Innovation Fostering in Accelerator Science and Technology

I.FAST Workshop 2022: Beam Diagnostics and Dynamics in Ultra-low Emittance Rings.

Overview of the Longitudinal bunch by bunch Feedback at DAΦNE

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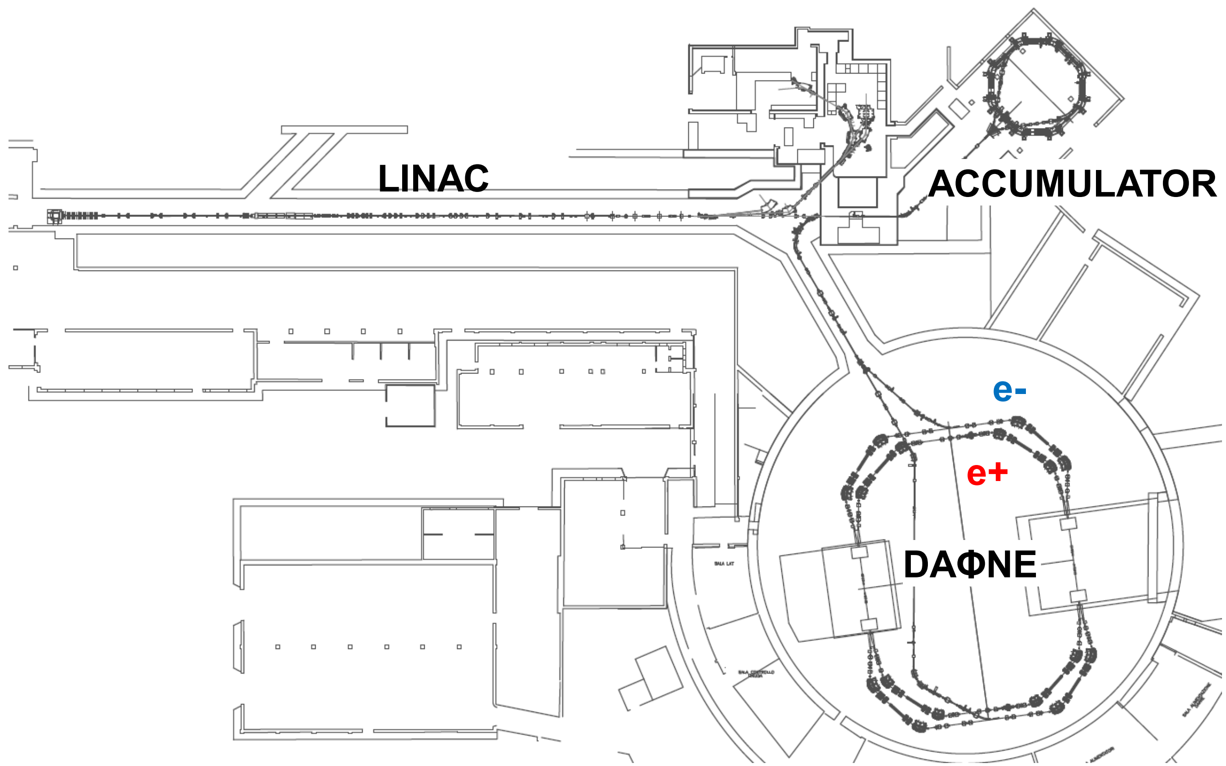
Introduction

DAΦNE is an electron-positron collider in operation at LNF for physics experiments since 1999.

- **It is composed of an injection system and two rings (~97 m)**, one per type of beam.
- It operates with (usually) **100 bunches at 510 MeV,** with a **time interval of 2.7 ns** between each other**.** Typical **stored currents** are in the range of **1 A / 2 A**.

Presently DAFNE is running for the SIDDHARTA-2 apparatus. The latter is being developed in order to perform measurements of kaonic deuterium X-ray transitions to the fundamental level.



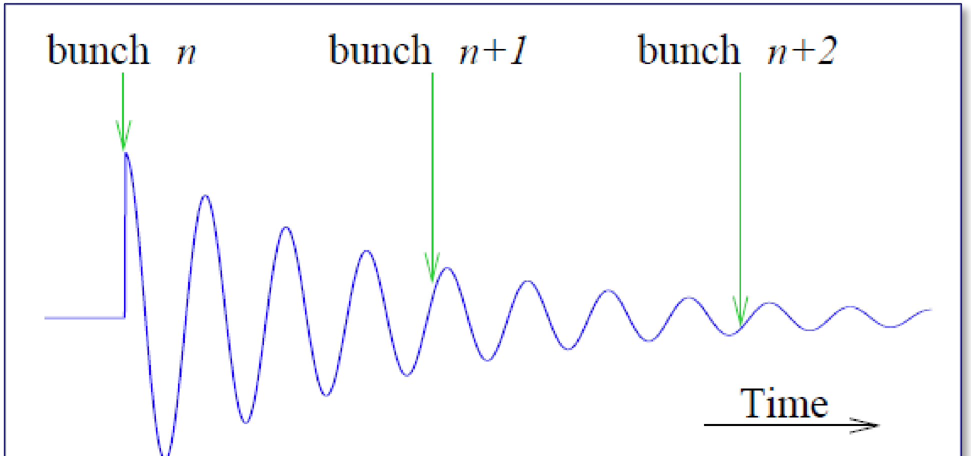
(see: DAFNE Commissioning for SIDDHARTA-2 experiment. C.Milardi et al. EPAC2021, Campinas, Brasil, 1997)

Introduction

- **Due to the high circulating beam-current and the presence of HOMs** in the RF accelerating cavity, longitudinal and transversal **coupled-bunch instabilities** can severely limit the performance of the machine.
  - These instabilities grow exponentially with time and can lead to beam loss.
  - In DAΦNE main rings the combination of high current, low energy and short bunch interval enhances these instabilities.

Origin of Coupled-bunch instabilities:

Oscillatory electric fields (wakefields) excited (mostly) in the RF cavity by the bunches, which interfere with the bunches arriving in the structure afterwards.



courtesy of D.Teytelman

Feedback Overview

- There are a total of **six <u>independent</u> feedback systems**.
  - Two for the longitudinal phase (e+ and e-),
  - two for the vertical position (e+ and e-),
  - two for the horizontal position (e+ and e-).

- The feedback systems act on a **<u>bunch by bunch</u>** basis and in **<u>real-time</u>**. They adjusts the phase (longitudinal feedback), the horizontal and vertical position (transverse feedbacks) **<u>independently</u> for each bunch** (spaced by 2.7 ns).

- In order to do so, at the passage of the n^{th} bunch, each system read the relevant property of it (phase, vertical and horizontal position), elaborates a proper correction signal and applies it to that specific bunch (after few turns).

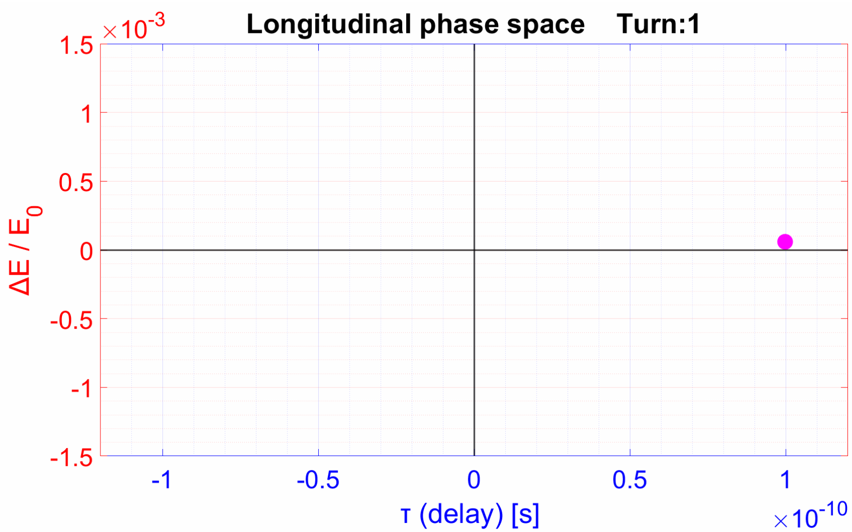
The general architecture for longitudinal and transversal feedback systems is similar.

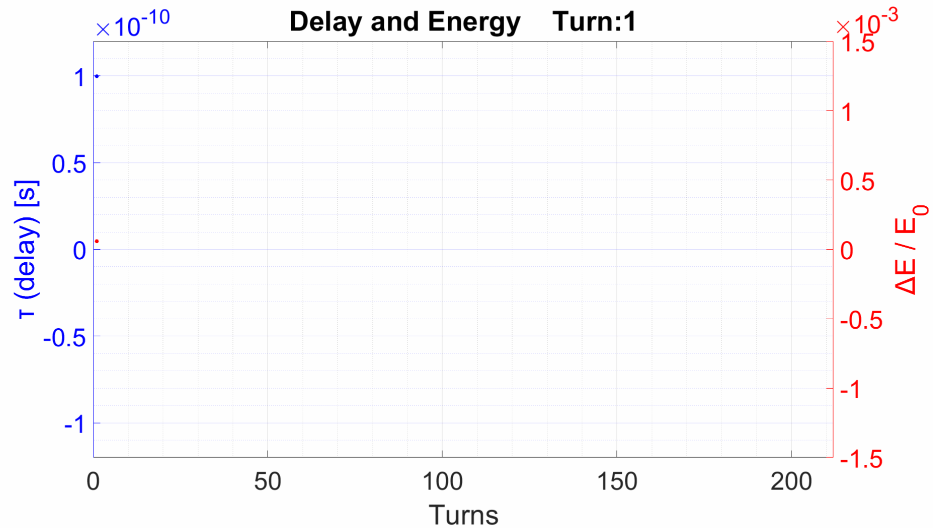
For this presentation, we will focus on the longitudinal feedbacks.

Longitudinal oscillations

Simple case:

- One bunch (considered as a single macro particle) circulating at relativistic speed in a storage ring.
- Absence of any kind of perturbation.
- No feedback.
- Only small energy oscillations.





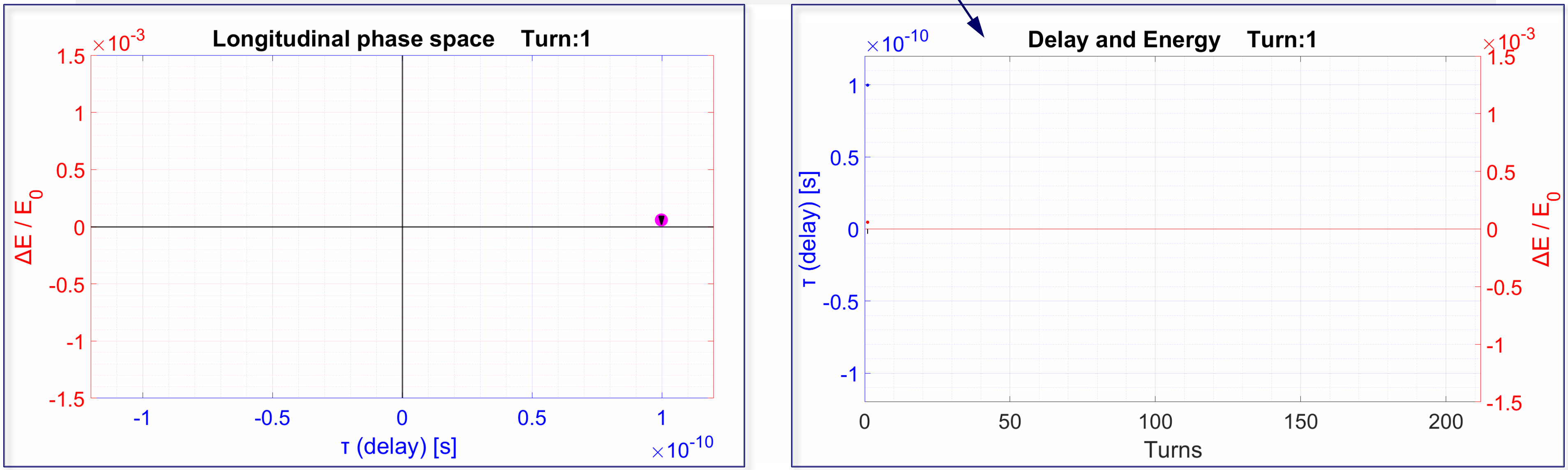
Feedback action

The action of the feedback consists in **individual longitudinal kicks** to each bunch and for each turn (excluding decimation tecniques).

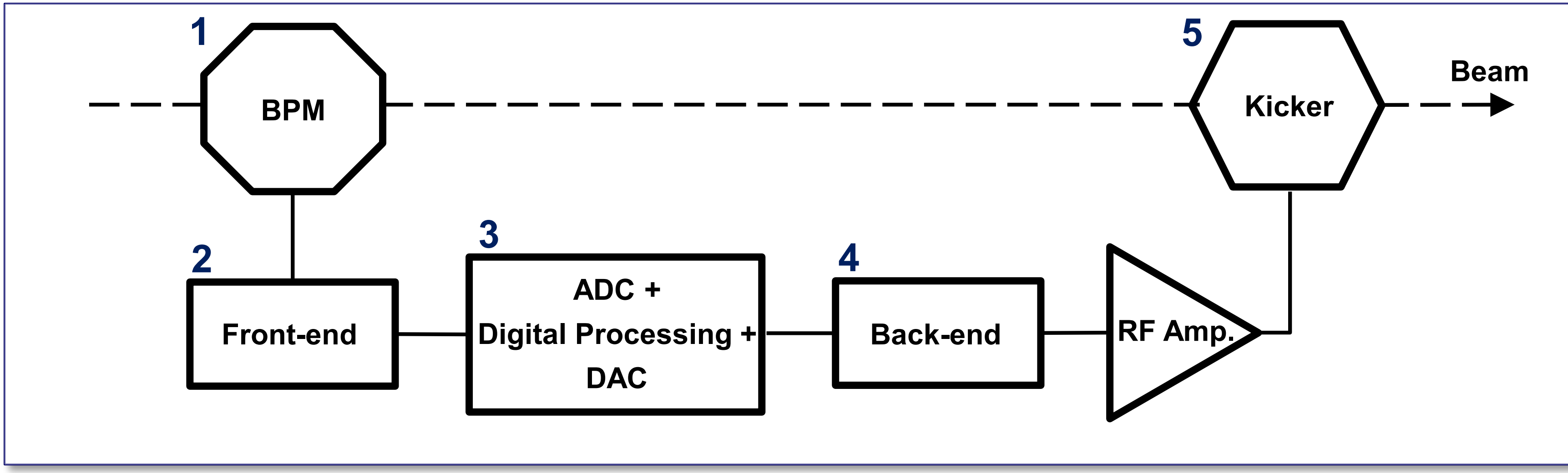
Each turn and for each bunch:

- Delay (phase) is measured.
- Correction signal (longitudinal kick) is elaborated.
- Longitudinal kick is applied.

Since we are measuring the delay **τ** (phase φ), but we are going to modify the energy of the bunches, **the correction signal is simply calculated as the measured delay τ (phase φ), shifted by π/2** (in respect of the synchrotron oscillation frequency). Thus, we obtain and apply (after few turns) a **correction signal**, which **is in anti-phase with the energy oscillations**. This will damp the bunch oscillations.



