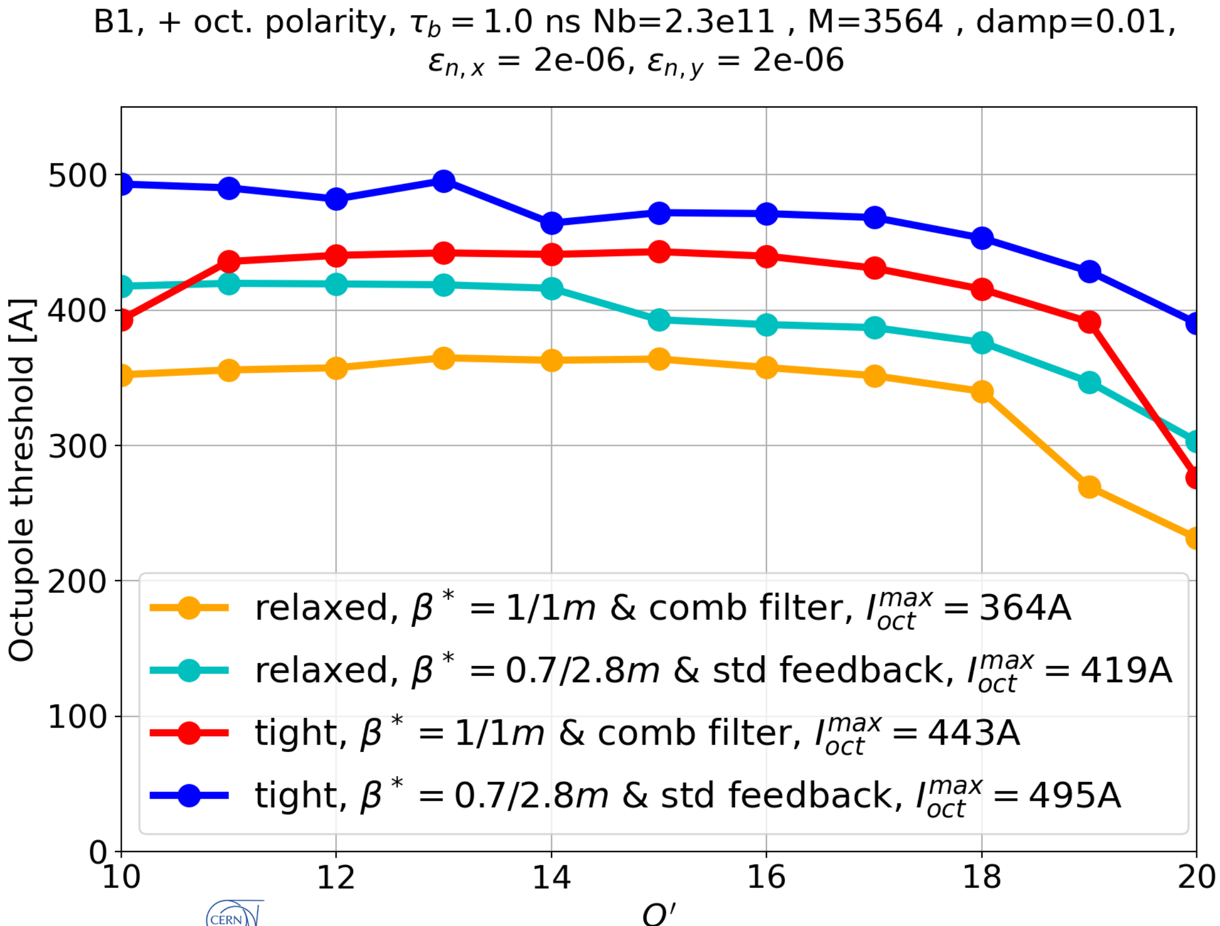


Impact of mode decreases by **an order of magnitude**, **but** assumes tune known within ±5.10^{-3}
⟹ Bunch-by-bunch tune shift measurements planned for 2024.
⟹ Multibunch effects to be studied

Reduction of CC β function with flat optics is another mitigation.

HL-LHC overall transverse stability

- Collimator settings were assumed relaxed in the latest scenario for run 4 down to β^*=20 cm, but tight settings are also on the table:



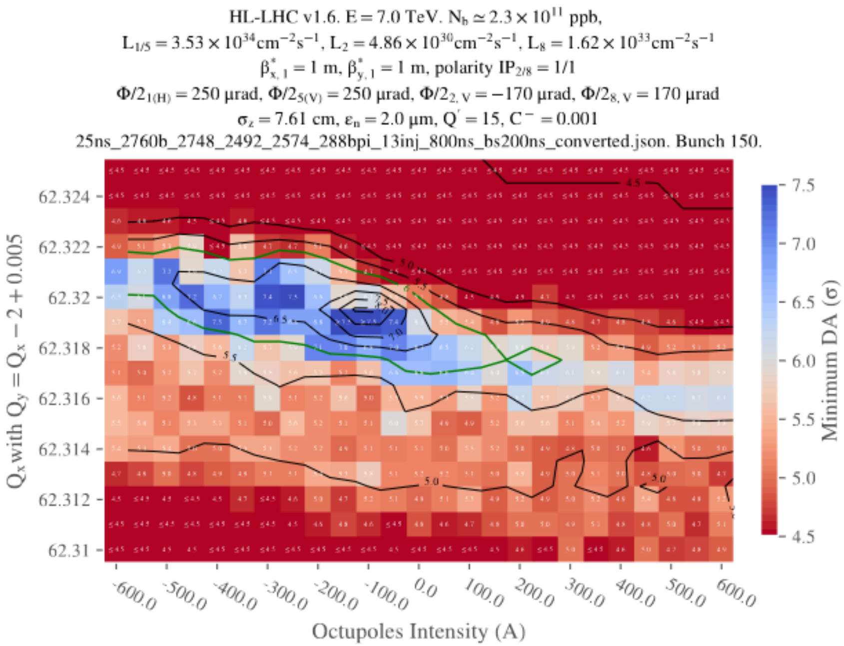
⟹ Tight settings give less stability, but are still manageable

⟹ it also depends on dynamic aperture (see next slide)

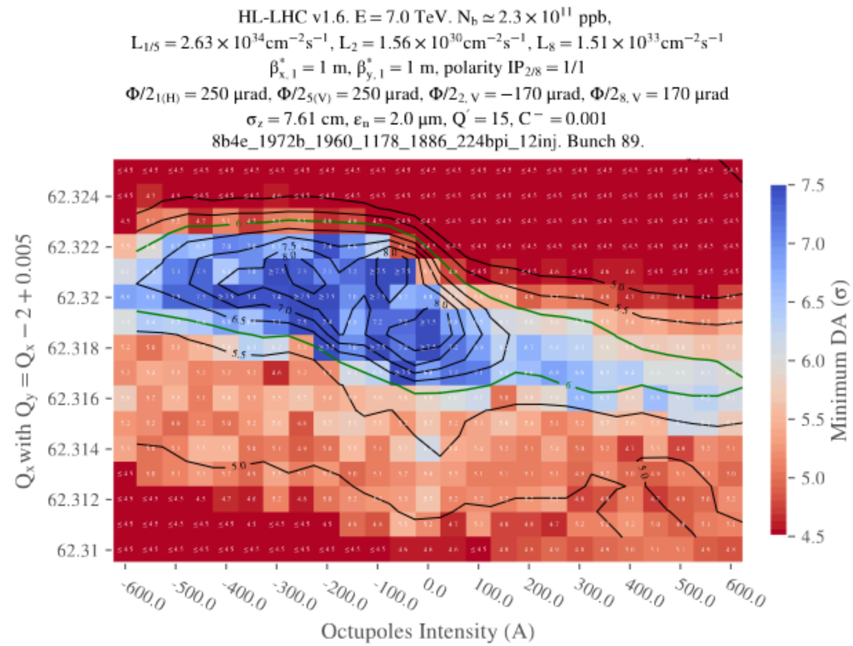
Dynamic aperture (DA)

- Dynamic aperture in most critical phase of cycle strongly affected by octupole current, and also crucially depends on Q’ / filling scheme:
  - ⟶ lifetime could be an issue.

baseline filling scheme



8b4e filling scheme



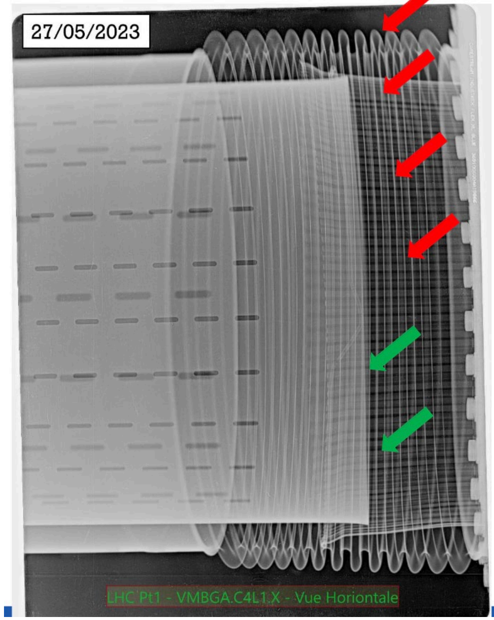
See also ***R. De Maria***’s *poster, THBP21, HB’23*

Courtesy ***C. Droin, S. Kostoglou, G. Sterbini***, *13th HL-LHC Collaboration Meeting, 27/09/2023*

Additional considerations

- Local heating in sensitive devices:
  - incident on a RF vacuum module (A4L1) in 2023 ⟶ several two-beam RF vacuum modules found nonconforming and will be replaced (see ***G. Bregliozzi*** et al, 76th IWG, 30/08/2023),

  ⟶ LHC intensity limited to $1.6 \cdot 10^{11}$ p+/b in 2023, and impedance studies ongoing (see ***C. Antuono*** et al., 76th IWG, 30/08/2023).



