# RF Feedback

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**CERN**

The CERN Accelerator School

**Advanced Accelerator Physics**

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# Outline

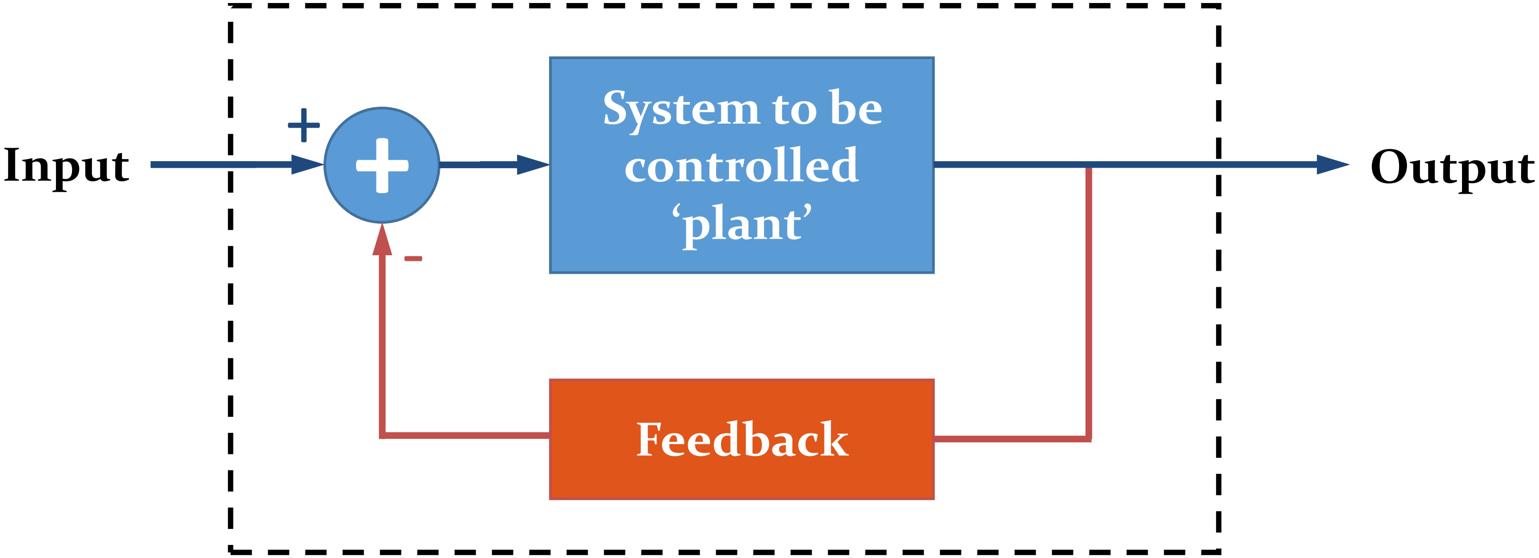
- **Introduction**
- **Direct RF feedback**
  - **Globally reduce a cavity impedance**
- **Long delay feedback**
  - **Reduce impedance at revolution frequency harmonics**
- **Global feedback**
  - **Detect and fight the effect of an instability**
  - **Time and frequency domain**
- **Summary**

# Introduction

# Why feedback?

- **Open loop system subject to**
  - → **Imperfections**
  - → **Perturbations**

→ **Feed output back to input → correction**



→ **New system with new dynamics**

- **Control parameters of system**
- **Make naturally unstable system stable again**

# Why RF feedback?

Smaller longitudinal emittance

Higher beam current

More luminosity

Better longitudinal quality

All bunches identical

More peak intensity

**Image current of beam induces voltage surrounding structure**

→ RF cavities particularly affected due to intentionally large impedance

→ Longitudinal instabilities

→ Degradation of longitudinal beam quality

**How to improve?**

→ RF feedback

# Tree of RF feedback systems

- Control longitudinal parameters
- Longitudinally unstable beam
- Beam induced voltage

RF system identified as source

Source unknown

Feedback close to cavity

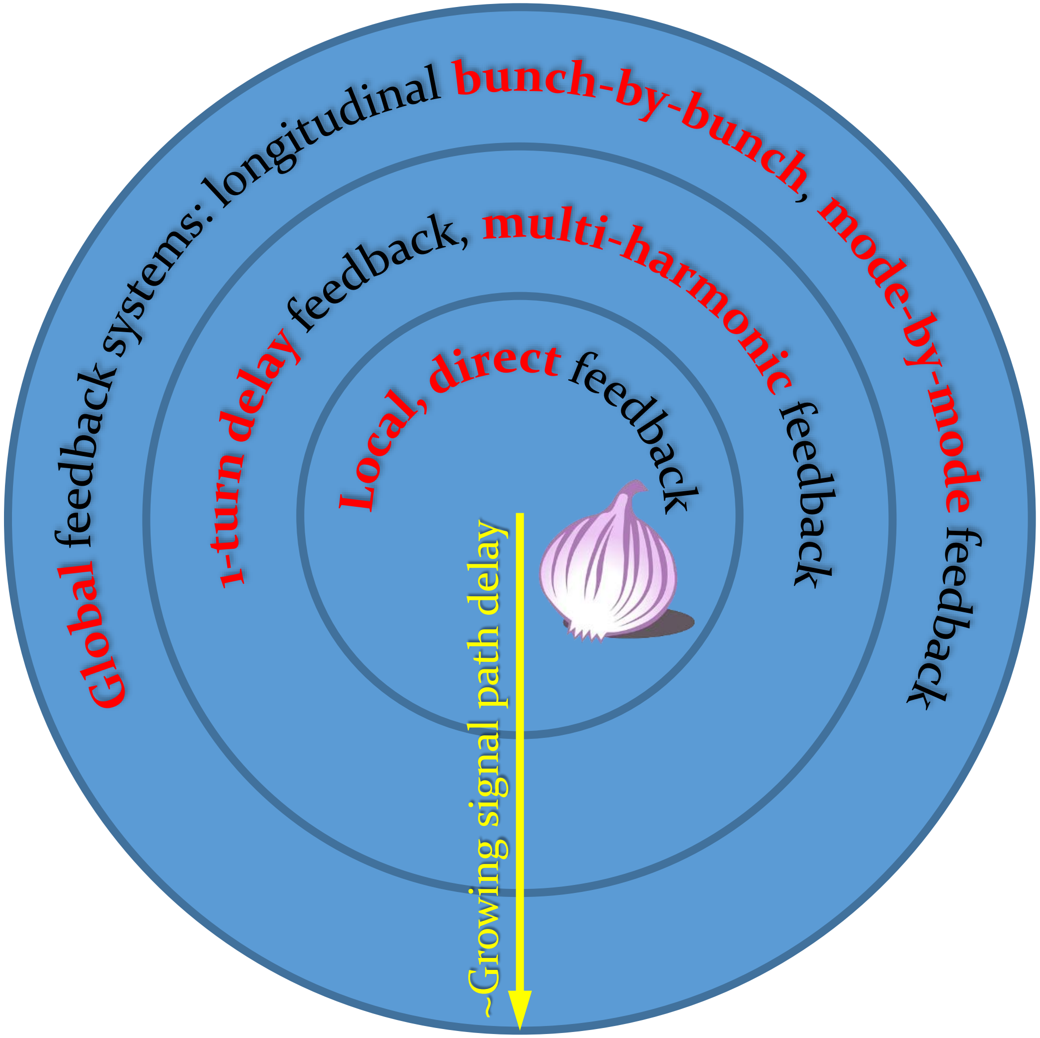
Far away (delay)

Local, direct feedback

Long delay feedback

Global feedback

# Onion model of RF feedback



Global feedback systems: longitudinal bunch-by-bunch, mode-by-mode feedback

1-turn delay feedback, multi-harmonic feedback

Local, direct feedback

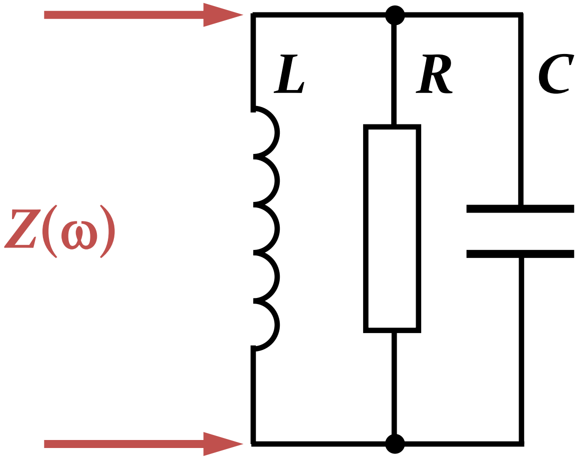
~Growing signal path delay

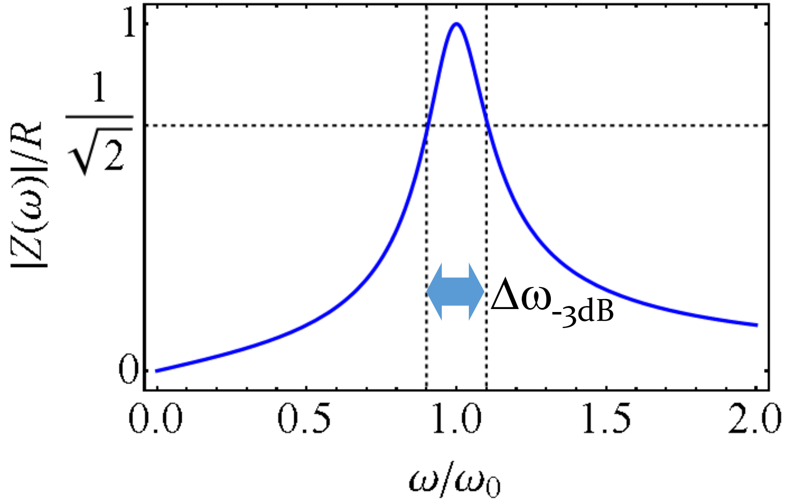
# Direct RF feedback

Local, direct feedback

# Cavity parameters

- **The resonance of a cavity can be understood as simple parallel resonant circuit described by *R, L, C***



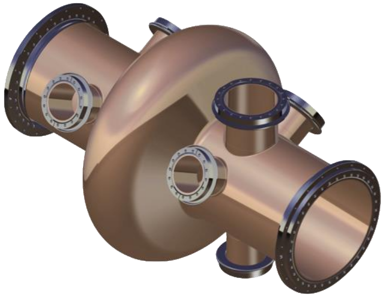


$$Q = \omega_0 RC = \frac{R}{\omega_0 L} \qquad Z(\omega) = \frac{R}{1 + iQ\left(\frac{\omega^2 - \omega_0^2}{\omega\omega_0}\right)} \simeq \frac{R}{1 + 2iQ\frac{\Delta\omega}{\omega_0}}$$

→ **Resonant circuit can also be described by *R, R/Q,* $\omega_o$ or any other set of three parameters**

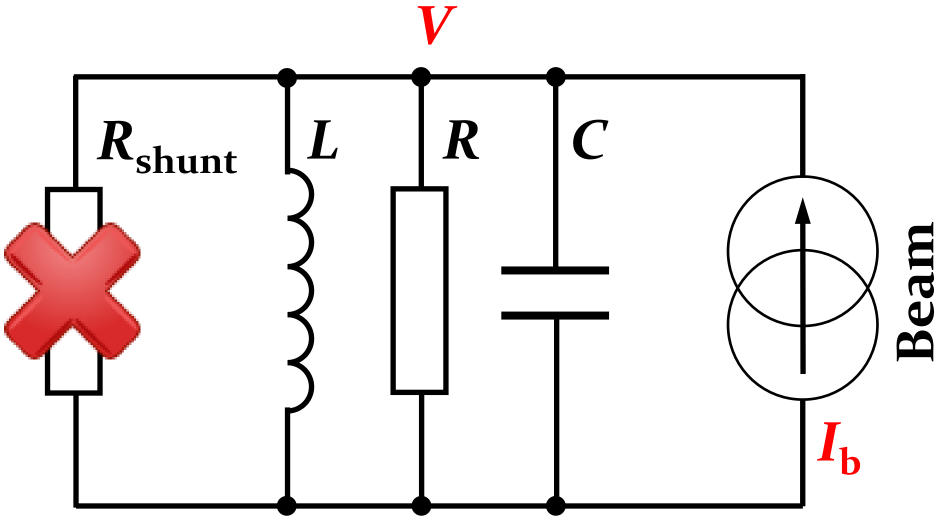
# Objective of local impedance reduction

- Induced voltage in cavity may cause
  1. Dephasing of total cavity voltage
  2. Longitudinal instability



→ Reduce beam induced voltage

→ Reduce cavity impedance experienced by the beam



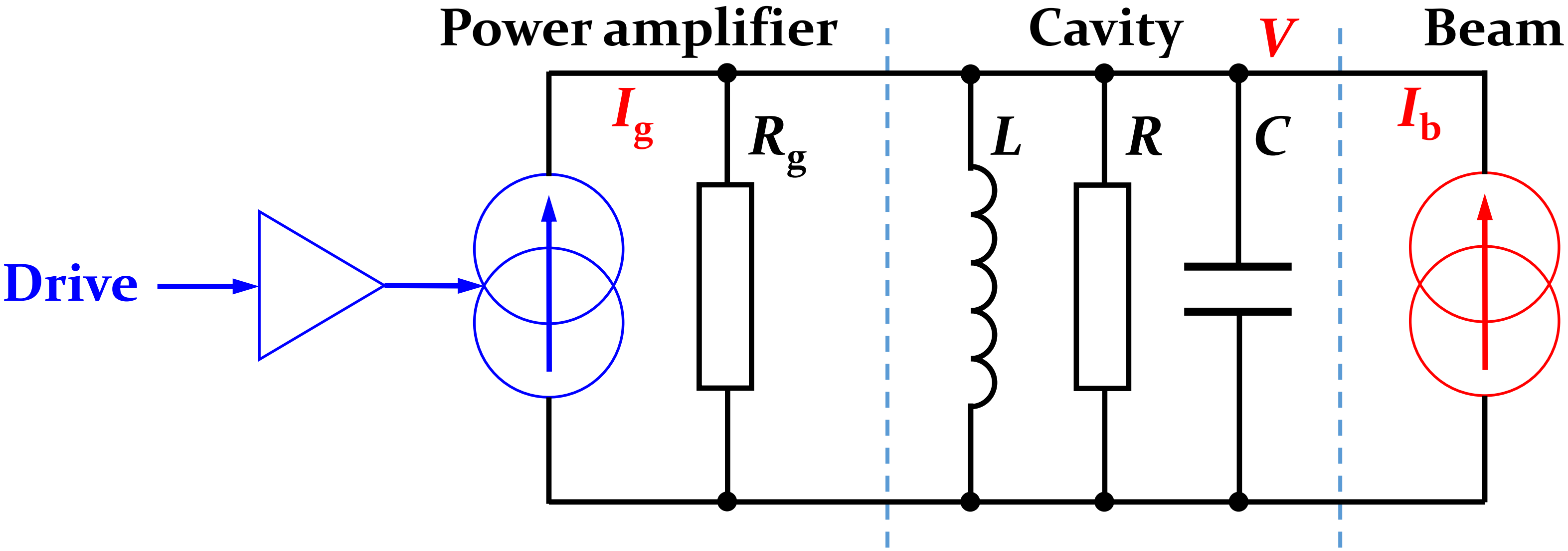
✓ Beam induced voltage reduced: $R/(R+R_{\text{shunt}})$

\- Power for given voltage increased: $(R+R_{\text{shunt}})/R$ → $$$

# Direct feedback

- **Use amplifier to counteract beam induced voltage**

→ **Decrease only apparent impedance experienced by beam**



# Direct feedback

- **Use amplifier to counteract beam induced voltage**

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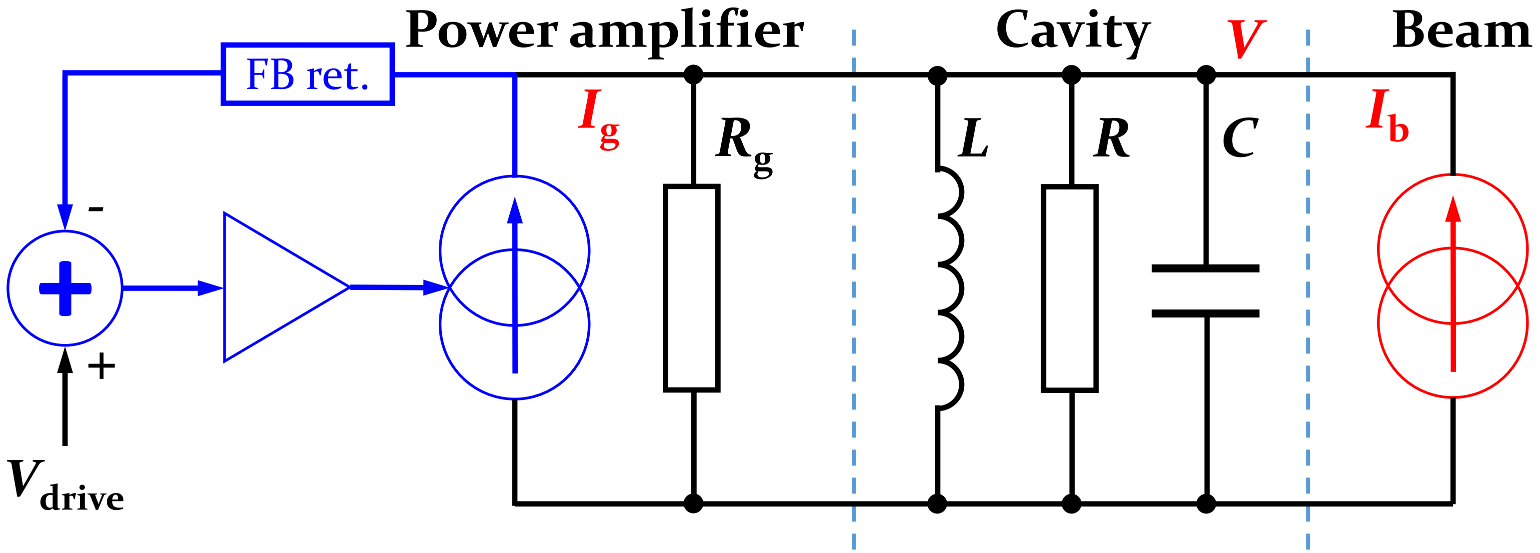


