Electron cloud

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Joint Accelerator Performance Workshop 2024
Royal Plaza Montreux & Spa, Montreux, Switzerland
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Outline

SPS

- Scrubbing

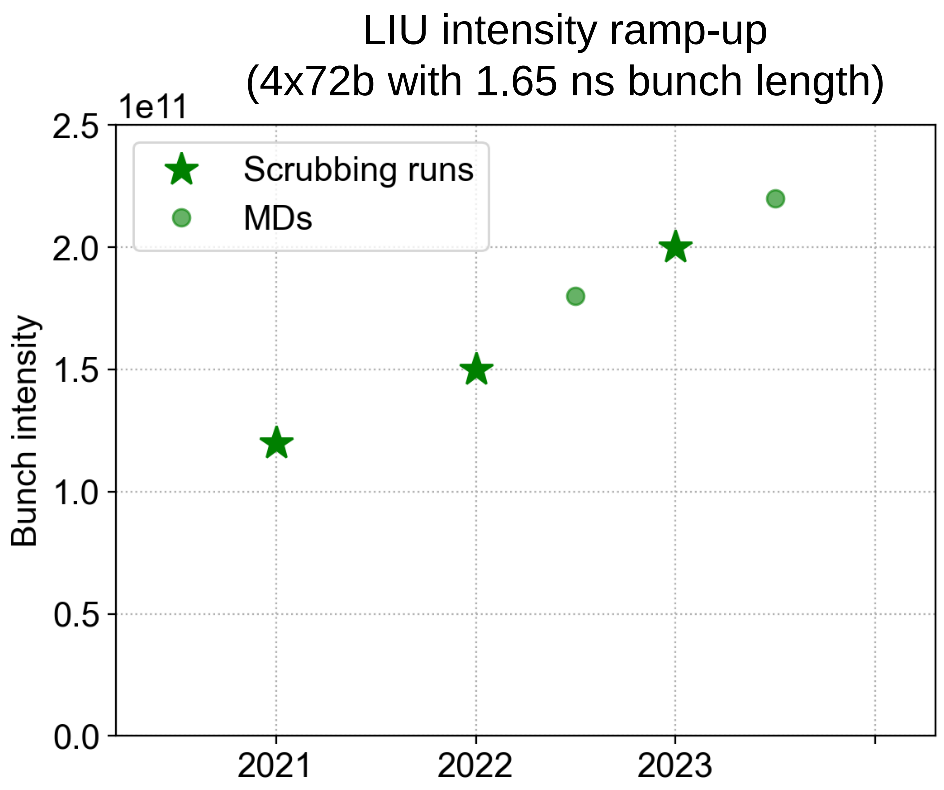
LHC

- Heat loads
  - Evolution, status and prospects
  - Modelling and measurements

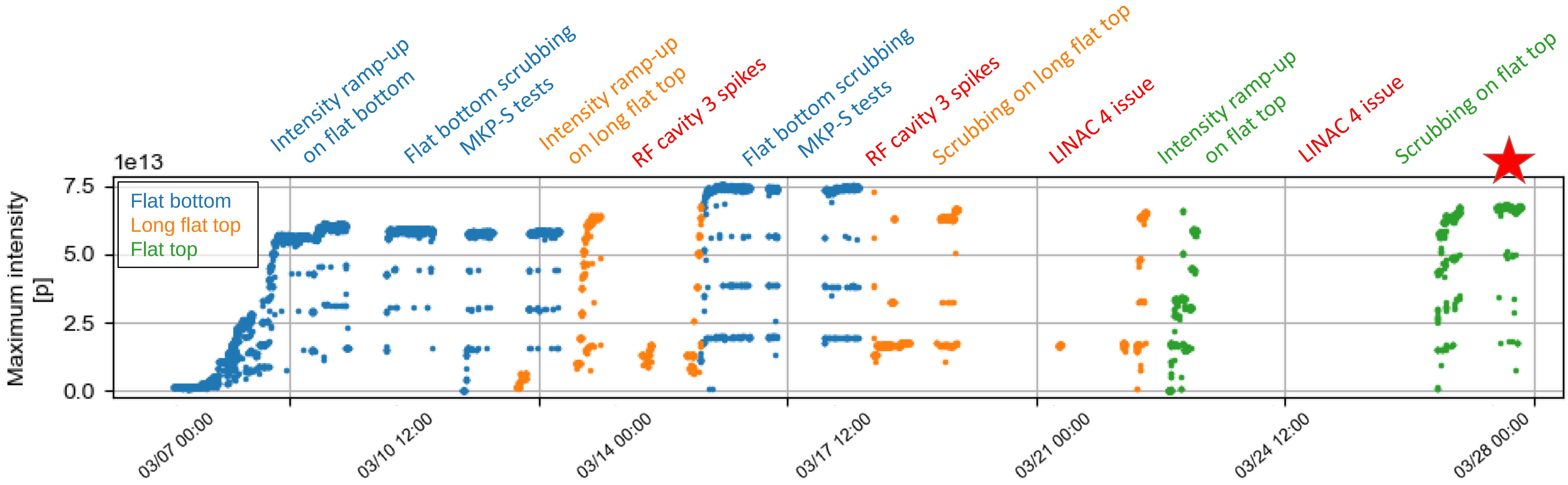
- Beam dynamics – models and measurements
  - Stability with negative octupole polarity
  - Impact of phase knob
  - Slow losses in collision

SPS scrubbing runs – electron cloud mitigation

- Since 2021, yearly month-long scrubbing runs have taken place before the start of physics
  - Condition newly installed equipment and vented areas after LS or YETS
  - Prepare the machine for LIU beams (4x72b) – gradually increasing bunch intensity on the ramp



2024 scrubbing run



Vented areas conditioned within a few days (no critical new equipment installed in YETS)

RF cavity pressure spikes appeared after restoring 2023 beam on long flat top cycle – dictated scrubbing pace for the rest of the run (MKP-L and MKDH scrubbing in the shadow of RF)

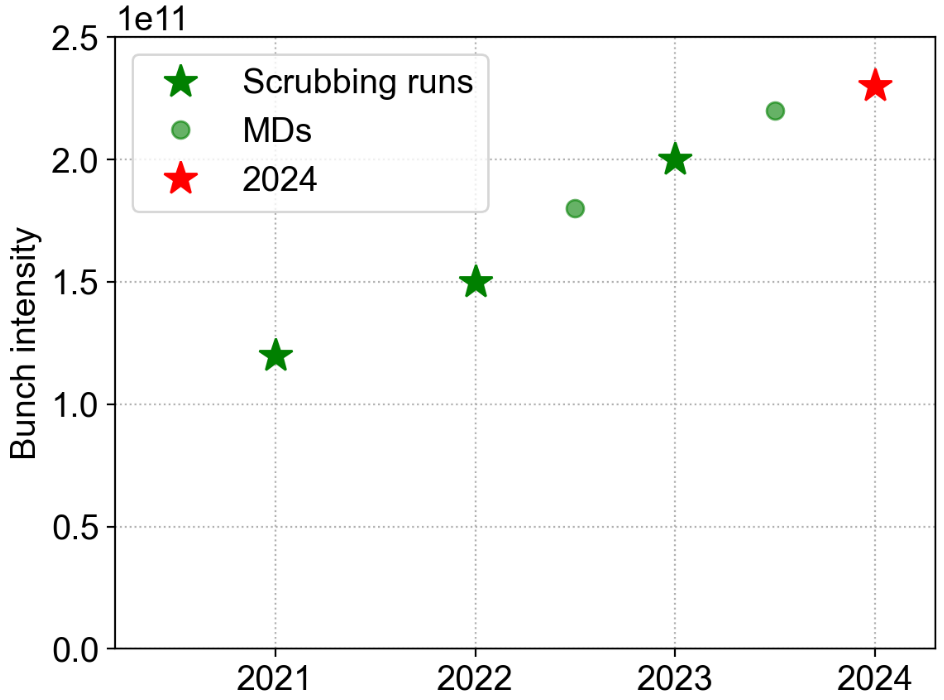
Finally reached LIU beam, 4x72b with 2.3e11 p/b and 1.65 ns bunch length at flat top, after 3 weeks of scrubbing

Status and plans for 2025

- The standard LIU beam finally achieved during scrubbing in 2024 (although lower brightness)
  - Could not be reproduced later during the year due to RF issues
  - → RF cavities may still need further conditioning with this beam

- In 2025, a week of scrubbing is scheduled
  - Should need ~3 days for scrubbing vented regions (no critical new equipment to condition)
  - Remaining time for recovering the LIU beam

- Work on LIU beam optimisation and reliability will be needed beyond the scrubbing run



Heat load evolution in Run 3

2022

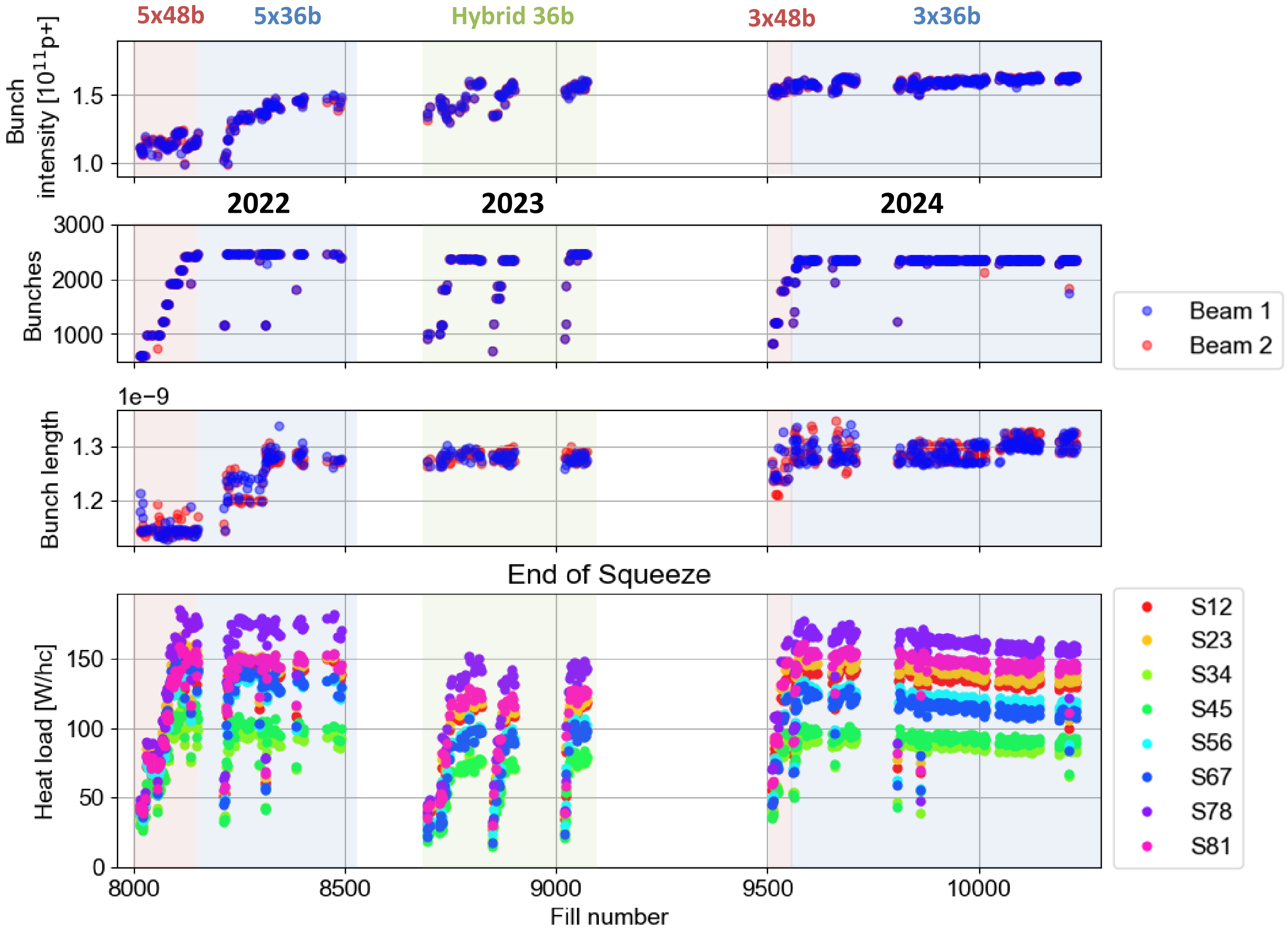
- Operating at constant heat load
- Adjusting number of bunches, bunch intensity and bunch length to heat load

2023

- Short run with hybrid scheme

2024

- Similar beam parameters all year
- Decreasing heat load in all sectors → scrubbing!



