LHC Injectors Upgrade

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Observation and (active) damping of longitudinal coupled-bunch instabilities

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ICFA Mini-Workshop on
Impedances and Beam Instabilities in Particle Accelerators
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CERN

Overview

- Introduction
  - Longitudinal coupled-bunch instabilities
- Active stabilization
  - Frequency domain wideband coupled-bunch feedback
  - Beneficial effect on stability
  - Quadrupolar coupled-bunch oscillations
- Coupled-bunch instabilities at flat-top
  - Damping with feedback
  - Passive damping: Landau cavity
- Maximum intensity reach
  - Longitudinal emittance along batch
- Summary

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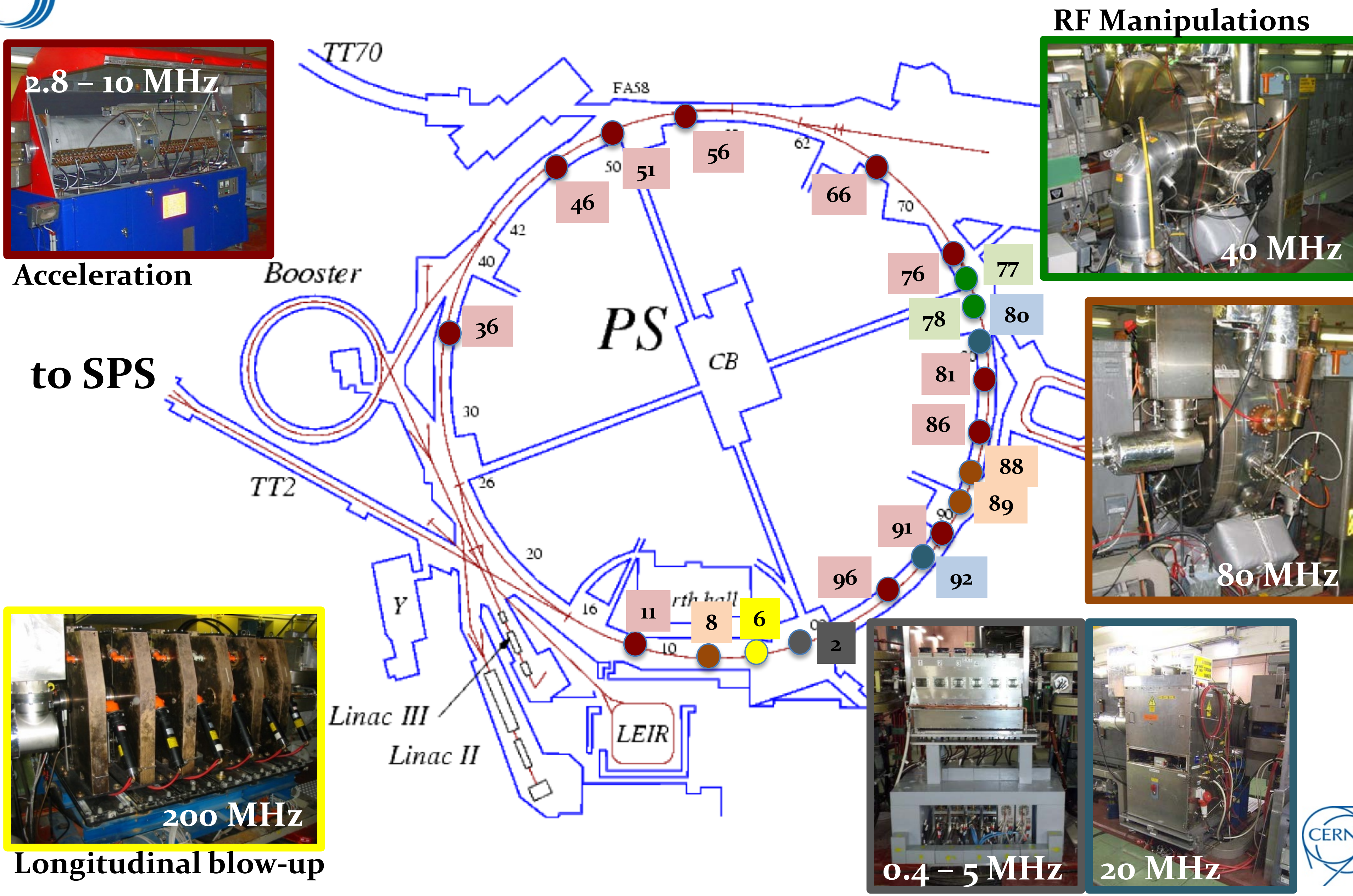
Introduction and motivation

- **LIU/HL-LHC projects:**
  - Double intensity per bunch from $1.3 \cdot 10^{11}$ ppb to $2.6 \cdot 10^{11}$ ppb
- **Major limitation for LHC-type beams in PS:** Longitudinal coupled-bunch instabilities during acceleration and on flat-top
- **Feedback test system available for studies since 2016**
  - Prototype Finemet cavity up with 6 gaps (~6 kV)
  - Prototype digital LLRF with 10 signal processing chains, covering all possible oscillation modes

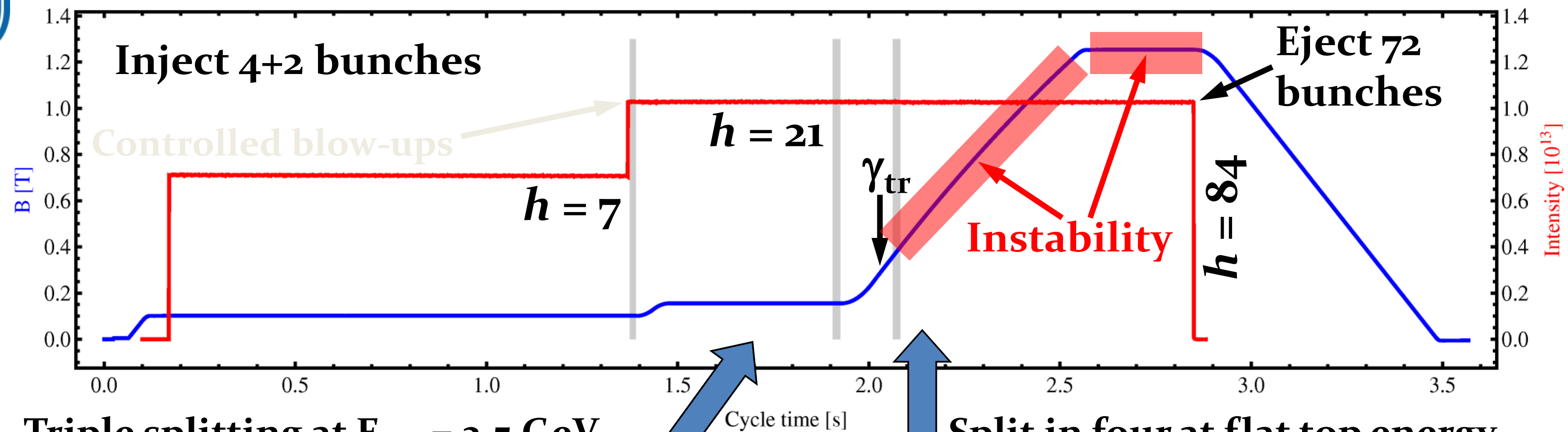
→ New range of longitudinal beam parameters accessible

- **Additional measures to improve stability?**
  → Use 20 or 40 MHz RF systems as Landau cavity at flat-top

RF systems in the PS

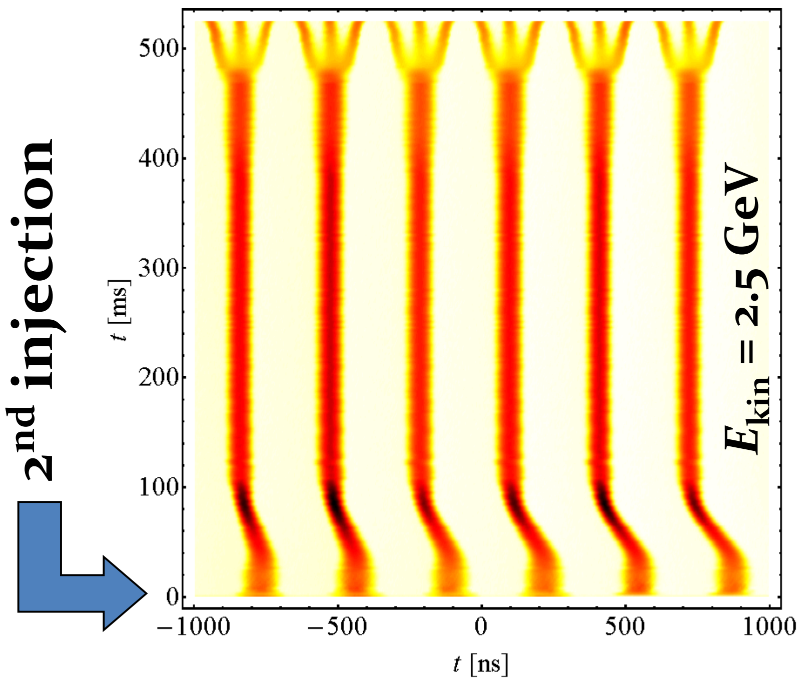


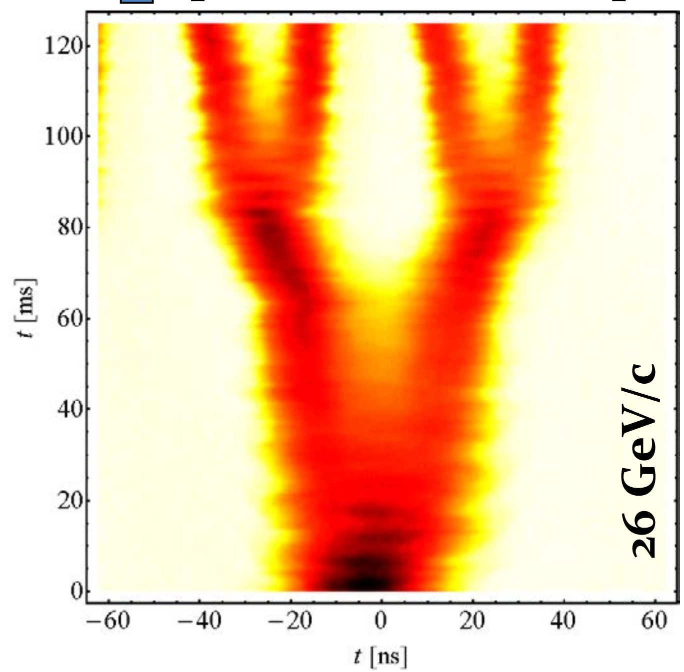
LHC-type beam with 25 ns spacing in the PS



Triple splitting at E_{kin} = 2.5 GeV

Split in four at flat top energy





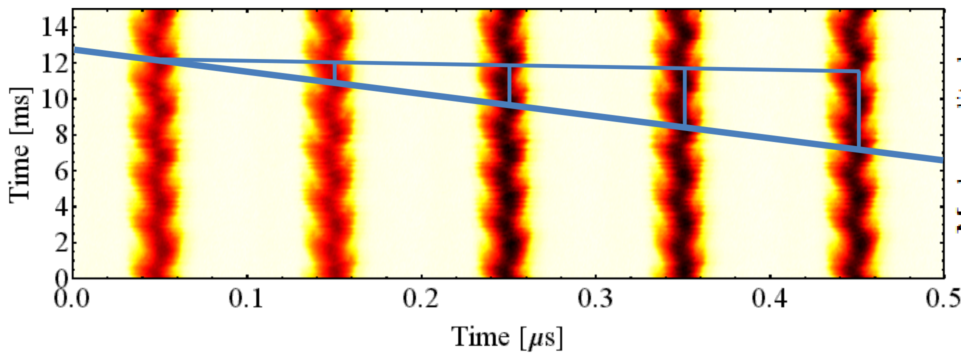
→ **Each bunch from the Booster divided by 12 → 6 × 3 × 2 × 2 = 72**

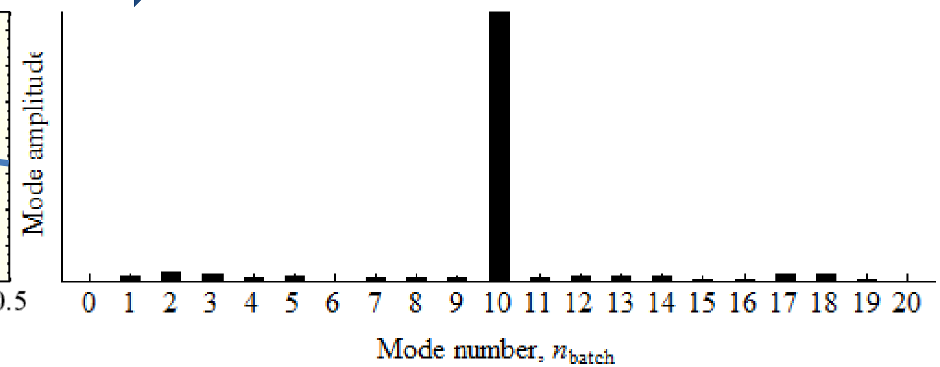
Coupled-bunch oscillations in the CERN PS

- **Oscillation of bunch position (dipole) or bunch length (quadrupolar)**

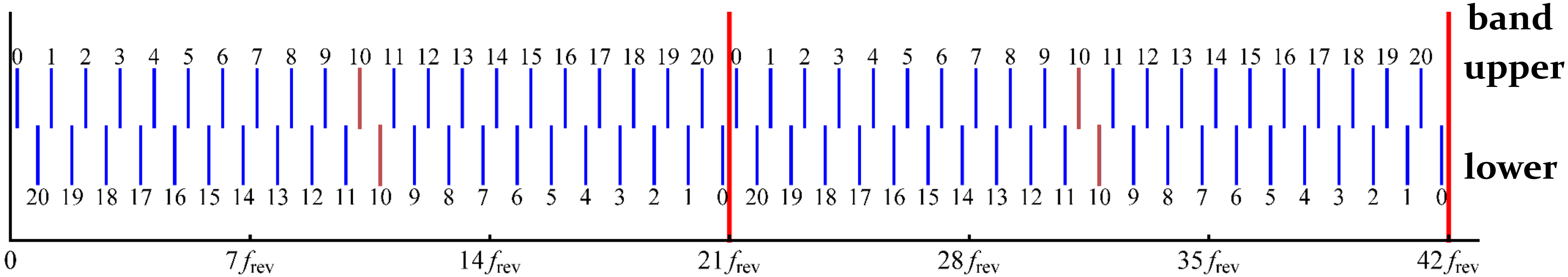
→ Time domain

Dipole oscillation, 2π·10/21 phase advance → **Corresponding mode spectrum**





→ Frequency domain (case of h = 21)

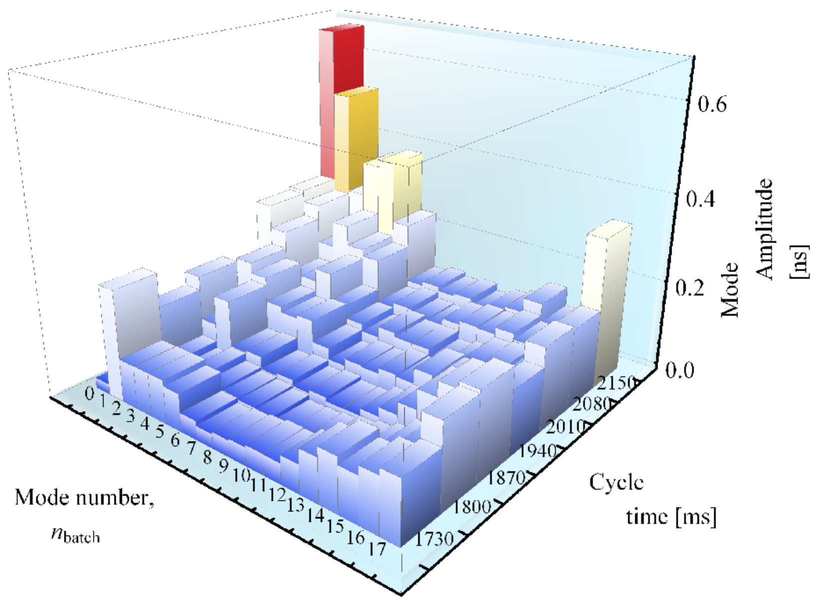


→ **Instability: Synchrotron frequency, f_s, side-bands of $n \cdot f_{\text{rev}}$**

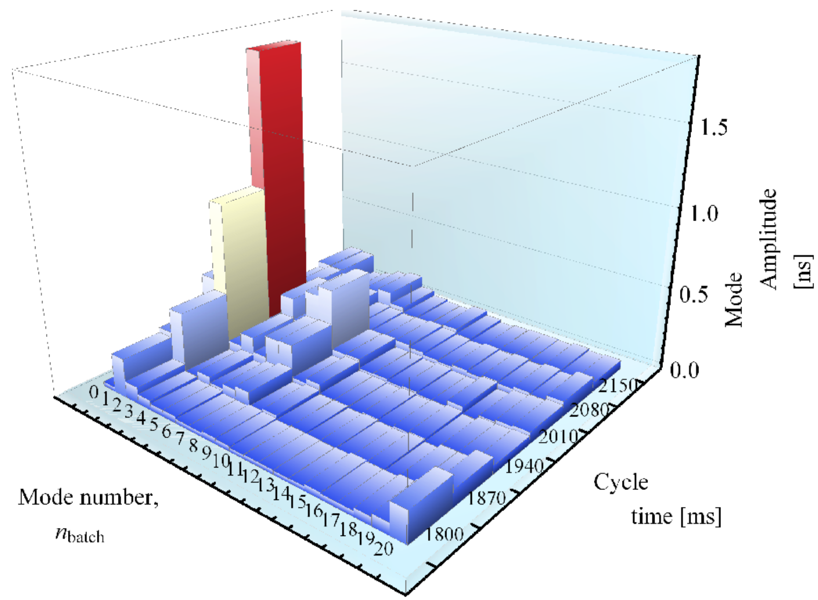
Observations along the cycle

Mode spectrum during acceleration (~10 cycle average):

