HL-LHC filling schemes: possible optimization

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Many thanks to:

C. Schwick and the LPC for filling scheme webtools
(ad-hoc features developed for these studies)

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Outline

- **Constraints**
- **Standard scheme (72b trains)**
  - Can we squeeze in a few more bunches?
- **Trains of 48b:**
  - 5x48 vs 6x48
- **Mixed schemes**
  - Mixing 25 ns and 8b4e in the SPS and in the LHC
- **Final remarks**

Constraints on filling scheme design

In the following we assume (as in Run 2):

- **Gap between injections into the SPS (T_{MKP}):** 200 ns (7 slots)
- **Gap between injections into the LHC (T_{MKI}):** 800 ns (31 slots)

- **Abort gap length:** 3.05 μs (121 slots)

- **Kicker pulses** (MKI, MKE) long enough to inject **4x80b into the LHC**

- The **first injection** consists in a short batch (8b or 12b)
    - These are left **non-colliding** in IP1&5

- **All other bunches are colliding in IP1/**5

- As close as possible to **four-fold symmetry** to maximize number of collisions in **IP8**

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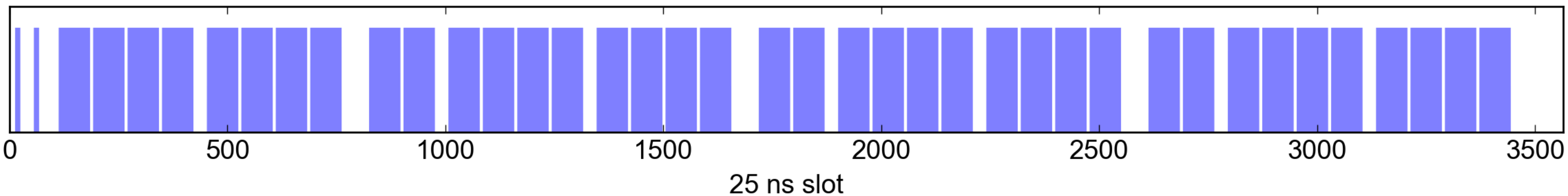
(4 x 72b) scheme - baseline

This is the **HL-LHC baseline scheme** (assumed in TDR)

25ns_2760b_2748_2495_2560_288bpi_14inj_800ns_bs200ns_STD



Scheme name: 25ns_2760b_2748_2495_2560_288bpi_14inj_800ns_bs200ns_STD

N. collisions	
ATLAS/CMS:	2748
LHCb:	2560
ALICE:	2495

N. bunches: 2760

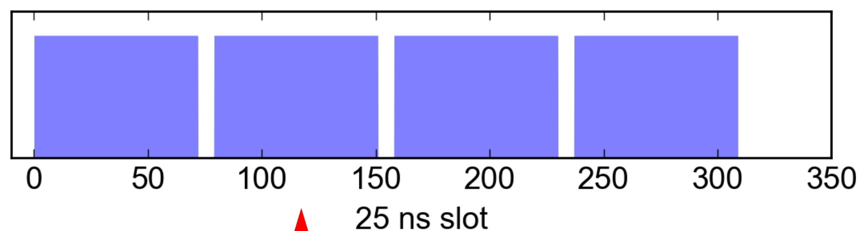
N. injections: 13

Unused(*): 122 slots (3.4% LHC)

(*) Not used by bunches, kicker rise-times, abort-gap

Patterns from the injectors:

(4 x 72b)

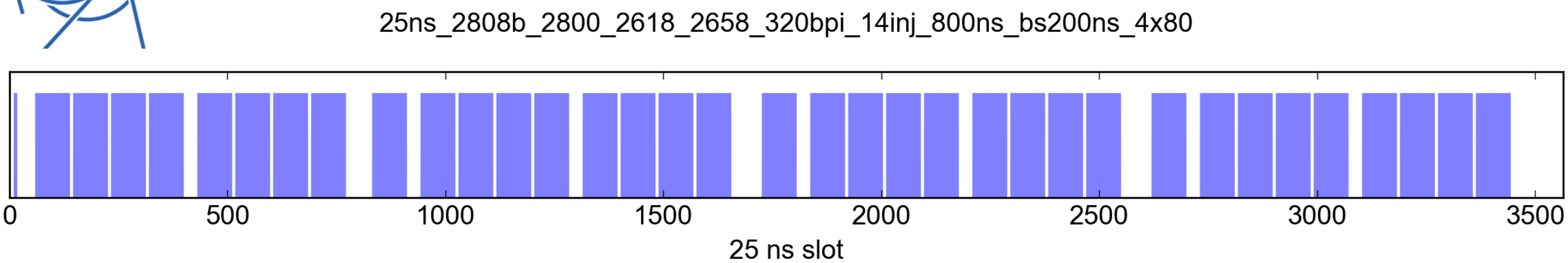


Requires trains of 72b from the injectors

There is some **unused space in the ring**, but it cannot be used if the injectors can provide only trains of 72b

(4 x 80b) scheme

Can we gain something better by using **trains of 80b**?

