Run 4 operational scenario

Nicolas Mounet and Rogelio Tomás, for WP2

With lots of input from C. Accettura, C. Antuono, G. Arduini, H. Bartosik, P. Baudrenghien, B. Bradu, R. Bruce, O. Brüning, X. Buffat, R. Calaga, R. De Maria, J. Dilly, C. Droin, I. Efthymiopoulos, L. Fiscarelli, A. Foussat, L. Giacomel, M. Giovannozzi, G. Iadarola, S. Izquierdo Bermudez, I. Karpov, S. Kostoglou, B. Lindström, E. MacLean, L. Mether, E. Métral, F.-X. Nuiry, Y. Papaphilippou, K. Paraschou, T. Pugnat, S. Redaelli, G. Rumolo, B. Salvant, L. Sito, G. Sterbini, H. Timko, E. Todesco, M. Zampetakis, C. Zannini, M. Zerlauth

14th HL-LHC collaboration meeting – 07/10/2024

Run 4 operational scenario

- Current baseline: review magnets field quality, DA, stability, luminosity estimate
- Review of limitations with current baseline and possible optimisations:
  - Magnets field quality
  - Stability: negative octupoles, rematched optics and collimator optimisation
  - DA (flat vs round, crossing angle reduction)
  - e-cloud situation and impact on filling scheme
  - Aperture
  - Luminosity: Flat VH, crossing angle reduction

Run 4 operational scenario: current baseline

- Assumptions (R. Tomás et al, HL-LHC Run 4 proton operational scenario, CERN-ACC-2022-0001):
  - **β^*=1 m** at flat top, down to **20 cm** at the end of levelling
  - Luminosity levelled at **5.10^{34} cm^{-2} s^{-1}** in IP1/5 (2.10^{33} cm^{-2} s^{-1} in IP8) – after 20 minutes of cryo ramp-up starting at half luminosity.
  - Chromaticity **Q'=+15**
  - Half crossing angle **250 μrad** (H in IP1, V in IP5), with compensating **crab cavity** crabbing angle at **190 μrad**
  - **$2.3\ 10^{11}$** p+/bunch at flat top, **$2.2\ 10^{11}$** in collisions.
  - **Relaxed** collimator settings (primaries at 8.5 σ)
  - Two options: **standard** or **BCMS** (resp. 2744 or 2760 bunches)
  - Horizontal / vertical emittances at **2.3 / 2.1 μm** for **standard** and **2 / 1.7 μm** for **BCMS**, at flat top (resp. **2.5** and **2.2 μm** in collisions).
  - Number of events per crossing in IP1&5 (std/BCMS): **130/132**
  - **Octupole** (**positive polarity**): **380/460 A** for std/BCMS at flat top, **120 A** (equivalent to 60 A when considering ATS factor) during levelling assuming **witness bunches** have four times less brightness than the others.

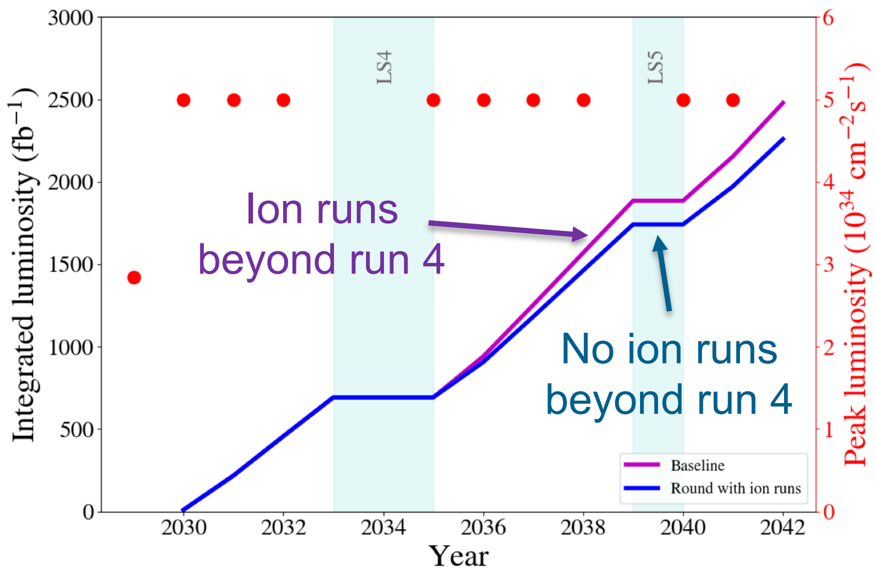
Run 4 operational scenario: current baseline

- Assumptions on operational days (M. Zerlauth et al, EDMS 2902691):

year	ppb [1e11]	beta* [cm]	CC	Virt. Lumi	PU	YETS days	Commissionig	Scrubbing	MD days	Special runs	Int ramp-up	Proton physics	Ion physics	Int. Lumi [fb-1]
2029	1.8	30	off	3,9	101	189	80	10	12	5	**20**	**6**	**29**	9,6
2030	2.2	25	on	10.3	132	105	40	1	20	5	**15**	**136**	**29**	208
2031	2.2	20	on	13.5	132	105	25	1	20	7	**10**	**154**	**29**	238,8
2032	2.2	20	on	13.5	132	105	25	1	20	9	**10**	**152**	**29**	235,7

- **Total integrated luminosity** estimate (with/without ion runs after Run 4) – with **3 runs** (10 years):
- With **BCMS: +1 %** (but it also depends on several unknowns, e.g. emittance growth, transverse tails).

(Note that **~460 fb^{-1}** should be added for the **LHC runs)**



S. Kostoglou, *228th WP2 meeting*, *02/07/2024*

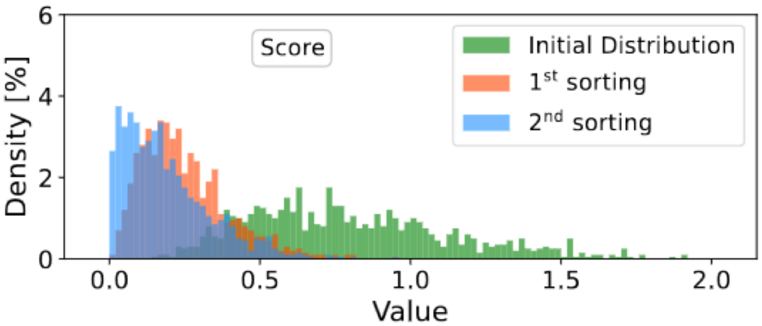
Magnets field quality (with WP3)

- **Voltage spikes** (30-70 ms long) on MQXFAs at high current (13-15 kA):
  - very few spikes, that do not occur at steady nominal current
  - not too worrying at this stage, but field measurements ongoing at CERN

G. Ambrosio, A. Ben Yahia, et al, WP2/WP3 meeting, 24/04/2024

- **Impact of D2 multipole errors** (*T. Pugnat & J. Dilly, WP2/WP3 meeting, 24/04/2024*):
  - a2 not problematic, b3 imbalance between apertures could be an issue
  - impact of b2 still to be studied
  - envisaging other combinations of D2 coils to equalize multipoles between the 2 apertures
  - Latest news: **DA from b3 in D2 is ok** – see ***T. Pugnat***, *230th WP2 meeting, 03/09/2024*

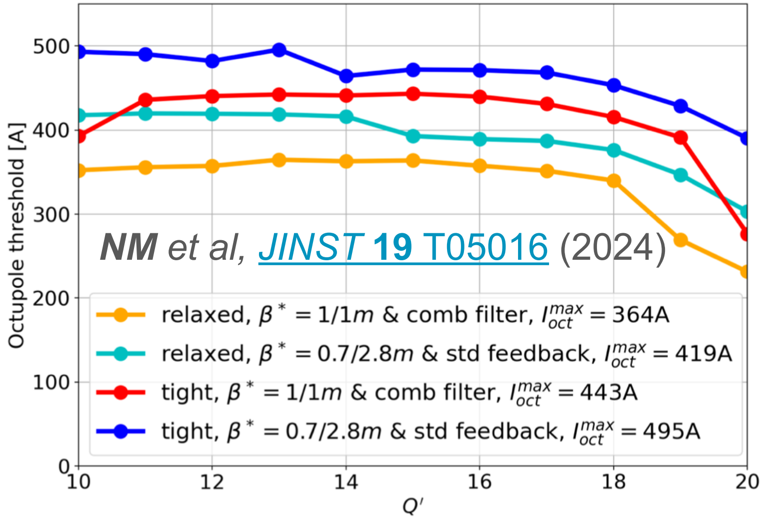
- **MQXF field quality (FQ)** (*G. Ambrosio, WP2/WP3 meeting, 24/04/2024*)
  - pairing within a pool of three magnets (in a cryostat) is now envisaged to improve FQ.
- **Sorting** (see *T. Pugnat, WP2/WP3 meeting, 30/04/2024, and A. Wegscheider, 222nd WP2 meeting, 21/11/2023*)
  - **Promising results on beta-beating:**