18 bunches in h = 21



21 bunches in h = 21



→ **Clean mode spectra for full ring with 21 bunches in h = 21**

→ **Mode n = 2 strongest, as independently found in simulations**

→ **More complicated spectra with 18 bunches (filling pattern)**

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  - **Quadrupolar coupled-bunch oscillations**
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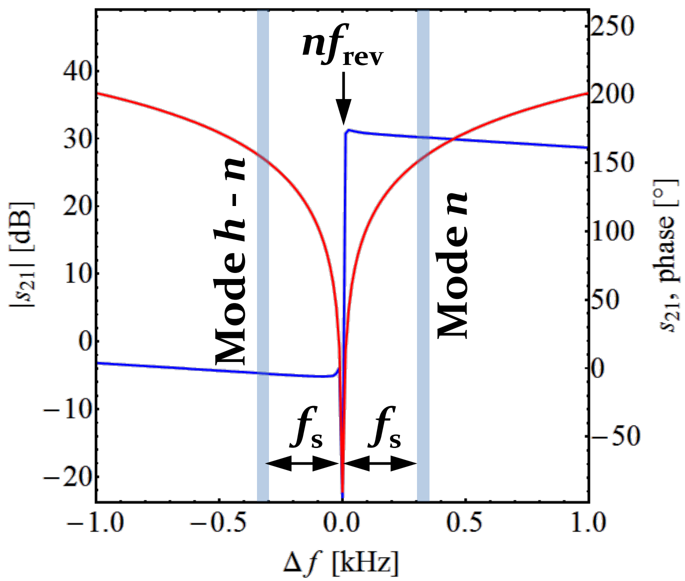
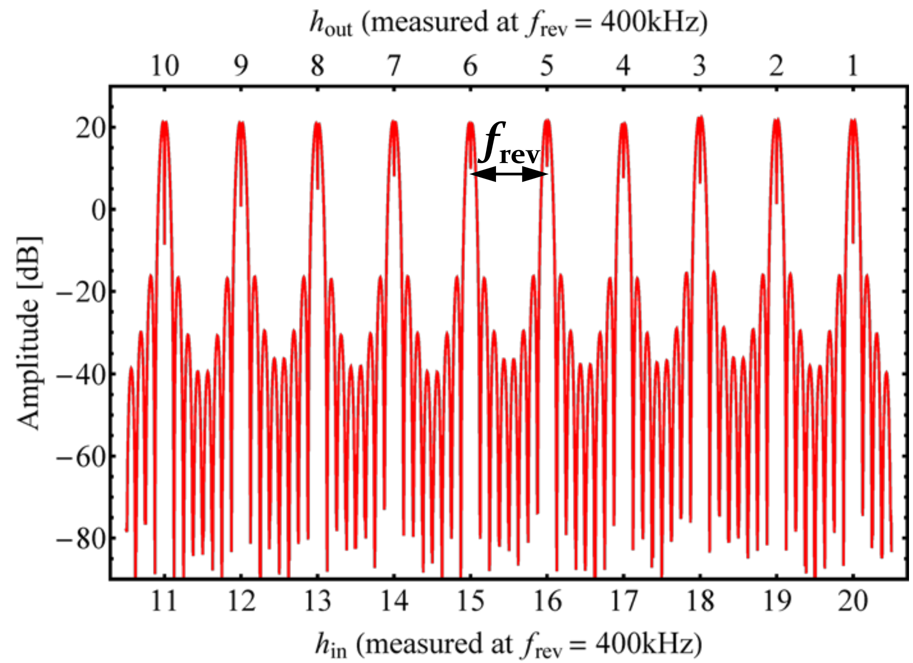
Frequency domain feedback

- **Suppress f_s side-bands by actively compensating them**
  - → **Remove spectral components at $n \cdot f_{rev}$ and amplify $n \cdot f_{rev} \pm f_s$**
  - → **Robust: insensitive to bunch positions and filling pattern**

F. Pedersen et al., PAC1977

Filter transfer function





→ **Harmonic of f_{rev} attenuated by more than 40 dB compared to sidebands at $\pm f_s$ (~300 Hz) → Extremely narrow: $f_s / f_0 \sim 6 \cdot 10^{-4}$**

→ **Precise 180° phase jump at center frequency**

→ **Ten notches covering all 20 possible modes (h = 21), other than n = 0**

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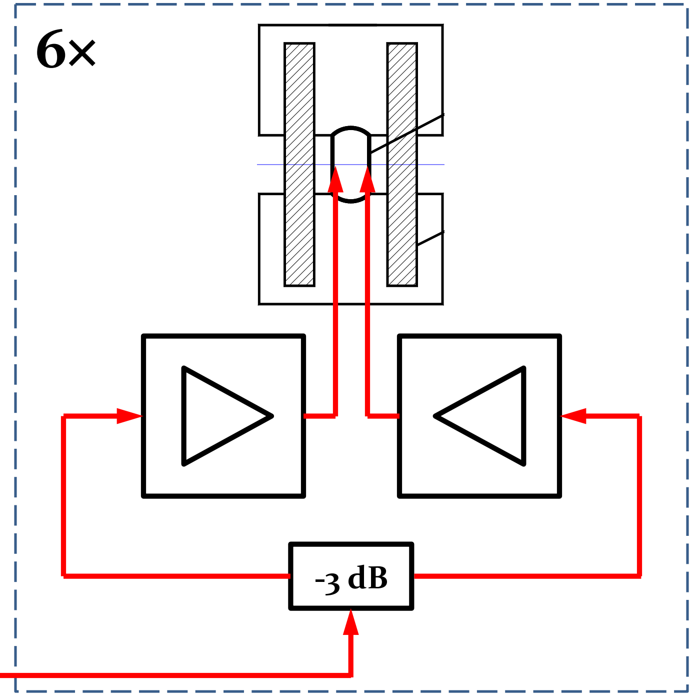
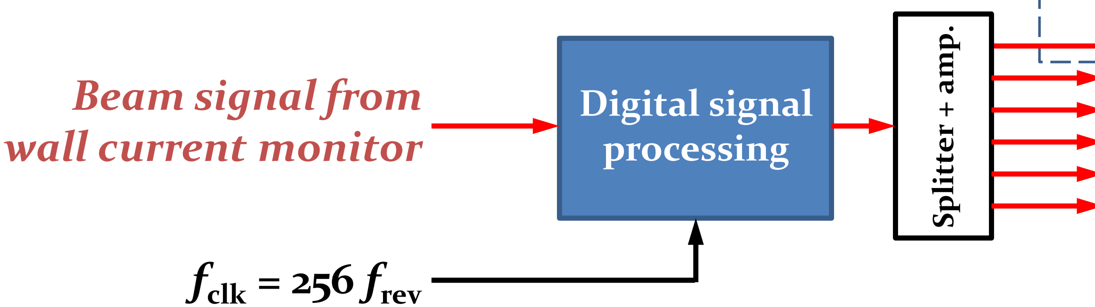
PS coupled-bunch feedback overview

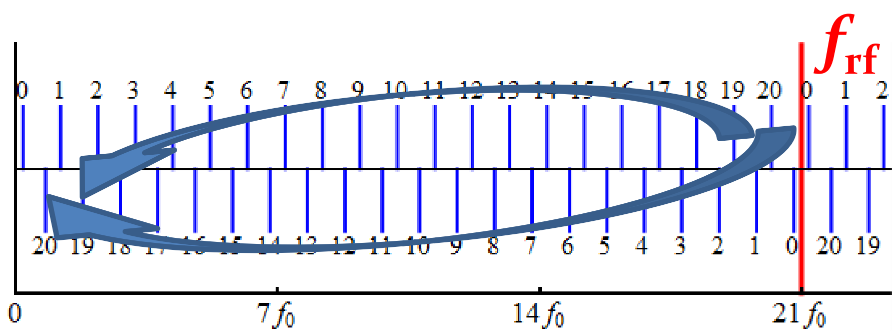
Six-cell Finemet cavity:

→ V_{RF} up to 6 kV from 0.4 to 5 MHz





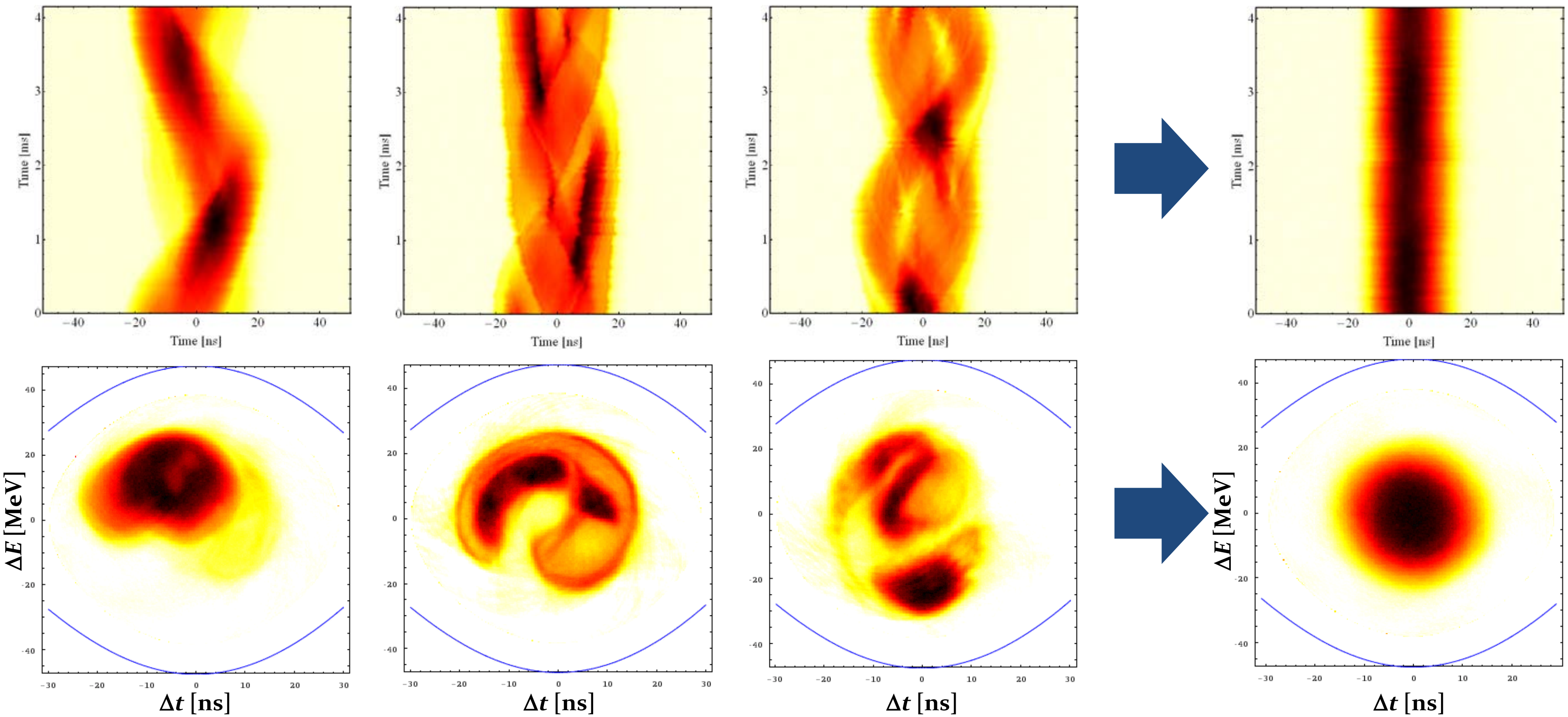
- Detect f_s sidebands at 11...20 f_{rev}
- Drive kicker cavity at 1...10 f_{rev}



Stability during acceleration

- **Longitudinal stability at arrival on flat-top, $N_b = 4 \cdot 2.0 \cdot 10^{11}$ ppb**

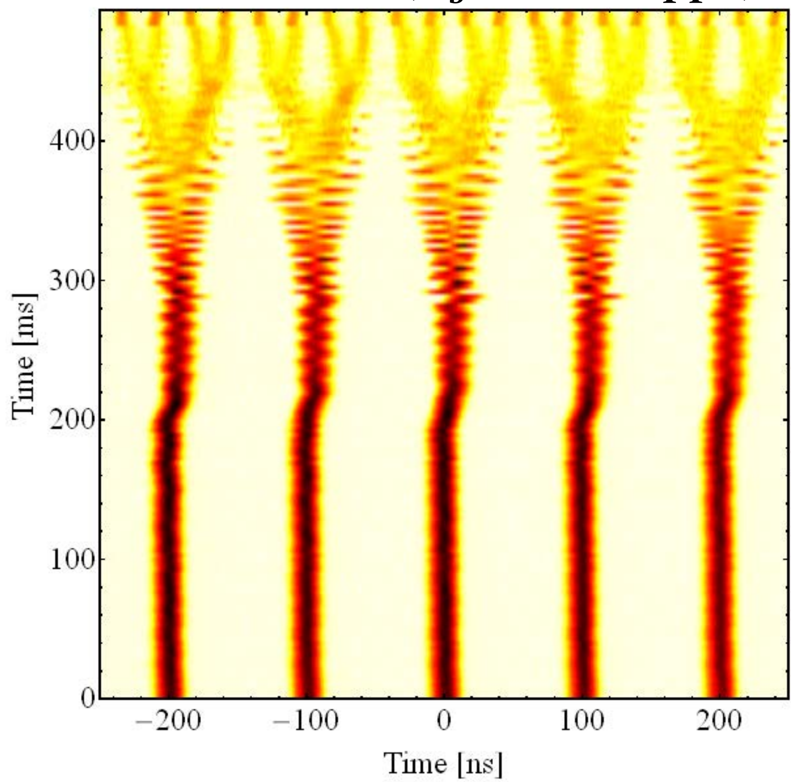
Feedback off (bunch 12, cycle #1) | **Feedback off (bunch 12, cycle #2)** | **Feedback off (bunch 12, cycle #3)** | **Feedback on (every cycle)**



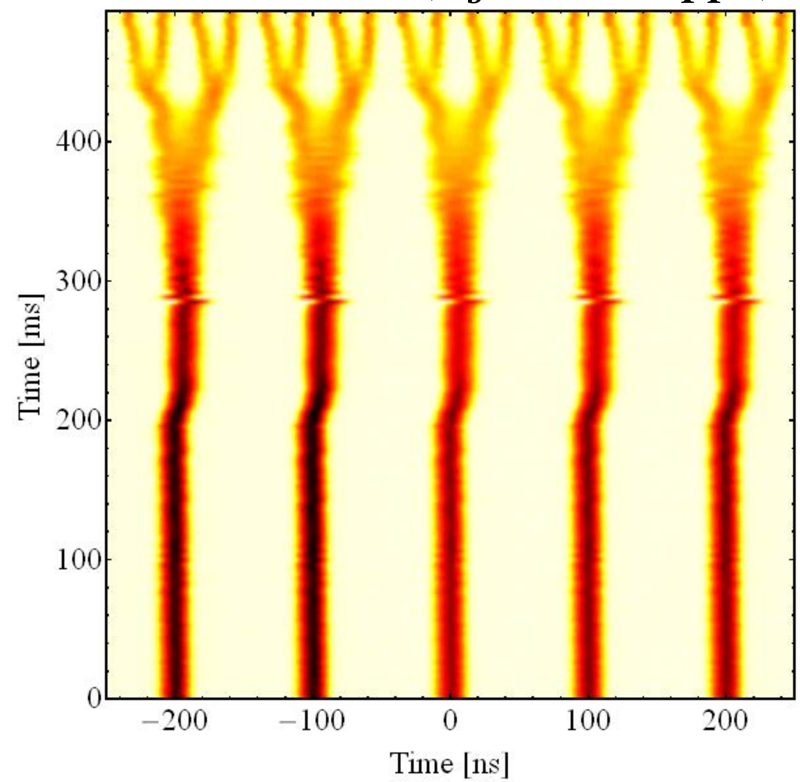
Final part of acceleration and flat-top

- **Arrival at flat-top and high-energy splittings**
- **Mode pattern changes due to impedance**

Feedback off ($N_b = 1.8 \cdot 10^{11}$ ppb)



Feedback on ($N_b = 1.8 \cdot 10^{11}$ ppb)



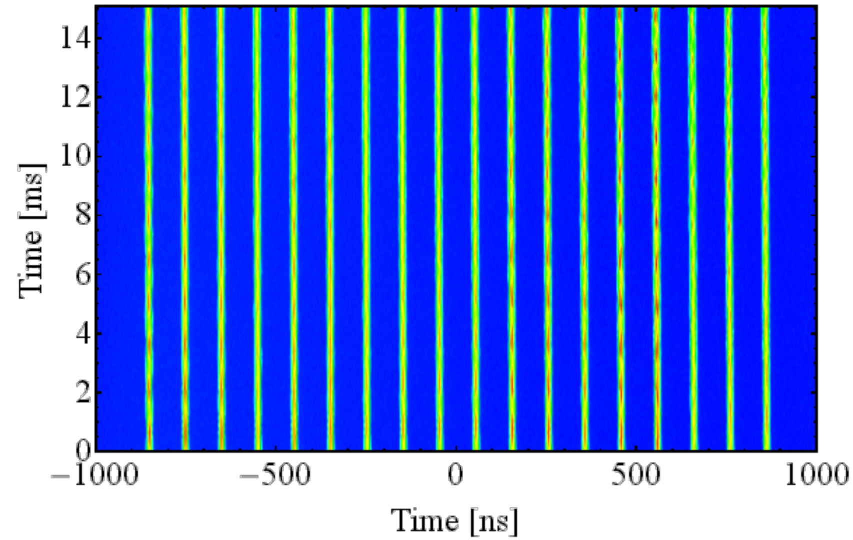
→ **Significant improvement of longitudinal stability with feedback**

