LHC Injectors Upgrade

CERN

LHC Injectors Upgrade

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

CERN

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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Introduction and motivation

→ **Main strategies to mitigate instabilities with feedback**

Reduce cavity impedances **locally**	Fight instabilities **globally**
• **RF system identified as driving impedance source** → Poster: A. Lasheen • **Separate feedback per RF station** • **Reduce impedance at relevant freq.:** $nf_{rev} \pm mf_S$ → **Cure the cause,** not the consequence	• **Driving impedance source not known** • **Detects beam instability and reduces it** • **Mostly dedicated to specific stability issue** → **Cure consequence** when cause unknown

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):**

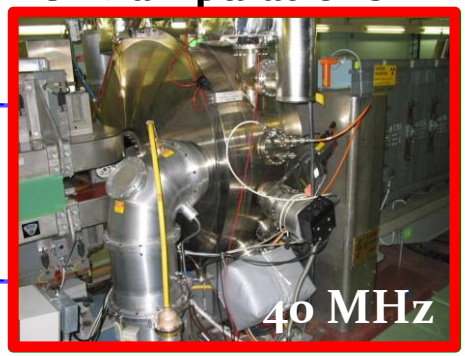
$1.3 \cdot 10^{11}$ p/b (2015) → $2.6 \cdot 10^{11}$ p/b (2018)

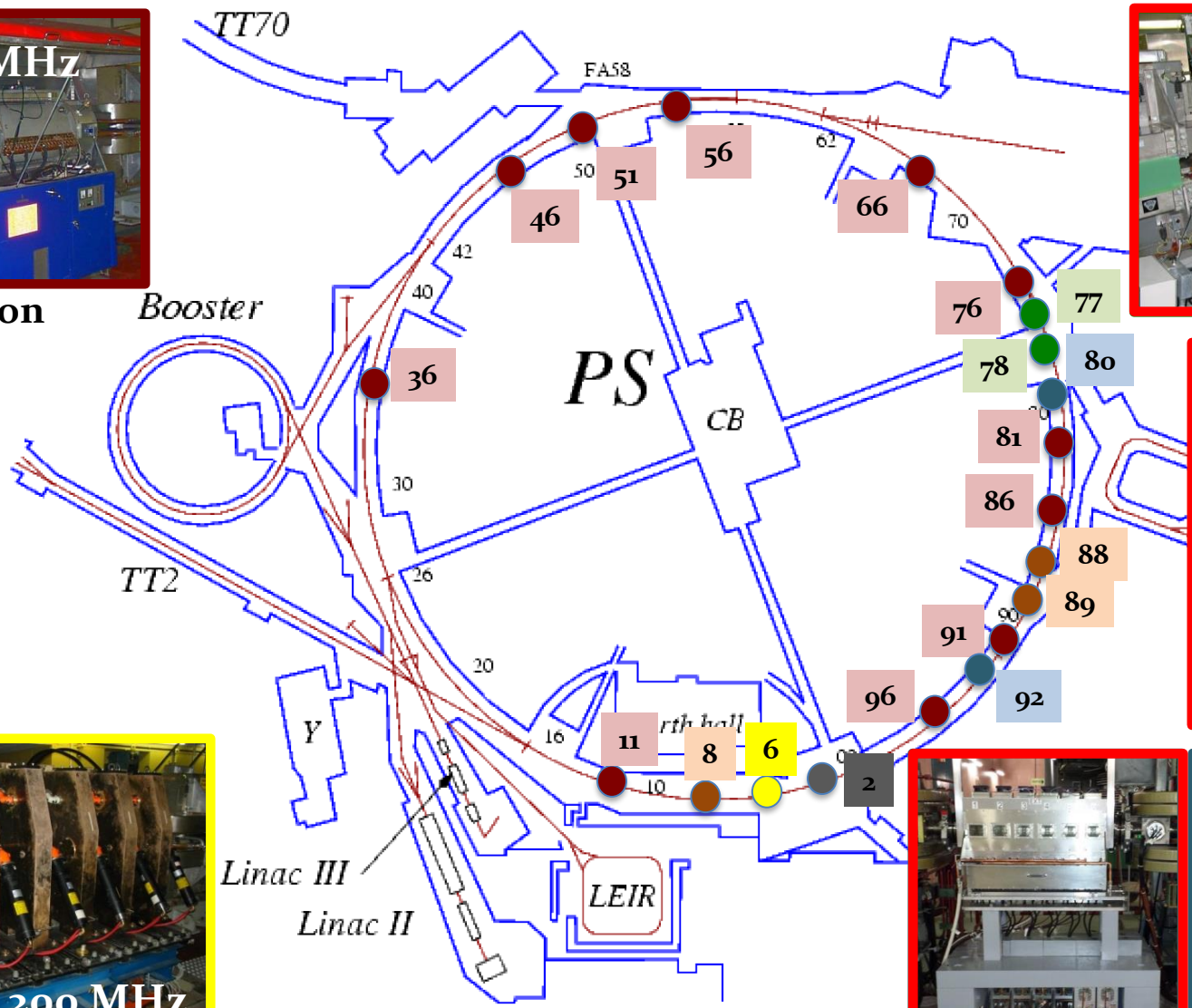
→ **Extensive use of longitudinal feedbacks to keep instabilities under control**

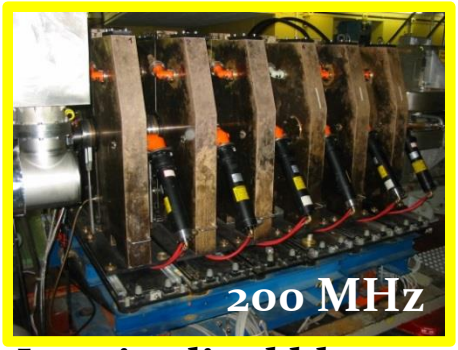
RF systems in the PS

Acceleration

RF Manipulations







Longitudinal blow-up

Longitudinal oscillation of bunches

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

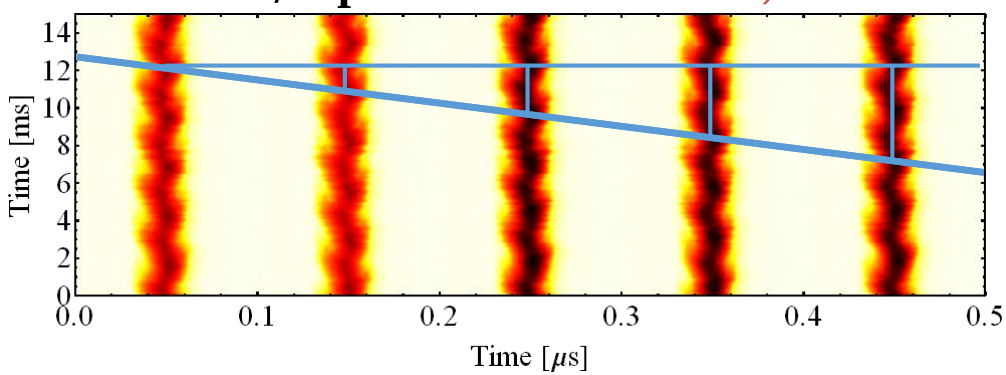
Time domain	Frequency domain
• Measure phase of each bunch • Time domain multiplex → Apply kick to bring phase or energy back to reference pos.	• Measure spectral component corresponding to mode • Detect sidebands at $\pm mf_S$ → Apply kick to remove that spectral component
→ "Bunch-by-bunch"	→ "Mode-by-mode"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

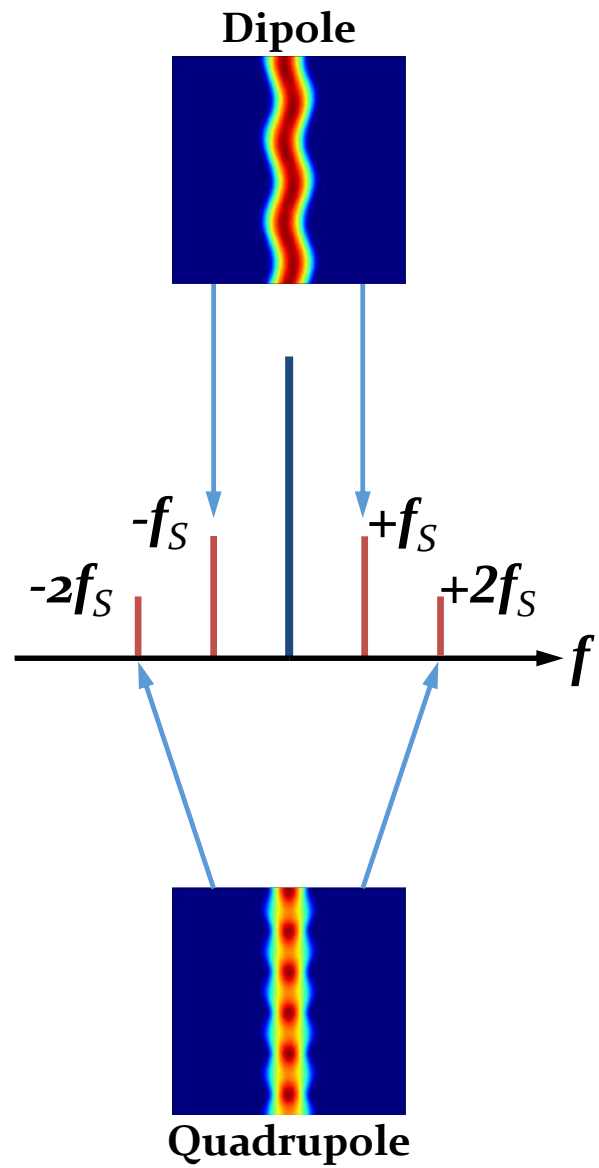
Frequency domain: Mode-by-Mode

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

$$f = nf_{\mathrm{rev}} \pm mf_{\mathrm{S}}$$

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





Frequency domain: Mode-by-Mode

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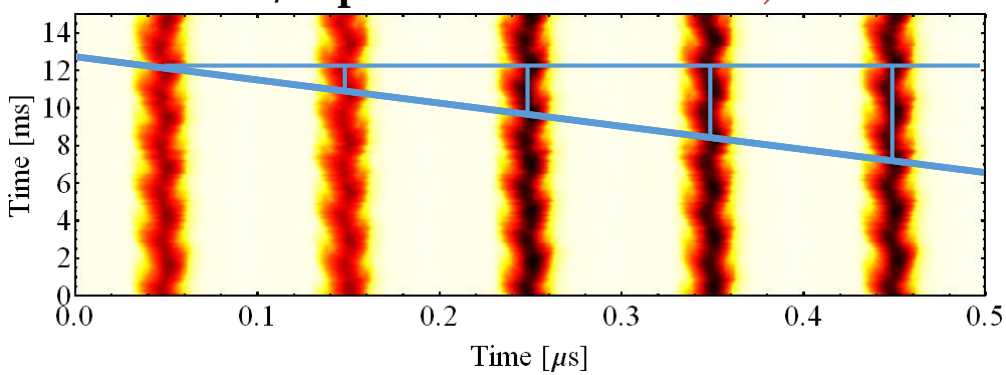
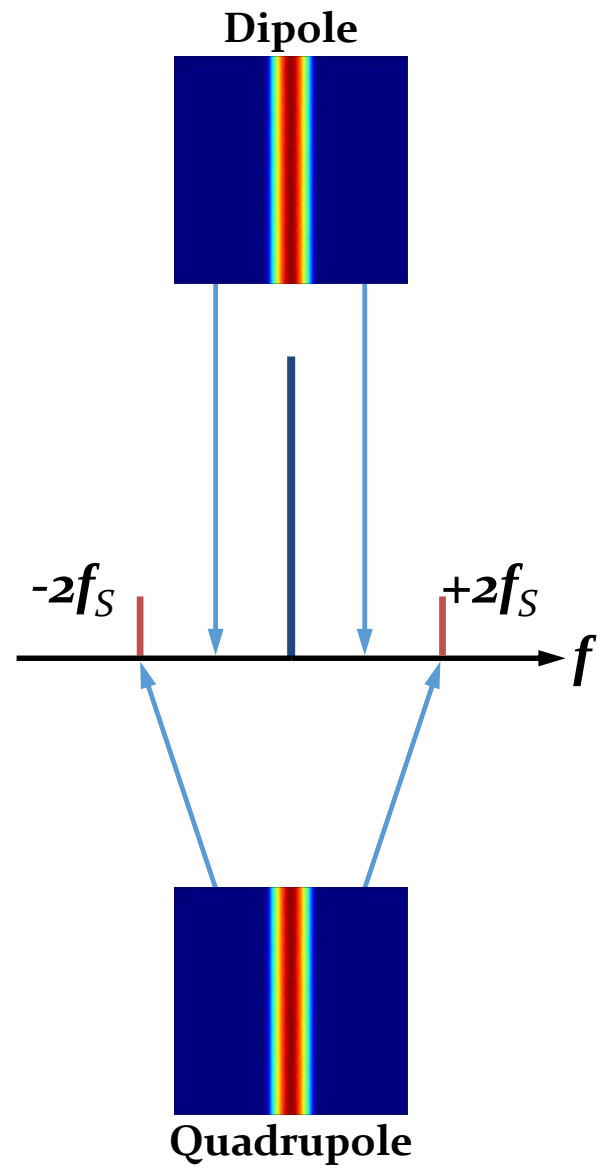


