LHC Injectors Upgrade

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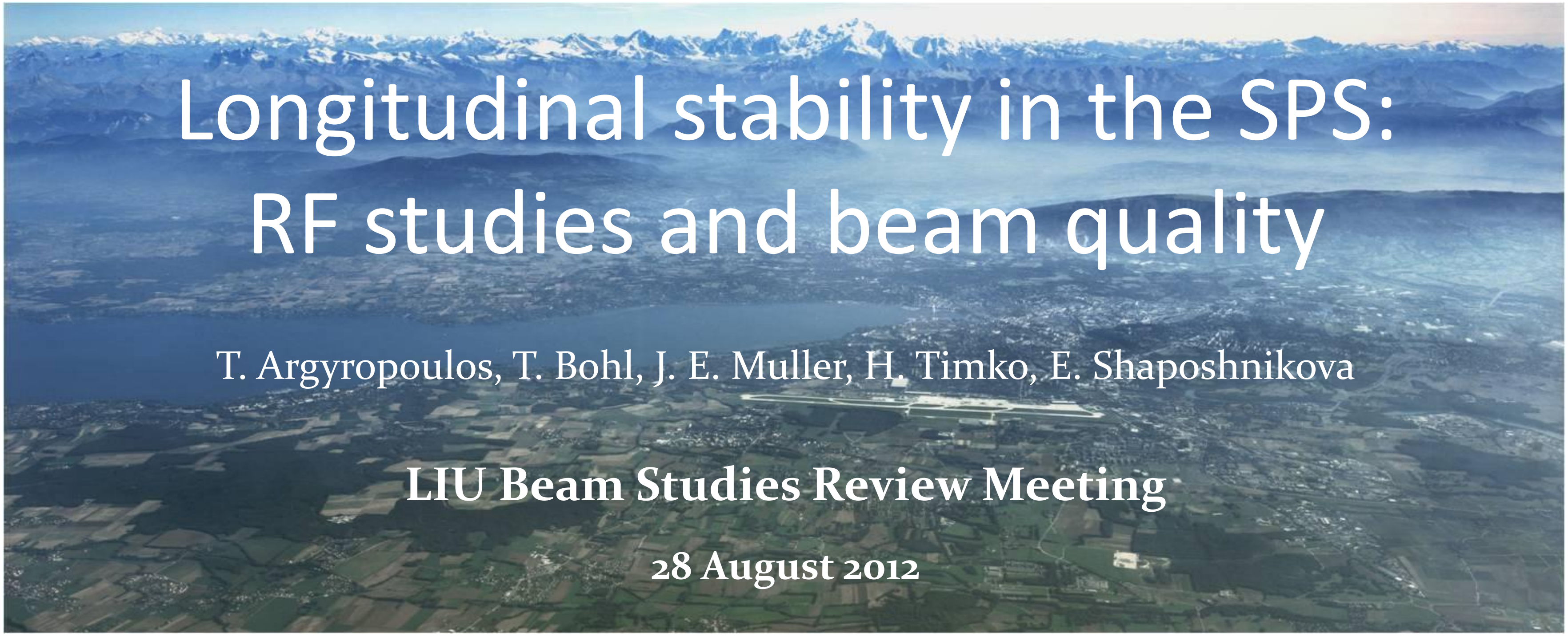

Longitudinal stability in the SPS: RF studies and beam quality

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LIU Beam Studies Review Meeting

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MD goals (topics) for this year

- ☐ **Define the longitudinal instability thresholds at flat bottom and flat top in single RF** for:
  - Single bunch
  - Single or more batches

  →Identify the nature of instability (coupled/single bunch/batch)

  →Verify or revise the current SPS longitudinal impedance model → used in simulations

- ☐ **Improve the LHC beam quality in Q26**→ initiated by BQM rejections/poor beam quality in the middle of June

- ☐ **Longitudinal impedance identification using long injected bunches (~25 ns) with RF off** → initiated by observations of high frequency pattern on the nominal SPS bunches at flat bottom and an increase of the average bunch length of the batches along the flat bottom

- ☐ **Set up the 50 ns LHC beam in the new SPS optics with low γ_t (Q20) with N_p~(1.5 - 1.6)x10^{11} p/b on flat top** → make it operational
  - Optimize capture losses and overall transmission
  - Achieve beam stability with acceptable beam parameters (bunch length)
  - Q20/Q26 comparison

Outline

☐ LHC 50 ns beam quality (in Q26)

☐ Longitudinal impedance identification

☐ Instability thresholds in a single RF for
  - single bunch
  - single 50 ns batch

☐ LHC 50 ns beam in the SPS Q20

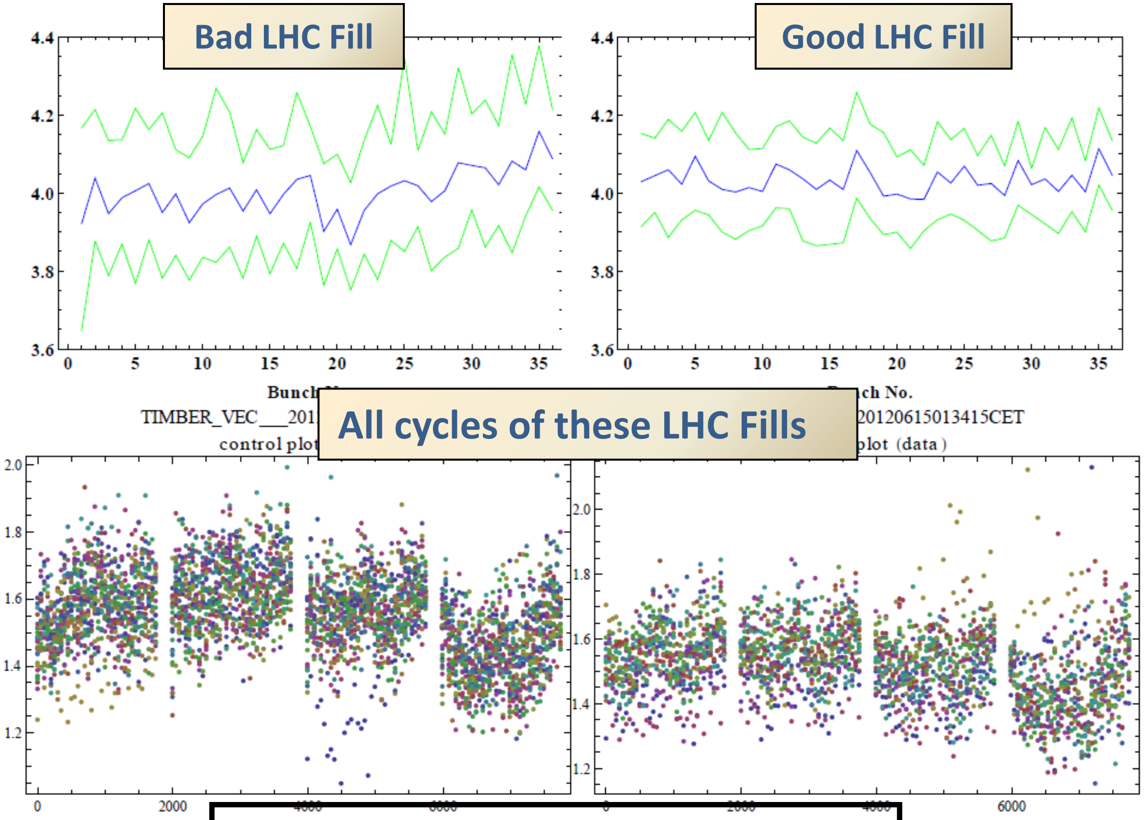
☐ Summary of MDs

☐ Questions after LS1

LHC 50 ns beam quality

- ❑ **The beam quality was degraded in the mid of June** → BQM rejections for LHC

