LHC Injectors Upgrade

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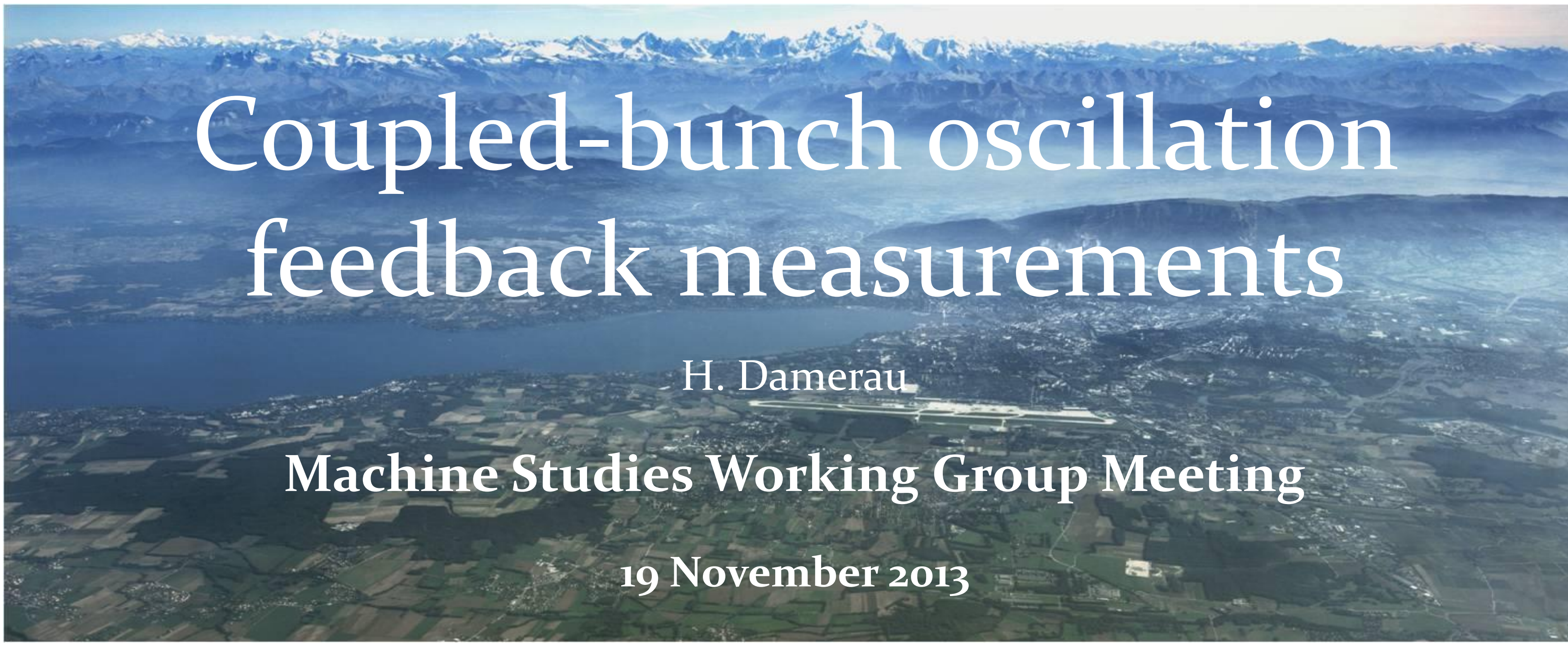

Coupled-bunch oscillation feedback measurements

H. Damerau

Machine Studies Working Group Meeting

19 November 2013

Many thanks to R. Garoby, S. Gilardoni, S. Hancock, M. Migliorati, M. Paoluzzi, E. Shaposhnikova, L.Ventura

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Overview

- Introduction
- Measurements and mode analysis
- Mode spectra without feedback
- Excitation, symmetry of modes
- Mode scans
- Damping rates and kick strength
- Cross-damping
- Summary

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Introduction

- To control longitudinal coupled-bunch oscillations, a new wide-band kicker cavity is being installed during LS1
- For MD studies, the spare 10 MHz cavity C10-11 can be used as kicker cavity for the feedback
  - → Low bandwidth, thus only specific modes to be damped
  - → But huge kick voltage available for MDs
- Difficulties to perform tests in 2012 as the coupled-bunch feedback was required for high-intensity beams to the LHC

→ Extensive studies during short 2013 run measuring

- mode spectra along the cycle,
- damping rate versus feedback gain, intensity, emittance, energy,
- longitudinal kick voltage and
- feedback in cross-damping configuration.

Coupled-bunch oscillations, time domain

- **Bunches oscillate with different phases (and amplitudes)**

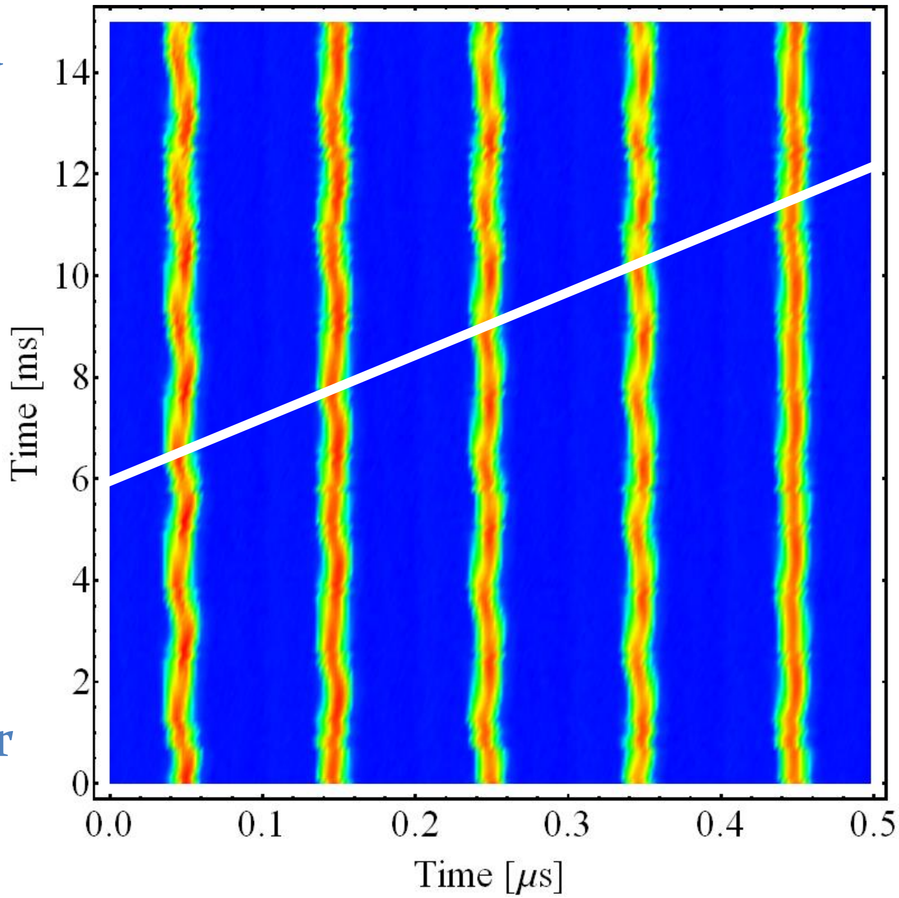
- **Mode number *n* defined by phase advance from bunch-to-bunch:**

$$\Delta\phi = 2\pi\, n/h$$

- **Additionally the bunches may oscillate dipolar ($m = 1$), quadrupolar ($m = 2$), sextupolar ($m = 3$), etc.**

- **Present analysis: dipolar modes, $m = 1$**

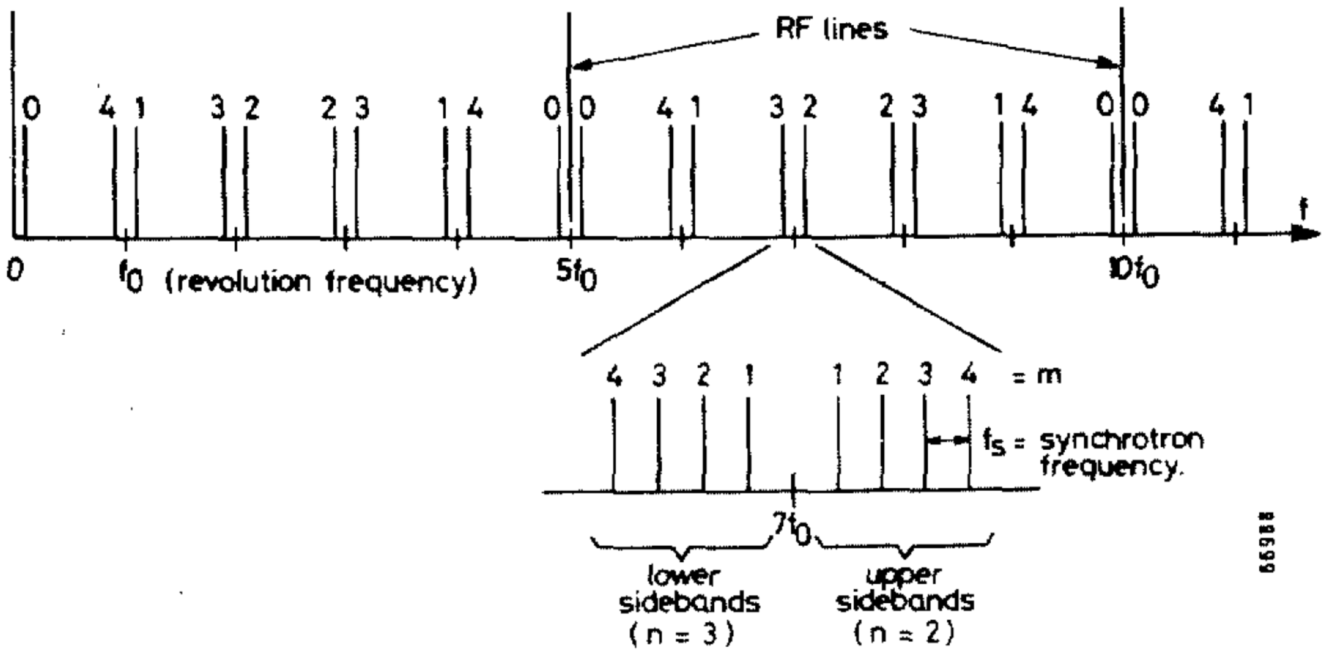
Example of an n = 12 mode ($\Delta\phi \approx 206°$)



→ How does this look like in frequency domain?