Quadrupole oscillations after transition

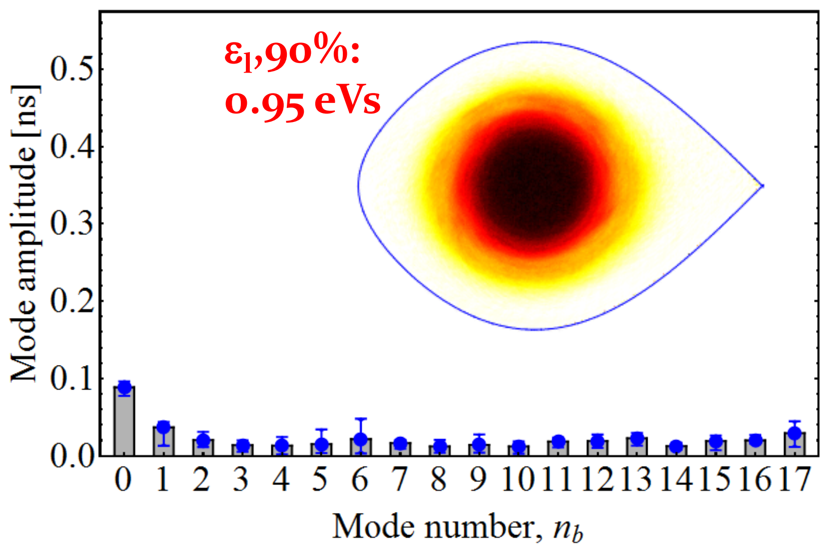
- **Emulating higher intensity by increasing density N_b/ε_l**

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

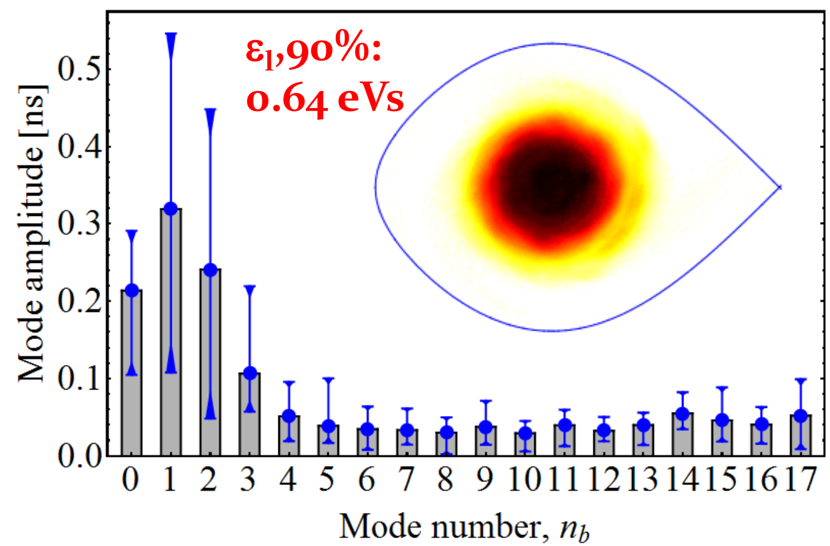
→ **Measurements at $4 \cdot 2.0 \cdot 10^{11}$ ppb**



Nominal emittance: ε_l,90%: = 0.95 eVs



Reduced emittance: ε_l,90%: = 0.64 eVs



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

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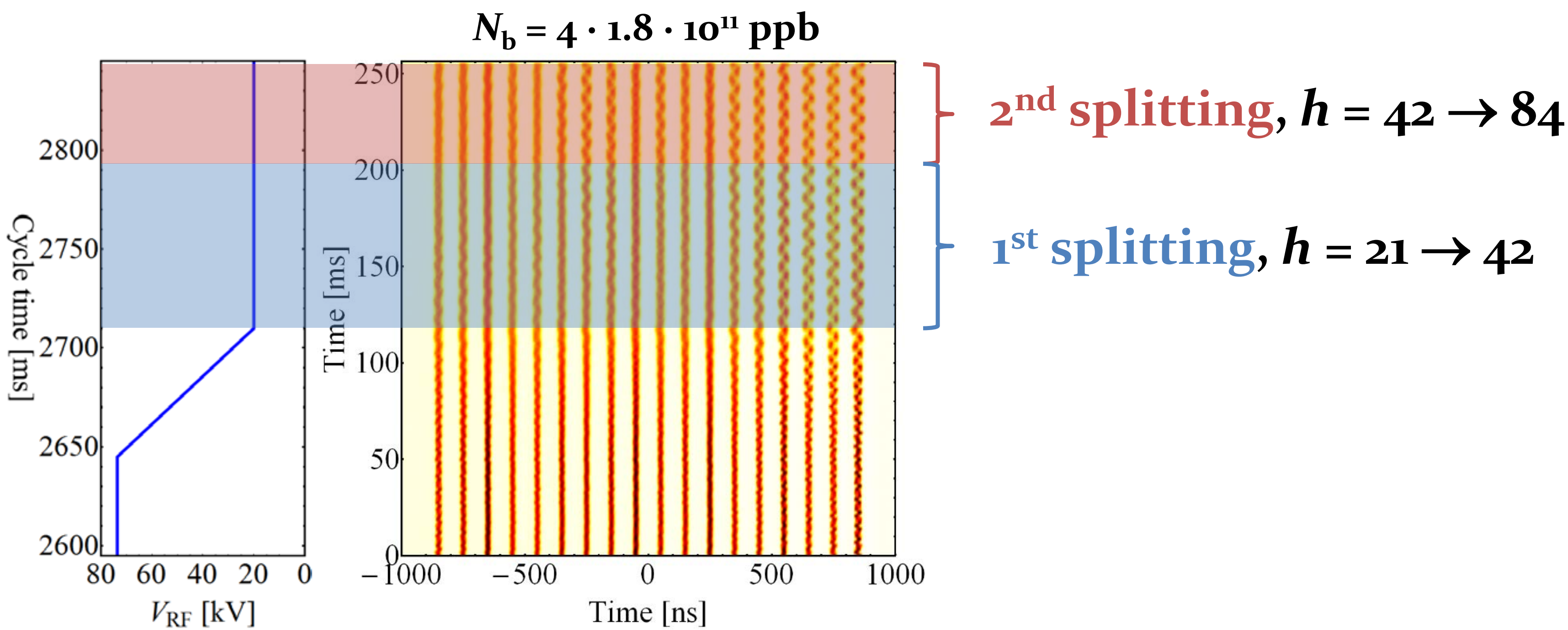
Instability at flat-top

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

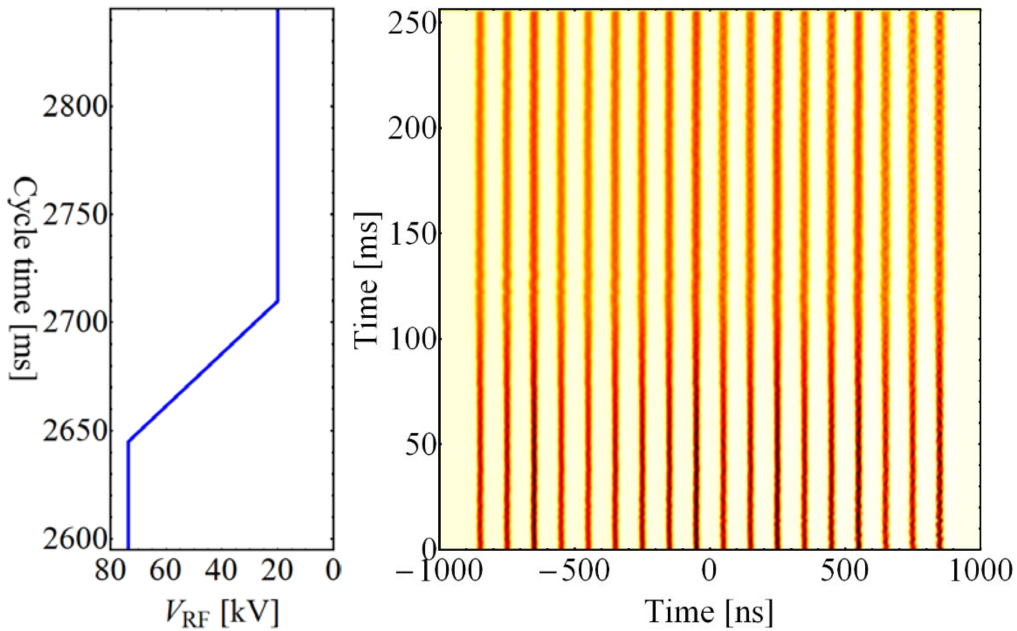


- Dipole coupled bunch oscillations build up along the batch
  - → Low $2Q/\omega_0$ impedance source decaying during ~400 ns gap
- Already well developed at start of first splitting manipulation

Instability at flat-top

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

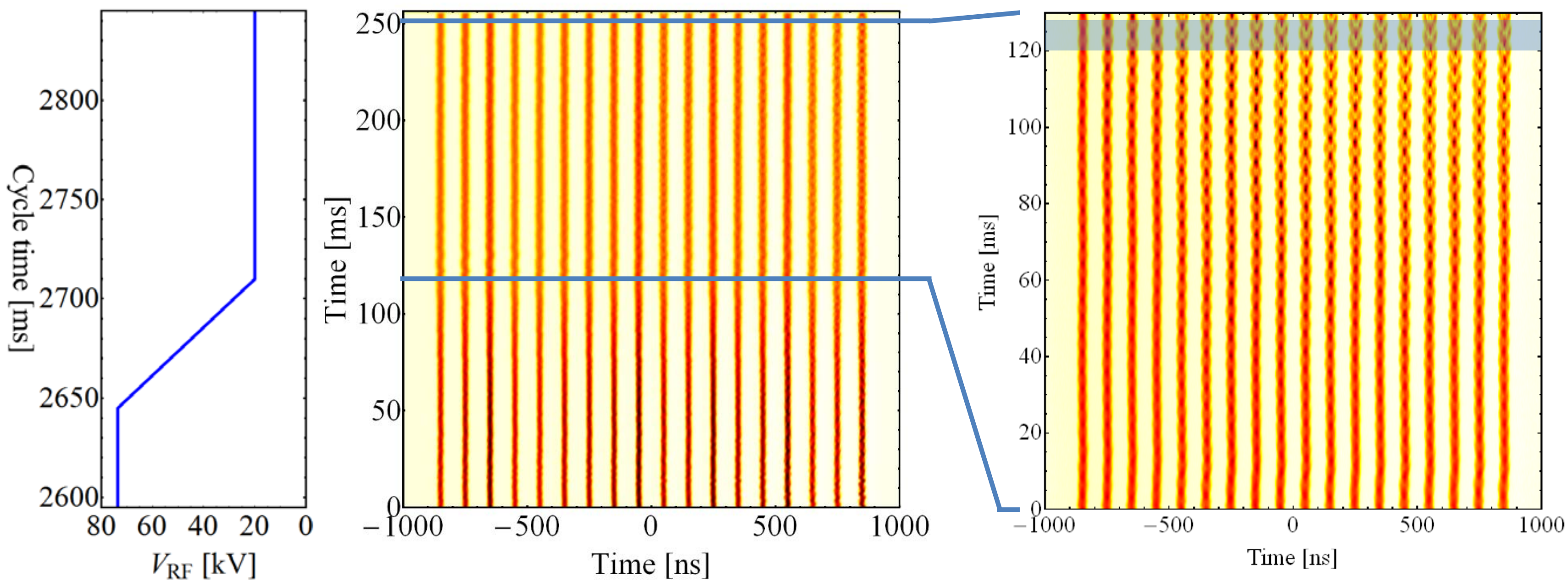
$N_b = 4 \cdot 1.8 \cdot 10^{11}$ ppb



Instability at flat-top

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

$N_b = 4 \cdot 1.8 \cdot 10^{11}$ ppb **$N_b = 4 \cdot 2.0 \cdot 10^{11}$ ppb**



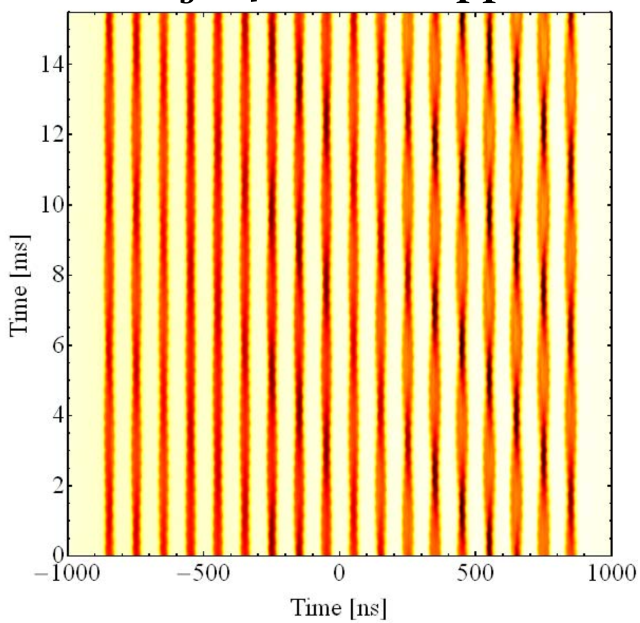
- **Dipole coupled-bunch oscillations well damped**
- **Again quadrupolar oscillations at ~$4 \cdot 2 \cdot 10^{11}$ ppb**

  → **Not damped by feedback system? → Mode analysis**

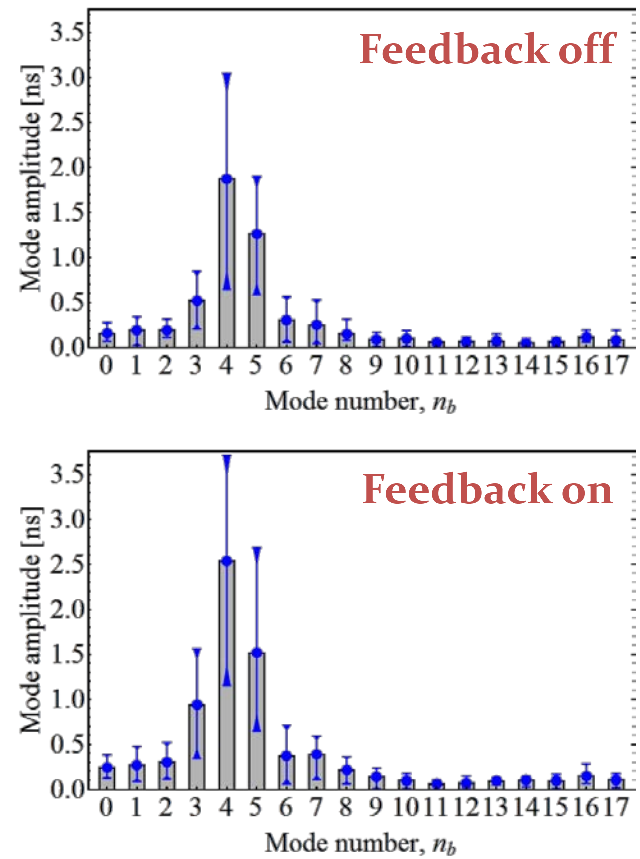
Quadrupole oscillations with feedback?

- **Side-bands at ±2f_S also pass the filters of the coupled-bunch feedback**
  - → **BUT: phase advance wrong (set for dipole oscillation damping)**

$N_b = 4 \cdot 2.0 \cdot 10^{11}$ ppb



Quadrupole mode spectrum



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

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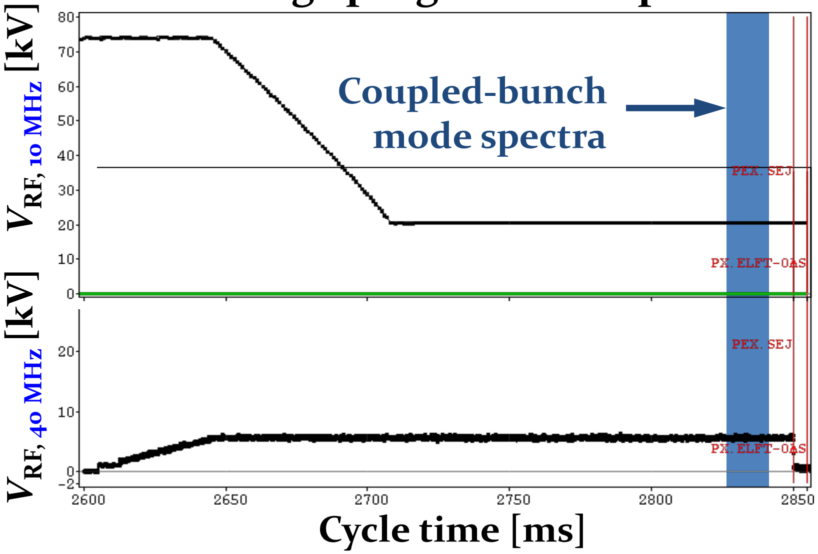
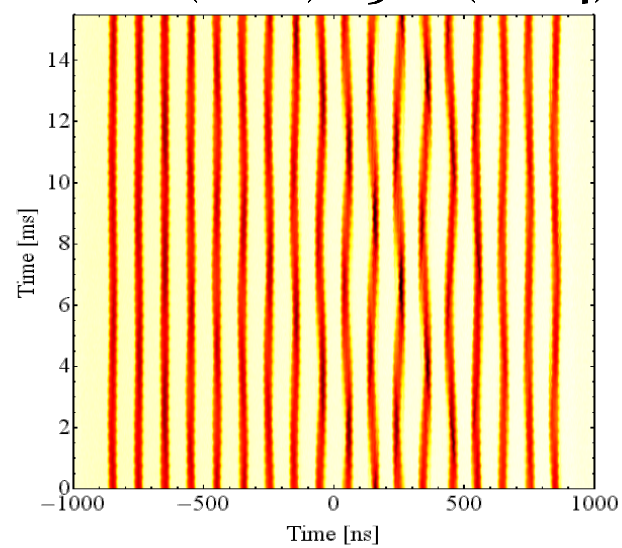
High-frequency cavity as Landau RF system