Evolution in 2024

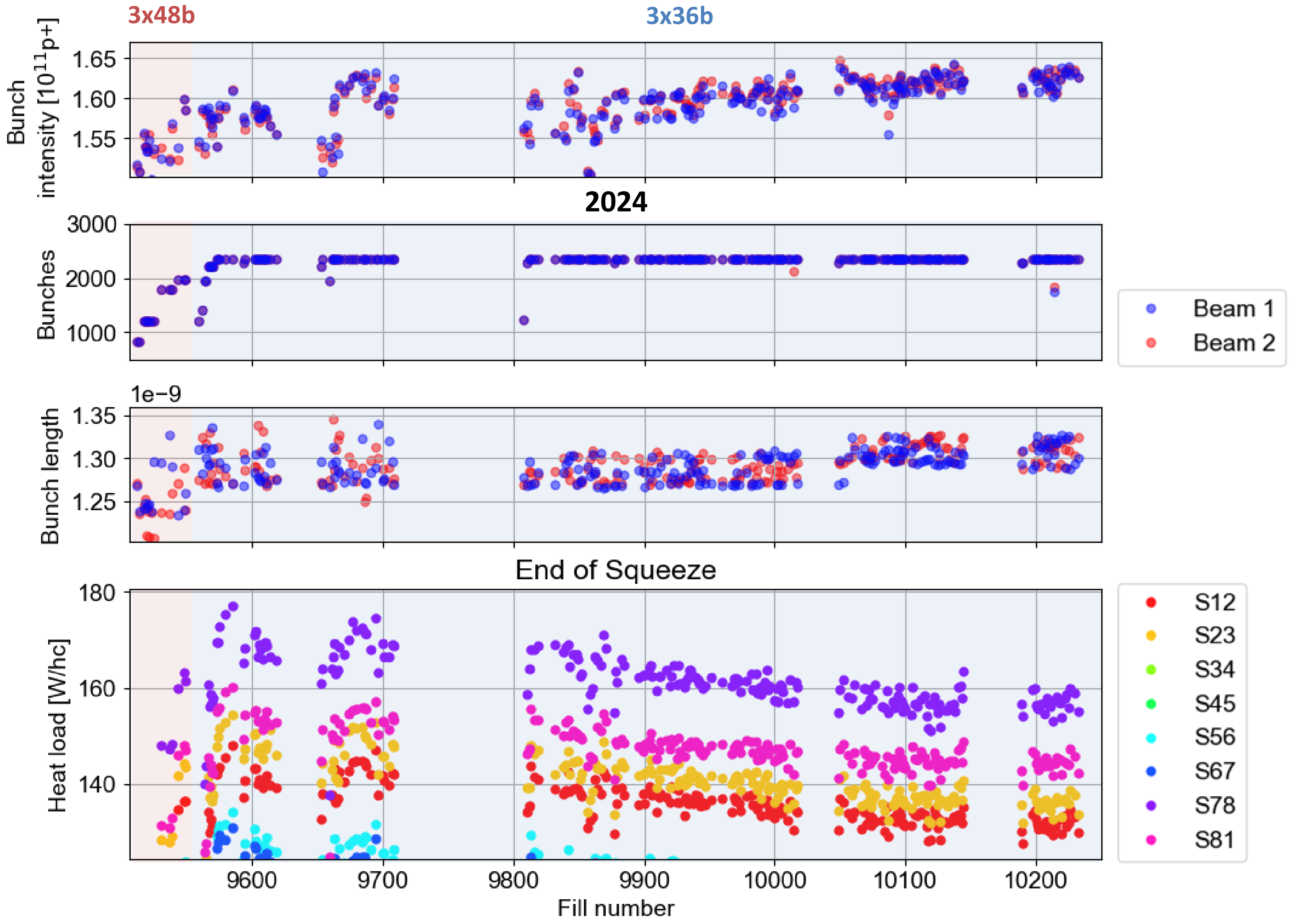
At any given time, the heat loads show a spread of 5-10 W/hc

- Spread in beam parameters
- Measurement precision

→ Trends visible only long-term

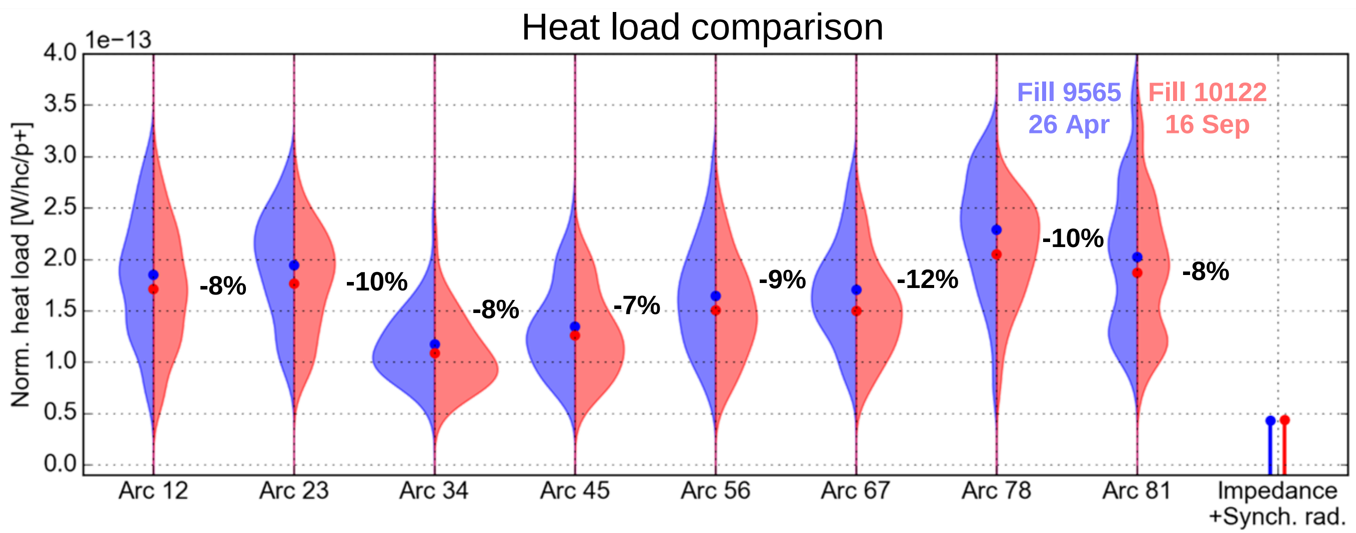
- During 2024, heat load in S78 and other sectors decreased by ~10%

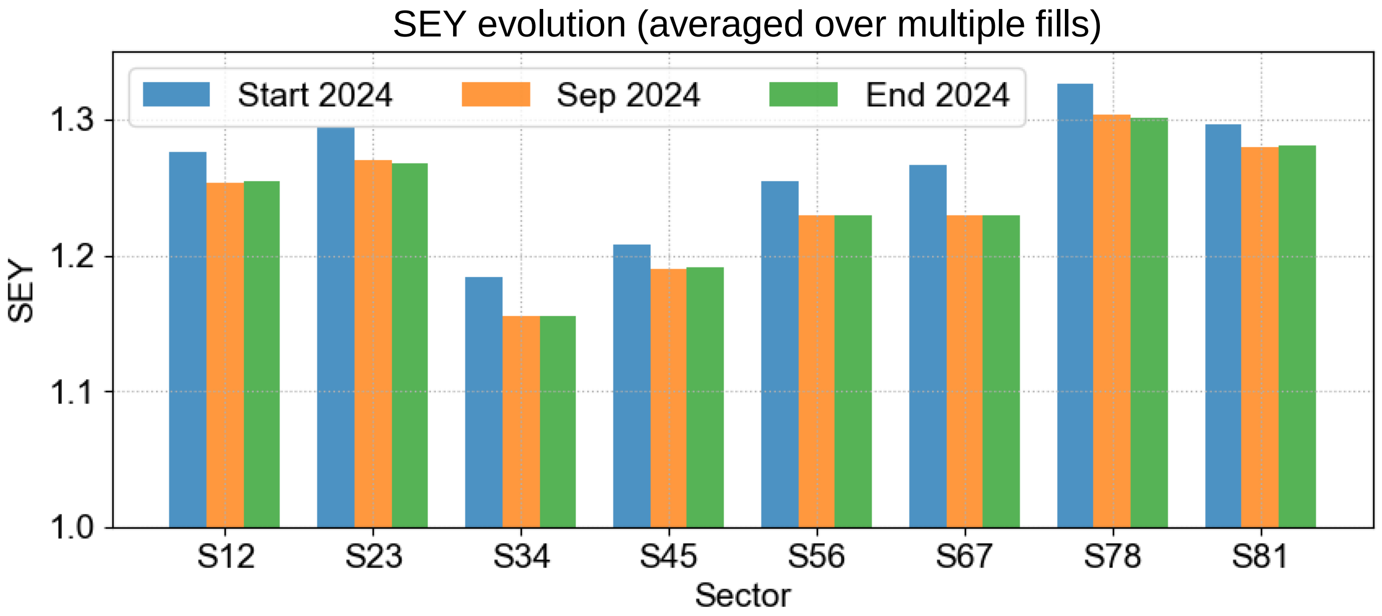
- No apparent evolution over last ~150 fill numbers



Evolution in 2024

- A comparison of fills with similar beam parameters confirm ~10% heat load reduction between April and September
  - Corresponds to reduction of reconstructed SEY values by 0.02 – 0.04, e.g. 1.33 → 1.30 in S78
- No evolution in reconstructed SEY either over last month of operation
  - In the very best case, scrubbing will continue at the same pace also in 2025
  - More likely, scrubbing will slow down – we may be seeing the beginning of that (TBC in 2025)



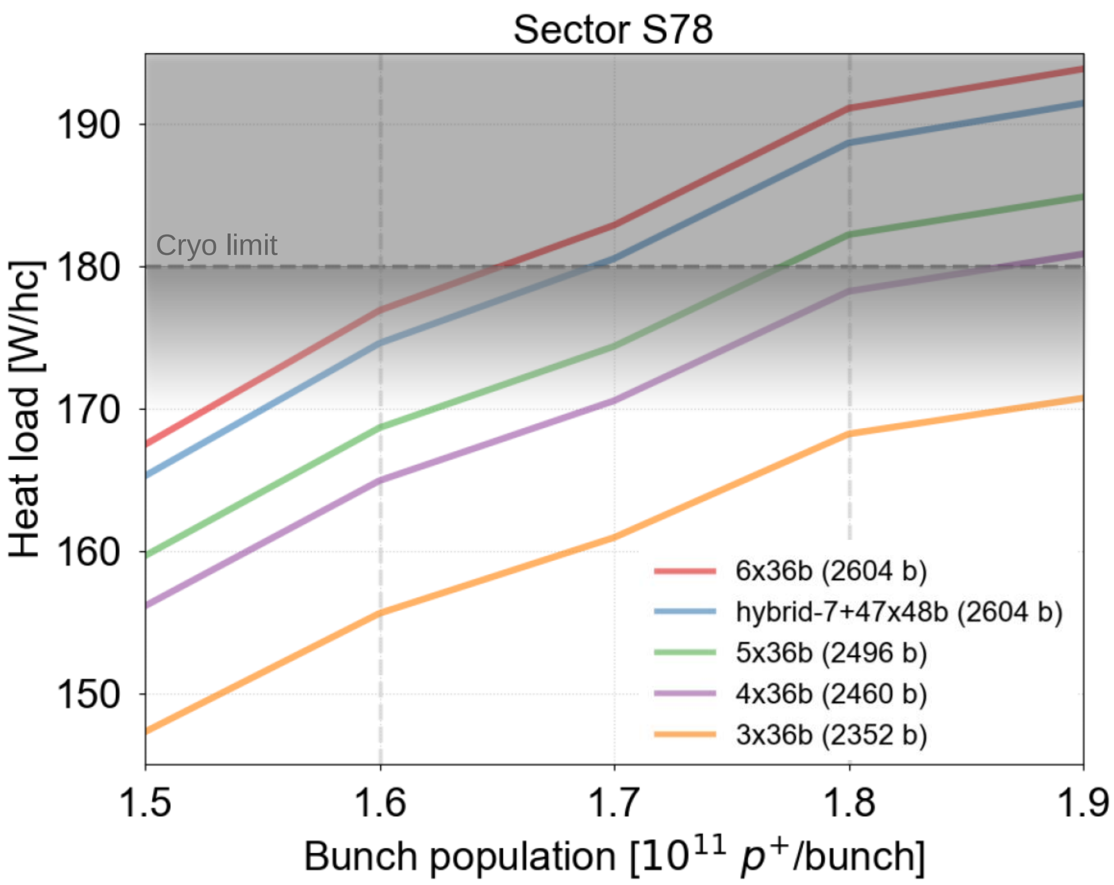


Filling scheme options for 2025

- With the additional 10% of scrubbing, there is margin on the cryo capacity to increase the total intensity
  - We could have increased the number of bunches and/or bunch intensity already in the second half of 2024

- Filling schemes with trains of 36b (pure 25 ns beam) remain good options

- New hybrid schemes, using trains of 48b and 8b+4e with 48b instead of 56b (at injectors' request) also studied
  - Interesting mainly if pushing the number of bunches



Predictions based on end-2024 status
Assuming 1.30 ns bunch length at flat top

Filling scheme options for 2025

	N_b	Collisions IP1/5	IP2	IP8	S78 heat load [W/hc] 1.6e11	1.8e11	Heat load per bunch	N_{bpi}	N_{inj}	SPS flat bottom [s]
6x36b	**2604**	2592	2097	2059	177	191	+1.1%	216	13	18
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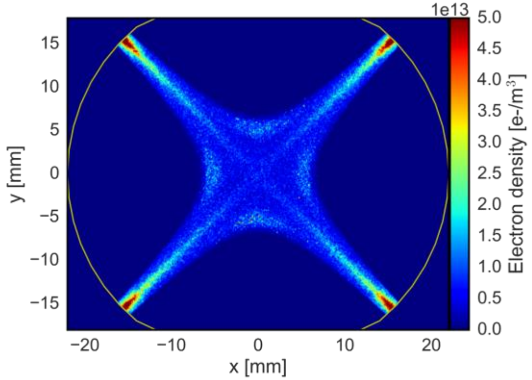
- Heat load differences between Nx36b-schemes comes mainly from the number of bunches, while the difference in heat load per bunch is around 1% ≈ 2 W/hc
  - → It makes sense to choose a filling scheme that allows adjusting the heat load to the cryo capacity by adapting the number of bunches (considering that neither heat load measurements nor predictions are 100% precise)
  - → Also gives more flexibility for optimising heat load & performance as a function of the bunch intensity

