# Preparation for HL-LHC Run 4 scenarios

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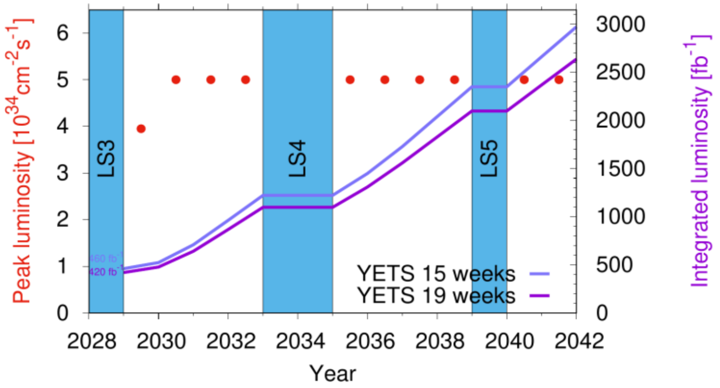
# HL-LHC schedule and Run 4 ramp-up




Potential HL-LHC schedule and performance for ATLAS/CMS. Heavy ion runs considered at the end of each year.

<u>No surface treatments</u>: 22% to 30% integrated lumi loss.
<u>Partial mitigations</u>: high pile-up, hybrid scheme, low-β*
<u>Pure 8b+4e</u>: heat load <120 W/h-cel in the worst case.

Run 4 aims at approaching 250 fb$^{-1}$ in the last year after ramping up phase.

| 15 Weeks EYETS | pp | Yets | Commissioning | Scrubbing | Ion + comm. | OP efficiency | ∫ L dt |
|---|---|---|---|---|---|---|---|
| year | | | | | | | [fb$^{-1}$] |
| 2029 | 90 | 105 | 80 | 10 | 34 | 0.4 | 64 |
| 2030 | 120 | 105 | 60 | 2 | 34 | 0.5 | 185 |
| 2031 | 160 | 105 | 25 | 2 | 34 | 0.5 | 254 |
| 2032 | 160 | 105 | 25 | 2 | 34 | 0.5 | 260 |
| Run 5 avg | 172 | 105 | 27 | 2.5 | 34 | 0.5 | 280 |
| Run 6 avg | 190 | 105 | 25 | 2 | 34 | 0.5 | 309 |

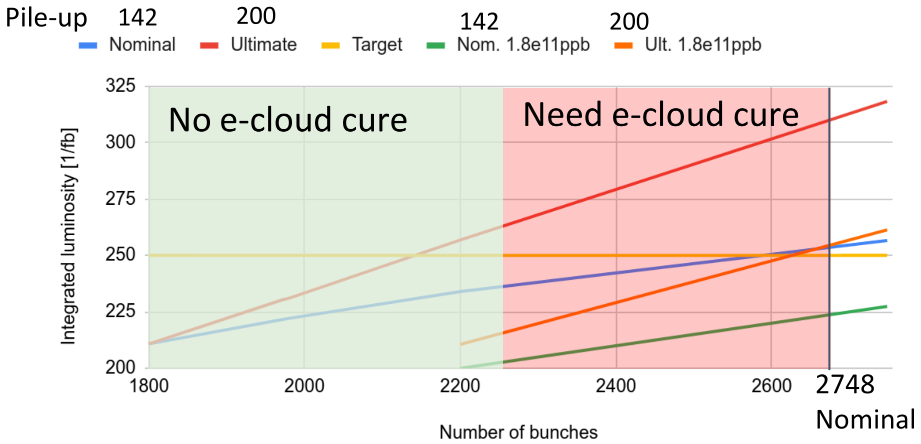
The ramping up phase is needed to account for learning new beam equipment and detectors and address unknown issues

19 Weeks YETS requires 7.5 $10^{34}$ cm$^{-2}$s$^{-1}$ to reach >3000 fb$^{-1}$ .

Present state e-cloud limitation is already challenging Run 4 and HL-LHC, requiring a review of the baseline parameters.

# Run 4 and e-cloud limitations

2.5h Turn-around, 50% OP. efficiency




| $N_{Bunches}$ for 2.3 $10^{11}$ and 7 TeV | $N_b$ | 8b+4e |
|---|---|---|
| Cured by task force! | 2748 | 0% |
| Not worse than 2022 | 2250 | 65% |
| Worsen like 2018-2022 (25% in S78) | 2100 | 84% |
| Worst case | 1972 | 100% |

E-clouds limitation reduce by 30% HL-LHC capabilities.
To recover 3000fb$^{-1}$, one needs:

- pile-up of 200
- exceed 5 $10^{34}$cm$^{-2}$s$^{-1}$ to recover
- flat optics

amd fills to get shorter and performance more sensitive to turn-around time.

2.3 $10^{11}$ are essential to HiLumi.
Injectors should inject 2.3 $10^{11}$ as soon as possible in the LHC to study

- Study E-cloud in the LHC
- Discover unknown hardware limits (if any) on time before LS3.

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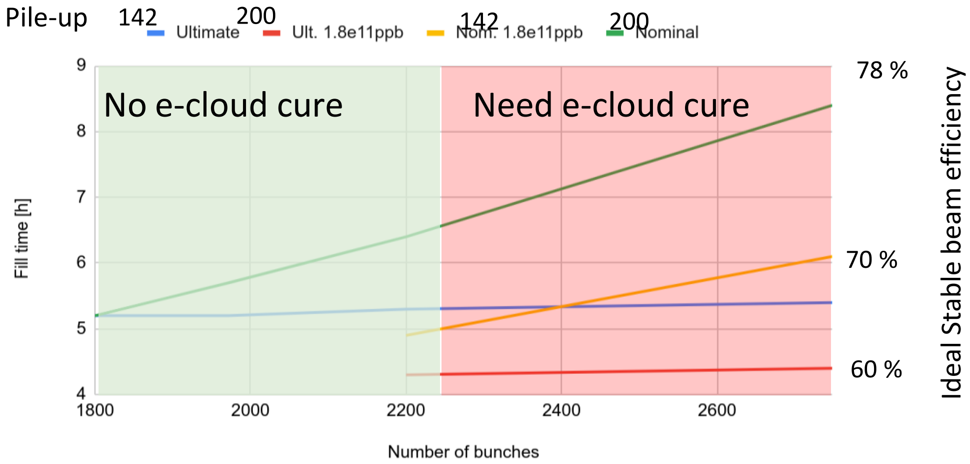


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# Impact of e-cloud limit at 2200 bunches and mitigations (lev. lumi limited to nominal)

For all cases: $L_{lev.} = 5\times10^{34}cm^{-2}/s$, crossing angle = 500 μm

| # of bunches | β*x,y [cm] | $L_{int}$ [$fb^{-1}$] | $ppb_{endLev}$ $ppb_{end}[10^{11}]$ | Pile-up | Fill length [h] | Hardware / comment |
|---|---|---|---|---|---|---|
| 2748 | 20, 20 | 242 | 1.40-1.18 | 131 | 7.3 | baseline |
| 2200 | 20, 20 | 215 | 1.60-1.27 | 164 | 5.6 | Lifetime!? |
| 2200 | 15, 15 | 226 | 1.43-1.17 | 164 | 6.1 | +MS10+BETS |
| 2200 | 18, 9 | 234 | 1.30-1.09 | 164 | 6.6 | +MS10+BETS |
| 1972 | 18,9 | 221.6 | 1.40-1.1 | 180 | 5.7 | +MS10+BETS |
| 2200 | 18, 7.5 | 237 | 1.26-1.05 | 164 | 6.6 | +MS10+CuCD+BETS |

E-cloud with only 8b4e mitigation reduces performance by about 11% with respect to 242 $fb^{-1}$ when resorting to 200 pile-up.

DA and lifetime challenged by the larger bunch intensity, to be studied.

MS10, CuCD, BETS upgrade would be needed both for lifetime and performance.

# Impact of e-cloud limit at 2200 bunches and 200 pile-up

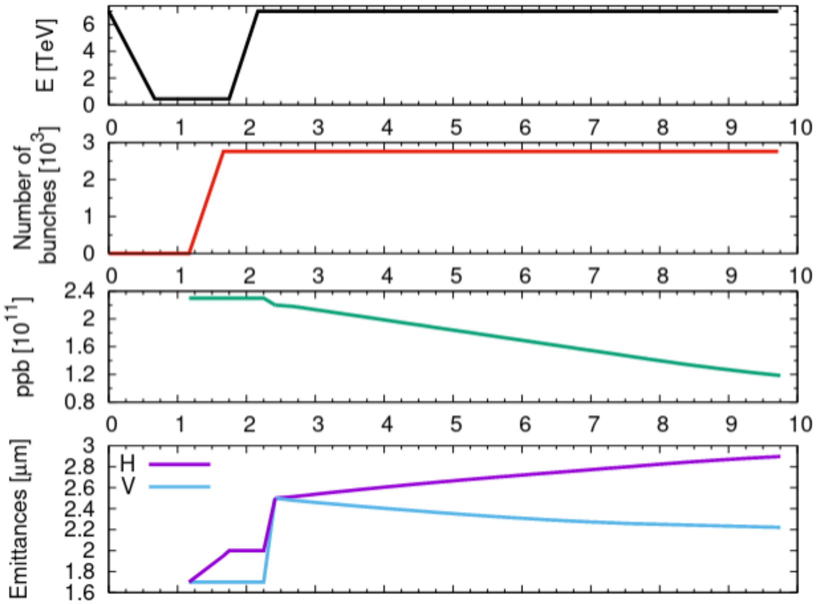
For all cases with 2200 bunches: **$L_{lev.}$ = $6.1\times10^{34}cm^{-2}/s$,** crossing angle = 500 μm

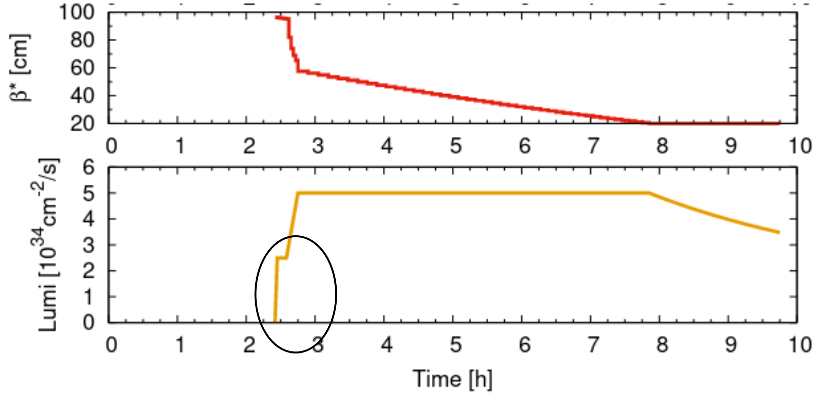
| # of bunches | $\beta$*x,y [cm] | $L_{int}$ [$fb^{-1}$] | $ppb_{endLev}$ $ppb_{end}$[$10^{11}$] | Pile-up | Fill length [h] | Hardware / comment |
|---|---|---|---|---|---|---|
| 2748 | 18, 9 | 318.2 | 1.40-1.13 | 200 | 5.4 | |
| 2748 | 20, 20 | | | 200 | | Lifetime? |
| 2200 | 20, 20 | 229 | 1.76-1.30 | 200 | 4.9 | Lifetime!!? |
| 2200 | 15, 15 | | | 200 | | +MS10+BETS |
| 2200 | 18, 9 | 257 | 1.44-1.15 | 200 | 5.2 | +MS10+BETS |
| 2200 | 18, 7.5 | 261 | 1.40-1.11 | 200 | 5.4 | +MS10+CuCD+BETS |
| 1972 | 18, 9 | 231 | 1.40-1.10 | 200 | 5.2 | +MS10+BETS |

Ultimate scenario brings very little improvement (far from the 320 $fb^{-1}$) with DA and lifetime even more challenged -> Very important to fix arc78 for Run 4 !

# HL-LHC luminosity cycle

Injection, ramp&squeeze, cryo-jump, lumi-levelling, lumi-decay, rampdown




Cryo step at $2.5\times10^{34}cm^{-2}s^{-1}$ for 10 min and then linear ramp to stabilize heat extractions. Experience could allow to reduce it.

CC noise, without feedback, causes loss of 1-3% in lumi. To be updated when feedback performance estimate is known.

As usual: IBS and SR. Minimum turn-around time 2.5h.

HL-LHC Run 4 proton operational scenario, R Tomas et al, CERN-ACC-2022-001

# BETS and optics flexibility

Needs to ramp-up and unknown requires flexibility in beta* at flat top, collapse, start of levelling, end of levelling.

$\beta_x$ at TCDQ cannot be stabilized for the entire range of tele-index factors needed for all possible scenarios.

TCDQ gaps cannot be changed at flat top with present BETS:

- Not possible to  squeeze to the minimum β* for all scenarios.
- Braking modularity of the ramp.

| β* | Tele-index | $\beta_x$ TCDQ | BETS upgrade |
|---|---|---|---|
| Collision | 1/1 - 1/0.5 (CC) | tbc | no tbc |
| 20 | 2.5/2.5 | 512/512 | no |
| 15 | 3.3/3.3 | 512/500 | at the limit |
| 9/18 | 5.5/2.7 | far tbc | yes |
| 7.5/15 | 6.6/3.3 | far tbc | yes |
| Anti-ATS (tbc) | 0.3/0.3 | yes tbc | yes tbc |

BETS needs upgrade enable gap change at flat top to for fully exploit β* and needed operational flexibility

# HL-LHC orbit and alignment aspects

HL-LHC alignment constraints in LSS1/5:

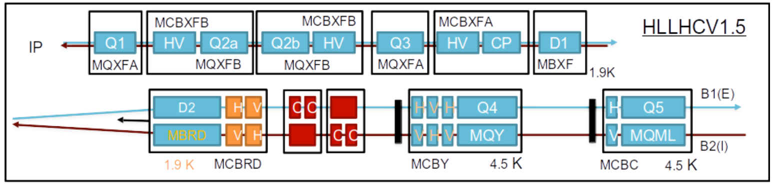
- Orbit at the crabs < 0.5 mm [New for HL-LHC]
- IP position vs inner tracker < 0.5 mm

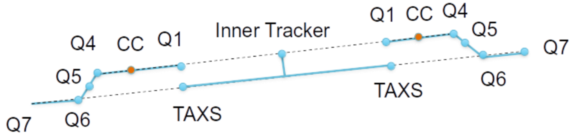
Orbit correctors can cope with triplet misalignment up to 0.5 mm (maximum ground motion expected in 1 year).

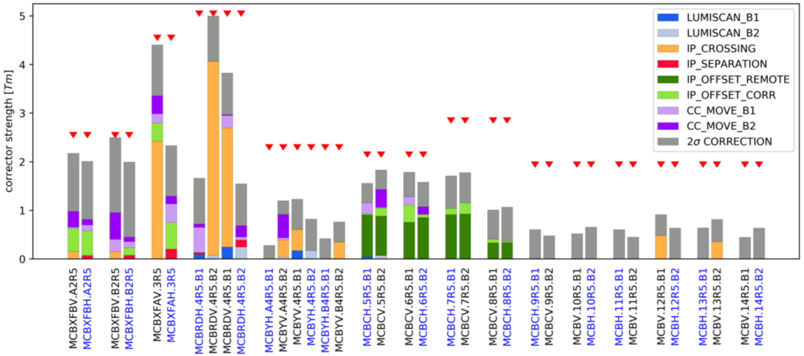
Corrector would require considerable strengths and are not optimally correcting orbit (very large offsets in triplets and crab cavities).

HL-LHC choice extended FRAS (initially introduced for ALARA) to be used to obtain long term orbit stability.

- Lumi scan: 100 um
- IP Crossing: 295 μrad
- IP Separation: 0.75 mm
- IP Offset FRAS: 2 mm
- IP Offset Corr: 0.5 mm
- CC Move: 0.5 mm
- 2σ CORR: 0.5 mm transverse offset - 0.1 mrad roll – transfer fun. 20 units



# FRAS usage scenarios during year

| Period | FRAS Activity | Expected range |
|---|---|---|
| During beam commissioning. | Reduce orbit corrector strength during first orbit optimization (safe beam/injection) using FRAS on the quadrupoles to compensate for fiducialization uncertainty | +- 250 um |
| After first collisions during beam commissioning if IP outside 0.5 mm from the inner target. | Re-align Q5L-Q5R  to new target | +-2 mm from 2029! |
| During year-end technical stops | Re-align equipment to past values using FRAS and recover FRAS neutral positions using manual alignment | +-2 mm |
| If ground motion or mechanical deformation exceed 0.5 mm in the middle of a run (not likely) | Re-align equipment to past values using FRAS | +- 500 um |

Open points:

- Can orbit beam response (direct, precise, accurate) be also used to steer re-alignments?
- Can we apply more frequent adjustments to keep the machine stable, rather than accumulating misalignents until reaching the limit:

  Advantages: stable orbit, stable corrections, stable beam-lifetime, reduced commissioning time

  Challenges: FRAS movements needs to be predictable and reproducible, understand well mechanics under fatigue conditions

# Conclusion

Present e-cloud limitation on the number of bunches has a strong impact on HL-LHC potential.

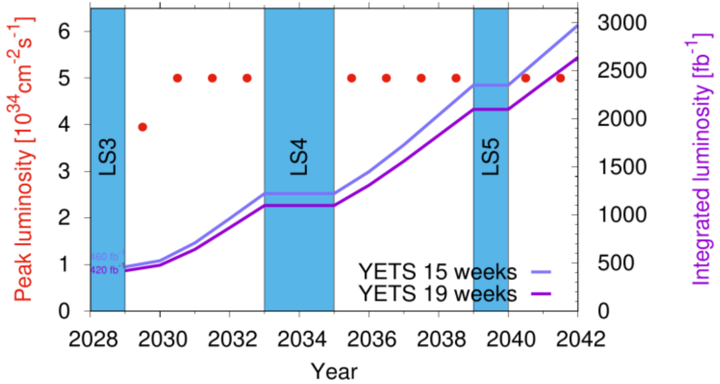
Using margins reserved for ultimate performance it possible to mitigate, on paper, the integrate luminosity loss as soon as Run 4.

This requires 200 pile-up, 2.3 $10^{11}$, flat optics, BETS upgrade and 2.5 hour average turn-around time.

HL-LHC has a new needs and new hardware system to maintaining orbit stability around the interaction point, that needs to be operation from the first year of operation.

# Back-up

# HL-LHC schedule and Run 4 ramp-up

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Heavy ion runs considered at the end of each year.

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| year | | | | | | | [$fb^{-1}$] |
| 2029 | 80 | 133 | 80 | 10 | 29 | 0.4 | 57 |
| 2030 | 107 | 133 | 60 | 2 | 29 | 0.5 | 165 |
| 2031 | 142 | 133 | 25 | 2 | 29 | 0.5 | 225 |
| 2032 | 142 | 133 | 25 | 2 | 29 | 0.5 | 231 |
| Run 5 avg | 154 | 133 | 27 | 2.5 | 29 | 0.5 | 299 |
| Run 6 avg | 166 | 133 | 25 | 2 | 29 | 0.5 | 303 |

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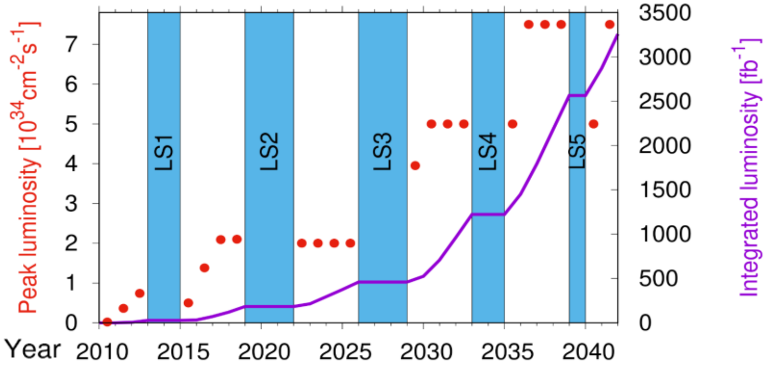
# Ultimate + 19 weeks YETS

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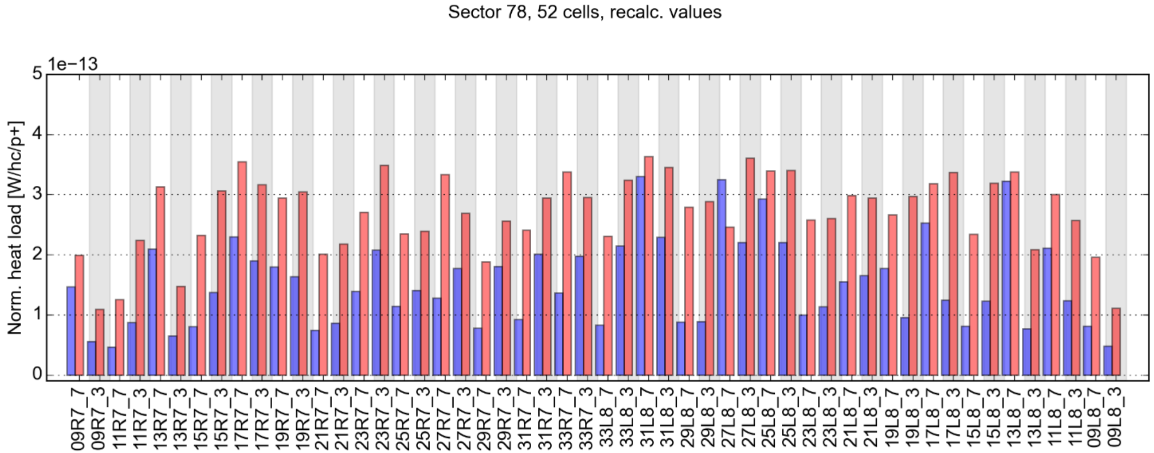
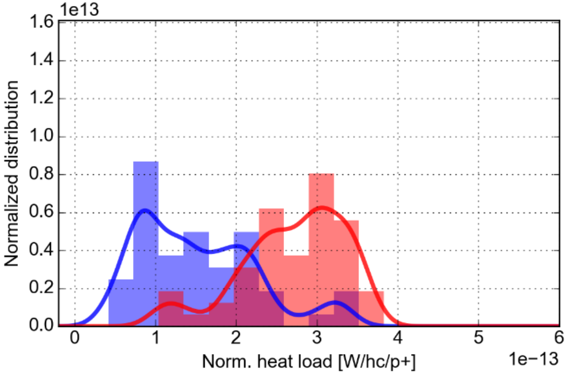
# Current conditioning state in S78

## Cell-by-cell heat load comparison w.r.t 2018



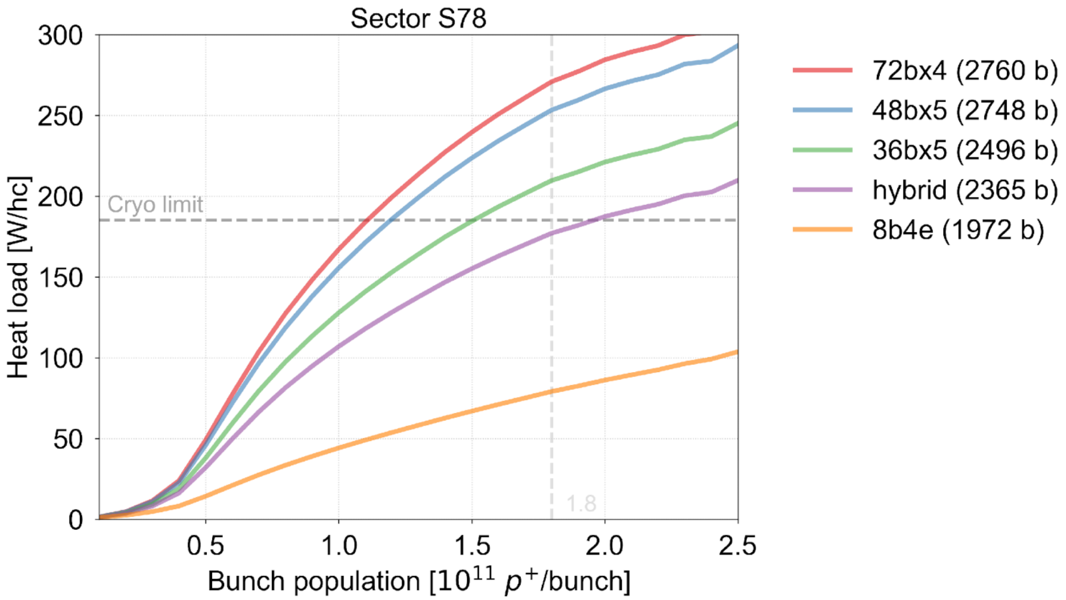




| | | |
|---|---|---|
| Fill | 7252 | 8484 |
| Started on | 03 Oct 2018 01:41 | 25 Nov 2022 06:56 |
| T_sample [h] | 1.40 | 7.70 |
| Energy [GeV] | 6499 | 6799 |
| N_bunches (B1/B2) | 2556/2556 | 2462/2462 |
| Intensity (B1/B2) [p] | 2.82e14/2.85e14 | 2.65e14/2.75e14 |
| Bun.len. (B1/B2) [ns] | 1.09/1.12 | 1.13/1.13 |
| H.L. S78 (avg) [W] | 86.07 | 146.00 |
| H.L. S78 (std) [W] | 41.15 | 34.19 |
| H.L. exp. imped. [W] | 8.89 | 8.14 |
| H.L. exp. synrad [W] | 12.07 | 13.76 |
| T_nobeam [h] | 0.20 | 0.20 |

## Estimated intensity reach

The intensity reach for different filling schemes is determined by the limitation in S78

| | 4x72b | 5x48b | 5x36b | hybrid | 8b+4e |
|---|---|---|---|---|---|
| Bunches per beam | 2760 | 2748 | 2496 | 2365 | 1972 |
| Bunch intensity | 1.1 | 1.2 | 1.5 | 1.9 | - |



# Achievable performance for HL-LHC

- Assuming heat loads increased by ~25 % with respect to 2022 (pessimistic)

| Scenario | Pile-up | Lev. lumi $10^{34}$ $cm^{-2}$ $s^{-1}$ | Bunch intensity | N. bunches | Heat load W/h-cell | Needs surface treatment | Int. lumi (*) $fb^{-1}$/day |
|---|---|---|---|---|---|---|---|
| Baseline 130 | 130 | 5 | $2.2 \times 10^{11}$ | 2748 | 420 | Yes | 3.3 |
| Baseline 200 | 200 | 7.5 | $2.2 \times 10^{11}$ | 2748 | 420 | Yes | 4.2 (4.4 with flat) |
| 8b4e | 200 | 5.4 | $2.2 \times 10^{11}$ | 1972 | ~120 | No | 3.0 (3.2 with flat) |
| hybrid | 200 | 5.75 | $2.2 \times 10^{11}$ | 2110 | 190 | No | 3.2 (3.4 with flat) |

+30%

- Assuming no degradation with respect to 2022 (optimistic)

| Scenario | Pile-up | Lev. lumi $10^{34}$ $cm^{-2}$ $s^{-1}$ | Bunch intensity | N. bunches | Heat load W/h-cell | Needs surface treatment | Int. lumi (*) $fb^{-1}$/day |
|---|---|---|---|---|---|---|---|
| Baseline 130 | 130 | 5 | $2.2 \times 10^{11}$ | 2748 | 330 | Yes | 3.3 |
| Baseline 200 | 200 | 7.5 | $2.2 \times 10^{11}$ | 2748 | 330 | Yes | 4.2 (4.4 with flat) |
| 8b4e | 200 | 5.4 | $2.2 \times 10^{11}$ | 1972 | ~90 | No | 3.0 (3.2 with flat) |
| hybrid | 200 | 6.1 | $2.2 \times 10^{11}$ | 2250 | 190 | No | 3.4 (3.6 with flat) |

+22%

(*) Approximate lumi estimates (to be refined)