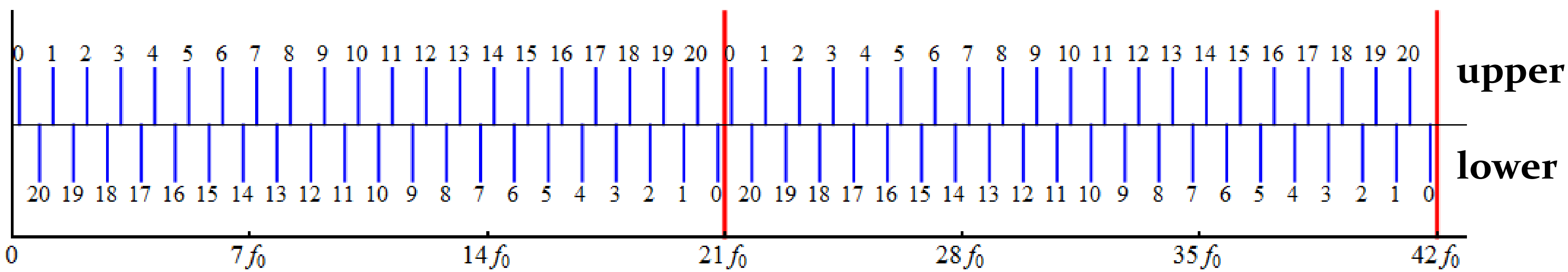
Coupled-bunch oscillations, freq. domain

→ **Synchrotron frequency sidebands of the f_{rev} harmonics:**

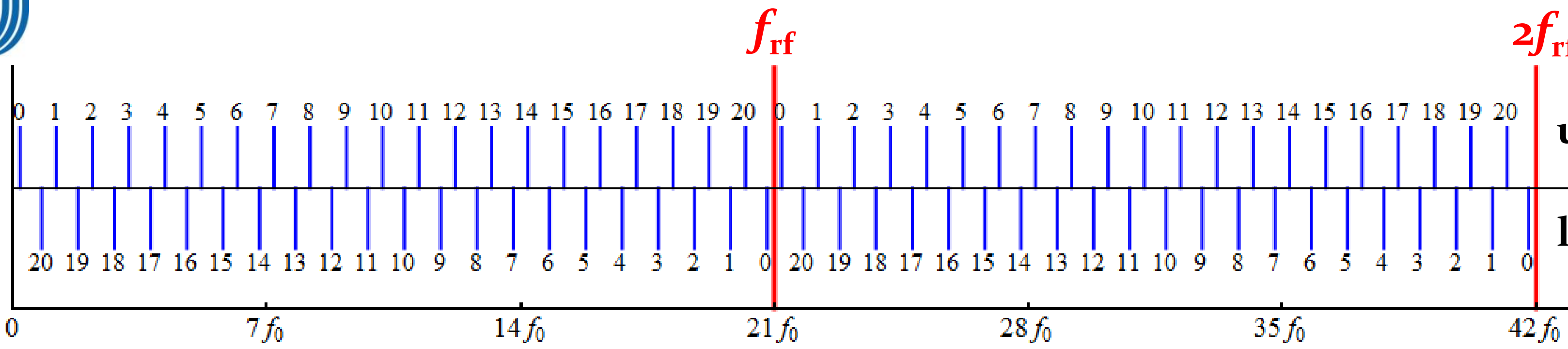


F. Pedersen, F. Sacherer, PAC77, pp. 1397-1399

→ **In the case of LHC-type beams in the PS (h = 21)**



Coupled-bunch oscillations, freq. domain



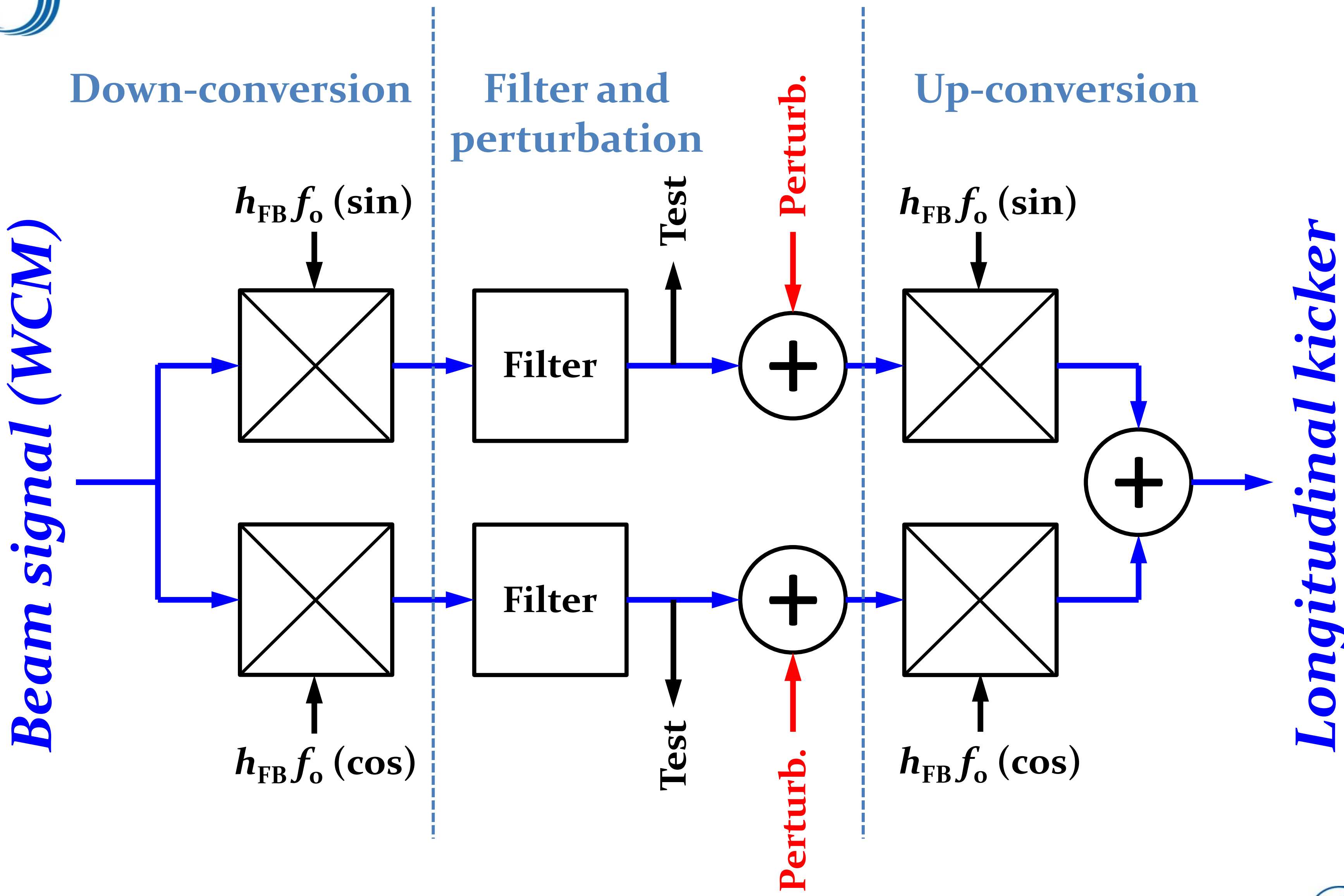
→ **Each mode *n* is observable as an upper side-band of $n f_o$ or as a lower sideband of $(h - n)f_o$**

→ **Damper: Suppress synchrotron frequency side-bands**

→ **Damping and excitation of mode *n* may be achieved at:**

Detection		Excitation		
harmonic	Side-band	harmonic	Side-band	
n	upper	*n*	upper	normal
h - n	lower	*h - n*	lower	normal
h - n	lower	*n*	upper	cross
n	upper	*h - n*	lower	cross

Frequency domain feedback system



J.-L. Vallet, https://ab-div.web.cern.ch/ab-div/Meetings/APC/2005/apc050609/JL_Vallet_slides.pdf

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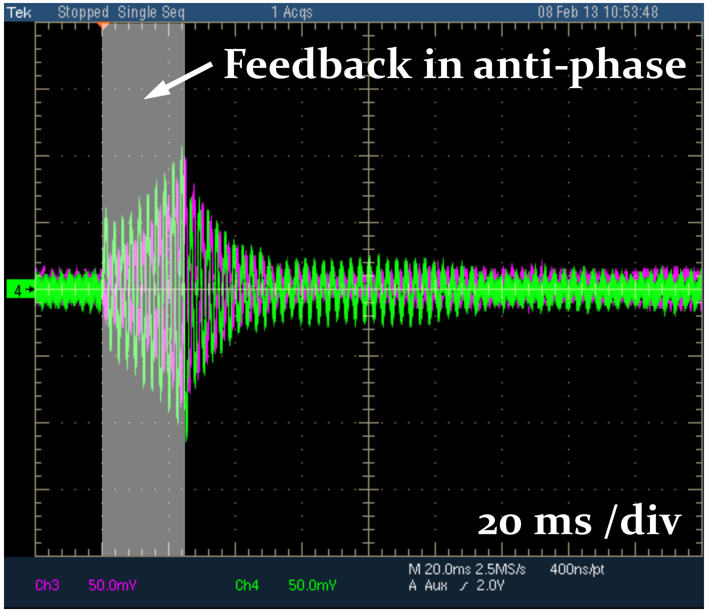
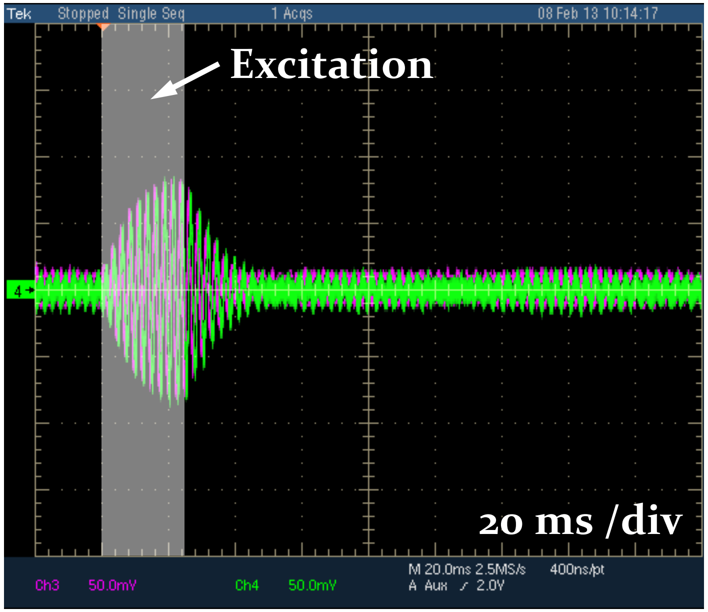
Measurements (1/2)

Beam energy, E	13 GeV(C1800) - 15 GeV(C1850), or scan 9 GeV to 26 GeV
RF voltage	~165 kV
Synchrotron frequency, f_s	~400 Hz
Longitudinal emittance	<0.7 eVs, pushed to stab. limit