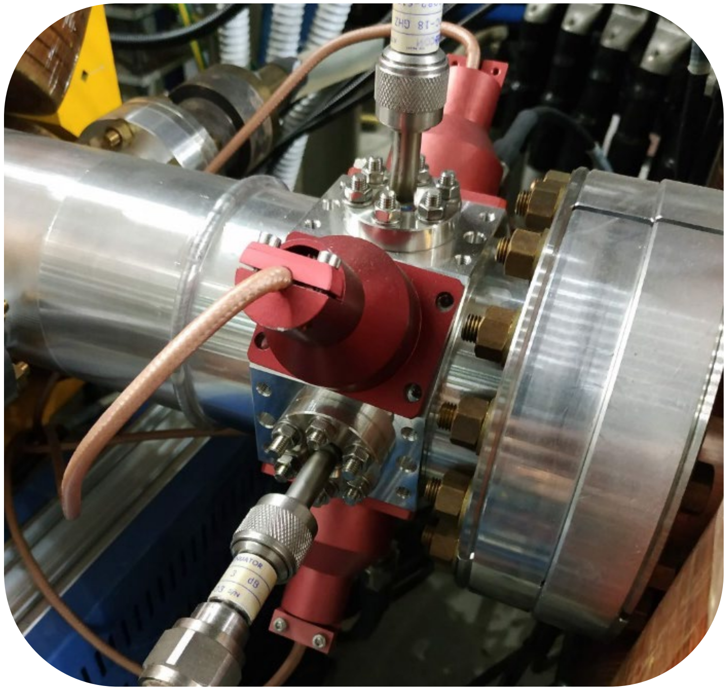
Longitudinal Feedback

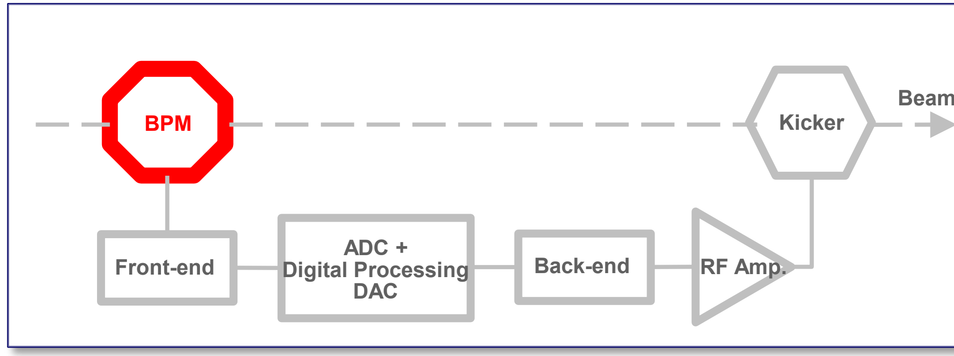


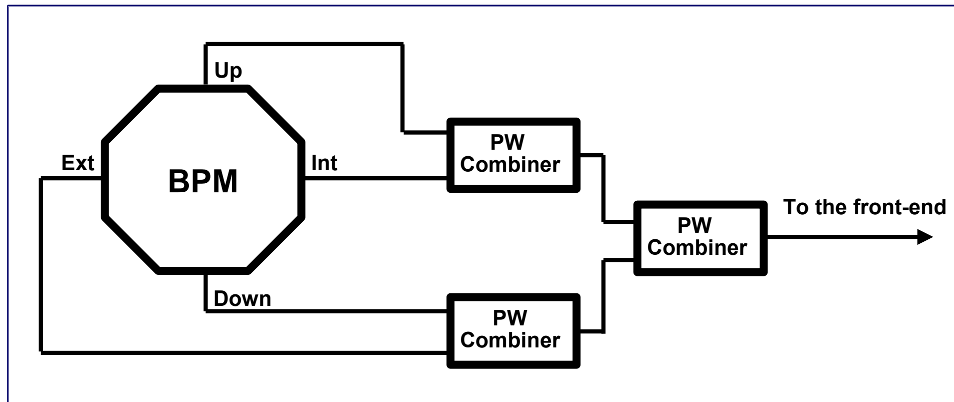
The longitudinal feedback acts on the phase of the bunches. It applies a correction signal in the form of a longitudinal kick (by means of a RF cavity).

1. The four signals (up, down, left, right) of one **BPM** are summed together and sent to the front-end electronics.
2. The **front-end** electronics “transform” the SUM signal in order to get a signal which is proportional to the phase (delay) of the bunch.
3. The latter is then **digitized** and the correction signal is **digitally elaborated** and **converted to analog** (DAC).
4. The **back-end** electronics “produce” the excitation signal for the kicker, based on the DAC output.
5. The signal **(amplified by RF amp.)** is then supplied to the **kicker**. The latter modifies the bunch energy (by means of a longitudinal kick) with the aim of restoring the bunch synchronous phase.

Broad-band Button BPM





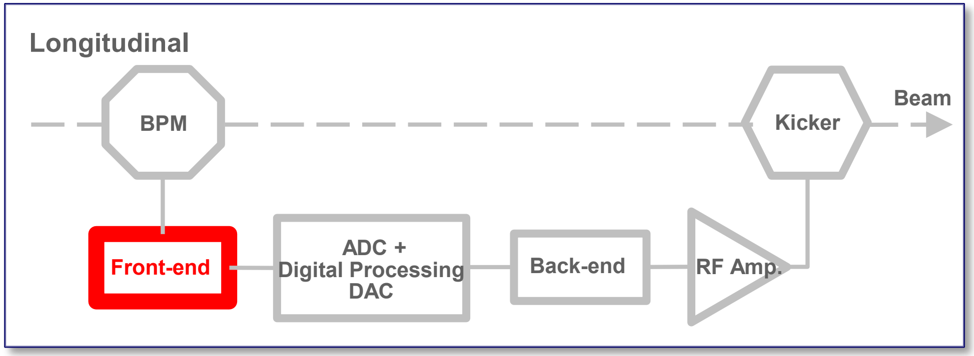


The BPM used in the feedback are specifically designed for it:

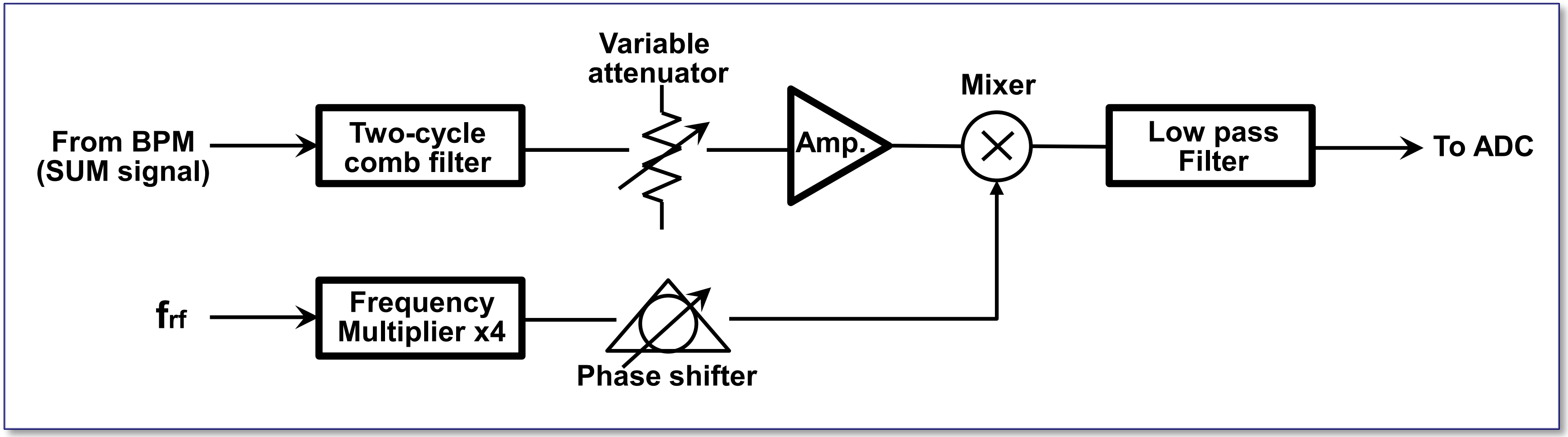
- **Transfer Impedance is ~0.5 Ω** (higher than the ordinary BPM in the same section) and sufficiently flat at the working frequencies.
- Negligible effects on the beam.

(see: DAFNE broad-band button electrodes. F.Marcellini, M.Serio, A.Stella, M.Zobov. Nuclear Instruments & Methods in Physics Research, 1997)

DIMTEL FBE 368L (Front-end)

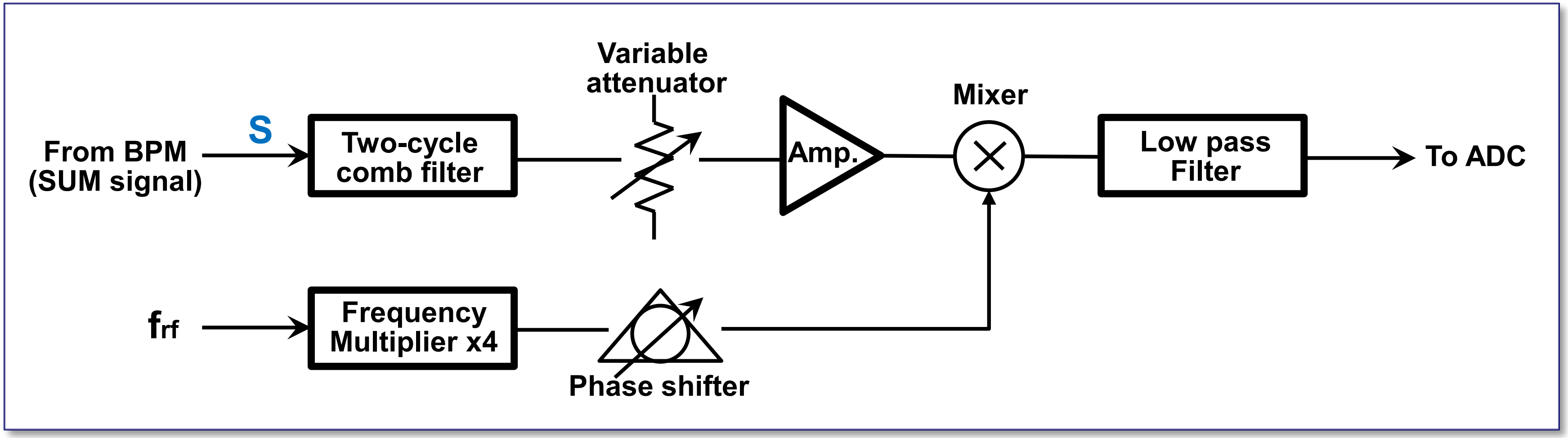


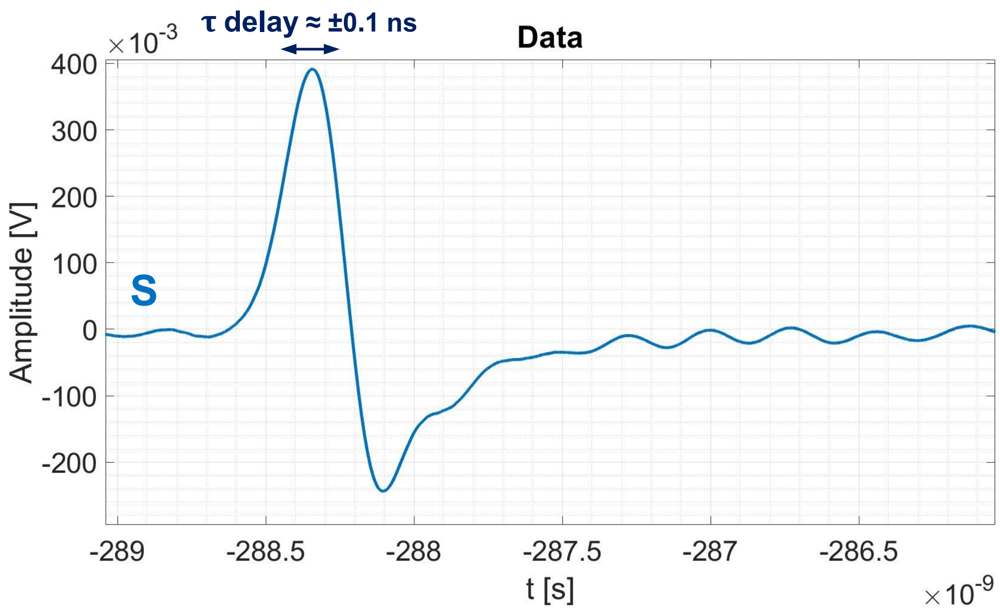
The Front-end main functionality is to transform the phase of the BPM signals into an amplitude signal (to be digitized later on).



Variable attenuator and phase shifters values are controllable via software.

DIMTEL FBE 368L (Front-end)





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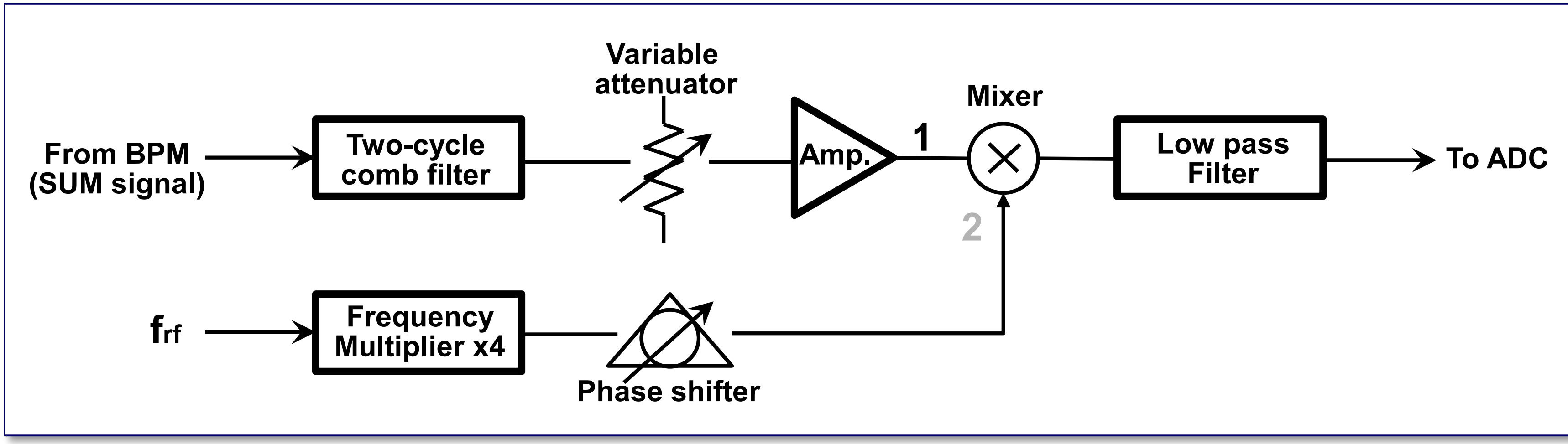