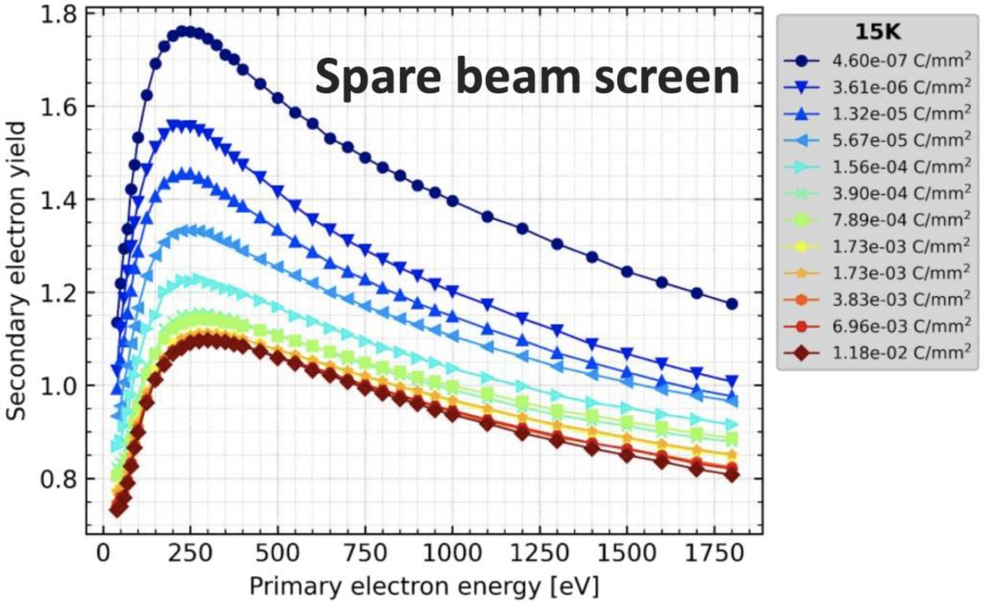
See presentation by X. Buffat this afternoon for further performance considerations

Modelling

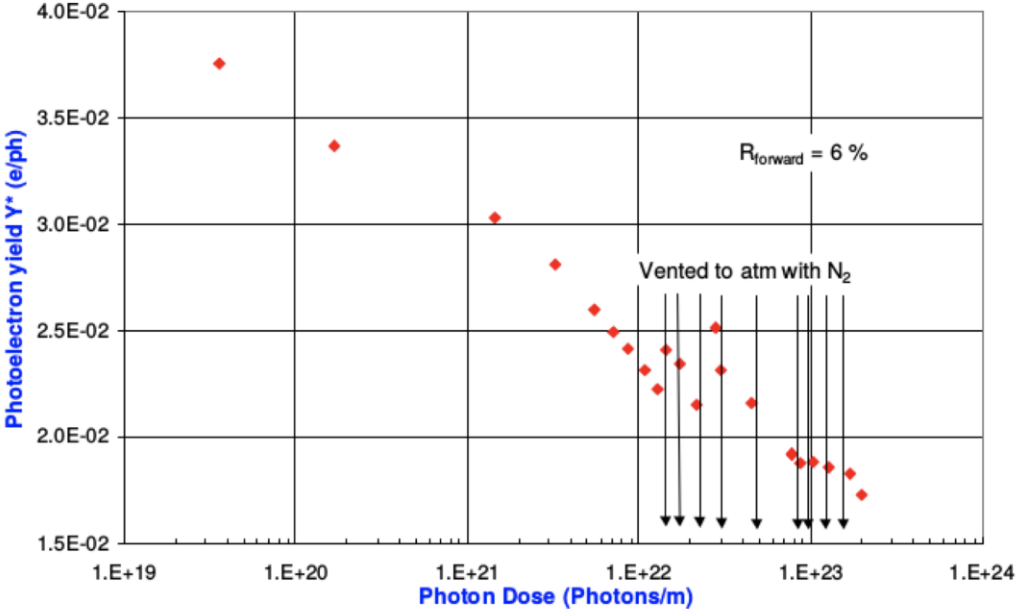
- The heat loads are modelled with electron cloud build-up simulations (PyECLOUD)
  - Simulates electron motion under the influence of the beam and magnetic fields
- Relies on parameterisations of surface properties, measured over past ~30 years
  - Secondary electron emission yield (energy and incidence angle dependence)
  - Photoelectron emission yield (from synchrotron radiation at flat top)
  - Energy spectra of emitted electrons



[V. Petit et al, JAP'23]

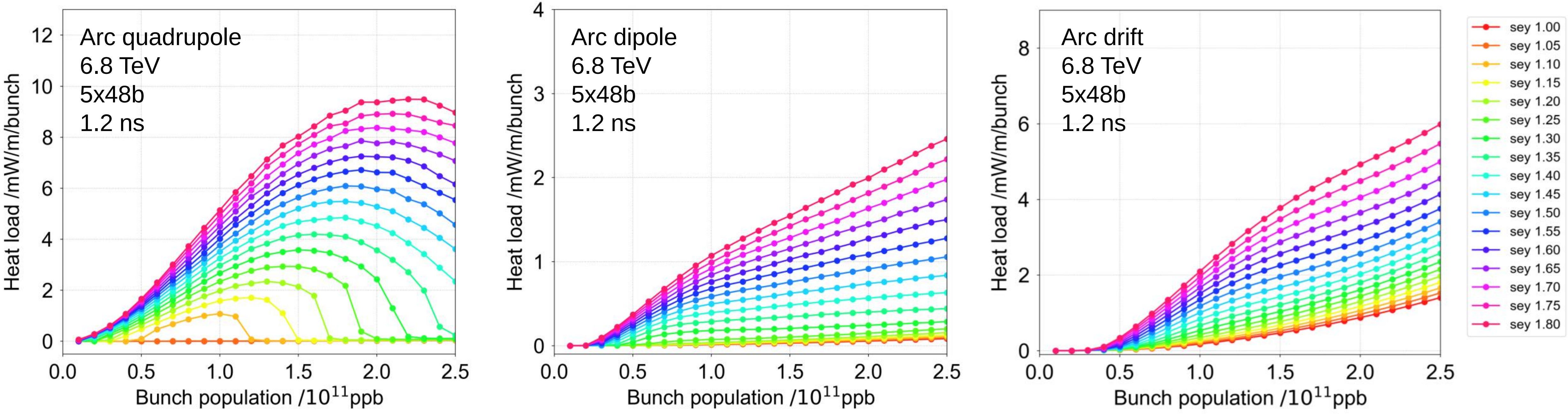


[V. Baglin et al, Chamonix 2001]



Modelling

- Heat load estimated as a function of the SEY, magnetic field, beam energy, intensity, bunch length and filling scheme
  - Half-cell heat load obtained by adding contributions from all the main lattice elements
  - Matching the measured heat load in each half-cell to the simulated ones determines cell-by-cell SEY values, which are then be used for heat load predictions with different beam conditions



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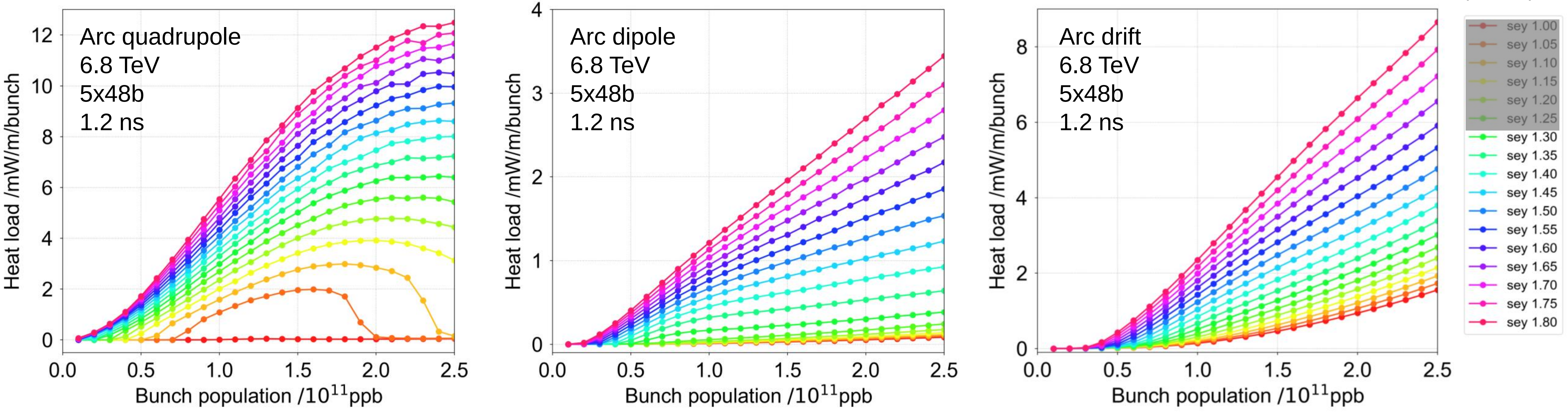
- Model depends also on assumed surface parameters, e.g. SEY curve (Cu2O vs CuO) and photoelectron yield
  → must be determined with dedicated parameter scans

Simulations with parameterisation of SEY curves for CuO shown by V. Petit at JAP'23

Excluded in principle

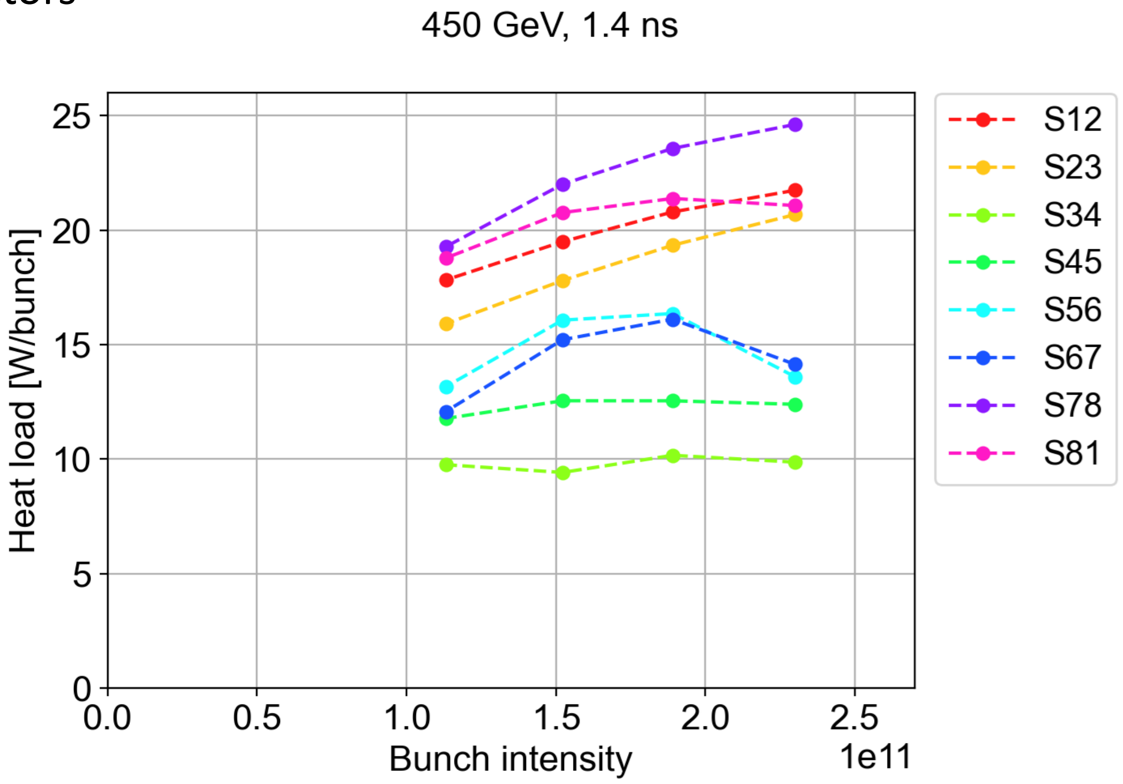


Heat load with high intensity

- Measured heat load at injection with up to 2.3e11 p/b with ≧ 972 bunches (MD5)

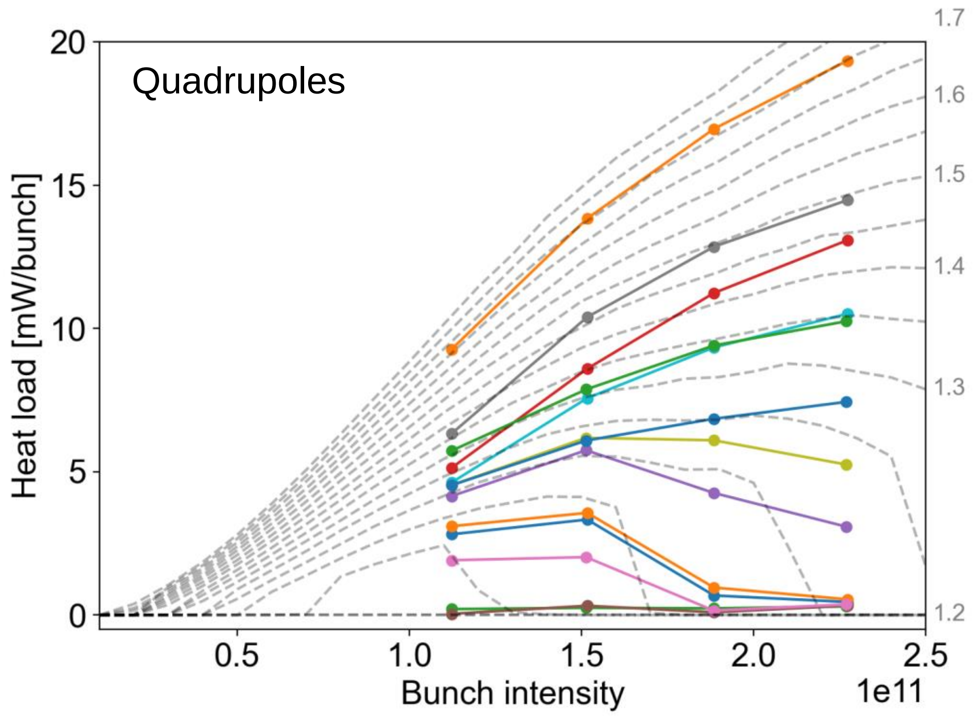
- Large difference in bunch intensity dependence between sectors
  - Decreasing for high intensity in sectors 56, 67 and to some extent 81(!) – as expected in Run 2
  - Increasing with intensity in sectors 12, 23 and 78
  - No clear intensity dependence in sectors 34 and 45 (measurement accuracy also lower)