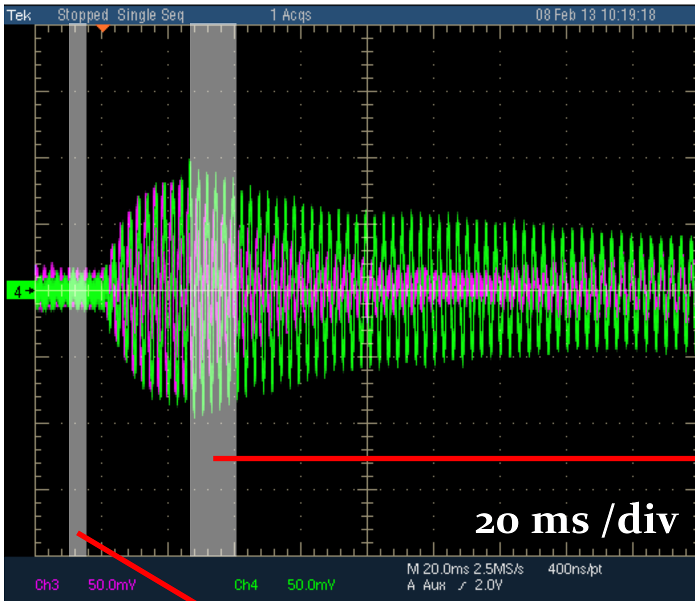
1. **Feedback in anti-phase to adjust optimum phase**
2. **Inject perturbation close to f_s (max. at ~ 395 Hz)**



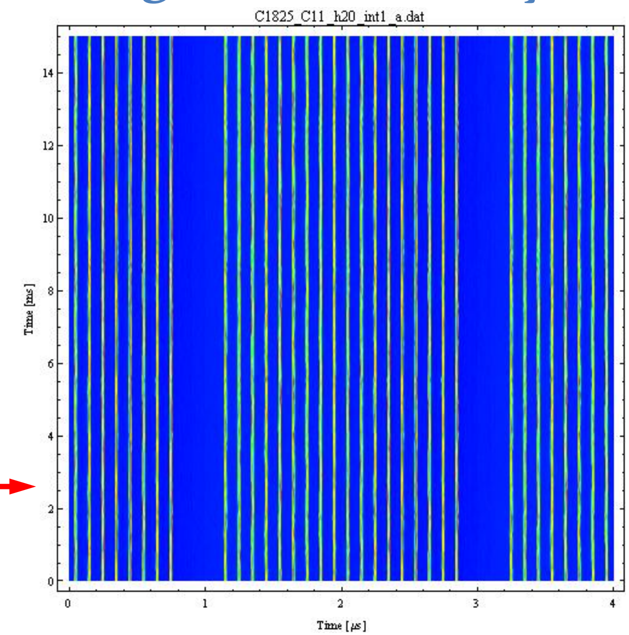


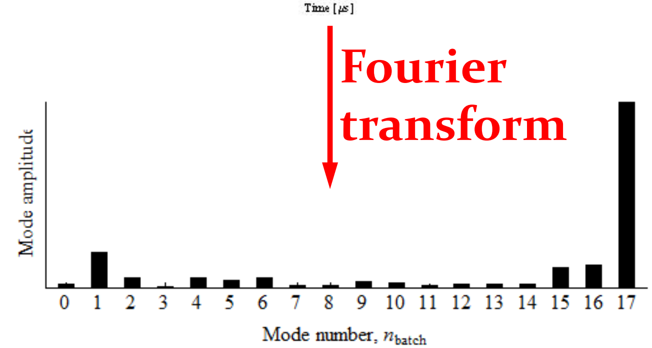
Measurements (2/2)

3. Excite with perturbation and observe natural decay

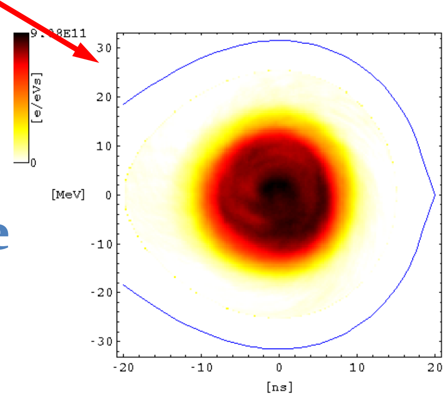


4. Time domain mountain range data for analysis





5. Long. emittance



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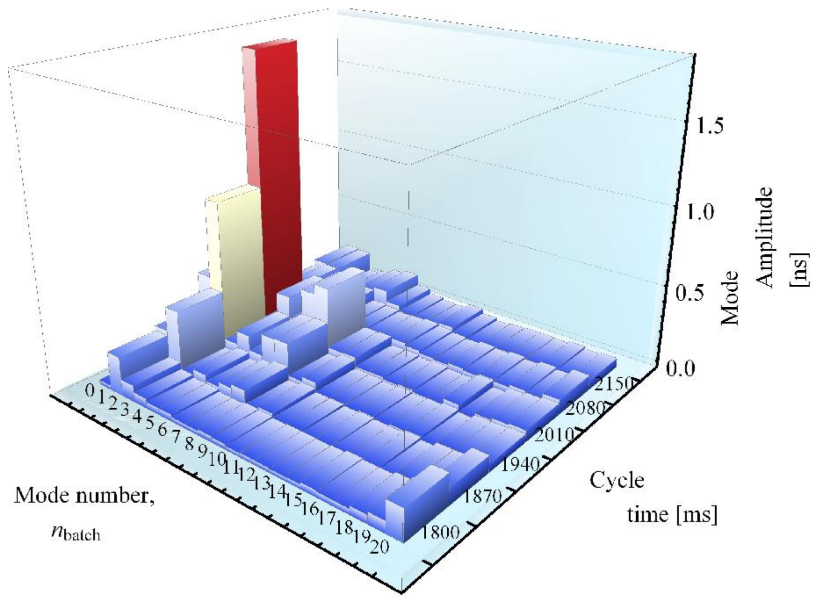
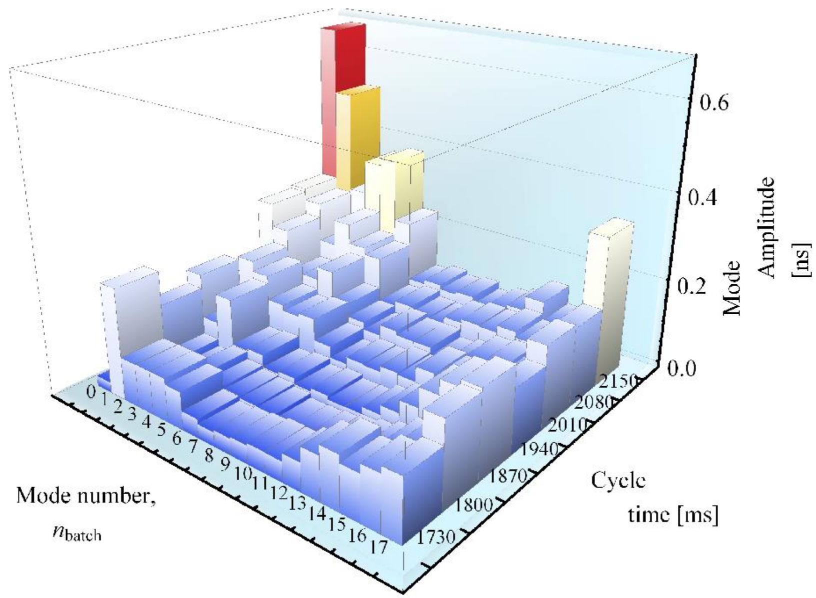
Observations along the cycle

Mode spectrum during acceleration (~10 cycle average):

21 bunches in *h* = 21



18 bunches in *h* = 21



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

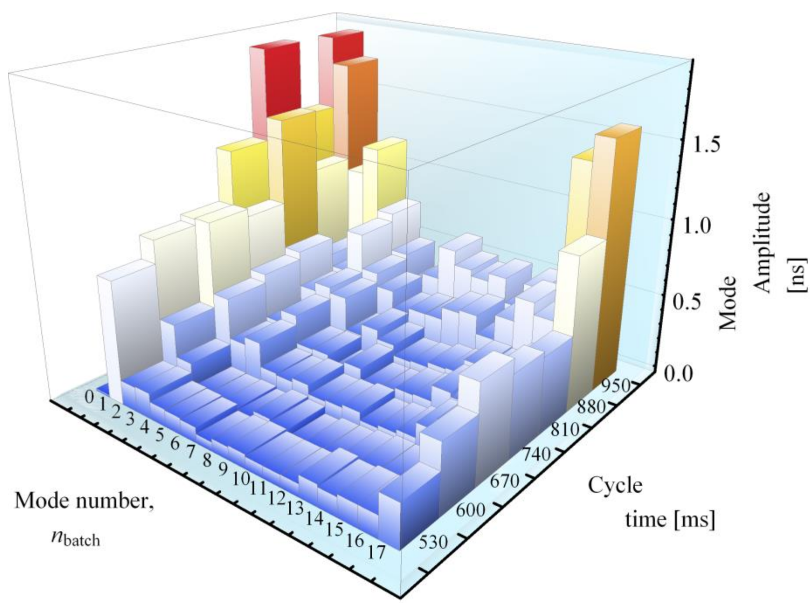
→ **Mode *n* = 2 strongest, as independently found in simulations**

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

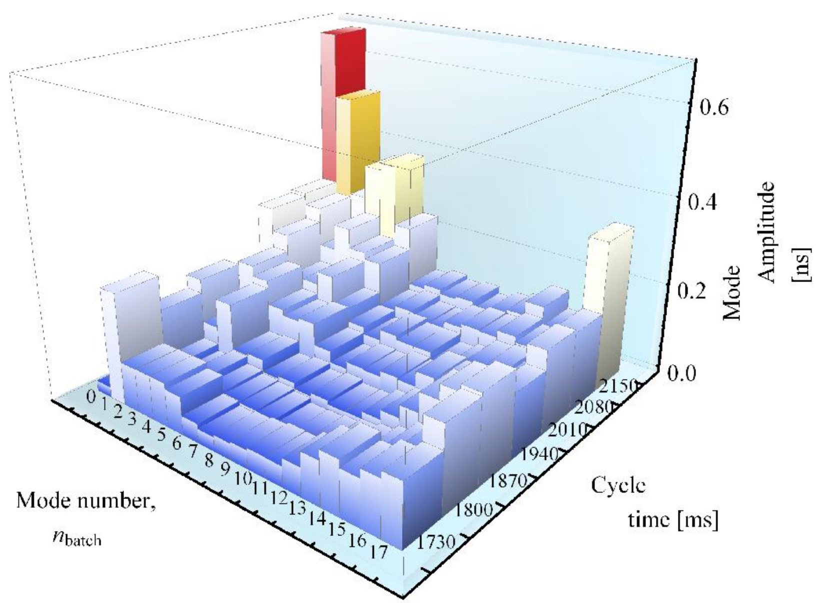
Observations along the cycle

Mode spectrum during acceleration (~10 cycle average):

