An overview of the longitudinal bunch by bunch Feedback at DAΦNE

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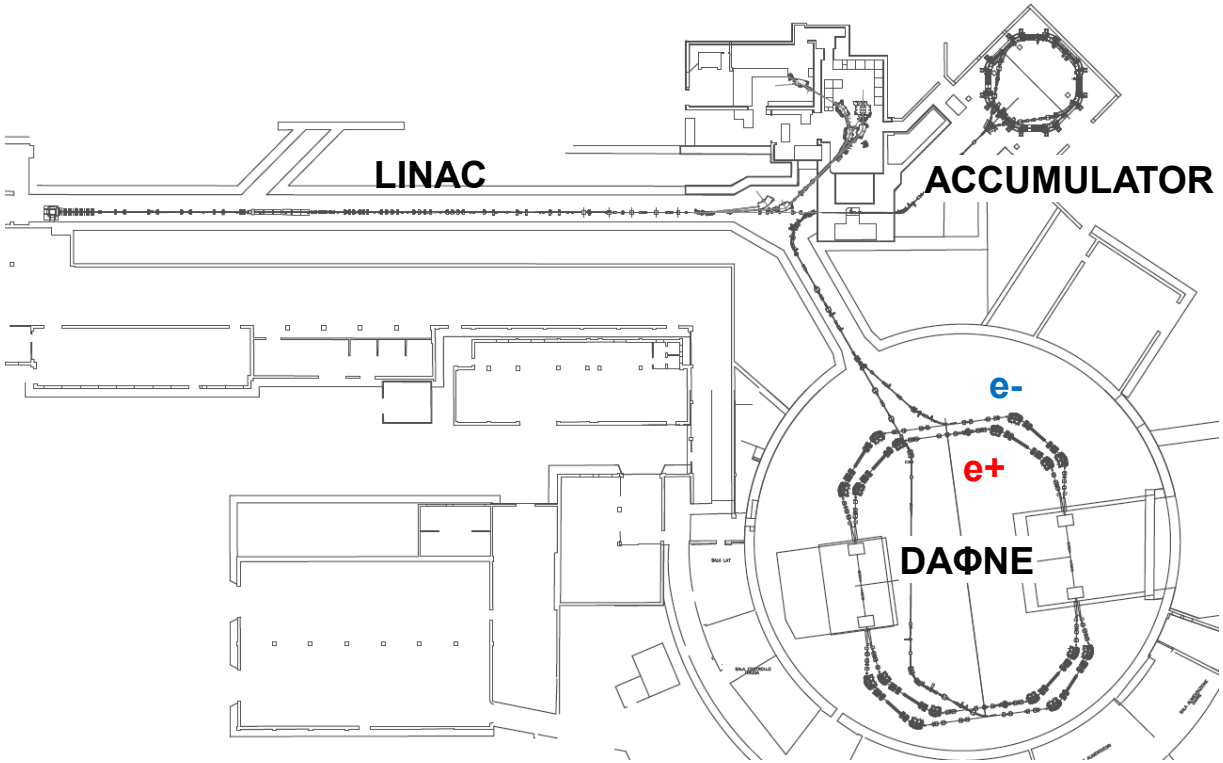
Introduction

