LHC Injectors Upgrade

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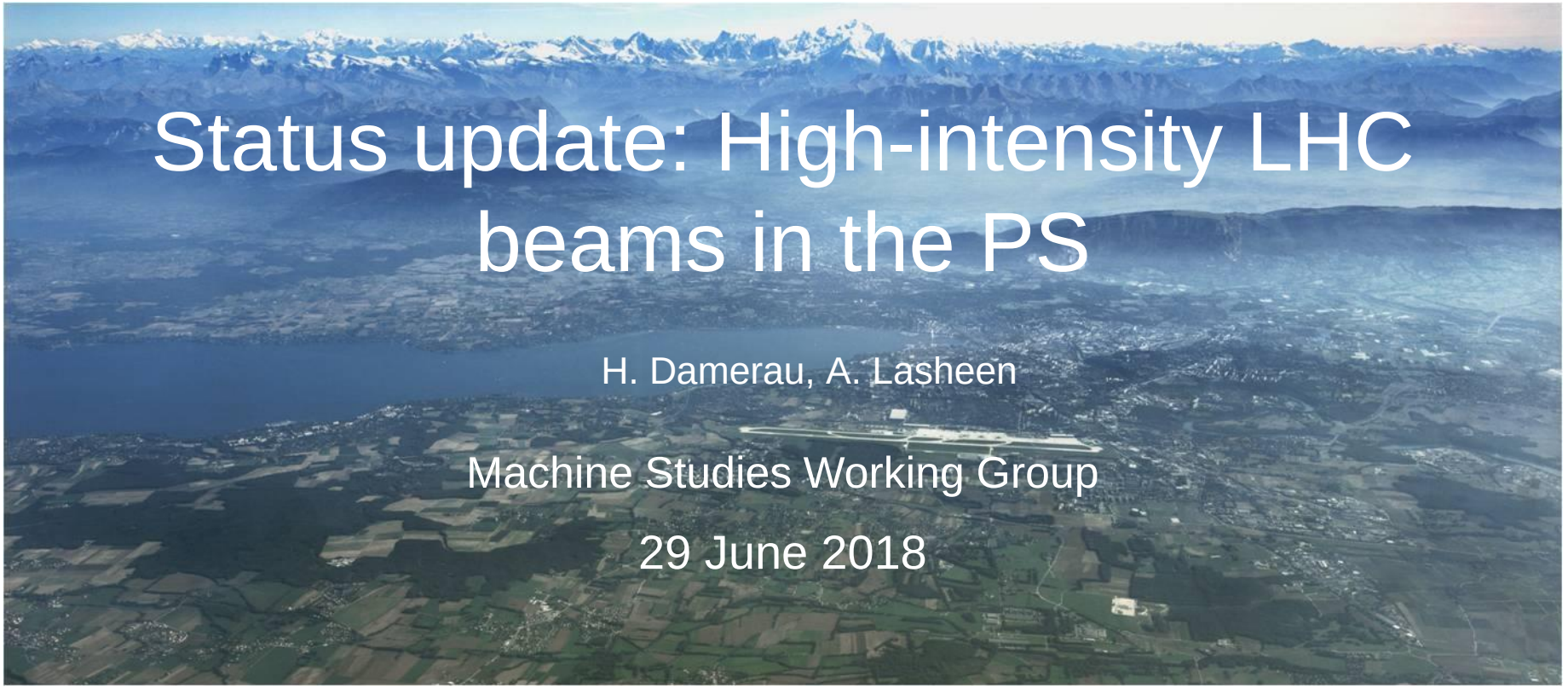

Status update: High-intensity LHC beams in the PS

H. Damerau, A. Lasheen

Machine Studies Working Group

29 June 2018

Many thanks to F. Bertin, G. Favia, M. Haase, A. Huschauer, M. Morvillo, E. Shaposhnikova, M. Vadai

CERN

Overview

- **Introduction**
- **Observations at high intensity**
  - Comparison of 2017 and 2018 data
  - Standard 72-bunch beam
  - BCMS beam
- **Changes during YETS2017/18**
  - RF
  - Vacuum interventions
- **High-frequency cavity impedances and feedback**
- **Summary and outlook**

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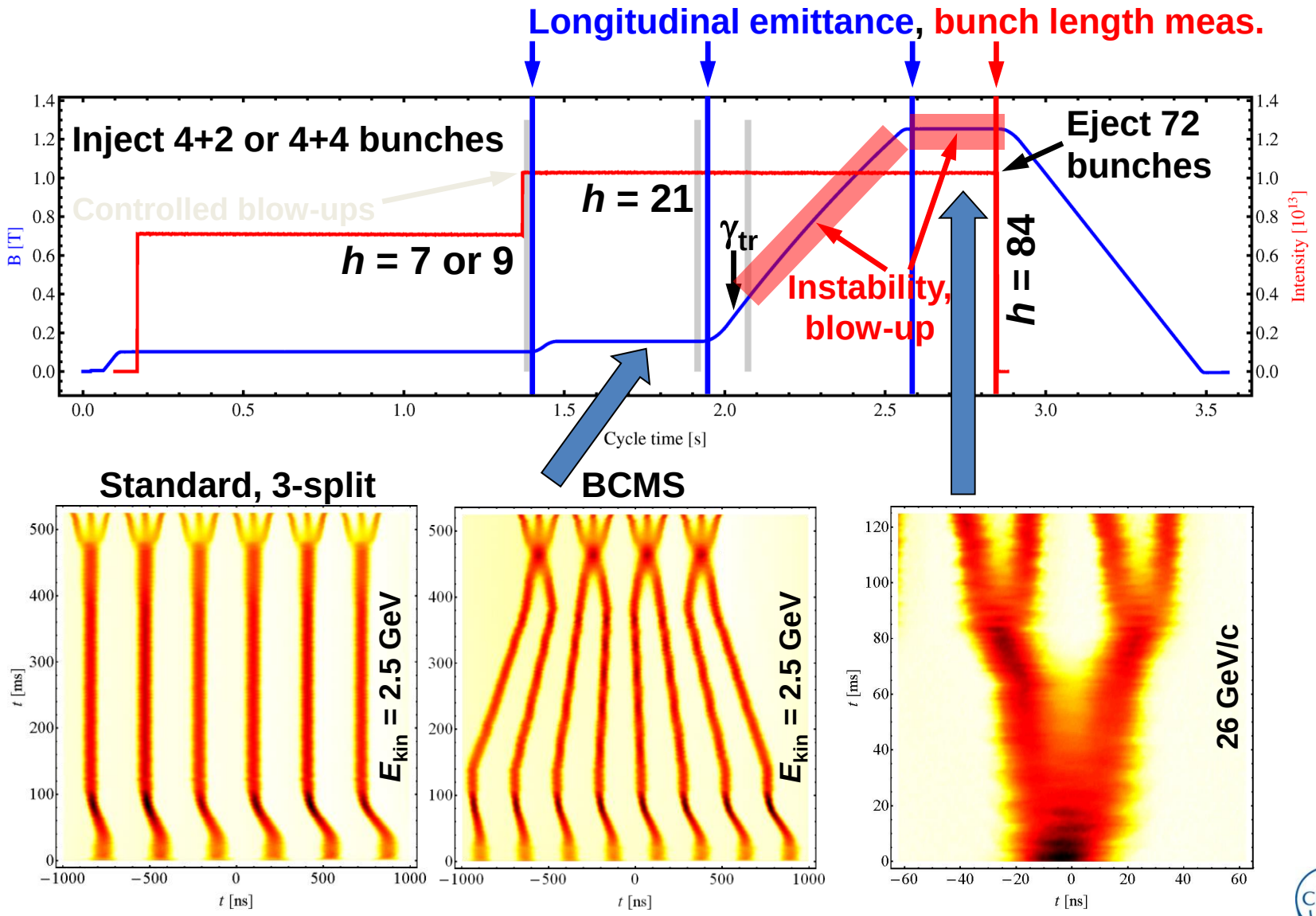
LHC-type beams with 25 ns spacing in the PS



Higher intensity?

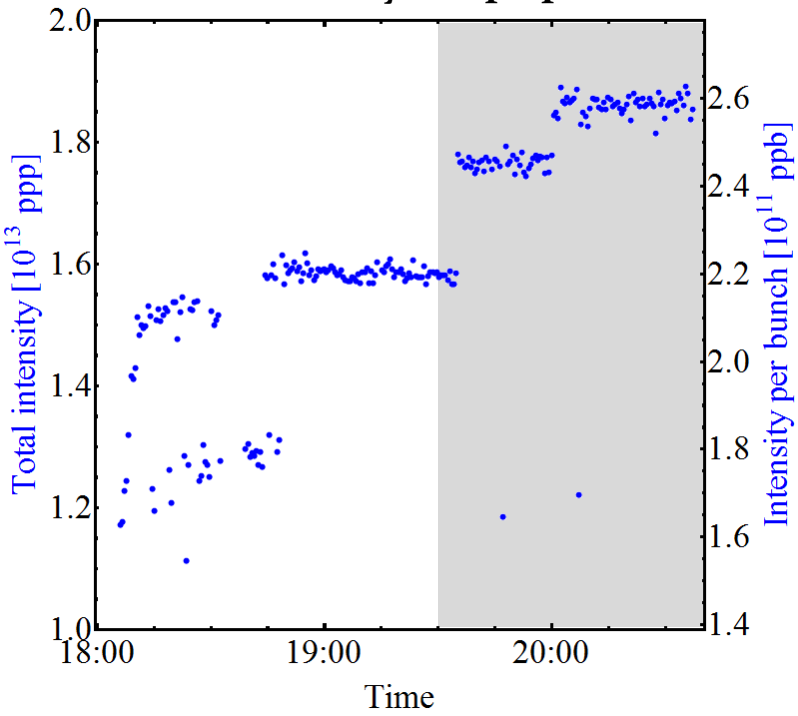
Pushing intensity at expense of larger longitudinal emittance