18 bunches in h = 21, 2009 data



18 bunches in h = 21, 2013 data



→ **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)**

→ **Qualitatively well reproducible over several years**

  → **Absolute mode amplitudes depend on N_b and ε_l**

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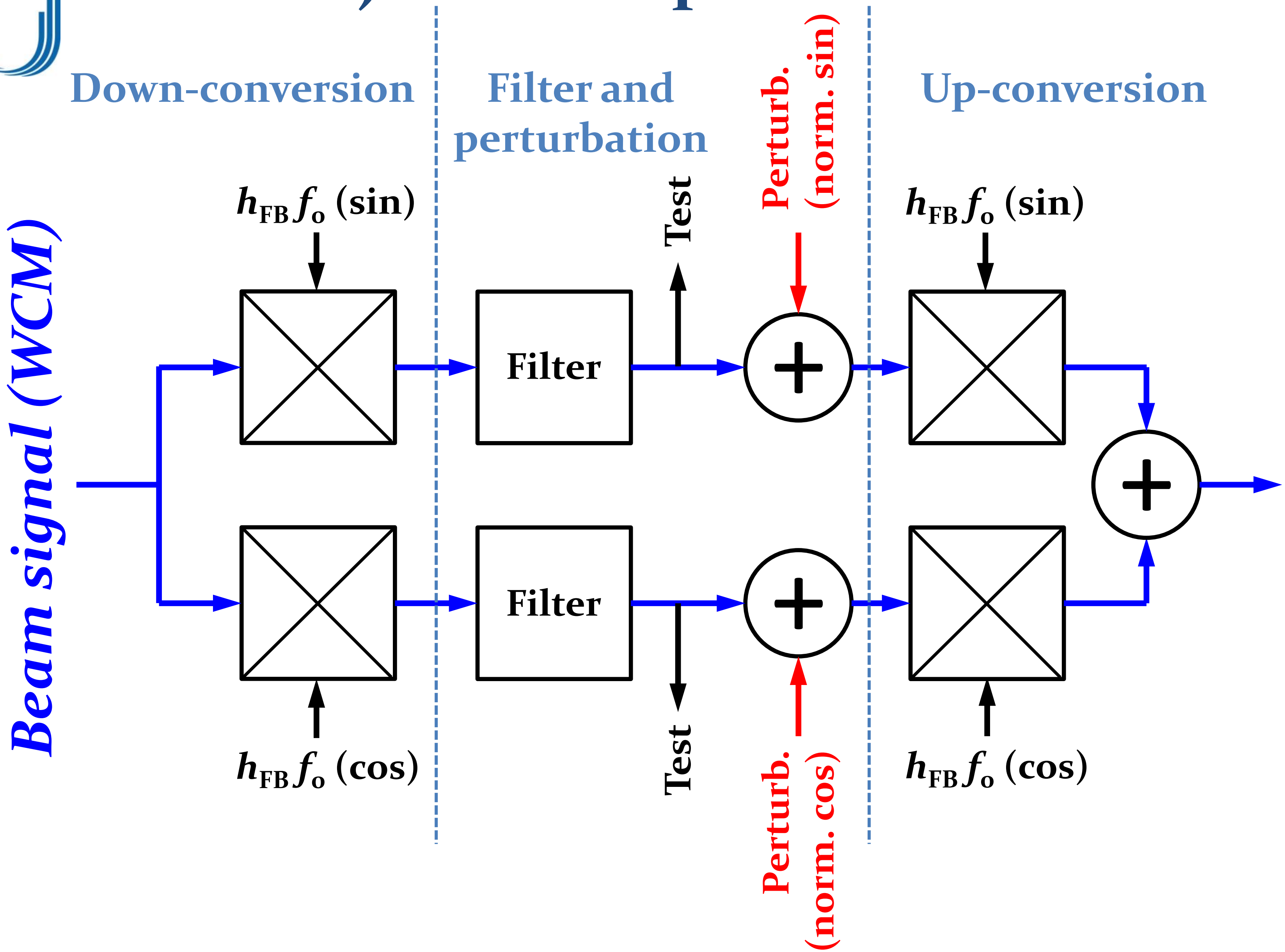
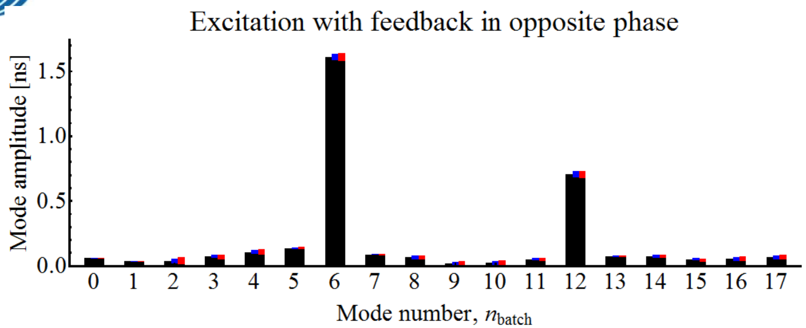
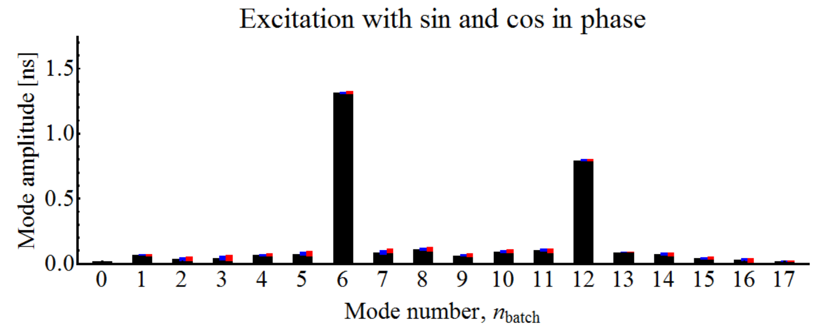
Injection of perturbation

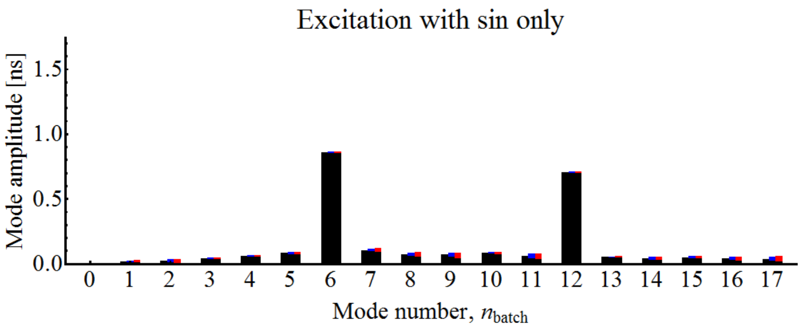


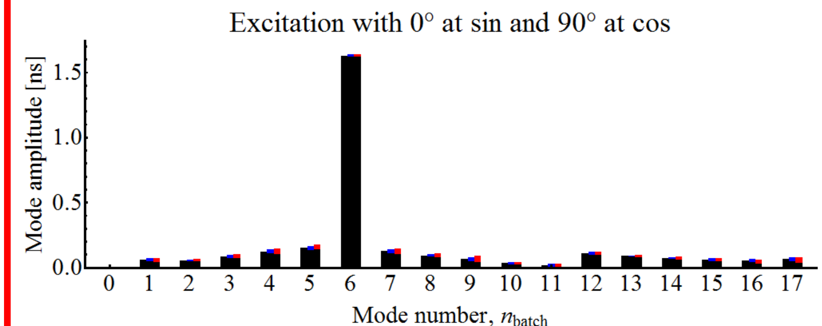
→ **Swap phasing of injected perturbation, perturb only sin/cos**

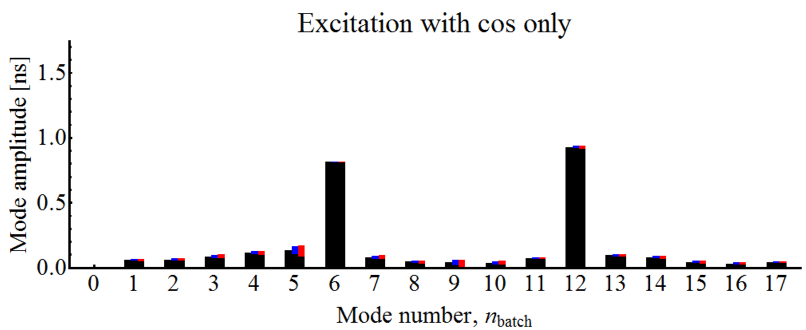
Excitation (feedback at h_{FB} = 14, 18b)