- **No sidebands at $+/-f_S$**
  → Dipole oscillations removed
- **No sidebands at $+/-2f_S$**
  → Quadrupole oscillations removed



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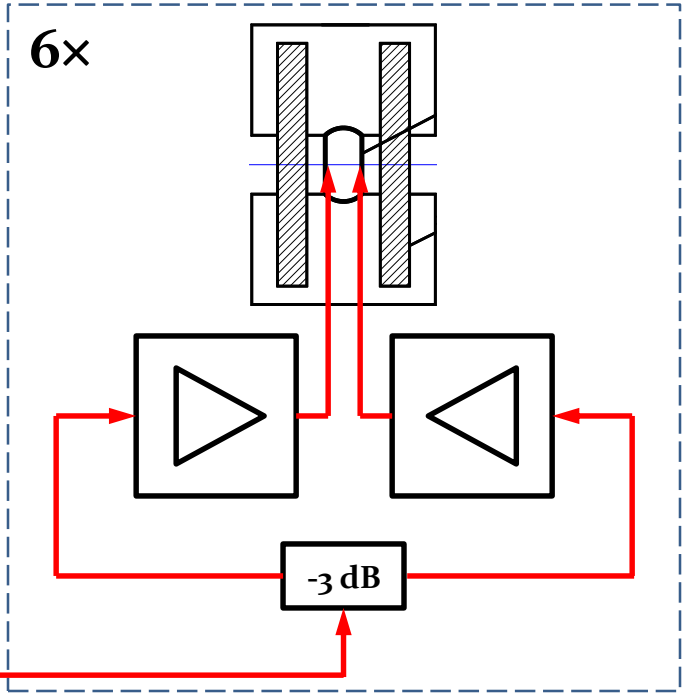
PS coupled-bunch feedback overview

Six-cell Finemet cavity:

→ V_{RF} up to 6 kV from 0.4 to 5 MHz



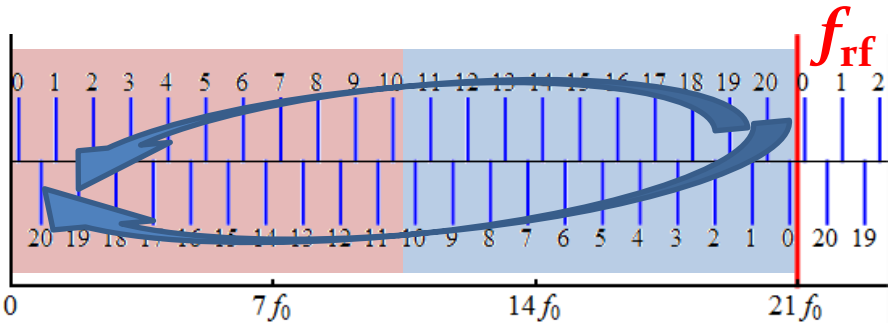
Beam signal from wall current monitor

Digital signal processing

Splitter + amp.

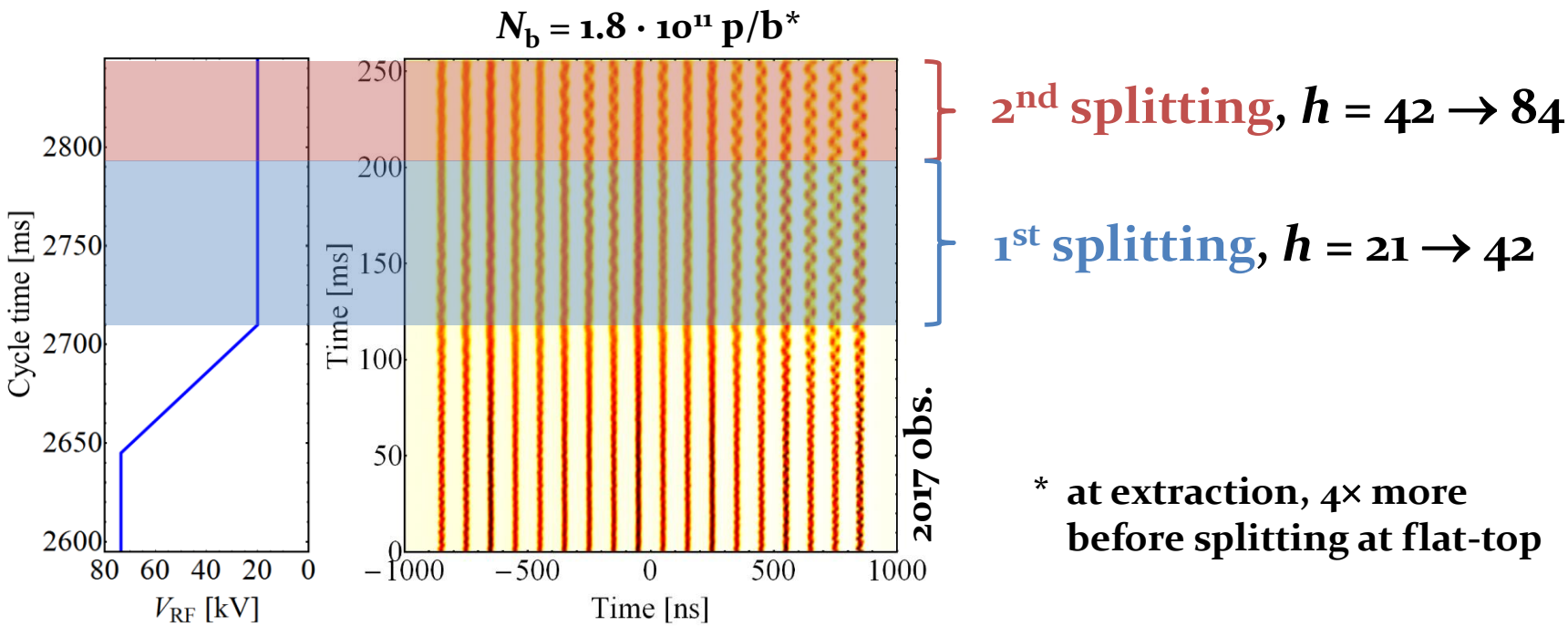
$f_{clk} = 256\, f_{rev}$

- **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**

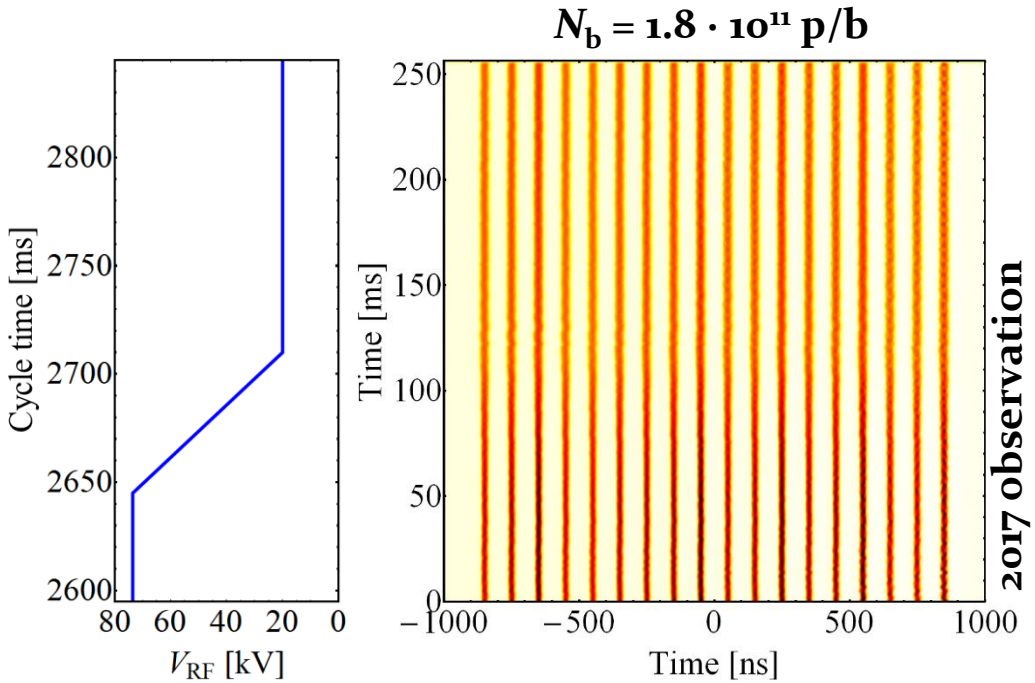


* at extraction, 4× more before splitting at flat-top

- **Dipole coupled bunch oscillations build up along the batch**
  → Low $2Q/\omega_0$ impedance source decaying during ~400 ns gap
- **Already well developed at start of first splitting manipulation**

Instability at flat-top in PS

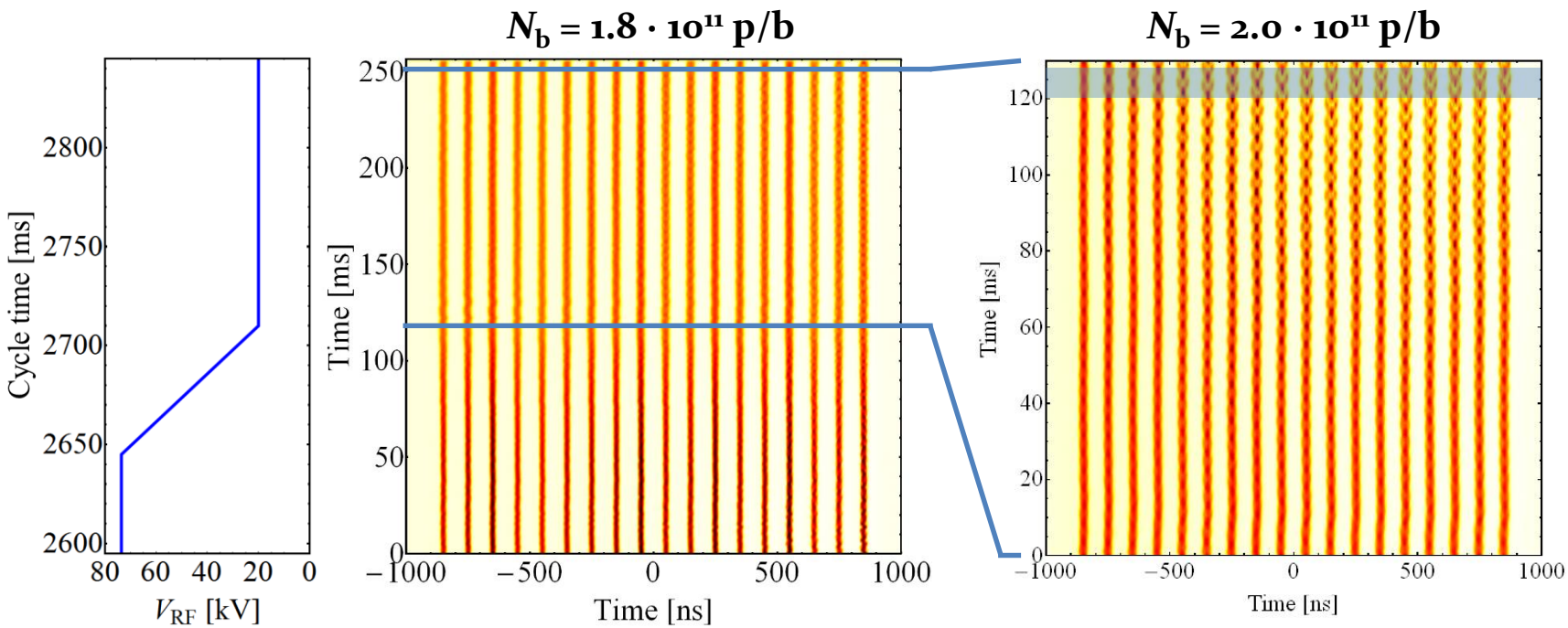
- **Stop RF manipulations at flat-top to observe evolution of stability**
- **Coupled-bunch feedback enabled → significant improvement**



- **Damps dipole coupled-bunch oscillations**
  → **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 → significant improvement**