- **Proof-of-principle test adding 20/40 MHz at flat-top in 2016**
  - → Nominal intensity of $4 \cdot 1.3 \cdot 10^{11}$ ppb without coupled-bunch feedback
  - → Bunch shortening (BS, in-phase) and lengthening (BL, counter-phase)

Voltage program example



20 kV (h = 21) + 5 kV (h = 84)



→ **No significant stability change in BL mode**

High-frequency cavity as Landau RF system

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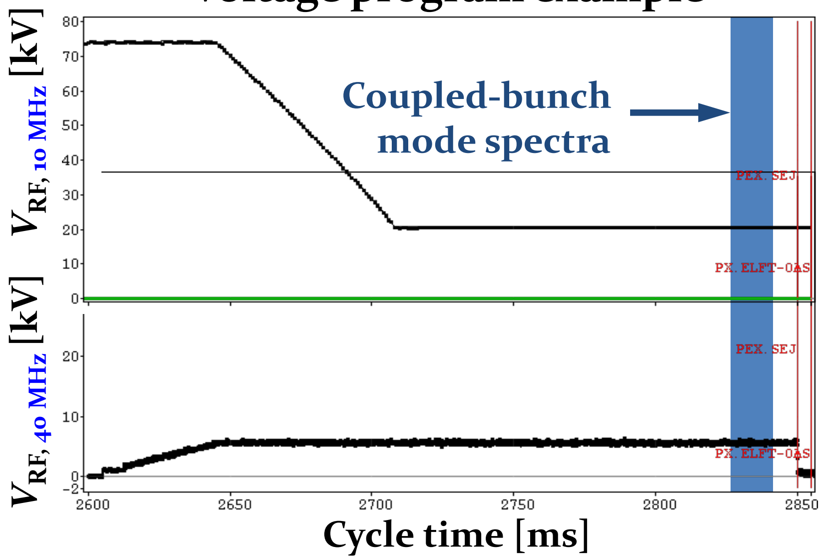
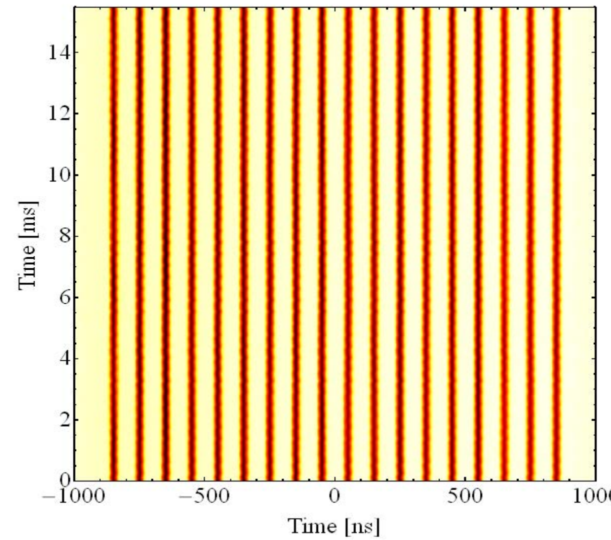


20 kV (h = 21) + 5 kV (h = 84)



→ **Much improved stability in BS mode**

→ **Similar condition than in the SPS with 200/800 MHz RF systems**

E. Shaposhnikova et al., PAC2005

Damping of quadrupole instability

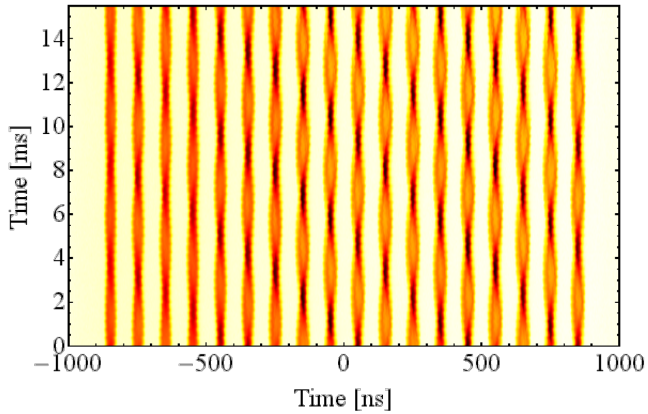
→ $N_b = 4 \cdot 2 \cdot 10^{11}$ ppb together with dipole coupled-bunch feedback

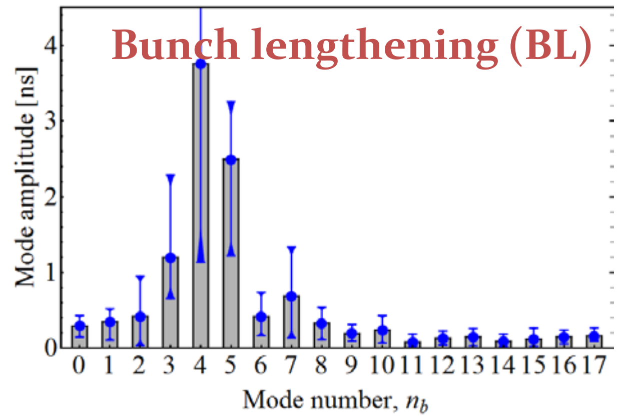
→ Bunch shortening (BS, in-phase) and lengthening (BL, counter-phase)

→ Reduce higher harmonic voltage down to ratio $V_{40\,\mathrm{MHz}}/V_{10\,\mathrm{MHz}} = 0.1$

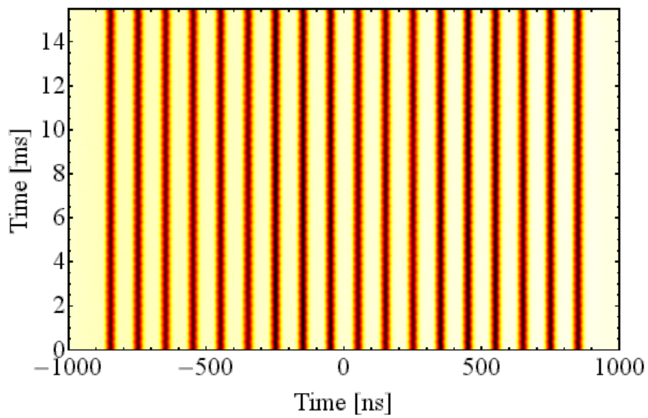
20 kV (h = 21) + 2 kV (h = 84)

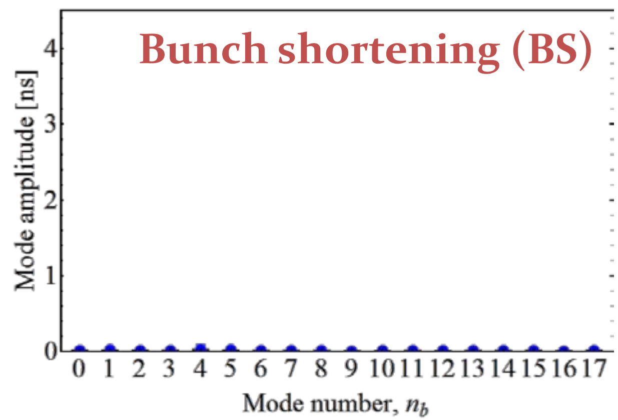
Quadrupole mode spectrum





No effect





Stable

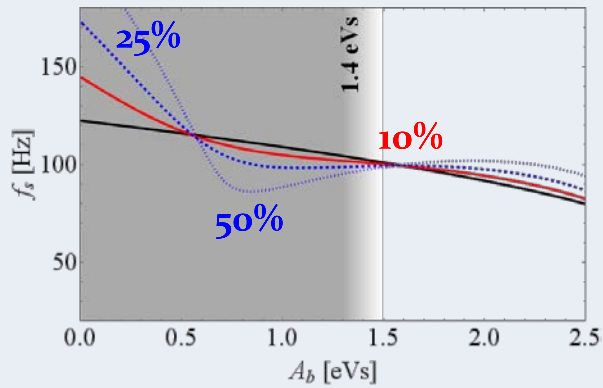
→ Encouraging results with combination 10 MHz/40 MHz

Synchrotron frequency distributions

	In-phase (bunch shortening)	Counter-phase (lengthening)

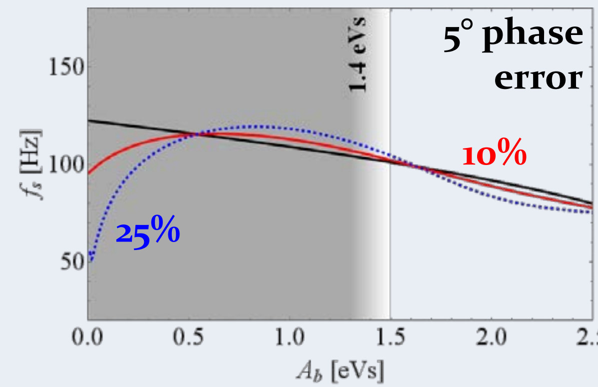
h = 21 (20 kV) + h = 84 (harmonic ratio: 4)

In-phase (bunch shortening)



→ Much improved stability

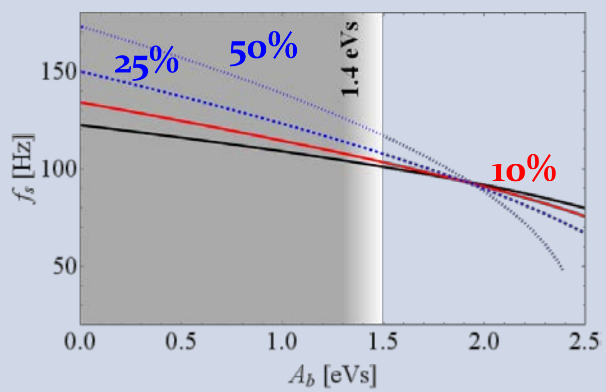
Counter-phase (lengthening)



→ Little effect on stability

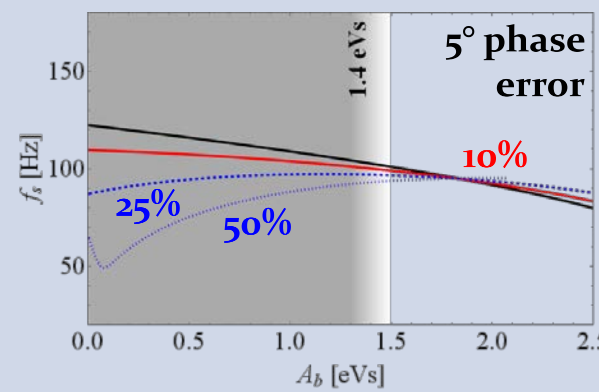
h = 21 (20 kV) + h = 42 (harmonic ratio: 2)

In-phase (bunch shortening)



→ Slightly improved stability

Counter-phase (lengthening)



→ Slightly improved stability

- Only one MD in 2016: promising → Study systematically in 2017

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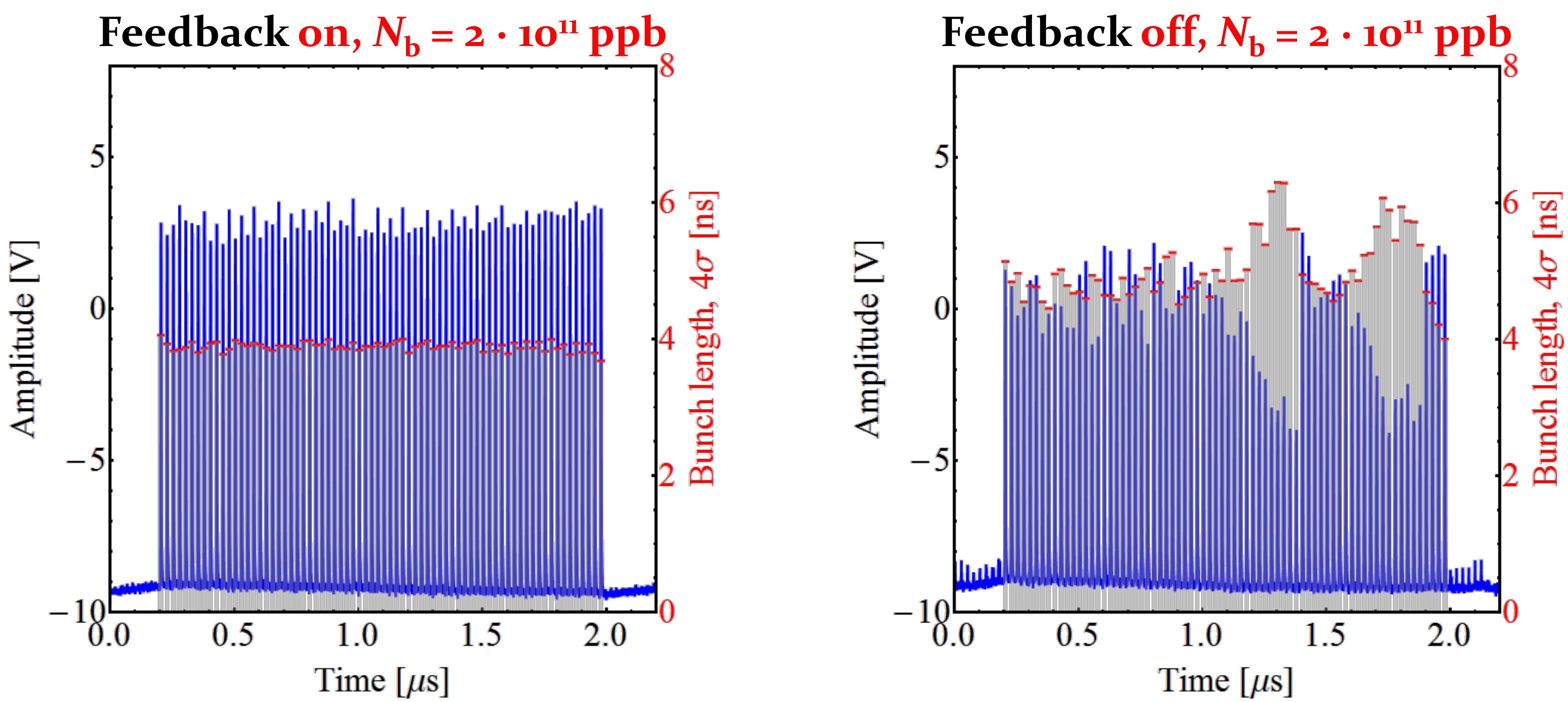
Maximum intensity at extraction

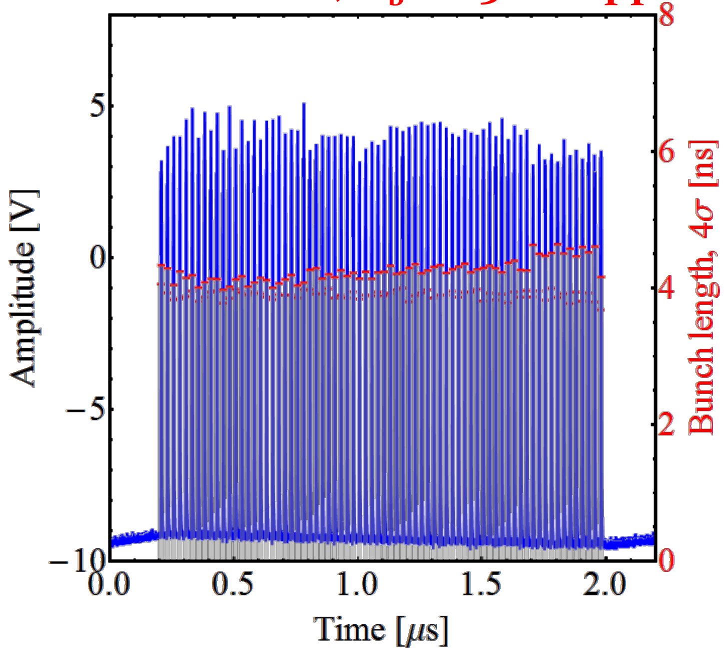
- **Coupled-bunch feedback significantly improves beam stability**
  - → **Regularly delivered ~2 · 10¹¹ ppb with nominal longitudinal emittance of ε_l = 0.35 eVs and bunch length of 4σ = 4 ns (Gaussian fit)**
  - → **Beam quality as at ~1.3 · 10¹¹ ppb without feedback**



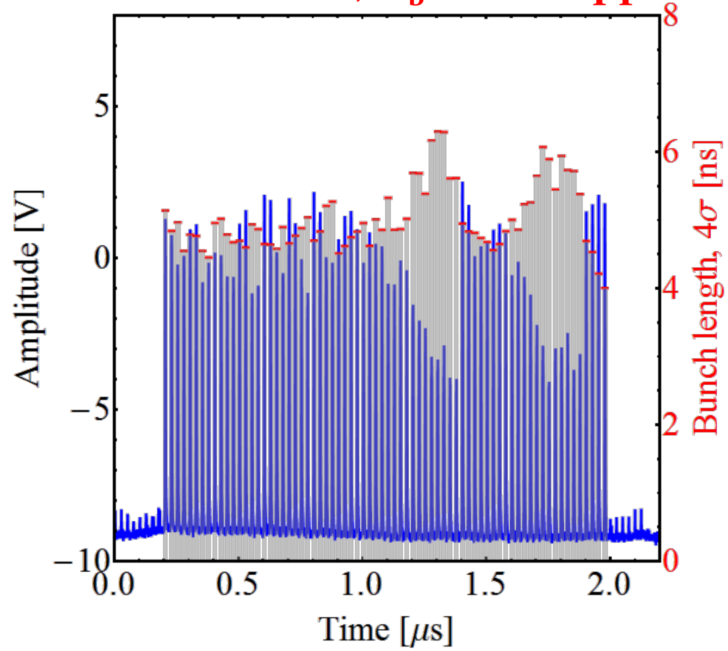
Maximum intensity at extraction

- **Coupled-bunch feedback** significantly improves beam stability
  - → **Regularly delivered** ~$2 \cdot 10^{11}$ ppb with nominal longitudinal emittance of $\varepsilon_l = 0.35$ eVs **and** bunch length of $4\sigma = 4$ ns (Gaussian fit)
  - → **Beam quality as at ~$1.3 \cdot 10^{11}$ ppb without feedback**