- ❑ Comparing two consecutive fills with bad and good beam quality and similar intensities (N_p ~ 1.5×10^{11} p/b at flat top):



Bad LHC Fill

Good LHC Fill

All cycles of these LHC Fills

Difference: probably PSB adjustments

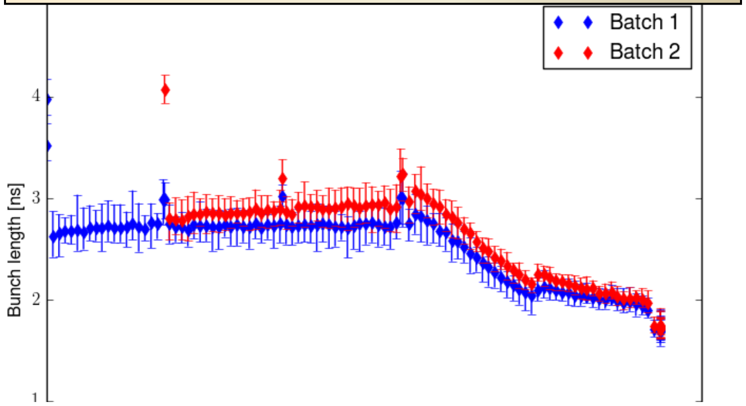
- ➢ At these intensities SPS is very sensitive to beam quality coming from PS (at the limit of stability)

T. Bohl, LIU-SPS BD WG 21/06/2012

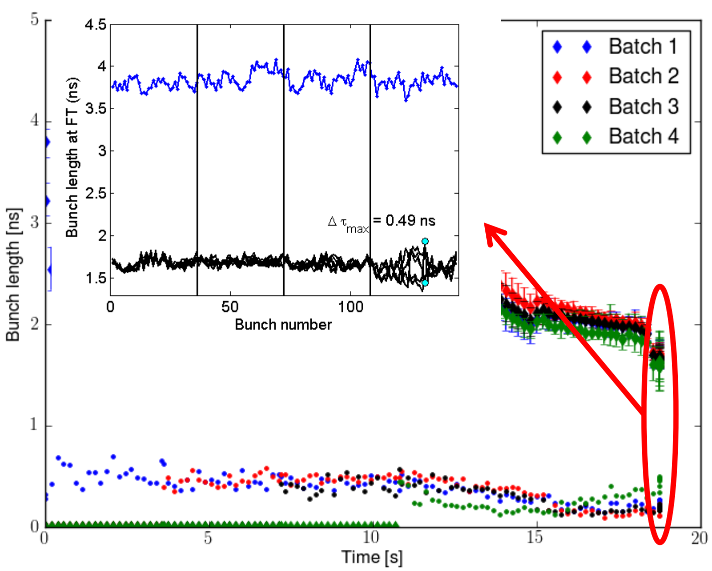
LHC 50 ns beam quality

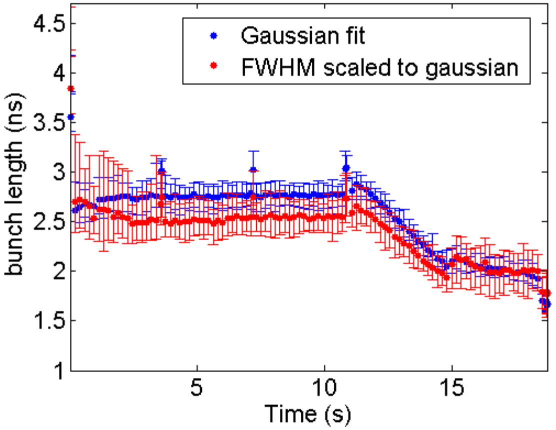
❑ Detailed measurements (MD Week 25)

Bunch length evolution along the cycle
Measurements on 18/06/2012

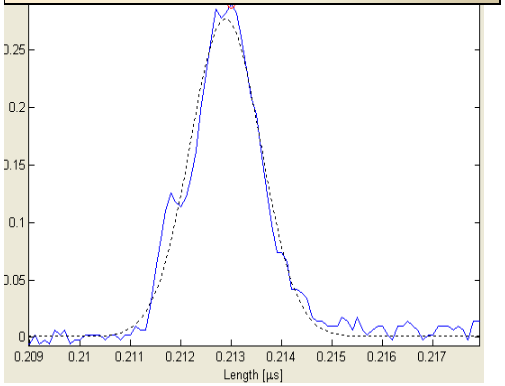


- Bunch intensity 1.6 x 10^{11}, **higher than for LHC filling at that time**
- Batches are **unstable** on flat bottom → beam blows up: big bunch tails (difference between Gaussian fit and scaled FWHM)
- Different optimum settings for filing with 2 and 4 batches. Why?