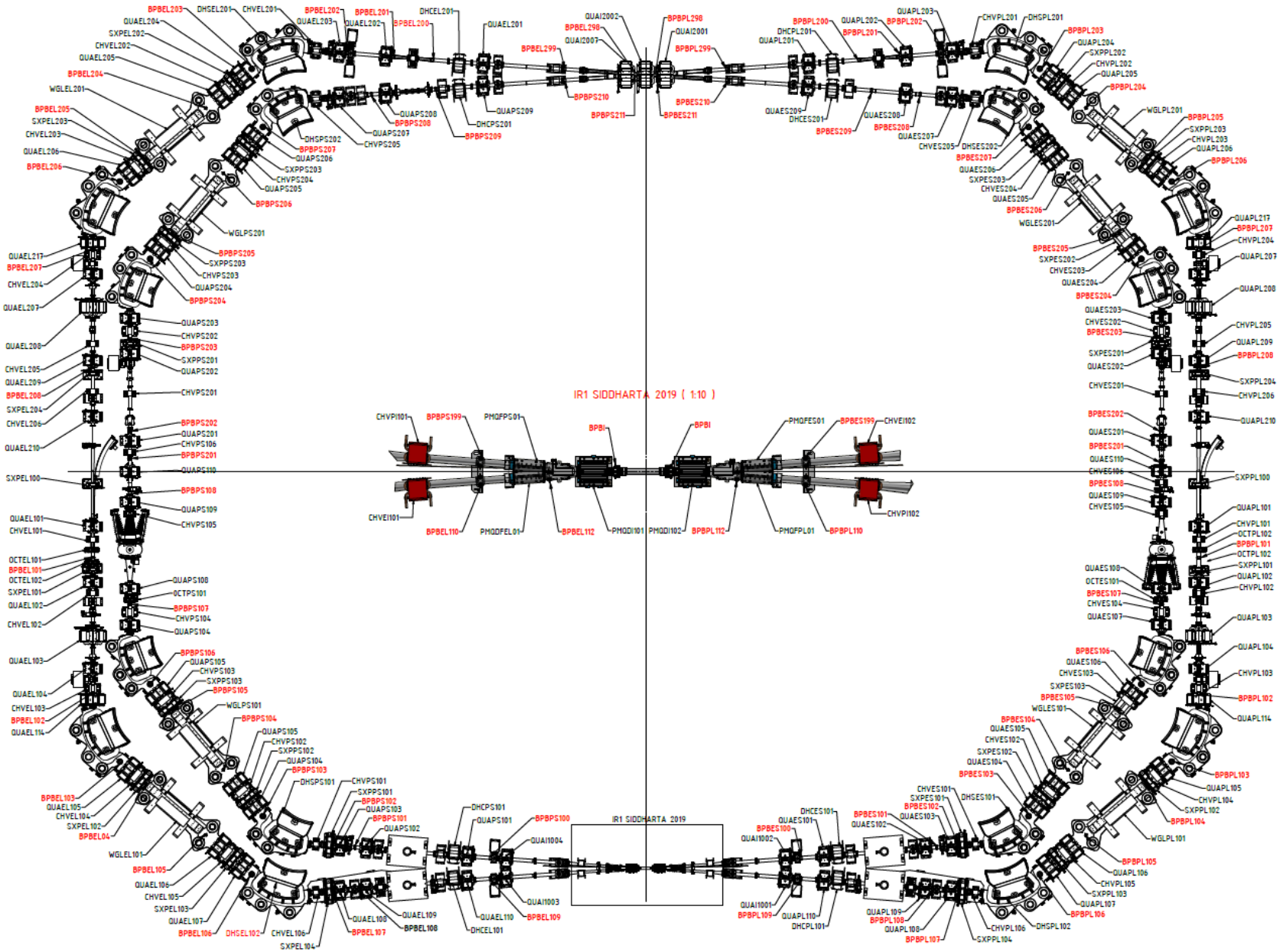
- **DAΦNE is an electron-positron collider** in operation at LNF for physics experiments since 1999.
  - **It is composed of an injection system and two rings (~97 m)**, one per type of beam.
  - It operates with (usually) **90 bunches at 510 MeV,** with a **time interval of 2.71 ns** between each other**.** Typical **stored currents** are in the range of **1-2 A**.

Presently DAFNE is completing the commissioning phase, intended to optimize the collision conditions in view of the run with the SIDDHARTA-2 apparatus. The latter is being developed in order to perform measurements of kaonic deuterium X-ray transitions to the fundamental level.