Feedback on, $N_b = 2.3 \cdot 10^{11}$ ppb

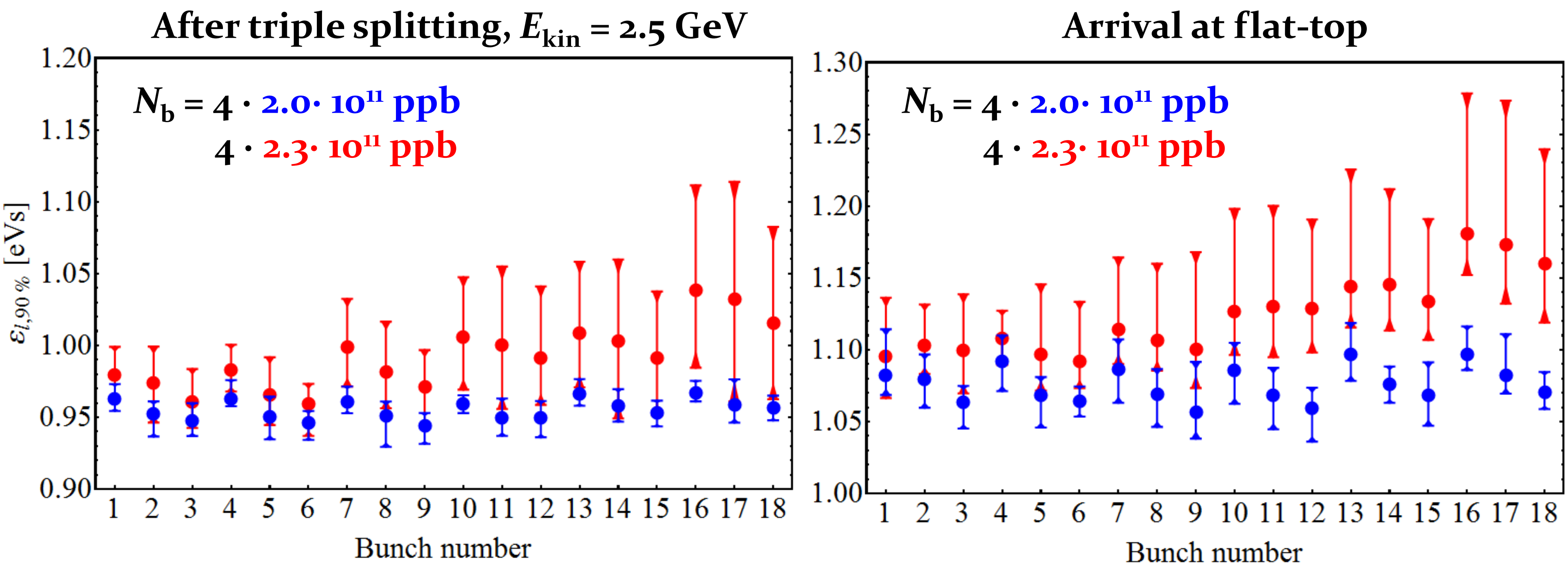


Feedback on, $N_b = 2 \cdot 10^{11}$ ppb



Longitudinal emittance along batch

- Above bunch intensities of $2 \cdot 10^{11}$ ppb beam quality degrades
- Emittance along batch increase



→ Again first few bunches much less affected than tail of batch

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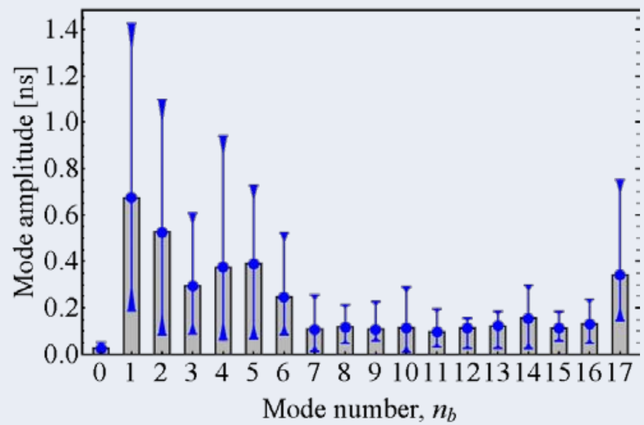
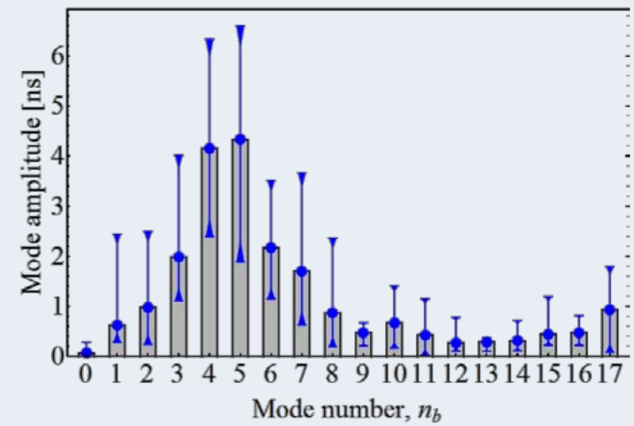
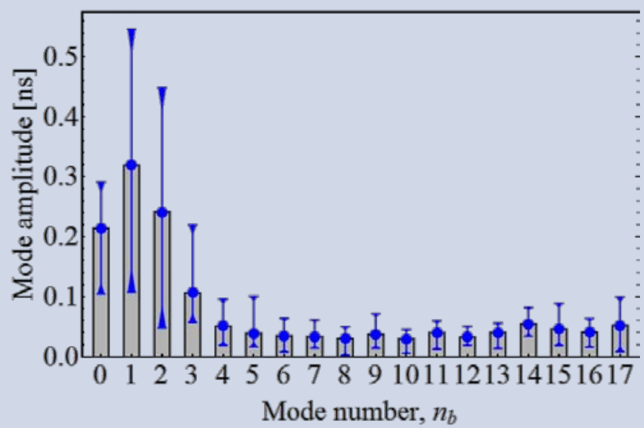
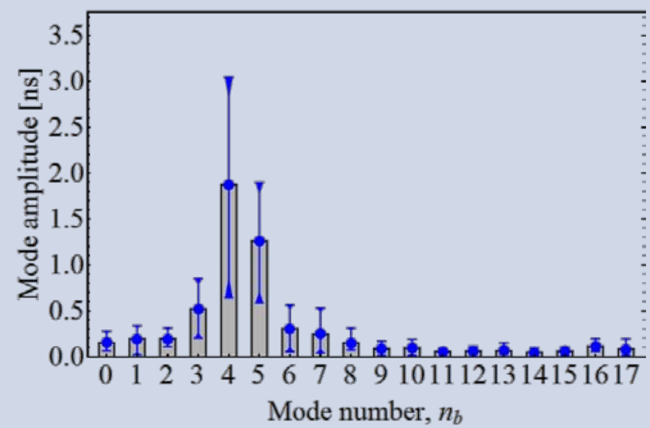
Summary of coupled-bunch mode

- **Mode pattern changes at flat-top, as observed for dipole oscillations**

	Acceleration	Flat-top
Dipole (2013/2016 data)		
Quadrupole (2017 data)		

→ **Measurements of coupled-mode spectra reproducible over years**

Summary

- **Prototype frequency domain coupled-bunch feedback**
  - → **Six-gap wideband Finemet cavity covering f_{rev} to $hf_{rev}/2$**
  - → **Ten-channel signal processing covering all possible modes**
- **Extensive studies with Finemet coupled-bunch feedback**
  - → **Dipolar oscillations well handled**
  - → **Bunch intensity of $2.0 \cdot 10^{11}$ ppb regularly delivered with excellent longitudinal beam quality**
- **Effects at higher intensity**
  - → **Quadrupolar coupled-bunch instabilities → Not damped by feedback**
  - → **Uncontrolled emittance blow-up along the batch**
  - → **Low $2Q/\omega_0$ source impedance(s) → Impedance modeling**
- **Complementary stabilization techniques**
  - → **High frequency cavity as Landau RF system?**
  - → **Damping of quadrupole oscillations at flat-top**
  - → **New RF system covering frequency sweep during acceleration?**

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

CERN

Spare slides

Timeline

2003/2004	• Coupled-bunch instability with LHC-type beams observed
2005	• Analog feedback covering modes $n_b = 1/20$ and $n_b = 2/19$ • Two accelerating cavities as feedback kickers https://ab-div.web.cern.ch/ab-div/Meetings/APC/2005/apc050609/JL_Vallet_slides.pdf
2006/2007	• Study of coupled-bunch oscillations http://accelconf.web.cern.ch/AccelConf/p07/PAPERS/FRPMN069.PDF
2008-2011	• Mode scans along the cycle under various conditions • Instability scales with longitudinal bunch density http://accelconf.web.cern.ch/AccelConf/HB2010/papers/mopd52.pdf
2012/2013	• Excitation scans using existing coupled-bunch feedback • All modes are well decoupled from each other • Demonstration of cross-damping (band change) http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/tupwa044.pdf
2014 (LS1)	• Installation of Finemet wide-band kicker • Beam-loading reduction feedback http://accelconf.web.cern.ch/AccelConf/IPAC2014/papers/tupri060.pdf
2015	• Excitation of coupled-bunch modes • Damping of all modes simultaneously, $1.7 \cdot 10^{11}$ ppb reached http://accelconf.web.cern.ch/AccelConf/ipac2016/papers/tupor028.pdf
2016	• Performance study, $2.0 \cdot 10^{11}$ ppb operationally reached

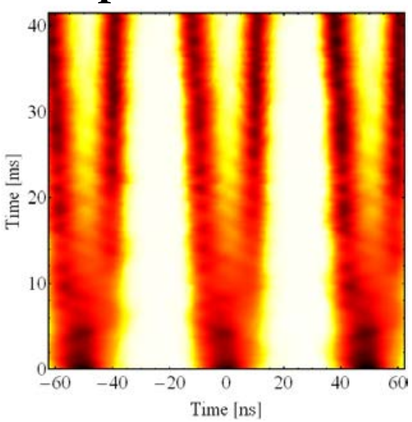
Impedance at high frequency and highest intensity

Effect of 80 MHz cavity impedance

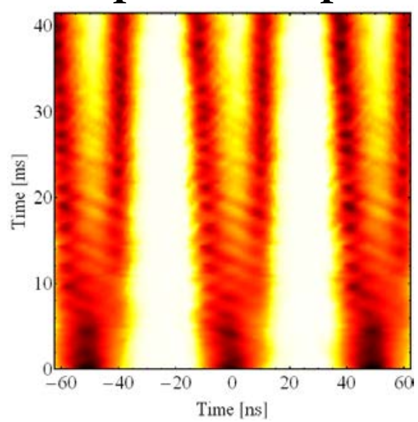
- **80 MHz cavity for lead ions tuned to 135 kHz below proton frequency, but 3 dB bandwidth about 0.7 MHz**

→ 80 MHz structure during *h* = 42 → 84 splitting

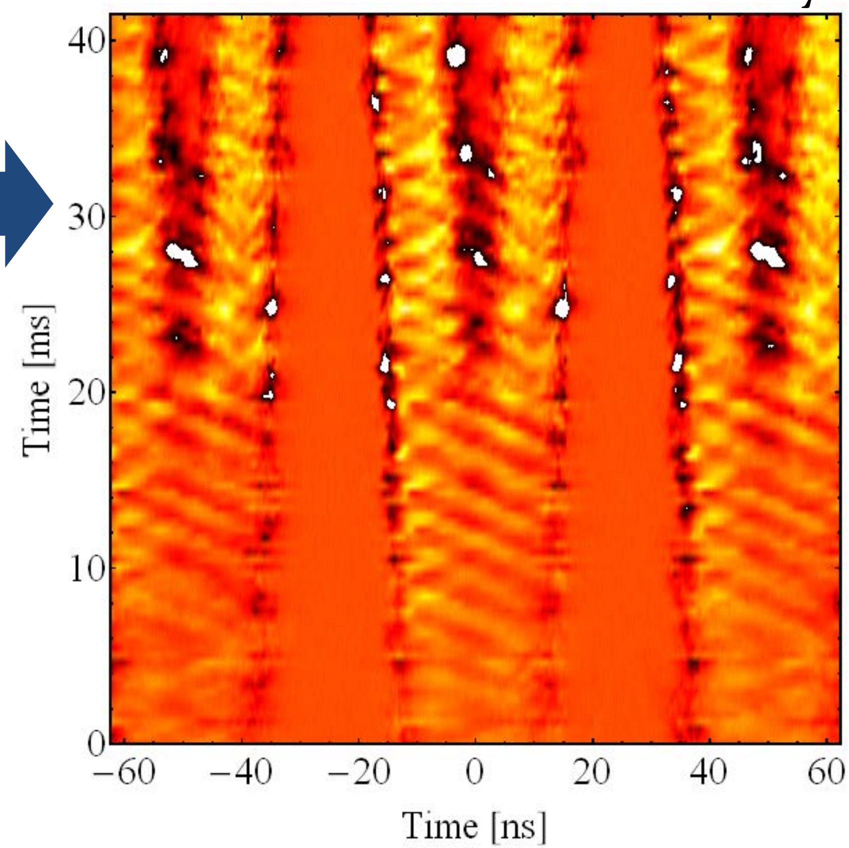
Gap C80-08 closed



Gap C80-08 open



Averaged difference, with and without effect of 80 MHz ion cavity



- **Perturbation visible at $1.6 \cdot 10^{11}$ ppb**

→ Effect on beam quality?

80 MHz cavity impedance

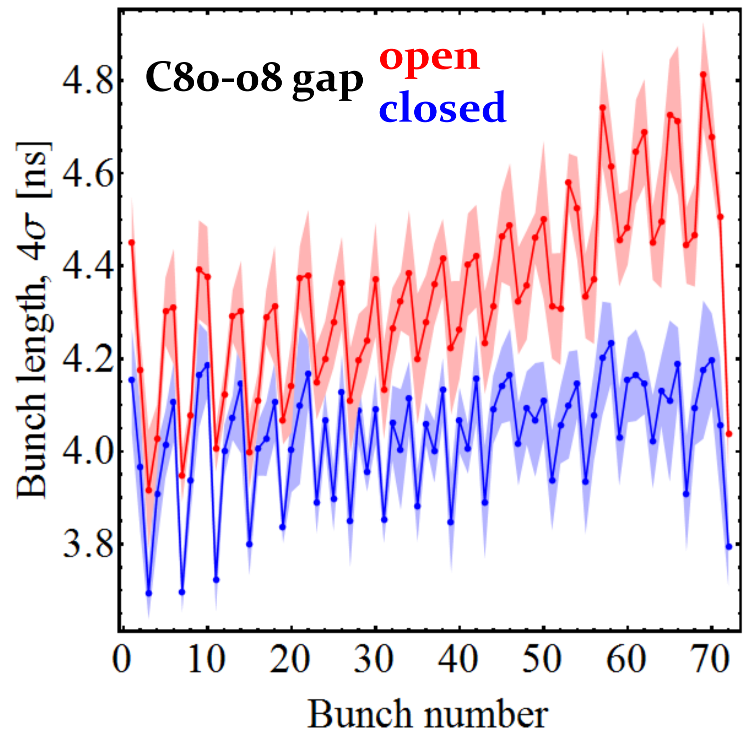
Emittance at arrival on flat-top (4 final bunches)

Cavities with gap open	ε_{RMS} [eVs]
C40-78, C80-88, C80-89	0.231
C40-78, C80-88, C80-89 **and C80-08** (at ion frequency)	0.238

Average bunch length at extraction

Cavities with gap open	$4\sigma_{Gauss}$ [ns]
C40-78, C80-88, C80-89	4.03
C40-78, C80-88, C80-89 **and C80-08** (ion frequency)	4.34

Bunch length at extraction



http://cds.cern.ch/record/1141522/files/AB-Note-2008-052-MD.pdf

→ **Minor emittance blow-up at arrival on flat-top, but**

→ **~0.3 ns longer bunches due to impedance of additional 80 MHz cavity**

→ **Expect improvement with new multi-harmonic feedbacks**

Higher intensity?