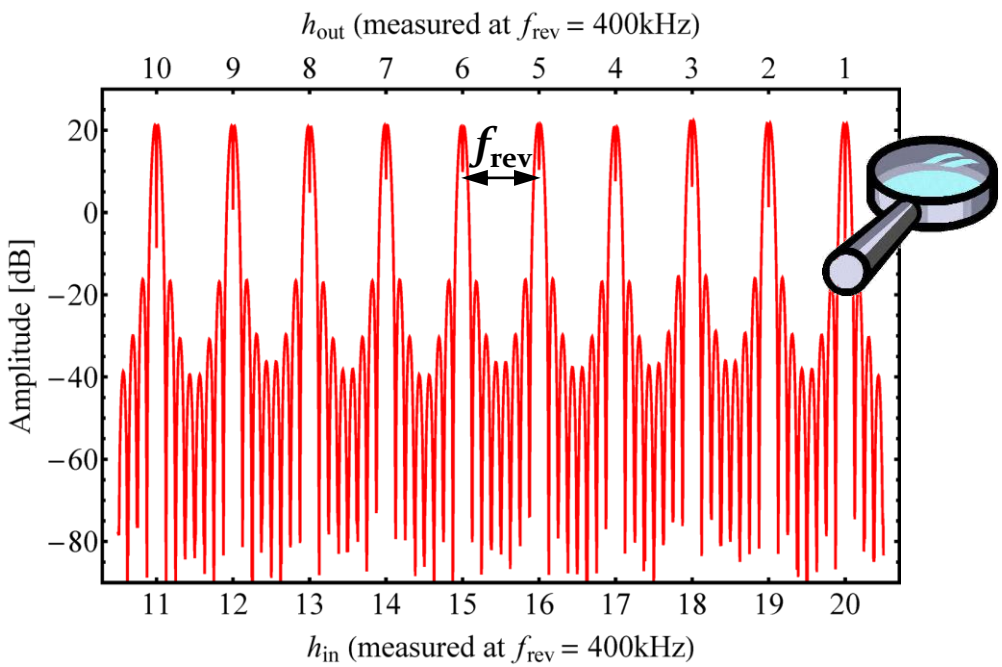


- **Damps dipole coupled-bunch oscillations**
- **Quadrupole oscillations at ~$2 \cdot 10^{11}$ p/b**

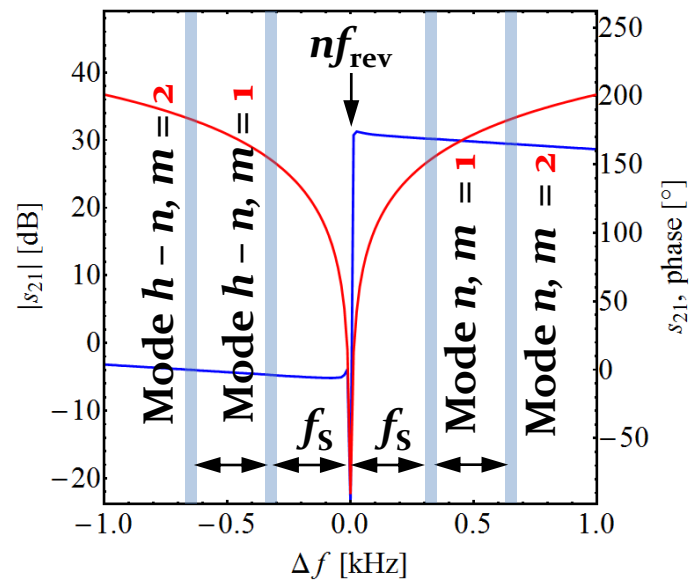
  → **Not damped by present feedback system**

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**



Filter transfer function



F. Pedersen et al., PAC1977

→ **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:

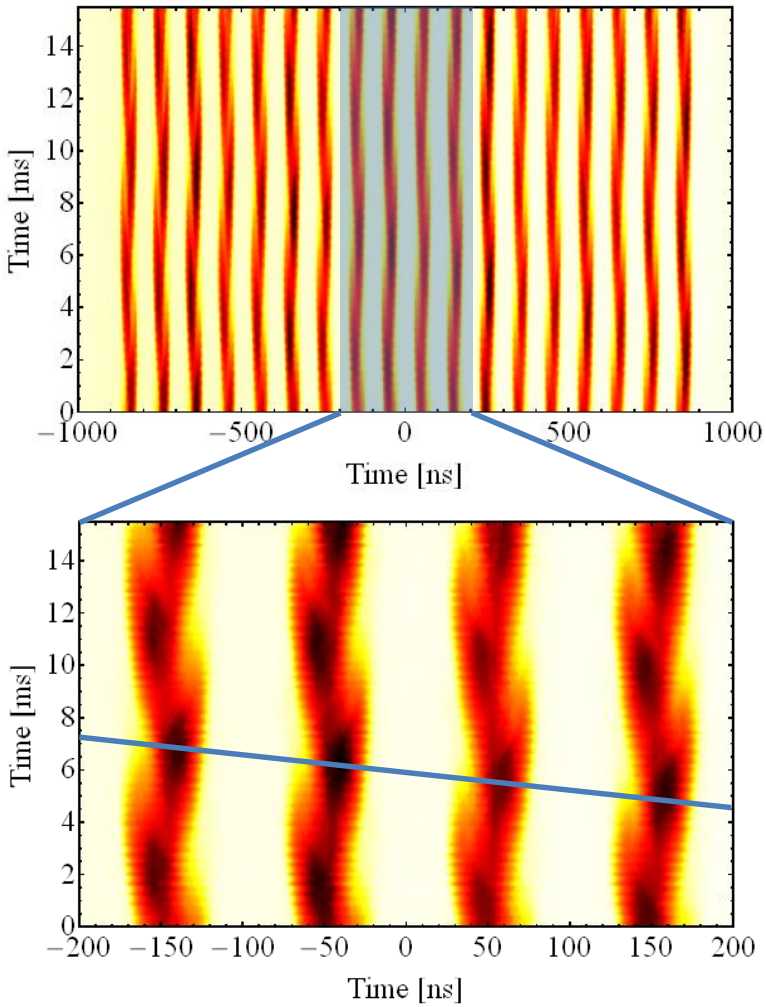
1. **Is existing longitudinal kicker cavity suitable for quadrupole mode damping?**
   - → **What cannot be excited, cannot be damped**
   - → **Try to excite quadrupole coupled-bunch oscillation**
   - → **Compare excitation efficiency with excitation of dipole modes**

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

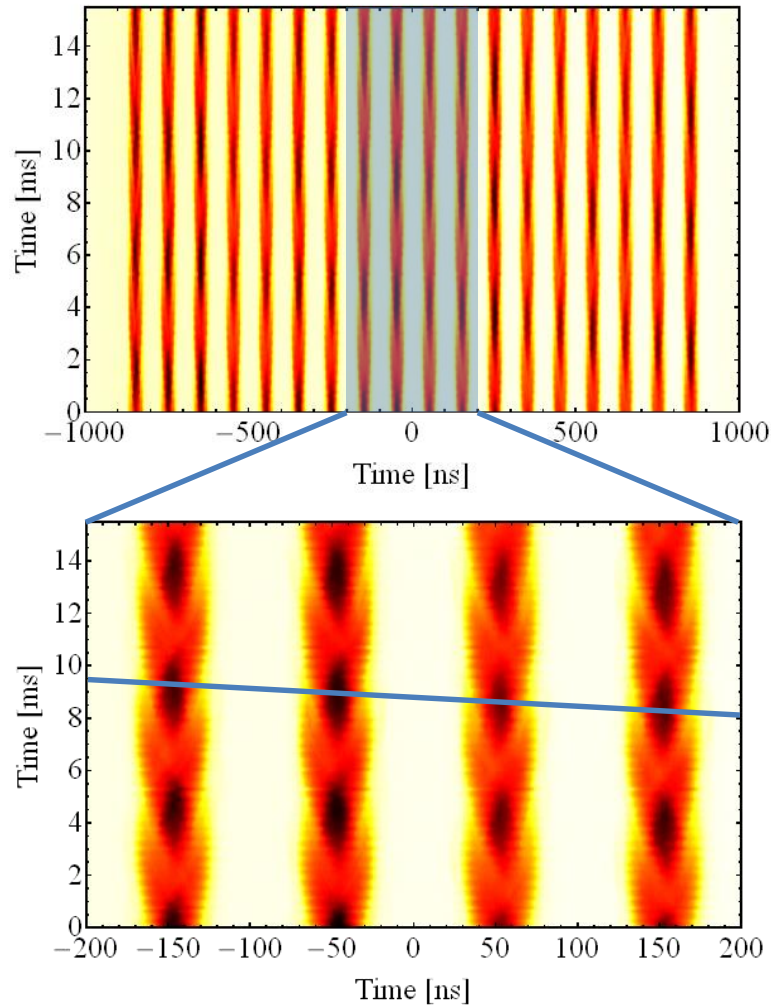
Measure efficiency of dipole and quadrupole mode excitation at PS flat-top

Sideband at ~f_S of $20f_{rev}$



→ Dipole oscillation

Sideband at ~$2f_S$ of $20f_{rev}$

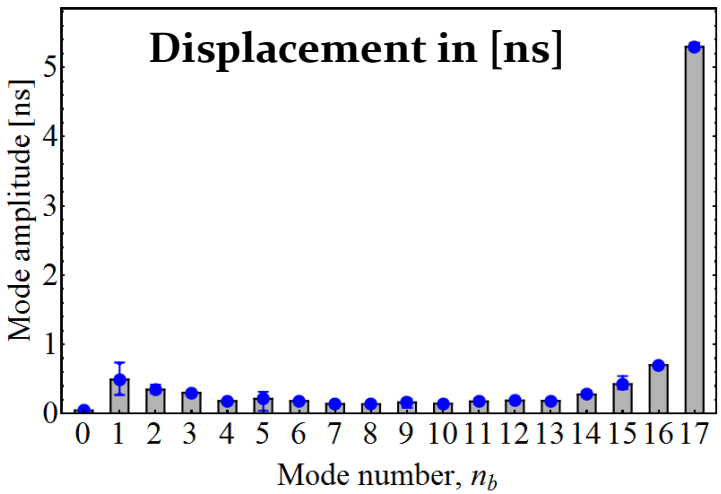


→ Quadrupole oscillation

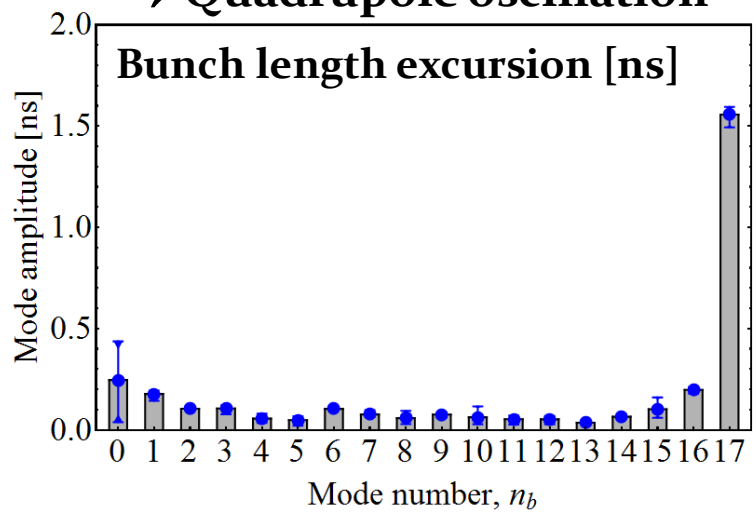
Efficiency of excitation

- **Excitation with same voltage at $20f_{rev} \pm f_{rev}$ or $20f_{rev} \pm 2f_{rev}$**

→ Dipole oscillation



→ Quadrupole oscillation



→ **Excitation of quadrupole oscillations possible**

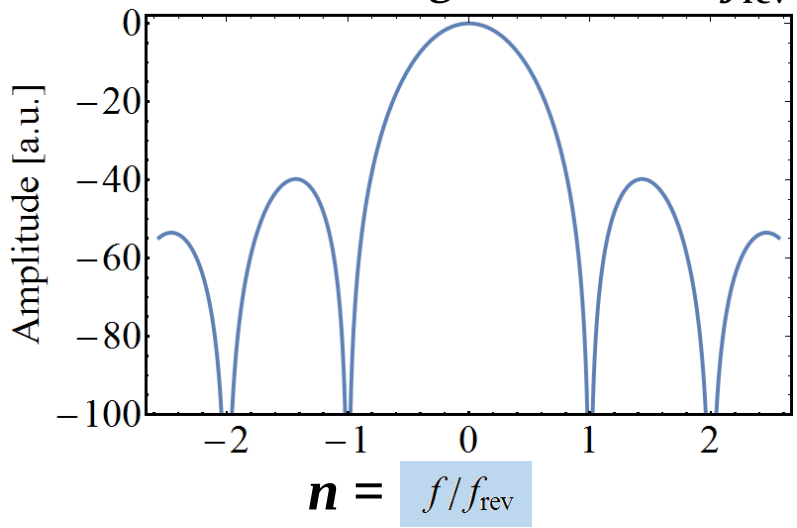
→ **Expected symmetry of $n = 20$ and $n = h - 20 = 1$ modes**

