



Longitudinal beam quality monitoring

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ICFA Mini-Workshop on
“Mitigation of Coherent Beam Instabilities in particle accelerators”
Zermatt, 25/09/2019

With inputs from: H. Damerau, I. Karpov, A. Lasheen, J. E. Muller, G. Papotti, E. Shaposhnikova, H. Timko,

Why to monitor longitudinal beam quality?

- Reliable monitoring of the longitudinal beam quality is very important in machine operation.
Ensures machine safety and efficiency
- Quick observation of beam degradation → **efficient reaction in case of problems** (controlled beam dump, preventing beam extraction, etc.)
- Identify unwanted particle population in circular accelerators (satellite bunches, particles in abort-gap region, etc.)
- Longitudinal beam parameters can be used as feedback to other beam manipulations (controlled emittance blow-up in the LHC)
- Quickly spot hardware problems (RF cavities trips, errors in the phase of successive LINAC modules, errors in the LLRF loops, problems in RF manipulations etc.)
- Especially crucial during machine commissioning and machine studies
- ...

What is longitudinal beam quality

The criteria of longitudinal beam quality vary from one machine to the other, depending on:

- ❑ The beam pattern → **Single- or multi- bunch beams**
- ❑ The type of accelerated particles → **Hadrons or electrons**
Large variability on the RF frequencies (up to tens of GHz) → **large variation in bunch lengths** (down to fs level)
- ❑ Specific needs of each machine on what should be monitored → define requirements in resolution and frequency of the measurement:
 - **Bunch instabilities** → fast acquisitions of the beam but smaller resolution (depending on the single-bunch mode)
 - **Bunch distribution** → higher resolution but less frequent acquisitions, special mean to resolve the bunch tails
 - **Long term evolution of the beam parameters** → smaller resolution and acquisition rate

Longitudinal beam parameter diagnostics

- ❑ The variability of the beam parameters for the different types of accelerators define the measurement approach.
 - accurate and reliable measurement of the longitudinal bunch parameters (bunch shape, length, position, emittance)**

- ❑ Large variety of diagnostics:
 - pick-ups, wall-current monitors (WCM), RF zero-phasing, transverse deflecting cavities, beam shape monitors , etc.
 - or by using the synchrotron radiation to reconstruct the bunch distribution, streak camera, coherent radiation etc.

- ❑ Big development in this domain.
 - Measurements of bunches with length of a few fs have been achieved!

Outline

This talk will be mainly focused on CERN accelerators (mainly SPS and LHC)

Bunch size of the order of a few ns → bunch profiles measured by wall-current monitors (bandwidth up to several GHz) together with fast-sampling oscilloscopes.

- ❑ Monitoring of single bunches
 - Intra-bunch motion
 - Bunch evolution during cycle

- ❑ Multi-bunches

- ❑ The Beam Quality Monitor in the CERN SPS and LHC

- ❑ Observation of bunch phases in the LHC

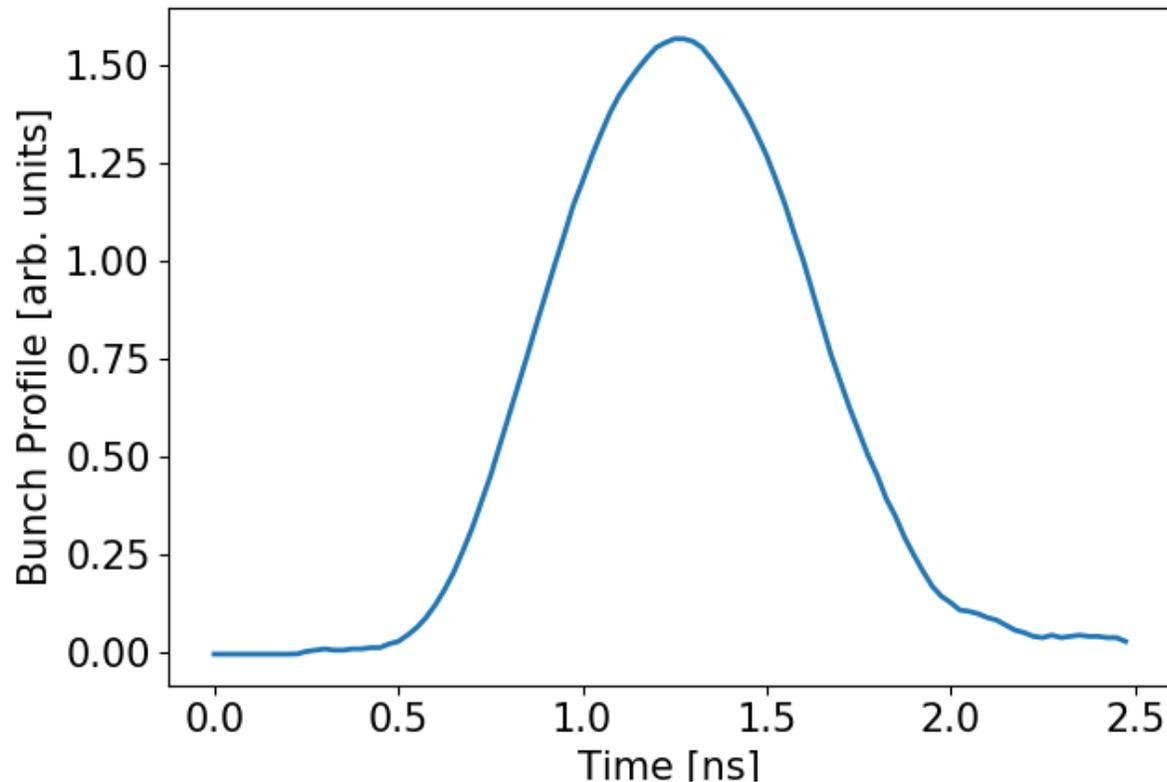
- ❑ Summary

Monitoring of single bunches

Need of reliable and accurate longitudinal diagnostics:

- Most of the times: **bunch position and length** are enough (for beam instabilities)
- But often a detailed knowledge of the **longitudinal bunch profile** is needed (higher mode of instabilities, RF manipulations, luminosity calculations, etc.)

Example of bunch profile measurement in LHC



High resolution bunch profile measurement at the moment of injection into the LHC

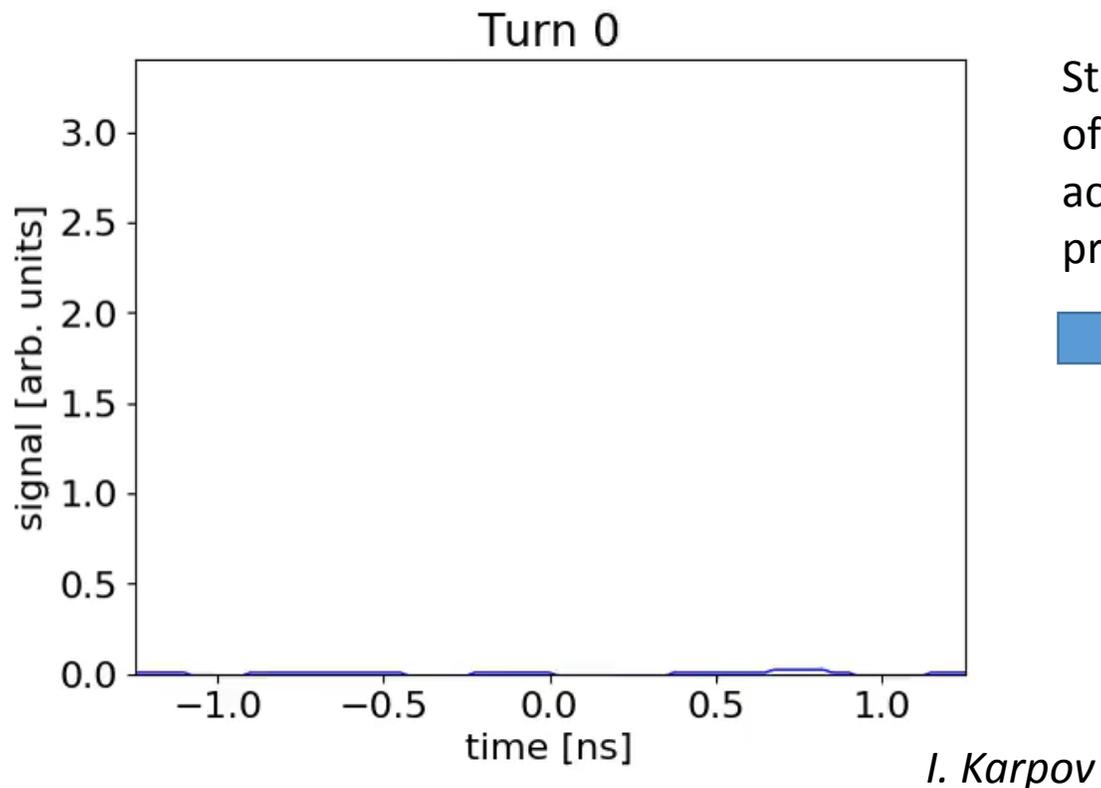
Measured by a **WCM** of bandwidth **~3GHz** and **scope sampling rate at 40 GS/s**.