Pushing intensity at expense of larger longitudinal emittance

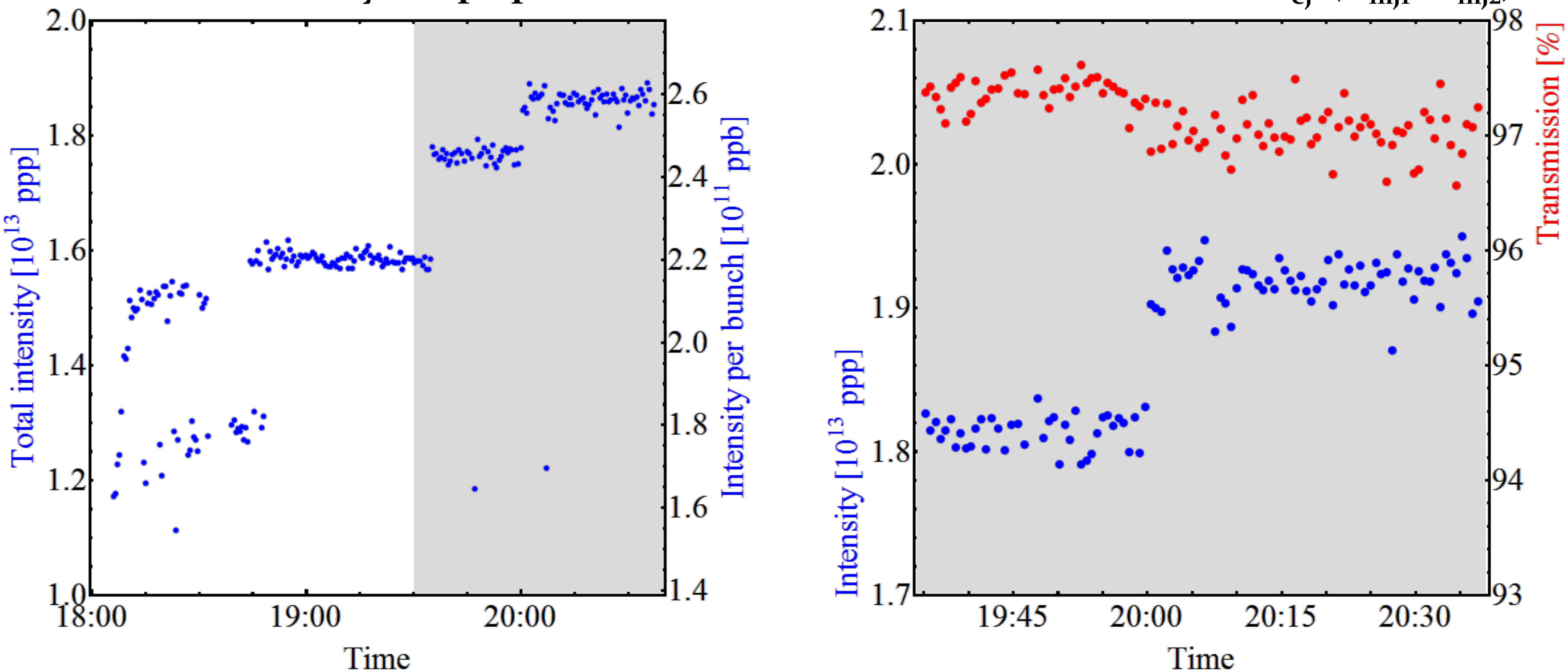
→ Bare minimum of 40/80 MHz cavities with gap open (C40-78, C80-88, C80-89)

→ Trips of remaining cavities C40-78 and C80-08 due to beam loading

→ Measurements difficult to perform, almost like dedicated MDs

Intensity ramp up

Overall transmission $N_{ej}/(N_{inj1}+N_{inj2})$



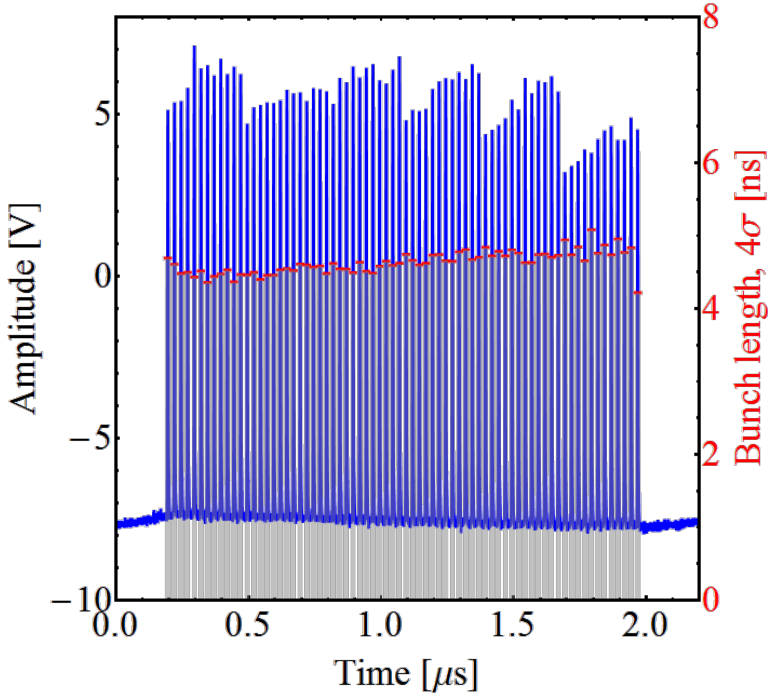
→ **Excellent transmission up to $2.6 \cdot 10^{11}$ ppb, even with $\varepsilon_l > 0.35$ eVs**

→ **No further RF issues related to intensity**

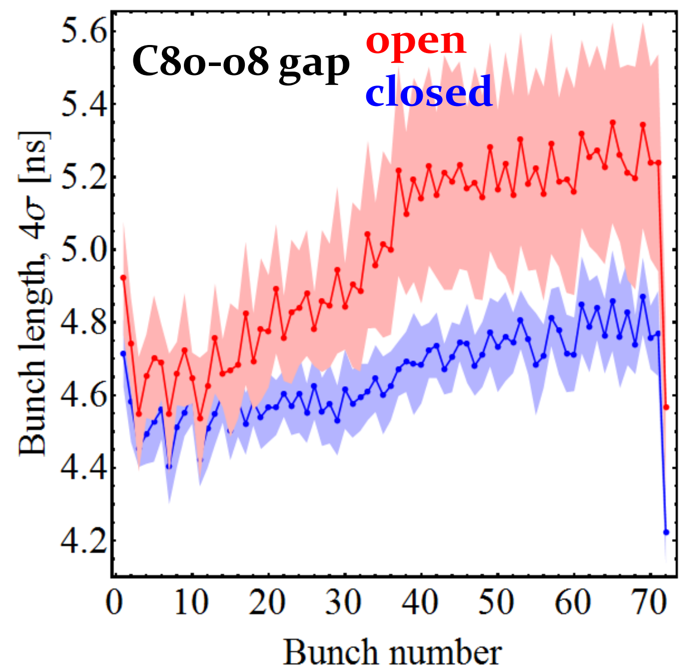
Longitudinal beam quality

Longitudinal parameters at LIU/HL-LHC baseline intensity: 2.6 · 10^{11} ppb

→ Additional longitudinal blow-up



- **Average ε_l at arrival on flat-top: 0.3 eVs (RMS, 4 final bunches)**
- **Corresponds to ~0.45…0.5 eVs per bunch in usual convention**



- **Bunch length increase along the batch**

  → Onset of instability

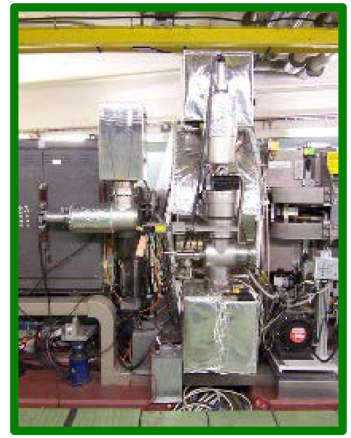
Impedance modeling

Further impedances from RF systems

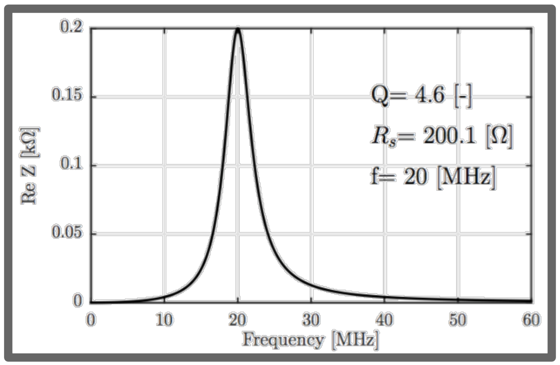
Finemet

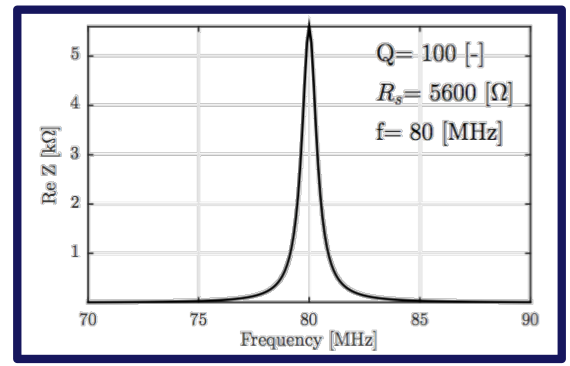
20 MHz

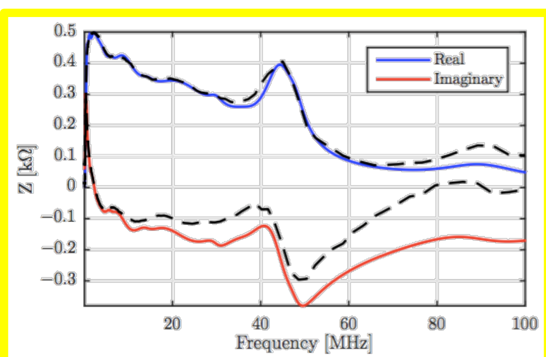
40 MHz

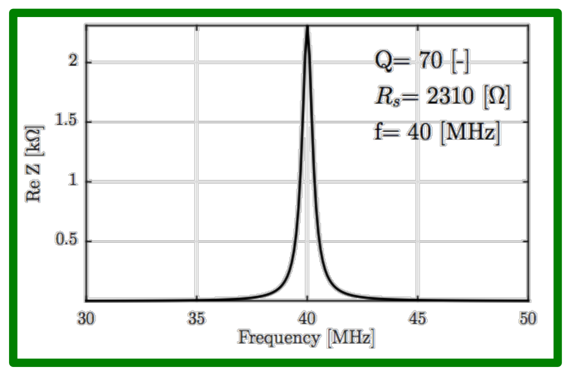


80 MHz



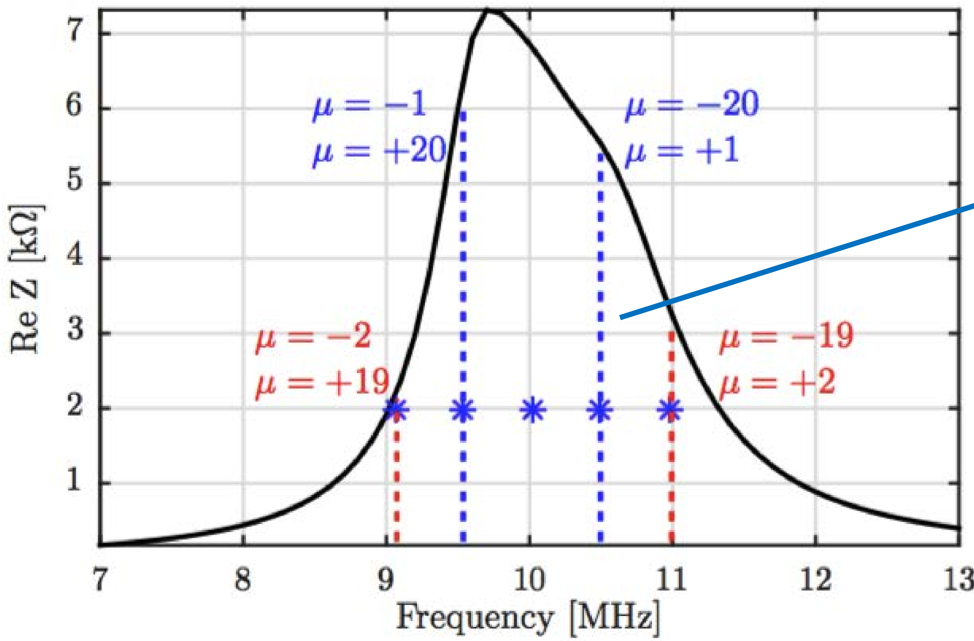




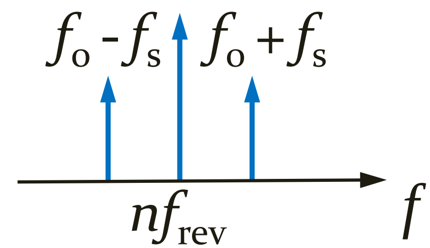


→ Little effect in simulations

Simplified mechanism of instability



Each dashed line stays for:



- **Asymmetry of cavity impedance at synchrotron frequency side-bands of revolution frequency harmonics, e.g.,**

→ **Impedance $h_{RF} + 2f_{rev} + f_s$ larger than impedance at $h_{RF} - 2f_{rev} - f_s$**

→ **Corresponding coupled-bunch mode $n_b = 2$ unstable**

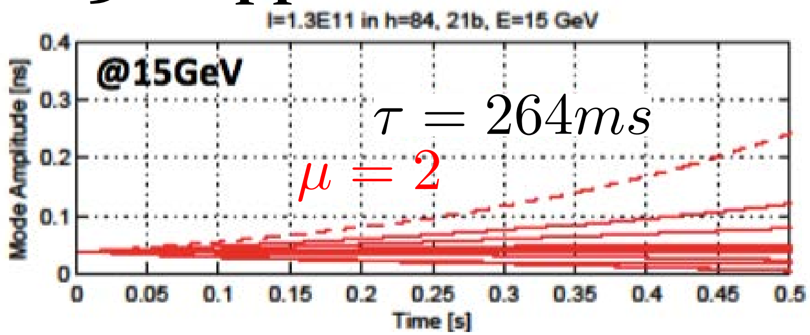
→ **Smaller impedance asymmetry $h_{RF} \pm f_{rev}$ for $n_b = 1$ mode**

Simulations with 21 bunches in h = 21

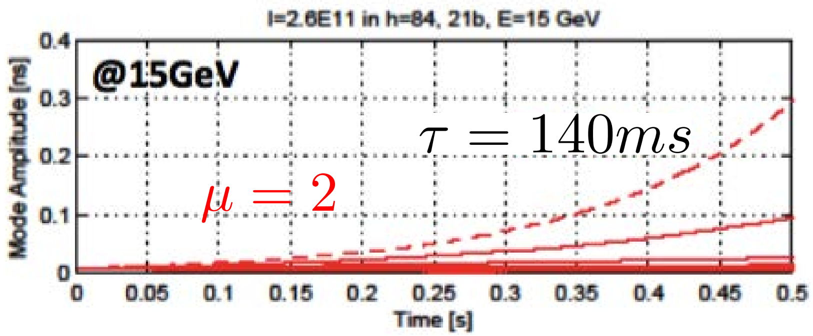
Previous impedance model

→ Single macro-particle per bunch

- **1.3 10^{11} ppb**



- **2.6 10^{11} ppb**

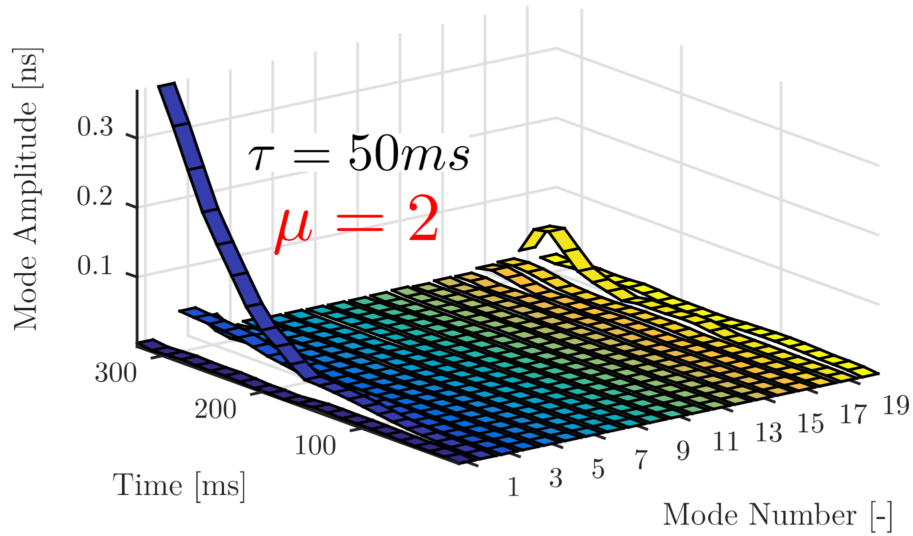


→ **Twice shorter rise time when doubling intensity**

Updated impedance model

→ Multiple particles per bunch, length ~ 1 m

- **2.6 10^{11} ppb**



→ **Mode 2 grows faster than mode 1, as expected**

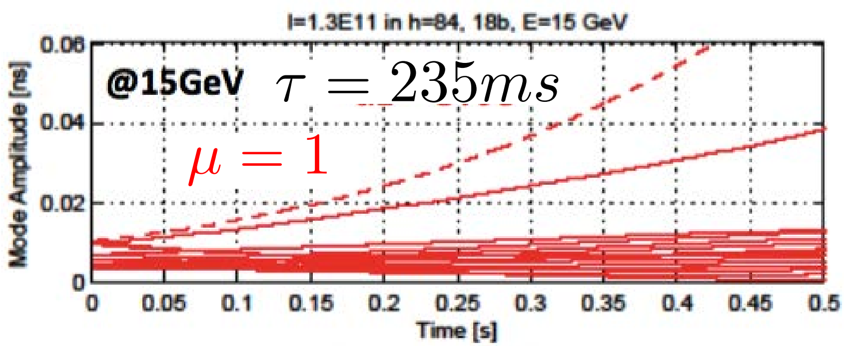
→ **Four times larger impedance translates in three times shorter rise time**