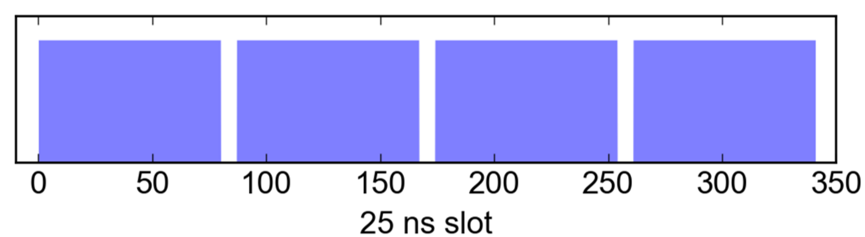



```
Scheme name: 25ns_2808b_2800_2618_2658_320bpi_14inj_800ns_bs200ns_4x80
```

```
   N. collisions
ATLAS/CMS:      2800 (+1.9%)
LHCb:           2658 (+3.8%)
ALICE:          2618 (+4.9%)

N. bunches:     2808

N. injections: 12

Unused:         126 slots
                (3.5% LHC)
```

Patterns from the injectors:

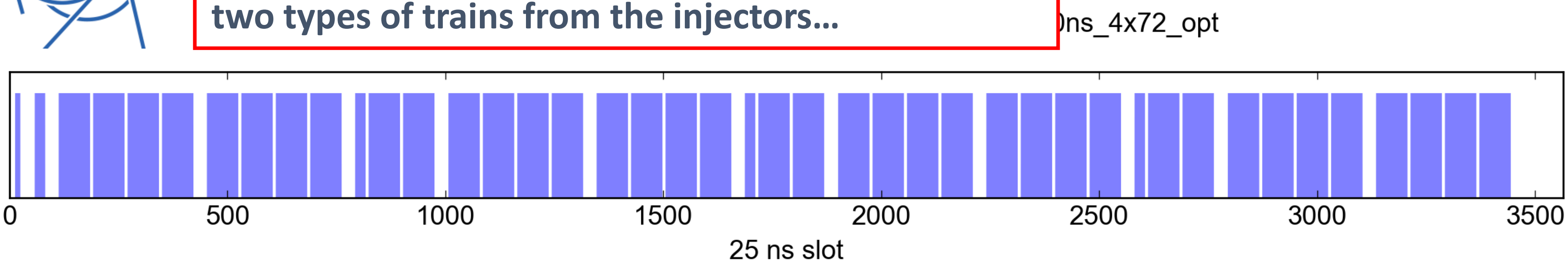
(4 x 80b)



We can gain **2% more collisions in IP1&5** w.r.t. to the baseline, but **there is still quite some unused space in the ring**

Optimized (4 x 72b) scheme

We can better exploit the used space by requesting **two types of trains from the injectors…**



Scheme name: 25ns_2844b_2832 … bs200ns_4x72_opt

Number of collisions in IP1&5 **increased by 3%** w.r.t. the baseline.

N. collisions	
ATLAS/CMS:	2832 (+3.1%)
LHCb:	2631 (+2.8%)
ALICE:	2560 (+2.6%)

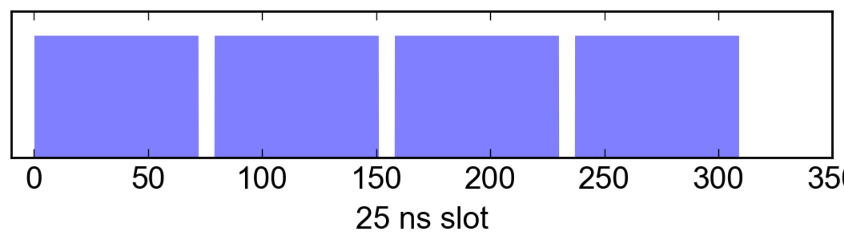
N. bunches: 2844

N. injections: 13

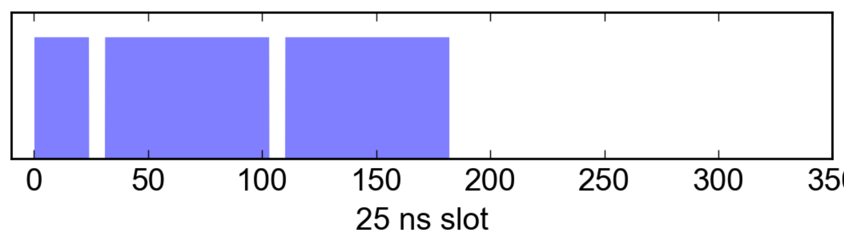
Unused: 17 slots (0.5% LHC)