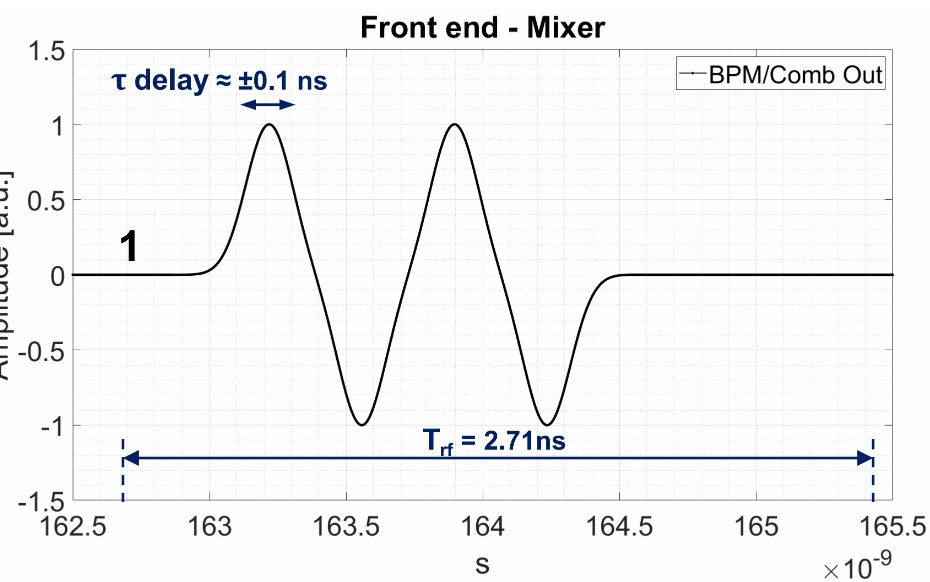

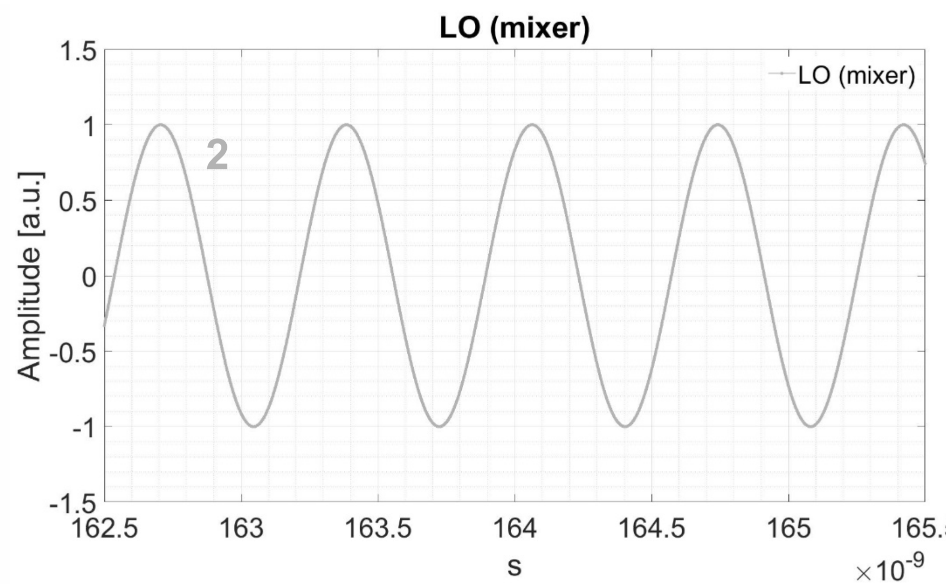

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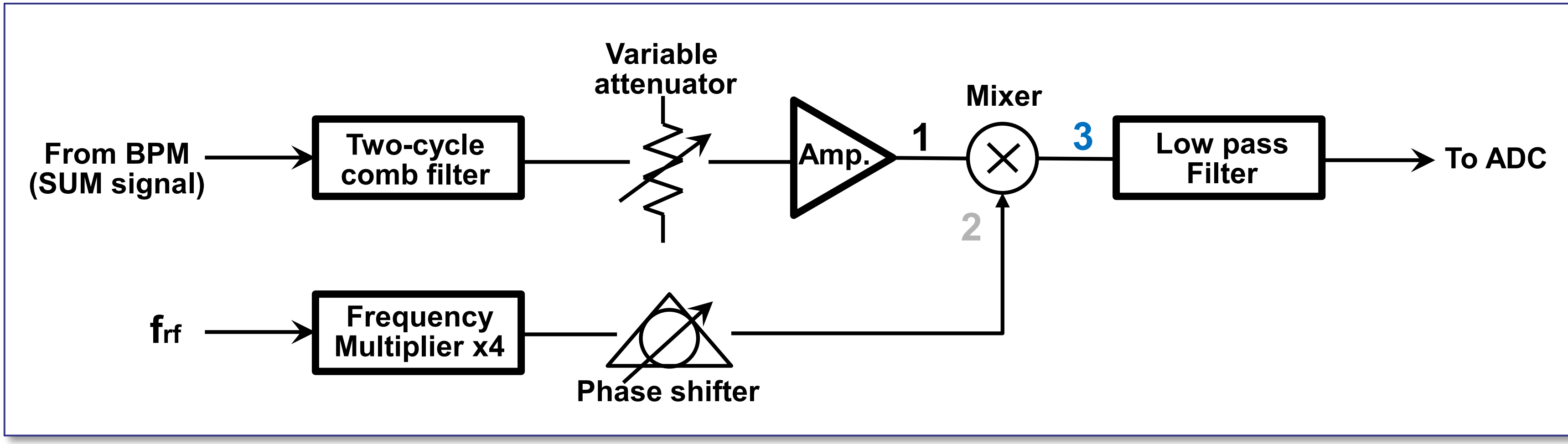
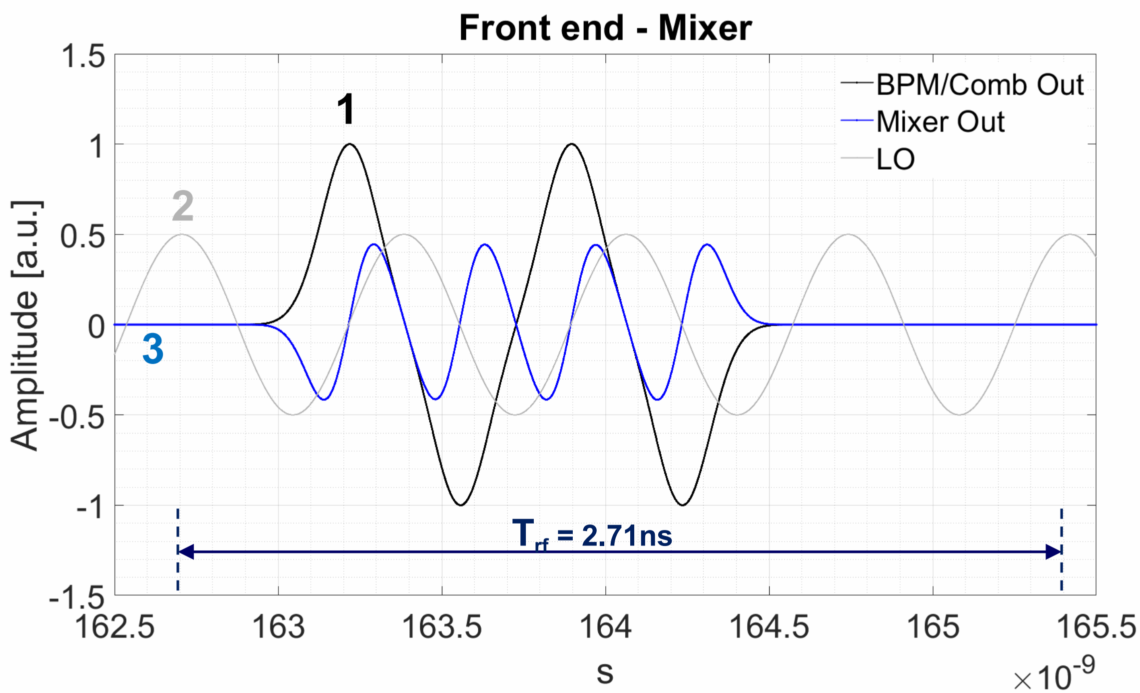
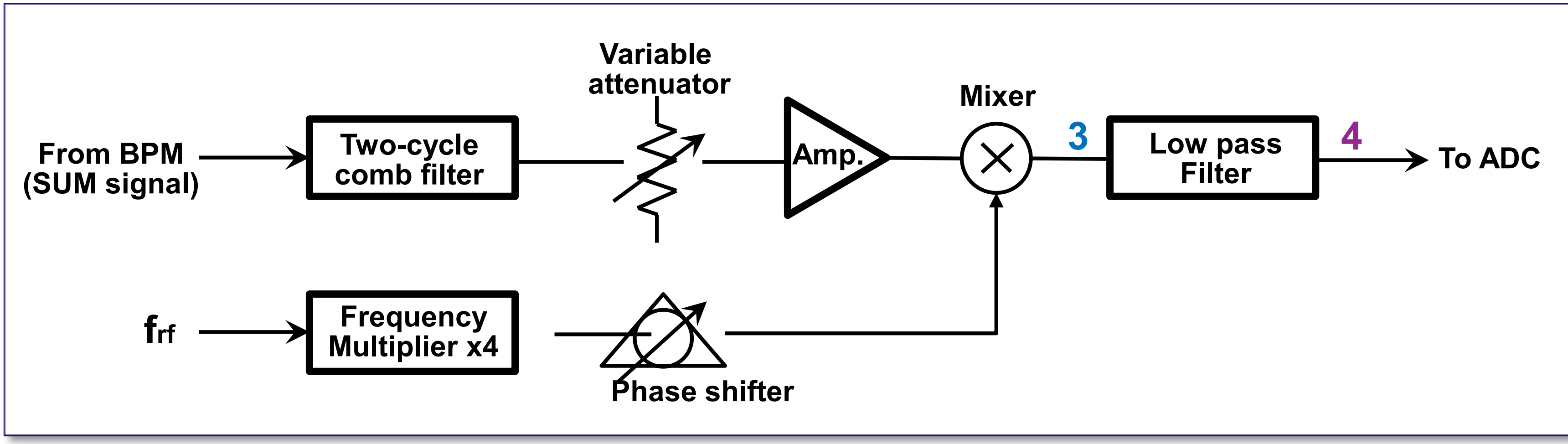


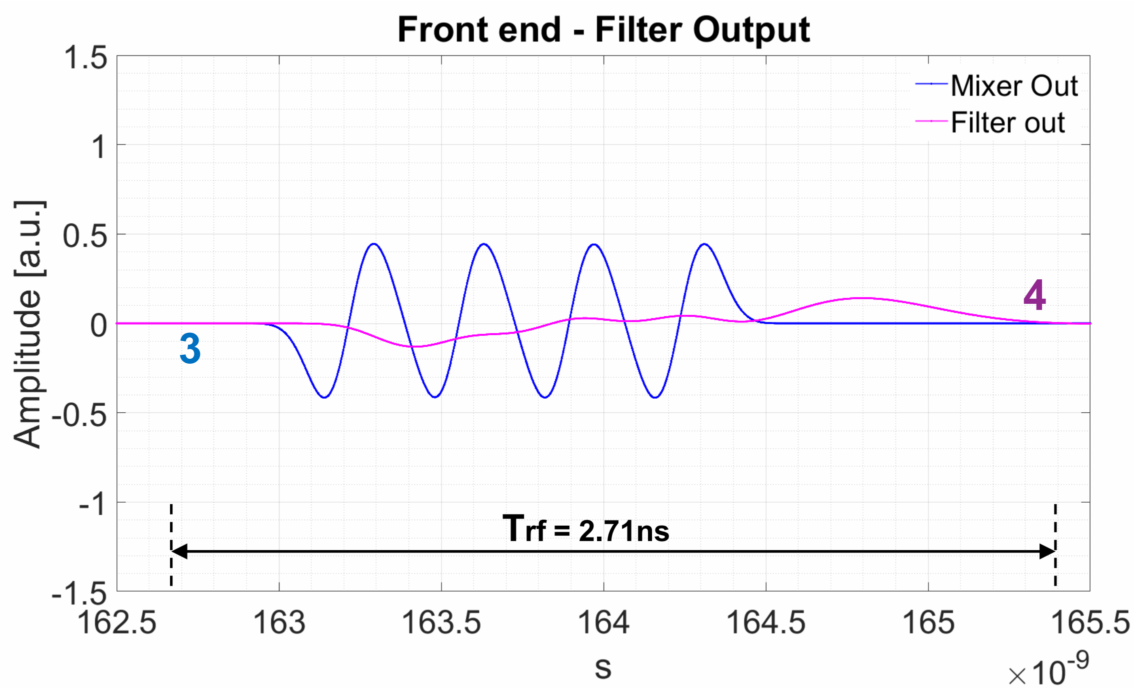


DIMTEL FBE 368L (Front-end)

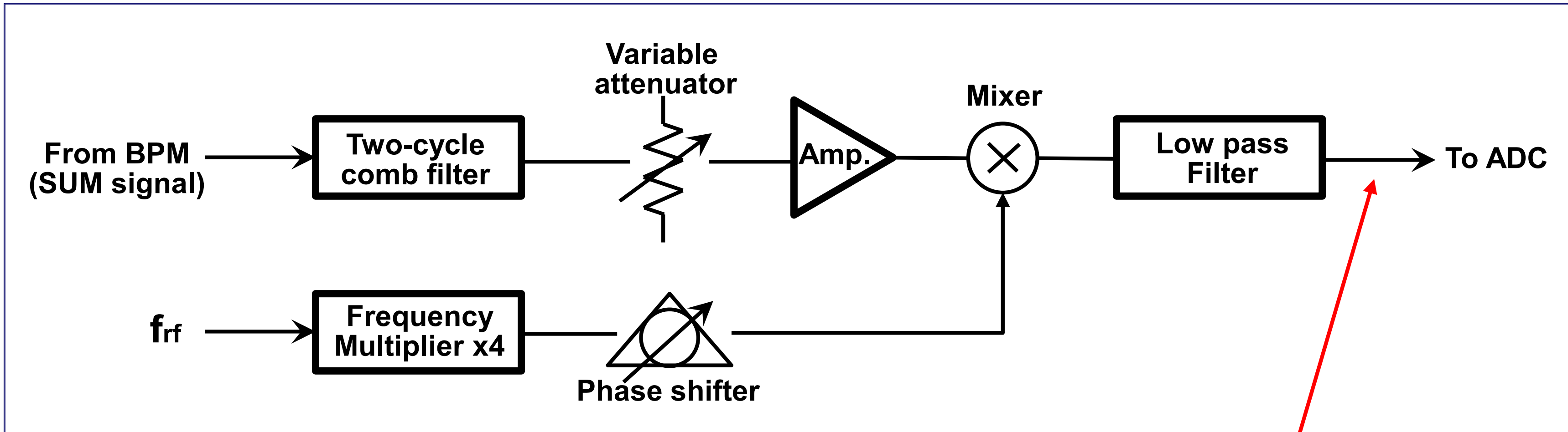


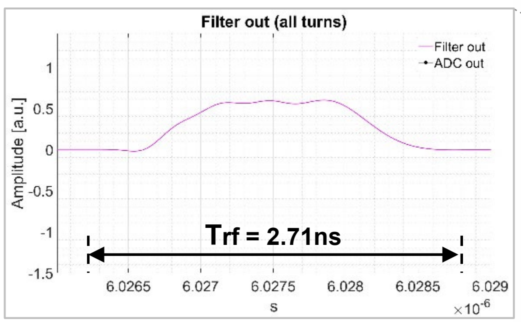
Bessel 4th ord. Low Pass Filter with f_{cut}=1,1 GHz (~$3 \cdot f_{rf}$).

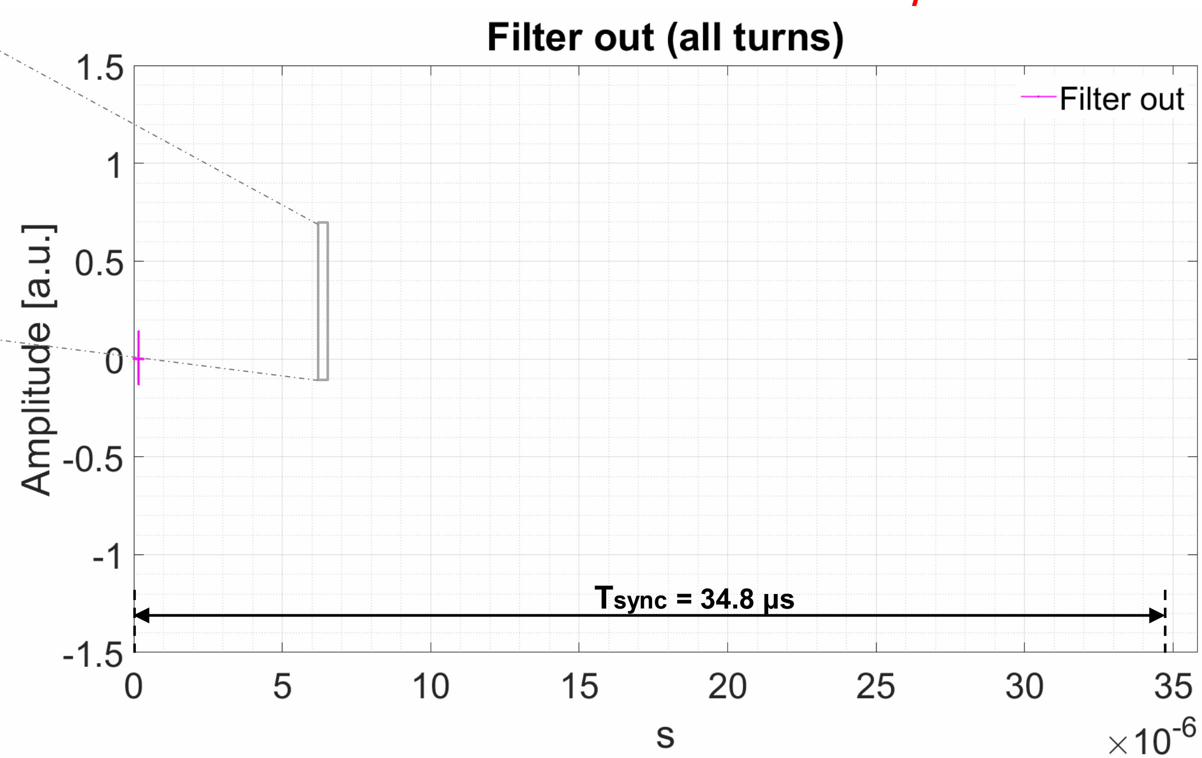
The output pulse should not last more than T_{rf} = 2.71 ns, otherwise crosstalk between bunches will appear, degrading the feedback performances.



DIMTEL FBE 368L (Front-end)

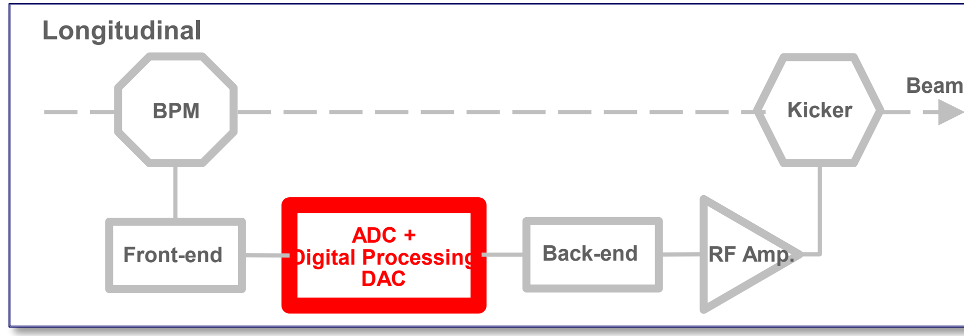






- **One bunch for 110 machine turns.**
- **$f_{sync.}$ = 28.7 kHz**
- **Decimation (ADC) = 6**

DIMTEL iGP-120F

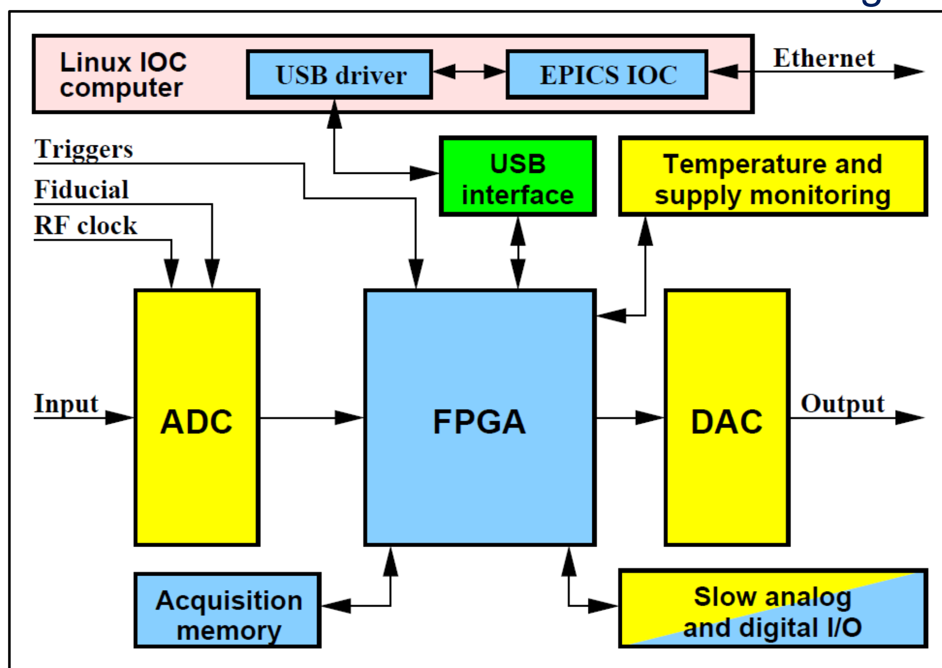


It represents the core of the system. It elaborates the correction signal, based on the phase measurements.