Courtesy ***G. Bregliozzi***

- Limitations on the RF power:
  - strong injection transients and high average power required, beyond the capability of present system (see ***T. Argyropoulos*** et al., LHC Chamonix Workshop 2023)

  ⟶ New high-efficiency klystrons needed for baseline and hybrid schemes.

Summary and outlook

- Number of bunches will probably be limited by e-cloud effect (heat load essentially), at least in the first HL-LHC run:
  - project proposed to start treating the surface of beam screens
  - depending on project advancement and beam screen surface after next shutdown, several options from baseline to 8b4e, via hybrid scheme,
  - Q' might need to be very high at flat top (>15) – impact on DA.
- Regarding transverse stability and its impact on bunch intensity:
  - octupole current depends on option chosen for crab cavity fundamental mode mitigation, and collimator settings,

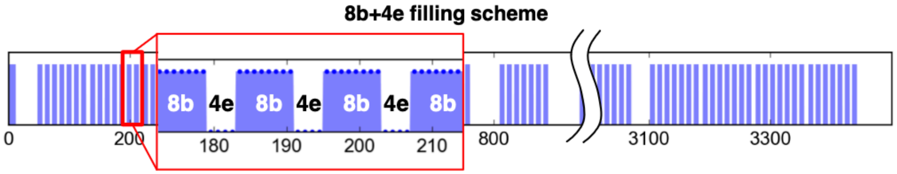
  ⟶ affect DA and lifetime during the collision process (separation collapse).
- Studies ongoing:
  - decrease collimator impedance (IR7 & IR3 optics optimisation),
  - flat optics,
  - DA optimisation (see ***R. De Maria****'s poster*, *THBP21*, HB'23, and also ***K. Paraschou****'s poster, THBP20*, HB'23),
  - multibunch effects (crab cavities; 8b4e / hybrid filling schemes).

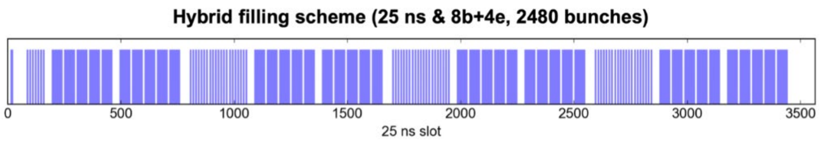
HiLumi
HL-LHC PROJECT

Appendix

e-cloud: filling scheme mitigation

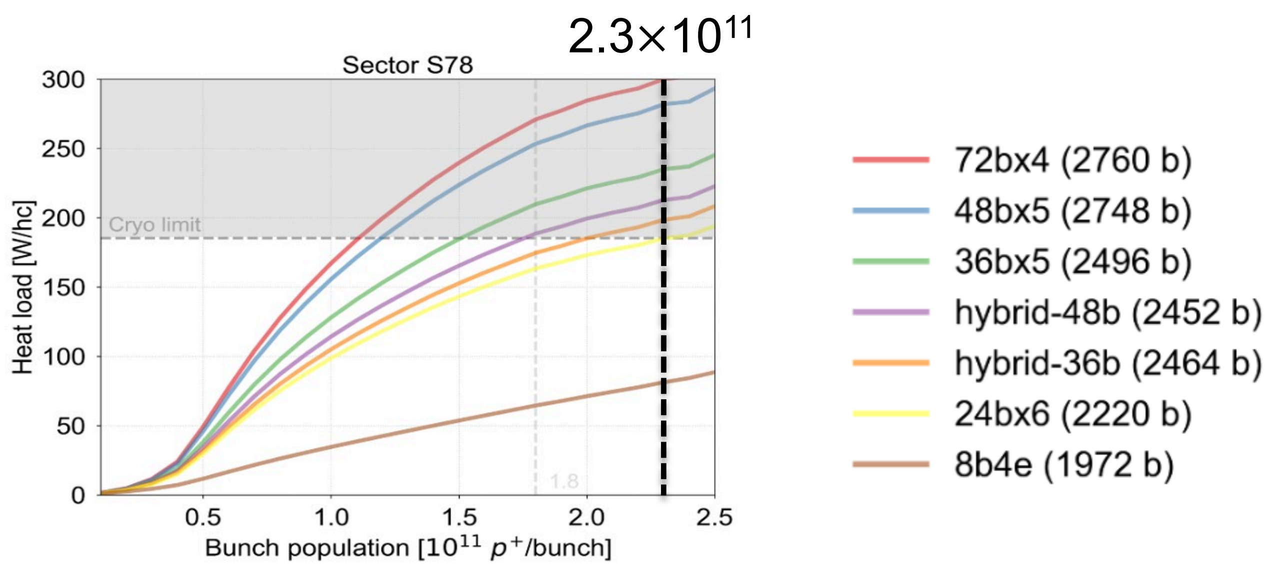
- 8b+4e very effective to reduce heat load (>55%) but limits the bunches to <2000
- Hybrid schemes (mix 25 ns with 8b+4e) is the best compromise (& tunable)