T. Pugnat et al, THPC16, IPAC'24
M. Giovannozzi, this meeting

Transverse impedance & stability

- In general, **transverse stability is less critical** than past predictions, as **LIU beams** were observed to have **tails** (past predictions considered no tails).
- On the other hand, the fundamental mode of the crab cavity became a concern.
- **Stability limits revised**: octupole threshold vs Q'



Assumptions: Gaussian transverse **tails**, positive octupole polarity, latency effect included

$\Longrightarrow$ **Limit depends on CC and its mitigation**

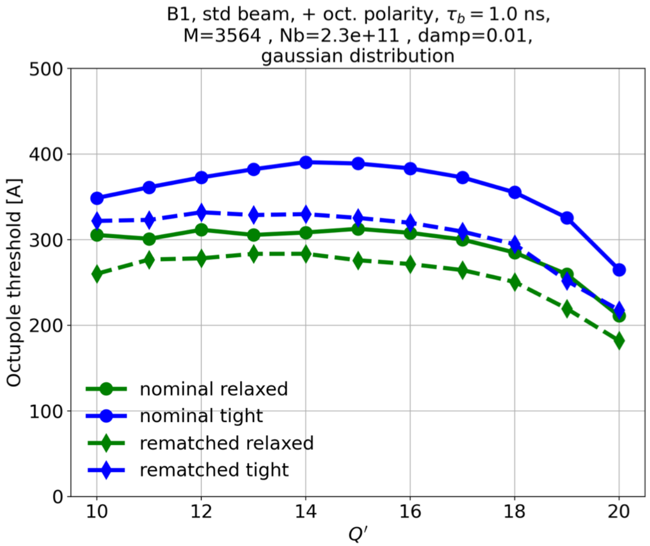
In case comb filter has issues**, flat optics** is an efficient backup mitigation.

See also ***L. Giacomel***, this meeting

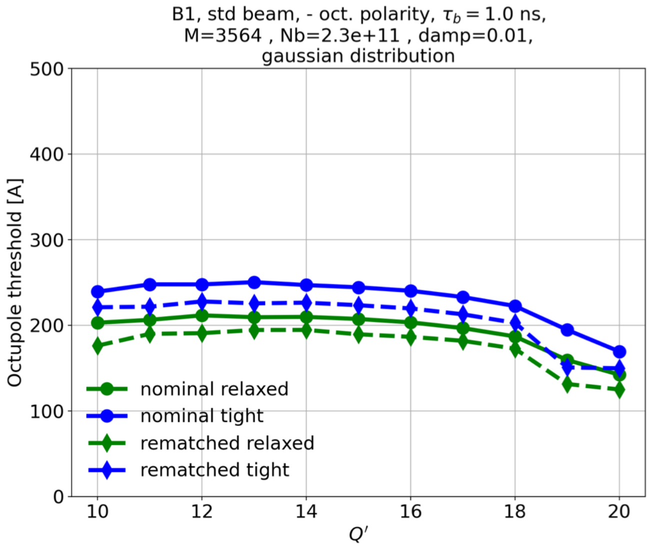
Transverse impedance & stability

- **Negative octupole polarity can help** (particularly true with tails)
  → tested in MD
- **Collimator impedance** can be further optimised with **rematched optics, or relaxed IR3 settings**:

Positive octupole polarity



Negative octupole polarity



→ IR3 & IR7 optics validated in MD (see R. De Maria and B. Lindström, LSWG, 02/07/2024, and this meeting)

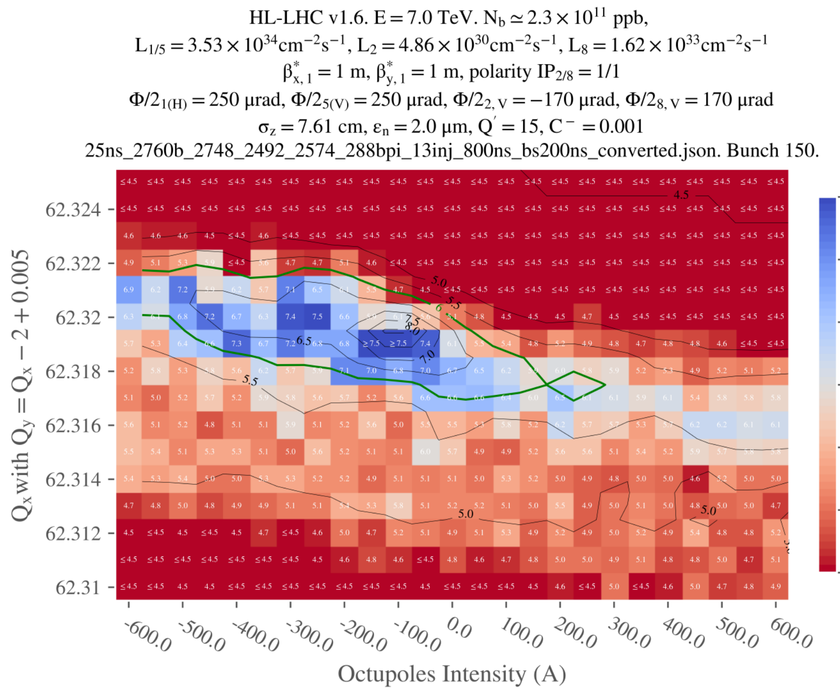
- Another potential reduction: **"sweet spot" found in MD, around Q'=20** (see ***X. Buffat**, this meeting*)

***L. Giacomel**, 224th WP2 meeting, 11/12/2023*
***L. Giacomel / B. Lindström**, WP2/WP5 meeting, 27/02/2024; this meeting*

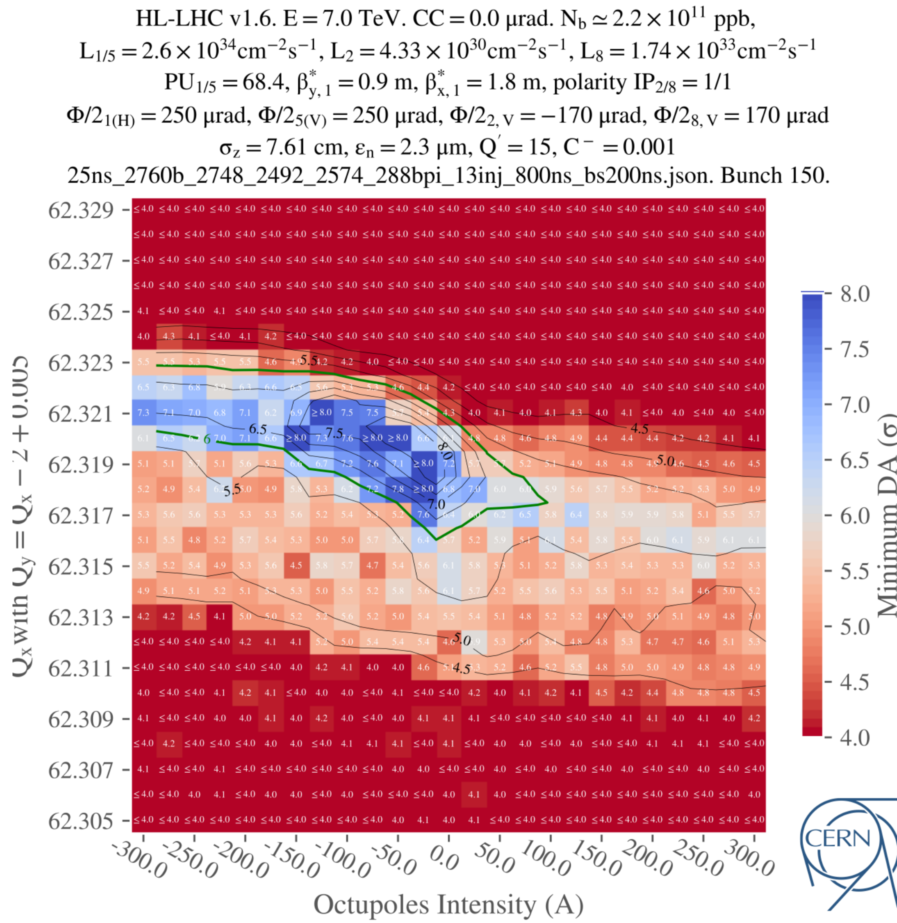
Dynamic Aperture (DA)

