LHC Injectors Upgrade

SAPIENZA
UNIVERSITÀ DI ROMA

LHC Injectors Upgrade

Overview of Longitudinal Coupled-Bunch Instability in the CERN PS

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Acknowledgements: H. Damerau, S. Gilardoni, M. Migliorati, M. Paoluzzi, C. Rossi, G. Sterbini.

Outlook of the Talk

- Coupled-Bunch Instabilities in the CERN PS: State of the Art
- Determine the source of CB instabilities in the PS
- Develop an original algorithm to analyze the CB motion
- Coupled-Bunch Feedback System Commissioning and Performances
- Damping of CB instabilities: first results with the new feedback system

❖ Coupled-Bunch Instabilities in the CERN PS: State of the Art

Longitudinal CB Instabilities

- Interaction of charged particles/cavity → wakefields act back on the beam and produce growth of oscillations
- If growth rate stronger than the natural damping → oscillation gets unstable
- Wakefields are proportional to the bunch charge→ **instabilities are current dependent**

Cross-talk of bunches which are coupled with the machine impedance

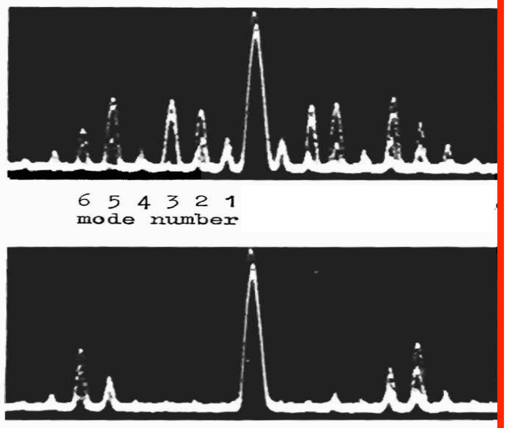
LHC Injectors Upgrade Program requirements

- All cavities tuned in h=21 during acceleration → Coupled-bunch instabilities driven by the longitudinal impedance

- With LIU double the intensity → **Longitudinal stability to reach $2.6 \cdot 10^{11}$ ppb**

CB instabilities driven by cavities are the problem to attack in the frame of the LIU project → **Reliable beam delivery to the high-luminosity (HL) LHC**

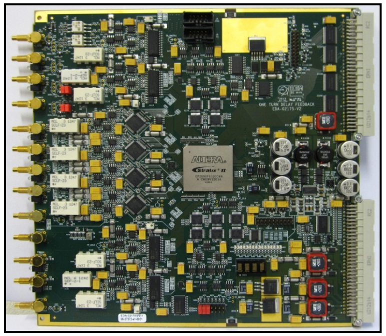
Coupled Bunch Instability at CERN



Compensation techniques:
- ✧ **Spread in f_s**
- ✧ **Landau damping**

LHC Injectors Upgrade programme (LIU)

Compensation technique:
- ✧ Coupled bunch feedback is used to compensate CB instabilities and spare cavity (C11) is used as longitudinal damper.



Compensation technique:
- ✧ **Fully digital LLRF and new dedicated damper cavity**

1971 | **2005** | **2013** | **LS1** | **2015**

J.-L. Vallet, "*Amortissement des Instabilites Longitudinales de Modes Couples*," unpublished presentation (APC), 2005.

Compensation techniques:
- ✧ **Analog FB system and C86-96 as long. damper**

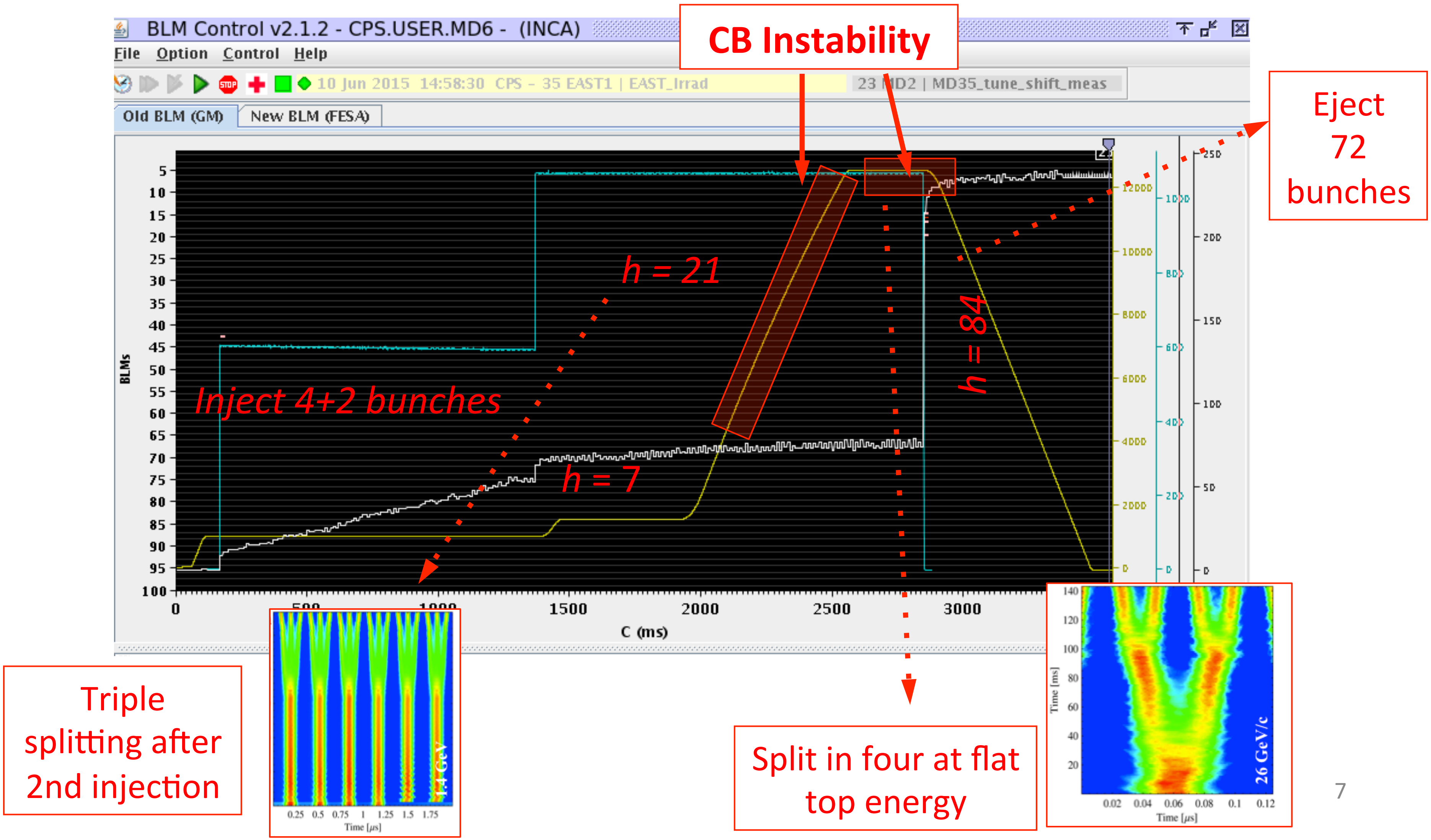
First observation at CERN of CB instability