Patterns from the injectors:

(4 x 72b)



(24b) + (2 x 72b)

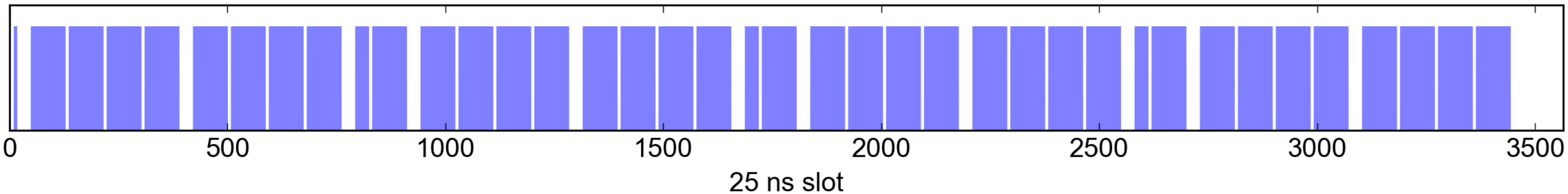


The **space** in the ring is now **almost fully used**.

Optimized (4 x 80b) scheme

We can use both strategies together

25ns_2904b_2896_2656_2734_320bpi_12inj_800ns_bs200ns_4x80b_opt



Scheme name: 25ns_2904b_2896_2656_2 … x80b_opt

A **train of 32b** could be produced with the same technique used for the 80b (removing one bunch in H21 in the PS)

N. collisions	
ATLAS/CMS:	2896 (+5.4%)
LHCb:	2734 (+6.8%)
ALICE:	2656 (+6.5%)

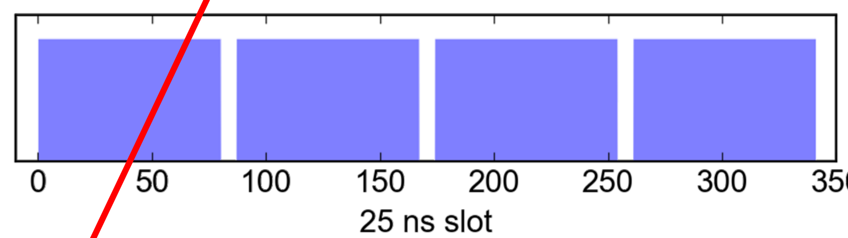
N. bunches: 2904

N. injections: 12

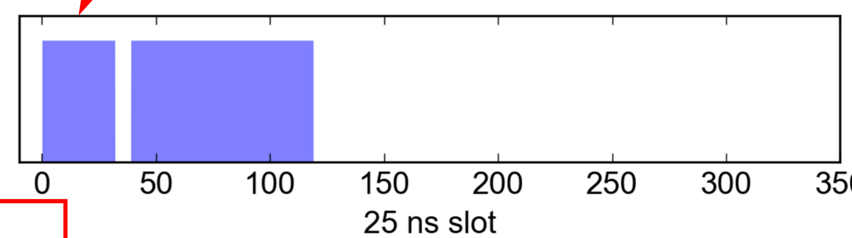
Unused: 9 slots (0.3% LHC)

Patterns from the injectors:

(4 x 80b)



(32b) + (80b)



We could have **>2900b in the LHC** and increase the **number of collisions by 5.4% w.r.t. baseline**.