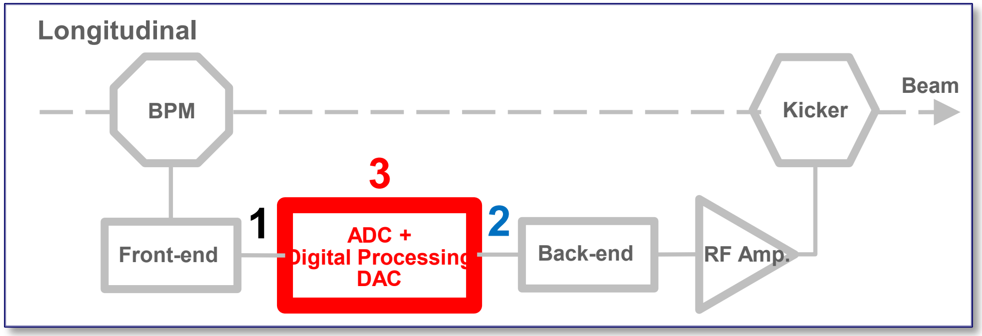
Parameter	Value
Operating Frequency	368 MHz
ADC resolution	8 bits
ADC input bandwidth	1.26 GHz
ADC input Full scale	200 $mV_{p\text{-}p}$
Number of FIR taps	16
Shift Gain (output adjustment)	2^0 - 2^7
DAC resolution	12 bits
DAC rise time (10%-90% FS)	under 250 ps
DAC fall time (90%-10% FS)	under 350 ps
DAC Full Scale	500 $mV_{p\text{-}p}$

All the parameters and functionalities are controllable via software.

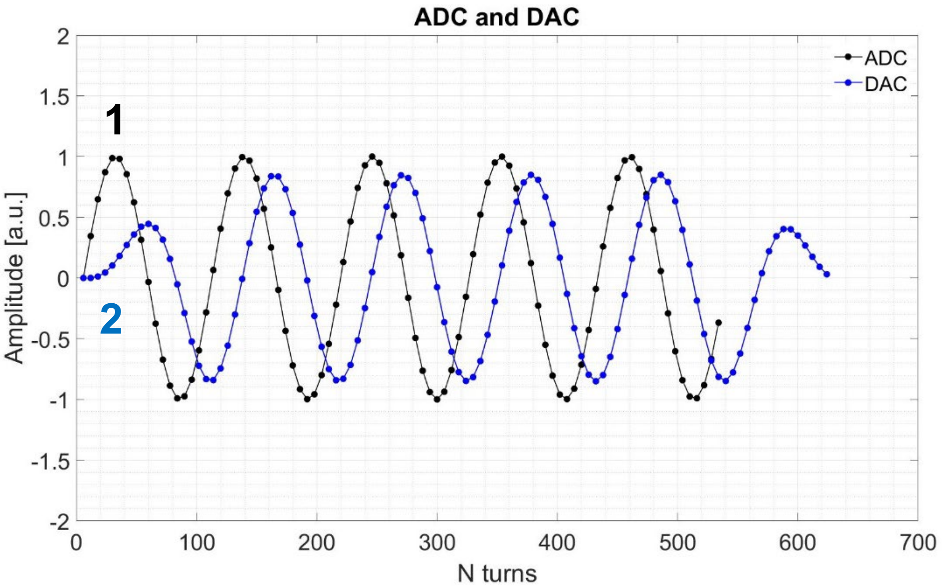
Block Diagram

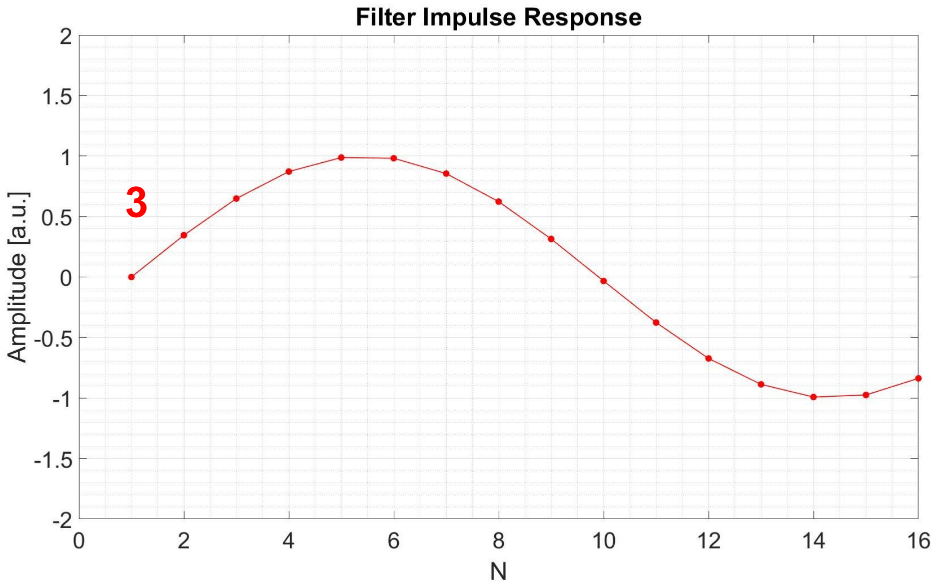


DIMTEL iGP-120F

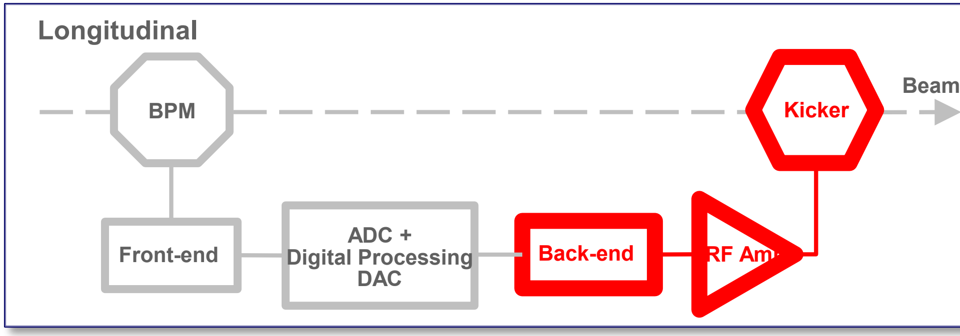


By means of a **sinusoidal digital filters** (16 taps), we obtain the **correction signal** for the n-th bunch. In first approximation, **the filter applies a gain** (user-selectable) and **a phase shift of -π/2** to the digitized signal.



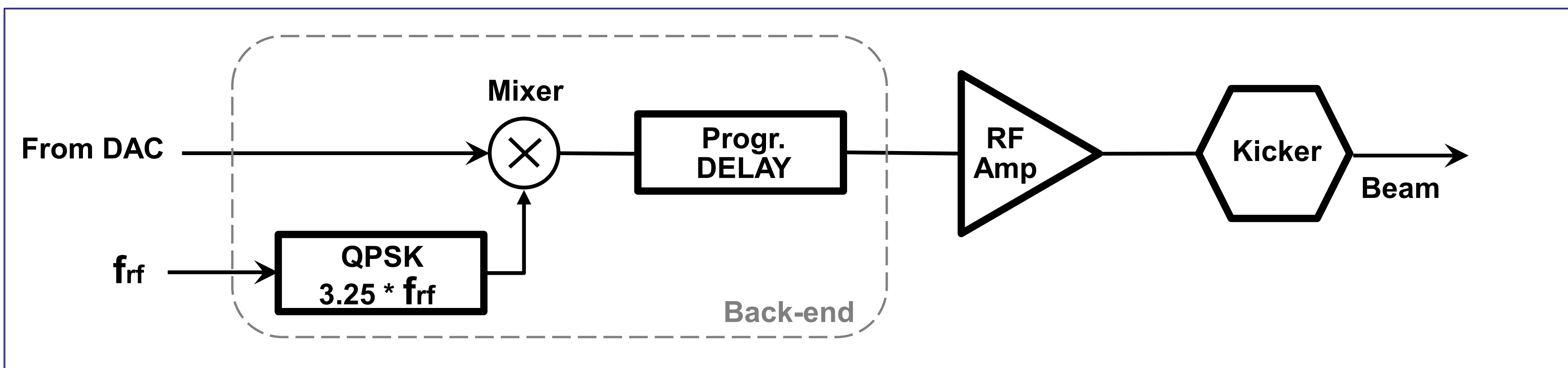


Dafne Long. Feedback (back-end)

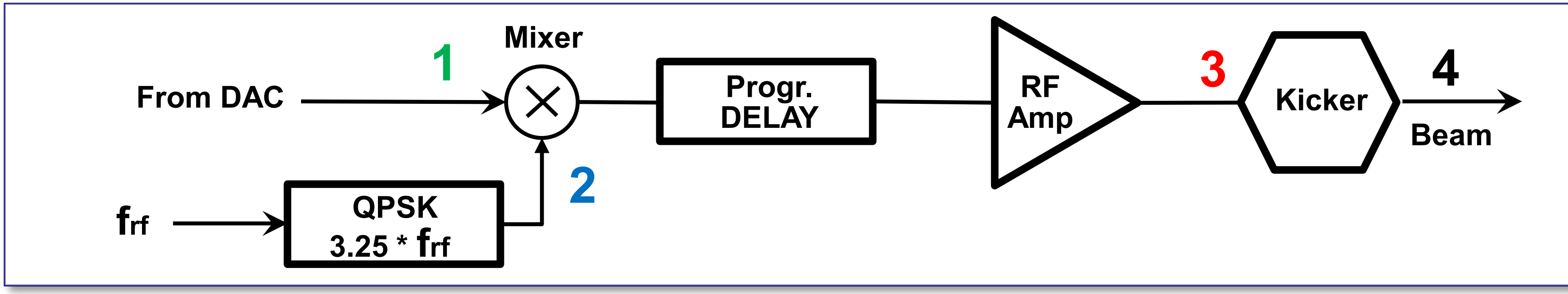


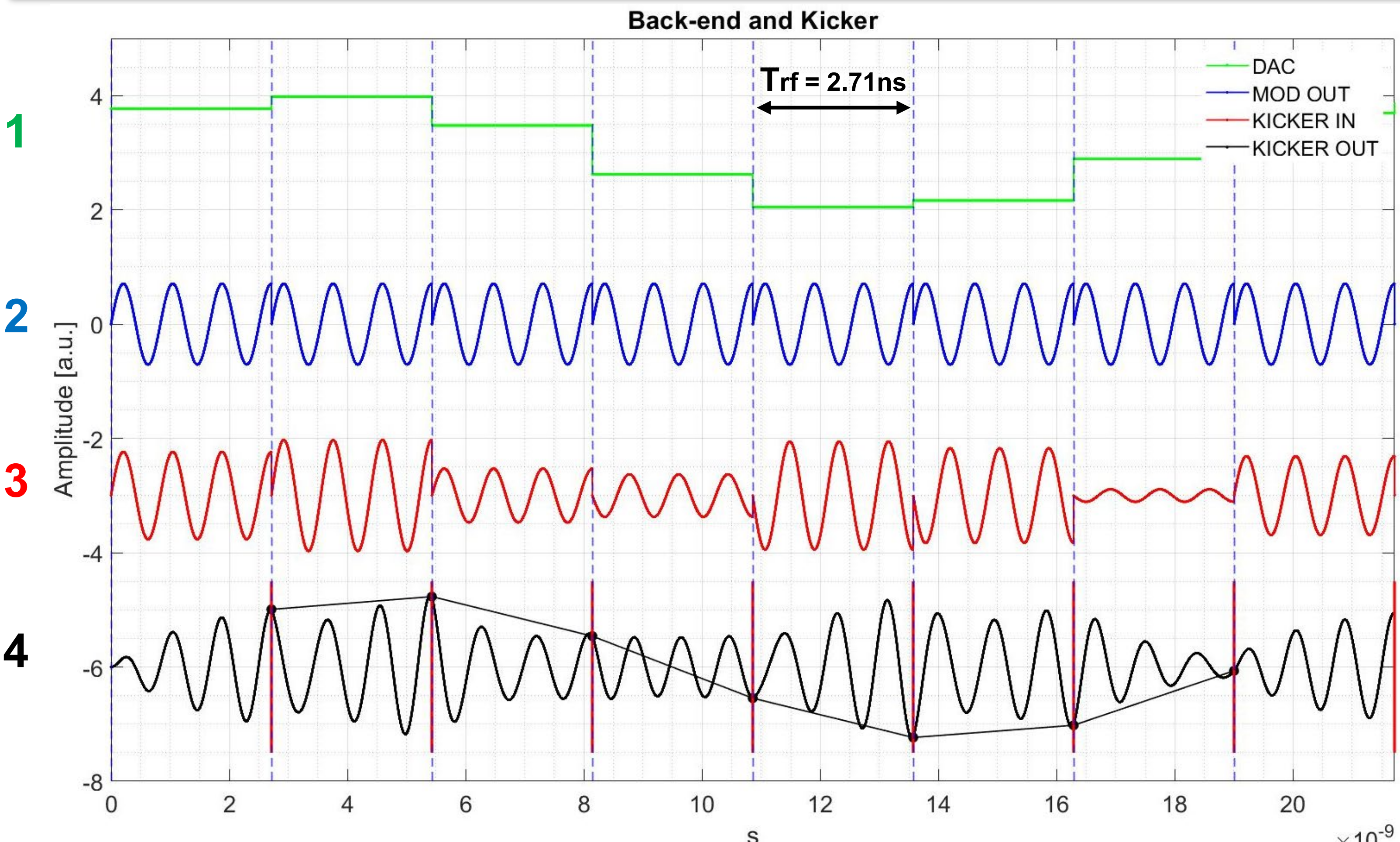
The back-end main functionalities are:

- to produce an excitation signal for the Kicker, based on the output of the DAC.
- To adjust the signal delay in order to synchronize the passage of the bunches with the "correction kick" (by means of a Programmable Delay Line).