- ✧ *"Damping of the Longitudinal Instability in the CERN PS "*, D. Boussard and J. Gareyte, CERN, Geneva
- ✧ *"Study and compensation of coherent longitudinal instability in the CERN PS"*, D. Boussard, J. Gareyte, D. Kohl, CERN, Geneva

The CERN Proton Synchrotron

The CERN PS is a synchrotron dominated by a MULTI-HARMONIC RF system that allows to perform different kind of gymnastic on the beam.

In the chain of injectors is responsible for creating the beam train structure.



Multi-harmonic RF System

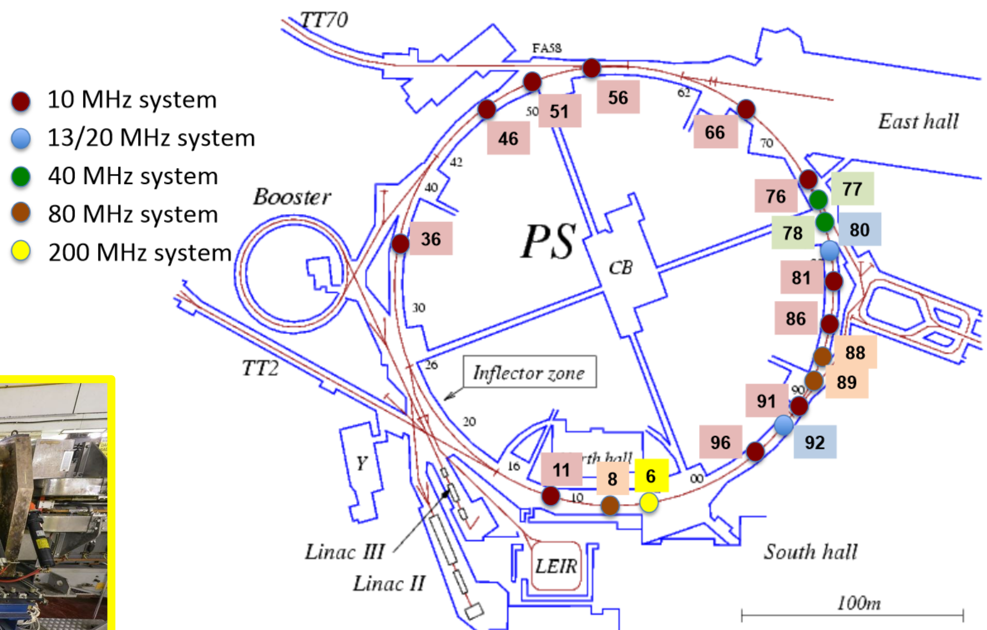
10 MHz

Ferrite loaded cavity
Freq. range 2.8 – 10 MHz
2 RF gaps / cavity
20 kV / cavity
Built in 1975,
upgraded in 1988

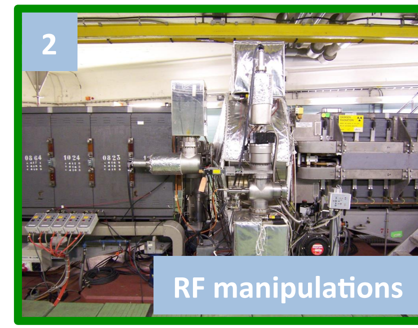
20 MHz

Ferrite loaded cavity
2 RF gaps / cavity
20 kV / cavity peak
Built in 2002

24 (+1) cavities from 2.8 to 200 MHz

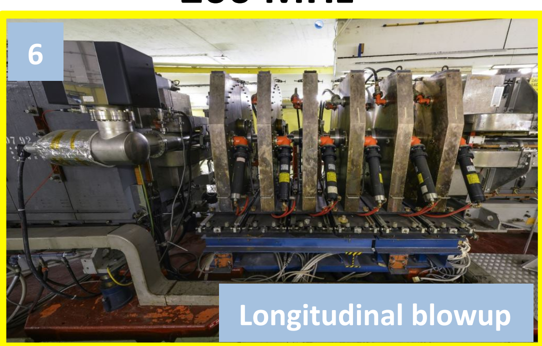


40 MHz



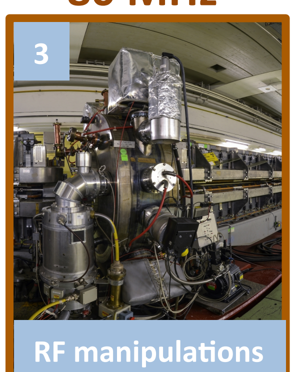
Vacuum reentrant cavity
1 RF gap / cavity
300 kV / cavity
Built in 1996