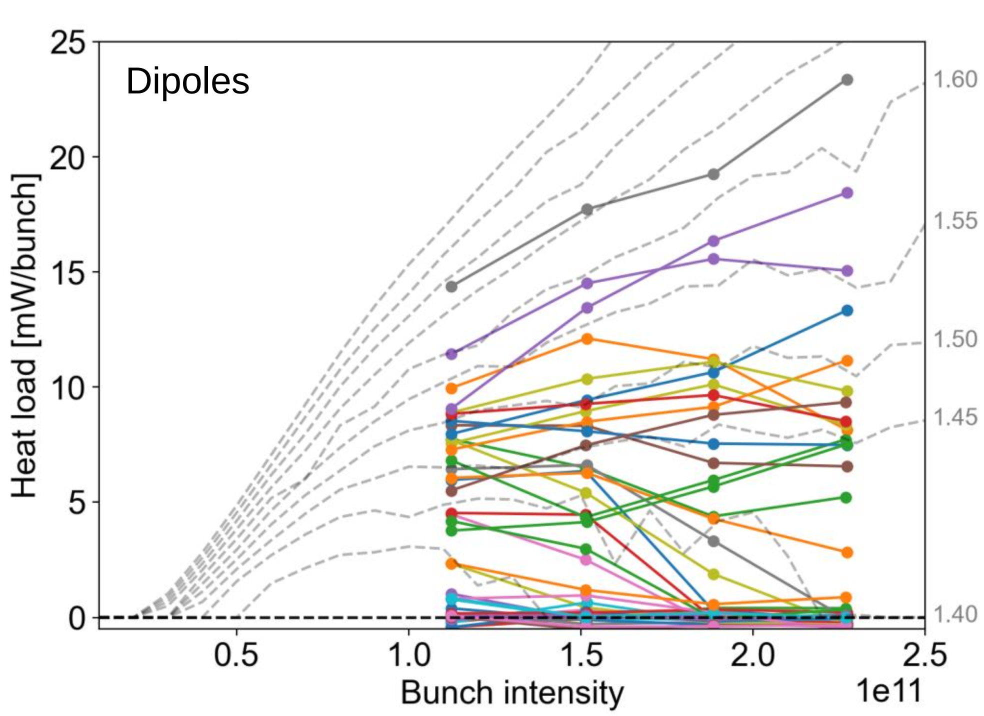
- Measurements at one intensity are not sufficient to determine intensity dependence (why we need scans)



Instrumented cell heat loads

- 8 half-cells are equipped with additional thermometers to measure heat load per magnet aperture
  - Quadrupoles match well with simulated curves, with SEY: 1.05 – 1.7
  - Dipoles match reasonably, but there are many more diverging curves, with SEY: 1.3 – 1.65+
    - The exposed part of the surface varies with the bunch intensity, as the electron stripes move
    - The beam screens are 4.5x as long as the quadrupoles, surface variations more likely
  - Matched SEY in many apertures still much higher than expected for scrubbed surfaces



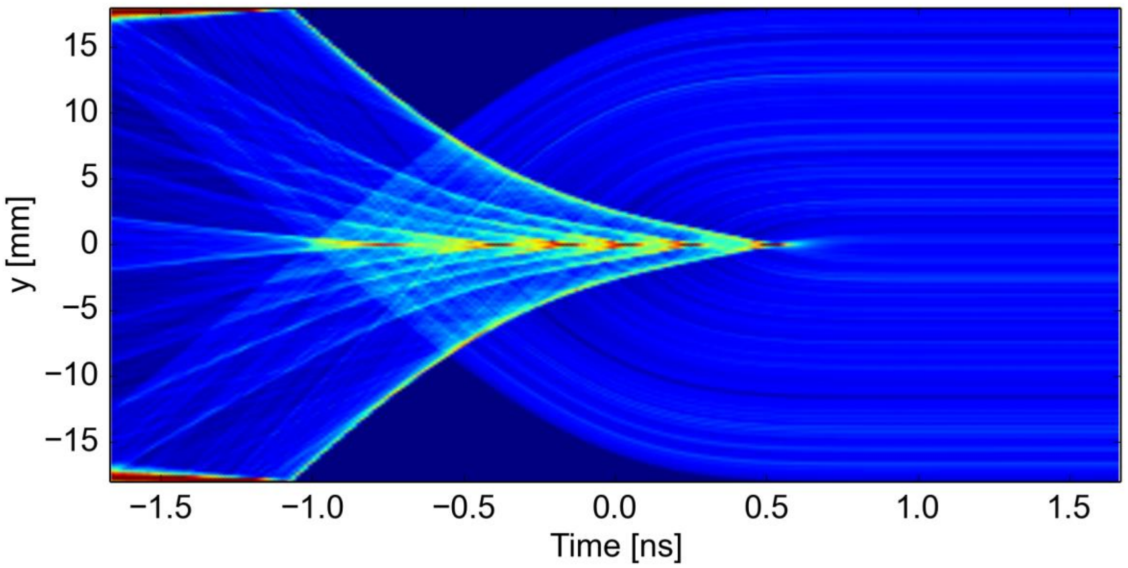


Electron cloud and beam dynamics

To model the impact of electron clouds on the beam, we can use build-up simulations together with beam particle tracking tools (PyHEADTAIL, Xsuite), often starting from saved electron distributions

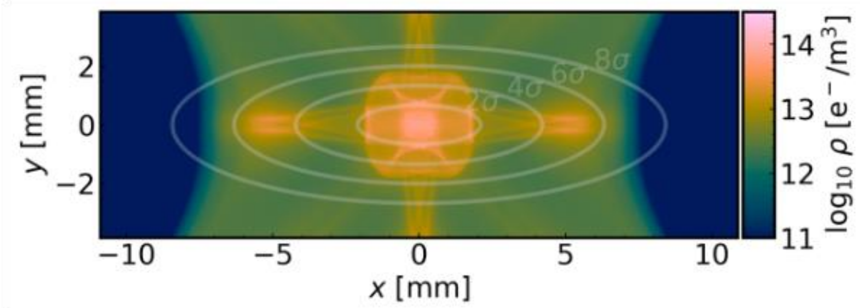
Coherent instabilities

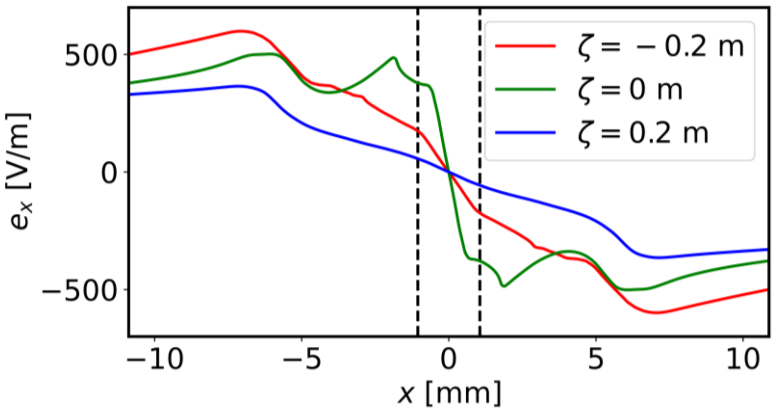
- Track full (macroparticle) beam through the machine
- Interaction with the e-cloud modelled self-consistently, considering the impact of the two charge distributions on each other (strong-strong regime)



Incoherent effects

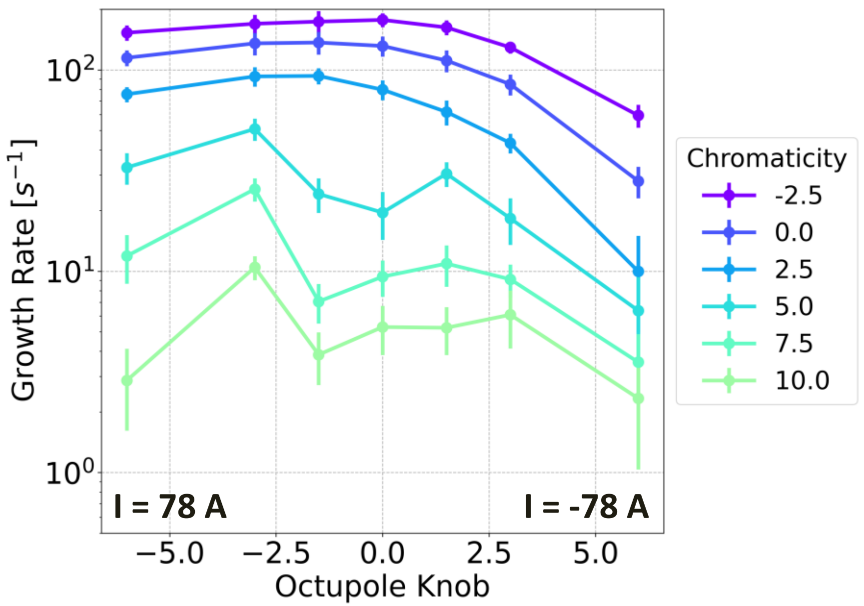
- Track single particles with non-linear machine lattice
- Non-linear e-cloud forces modelled through saved maps of the electron field (weak-strong regime)

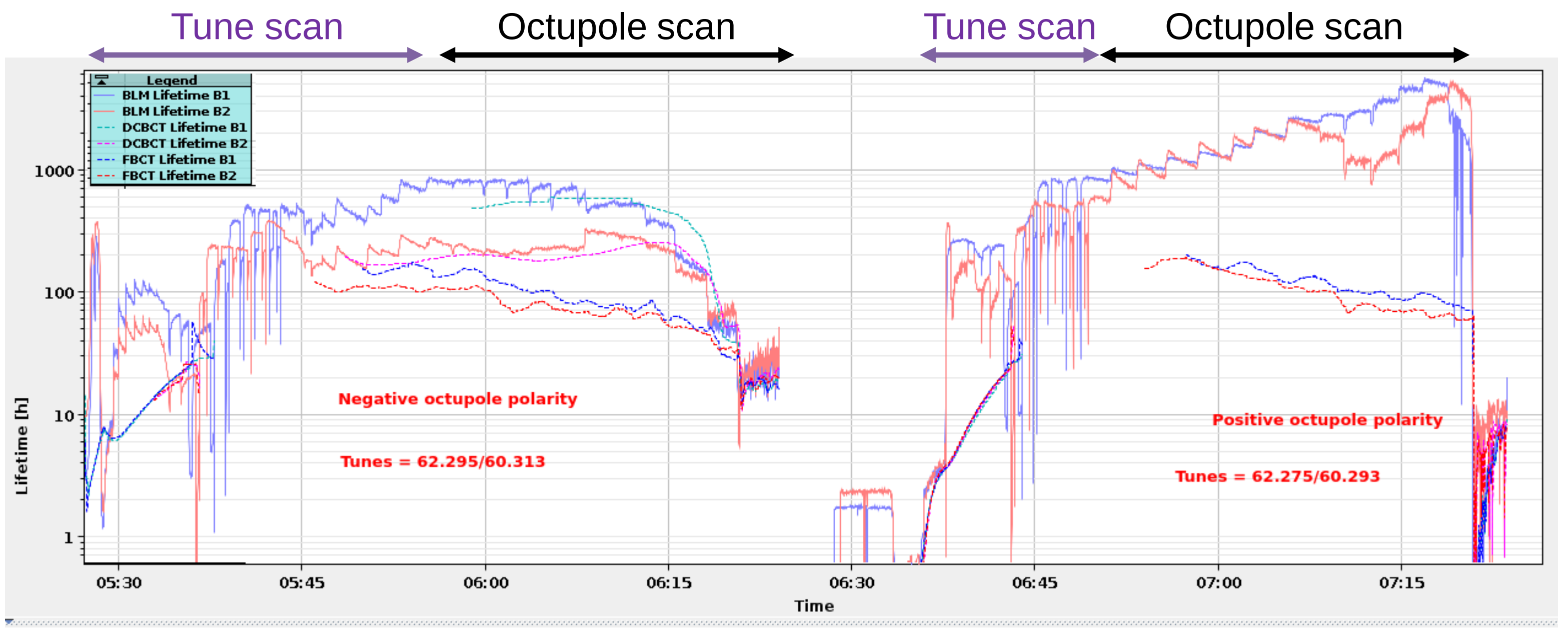




Stability at injection with negative octupole polarity

- Simulations performed pre-Run 3, show stronger suppression of the instability from e-cloud in quadrupoles at injection with negative octupole currents
- Confirmed in measurements for 2024 beam parameters (MD5)
  - Similar stability with ~1 unit less in octupole knob (13 A) for negative polarity