Bunch length $\tau_{4\sigma}=1.37$ ns

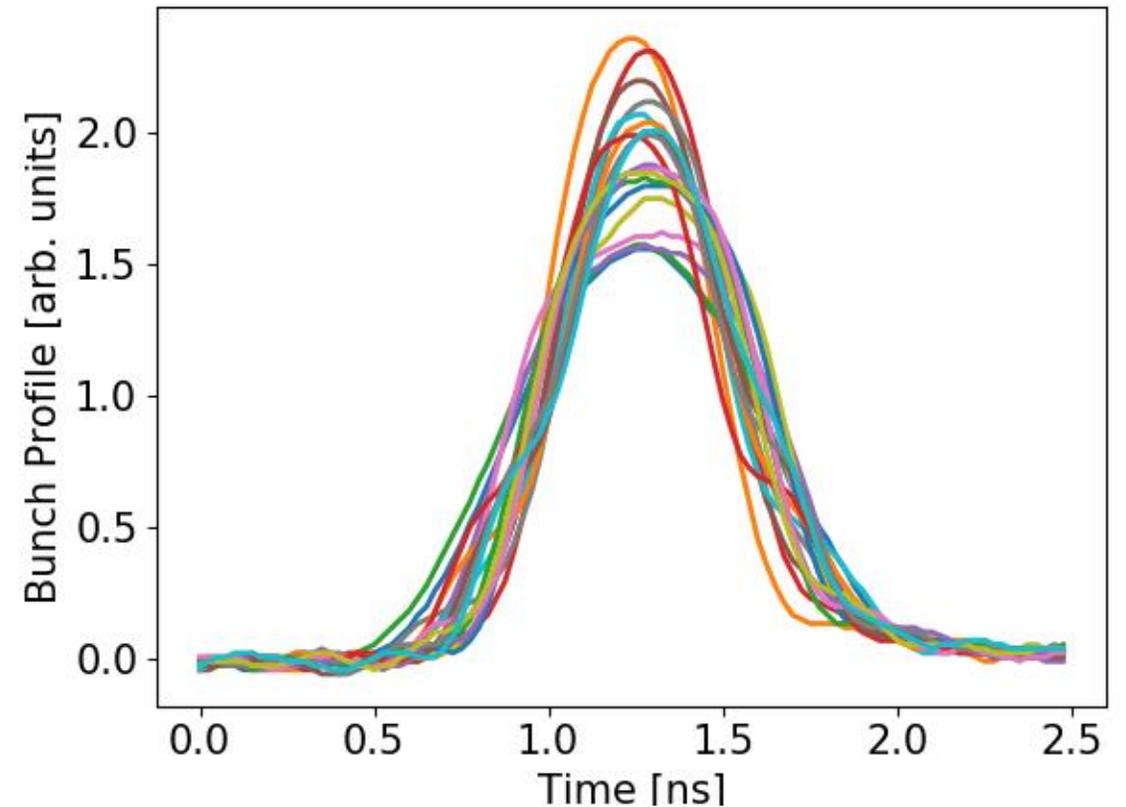
Intra-bunch motion - instabilities

Measurements to resolve well the synchrotron frequency (or a few f_s periods):
depending on the mode of instability and the synchrotron frequency, **a few thousands of acquisitions** can be needed → easily achieved for single bunches

Example of non-rigid dipole oscillations in the LHC



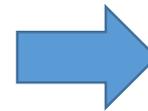
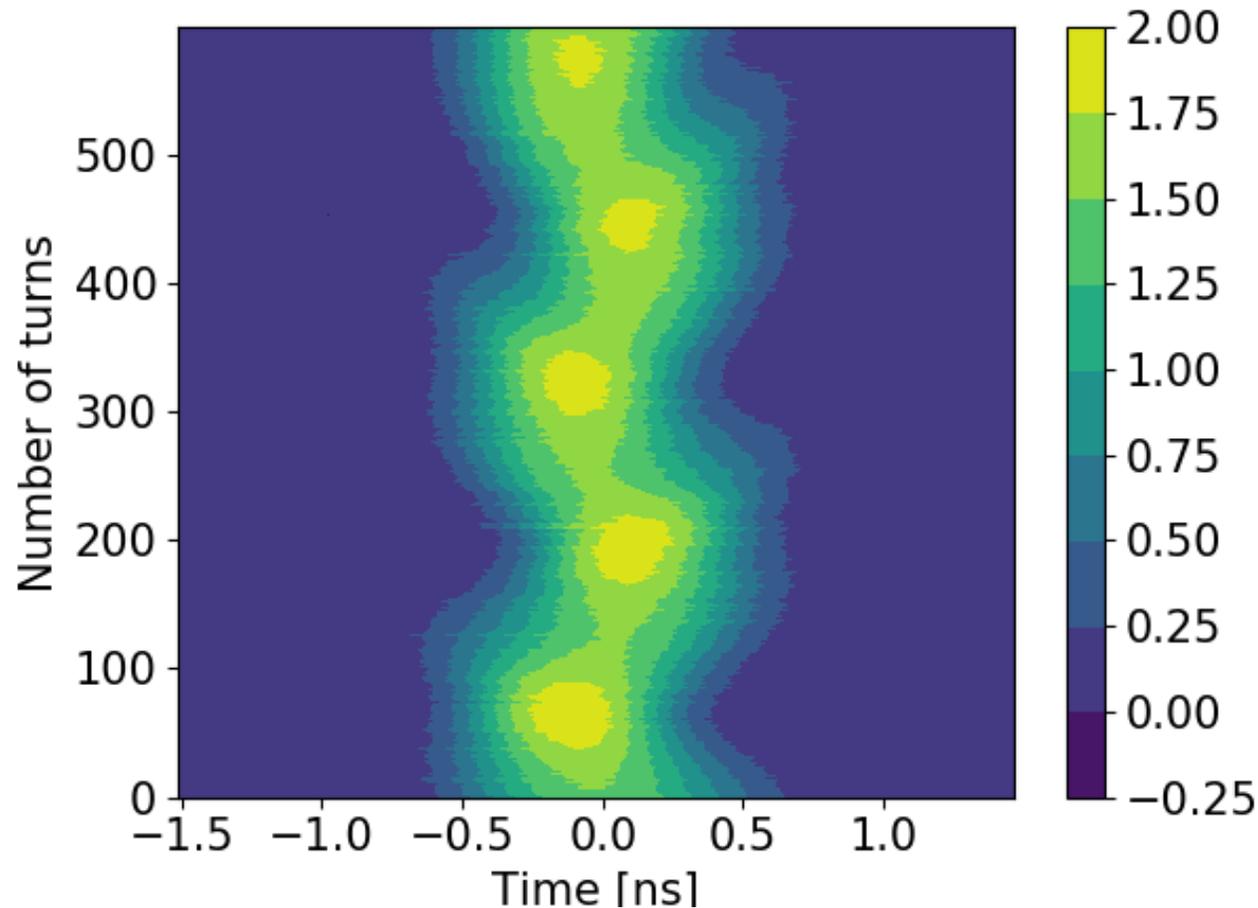
Static plot
of the
acquired
profiles



Intra-bunch motion

Other means to illustrate the measurements can be easier for the users to understand

Waterfall plot: dipole oscillations at injection in the LHC

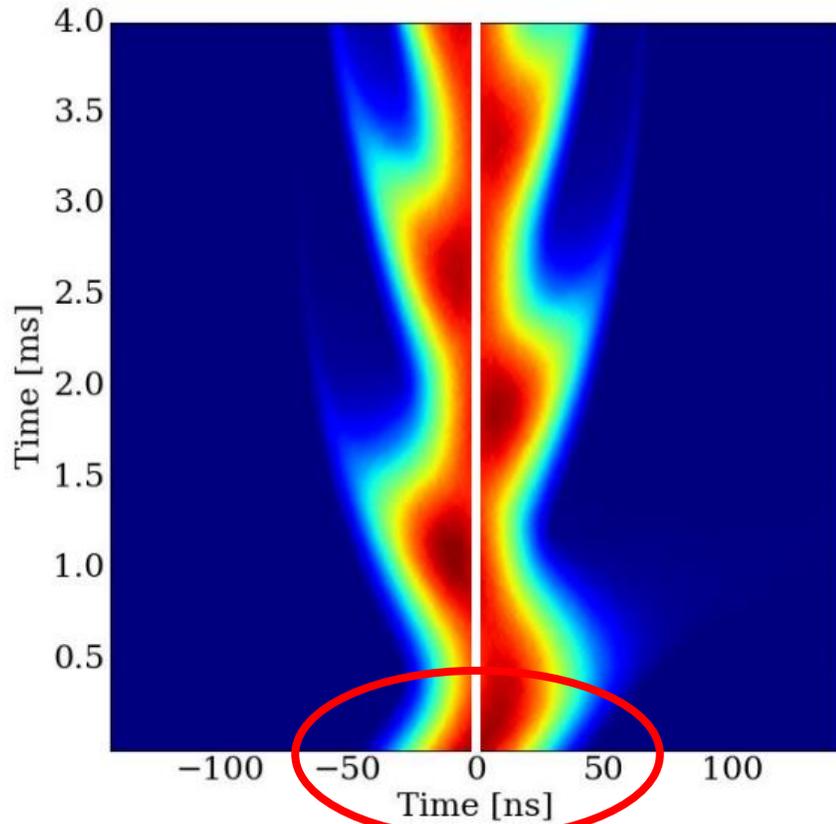


Apart from better visualisation of the bunch motion **it can be used to quickly detect phase and energy errors.**