200 MHz



Pill-box cavity
1 RF gap / cavity
6 cavities
50 kV / cavity
Built in 1979

80 MHz

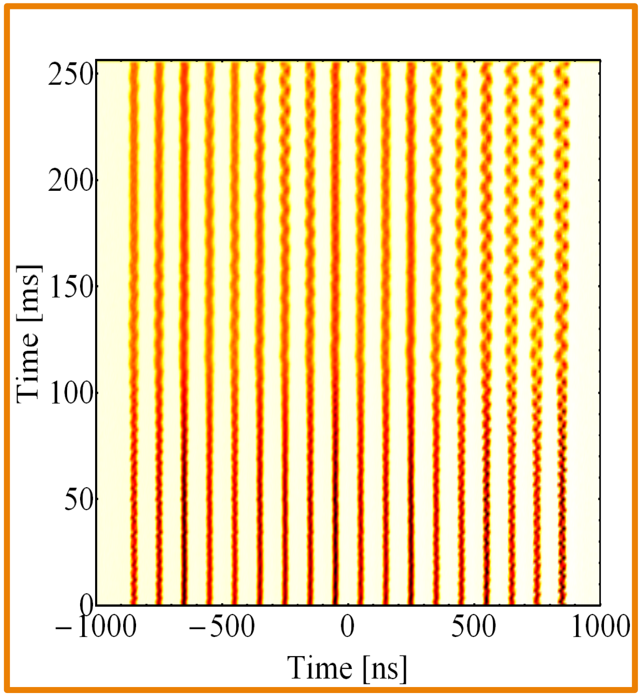


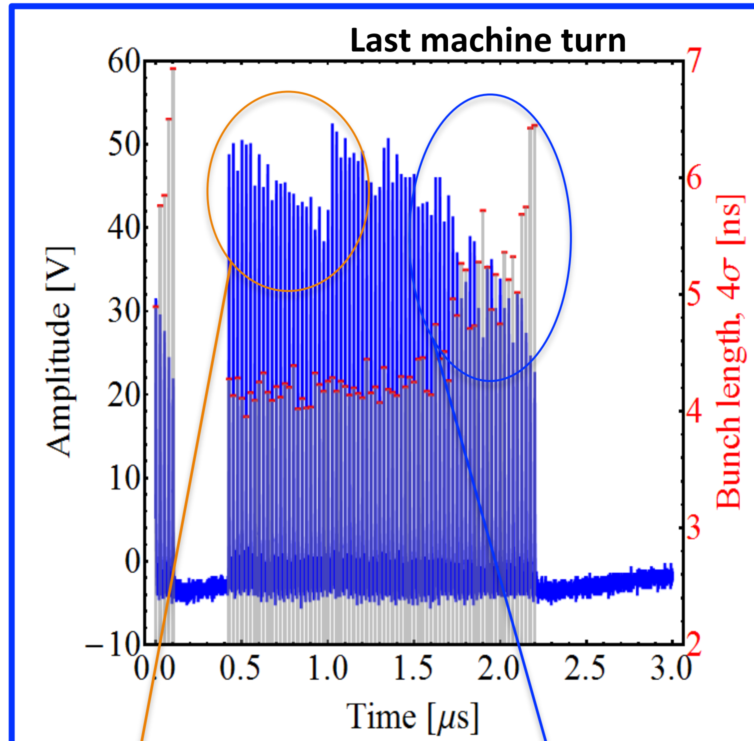
Vacuum reentrant cavity
1 RF gap / cavity
300 kV / cavity
Built in 1997

Finemet Cavity

Wide-band cavity 0.4 – >5.5 MHz
V_{RF} = 5 kV
Transistor solid state amplifiers
Built in 2014

Two major issues observed during **acceleration** and at **extraction**.





Observation of dipolar oscillation with a well defined phase relation → CB oscillations

Reduced intensity → issue for beam beam in LHC

Bunch length not in the range of 4 ns required from SPS.

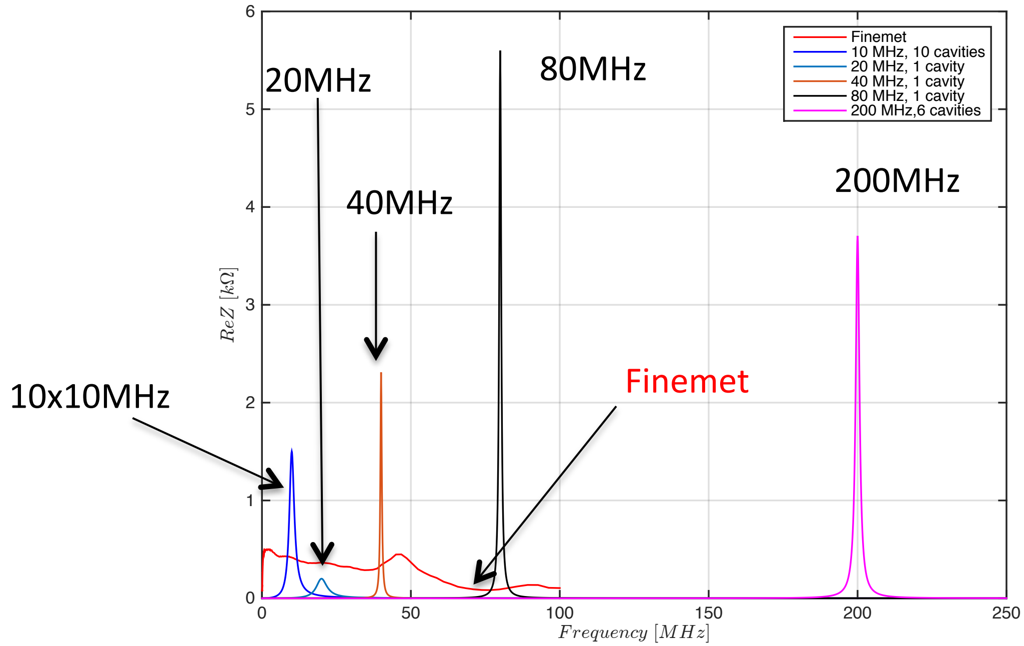
LHC
Intensity limitations

SPS
Bunch length limitations

- Determine the source of CB instabilities in the PS

1) Impedance model

The PS has a complex RF system. Thanks to the help of the impedance team, all cavities have been studied and a model of the machine impedance has been developed to be used in simulations.



Cavities are tunable

Longitudinal impedance function of time.