- **Gap signal, $V$: Beam and generator contributions**
- **Drive signal, $V_{drive}$: Pure generator**

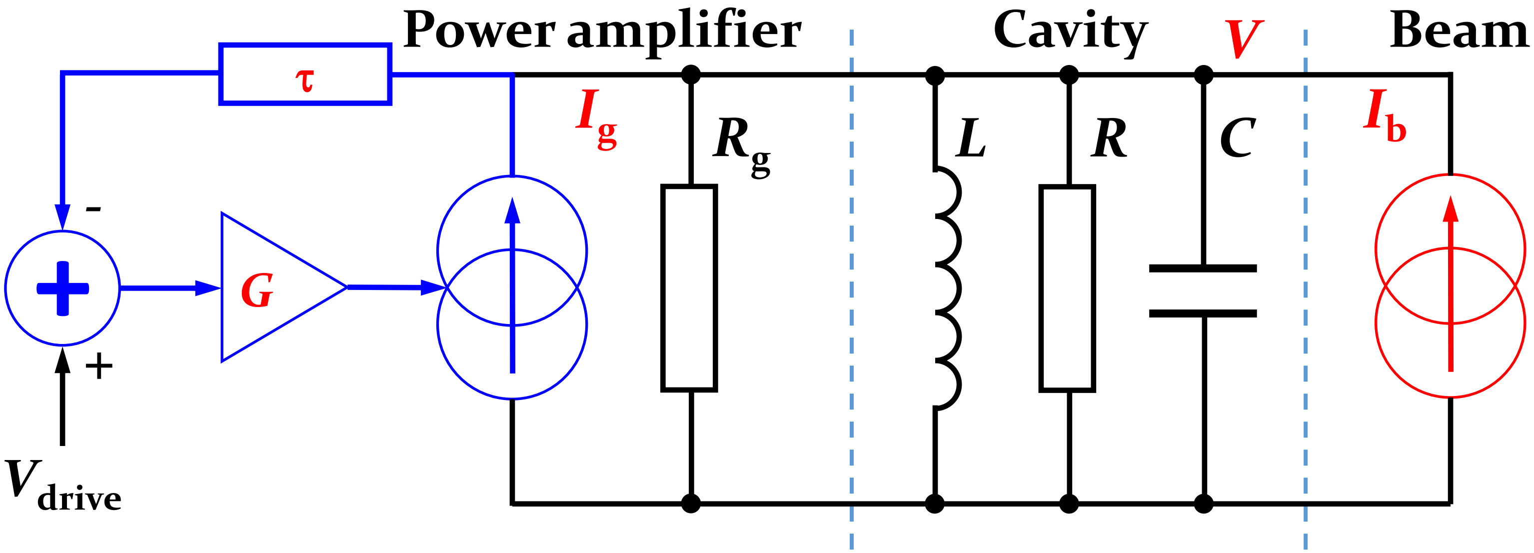
→ **Compare drive signal (no beam) with gap (beam and generator)**

→ **Amplify inverted difference**

# Direct feedback

- **Use amplifier to counteract beam induced voltage**

→ **Decrease only apparent impedance experienced by beam**

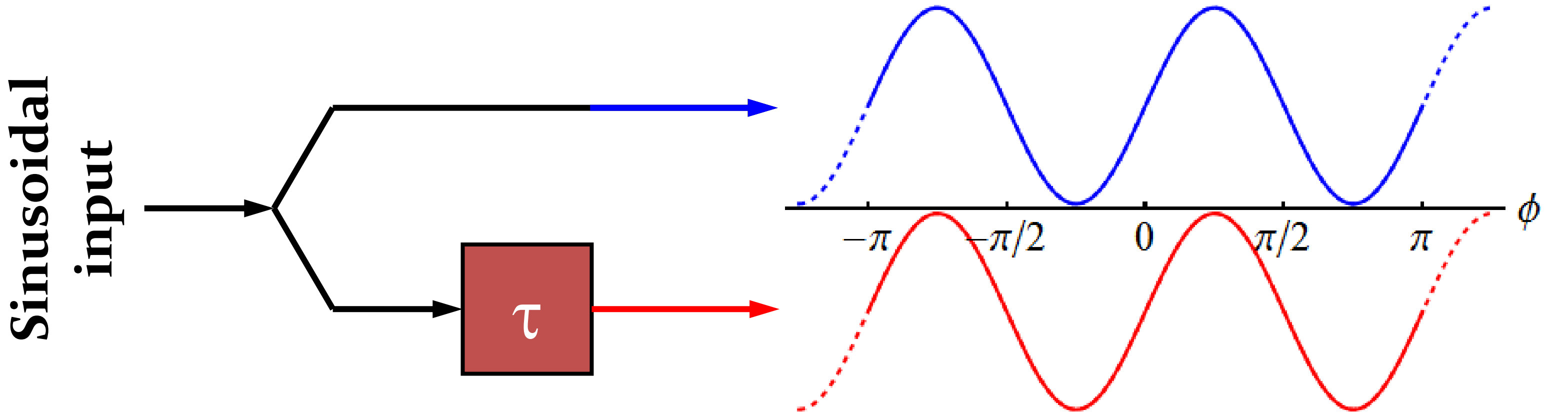


→ **Feedback parameterized by**

- **Open loop gain, *G***
- **Total loop delay, τ → frequency dependent phase shift**

# Issue with delay

- **Dephasing due to physical delay**



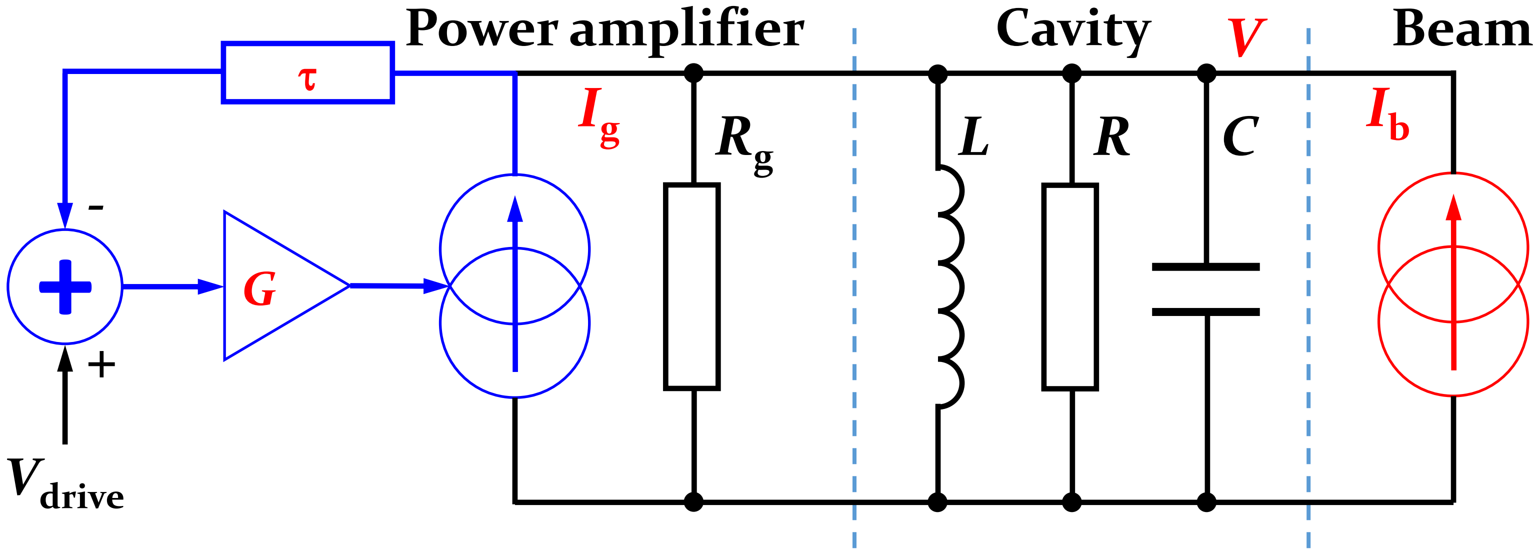
- **Delay is natural enemy of every feedback system**
  - → Propagation delay in cables and electronics
  - → Latency of conversion and signal processing

→ **Phase rotation of complex signal:** $e^{-i(\omega-\omega_0)\tau} = e^{-i\Delta\omega\tau}$

# Direct feedback

- **Use amplifier to counteract beam induced voltage**

→ **Decrease only apparent impedance experienced by beam**



→ **Total current in cavity ($V_{\text{drive}} = 0$):**

$$I_t(\omega) = I_b(\omega) + I_g(\omega)$$

$$\Downarrow$$

$$I_g(\omega) = -V_t(\omega) G e^{-i\Delta\omega\tau}$$

# Impedance with direct feedback

- **Total cavity voltage:**

$$V_{\mathrm{t}}(\omega) = \frac{I_{\mathrm{b}}(\omega)Z(\omega)}{1 + Z(\omega)Ge^{-i\Delta\omega\tau}}$$

- **Impedance with feedback:**

→ **Differential change of cavity, *$dV_{\mathrm{t}}$* voltage for beam induced current, *$dI_{\mathrm{b}}$***

$$Z_{\mathrm{fb}}(\omega) = \frac{dV_{\mathrm{t}}(\omega)}{dI_{\mathrm{b}}(\omega)} = \frac{Z(\omega)}{1 + Z(\omega)Ge^{-i\Delta\omega\tau}}$$

$$\Downarrow$$

$$Z(\omega) \simeq \frac{R}{1 + 2iQ\frac{\Delta\omega}{\omega_0}} \simeq \frac{R}{2iQ\frac{\Delta\omega}{\omega_0}}$$

$$\Downarrow$$

$$|\angle Z(\omega)| \simeq \frac{\pi}{2}$$

# Stability with feedback

- **Dephasing due to loop delay at $\Delta\omega_\tau$**

$$\Delta\phi_\tau = \Delta\omega_\tau \cdot \tau$$

- **Which dephasing results in unity absolute loop gain?**

**Open loop:** $G|Z(\Delta\omega_\tau)| = G\frac{R}{2Q\frac{\Delta\phi_\tau}{\omega_0\tau}} = 1$

$$\Delta\phi_\tau = G\frac{R}{Q}\frac{\omega_0\tau}{2}$$

- **Phase margin defined as**

$$\Delta\phi_\mathrm{m} = \pi - \frac{\pi}{2} - \Delta\phi_\tau = \frac{\pi}{2} - G\frac{R}{Q}\frac{\omega_0\tau}{2}$$

# Stability with feedback

→ **Phase margin:**

$$\Delta\phi_{\mathrm{m}} = \frac{\pi}{2} - \Delta\phi_{\tau} = \frac{\pi}{2} - G\frac{R}{Q}\frac{\omega_0\tau}{2}$$

$$\Delta\phi_{\mathrm{max}} = \frac{\pi}{4}$$

- **Conventional stability limit defined for**

→ **Maximum stable gain:**

$$G_{\mathrm{max}} = \frac{\pi}{2}\frac{1}{R/Q}\frac{1}{\omega_0\tau}$$

# Impedance with feedback

- **Normalized impedance:**

$$Z_{\mathrm{fb}}(\omega) = \frac{\frac{1}{G}}{\frac{1}{GR} + e^{-i\Delta\omega\tau} + \frac{4}{\pi} i \frac{G_{\max}}{G} \Delta\omega\tau}$$

**Amplifier**

$Z(\omega)$

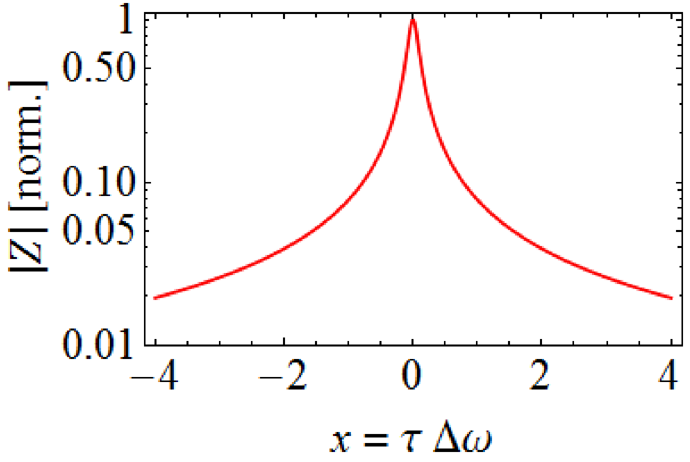
Cavity with direct feedback

**Beam**

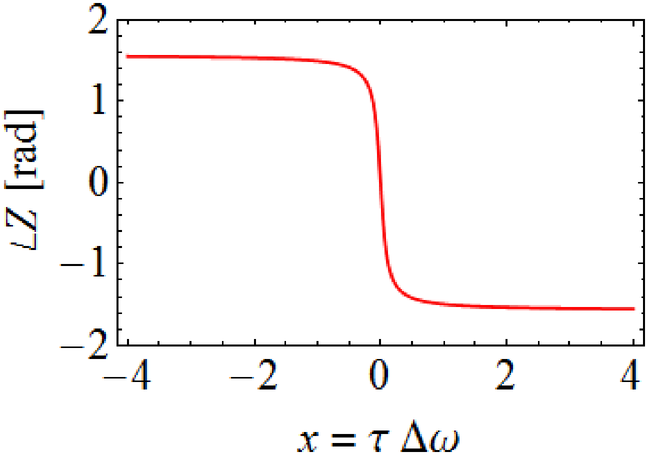
$Z_{\mathrm{fb}}(\omega)$

$$Z_{\mathrm{fb}}(\omega_0) = \frac{R}{1+GR}$$

$G/G_{\max} = 0.00$

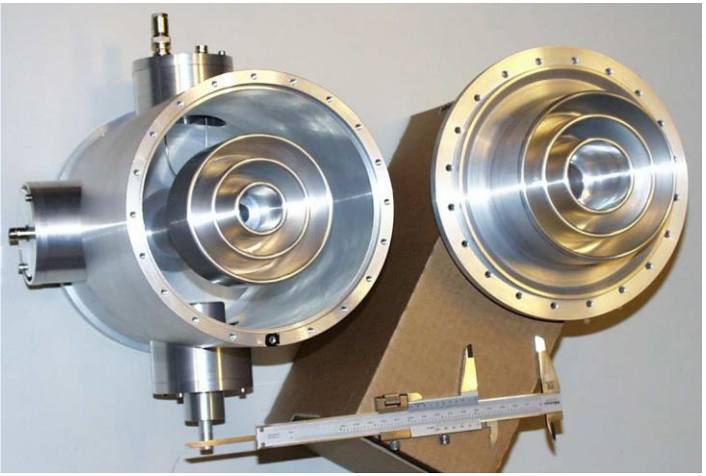


Phase margin: 90.00°



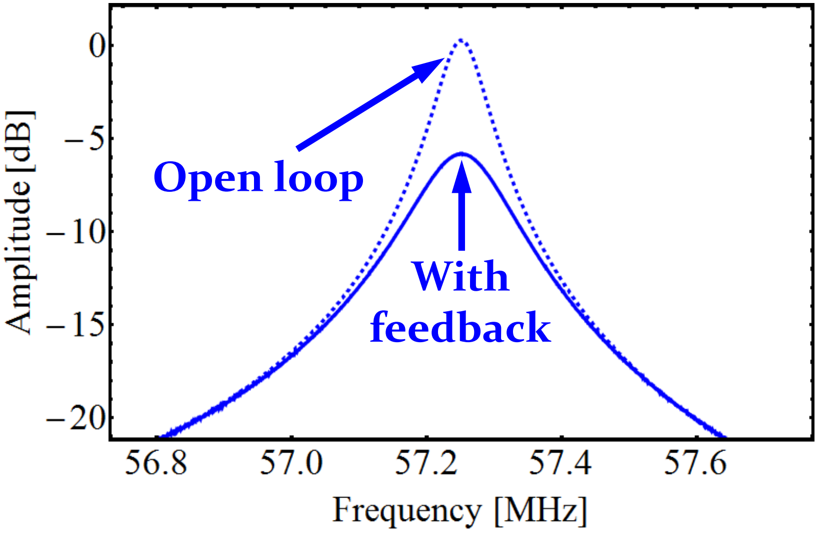
# Example: direct feedback lab experiment