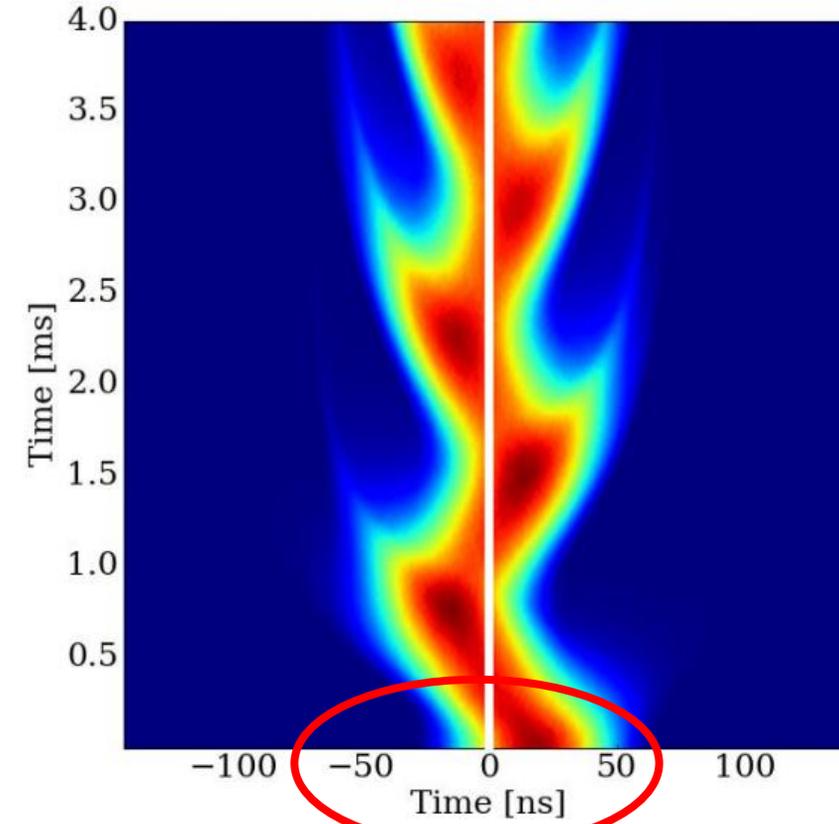
Intra-bunch motion

Other means to illustrate the measurements can be easier for the users to understand

Equivalent dipole oscillations at injection initiated by energy and phase errors



Energy error at injection



Phase error at injection

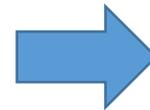
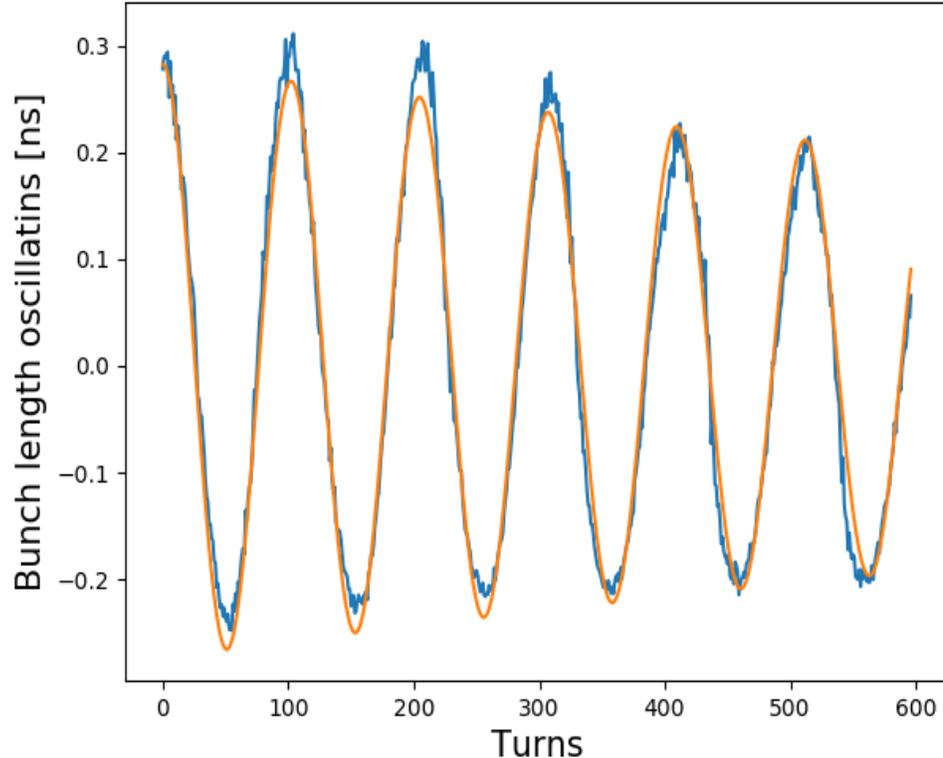
H. Damerou

Intra-bunch motion – data analysis

Fitting the acquired bunch profiles provides information on the **bunch lengths, positions** → can be further analysed to extract other information (bunch intensities, frequencies of oscillations etc.)

Bunch length oscillations at LHC injection

B1 - V = 6 MV - $f_s = 54.9$ Hz - damping time = 0.15 s



Fitting the bunch oscillations at injection (RF voltage mismatch) can provide information about the synchrotron frequency → **Detect problems in the RF Voltage amplitude**

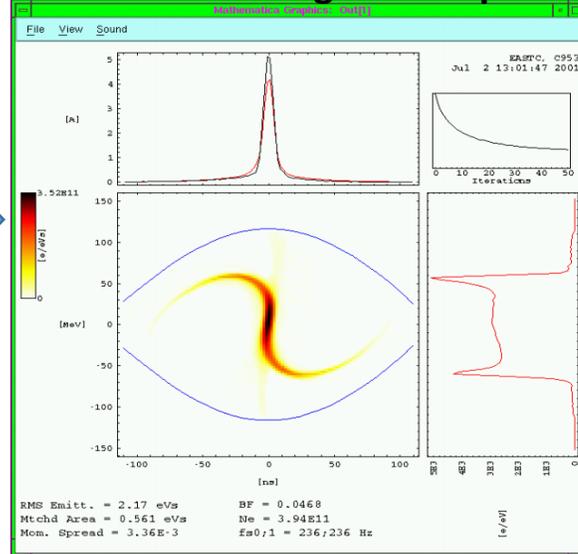
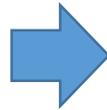
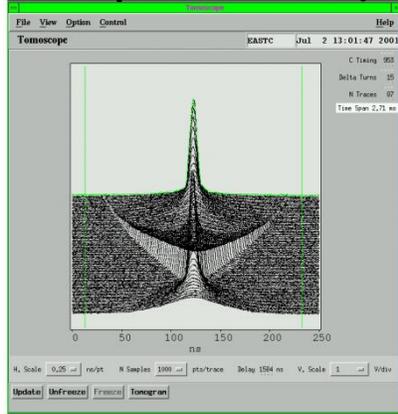
Intra-bunch motion - Tomography

- ❑ Reconstruction of the longitudinal phase space distribution by performing **longitudinal tomography**
 - Visualizing a bunch in the longitudinal plane.
 - Knowledge of the particle distribution → **calculation of longitudinal emittance and momentum spread**, with a much **better precision** than is possible from the observation of a bunch profile.
Very important in analytical calculations and macro-particle simulations of beam instabilities!
- ❑ Originally developed at CERN PS → investigate the complex RF manipulations (bunch splitting, merging, rotation, etc.)
- ❑ Based on measurements of bunch profiles (at least half synchrotron frequency period) → **high quality bunch profile signal is needed** → correction for the transfer function of the system is essential
- ❑ Takes as input several machine parameters (magnetic bending field, RF voltage, etc.) → should be accurately known
- ❑ **Well-established operational tool in all machines of the CERN PS Complex**

