Update on electron cloud studies

L. Mether, K. Paraschou

On behalf of:

WP2, the Electron cloud team and the Beam-Induced Heat Load task force

14th HL-LHC Collaboration meeting
Genoa, Italy
7-10 October 2024

Outline

- LHC electron cloud heat loads
  - Run 3 summary and 2024 status
  - Implications for Run 3 and HL-LHC
  - Cryo capacity revisions and impact on HL-LHC

- Beam stability and incoherent effects
  - Stability and incoherent effects at injection
  - Stability and slow losses in collision
  - Triplet simulations

- Other studies
  - Coherent tune shifts from e-cloud
  - Observations from LESS-treated beam pipe

- Conclusions

Heat load evolution in Run 3

2022

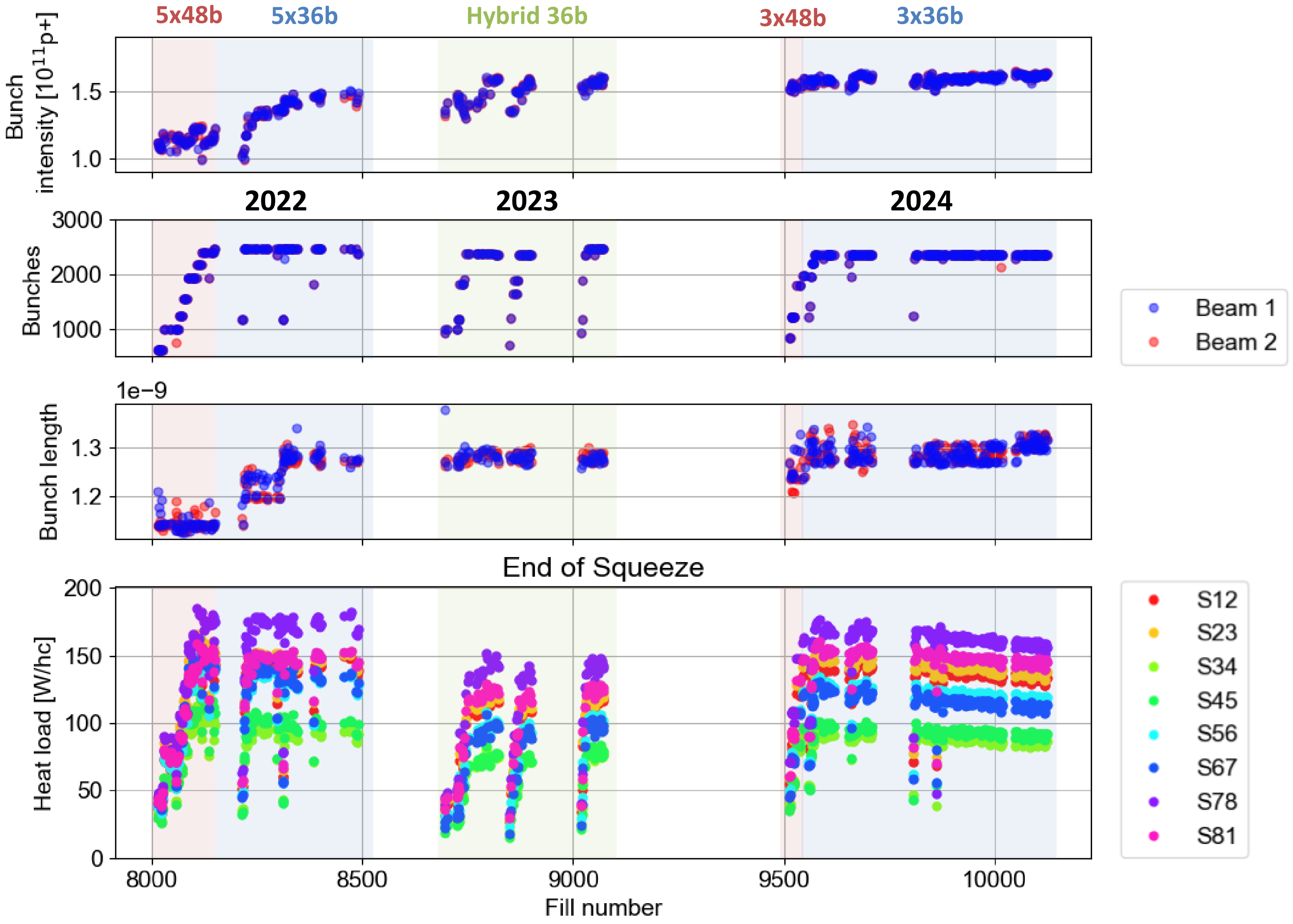
- Limited by heat load in S78
- Running with constant heat load, adjusting number of bunches, bunch intensity and bunch length

2023

- Short run with hybrid scheme at roughly constant heat load
- Bunch intensity limited to 1.6e11 ppb, due to RF module heating

2024

- Switched back to 25 ns beam, since bunch intensity limited to 1.6e11 ppb
- Limited by cryo at the beginning of the year → revised cryo capacities
- Fixed beam parameters for most of the year → decreasing heat load



Scrubbing in Run 3

2022

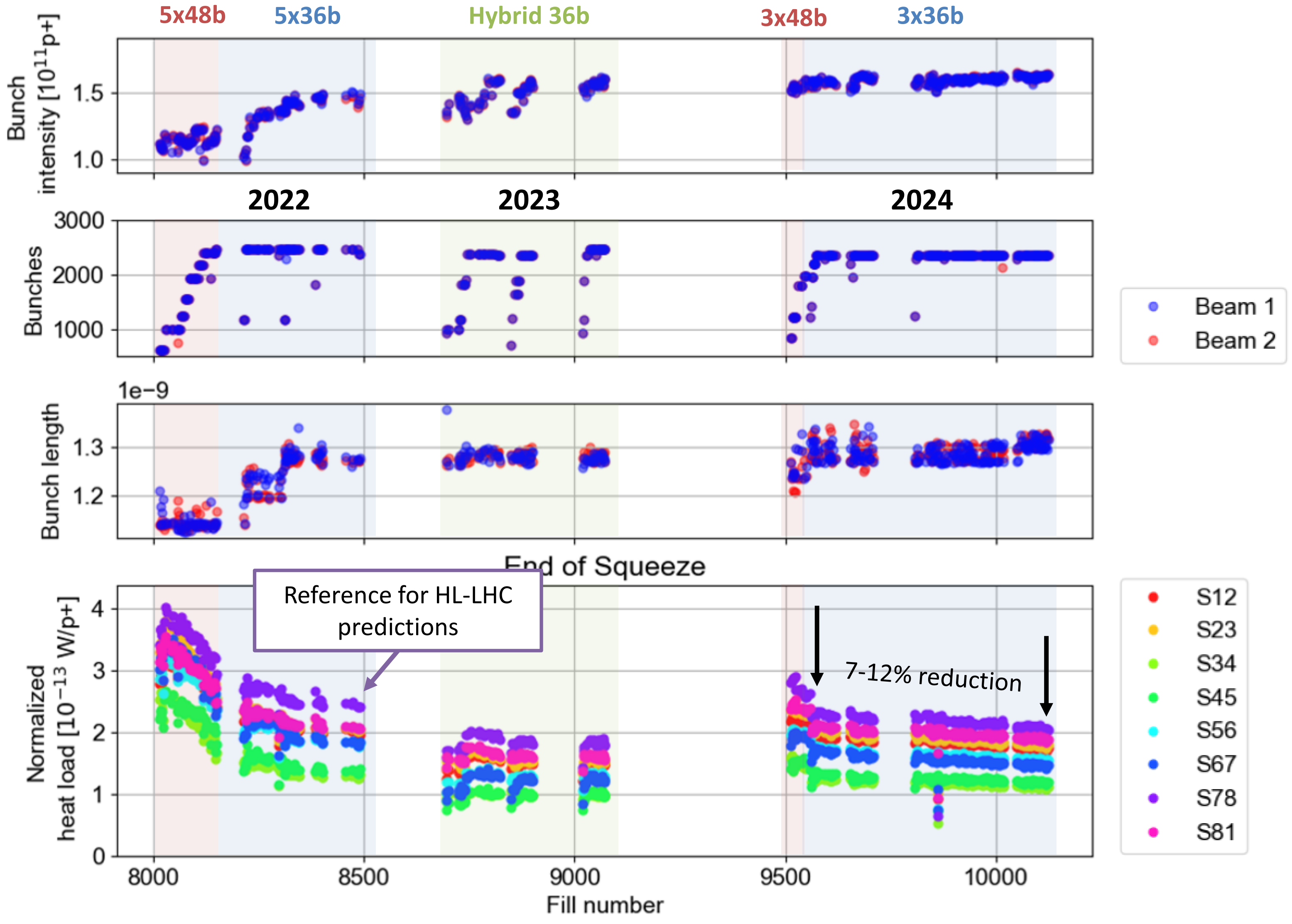
- Clear scrubbing, but difficult to assess pace due to many changes in beam parameters
- Signs of scrubbing slowing down by the end of the year

2023

- Very mild signs of scrubbing
- Difficult to disentangle scrubbing from varying parameters between the 25ns and 8b+4e beam types