Outline

- **Constraints**
- **Standard scheme (72b trains)**
  - Can we squeeze in a few more bunches?
- **Trains of 48b:**
  - 5x48 vs 6x48
- **Mixed schemes**
  - Mixing 25 ns and 8b4e in the SPS and in the LHC
- **Final remarks**

Schemes based on trains of 48b

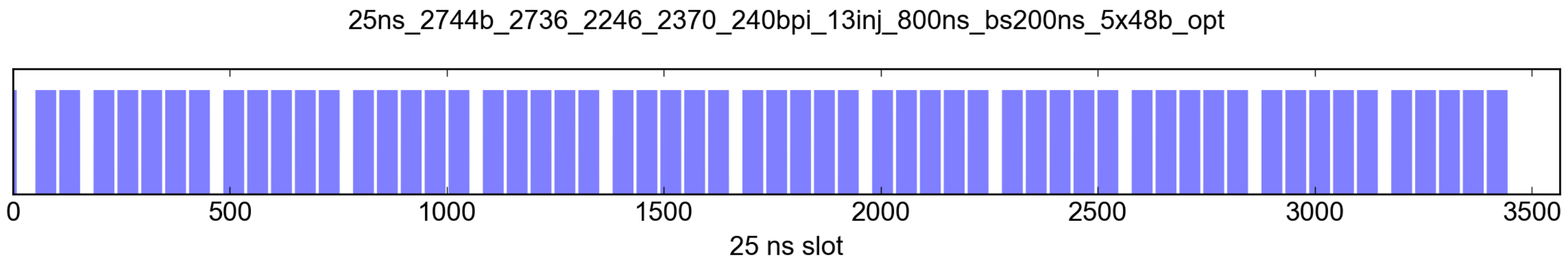
Trains of 48b can be useful to **mitigate different issues**:

- Filling schemes made of trains of 48b produce **less e-cloud** (-10% w.r.t. 72b)

- Trains of 48b **can be produced with BCMS scheme**:
  - **25% higher brightness** w.r.t. standard production
  - **Backup** in case of un-expected **emittance blow-up**

- Can also be produced with STD scheme using **single-batch transfer from PSB to PS**:
  - Same brightness as baseline
  - Very short injection plateau in PS (no second injection)
  - Shorter injection plateau in SPS
  - Can be used to **mitigate issues with losses/blow-up at low-energy in PS/SPS**
  - Can give slightly shorter injection time

Optimized (5 x 48b) scheme

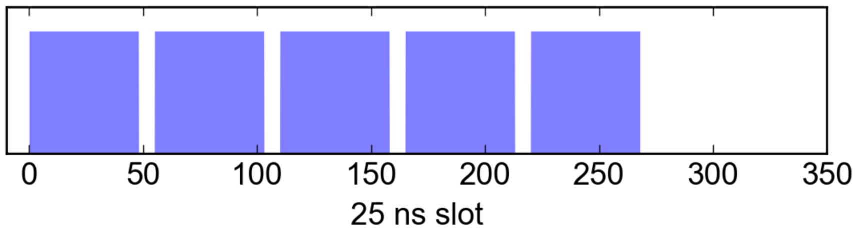



```
Scheme name: 25ns_2744b_2736_2246_2370_240bpi_13inj_800ns_bs200ns_5x48b_opt
```

```
   N. collisions
ATLAS/CMS:      2736 (-0.4%)
LHCb:           2370 (-7.4%)
ALICE:          2246 (-10.0%)

N. bunches:     2744

N. injections: 13

Unused:         12 slots
                (0.3% LHC)
```

Patterns from the injectors:

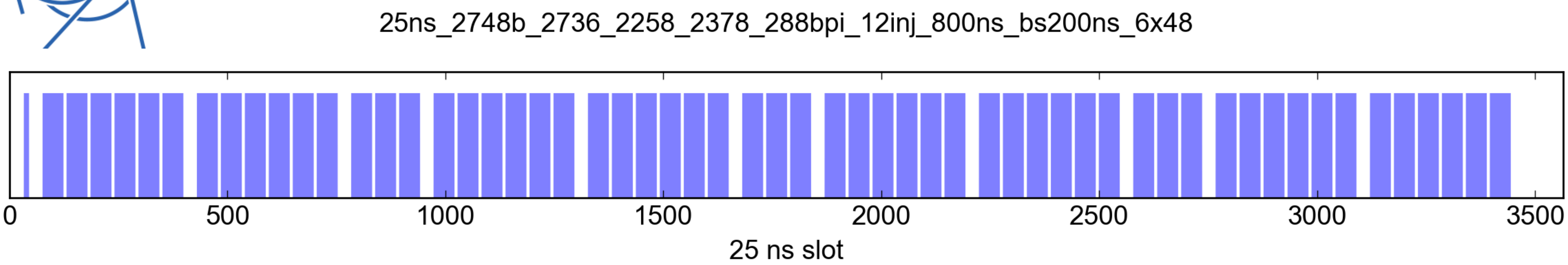
(5 x 48b)



- Using injections of **5x48b** we can get the **same number of collisions in IP1&5 as for the baseline scheme**
- Less collisions in IP2 and IP8