Intra-bunch motion – Tomography examples

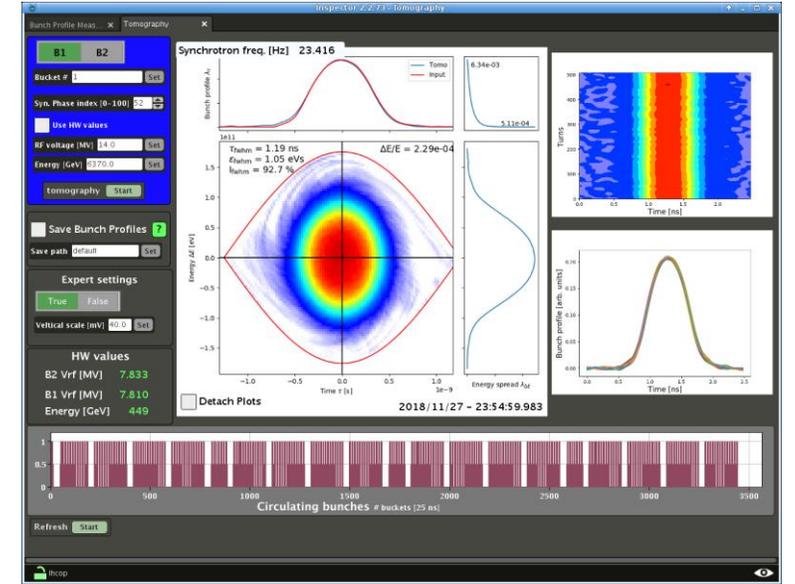
Bunch rotation in the CERN PS

Bunch profile meas. (WCM) Reconstructed longitudinal phase-space

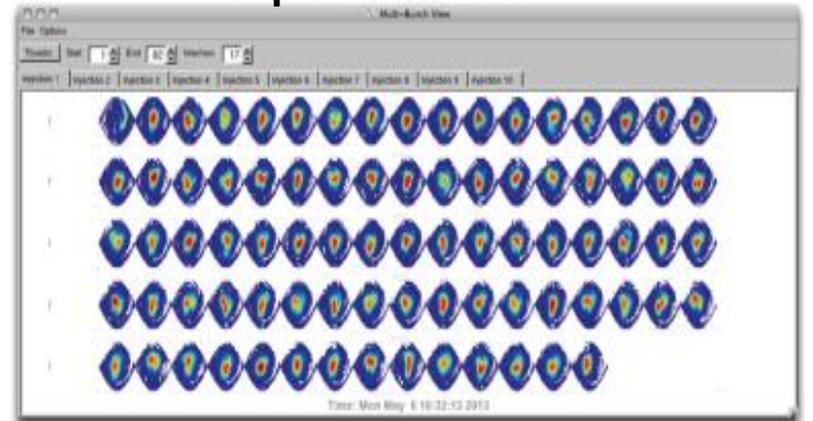


S. Hancock, J. Sanchez Alvarez,
PS/RF/Note 2001-010

LHC Tomography 2018 - Pb ion bunch

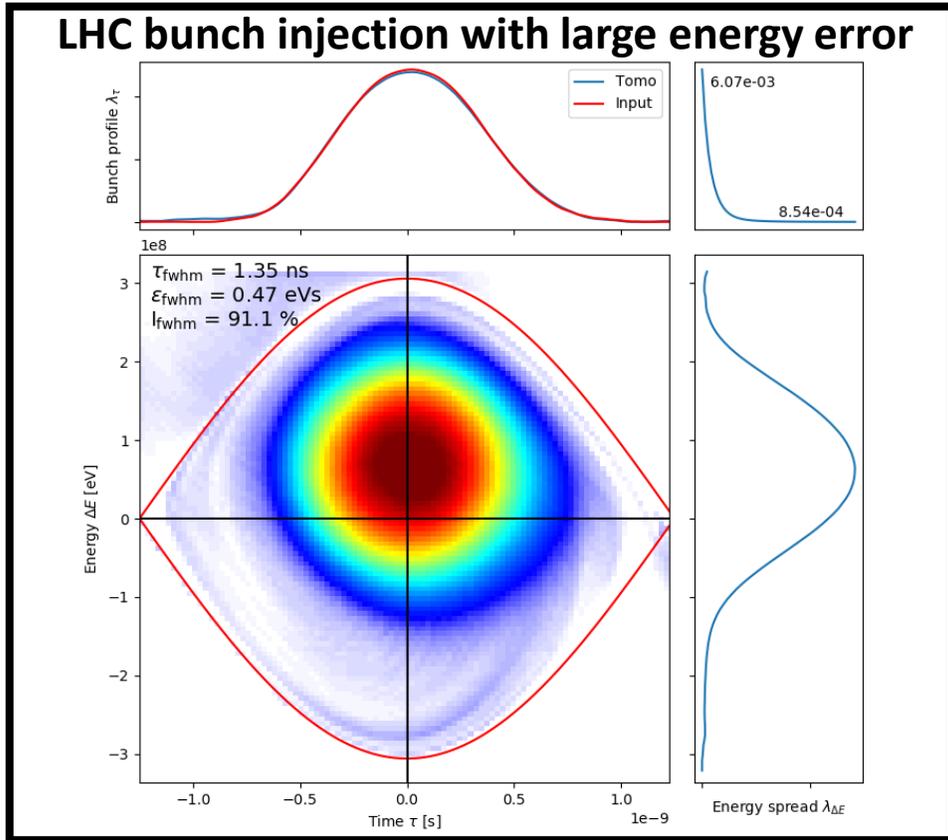


Fermilab Recycler ring – Slip stacked beam



Tomography very important at certain times in the cycle → **beam injection, extraction, RF manipulations** (bunch splitting, rotation, slip-stacking recapture etc.)

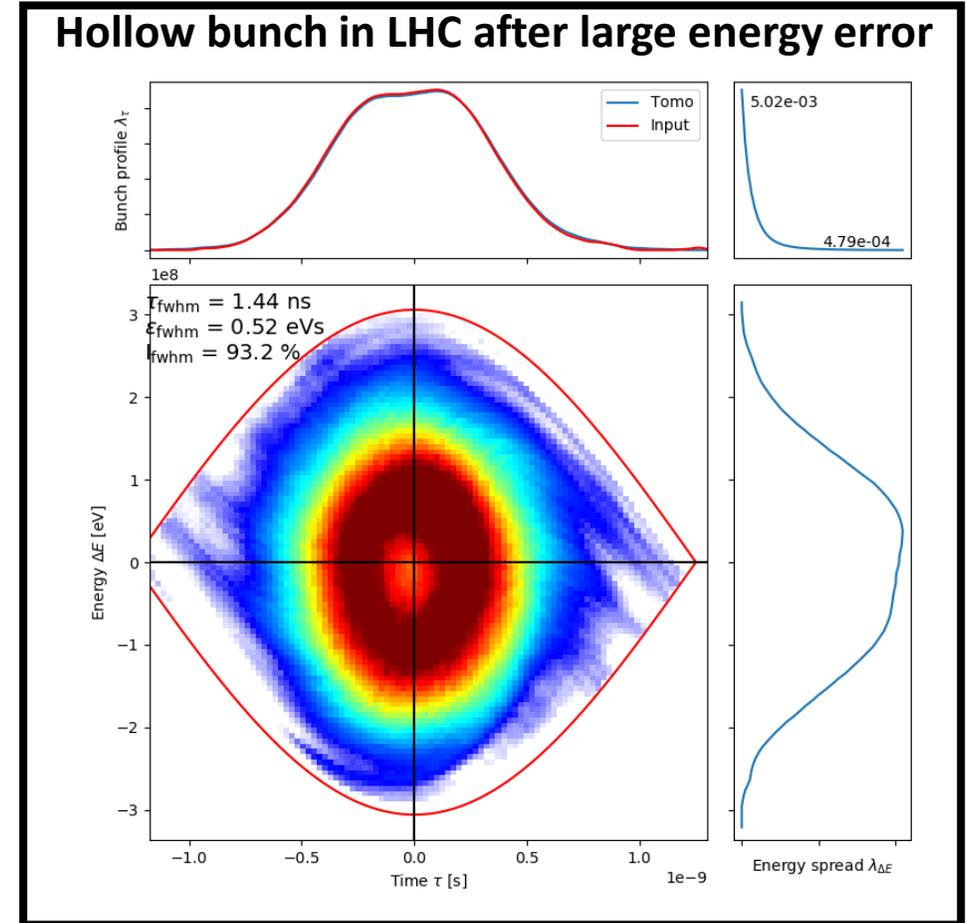
Intra-bunch motion – Tomography examples