2) MuSiC Simulation code

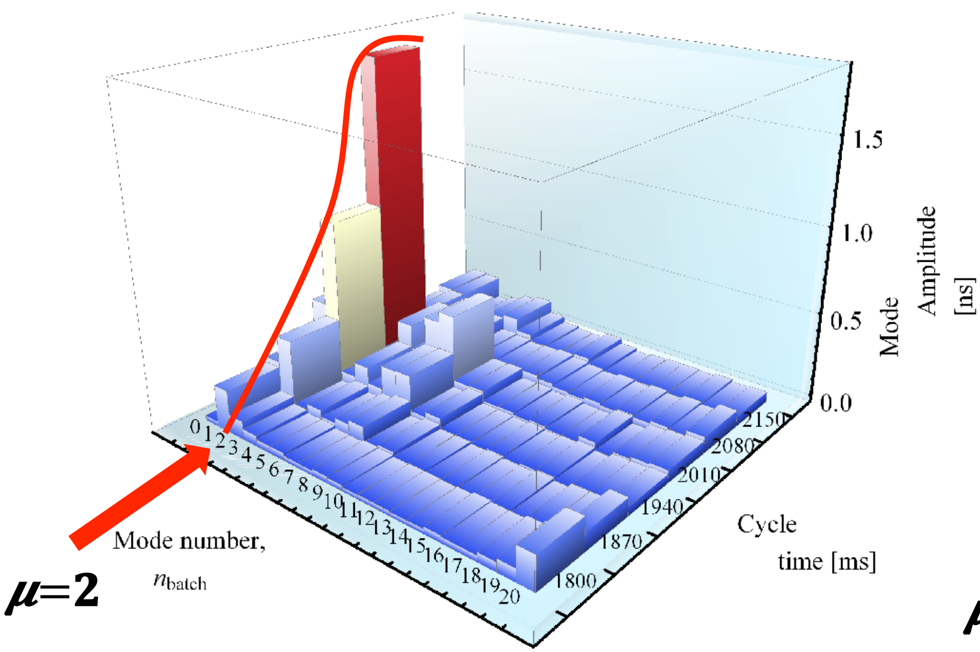
MuSiC is a new Multibunch/multiparticle Simulation Code which simulates the longitudinal beam dynamics under the simultaneous effect of short range and long range wakefields.

- The impedance of resonant modes is used directly instead of the wakefield.
- The impedance is fitted with multiple resonators.

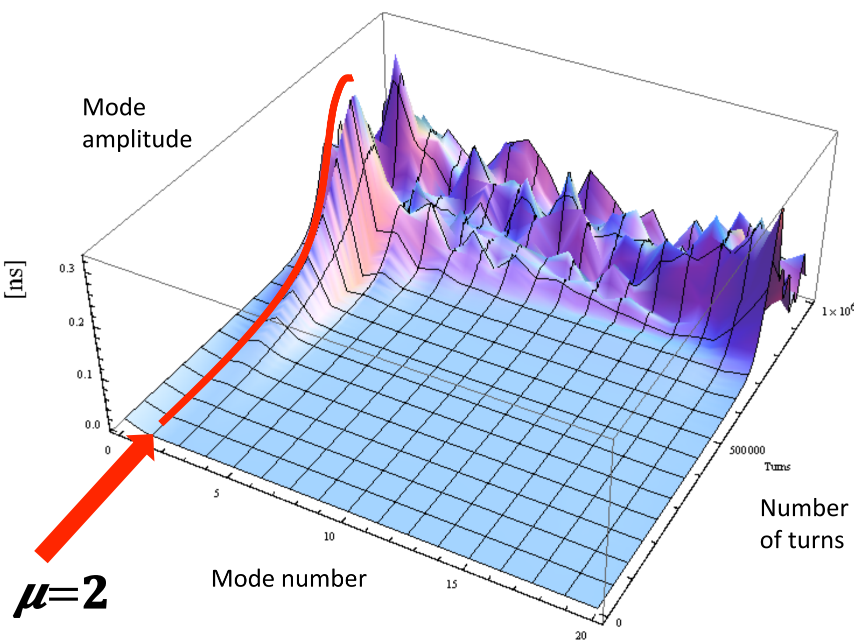
3) Benchmark Simulations & Measurements

From simulations the contribution of the Finemet cavity to the coupled bunch instability is negligible compared to the stronger effect of the 10 MHz cavities.

Measurements



Simulations with 10 MHz +
Finemet impedance model



10 MHz cavities impedance is supposed to be the main source of coupled-bunch instability in the PS.

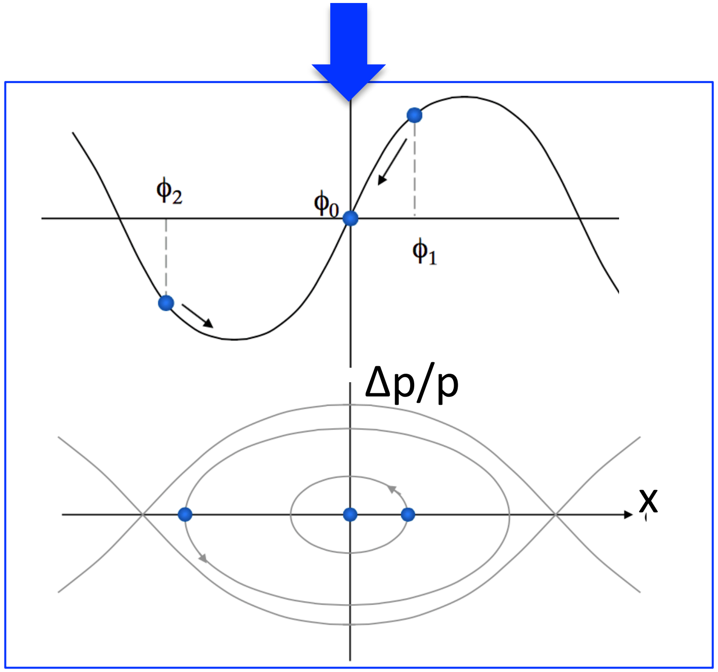
❖ Develop an original algorithm to analyze the CB motion

Develop a **tool** to **analyse measurement data and extrapolate the mode analysis** in order to evaluate the stability/instability in the different operational conditions in particular to determine the behavior of the longitudinal CB feedback.