→ Bare minimum of 40/80 MHz cavities with gap open (C40-78, C80-88, C80-89)

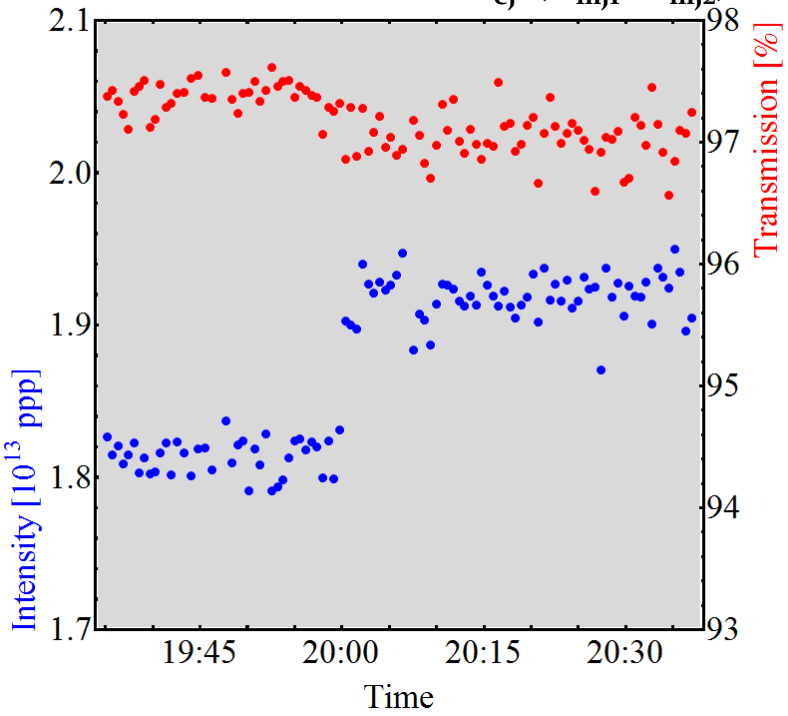
→ Trips of remaining cavities C40-78 and C80-08 due to beam loading

→ Measurements difficult to perform, almost like dedicated MDs

Intensity ramp up



Overall transmission $N_{ej}/(N_{inj1}+N_{inj2})$



→ **Excellent transmission up to 2.6 · 10¹¹ ppb, even with ε_l > 0.35 eVs**

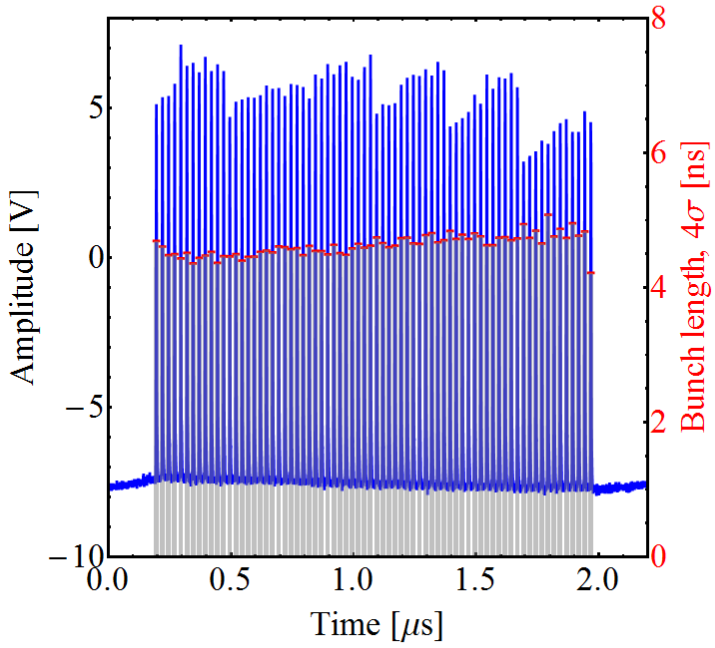
→ **No further RF issues related to intensity**

Longitudinal beam quality

Injector MD Days 2017

Longitudinal parameters at LIU/HL-LHC baseline intensity: 2.6 · 10¹¹ ppb

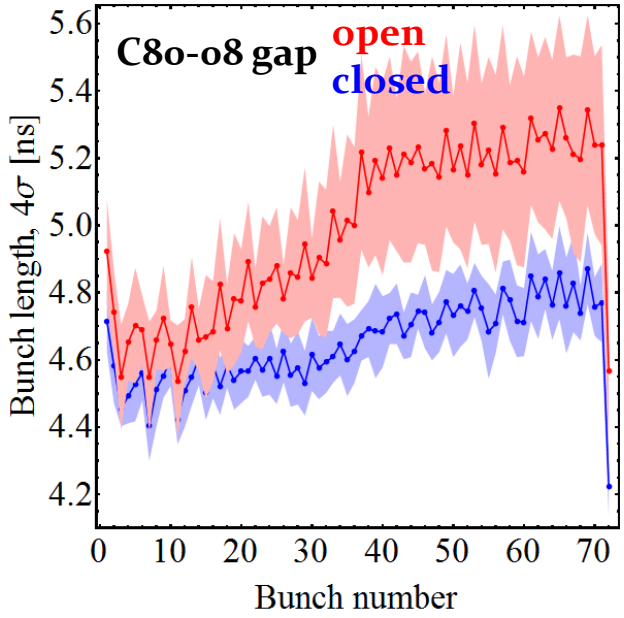
→ Additional longitudinal blow-up



- **Bunch length increase along the batch**

  → **Onset of instability**

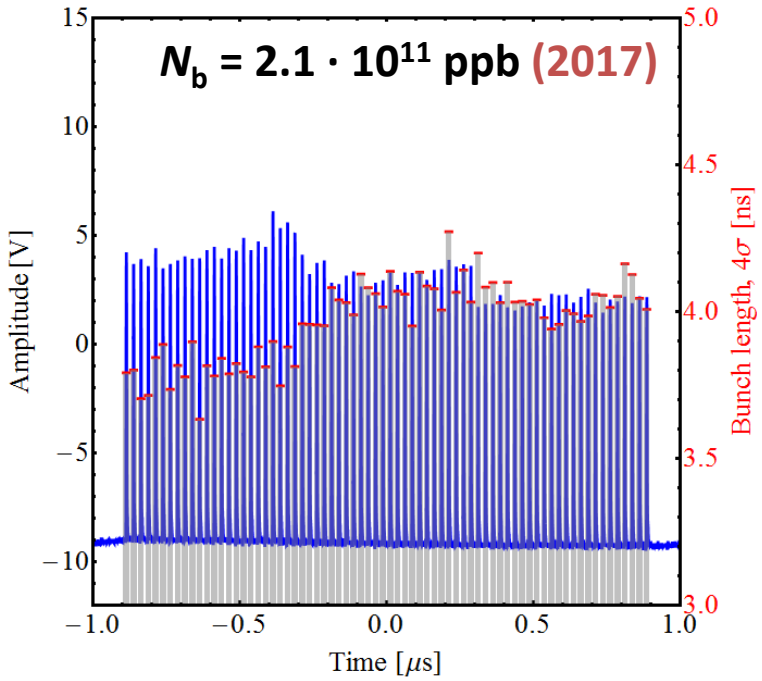
- **Average ε_l at arrival on flat-top: 0.3 eVs (RMS, 4 final bunches)**
- **Corresponds to ~0.45…0.5 eVs per bunch in usual convention**



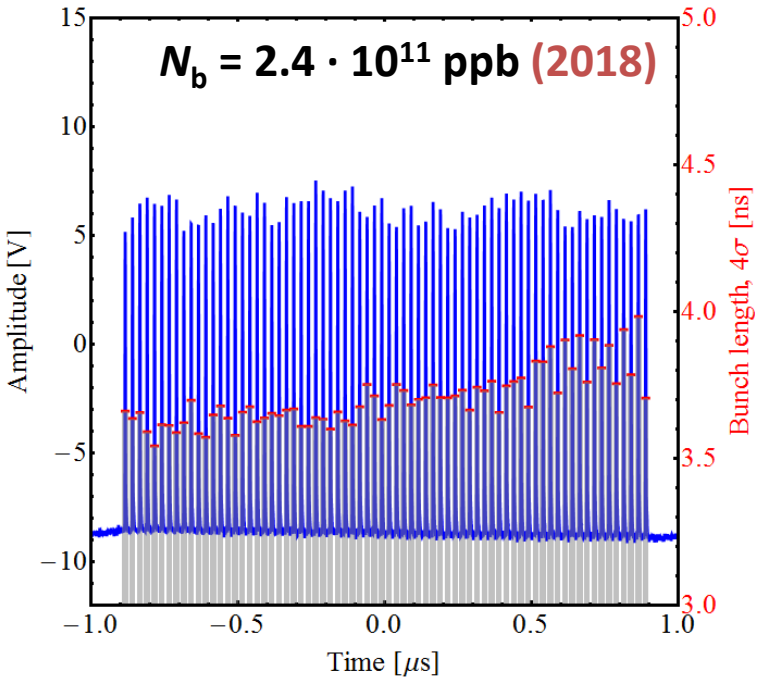
LHC25ns (standard), 72 bunches

- **Beam seems longitudinally in better shape than in 2016/2017**
  - Standard beam stable beyond $2 \cdot 10^{11}$ ppb, more for BCMS
  - Change with respect to 2016 and 2017 not fully understood