After filamentation
and issues with the
phase-loop



Generation of hole
in the bunch
distribution →
preserved until the
beginning of the
ramp (~30 min
later)



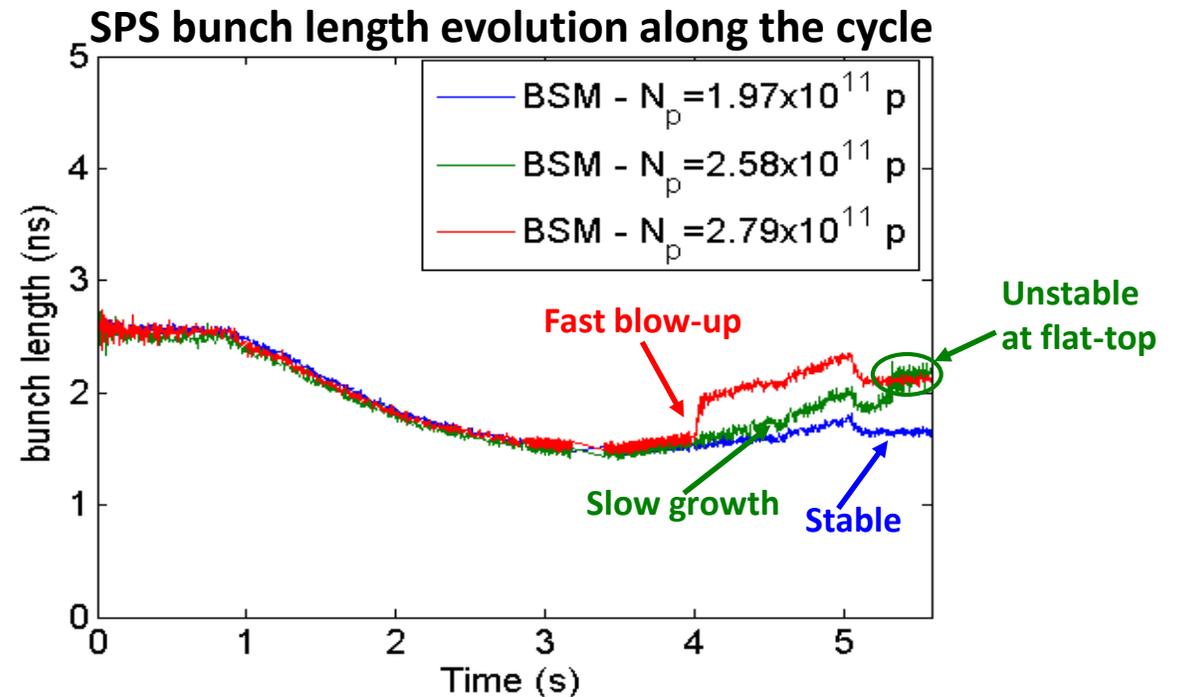
A general, common operational tool for bunch tomography is going to be implemented in all CERN machines after the start-up

Bunch evolution along the cycle

- ❑ Cycle times can vary from a few seconds to many hours (LHC case) → acquisition should be less frequent
- ❑ Visualization is based on the evolution of beam parameters (bunch lengths, positions) → **fast fitting algorithms needed in operation** → **Full Width Half-Maximum (FWHM)** is mainly used at CERN (also beam stability is defined by the bunch core)
- ❑ No possible to measure instability growth rates but can be used to **check global beam stability** and **instability thresholds**

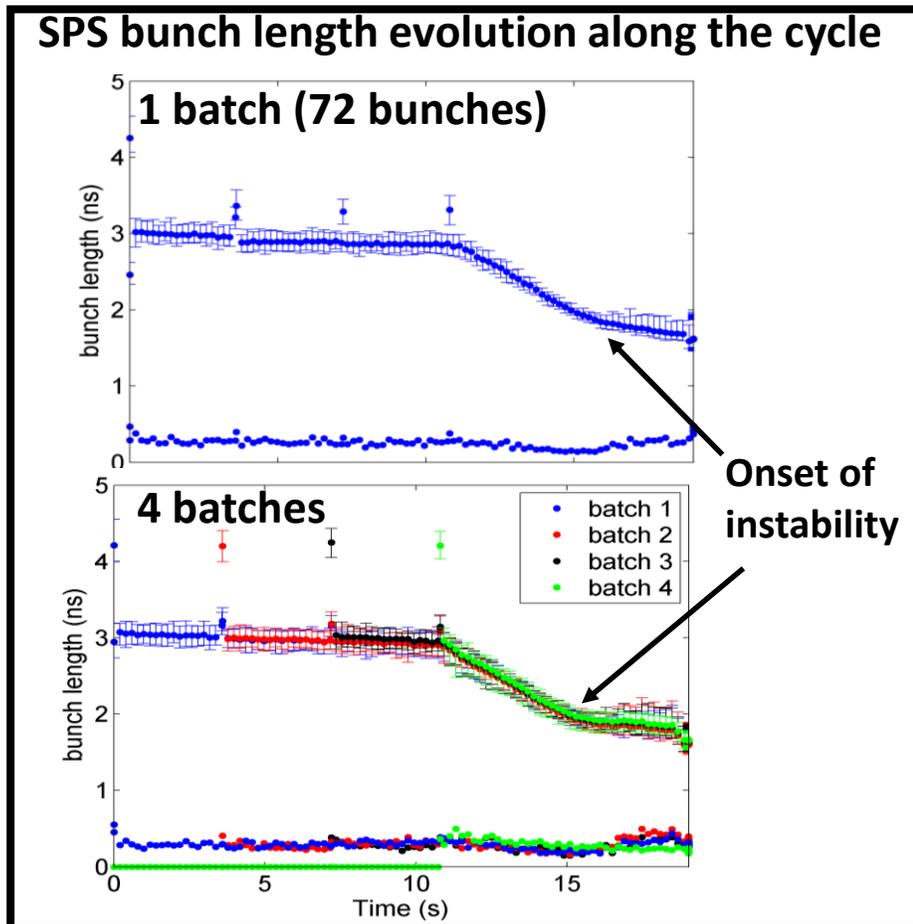
Bunch length evolution at CERN SPS in double harmonic operation (Bunch Shortening Mode) for different intensities

- **Stable bunch**
- **Slow instability** → slow emittance blow-up during the ramp, bunches unstable at flat top
- **Fast instability** → fast emittance blow-up (microwave) and bunches stable at flat top