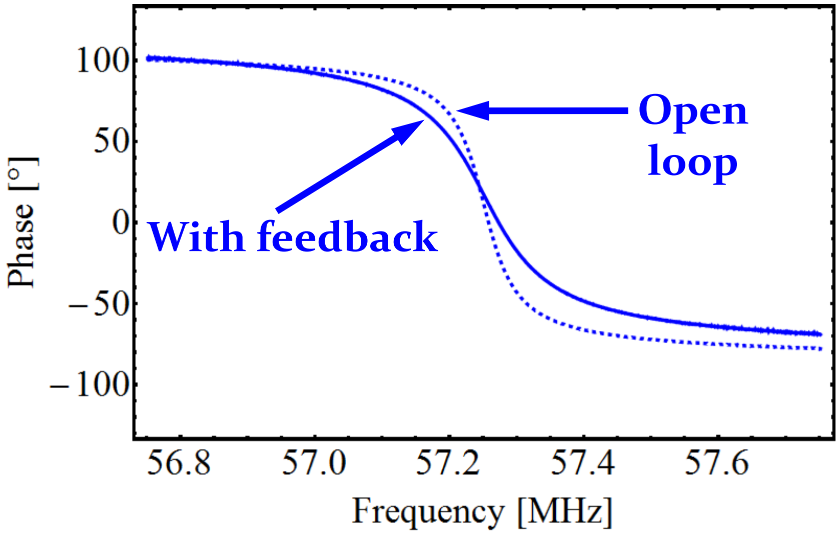
- Coaxial cavity, $f_o \approx 57$ MHz
- ‘Power’ amplifier: ~10 mW



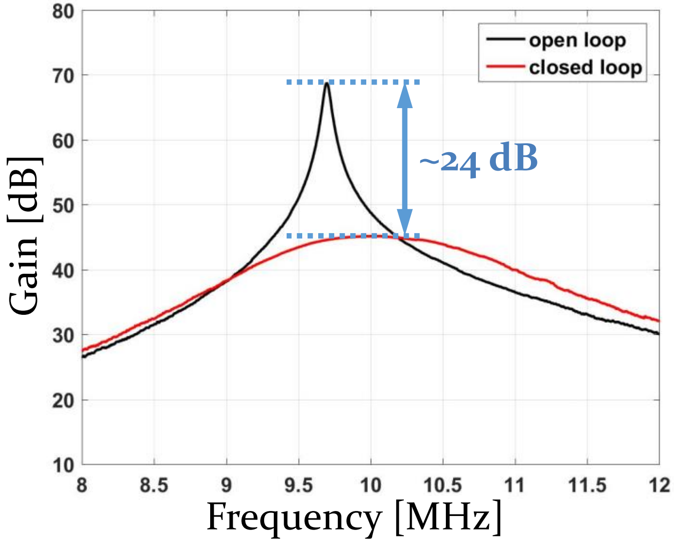
→ No risk of damage

→ Usually more:
Tens to hundreds of kilowatts

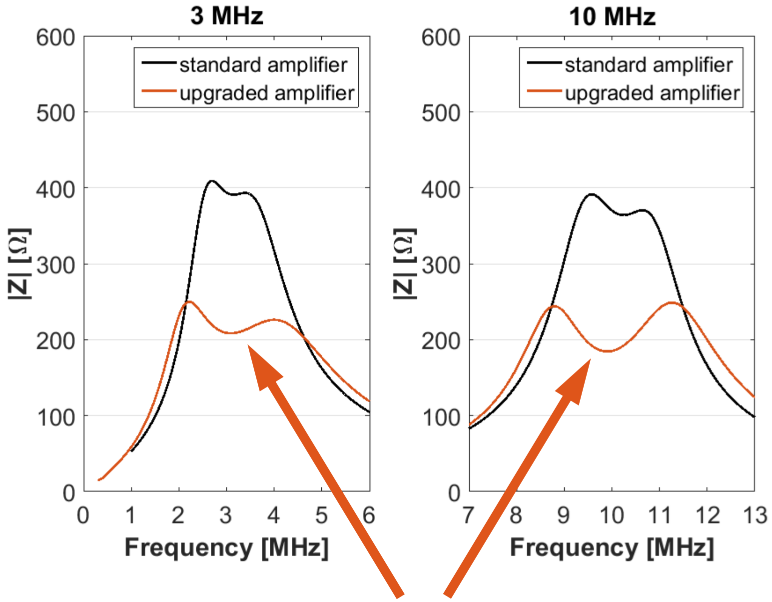

Measured transfer function


Phase

# Example: 10 MHz RF system in CERN PS



Transfer function with and without feedback



More feedback gain

Pushed to stability limit

- **Feedback gain of 24 dB**

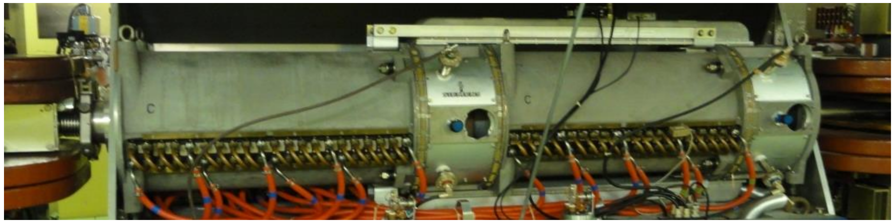
→ **Equivalent impedance,**
**$Z_{\mathrm{fb}}(\omega)$ reduced by more than order of magnitude**

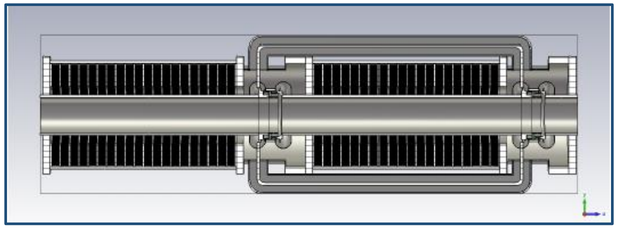
→ **Impedance for amplifier remains unchanged, $Z(\omega)$**

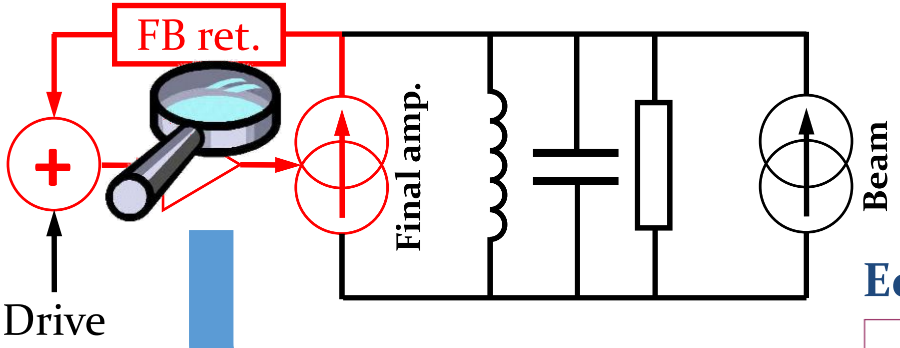
Local, direct feedback

# Example: CERN PS 10 MHz cavity feedback

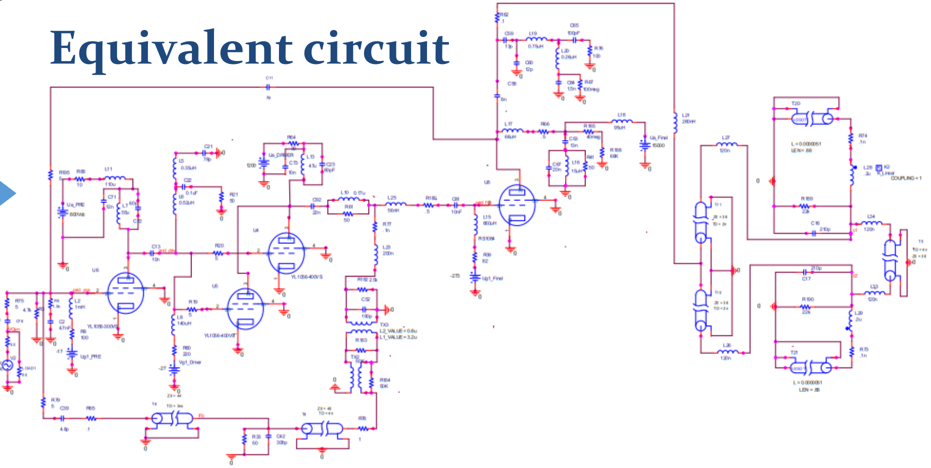
- 10 + 1 ferrite loaded cavities, tunable from 2.8…10 MHz
- Two resonators excited in parallel by one amplifier







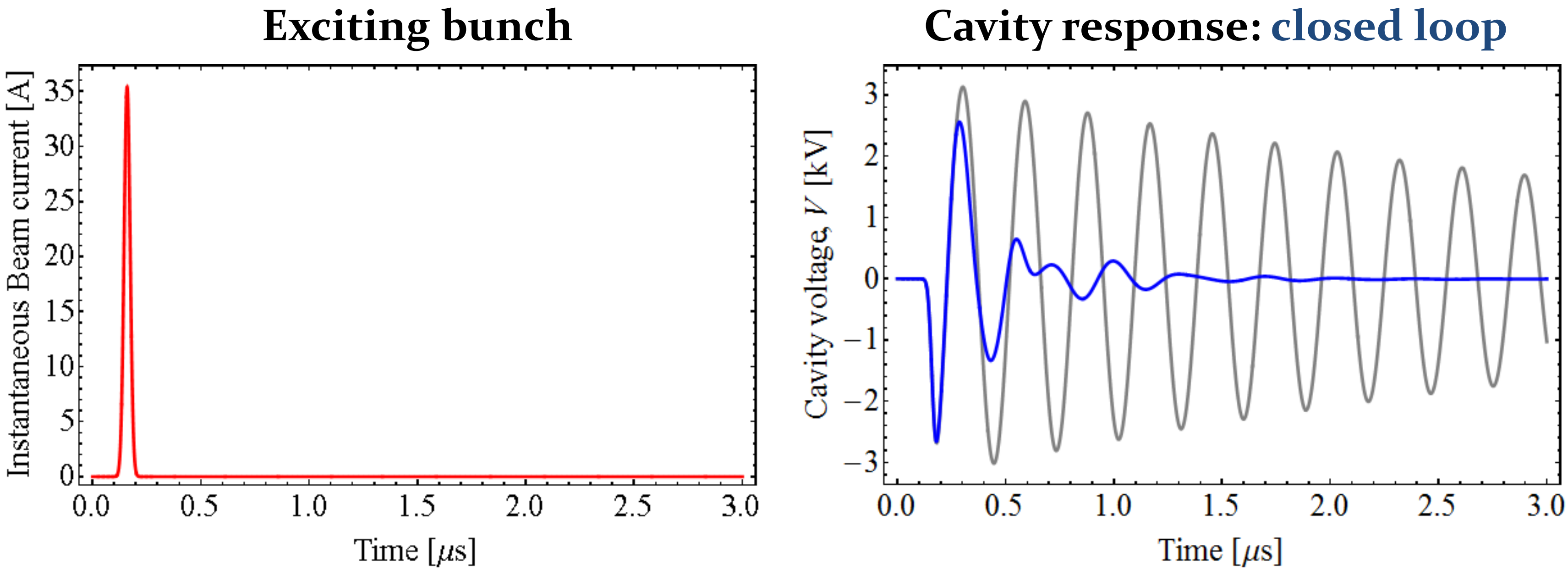
**Equivalent circuit**



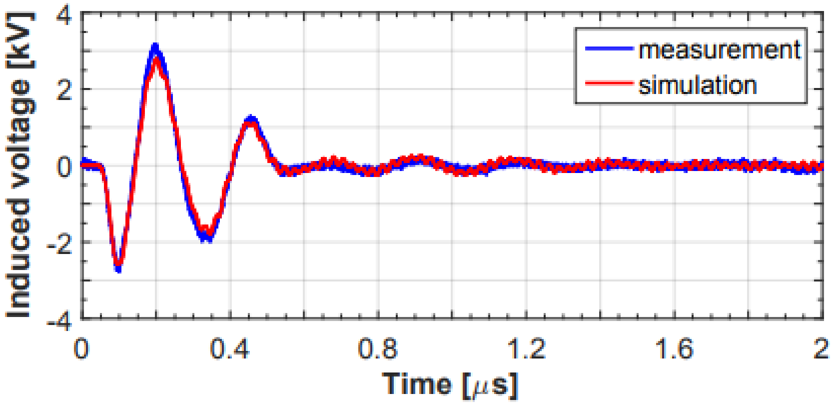
→ Realistic amplifier behaviour with higher order modes

# Modelling a real cavity – time domain

- **Time domain response of cavity and amplifier**



→ **Comparing with measured response to beam excitation**



→ **No instantaneous damping due to inherent delay**

→ **Filling time significantly reduced with feedback**

# Limitations of direct feedback

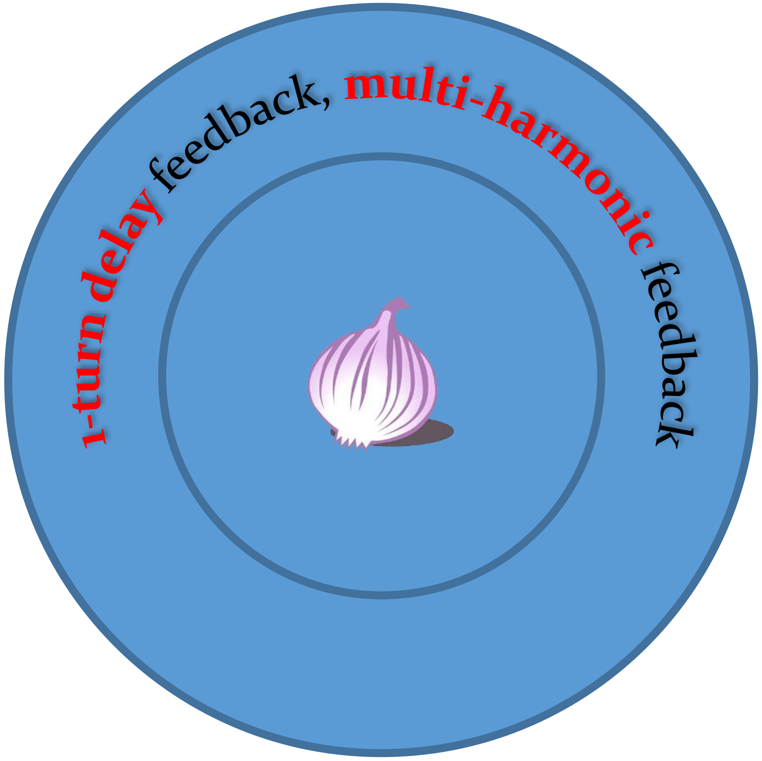
- **Contributions to maximum feedback gain**

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

$$= \frac{\pi}{2}\cdot\frac{1}{R}\cdot\frac{1}{\Delta\omega_{-3\mathrm{dB}}}\cdot\frac{1}{\tau}$$

1. **Decrease shunt impedance → not a good idea**
2. **Reduction of delay has physical limits**
   - → How close can amplifier be to cavity?
   - → Minimum delay of feedback chain?
3. **Decrease bandwidth**
   - → Reduce bandwidth of feedback chain instead of cavity?