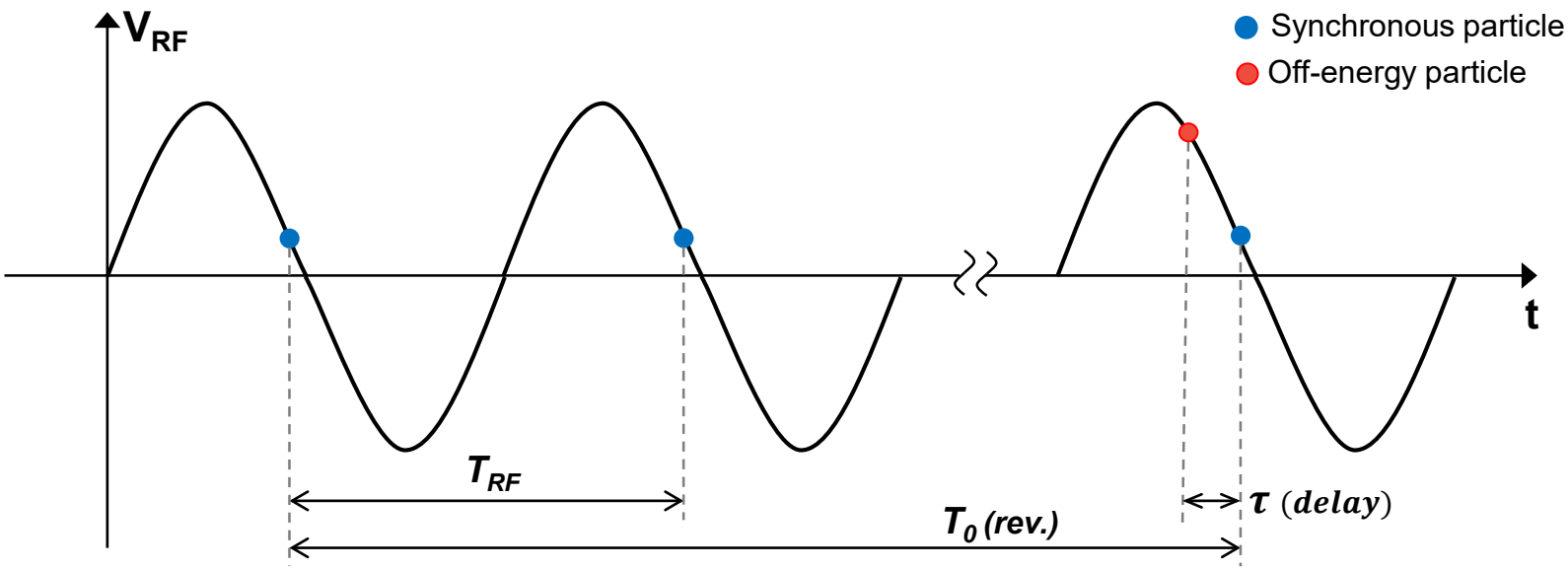
(see: DAFNE Commissioning for SIDDHARTA-2 experiment. C.Milardi et al. EPAC2021, Campinas, Brasil, 1997)

DAFNE Layout



Longitudinal Dynamics Introduction

Particles in a storage ring do not all have the nominal energy. Their energy will deviate from the nominal energy, performing **oscillations** around it (named synchrotron oscillations). This means that the particles will have **different revolution periods**. We will discuss about the latter in terms of a **delay** τ referred to the nominal revolution period (T_0) of the synchronous particle.



- V_{RF} is the RF cavity voltage
- T_0 is the nominal revolution period (325.73 ns).
- T_{RF} is RF cavity period (2.71 ns), which coincides with the time distance between subsequent bunches (when all the RF buckets are filled)
- τ is the delay of an off-energy bunch, referred to the synchronous particle

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 $d_r \ll \omega_s$)