- **End of collapse**, scanning octupole current:

Round



Flat (note that octupoles are more effective than for round – ATS)



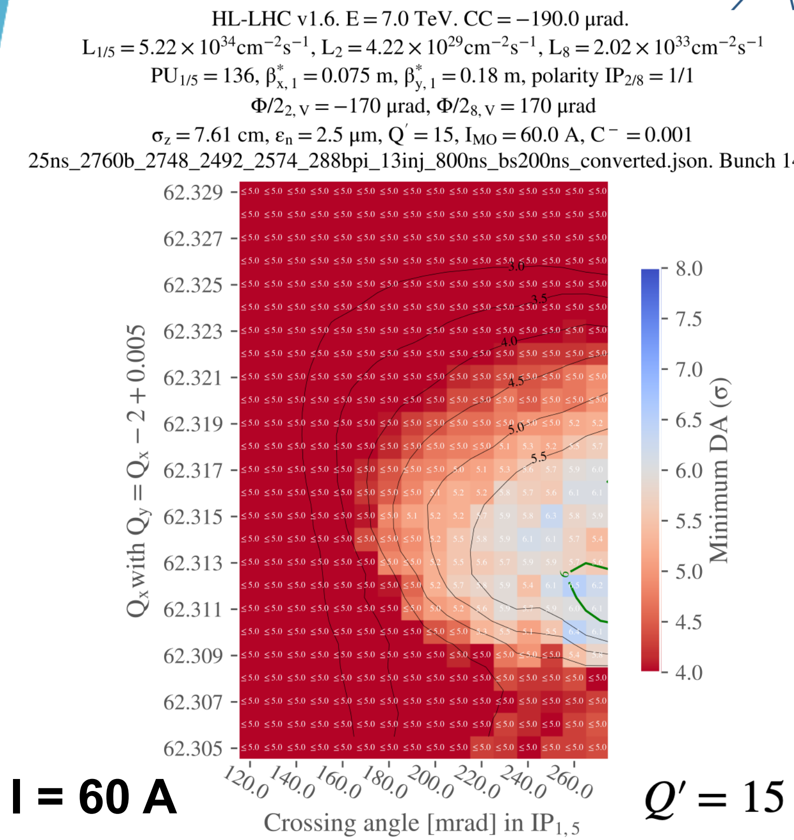
⟹ DA remains tight for >300 A in octupoles needed for stability.

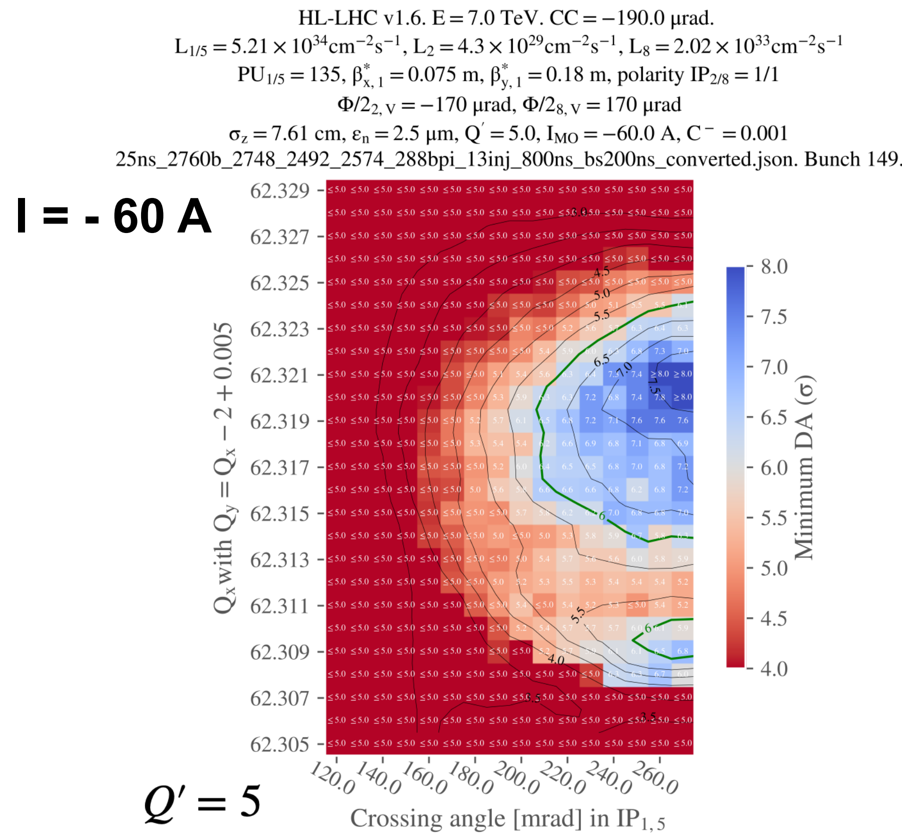
⟹ but **negative octupole polarity** will help, especially in **flat optics**.

***C. Droin** et al, THPC77, IPAC'24, **G. Sterbini**, 219th WP2 meeting, 21/09/2023, and **S. Kostoglou**, this meeting*

Dynamic Aperture (DA)

- **End of leveling**, scanning crossing angle (**flat optics** with β*=7.5/18 cm)



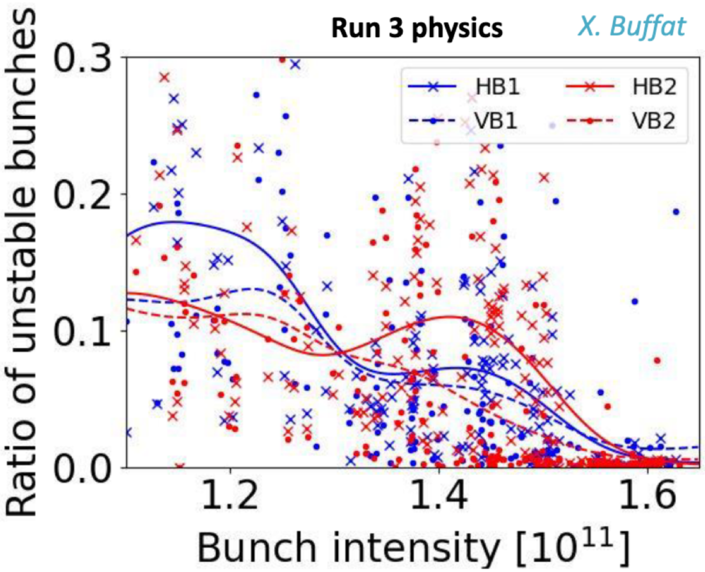


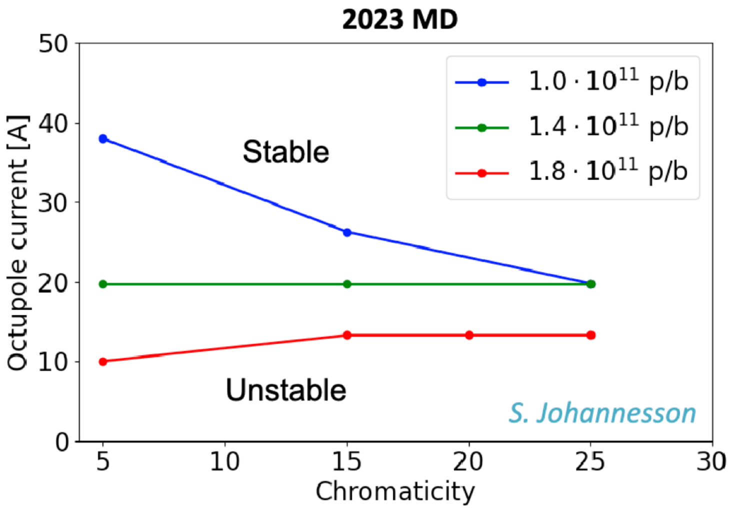
⟹ With **low Q' and negative octupoles**, one could reduce further the crossing-angle. Q'=6 is already operational in the LHC during levelling.