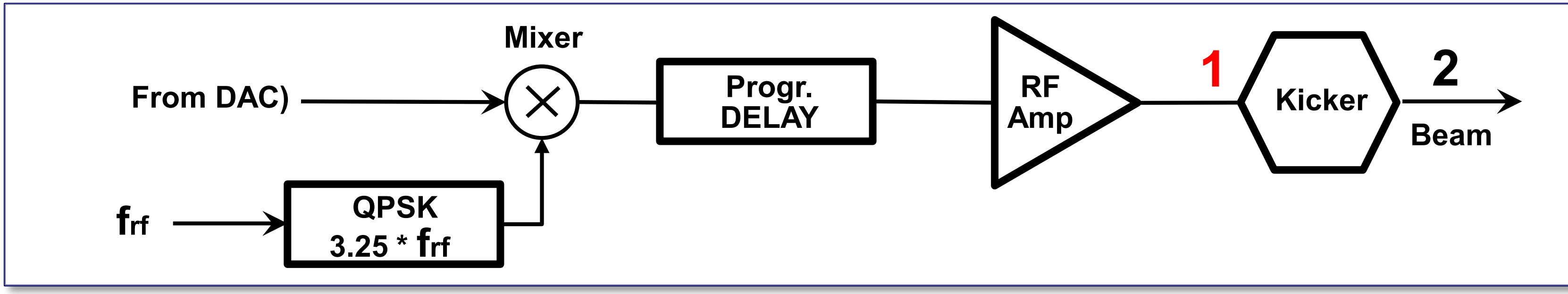


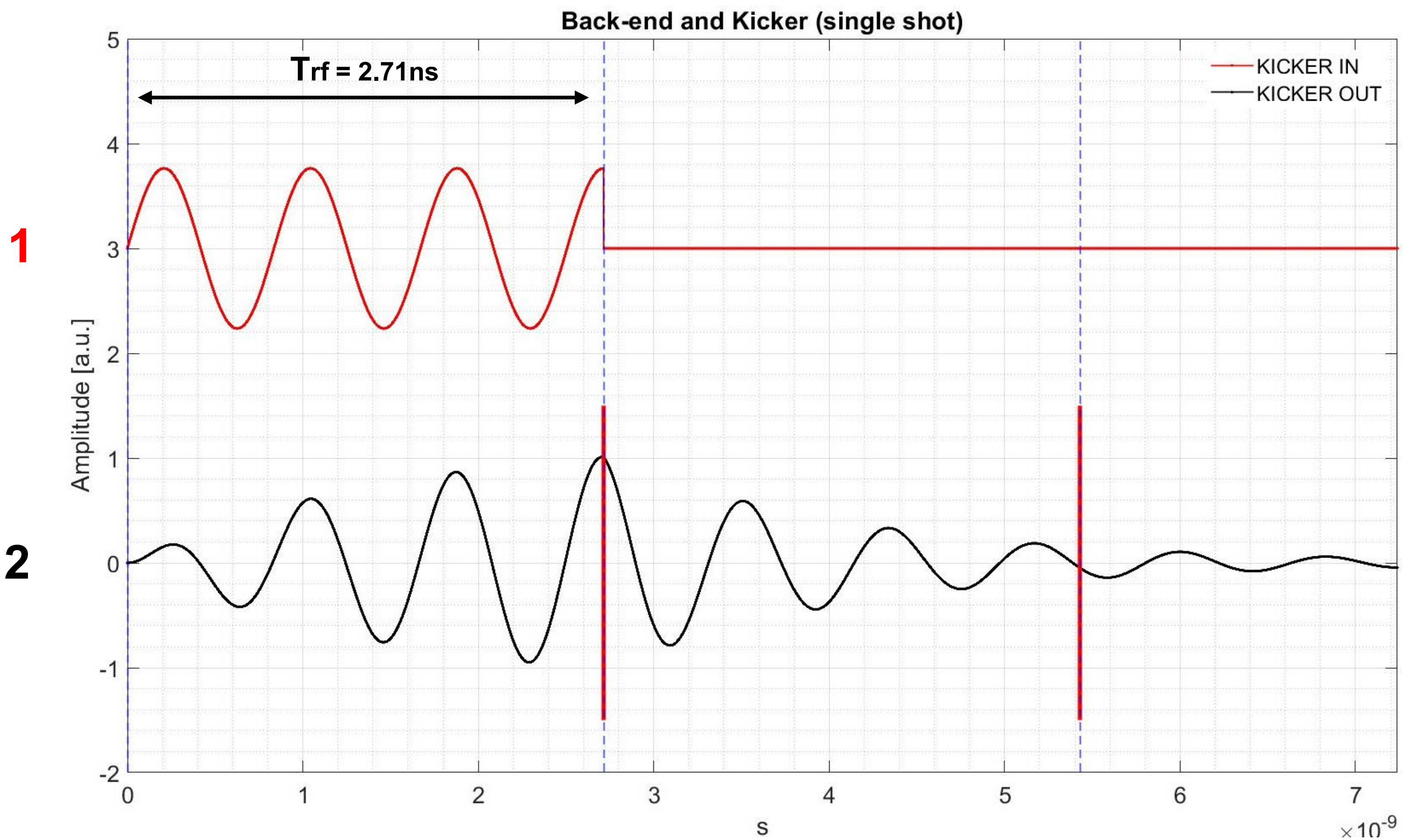
Longitudinal Feedback Back-end



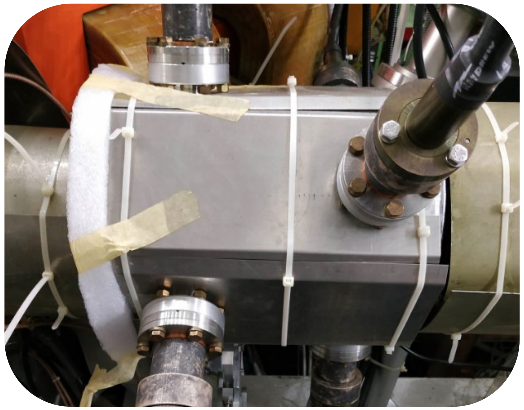


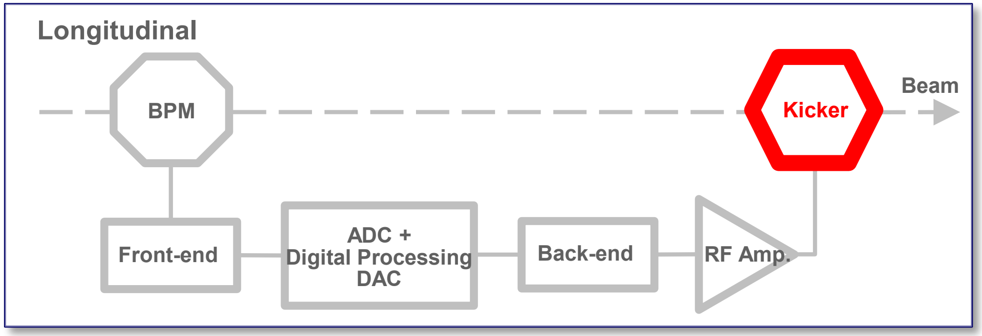
Longitudinal Feedback Back-end

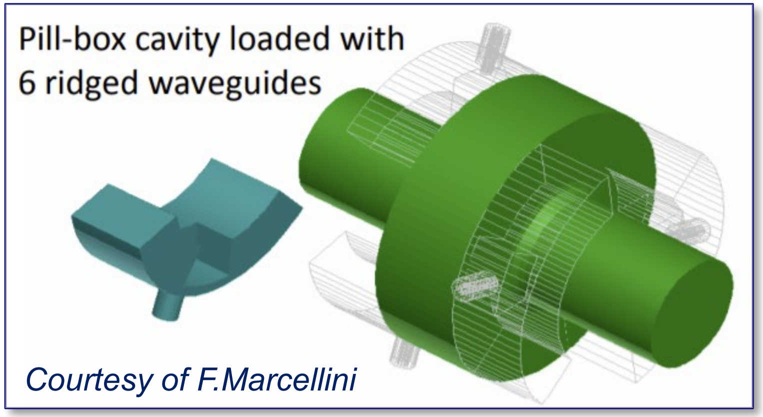




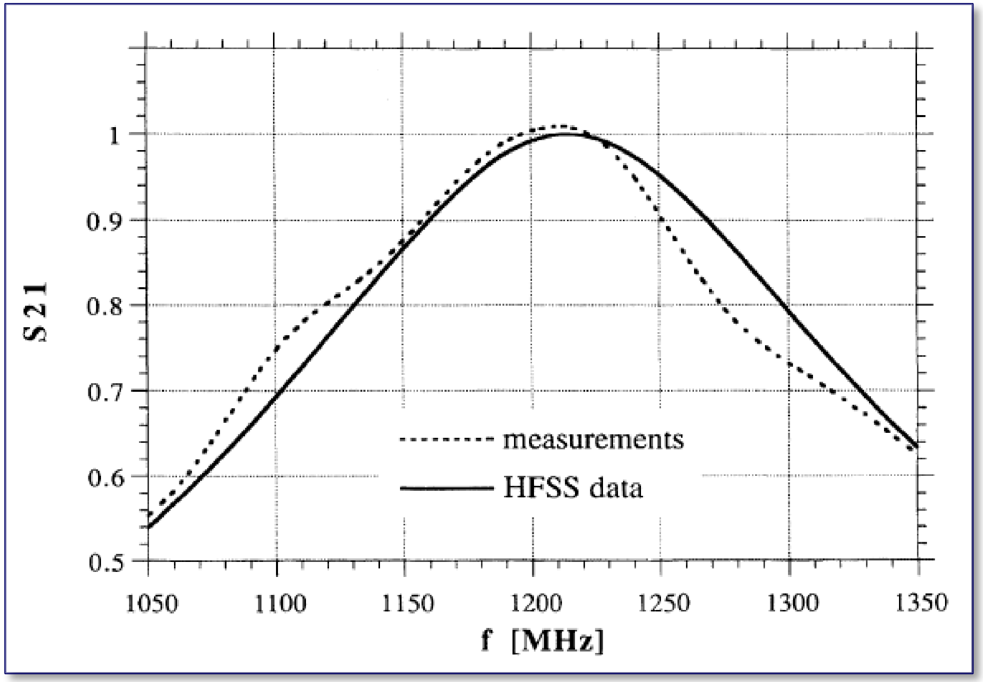
Longitudinal Feedback Kicker







Transmission coefficient



TM010 (main mode):

Res. Frequency = 3.25 x f_{rf} (~1.2 GHz)

BW ~220 MHz

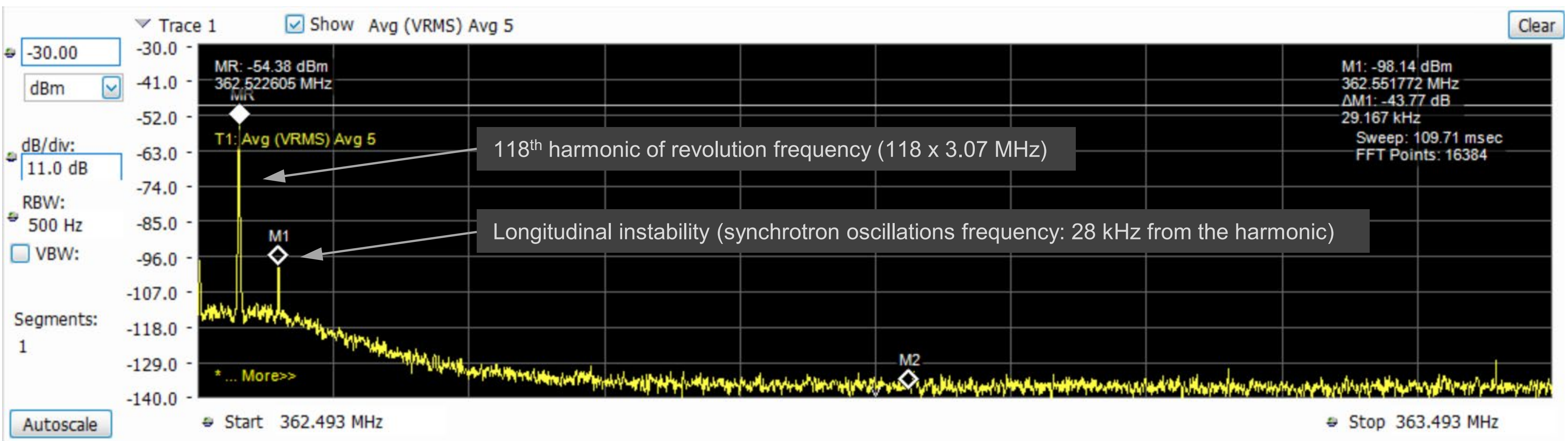
(see: A Waveguide overloaded Cavity as Longitudinal Kicker for the DAFNE Bunch-by-bunch feedback system. R.Boni, A.Gallo, A.Ghigo, F.Marcellini, M.Serio, M.Zobov. Particle Accelerators, 1996, Vol.52, pp 95-113)

Instabilities measurements

Beam Spectrum

In order to observe beam instabilities during operations, beam spectrum is measured from the combination of signals (V_{up} - V_{down}) + (V_{left} - V_{right}) from one BPM. The latter is in first approximation a Dirac comb.

- Instabilities will appear as side bands on every harmonic.
- Longitudinal instabilities will appear as phase modulations of the beam spectrum with a frequency dependent on synchrotron tune.
- Transversal instabilities will appear as amplitude modulation of the beam spectrum with a frequency dependent on the horizontal and vertical tunes.
- This will measure the spectrum of all the bunches combined, but it is also possible to measure the spectrum of single bunches, by utilizing the DIMTEL signal processor used for the feedbacks.



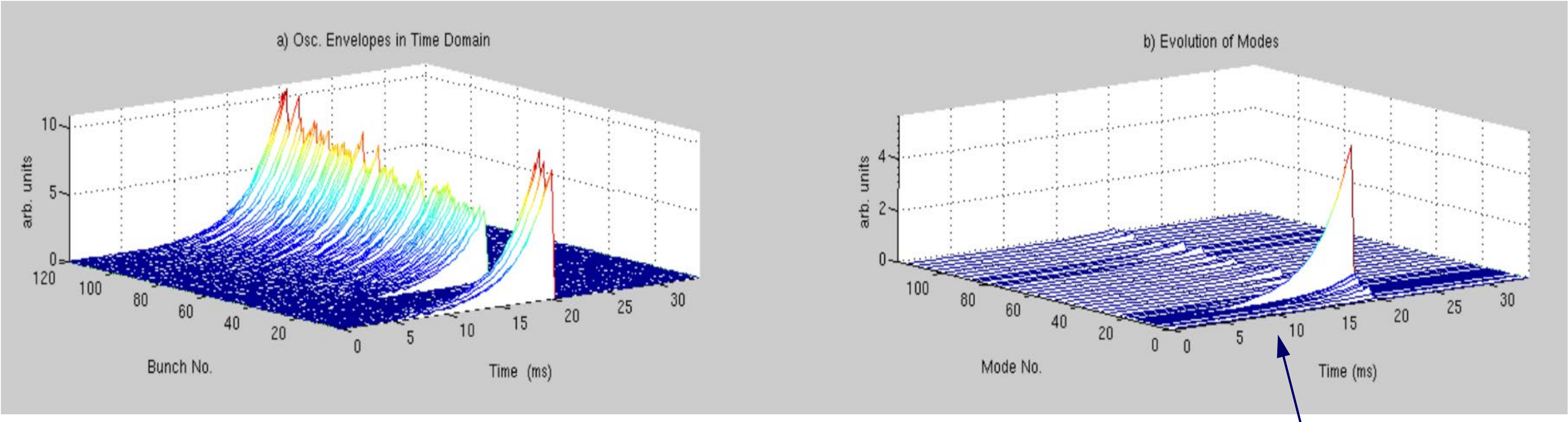
Example of beam spectrum with Positron beam (100 bunches) with I_{avg} = 150 mA. Long. feedback turned off.

Characterizing instabilities

In order to characterize beam instabilities the following method is applied (developed at SLAC):

- While beam is circulating, upon some trigger, **feedback is turned off**.
- Instabilities during this time will grow. **Phase and position of each bunch is recorded**.
- **Feedback is turned on** after an adjustable time window, in order to avoid beam loss.

By performing this type of measurement, it is possible to characterize instabilities (which modes are predominant, how quick the instabilities rise) and how well the feedback (once turned on) will damp them.



An example of the measurement performed with the longitudinal feedback on positron beam (100 bunches) with I_{avg} = 730 mA

Conclusions

- The feedback system (the longitudinal in particular) is extremely important to DAΦNE operations. Without it, bunch-coupling effects limit the maximum current stored in the rings to few hundreds of mA. By using the feedback systems it is possible to reach 1A / 2A (range of currents used currently).
- The feedback system was constantly updated and maintained during the long DAΦNE operations (~22 years), by implementing new hardware, software and by reconfiguring it.
- A measurement campaign is on going on the signals involved in the system (e.g. the BPM output) in order to evaluate and minimize any possible source of noise and interferences, which could degrade the system performances.

Thank you for your attention!

Spares

Spares

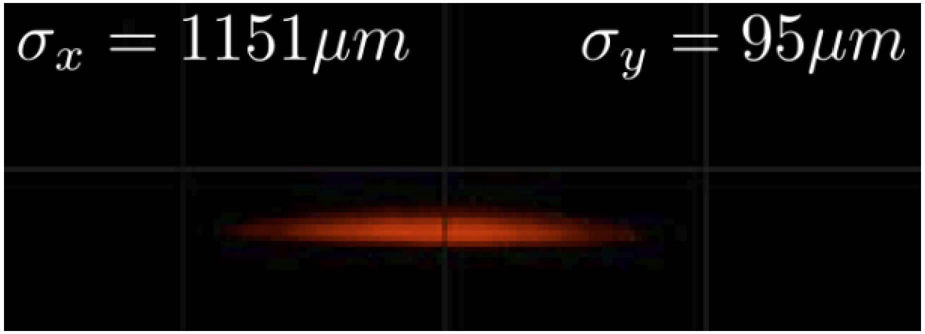


Figure 1: Electron beam profile as measured at the SLM, for a current of 500 mA stored in 100 bunches, after setting the Crab-Waist Sextupoles at 1/3 of the nominal strength. The beam vertical size is at the level of the diagnostics resolution.

	DAΦNE native	DAΦNE Crab-Waist
Energy (MeV)	510	510
$\theta_{cross}/2$ (mrad)	12.5	25
ε_x (mm•mrad)	0.34	0.28
β_x^* (cm)	160	23
σ_x^* (mm)	0.70	0.25
$\Phi_{Piwinski}$	0.6	1.5
β_y^* (cm)	1.80	0.85
σ_y^* (μm) low current	5.4	3.1
Coupling, %	0.5	0.5
Bunch spacing (ns)	2.7	2.7
I_{bunch} (mA)	13	13
σ_z (mm)	25	15
N_b	120	120

Colliding Beams have:
- *low E*
- *high currents*
- *short bunch spacing 2.7 nsec*
- *long damping time*

Longitudinal oscillations

Simple case:

- One bunch (considered as a single macro particle) circulating at relativistic speed in a storage ring.
- Absence of any kind of perturbation.
- No feedback.
- Only small energy oscillations.