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

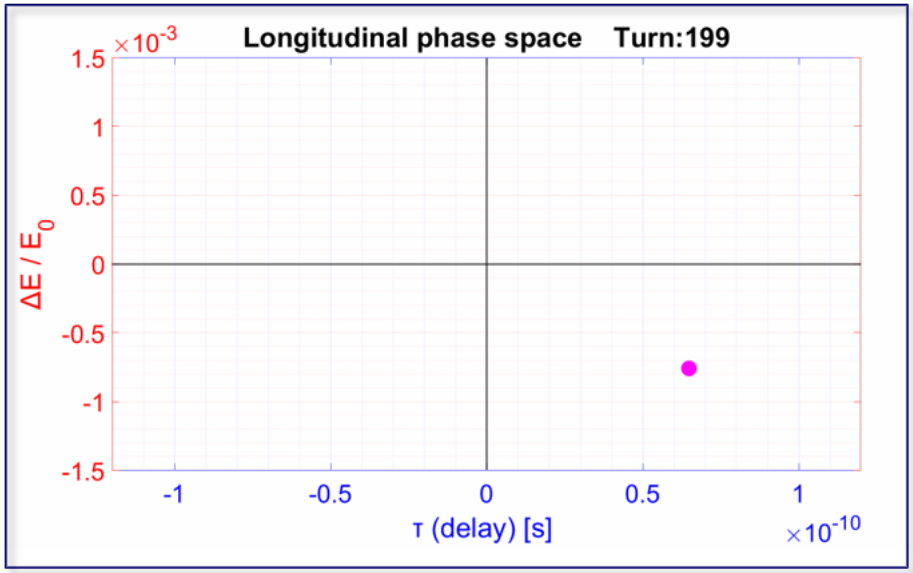
$\varphi = -2\pi f_{RF} \cdot \tau$

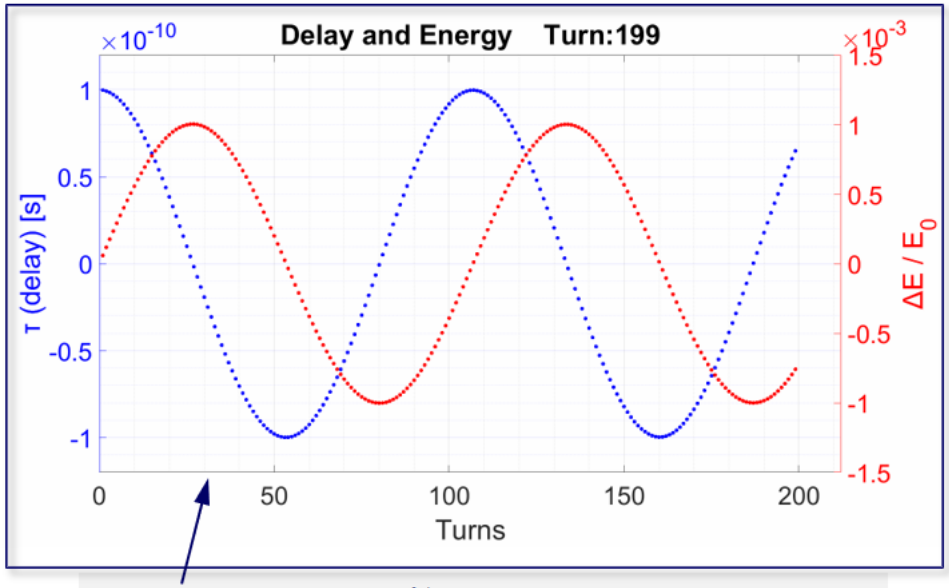
phase of the bunch (referred to the synchronous phase) could be used instead.

A and Θ_0 depend on the initial conditions.

Similarly for $\Delta E/E_0$:

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





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

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

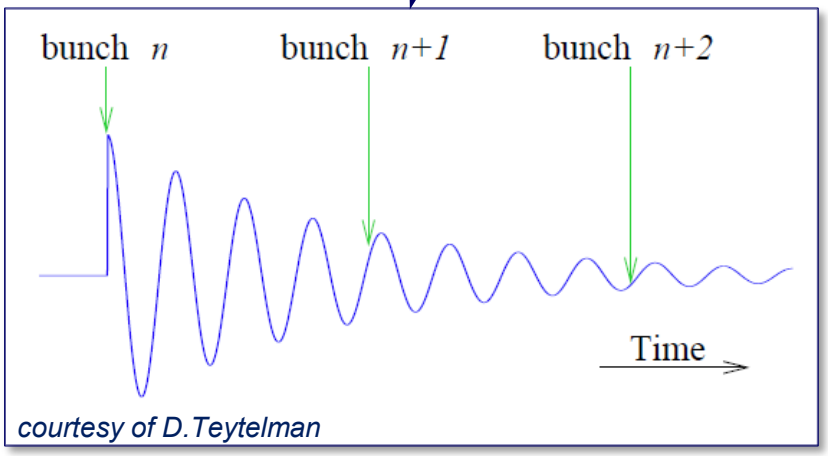
Coupled bunch instabilities

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.



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

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

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.

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

Introducing the Longitudinal Feedback

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

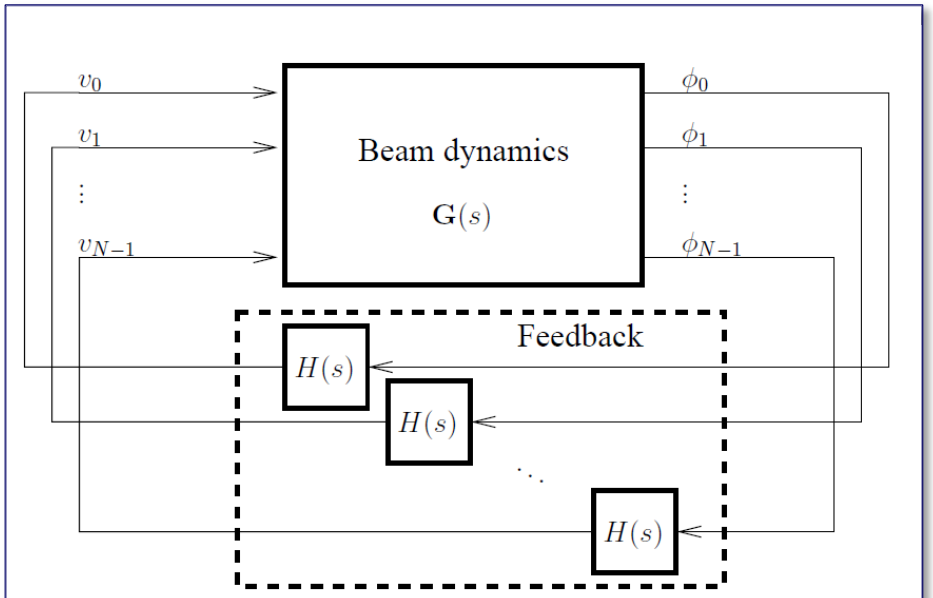
$$\ddot{\tau}_n + 2d_r\dot{\tau}_n + \omega_s^2\tau_n = -\frac{\alpha_c e}{E_0 T_0}\cdot V_n^{wk}(t)$$