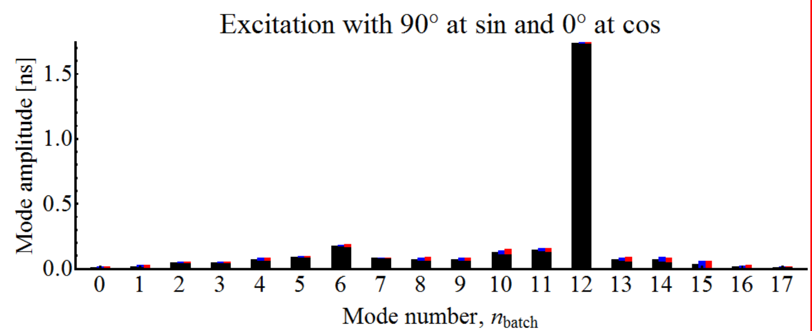












Single side-band → single mode

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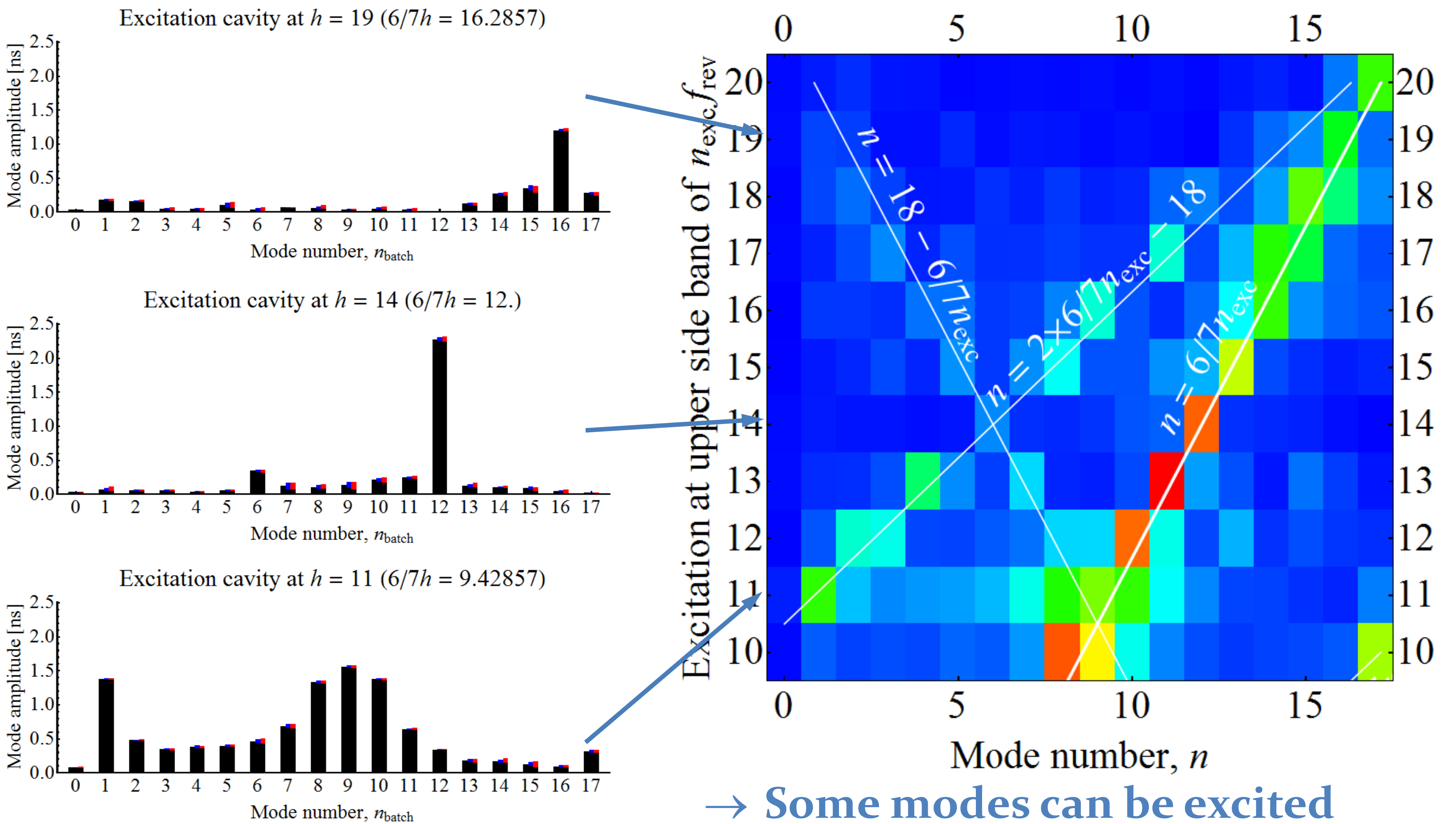
Mode scan with 18 bunches in h = 21

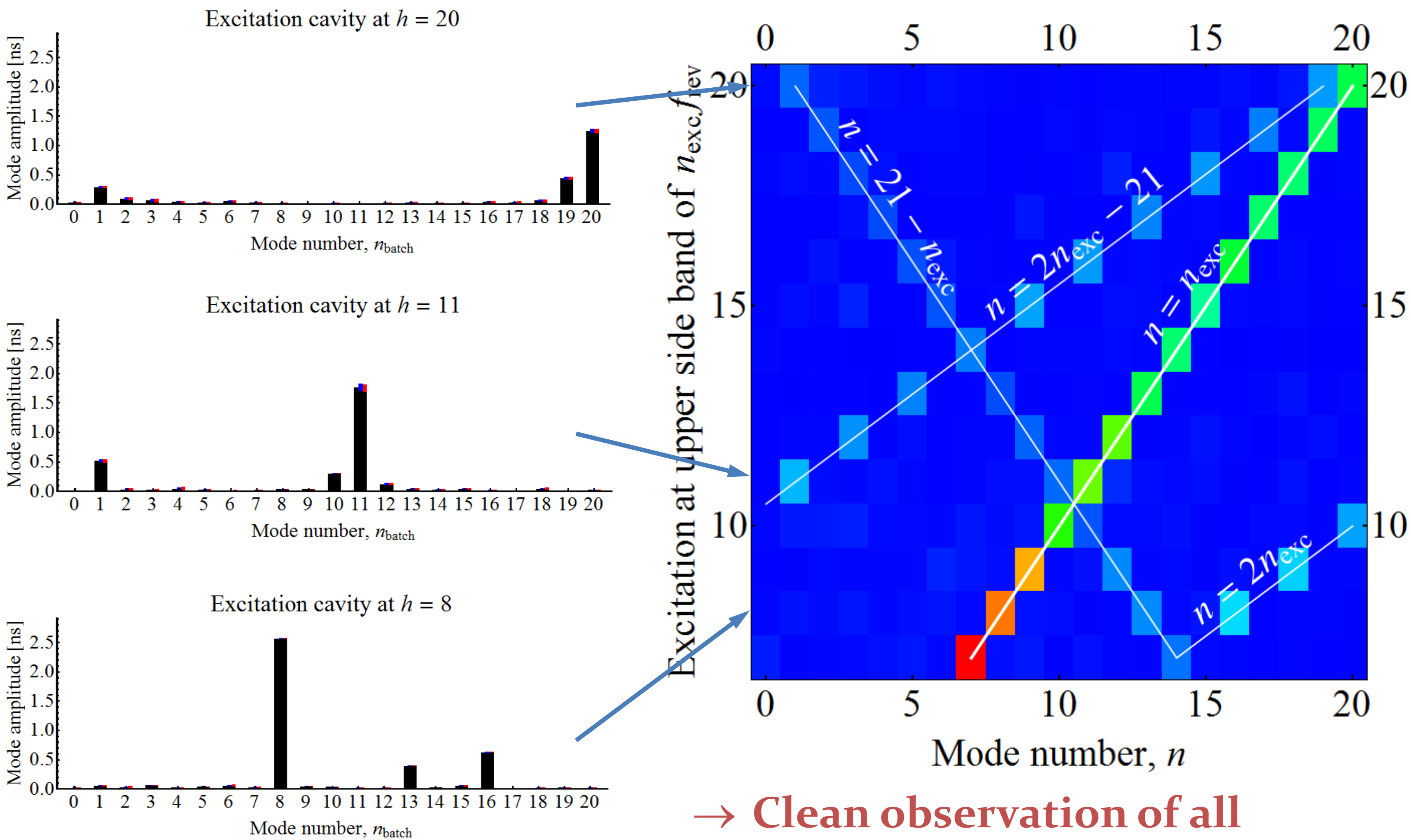
Excite each mode individually and measure mode spectrum



→ **Some modes can be excited very cleanly, others as a mixture; artefact?**

Mode scan with 21 bunches in $h = 21$

Excite each mode individually and measure mode spectrum



→ **Clean observation of all possible modes**

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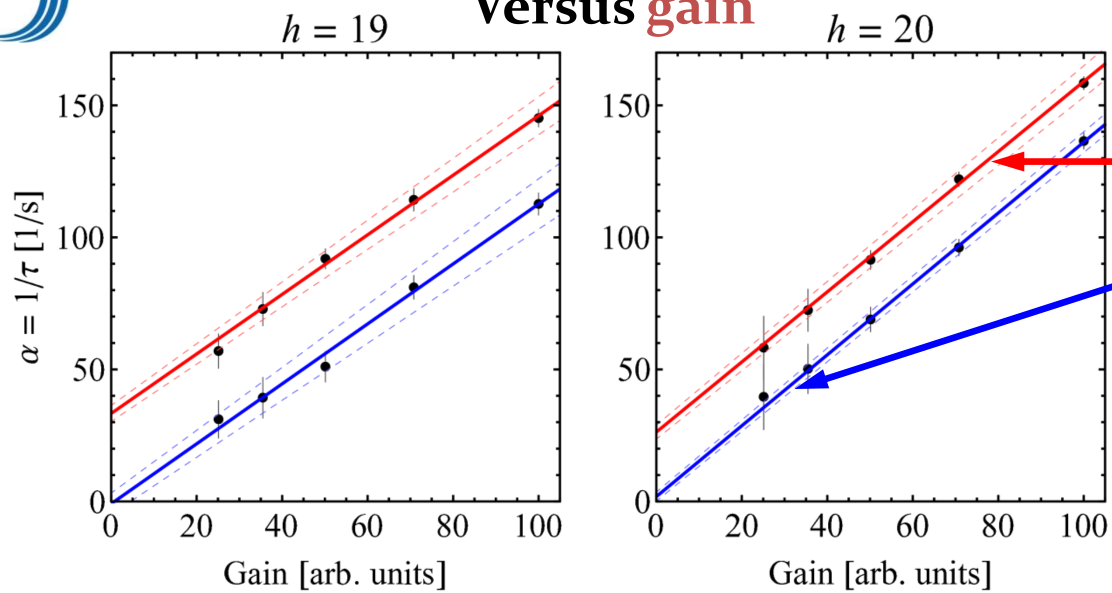
Damping rate versus gain and intensity