***L. Mether**, [210th WP2], 13/12/2022*

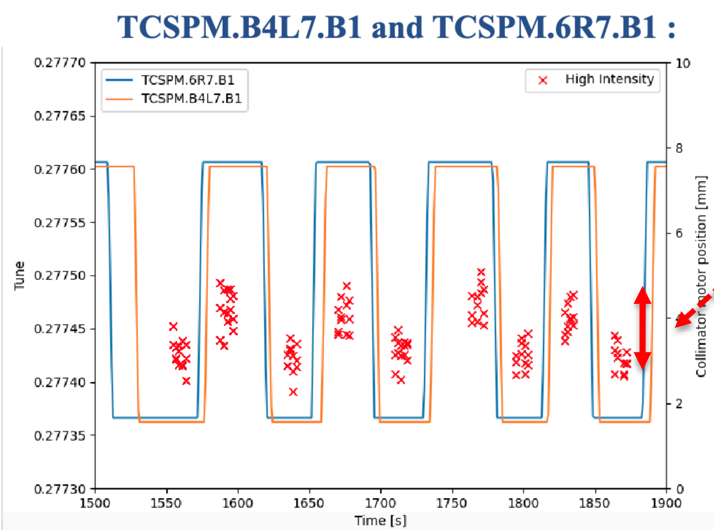
⟹ Strong impact of filling scheme on intensity reach:



***L. Mether**, LHC Chamonix workshop, 23/01/2023*

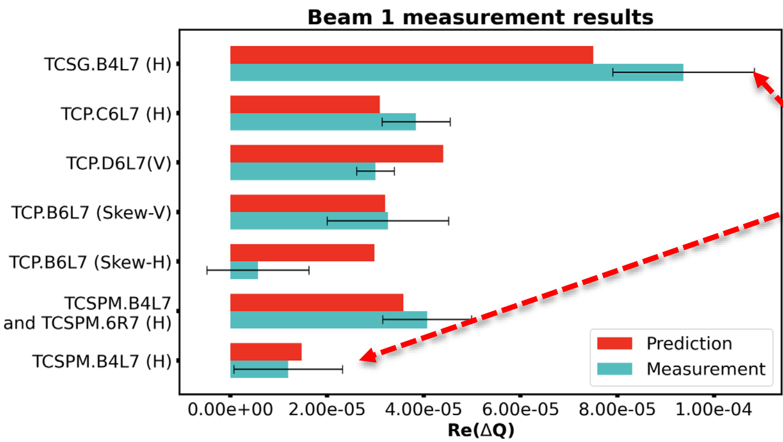
LHC machine development studies

- Tune shift from collimators measured during LHC Run 3:

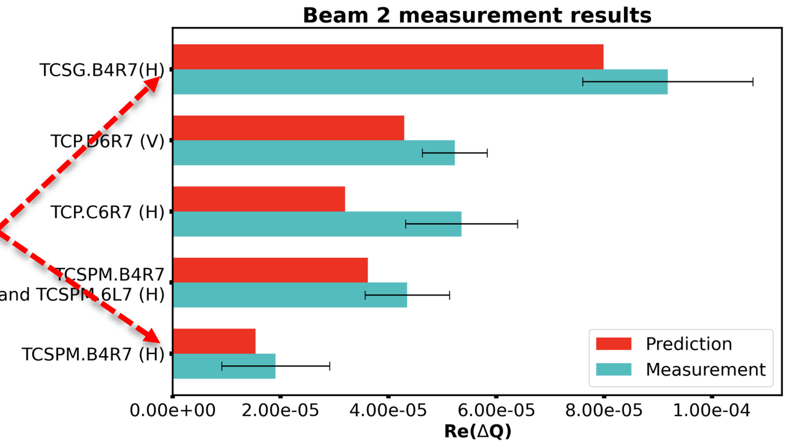


Back-and-forth motion of the jaws to check tune shift from impedance of single collimators

Adnan Kurtulus, [ABP-CEI meeting 15/12/2022]