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

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

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 nth 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 each of the six feedback systems is similar.

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

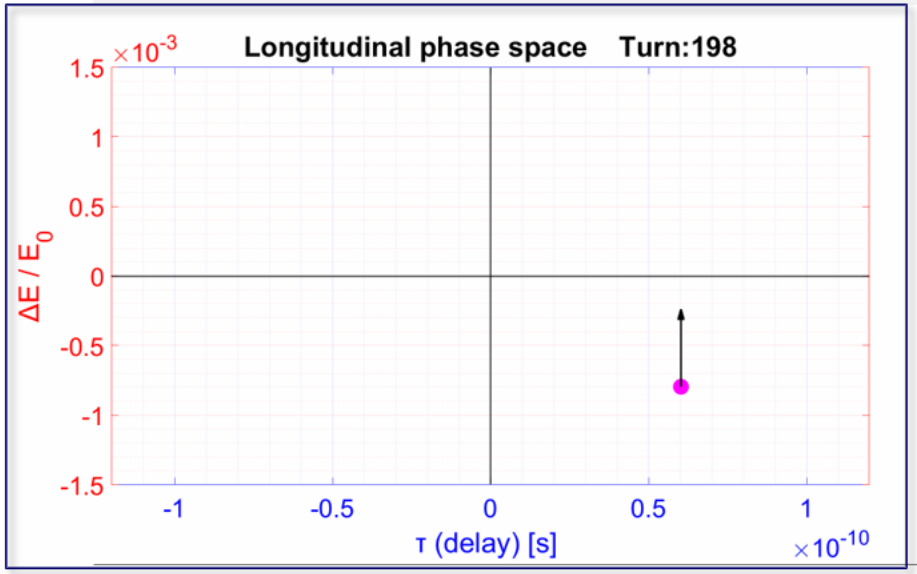
Feedback action

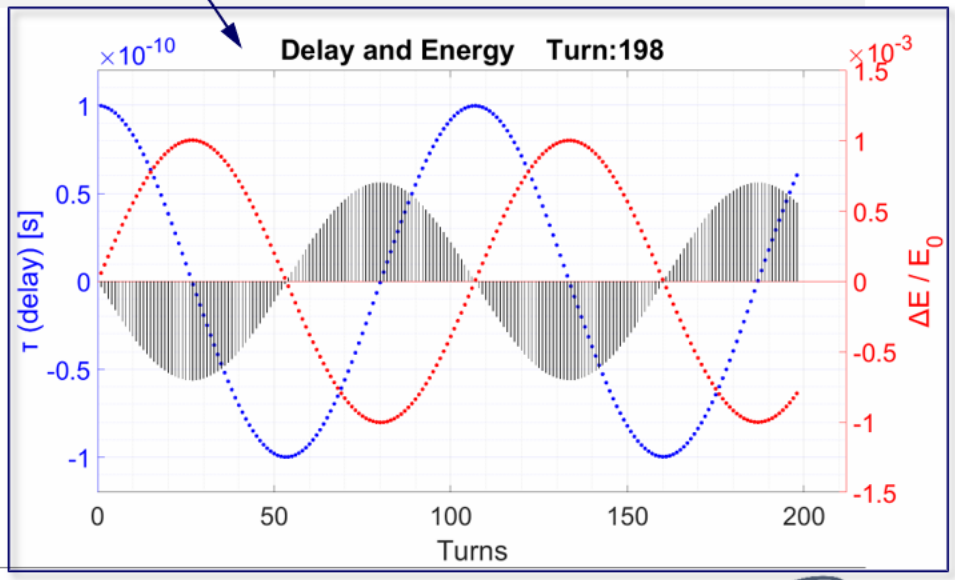
The action of the feedback consists in **individual longitudinal kicks** to each bunch and for each turn (excluding decimation tecniques).