Bunch profile/length last turn



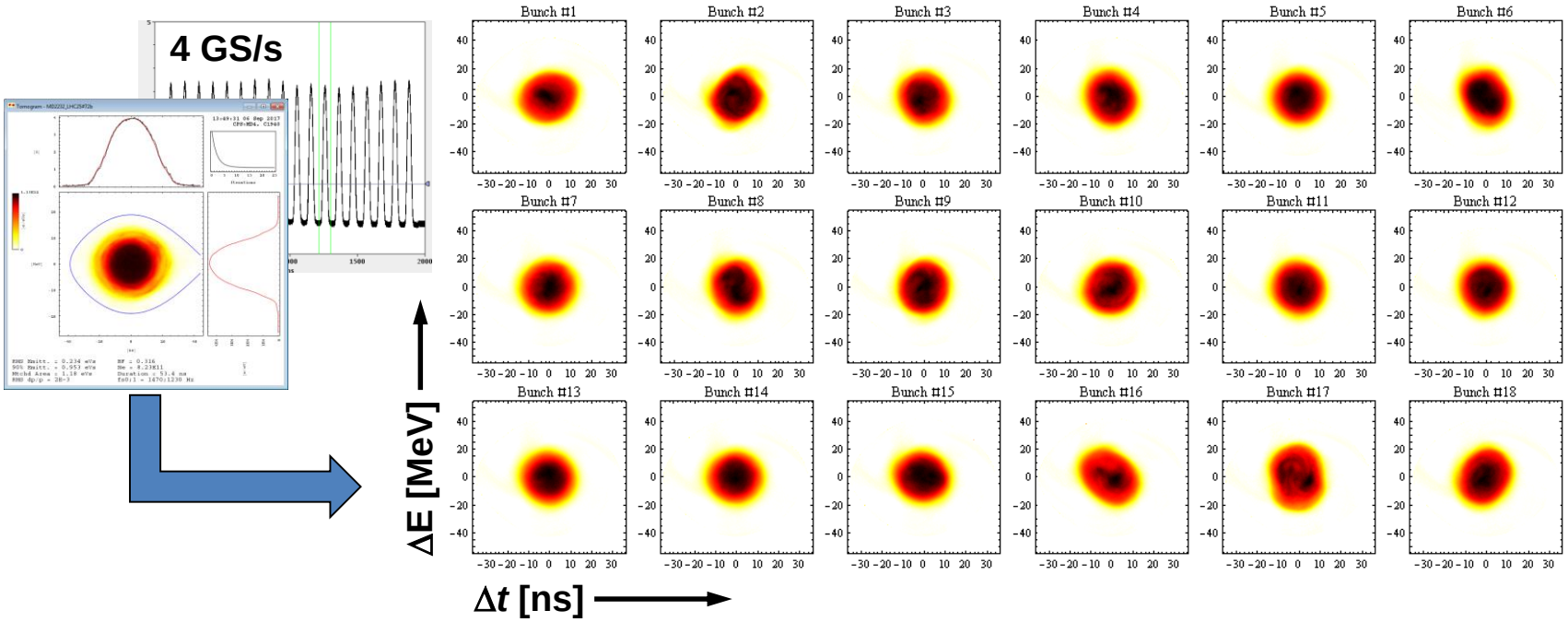
Bunch profile/length last turn



→ **Clearly shorter bunches at extraction compared to 2017**

Multi-bunch tomography

- **Record almost full turns with 4 GS/s**
- **Reconstruct longitudinal distribution of each bunch individually**



→ **Common foot-tangent fit definition (0.35 eVs/b) varies with bunch shape**

→ **Choice of analysing statistical emittances (90%), $\varepsilon_{l,\text{foot-tangent}} \approx 1.4\ \varepsilon_{l,90\%}$**

→ **10 cycle average to reduce and evaluate cycle-to-cycle fluctuations**

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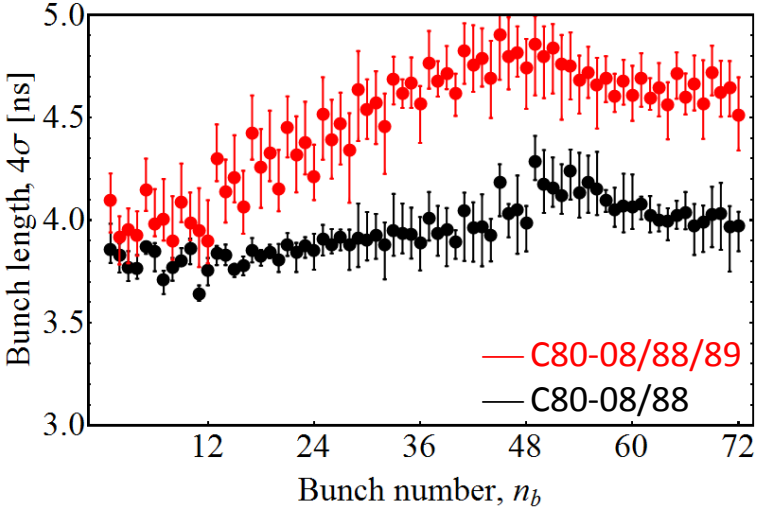
LHC25ns (72 bunches), final bunch length

- **Bunch length along the batch, 4σ Gaussian fit**
- **Compare two and three 80 MHz cavities with gaps open**

Bunch length at extraction
N_b = 2.1 · 10^{11} ppb (2017)



Bunch length at extraction
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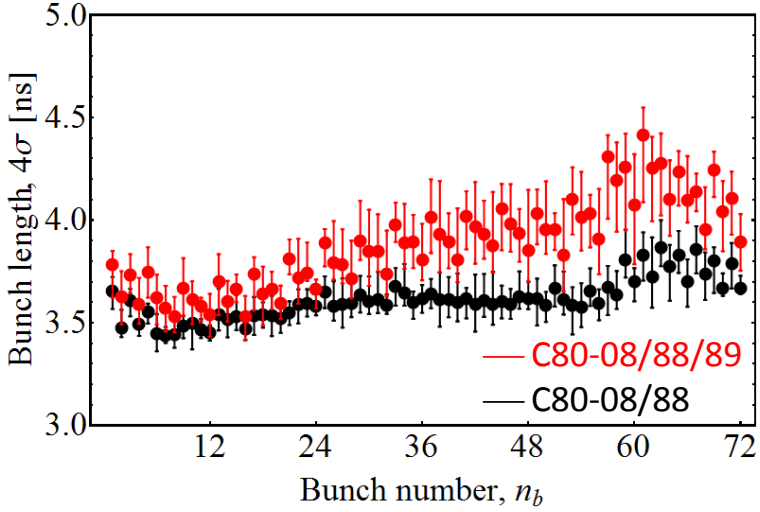

→ **Bunch length dominated by rotation or longitudinal emittance?**

LHC25ns (72 bunches), final bunch length

- **Bunch length along the batch, 4σ Gaussian fit**
- **Compare two and three 80 MHz cavities with gaps open**

Bunch length at extraction
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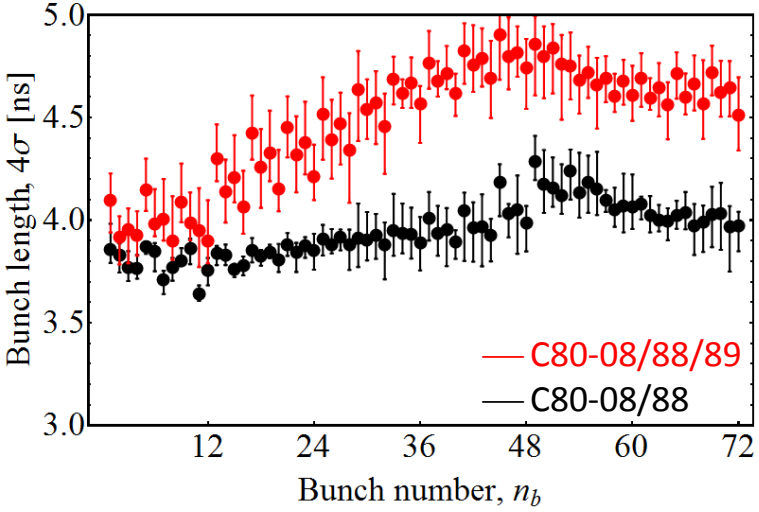
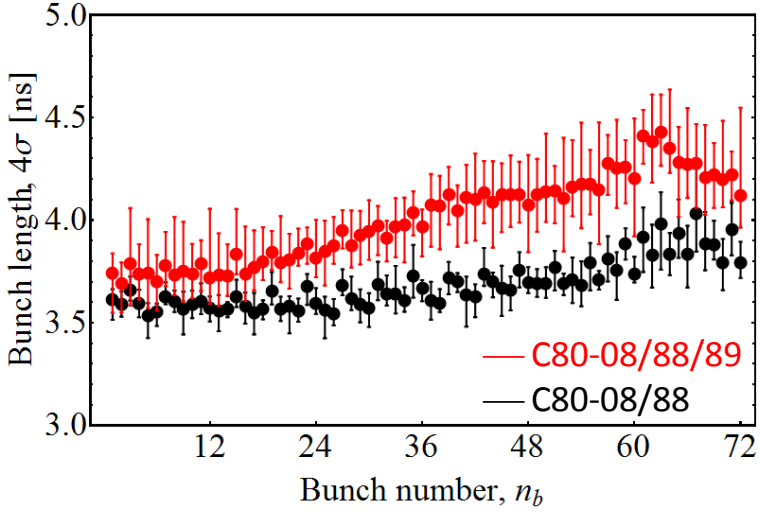


Bunch length at extraction
N_b = 2.4 · 10^{11} ppb (2018)