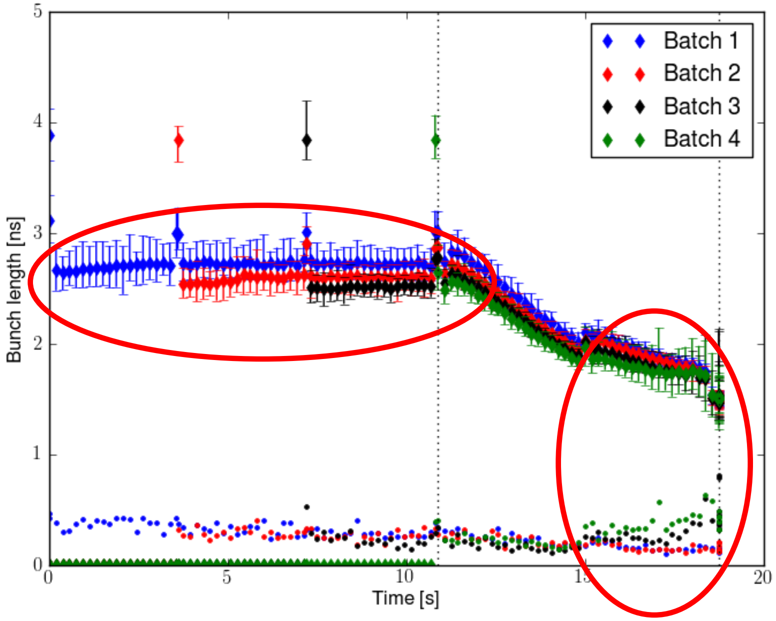


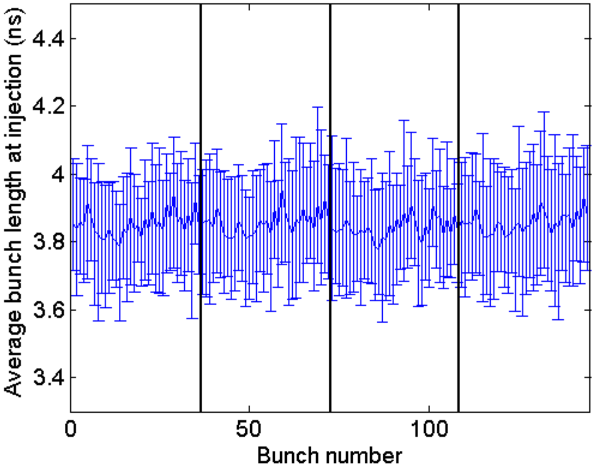
Typical bunch profile -Time(cycle)~3s



LHC 50 ns beam quality

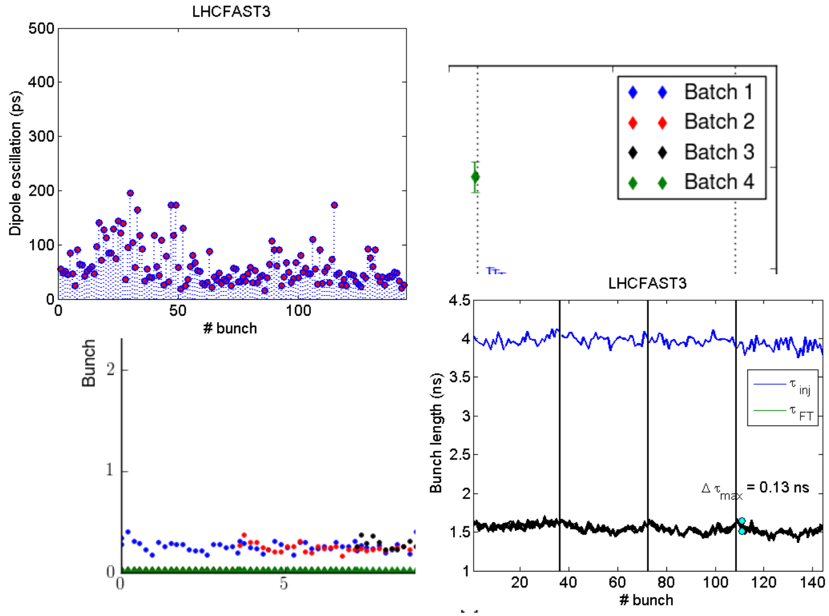
More measurements in the dedicated MD (Week 26) at 25/06/2012

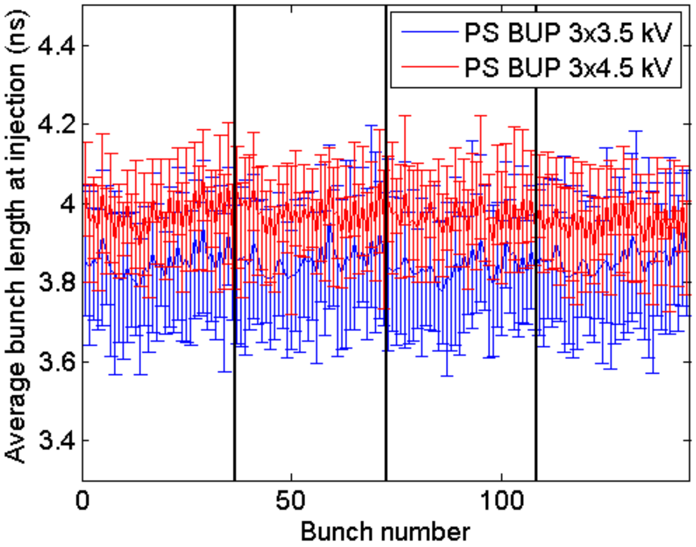




- Bunch intensity ~1.5 x 10^{11} p/b at flat top
- Similar observations as on 18th June:
  - Unstable bunches at flat bottom
  - Batch 4 unstable at the end of acceleration ramp or flat top
- Large spread in the injected bunch lengths with the nominal emittance blow up in the PS (3x3.5 kV) → correlated with instabilities in the SPS

LHC 50 ns beam quality





- **4th batch unstable at the end of ramp**
  → less (no) time spend on flat bottom → smaller emittances → SPS controlled BU is not optimum and less efficient

  Solution 1: take out the 4th dip in the 200 MHz RF Voltage program (const at 3 MV at flat bottom) → blow-up the beam with more mismatched voltage
  Cost: slightly worse transmission (typically 1%)

  OPERATIONAL

  Solution 2: increase injected emittance: controlled emittance BU in the PS
  from ε_L~0.35 eVs (3x3.5 kV)
  to ε_L~0.38 eVs (3x4.5 kV)

  Improves also the uniformity of the injected bunch lengths → more stable bunches coming from PS

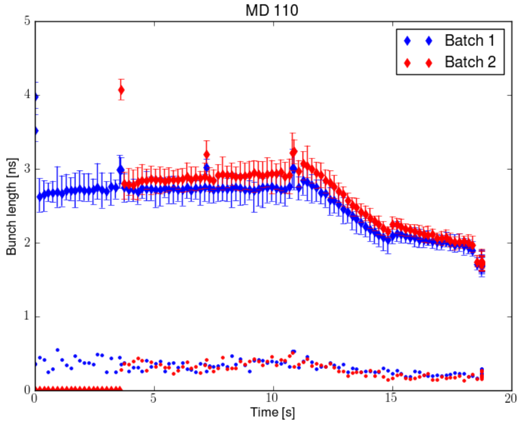
  NOT YET OPERATIONAL

- Modifications of the 800 MHz RF Voltage didn't help the beam quality

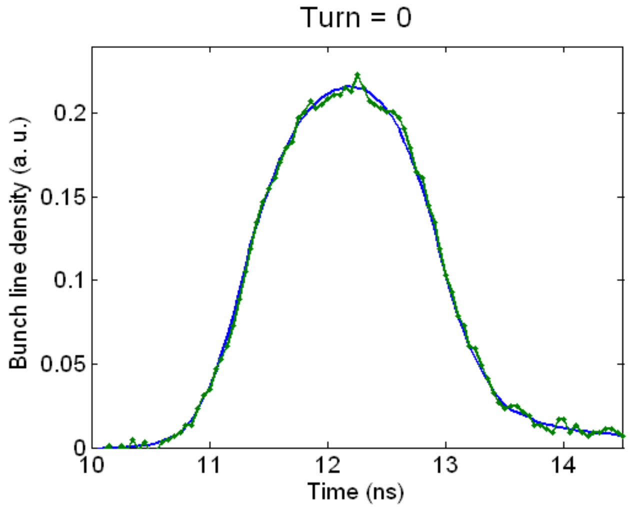
Longitudinal impedance identification

The impedance identification measurements in W28 and W30 were initiated by:

- The increase of the average bunch length of the batches along the flat bottom



- Observations of high frequency pattern on the nominal single bunches at flat bottom after loss of Landau damping (see later)



Longitudinal impedance identification

Same method used in the past (**Measuring the Resonance Structure of Accelerator Impedance with Single Bunches,** T. Bohl, T. Linnecar, and E. Shaposhnikova, PRL, 1998)

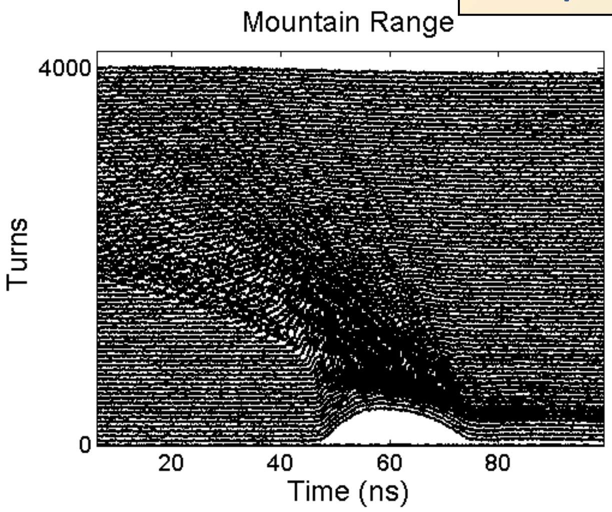
Experimental conditions:

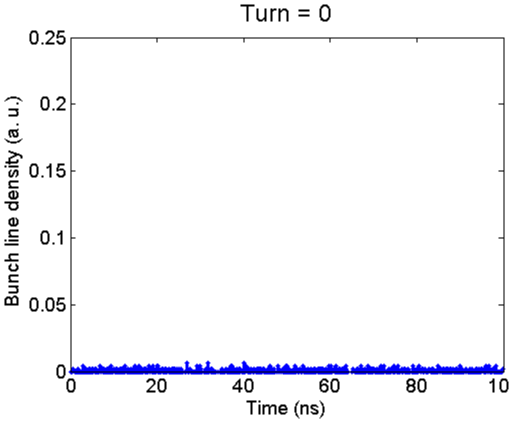
- Long single proton bunches (ε_L(90%) ~ (0.23 – 0.26) eVs – τ_{inj}~ (25-30) ns)
- Small momentum spread (to be more unstable and debunch slowly)
- Intensity scan from 0.5×10^{11} to 2.0×10^{11} p
- SPS RF off

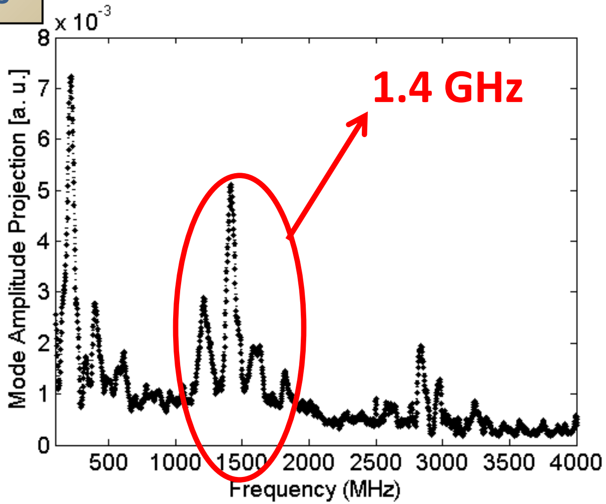
Method:

Acquisitions of beam profiles for a period of ~90 ms after injection each 10 turns.
followed by a Fourier analysis → The presence of resonant impedances with high R/Q and low Q leads to line density modulation at the resonant frequencies

Example with $N_p=1.58\times10^{11}$ and $\tau_{inj}(4\sigma)$ = 28.5 ns

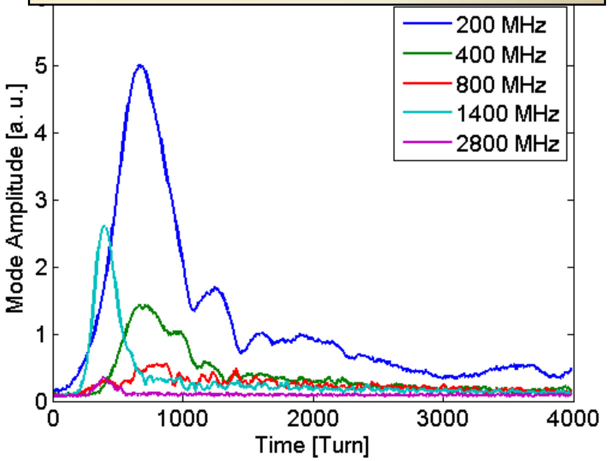






Longitudinal impedance identification

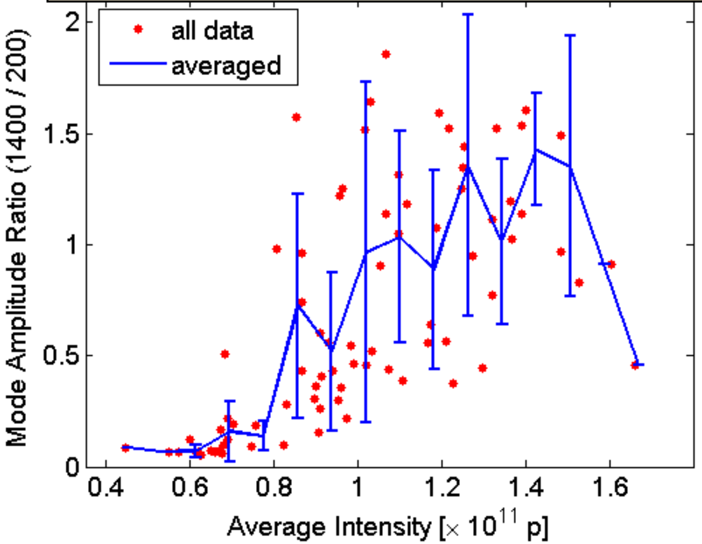
Mode amplitude versus Time



- Averaged for all (15) acquisitions with intensity ~1x10^{11} p

- The mode amplitude at 1.4 GHz peak is developing faster than the main at 200 MHz

Mode amplitude ratio of 1.4/0.2 versus Intensity



- Strong peak above N_p ~ 8x10^{10} p
  Already observed in measurements in 2001 and 2007 – this impedance was always there!

