Active methods of suppressing longitudinal multi-bunch instabilities

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ICFA Mini-Workshop on Impedances and Beam Instabilities in Particle Accelerators
26/09/2019

Many thanks to P. Baudrenghien, J. Galindo, M. Haase, G. Hagmann, M. Paoluzzi, D. Perrelet, E. Shaposhnikova, F. Tamura
Overview

• Introduction
  • Motivation
  • Global and local longitudinal feedback systems

• Global coupled-bunch feedback
  • Dipole coupled-bunch oscillation damping
  • Studies for damping of quadrupole coupled-bunch instabilities

• Local multi-harmonic feedback
  • Reduction of high-frequency cavity impedances
  • Uncontrolled emittance blow-up along bunch train

• Summary
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• Summary
Introduction and motivation

→ Main strategies to mitigate instabilities with feedback

<table>
<thead>
<tr>
<th>Reduce cavity impedances locally</th>
<th>Fight instabilities globally</th>
</tr>
</thead>
<tbody>
<tr>
<td>• RF system identified as driving impedance source → Poster: A. Lasheen</td>
<td>• Driving impedance source not known</td>
</tr>
<tr>
<td>• Separate feedback per RF station</td>
<td>• Detects beam instability and reduces it</td>
</tr>
<tr>
<td>• Reduce impedance at relevant freq.: $n f_{\text{rev}} \pm m f_S$</td>
<td>• Mostly dedicated to specific stability issue</td>
</tr>
<tr>
<td>→ Cure the cause, not the consequence</td>
<td>→ Cure consequence when cause unknown</td>
</tr>
</tbody>
</table>
Introduction and motivation

• Intensity with LHC-type multi-bunch beams doubles in injectors at CERN

• Major limitations for LHC-type beams in PS:
  1. Longitudinal coupled-bunch instabilities during acceleration above transition and at flat-top
  2. Uncontrolled emittance blow-up towards end of train

→ Intensity required for LIU/HL-LHC achieved at PS extraction (trains of 72 bunches spaced 25 ns):

\[ 1.3 \times 10^{11} \text{ p/b (2015)} \rightarrow 2.6 \times 10^{11} \text{ p/b (2018)} \]

→ Extensive use of longitudinal feedbacks to keep instabilities under control
RF systems in the PS

Acceleration

2.8 – 10 MHz
to SPS

Longitudinal blow-up

200 MHz

RF Manipulations

40 MHz

80 MHz

20 MHz

0.4 – 5 MHz

RF systems in the PS

200 MHz

Longitudinal blow-up

200 MHz

0.4 – 5 MHz

20 MHz
Longitudinal oscillation of bunches

- Longitudinal bunch oscillations can be damped in time or frequency domain

<table>
<thead>
<tr>
<th>Time domain</th>
<th>Frequency domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Measure phase of each bunch</td>
<td>• Measure spectral component corresponding to mode</td>
</tr>
<tr>
<td>• Time domain multiplex</td>
<td>• Detect sidebands at $\pm mf_s$</td>
</tr>
<tr>
<td>→ Apply kick to bring phase or energy back to reference pos.</td>
<td>→ Apply kick to remove that spectral component</td>
</tr>
<tr>
<td>→ “Bunch-by-bunch”</td>
<td>→ “Mode-by-mode”</td>
</tr>
<tr>
<td>→ Most common in machines with quasi-constant $f_{\text{rev}}$</td>
<td>→ Independent of bunch timing: sweeping $f_{\text{rev}}$</td>
</tr>
<tr>
<td>→ Electron storage rings</td>
<td>→ Proton synchrotrons</td>
</tr>
<tr>
<td>→ Complex when $f_{\text{rev}}$ sweeps</td>
<td>→ Complex in time domain</td>
</tr>
</tbody>
</table>
Frequency domain: Mode-by-Mode

- Suppress components in beam spectrum
- Fixed phase advance from bunch-to-bunch creates sideband at $nf_{\text{rev}}$

\[ f = n f_{\text{rev}} \pm m f_S \]

\[ 2\pi \cdot 10/21 \text{ phase advance: } n = 10, \; m = 1 \]
Frequency domain: Mode-by-Mode

- Suppress components in beam spectrum
- Fixed phase advance from bunch-to-bunch creates sideband at $nf_{\text{rev}}$
  \[ f = n f_{\text{rev}} \pm m f_S \]

