Instabilities and Feedback Systems

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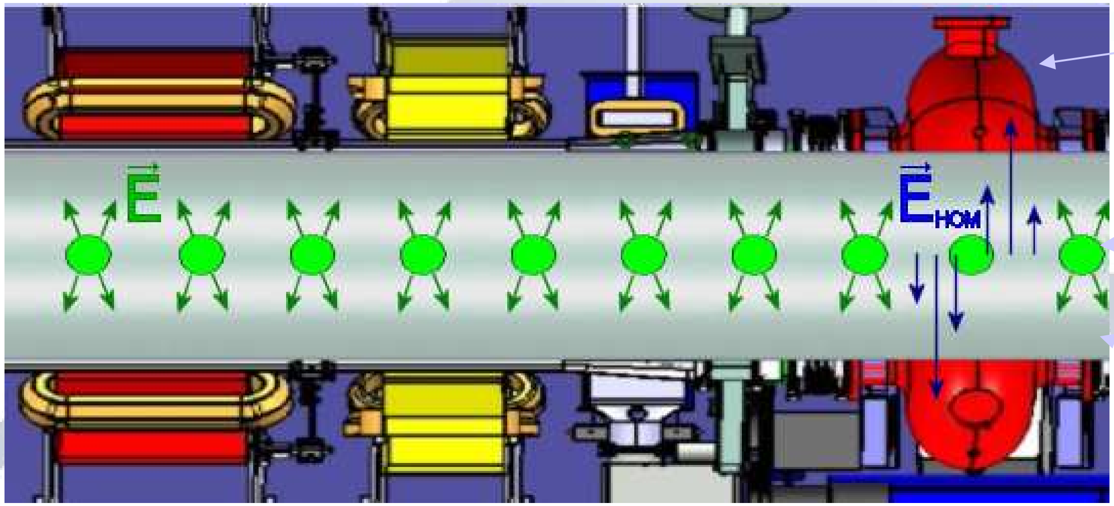
Outline

- Coupled-bunch instabilities
- Basics of feedback systems
- Feedback system components
- Integrated diagnostic tools
- Conclusions

Coupled-bunch instabilities

- Beam in a storage ring made of bunches of charged particles
- Transverse (betatron) and longitudinal (synchrotron) oscillations normally damped by natural damping
- Interaction of the electromagnetic field with metallic surroundings (“wake fileds”)
- Wake fields act back on the beam and produces growth of oscillations
- If the growth rate is stronger than the natural damping the oscillation gets unstable
- Since wake fields are proportional to the bunch charge, the onset of instabilities and their amplitude are normally current dependent



Example: interaction with an RF cavity can excite its **H**igher **O**rder **M**odes (HOM)

Bunch

“Zoomed” beam pipe

Storage ring based particle accelerators

High brightness in synchrotron light sources

High luminosity in high energy physics experiments

Storage of intense particle beams

High currents

Many bunches

The interaction of these beams with the surrounding metallic structures gives rise to collective effects called "coupled-bunch instabilities"

Large amplitude instabilities can cause beam loss

- Limitation of the stored current to low values

If the growth of instability saturates, the beam may stay in the ring

- Large instabilities degrade the beam quality: brightness or luminosity

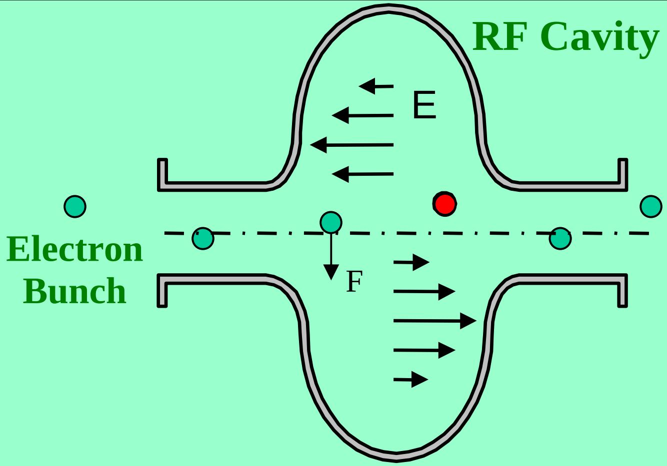
Sources of instabilities

Cavity High Order Modes (HOM)

High Q spurious resonances of the accelerating cavity excited by the bunched beam act back on the beam itself

Each bunch affects the following bunches through the wake fields excited in the cavity

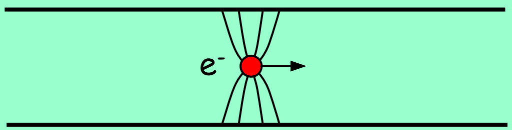
The cavity HOM can couple with a beam oscillation mode having the same frequency and give rise to instability



Resistive wall impedence

Interaction of the beam with the vacuum chamber (skin effect)

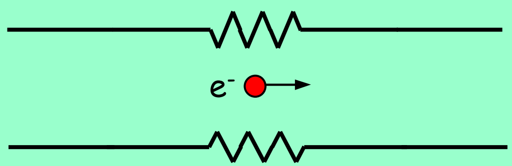
Particularly strong in low-gap chambers and in-vacuum insertion devices (undulators and wigglers)



Interaction of the beam with other objects

Discontinuities in the vacuum chamber, small cavity-like structures, ...

Ex. BPMs, vacuum pumps, bellows, ...

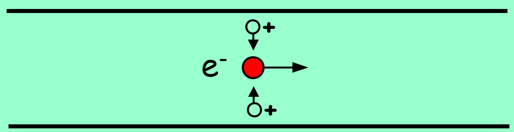


Ion instabilities

Gas molecules ionized by collision with the electron beam

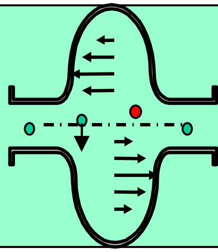
Positive ions remains trapped in the negative electric potential

Produce electron-ion coherent oscillations

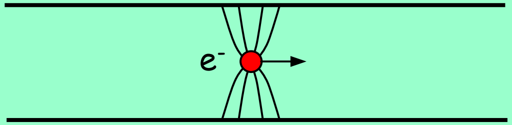


Passive cures

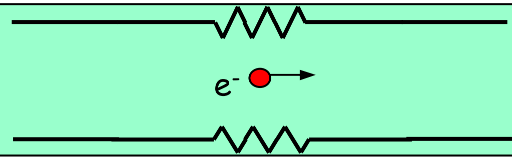
Cavity High Order Modes (HOM)
Thorough design of the RF cavity
Mode dampers with antennas and resistive loads
Tuning of HOMs frequencies through plungers or changing the cavity temperature



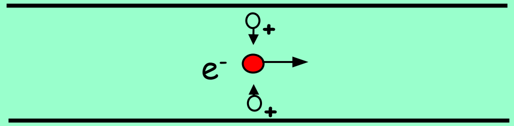
Resistive wall impedance
Usage of low resistivity materials for the vacuum pipe
Optimization of vacuum chamber geometry



Interaction of the beam with other objects
Proper design of the vacuum chamber and of the various installed objects



Ion instabilities
Ion cleaning with a gap in the bunch train



Landau damping by increasing the tune spread
- Higher harmonic RF cavity (bunch lengthening)
- Modulation of the RF
- Octupole magnets (transverse)

Active Feedbacks

Equation of motion of one particle: harmonic oscillator analogy

"x" is the oscillation coordinate (transverse or longitudinal displacement)

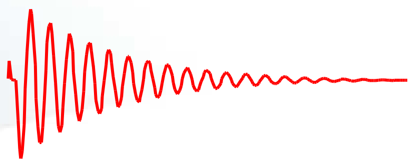
Natural damping

Betatron/Synchrotron frequency:
tune (ν) ***x revolution frequency*** (ω_0)

$$\ddot{x}(t) + 2D\,\dot{x}(t) + \omega^2 x(t) = 0$$

If $\omega \gg D$, an approximated solution of the differential equation is a damped sinusoidal oscillation:

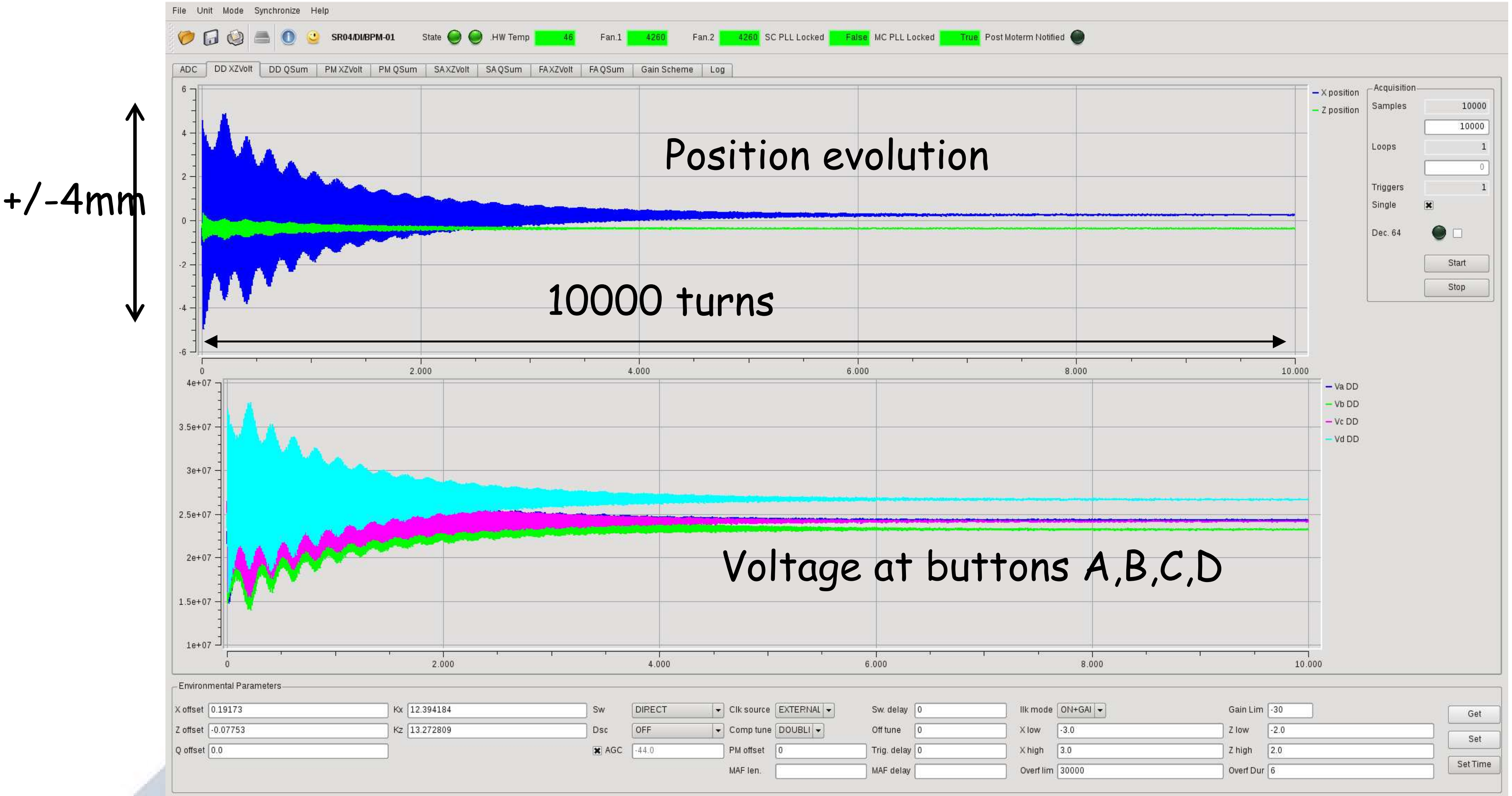
$$x(t) = e^{-\frac{t}{\tau_D}} \sin(\omega t + \varphi)$$



where $\tau_D = 1/D$ is the "damping time constant" (D is called "damping rate")