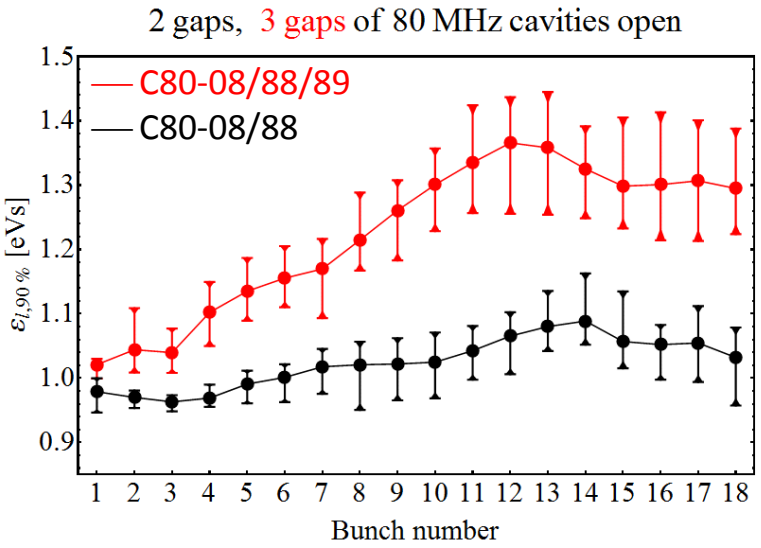


→ **Bunch length dominated by rotation or longitudinal emittance?**

LHC25ns (72 bunches), emittance at flat-top

- **Multi-bunch tomography at arrival on flat-top (before 4-split)**

Emittance, ε_l at flat-top arrival
$N_b = 2.1 \cdot 10^{11}$ ppb (2017)



Emittance, ε_l at flat-top arrival
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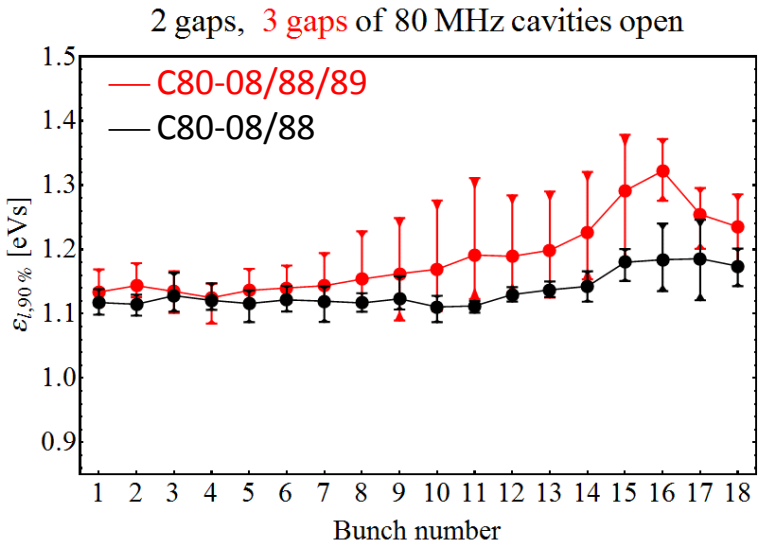


- **Longitudinal emittance at flat-top initially ~10% larger**

  → Shorter bunches with larger emittance → rotation parameters

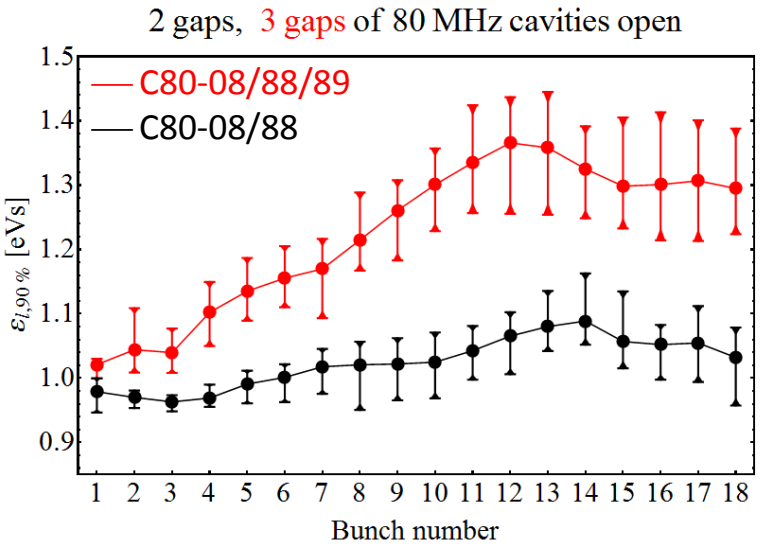
- **Intensity during 2018 measurements ~15% above 2017 values**

→ **Effect of 3rd 80 MHz cavity gap seems less strong**

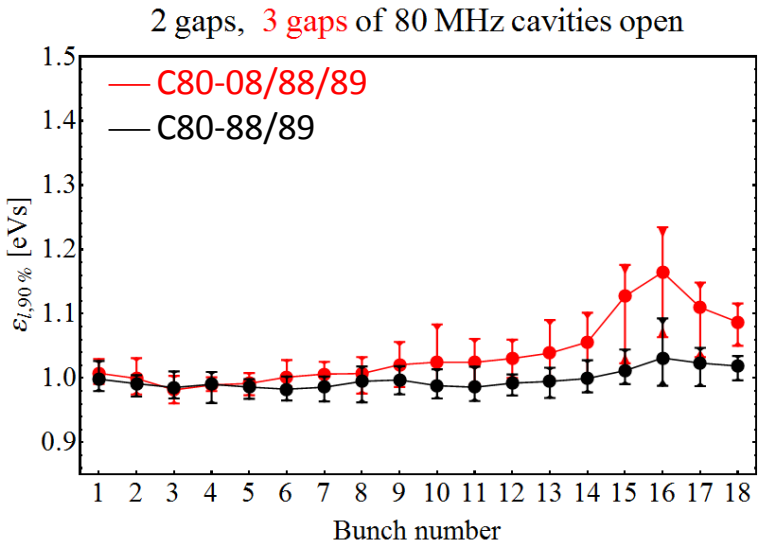
LHC25ns (72 bunches), emittance at flat-top

- **Multi-bunch tomography at arrival on flat-top (before 4-split)**

Emittance, ε_l at flat-top arrival
$N_b = 2.1 \cdot 10^{11}$ ppb (2017)



Emittance, ε_l at flat-top arrival
$N_b = 2.1 \cdot 10^{11}$ ppb (2018)



- **Comparison of very similar longitudinal parameters**

→ **Significantly smaller emittance growth along the batch**

→ **Beam seems more stable than in previous years**

LHC25ns (72 bunches), emittance at flat-top

- **Multi-bunch tomography at arrival on flat-top (before 4-split)**

Emittance, ε_l at flat-top arrival
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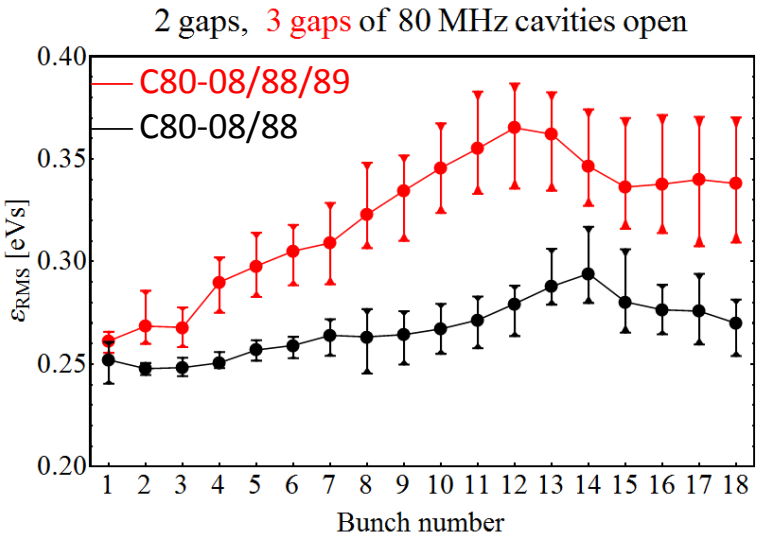

Emittance, ε_l at flat-top arrival
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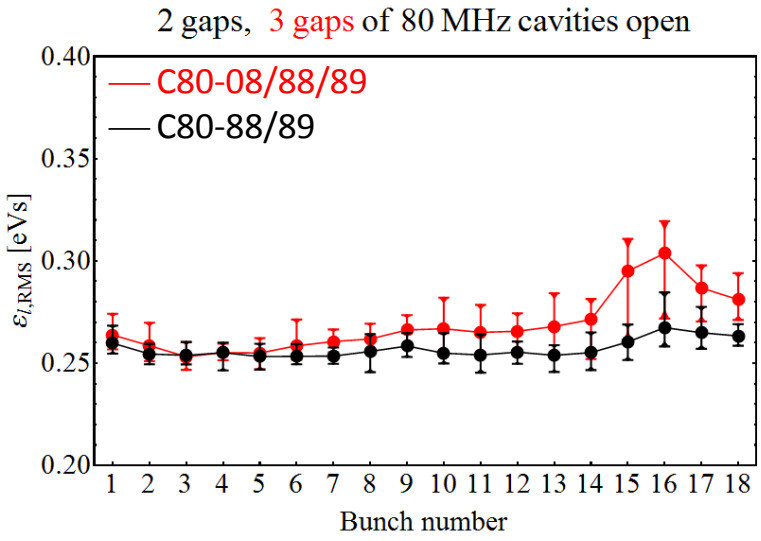