Versus gain

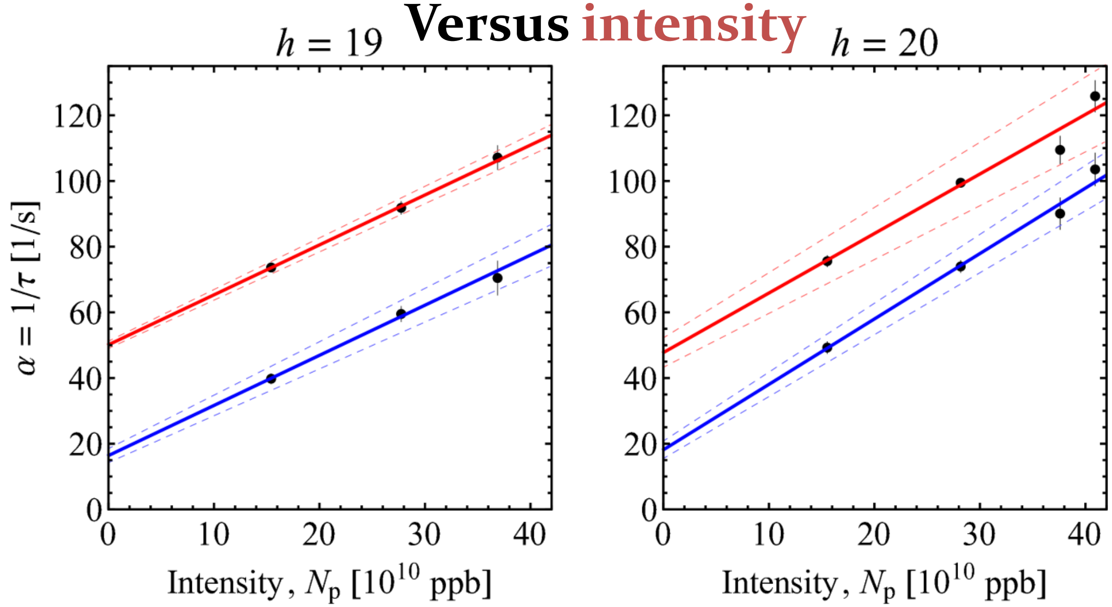


Measured damping rate with feedback on

Corrected for natural damping

- ✓ **Zero damping at zero gain**
- ✓ **Natural damping independent from gain**

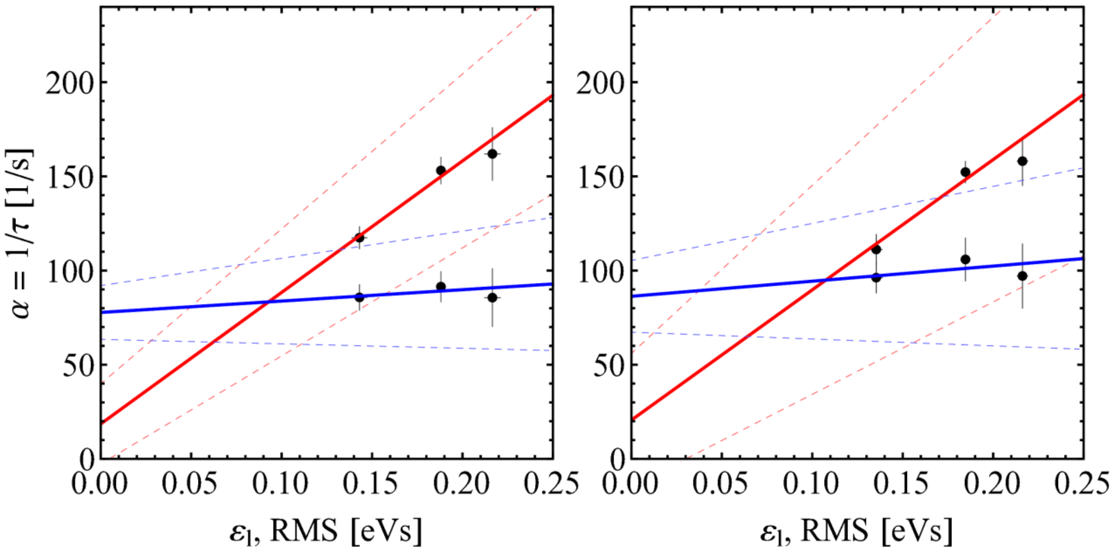
Versus intensity



- ✓ **Damping increases with intensity, more signal for given CB oscillation amplitude**
- \- **Saturation leads to non-zero damping with zero N_p?**

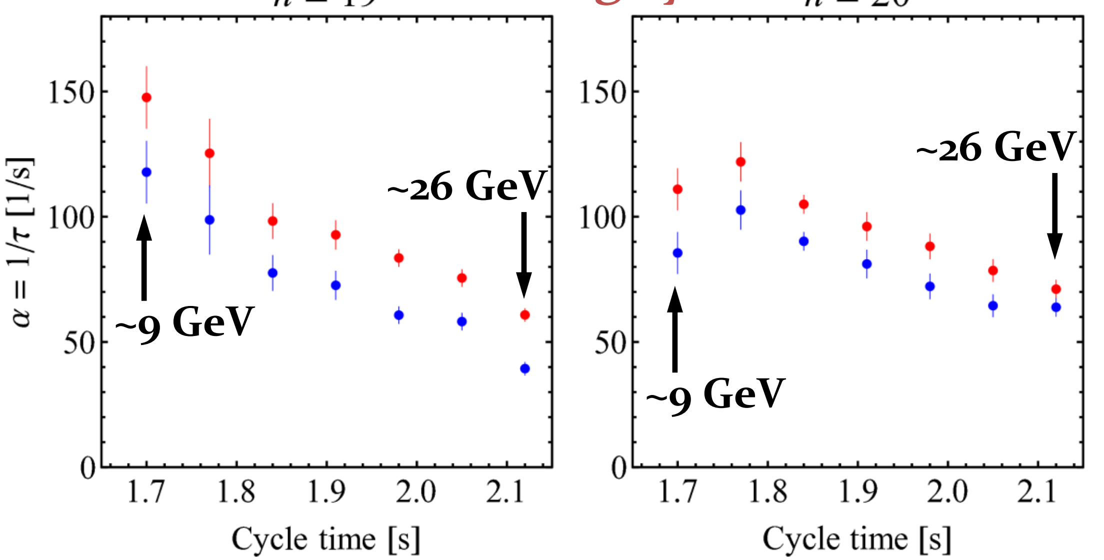
Damping rate versus ε_l and cycle time

Versus ε_l (RMS)



- ✓ **Uncorrected: damping efficiency increases for larger ε_l**
- → **Reduced natural stability for smaller ε_l**
- ✓ **Corrected damping independent from ε_l**

During cycle

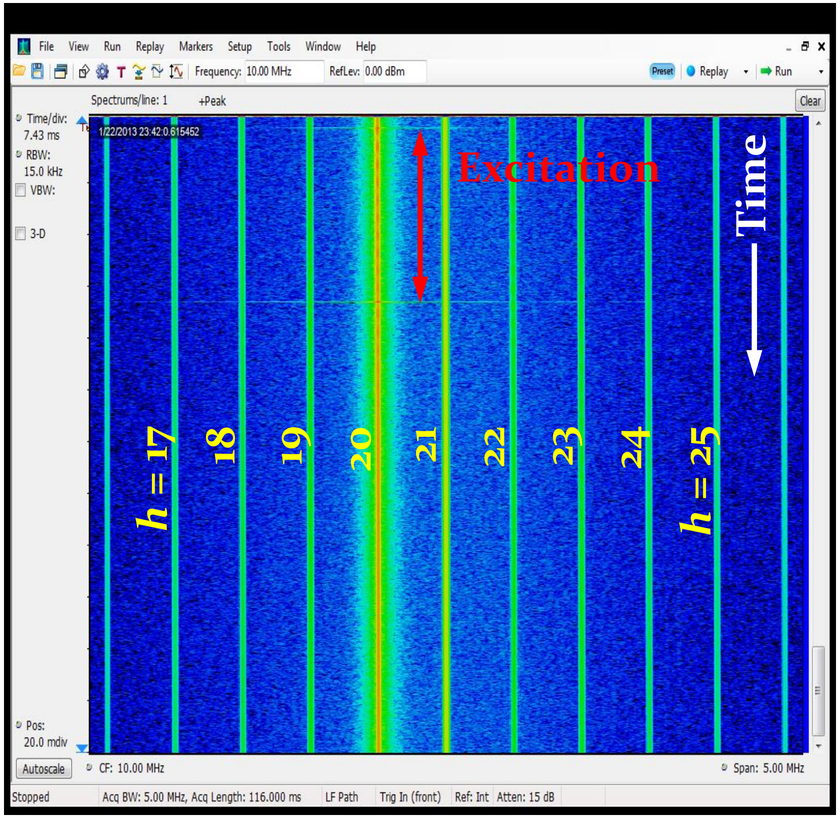


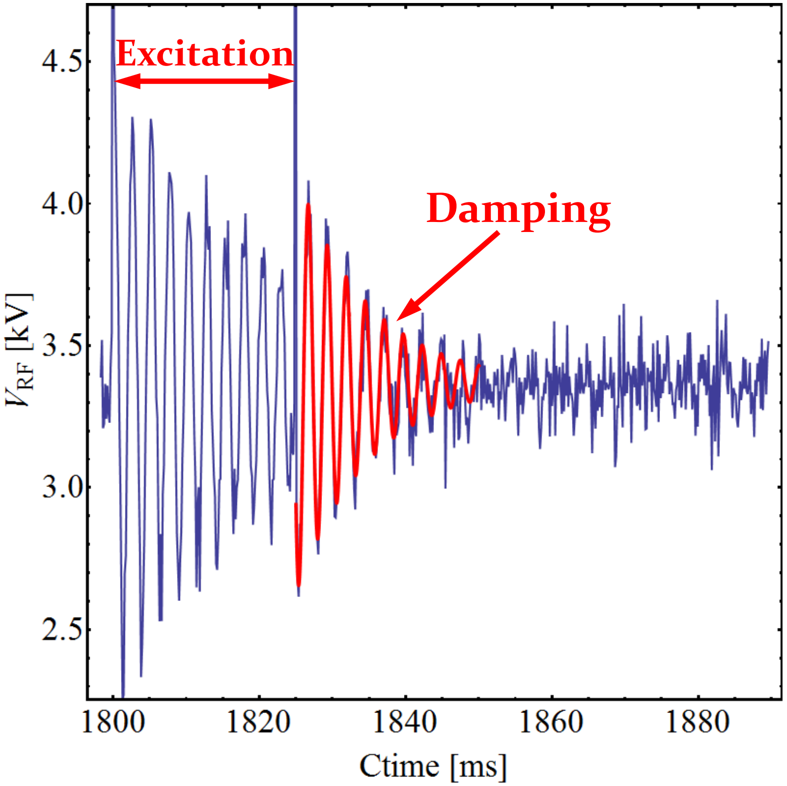
$$\alpha_{\mathrm{FB}} = \frac{\eta f_{\mathrm{rev}} e_0}{4\pi f_s E \beta^2} g \quad \text{with} \quad [g] = \mathrm{V/s}$$

- → **Damping efficiency reduces at higher energy**
- → **To be checked with simulations**

Kick voltage measurement

1. Time resolved spectrum of C10-11 cavity return
2. Extract an normalize relevant harmonic





→ Amplitude modulation from carrier (at hf_o) and f_s side-band ($hf_o \pm f_s$)