Excited oscillations (ex. by quantum excitation) are damped by natural damping (ex. due to synchrotron radiation damping). The oscillation of individual particles is uncorrelated and shows up as an emittance growth

Damping time after injection into SR



Coherent Bunch Oscillations

Coupling with other bunches through the interaction with surrounding metallic structures addd a "driving force" term *F(t)* to the equation of motion:

$$\ddot{x}(t)+2D\,\dot{x}(t)+\omega^2 x(t)=F(t)$$

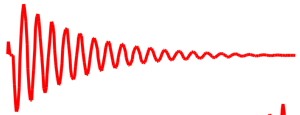
Under given conditions the oscillation of individual particles becomes correlated and the centroid of the bunch oscillates giving rise to coherent bunch (coupled bunch) oscillations

Each bunch oscillates according to the equation of motion:

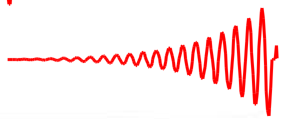
$$\ddot{x}(t)+2(D-G)\dot{x}(t)+\omega^2 x(t)=0$$

where $\tau_G = 1/G$ is the "growth time constant" (G is called "growth rate")

If $D > G$ the oscillation amplitude decays exponentially



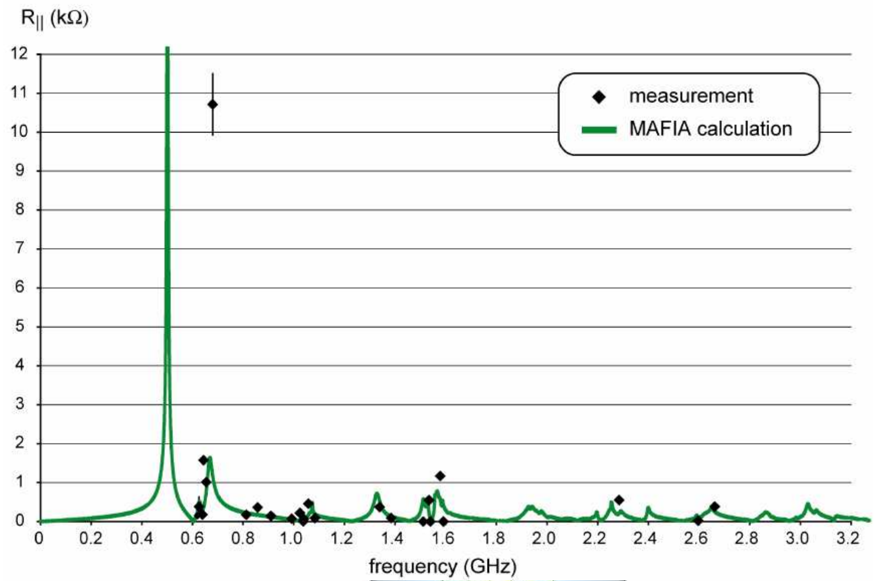
If $D < G$ the oscillation amplitude grows exponentially

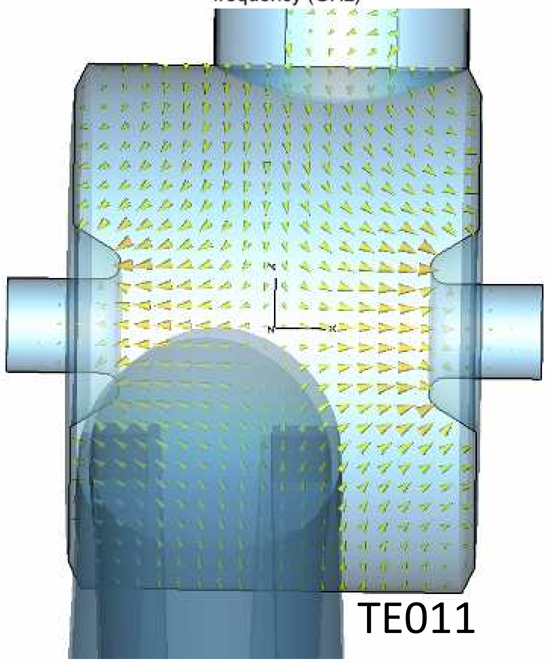


as: $x(t)=e^{-\frac{t}{\tau}}\sin(\omega t+\varphi)$ where $\frac{1}{\tau}=\frac{1}{\tau_D}-\frac{1}{\tau_G}$

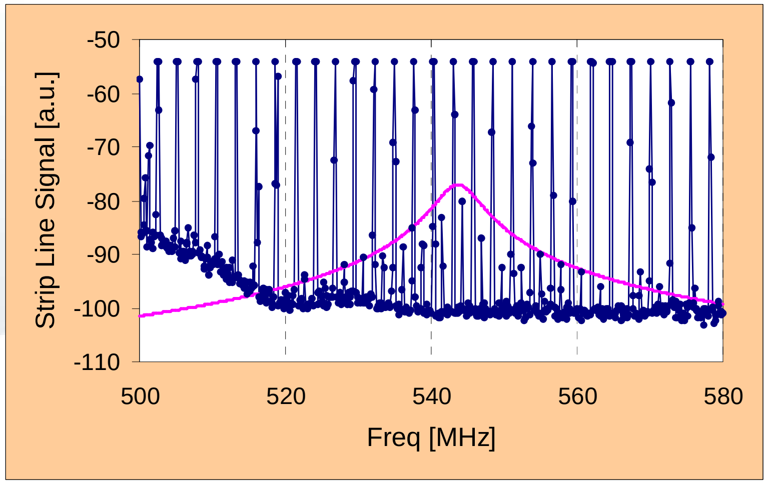
Since G is proportional to the beam current, if the latter is lower than a given current threshold the beam remains stable, if higher a coupled bunch instability is excited

HOM unstability





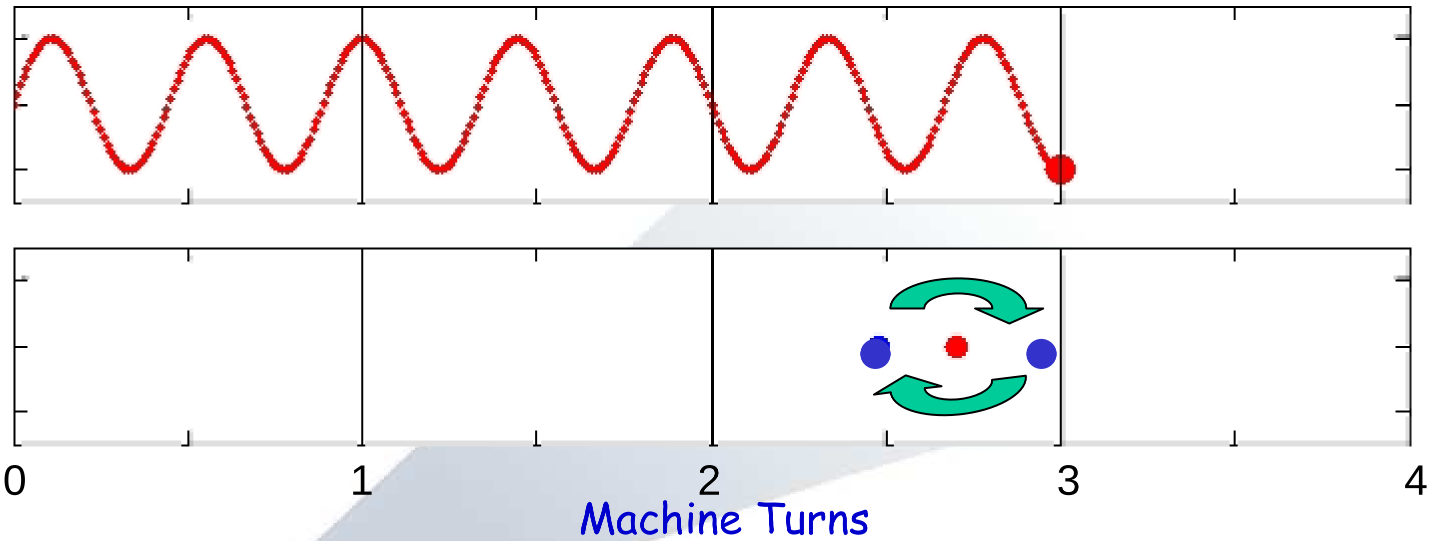
TE011



Beam is unstable around a HOM frequency

Multi-bunch modes

Typically, betatron tune frequencies (horizontal and vertical) are higher than the revolution frequency, while the synchrotron tune frequency (longitudinal) is lower than the revolution frequency



Ex.