→ **Less efficient by a factor of 2-3 (depending on bunch length)**

→ **Damping of quadrupole coupled-bunch oscillation feasible with existing longitudinal kicker cavity**

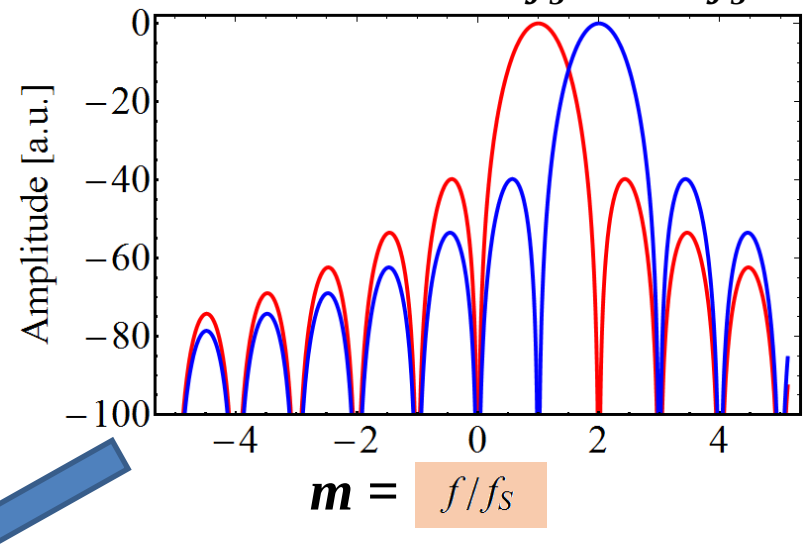
Signal processing for combined damping

1. Filter beam signal around nf_{rev}



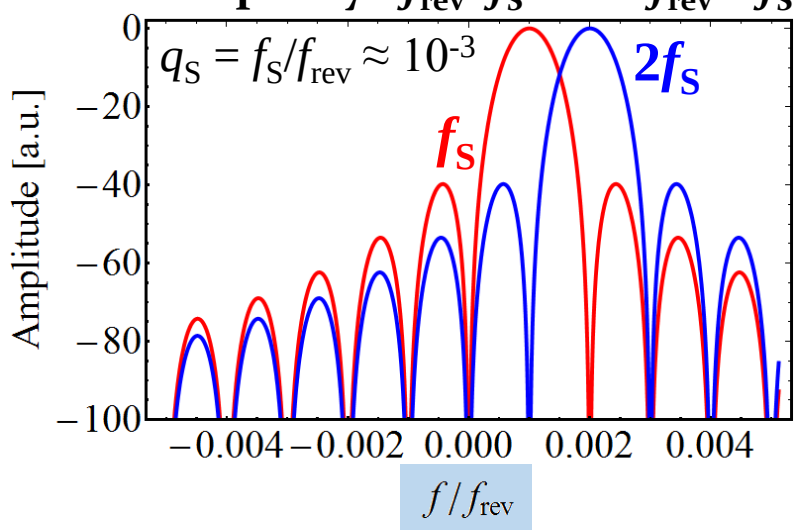
⊗

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



Y. Sugiyama et al., IEEE RT2018

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



→ **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

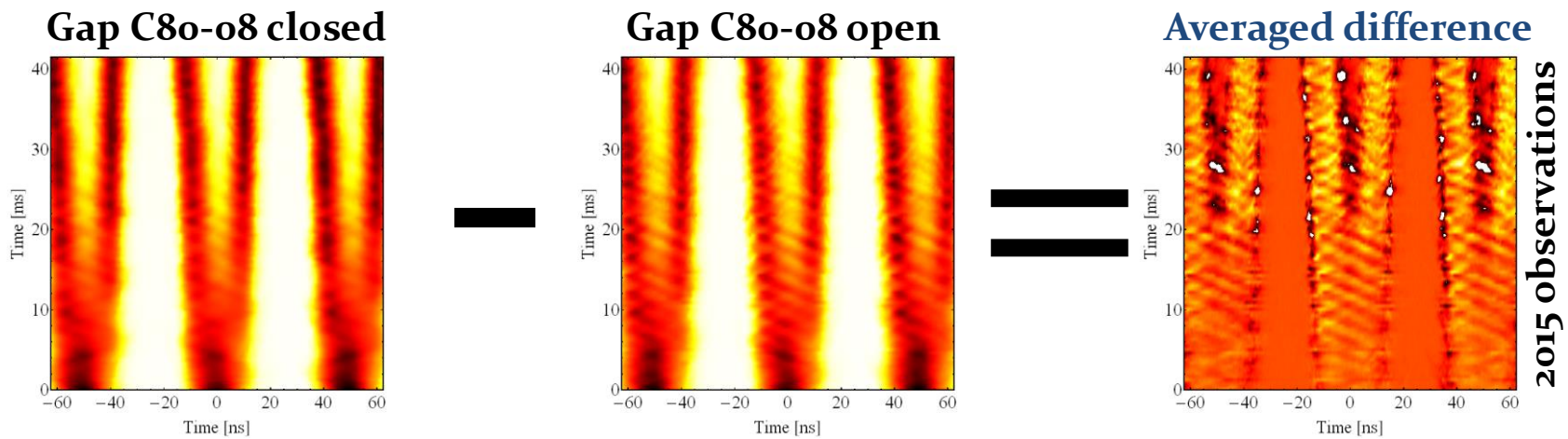
- 3 vacuum resonators at 80 MHz with feedback

→ 2 needed for proton bunch rotation

→ 1 for ion bunch shortening

RF system parameters	Direct FB	No FB
Loaded shunt impedance, R	5.6 kΩ	1.26 MΩ
Loaded quality factor, Q	100	11800
Direct feedback gain	~40 dB	none

→ **Switchable impedance:** Compare impedance of 2 or 3 cavities with gap open



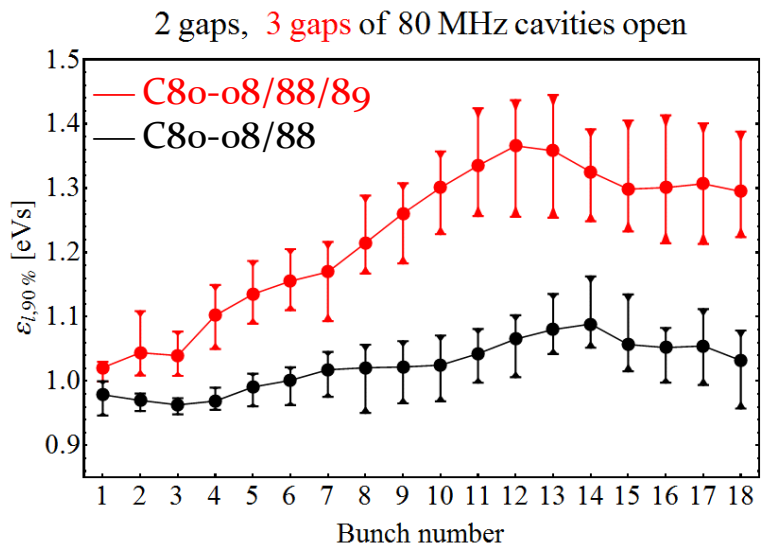
→ Indication that 80 MHz critical for longitudinal beam quality

→ Perturbations visible already at intensity of $N_b \approx 1.6 \cdot 10^{11}$ p/b

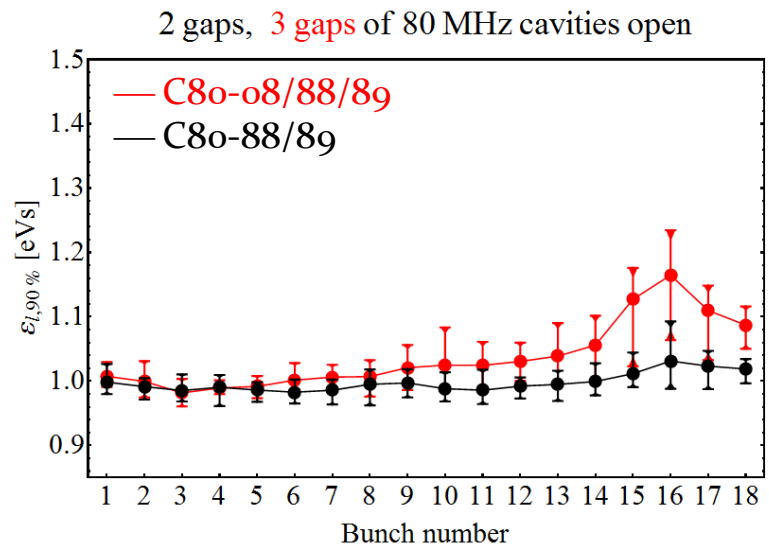
Effect of 80 MHz impedance in emittace

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

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



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

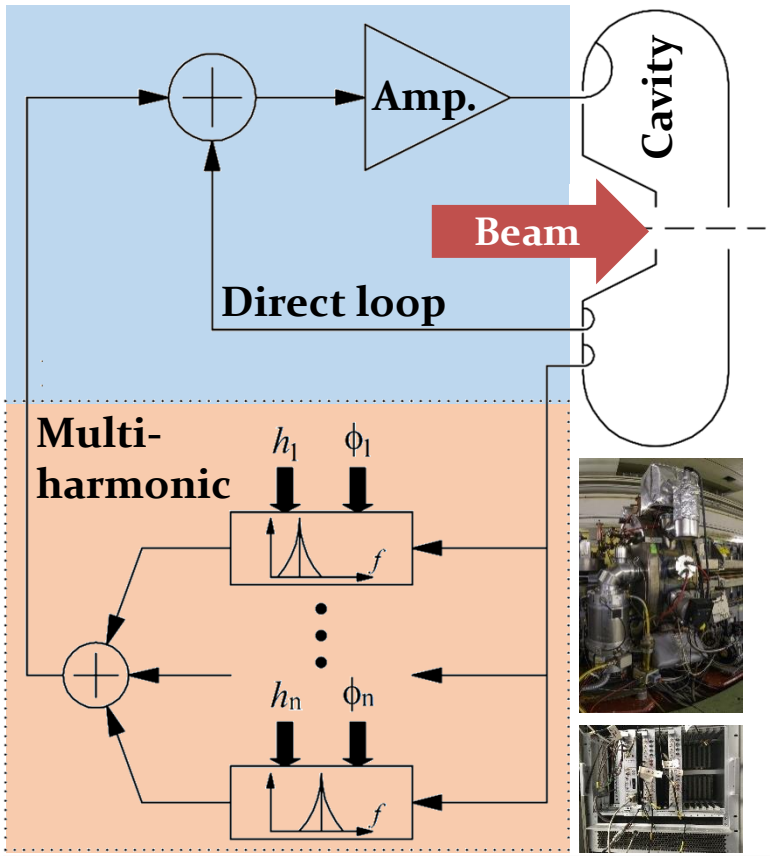


→ **Impedance of third cavity 80 MHz causes uncontrolled emittance blow-up at tail of batch**

→ **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**

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

→ **Minimize loop delay, τ**

→ **Reduce loop bandwidth to damp only close to $n \cdot f_{\mathrm{rev}}$**

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

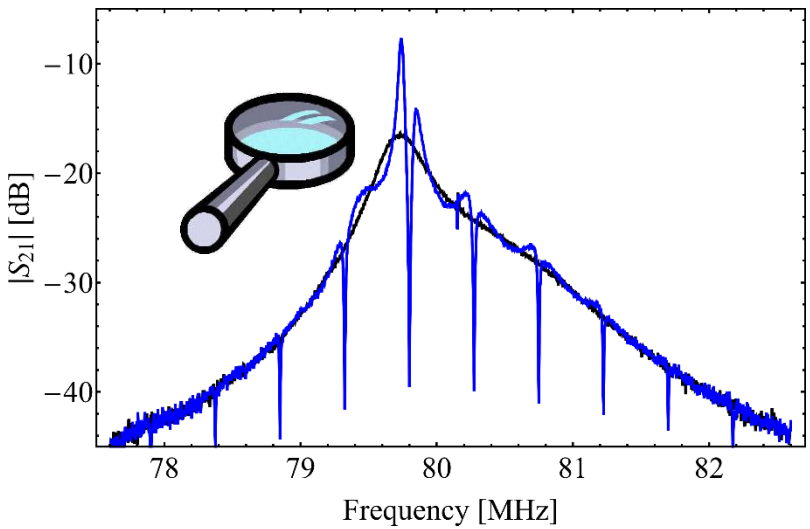
→ **Similar configuration in other accelerators at CERN**