***C. Droin** et al, THPC77, IPAC'24, and 230th WP2 meeting, 03/09/2024,*
***G. Sterbini**, 219th WP2 meeting, 21/09/2023, and **S. Kostoglou**, this meeting*

e-cloud: LHC news

- **E-cloud situation degraded during LS1/LS2**, leading to **increased heat load.**
- **Cryo capacity estimates in several sectors have been lowered** (operation in S78 more limited than estimated in heaters measurements)
  ⟶ moved to **3x36 bunches** per train (2350 bunches with ~1.6 x 10^{11} p+/b).
- Still, some good news: **stability improvement with high bunch intensity**, leading to **lower Q' / octupole current needed at injection for HL.**
- **Negative octupole polarity** remains to be tested at injection in the LHC.



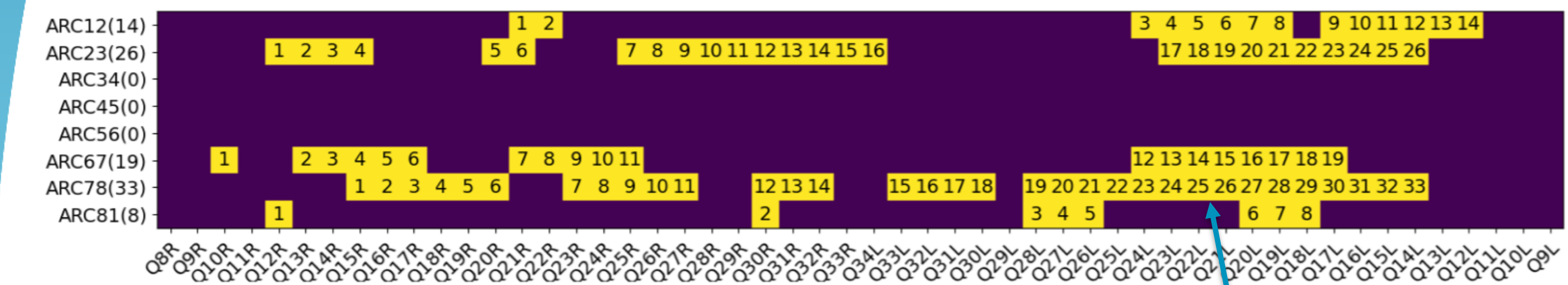


L. Mether, *HiLumi special joint WP2/WP3 Meeting, 23/01/2024, and this meeting*

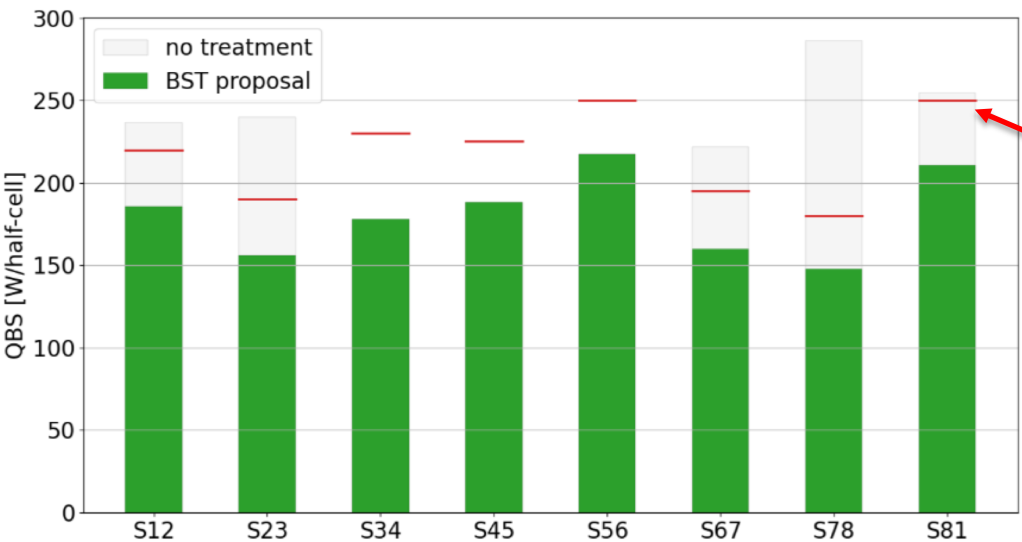
X. Buffat, *2024 LHC Chamonix workshop, 31/01/2024*

e-cloud: beam-screen surface treatment (BST)

- Partial cure foreseen in LS3: **in situ surface treatment** (see ***V. Petit***, *LHC Chamonix workshop, 23/01/2023*) – ***LHC consolidation***, *not within HiLumi project*



100 half-cells to be treated



Cryo capacity

⇒ ~15% margin in all sectors if no further degradation

B. Bradu, *228th WP2 meeting, 02/07/2024*

G. Rosaz, *2024 LHC Chamonix workshop, 31/01/2024*

e-cloud: filling scheme mitigation

- Filing schemes containing **8b+4e trains** (“**hybrid**”) are an effective means to reduce e-cloud
  - absolutely necessary without BST
  - could be necessary with BST if **significant further degradation occurs in sectors with little margin**

L. Mether, 228th WP2 meeting, 02/07/2024, and this meeting

Scenario	Beam	N bunches	8b+4e	BST	LS3 degradation	Int. lumi/day [fb^{-1}]	
Baseline	5x48b	2748	-	Yes	No	3.4	ref
Degraded S56	Hybrid	2590	17%	Yes	~40%	3.2	-6%
Degraded S45	Hybrid	2460	32%	Yes	~70%	3	-12%
No BST	Hybrid	~~2320~~	~~47%~~	No	No	~~2.8~~	~~-18%~~
No BST	Hybrid	~~2470~~	~~30%~~	No	No	~~3~~	~~-12%~~
No BST	Hybrid	2260	54%	No	No	2.7	-21%
Worst case	8b+4e	1972	100%	No/Yes	Yes	2.4	-30%

Rough luminosity estimates with LPC calculator, assuming μ=130, n_b=2.3 x 10^{11} p, L_{lev}= < 5e-34 cm^{-2} s^{-1}

LS2 degradation of S78 was ~80%

With reduced cryo capacities

Aperture

Crossing:
V IP1 / H IP5

- **Aperture** updates with round and flat optics:

	TDR Round	New Round	Flat CC HV	Flat CC HV	Flat CC VH	Flat CC VH
β* Xing/Sep [cm]	15/15	15/15	18/9	18/7.5	18/7.5	18/8
Xing angle [μrad]	±295	±250	±240	±240	±240	±240
Crossing plane IP5	V (or H)	V (or H)	V	V	H	H
Aperture in Pt. 5	12.5	13.1	13.7	12.6	12.4	12.8
MKD-TCT [°] IP5 [B1/B2]	30/31	30/31	40/45	51/54	27/25	27/25
H Ap. Protected Ti./Re.	11.9/12.9	11.9/12.9	13.3/14.3	14.1/15.1	11.7/12.7	11.7/12.7
Ap. Margin [σ], Tight	0.6	1.2	0.4	-1.5	0.7	1.1
Ap. Margin [σ], Relaxed	-0.4	0.2	-0.6	-2.5	-0.3	0.1

TCT-TCDQ retraction (thus protected ap.) closely linked to MKD-TCT phase advance

R. De Maria

Round and flat (VH) are similar for aperture

- The choice of the **flat VH optics** implies **inverting the crab cavities**. Such an inversion was always assumed to be possible, even after LS3. Nevertheless, it should be decided sufficiently well in advance.