Simulations with 18 bunches in $h = 21$

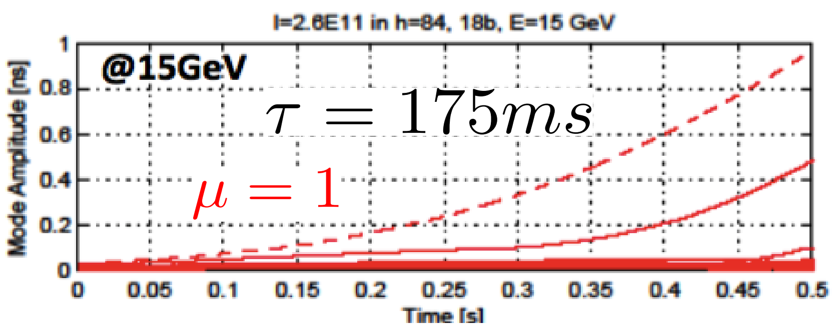
Previous impedance model

→ Single macro-particle per bunch

- **$1.3\ 10^{11}$ ppb**

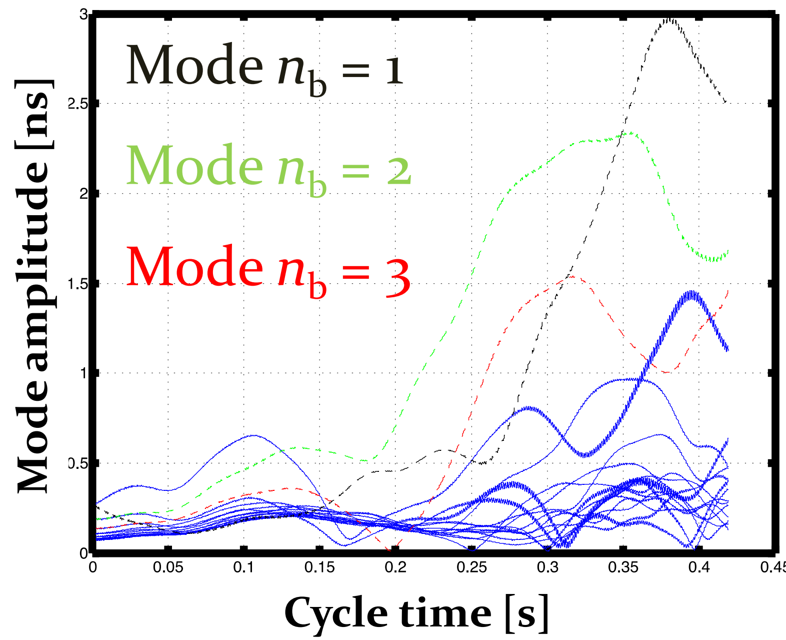


- **$2.6\ 10^{11}$ ppb**



Updated impedance model

→ Multiple particles per bunch, length ~ 1 m

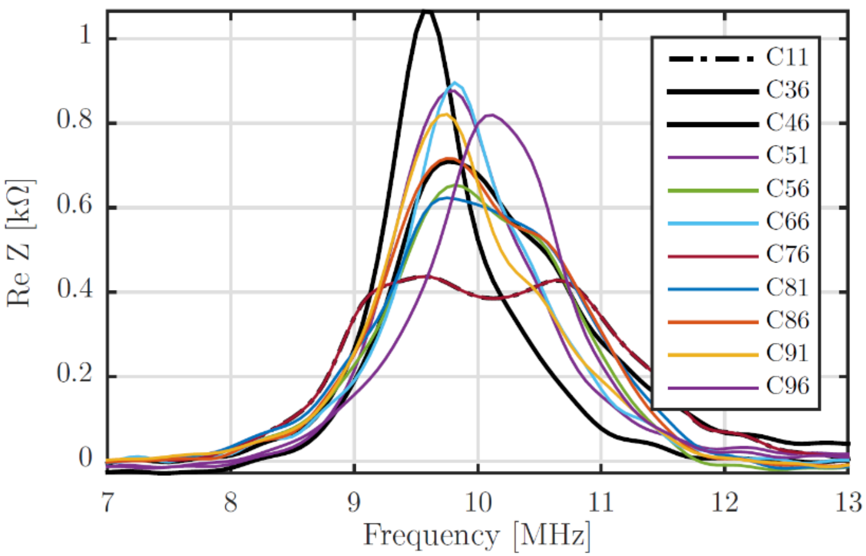


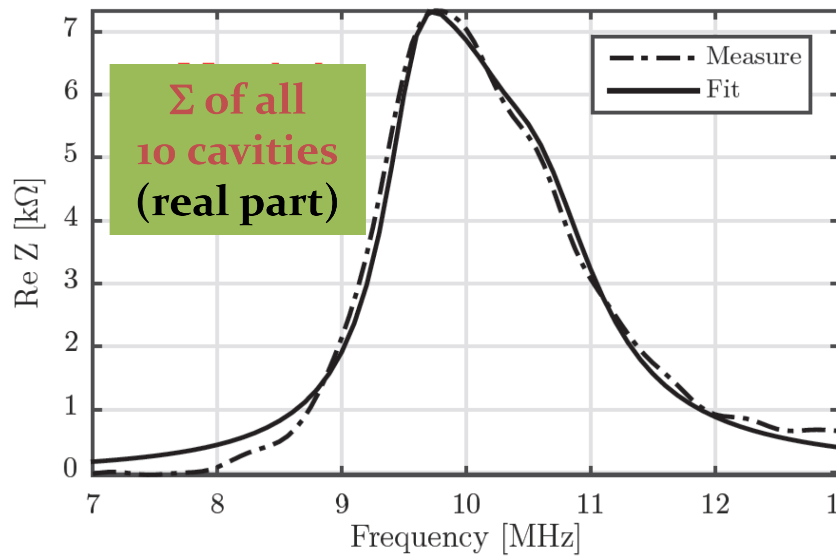
→ **Rise times not well defined**

→ **Stays of the order of ~50 ms**

New 10 MHz cavity impedance model

- **Studies revealed that 10 MHz cavity four times larger than previously assumed (G. Favia)**





$$Z(\omega) = \sum_{i=1}^{3} \frac{R_{Si}}{1 + iQ_i\left(\frac{\omega_{Ri}}{\omega} - \frac{\omega}{\omega_{Ri}}\right)}$$

Q	R_S [kΩ]	f_{RF} [MHz]
14	4	9.6
9.5	3.5	10
9	3.15	10.6

→ Total impedance modelled as three resonators (fit of real part of impedance)

→ Input for MuSiC code (M. Migliorati)

Coupled-bunch feedback implementation

Time domain vs. frequency domain

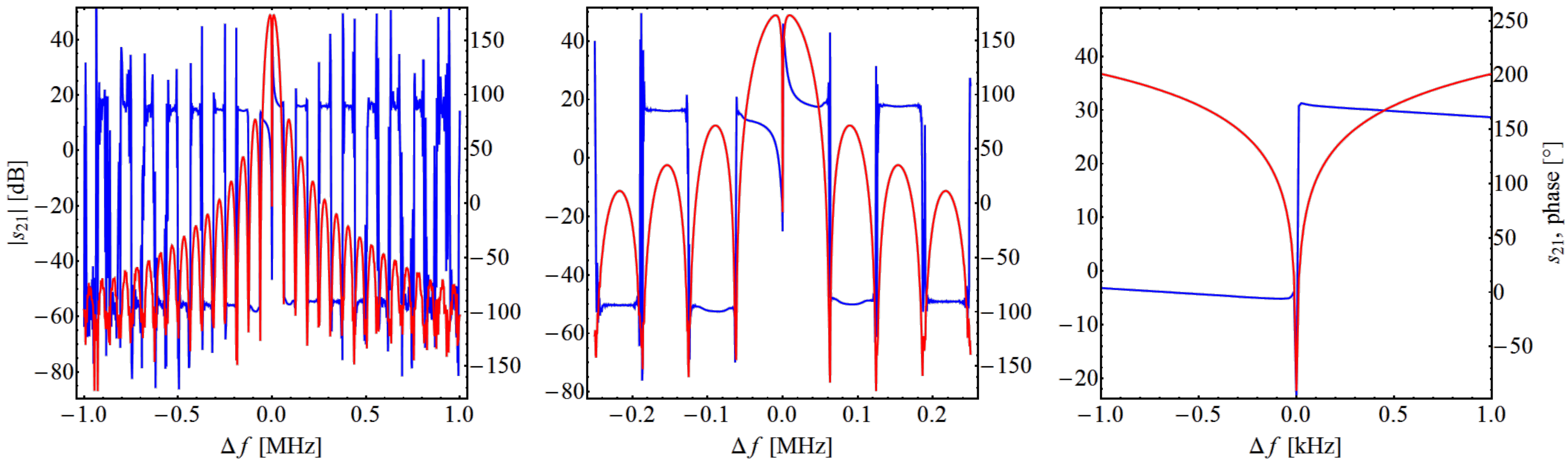
Time domain	Frequency domain
+ Damping independent from mode pattern	+ Instability shows similar bunch-to-bunch phase advance
+ **Feedback action directly observable**	+ Gain, delay and phase adjustable per harmonic/mode → compensates Finemet cavity transfer function
+ Few adjustment parameters	+ **No need for physical delay**
– Synchronous bunch clock, **difficult during RF manipulations**	+ **Insensitive to bunch phases and filling patter →** no need for bunch clock
– **Physical delay** for time-of-flight compensation	– Many parameters to be adjusted → only easy for cavity with fixed impedance
– Separate **compensation of Finemet cavity transfer function**	– **Requires sharp filters** to extract synchrotron frequency side-bands
• Limited experience	• Experience with previous coupled-bunch feedback

→ Frequency domain approach chosen

Filtering of f_s sidebands

Transfer function measurements for one signal processing chain

- f_{center} = 10 MHz corresponding to h_{CB} = 20 at f_{rev} = 500 kHz

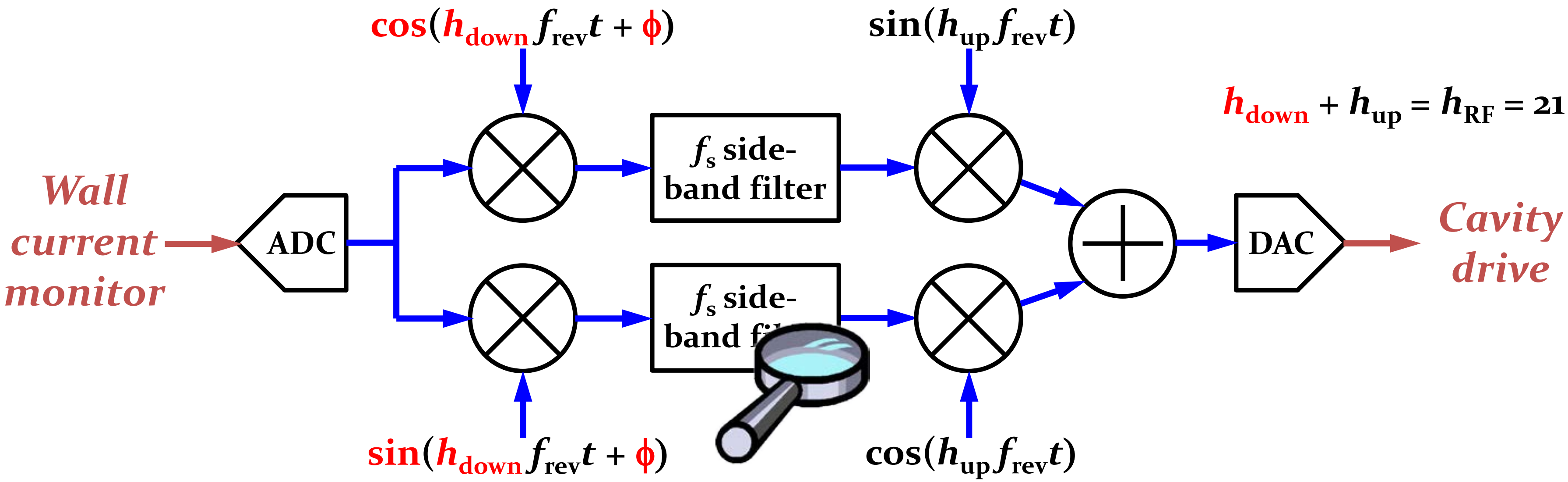


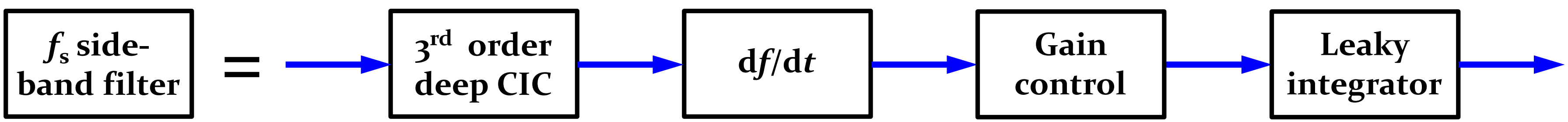
→ **Harmonic of f_{rev} attenuated by more than 40 dB compared to sidebands at ± fs (~300 Hz)**

→ **Precise 180° phase jump at center frequency**

→ **Notches covering all other f_{rev} multiples and their f_s sidebands**

Tracking filters – coupled-bunch damping

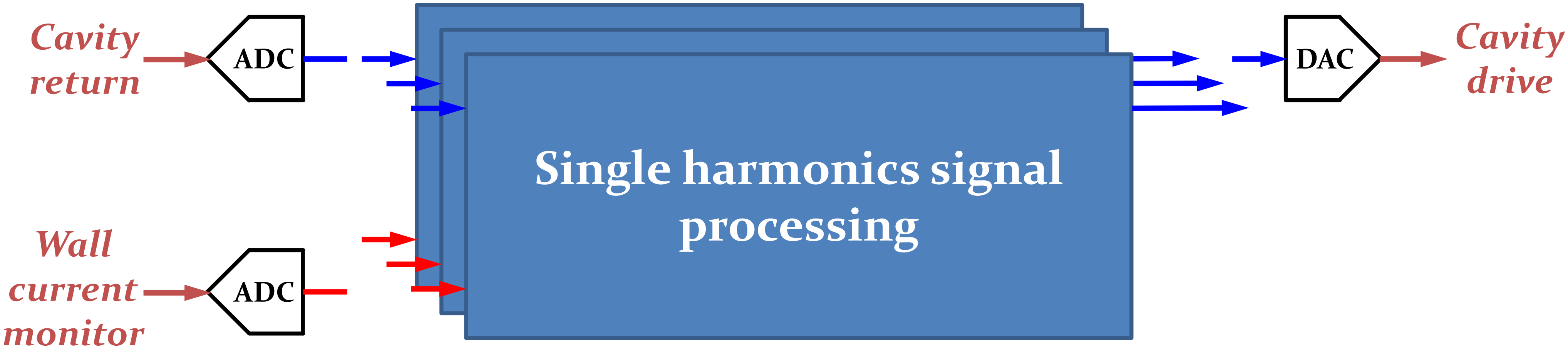


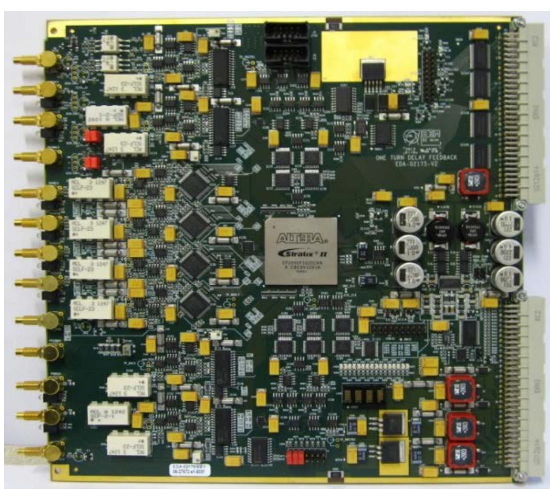


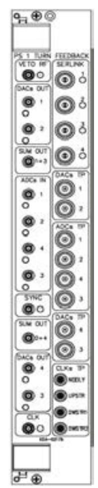
- Sharp attenuation to separate $\pm f_s$ of sidebands from f_{rev} harmonics
- Sharp 180° phase jump at center frequency
- Programmable gain, delay and phase
- Demodulation (at h_{down})/modulation (at h_{up}) at different harmonics
- Sideband inversion for cross-damping

Extension to multiple harmonics

→ **Straight-forward extension to multiple harmonics**





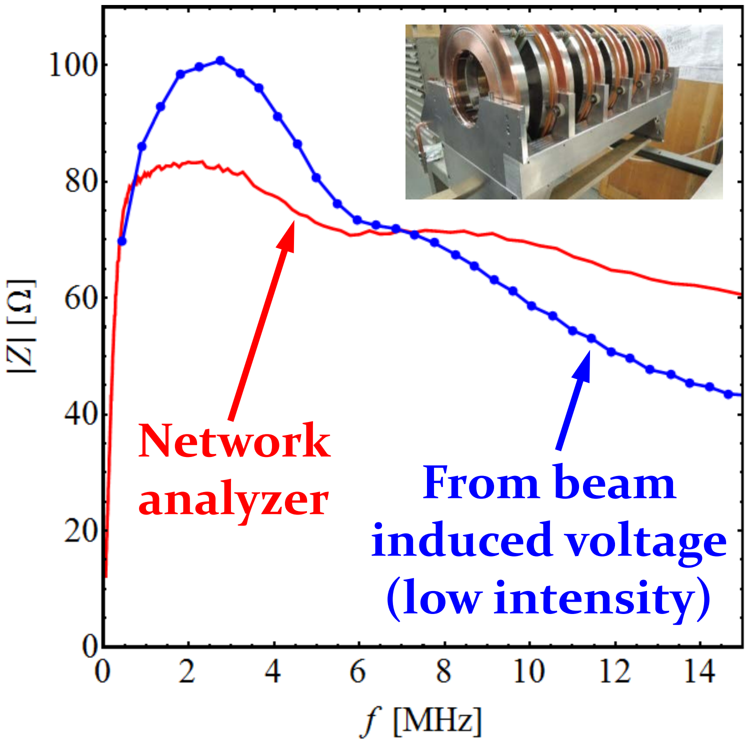


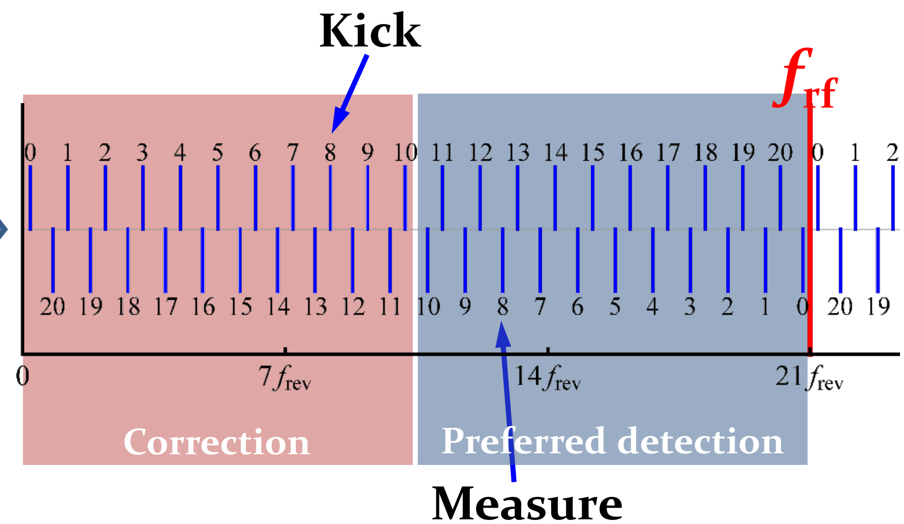
EDA-2175, D. Perrelet

- **PS 1-turn delay feedback hardware (4 modules)**
- **3 harmonics per board**
- **12 harmonics to reduce beam induced voltage**
- **Beam synchronous clock**