2024

- Slow scrubbing evident in all sectors
- Heat load reduced by 7-12% in the different sectors during 2024
- A few percent more w.r.t. 2022



Implications for Run 3 and beyond

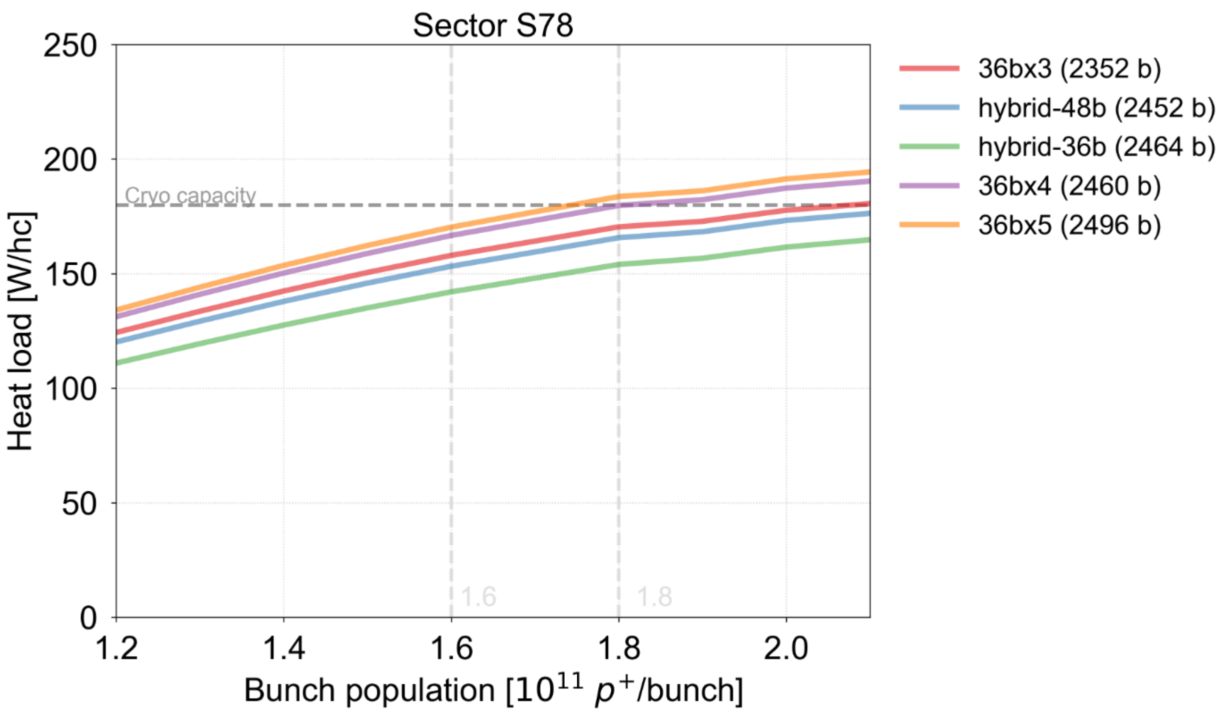
- For LHC in Run 3, hybrid schemes may not be necessary to reach ~2450 bunches with 1.8e11 ppb

- Using hybrid schemes for some amount of time to gain operational experience as a back-up for HL-LHC has been proposed

  - The impact on emittance of time spent at flat bottom in the SPS vs LHC could be quantified

  - Dependence of injection losses on train length could be evaluated after improvements in 2024

  - Time for optimisation of emittance and intensity variations between the two beam types in the injectors

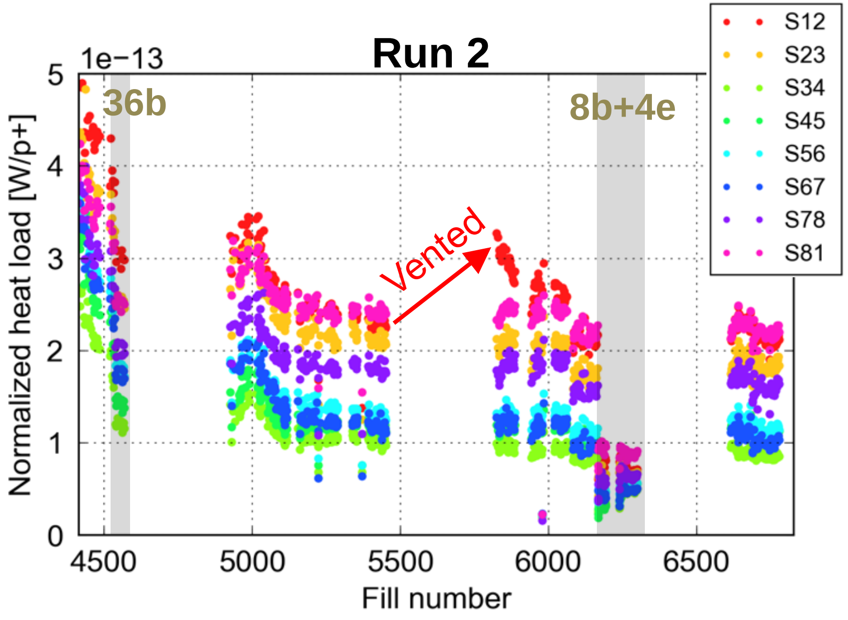


Heat load measurements at injection with up to 2.3e11 ppb planned in MD5

- Limited to < 1000 bunches, due to beam-induced heating in RF modules

Implications for Run 3 and beyond

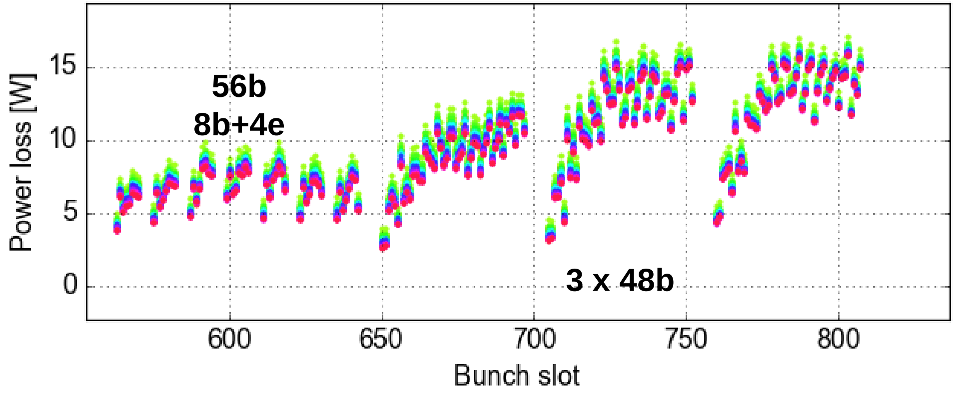
- In Run 2, very little evolution of heat loads observed after 2016 → is scrubbing slower in Run 3?
  - When increasing the bunch intensity, we may be scrubbing slightly different areas of the dipole beam screens
  - Scrubbing with shorter trains is also less efficient



- Assuming that mainly saturated e-clouds scrub, 48b schemes have a much higher scrubbing potential than 36b schemes, since the rise time of the e-cloud is around 20-30 bunches

  → 3x36b (2352b) has 95%-55% of the scrubbing potential of the hybrid-48b scheme (2452b)

  → Optimising the filling scheme for scrubbing, even temporarily limiting the number of bunches(?), may have a positive impact on integrated luminosity over time



Cryo capacities

- The cryogenics capacities in several sectors have been revised after the observed discrepancy for S78 between measurements with heaters and operation with beam
  - The main impact on HL-LHC is an adjustment in the selection of half-cells for the beam screen treatment (BST)

    → Reduced margin per untreated cell in some sectors

[B. Bradu]

	S12	S23	S34	S45	S56	S67	S78	S81
Number of cells	16	23	0	3	0	24	26	8
Margin per cell [W]	40	40	50	45	60	40	40	55
Margin per untreated cell [W]	60	75	50	45	60	80	80	65

	S12	S23	S34	S45	S56	S67	S78	S81
Number of cells	**14**	**26**	0	**0**	0	**19**	**33**	8
Margin per cell [W]	**35**	**35**	50	**35**	**35**	**35**	**30**	**40**
Margin per untreated cell [W]	**45**	**70**	50	**35**	**35**	**55**	**90**	**45**

- S12: 220
- S23: 205 → 190
- S34: 230
- S45: 225
- S56: 250 → 275 → 250
- S67: 195
- S78: 195 → 225 → 215 → 180
- S81: 275 → 210 → 265 → 250

After 2024 operation

After heater measurement

S78 optimised configuration

Annual meeting 2023

Lowest margin for degradation in S45 and S56

- Both have roughly similar heat loads to that of S78 in Run 2, so could degrade similarly in LS3 (~100 W/cell with HL-LHC beam parameters)

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Annual meeting 2023 → S78 optimised configuration → After heater measurement → After 2024 operation

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	S12	S23	S34	S45	S56	S67	S78	S81
Number of cells	**16**	**30**	0	**4**	**3**	**23**	**36**	8
Margin per cell [W]	**40**	**45**	50	**45**	**40**	**45**	**40**	40
Margin per untreated cell [W]	**60**	**100**	50	**50**	**45**	**80**	**135**	45