Lifetime with negative polarity worse than with positive polarity

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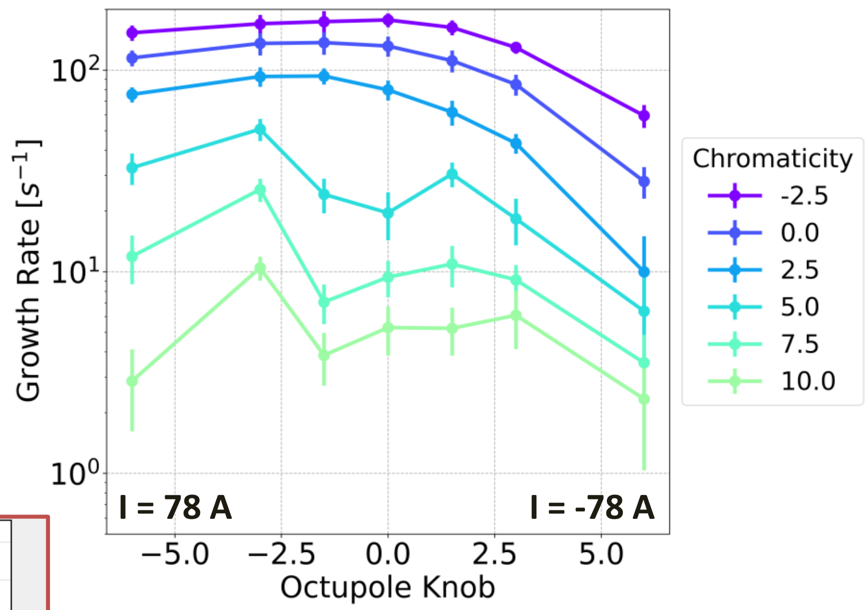
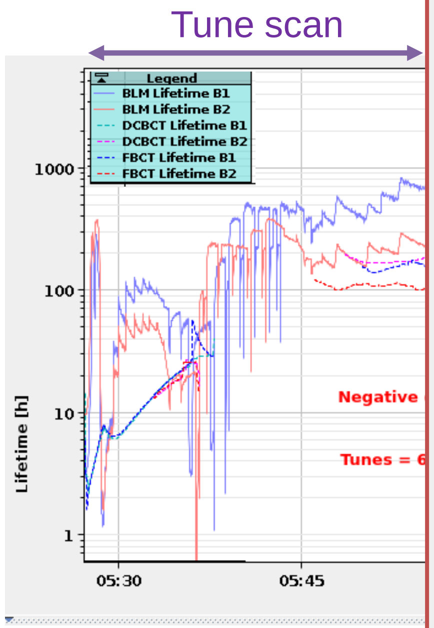
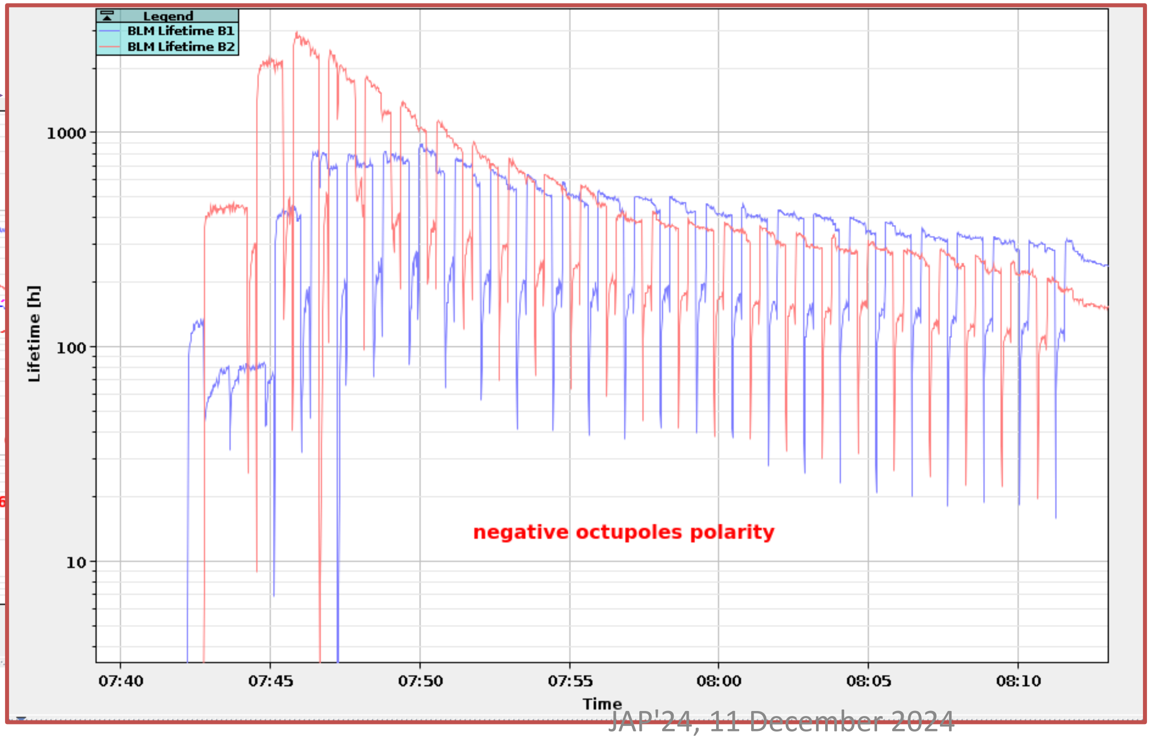






Lifetime with negative polarity worse than with positive polarity

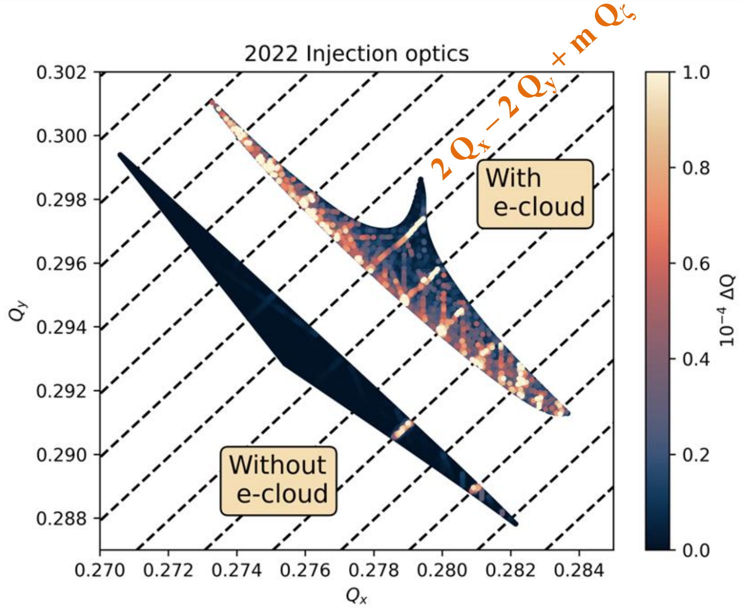
- But remained > 100 h for injection of physics fill with optimised tunes (0.295/0.313)

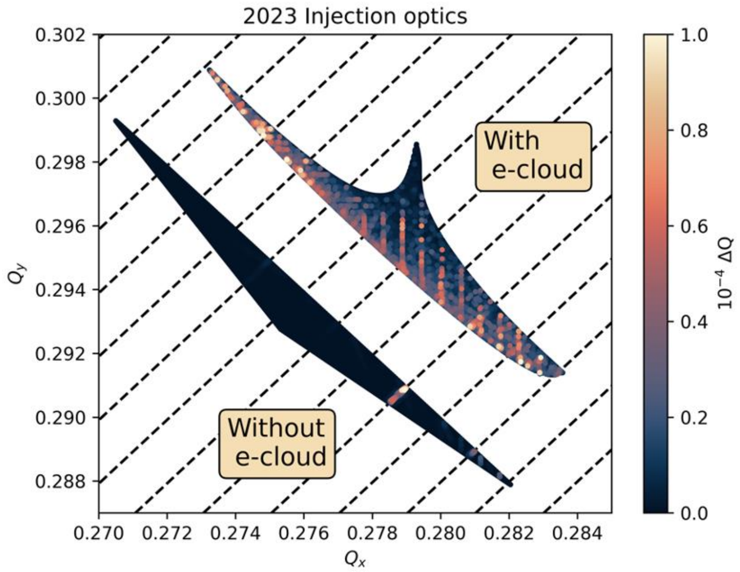
Incoherent effects at injection

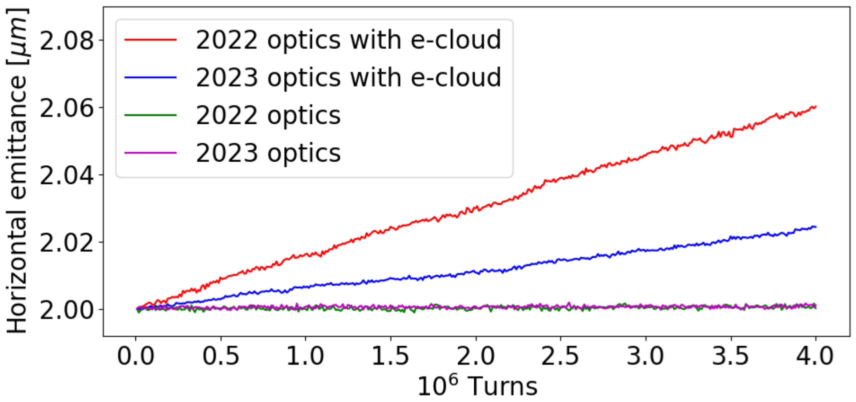
- The large electron density at the beam location in the arc quadrupoles causes emittance growth and reduced beam lifetime
  - Incoherent e-cloud simulations identified synchro-betatron resonances as main cause

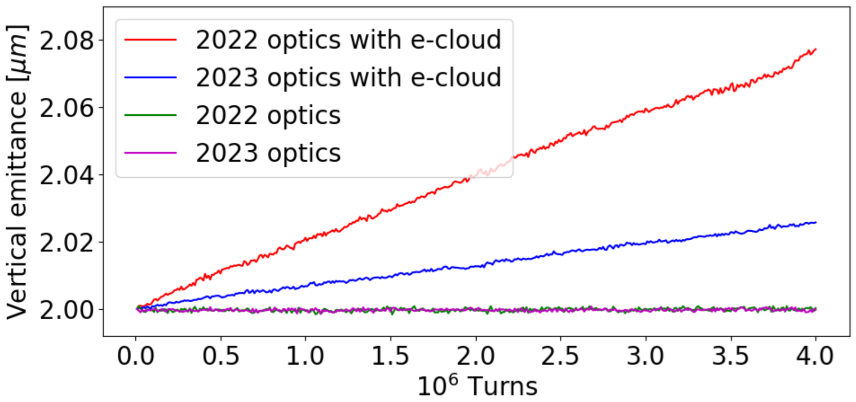
- New "phase knob" for injection optics introduced in 2023
  - Arc-by-arc phase advance change to mitigate octupolar resonances from lattice octupoles and e-cloud

→ Significant reduction in synchro-betatron resonances and emittance growth in simulations







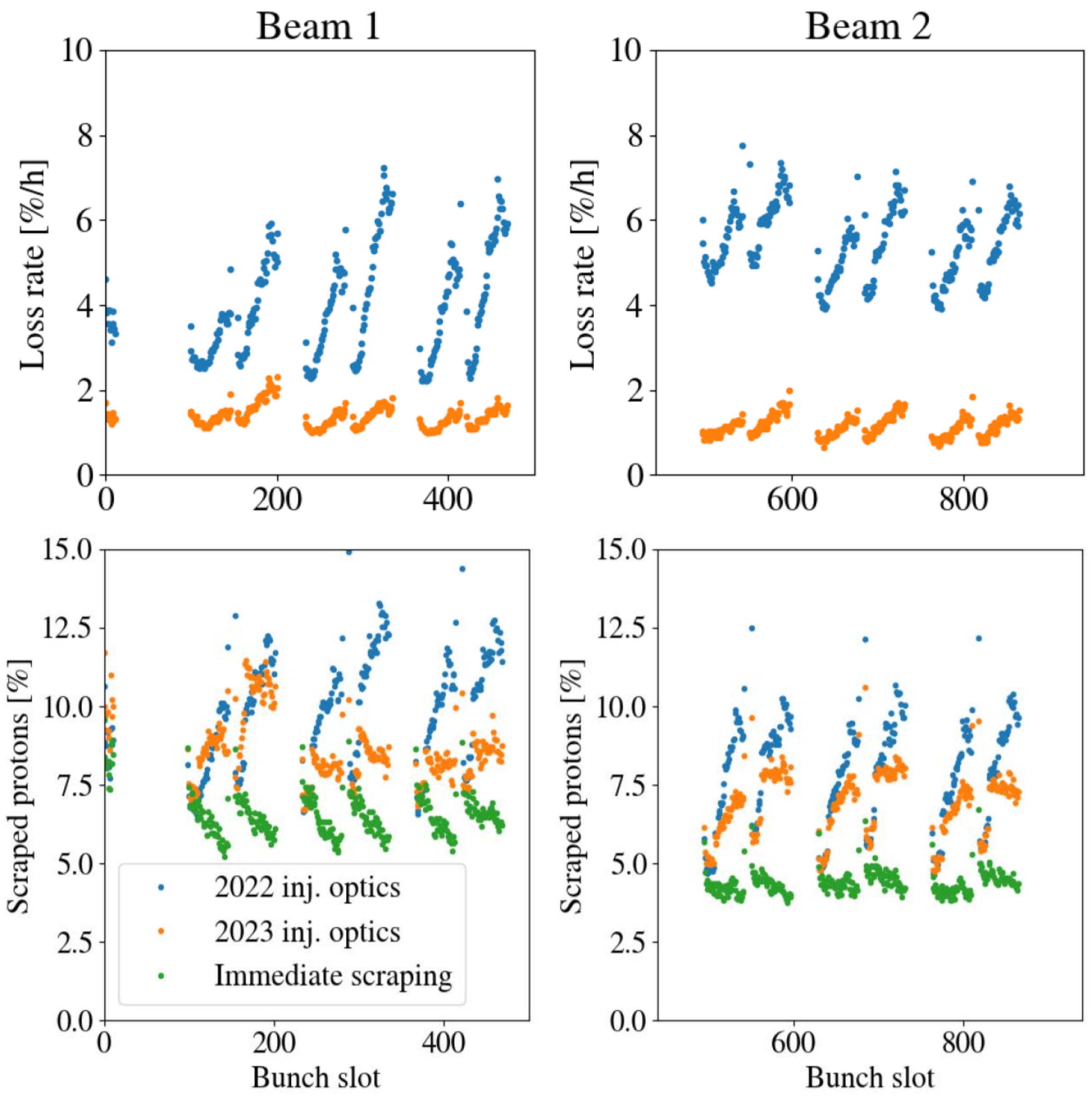


Incoherent effects at injection

Impact of phase knob assessed with dedicated measurements (MD2)