Vertical

Tune = 2.25

Longitudinal

Tune = 0.5

Although each bunch oscillates at the tune frequency, there can be different modes of oscillation, called multi-bunch modes depending on how each bunch oscillates with respect to the other bunches

Multi-bunch modes

Let us consider M bunches equally spaced around the ring

Each multi-bunch mode is characterized by a bunch-to-bunch phase difference of:

$$\Delta\Phi = m\frac{2\pi}{M}$$

m = multi-bunch mode number (0, 1, .., M-1)

Each multi-bunch mode is associated to a characteristic set of frequencies:

$$\omega = pM\omega_0 \pm (m+\nu)\omega_0$$

Where:

p is and integer number $-\infty < p < \infty$

ω_0 is the revolution frequency

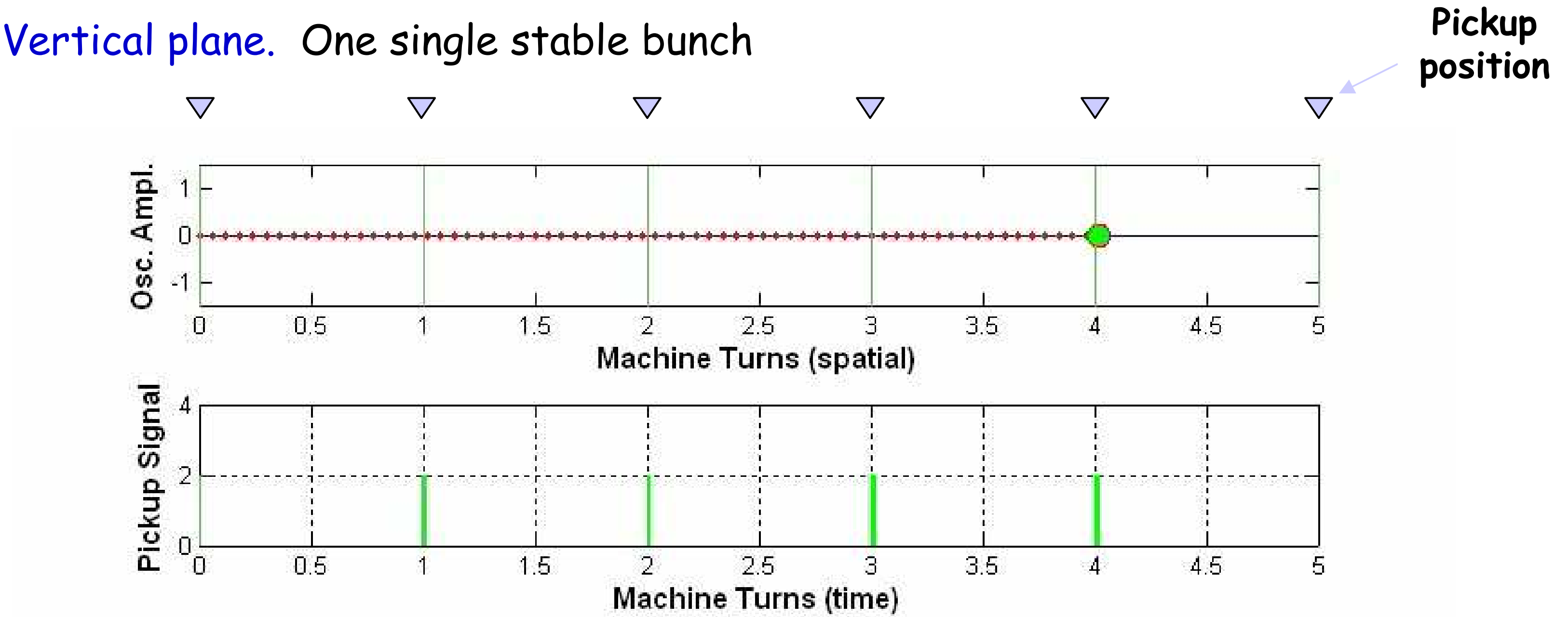
$M\omega_0 = \omega_{rf}$ is the RF frequency (bunch repetition frequency)

ν is the tune

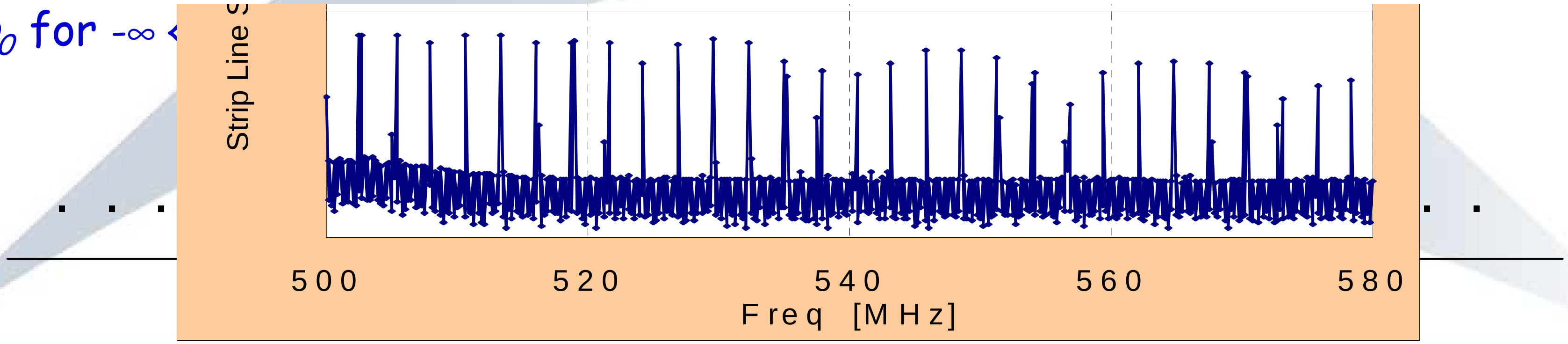
Two sidebands at $\pm(m+\nu)\omega_0$ for each multiple of the RF frequency

Multi-bunch modes: Stable

Vertical plane. One single stable bunch

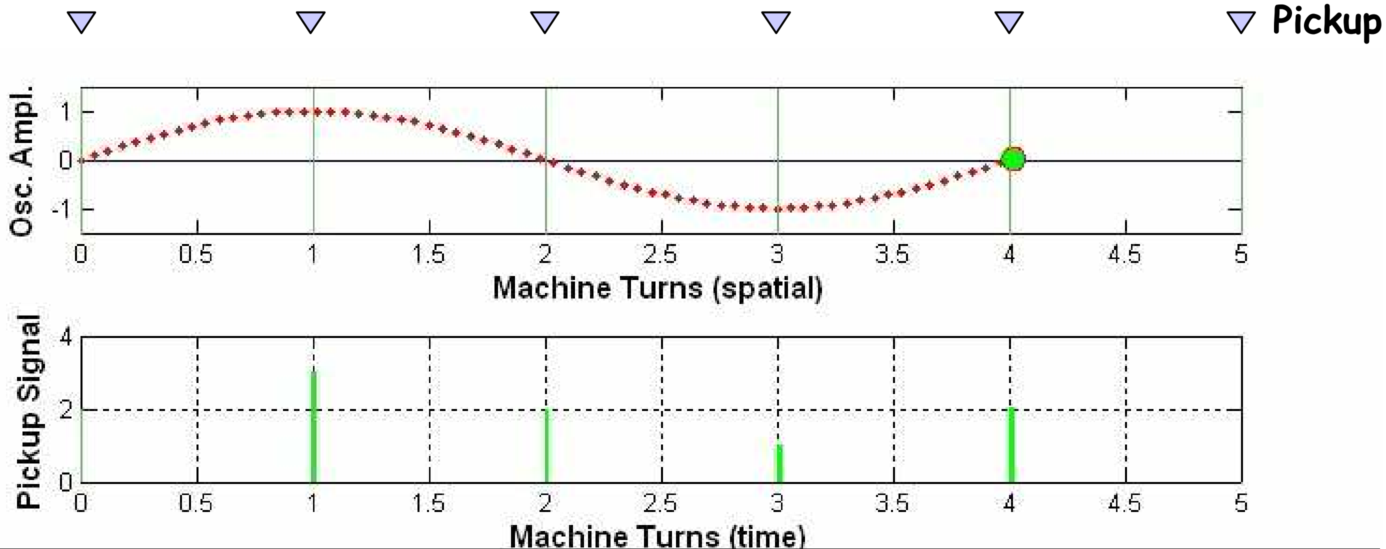


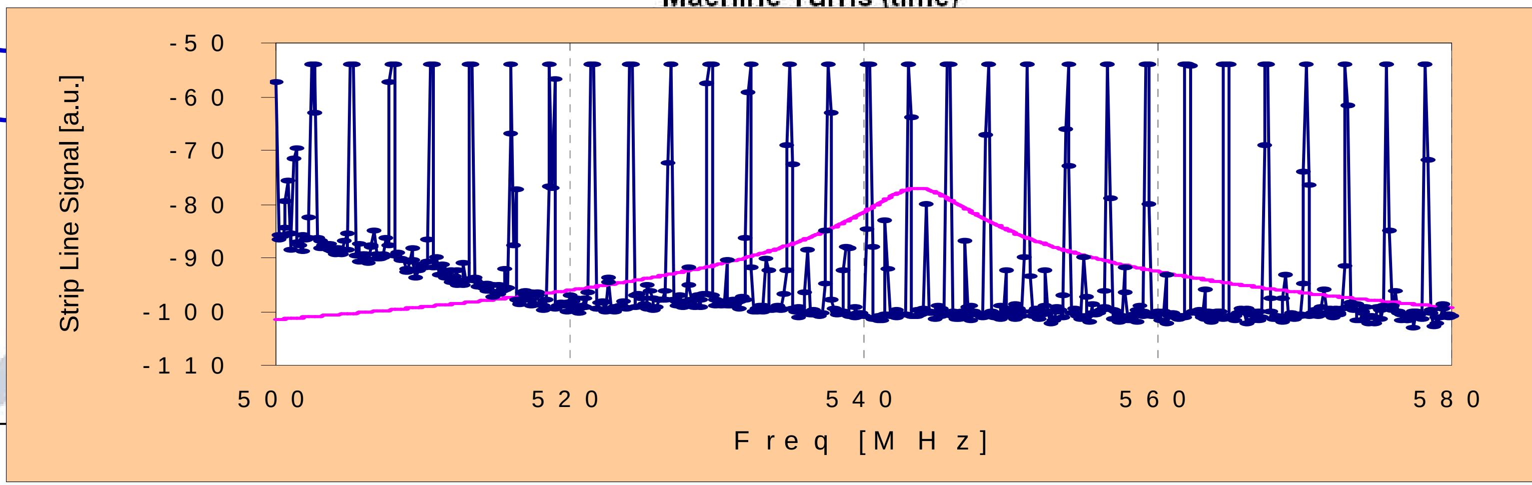
Every time the bunch passes through the pickup (▽) placed at coordinate 0, a pulse with constant amplitude is generated. If we think it as a Dirac impulse, the spectrum of the pickup signal is a repetition of frequency lines at multiple of the revolution frequency: $p\omega_0$ for $-\infty$ <



Multi-bunch modes: Instable

One single unstable bunch oscillating at the tune frequency $\nu\omega_0$: for simplicity we consider a vertical tune $\nu < 1$, ex. $\nu = 0.25$. $M = 1 \rightarrow$ only mode #0 exists



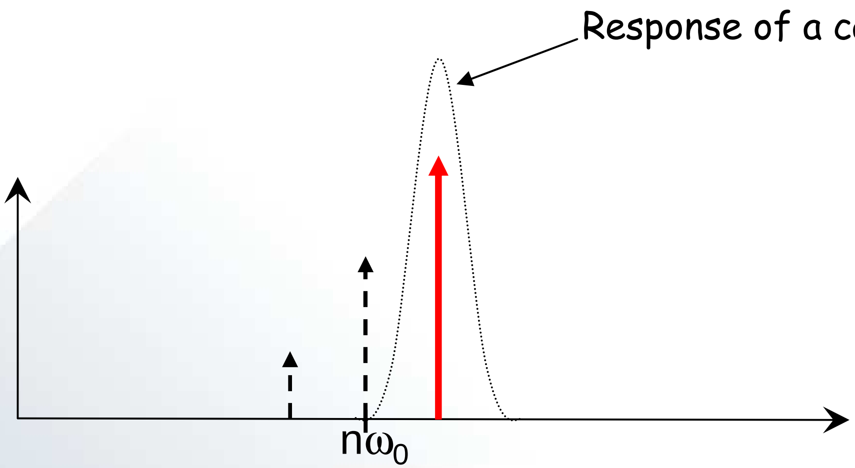


cy $\nu\omega_0$

See movies

Multi-bunch modes: coupled-bunch instability

One multi-bunch mode can become unstable if one of its sidebands overlaps, for example, with the frequency response of a cavity high order mode (HOM). The HOM couples with the sideband giving rise to a coupled-bunch instability, with consequent increase of the sideband amplitude