Lowest margin for degradation in S45 and S56

Risk reduced if 120 cells or more can be treated

(~100 W/cell with HL-LHC beam parameters)

Performance estimates for Run 4

- The HL-LHC baseline scenario is possible only after beam screen treatment
  - Without treatment, the number of bunches would be limited to ~2300 using hybrid schemes, and further degradation could bring further limitations

- Even with treatment, degradation of beam screens in untreated cells and sectors can limit the performance, e.g. if S56 or S45 degrades similarly to S78
  - Hybrid filling schemes help to mitigate the loss of luminosity
  - Impact is smaller than from an untreated S78, due to higher cryo capacity

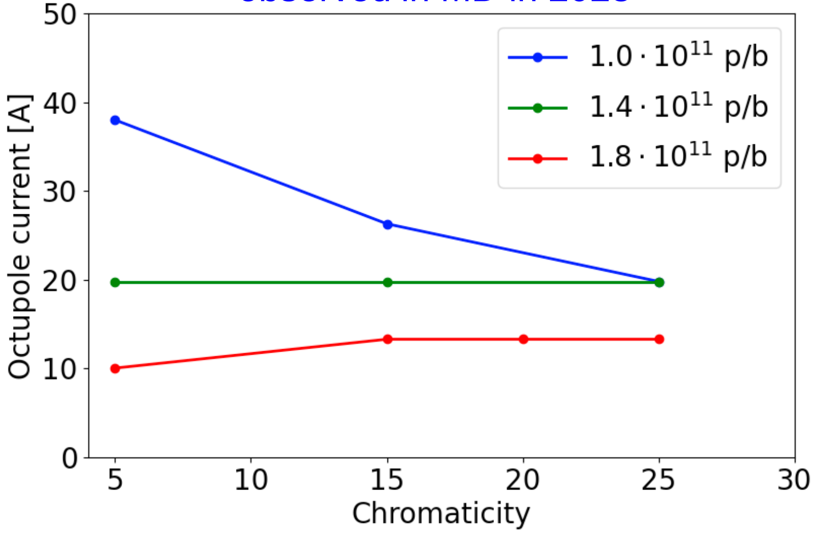
- The 8b+4e beam is always a fall-back solution in case of severe further degradation, but is unlikely to be needed

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 (S78)	Hybrid	2260	54%	No	No	2.7	-21%
Worst case	8b+4e	1972	100%	No/Yes	Yes	2.4	-30%

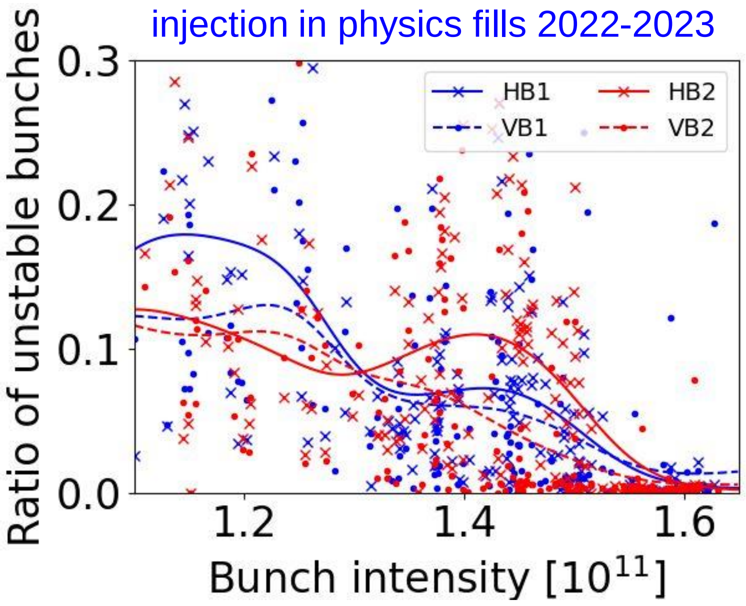
Instabilities from quadrupoles at injection

- Favourable scaling with intensity of transverse instabilities from electron cloud in the quadrupoles at injection energy has been confirmed in both dedicated measurements and operation in 2022-2023

Improvement in stability observed in MD in 2023

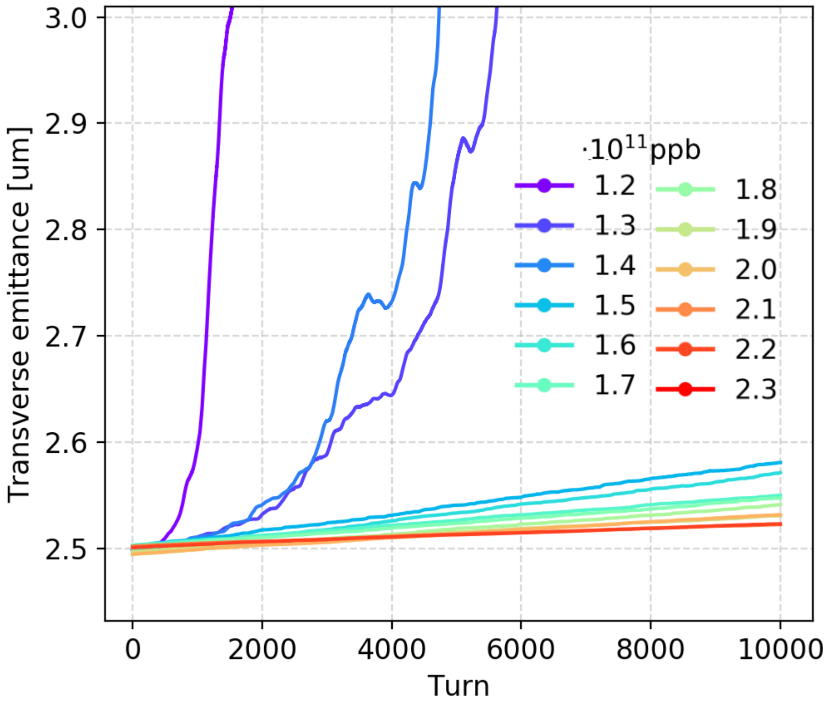


Reduction of unstable bunches at injection in physics fills 2022-2023



[X. Buffat]

Consistent with predictions from macro-particle simulations



- Stability measurements with negative octupole current planned in MD5

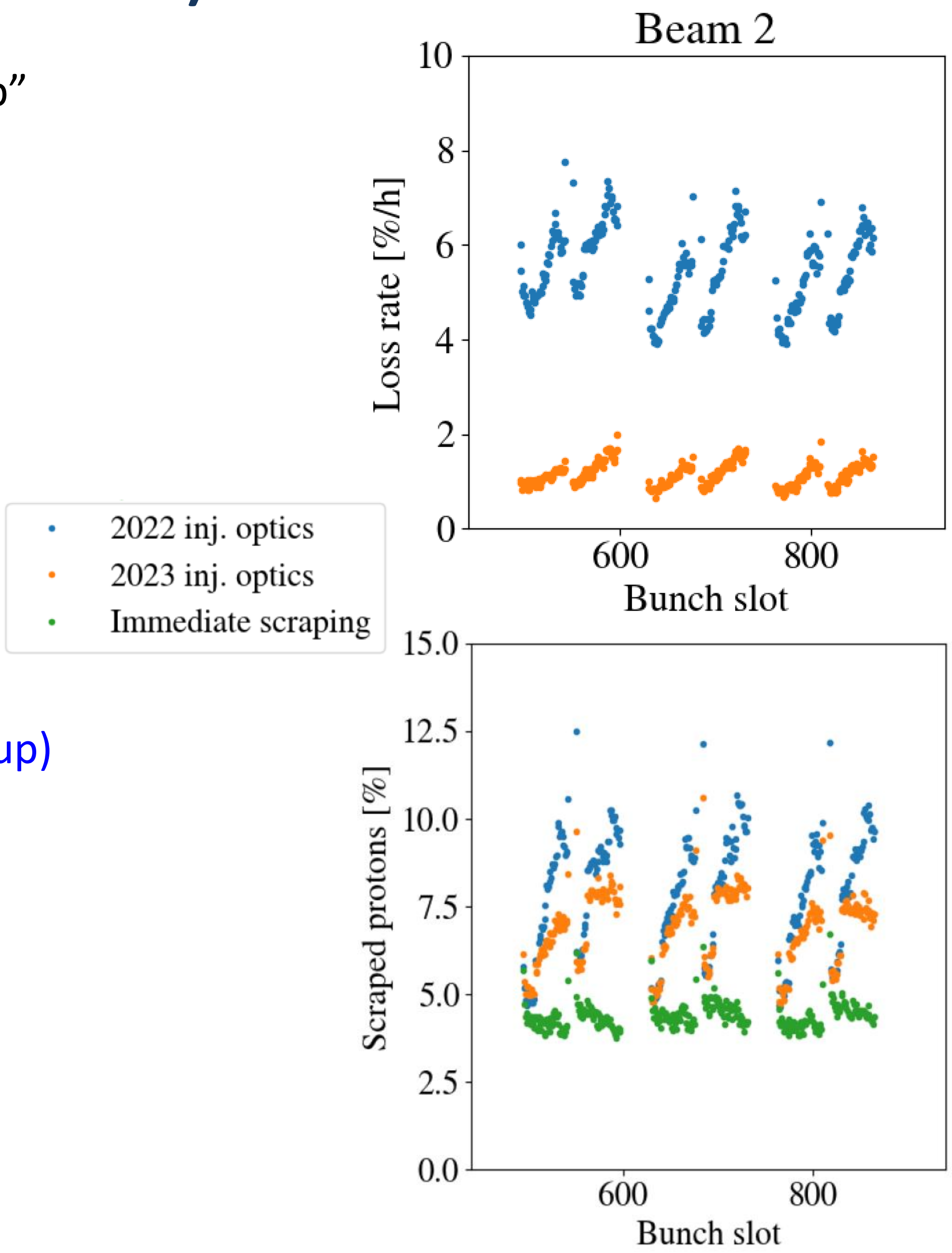
2023 Injection optics (phase knob) - MD

New injection optics introduced in 2023 in the form of the ”phase knob”