Each turn and for each bunch:

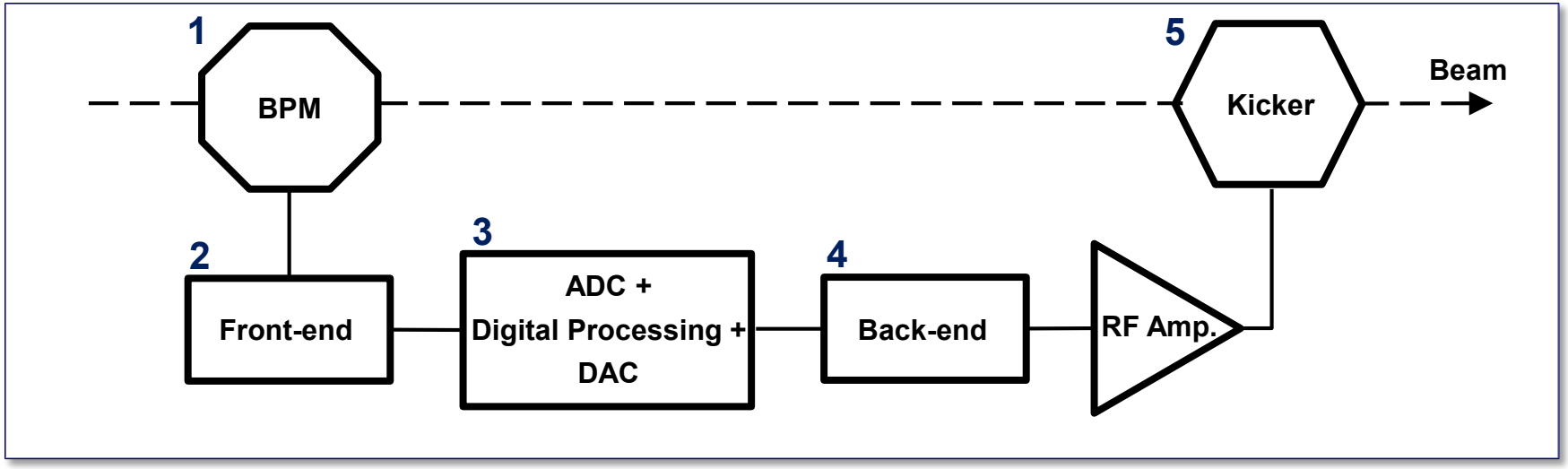
- Delay (phase) is measured.
- Correction signal (longitudinal kick) is elaborated.
- Longitudinal kick is applied.

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.