- **Comparison of very similar longitudinal parameters**

→ **Significantly smaller emittance growth along the batch**

→ **Beam seems more stable than in previous years**

→ **Similar behaviour for RMS and 90% emittance**

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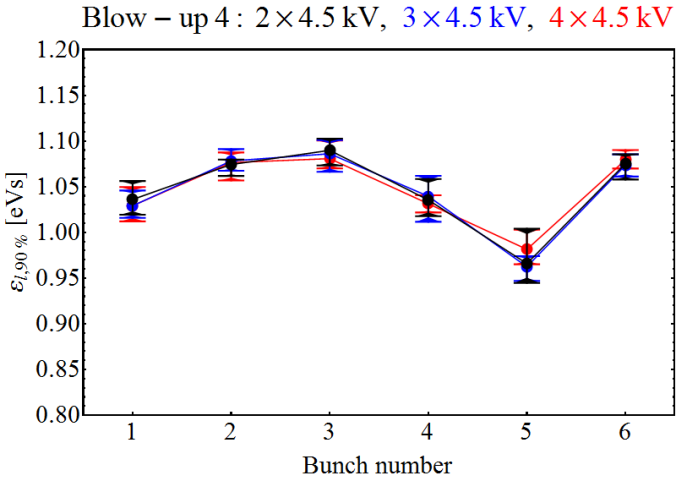
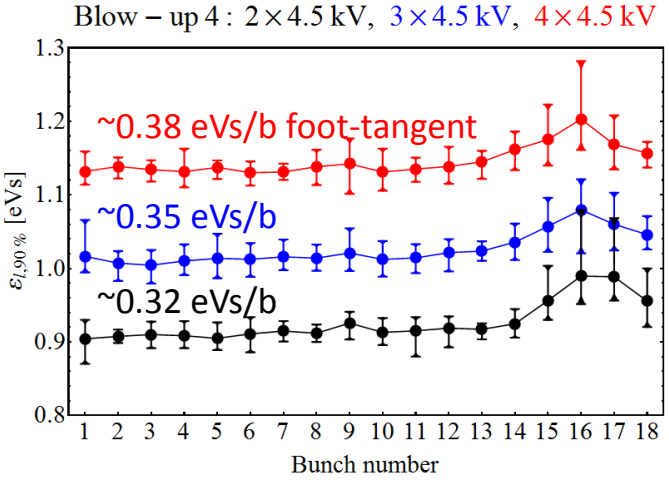
LHC25ns (72 bunches), emittance during cycle

- **Intensity per bunch at extraction, $N_b = 2.4 \cdot 10^{11}$ ppb**

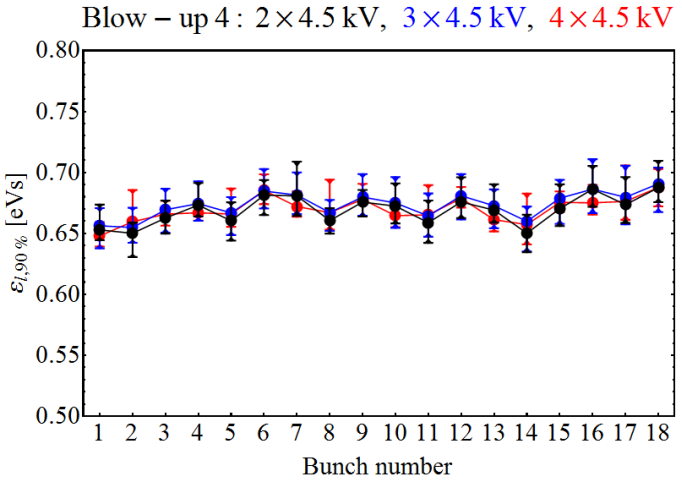
ε_l, start of acceleration



ε_l, arrival at flat-top



ε_l, after intermediate plateau



→ **Emittance measurements very reproducible**

- Cycle-to-cycle
- During several hours

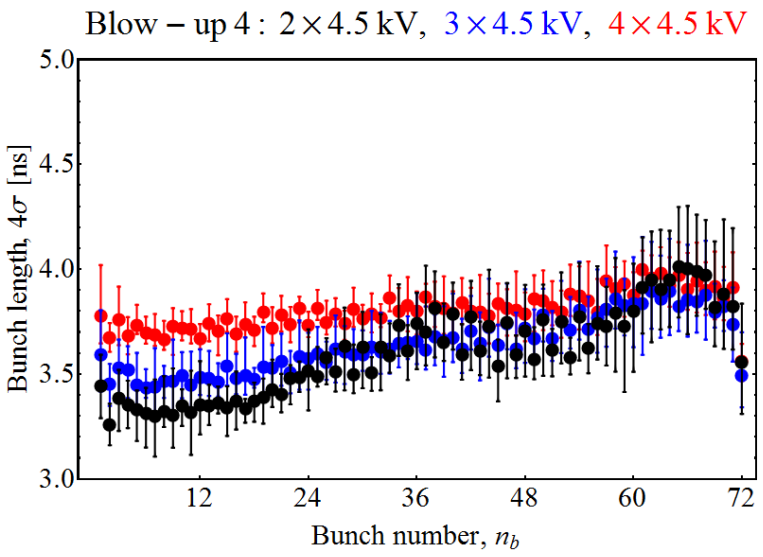
→ **Little dependence of growth along batch on absolute ε_l**

LHC25ns (72 bunches), length at extraction

- **Beam parameters at ~2.4 · 10^{11} ppb**

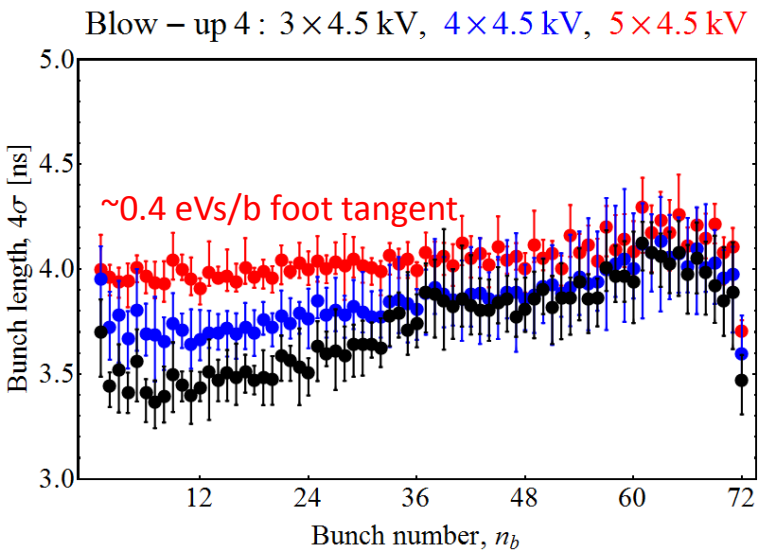
Bunch length at extraction

N_b = 2.4 · 10^{11} ppb



Bunch length at extraction

N_b = 2.6 · 10^{11} ppb



→ **Pushing intensity beyond 2.4 · 10^{11} ppb requires blow-up to > ~0.35 eV/bunch (foot-tangent fit)**

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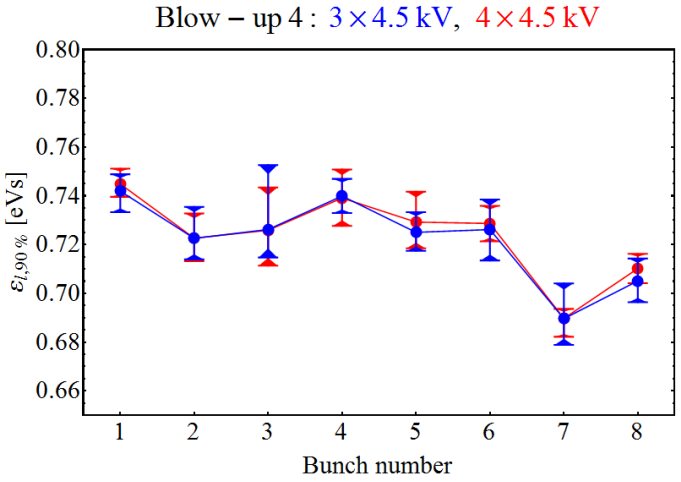
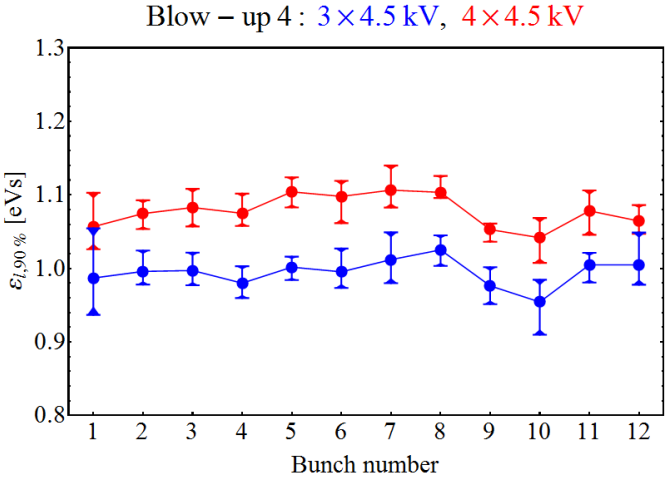
LHC25ns (BCMS, 48 bunches), emittance