1. Both "non e-cloud" and "e-cloud" losses greatly reduced

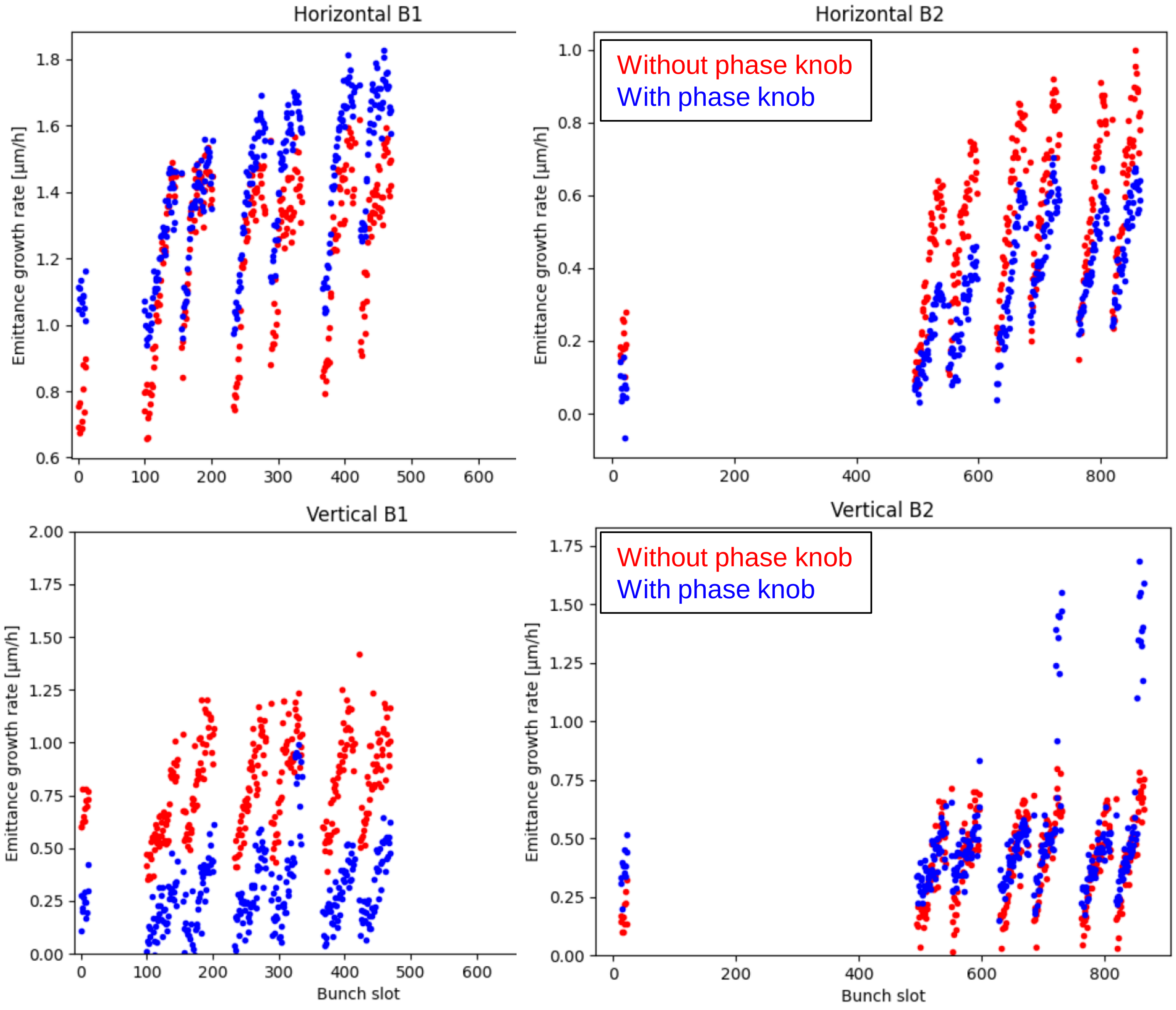
2. "Electron cloud" halo formation reduced



Incoherent effects at injection

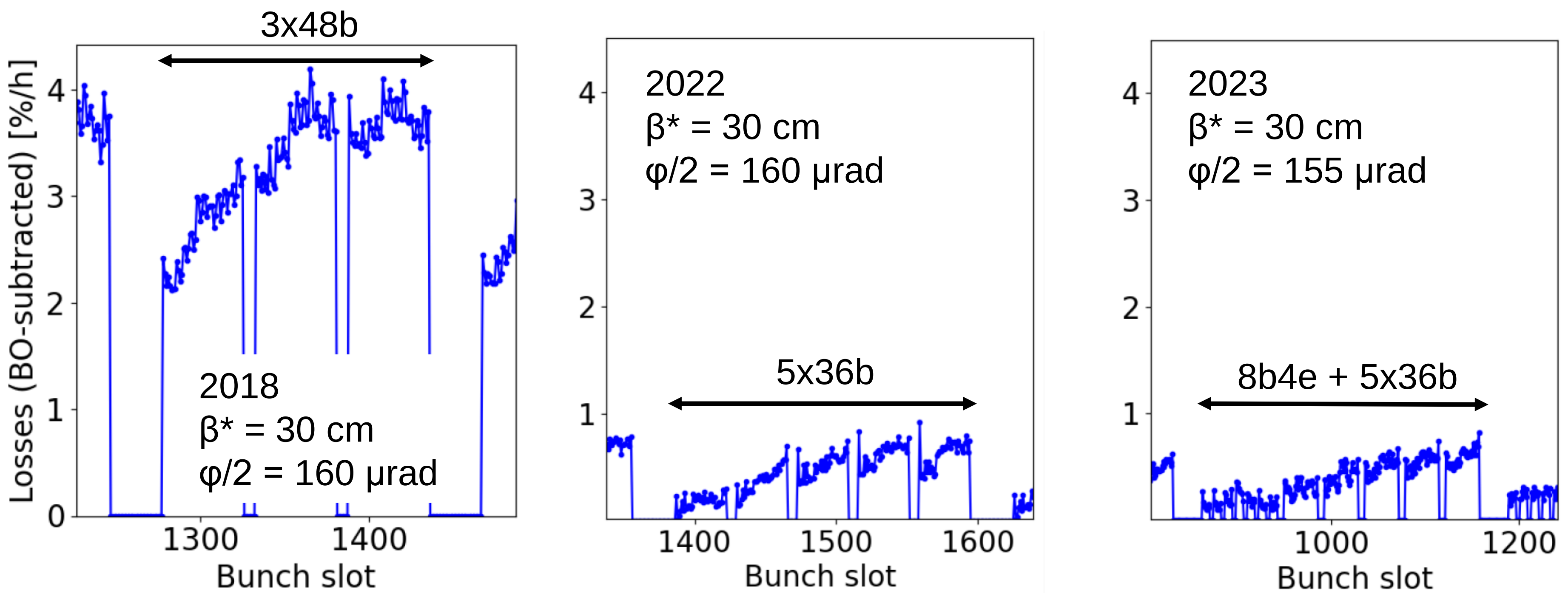
Impact of phase knob assessed with dedicated measurements (MD2)

1. Both “non e-cloud” and “e-cloud” losses greatly reduced
2. “Electron cloud” halo formation reduced
3. Spread in bunch-by-bunch BSRT emittances reduced
   - Although it doesn’t always imply smaller emittance growth rate



Slow losses during stable beams

- 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



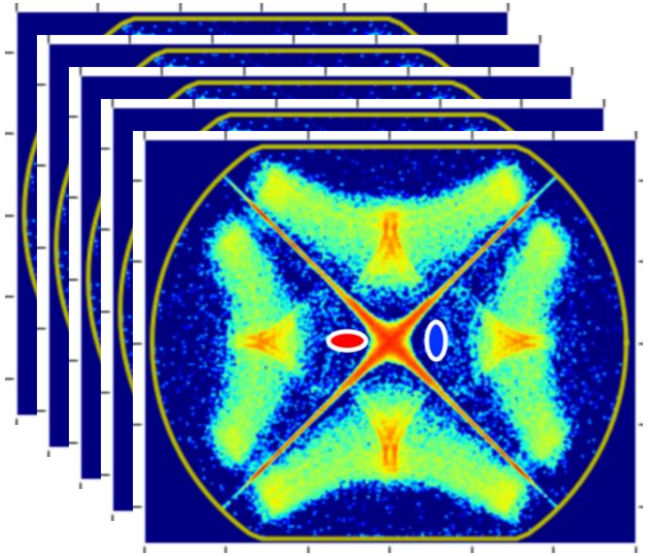
The relative losses are smaller in Run 3 than in Run 2

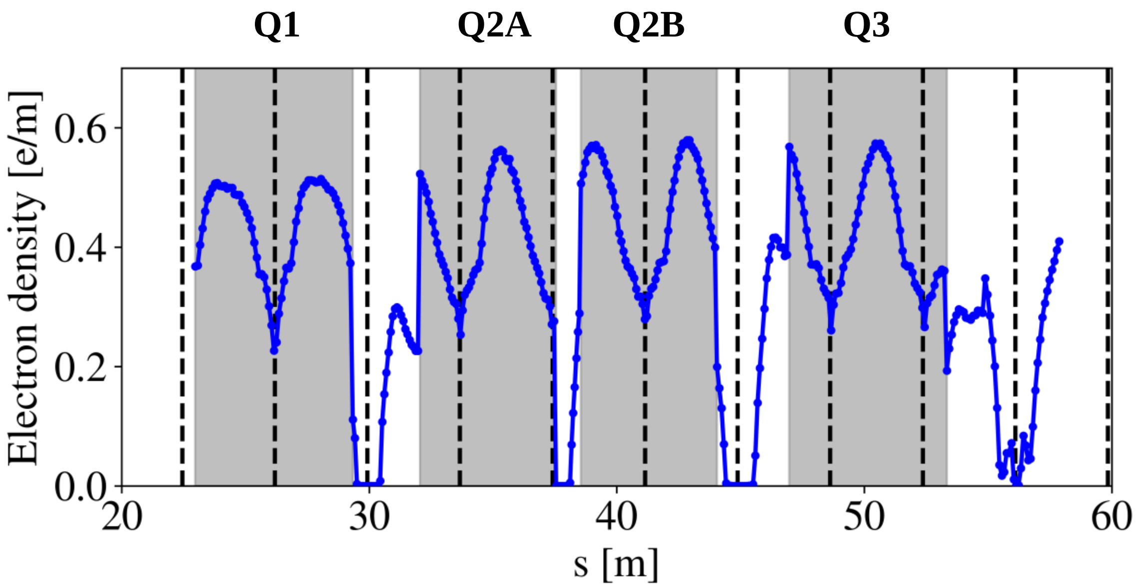
- Long-term tracking simulations, including longitudinally resolved e-cloud in the triplets and beam-beam effects, have been performed for the first time this year

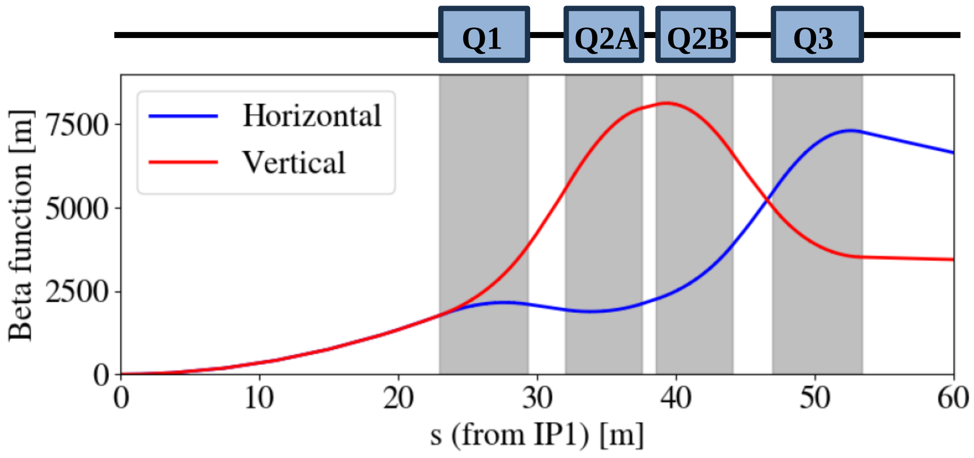
Effective e-cloud in the Inner Triplet

- Simulations of the Inner Triplet are complicated by:
  - Presence of the two beams with varying offset along the triplet
  - Large changes in the beta functions

- Electron cloud strongly depends on delay between two beams
  → Around 400 e-cloud slices per triplet needed for resolution