2π·10/21 phase advance: $n = 10, m = 1$

- No sidebands at $+/\pm f_S$
  → Dipole oscillations removed
- No sidebands at $+/\pm 2f_S$
  → Quadrupole oscillations removed
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PS coupled-bunch feedback overview

Six-cell Finemet cavity:
→ $V_{RF}$ up to 6 kV from 0.4 to 5 MHz

Beam signal from wall current monitor

Digital signal processing

$f_{clk} = 256 f_{rev}$

- Detect $f_s$ sidebands at 11...20 $f_{rev}$
- Drive kicker cavity at 1...10 $f_{rev}$
Instability at flat-top in PS

- Stop RF manipulations at flat-top to observe evolution of stability

\[ N_b = 1.8 \cdot 10^{11} \text{ p/b} \]

- Dipole coupled bunch oscillations build up along the batch
  \[ \rightarrow \text{Low } 2Q/\omega_0 \text{ impedance source decaying during } \sim 400 \text{ ns gap} \]
- Already well developed at start of first splitting manipulation

2\textsuperscript{nd} splitting, \( h = 42 \rightarrow 84 \)

1\textsuperscript{st} splitting, \( h = 21 \rightarrow 42 \)

* at extraction, 4× more before splitting at flat-top
Instability at flat-top in PS

- Stop RF manipulations at flat-top to observe evolution of stability
- Coupled-bunch feedback enabled $\rightarrow$ significant improvement

$N_b = 1.8 \cdot 10^{11}$ p/b

- Damps dipole coupled-bunch oscillations
  $\rightarrow$ Limited by strength (maximum voltage) of longitudinal kicker
Instability at flat-top in PS

- Stop RF manipulations at flat-top to observe evolution of stability
- Coupled-bunch feedback enabled $\rightarrow$ significant improvement

\[
N_b = 1.8 \cdot 10^{11} \text{ p/b}
\]

\[
N_b = 2.0 \cdot 10^{11} \text{ p/b}
\]

- Damps dipole coupled-bunch oscillations
- Quadrupole oscillations at $\sim 2 \cdot 10^{11} \text{ p/b}$
  $\rightarrow$ Not damped by present feedback system
Signal processing

- Suppress $f_s$ side-bands by actively compensating them
  - Remove spectral components at $n \cdot f_{rev}$ and amplify $n \cdot f_{rev} \pm f_s$
  - Keep only synchrotron frequency sidebands

- Ten notches covering all 20 possible modes ($h = 21$), other than $n = 0$
- Relative phase advance of quadrupole and dipole mode fixed
- Simultaneous damping of both modes impossible with this processing
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Quadrupole damping?

Main questions:

1. **Is existing longitudinal kicker cavity suitable for quadrupole mode damping?**
   - What cannot be excited, cannot be damped
   - Try to excite quadrupole coupled-bunch oscillation
   - Compare excitation efficiency with excitation of dipole modes

2. **How to adapt signal processing?**
   - Separate sidebands at $\pm f_s$ (dipole) from $\pm 2f_s$ (quadrupole)
   - Independent signal processing to set phase advance
Excitation of oscillations

Measure efficiency of dipole and quadrupole mode excitation at PS flat-top

Sideband at $\sim f_S$ of $20f_{\text{rev}}$

$\rightarrow$ Dipole oscillation

Sideband at $\sim 2f_S$ of $20f_{\text{rev}}$

$\rightarrow$ Quadrupole oscillation
Efficiency of excitation

- Excitation with same voltage at $2nf_{\text{rev}} \pm f_{\text{rev}}$ or $2nf_{\text{rev}} \pm 2f_{\text{rev}}$

$\rightarrow$ Dipole oscillation

$\rightarrow$ Quadrupole oscillation

$\rightarrow$ Excitation of quadrupole oscillations possible
$\rightarrow$ Expected symmetry of $n = 20$ and $n = h - 20 = 1$ modes
$\rightarrow$ Less efficient by a factor of 2-3 (depending on bunch length)

$\rightarrow$ Damping of quadrupole coupled-bunch oscillation feasible with existing longitudinal kicker cavity
Signal processing for combined damping

1. Filter beam signal around $nf_{\text{rev}}$

$$n = \frac{f}{f_{\text{rev}}}$$

→ Keep only $nf_{\text{rev}} \pm f_S$ and $nf_{\text{rev}} \pm 2f_S$

$$q_S = \frac{f_S}{f_{\text{rev}}} \approx 10^{-3}$$

2. Filter around $\pm f_S$ and $\pm 2f_S$

$$m = \frac{f}{f_S}$$

→ Individual filter per $f_S$ sideband

→ Independent control of phase advance for dipole and quadrupole oscillations

→ Beam test in PS after LS2?
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Perturbation due to 80 MHz cavity impedance