# Feedback with delay



**1-turn delay** feedback, **multi-harmonic** feedback

# Feedback with delay

## Why?

→ **Loop delay cannot be made short: amplifier not close enough to cavity**

→ **Cavity to be damped has large bandwidth**

→ **Need impedance reduction beyond stability limit of direct feedback**

## How?

→ **Cleverly use the properties of the beam spectrum**

→ **Profit from of slow synchrotron motion**

# Longitudinal beam spectrum

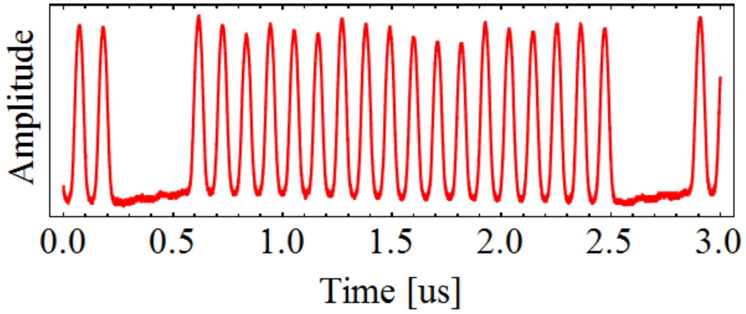
# Longitudinal beam spectrum

- **Circular accelerator**
  - → **Beam signal periodic with revolution frequency:** $\omega_{\mathrm{rev}}$

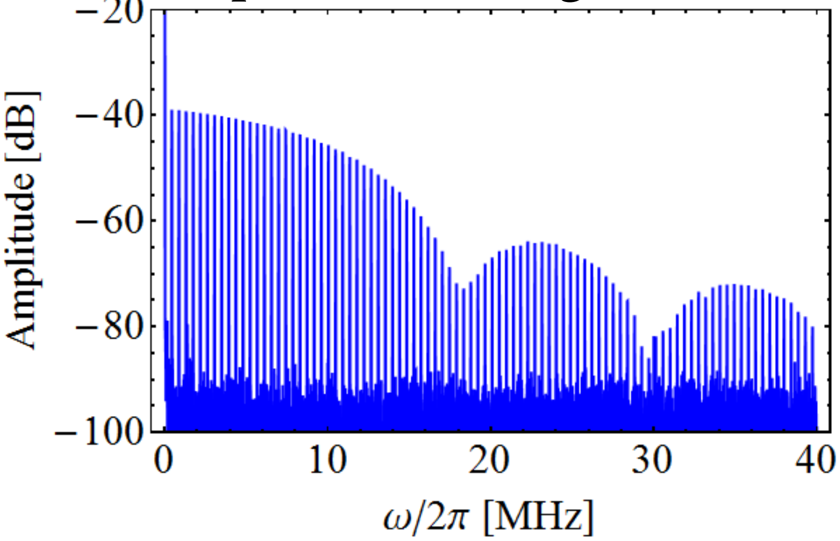
→ **Spectral components at:**

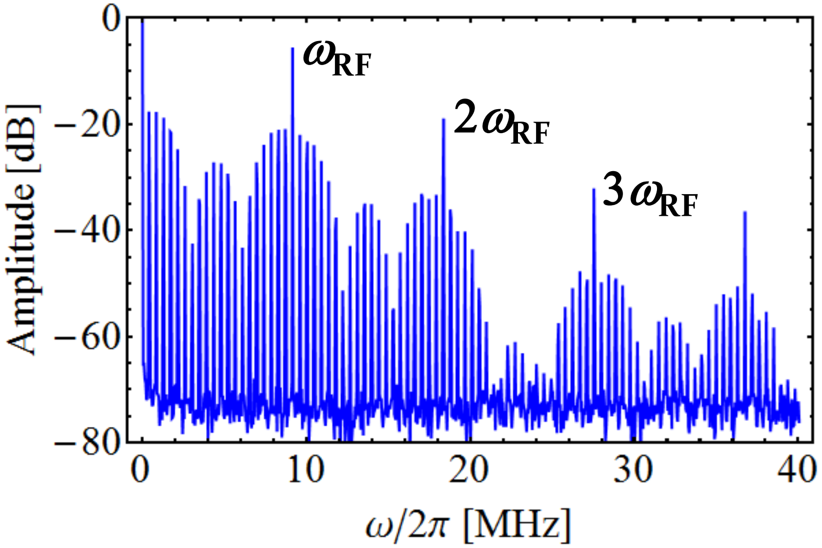
$$\omega = n\omega_{\mathrm{rev}}$$

**Multi-bunch beam**



**Spectrum of single bunch**

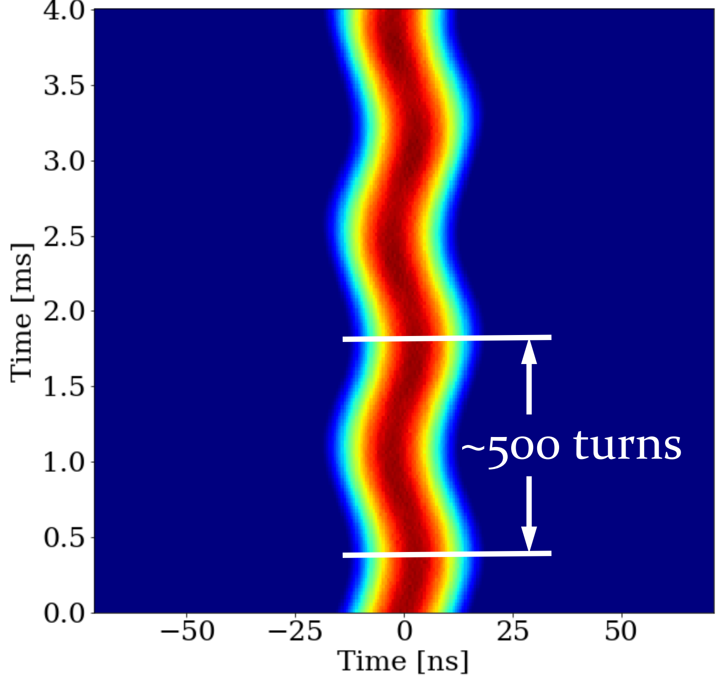




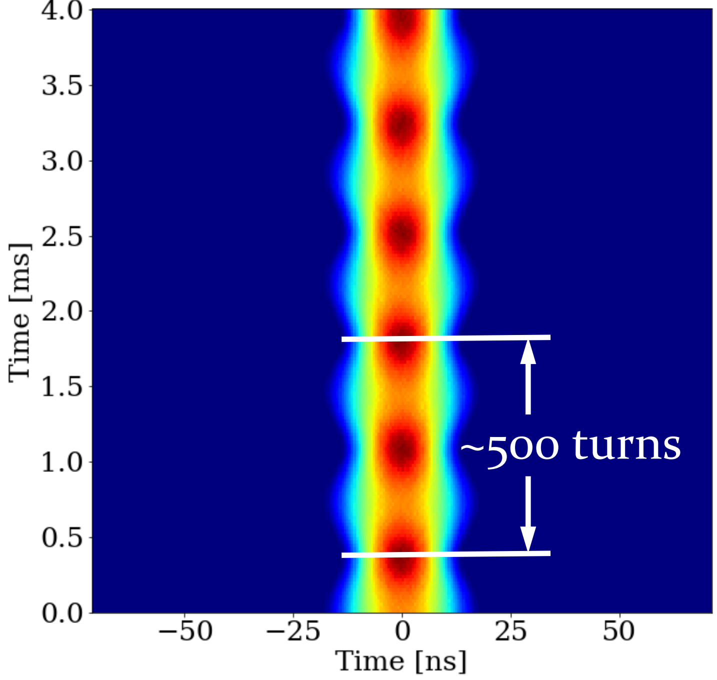
# Longitudinal beam spectrum

- **Longitudinally unstable bunches may perform oscillations**
  - → **Synchrotron frequency is basic periodicity:** $\omega_S$

**Oscillation with $\omega_S$: dipole**



**Oscillation with $2\omega_S$: quadrupole**



→ **Adds sidebands at $\omega_{rev}$ harmonics:** $\omega = n\omega_{\mathrm{rev}} \pm m\omega_S$

→ **Sidebands usually close to $\omega_{rev}$ harmonic since** $\omega_S \ll \omega_{\mathrm{rev}}$

# Beam spectrum

→ Beam can only induce voltage at frequencies

$$\omega = n\omega_{\mathrm{rev}} \pm m\omega_S$$

→ Relevant frequencies from RF point of view

$$\omega = \omega_{\mathrm{RF}} \pm n\omega_{\mathrm{rev}} \pm m\omega_S$$

→ Feedback only needs to damp these frequency components

→ Can one profit from this property for RF feedback beyond conventional stability limit?

# Periodic filters

# Periodic notch and comb filters

- Transfer function periodic in frequency

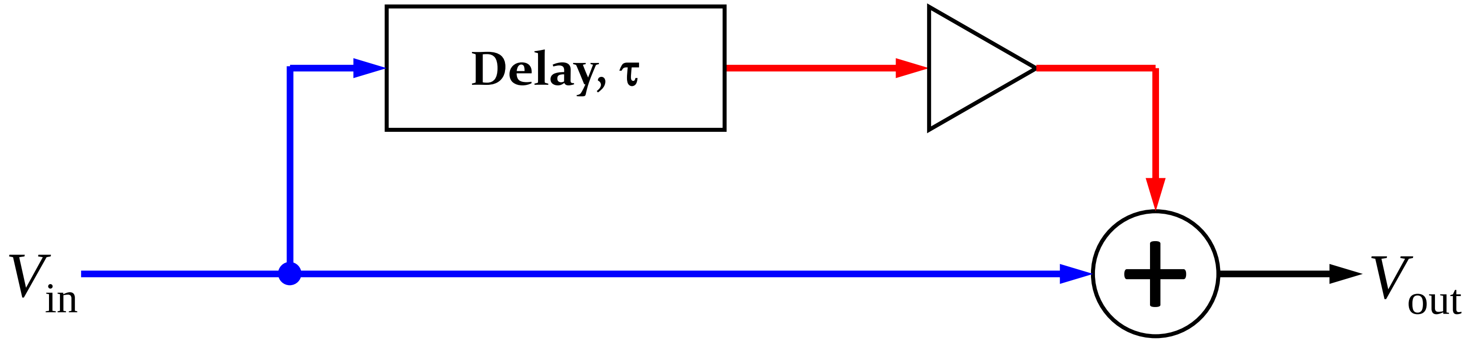
$$H(\omega) = H(\omega \bmod \omega_0)$$

- Niche application in communication technology
  - → Who wants to listen to multiple radio stations at the same time?
- Very useful for circular accelerators thanks to properties of beam spectrum

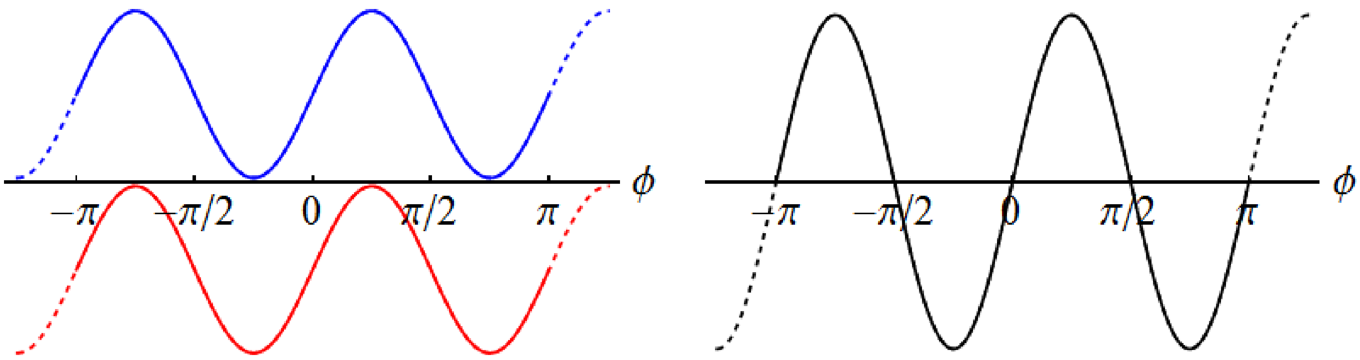
→ How to build such filters?

# Periodic notch and comb filters

- **Add signal with itself, but delay by a fixed delay, τ**



- **Addition (maxima) or subtraction (minima)**



$$y(t) = x(t) + x(t - \tau)$$

# Periodic notch and comb filters

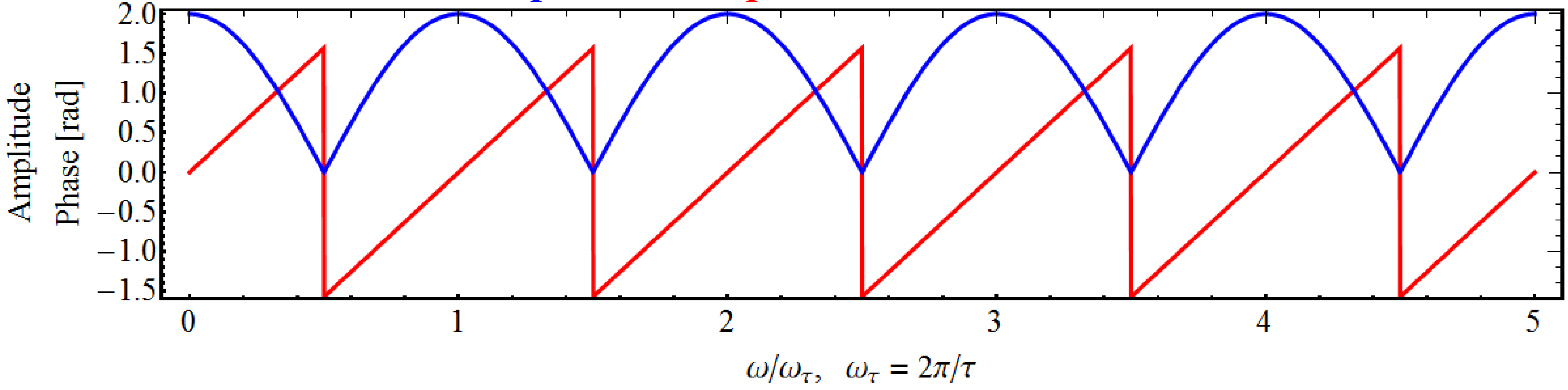
- **Add signal with itself, but delay by a fixed delay, τ**

$$x(t) = e^{i\omega t}$$

$$\begin{aligned} y(t) &= x(t) + x(t-\tau) \\ &= e^{i\omega t} + e^{i\omega(t-\tau)} \\ &= e^{i\omega t}\left(1 + e^{-i\omega\tau}\right) \end{aligned}$$

- **Addition (maxima) or subtraction (minima)**

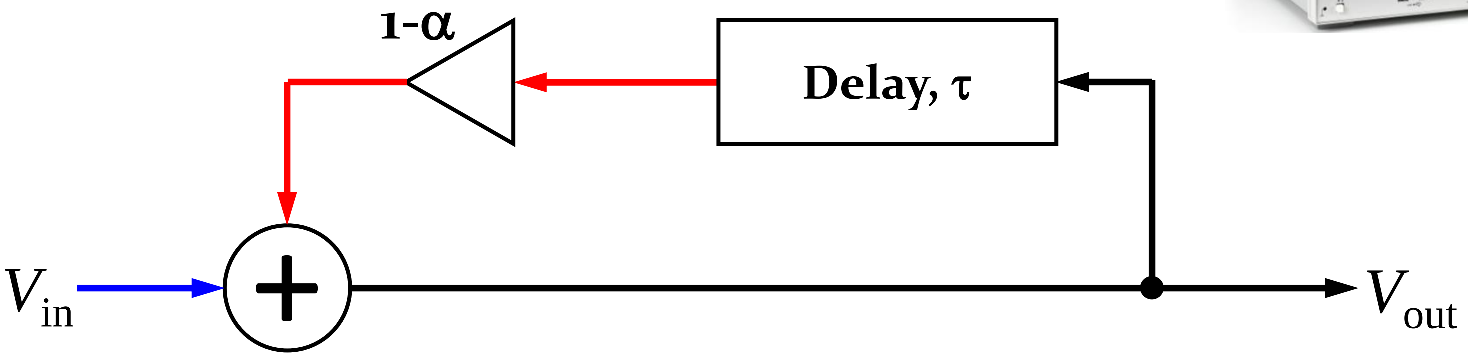
**Amplitude and phase filter transfer function**



**→ Filter to remove (notch) revolution frequency harmonics**

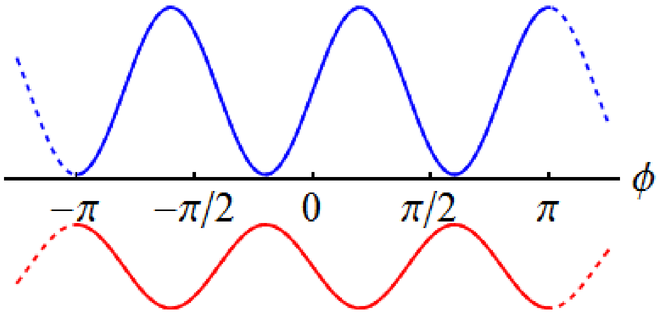
# Periodic notch and comb filters

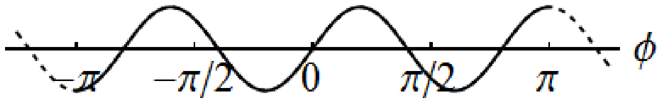
- Delay output signal by τ and add to input signal



- Addition (maxima) or subtraction (minima)

$$y(t) = x(t) + y(t - \tau)$$





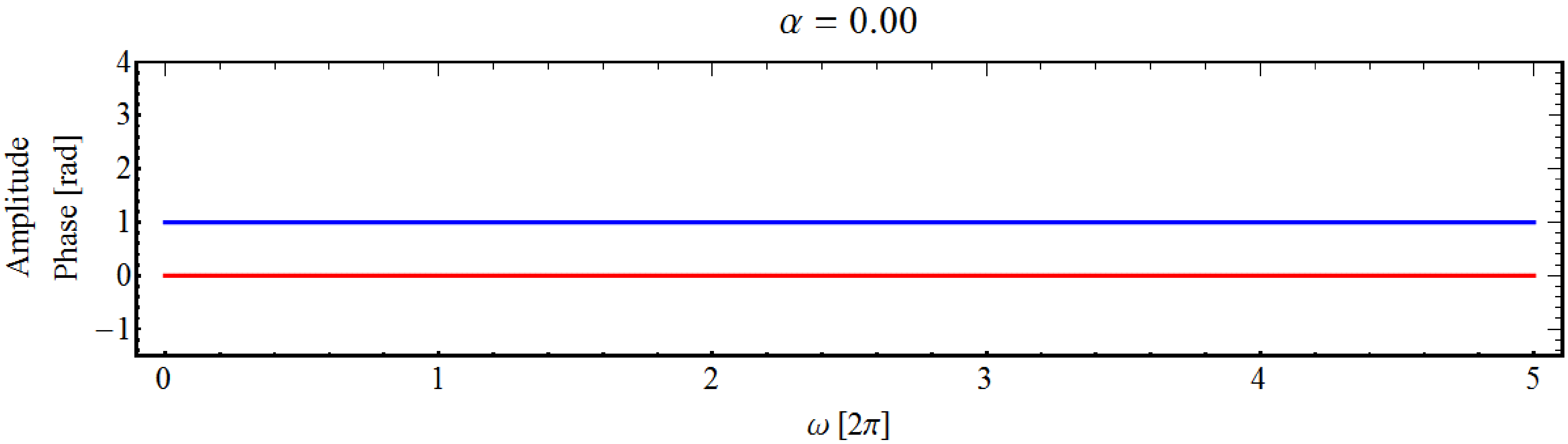
# Periodic notch and comb filters

- **Delay output signal by τ and add to input signal**

$$y(t) = x(t) + y(t-\tau)$$

- **Ansatz:** $y(t) = ae^{i\omega t}$ $\qquad$ $y(t) = e^{i\omega t} \cdot \dfrac{1}{1 - e^{i\omega\tau}}$