These measurements are used now for impedance evaluation through simulations. Very preliminary: R/Q ~ 30 kOhm, Q~7

Instability thresholds in a single RF – Single bunch

- **Measurements in W17:**

  Plan: Find the instability thresholds at FT for single bunch in single RF for Q26 and Q20 optics

  Aim: Use these results to compare with simulations → verify the current SPS longitudinal impedance model

Due to many problems (POPS, RF TX were tripping) limited data

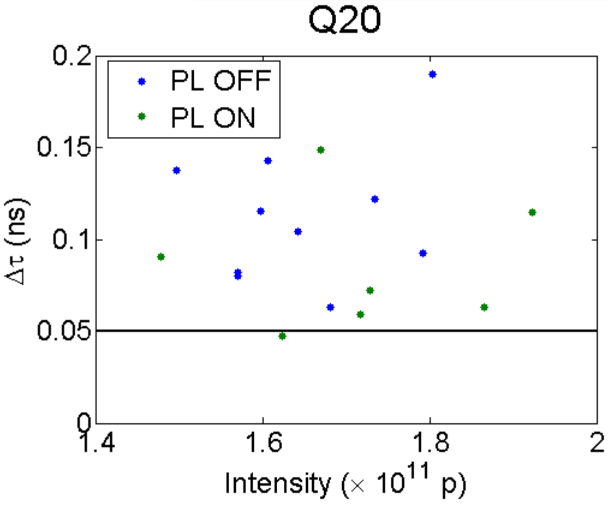
Results for ε_L~ 0.3 - 0.35 eVs:

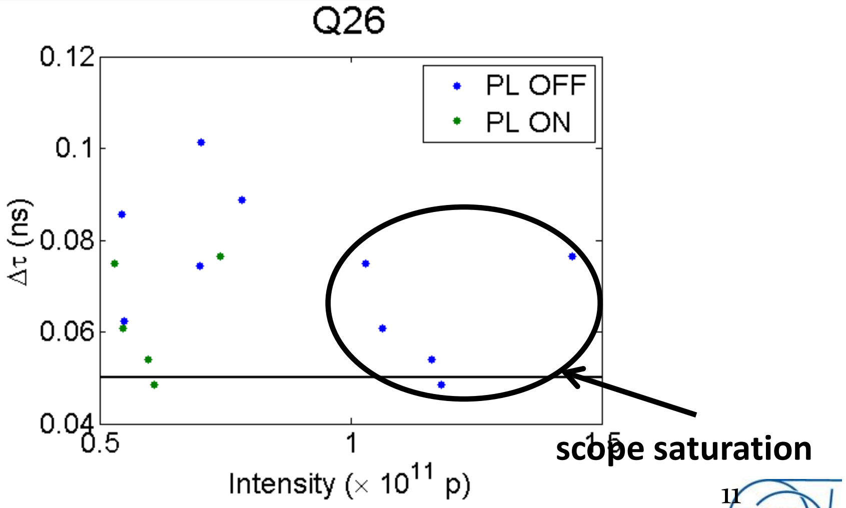
Q20 : intensity threshold at flat top > 1.5×10^{11}

Q26 : intensity threshold at flat top ~ 1.0×10^{11}

Δτ : bunch length amplitude oscillations during the ramp

The horizontal line in the plots indicates the noise level





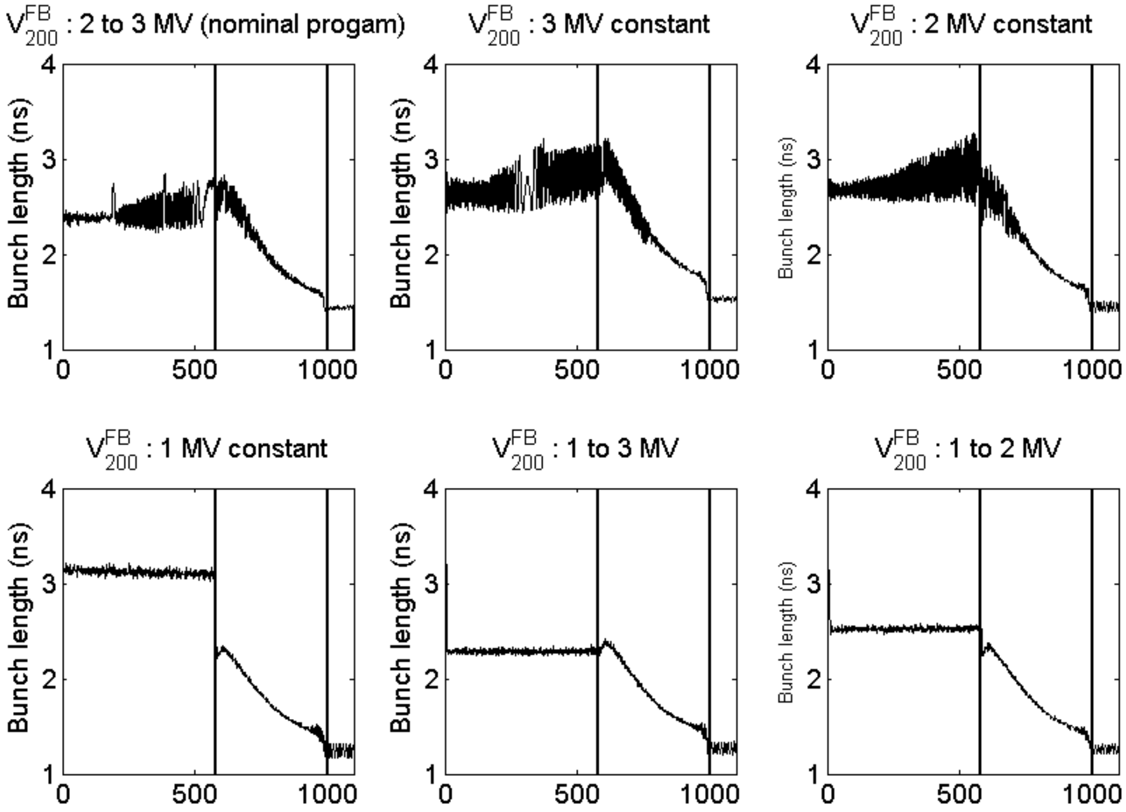
scope saturation

Instability thresholds in a single RF – Single bunch

- **Measurements in W34 (last week, preliminary results):**
  - Only in Q26
  - Phase Loop ON and OFF (for better comparison with simulations)