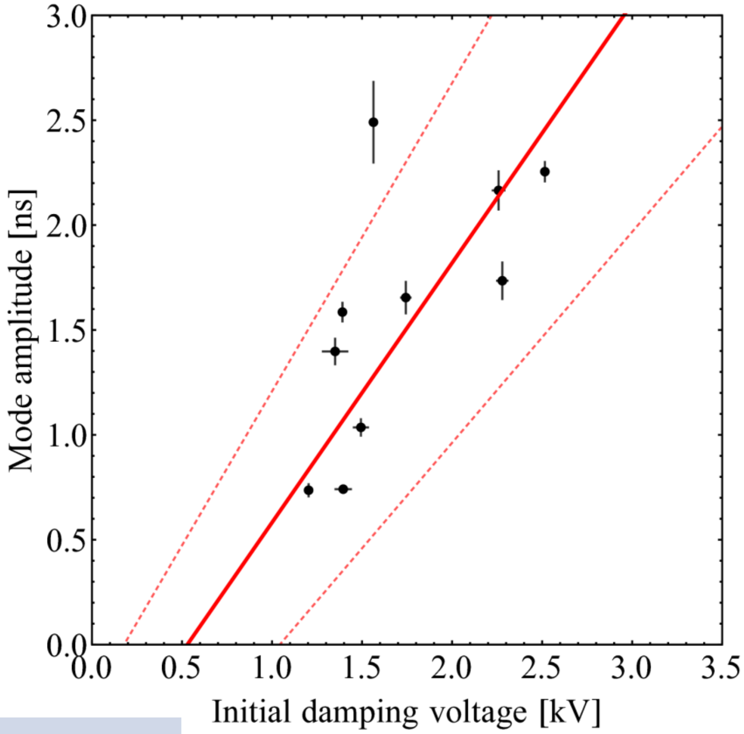
→ Fit gives initial damping amplitude and time (+ f_s and phase)

Kick voltage versus oscillation amplitude

- Excite a coupled-bunch oscillation and measure its amplitude
- Observe maximum damping voltage required

- Only order of magnitude for kick voltage

→ Overestimate expected as feedback normally started before oscillations are well developed



Basic specifications of kicker cavity:

Frequency range	**0.4 to 5.5 MHz**
RF voltage per sideband, V_{mode}	**~ 1 kV**
Maximum total RF voltage, V_{max}	**~ 5 kV**
Un-damped shunt impedance at $n \cdot f_{rev}$	**< 200 Ω**

M. Paoluzzi, H.D., CERN-ACC-NOTE-2013-0019

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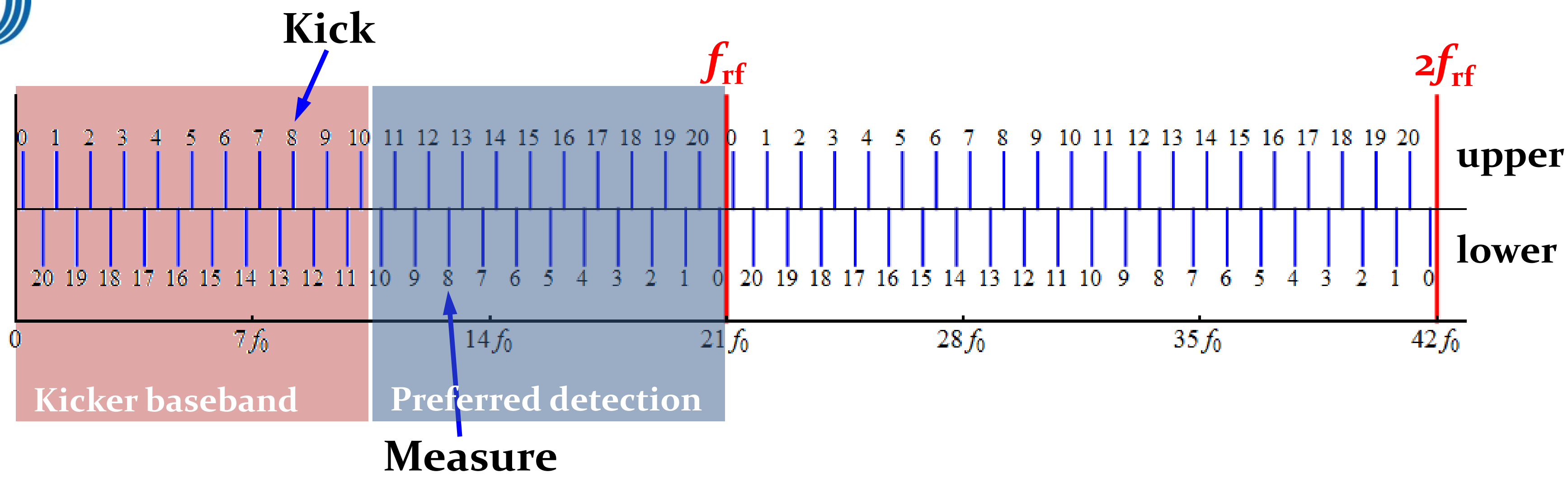
Cross-damping



→ Each mode n is observable as an upper side-band of $n\,f_o$ or as a lower sideband of $(h - n)f_o$

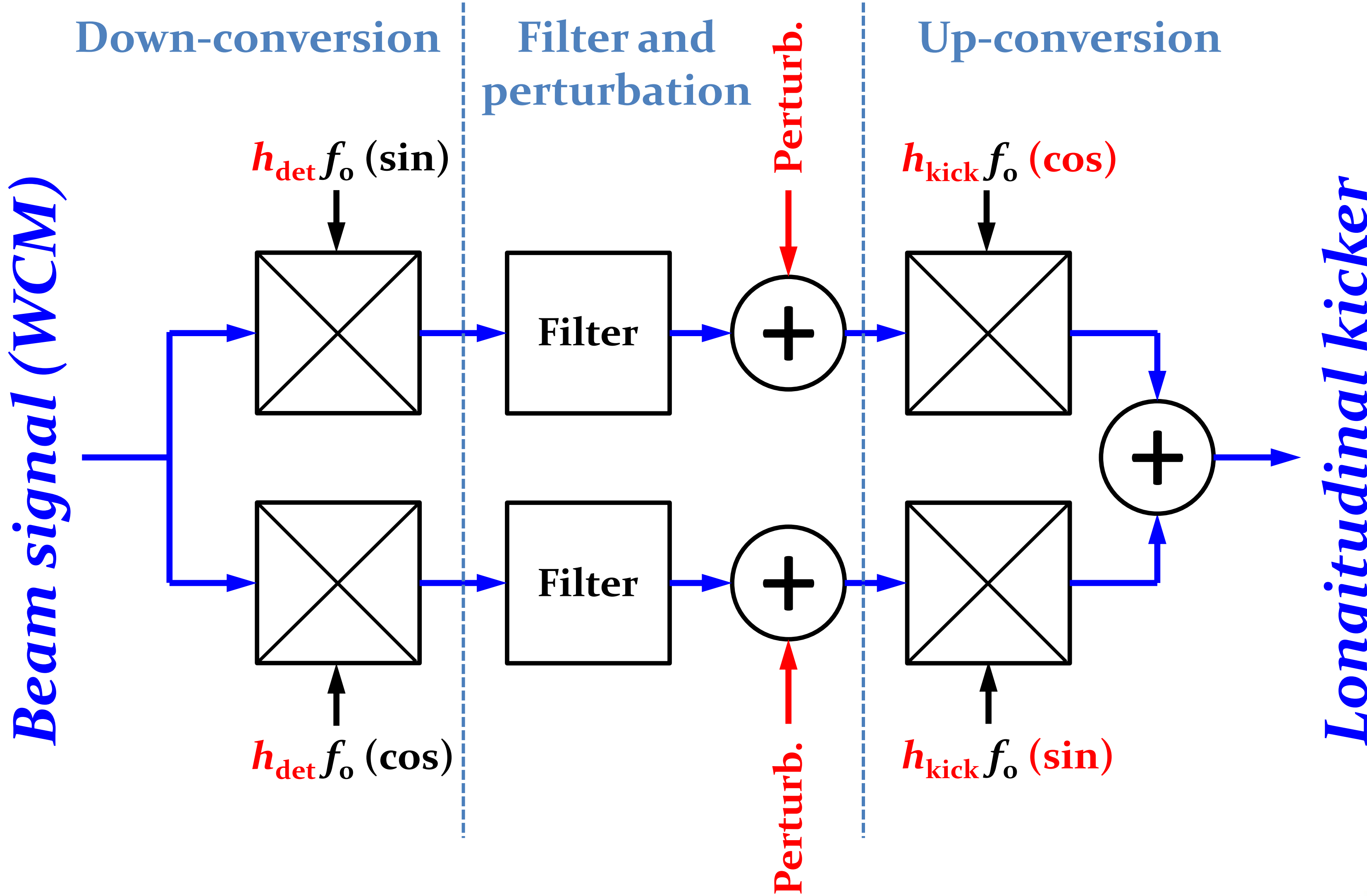
→ Important for PS longitudinal feedback:

- → Detection easier at h_{FB} = 10…20
- → Longitudinal kicker easier at h_{FB} = 1…11

→ **How can this be checked with the existing feedback?**

Cross-damping, $h_{\text{det}} + h_{\text{kick}} = h_{\text{RF}} = 21$

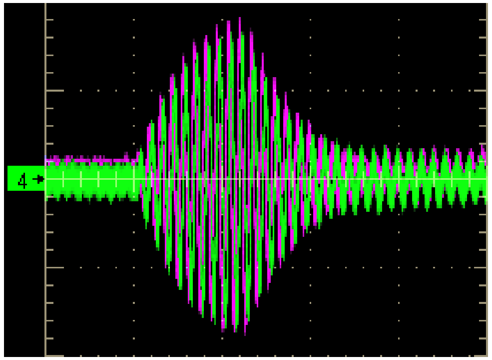
- Need to flip side-bands: lower ↔ upper

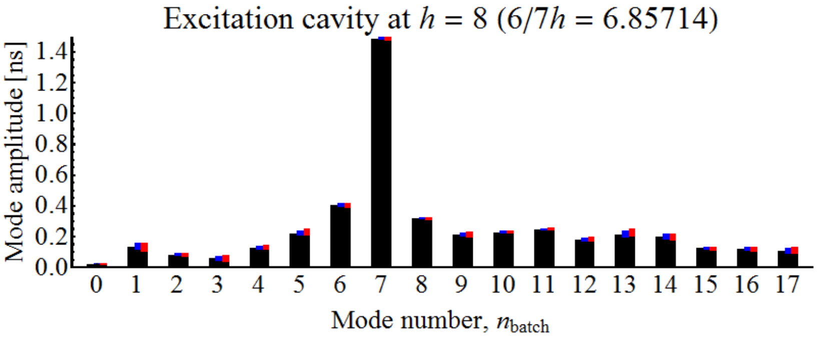


→ Swap sin/cos of LO signals to down- or up-conversion mixers

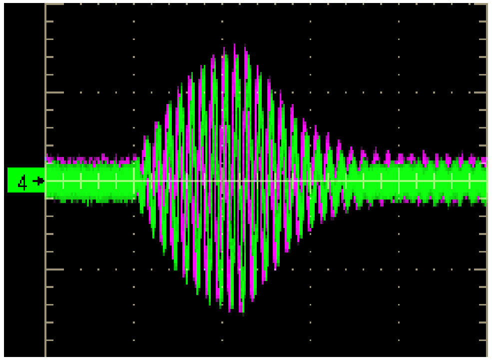
Test with feedback crossed

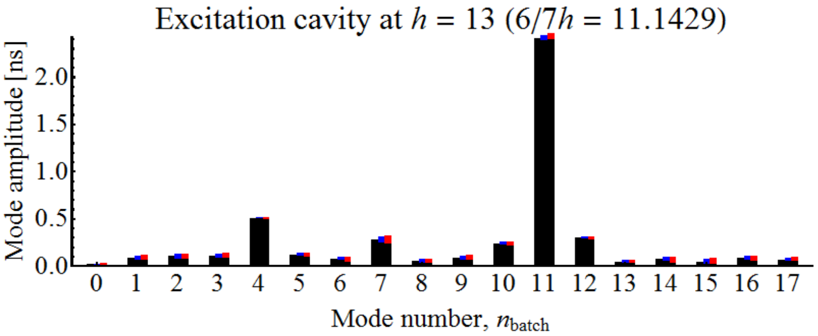
Detect at $h_{det} = 13$ → damp with C10-11 at $h_{kick} = 8$