Multi-bunch case

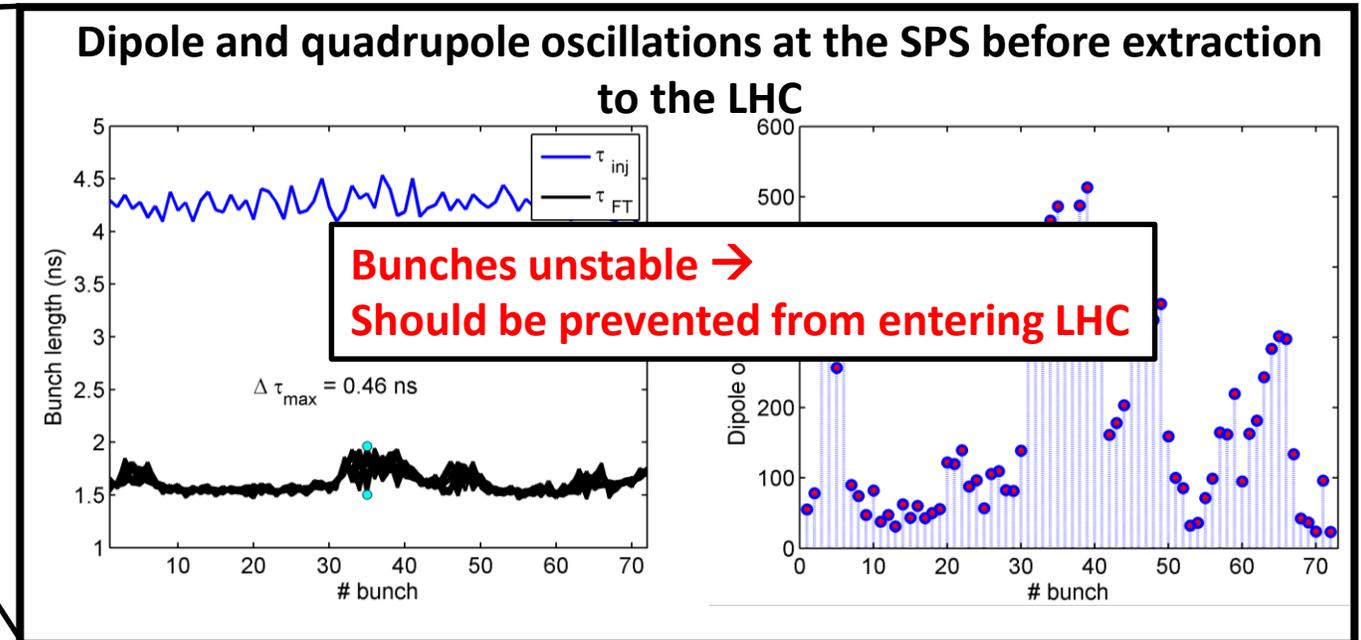
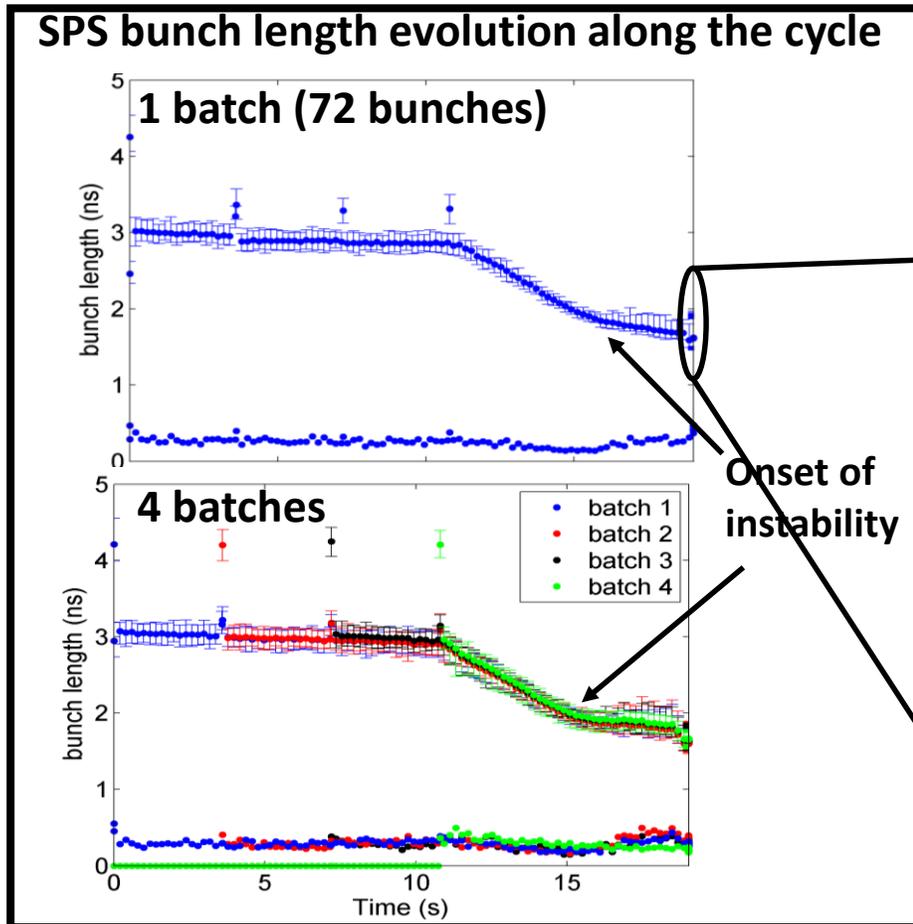
- ❑ Similar plots can be used to visualize the longitudinal beam quality in the case of multi-bunched beams
Only mean bunch length with an error bar indicating the spread inside the bunch.
- ❑ Fast analysis of the acquired bunch profiles
Even less frequent acquisitions and sometimes need to reduce the time resolution!



Multi-bunch case

- ❑ Similar plots can be used to visualize the longitudinal beam quality in the case of multi-bunched beams
Only mean bunch length with an error bar indicating the spread inside the bunch.
- ❑ Fast analysis of the acquired bunch profiles
Even less frequent acquisitions and sometimes need to reduce the time resolution!

- ❑ We can always **zoom into special instances** during the cycle to look into more details the intra-bunch motion
 - Frequent acquisitions (resolve f_s period) of high resolution
 - Similar plots as before



The Beam Quality monitor

- ❑ The importance of monitoring the longitudinal beam quality led to the implementation of the **Beam Quality Monitor (BQM)** in the SPS and LHC operation (G. Papotti, IPAC2011).
- ❑ The BQM monitors longitudinal beam parameters (beam pattern, bunch lengths, bunch positions, intensities) on a **cycle-by-cycle basis** (bunch profiles measurements by WCM) → **Fast algorithms for online analysis (FWHM)**
- ❑ **In the SPS: ensures the beam quality at extraction to meet the LHC needs** → beam stability (dipole, quadrupole oscillations), requested beam pattern, bunch uniformity, no satellite bunches, no bunches in the abort gap region.
- ❑ **Triggers the SPS emergency beam dump** in case any of the checks is not passed.