Difficult to measure accurately due to strong dependence on bunch parameters (emittance and distribution)

Examples of bunch length evolution along the cycle for different 200 MHz RF voltage configurations



- Bunch intensity ~1.1 x 10^{11} p at injection
- Phase loop ON

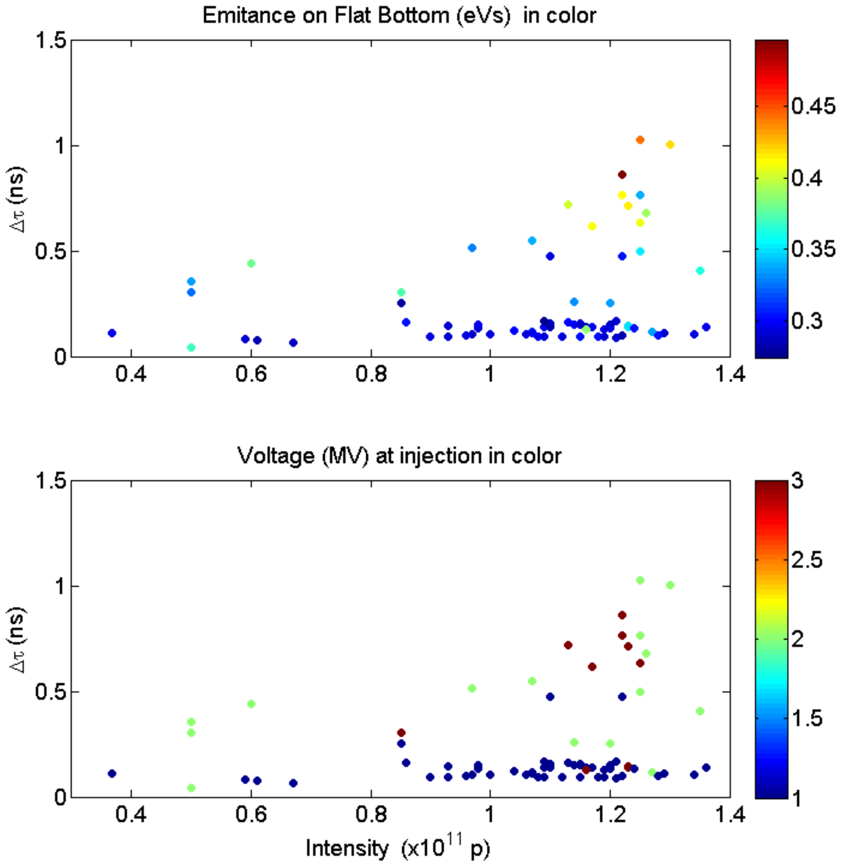
➢ **Large voltage mismatch (2-3 MV, as n nominal operation)** → strong quadruple oscillations due to loss of Landau damping → **instability growth on flat bottom**

➢ **Small voltage mismatch (1 MV)**→ larger synchrotron frequency spread → **beam is more stable**
Can not be used in operation due to beam loading in the 200 MHz RF system → beam loss

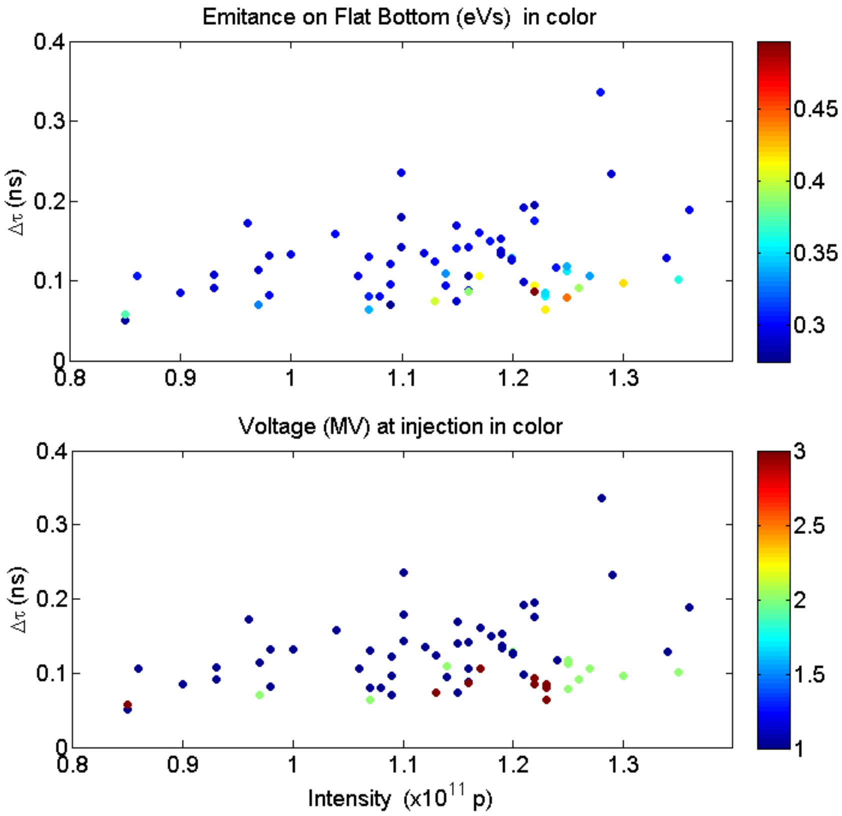
Instability thresholds in a single RF – Single bunch

- ☐ Bunches injected at 1 MV are stable at flat bottom (ε_L~0.28 – 0.35 eVs)
- ☐ Become unstable at the end of ramp – flat top with $N_p > 1\text{x}10^{11}$ p
- ☐ Bunches injected in 2-3 MV blown up at flat bottom → stable at flat top (these int.)