- 3 vacuum resonators at 80 MHz with feedback
  → 2 needed for proton bunch rotation
  → 1 for ion bunch shortening
→ Switchable impedance: Compare impedance of 2 or 3 cavities with gap open

<table>
<thead>
<tr>
<th>RF system parameters</th>
<th>Direct FB</th>
<th>No FB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loaded shunt impedance, $R$</td>
<td>5.6 kΩ</td>
<td>1.26 MΩ</td>
</tr>
<tr>
<td>Loaded quality factor, $Q$</td>
<td>100</td>
<td>11800</td>
</tr>
<tr>
<td>Direct feedback gain</td>
<td>~40 dB</td>
<td>none</td>
</tr>
</tbody>
</table>

→ Indication that 80 MHz critical for longitudinal beam quality
→ Perturbations visible already at intensity of $N_b \approx 1.6 \cdot 10^{11}$ p/b
Effect of 80 MHz impedance in emittance

• Longitudinal multi-bunch tomography at arrival on flat-top

> Impedance of third cavity 80 MHz causes uncontrolled emittance blow-up at tail of batch

> Threshold effect when moving from ~11 kΩ to ~17 kΩ at 80 MHz
Impedance reduction of 80 MHz cavities

How to reduce coupling impedance?

- Optimize direct feedback loop

\[
G_{\text{max}} = \frac{\pi}{2} \frac{1}{R/Q} \frac{1}{\omega_0 \tau} \\
= \frac{\pi}{2} \frac{1}{R} \frac{1}{\Delta \omega_{-3\text{dB}}} \cdot \frac{1}{\tau}
\]

→ Minimize loop delay, \( \tau \)

→ Reduce loop bandwidth to damp only close to \( n \cdot f_{\text{rev}} \)

→ 1-turn delay (comb-filter) or multi-harmonic feedback

→ Similar configuration in other accelerators at CERN

→ Poster: Ivan Karpov
Impedance reduction of 80 MHz cavities

- Important impedance reduction about 20 dB: $R_s \rightarrow R_s/10$
- Only at the relevant revolution frequency harmonics

- Phase of notches dynamically adjusted: symmetric during full cycle
- Notch bandwidth sufficient for several $f_S$ sidebands
  - Limited by electrical stability due to phase error at $nf_{rev} \pm \Delta f$
Beam induced voltage in 40/80 MHz cavities

- Effect of additional feedback on beam induced voltages

Spectrum during cycle

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>on</td>
</tr>
<tr>
<td>80</td>
<td>on</td>
</tr>
</tbody>
</table>

→ Impedance reduction of ~20 dB confirmed with beam
Effect on uncontrolled blow-up?

→ Multi-bunch tomography to quantify beneficial effect on emittance

→ Multi-harmonic feedbacks completed on all 40 MHz and 80 MHz cavities

→ Now operated during complete cycle

→ Major contribution in 2018 to reach HL-LHC intensities
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## Combination of feedbacks in the PS

<table>
<thead>
<tr>
<th>Feedback type</th>
<th>Remarks</th>
<th>RF system, $f_{res}$ [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2.8…10</td>
</tr>
<tr>
<td>Direct</td>
<td>• Delivers base impedance reduction</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>• Reduction of transient beam loading</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• <strong>Impossible to operate without</strong></td>
<td></td>
</tr>
<tr>
<td>1-turn delay</td>
<td>• Reduction of transient beam loading</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>• <strong>Little effect on coupled-bunch instabilities</strong></td>
<td></td>
</tr>
<tr>
<td>Multi-harmonic</td>
<td>• When 1-turn del. FB not applicable</td>
<td>(✓)</td>
</tr>
<tr>
<td>Coupled-bunch (mode domain)</td>
<td>• Controls dipole coupled-bunch oscillations</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• <strong>Studying extension to quadrupole mode damping</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dedicated Finemet cavity as longitudinal kicker</td>
</tr>
</tbody>
</table>

→ **Total of 35 longitudinal feedback loops for LHC-type beams**
Summary

• Combination of local and global feedbacks
  → Reduce driving impedances → Cure source
  → Damp instability → Minimize consequence