- **Addition (maxima) or subtraction (minima)**

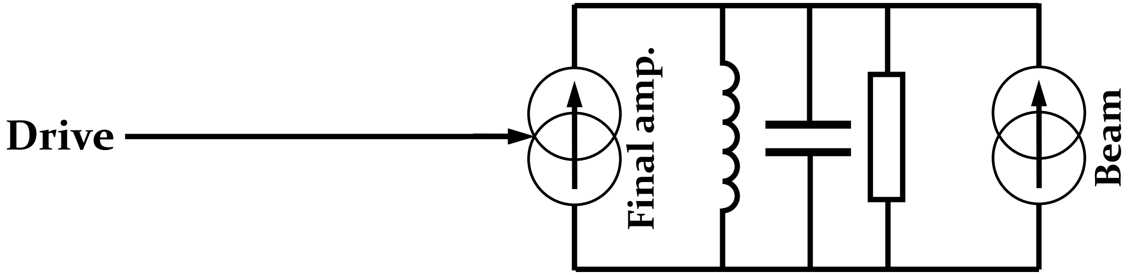


→ **Remove everything but revolution frequency harmonics**

# Feedback with periodic filters

# 1-turn delay feedback

1. **Comb filter** to extract revolution frequency harmonics
2. **Delay** to complete physical delay of cables and signal processing to **1 revolution period**



# 1-turn delay feedback

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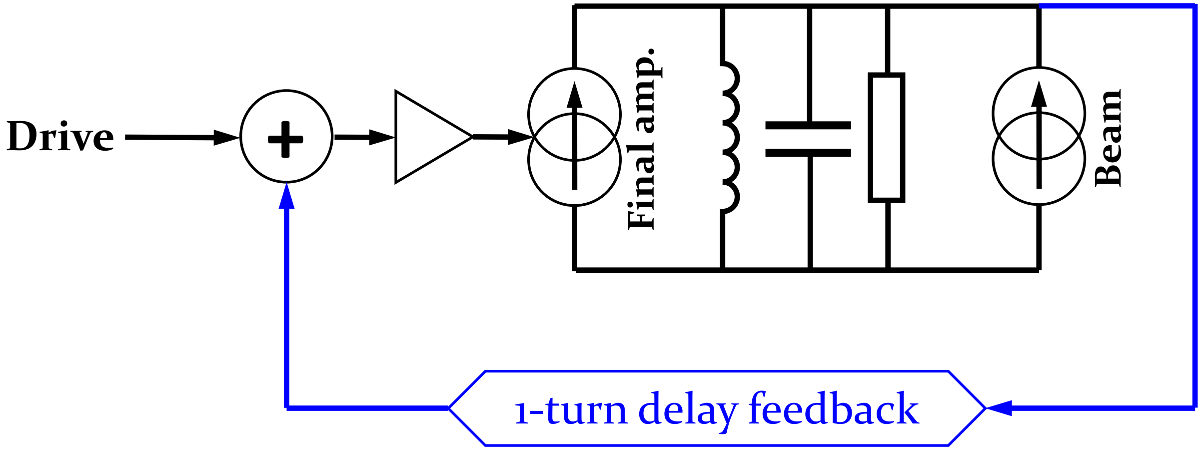

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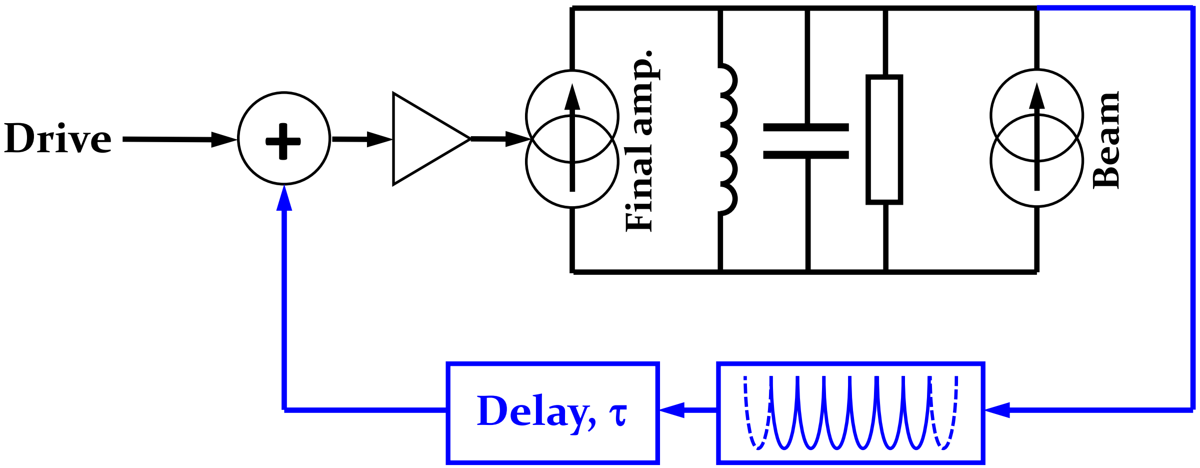


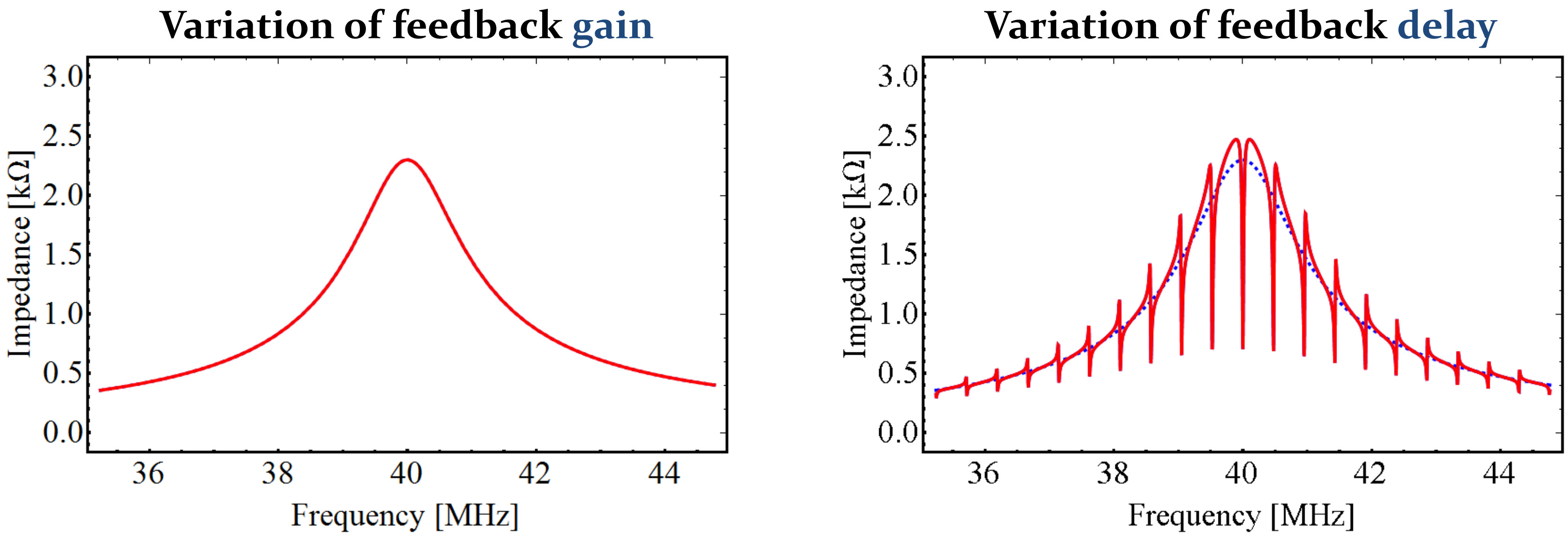
$$G \rightarrow GH(\omega)$$

$$\begin{aligned} Z_{\mathrm{fb}}(\omega) &= \frac{Z(\omega)}{1+Z(\omega)Ge^{-i\Delta\omega\tau}} \\ \rightarrow Z_{\mathrm{1tfb}}(\omega) &= \frac{Z(\omega)}{1+Z(\omega)GH(\omega)e^{-i\Delta\omega\tau}} \end{aligned}$$

# Cavity transfer function with 1-turn delay FB

- → **Transfer function with comb filter**

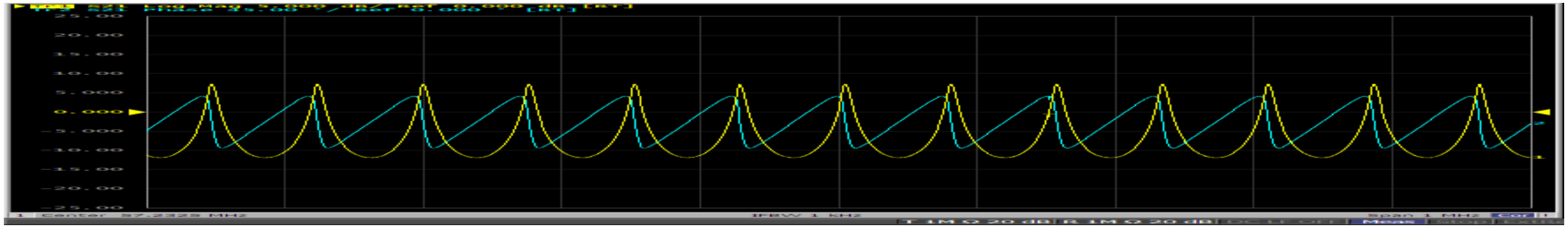
$$\rightarrow Z_{1\mathrm{tfb}}(\omega) = \frac{Z(\omega)}{1 + Z(\omega)GH(\omega)e^{-i\Delta\omega\tau}}$$

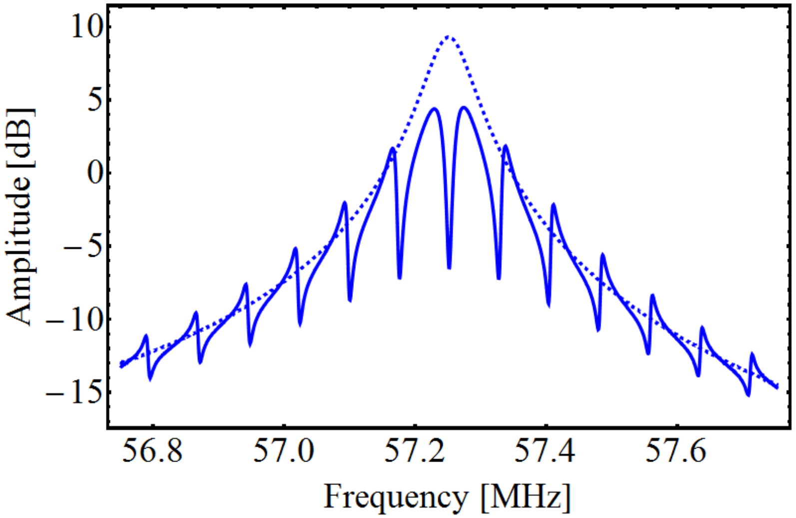


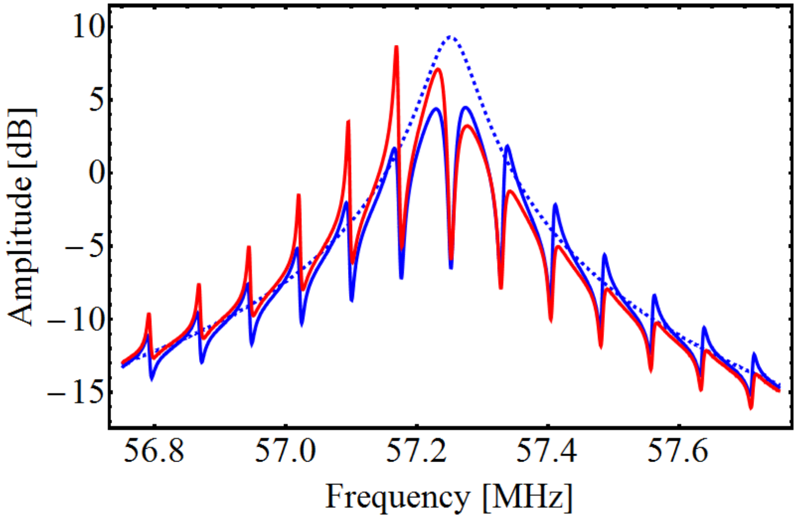
- → **Impedance between revolution frequency harmonics**
  - → **Not excited by beam, but potential issue for stability**
- → **Total delay very critical**

# Example: long delay feedback lab experiment

- **1-turn delay feedback around 57 MHz resonator**
  - → Analogue comb filter with ~2.5 km optical fiber delay
  - → Accelerator with $f_{\text{rev}} \approx 76$ kHz ($2\pi R \approx 4$ km circumference)

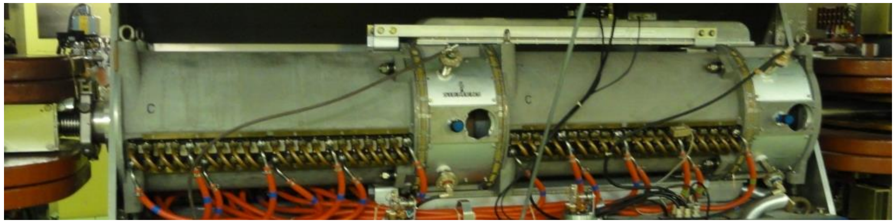


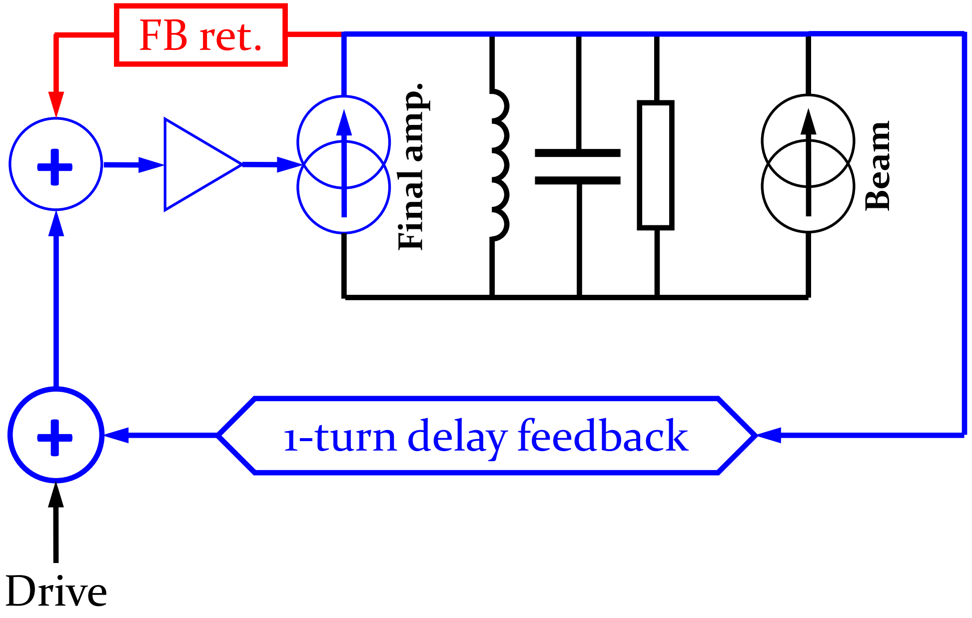

Open/closed loop transfer function


+2/-2 ns delay error (+/-1.4 · $10^{-4}$)

# Example: 1-turn delay in CERN PS

- **Combination of direct and 1-turn delay feedback**





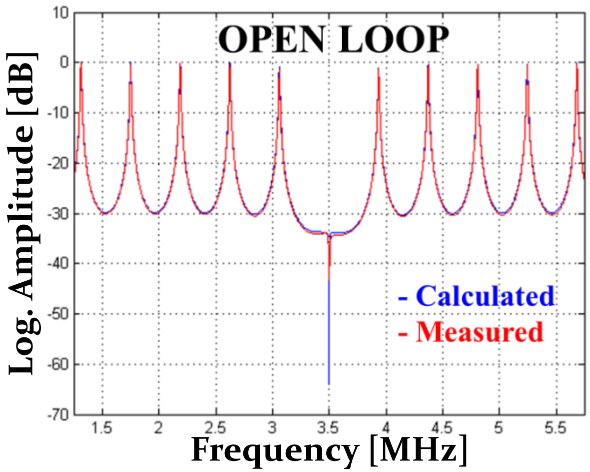
**- Fast wide-band feedback around amplifier (internal)**
**→ Gain limited by delay**