→ **Poster: Ivan Karpov**

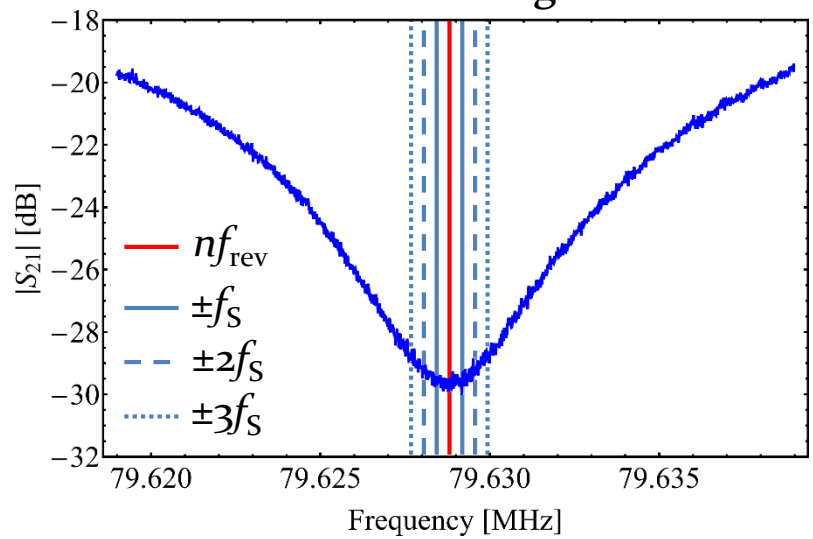
Impedance reduction of 80 MHz cavities

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

Open and closed loop transfer function



Zoom around single notch



✓ **Phase of notches dynamically adjusted: symmetric during full cycle**

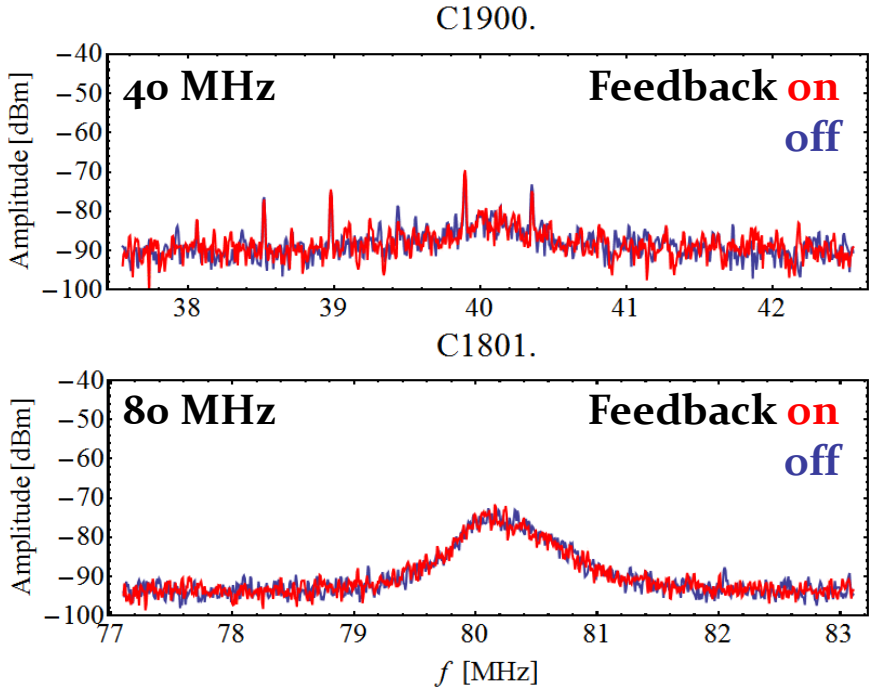
✓ **Notch bandwidth sufficient for several f_S sidebands**

→ **Limited by electrical stability due to phase error at $nf_{rev} \pm \Delta f$**

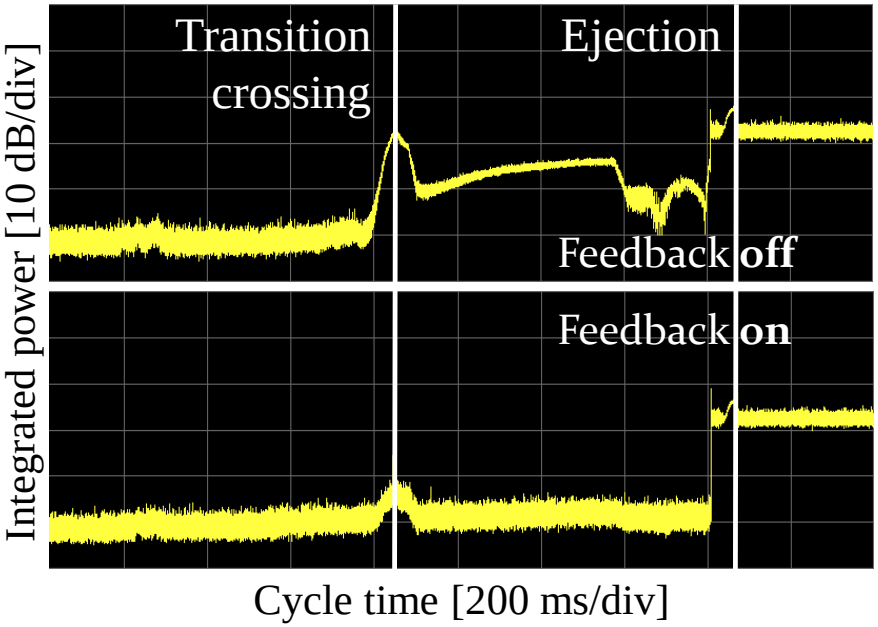
Beam induced voltage in 40/80 MHz cavities

- **Effect of additional feedback on beam induced voltages**

Spectrum during cycle



Beam induced power within 40 ± 3 MHz



→ **Impedance reduction of ~20 dB confirmed with beam**

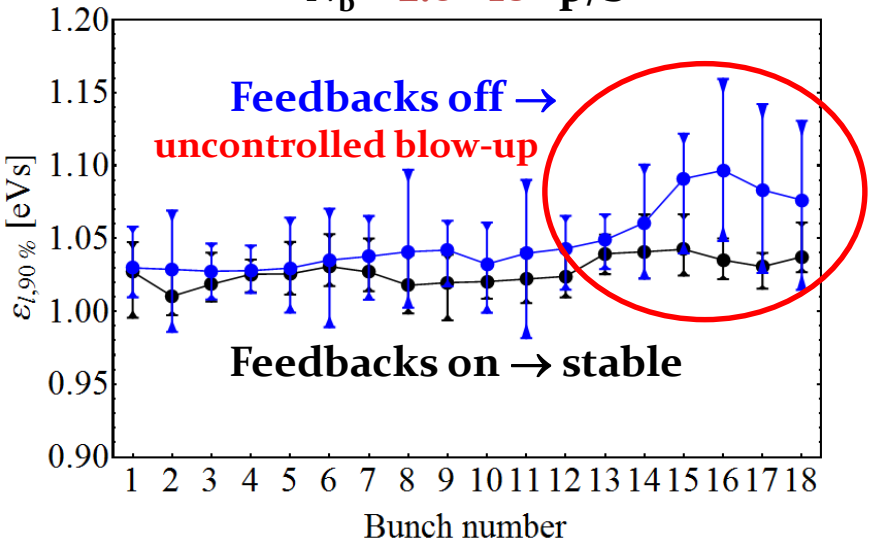
Effect on uncontrolled blow-up?

→ **Multi-bunch tomography to quantify beneficial effect on emittance**

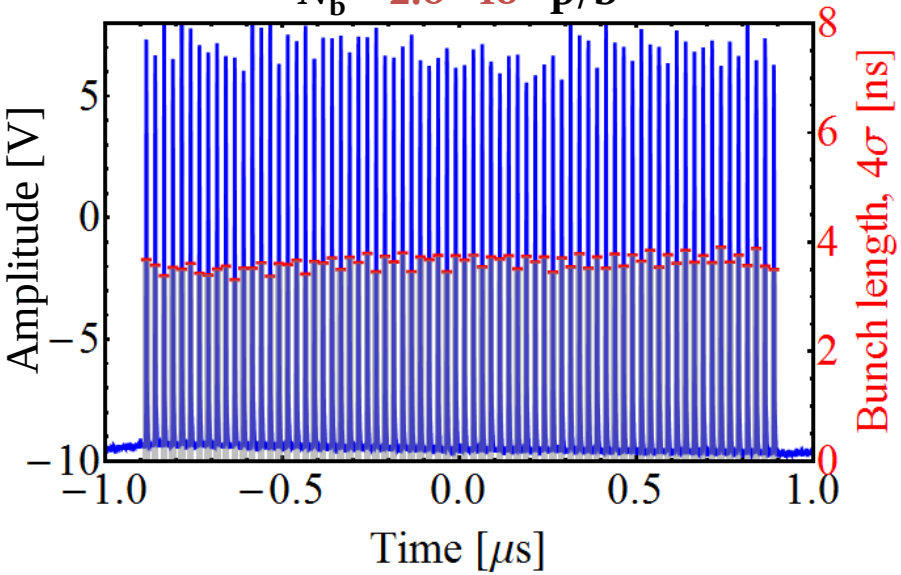
→ **Multi-harmonic feedbacks completed on all 40 MHz and 80 MHz cavities**

→ **Now operated during complete cycle**

Longitudinal emittance at flat-top
$N_b = 2.6 \cdot 10^{11}$ p/b



Bunch profile/length last turn
$N_b = 2.6 \cdot 10^{11}$ p/b



→ **Major contribution in 2018 to reach HL-LHC intensities**

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Combination of feedbacks in the PS

Feedback type	Remarks	RF system, f_{res} [MHz]			
		2.8...10	20	40	80
Direct	• Delivers base impedance reduction • Reduction of transient beam loading • **Impossible to operate without**	✓	✓	✓	✓
1-turn delay	• Reduction of transient beam loading • **Little effect on coupled-bunch instabilities**	✓			
Multi-harmonic	• When 1-turn del. FB not applicable		(✓)	(✓)	(✓)
Coupled-bunch (mode domain)	• Controls dipole coupled-bunch oscillations • **Studying extension to quadrupole mode damping**	Dedicated Finemet cavity as longitudinal kicker			

→ **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 10^{11} p/b as required for HL-LHC

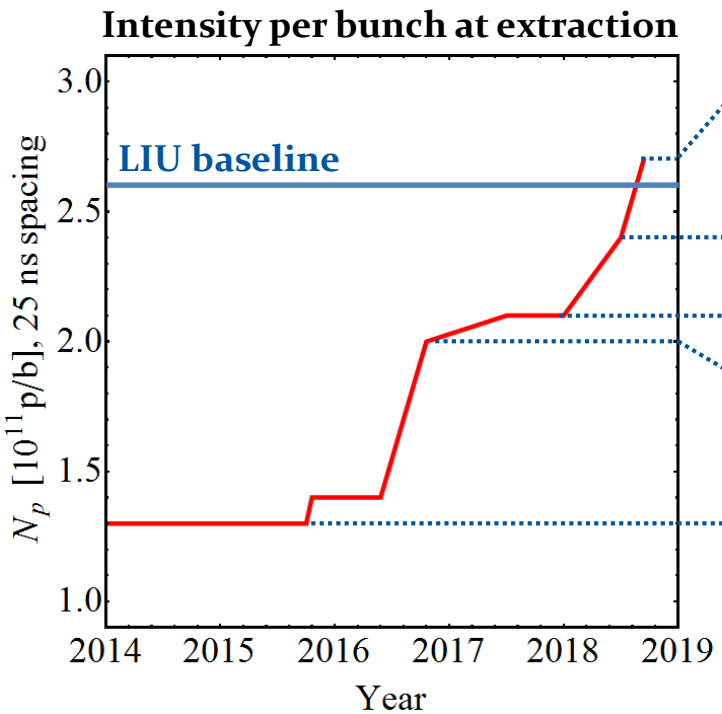
- **Coupled-bunch feedback**
  - → Damping of dipole modes only so far
  - → Preliminary studies to add higher order (quadrupole) mode damping

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

Spare slides

Intensity evolution (25 ns, 72 bunches)