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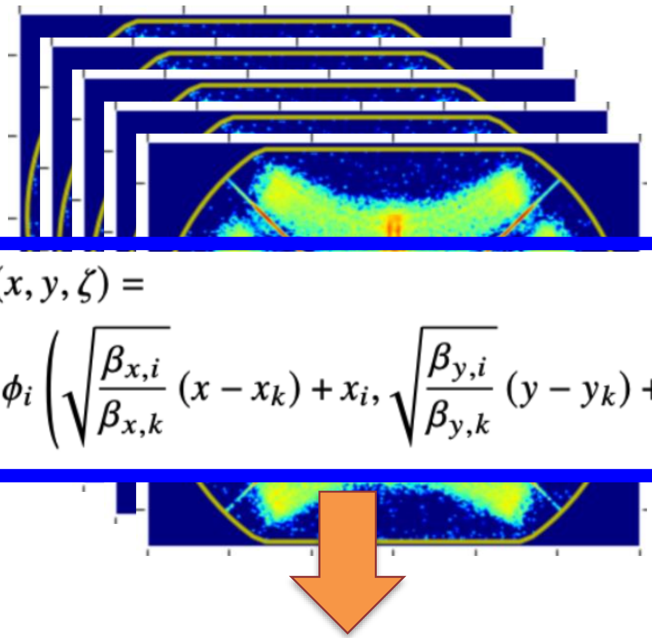
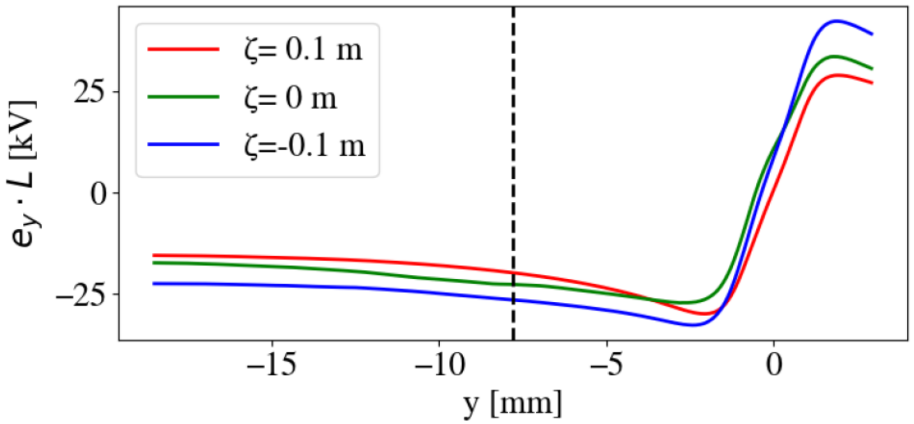
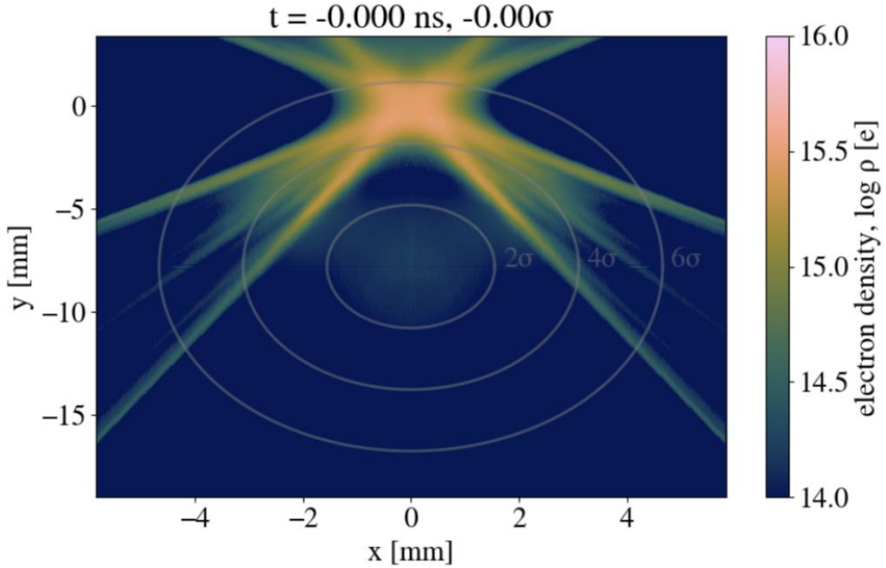
- Electron cloud strongly depends on delay between two beams
  → Around 400 e-cloud slices per triplet needed for resolution
- Method developed to lump slices into single e-cloud per triplet
- E-cloud forces become strongly non-linear at large amplitudes of oscillation



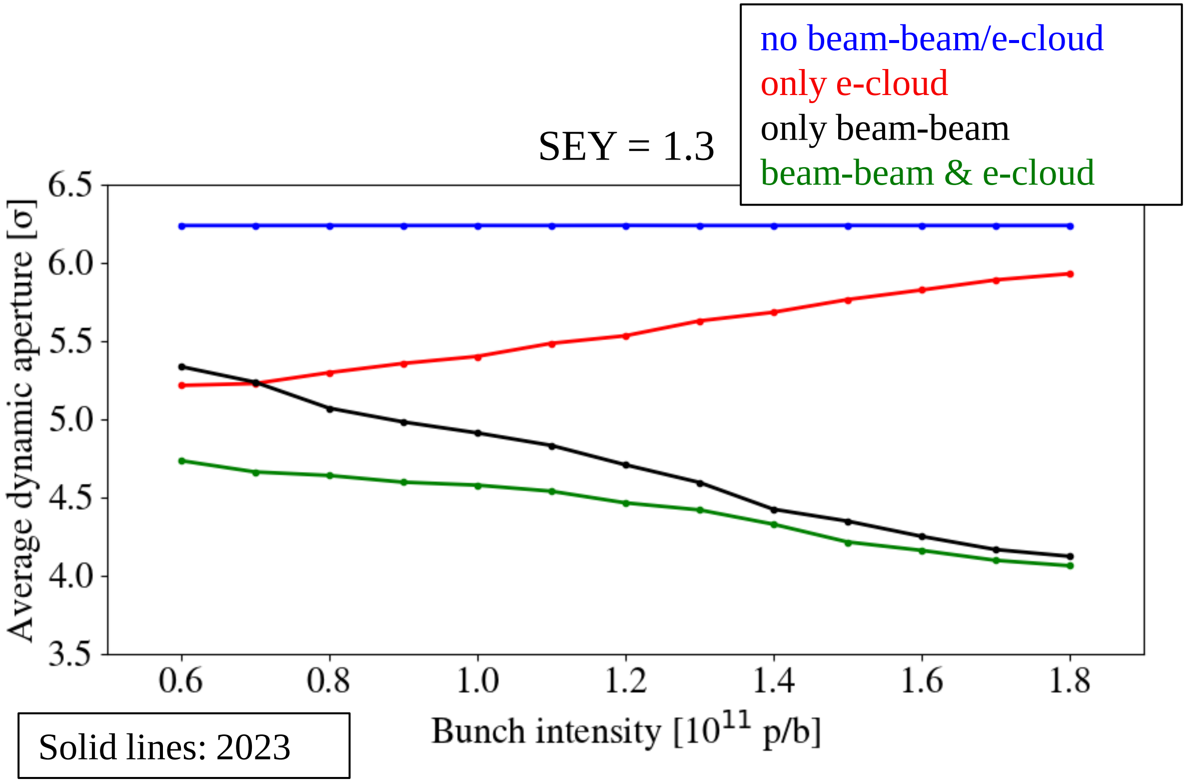
$$\Phi(x,y,\zeta) = \sum_i \phi_i\left(\sqrt{\frac{\beta_{x,i}}{\beta_{x,k}}}(x-x_k)+x_i, \sqrt{\frac{\beta_{y,i}}{\beta_{y,k}}}(y-y_k)+y_i, \zeta\right)$$





Inner Triplet simulations

- Dynamic aperture simulations show that e-cloud in the triplet scales favorably with increasing intensity
    - Electron cloud effects can become as strong as beam-beam effects at low bunch intensities (stronger effect for larger SEY)
    - Dominated by beam-beam at high intensities



2023:
β* = 30cm,
x-ing = 160μrad

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

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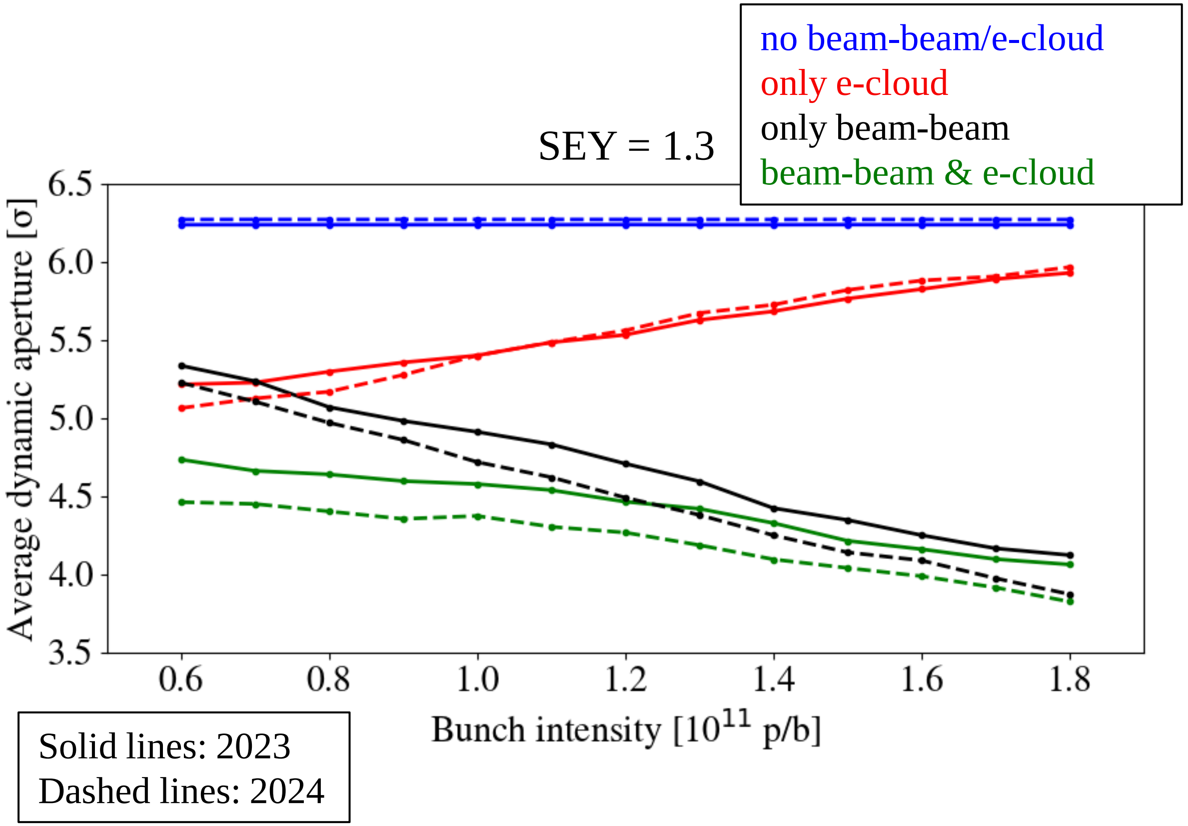
- The electron cloud contribution does not depend strongly on the specific optics configuration



2023:	2024:
β* = 30cm,	β* = 30cm,
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  - Electron cloud effects can become as strong as beam-beam effects at low bunch intensities (stronger effect for larger SEY)
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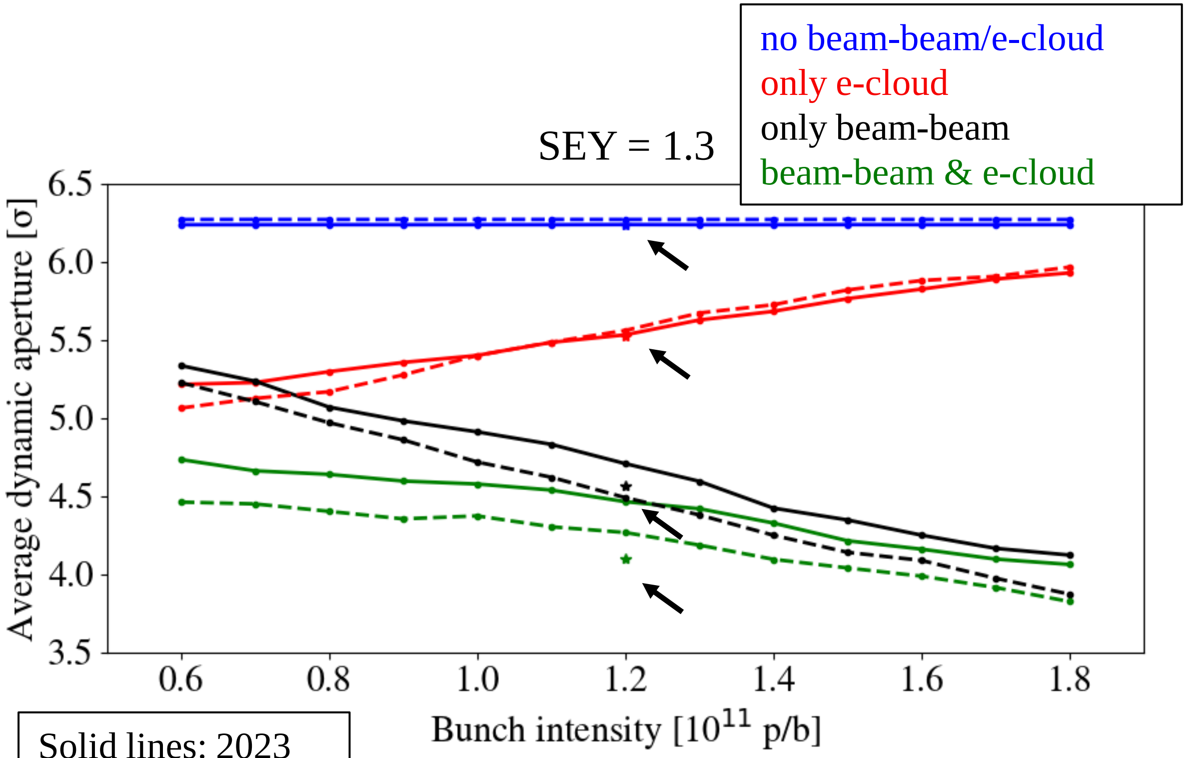
- The electron cloud contribution does not depend strongly on the specific optics configuration
  - Including with flat optics



Solid lines: 2023
Dashed lines: 2024
Stars: 2025(?)