The delay of a particle τ, referred to the synchronous particle is governed by the following **damped harmonic oscillator** equation:

$$\boxed{\ddot{\tau} + 2d_r\dot{\tau} + \omega_s^2\tau = 0}$$

- ω_s is the synchrotron oscillation angular frequency.

$$\omega_s^2 = \frac{\alpha_c e}{E_0 T_0}\dot{V}_{rf0}$$

- d_r is the synchrotron radiation damping rate.

$$d_r = \frac{D}{2T_0} \text{ with } D = \left(\frac{dU_{rad}}{dE}\right)_0$$

- α_c is the momentum compaction factor.
- E_0 is the nominal energy.
- T_0 is the revolution period.
- $\dot{V}_{rf}(0)$ is the derivative (in respect of time) of the voltage of the RF cavity, calculated at $\tau = 0$ (synchronous particle)
- D is the derivative (in respect of energy) of the energy lost by Synchrotron Radiation, calculated at E_0 (synchronous particle)

Longitudinal oscillations

$$\ddot{\tau} + 2d_r\dot{\tau} + \omega_s^2\tau = 0$$

(for $d_r \ll \omega_s$)

$$\tau(t) = A \cdot e^{-d_r t} \cdot \cos(\omega_s t - \Theta_0)$$

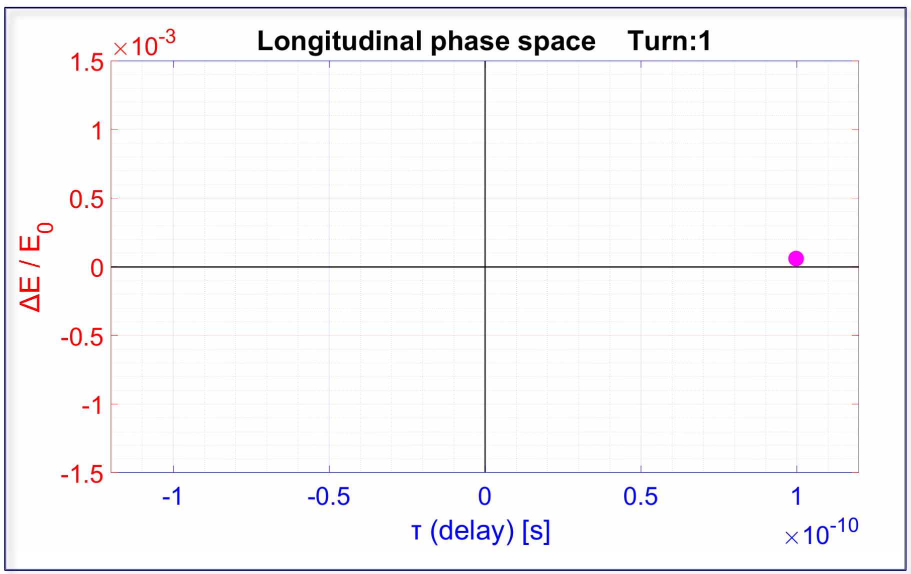
$\varphi = -2\pi f_{RF} \cdot \tau$

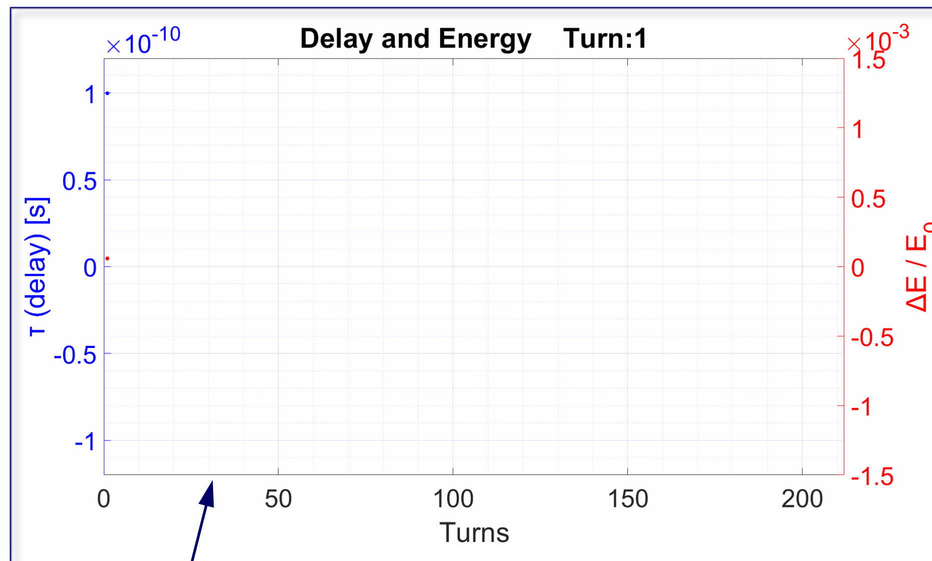
phase of the bunch (referred to the synchronous phase) could be used instead.

A and Θ_0 depend on the initial conditions.

Similarly for $\Delta E/E_0$:

$$\frac{\Delta E}{E_0}(t) = \frac{\omega_s}{\alpha_c} \cdot A \cdot e^{-d_r t} \cdot \cos\left(\omega_s t - \Theta_0 - \frac{\pi}{2}\right)$$





Exponential decay ($e^{-d_r t}$) is not visible on this time scale. $1/d_r$=0.0187 s (~57.000 turns)

Animations based on simulations of D. Quartullo for DAFNE.

See also: The Physics of Electron Storage Rings, M.Sands

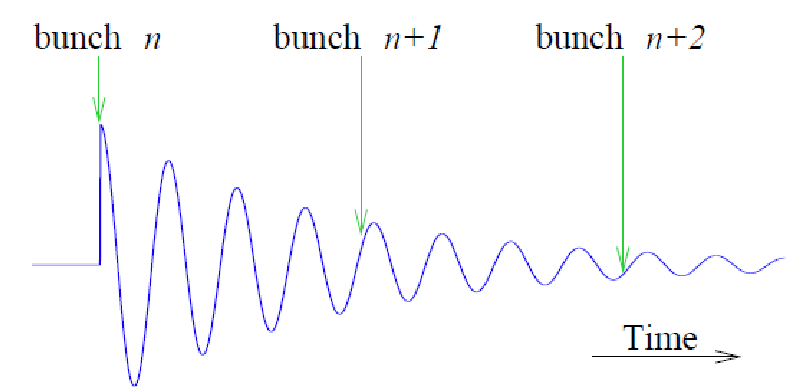
Coupled bunch instabilities

To expand our simple case, we can now imagine to have **multiple bunches**:

- coupled-bunch synchrotron (dipole) oscillations will appear and affect the longitudinal dynamics of each bunch.

Origin of Coupled-bunch instabilities:

Oscillatory electric fields (wakefields) excited (mostly) in the RF cavity by the bunches, which interefere with the bunches arriving in the structure afterwards.



courtesy of D.Teytelman

$$\ddot{\tau}_n + 2d_r\dot{\tau}_n + \omega_s^2\tau_n = 0$$

$$\ddot{\tau}_n + 2d_r\dot{\tau}_n + \omega_s^2\tau_n = -\frac{\alpha_c e}{E_0 T_0}\cdot V_n^{wk}(t)$$

Coupled-bunch oscillations are represented by a driving force, that potentially will make the bunch oscillations unstable.
The higher the circulating current, the higher the coupled-bunch oscillations.

<u>Coupled bunch instabilities analysis will be presented by D.Quartullo in the upcoming presentation.</u>

see : SLAC-Report-633. D.Teytelman, 2003

Introducing the Longitudinal Feedback

The **feedback** is implemented to **counter the coupled-bunch instabilities**.

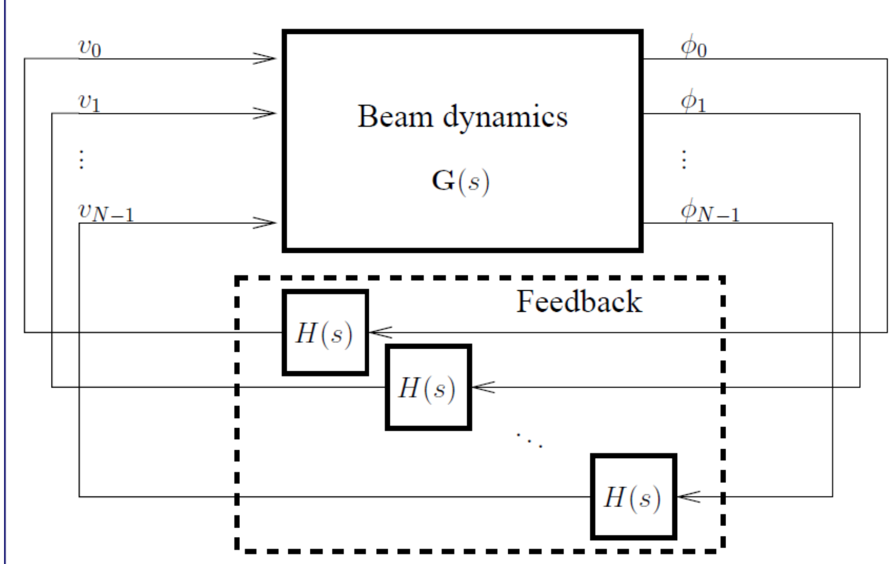
$$\ddot{\tau}_n + 2d_r\dot{\tau}_n + \omega_s^2\tau_n = -\frac{\alpha_c e}{E_0 T_0}\cdot V_n^{wk}(t)$$

$$\ddot{\tau}_n + 2d_r\dot{\tau}_n + \omega_s^2\tau_n = \frac{\alpha_c e}{E_0 T_0}\left(V_n^{fb}(t) - V_n^{wk}(t)\right)$$

The feedback acts as a **driving force** to stabilize the oscillations.

Eventhough the coupled-bunch instabilities create a correlation between the bunches, the DAFNE **feedback system treats each bunch separately**.

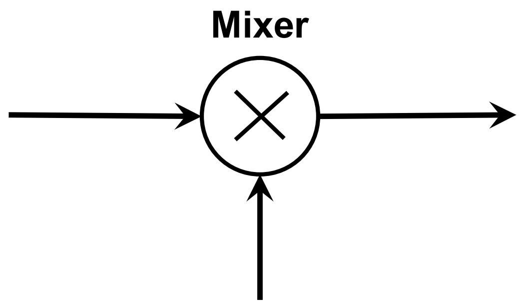
This is equivalent to have a separate feedback loop associated with each bunch.



courtesy of D.Teytelman

Mixer

$$Y_{IN}(t) = A_{IN}\sin(\omega_{IN}t + \varphi_{IN})$$



$$Y_{OUT}(t) = Y_{IN}(t)\cdot Y_{LO}(t)$$

$$Y_{LO}(t) = A_{LO}\cos(\omega_{LO}t + \varphi_{LO})$$

$$Y_{OUT}(t) = \frac{1}{2}A_{LO}A_{IN}\cdot[\sin((\omega_{IN}-\omega_{LO})t + (\varphi_{IN}-\varphi_{LO})) + \sin((\omega_{IN}+\omega_{LO})t + (\varphi_{IN}+\varphi_{LO}))]$$

In our case:
$\omega_{IN} = \omega_{LO} = 4\cdot\omega_{RF}$
$A_{LO} = 1$
$\varphi_{LO} = 0°$

φ_{IN} is what we want to measure
For small angles: $\sin(\varphi_{IN}) \approx \varphi_{IN}$

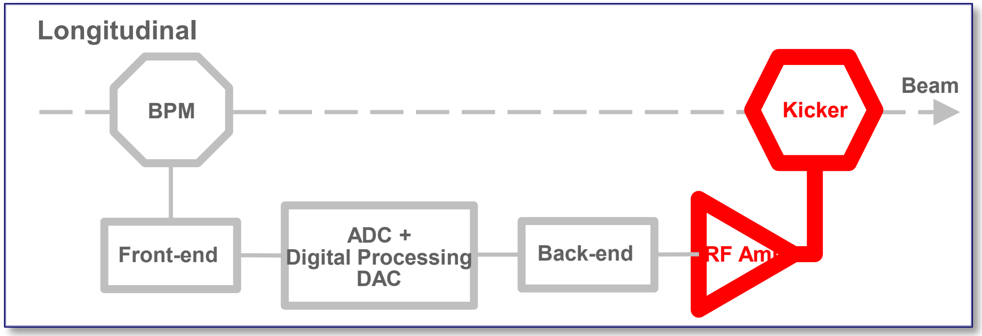
$$Y_{OUT}(t) = \frac{1}{2}A_{IN}\cdot\left[\boxed{\sin(\varphi_{IN})} + \boxed{\sin((8\cdot\omega_{RF})t + \varphi_{IN})}\right]$$

DC component

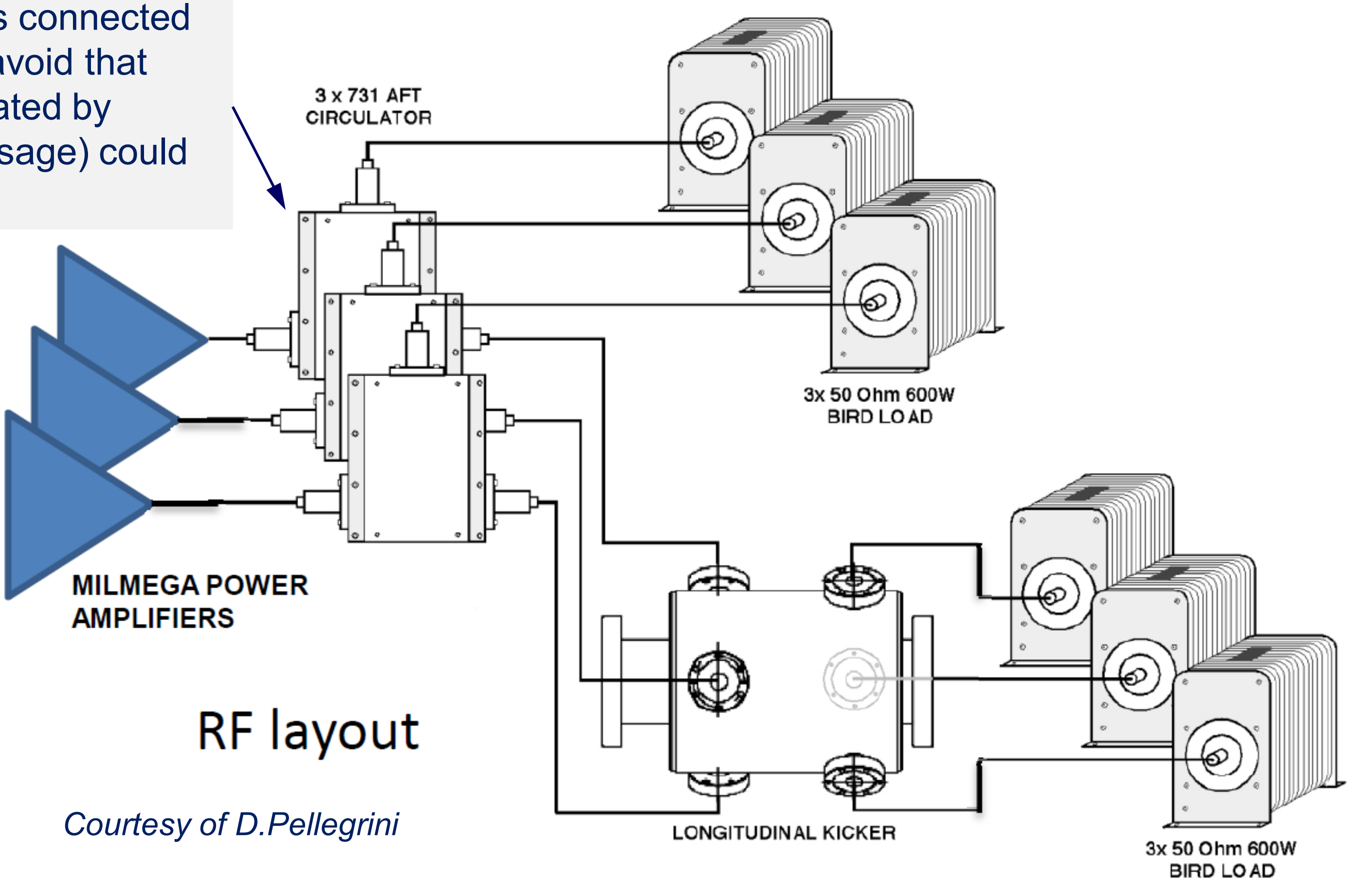
$8\cdot\omega_{RF}$ component
(it will be filtered out)

Power Amplifiers and Longitudinal Kicker

The correction signal is **split in three**, by means of a splitter with manually adjustable delays. The three signals are fed to the **three power amplifiers**. The output signals are provided to the longitudinal kickers through three ports.