Detect at $h_{det} = 8$ → damp with C10-11 at $h_{kick} = 13$





- **Tested combinations $h_{det/kick}$ = 8/13, 9/12 and 10/11**

→ Feedback behaviour as expected

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- **2013 run: excellent opportunity for tests**
  → No need for very high intensity beams to LHC
  → Coupled-bunch feedback and the spare cavity available

- **Clean mode scans: modes are well decoupled**
  → New feedback also to operate in the frequency domain
  → Similar signal processing as existing feedback, but digital and covering all harmonics simultaneously

- **Demonstrated working feedback with detection and excitation at different harmonics**
  → New feedback kicker operates at low band, 1…11 f_{rev}
  → Detection of coupled-bunch sidebands at 10…20 f_{rev}

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THANK YOU FOR YOUR ATTENTION!

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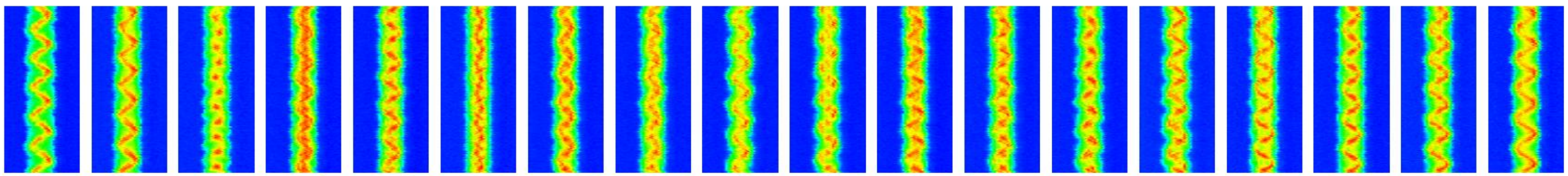
Mode analysis

Example with old data

Why not measuring in frequency domain with a spectrum analyzer?

- Revolution frequency f_{rev} sweeps along the cycle
- Spurious f_{rev} lines due to 6/7 filling (18 bunches in h = 21)
- Synchrotron side-bands very close to strong f_{rev} lines

Measurement in time domain:

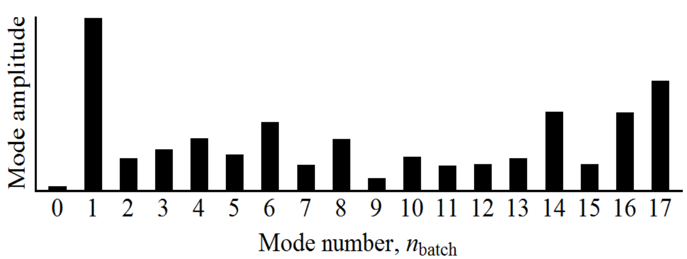


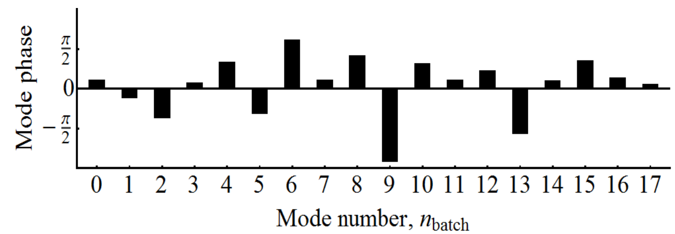
1. Fit position of each bunch during each frame
2. Dipole oscillations: fit sinusoidal function to motion of bunch

→ 18 oscillation amplitudes τ_n, 18 phases θ_n + f_s

3. Discrete Fourier transformation

→ 18 mode amplitudes τ_k, 18 mode phases θ_k

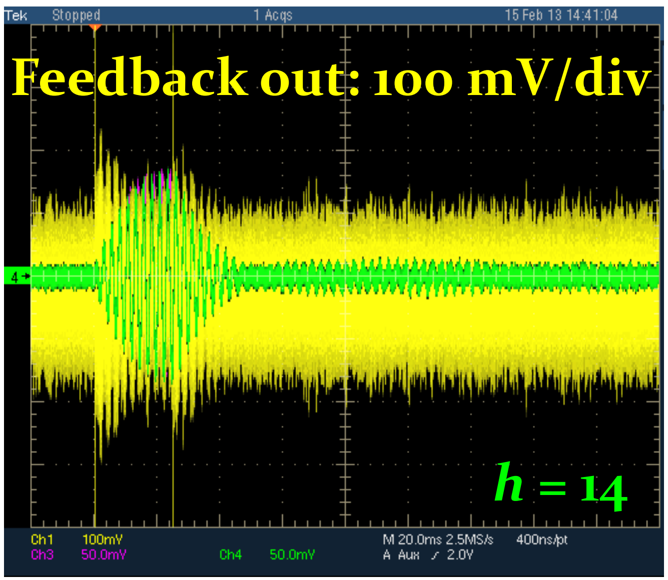




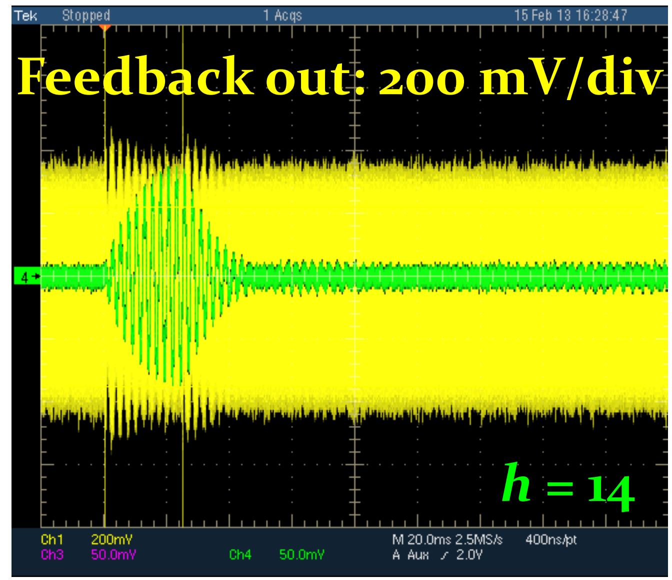
Residual carrier at f_0 harmonic (1/2)

- Due to an offset problem with the up conversion mixers, a spurious carrier is generated at the revolution frequency harmonic
  - → Significant power need from kicker cavity
  - → No contribution to feedback action

Offset well compensated



Normal operating condition

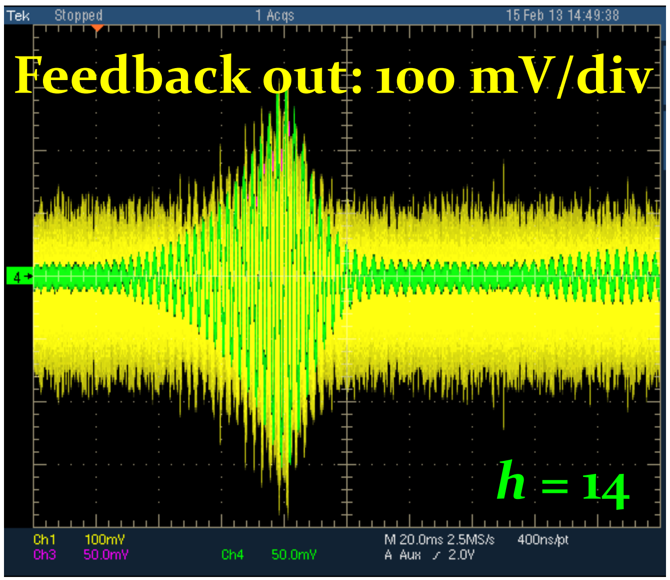


→ **Will be resolved with digital low-level hardware for the coupled bunch feedback after**

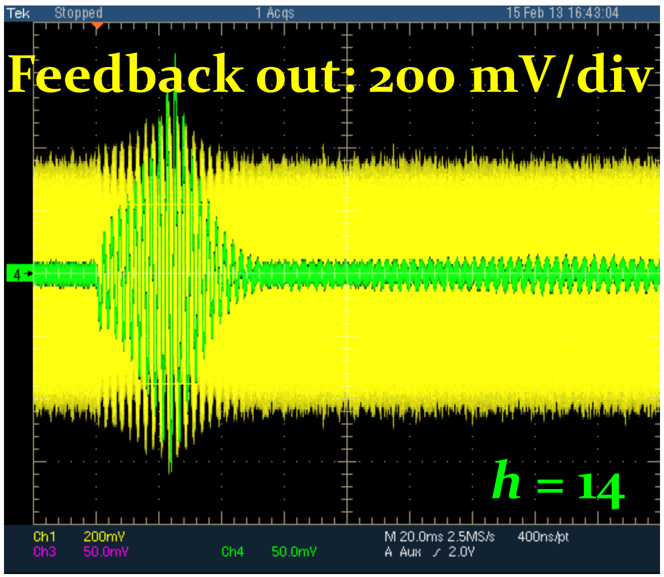
Residual carrier and f_0 harmonic (2/2)

- **Try anti-phase excitation with well compensated offset:**

Offset well compensated



Normal operating condition



→ **Residual carrier at revolution frequency harmonic excites the corresponding coupled-bunch mode**

- **For *h* = 14, this confirms earlier measurements, driving instabilities**
- **Unfortunately no data taken for *h* = 17…20; expect improved stability**

…too late…

What remains to be analyzed…

- Mode scans with 50 ns and 25 ns beams
- Damping times for modes around *h* = 19 and 20 along the cycle → OK
- Damping times versus longitudinal emittance, intensity and feedback gain → OK
- Coupled-bunch mode spectra without feedback nor excitation → OK

→ Extract relevant voltage requirement and estimate performance of new longitudinal damper → tbd