Impact of LS2 upgrade

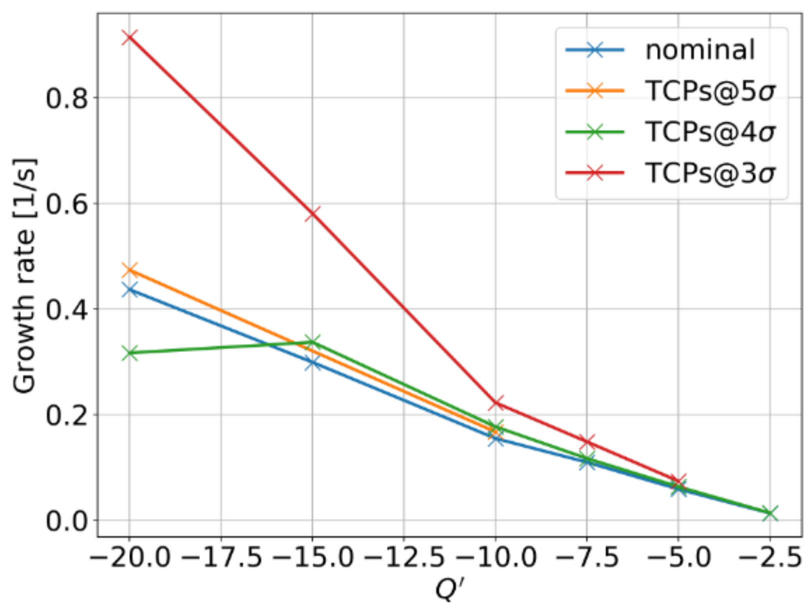


HL-LHC PROJECT

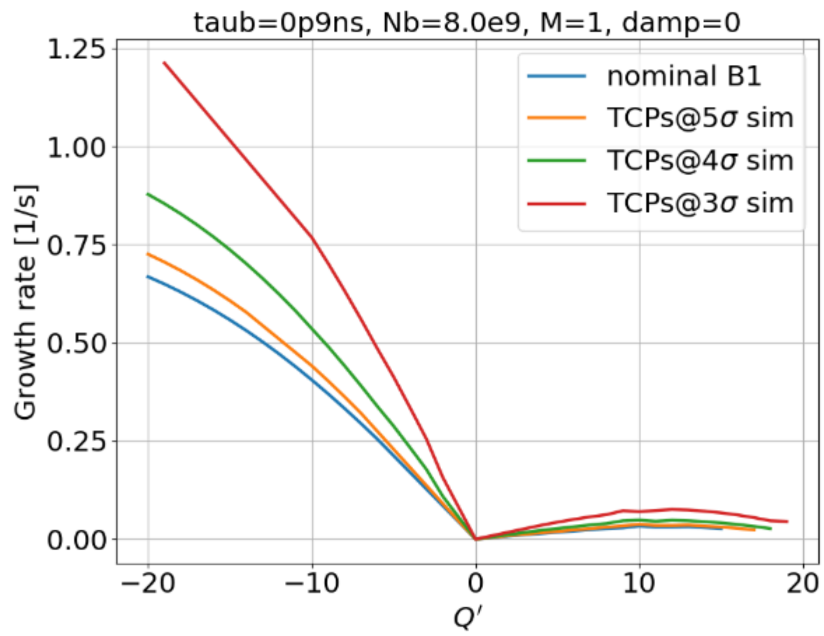
LHC machine development studies

- To probe the real part of the impedance: measurements of instability growth rates at injection

Measurements:



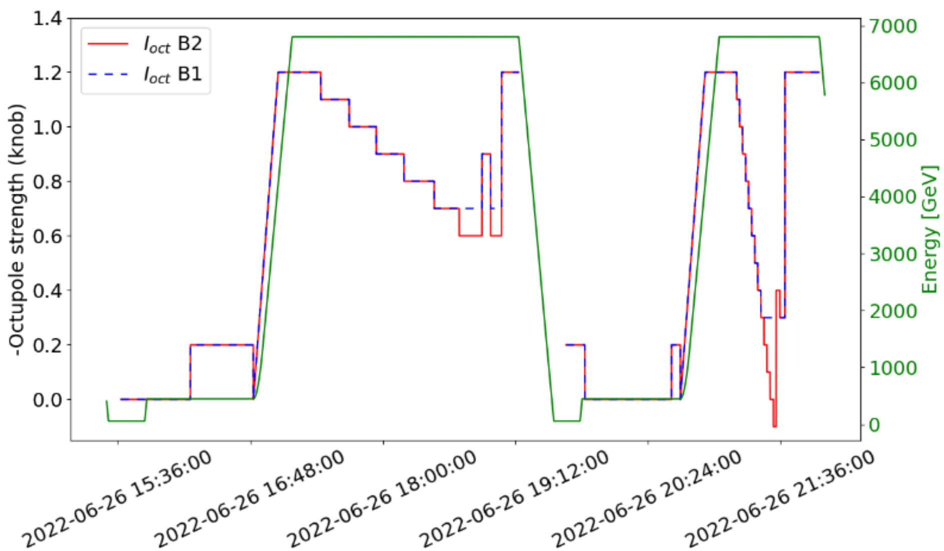
Simulations:



⟹ As for real tune shifts, relative agreement between measurements & model.