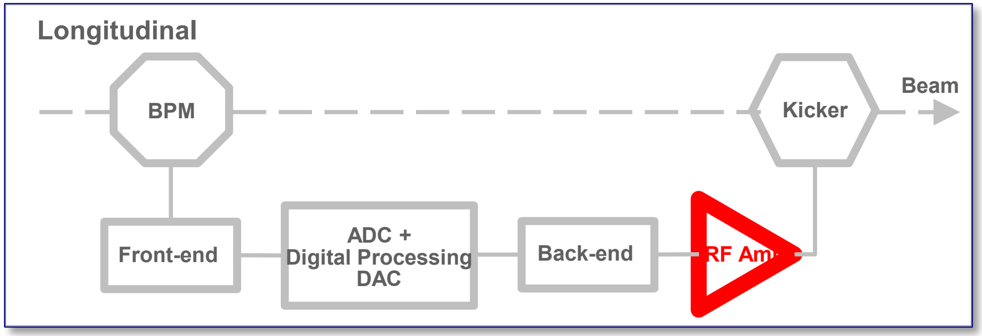
The longitudinal kicker is connected through **Circulators** to avoid that backward power (generated by reflections or bunch passage) could damage the Amplifiers.



RF layout

Courtesy of D.Pellegrini

MILMEGA AS0814-250R Power Amplifier

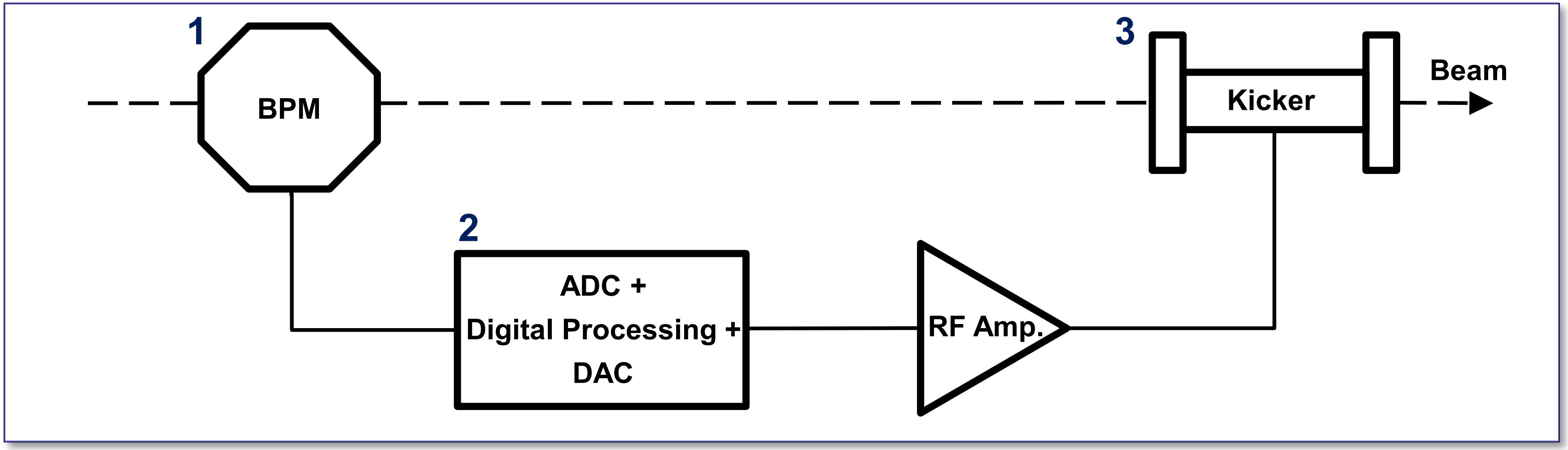


Nominal Parameter (if not specified)	Value
Operating Frequency	0.8-1.4 GHz (fin = 1.2 GHz)
Output Power at saturation	54 dBm
Output Power at 1dB gain compression	53.5 dBm
Input Power for rated output	5 dBm
Gain (measured at 1.2 GHz)	~58 dB
Gain variation with temperature	0.06 dB/C
Noise Figure (typical)	10 dB

– Each amplifier is associated with a control unit (MILMEGA IF001 Ctrl), interfaceable through GPIB (for basic operations and diagnostics).

– A custom modification on the hardware allows to check if the amplifiers are powered on directly from the control room (see next slides).

Horizontal and Vertical Feedback

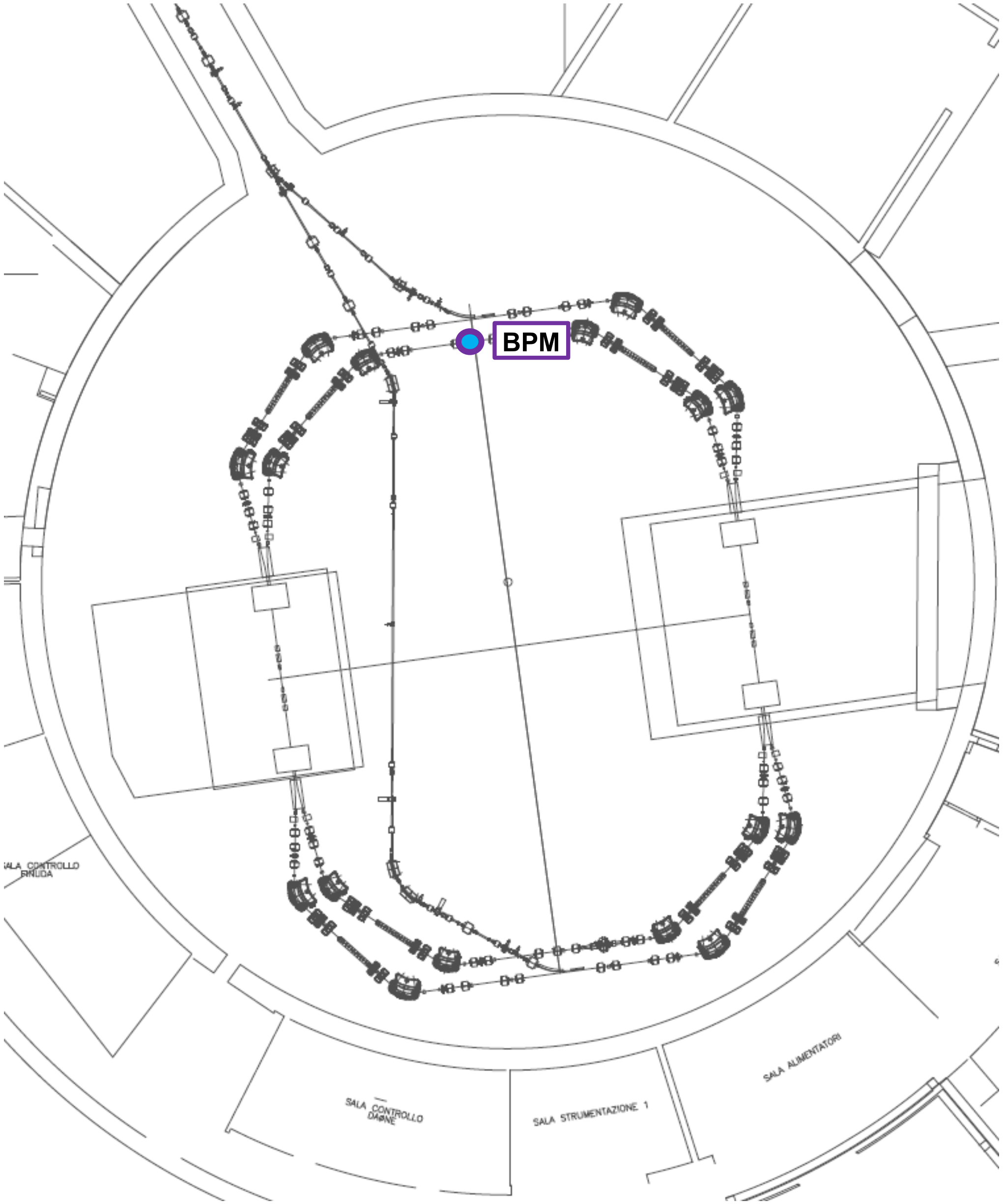


The transverse feedbacks acts on the horizontal and vertical position of the bunches. They apply a correction signal in the form of a transverse kick (by means of stripline kickers).

1. The signals from the horizontal (or vertical) electrodes of one **BPM** are subtracted and sent to the front-end electronics.
   Exception: Vertical e- and e+ feedbacks use only the signal from the bottom (up for e+) electrode of the BPM (BPBES 202 and BPBPS 202).
2. The latter is then **digitized** and the correction signal is **digitally elaborated** and **converted to analog** (DAC).
3. The signal (**amplified by RF amp**.) is then supplied to the horizontal (or vertical) **kicker**. The latter modifies the horizontal (or vertical) momentum (by means of a transverse kick) with the aim of restoring the bunch standard orbit.

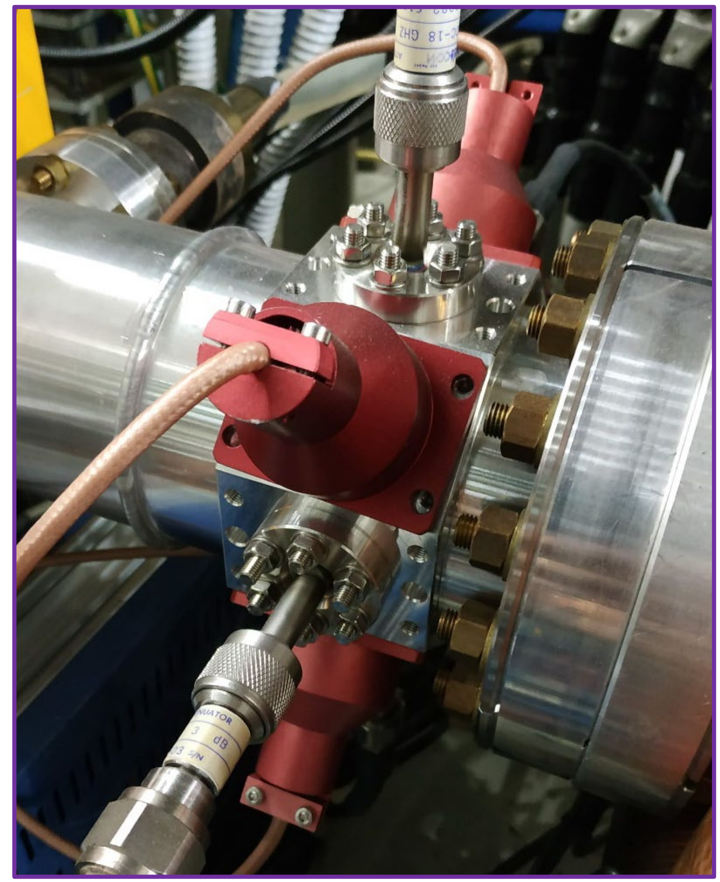
Detail of the transverse Feedbacks will be described in details in the future

Longitudinal e- Feedback

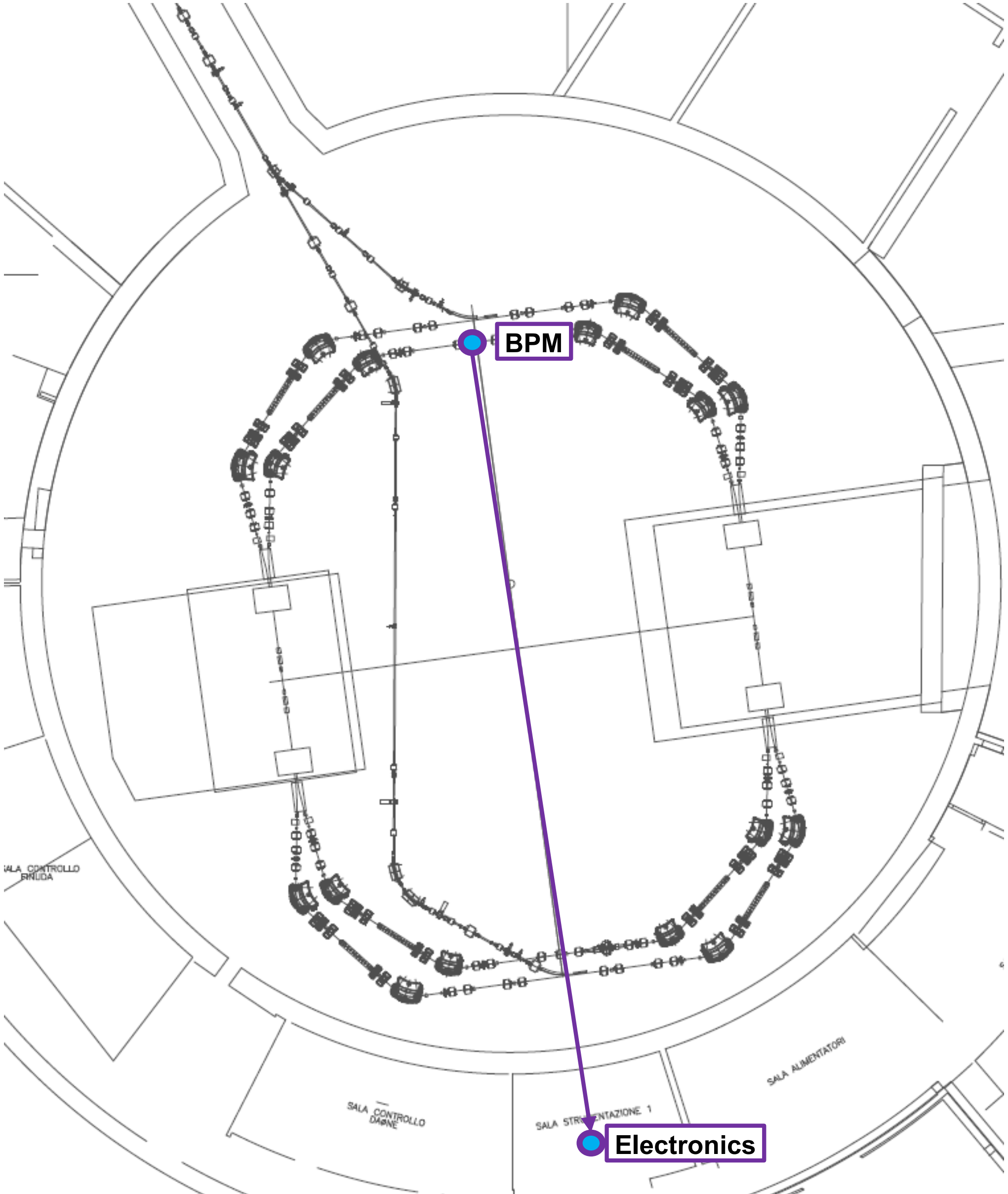


- **BPM** (BPBES 108)

The signals of the four electrodes are summed together (with power combiners) and sent to the electronics.



Longitudinal e- Feedback

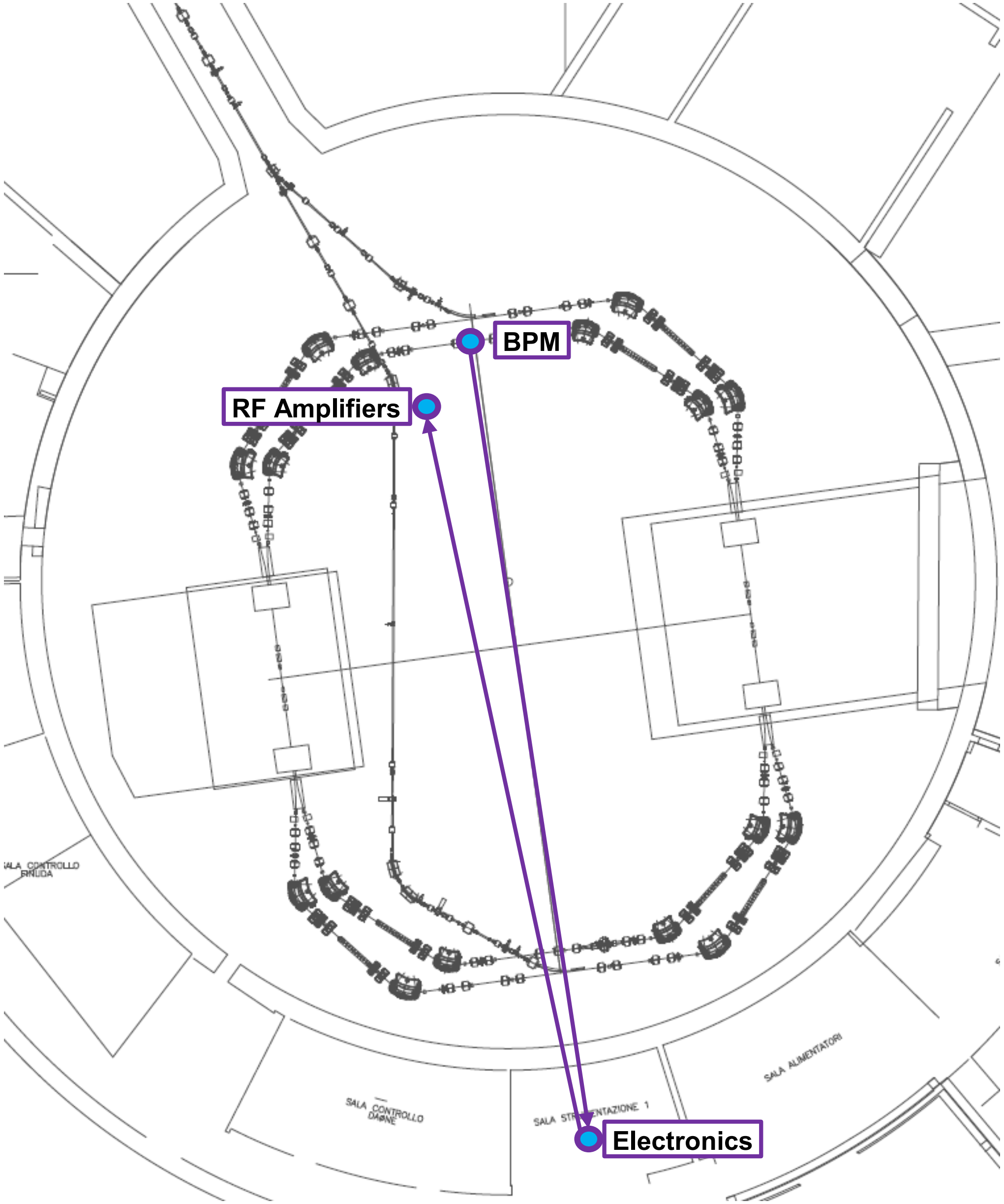


- ELECTRONICS

(instr. room – Rack 46 - multiple devices)

The analogue signal is adjusted (front-end) and digitized (ADC). The correction signal is calculated, transformed in an analogue signal (DAC), adjusted (back-end + delay unit) and sent to the RF amplifiers.