- **Intensity per bunch at extraction, $N_b = 2.6 \cdot 10^{11}$ ppb**

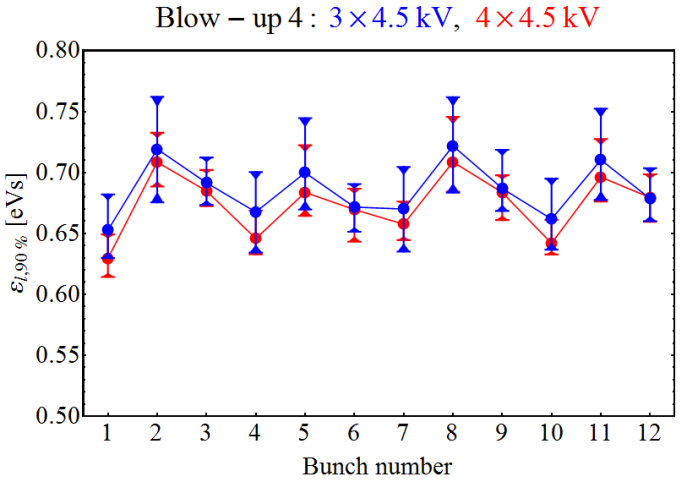
ε_l, start of acceleration



ε_l, arrival at flat-top



ε_l, after intermediate plateau



→ **Emittance measurements again very reproducible**

→ **Few percent blow-up at flat-bottom**

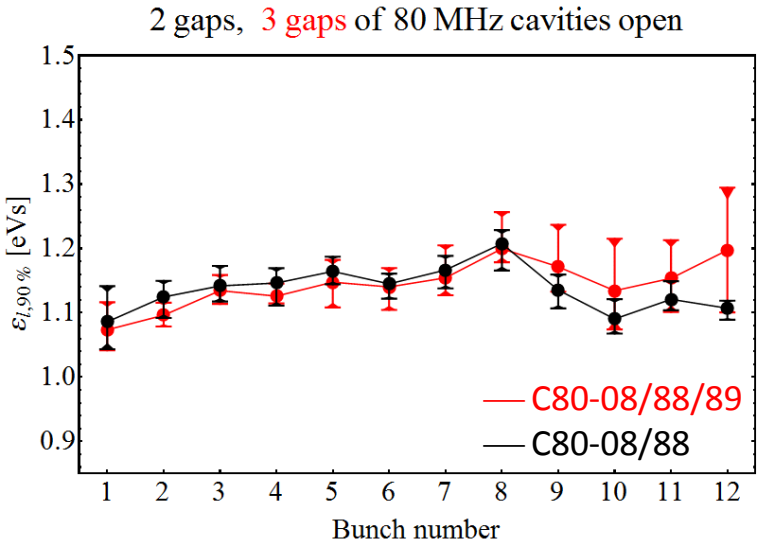
- Removed by controlled blow-up

→ **No growth along the batch**

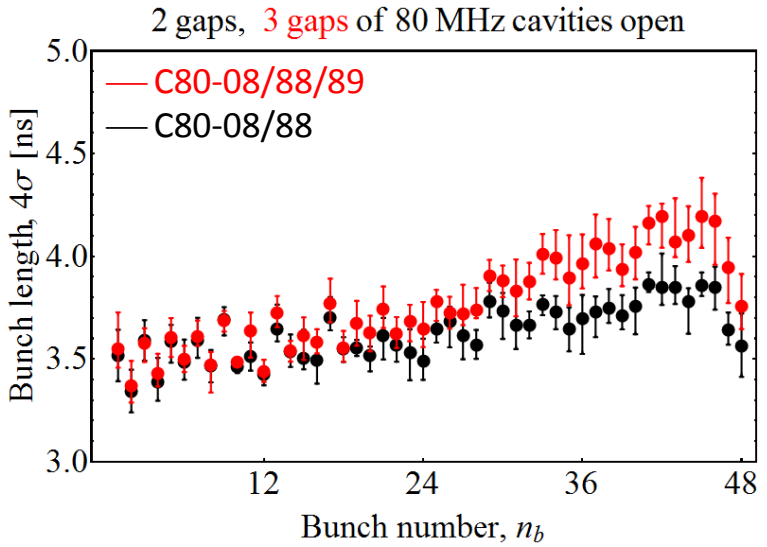
LHC25ns (BCMS, 48 bunches), bunch length

- **Intensity increased up to ~3 · 10^{11} ppb (1.5 · 10^{13} ppp in total)**

Emittance, ε_l at flat-top arrival
N_b = 3 · 10^{11} ppb



Bunch length at extraction
N_b = 3 · 10^{11} ppb



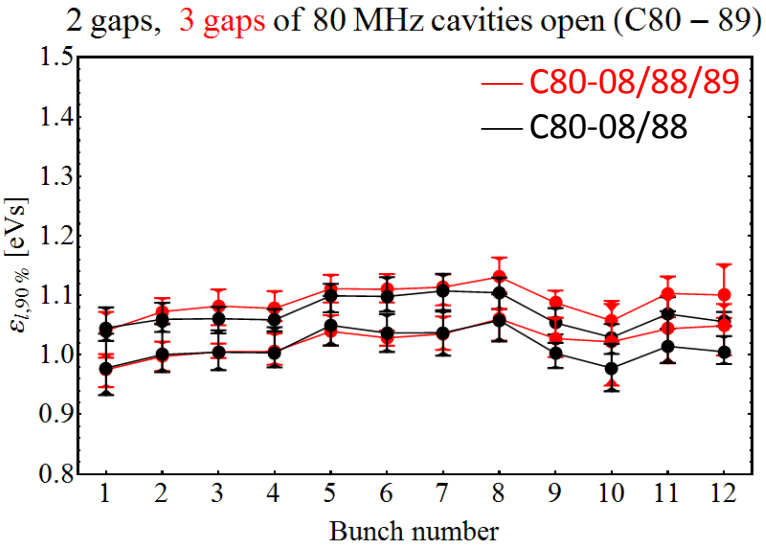
- **Emittance growth during RF manipulation at flat-top**
- **Little data from 2017 high-intensity BCMS beam for comparison**
- **Again, potential issue with ~10% too large emittance**

→ **Redo measurements at N_b = 2.6 10^{11} ppb and nominal ε_l**

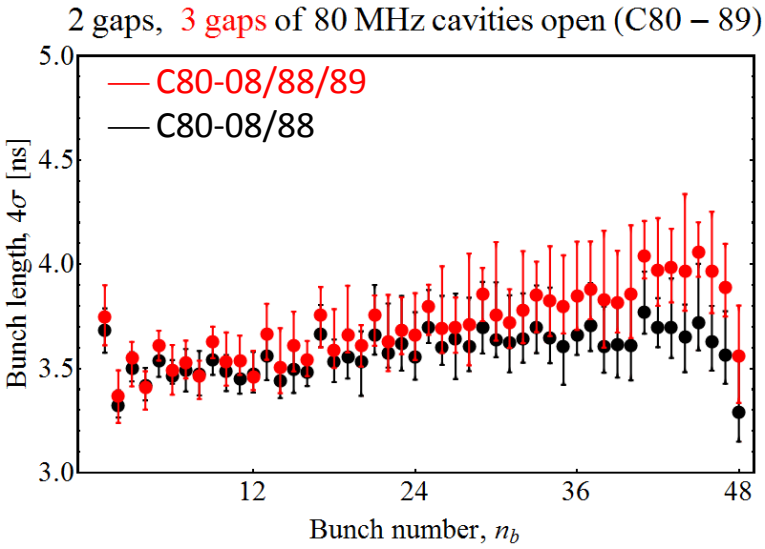
LHC25ns (BCMS, 48 bunches)

- **Beam parameters at ~2.6 · 10^{11} ppb**

Emittance, ε_l at flat-top arrival
N_b = 2.6 · 10^{11} ppb



Bunch length at extraction
N_b = 2.6 · 10^{11} ppb



- **Little data from 2017 high-intensity BCMS beam for comparison**
- **Again, potential issue with ~10% too large emittance**

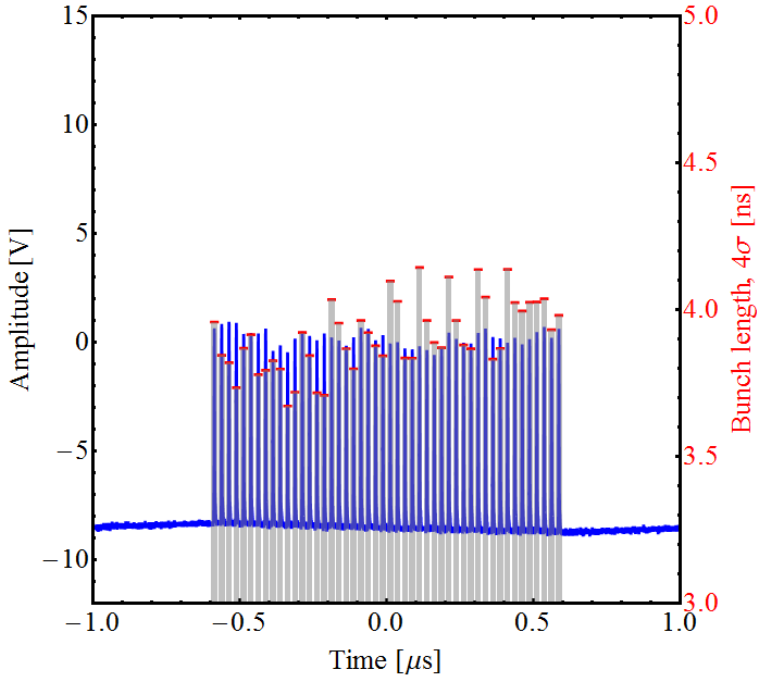
→ **Emittance dependent blow-up during high-energy manipulations**

LHC25ns (BCMS), 48 bunches, bunch length

- **Bunch length along the batch, 4σ Gaussian fit**
- **Examples for 2017 operational and 2018 high-intensity beams**