Multi-harmonic feedbacks
C40-78 as Landau RF system

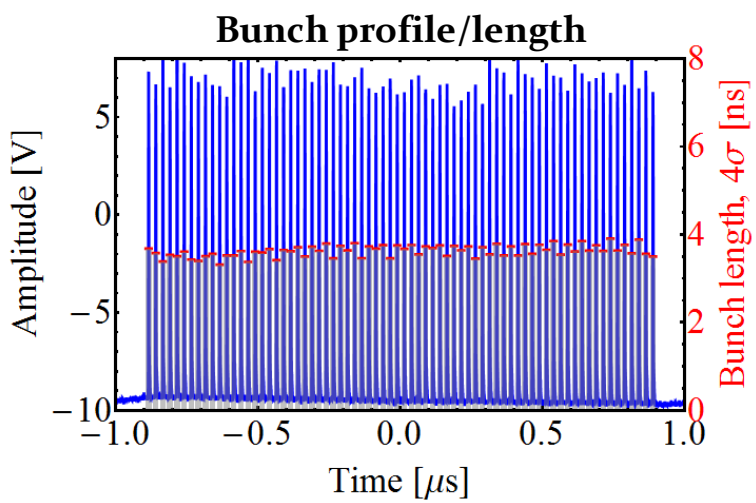
Suspected feedback saturation

Optimization 2017

Finemet dipole-mode
coupled-bunch feedback

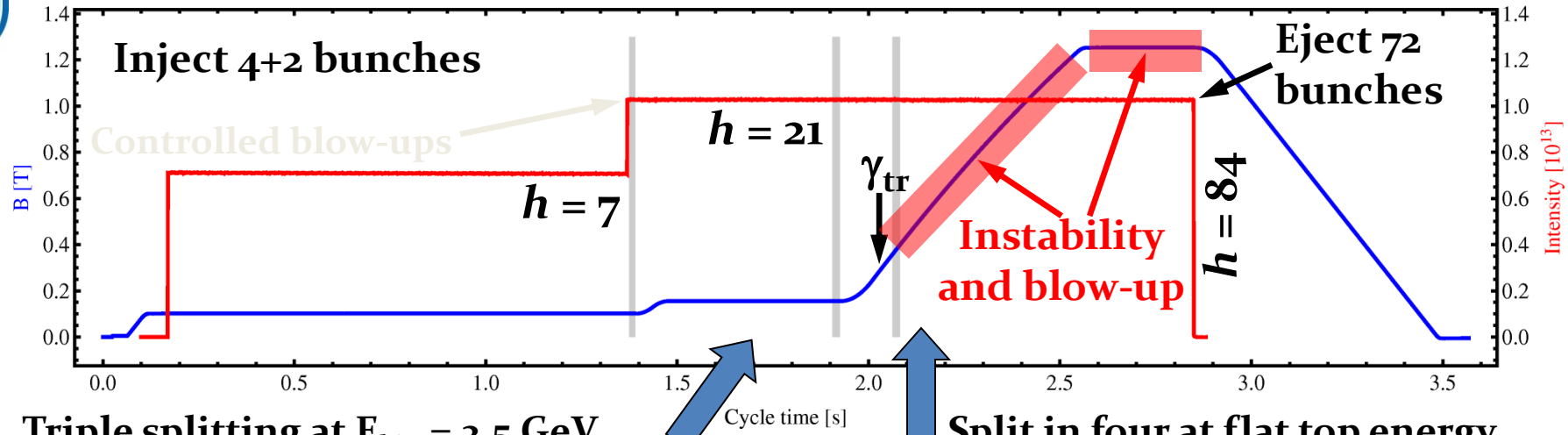
Reach with C10-86/96 coupled-bunch feedback (2005)*

*Intensities >1.3 · 10^{11} p/b were delivered <2016, but not with sufficient quality for LHC



→ **LIU baseline of 2.6 · 10^{11} p/b finally within reach**

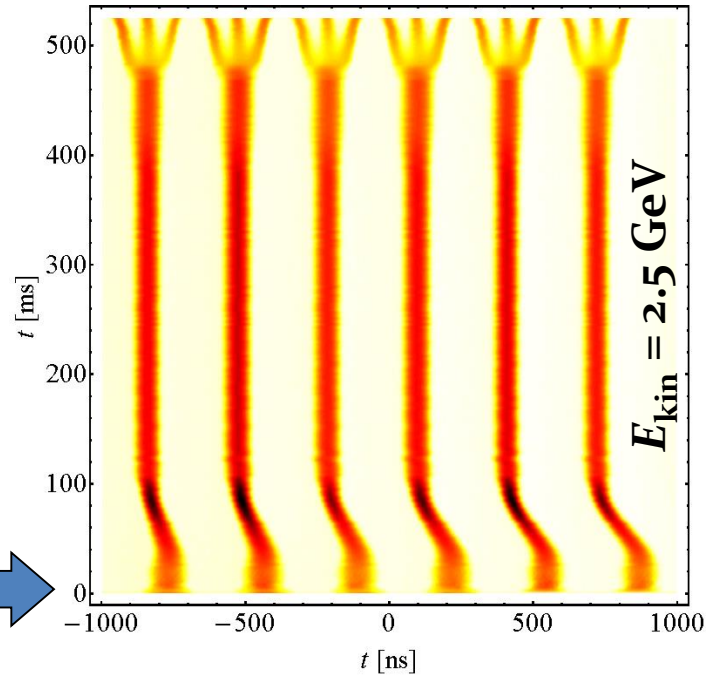
LHC-type beam with 25 ns spacing in the PS

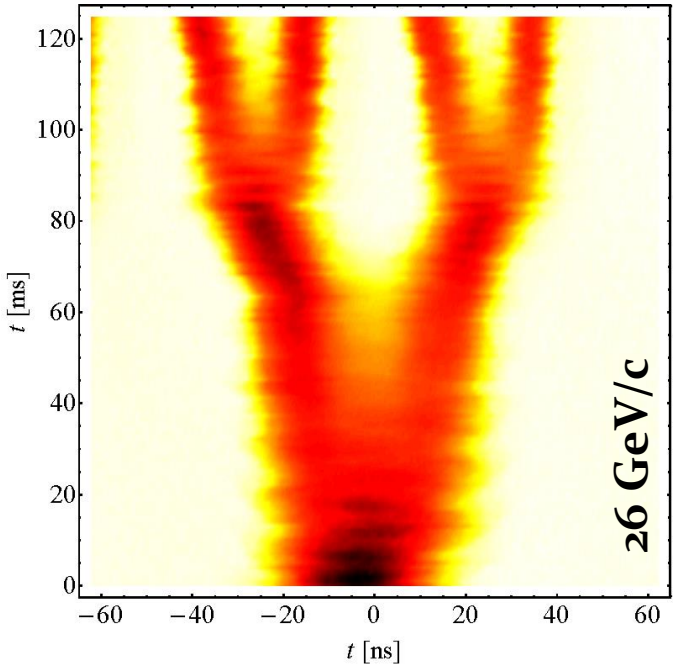


Triple splitting at E_{kin} = 2.5 GeV

Split in four at flat top energy

2nd injection



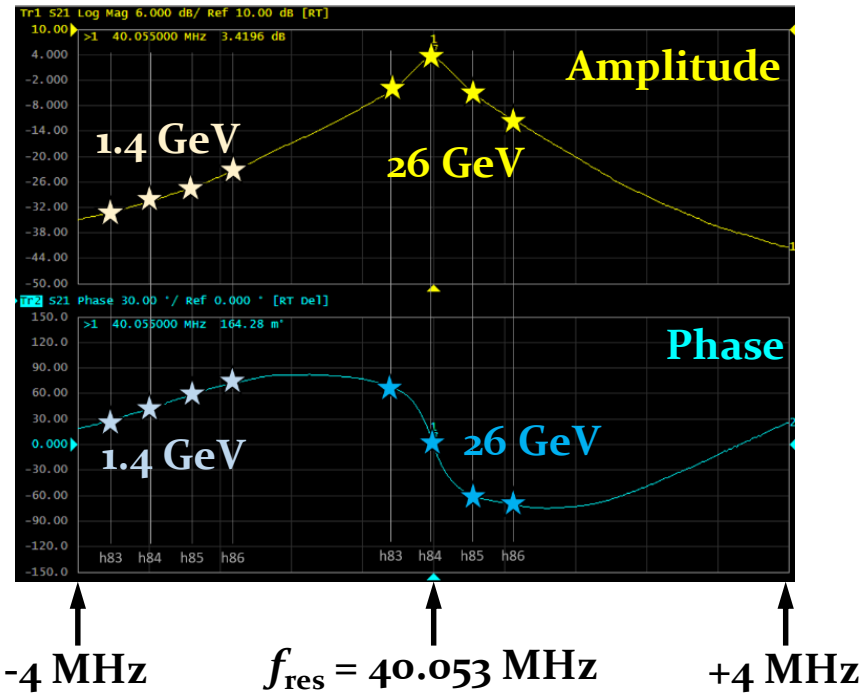


Impedance reduction 40/80 MHz cavities

Main technical challenges:

1. Phase of cavity impedance not linear
2. Cavity resonance at fixed resonance while f_{rev} sweeping

40 MHz cavity transfer function



→ Periodic filters of conventional 1-turn delay feedback not adapted

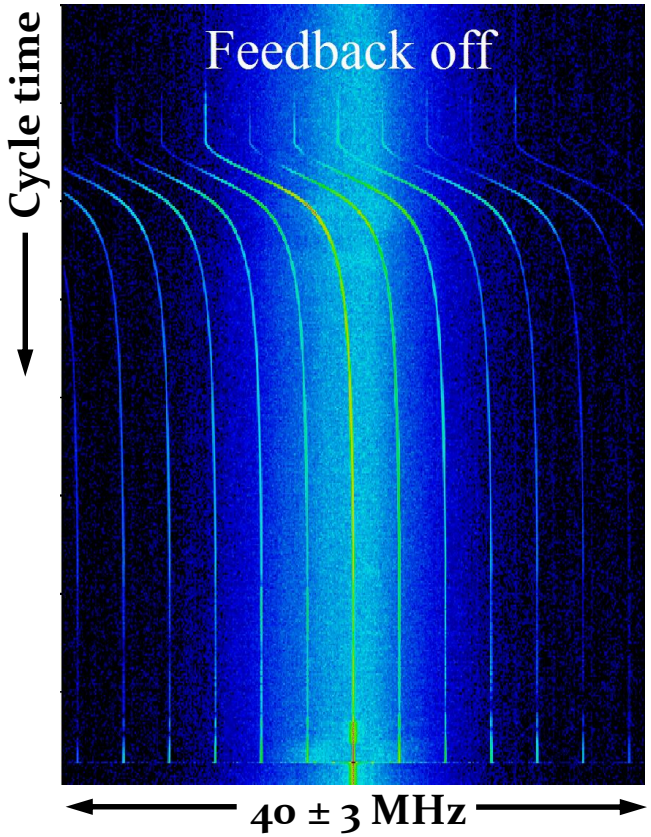
→ Independent feedback channels per harmonic

→ Dynamic phase adjustment according to f_{rev}

Effect on uncontrolled blow-up?