- Arc-by-arc phase advance change to mitigate:
  - Octupolar resonances from landau octupoles
  - Octupolar synchro-betatron resonance from electron cloud in main quadrupoles

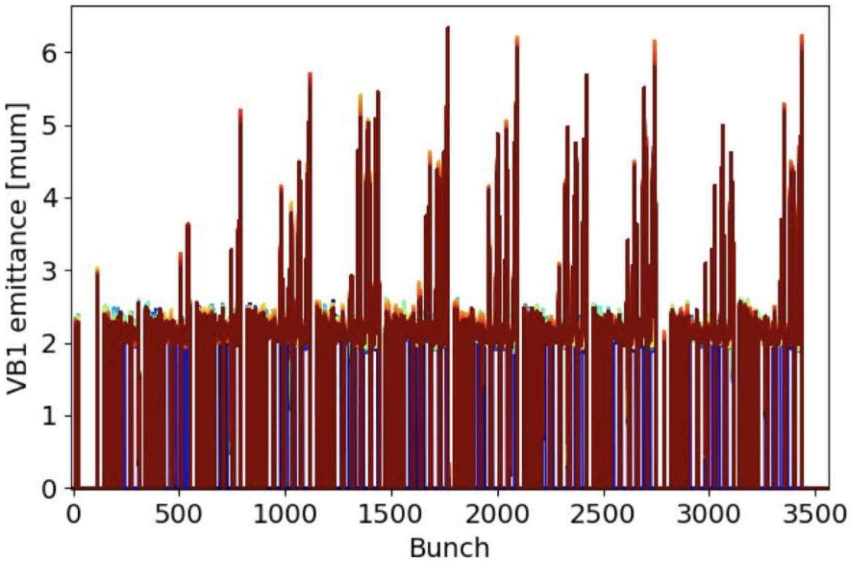
- Dedicated measurements in LHC MD2 (2024):
  1. Both “non e-cloud” and “e-cloud” losses greatly reduced
  2. “E-cloud” halo formation reduced
  3. Spread in bunch-by-bunch BSRT emittances reduced (see backup)

- Note: For Run 4, phases should be adjusted according to outcome of Beam Screen Treatment project

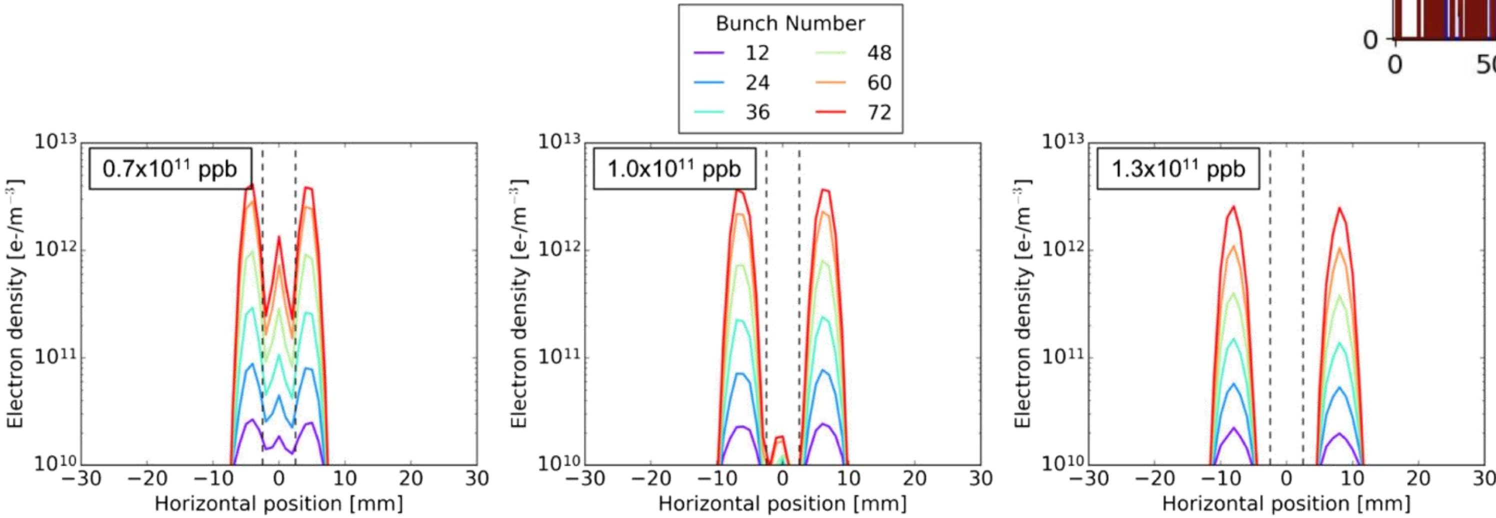


Instabilities from dipoles at collision energy

- Vertical instabilities due to growth of central dipole stripe with decreasing bunch intensity at the end of stable beams are systematically observed, but usually only when IP1 or 5 is separated for luminosity scans
    - Lower chromaticity in collision has not significantly changed the picture *(see previous talk by X. Buffat)*
    - Precise mechanism, including the impact of IP separation, to be studied by coming PhD student on e-cloud instabilities (partially funded by HL-LHC)



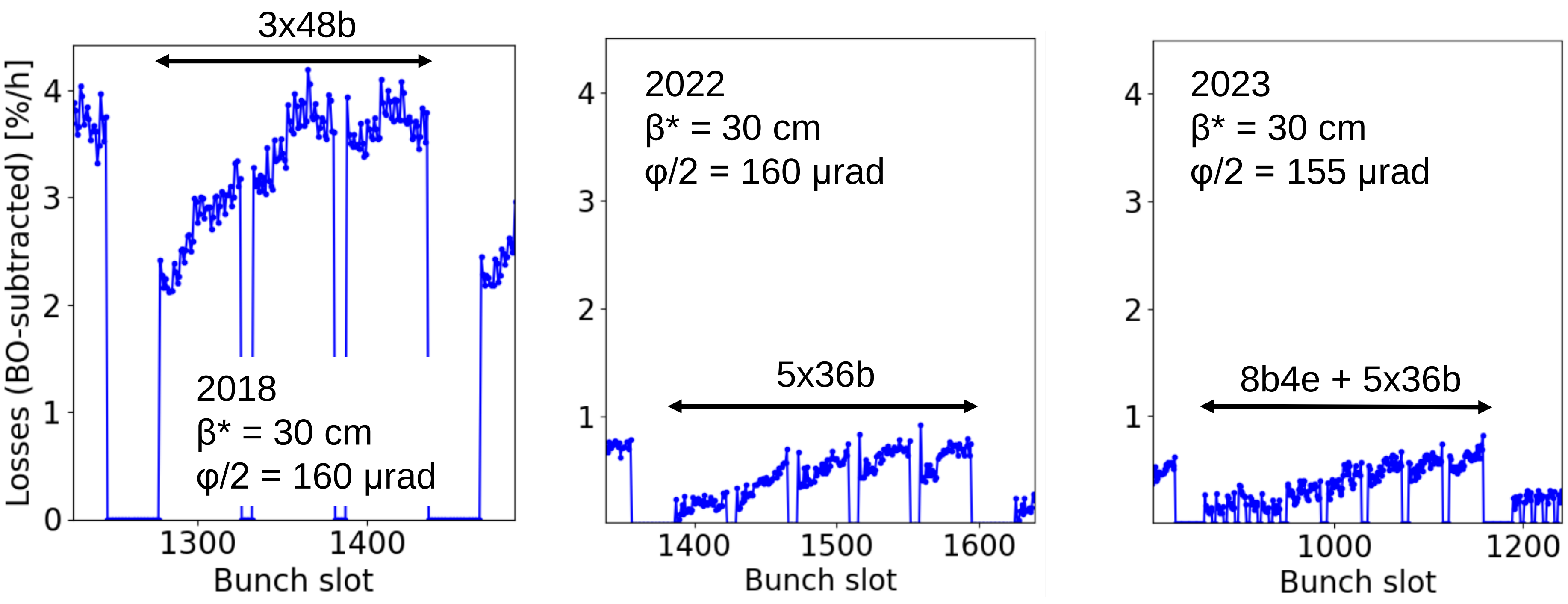
[X. Buffat]