Results at flat bottom



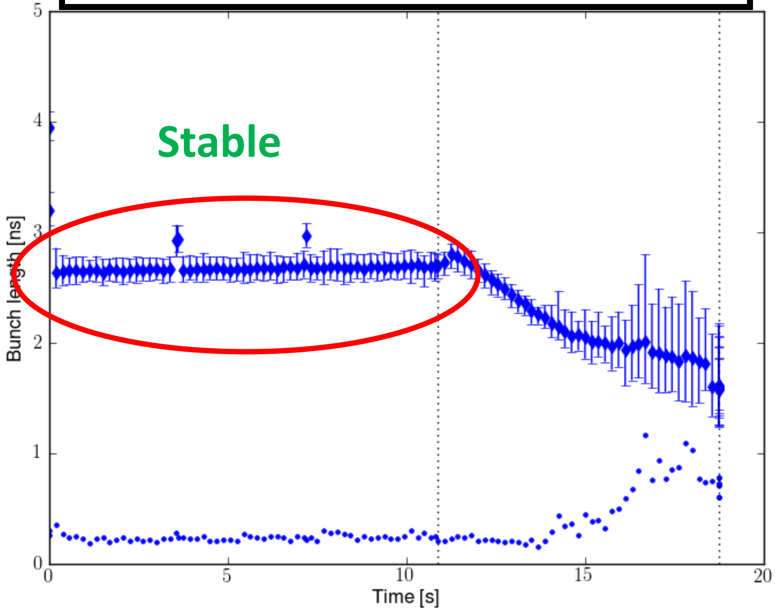
Results at flat top



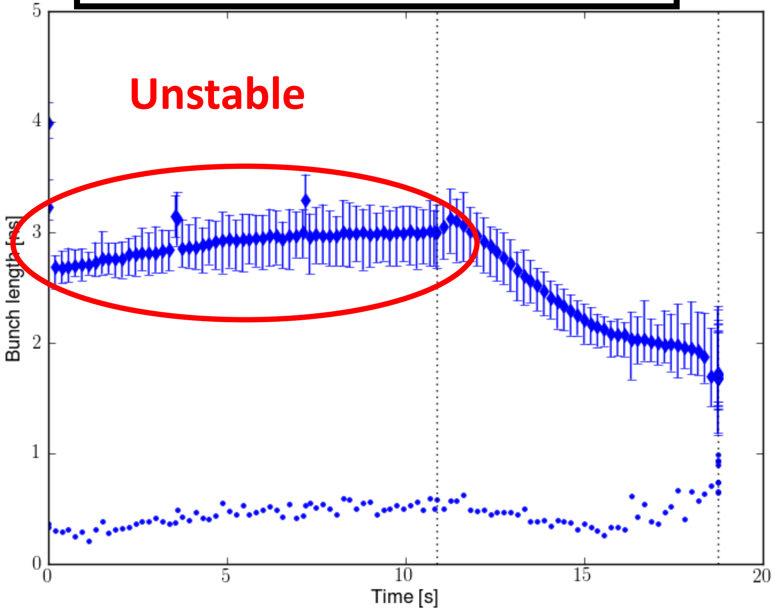
Instability thresholds in a single RF – Single batch

- **Measurements in Week 26 – Flat Bottom:**

Intensity ~ 1.47×10^{11} p/b at injection



Intensity ~ 1.8×10^{11} p/b at injection



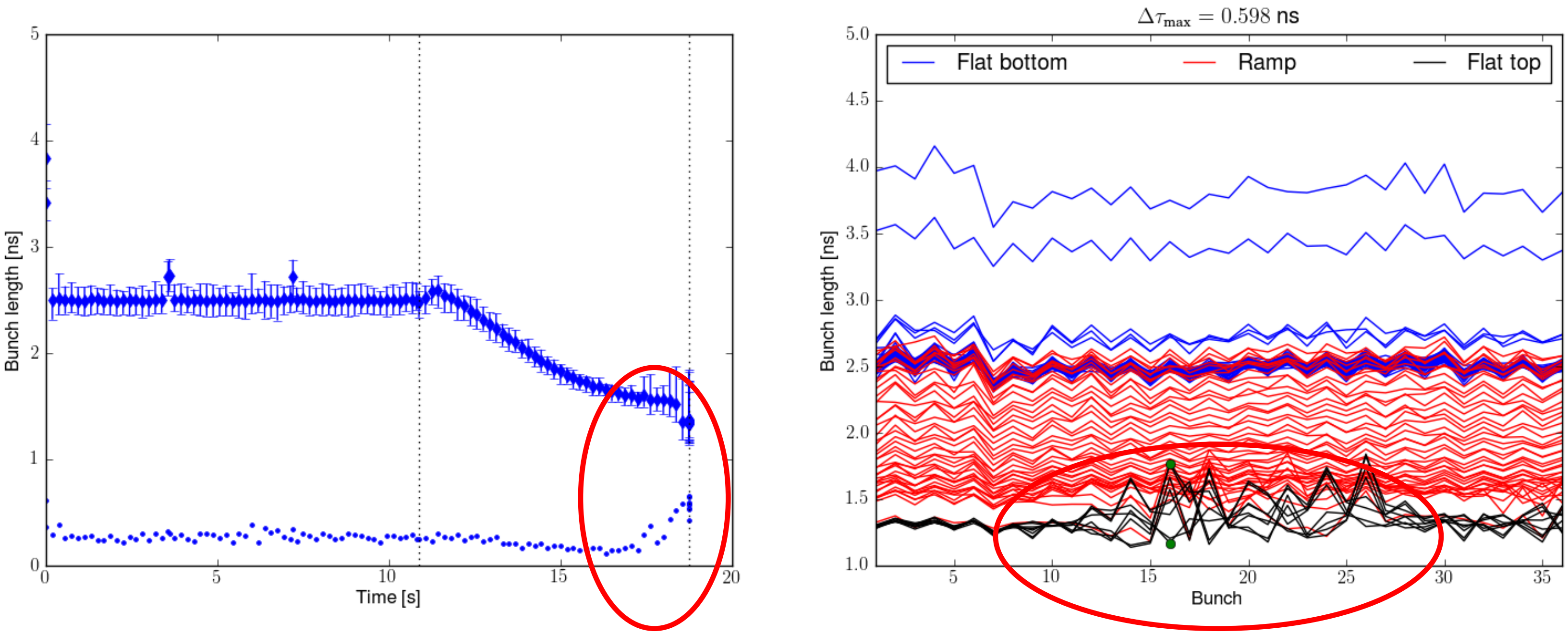
$1.5\times10^{11} < N_{th} < 1.8\times10^{11}$ p/b

- Issues when LHC was asking these intensities – instability threshold in Q26!
- Threshold is close (above) **the single bunch threshold for similar (higher) longitudinal emittance** → is this a single bunch effect?

Instability thresholds in a single RF – Single batch

- ❑ **Measurements in Week 26 – Flat Top:**

  Beam is unstable at the end of ramp even below 0.4×10^{11} p/b !