Synchrotron Radiation Monitor showing the transverse beam shape

Effects of coupled-bunch instabilities:

- ☹ increase of the transverse beam dimensions
- ☹ increase of the effective emittance
- ☹ beam loss and max current limitation
- ☺ increase of lifetime due to decreased Touschek scattering (dilution of particles)

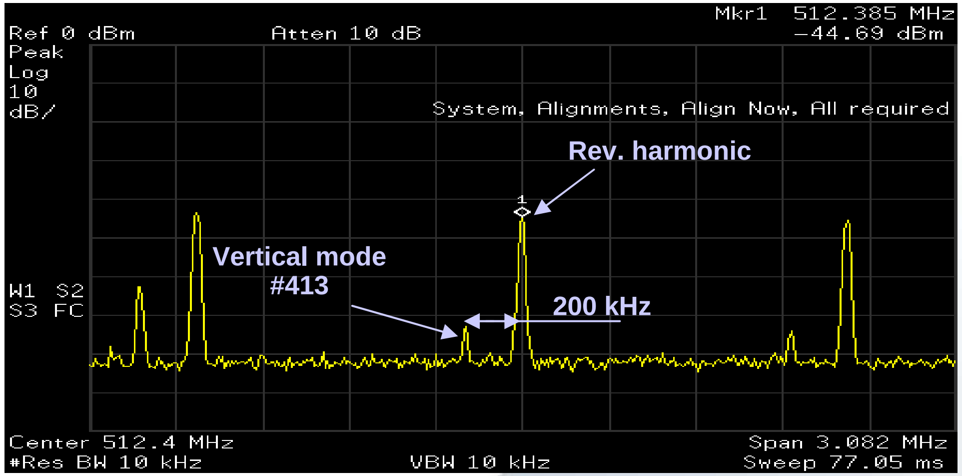
Real example of multi-bunch modes

ELETTRA Synchrotron: f_{rf}=499.654 Mhz, bunch spacing≈2ns, 432 bunches, f_0 = 1.15 MHz

ν_{hor}= 12.30(fractional tune frequency=345kHz), ν_{vert}=8.17(fractional tune frequency=200kHz)

ν_{long} = 0.0076 (8.8 kHz)

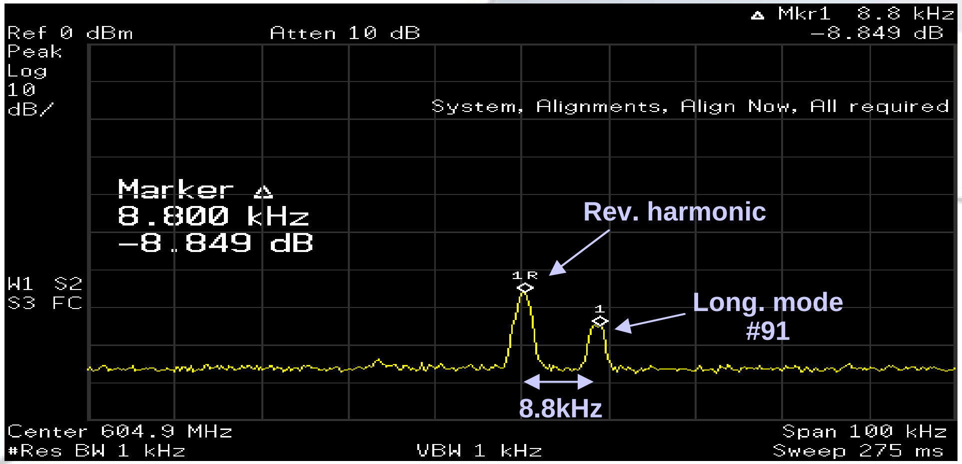
$$\omega = pM\omega_0 \pm (m+\nu)\omega_0$$



Spectral line at 512.185 MHz

Lower sideband of $2f_{rf}$, 200 kHz apart from the 443rd revolution harmonic

→ vertical mode #413



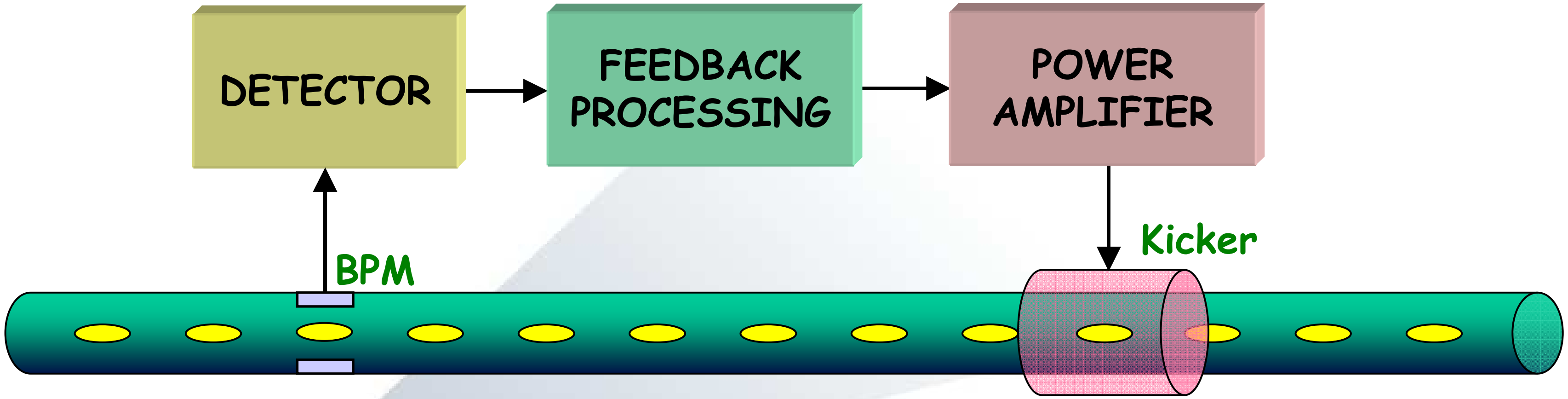
Spectral line at 604.914 MHz

Upper sideband of f_{rf}, 8.8kHz apart from the 523rd revolution harmonic

→ longitudinal mode #91

Feedback systems

A multi-bunch feedback system detects the instability using one or more Beam Position Monitors (BPM) and acts back on the beam to damp the oscillation through an electromagnetic actuator called kicker



BPM and detector measure the beam oscillations

The feedback processing unit generates the correction signal

The RF power amplifier amplifies the signal

The kicker generates the electromagnetic field

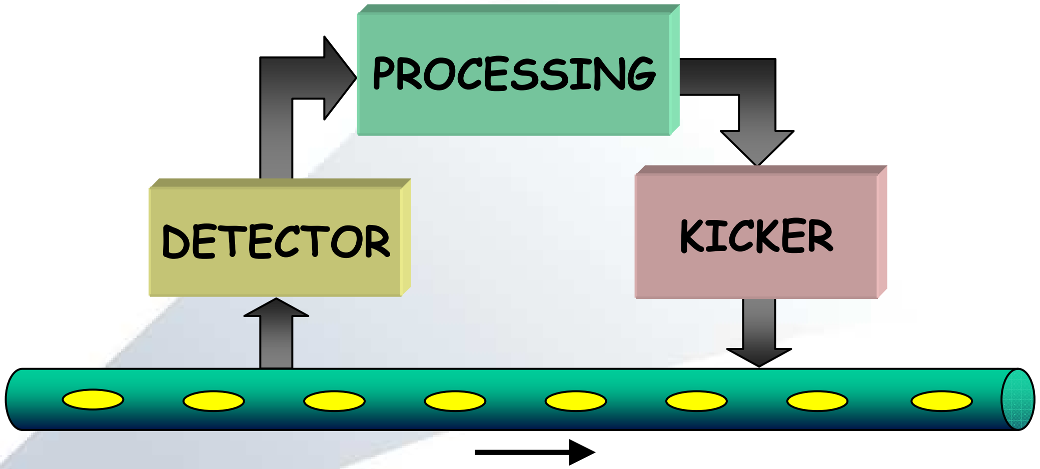
Feedback Damping Action

The feedback action adds a damping term D_{fb} to the equation of motion

$$\ddot{x}(t)+2(D-G+D_{fb})\,\dot{x}(t)+\omega^2 x(t)=0$$

Such that $D-G+D_{fb} > 0$

A multi-bunch feedback detects an instability by means of one or more Beam Position Monitors (BPM) and acts back on the beam by applying electromagnetic 'kicks' to the bunches

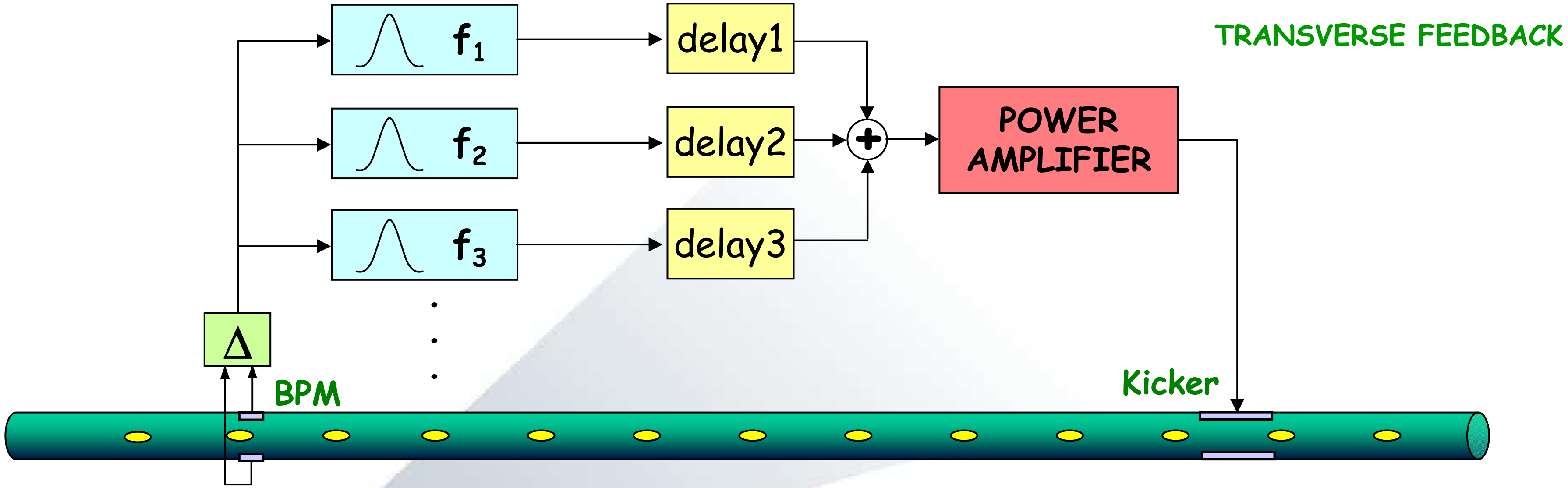


In order to introduce damping, the feedback must provide a kick proportional to the derivative of the bunch oscillation