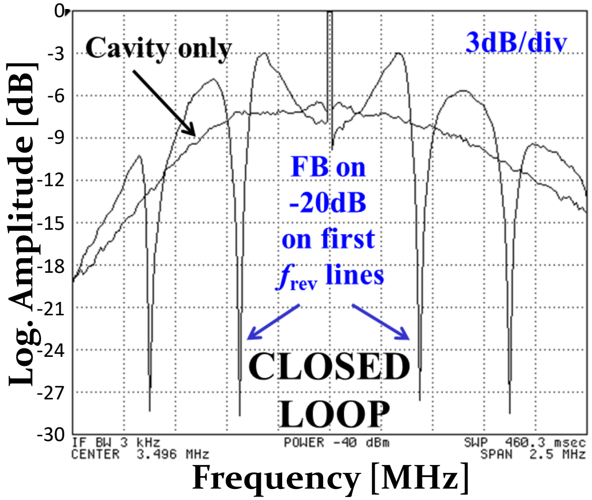
**- 1-turn delay feedback**
**→ High gain at $n \times f_{\mathrm{rev}}$**

# Example: 1-turn delay in CERN PS

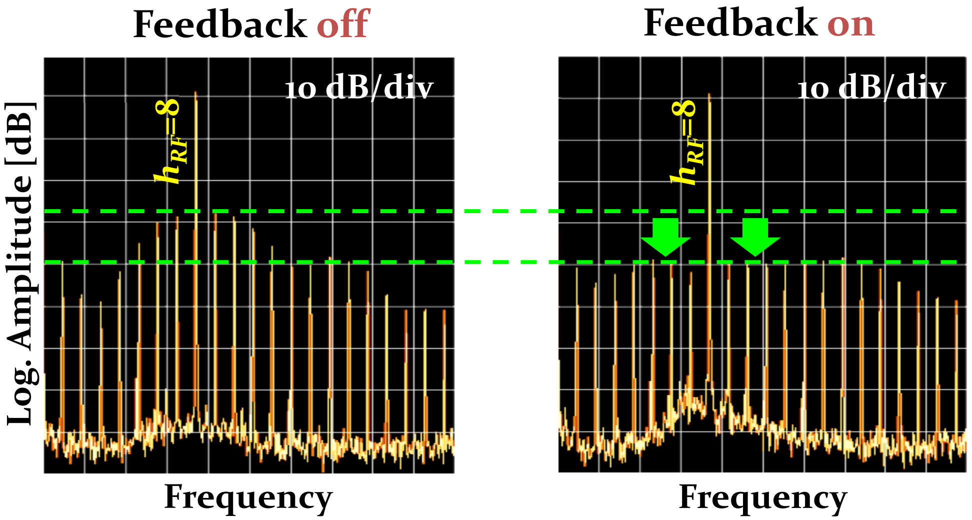
→ **Reduce cavity impedance beyond stability limit of wide-band FB**

**Open/closed loop transfer functions**





**Spectrum at cavity gap return**



→ **Important additional impedance reduction**

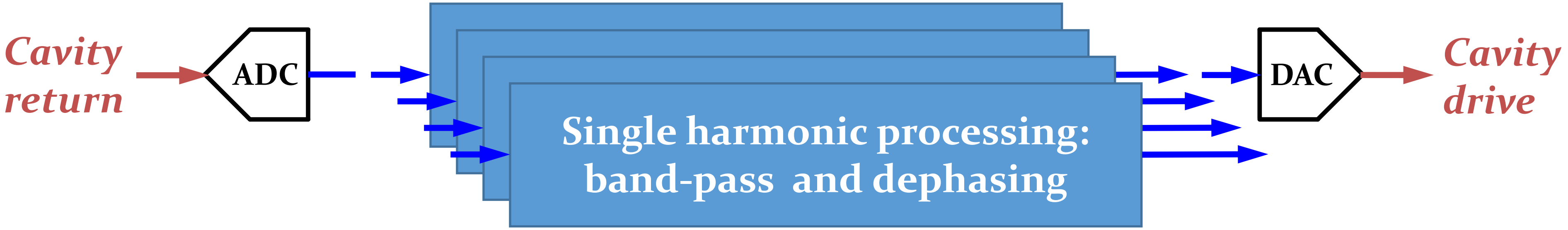
→ **Clever usage of beam periodicity in circular accelerator**

# Multi-harmonic feedback

# Treat each harmonic independently

- **Separate feedback loop by harmonic**
  - → **Full flexibility of individual loop parameters**

→ **Empowered by processing power of modern digital hardware**



*Cavity return*

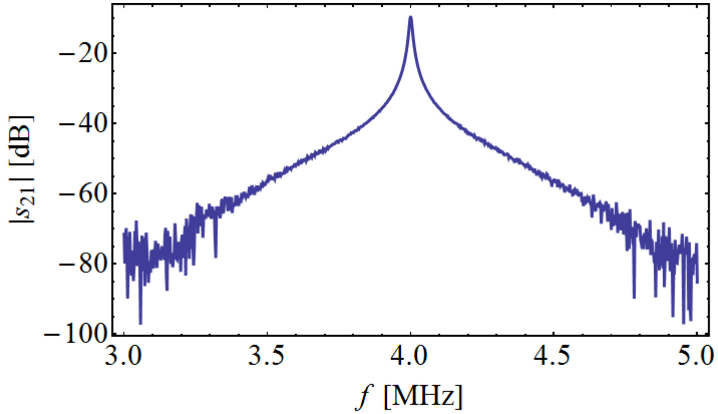
ADC

**Single harmonic processing: band-pass and dephasing**

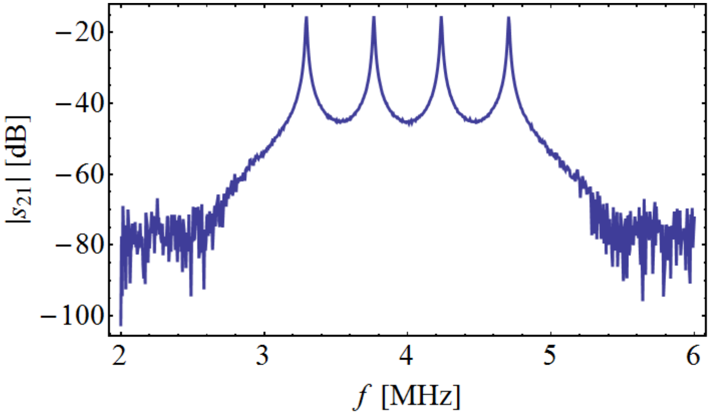
DAC

*Cavity drive*

**Open loop transfer function**



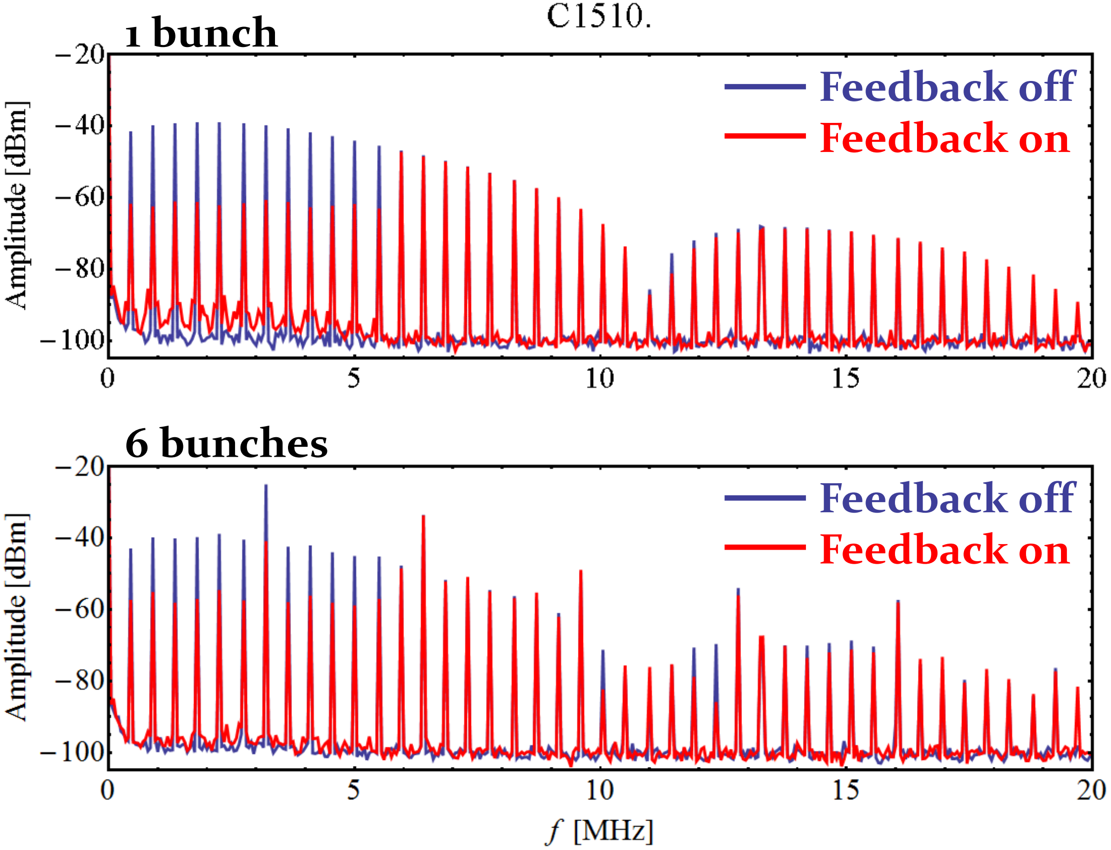
**4 adjacent harmonics**



# Example: Damping of wide-band cavity

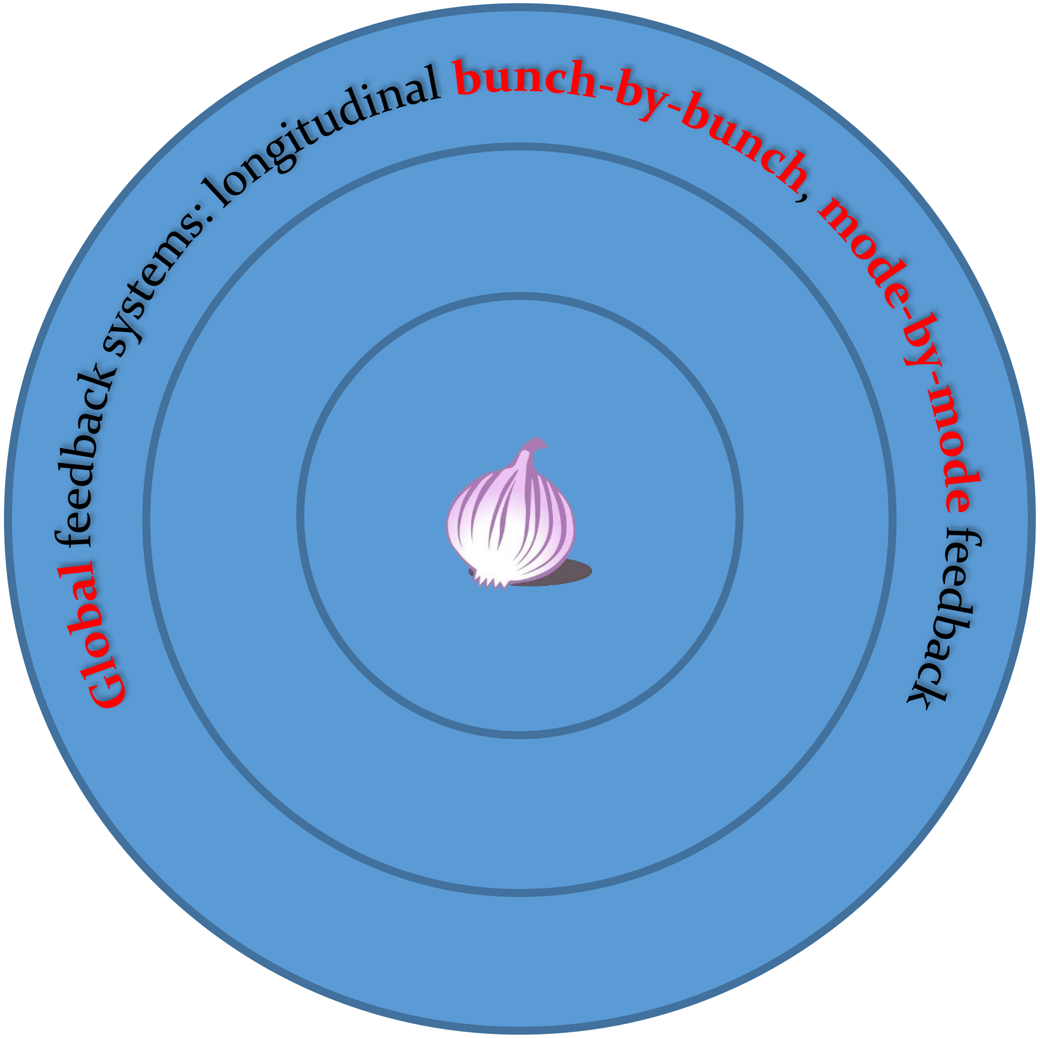
- Multi-harmonic feedback reduces beam induced voltage
- First 12 revolution frequency harmonics damped

**Spectrum of beam induced voltage**



→ **Damping beyond stability limit of direct feedback**

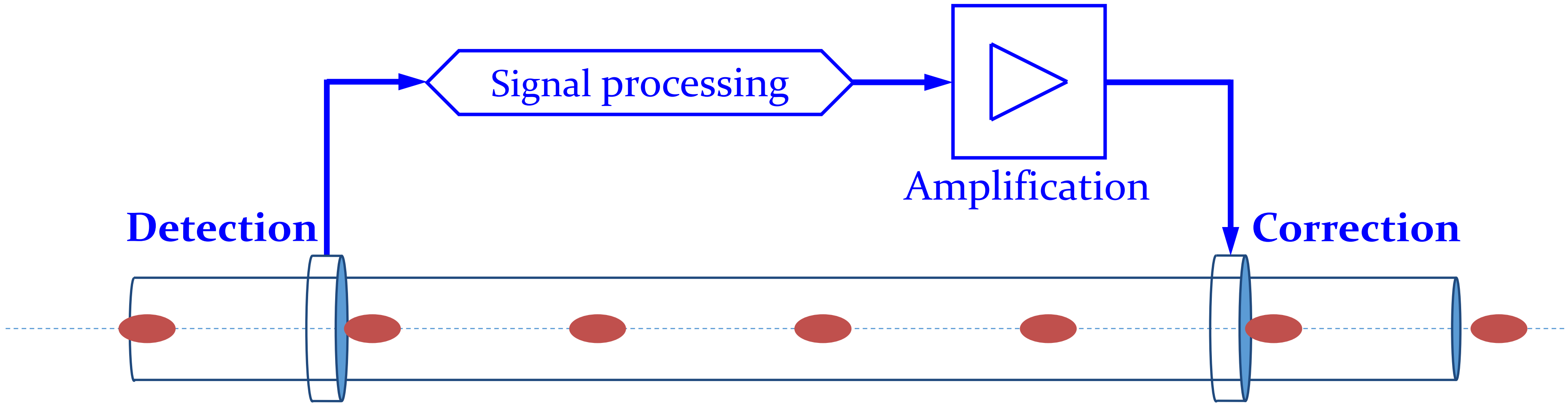
# Global feedback



**Global** feedback systems: longitudinal **bunch-by-bunch**, **mode-by-mode** feedback

# Global RF feedback

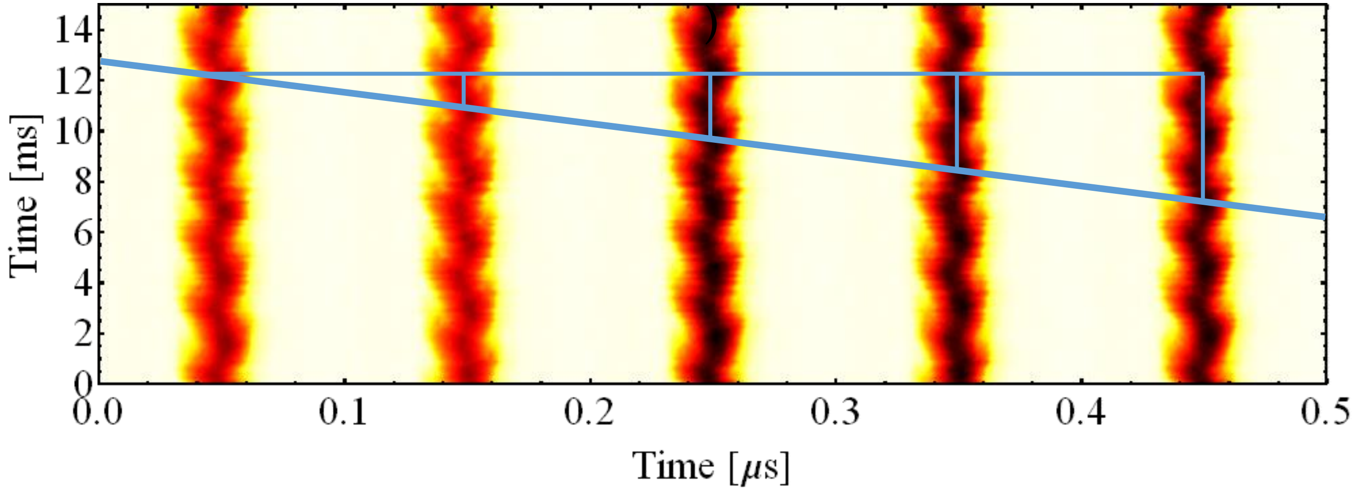
1. **Detect derivation of beam**
   → Transverse: position offset
   → **Longitudinal: phase offset**



2. **Signal processing to filter relevant information**
3. **Amplify and apply correction**
   → **Drive dedicated kicker**
   → **Drive accelerating cavities as longitudinal kickers**