• PS case:
  → Direct feedbacks for all cavities (except 200 MHz)
  → 1-turn delay feedbacks → Little effect on coupled-bunch instabilities

• New multi-harmonic feedbacks for 20, 40, 80 MHz cavities
  → Removes uncontrolled blow-up towards tail of bunch train
  → Little effect on coupled-bunch instabilities

✓ Reached intensity of $2.6 \times 10^{11}$ p/b as required for HL-LHC

• Coupled-bunch feedback
  → Damping of dipole modes only so far
  → Preliminary studies to add higher order (quadrupole) mode damping
LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!
Spare slides
Intensity evolution (25 ns, 72 bunches)

- LIU baseline of $2.6 \cdot 10^{11}$ p/b finally within reach
- Multi-harmonic feedbacks
- C40-78 as Landau RF system
- Suspected feedback saturation
- Optimization 2017
- Finemet dipole-mode coupled-bunch feedback
- Reach with C10-86/96 coupled-bunch feedback (2005)*

*Intensities $>1.3 \cdot 10^{11}$ p/b were delivered <2016, but not with sufficient quality for LHC
Inject 4+2 bunches

Controlled blow-ups

$h = 7$

Eject 72 bunches

$\gamma_{tr}$

Instability and blow-up

$\gamma = 21$

$\gamma = 84$

Triple splitting at $E_{\text{kin}} = 2.5$ GeV

Cycle time [s]

Split in four at flat top energy

$E_{\text{kin}} = 2.5$ GeV

2nd injection

$LHC$-type beam with 25 ns spacing in the PS

$E_{\text{kin}} = 2.5$ GeV

$26$ GeV/c
Impedance reduction 40/80 MHz cavities

Main technical challenges:
1. Phase of cavity impedance not linear
2. Cavity resonance at fixed resonance while $f_{\text{rev}}$ sweeping

40 MHz cavity transfer function

→ Periodic filters of conventional 1-turn delay feedback not adapted
→ Independent feedback channels per harmonic
→ Dynamic phase adjustment according to $f_{\text{rev}}$
Effect on uncontrolled blow-up?

→ Multi-bunch tomography to quantify beneficial effect on emittance

Beam induced spectrum
C80-88, feedback on/off

→ Multi-harmonic feedbacks completed on all 40 MHz and 80 MHz cavities

→ Now operated during complete cycle

→ Major contribution in 2018 to reach LIU intensities

![Plot showing longitudinal emittance at flat-top with feedbacks on and off.](image)
Mode-by-mode feedback at CERN PS

- $h_{\text{RF}} = 21 \rightarrow 21$ possible oscillation modes in total
  - Zero mode stabilized by beam phase loop
  - Mode pairs $n_1 + n_2 = h_{\text{RF}}$: different sidebands of same $f_{\text{rev}}$ harmonic
  - 10 signal processing channels in parallel
  - Independently adjustable phase and gain for each channel
Stability during acceleration

- Longitudinal stability at arrival on flat-top, $N_b = 4 \cdot 2.0 \cdot 10^{11}$ p/b
Quadrupole oscillations after transition

- Emulating higher intensity by increasing density $N_b/\varepsilon_i$

→ Quadrupole instabilities observed right after transition crossing

→ Measurements at $2.0 \cdot 10^{11}$ p/b

Nominal emittance: $\varepsilon_{i,90\%} = 0.95$ eVs

Reduced emittance: $\varepsilon_{i,90\%} = 0.64$ eVs

→ No damping from coupled-bunch feedback
Excitation of dipole oscillation modes

→ Generate small RF voltage at $n \cdot f_{\text{rev}} \pm f_S$ and analyze oscillation

→ Defined kick strength for wide-band kicker cavity
Choice of frequency ranges: cross-damping

1. Detect $f_s$ sidebands at $11\ldots20\ f_{\text{rev}}$
2. Correct beam at $1\ldots10\ f_{\text{rev}}$

→ 20 modes → 10 signal processing chains

Best shunt impedance: 0.4 to 5 MHz
Tracking filters – coupled-bunch damping

- Sharp attenuation to separate $\pm f_s$ of sidebands from $f_{rev}$ harmonics
- Sharp $180^\circ$ phase jump at center frequency
- Programmable gain, delay and phase
- Demodulation (at $h_{down}$)/modulation (at $h_{up}$) at different harmonics
- Sideband inversion for cross-damping