Circulant Matrix Approach (1/2)

A circulant matrix is formed by a vector *c* by **cyclically permuting the entries**.
<u>The filled PS train has a circulant symmetry, so the evolution in the longitudinal phase space of the machine can be described using a block circulant matrix.</u>

A bunch oscillating with synchrotron oscillation is rotating in the phase space.



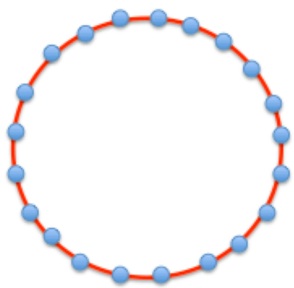
$$\begin{pmatrix} x_1 \\ \Delta p_1/p \\ \cdots \\ \cdots \\ x_{n_b} \\ \Delta p_{n_b}/p \end{pmatrix}_{n+1} = \mathbf{M} \times \begin{pmatrix} x_1 \\ \Delta p_1/p \\ \cdots \\ \cdots \\ x_{n_b} \\ \Delta p_{n_b}/p \end{pmatrix}_{n}$$

Evolution of n_b bunches in the normalized longitudinal phase space described with a stationary block circulant matrix **where each block represents a rotation matrix.**

The matrix solving the phase space system is a circulant matrix M and so the system stability can be studied by finding the eigenvalues and eigenvectors of the matrix M if the matrix can be put in diagonal form.

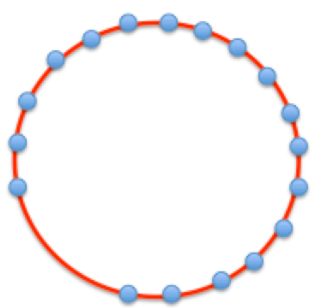
Circulant Matrix Approach (2/2)

- ## Circulant problem (Case of 21 bunches in h=21)



  - The train of bunches is regularly distributed along the machine azimuth
  - Independently from the impedance, if the problem is circulant, all the modes of the system are well known → eigenvectors are known and eigenvalues can be easily evaluated.

- ## NON-Circulant problem (Case of 18 bunches in h=21)



  - Circularity of the problem is lost
  - What comes from the mode analysis **is not a modal base**.
  - The impedance determine the modes of the system
  - **Developed an algorithm to identify the evolution matrix of the system.**

Algorithm in short

IPAC 2015

SIMULATIONS AND MEASUREMENTS OF LONGITUDINAL COUPLED-BUNCH INSTABILITIES IN THE CERN PS

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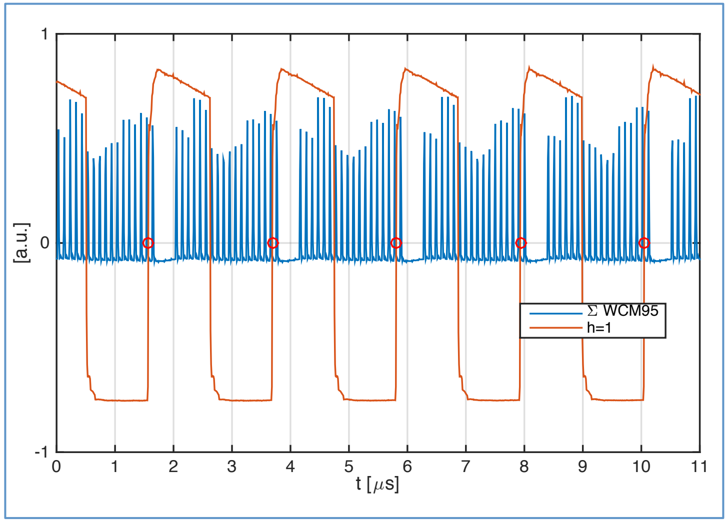
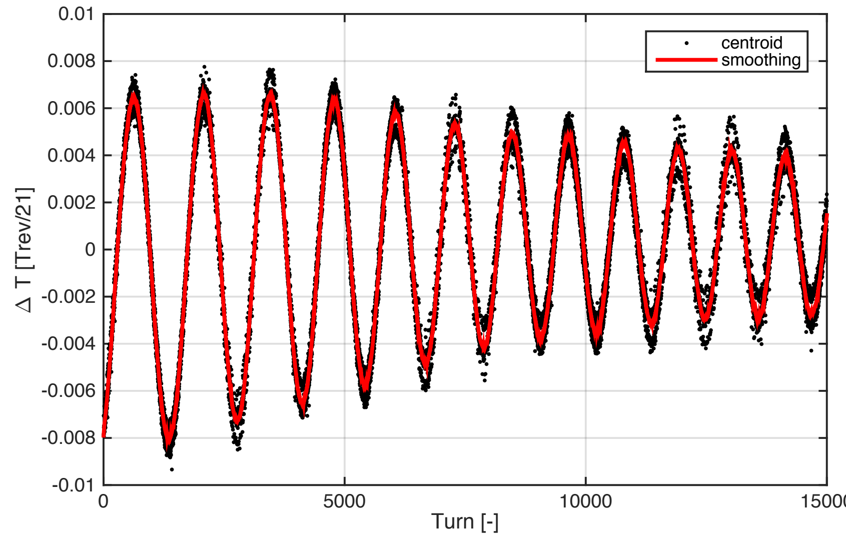
H. Damerau, G. Sterbini, CERN, Geneva, Switzerland

The longitudinal pickup read only the beam position x_i



Centroid evolution $X_i = a \cdot e^{j\phi}$



- **IDFT(X_i) → CB mode evolution**
- **From the IDFT of the centroids it is possible to reconstruct each rotation block of M.**

$$\begin{pmatrix} x_1 \\ \Delta p_1/p \\ \cdots \\ \cdots \\ x_{n_b} \\ \Delta p_{n_b}/p \end{pmatrix}_{n+1} = \mathbf{M} \times \begin{pmatrix} x_1 \\ \Delta p_1/p \\ \cdots \\ \cdots \\ x_{n_b} \\ \Delta p_{n_b}/p \end{pmatrix}_{n}$$

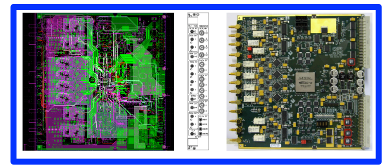
❖ Coupled-Bunch Feedback System Commissioning and Performances

In the frame of the LHC Injectors Upgrade project in 2014 a new wide-band Finemet cavity has been installed in the Proton Synchrotron as a part of the coupled-bunch feedback system.