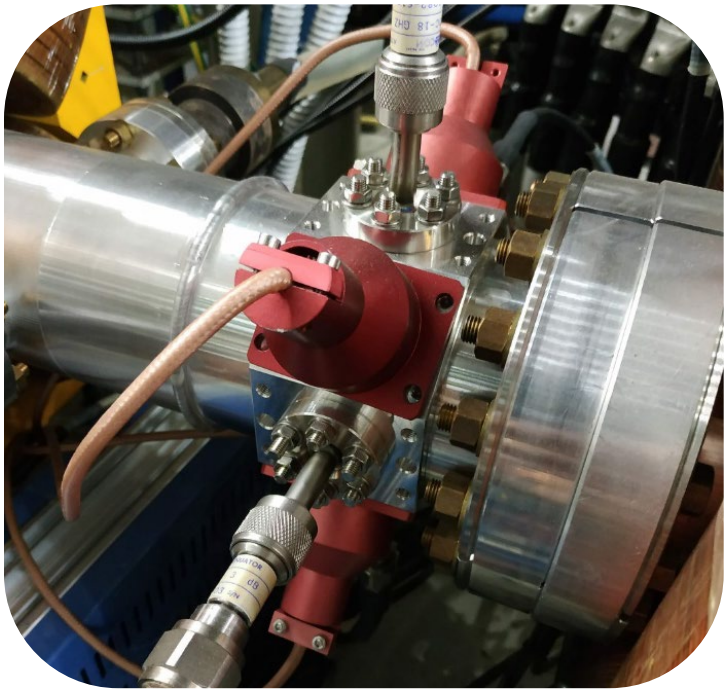
Longitudinal Feedback

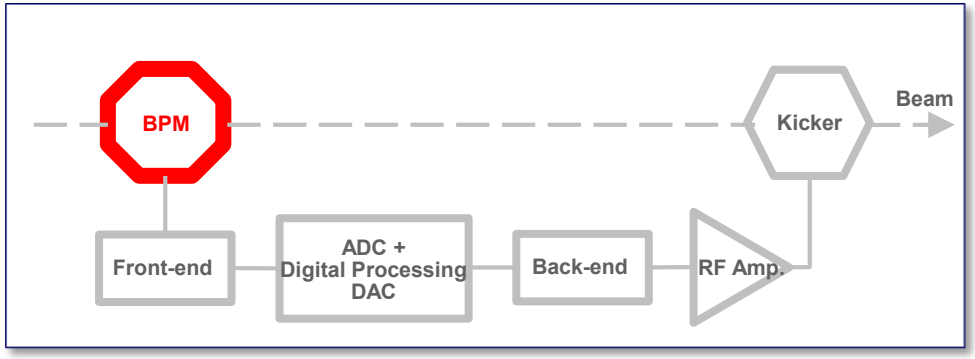


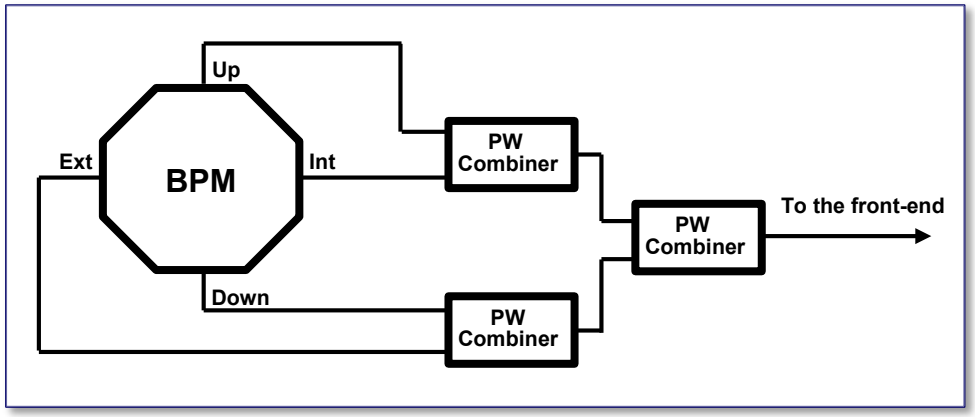
The longitudinal feedback acts on the phase of the bunches. It applies a correction signal in the form of a longitudinal kick (by means of a RF cavity).