Crucial for machine safety and efficiency

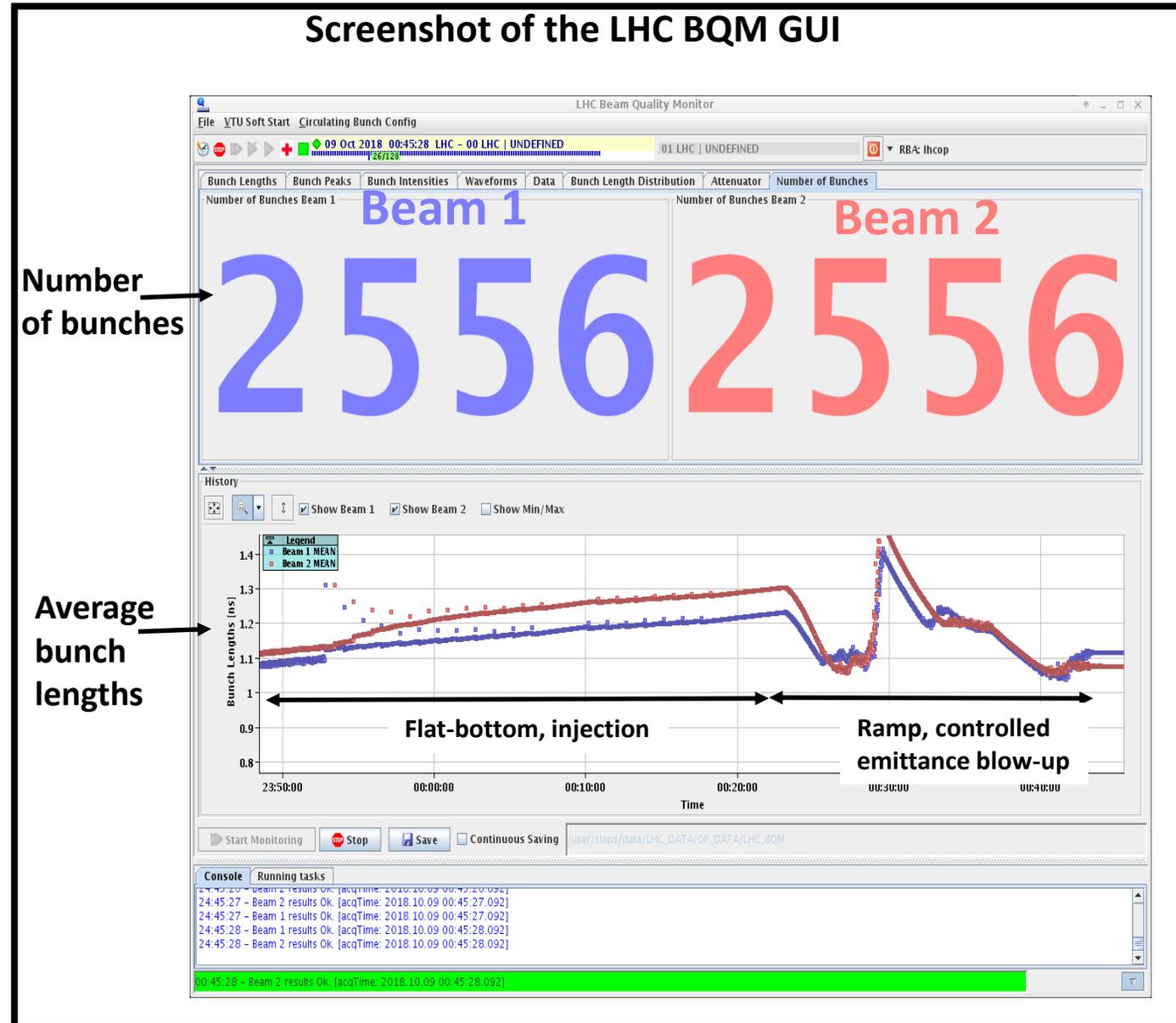
Screenshot of the SPS BQM GUI

The screenshot displays the SPS Beam Quality Monitor interface. On the left, the 'Expected Beam Pattern' section is highlighted with a red box and labeled 'Beam pattern'. It shows parameters: Bunch Spacing: 25 ns, Number of Bunches per Batch: 48, Number of Batches: 3, and Batch Spacing: 200 ns. Below this, the 'Settings' section is highlighted with a red box and labeled 'Settings: can be modified by the operators'. It includes various thresholds and status indicators, such as 'BQM Beam Dump: Enabled', 'Verify Pattern: Enabled', 'Non PPM Attenuator: 18 dB', 'PPM Attenuator: 21 dB', 'Bunch Length Min Threshold: 0.95 ns', 'Bunch Length Max Threshold: 1.95 ns', 'Bunch Length Standard Deviation: 0.50 ns', 'Number of Bunches Max: 144', 'Number of Allowed Long Bunches: 0', 'Bunch Peak Min Threshold: 0.000 V', 'Bunch Peak Max Threshold: 0.450 V', and 'Bunch Peak Standard Deviation: 0.060 V'. On the right, the 'Results' table is shown, with a red box highlighting a row where 'Status' is 'Error' and 'Warnings' are present. A text box next to the table states: 'Each line shows analysis for a cycle. Any failure (red box) prevents extraction'. The table columns include Time, Cycle, Master, Dump, Beam, 1st B., Bu le., Bu Le., Bu Pe., Bu Pe., Bu Int., # Bu., Stability, Satelli., Pattern, Doub., and Warni... The status of each row is indicated by a color-coded box (green for OK, red for Error).

The LHC BQM

- Similarly, the LHC BQM provides information of the longitudinal beam parameters along the cycle:
 - Average, maximum and minimum bunch lengths (FWHM)
 - Filling pattern of the circulating beam
 - prevents injections where beam is present
 - verifies it with respect to the one in configuration database
- Less frequent measurement (every 1s) → **no dipole or quadrupole oscillations** measured (no stability check)
- But the **average bunch length** measurement is used for **feedback in the controlled longitudinal emittance blow-up** → vital to avoid longitudinal instabilities due to loss of Landau damping (see *talk of H. Timko*)

Screenshot of the LHC BQM GUI



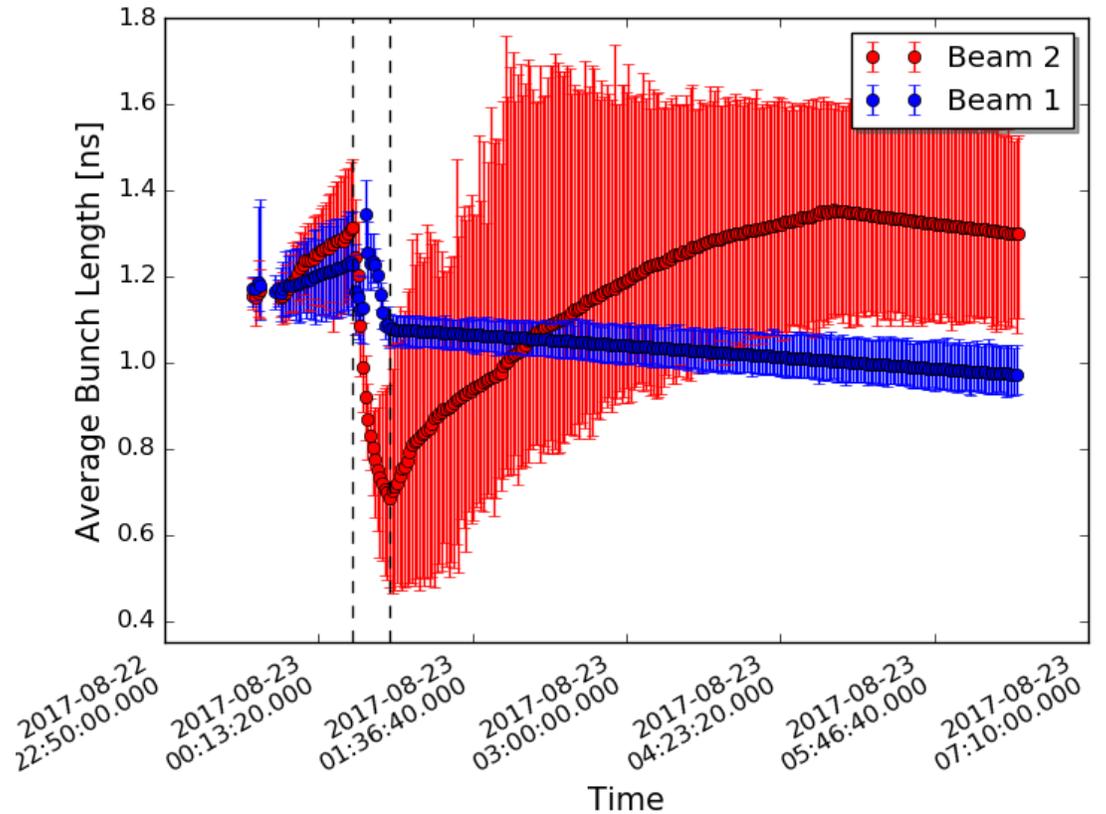
The LHC BQM

- ❑ All raw and analyzed data (for all bunches) are logged for offline analysis

Screenshot of the LHC BQM GUI – No phase loop and controlled emittance blow-up for Beam 2



Data
retrieved
from the
database



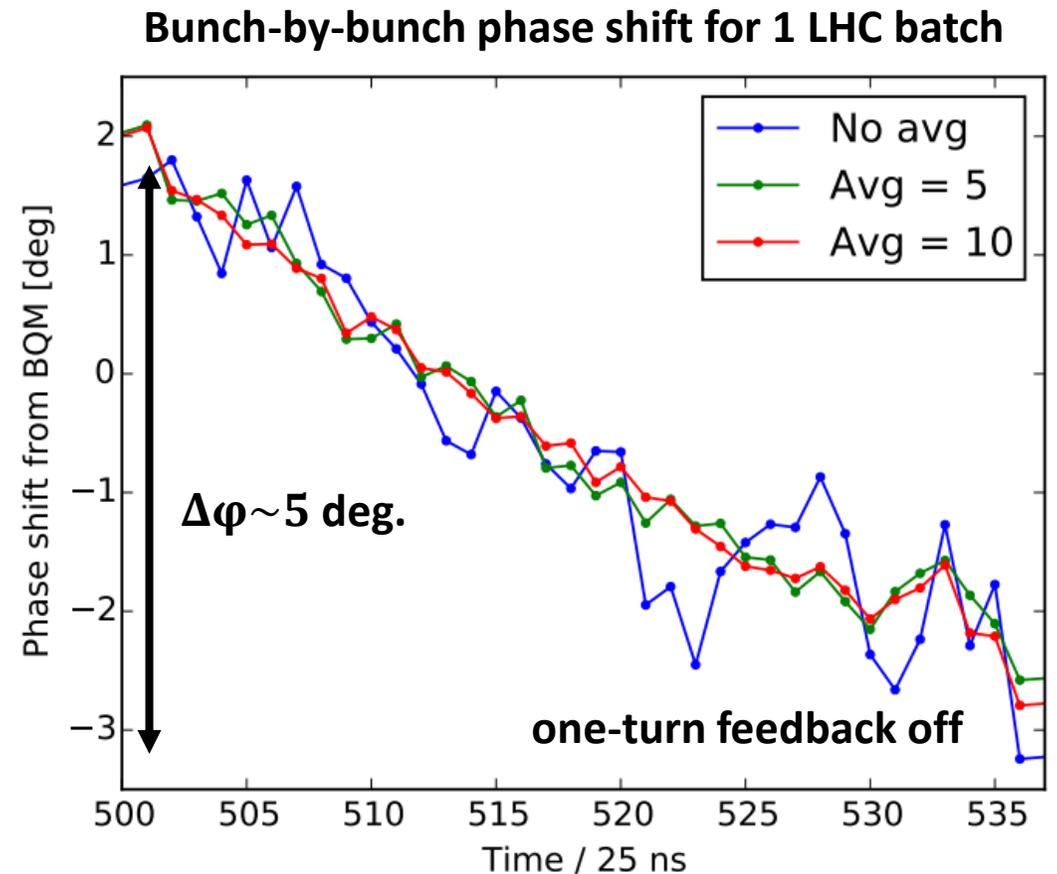
No beam dump is triggered by the LHC BQM

Observation of bunch phases in the LHC

□ Knowledge of the **bunch phases** is very important → **resistive impedance measurements, e-cloud monitoring**

□ Can be extracted from **bunch profiles acquisition in BQM**:

- Linear fit to the bunch positions, assuming constant distance between the buckets (2.5 ns)
- Averaging over a few measurements also reduces noise
- **But phase shift due to transient beam loading is also included** → larger than the phase shift due to other effects of interest (impedance: ~ 0.01 deg., e-cloud: ~ 0.1 deg.)