LHC machine development studies

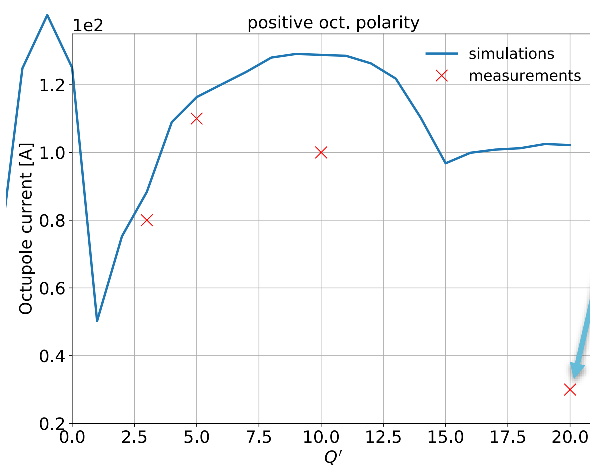
- Stability main quantity of interest: Octupole threshold
  - Latency effect (slow vs fast octupole decrease):

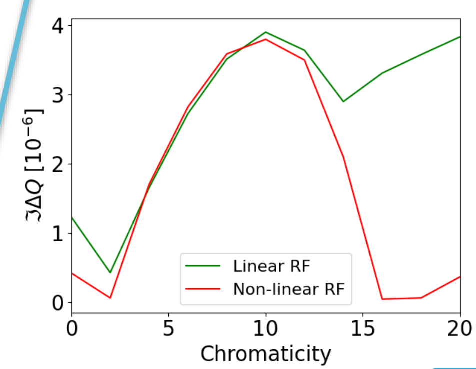


⟹ octupole must be ~twice higher when staying a long time at the same octupole current (*S. Furuseth & X. Buffat*, [Eur. Phys. J. Plus 137, 506, 2022]())

Subject of intense studies – impact of non-linear bucket

  - Octupole threshold vs Q' (latency not included):

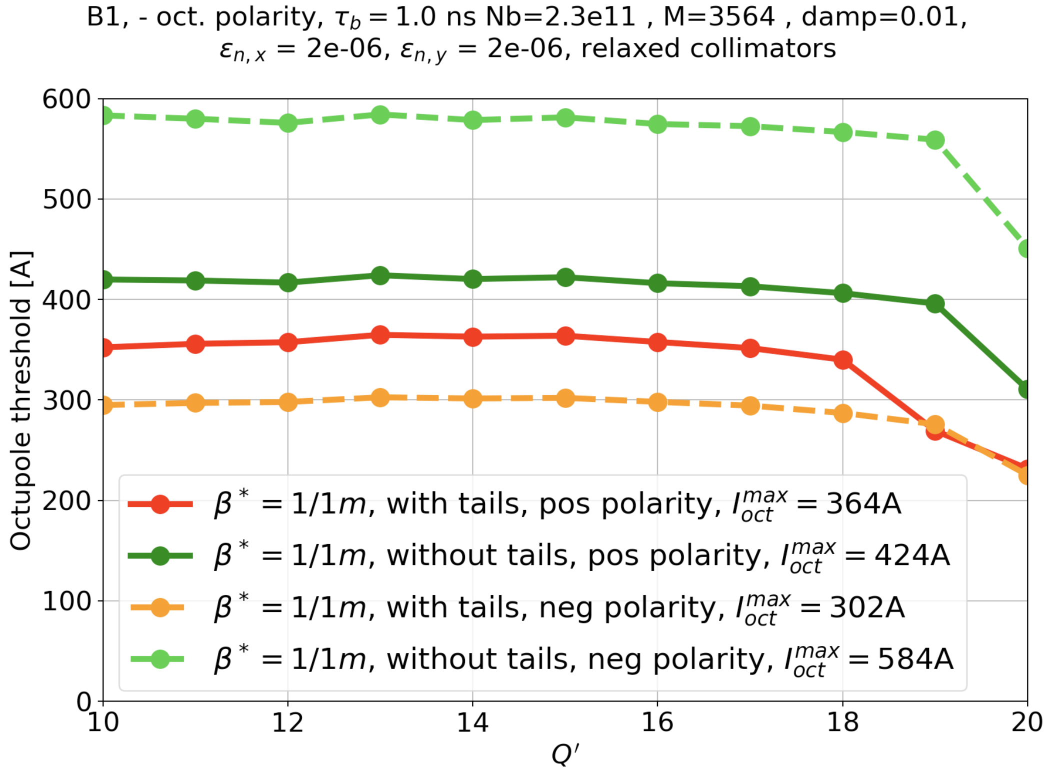




X. Buffat

HL-LHC overall transverse stability

- The model for transverse tails has been reviewed:
  - In the past tails assumed absent (parabolic bunch in transverse, tails cut at 3.2σ) – uncertainties on beam from LHC injectors (after LHC Injector Upgrade – LIU) + HEL
  - Now: LIU beam known to have tails, no HEL ⟶ **Gaussian tails assumed.**
  - It also means that **negative octupole polarity** is back in the game (better stability diagram in principle, but some compensations with long-range beam-beam):