# Longitudinal oscillation of bunches

- Longitudinally unstable beam, but driving source unknown
- Each bunch oscillation, but not with the same phase

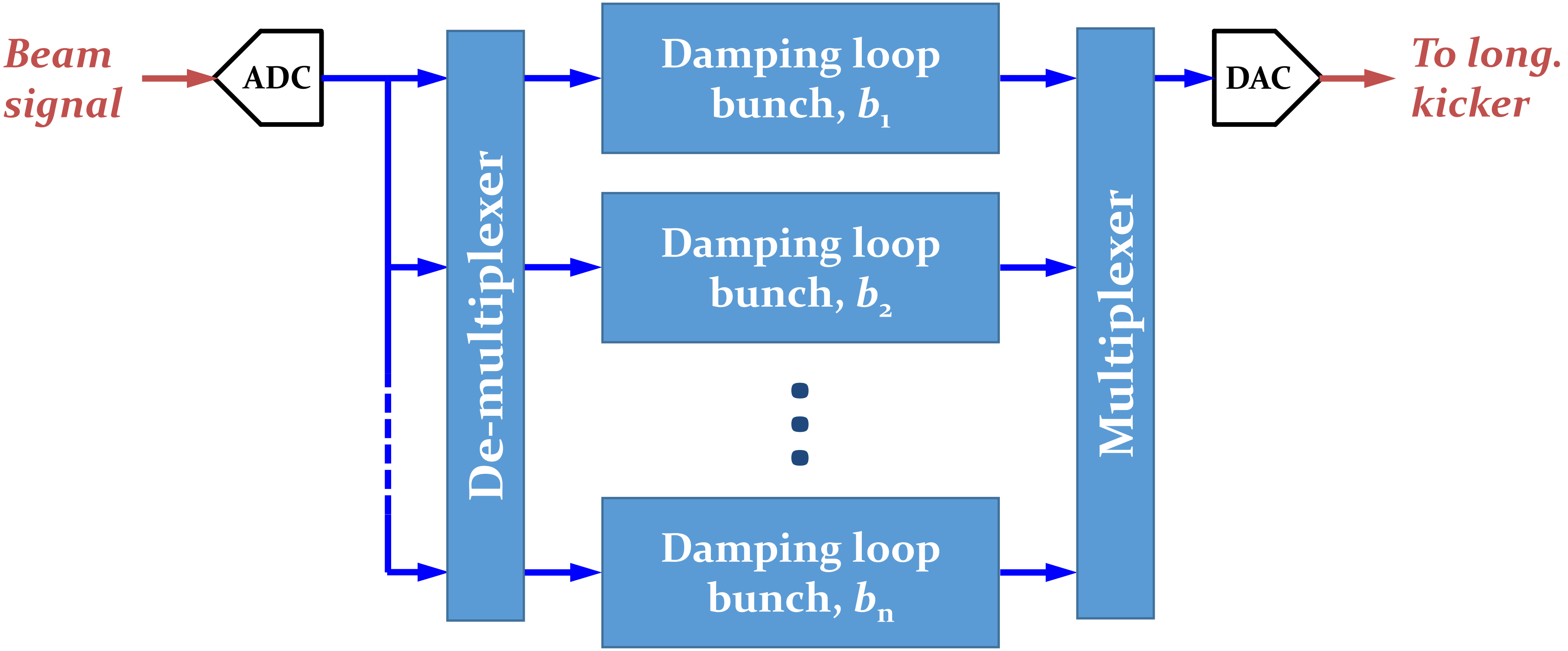


Bunches oscillating (dipole, 2π·10/21 phase advance)

| Time domain | Frequency domain |
|---|---|
| • Measure phase of each bunch<br>→ Apply kick to bring phase back to reference position | • Measure spectral component corresponding to mode<br>→ Apply kick to remove that spectral component |
| → “Bunch-by-bunch” | → “Mode-by-mode” |

# Time domain: Bunch-by-bunch feedback

- **Intuitive:** Measure oscillation of each bunch and correct



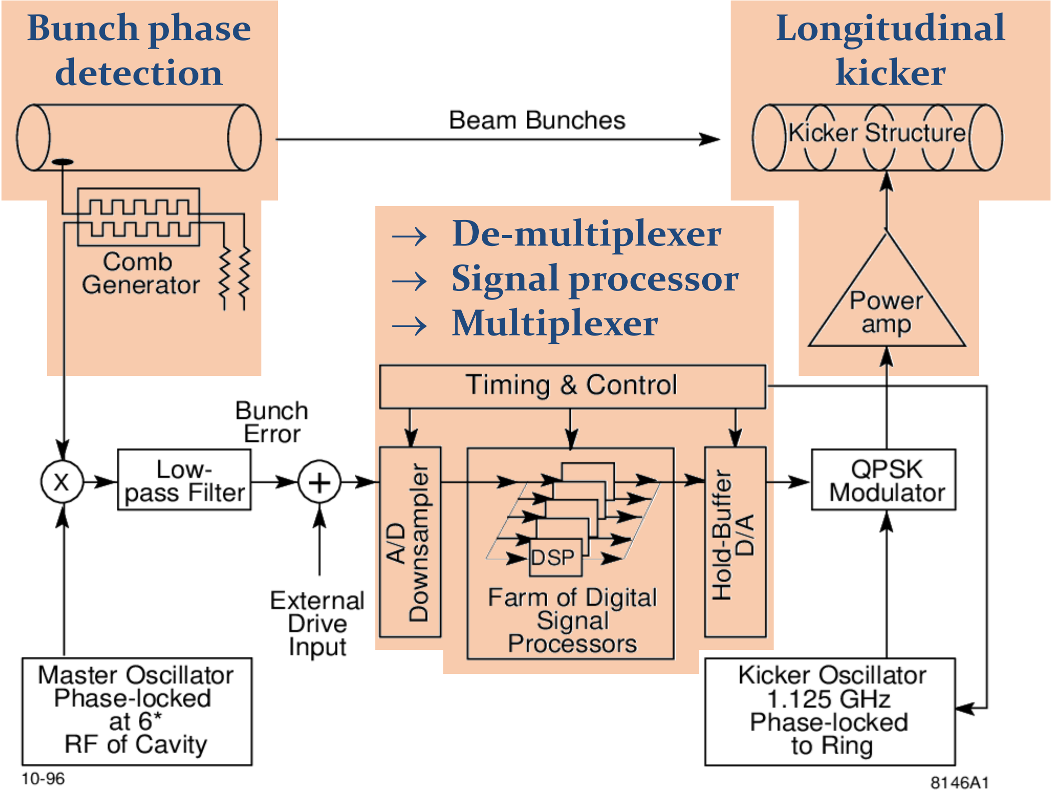
→ Multiple feedbacks in time domain multiplex

→ Flexible control (gain/phase) for each bunch

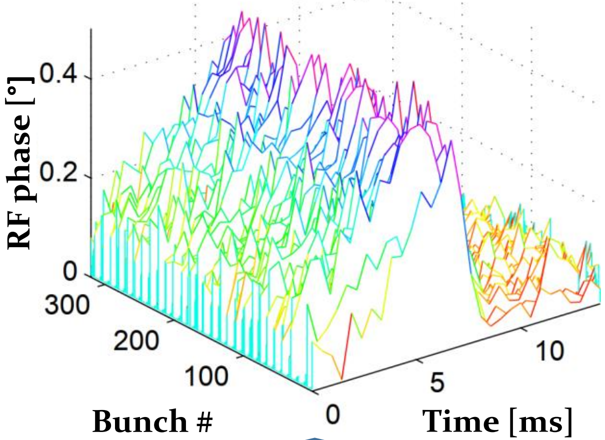
# Example: Bunch-by-bunch RF feedback

- **Multi-bunch feedback developed for electron storage rings:**

Used at Advanced Light Source (ALS) at LBNL, PEP at SLAC, DAϕNE at INFN-LNF, etc.

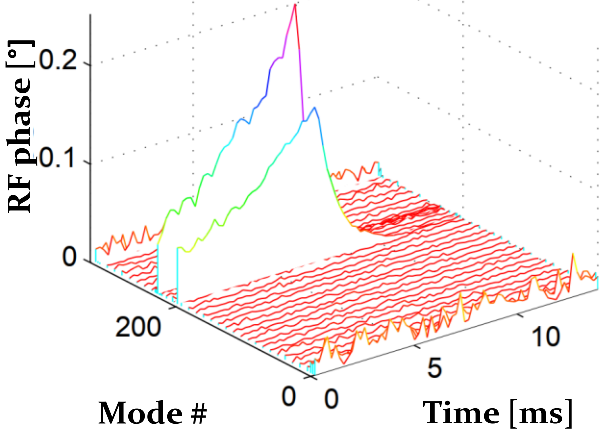


Bunches in time domain



FFT

Modes in frequency domain

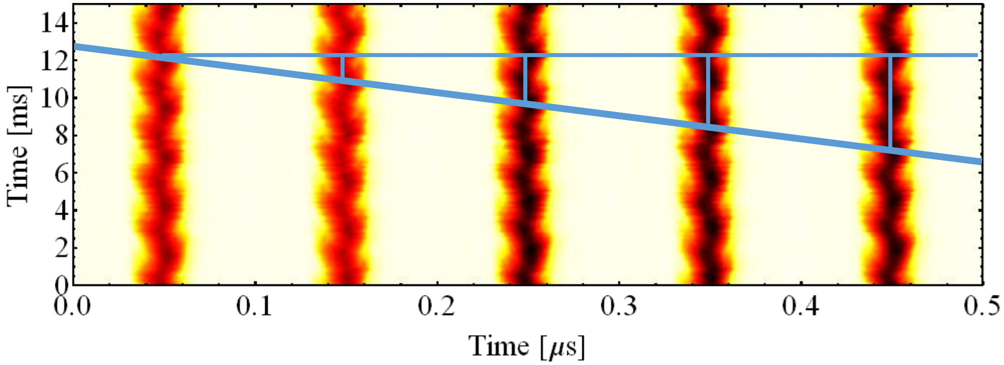


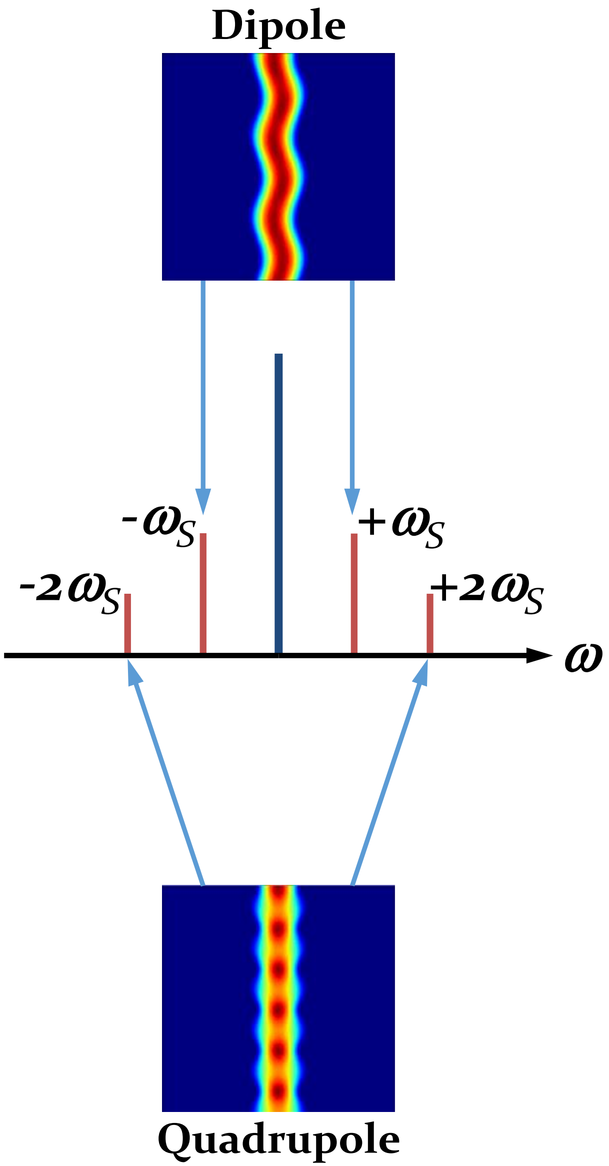
# Frequency domain: Mode-by-Mode

- **Less intuitive: Suppress components in beam spectrum**
- **Fixed phase advance from bunch-to-bunch creates sideband at $n\omega_{\text{rev}}$**

$$\omega = n\omega_{\text{rev}} \pm m\omega_S$$

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





# Frequency domain: Mode-by-Mode

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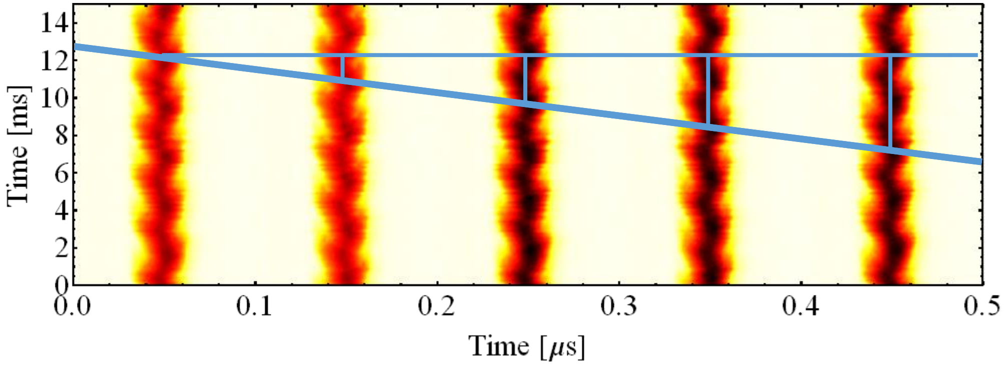
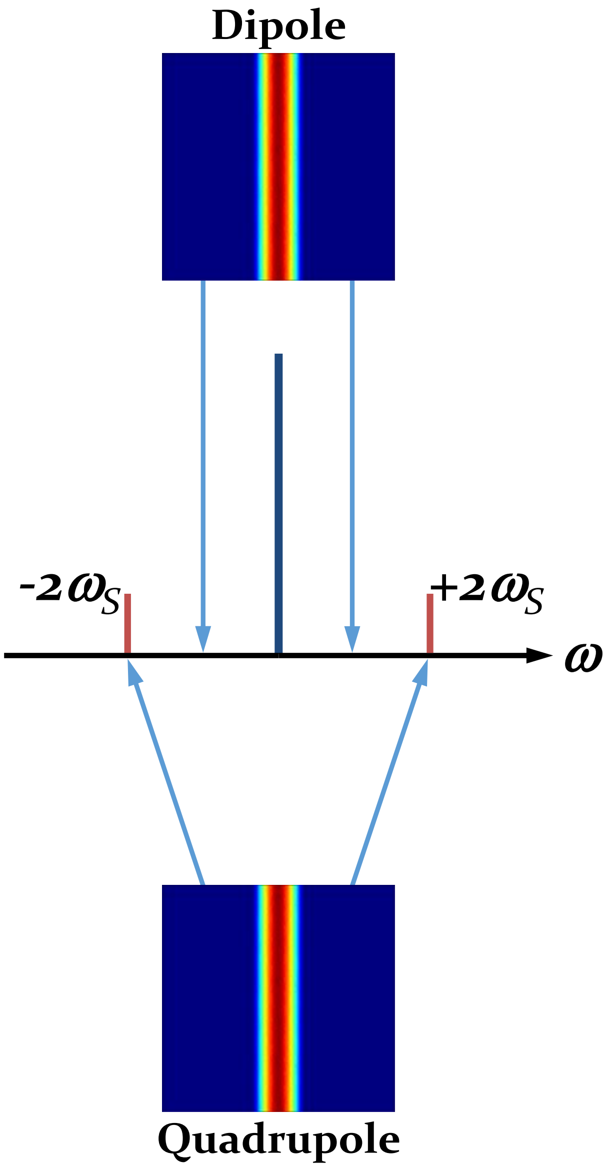
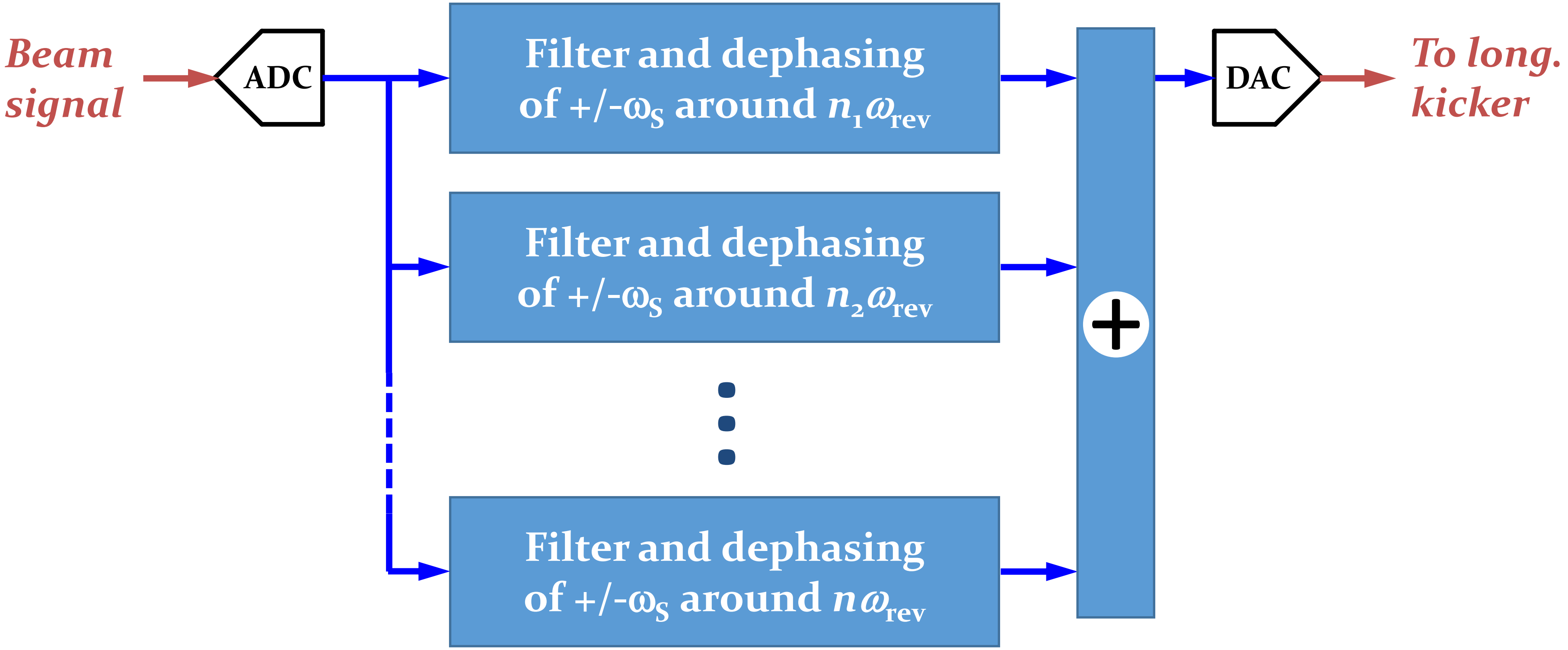