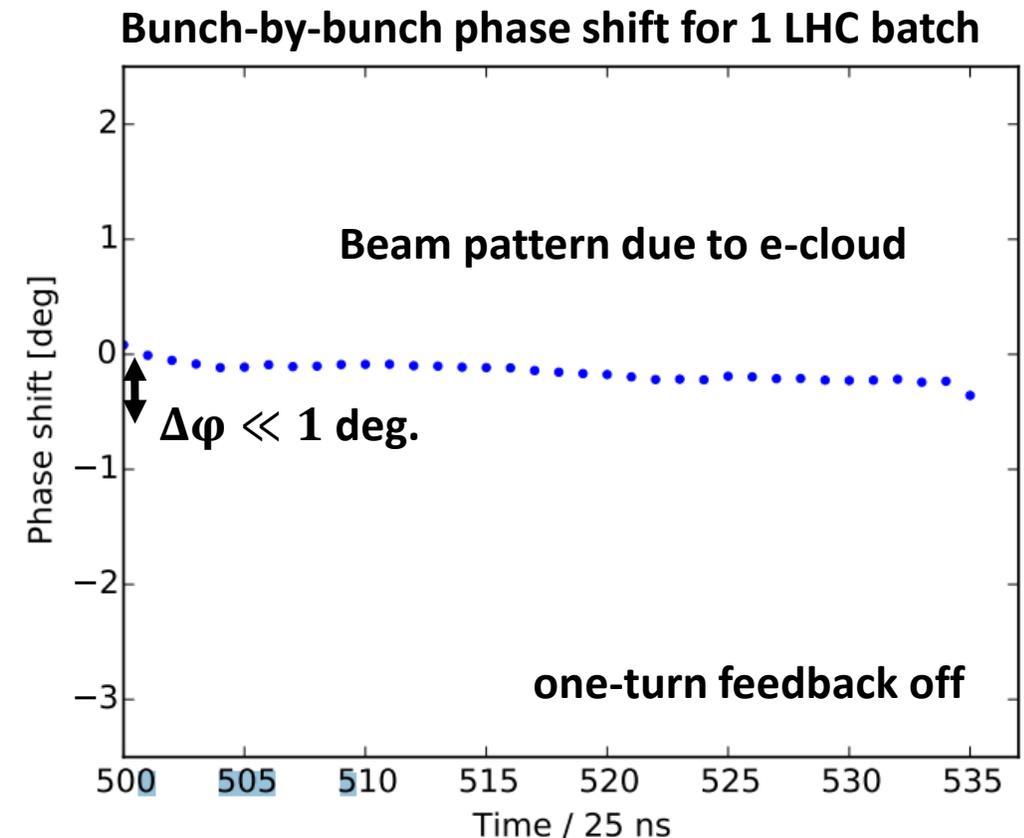


(a) From BQM

Observation of bunch phases in the LHC

- ❑ Beam phase module (PM) are installed for bunch phase measurements in the LHC (*J. E. Muller, Thesis 2016*) (similar to the one used for the phase-loop)
- ❑ PM determines the bunch phase as the difference between the beam phase measured from the WCM and the RF voltage phase → **beam loading is excluded**
- ❑ PM designed accuracy ~ 1 deg. (~ 0.01 required) → **corrections of systematics** were implemented and after a bit of **data processing the required accuracy was achieved!**
- ❑ PM data are transferred to a high-performance server known as ObsBox (*see talk of M. Soderen*) → **no memory limit**

Bunch-by-bunch synchronous phase is measured turn-by-turn → dipole oscillations can be reliably monitored



(b) From phase module

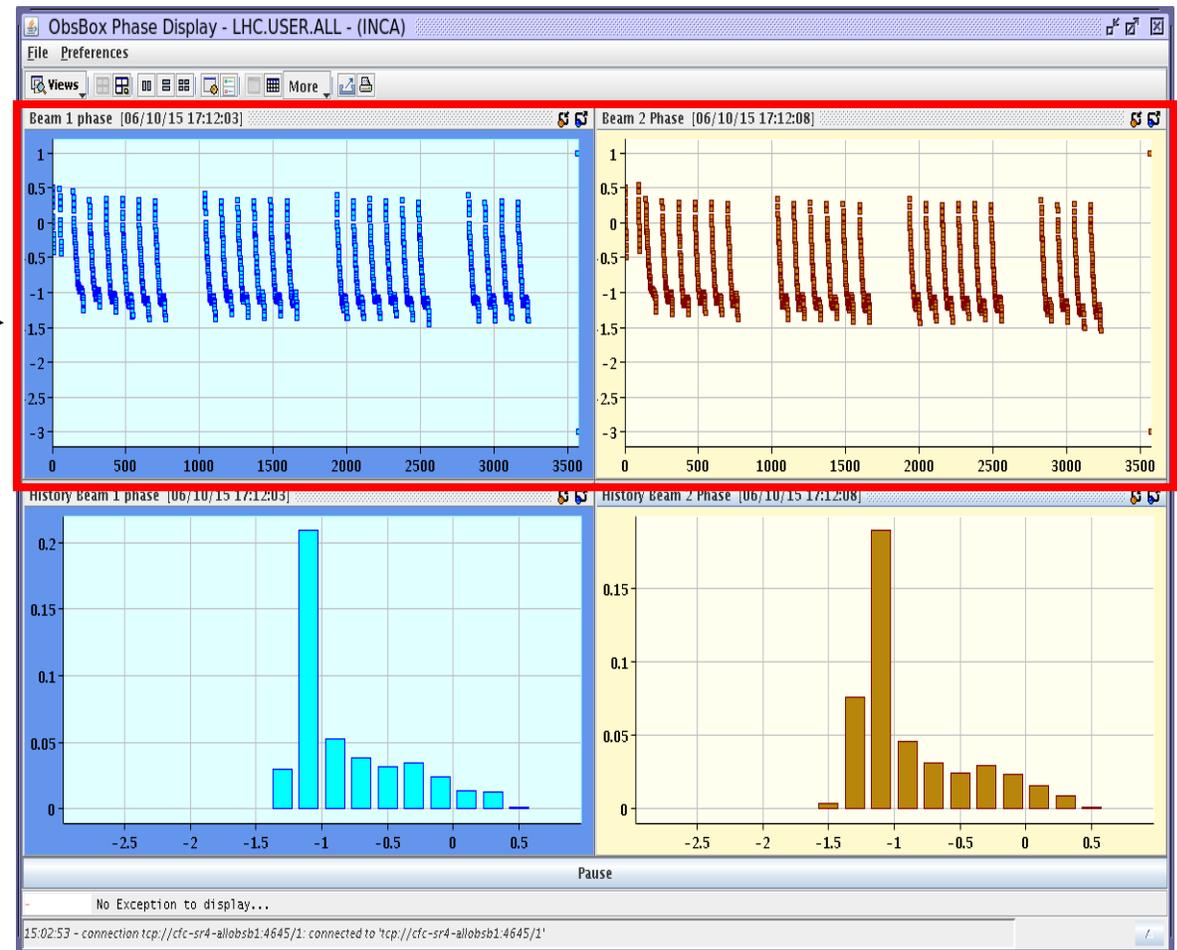
Observation of bunch phases in the LHC

- ❑ Bunch phases from PM as well as the RF voltage phase and amplitude are stored in the CERN logging database for any offline analysis
- ❑ **Diagnostic tool implemented in the LHC control room to monitor the e-cloud activity**, during scrubbing runs and in operation during the intensity ramp-up.

e-cloud signature
along the
bunch trains

→

Screenshot of the LHC bunch-by-bunch phase fixed display



Summary

- ❑ Longitudinal beam quality monitoring is one of the main key components for the safe, reliable and efficient operation of the particle accelerators.
- ❑ What needs to be monitored depends strongly on the needs, issues and beam parameters of each individual accelerator.
- ❑ For the CERN accelerator complex an accurate knowledge of the bunch profile is crucial both in the daily operation and during the various machine studies → generally measured with high bandwidth WCM.
- ❑ Single- and multi- bunch plots of the beam signal and the longitudinal parameters obtained, can be used to quickly identify instabilities or hardware problems → increase the reaction time.
- ❑ Other methods of measuring and monitoring the longitudinal beam quality are also used (not discussed here)
 - **Beam Synchrotron Light Monitor Longitudinal (BSRL):** LHC density monitor based on single-photon counting system measuring synchrotron light (*A. Jeff et al.*) → high dynamic range for satellite bunch detection and abort gap population monitoring.
 - **Peak-detected Schottky spectrum:** obtain the particle distribution in synchrotron frequencies (for stationary conditions) or to observe coherent bunch oscillations (*E. Shaposhnikova et al.*) → synchrotron frequency distribution inside the bunch important for beam stability (*see talk E. Shaposhnikova*)