Performance estimates for various options

Baseline (fb^{-1})	Round hybrid	Round BCMS	Flat 8/18 cm	Vbaseline extended ions	Round hybrid extended ions	Round BCMS extended ions	Flat 8/18 cm extended ions
2478.5	-10.55%	0.77%	3.28%	-8.85%	-18.45%	-8.13%	-5.79%

- In summary:
  - **Slight increase** with **BCMS (+1%)**
  - **+3%** with **flat optics** (**+4.5%** with **reduced crossing**)
  - **-9%** with **ions beyond run 4**
  - **-10%** with **hybrid**

Run	Year	Baseline	Baseline 220 urad	Flat 8/18 cm	Flat 8/18 cm 210 urad
4	2029	9.6	10.32	9.6	9.6
	2030	208	212.1	208	208
	2031	238.8	242.8	254.1	257.2
	2032	235.7	239.7	250.8	253.9
5	2035	248.5	252.3	256	259.2
	2036	311.7	316.2	320.5	324.3
	2037	316.4	321	325.3	329.2
	2038	316.4	321	325.3	329.2
6	2040	269.1	273.1	277	280.5
	2041	324.3	329	333.4	337.4
Total (fb^{-1})		2478.5	2517.5	2560	2588.5

+1.55 %   +1%

***S. Kostoglou**, 228th WP2 meeting, 02/07/2024, and this meeting*

Conclusions

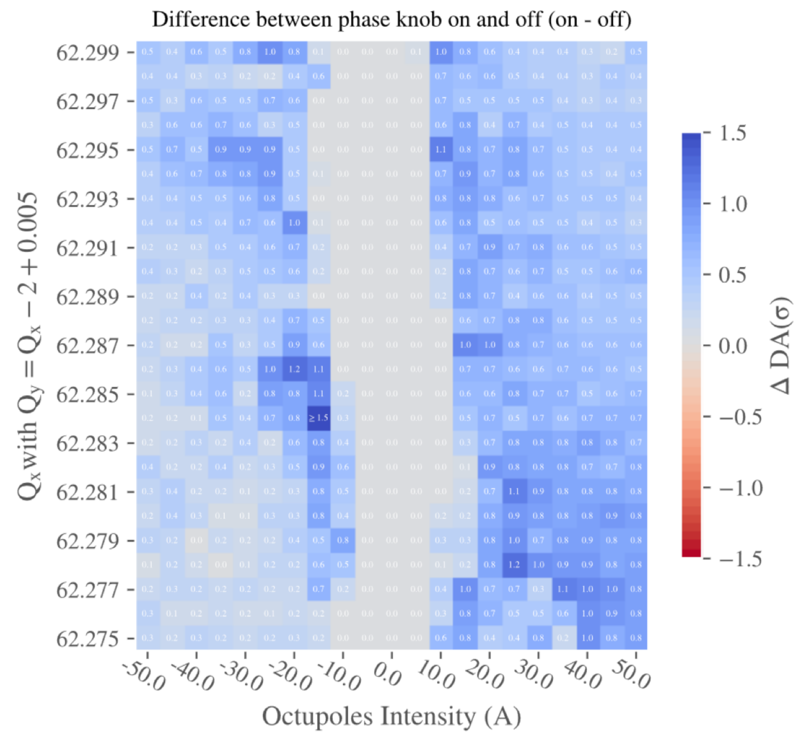
- Current baseline is robust in terms of stability, magnets field quality, aperture, and to some extent DA.
- Large unknowns remain regarding the e-cloud issue, with a possible impact on the filling scheme.
- Optimisations can be done:
  - for stability and DA risk mitigation: rematched optics and/or IR3 collimator optimisation; flat optics for crab cavity impedance; negative octupoles.
  - for luminosity: Flat VH optics, BCMS beam, and crossing angle reduction.

Backup

Dynamic Aperture: various investigations

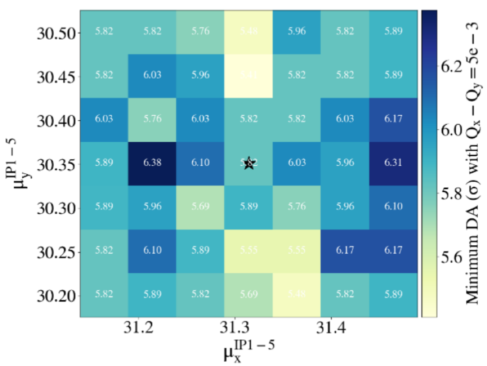
- Injection: **phase knob octupole compensation** (DA difference vs. oct.)

  C. Droin, 223rd WP2 meeting, 28/11/2023



- **Optimisation vs. phase advance** (start of levelling)

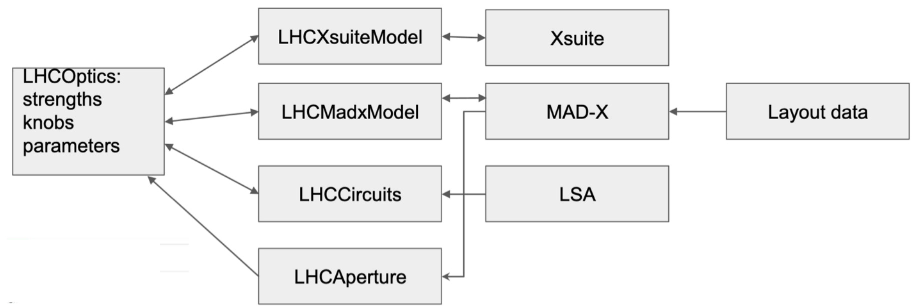
R. De Maria *et al, THBP21, HB'23*



- Single-particle DA with **flat optics and magnet errors** (*T. Pugnat, 220th WP2 meeting, 17/11/2023*) – marginally worse with flat, correction performance to investigate.
- **Impact of new IR3/IR7 optics** (see below) – DA minimally affected (***C. Droin***, WP2/WP3 meeting, *23/01/2024*).
- Assessing DA reproducibility (Xsuite) / exploring alternatives to min DA.
- **Beam-beam wire compensation: review** to take place on Oct. 14-15 (CERN), paper by **C. E. Montanari**, "Measurement of the nonlinear diffusion of the proton beam halo at the CERN LHC", under review

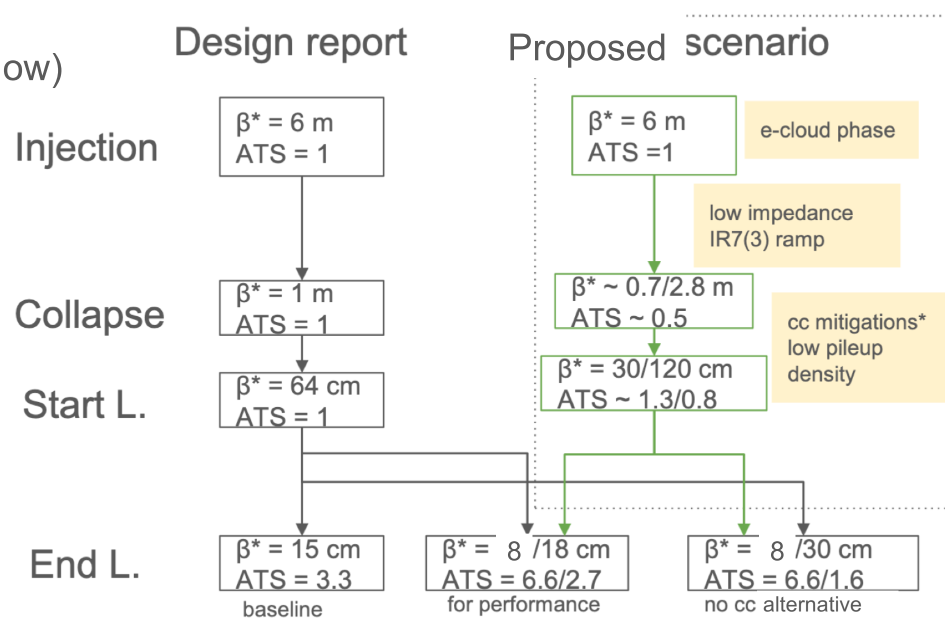
Optics and layout

- **New optics/layout version** (v1.8) – ***R. De Maria & Y. Angelis***, [227th WP2 meeting](), *28/05/2024.*
  - PPS2 added
  - first layout using only layout database data
  - layout approval in ~September.