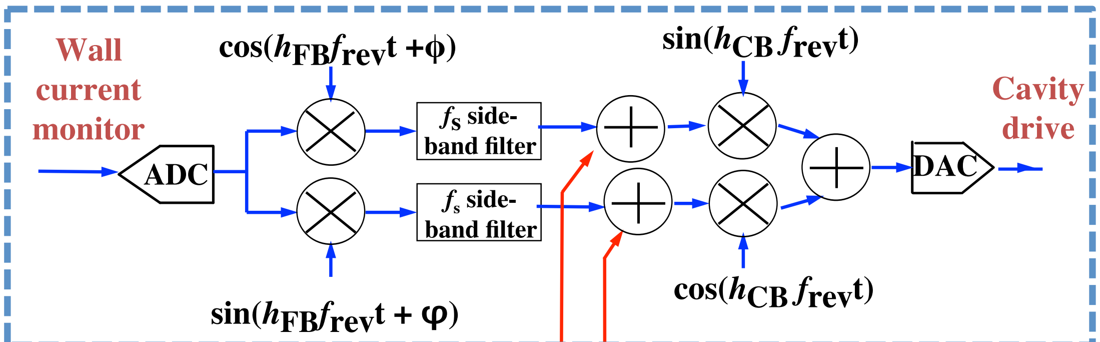
To explore the functionality of the Finemet cavity during 2015 a dedicated measurement campaign has been performed.

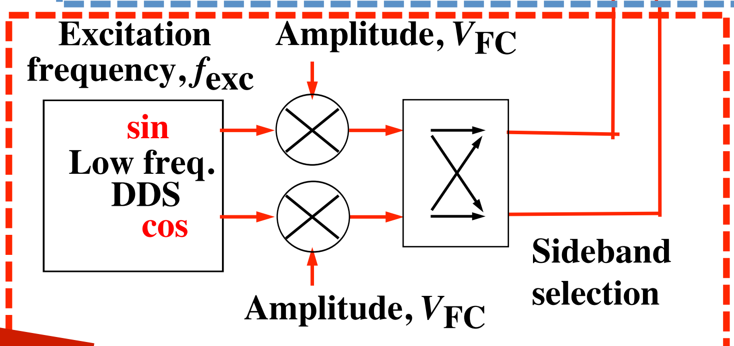
PS coupled-bunch feedback system

To explore the functionality of the Finemet cavity during 2015 a dedicated measurement campaign has been performed. The initial part of the chain has been substitute with an external perturbation → low frequency numerical oscillator in the firmware of the LLRF has been used to excite the beam with the Finemet cavity.



CB Feedback signal processing





Excitation Setup

2015

$$f_{CB} = h_{CB} f_{rev} \pm f_{exc}$$

1) With LS1 the **first wideband cavity** has been installed **in the PS**.
2) Wide-band cavity 0.4 → 5.5 MHz, V_{RF} = 5 kV
3) No acceleration, but damping of coupled-bunch oscillations
4) First installation of transistor power amplifiers (solid state) close to beam in PS.

The digital LLRF for the Finemet cavity detects synchrotron frequency side-bands indicating CB oscillations and feed them back to the beam via the Finemet cavity.

Excitation Measurements with the Finemet cavity

IPAC 2016

EXCITATION OF LONGITUDINAL COUPLED-BUNCH OSCILLATIONS WITH THE WIDE-BAND CAVITY IN THE CERN PS

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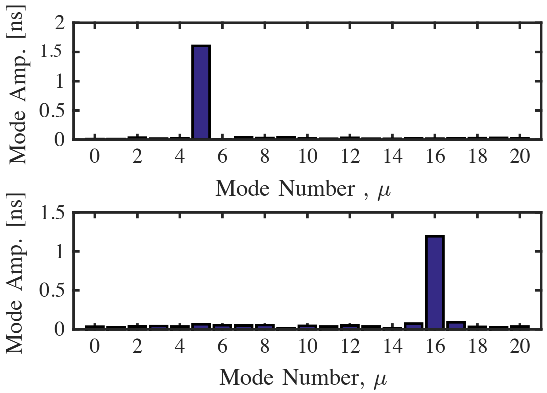
H. Damerau, G. Sterbini, CERN, Geneva, Switzerland

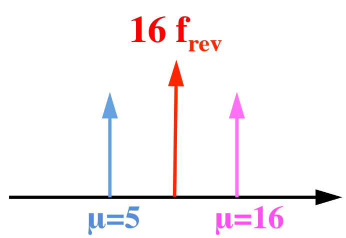
1) Frequency Scan

A preliminary set of measurements was necessary to explore the sensitivity of the excitation with the new wide-band cavity.