Since the oscillation is sinusoidal, the kick signal for each bunch can be generated by shifting by $\pi/2$ the oscillation signal of the same bunch when it passes through the kicker

Mode-by-mode feedback

A mode-by-mode (frequency domain) feedback acts separately on each unstable mode



An analog electronics generates the position error signal from the BPM buttons

A number of processing channels working in parallel each dedicated to one of the controlled modes

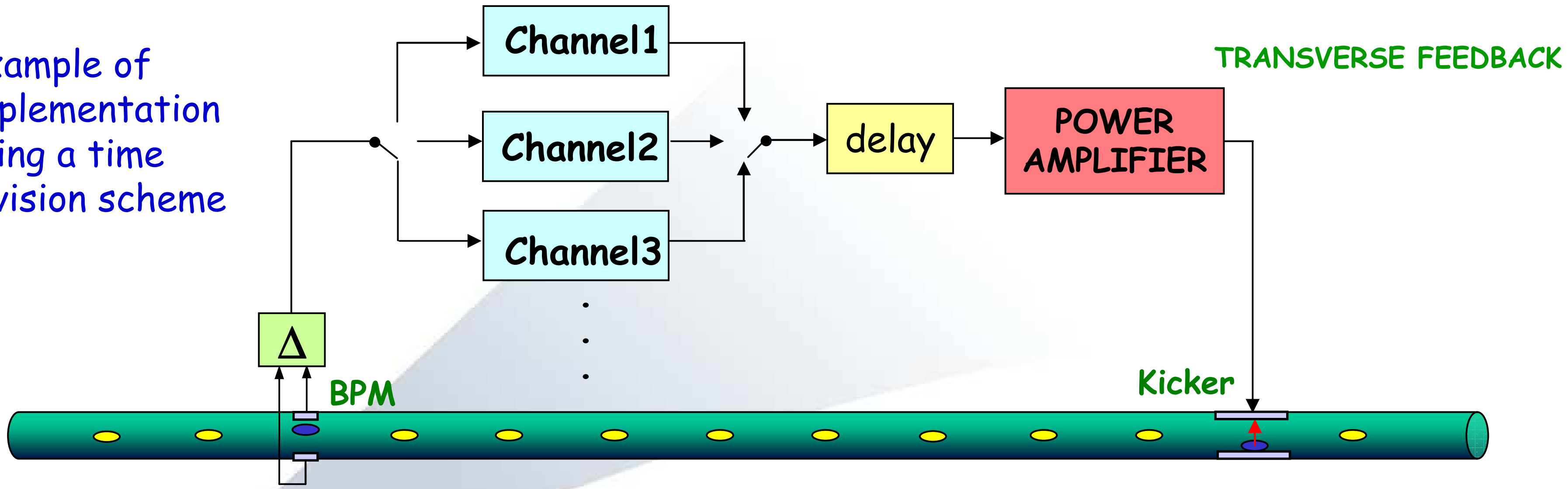
The signals are band-pass filtered, phase shifted by an adjustable delay line to produce a negative feedback and recombined

Bunch-by-bunch feedback

A bunch-by-bunch (time domain) feedback individually steers each bunch by applying small electromagnetic kicks every time the bunch passes through the kicker: the result is a damped oscillation lasting several turns

The correction signal for a given bunch is generated based on the motion of the same bunch

Example of implementation using a time division scheme

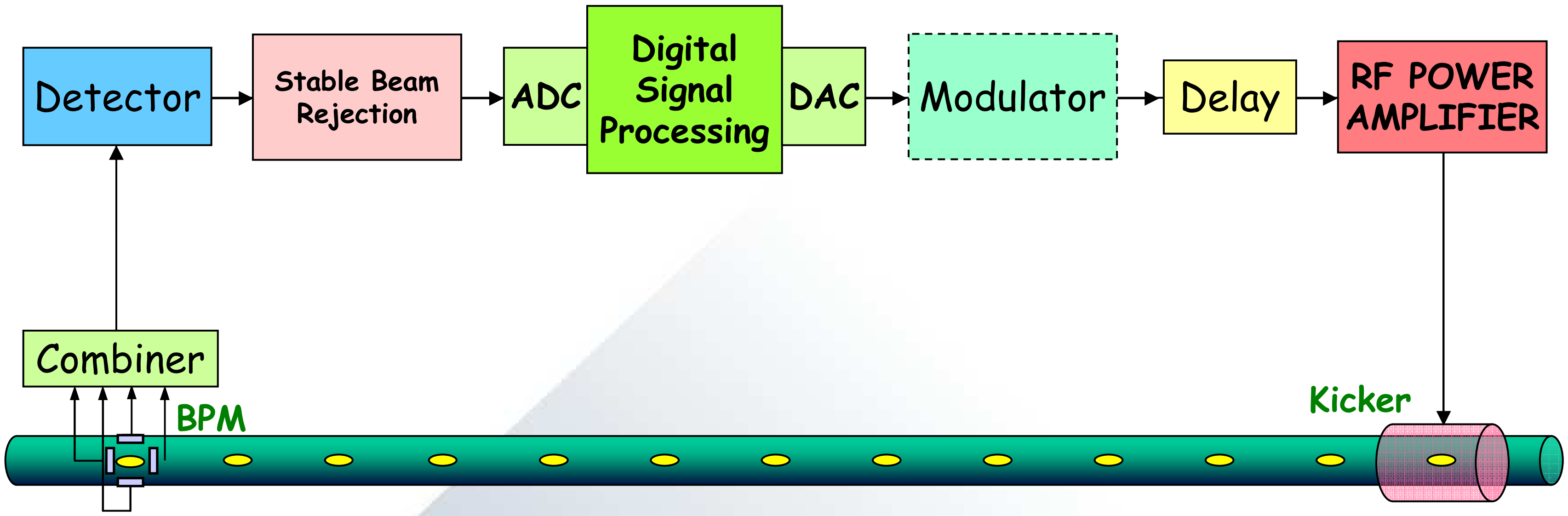


Every bunch is measured and corrected at every machine turn but, due to the delay of the feedback chain, the correction kick corresponding to a given measurement is applied to the bunch one or more turns later

Damping the oscillation of each bunch is equivalent to damping all multi-bunch modes

Digital bunch-by-bunch feedback

Transverse and longitudinal case



The combiner generates the X, Y or Σ signal from the BPM button signals

The detector (RF front-end) demodulates the position signal to base-band

"Stable beam components" are suppressed by the stable beam rejection module

The resulting signal is digitized, processed and re-converted to analog by the digital processor

The modulator translates the correction signal to the kicker working frequency (long. only)

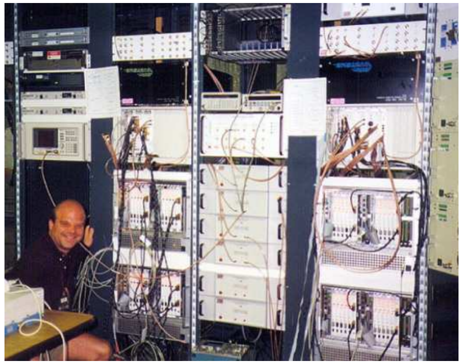
The delay line adjusts the timing of the signal to match the bunch arrival time

The RF power amplifier supplies the power to the kicker

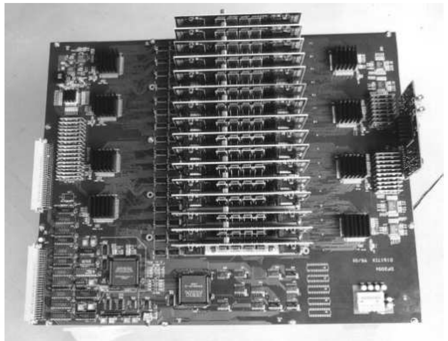
Examples of digital processors

- PETRA transverse and longitudinal feedbacks: one ADC, a digital processing electronics made of discrete components (adders, multipliers, shift registers, …) implementing a FIR filter, and a DAC

- ALS/PEP-II/DAΦNE longitudinal feedback (also adopted at SPEAR, Bessy II and PLS): A/D and D/A conversions performed by VXI boards, feedback processing made by DSP boards hosted in a number of VME crates



- PEP-II transverse feedback: the digital part, made of two ADCs, a FPGA and a DAC, features a digital delay and integrated diagnostics tools, while the rest of the signal processing is made analogically



- KEKB transverse and longitudinal feedbacks: the digital processing unit, made of discrete digital electronics and banks of memories, performs a two tap FIR filter featuring stable beam rejection, phase shift and delay

- Elettra/SLS transverse and longitudinal feedbacks: the digital processing unit is made of a VME crate equipped with one ADC, one DAC and six commercial DSP boards (Elettra only) with four microprocessors each

Examples of digital processors

- CESR transverse and longitudinal feedbacks: they employ VME digital processing boards equipped with ADC, DAC, FIFOs and PLDs

- HERA-p longitudinal feedback: it is made of a processing chain with two ADCs (for I and Q components), a FPGA and two DACs

- SPring-8 transverse feedback (also adopted at TLS, KEK Photon Factory and Soleil): fast analog de-multiplexer that distributes analog samples to a number of slower ADC FPGA channels. The correction samples are converted to analog by one DAC

- ESRF transverse/longitudinal and Diamond transverse feedbacks: commercial product 'Libera Bunch by Bunch' (by Instrumentation Technologies), which features four ADCs sampling the same analog signal opportunely delayed, one FPGA and one DAC

- HLS tranverse feedback: the digital processor consists of two ADCs, one FPGA and two DACs

- DAΦNE transverse and KEK-Photon-Factory longitudinal feedbacks: commercial product called 'iGp' (by Dimtel), featuring an ADC-FPGA-DAC chain

Amplifier and kicker

The kicker is the feedback actuator. It generates a transverse/longitudinal electromagnetic field that steers the bunches with small kicks as they pass through the kicker. The overall effect is damping of the betatron/synchrotron oscillations

The amplifier must provide the necessary RF power to the kicker by amplifying the signal from the DAC (or from the modulator in the case of longitudinal feedbacks)