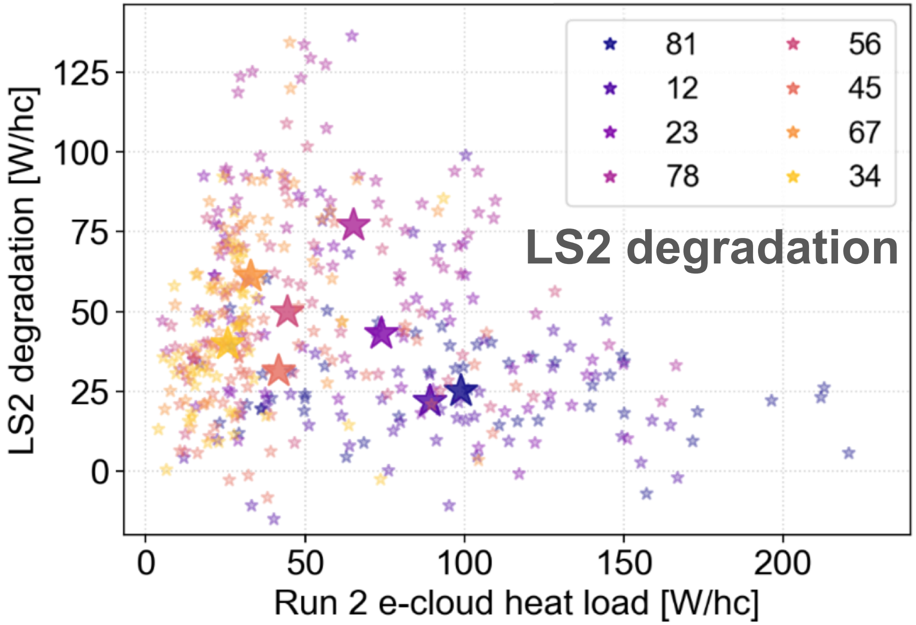
- **IR3/7 new optics** – ***B. Lindström*** (see next talk)
  - **tested in MDs**
  - promising impedance mitigation (see below)

- **New cycle proposal**:



e-cloud: possible degradation

- Further beam-screen degradation in LS3 can limit the number of bunches.

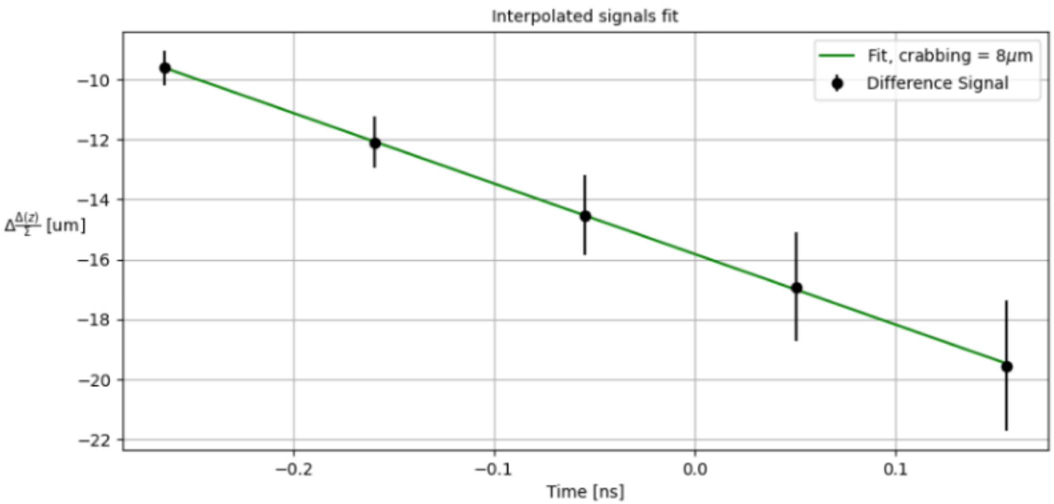


L. Mether, *HiLumi special joint WP2/WP3 Meeting*, *23/01/2024*

- High heat load cells degraded less ⟶ **BST does not remove potential for degradation** (as it is done on highest heat load cells)
- Assuming similar degradation for non-treated cells in LS3 and LS2, **treated cells roughly balance out the additional degradation**
- But resulting cryo limitations depend strongly on which cells/sectors degrade ⟶ **difficult to predict.**

Crabbing measurements & commissioning

- MDs in the LHC (2024) with **residual crabbing** from head-on beam-beam (inj.):



⟹ LHC residual crabbing **measurable** & conform to expectations

A. Fornara, *LSWG*, *02/07/2024*

- **Commissioning** and **conditioning** plans reviewed (***R. De Maria / R. Calaga (WP4) / D. Wollmann (WP7)***, WP2/WP4/WP7 joint meeting, *25/06/2024*):
  - Conditioning during hardware commissioning, continuing in operation
  - Proposal: first year with 1 MV, counter phased.
  - Impedance & noise measurements almost parasitically obtained
  - MD (or beam commissioning) tests to check full RF-ON sequence + CC-specific machine protection tests foreseen: interlocks, switch off cavities on one IP side, etc.

Update of performance estimates

- Baseline assumptions
  - intensity ramp-up included
  - **physics days** (***M. Zerlauth*** et al, EDMS 2902691, in preparation):

Run	Year	Efficiency	Bunch intensity (1e11 ppb)	β_x^* (cm)	β_y^* (cm)	CC	PU_{max}	Days Intensity ramp-up	Days Proton physics [1]	# colliding IP1/5 bunches [2]	# colliding IP8 bunches	Emit start of SB (μm)	IP1/5 crossing plane	IP1/5 φ/2 (μrad)	LHCb L_{peak} (1e33 Hz/cm²) [3]
4	2029	0.5	1.8	30	30	off	101	20	6	2748	2574	2.5	H/V	250	2
	2030	0.5	2.2	25	25	on	132	15	136	2748	2574	2.5	H/V	250	2
	2031	0.5	2.2	20	20	on	132	10	154	2748	2574	2.5	H/V	250	2
	2032	0.5	2.2	20	20	on	132	10	152	2748	2574	2.5	H/V	250	2
5	2035	0.5	2.2	15	15	on	132	15	152	2748	2574	2.5	H/V	250	2
	2036	0.5	2.2	15	15	on	132	10	195	2748	2574	2.5	H/V	250	2
	2037	0.5	2.2	15	15	on	132	10	198	2748	2574	2.5	H/V	250	2
	2038	0.5	2.2	15	15	on	132	10	198	2748	2574	2.5	H/V	250	2
6	2040	0.5	2.2	15	15	on	132	15	165	2748	2574	2.5	H/V	250	2
	2041	0.5	2.2	15	15	on	132	10	203	2748	2574	2.5	H/V	250	2