All space in the ring is used
→ **no room for further optimization**

Optimized (6 x 48b) scheme



Scheme name: 25ns_2748b_2736_2258_2378_288bpi_12inj_800ns_bs200ns_6x48

N. collisions	
ATLAS/CMS:	2736 (-0.4%)
LHCb:	2378 (-7.1%)
ALICE:	2258 (-9.5%)

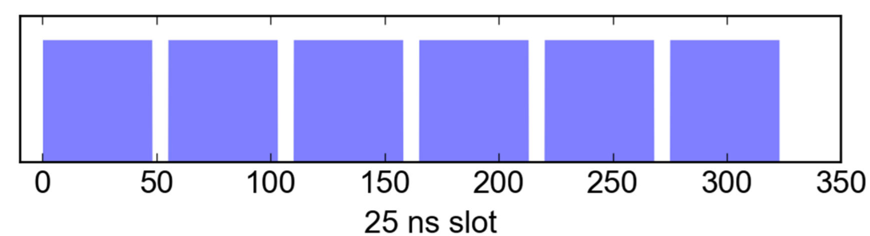
N. bunches: 2748

N. injections: 12

Unused: 32 slots (0.9% LHC)

Patterns from the injectors:

(6 x 48b)



- Using injections of **6x48b does not provide any gain with respect to injections 5x48b**
- Therefore **5x48b scheme is preferred** (shorter injection plateau in the SPS)

Summary table

- Having the possibility of injecting **two different patterns for the injectors** allows increasing the number of bunches in the LHC
- A further increase can be obtained using **trains of 80b**

Pattern from injectors	N. injections	Unused space	Collisions in IP1/5	Collisions in IP8	Collisions in IP2
(4 x 72b)	13	122 (3.4%)	2748 (ref.)	2560 (ref.)	2495 (ref.)
(4 x 72b) and (24b + 72b)	13	17 (0.5%)	**2832 (+3.1%)**	2631 (+2.8%)	2560 (+2.6%)
(4 x 80b)	12	126 (3.5%)	2800 (+1.9%)	2658 (+3.8%)	2618 (+4.9%)
(4 x 80b) and (32b + 80b)	12	9 (0.3%)	**2896 (+5.4%)**	2734 (+6.8%)	2656 (+6.5%)

- Using **injections of 5x48b** it is possible to have **the same number of collisions in IP1&5** as in the baseline (no further optimization possible)
- Injections of **6x48b do not provide any further gain** → 5x48b is preferred

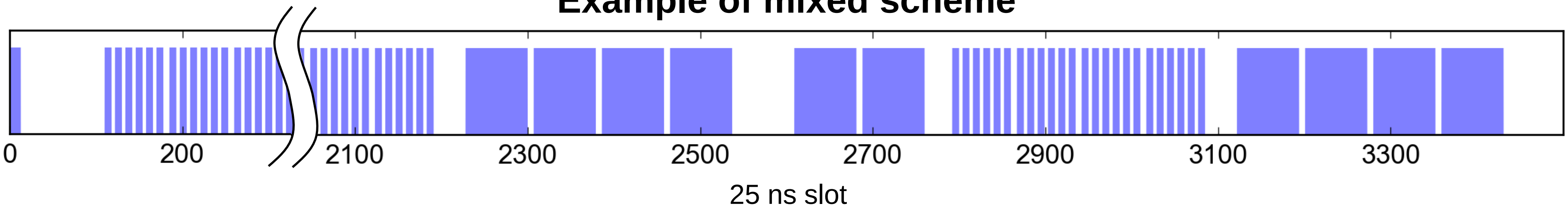
Pattern from injectors	N. injections	Unused space	Collisions in IP1/5	Collisions in IP8	Collisions in IP2
(5 x 48b)	13	12 (0.3%)	**2736 (-0.4%)**	2370 (-7.4%)	2246 (-10%)
(6 x 48b)	12	32 (0.9%)	**2736 (-0.4%)**	2378 (-7.1%)	2258 (-9.5%)

- **Constraints**
- **Standard scheme (72b trains)**
  - Can we squeeze in a few more bunches?
- **Trains of 48b:**
  - 5x48 vs 6x48
- **Mixed schemes**
  - Mixing 25 ns and 8b4e in the SPS and in the LHC
- **Final remarks**