- **No sidebands at $+/-\omega_S$**
  → **Dipole oscillations removed**
- **No sidebands at $+/-2\omega_S$**
  → **Quadrupole oscillations removed**



# Mode-by-Mode feedback

1. **Filter synchrotron frequency side-bands**
2. **Inject correction to remove them** → **Stable beam**

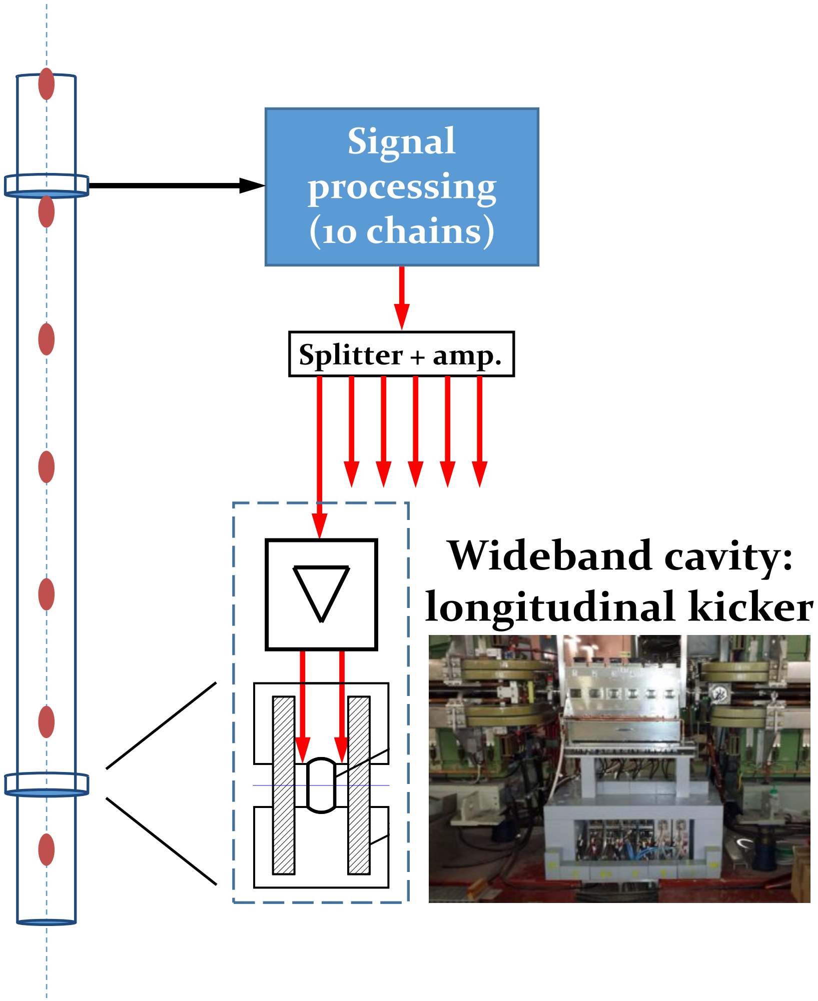


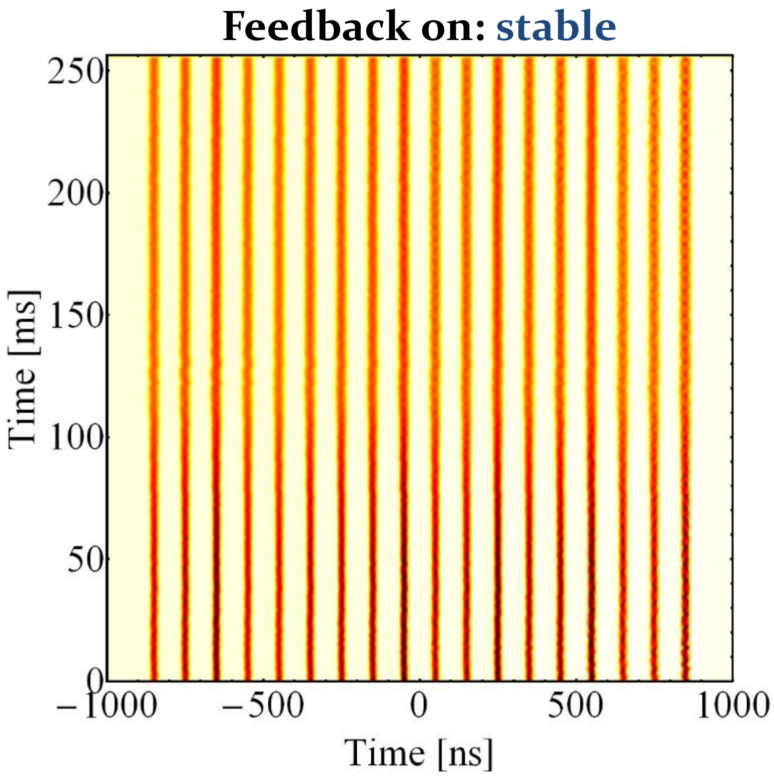
→ **Multiple feedbacks in parallel**

→ **Optimum parameters (phase, gain) for each harmonic of $\omega_{rev}$**

# Example: CERN PS coupled-bunch feedback

- Mode-by-mode dipole feedback
- 10 parallel processing chains → stabilize beam for LHC




Feedback on: stable

# Summary

1. Direct RF feedback
   → Globally reduce cavity impedance
2. Long delay feedback
   → Reduce impedance at revolution frequency harmonics
3. Global feedback
   → Just fix problems of (sometimes) not understood origin

- Chose feedback most appropriate to your problem
  → Prefer inner layers of feedback onion
  → Combination of different RF feedback types

- Delay is principal enemy of almost every RF feedback
  → Keep it short, you cannot beat causality!

# A big Thank You

## to all colleagues providing support, material and feedback

**Maria-Elena Angoletta, Philippe Baudrenghien, Thomas Bohl,
Giorgia Favia, Javier Galindo, Wolfgang Höfle, Erk Jensen,
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Daniel Valuch, Christine Völlinger, Manfred Wendt
and many more…**

# Thank you very much for your attention!

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- P. Baudrenghien, Low-level RF - Part I: Longitudinal Dynamics and Beam-Based Loops in Synchrotrons, CERN-2011-007, 2011, http://cds.cern.ch/record/1415913/files/p341.pdf

# Direct RF feedback on cavity

- You know the driving impedance → RF cavity
- You can be close to the cavity

| Advantages | Disadvantages |
|---|---|
| • Shunt impedance reduction of cavity resonance<br>• Robust, performance does not depend on beam parameters<br>• Excellent transient response | • Local feedback<br>• Amplifier must be close to cavity<br>• Feedback system per cavity |

# 1-turn delay/multi-harmonic feedback

- You know the driving impedance → RF cavity
- You cannot be close to the cavity

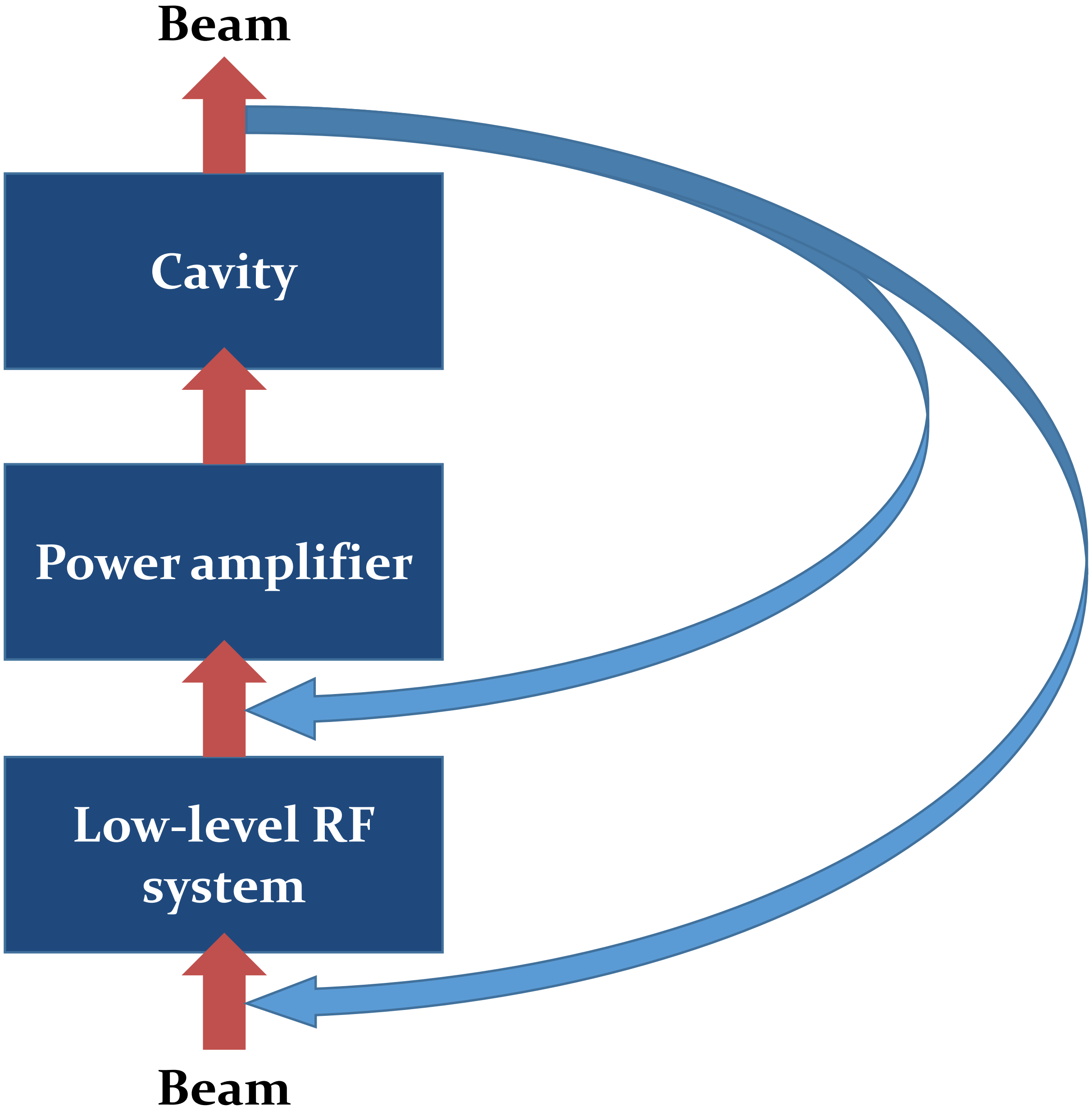
| Advantages | Disadvantages |
|---|---|
| • Shunt impedance reduction of cavity resonance at revolution frequency harmonics<br>• Used in combination with direct feedback | • Low bandwidth, slow response to transient effects<br>• Feedback system per cavity |

# Global feedback

- You do not know the source of the problem
- You observe and analyse the effect of an instability

| Advantages | Disadvantages |
|---|---|
| • Globally reduced consequence of instability<br>• One feedback sufficient to control instability | • Treats consequence, not cause of a problem<br>• Narrow range of application<br>• Dedicated longitudinal kicker |

# RF system overview



Beam

Cavity

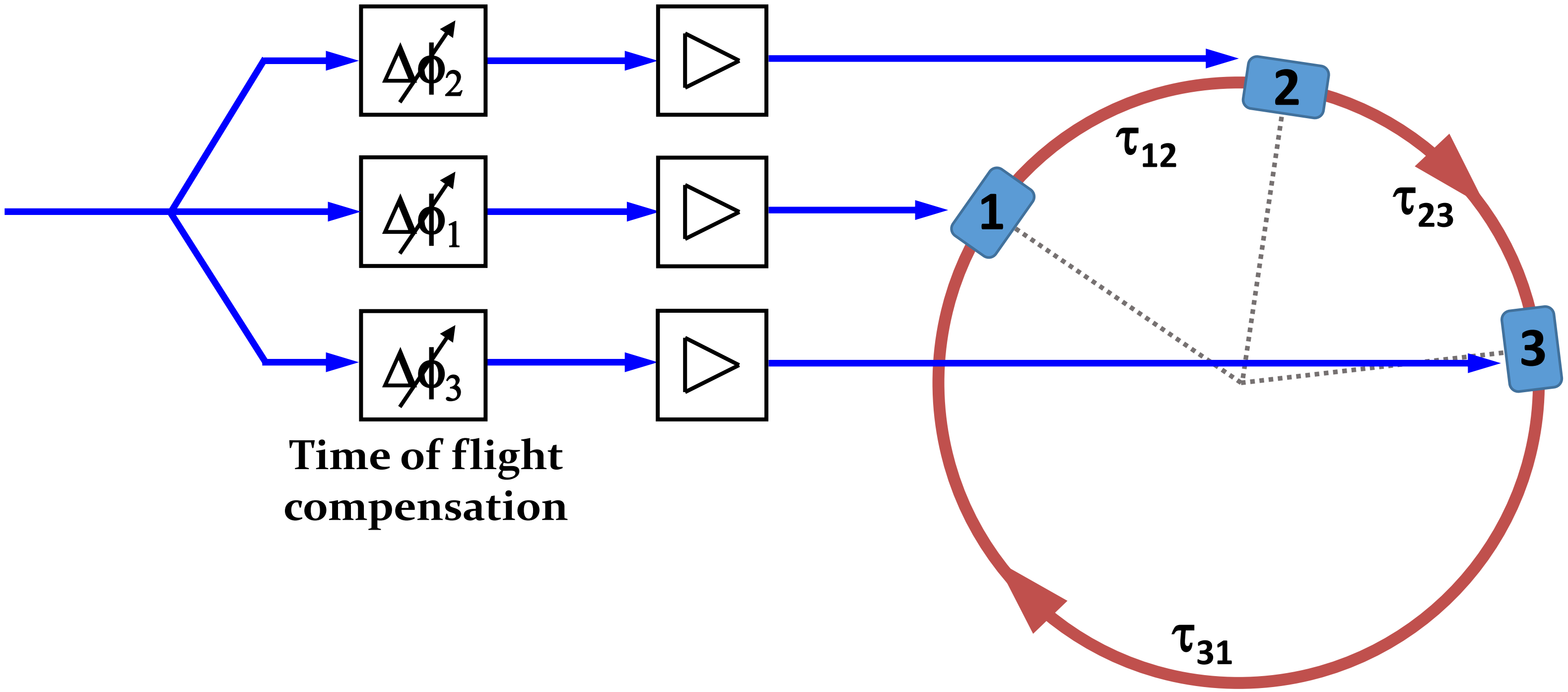
Power amplifier

Low-level RF system

Beam

# Application of global corrections

- Local **feedbacks** → **Act on individual RF stations**
- Global **feedbacks** → **Act on all RF stations simultaneously**



**Time of flight compensation**

→ **RF distribution to compensate time of flight between stations**

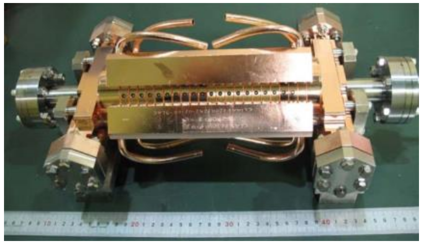
→ **All RF stations applying correction in unison**

# Frequency and wavelength ranges

PS longitudinal damper

PS main RF system

SPS 200 MHz



CLIC 12 GHz

100 kHz
3 km

1 MHz
300 m

10 MHz
30 m

100 MHz
3 m

1 GHz
30 cm

10 GHz
3 cm

100 GHz
3 mm

Long wave

Medium/
short wave

VHF

Microwave
links