→ **Multi-bunch tomography to quantify beneficial effect on emittance**

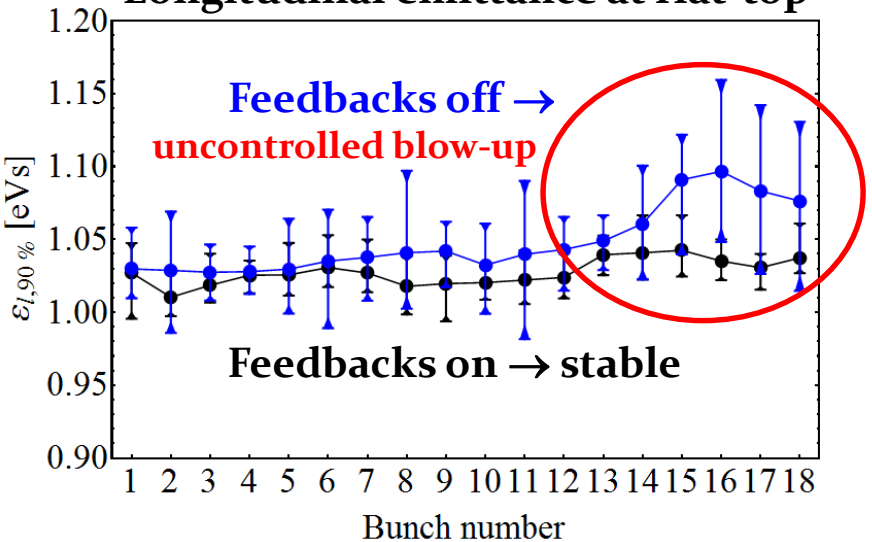
Beam induced spectrum
C80-88, feedback on/off



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

→ **Now operated during complete cycle**

Longitudinal emittance at flat-top



→ **Major contribution in 2018 to reach LIU intensities**

Mode-by-mode feedback at CERN PS

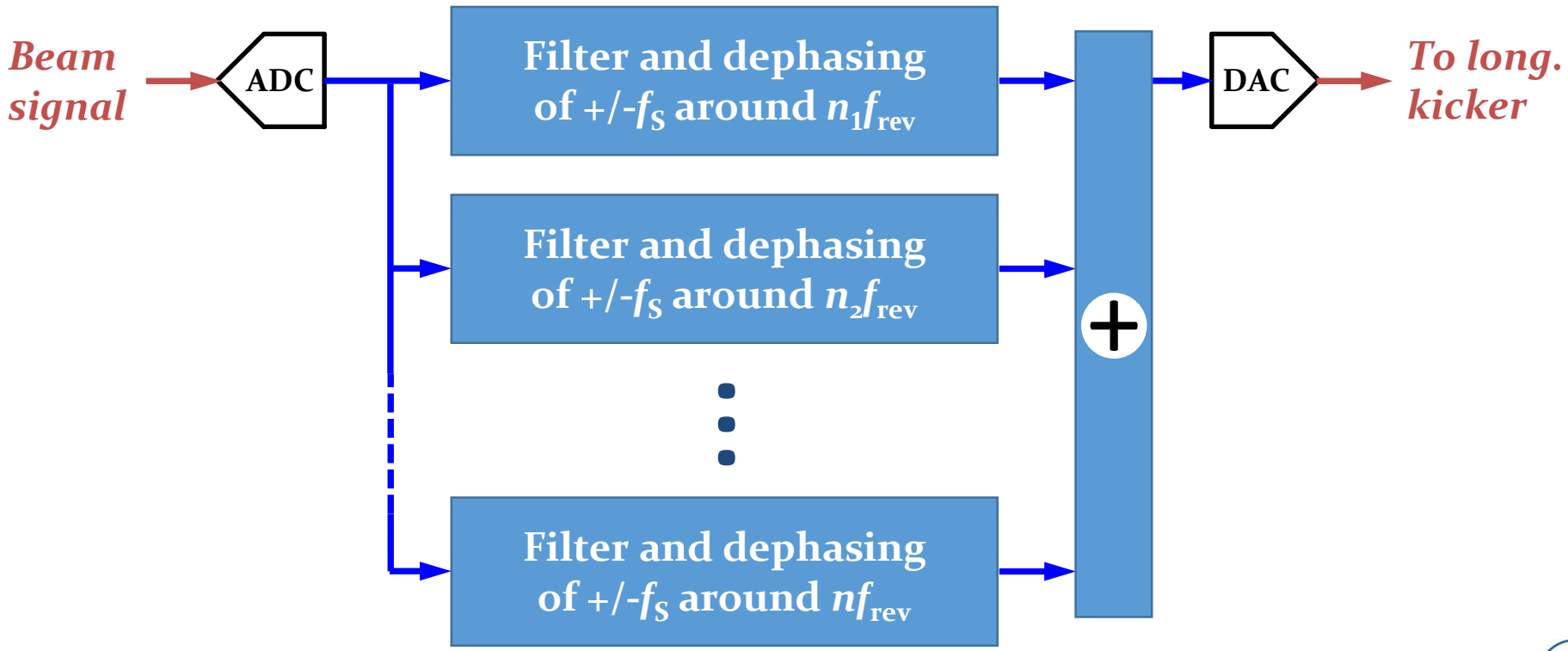
- $h_{RF} = 21 \rightarrow 21$ possible oscillation modes in total

→ Zero mode stabilized by beam phase loop

→ Mode pairs $n_1 + n_2 = h_{RF}$: different sidebands of same f_{rev} harmonic

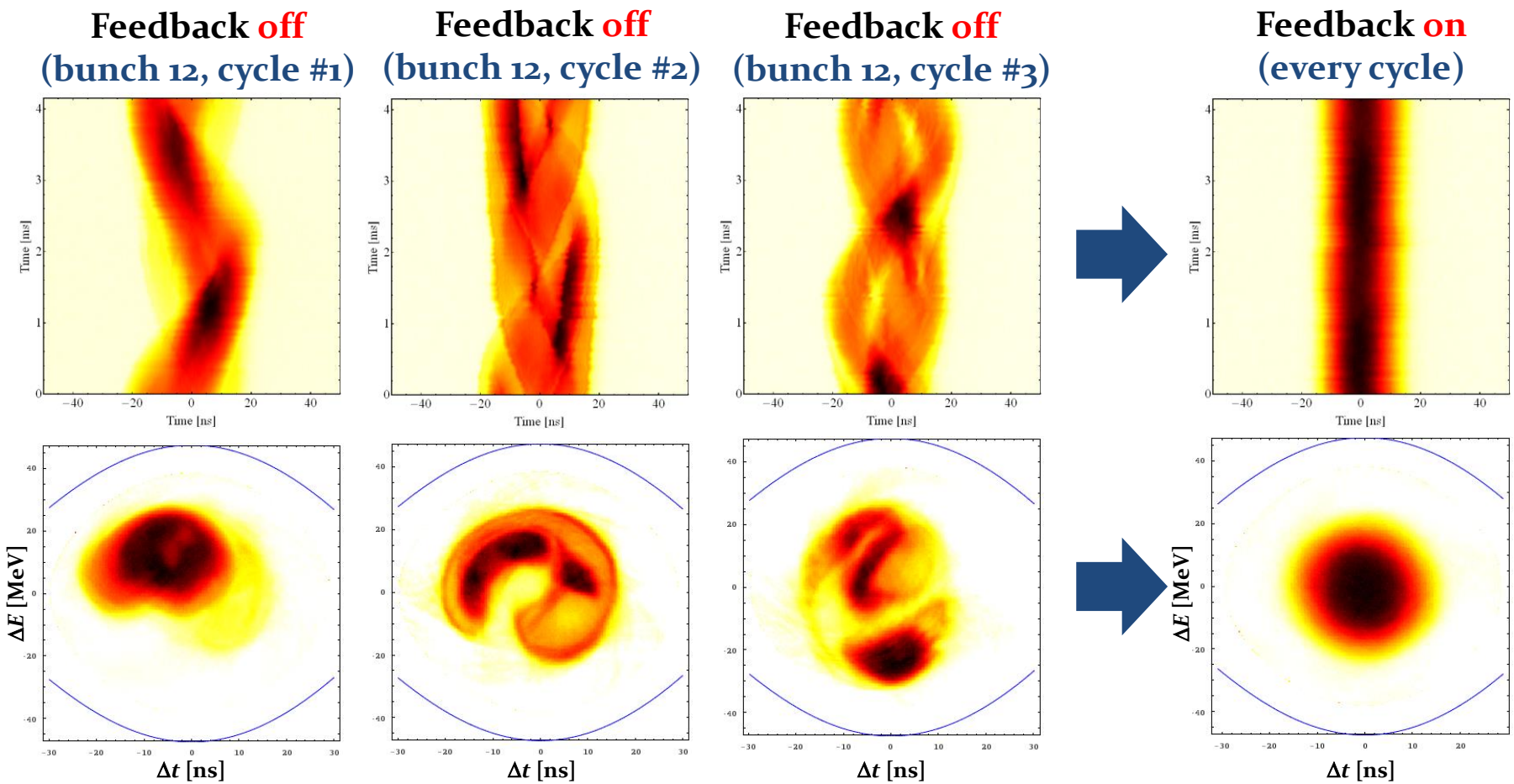
→ 10 signal processing channels in parallel

→ 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**

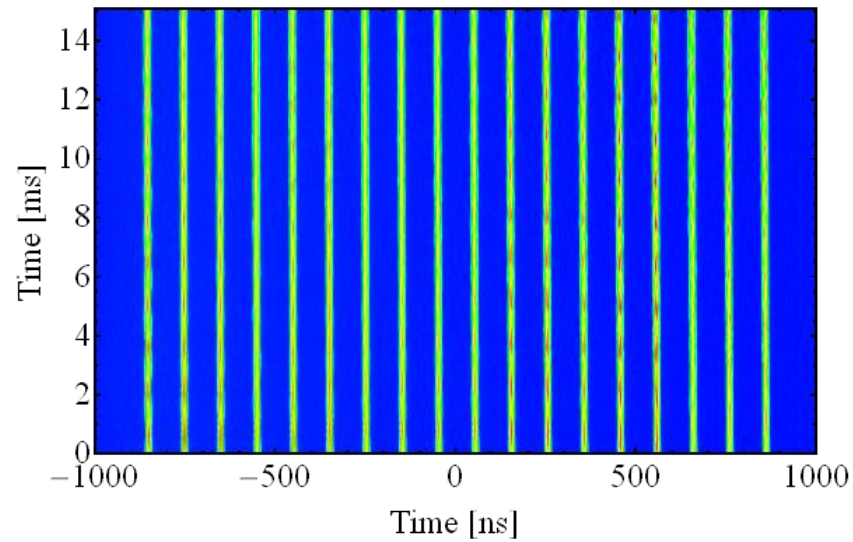


Quadrupole oscillations after transition

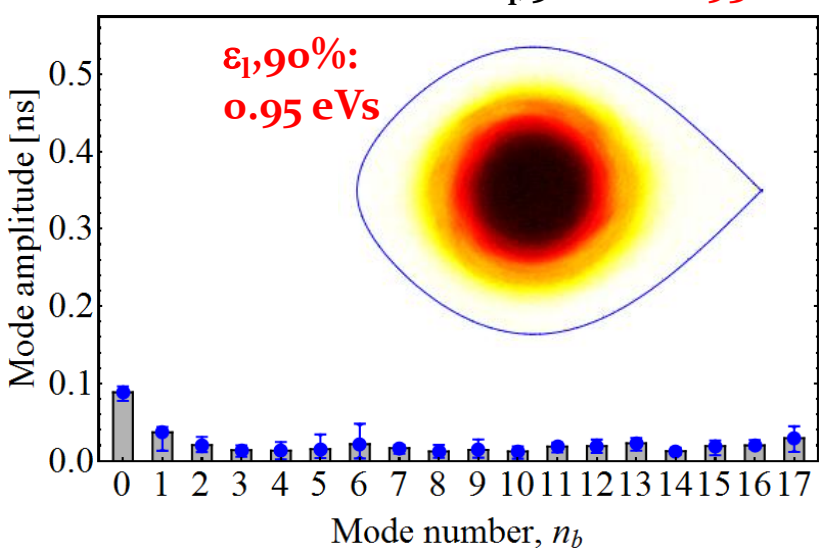
- **Emulating higher intensity by increasing density N_b/ε_l**

→ **Quadrupole instabilities observed right after transition crossing**

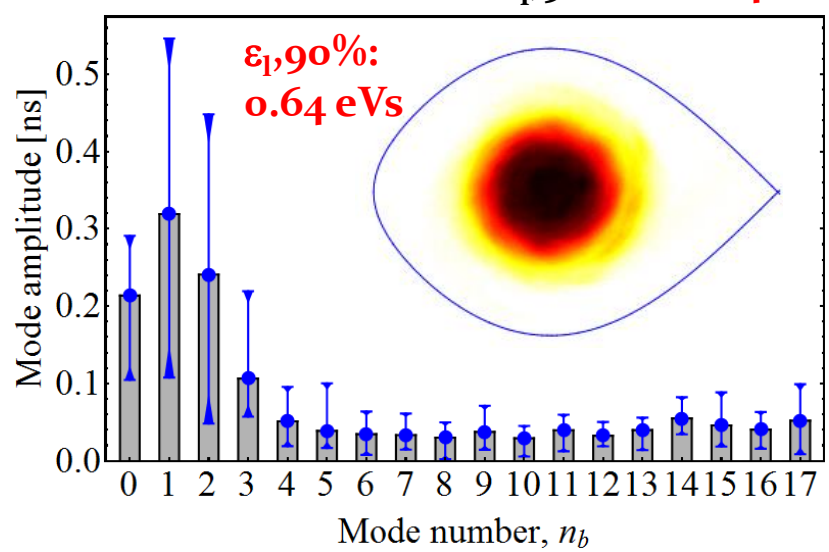
→ **Measurements at $2.0 \cdot 10^{11}$ p/b**