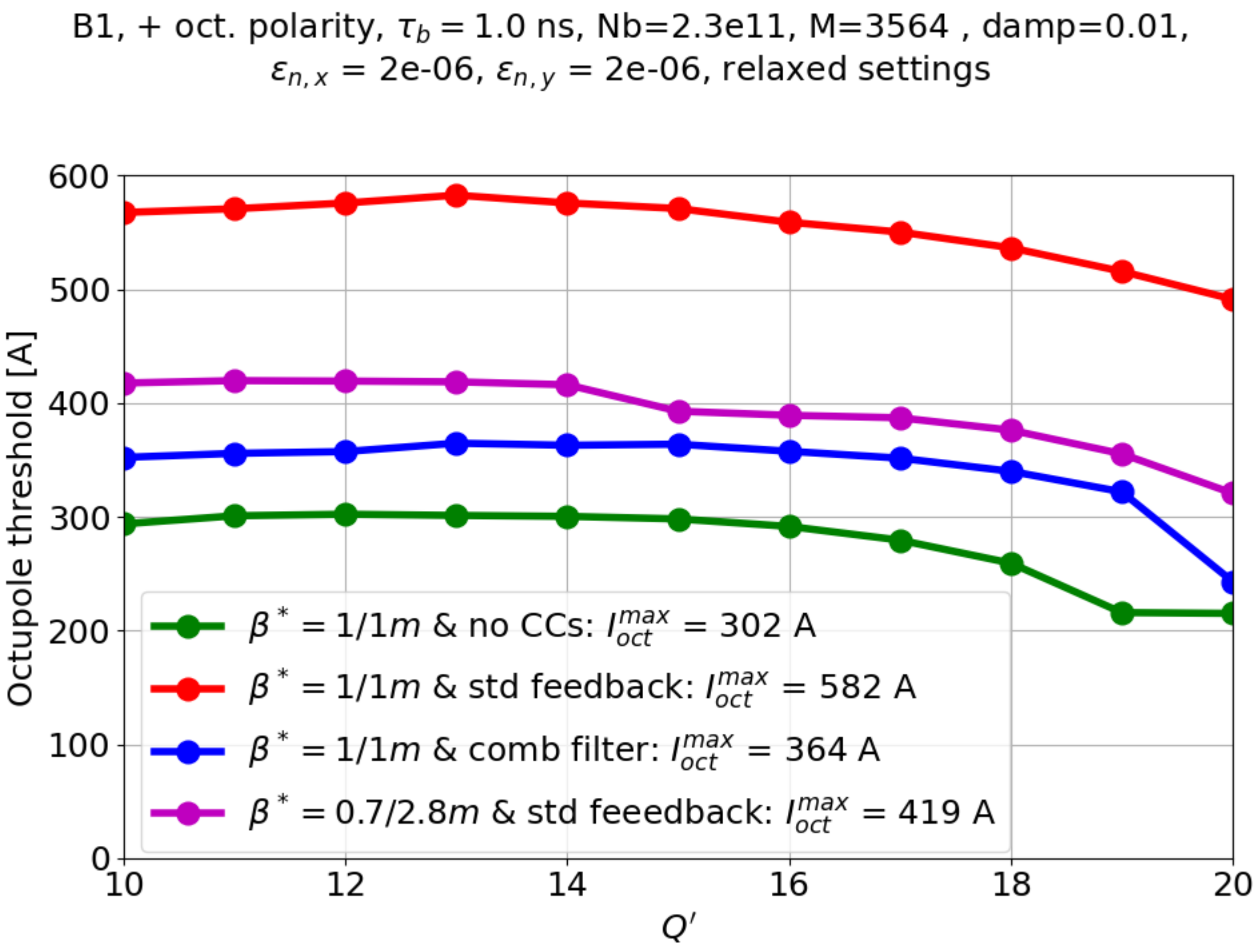
⟹ ~16% improvement with tails

⟹ with tails, negative polarity is better than positive, overall.

Note: here we assume the crab cavities comb filter is used.

HL-LHC overall transverse stability

- Impact of crab cavities fundamental mode and mitigation options:



⟹ Without any additional mitigation, huge impact of CCs (+280 A)