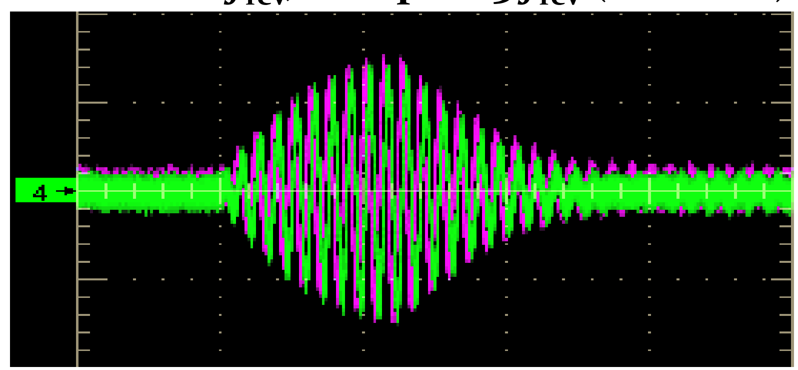
Choice of frequency ranges: cross-damping

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





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

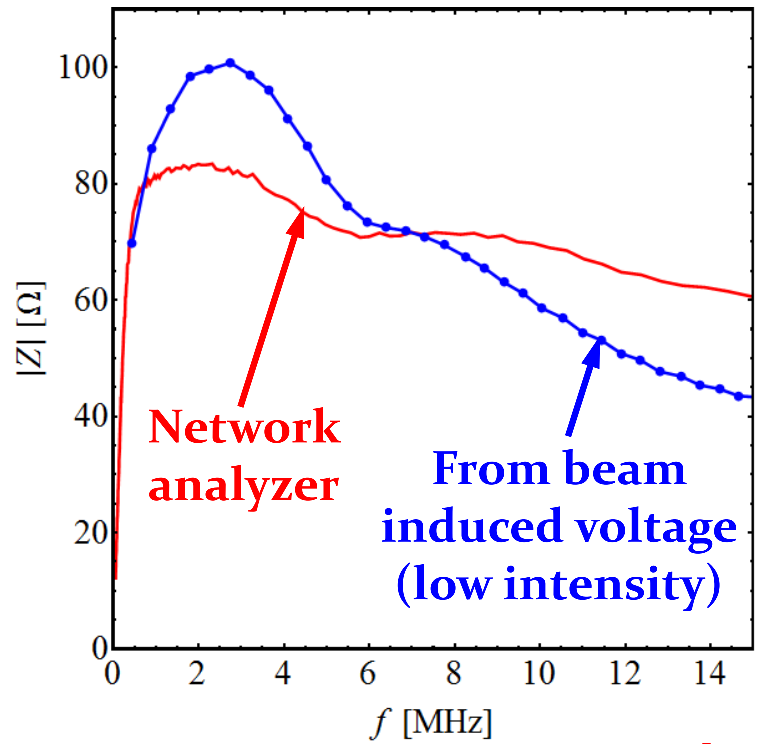


1. **Detect f_s sidebands at 11…20 f_{rev}**
2. **Correct beam at 1…10 f_{rev}**

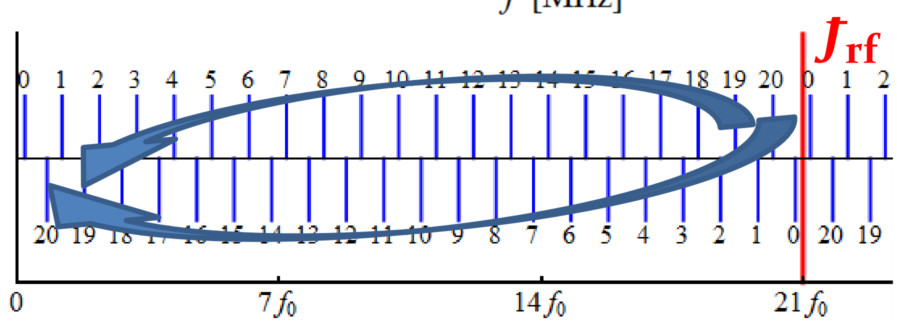
→ **20 modes → 10 signal processing chains**

Cross-damping

- **Profit from spectral symmetry:**
  - → **Avoid detection at low harmonics**
    - → **Detect at $f_{RF}/2 \ldots f_{RF}$**
  - → **Use maximum impedance of Finemet damper cavity**
    - → **Apply correction at $f_{rev} \ldots f_{RF}/2$**



- → **Inversion of side-bands**
- → **Must lock all numerical local oscillators to f_{rev}**

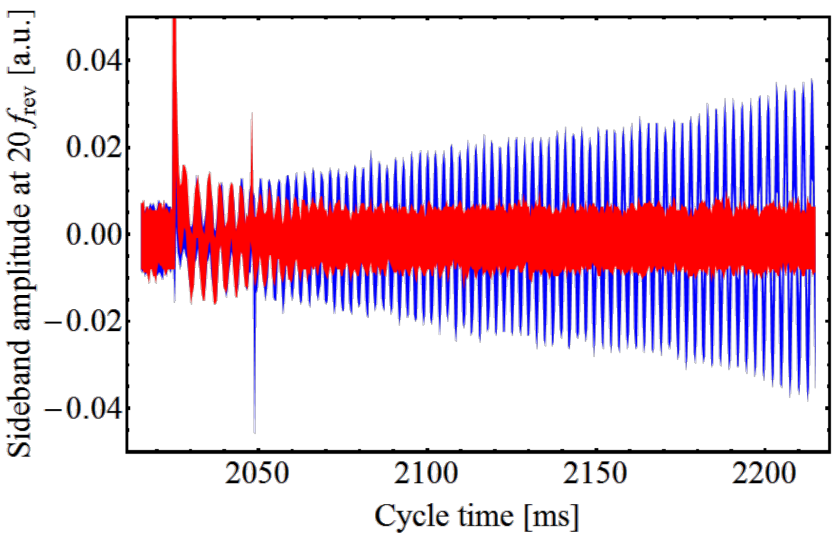


→ **With all RF sources synchronized cross-damping works as expected**

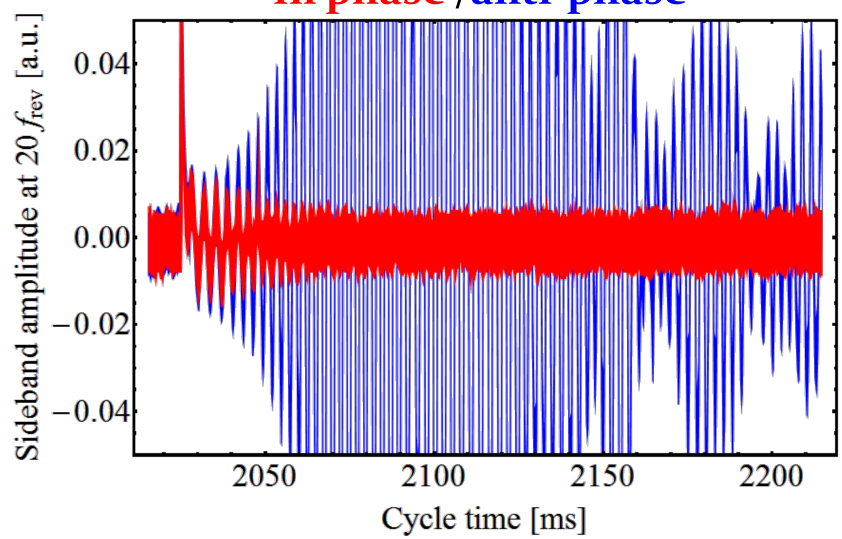
Cross-damping

- **Successfully commissioned with new hardware in 2015**
- **Synchronization of all RF sources for down- and up-conversion with respect to $h = 1$ (f_{rev})**

Feedback on and off



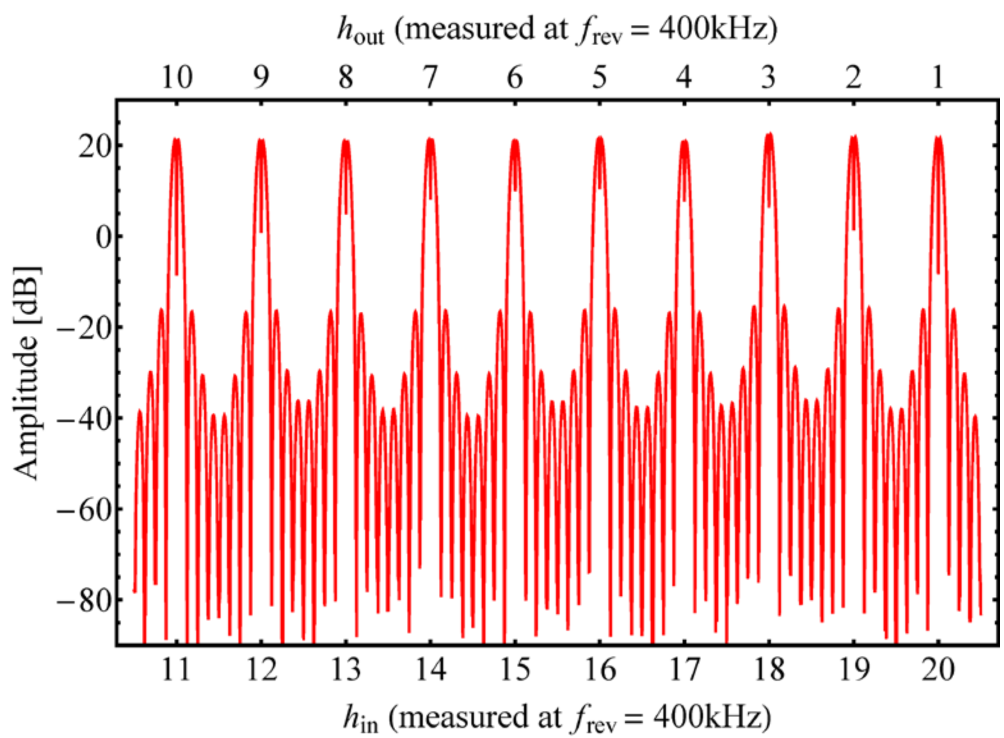
In phase /anti-phase

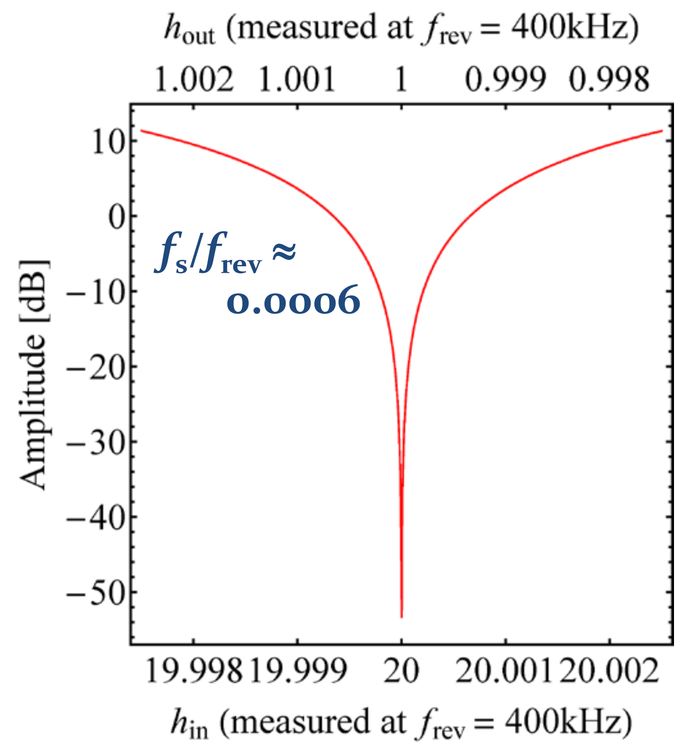


→ Intermittent state when synchronization missing

Measured transfer function of all harmonics

- **Difficult to measure due to freq. conversion: $f_{out} = h_{RF} f_{clk}/256 - f_{in}$**
  - → **Excitation sweeps upwards from 10.5 f_{rev} to 20.5 f_{rev}**
  - ← **Detection sweeps downwards from 10.5 f_{rev} to 0.5 f_{rev}**



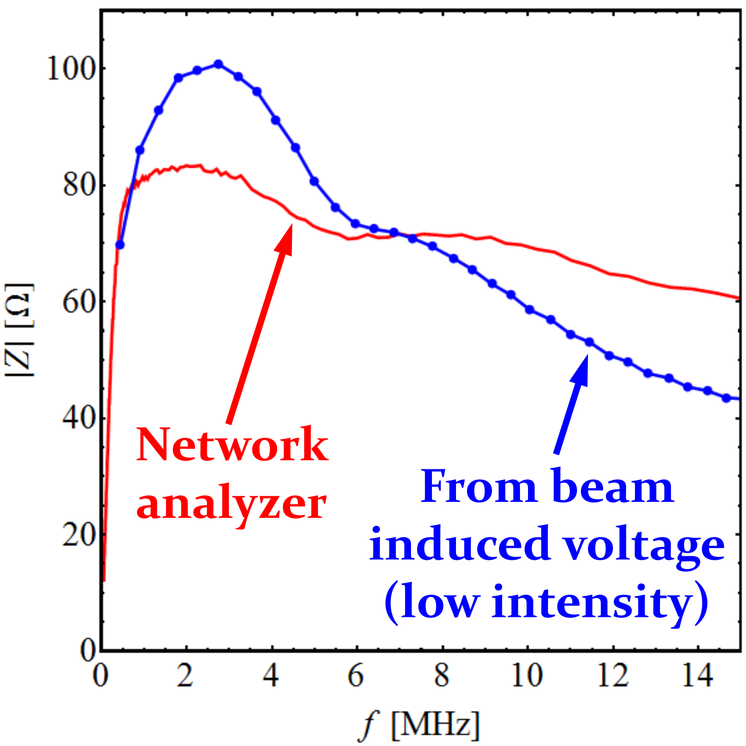


→ **Feedback design fully validated**

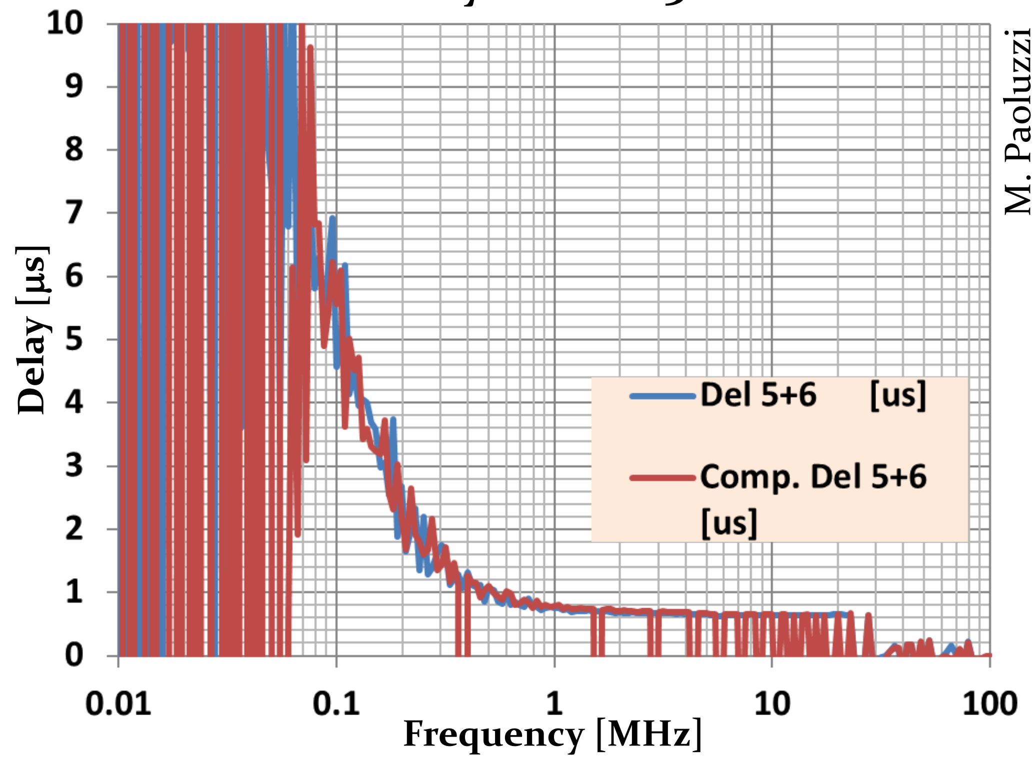
→ **All 10 signal processing channels operational**

Cavity impedance of PS Finemet cavity

Impedance per cell with amplifier



Delay of cells 5+6



→ **No tuning,** impedance unchanged during acceleration

→ **Impedance** quasi constant within 10% frequency range

→ **With** 20 dB reduction → ~10 Ω/cell (cf., e.g., wall current monitor: 6 Ω)

→ Harmonic dependent delay, **especially for low harmonics**

→ **Damping needed at** many harmonics: ~ f_{rev} to 40 f_{rev}