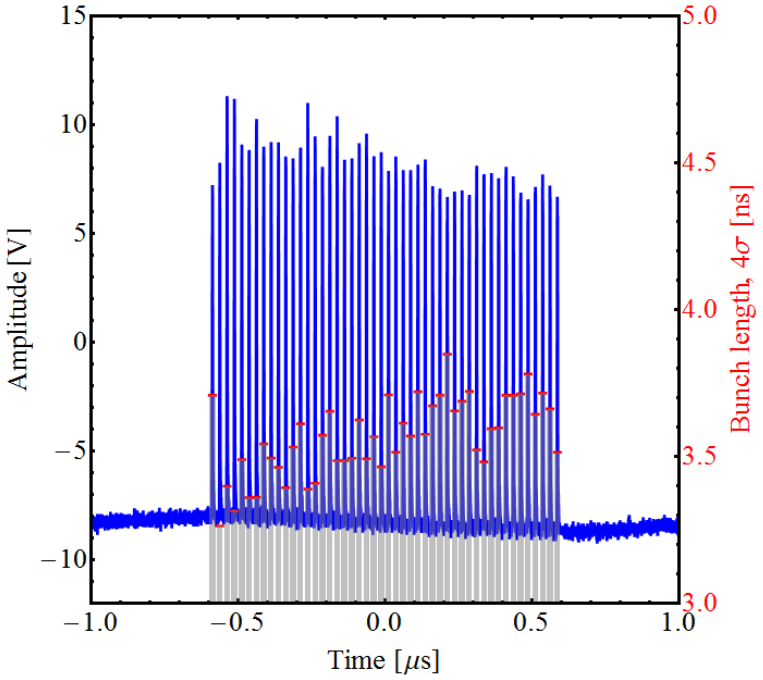
Bunch length at extraction

N_b = ~1.5 · 10^{11} ppb (2017)



Bunch length at extraction

N_b = 2.6 · 10^{11} ppb (2018)



→ **Triple splitting sensitive to transient beam loading**

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Changes during YETS2017/18

RF upgrades

- **New anode power converters 40 MHz and 80 MHz cavities**
  - No significant impedance change
  - Expected reduction (~35%) with new summing amplifier in direct feedback loop of cavity C80-88 not visible with beam
  - Re-measure impedance of C80-89 after technical stop changes
  - Saturation of feedback not visible with detected signals?
- **New power supplies for Finemet cavity amplifiers**
  - Coupled-bunch feedback not tripping anymore
  - Saturation of drive power with previous supplies?
  - ✓ **Beam based phase check of all six gaps after technical stop**
  - Evaluate differences of feedback operation with 4/6 gaps
- **New pre-driver amplifiers for 10 MHz cavities**
  - No effect on direct wide-band feedback
- **200 MHz amplifier upgrade**
  - Same coupling of cavities with amplifiers (final stage unchanged)
- **RF bypass measurement campaign**
  - Small number of non-conformities, as every year

→ **No modification of feedback setting-up procedures**

→ **None of the changes explains performance improvement**

Changes during YETS2017/18

Vacuum interventions

- **Septa SMH16, SEH23 and SMH42**
  - No additional RF shielding in swapped devices
  - Regular preventive maintenance
- **Wire scanner in SS54**
  - Prototype wire scanner of new design
  - Minor contribution to longitudinal impedance expected
- **Exchange of BGI instrument SS82**
  - No contribution to longitudinal impedance expected
- **Wire scanner SS85**
  - One-to-one exchange by identical unit
- **New BTV screen in magnet unit 41**
  - Minor contribution to longitudinal impedance expected

→ **Insignificant effect on longitudinal impedance expected**

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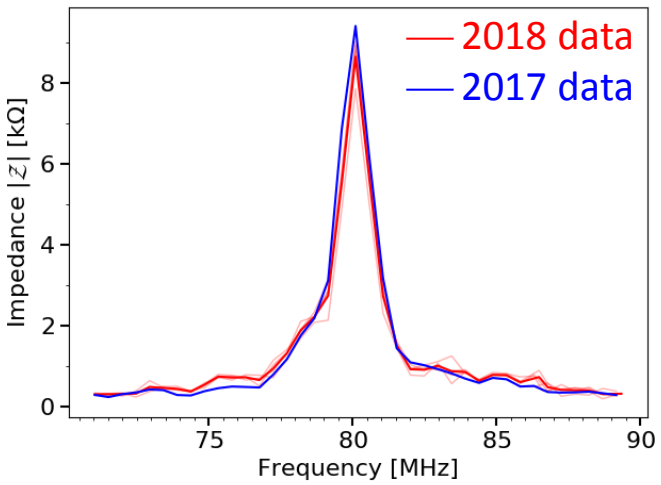
Impedance of 80 MHz cavities

G. Favia, A. Lasheen

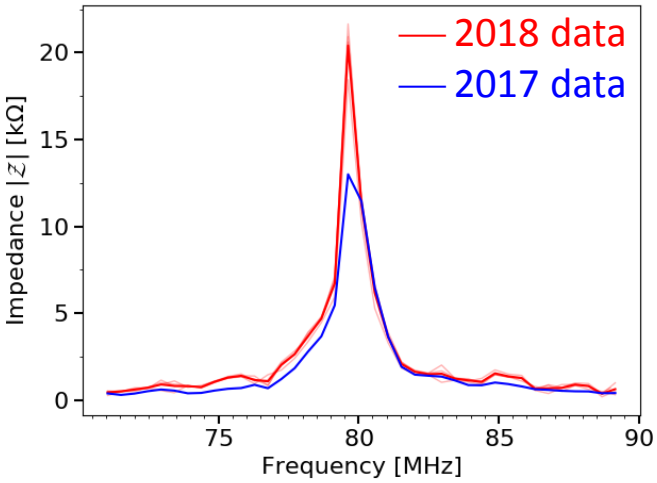
- **Same procedure as in 2017**
- **Preliminary results from beam-based impedance for 80 MHz cavities**

→ **No significant change in impedance**

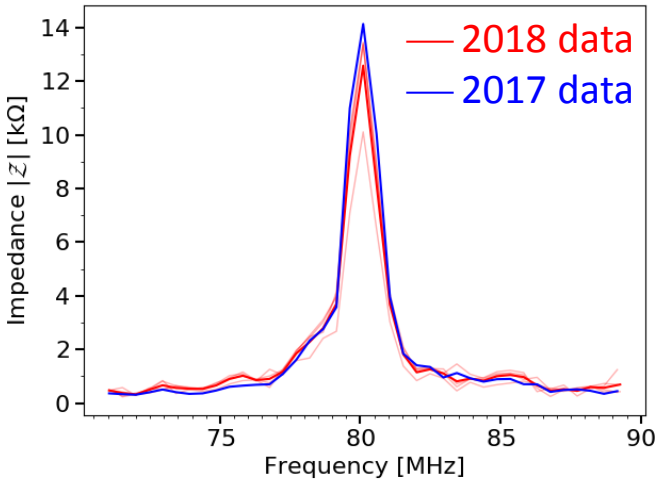
Cavity C80-08



Cavity C80-89 (tuned for Pb^{54+})



Cavity C80-88

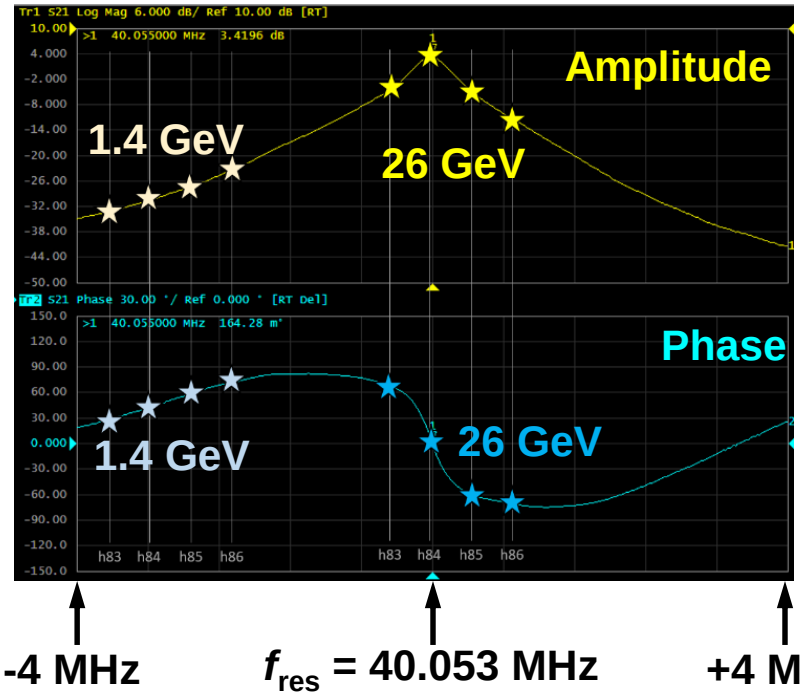


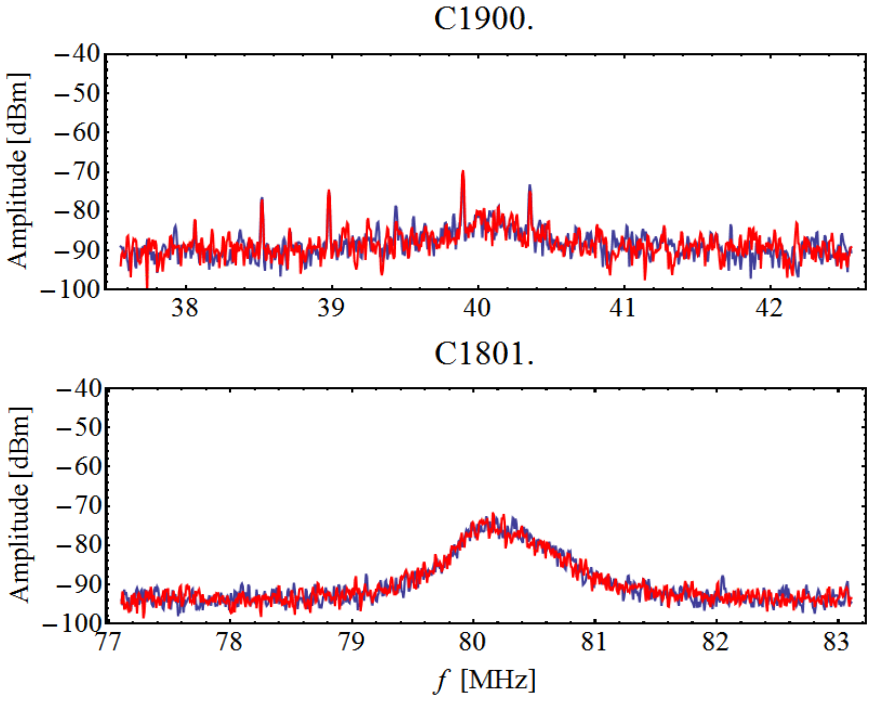
→ **To be completed with measurements of 40 MHz cavities and new measurements of modified C80-89 after technical stop**