Extended ions after run 4
⟶ 22-24 less days

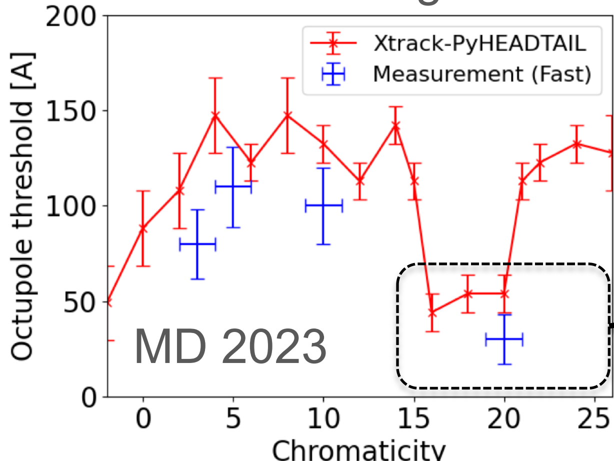
Hybrid: 2440 / 2240
BCMS: 2736 / 2370

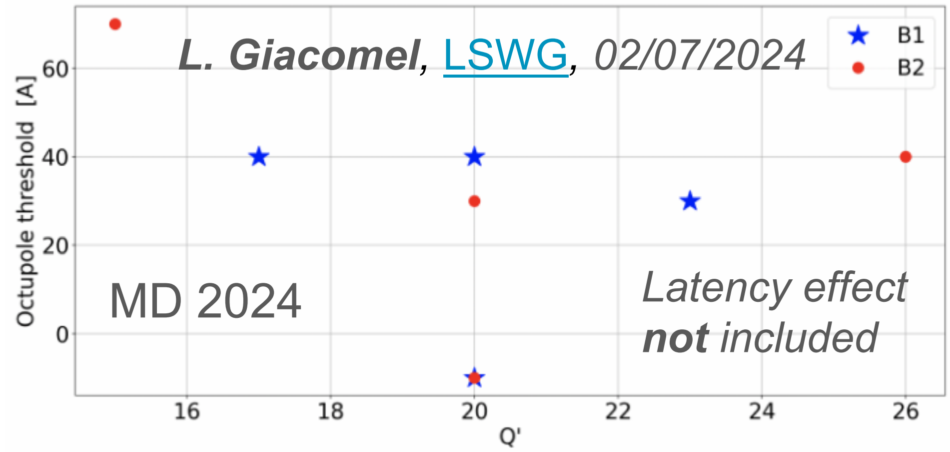
BCMS: 2.2

S. Kostoglou, *228th WP2 meeting*, *02/07/2024*

Transverse impedance & stability

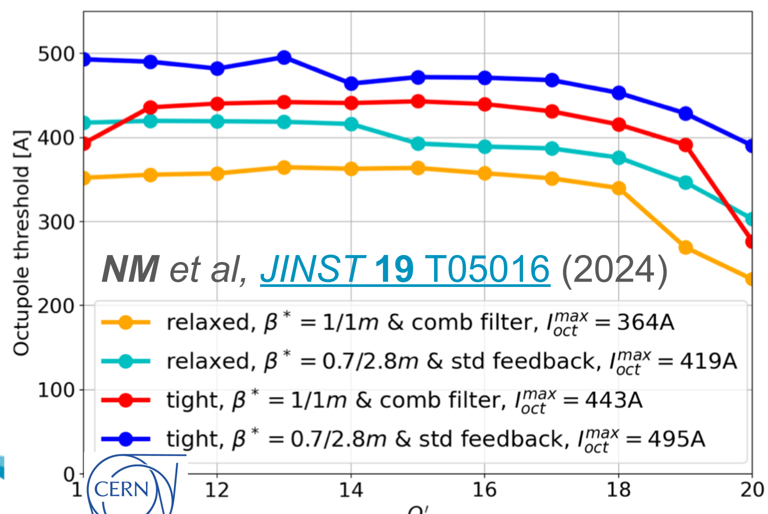
- **LHC MDs on octupole threshold:** potential large improvement at very high Q' from non-linear longitudinal motion





X. Buffat, [2024 LHC Chamonix workshop](), *31/01/2024,* and this meeting

- **Stability limits revised**: octupole threshold vs Q'



Assumptions: Gaussian transverse **tails**, positive octupole polarity, latency effect included

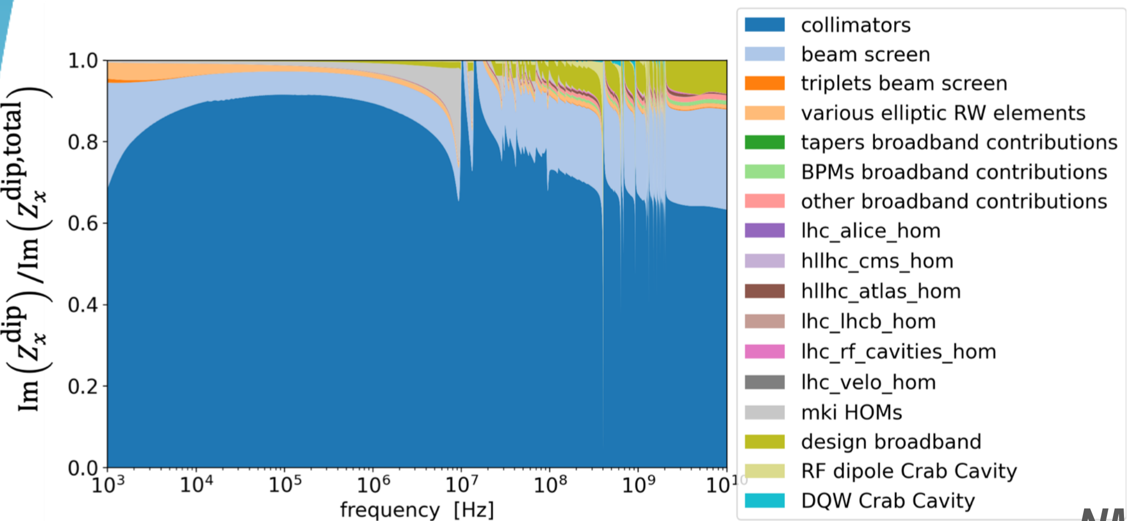
⟹ **Limit depends on CC and its mitigation** (flat optics, comb filter)

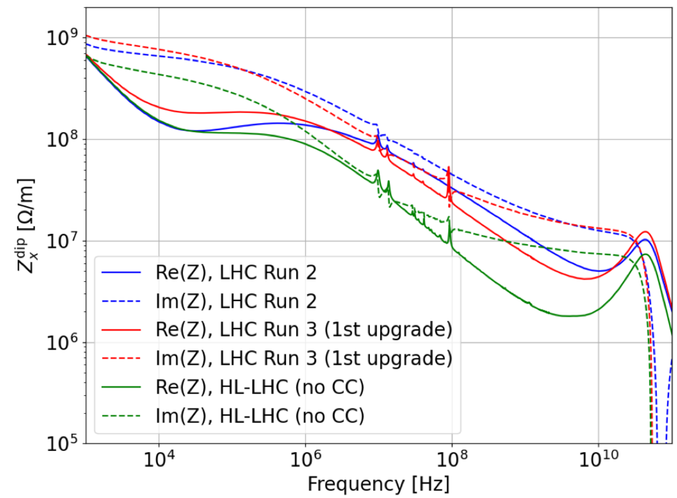
⟹ A few factors might help and are studied: **new optics + non-linear RF**

See also ***L. Giacomel***, this meeting

Transverse impedance & stability

- **Collimators** dominate transverse impedance ⟹ coll. upgrade beneficial:

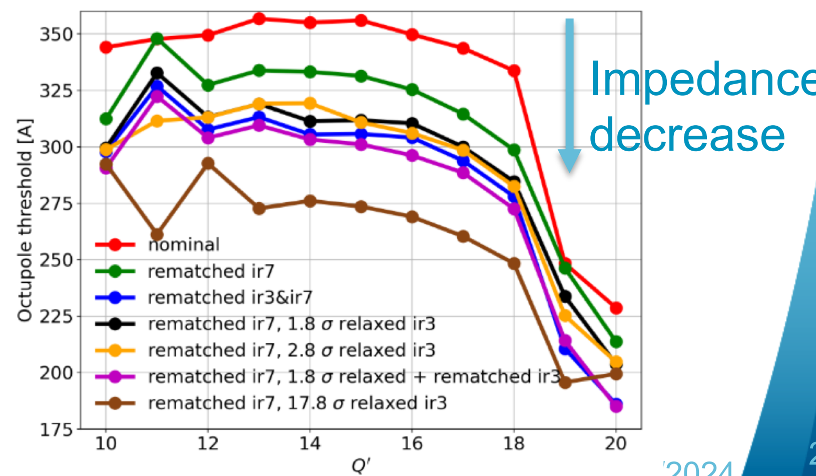




***NM** et al*, [*JINST* **19** T05016](#) (2024)

- **New optics for IR7** (see ***B. Lindström***, next talk), and in **IR3,** would decrease even further the impedance:

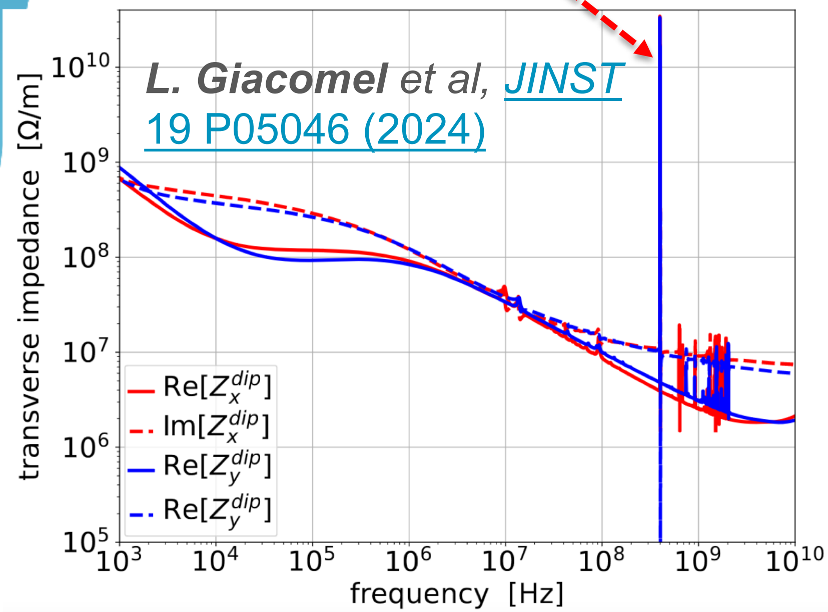
  ⟹ IR3 & IR7 optics validated in MD (see R. De Maria and B. Lindström, [LSWG](#), 02/07/2024)



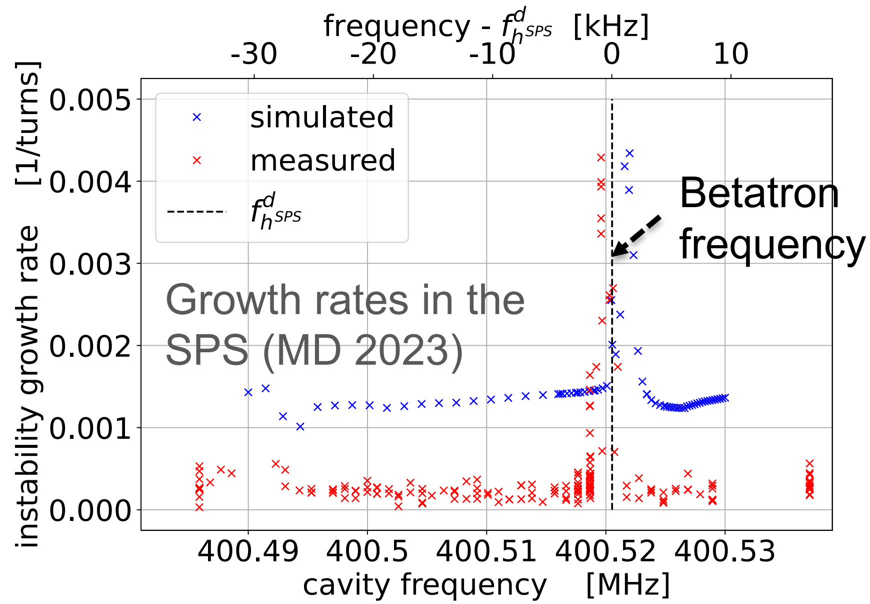
L. Giacomel, *[224th WP2 meeting](#), 11/12/2023*
L. Giacomel / B. Lindström, *[WP2/WP5 meeting](#), 27/02/2024; this meeting*

Crab cavities (with WP4) – impedance

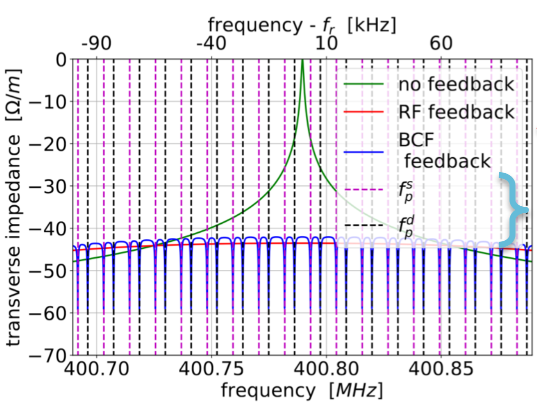
- Fundamental mode has a strong effect on transverse impedance:



L. Giacomel et al, JINST 19 P05046 (2024)



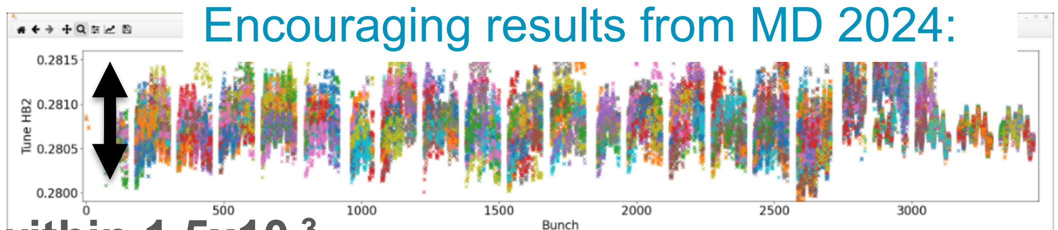
- Mitigations: **RF feedbacks** (std, **betatron comb filter**), **optics** (flat)



Lowering impedance at betatron frequencies

Tune acceptance (~5 10^{-3}) can be an issue.
⟶ Need to check multibunch tune shifts.

Encouraging results from MD 2024:



within 1.5x10^{-3}

L. Giacomel, LSWG, 02/07/2024

e-cloud: filling scheme mitigation

- Filing schemes containing **8b+4e trains** (“**hybrid**”) are an effective means to reduce e-cloud
  - absolutely necessary without BST
  - could be necessary with BST if **significant further degradation occurs in sectors with little margin**

L. Mether, *[228th WP2 meeting](), 02/07/2024*

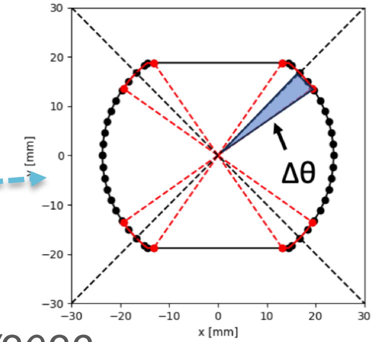
Scenario	Beam	N bunches	8b+4e	BST	LS3 degradation	Int. lumi/day [fb^{-1}]	
Baseline	5x48b	2748	-	Yes	No	3.4	ref
Degraded S56	Hybrid	2590	17%	Yes	~40%	3.2	-6%
Degraded S45	Hybrid	2460	32%	Yes	~70%	3	-12%
No BST	Hybrid	~~2320~~	~~47%~~	No	No	~~2.8~~	~~-18%~~
No BST	Hybrid	~~2470~~	~~30%~~	No	No	~~3~~	~~-12%~~
No BST	Hybrid	2260	54%	No	No	2.7	-21%
Worst case	8b+4e	1972	100%	No/Yes	Yes	2.4	-30%

Rough luminosity estimates with LPC calculator, assuming μ=130, n_b=2.3 x 10^{11} p, L_{lev}= < 5e-34 cm^{-2} s^{-1}

LS2 degradation of S78 was ~80%

With reduced cryo capacities

- It is **critical** to minimise any possible source of e-cloud, in particular in **high β** parts of the machine: **Q4 & Q5**
  ⟶ optimising laser treatment in corners of Q5
  ⟶ ongoing study for uncoated BPM in Q4/Q5.



K. Paraschou, *[221th WP2 meeting](), 24/10/2023*

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- R. De Maria, R. Bruce, X. Buffat, G. Iadarola, S. Kostoglou, M. Giovannozzi, B. Lindström, L. Mether, E. Métral, N. Mounet, S. Redaelli, G. Sterbini, R. Tomás, *High Luminosity LHC Optics Scenarios for Run 4*, IPAC'23, MOPL034, https://doi.org/10.18429/jacow-ipac2023-mopl034.
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