2023:	2024:	2025(?):
β* = 30cm,	β* = 30cm,	β* = 18cm/60cm,
x-ing = 160μrad	x-ing = 150μrad	x-ing = 150μrad

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Conclusions

- The additional 10% scrubbing leaves room to increase the number of bunches and bunch intensity
  - We should use it!
  - We should be able to reach 2400 bunches with 1.8e11 p/b with trains of 4-5x36b

- Our simulation tools enable studies of complex and diverse electron cloud effects
  - Heat load predictions are based on rigorous and extensive models, not extrapolations
  - The accuracy of all e-cloud simulations depend on having good models of the underlying surface properties
  - Constantly working to evaluate and improve these models (it’s not easy) – MDs are crucial to this end

CERN

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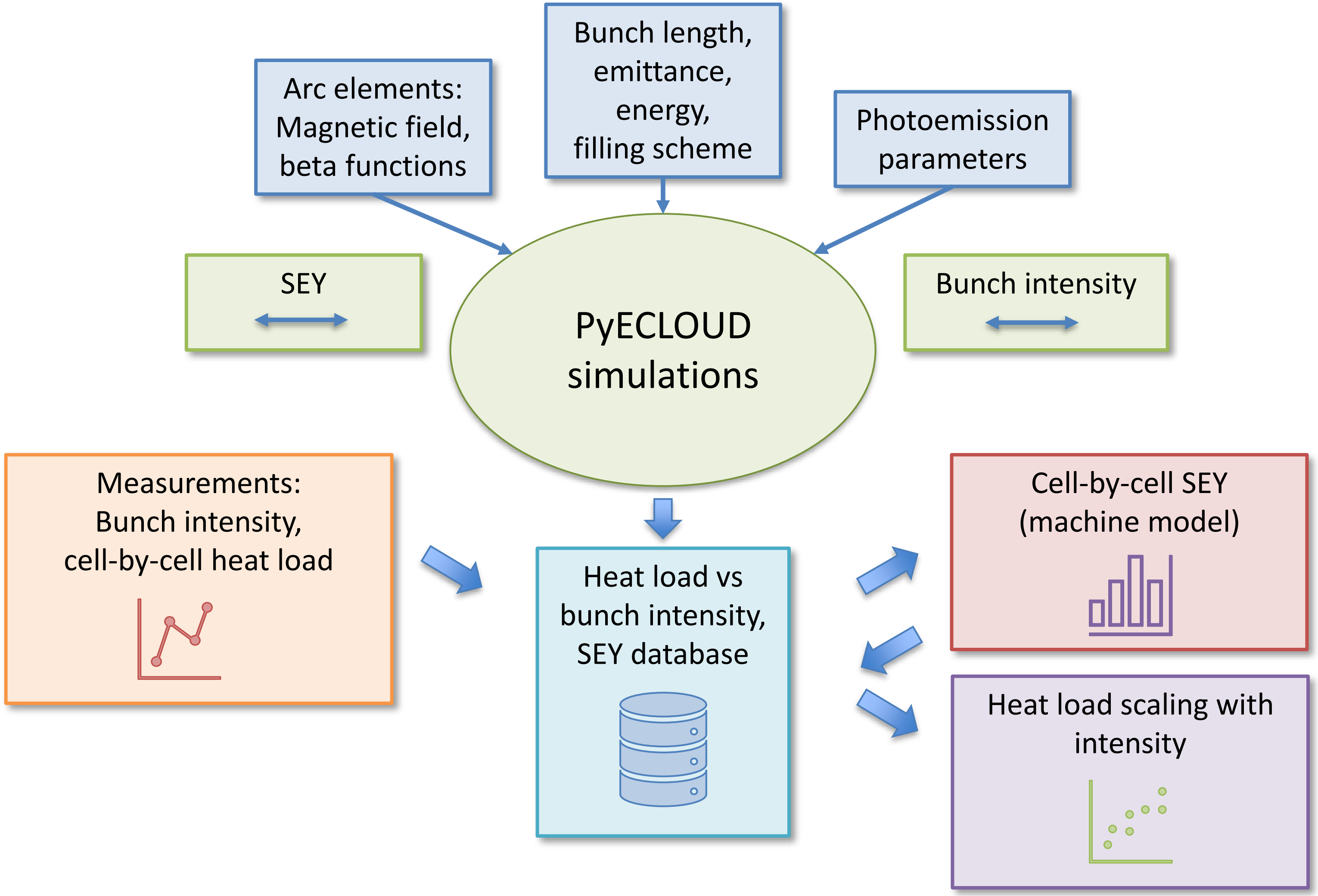
E-cloud simulation model

The SEY is inferred by comparing heat load measurements to simulation results with matching beam and machine parameters for different arc elements



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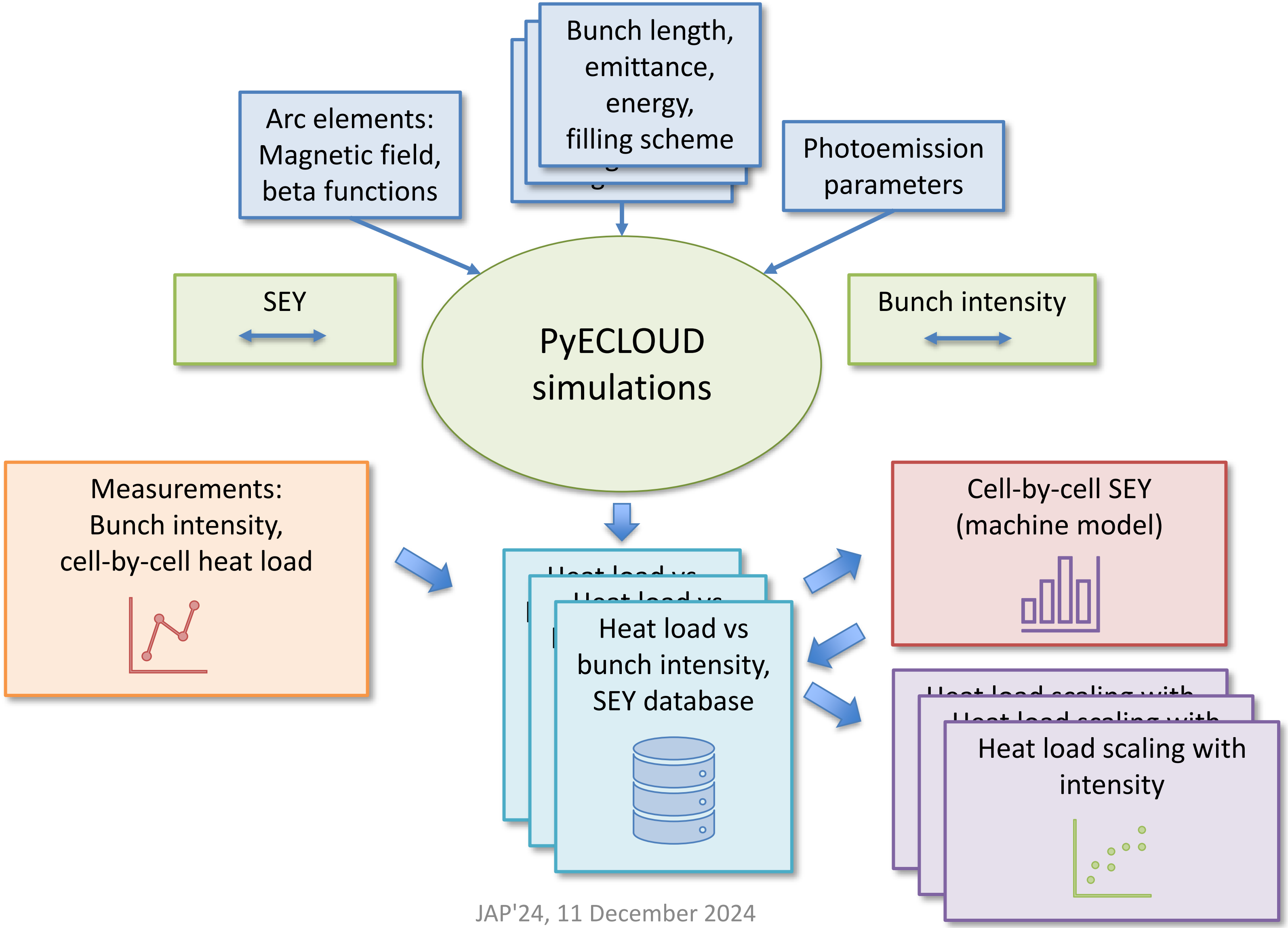
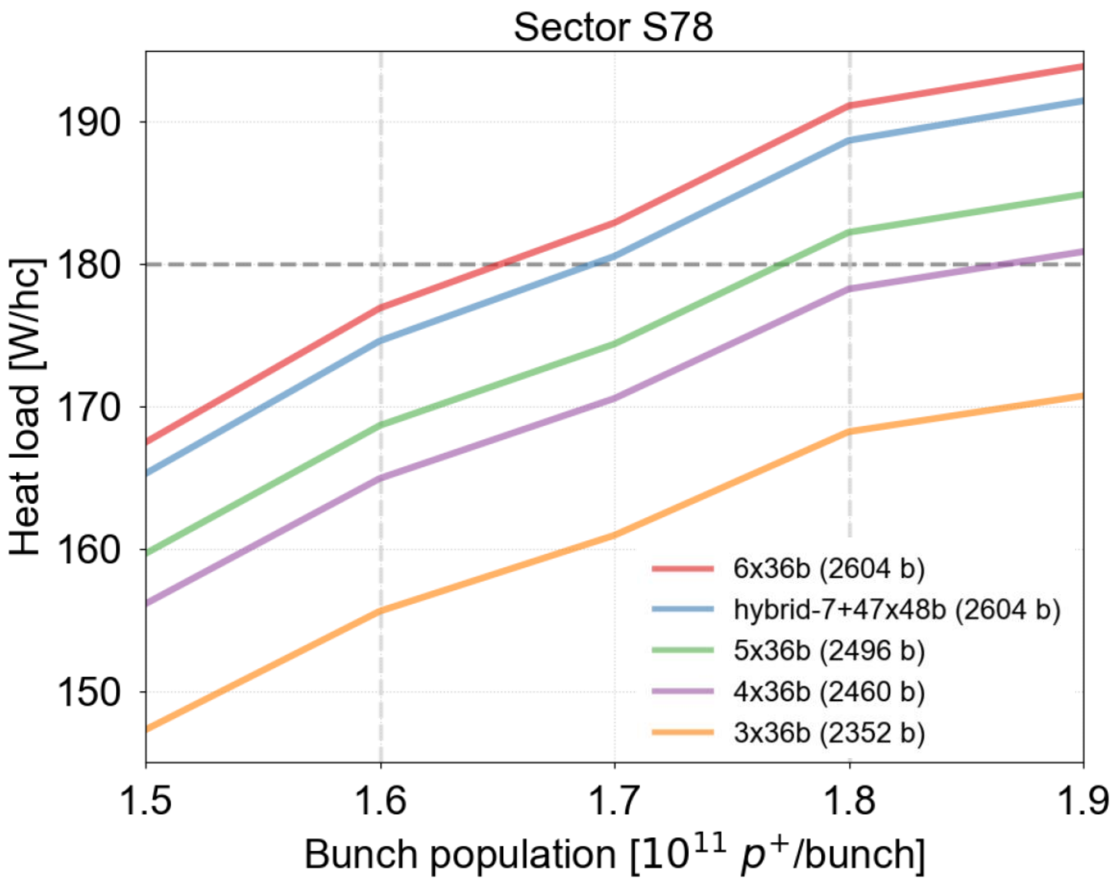


Filling scheme options for 2025

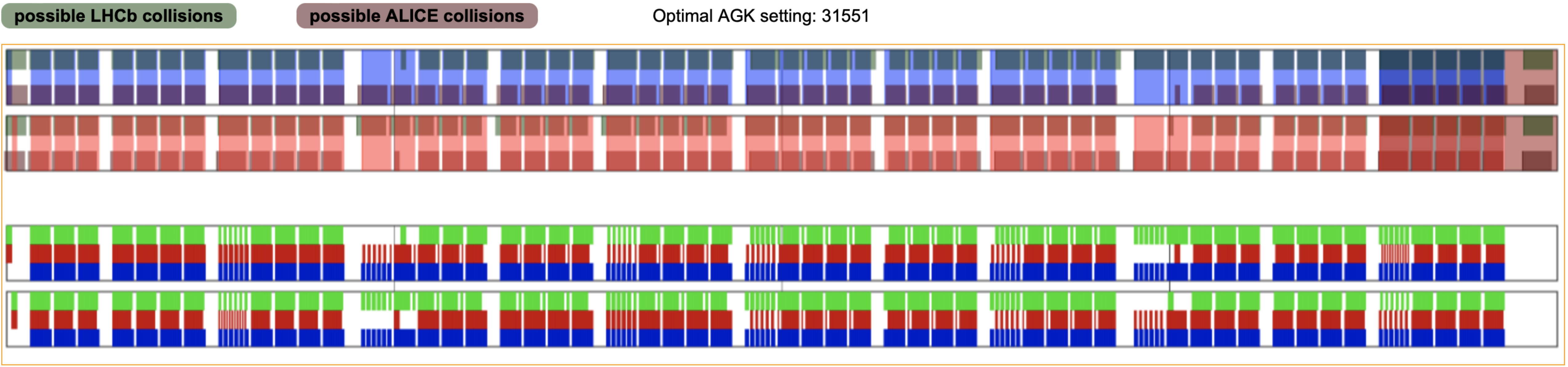
- With the additional 10% of scrubbing, the 2024 filling scheme (3x36b) has unnecessarily few bunches
  - 2450 – 2500 bunches should be achievable up to ~1.8e11 p/b in trains of 4-5x36b

- New hybrid schemes, using trains of 48b and 8b+4e with 48b instead of 56b could be of interest for pushing bunches
  - See presentation by X. Buffat this afternoon for further considerations



- Cryo capacity in S78 is 180 W/hc, with 175 W/hc estimated as a realistic upper limit in operation
- Predictions based on Fill 10230, 15 October, with 1.30 ns assumed bunch length at flat top

Hybrid-7+47x48b



Beam Info	
Bunches B1/B2	2604 / 2604
Injections B1/B2	13 / 13

Collisions	
ATLAS/CMS	2592
ALICE	2224 (85.8%)
LHCb	2313 (89.2%)
Non Colliding B1	0
Non Colliding B2	0

B1 classes : 0:0 1:55 2:0 3:236 4:0 5:325 6:12 7:1976

B2 classes : 0:0 1:72 2:0 3:219 4:0 5:308 6:12 7:1993

Instrumented cell heat loads

- 8 half-cells are equipped with additional thermometers to measure heat load per magnet aperture
  - Quadrupoles match well with simulated curves, SEY: 1.05 – 1.7
  - Dipoles match reasonably, but there are many more diverging curves, SEY: 1.3 – 1.65+
    - The exposed part of the surface varies with the bunch intensity, as the electron stripes move
    - The beam screens are 4.5x as long as the quadrupoles, surface variations more likely
  - Matched SEY in many apertures still much higher than expected for scrubbed surfaces