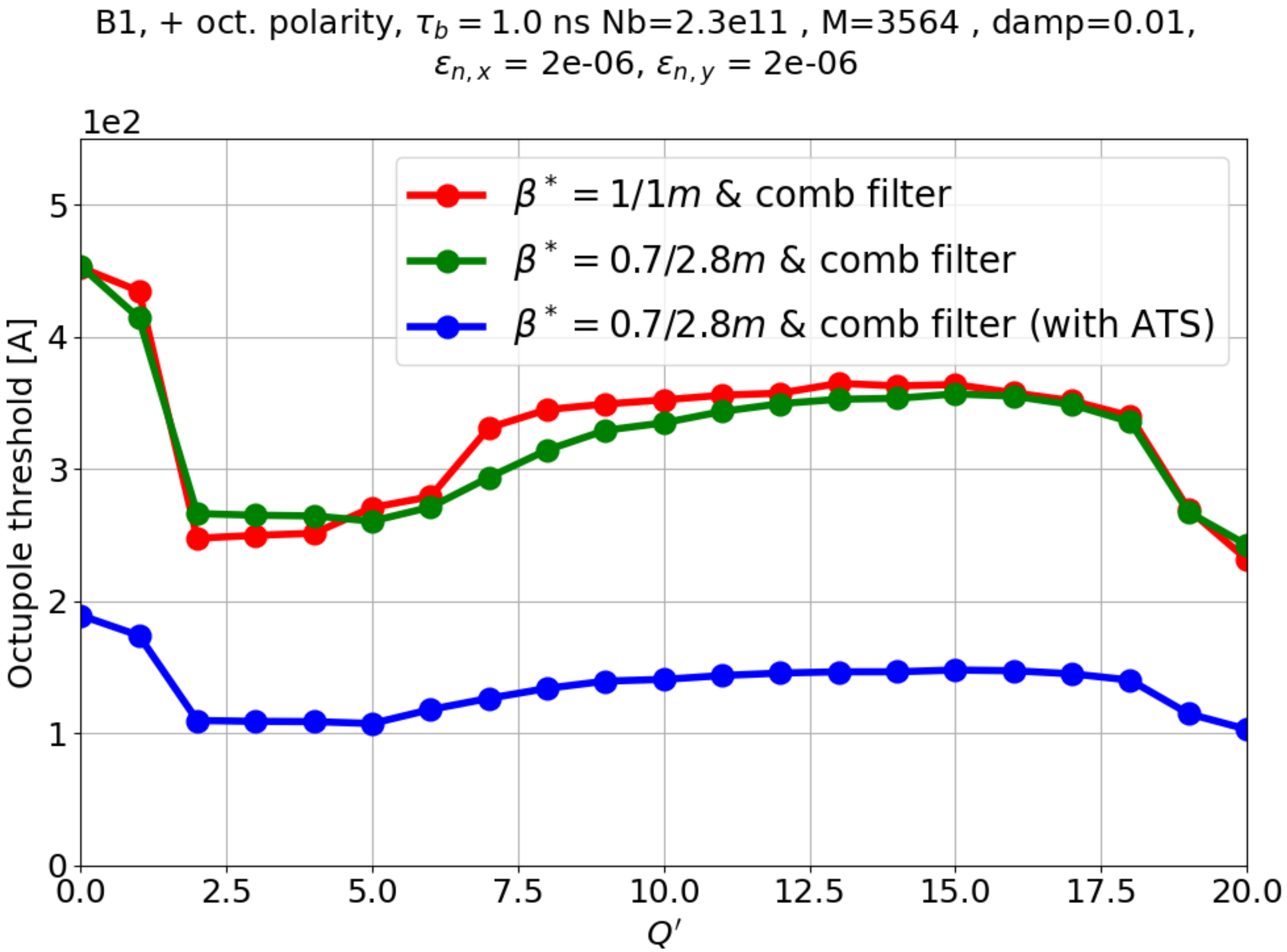
⟹ comb filter is the best mitigation (80% reduction)

⟹ std RF feedback with flat optics is a good backup option (60% reduction).

Note: the flat optics case also features a telescopic index (*S. Fartoukh*, PRST-AB, 16, p. 111002, 2013), but we have rescaled the octupole currents to a telescopic index of 1.

HL-LHC overall transverse stability

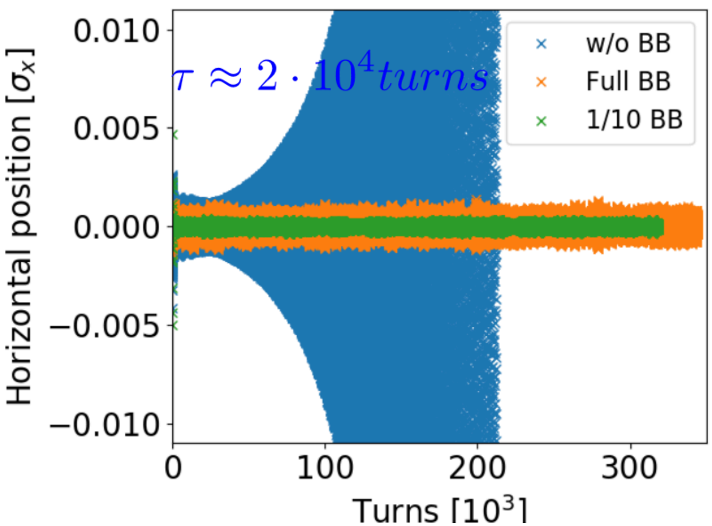
- Impact of optics choice:



Here there is no rescaling of the flat optics case (telescopic index is left unchanged)

Crab cavities: noise & amplitude feedback

- Heavy simulation effort to understand if Landau damping from beam-beam effects sufficient to damp instabilities from **CC amplitude feedback** used to mitigate noise issue (800 MHz demodulation)



Multibunch simulations in collisions with **Xsuite**, including **beam-beam, feedback & impedance effects**
$\Longrightarrow$ instability from feedback **stabilized by beam-beam**
… but 400 MHz demodulation preferable (no instability in the first place).

X. Buffat, *WP2/WP4 meeting*, *21/03/2023*

- Designing a faster approach to simulate multibunch instabilities: