Electron clouds in the LHC

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6th December 2023

Outline

1. SEY - Heat load Modelling
    - Overview
    - Remainder of Run 3
    - Comparison between models

2. Beam Degradation – Beam instabilities
    - During stable beams
    - During ramp
    - At injection

3. Beam degradation – Incoherent effects
    - Emittance growth at injection,
    - Slow losses during stable beams,
    - Halo population

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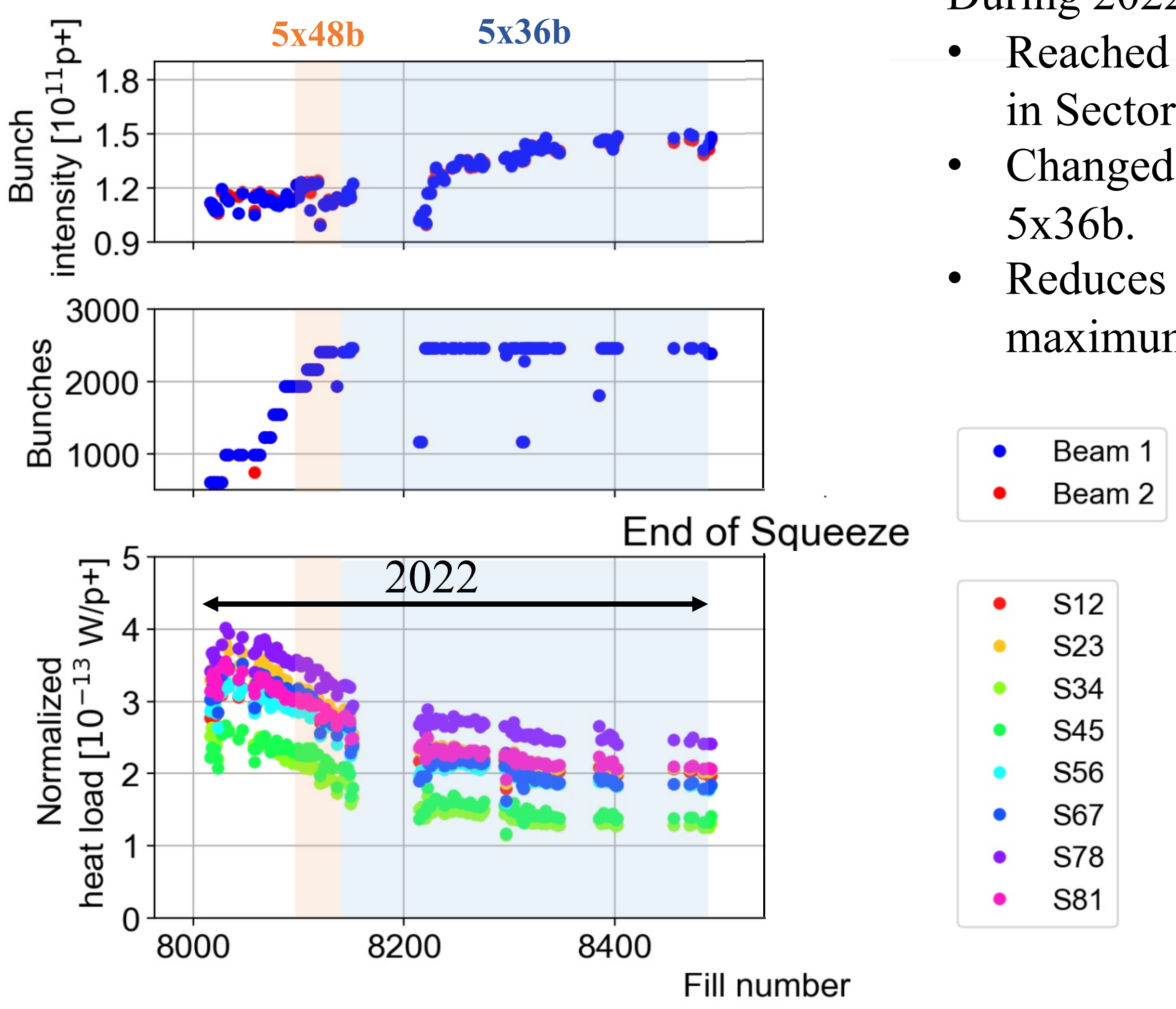
Heat load evolution - 2022



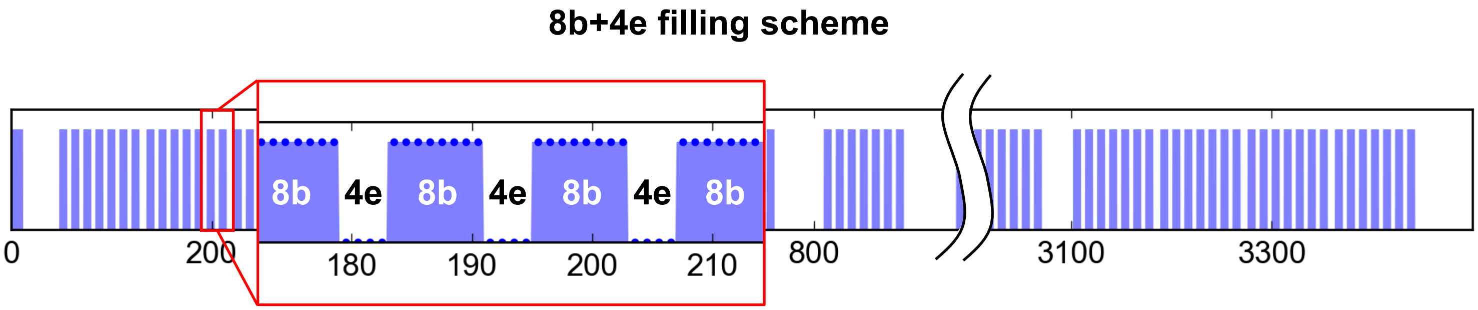
During 2022 intensity ramp-up:

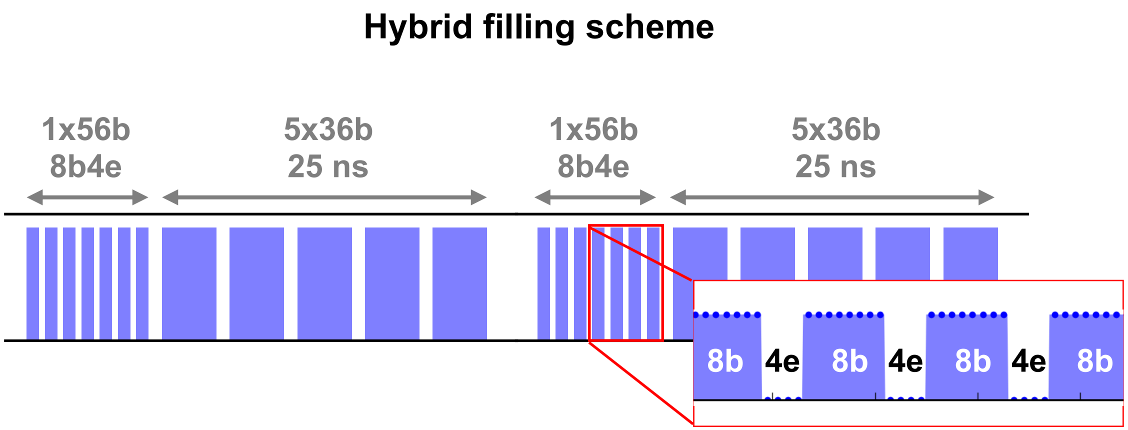
- Reached heat load limit (beam screen) in Sector 78.
- Changed filling scheme from 5x48b to 5x36b.
- Reduces heat load per proton but also maximum number of bunches.
    - Could fit a few more bunches.
    - Could continue raising bunch intensity.

8b4e - Hybrid scheme

The 8b+4e scheme introduces gaps already on the rising slope of the e-cloud build-up

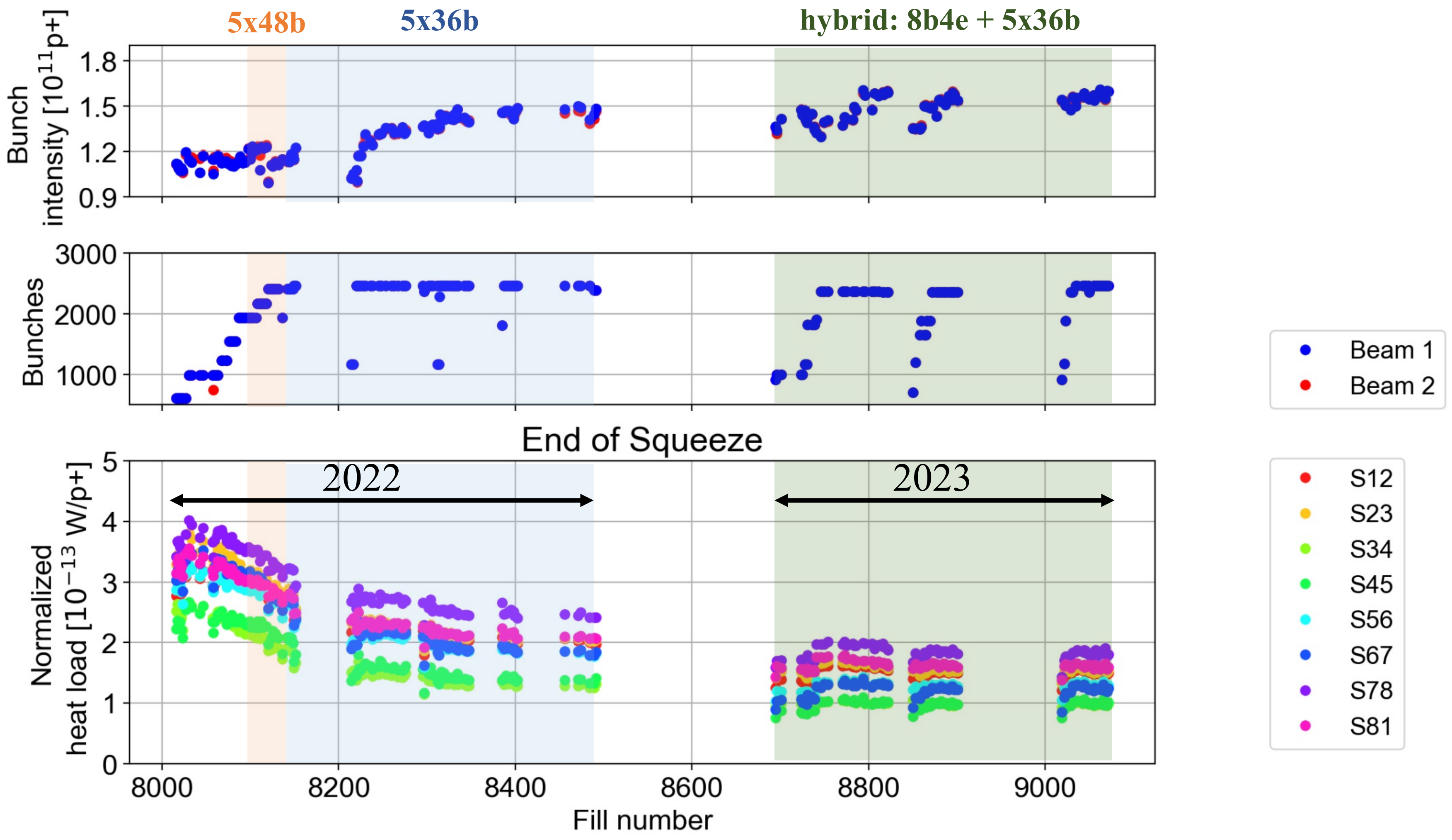
→The cloud never reaches full saturation level: significant reduction of e-cloud effects





- Trade-off between number of bunches and average heat load per bunch.

Heat load evolution - 2023

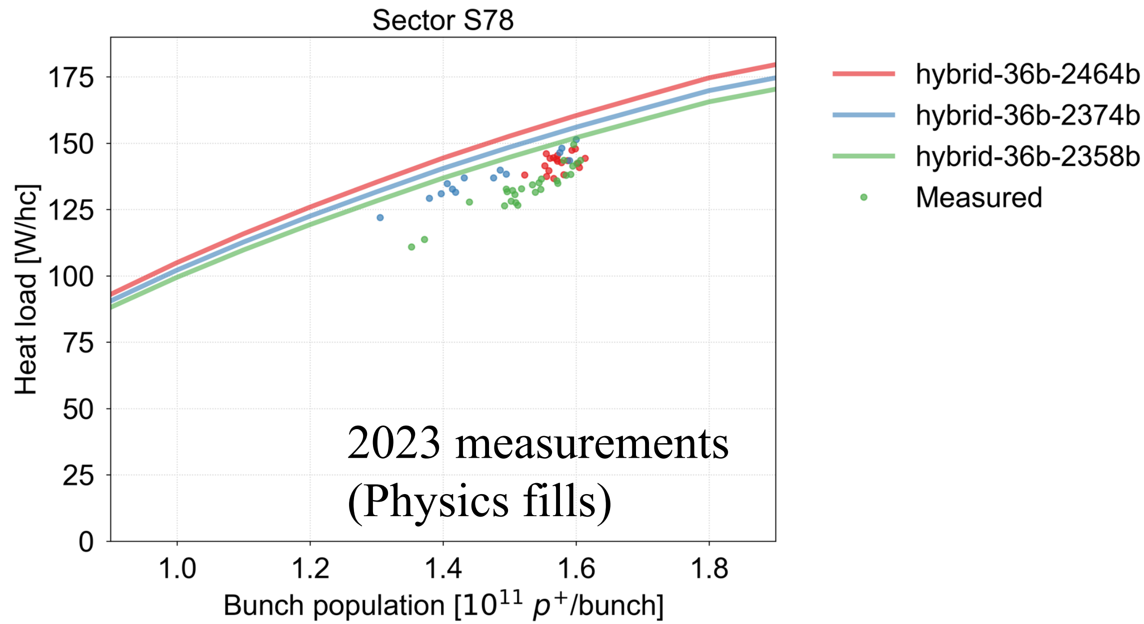


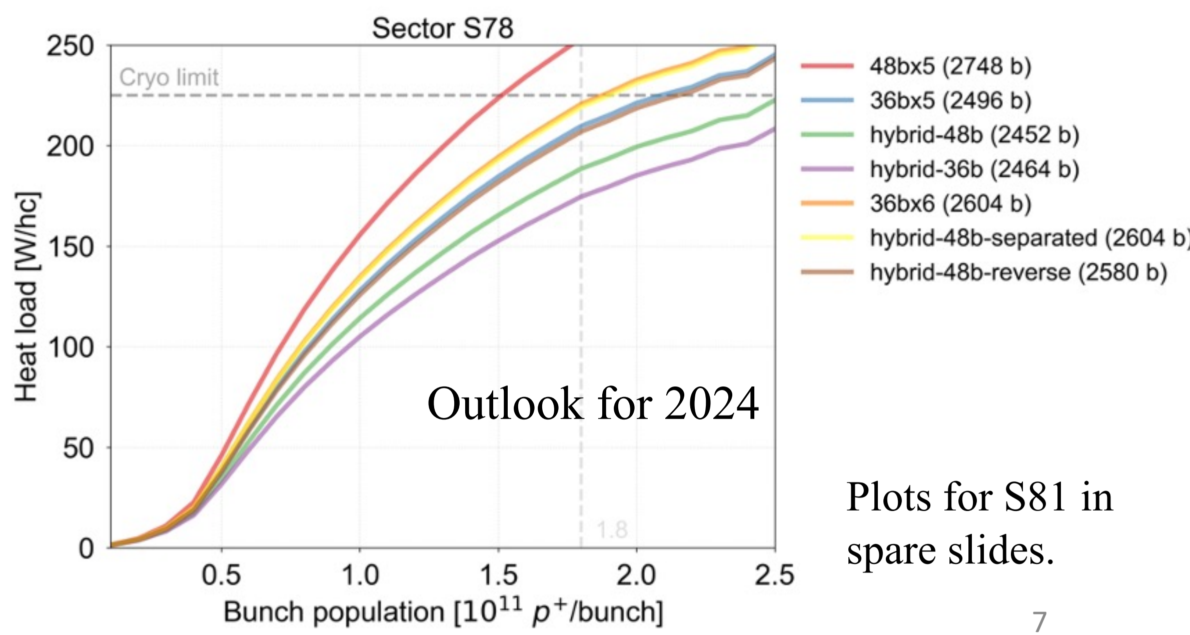
Optimized for luminosity by reducing heat load per proton:

- During 2022: Switch from 5x48b to 5x36b.
- For 2023: Switch to hybrid scheme: 8b4e + 5x36b

Heat load in 2023

- Measured heat load was slightly smaller than predicted by few %.
- Cryo limits reconfigured for more capacity in S78 (and less in S81). See Laurent's talk.
- Can we optimise filling scheme for more luminosity?





Plots for S81 in spare slides.

Options for remainder of Run 3

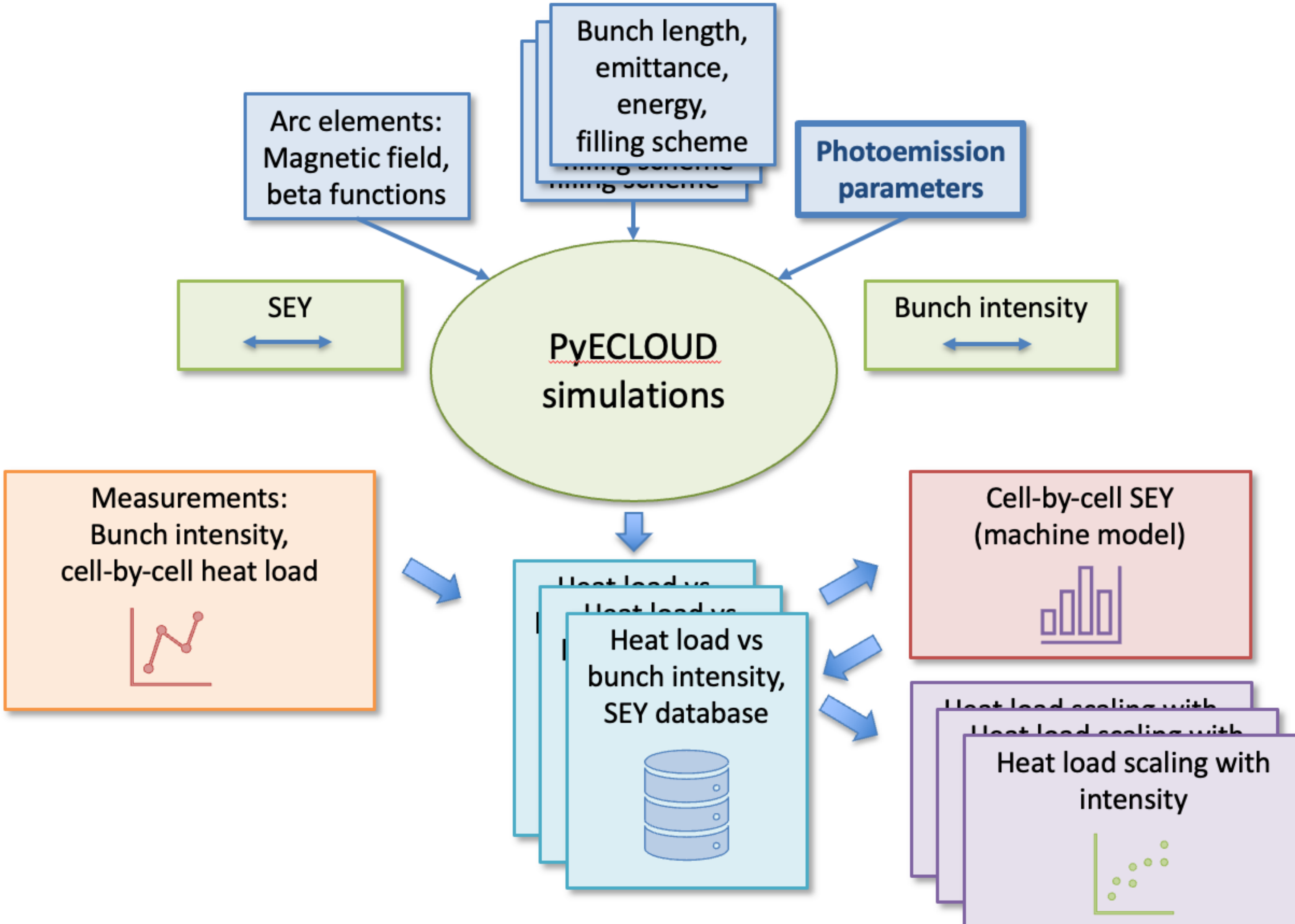
1.8 10^{11} p/b	Number of collisions			S78 Heat load [W/hc]	S81 Heat load [W/hc]	(Cryo less tight if we stay at lower bunch intensity)
Type	IP1/5	IP2	IP8			
hybrid-36b	2452	1889	2067	175 (-50)	146 (-44)	2023, large cryo margin
hybrid-48b	2440	1952	**2240**	189 (-36)	157 (-33)	Potential for more LHCb cols.
5x36b	2484	**2121**	**2260**	210 (-15)	173 (-17)	Pure 25ns, optimised IP2/8
6x36b	**2592**	2097	2059	**221 (-4)**	**183 (-7)**	Pure 25ns, cryo very tight
reverse hybrid-48b (1)	**2600**	1903	1924	**217 (-8)**	**179 (-11)**	Tight cryo margin, too long injections for MKI.
reverse hybrid-48b (2)	**2568**	1913	1956	207 (-18)	172 (-18)	Heat load reduction and SPS production should be tested.
separated hybrid-48b	**2592**	**2212**	**2206**	**219 (-6)**	**181 (-9)**	Tight cryo margin, requires multiple SPS cycles.

"Reverse" hybrid schemes: 8b4e part comes after the 25ns part in SPS.
"Separated" hybrid scheme: Separate injections of 8b4e and 25ns from SPS.

Note: Schemes do not include INDIVs or smaller trains for injection steering.
Further optimisation is hard. Cornered from everywhere.

The e-cloud simulation model

The e-cloud heat load can be estimated based on the SEY, which is inferred by comparing heat load measurements to simulations with matching beam and machine parameters.



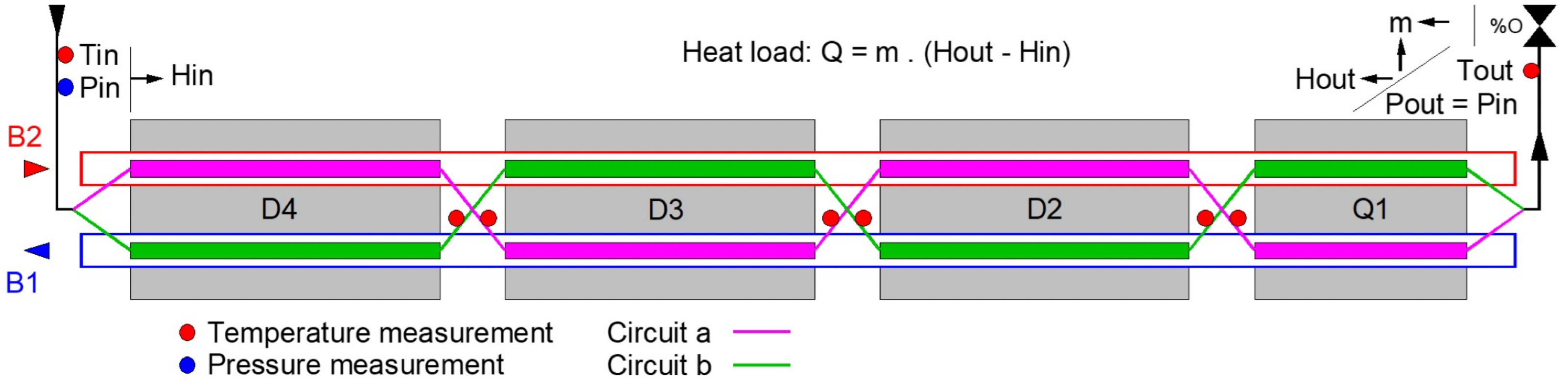
Typical half-cells – Instrumented half-cells

Typical half-cells:

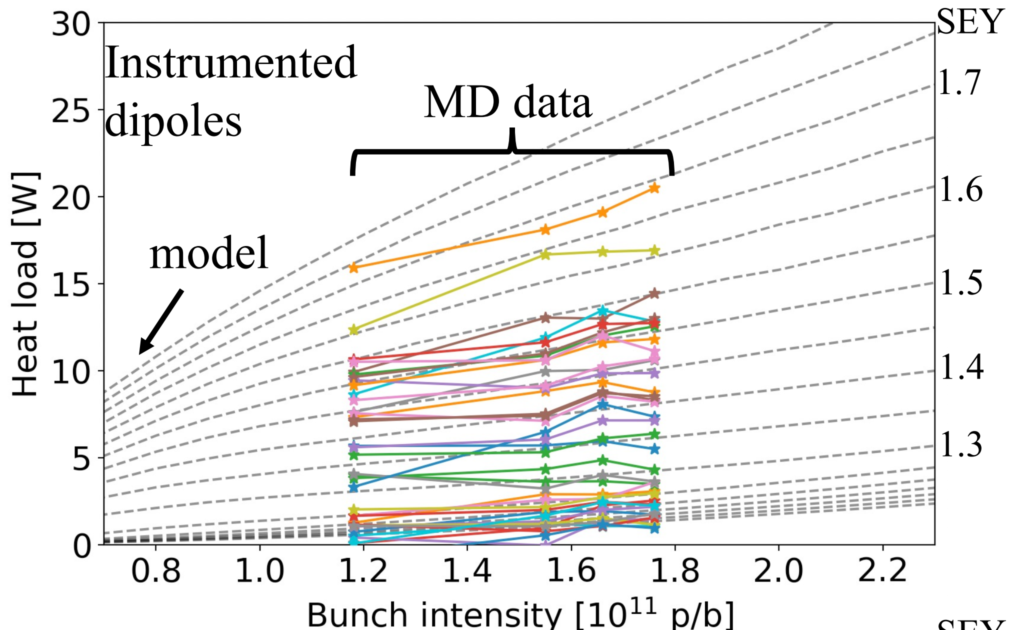
- 1 Heat load number for 3 dipole, 1 quadrupole + drift spaces (per beam)

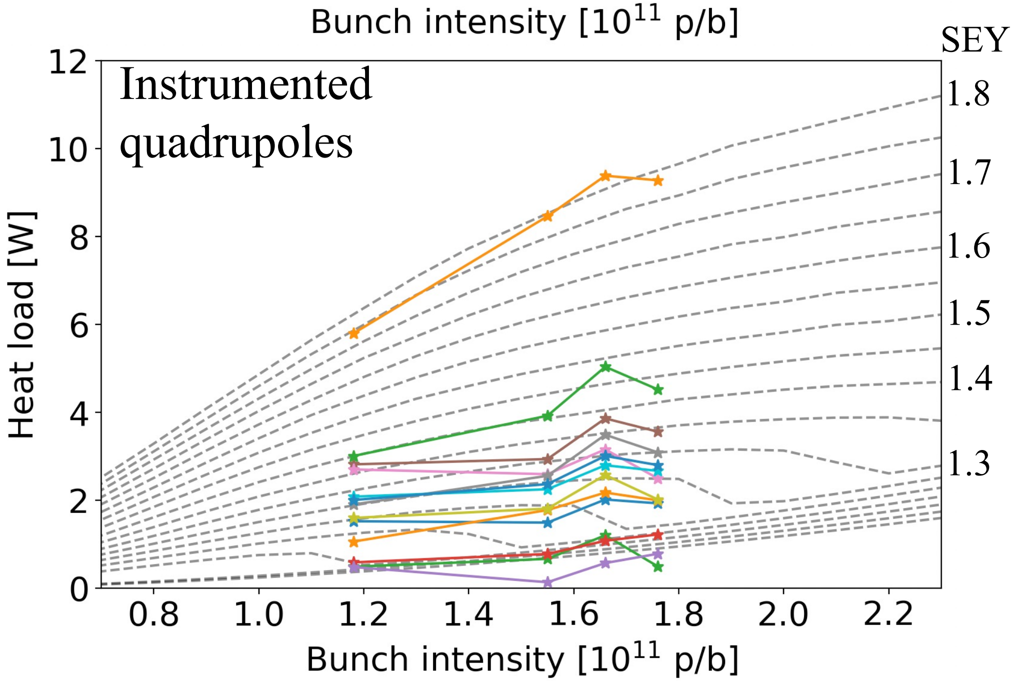
Instrumented cells:

- 1 Heat load number per dipole and quadrupole aperture → 8 heat load numbers
- Assumptions still need to be made for drift spaces.
- Only 8 half-cells are instrumented.
- Only 4 of them with reliable measurements in **all of the apertures**.



Instrumented half-cells modelling





- Data from 2022 MD8403.
- Aperture-by-aperture SEY fit

- Worst dipole SEY = 1.7
- Worst quadrupole SEY = 1.8
- Much higher than expected by lab measurements (Valentine's talk).

"Instrumented model"

1. Fit the SEY of each aperture.
2. Predict heat load for each aperture.
3. Sum over all apertures to obtain total heat load.

* Drift space is split equally among apertures (with same SEY as aperture).

"Uniform model"

1. Fit one SEY for entire halfcell.
2. Sum over dipoles, quadrupoles, drifts.

Instrumented cells vs cells with uniform SEY

			Prediction at 1.8 10^{11}p/b, 2748b		Prediction at 2.3 10^{11} p/b, 2748b	
Cell	SEY list [Q1B1, Q1B2, D2B1, D2B2, D3B1, D3B2, D4B1, D4B2]	SEY σ/μ	Instrumented Model [W]	Uniform Model [W]	Instrumented Model [W]	Uniform Model [W]
33R2_7	[1.79, 1.43, 1.49, 1.36, 1.52, 1.38, 1.42, 1.50]	6%	319	334 **(+5%)**	394	378 (-4%)
15R2_3	[1.35, 1.28, 1.42, 1.41, 1.30, **1.05**, 1.52, 1.37]	11%	233	235 **(+1%)**	293	248 (-15%)
31L2_3	[1.27, 1.27, 1.51, 1.46, **1.08**, 1.24, **1.17**, **1.00**]	15%	185	140 (-24%)	242	184 (-24%)
33L5_7	[**1.09**, **1.00**, **1.00**, **1.15**, 1.43, 1.32, 1.23, **1.16**]	12%	141	108 (-23%)	199	108 (-18%)

1. **Instrumented model:** each aperture modelled with a different SEY
2. **Uniform model:** SEY is modelled as uniform along the half-cell

- Some cells even exceed the cryo limit for a single half-cell (350 W).

- "Uniform model" underperforms in extrapolating when the SEY is far from uniform.
- **Measurements at higher bunch intensity** are extremely important for the SEY - Heat load model.

MD #1: Measurement of heat load with high bunch intensity

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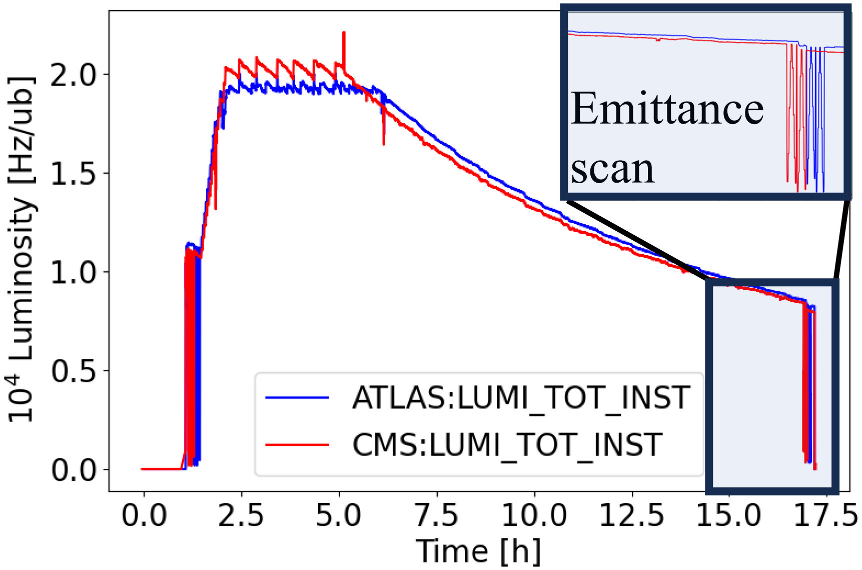
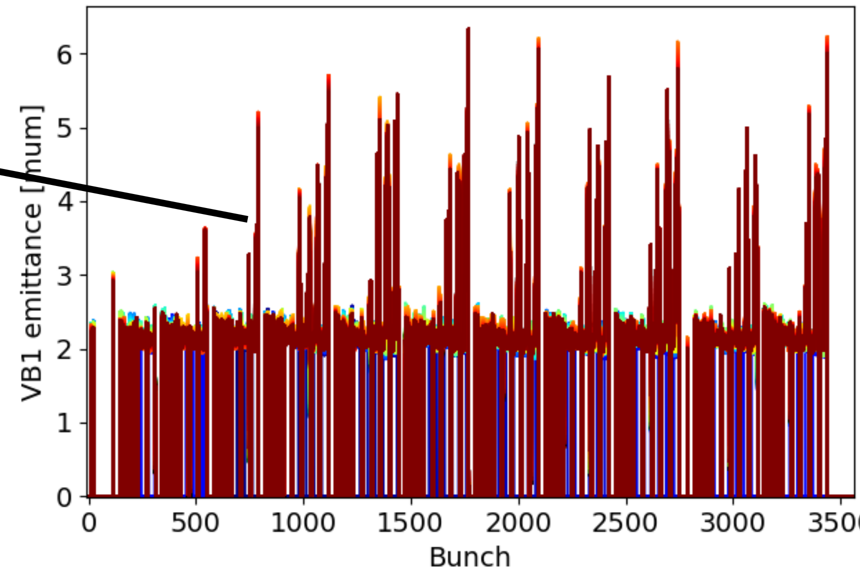
Beam stability at Flat top/stable beams





Run 2:

- Observed first in 2016 with 72b.
- Intensity range: 0.7 – 1.0 10^{11} p/b.
- Cured by increasing Q' to 22.
- Later in year was not observed again, even with Q' = 5.

Instability was "scrubbed away"

Run 3:

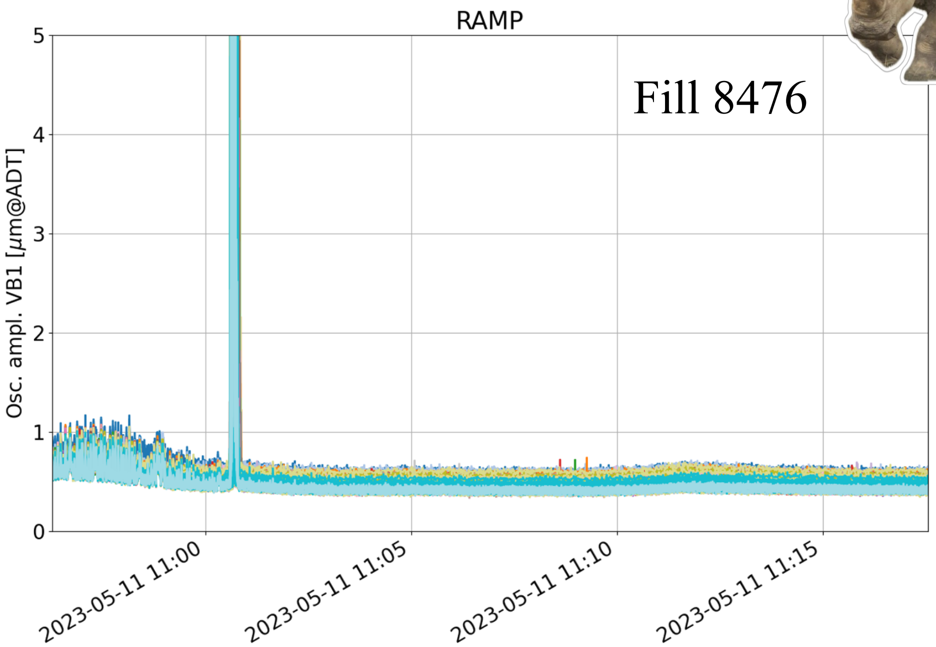
- Observed since beginning of Run, in all filling schemes (even with hybrid)
- Intensity range: 0.7 – 1.2 10^{11} p/b.
- Chromaticity is kept at Q' = 20.
- Instability still there during "emittance scans".

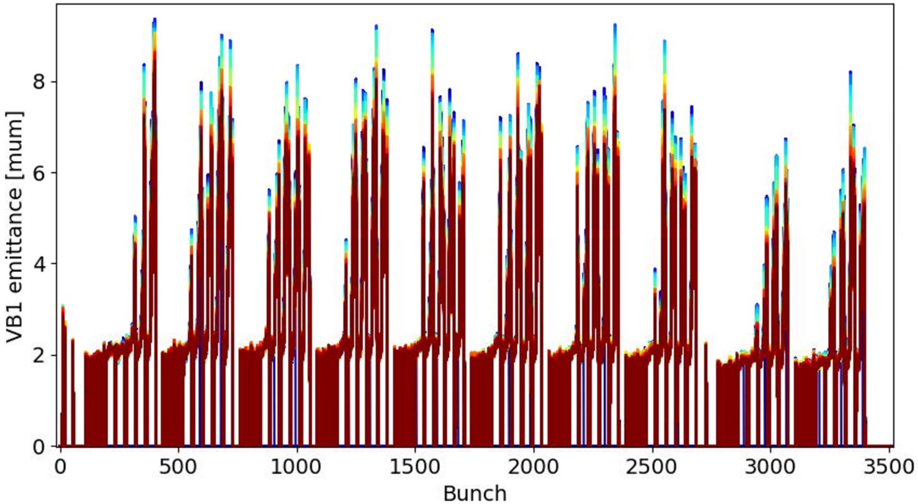
Instability cannot be "scrubbed away"

Instabilities not limiting performance yet.
However, they don't allow reducing chromaticity and affect lifetime indirectly.

Beam stability during the ramp

- "Violent" instabilities observed during the ramp for several fills. Always at the same point in the ramp.
- Instability always observed at point where the new 2023 injection optics knob is being removed (during ramp).
- Problem traced back to **bug in linear coupling correction during ramp**, which is now fixed.
- Instability not there after proper linear coupling correction.

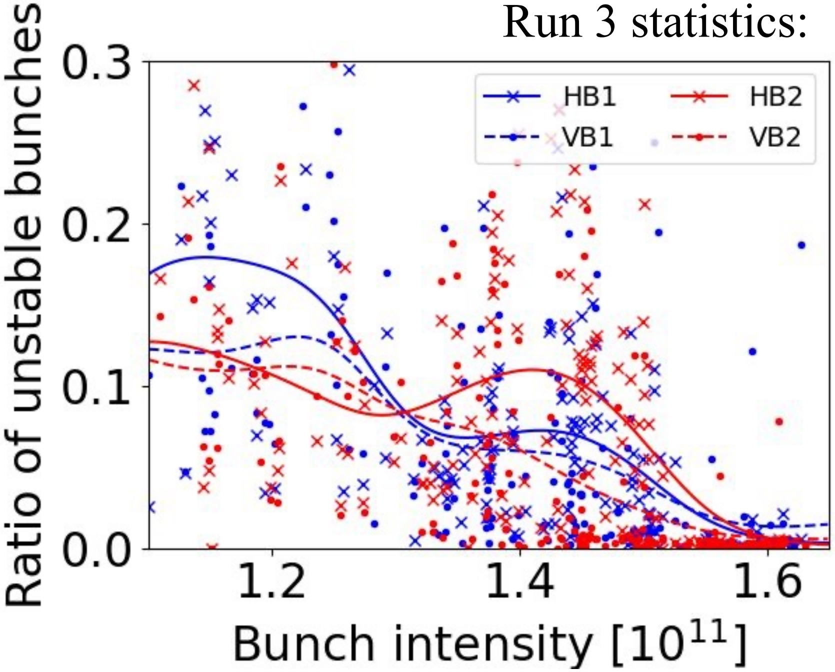




Beam instabilities at injection

- Run 1: No instabilities with 50ns.
- Run 2: Q' = 15, Ioct = 50 A
  Few instabilities even after scrubbing
  → Weak blowup (~ 0.2 μm)
- Run 3: Q' = 20, Ioct = 39 A
  Similar instabilities at "low" bunch intensities. Well mitigated in 2023 ($1.5\ 10^{11}$ p/b, hybrid scheme)
- Run 4: Q' = ?, Ioct = ? A

Run 3 statistics:

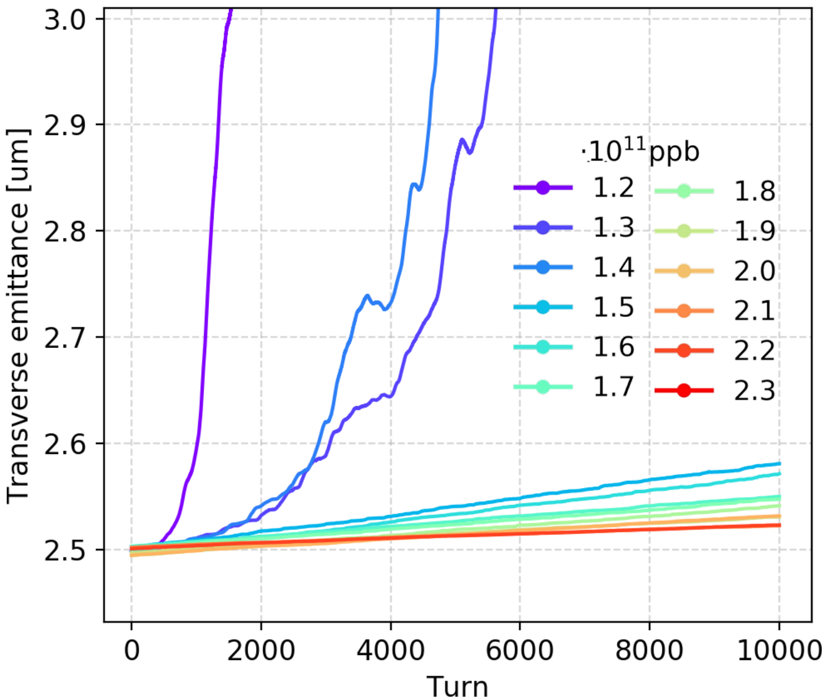


[X. Buffat]

- Were the instabilities scrubbed away in 2022/2023? ❌
- Did the increase in intensity help? ✅

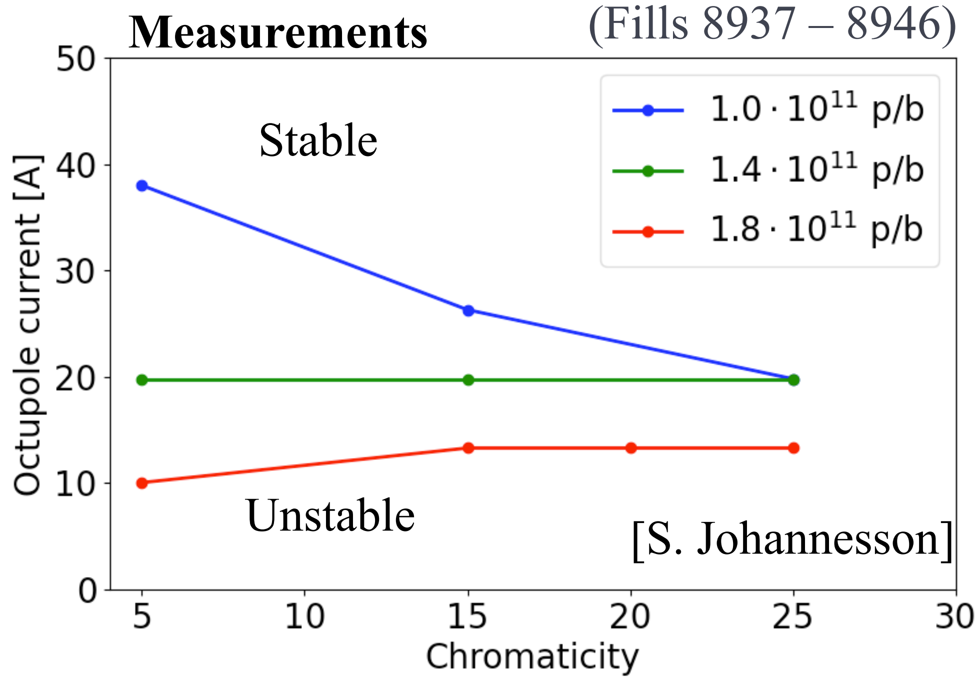
Beam instabilities at injection

Simulations,
instabilities driven by e-cloud in MQ



MD6845: Instability measurements with varying bunch intensity

(Fills 8937 – 8946)



Measurements confirm simulation predictions:

Higher bunch intensity reduces e-cloud coherent beam instabilities

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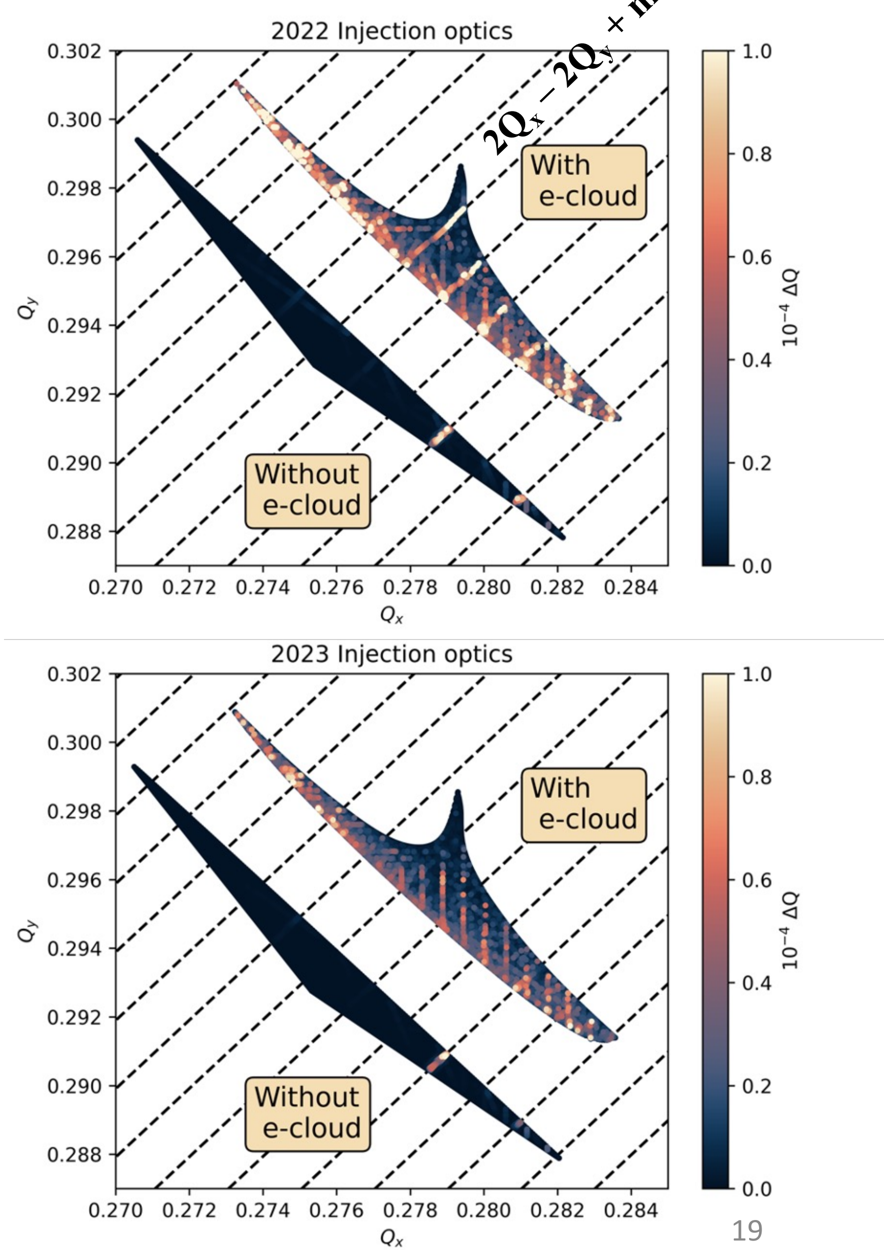
Optics and incoherent e-cloud effects at injection

- Electron cloud in main quadrupoles drives emittance growth at injection (in simulations)
- Synchro-betatron resonances have been identified as cause ($2Q_x - 2Q_y + mQ_\zeta = 4$)
- LHC Injection optics modified in 2023 with "phase knob" (see Tobias' talk) to correct octupolar resonances from:
    1. Lattice octupoles (in arcs)
    2. Electron clouds in quadrupoles

Simulations:

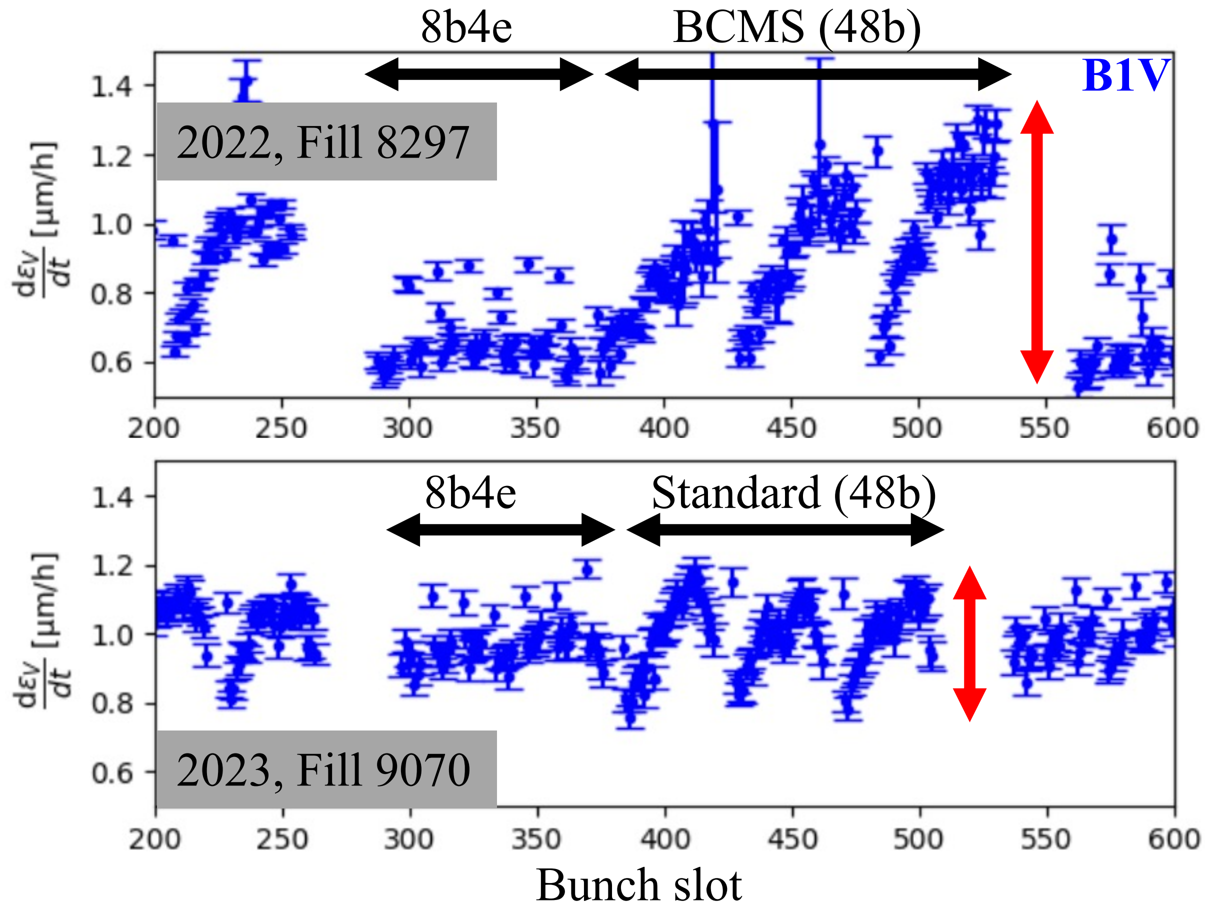
- **Synchro-betatron resonances are greatly reduced.**
- **Significant decrease of emittance growth and transverse halo population growth.**



Emittance growth at injection

- "8b4e" emittance growth seems larger.
- "e-cloud" emittance growth seems less in 2023.

- Different beams,
- Different beam screen state.



Is this the effect of 2023 injection optics?
Why is 8b4e different? Is it also the effect of the optics?

More details about emittance in Ilias' talk.

MD #2: Effect of injection optics on emittance growth and halo population at injection.

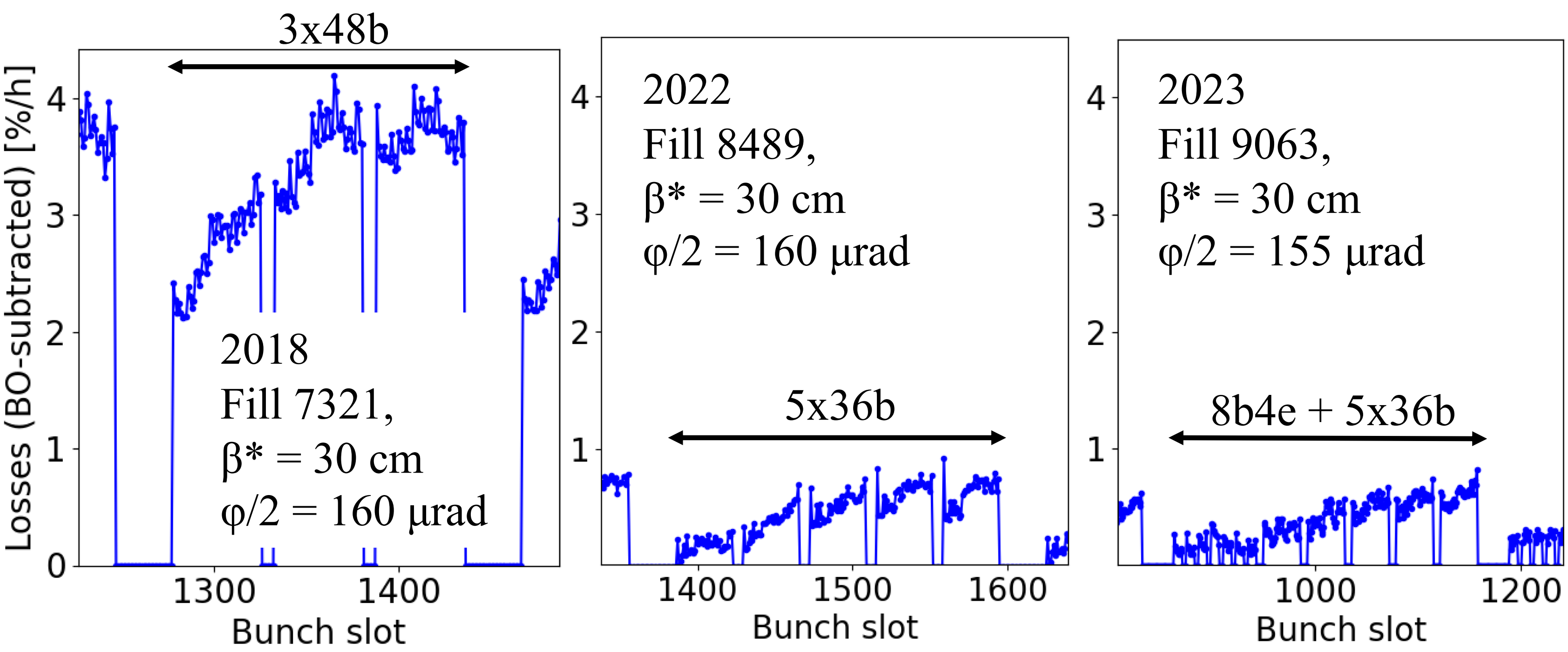
Slow losses during stable beams

During full duration of stable beams:

- Extra steady slow losses all with e-cloud pattern (tails of bunch trains)
- On top of luminosity burn-off.
- Typical in Run 2.

Source was already found to be the e-cloud in Inner Triplets (two-beam chambers).

- In Run 3 situation seems much better, possibly due to smaller emittances.
  Aiming for simulations of these losses within 2024.



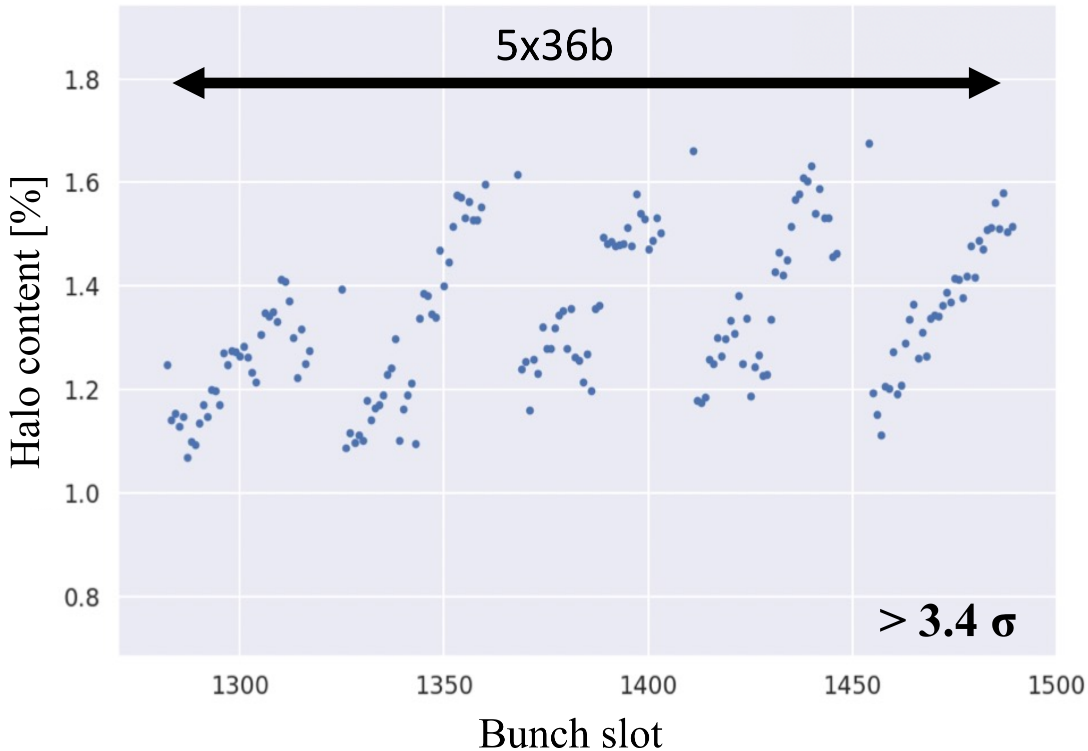
Halo population

MD8183
Work by Collimation team:
Milica Rakic, Pascal Hermes *et al*.

Measurement and analysis by collimation team:

- End-of-fill MD after 15 hours of stable beams.
- Beam scraping with TCP to 3.4 times the "reference" beam size (σ).
- FBCT to resolve bunch-by-bunch effects.
- Bunches towards tails of batches have more protons in transverse halo.

Clear signature of (incoherent) electron cloud effects.



*3.4 "reference" σ corresponds to around 5 times the "measured" σ.

Conclusion

- Small optimisations of filling schemes are possible to gain some few bunches. Not trivial.
- Instrumented cells give insight in SEY modelling. Model is ok for Run 3 target, but possible issues when extrapolating to Run 4.

- Discrepancy: Fitted SEY (1.7-1.8) ≫ lab measurements (1.3), see Valentine's talk.

- E-cloud degrades beam quality in several ways. No major limitation from beam dynamics effects yet, but each effect has small impact in delivered luminosity and bunch-by-bunch fluctuations.

MD requests:

1. Measurement of heat load with high bunch intensity.
2. Effect of injection optics on emittance growth and halo population at injection.
3. Heat load with a 25ns fill similar to end of 2022.
4. Heat load with a 50ns fill.
5. Study of bunch-by-bunch tune shifts.
6. Stability studies at injection for optimal operational conditions.

Thank you for your attention!
Konstantinos Paraschou

Spare slides

Options for remainder of Run 3

1.8 10^{11} p/b	Number of collisions			**S78 Heat load [W/hc]**	**S81 Heat load [W/hc]**	(Cryo less tight if we stay at lower bunch intensity)
Type	IP1/5	IP2	IP8			
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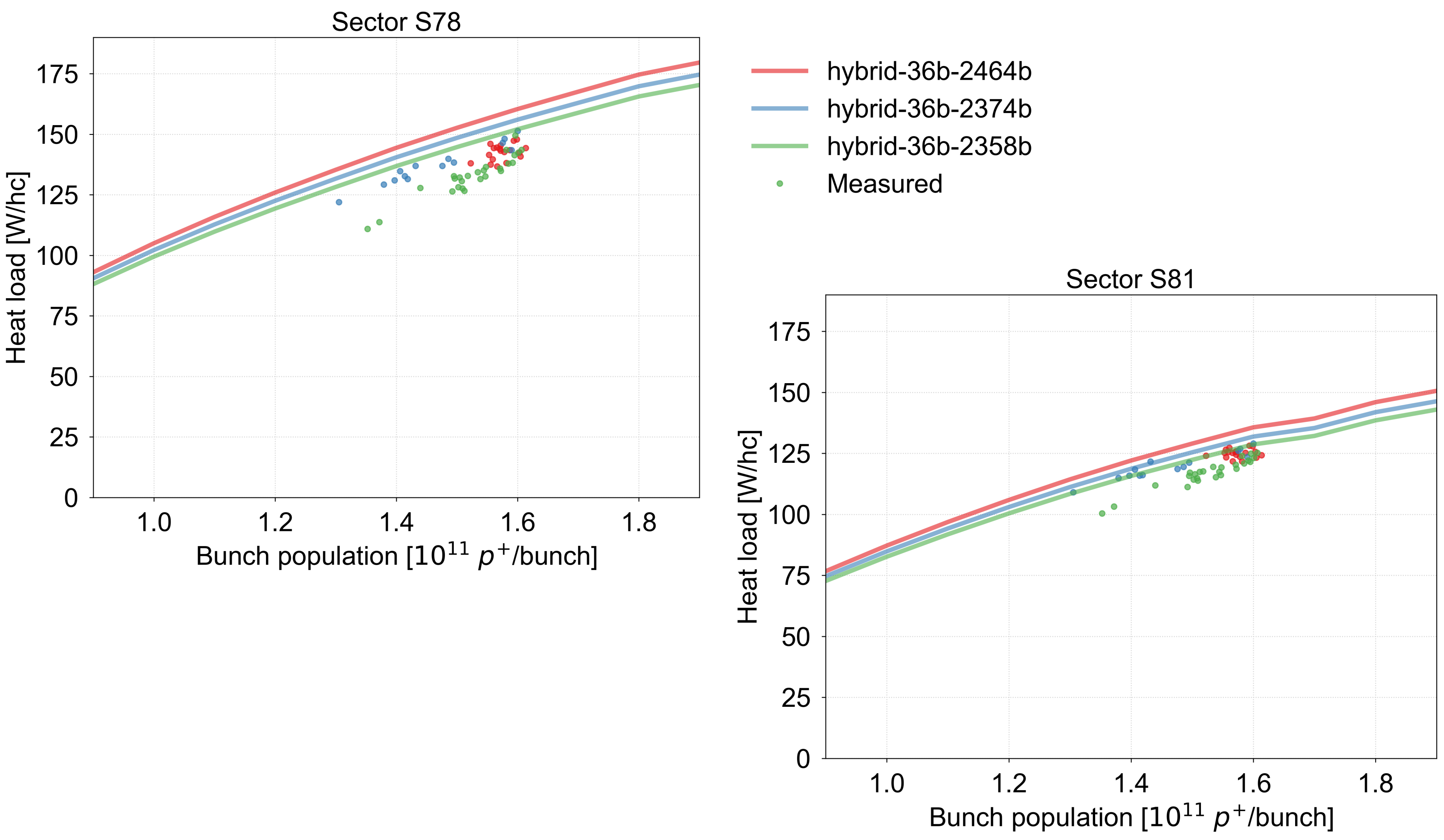
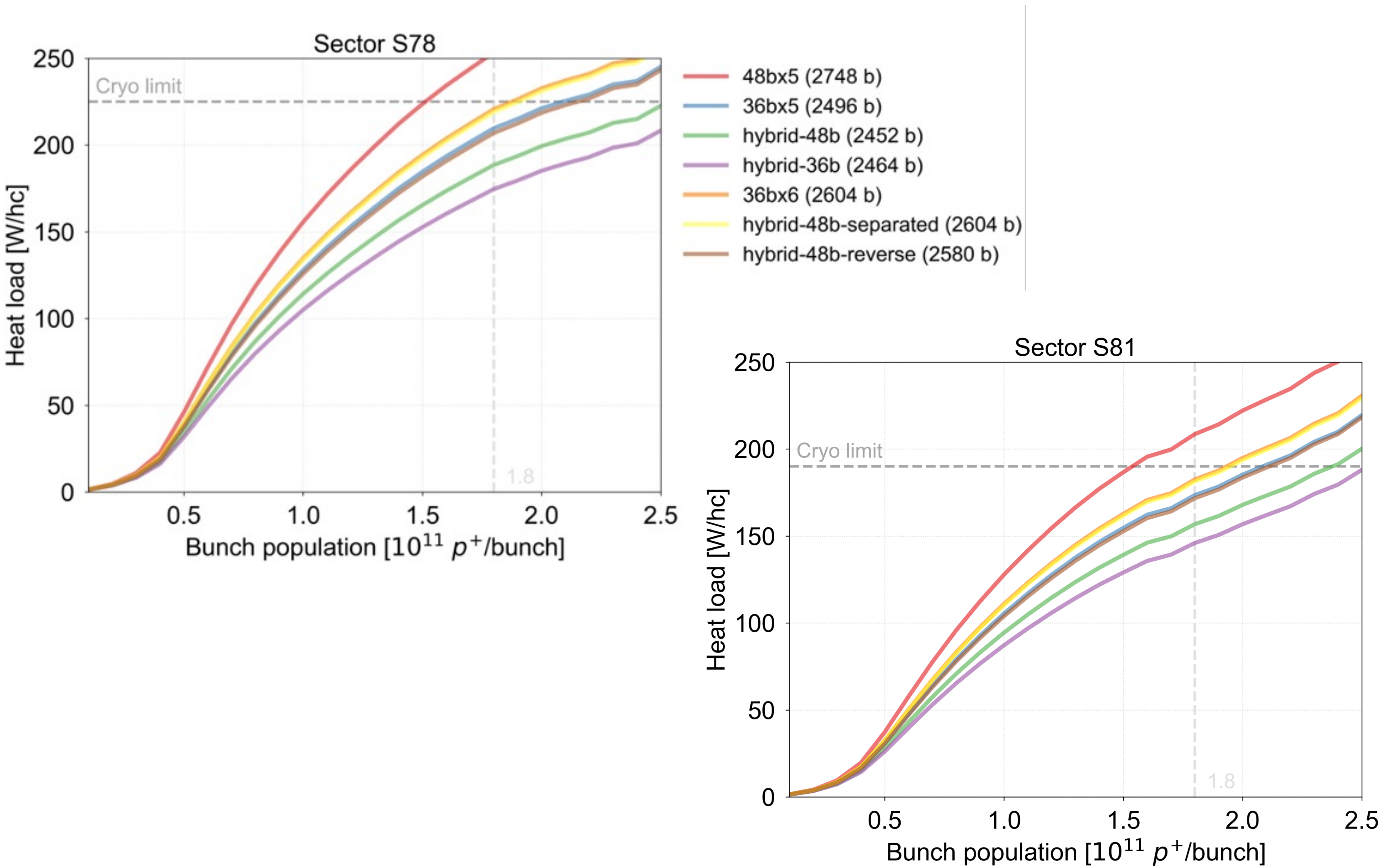
Note: Schemes do not include INDIVs or smaller trains for injection steering.
Further optimisation is hard. Cornered from everywhere.

Measurements in 2023



Model predictions S81



Slow losses during stable beams

Beam degradation in collision

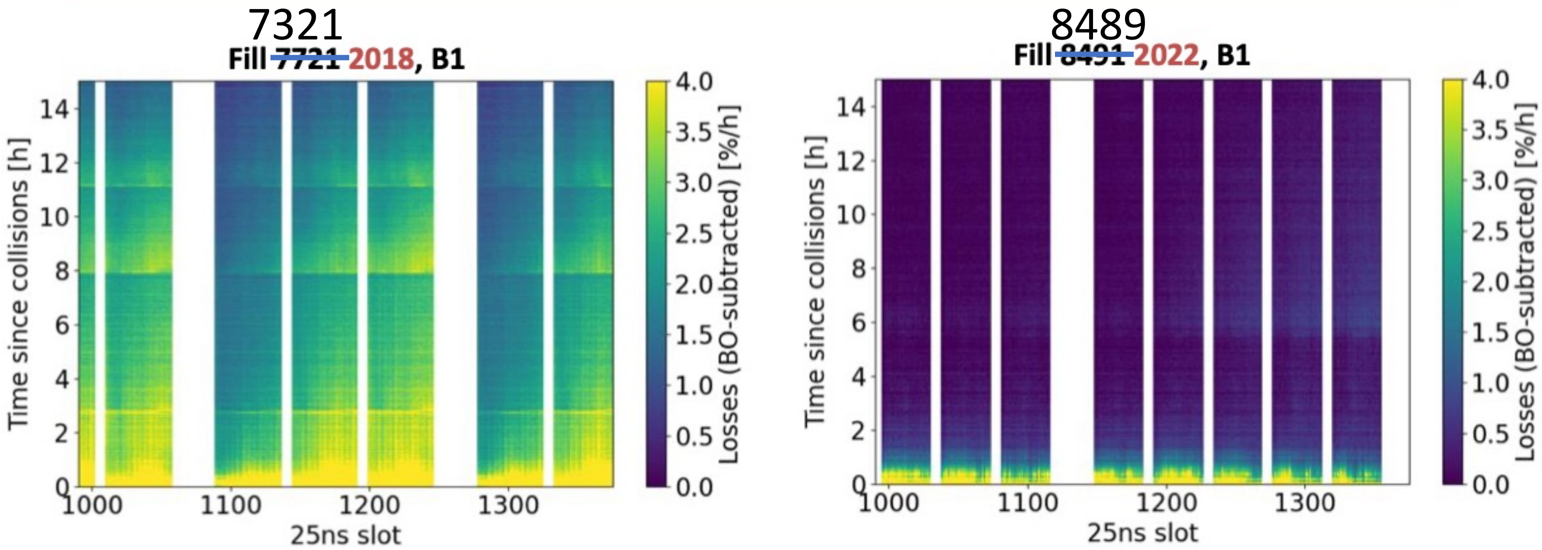
During Run 2, slow beam losses at tail of trains were systematically observed in collision

- Caused by e-cloud in the Inner Triplets, enhanced by the large beta functions

This year, we have seen much less of such losses

- Possibly due to i.a. more relaxed settings for the crossing angle and smaller emittances

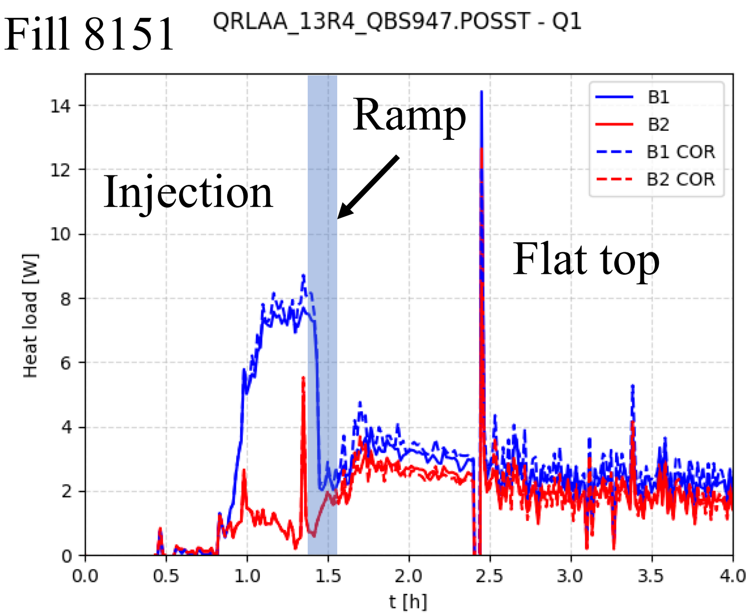
> → Similar beam quality for most of stable beams
> → Can compare fills at different times to find similar bunch intensities and lengths