Nominal emittance: ε_l,90%: = 0.95 eVs



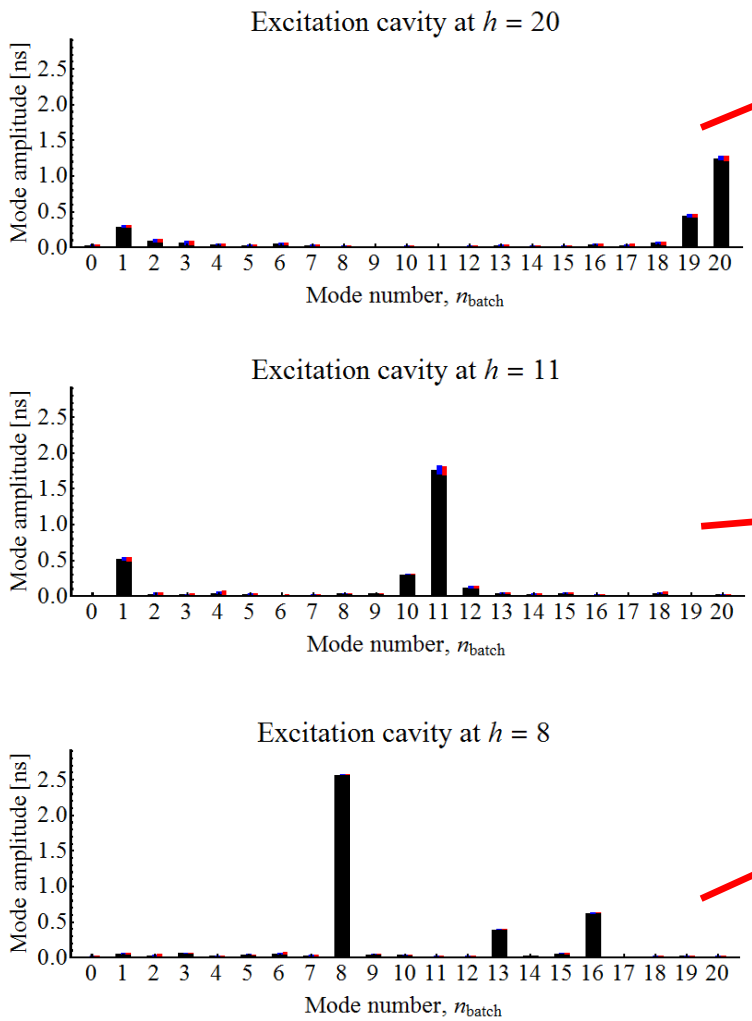
Reduced emittance: ε_l,90%: = 0.64 eVs

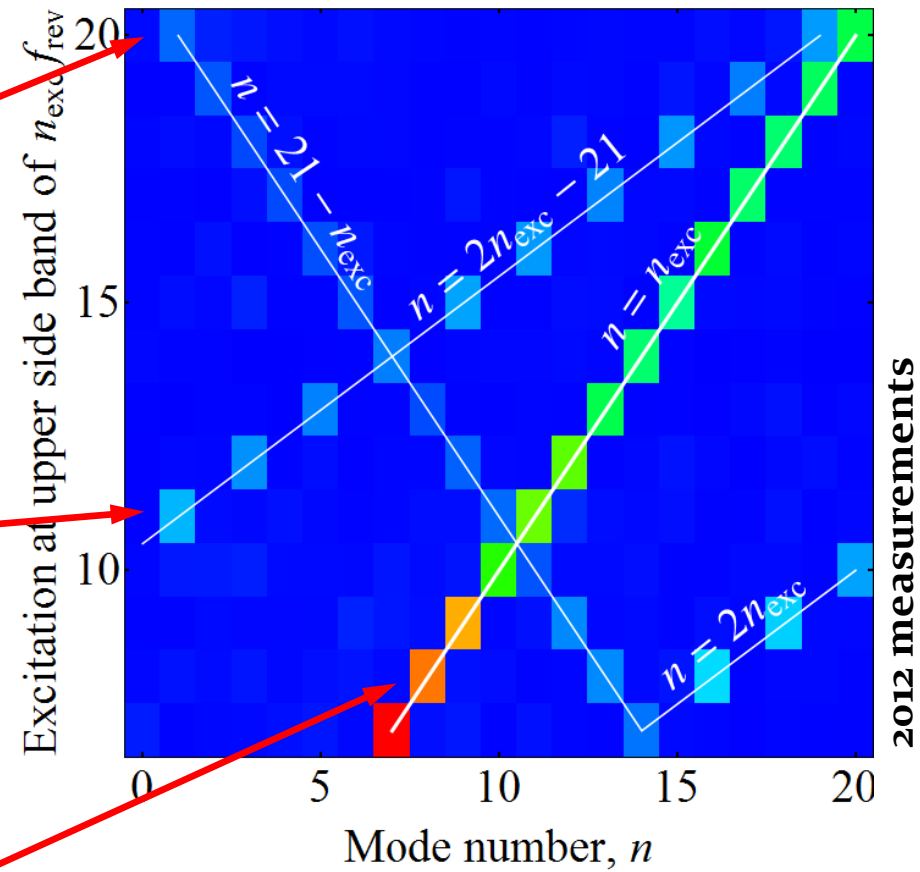


→ **No damping from coupled-bunch feedback**

Excitation of dipole oscillation modes

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

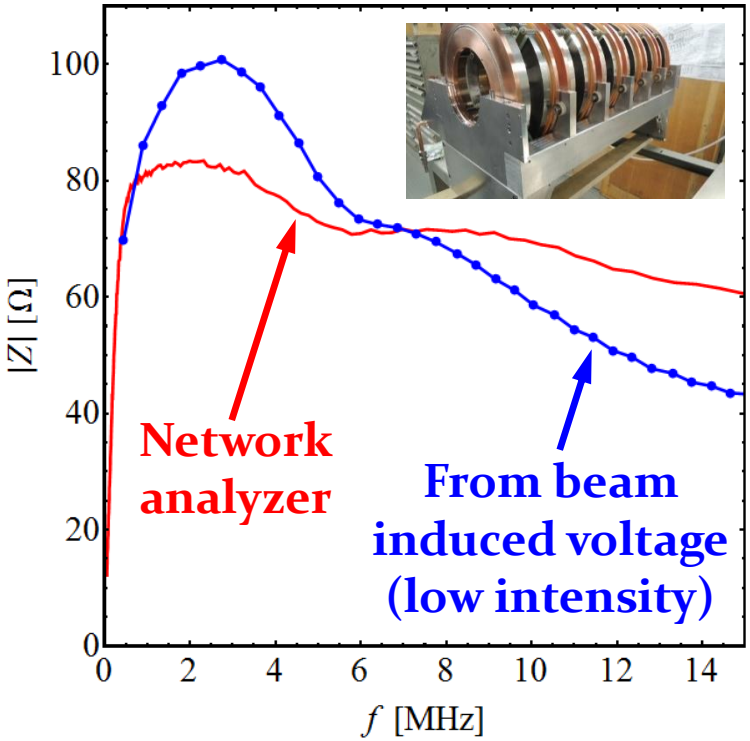


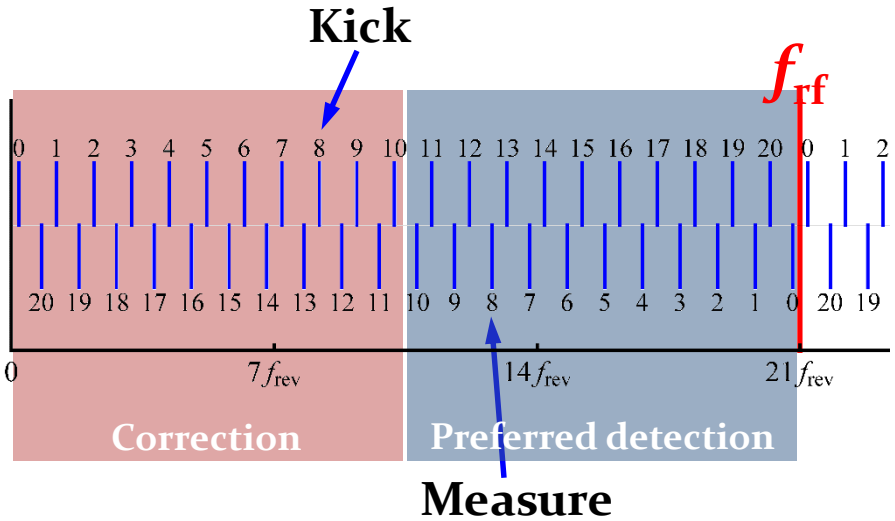


→ **Defined kick strength for wide-band kicker cavity**

Choice of frequency ranges: cross-damping

Impedance per cell with amplifier → **Best shunt impedance: 0.4 to 5 MHz**

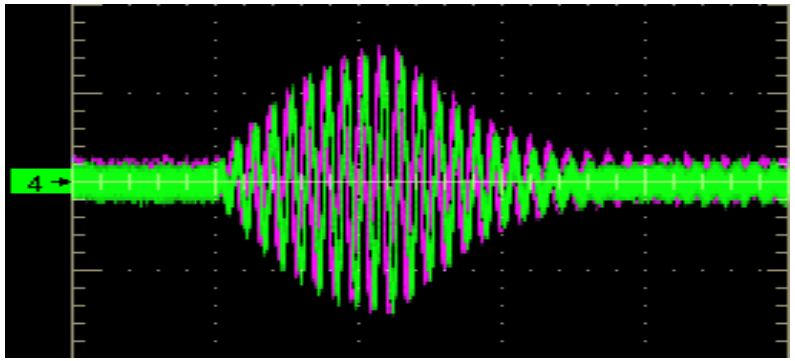




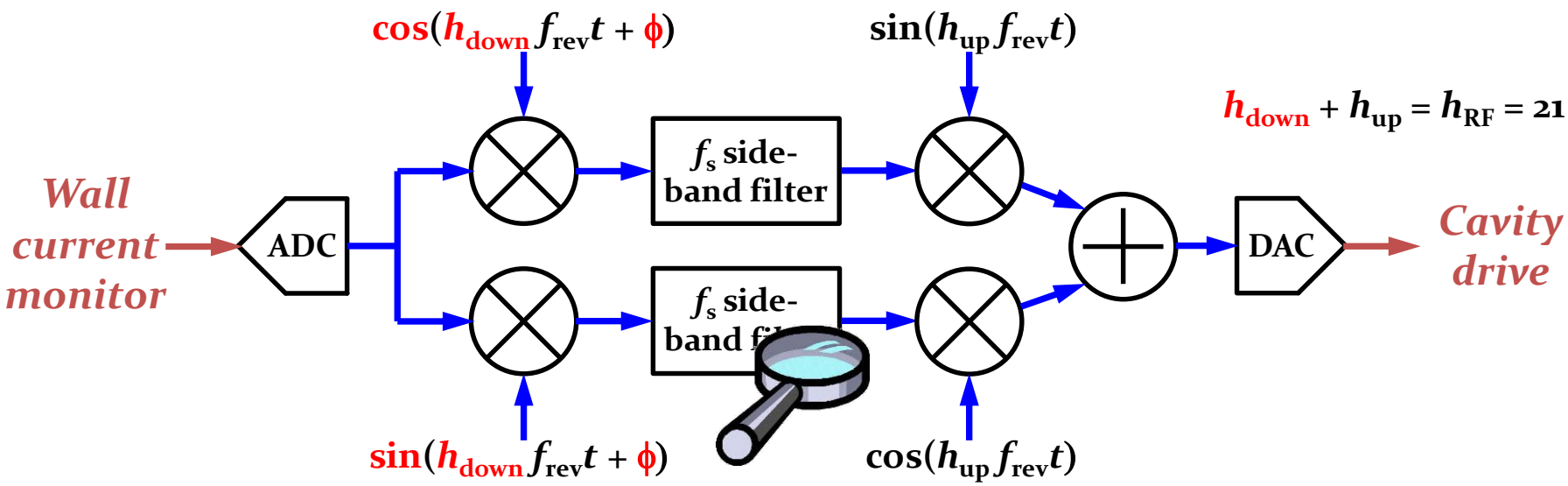
1. Detect f_s sidebands at 11…20 f_{rev}
2. Correct beam at 1…10 f_{rev}

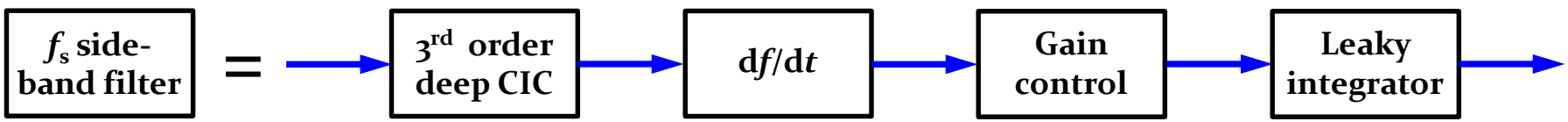
→ 20 modes → 10 signal processing chains

Detect at 8 f_{rev}, damp at 13 f_{rev} (2012 test)



Tracking filters – coupled-bunch damping





- Sharp attenuation to separate $\pm f_s$ of sidebands from f_{rev} harmonics
- Sharp 180° 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