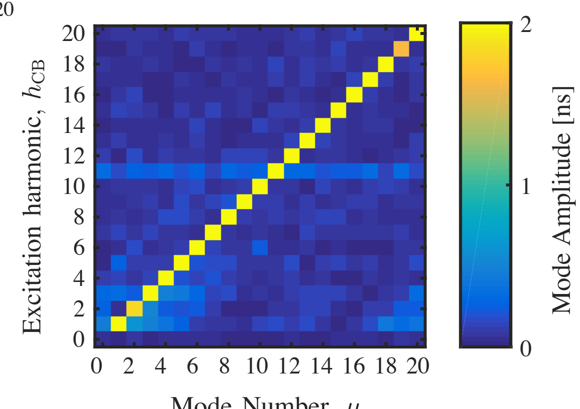
$$f = \mu f_{\mathrm{rev}} \pm f_{\mathrm{s}}$$ f_{rev}=476 kHz, f_s=390 Hz

2) Oscillation Mode Scan

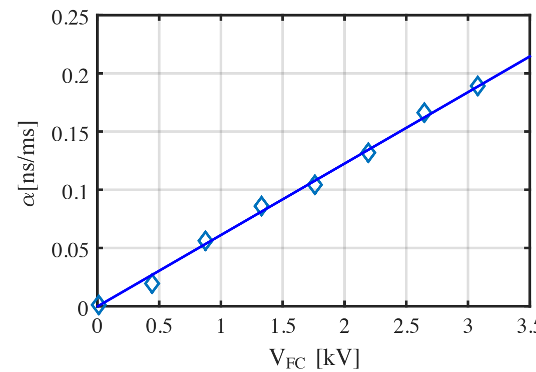




All modes can be excited individually



3) Excitation Voltage Scan



Linear excitation

The growth rate is proportional to the excitation voltage.

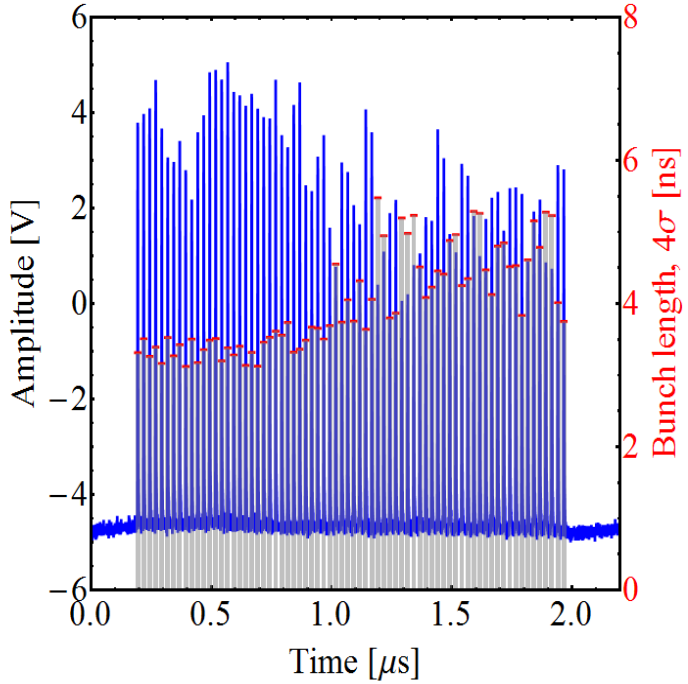
Finemet cavity interacts with the beam as expected

❖ Damping of CB instabilities: first results with the new feedback system

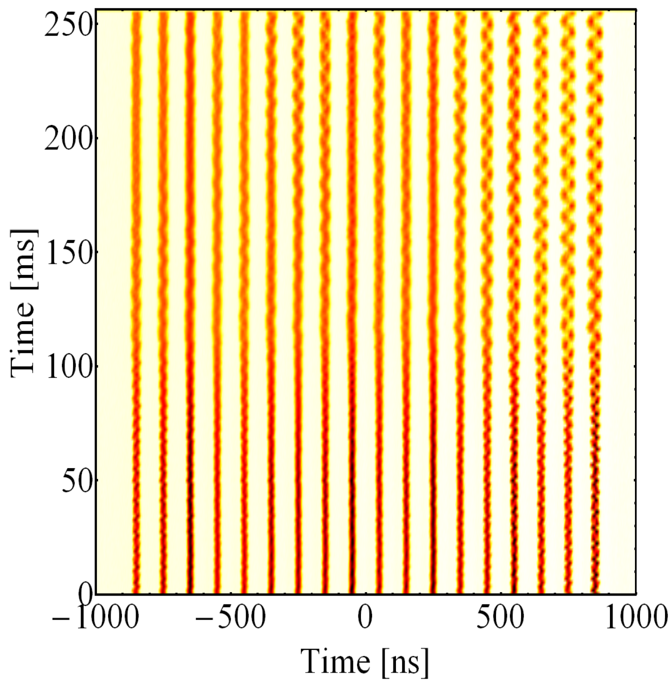
Intensity reach with coupled-bunch feedback

- Series of studies to increase intensity of nominal 72 bunch beam (at PS extraction)
- Explore limits of longitudinal stability with coupled-bunch feedback

Last turn, feedback off



Bunches on flat-top, feedback off



Intensity reach with coupled-bunch feedback

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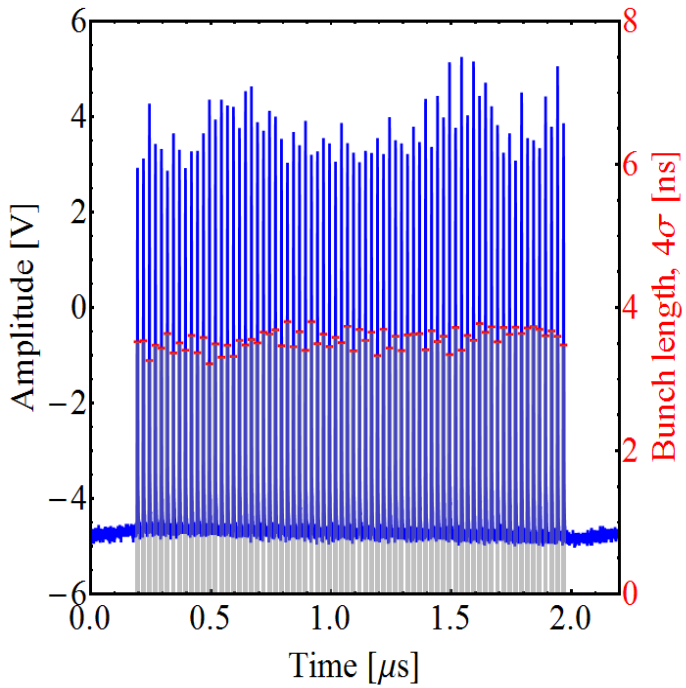
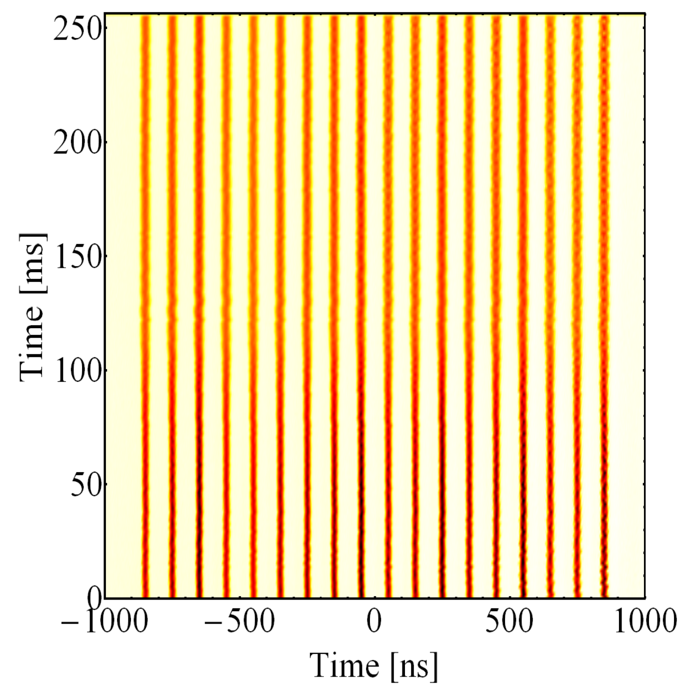