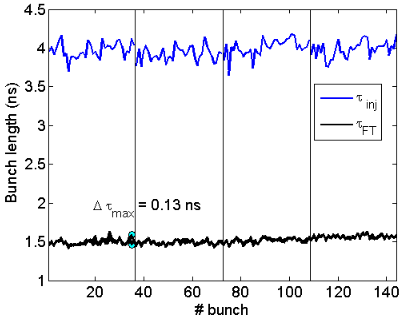


- ➢ At flat top multi-bunch **threshold is much lower than for single bunches** → **most probably due to** effect of 800 MHz beam loading (stronger for short bunches) → V_{bl} comparable to the 800 MHz voltage (when in operation) but only in completely **wrong phase** between the two RF systems (~π/2)
- ➢ Test planned next (last) MD with re-programmed phase with the 800 MHz on **but very difficult to take into account intensity and bunch shape** → FB and FF are absolutely necessary – should be operational after LS1 → time for commissioning!
- ➢ **Effect present also in a double RF operation (corrected by V_{rf} at 800 MHz)** → Controlled longitudinal emittance blow-up is always necessary (even in Q20), Vind depends strongly on bunch length (> factor 10 between FB and FT)

LHC 50 ns beam in SPS Q20

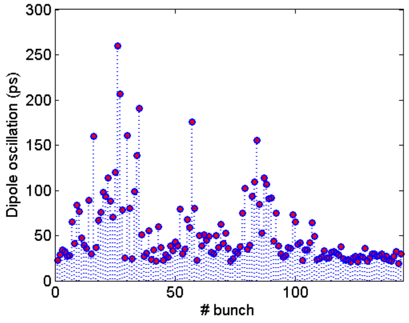
- ❑ **Measurements in floating MDs W30 and 32 and on 11/08 when injectd to LHC (intensities ~ 1.6x10^{11} p/b at flat top):**
  - **Stable beam on FB for these intensities (factor 3 gain is expected)**
  - **Without controlled emittance blow-up** :

    some dipole or quadrupole oscillations at the end of ramp or flat top:



τ_{FT} ~ 1.5 -1.6 ns and ε_{FT} ~ 0.4 - 0.46 eVs

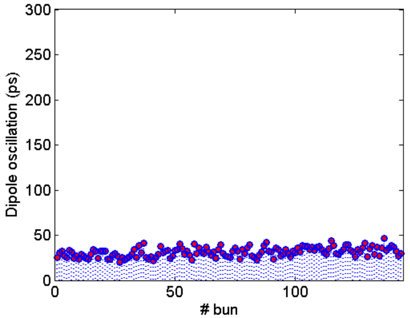
Beam was sent to the LHC!

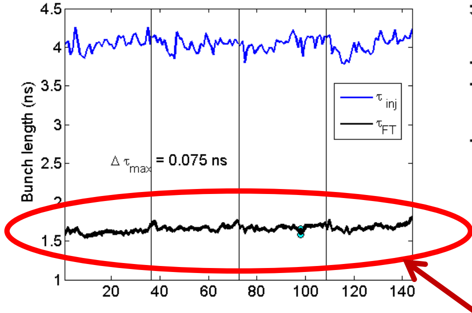


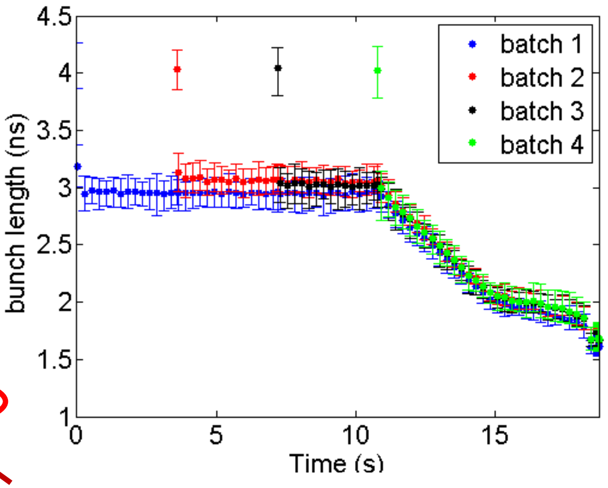
- **With controlled emittance blow-up:**

  stable beam along the cycle

  τ_{FT} ~ 1.55 – 1.75 ns and ε_{FT} ~ 0.42 – 0.53 eVs







Increase of bunch lengths along the batches at flat top – not understood

Summary of MD results (2012)

- ☐ **LHC beam quality in Q26**:
  - Unstable bunches at flat bottom for N > 1.5 10^{11}
  - Batch 4 spends no time at flat bottom → unstable at the end of ramp or flat top
  - Enhanced instabilities due to increased spread of incoming bunches
  - **Solutions:**
    - Take out the dips in the 200 MHz RF voltage program (**done**)
    - Introduce more time at flat bottom after the 4th injection (longer FB)
    - Increase emittance blow-up in the PS (3x4.5 kV) → more stable in PS → less spread of bunch parameters at injection in the SPS
  - **Cost**: more losses - about 1 %
  - **Q20 (still better with longer FB)**

- ☐ **Longitudinal impedance identification using long injected bunches (~25 ns) with RF off** :
  - Measurements as in the past (1997,2001,2007…) of the beam spectrum show a high mode amplitude at 1.4 GHz → low Q impedance to be identified

Summary of MD results (2012)

- **Longitudinal instability thresholds measured at flat bottom and flat top in single RF:**
  - **Single bunch** (ε_L~0.28 – 0.32 eVs):
    - Flat bottom: Loss of Landau damping due to injection V mismatch – stable with low (matched) capture voltage > 1.4×10^{11}
    - Flat top: - N_{th}~1×10^{11} p
  - **Single50 ns LHC batch:**
    - Flat bottom: $1.5\times10^{11} < N_{th} < 1.8\times10^{11}$ p/b → **similar to single bunch**
    - Flat top: $N_{th} < 0.4\times10^{11}$ → stronger effect of beam loading at 800 MHz RF (?)

- **50 ns LHC beam Q20**
  - **N_p~$(1.5 - 1.6)\times10^{11}$ p/b on flat top**
  - **Stable beam on FB**
  - Acceptable beam parameters at extraction (bunch length) – injected to LHC
  - Scaling of bunch length/stability between Q20 and Q26 as expected
  - **More possibilities with upgraded 200 MHz RF (LS2)**

Plans for the rest of 2012 (2013?)

MDs:

- ☐ High intensity 50&25 ns beam in Q20 → operational. And Q26? (losses increased in the first test)
- ☐ Study (thresholds) of single and multi-bunch instability at injection for Q26 and during ramp for Q20 and Q26 in a single and double RF systems
- ☐ Reference impedance measurements from quadrupole frequency shift at injection and stable phase shift (? – more difficult)

Simulations:

- ☐ Identify the impedance from comparison with measurements done with long (RF off) and short (RF on) bunches
- ☐ Reproduce the measured thresholds for single bunches (PL on/off)

Questions to be answered

- ☐ **Requirements for the 800 MHz system:**
  - 2^{nd} cavity operational (idle at the moment) – more voltage and better control
  - FB and FF for phase and voltage control under strong beam loading for the two cavities (work in progress)
  - Phase calibration (now based on bunch shape/stability)

- ☐ **What else do we need to know to estimate performance after LIU:**
  - Impedance source of longitudinal instabilities → measurements of HOMs in the 200 MHz and 800 MHz TW RF systems in labs (spares, not fully equipped) and in situ (tunnel) during LS1 (F. Caspers, E. Montesinos + new fellow/PhD student)
  - 1.4 GHz
  - Complete impedance model