The electron cloud challenge for the HL-LHC

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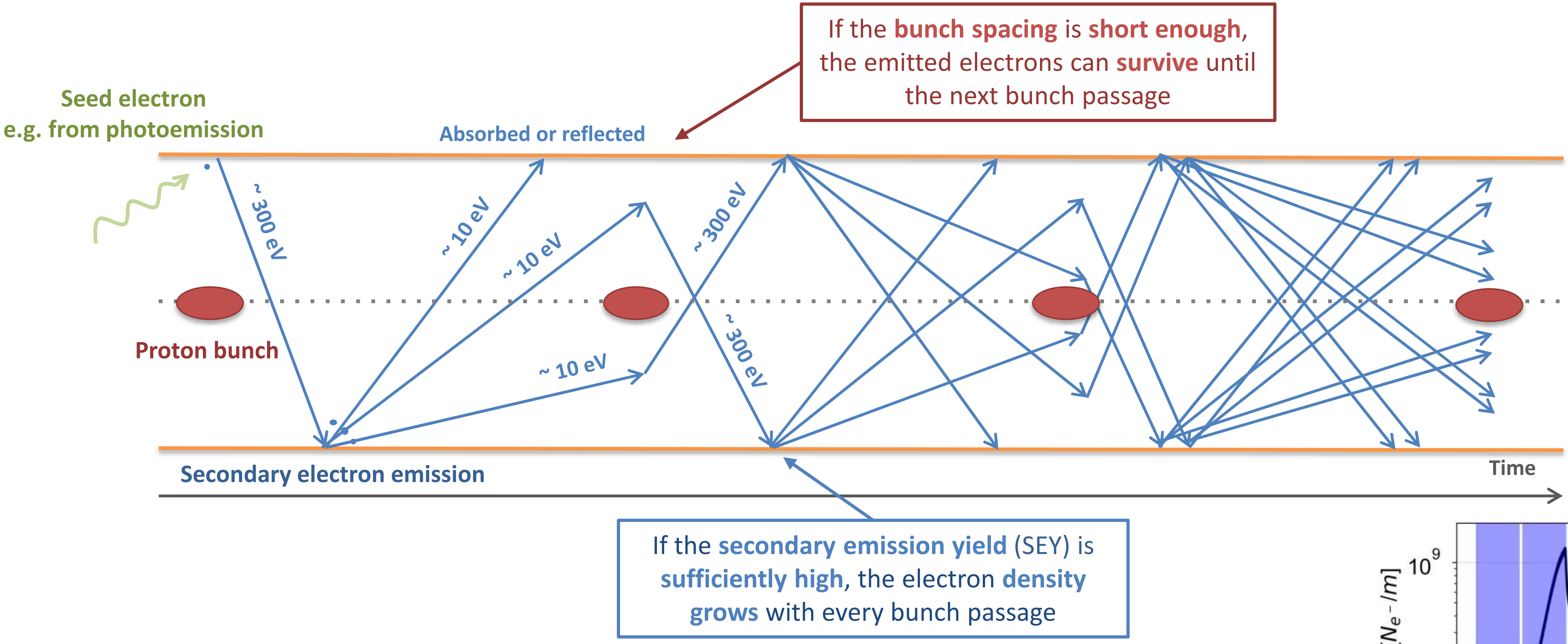
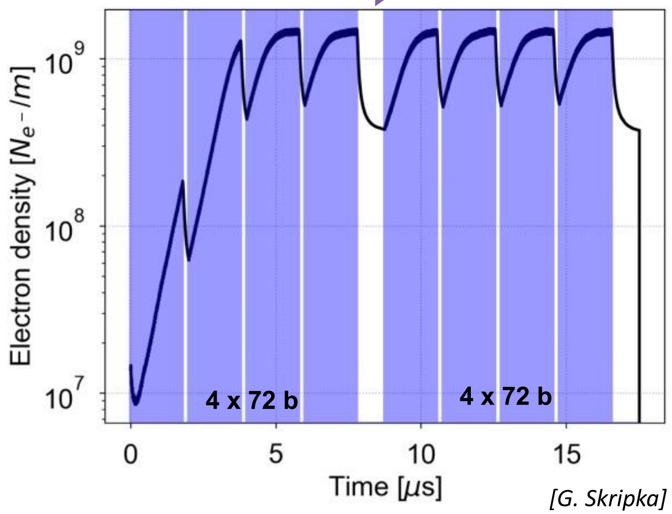
Electron cloud formation

- Electron clouds are the result of an avalanche multiplication of electrons in the vacuum chamber due to secondary electron emission



After several bunch passages, a dynamic equilibrium is reached: **the electron cloud**

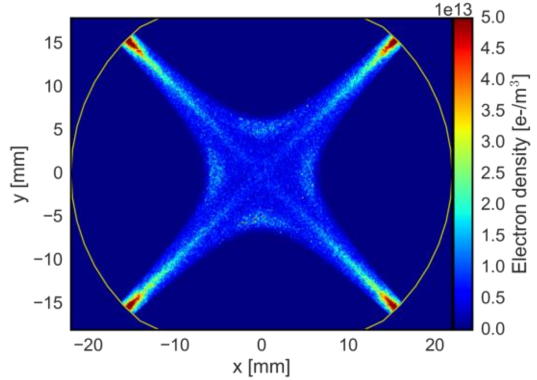


[G. Skripka]

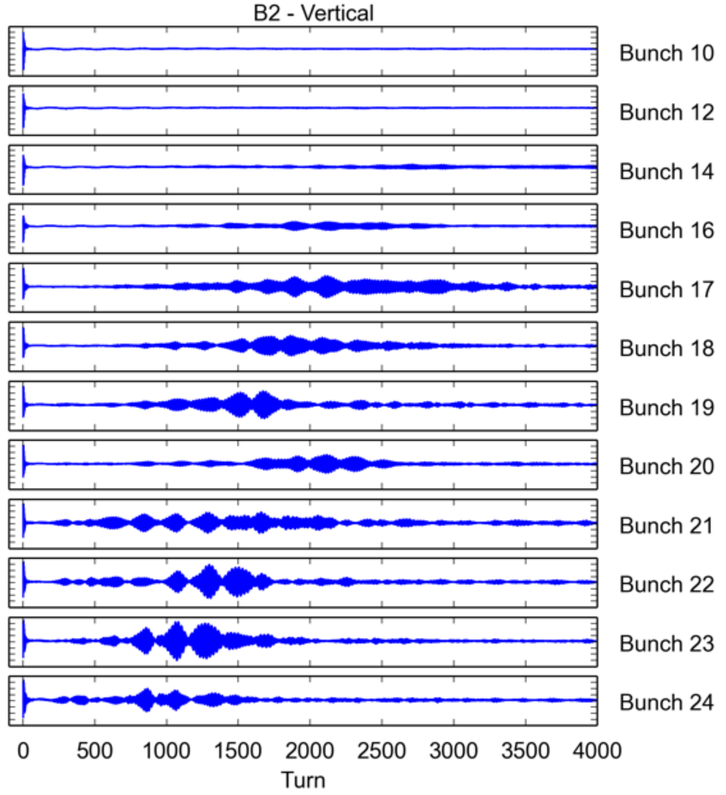
- Electron clouds can significantly impact the beam quality, through coherent instabilities and incoherent effects (emittance growth, losses), as well as the accelerator environment, e.g. by induced heat load and vacuum degradation

Electron cloud effects in the LHC

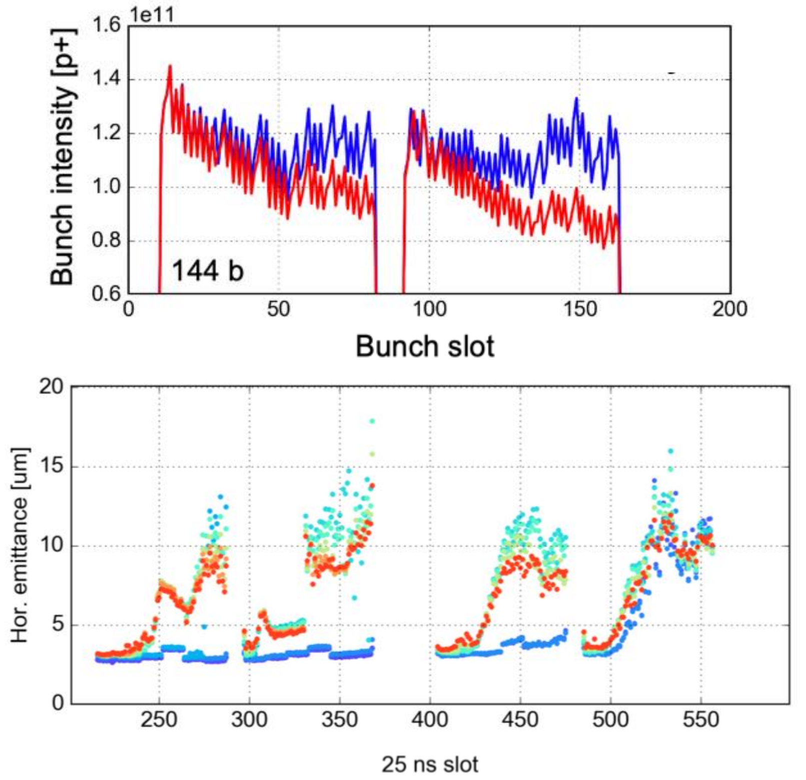
- Transverse instabilities, beam loss and emittance growth at injection energy
  - Caused by electron cloud in the arc quadrupoles
  - Instabilities partially mitigated with chromaticity, octupoles and feedback system



Transverse instabilities

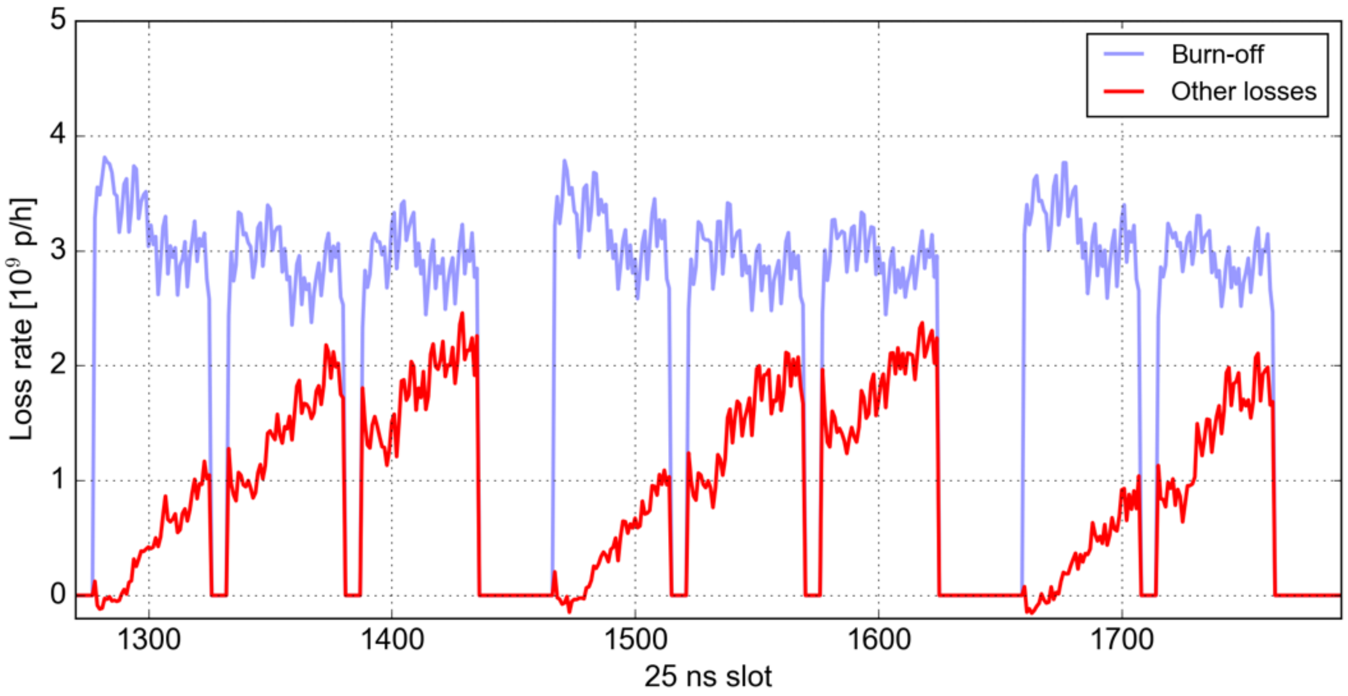


Beam loss and emittance growth



Electron cloud effects in the LHC

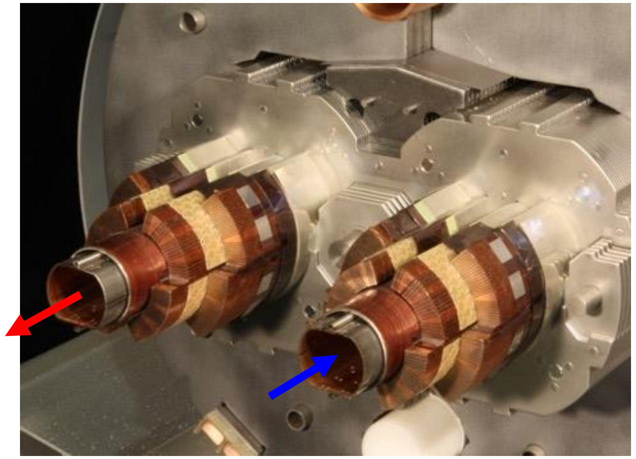
- Slow losses with colliding beams in addition to losses from luminosity burn-off
  - Caused by electron cloud in the final focusing quadrupoles, Inner Triplets, enhanced by the large beta functions

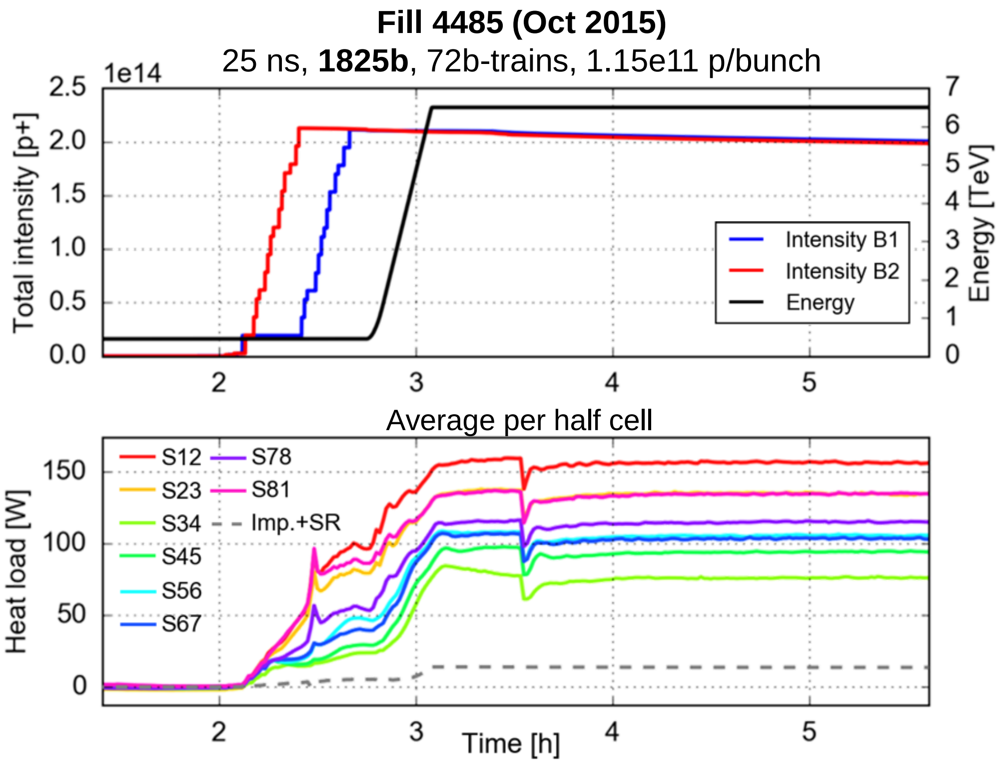


Electron cloud effects in the LHC

- Power deposition from the electrons flux on the beam screens of the superconducting arc magnets
  - Must be efficiently extracted by the cryogenics system to protect the magnets and ensure a stable vacuum, but limited capacity is available from the cryogenic system: 180 – 250 W/half-cell for the eight LHC arcs

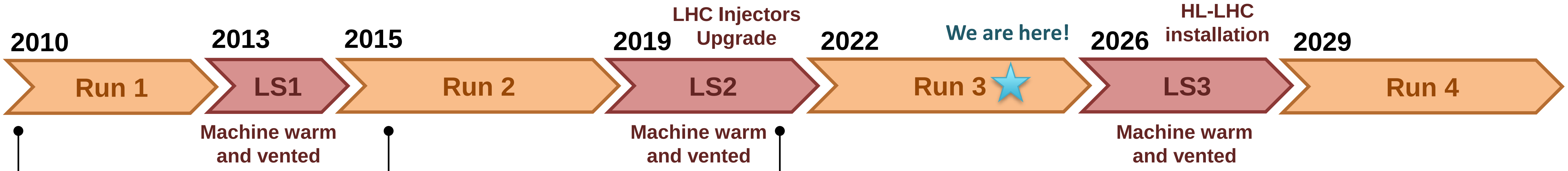
Heat load in the cryogenic magnets





LHC operation from start-up to HL-LHC

- This timeline raises two strong concerns for the HL-LHC:
  1. Electron cloud effects have increased after every long shutdown. Are likely to increase again after LS3?
  2. What is the impact of the required increase in beam intensity, number of bunches and beam energy?



Run 1:
- Bunch spacing: 150–50 ns
- Bunch intensity: **1.7e11 p**
- Max # of bunches: **1380**
- Beam energy: **3.5 - 4 TeV**

- **Mild electron cloud effects**, except for short pilot periods with 25 ns beams

Run 2:
- Bunch spacing: 25 ns
- Bunch intensity: **1.2e11 p**
- Max # of bunches: **2556**
- Beam energy: **6.5 TeV**

- **Systematic electron cloud effects, stronger than with 25 ns beams in Run 1**

Run 3:
- Bunch spacing: 25 ns
- Bunch intensity: 1.6-1.8e11 p
- Max # of bunches: **~2500**
- Beam energy: **6.8 TeV**

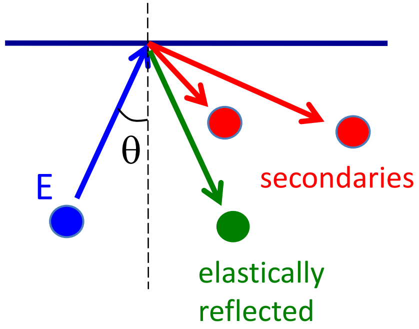
- **Systematic electron cloud effects, stronger than in Run 2**

Planned for HL-LHC:
- Bunch spacing: 25 ns
- Bunch intensity: **2.3e11 p**
- Max # of bunches: **~2750**
- Beam energy: **7 TeV**

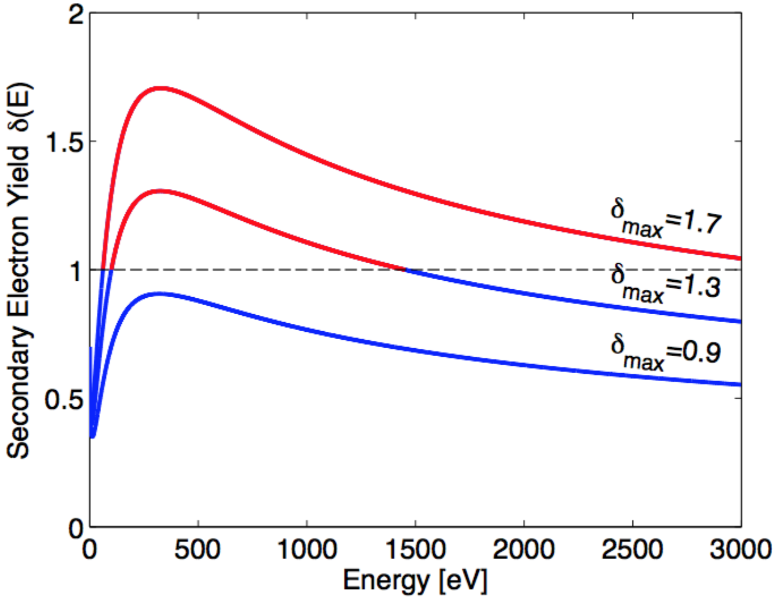
Electron cloud mitigation in the LHC

- The SEY is defined as the ratio between emitted and impacting electrons
  - A function of the energy and incidence angle of the impacting electrons

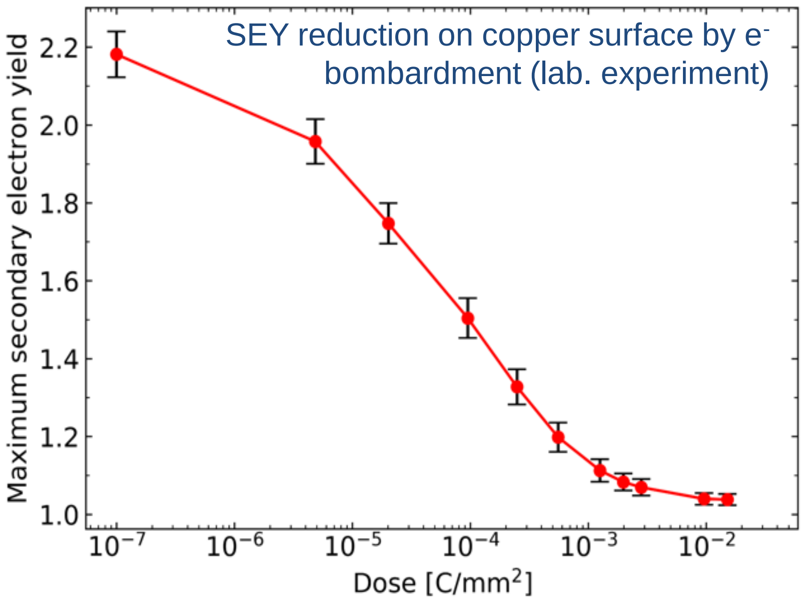
$$\delta(E,\theta) = \frac{I_{\text{emit}}}{I_{\text{imp}}(E,\theta)}$$



The SEY is typically parameterised by its maximum value δ_{max}



δ_{max} is usually high for air-exposed surfaces, but reduces with electron irradiation



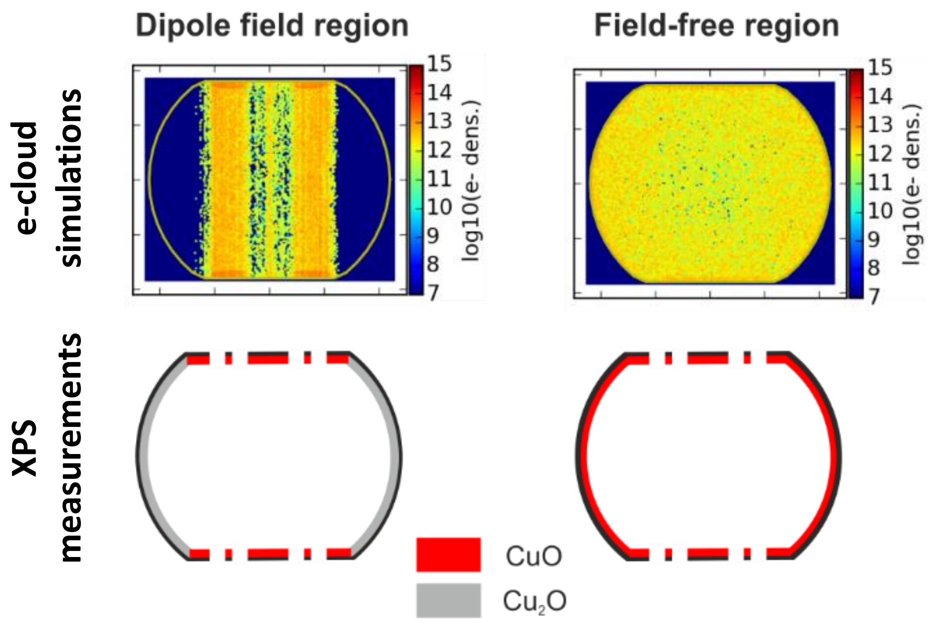
→ SEY reduces with irradiation by the electron cloud itself: beam-induced conditioning (**scrubbing**)

The **main electron cloud mitigation technique for the LHC** beam screens

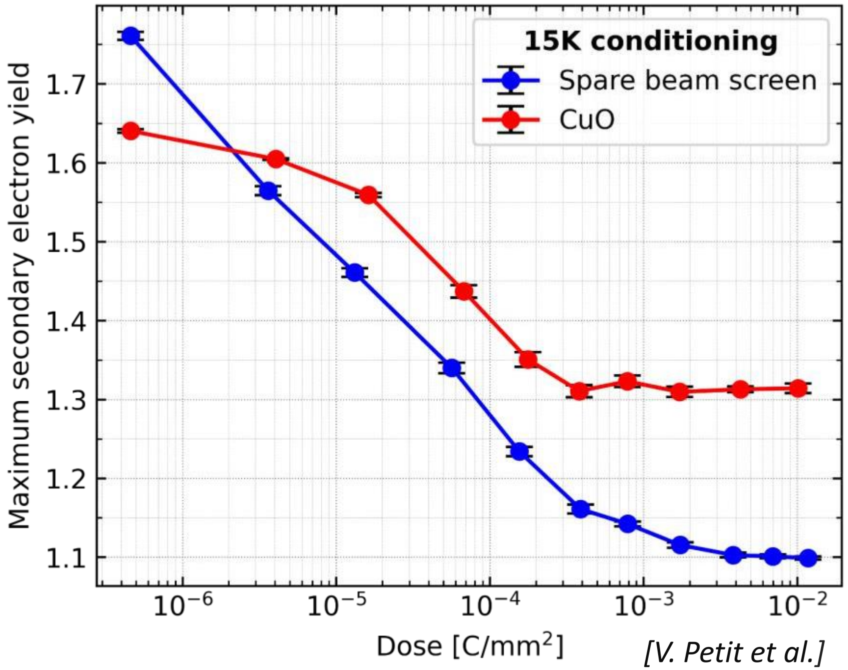
Beam screen degradation

- Analysis of beam screens extracted from the LHC during LS2 found a different copper oxide (CuO) in areas irradiated by the electron cloud on some of the extracted beam screens

- Believed to be caused by exposure to humid tunnel air during LS's and depletion of the surface carbon content, followed by electron irradiation at cryogenic temperature during operation



*[V. Petit et al., Commun Phys **4**, 192 (2021)]*



[V. Petit et al.]

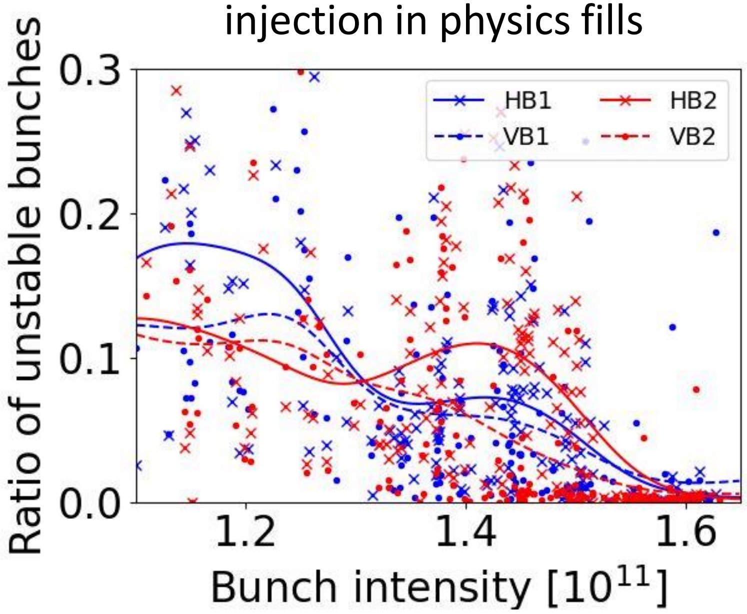
- CuO surfaces have a different SEY curve and worse conditioning behaviour with electron irradiation at cold compared to the regular beam screen surfaces (i.e. they do not scrub as well in the machine)

→ The probable cause of observed electron cloud increase

Scaling with intensity

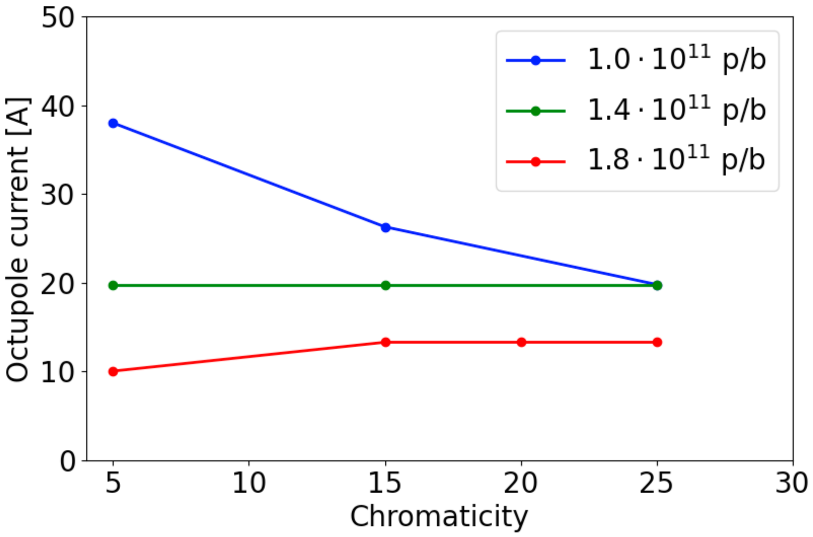
- Transverse instabilities have been found to scale favourably with bunch intensity

Reduction of unstable bunches at injection in physics fills

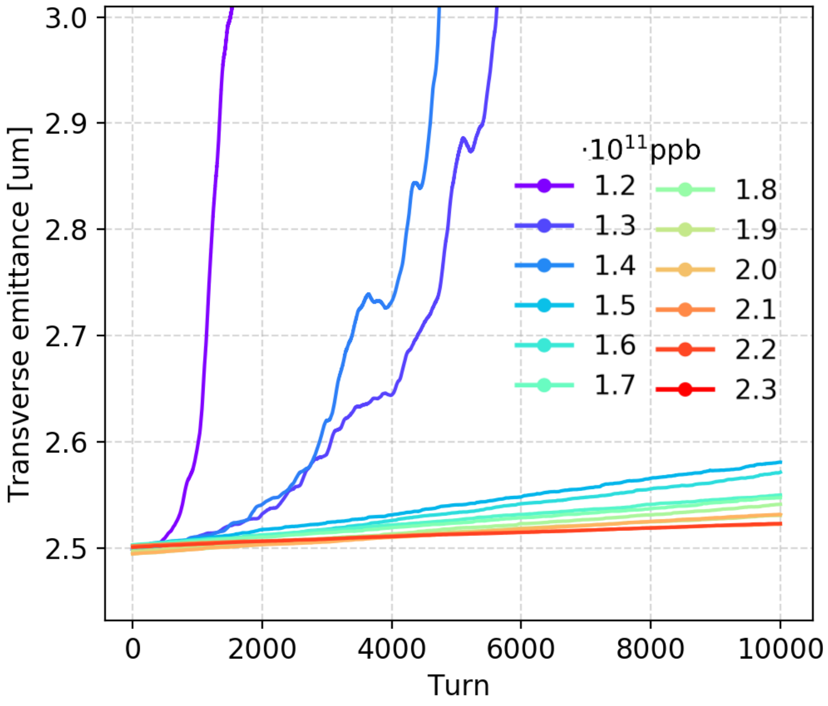


[X. Buffat]

Improvement in stability observed in dedicated studies

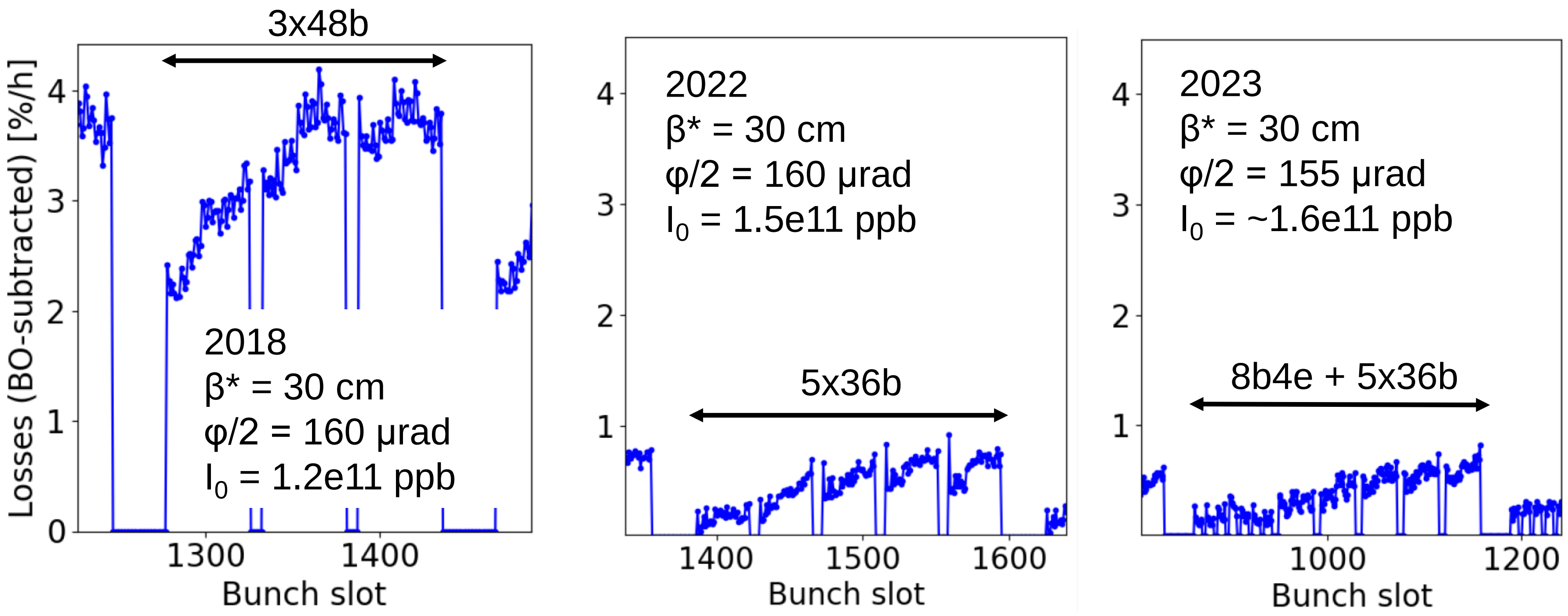


Consistent with predictions from macro-particle simulations



Scaling with intensity

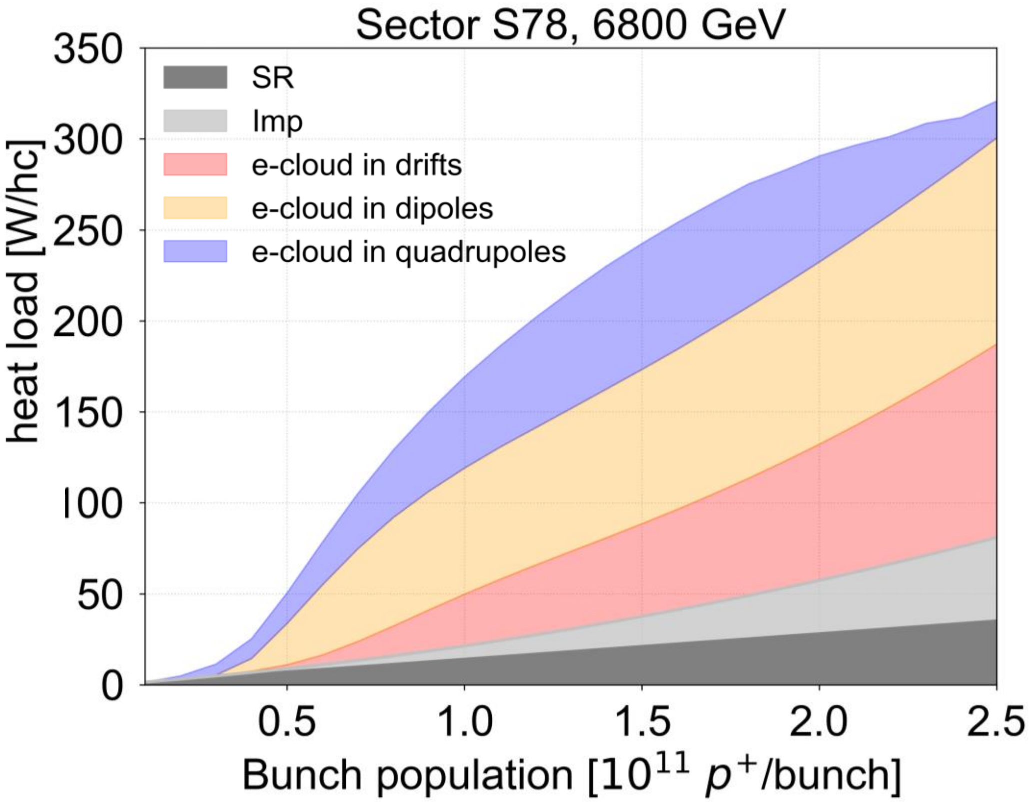
- An improvement can be seen also on incoherent effects such as the slow beam losses in collision
  - Amorphous carbon coating of HL-LHC triplet beam screens will reduce effect further



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

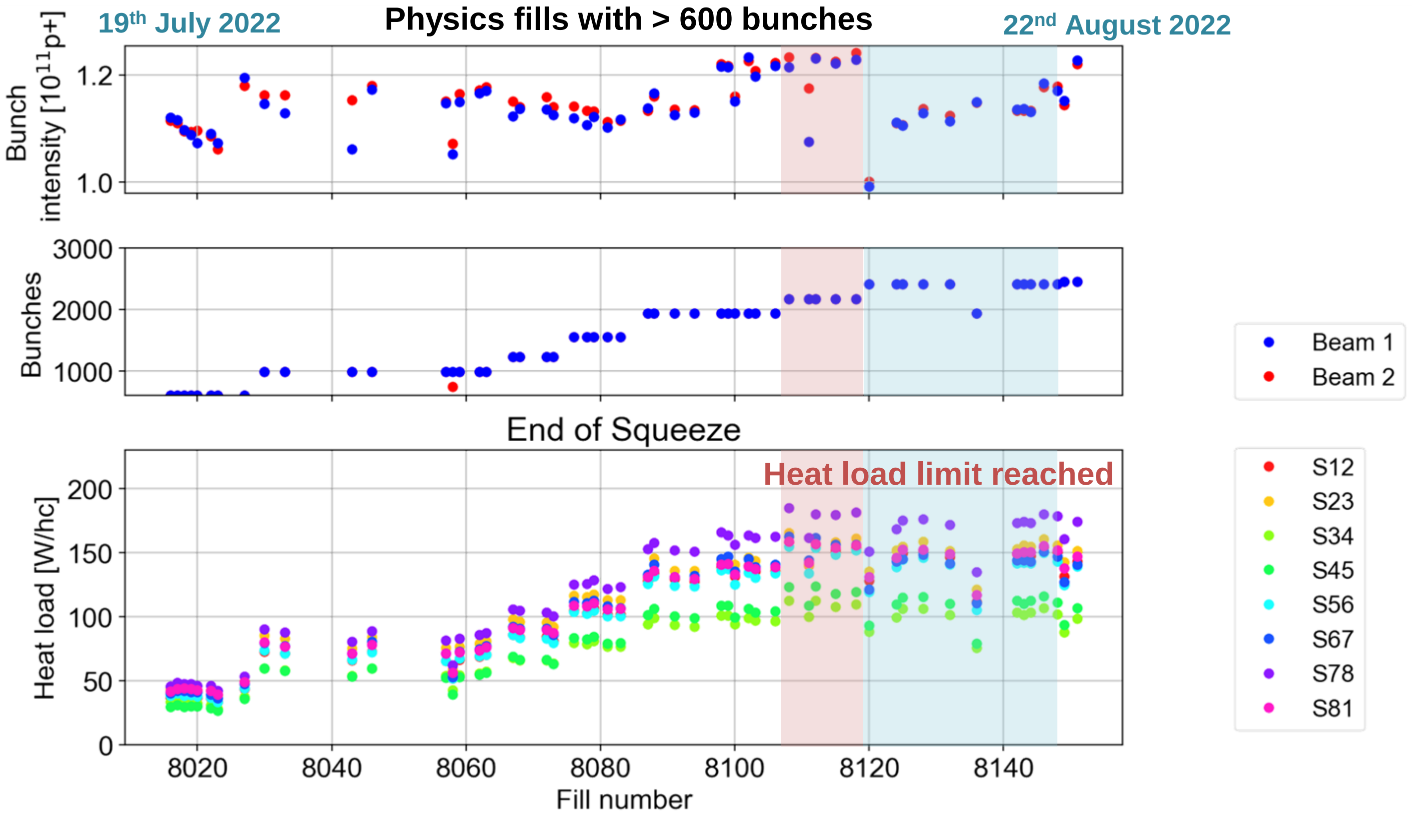
Scaling with intensity

- Unfortunately, the heat load, both from electron cloud and other competing sources, increases with intensity (and energy) → Less cryogenic capacity available for electron cloud, but more capacity needed
  - The heat load is likely to be the most critical electron cloud effect for HL-LHC



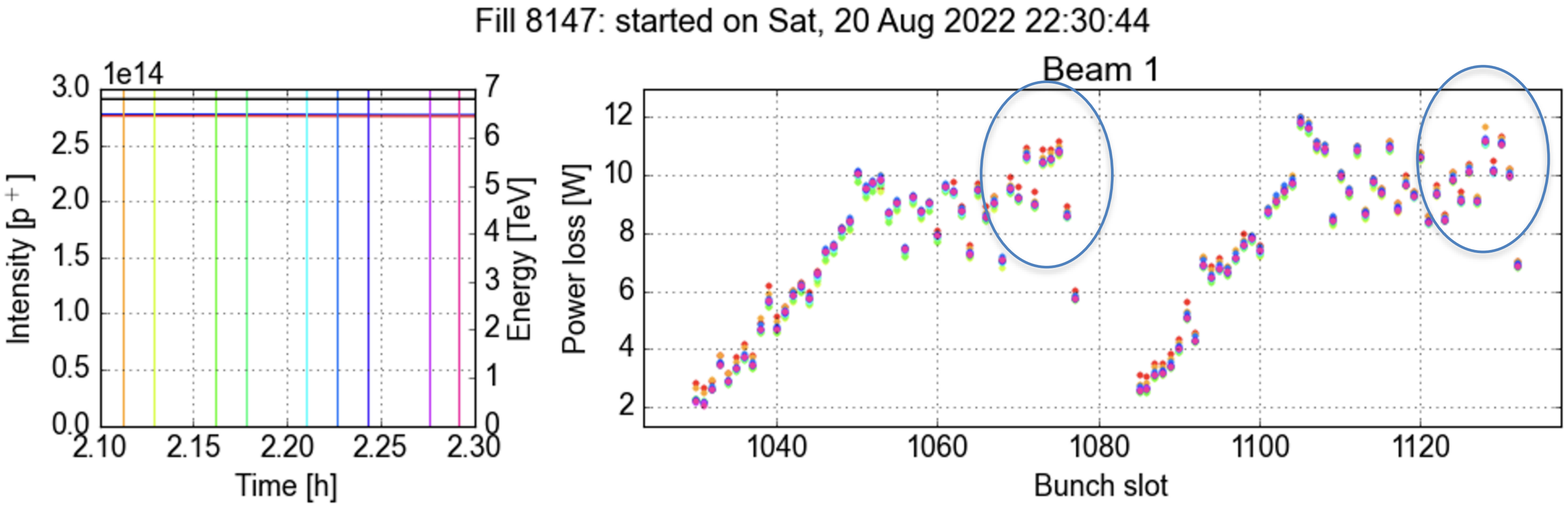
Heat load limitation

- Already now in Run 3, the heat load from electron cloud has limited the total intensity since the beginning of the run
  - Caused by a strong degradation after LS2 in S78, with the lowest available cooling capacity (180 W/half-cell), and made worse by the bunch intensity increase



Mitigation with filling schemes

- The only mitigation measure available on the short term, is reducing the train length to lower the average heat load
  - The drawback is a reduction in the number of bunches that can fit in the machine – need to find best balance between heat load and number of bunches



The electron cloud builds up in around 20 bunch passages – all the trailing bunches pass through a full cloud

→ By cutting the bunch trains shorter, a smaller fraction of bunches see the full electron cloud

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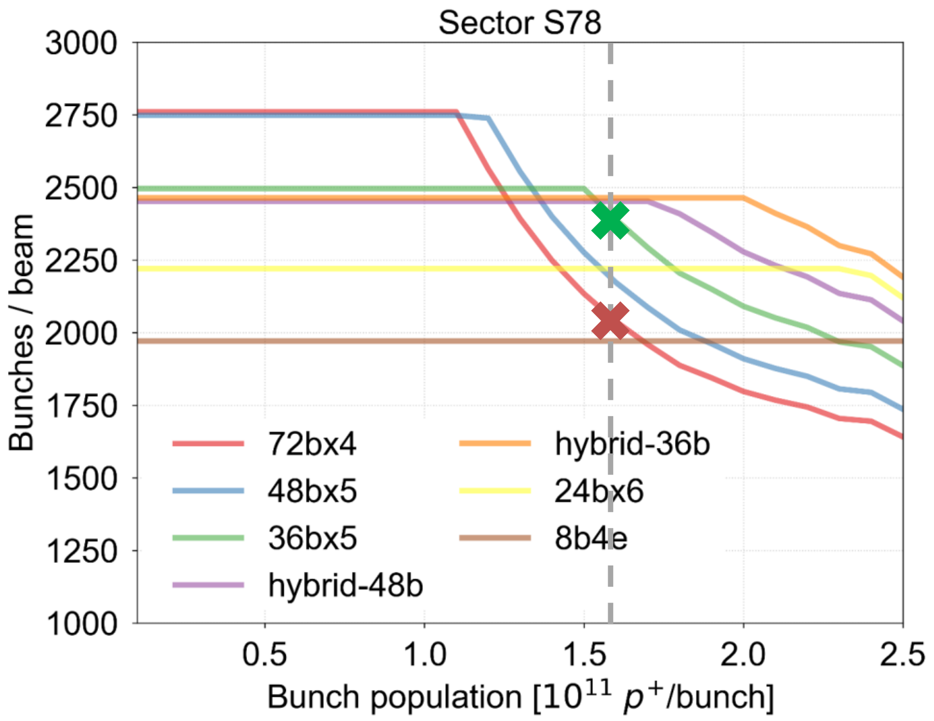

With 1.6e11 p/bunch, trains of 36 bunches are well suited, limiting the number of bunches by 10-15%

With the nominal bunch pattern (4 x 72b), only ~2100 bunches are allowed

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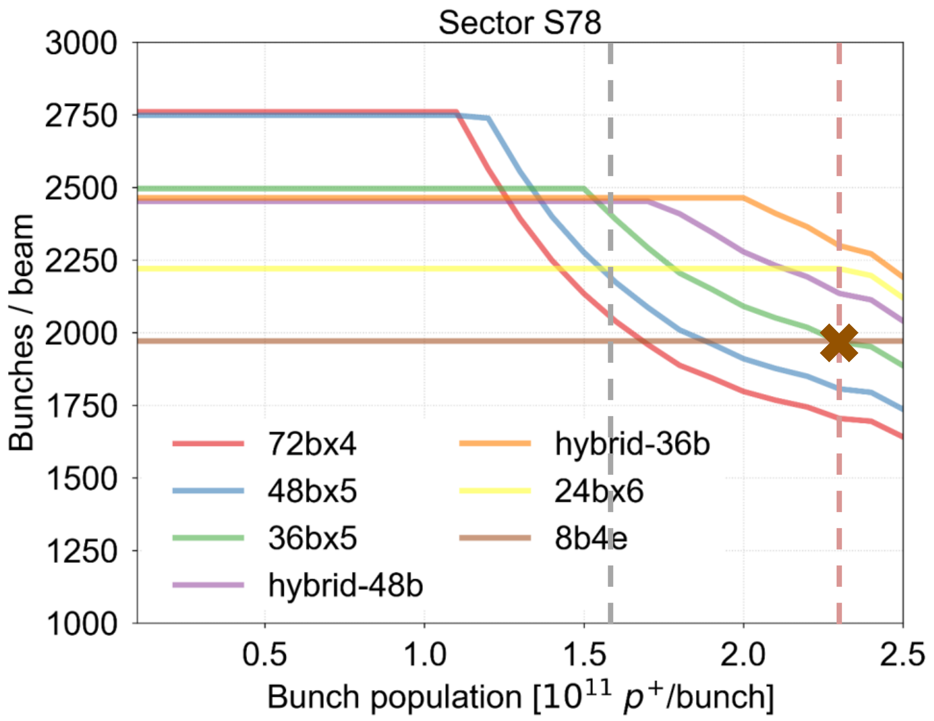
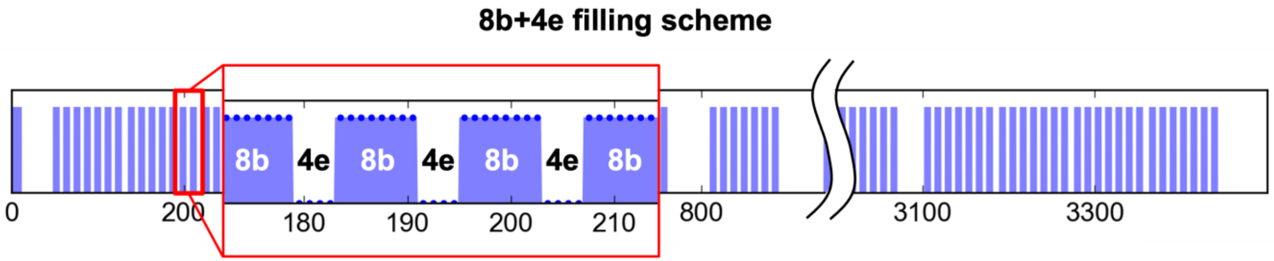


To increase bunch intensity further, strong suppression can be achieved with the "8b+4e" filling scheme, at the expense of 30% of the bunches



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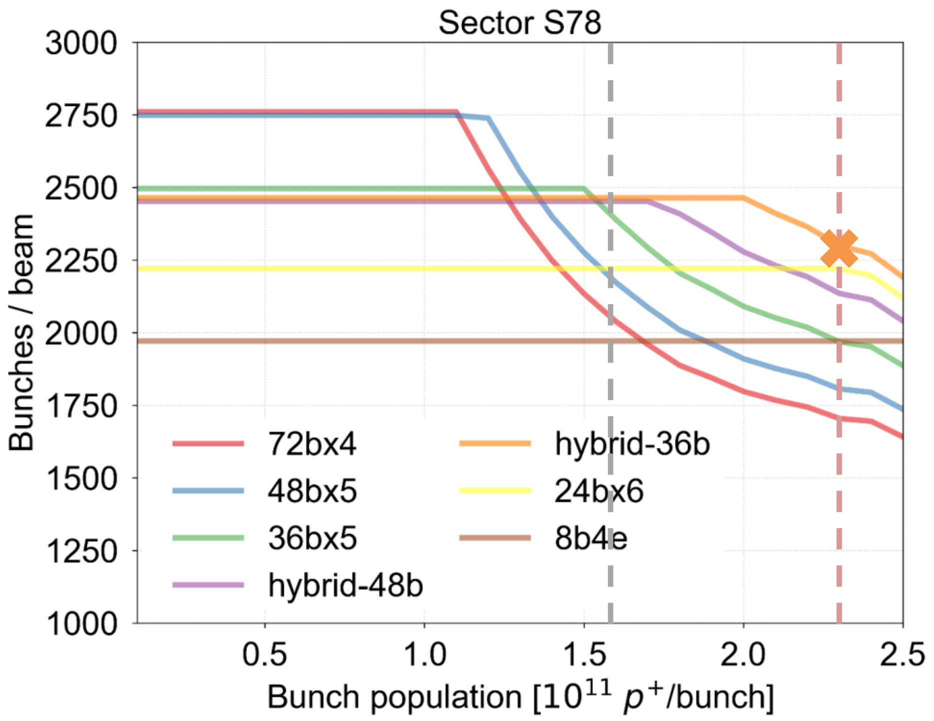
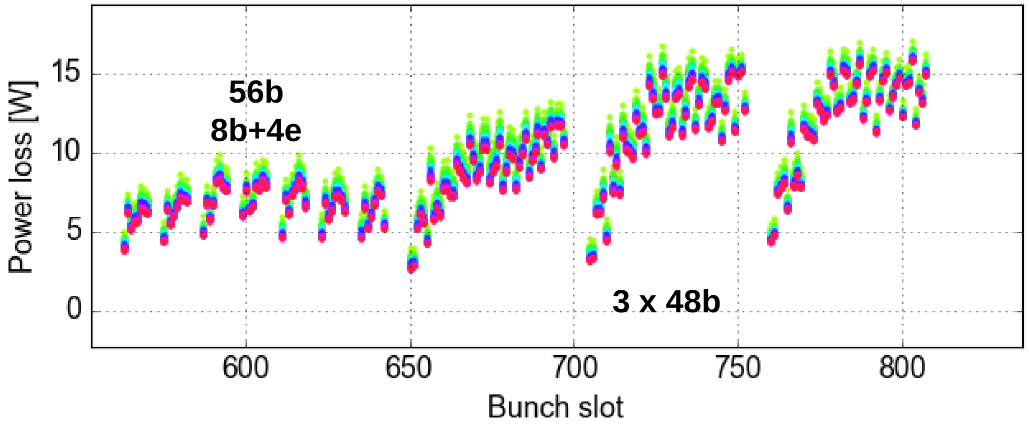


Hybrid filling schemes, where 8b+4e and 25 ns beam can be combined at an optimal ratio give a better performance



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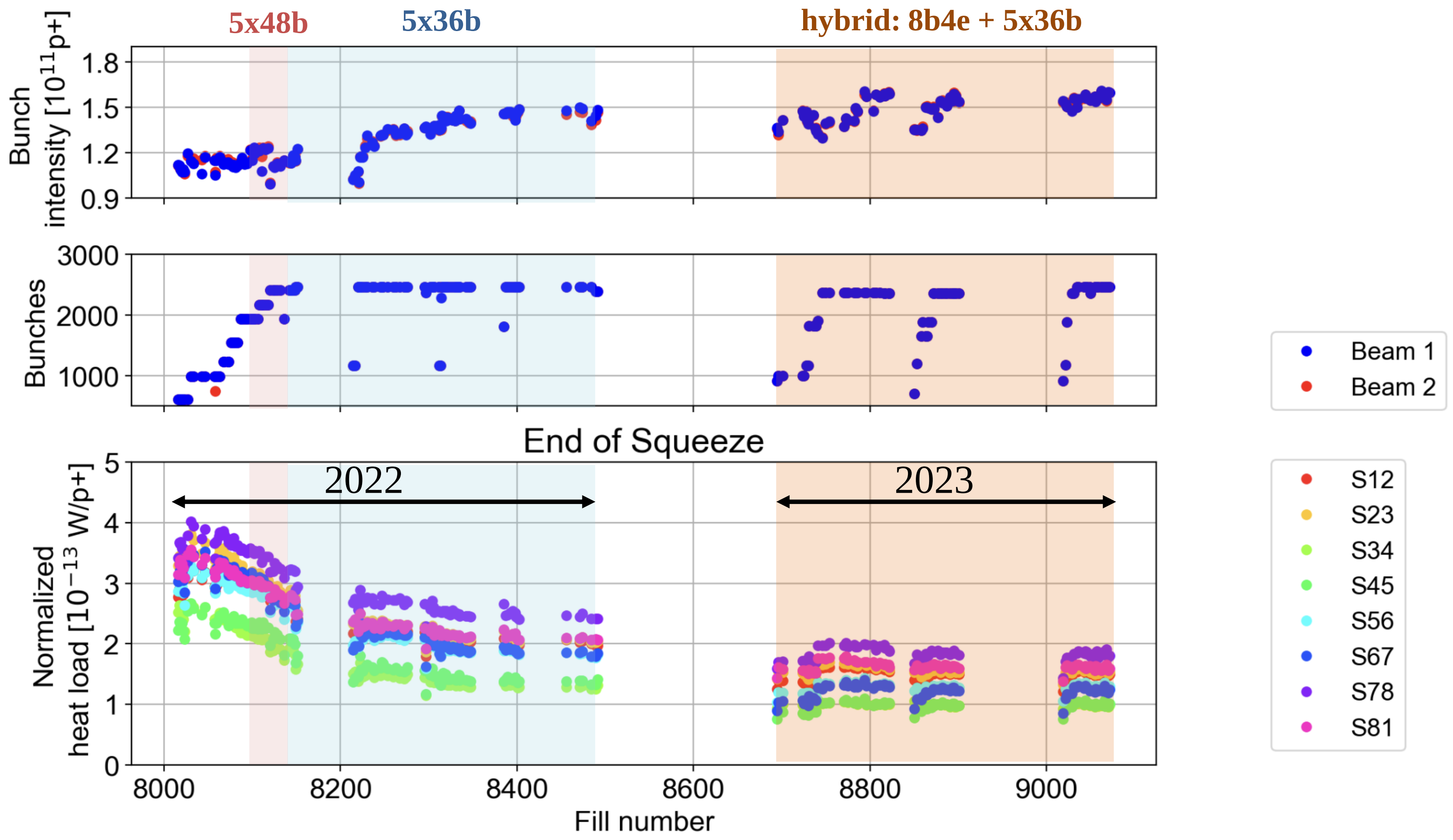
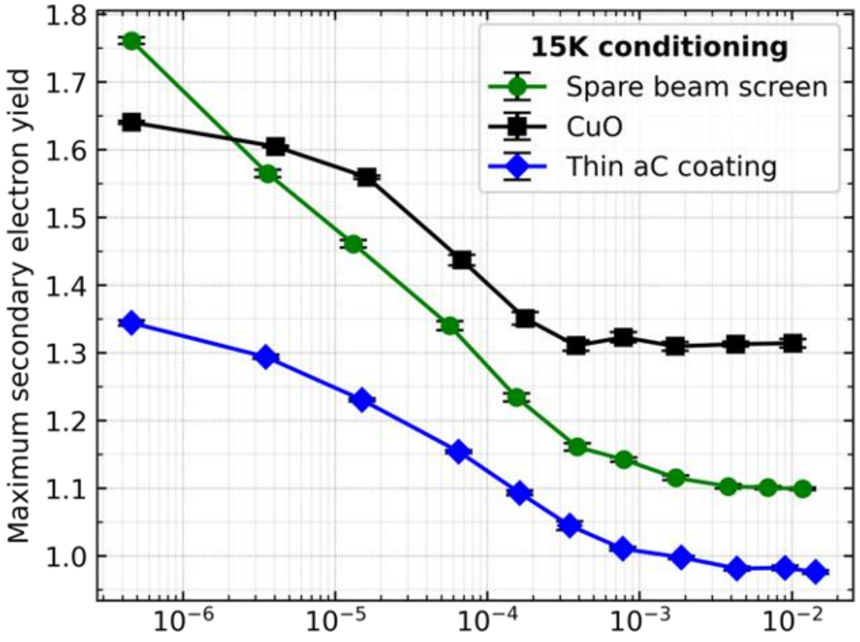
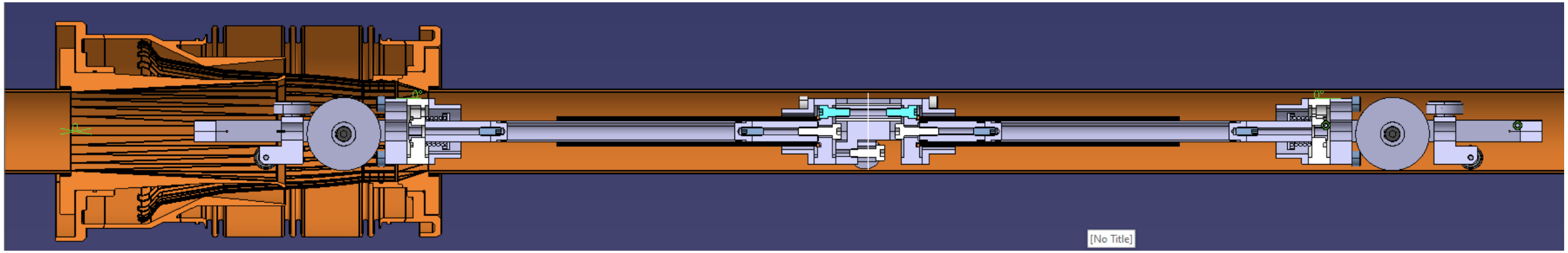


Beam screen treatment project

- To improve the situation for HL-LHC, the Beam Screen Treatment (BST) Project has been put in place
  - Development of a system for applying a thin carbon coating, in-situ in the LHC tunnel, to entire half-cells at a time
  - Should reduce the SEY of treated half-cells to levels below those of the standard beam screens



[V. Petit et al]



[G. Rosaz]

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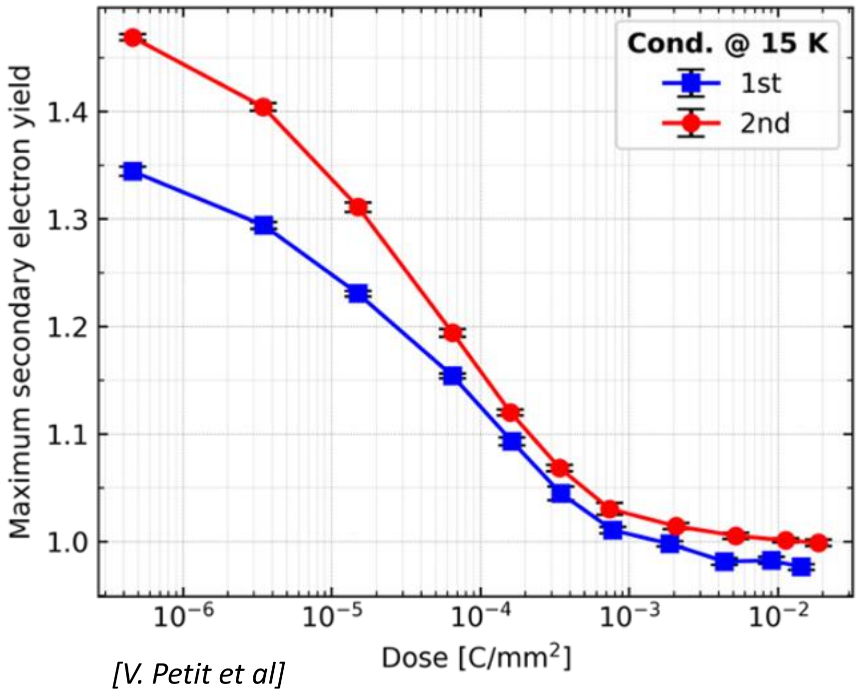
  - Development of a system for applying a thin carbon coating, in-situ in the LHC tunnel, to entire half-cells at a time
  - Should reduce the SEY of treated half-cells to levels below those of the standard beam screens
    - Robustness against degradation is being evaluated
  - Capacity to treat around 100 half-cells (roughly a quarter of the machine) in LS3, with the prospect to treat more in coming shutdowns if needed



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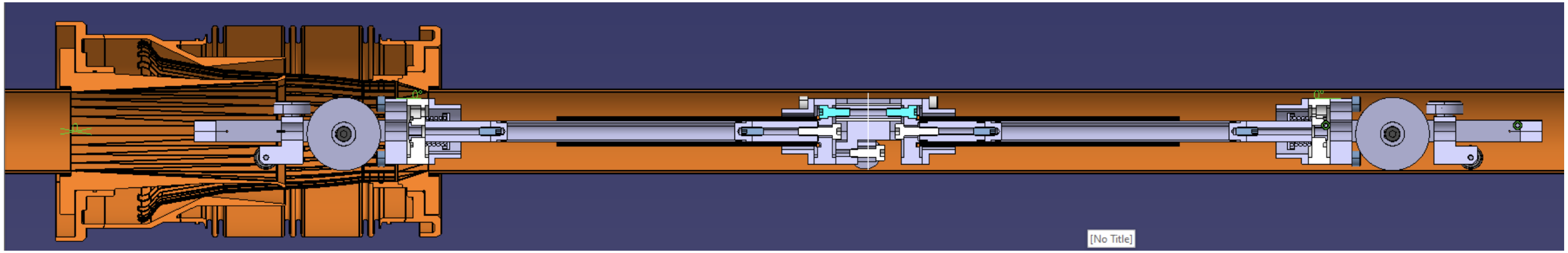
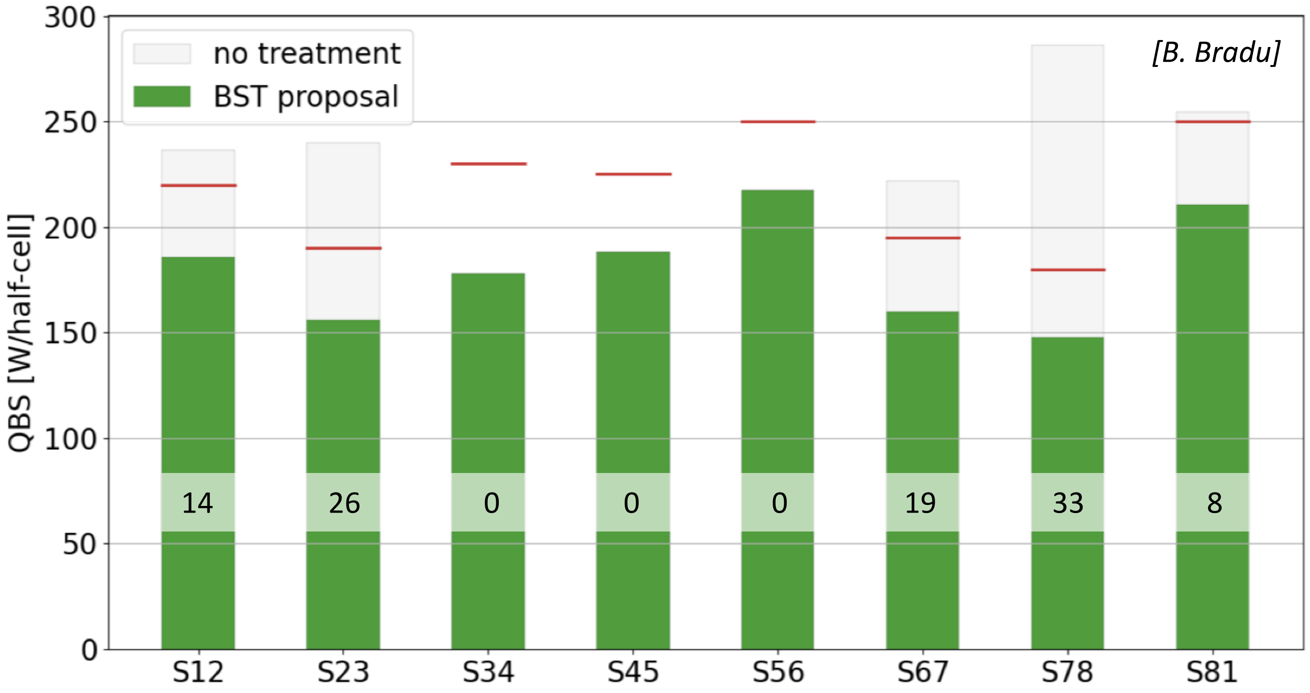


[G. Rosaz]

Beam screen treatment project

- The selection of half-cells to be treated is on-going
  - Estimated cryogenic margin per sector after treatment ranges from 30 to 50 W/half-cell
    - Effective margin for untreated cells is higher in sectors with many treated cells
  - For comparison, the degradation of S78 in LS2 corresponds to an estimated increase of ~100 W/hc with HL-LHC beam parameters



	S12	S23	S34	S45	S56	S67	S78	S81
Number of half-cells	14	**26**	0	**0**	**0**	19	**33**	8
Margin per half-cell	34	34	52	37	33	35	32	40
Margin per untreated half-cell	47	**68**	52	**37**	**33**	55	**88**	47

Prospects for Run 4

- The **HL-LHC baseline scenario is possible only after beam screen treatment**
  - With the current state of the beam screens, the number of bunches would be limited to at most ~2300 using hybrid schemes, and further degradation could bring further limitations

- Even with the beam screen treatment, degradation of beam screens in untreated cells and sectors can limit the performance, e.g. if S56 or S45 degrades to the current level of S78
  - Hybrid filling schemes help to mitigate the loss of luminosity

- The 8b+4e beam is always a fall-back solution in case of severe further degradation

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

Conclusions & outlook

- Electron cloud build-up leads to a wide range of effects that can considerably impact the machine performance

- The heat load from electron cloud is limiting the performance of the LHC already today and poses a significant risk for the HL-LHC performance
  - The beam screen treatment project is a necessary condition for the HL-LHC baseline scenario, but not necessarily a sufficient one, depending on the extent of further degradation in LS3

- Hybrid filling schemes, mixing 8b+4e and standard 25 ns beams allow to maximise the luminosity in case of persisting limitations from electron cloud

- As long as we don't know how to prevent degradation from long shutdowns, we risk running one step behind and having to catch-up with further beam screen treatment at each coming long shutdown, until the machine is mostly coated (towards middle or end of HL-LHC program)

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