A. Romano et al, Phys. Rev. Accel. Beams 21, 061002

Beam loss during collisions

- With the beams in collision, slow losses in addition to losses from burn-off (BO) are observed
  - Caused by e-cloud in the Inner Triplets, enhanced by the large beta functions



The relative losses are smaller in Run 3 than in Run 2

- Long-term tracking simulations including longitudinally resolved electron cloud in the triplets and beam-beam effects have been performed for the first time
  - They suggest that the increase in bunch intensity in Run 3 is largely responsible for the improvement

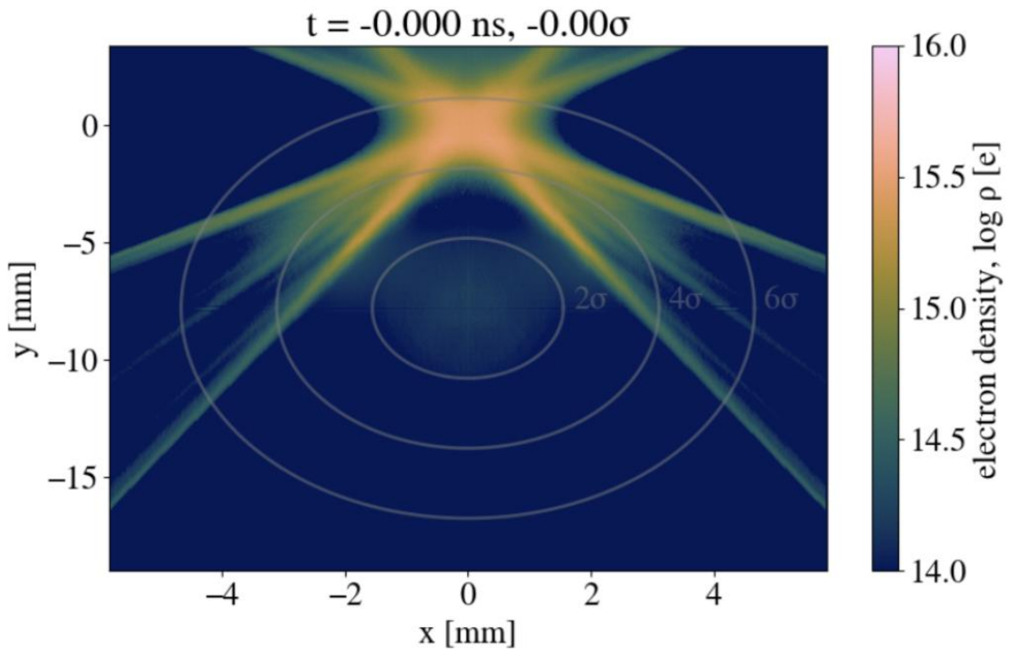
Effective e-cloud in LHC Inner Triplets

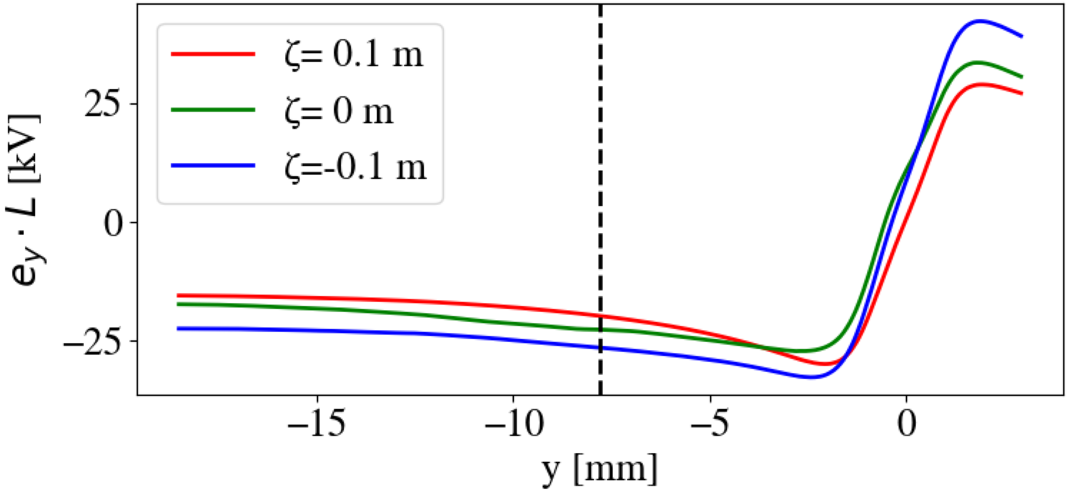
- Method developed for simulation of incoherent effect of e-cloud in the Inner Triplets in Xsuite

- Known to cause slow beam losses during stable beams
  Possibly also halo formation *(see P. Hermes talk)*

- Non-linear time-dependent forces
  - Forces become exceedingly non-linear at large amplitudes of oscillation

$$\Phi(x, y, \zeta) = \sum_i \phi_i \left(\sqrt{\frac{\beta_{x,i}}{\beta_{x,k}}} (x - x_k) + x_i, \sqrt{\frac{\beta_{y,i}}{\beta_{y,k}}} (y - y_k) + y_i, \zeta \right)$$





LHC Inner Triplets simulations

Dynamic aperture simulations:

- 1M turns, β* = 30 cm, 2023 configuration

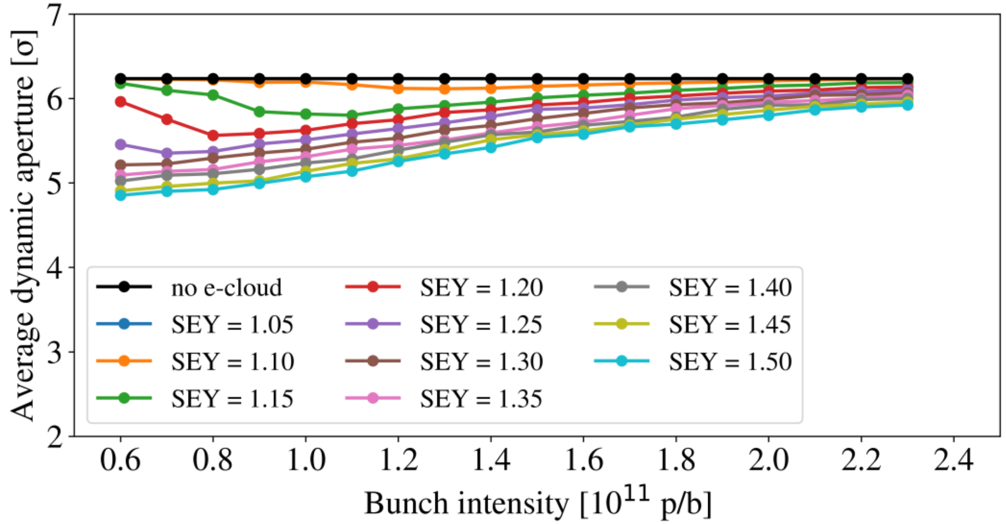
- E-cloud in triplet scales favorably with increasing intensity
  - E-cloud effects can become as strong as beam-beam effects at low bunch intensities

- Worse with larger Secondary Emission Yield (SEY)

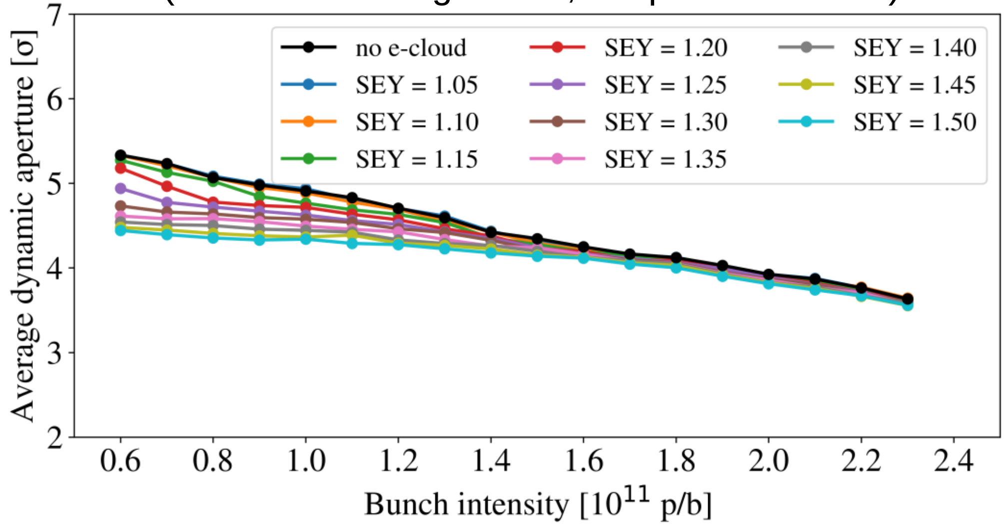
- Strategy to coat the new inner triplets with amorphous carbon remains a good solution

*Dynamic aperture only to be compared in relative and not with other studies

Without beam-beam effects:

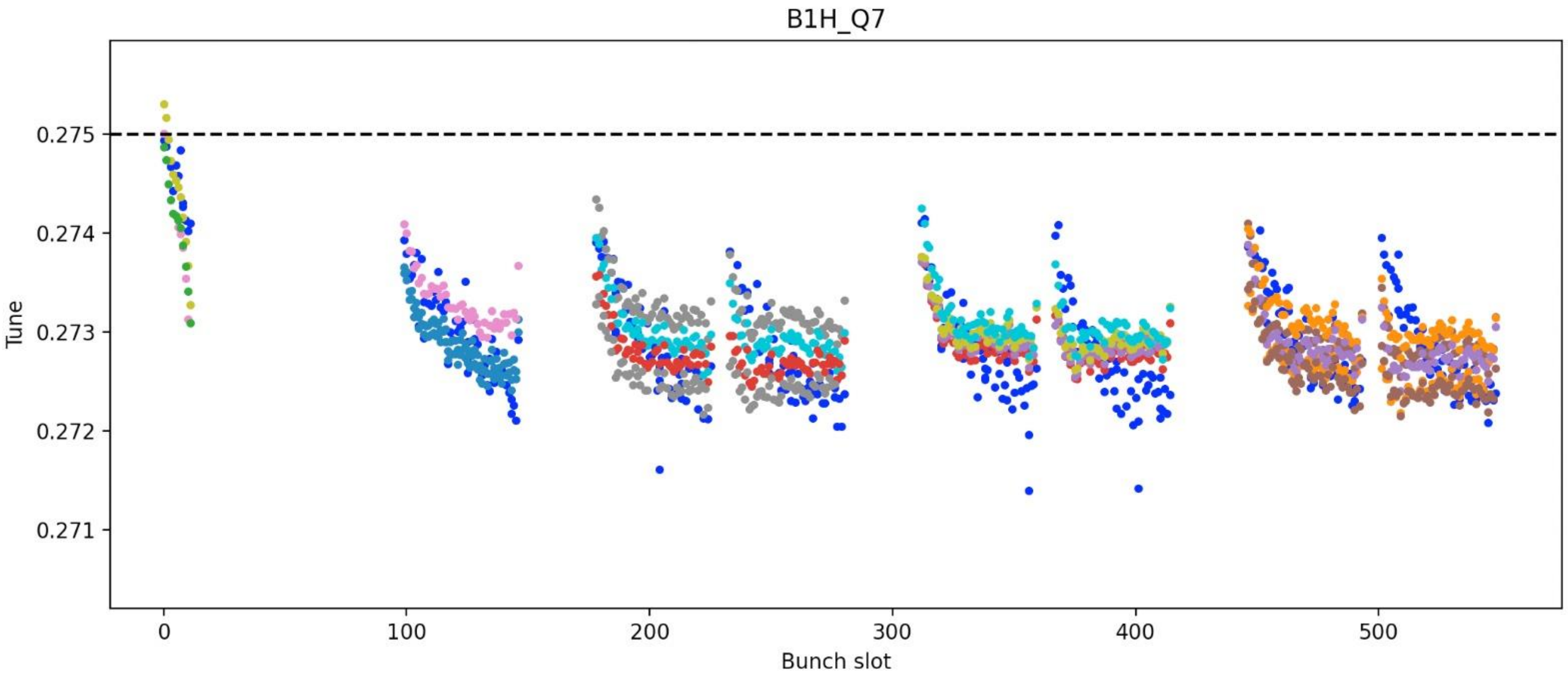


With beam-beam effects
(LHC 2023 configuration, unoptimised tunes):



Bunch-by-bunch tune shift MD

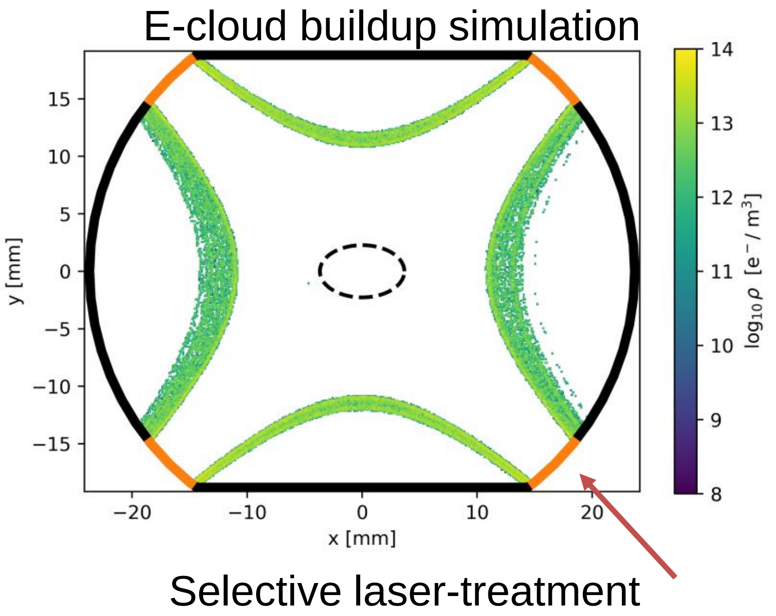
- Successful MD for measuring bunch-by-bunch tune shifts at injection
  - Measurements with varying bunch intensity 2.3e11, 2.0e11, 1.65e11, 1.2e11 ppb in trains of 2x48b (348b)
  - Different bunches and groups of bunches along trains kicked to compare with predictions from simulation

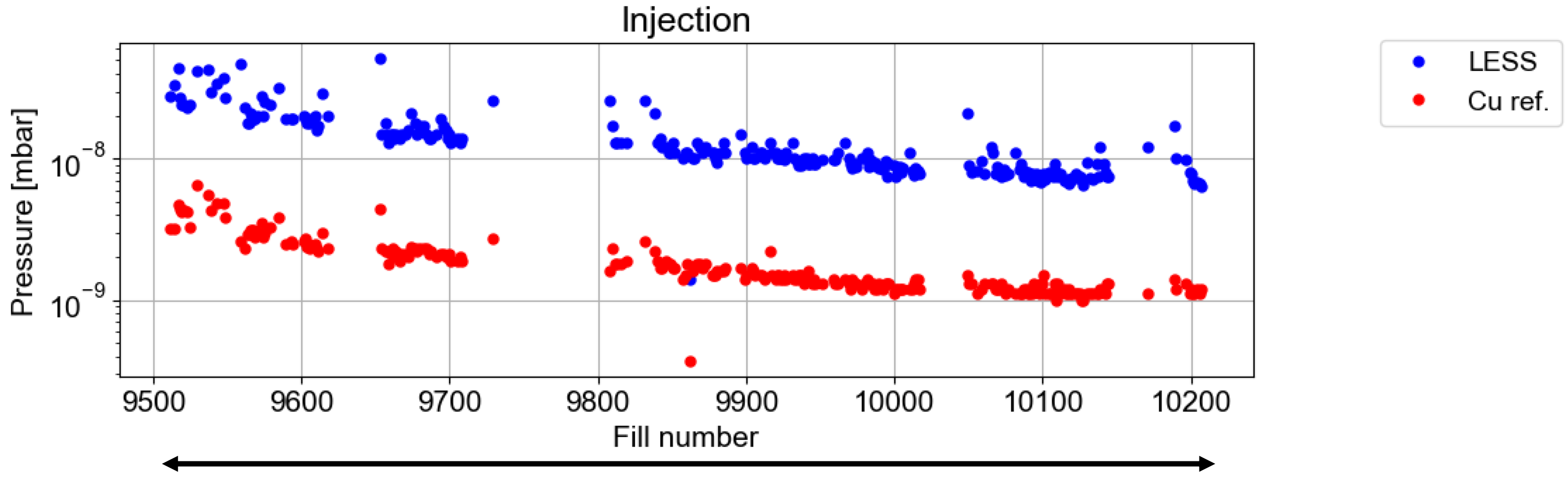


LESS treatment in LHC

Laser surface treatment (LESS) is explored for use in HL-LHC Q5 quadrupoles *(see talk by M. Zerlauth)*

- Agreement to aim for initial SEY of $\lesssim 1.5$, to allow the control of dust production during treatment *(see WP2 meeting Aug 23, 2022)*
- New warm laser-treated pipe installed in LHC IR6 during YETS23-24
  - Cu-coated pipe installed for reference
- Pressure evolution indicates both surfaces are conditioning well
  - Difference in pressure within the calibration uncertainty of gauges





Conclusions

- Heat loads remain the main concern for performance limitations from electron cloud in HL-LHC
  - Small reduction since 2022 brings some alleviation for rest of Run 3, but is no gamechanger

- BST is needed for HL-LHC baseline scenario
  - Margin for degradation in most sectors is not sufficient for another S78 degradation, S45 and S56 most worrying
  - Cryo capacity revisions mildly reduce margin for degradation, effect is mitigated with treatment of 20 more cells

- No major concerns found for beam stability and incoherent effects
  - Stability at injection improves with intensity
  - Benefit of phase knob on losses, halo population and emittance shown in MD
  - Newly developed simulations of e-cloud in triplets show benefit of increasing intensity, as observed in operation

- Several successful MDs in 2024
  - Bunch-by-bunch tune shifts at injection measured for several configurations with 2.3e11 ppb → 1.2e11 ppb
  - Stability with negative octupoles and heat load with up to 2.3e11 ppb at injection to be measured in MD5