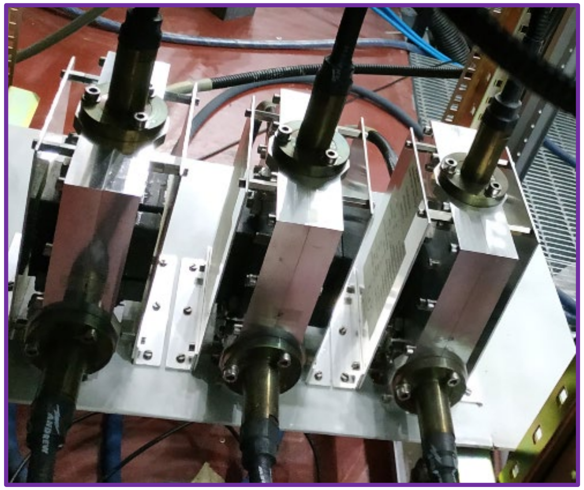
Longitudinal e- Feedback



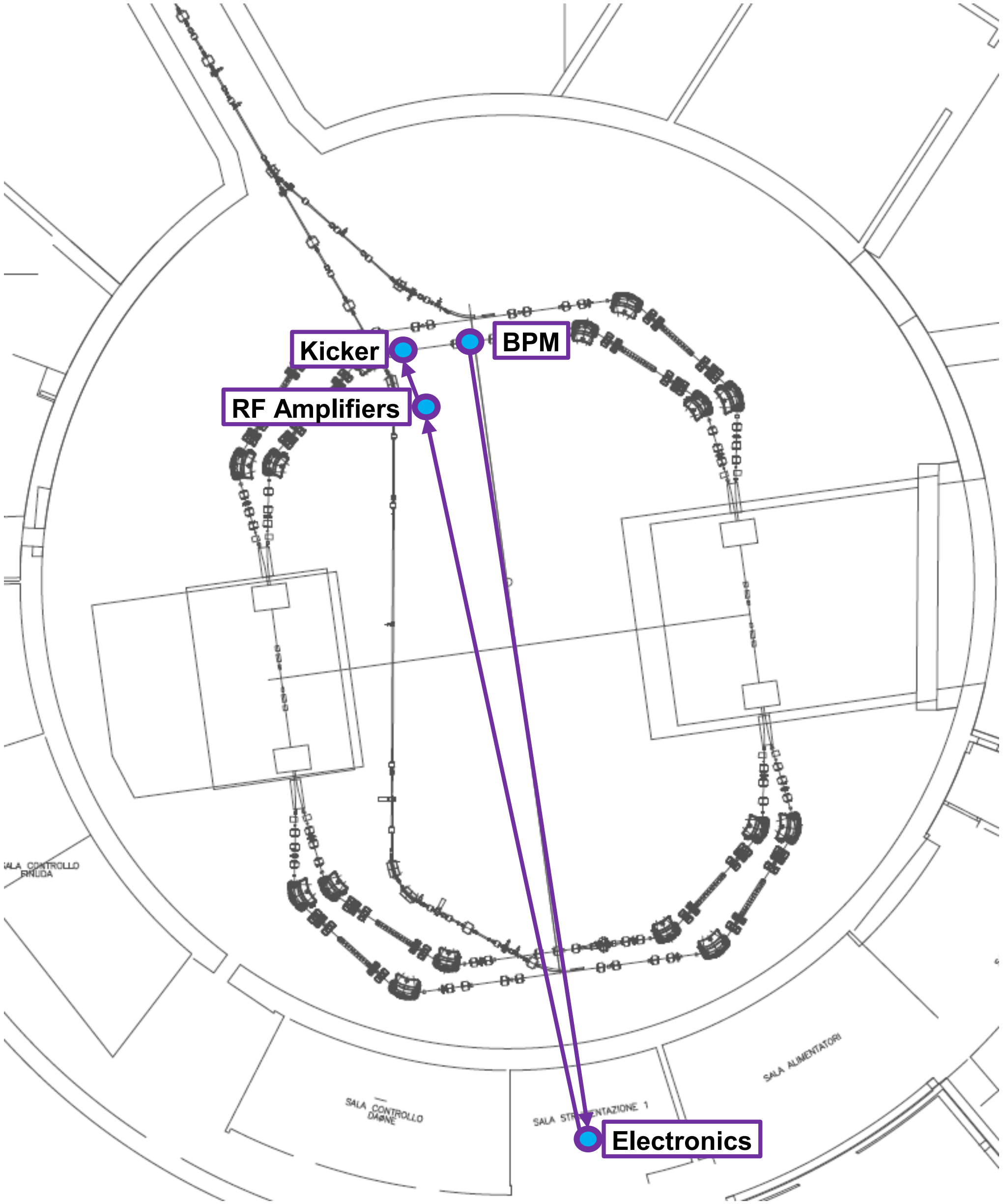
- RF AMPLIFIERS

(Rack 54 - Three units)

The correction signal is amplified and sent to the kicker (through circulators)

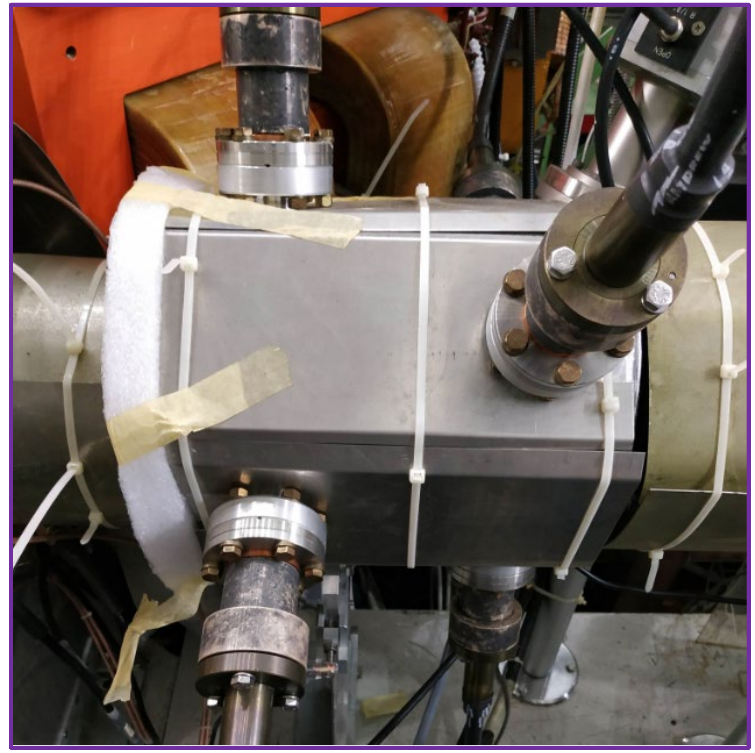


Longitudinal e- Feedback

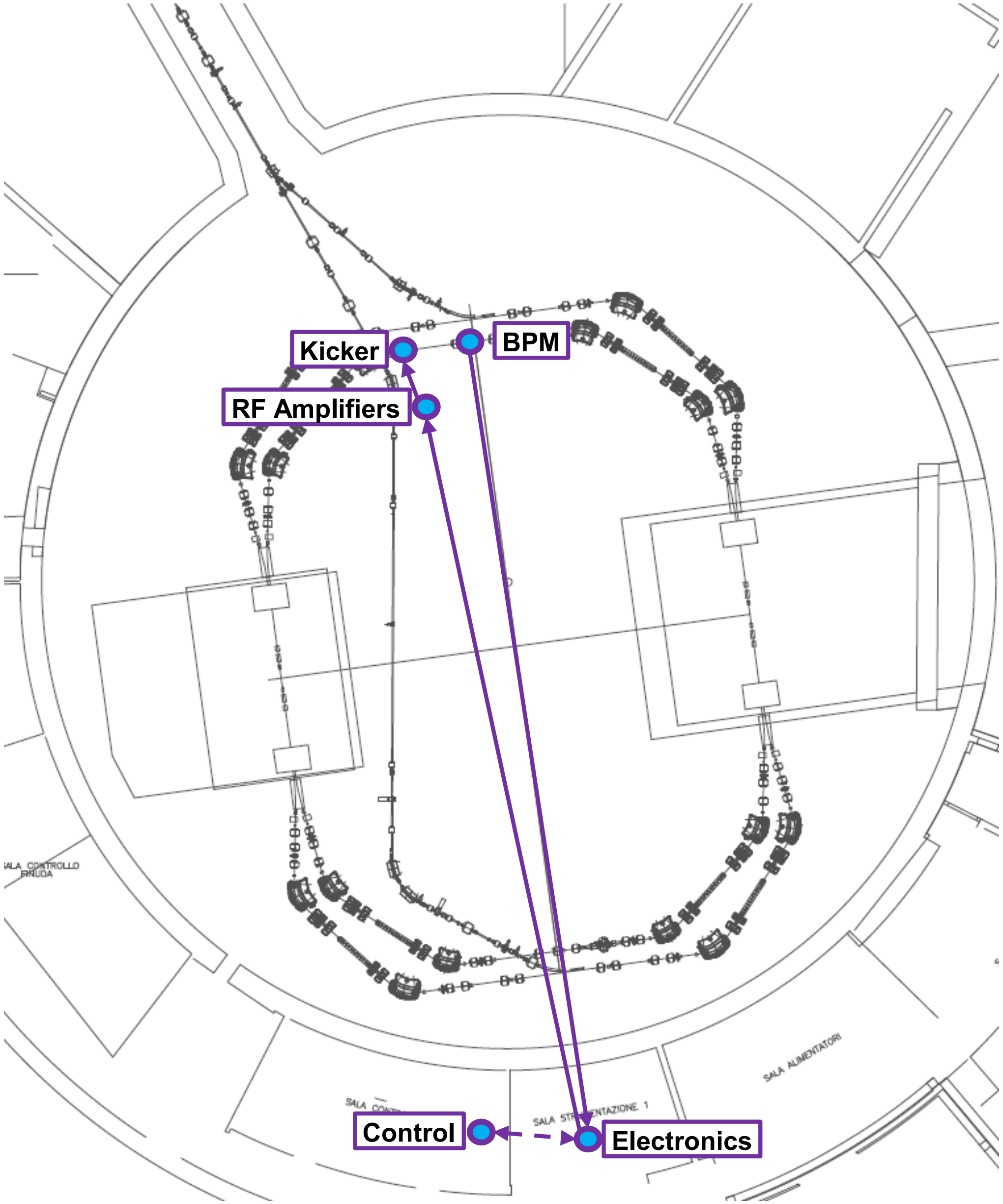


- KICKER

The correction signal is applied to the bunches with a longitudinal kicker (RF resonator).



Longitudinal e- Feedback



- **BPM** (BPBES 108)

The signals of the four electrodes are summed together (with power combiners) and sent to the electronics.

- **ELECTRONICS**

(instr. room – Rack 46 - multiple devices)

The analogue signal is adjusted (front-end) and digitized (ADC). The correction signal is calculated, transformed in an analogue signal (DAC), adjusted (back-end + delay unit) and sent to the RF amplifiers.

- **RF AMPLIFIERS**

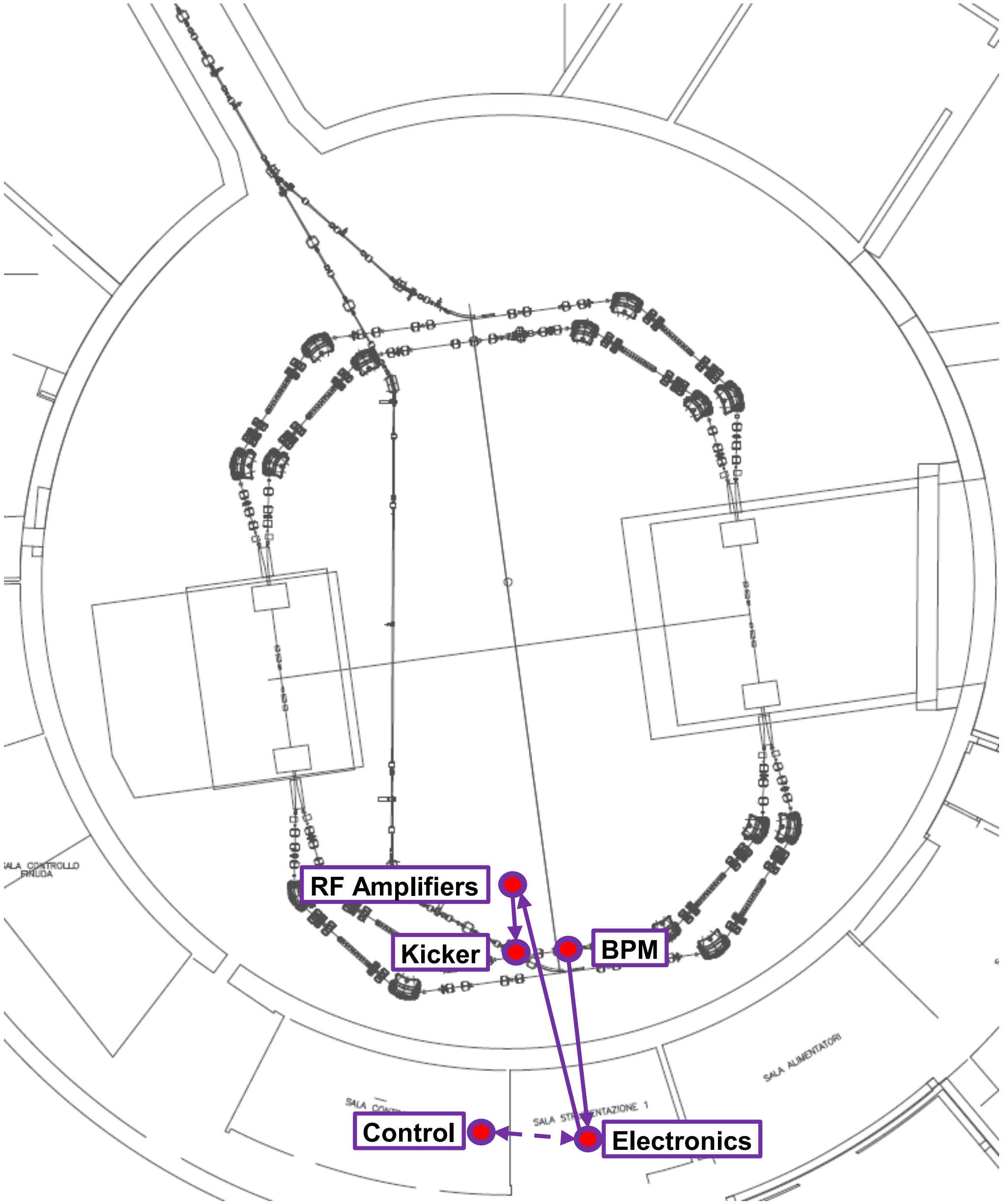
(Rack 54 - Three units)

The correction signal is amplified and sent to the kicker (through circulators)

- **KICKER**

The correction signal is applied to the bunches with a longitudinal kicker (RF resonator).

Longitudinal e+ Feedback



- **BPM** (BPBPS 108)

The signals of the four electrodes are summed together (with power combiners) and sent to the electronics.

- **ELECTRONICS**

(instr. room – Rack 46 - multiple devices)

The analogue signal is adjusted (front-end) and digitized (ADC). The correction signal is calculated, transformed in an analogue signal (DAC), adjusted (back-end + delay unit) and sent to the RF amplifiers.

- **RF AMPLIFIERS**

(Rack 51 - Three units)

The correction signal is amplified and sent to the kicker (through circulators)

- **KICKER**

The correction signal is applied to the bunches with a longitudinal kicker (RF resonator).