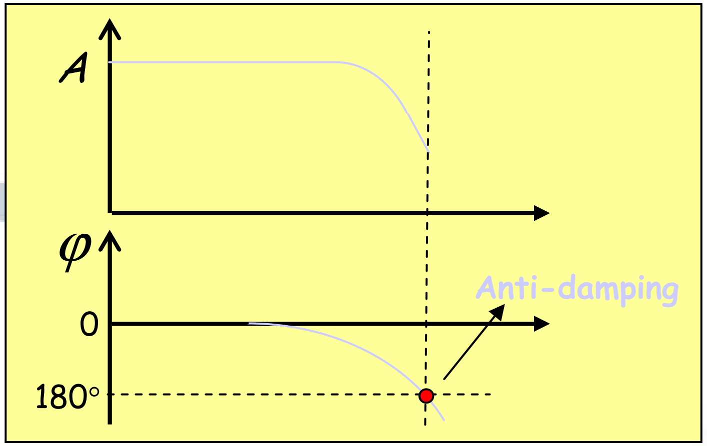
A bandwidth of at least $f_{rf}/2$ is necessary: from ~DC (all kicks of the same sign) to ~$f_{rf}/2$ (kicks of alternating signs)

The bandwidth of amplifier-kicker must be sufficient to correct each bunch with the appropriate kick without affecting the neighbour bunches. The amplifier-kicker design has to maximize the kick strength while minimizing the cross-talk between corrections given to adjacent bunches

Shunt impedance, ratio between the squared voltage seen by the bunch and twice the power at the kicker input:

$$R = \frac{V^2}{2P_{IN}}$$

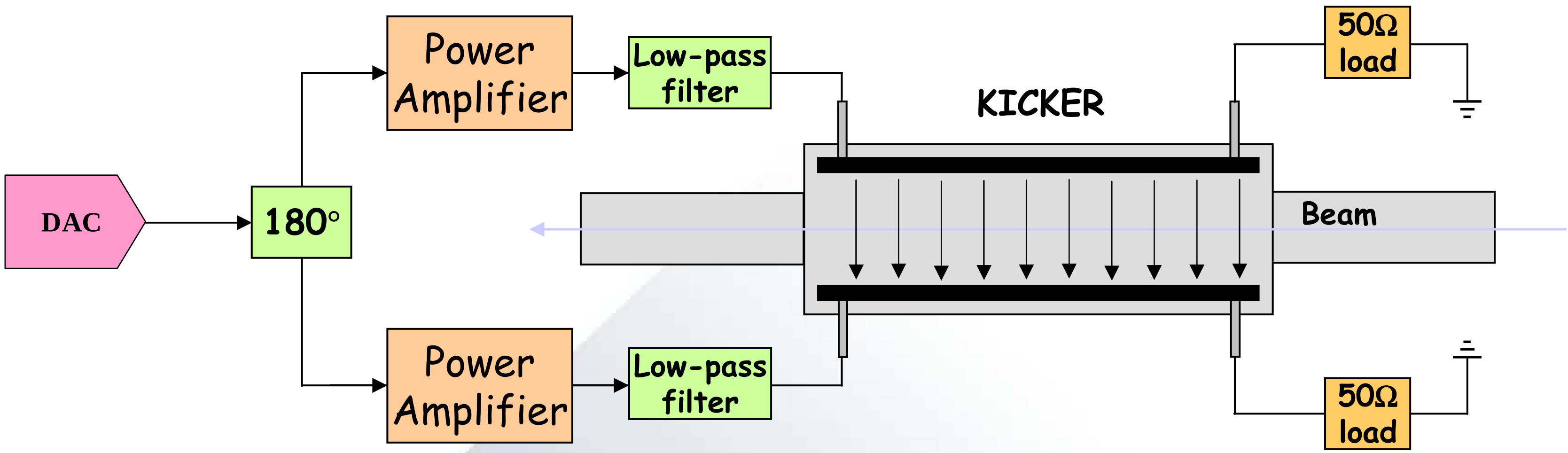
Important issue: the group delay of the amplifier must be as constant as possible, i.e. the phase response must be linear, otherwise the feedback efficiency is reduced for some modes and the feedback can even become positive

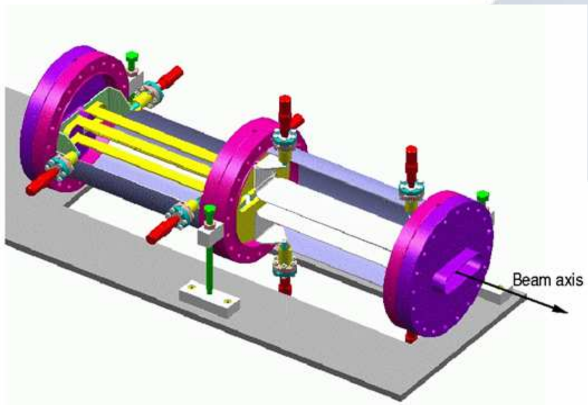


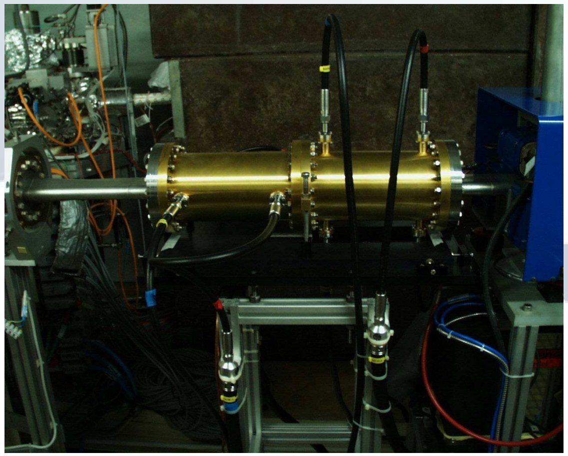
Kicker and Amplifier: transverse FB

For the transverse kicker a stripline geometry is usually employed

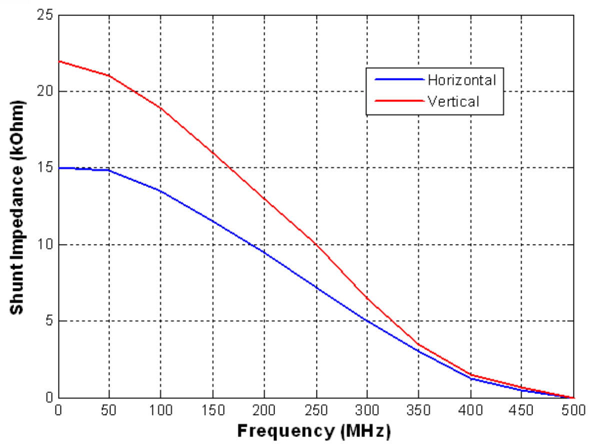
Amplifier and kicker work in the ~DC - ~$f_{rf}/2$ frequency range





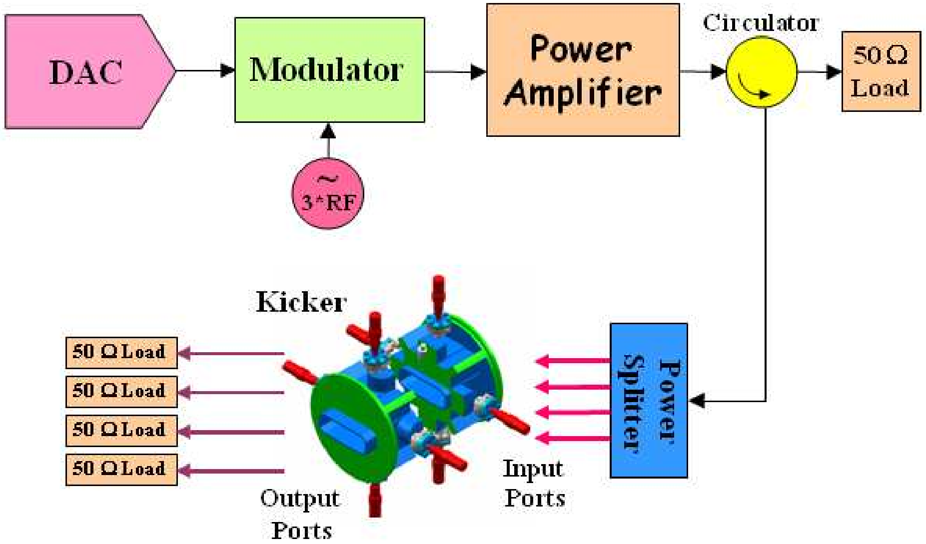


The ELETTRA/SLS transverse kicker (by Micha Dehler-PSI)



Shunt impedance of the ELETTRA/SLS transverse kickers

Kicker and Amplifier: longitudinal FB



A "cavity like" kicker is usually preferred

Higher shunt impedance and smaller size

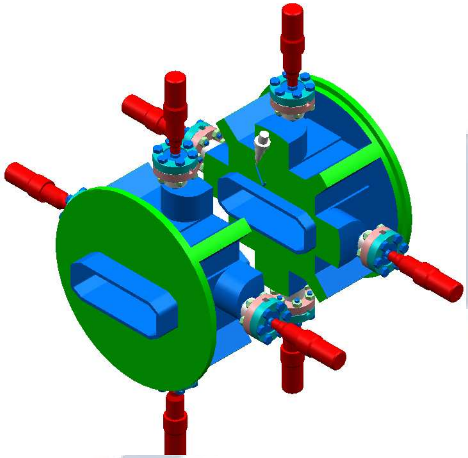
The operating frequency range is typically $f_{rf}/2$ wide and placed on one side of a multiple of f_{rf}:

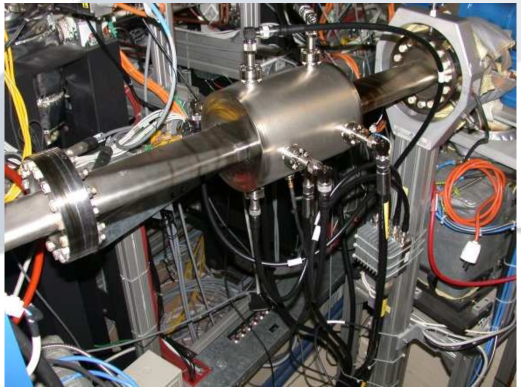
ex. from $3f_{rf}$ to $3f_{rf}+f_{rf}/2$

A "pass-band" instead of "base-band" device

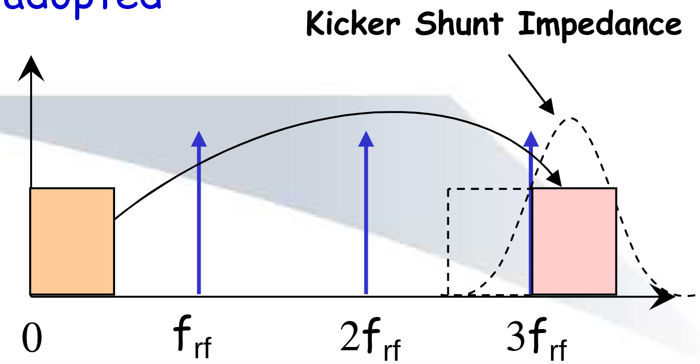
The base-band signal from the DAC must be modulated, i.e. translated in frequency

A SSB (Single Side Band) amplitude modulation or similar techniques (ex. QPSK) can be adopted