Beam measurements with feedback

- **Reduce cavity impedance at $n \cdot f_{rev}$ with adaptive filter bank feedback**
  - → **Prototype validated in 2017 for both 40 MHz and 80 MHz RF system**

40 MHz cavity transfer function





→ **Significant reduction of beam induced voltage**

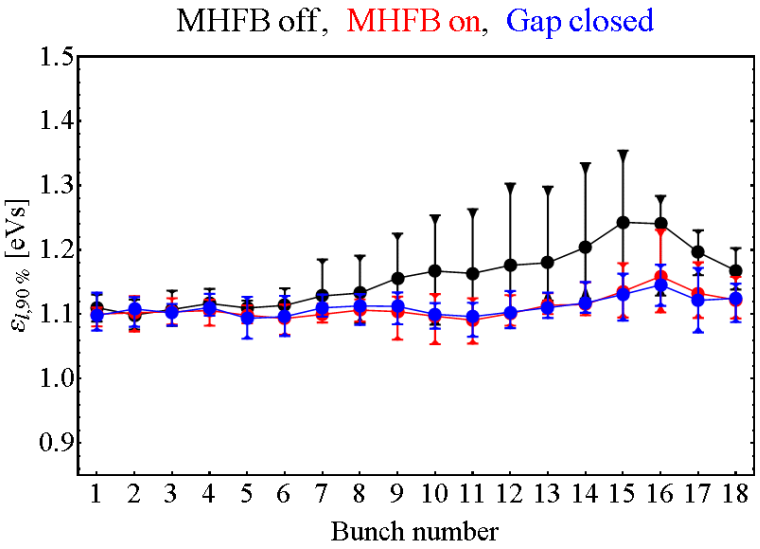
→ **Impact on longitudinal beam quality?**

Multi-harmonic feedback on 80 MHz cavity

- **Effect of multi-harmonic feedback at ~2.1 · 10^{11} ppb**

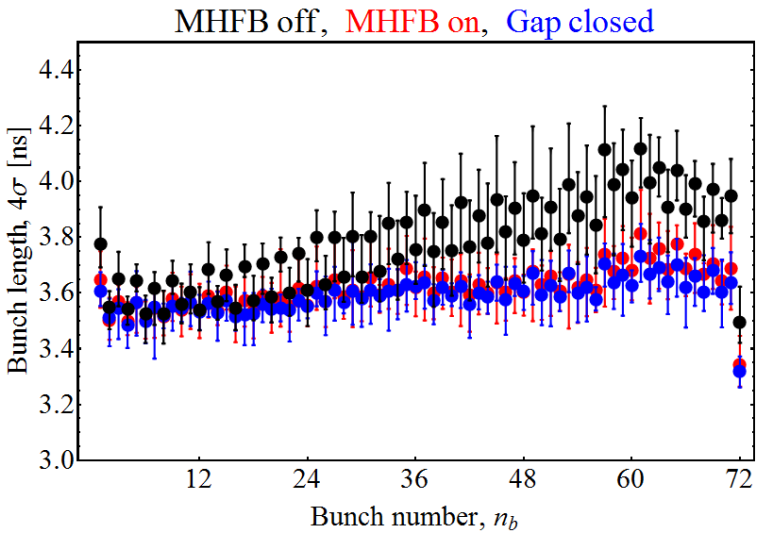
Emittance, ε_l at flat-top arrival

N_b = 2.1 · 10^{11} ppb



Bunch length at extraction

N_b = 2.1 · 10^{11} ppb

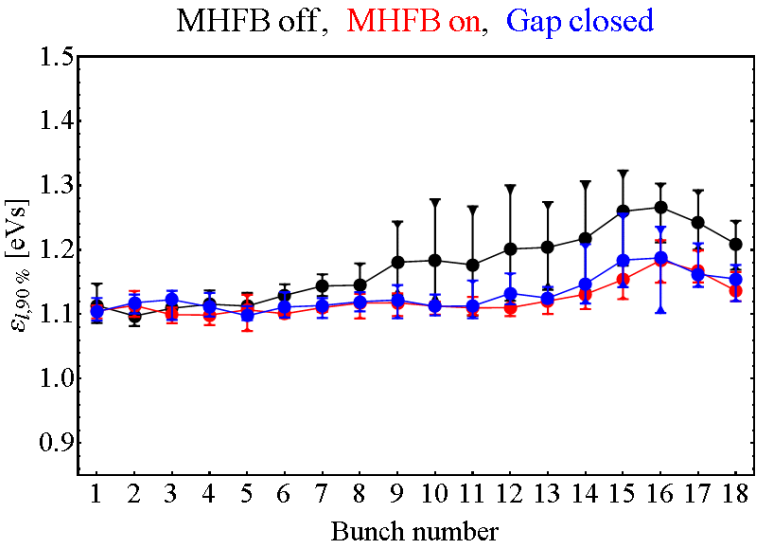


Multi-harmonic feedback on 80 MHz cavity

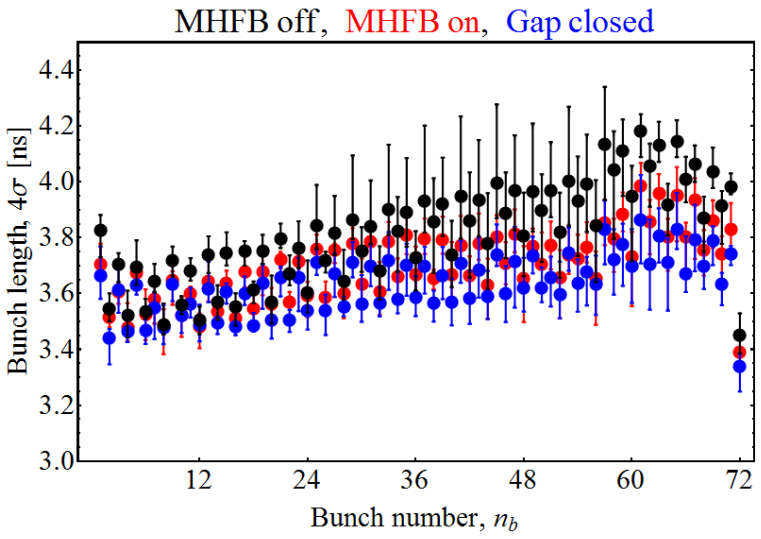
F. Bertin

- **Effect of feedback at ~2.1 and 2.4 · 10^{11} ppb**

Emittance, ε_l at flat-top arrival
N_b = 2.4 · 10^{11} ppb



Bunch length at extraction
N_b = 2.4 · 10^{11} ppb



- **Very promising results with multi-harmonic feedback**

  → Emittance and bunch length as if gap was mechanically closed

- **Preparing installation on both 80 MHz cavities used for protons**

Overview

- Introduction
- Observations at high intensity
  - Comparison of 2017 and 2018 data
  - Standard 72-bunch beam
  - BCMS beam
- Changes during YETS2017/18
  - RF
  - Vacuum interventions
- High-frequency cavity impedances and feedback
- **Summary and outlook**

Summary

- **New anode power converters of 40 and 80 MHz cavities**
  - ✓ Operation at highest intensities much more reliable
- **New power supplies for amplifiers of Finemet cavity**
  - ✓ Coupled-bunch feedbacks active until extraction
  - ✓ No spurious cavity trips anymore

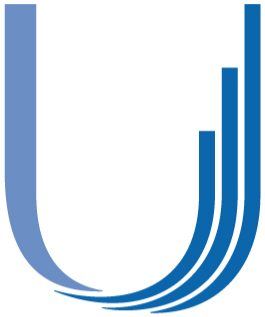
- **Standard 25 ns, 72-bunch beam**
  - About 15% higher beam intensity, 2.1 $\rightarrow$ 2.4 · 10^{11} ppb
- **BCMS 25 ns, 72-bunch beam**
  - LIU intensity of 2.6 · 10^{11} ppb potentially within reach
- **Uncontrolled emittance growth for tail bunches at flat-top**
- **Beam quality to be checked in SPS, as far as possible**

- **However: Still investigating source of improvement in 2018**
- **If not understood, may flip back to pre-2018 conditions**

Outlook

Future studies with beam in 2018

- Set-up **BCMS beam at 2.1 and 2.6 · 10^{11} ppb** with smallest possible longitudinal emittance
  - **Experience in SPS at ~2.1 · 10^{11} ppb with 2018 BCMS**
- Complete **cavity impedance studies**
  - **Re-measure 80 MHz cavity, C80-89 following improvements during technical stop**
- Check influence of **longitudinal** blow-up on **distribution**
  - **Post acceleration to quantify tails**
- Multi-harmonic feedback on multiple 40 and 80 MHz cavities
  - **Reduction of emittance growth along batch at flat-top**



LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!