CERN

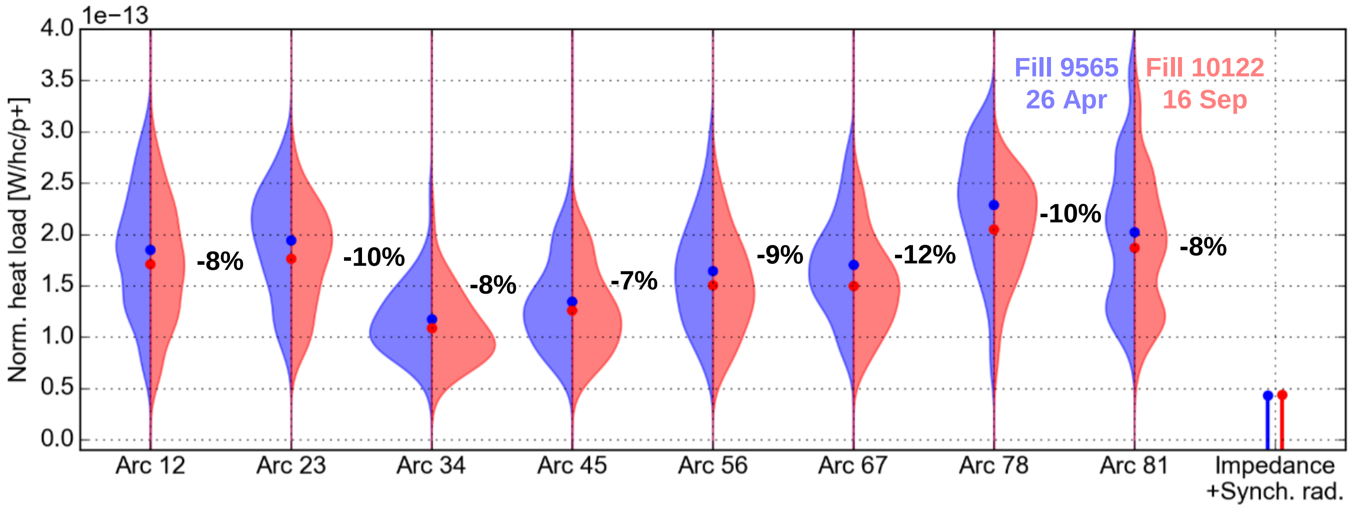
Changes since previous filling scheme analysis

Further scrubbing since end of 2022

- The sector average heat loads have reduced by 10-15% since the end of 2022
  - In 2024 alone, the heat loads have decreased by 7-12%

Cryo capacity update

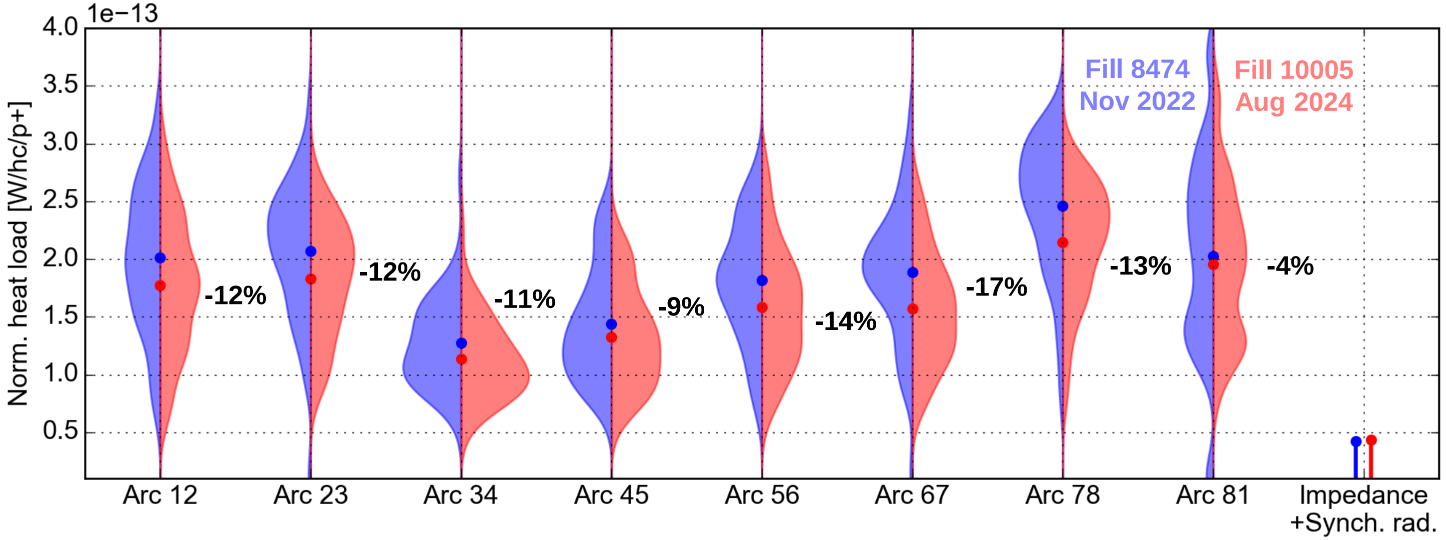
- Cryo capacity in S78 revised to **180 W/hc** (vs 215 W/hc estimated before 2024 run)
  - Based on findings by TE-CRG at the beginning of the 2024 run



Fill	9565	10122
Started on	26 Apr 2024 03:13	16 Sep 2024 18:29
T_sample [h]	1.80	1.60
Energy [GeV]	6799	6799
N_bunches (B1/B2)	1959/1959	2352/2352
Intensity (B1/B2) [p]	3.11e14/3.10e14	3.83e14/3.84e14
Bun.len. (B1/B2) [ns]	1.30/1.32	1.29/1.32
H.L. exp. imped. [W]	10.83	13.88
H.L. exp. synrad [W]	15.81	19.57
H.L. exp. imp.+SR [W/p+]	4.29e-14	4.36e-14
T_nobeam [h]	0.70	0.45

Heat load comparison to 2022

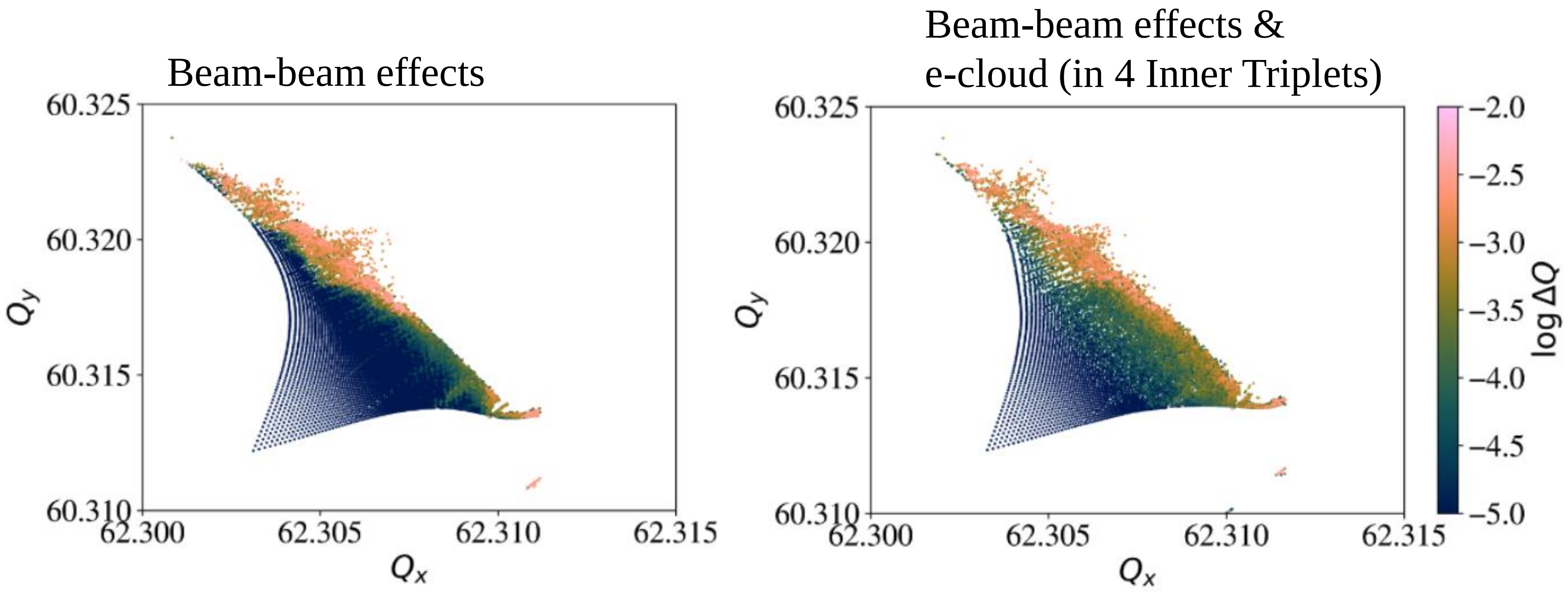
- The difference in filling scheme (5x36b vs 3x36b) accounts for a few percent



NB: Seemingly small evolution in S81 partly due to several faulty temperature sensors in 2022

	(blue)	(red)
Fill	8474	10005
Started on	24 Nov 2022 05:17	14 Aug 2024 22:35
T_sample [h]	2.00	2.90
Energy [GeV]	6799	6799
N_bunches (B1/B2)	2462/2462	2352/2352
Intensity (B1/B2) [p]	3.67e14/3.62e14	3.72e14/3.75e14
Bun.len. (B1/B2) [ns]	1.27/1.27	1.27/1.29
H.L. exp. imped. [W]	12.44	13.55
H.L. exp. synrad [W]	18.57	19.03
H.L. exp. imp.+SR [W/p+]	4.26e-14	4.36e-14
T_nobeam [h]	0.40	1.70

Frequency Map Analysis



- Tracking over 100 000 turns, tune evaluated over:
  - First 50 000 turns,
  - Last 50 000 turns.

Difference in tune → tune is not constant and so trajectory is chaotic.

- E-cloud doesn't cause a significant tune-shift (compared to beam-beam effects)
- Visible effect of e-cloud → increase of non-linearities deeper into core.

Dynamic aperture
Tune scan

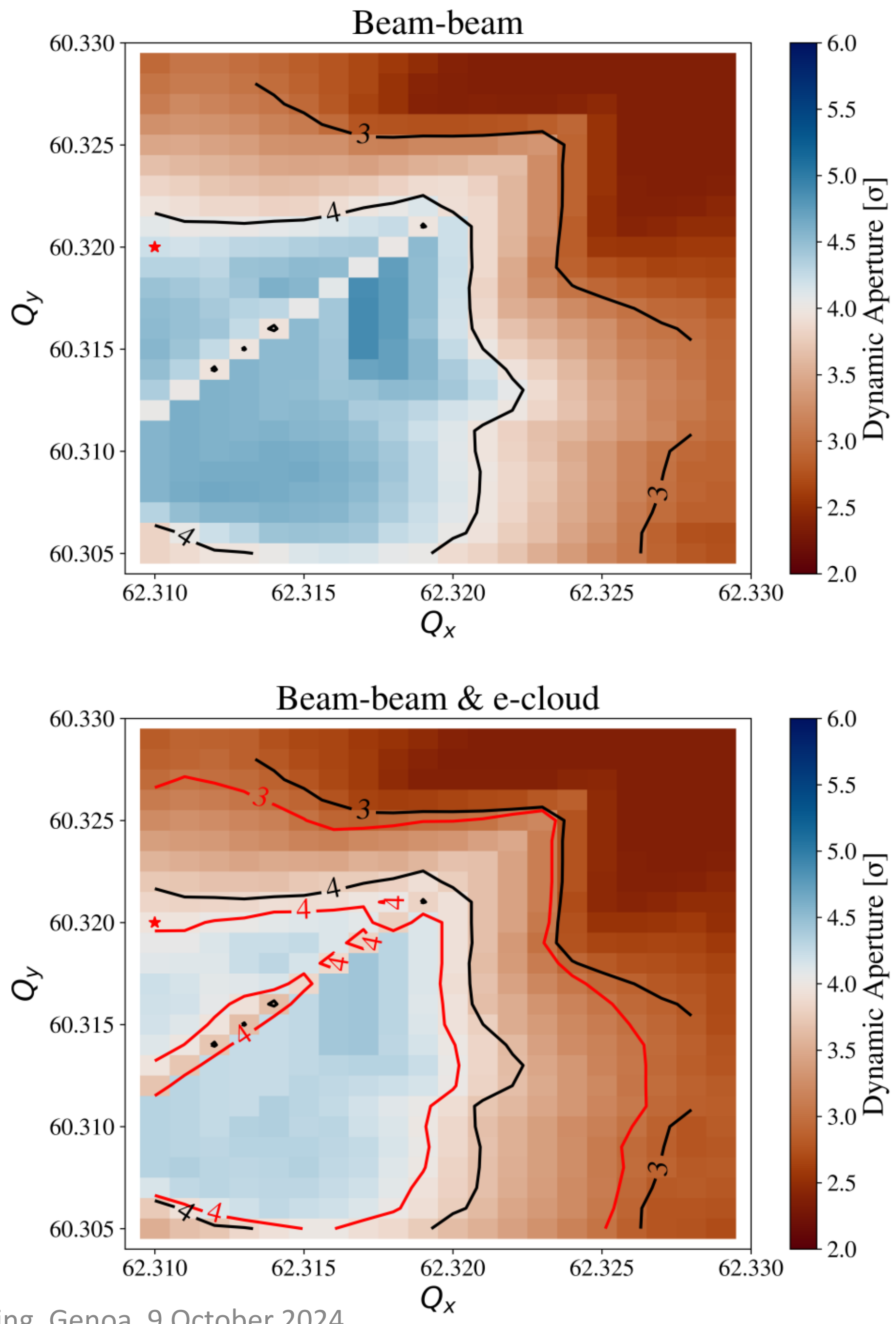
Dynamic aperture over 1 000 000 turns, including the e-clouds in the 4 inner triplets (left and right of i.p. 1 and 5). Simulations varying the working point.

- E-cloud effects cause a reduction of dynamic aperture for all tunes.
- The optimal working point remains similar.

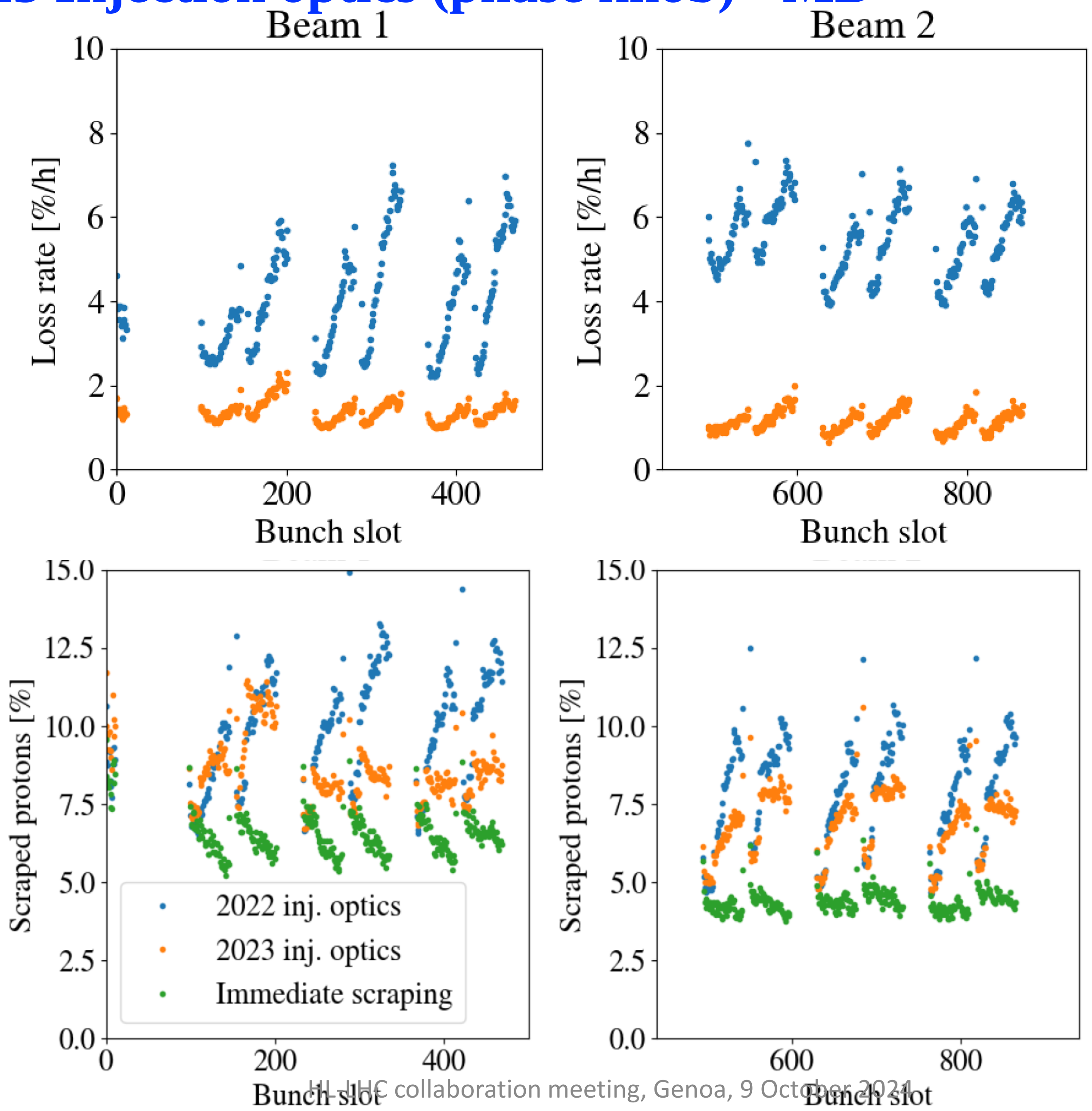
Simulation parameters:

Bunch intensity = 1.2 10^{11} p/b

SEY = 1.30



2023 Injection optics (phase knob) - MD



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