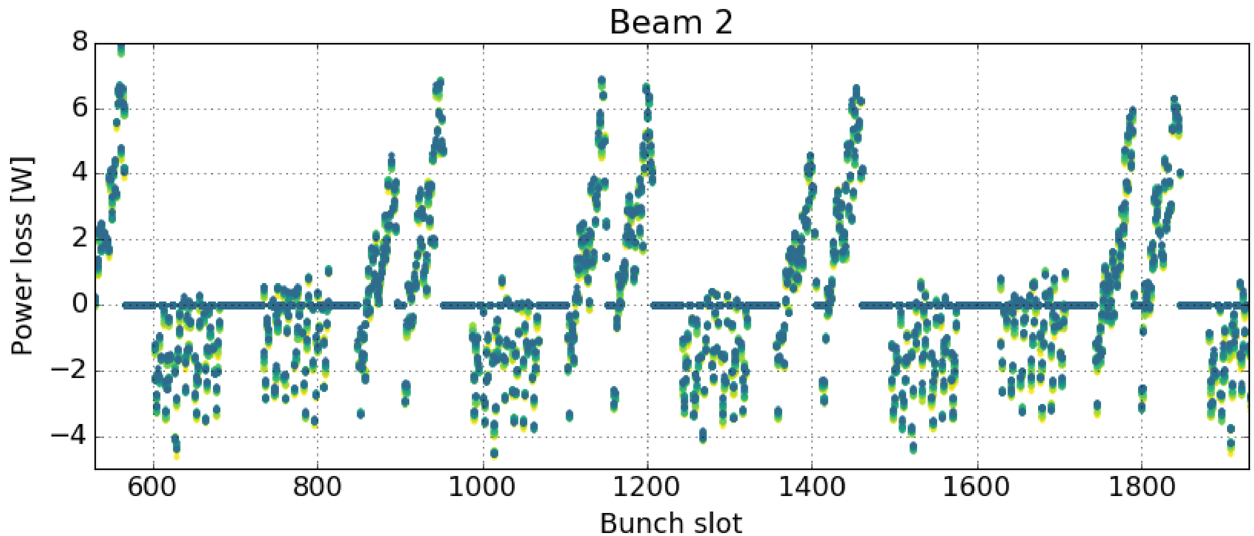
Standard **25 ns** trains and **8b4e** trains can be **combined** in the same filling scheme to **mitigate e-cloud effects**

→ It can be done **both starting from 72b and 48b filling scheme**

Example of mixed scheme

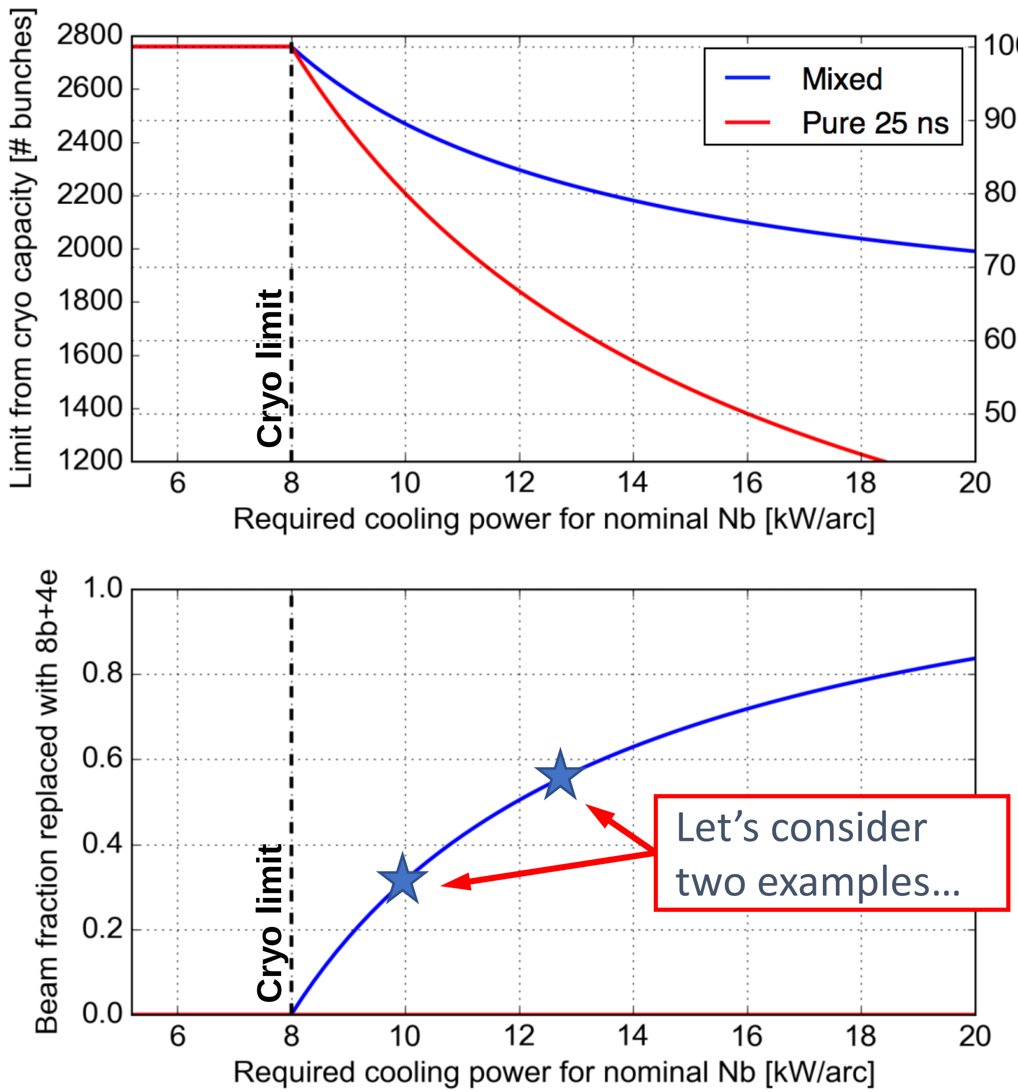


Confirmed in MD in 2016



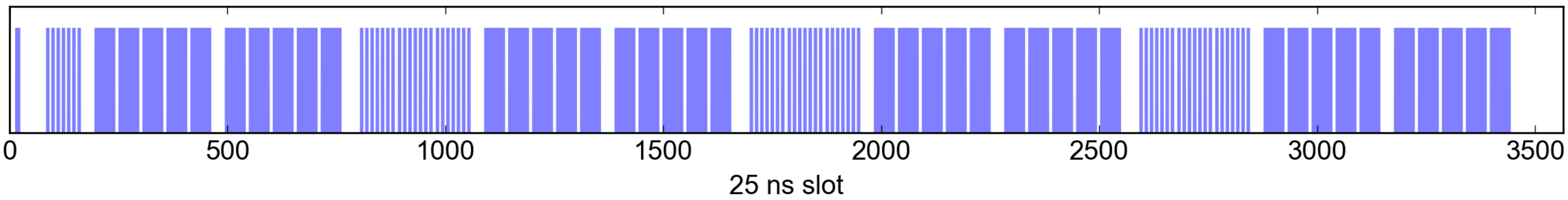
Measurement ***J. Esteban Muller***

The **share between 8b+4e and 25 ns strains can be changed** to match the excess of heat load



Mixed scheme – example 1

25ns_2492b_2480_2048_2301_240bpi_13inj_800ns_bs200ns_run3_study_corrected




```
Scheme name: 25ns_2492b_2480_2048_2301_240bpi_13inj_800ns_bs200ns_run3st_co
```

```
   N. collisions
ATLAS/CMS:      2480 (-9.8%)
LHCb:           2301 (-10.1%)
ALICE:          2048 (-17.9%)
```

```
N. bu
```

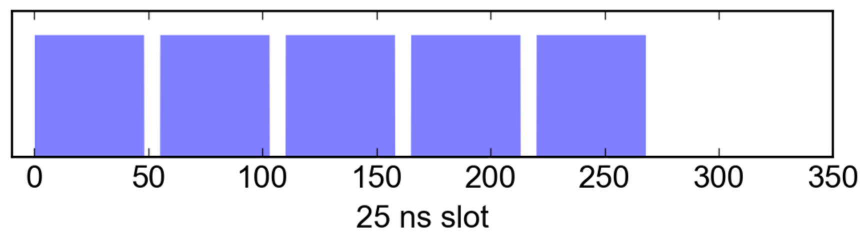
Again **two types of injections from the SPS**

```
N. injections: 13
```

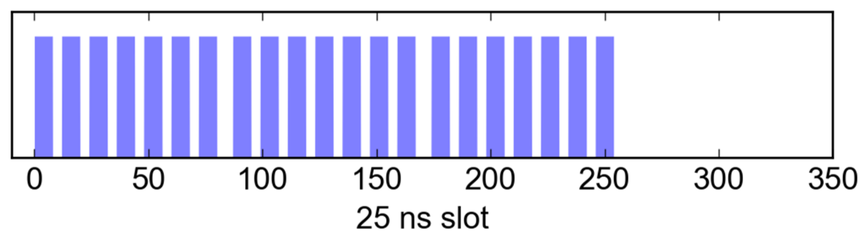
```
Unused:         73 slots
                (2.0% LHC)
```

Patterns from the injectors:

(5 x 48b)



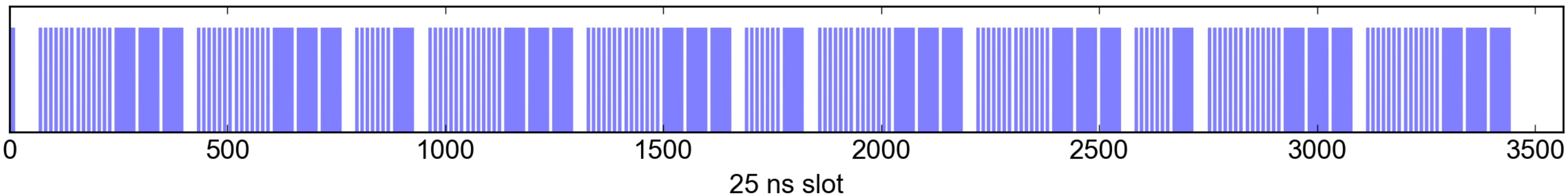
(3 x 56b)



Reduces heat load by 20% w.r.t. baseline (with 10% less collisions in IP5&5)

Mixed scheme – example 2

25ns_2372b_2360_1784_2216_256bpi_12inj_800ns_bs200ns_run3study



`Scheme name: 25ns_2372b_2360_1784_2216_256bpi_12inj_800ns_bs200ns_run3study`

```
   N. collisions
ATLAS/CMS:      2360 (-14%)
LHCb:           2216 (-13%)
ALICE:          1784 (-28%)
```

N.

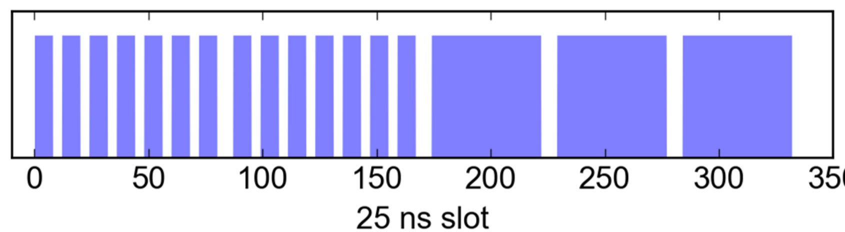
N.

To achieve the required share **mixing need to be made in the SPS**

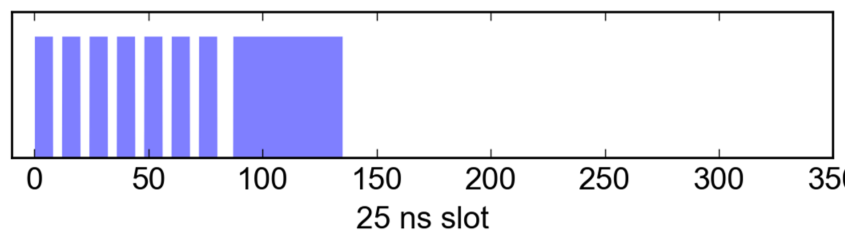
```
Unused:         29 slots
                (0.8% LHC)
```

Patterns from the injectors:

(2 x 56b) + (3 x 48b)



(56b) + (48b)



Reduces heat load by 40% w.r.t. baseline (with **14%** less collisions in IP5&5)

Outline

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- **Trains of 48b:**
  - 5x48 vs 6x48
- **Mixed schemes**
  - Mixing 25 ns and 8b4e in the SPS and in the LHC
- **Final remarks**

Summary and final remarks

- Run 1 and Run 2 have shown that **injectors flexibility is a powerful tool to mitigate issues and push performance** (e.g. high-intensity 50 ns, 36b scheme, BCMS, 8b4e)
  → These capabilities should be certainly preserved and enhanced for HL-LHC

- For several schemes (both for problem-mitigation and performance enhancement) it would be **desirable to inject two kinds of bunch trains within the same filling scheme**
  → Combined with possibility of having trains of **80b**, it allows obtaining **~2900b colliding in IP1&5**
  → Allows using **mixed 8b4e/25ns** schemes to fight e-clouds

(Obvious?) reminder: reliability is equally or more important than beam parameters!

→ we can really gain in integrated luminosity from "complex" schemes only if:
  - Injectors availability remains high
  - Beam preparation stays in the shadow of LHC ramp-down and setup
  - Injection process is smooth and efficient