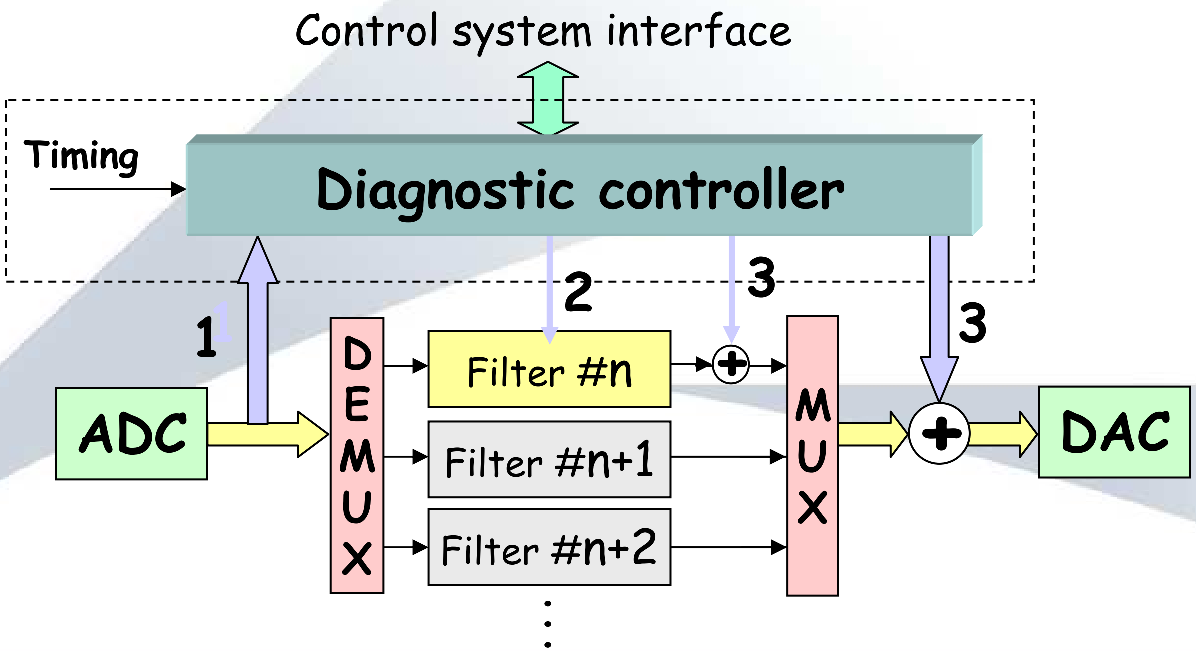
The ELETTRA/SLS longitudinal kicker (by Micha Dehler-PSI)



Integrated diagnostic tools

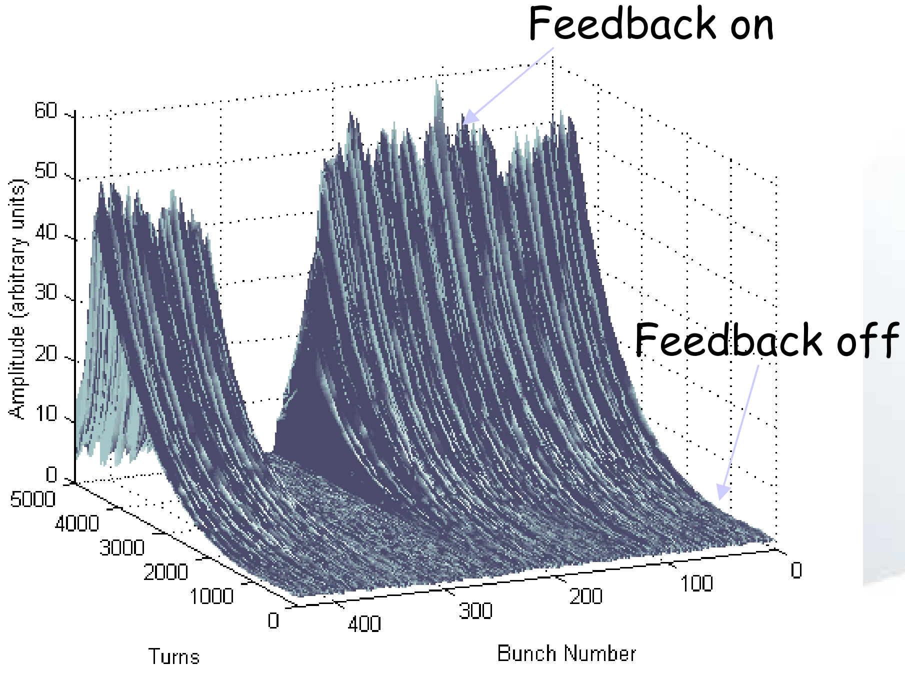
A feedback system can implement a number of diagnostic tools useful for commissioning and optimization of the feedback system as well as for machine physics studies:

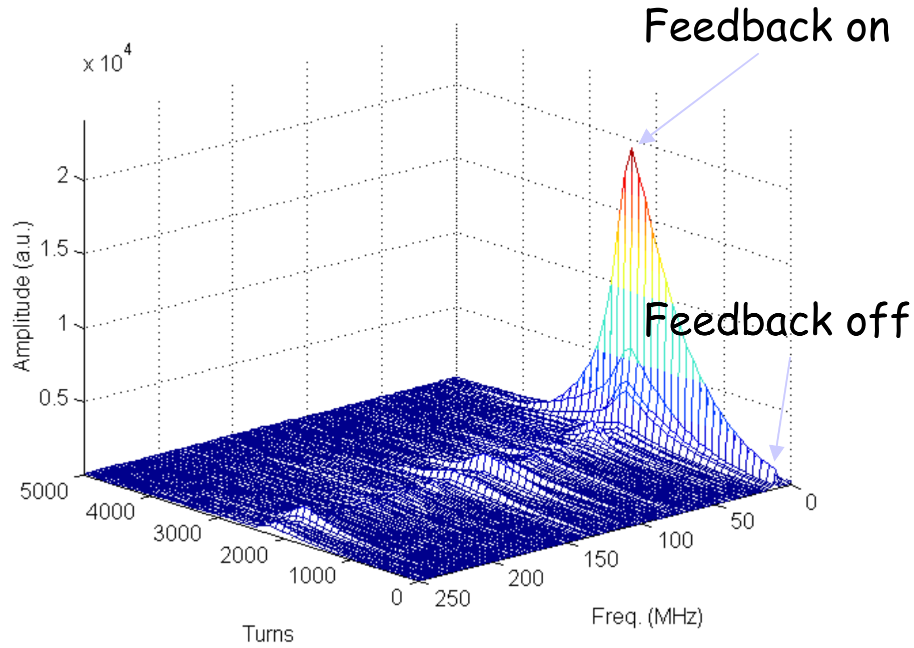
1. ADC data recording: acquisition and recording, in parallel with the feedback operation, of a large number of samples for off-line data analysis
2. Modification of filter parameters on the fly with the required timing and even individually for each bunch: switching ON/OFF the feedback, generation of grow/damp transients, optimization of feedback performance, …
3. Injection of externally generated digital samples: for the excitation of single/multi bunches



Grow/damp transients: 3-D graphs

Grow/damp transients can be analyzed by means of 3-D graphs





Evolution of the bunches oscillation amplitude during a grow-damp transient

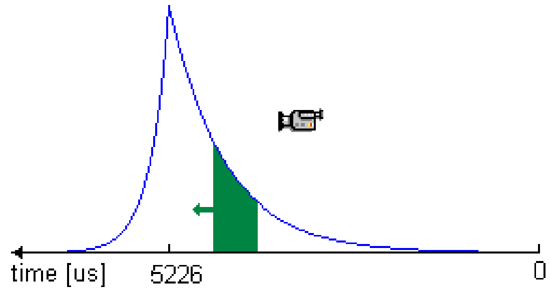
Evolution of coupled-bunch unstable modes during a grow-damp transient

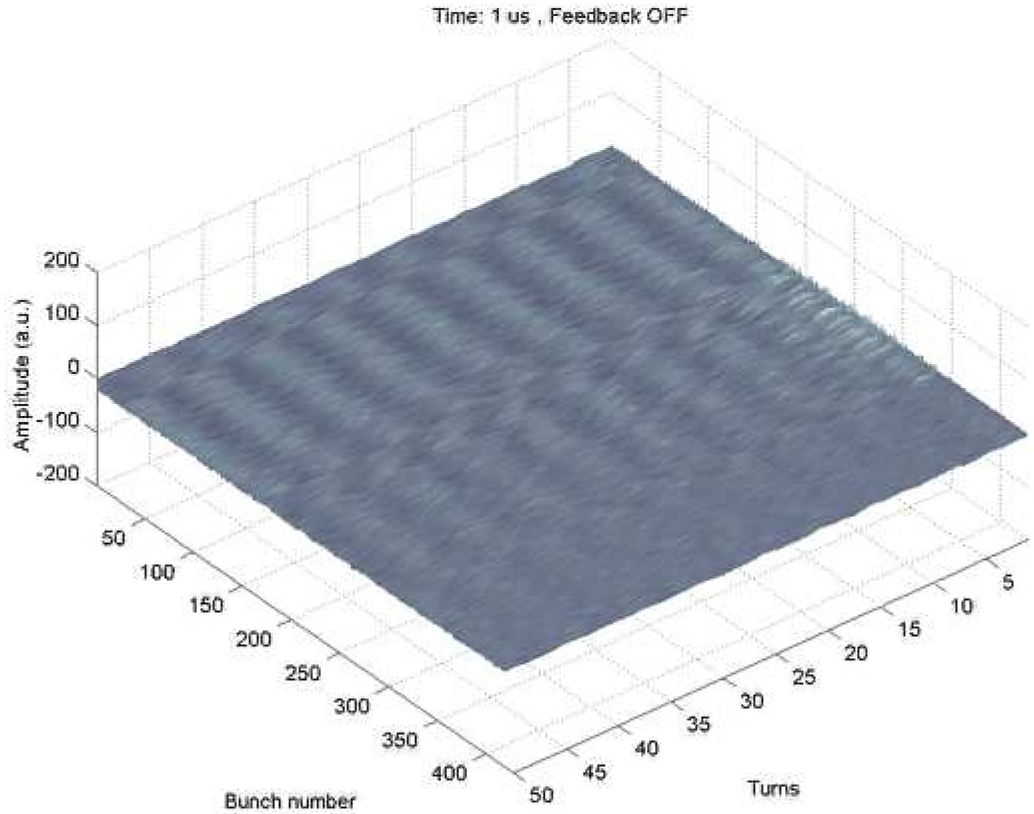
Grow/damp transients: real movie

'Movie' sequence:

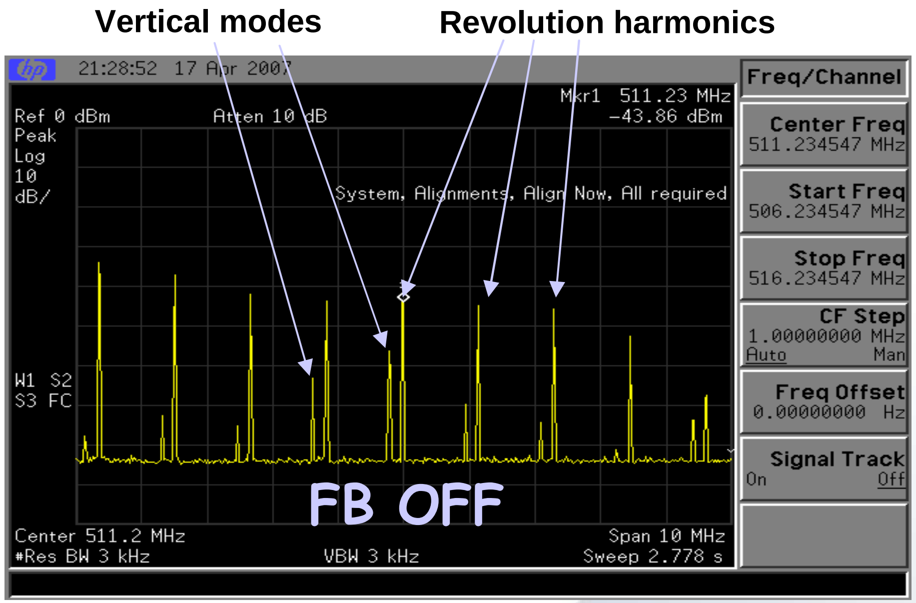
1. Feedback OFF
2. Feedback ON after 5.2 ms

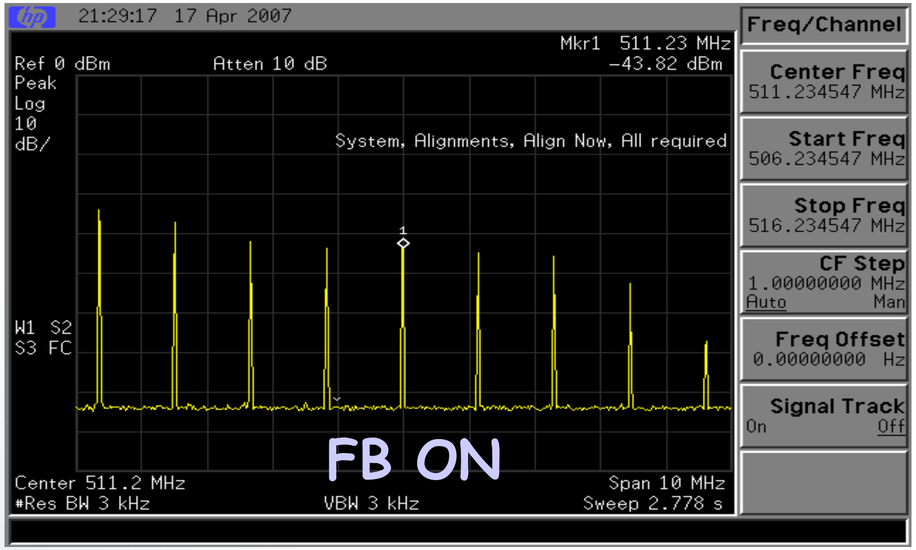
'Camera' view slice is 50 turns long (about 43 μs)

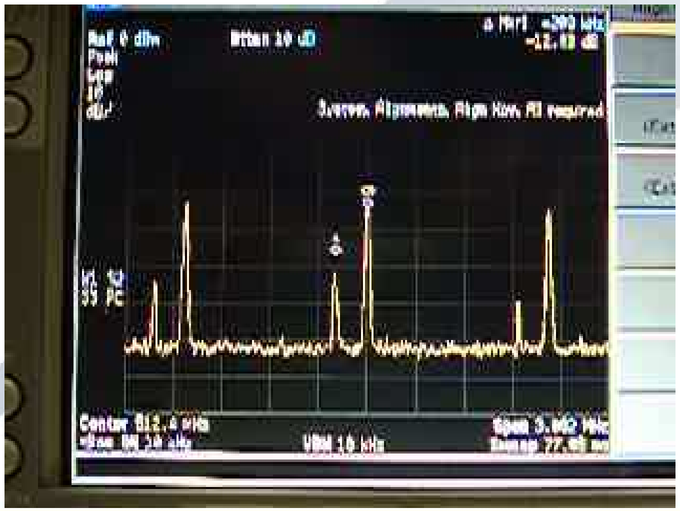




Effects of a feedback: beam spectrum







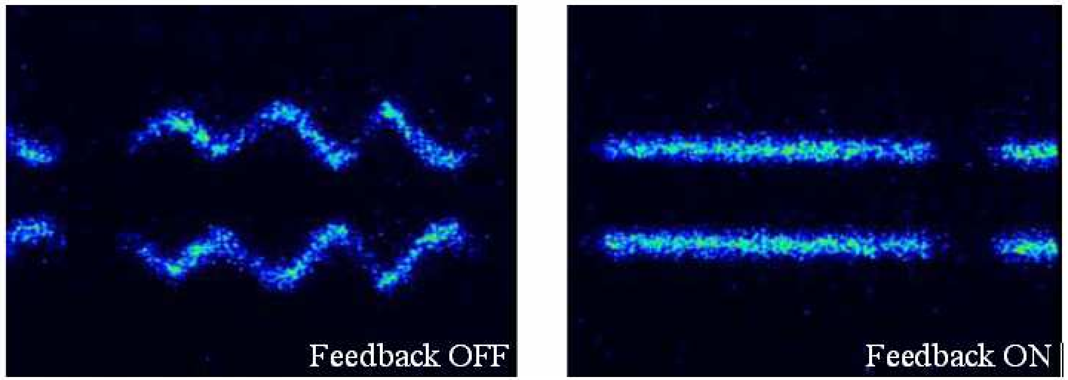
Spectrum analyzer connected to a stripline pickup: observation of vertical instabilities. The sidebands corresponding to vertical coupled-bunch modes disappear as soon as the transverse feedback is activated

Effects of a feedback: beam profiles

Transverse

Synchrotron Radiation Monitor images taken at TLS

Longitudinal

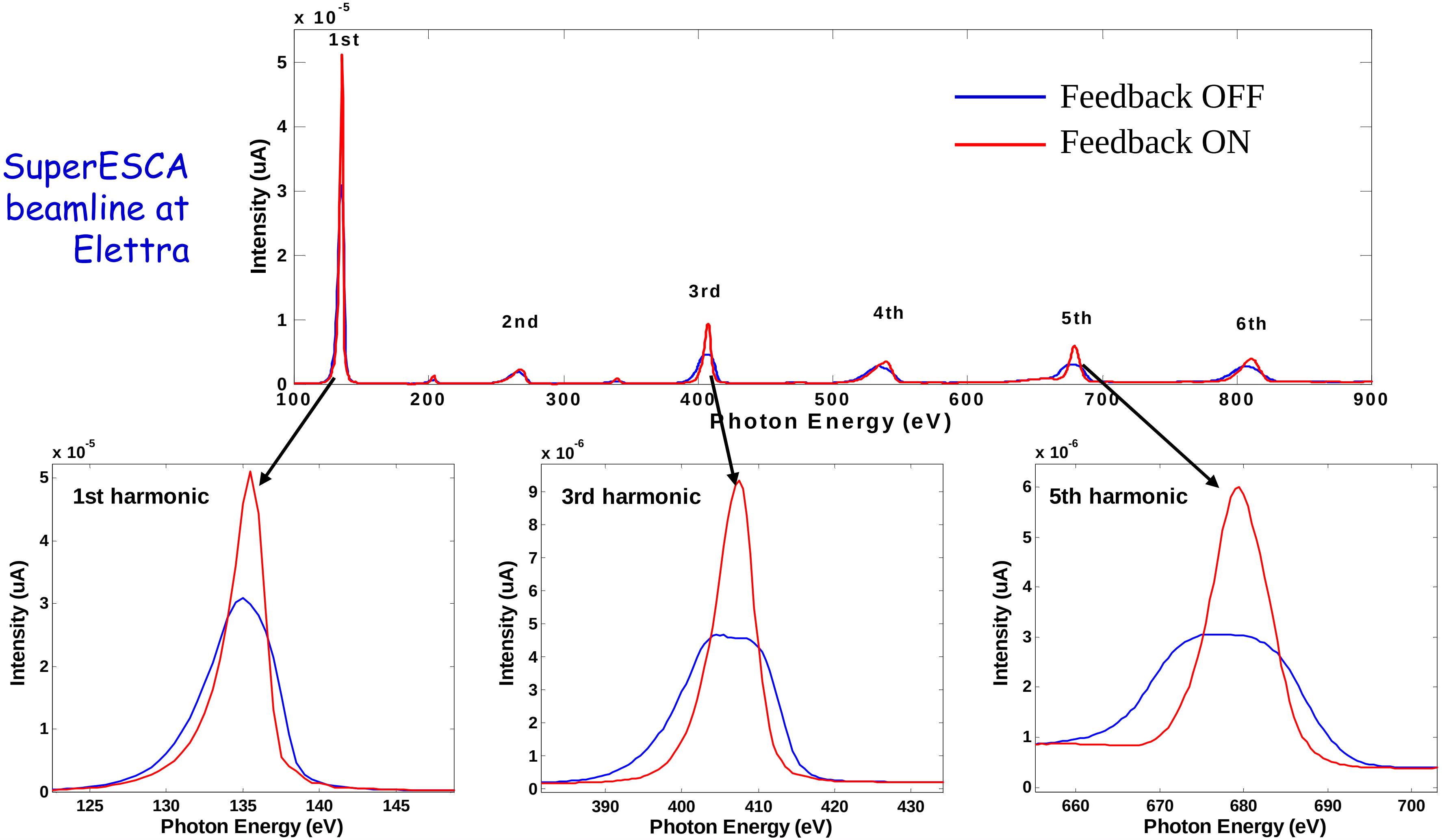


Images of one machine turn taken with a streak camera in 'dual scan mode' at TLS. The horizontal and vertical time spans are 500 and 1.4 ns respectively

Effects of a feedback: photon beam spectra

Effects on the synchrotron light: spectrum of photons produced by an undulator
The spectrum is noticeably improved when vertical instabilities are damped by the feedback

SuperESCA beamline at Elettra



Conclusions

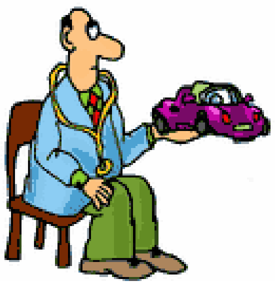
- Feedback systems are indispensable tools to cure multi-bunch instabilities in storage rings

- Technology advances in digital electronics allow implementing digital feedback systems using programmable devices

- Digital signal processing theory widely used to design and implement filters as well as to analyze data acquired by the feedback

- Feedback systems not only for closed loop control but also as powerful diagnostic tools for:
  - optimization of feedback performance
  - beam dynamics studies

- Many potentialities of digital feedback systems still to be discovered and exploited



Thank you

Questions?