Bunch population of ~$2.2 \cdot 10^{11}$ ppb regularly reached
Beam delivered for high-intensity studies in SPS

Summary

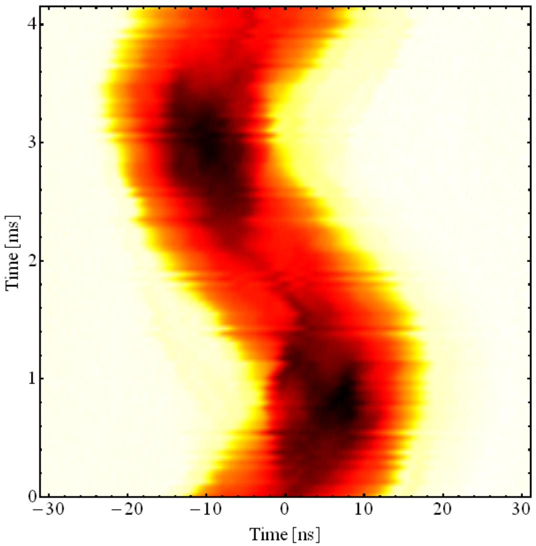
- The **impedance model** of the multi-harmonic RF system has been implemented in the simulation code.
- **10 MHz RF system** proved to be the **cause of CB instabilities** in the machine, **measurements crosschecked with simulations**
- LS1, installation of the **Finemet cavity** as longitudinal damper. Simulation proved that its **contribute to CB instability is negligible** compared to the stronger effect of the 10 MHz cavities.
- A **CB mode analysis technique** has been developed by using the **circulant matrices formalism**. The mathematical model has been applied to the measured data and benchmarked with simulations. Both circulant and not circulant case have been addressed.
- The complete prototype **feedback** chain of pick-up, digital processing and Finemet kicker has been **installed and commissioned.** First tests confirm that **coupled-bunch oscillations can be damped by the Finemet cavity in closed loop.**

What is next?

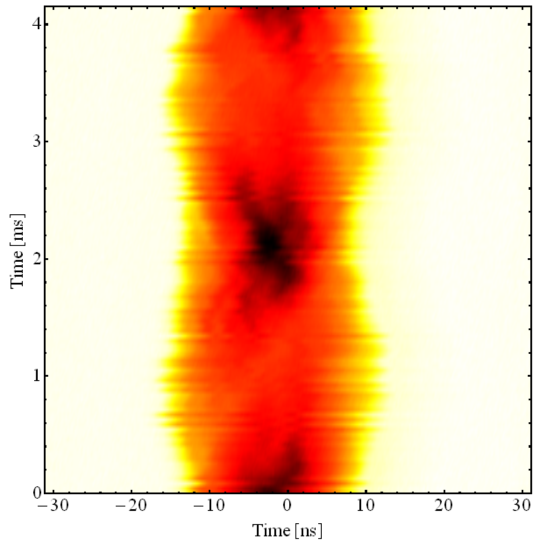
- New **impedance model** results from recent measurements: simulations need to be done to check the CB instabilities behaviour for the foreseen LIU beam.

- Even if dipolar modes seem to be well stabilized, quadrupolar oscillation could be an issue ……

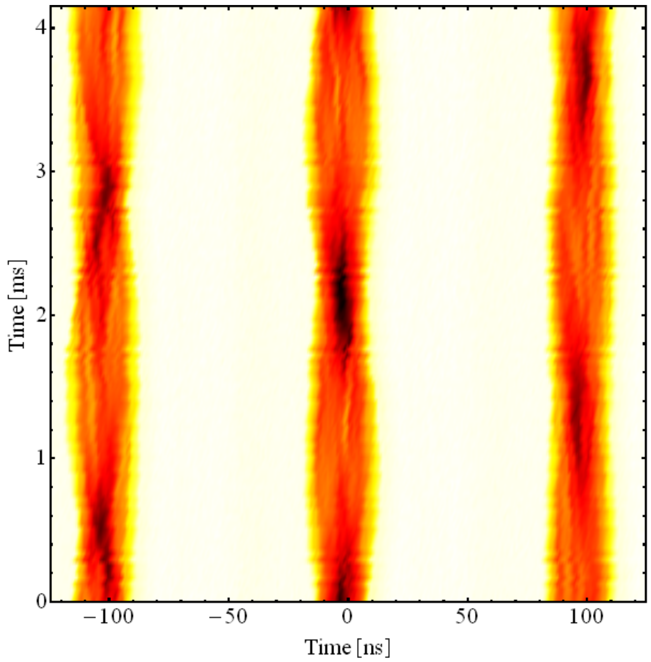
Feedback off



Feedback on



Quadrupolar coupled-bunch?



LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

CERN