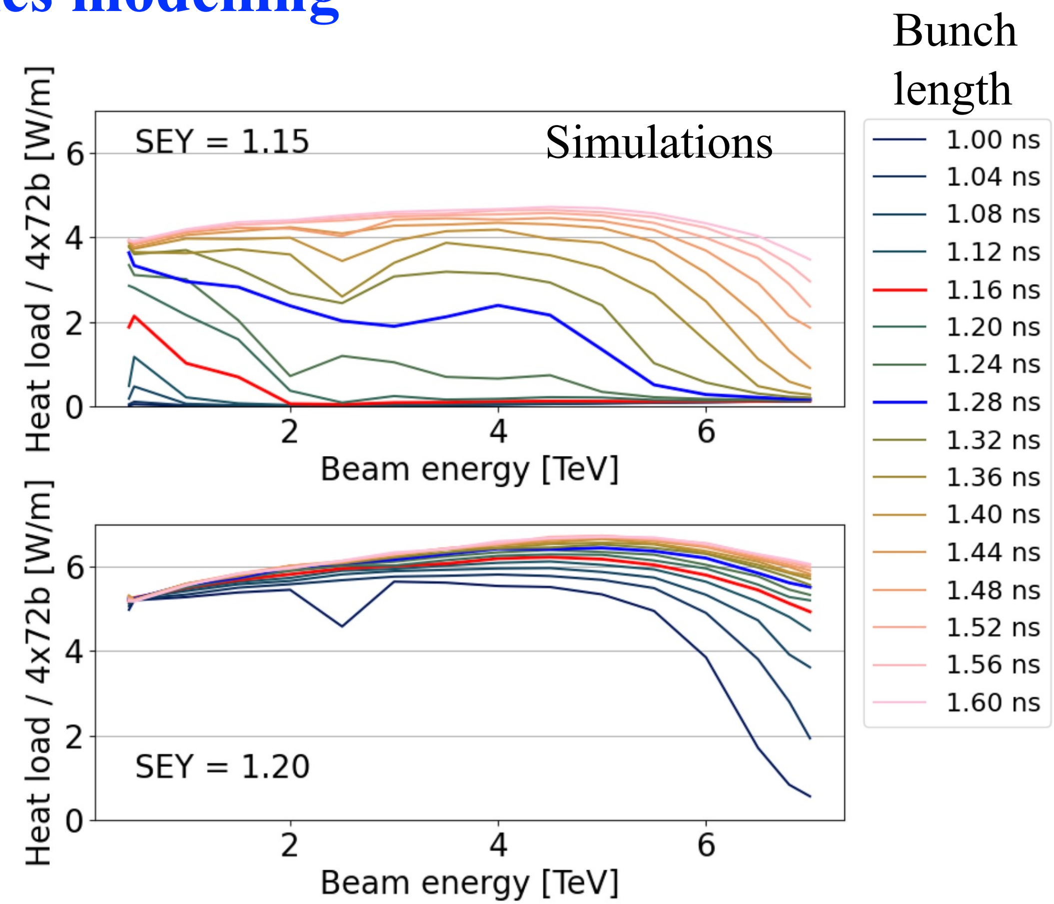


Filling scheme LPC links

Hybrid-36b:
https://lpc.web.cern.ch/schemeEditor.html?user=lpc&scheme=Studies/25ns_2464b_2452_1889_2067_236bpi_mixed5x36b.json
Hybrid-48b:
https://lpc.web.cern.ch/schemeEditor.html?user=lpc&scheme=Studies/25ns_2452b_2440_1952_2240_248bpi_12inj_mixed.json
5x36b:
https://lpc.web.cern.ch/schemeEditor.html?user=gianni&scheme=20220809_36b_scheme/25ns_2496b_2488_2121_2260_144bpi_20inj_800ns_bs200ns.json
6x36b:
https://lpc.web.cern.ch/schemeEditor.html?user=lotta&scheme=LHC-2024/25ns_2604b_2592_2097_2059_6x36bpi_13inj_800ns_bs200ns.json
Reverse hybrid-48b 1:
https://lpc.web.cern.ch/schemeEditor.html?user=lotta&scheme=LHC-2023/25ns_2612b_2600_1903_1924_hybrid_25ns_5x48b_8b4e_1x56b_11inj.json
Reverse hybrid-48b 2:
https://lpc.web.cern.ch/schemeEditor.html?user=lotta&scheme=LHC-2023/25ns_2580b_2568_1913_1956_hybrid_8b4e_1x56b_25ns_5x48b_10inj.json
Separated hybrid-48b:
https://lpc.web.cern.ch/schemeEditor.html?user=lotta&scheme=LHC-2024/25ns_2604b_2592_2211_2204_separated_hybrid_25ns_5x48b_8b4e_3x56b_13inj.json

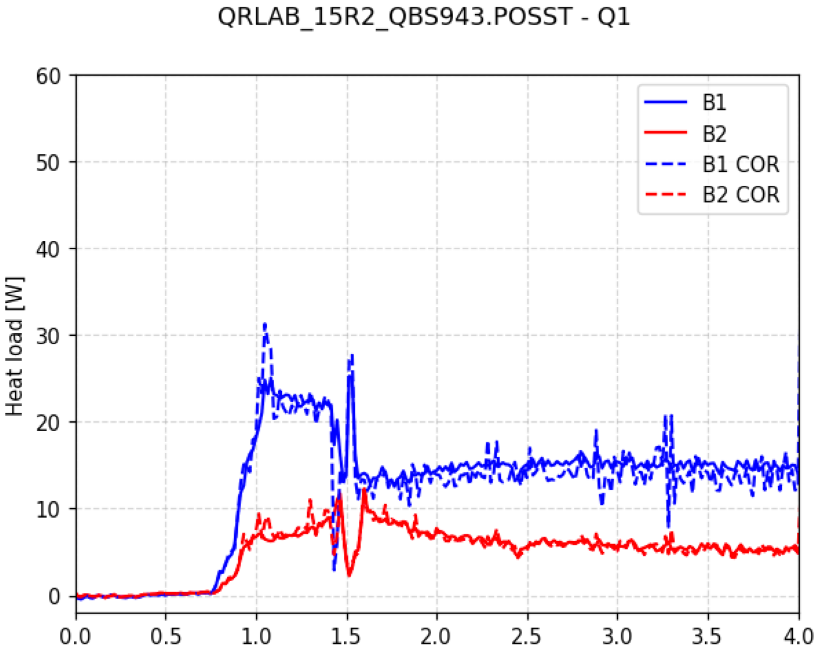
Instrumented quadrupoles modelling

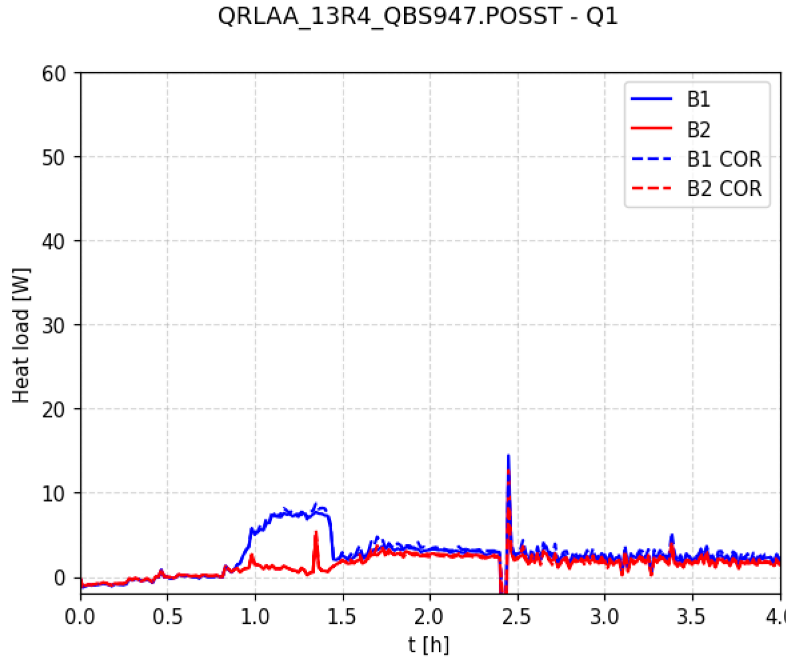


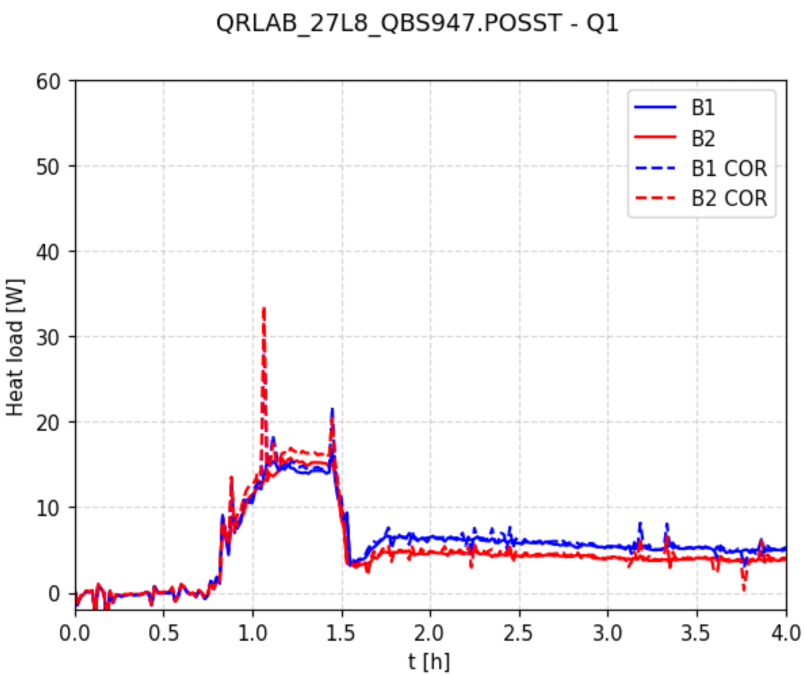


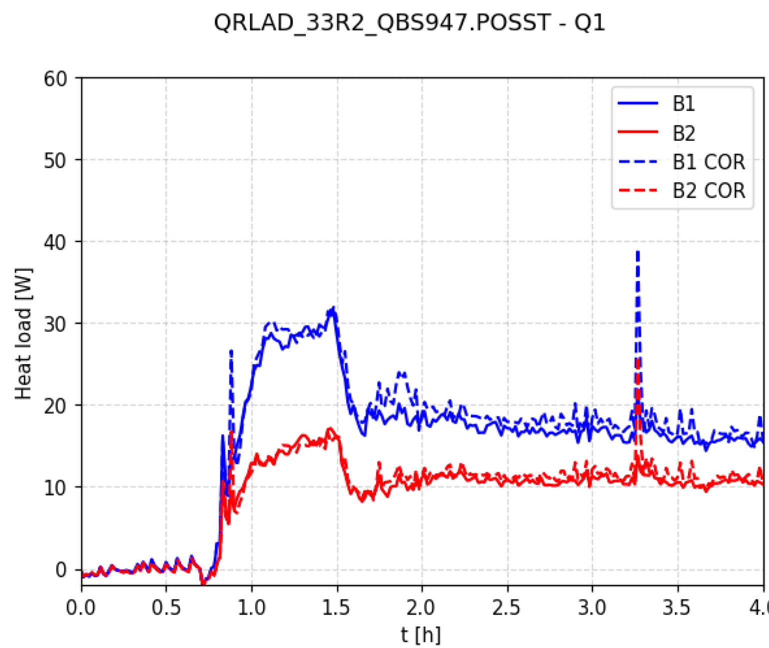
- Curious effect observed in instrumented quadrupoles:
  Heat load goes down with intensity.

Simulations show same behaviour but only when close to the multipacting threshold.
Multipacting threshold at *slightly* larger SEY for higher beam energies.


QRLAB_15R2_QBS943.POSST - Q1
Heat load [W]
B1
B2
B1 COR
B2 COR


QRLAA_13R4_QBS947.POSST - Q1
Heat load [W]
t [h]
B1
B2
B1 COR
B2 COR


QRLAB_27L8_QBS947.POSST - Q1
Heat load [W]
t [h]
B1
B2
B1 COR
B2 COR


QRLAD_33R2_QBS947.POSST - Q1
Heat load [W]
t [h]
B1
B2
B1 COR
B2 COR