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





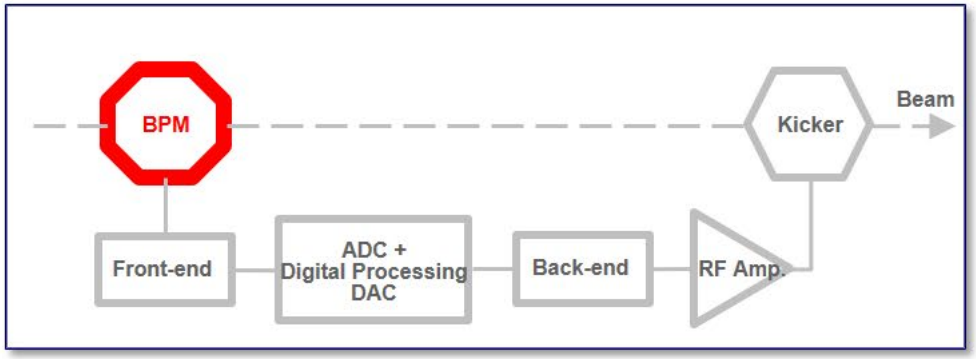


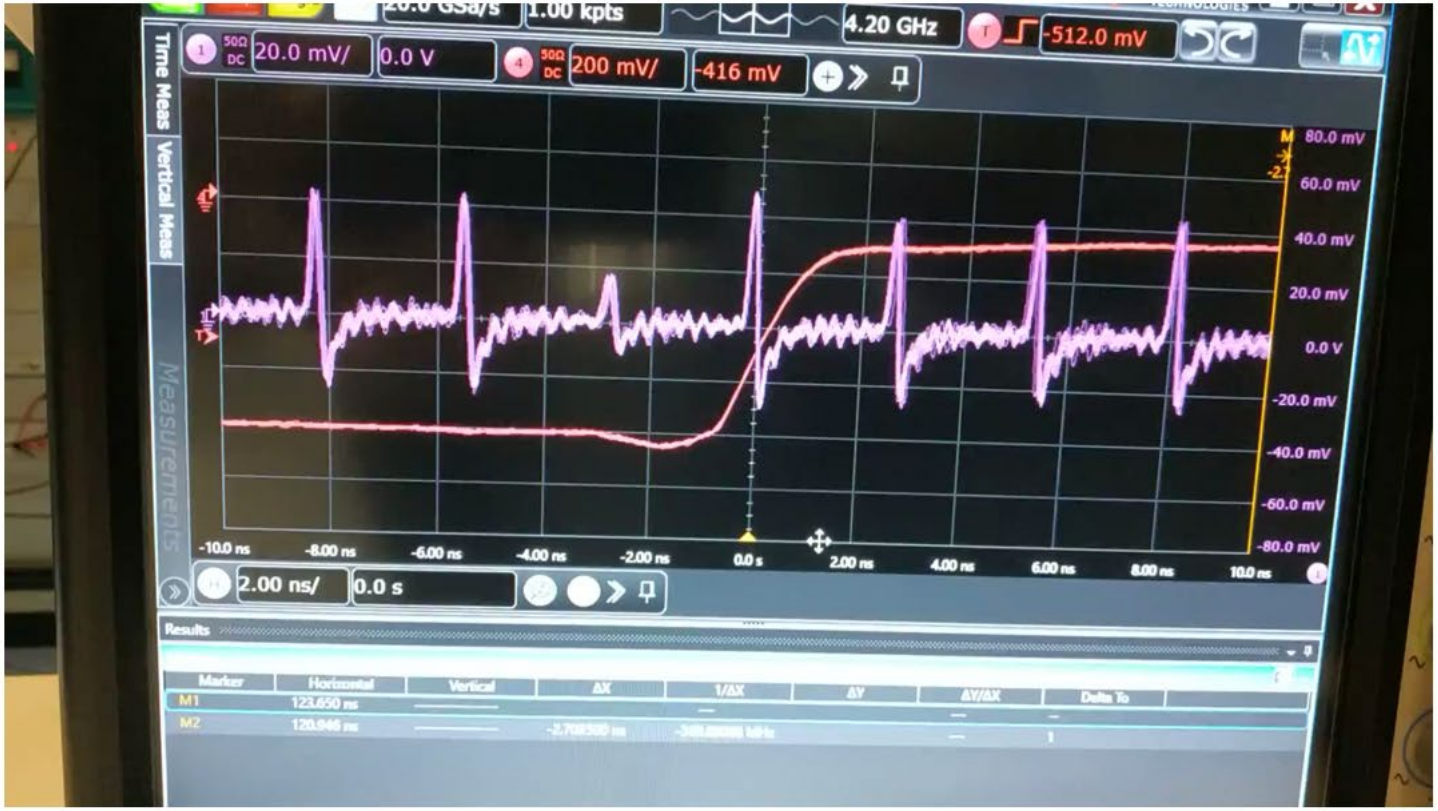
The BPM used in the feedback are specifically designed for it:

- **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.

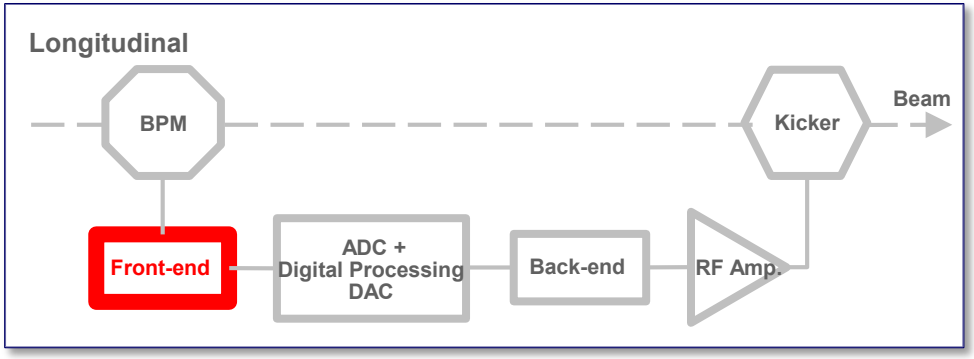
(see: DAFNE broad-band button electrodes. F.Marcellini, M.Serio, A.Stella, M.Zobov. Nuclear Instruments & Methods in Physics Research, 1997)

Broad-band Button BPM

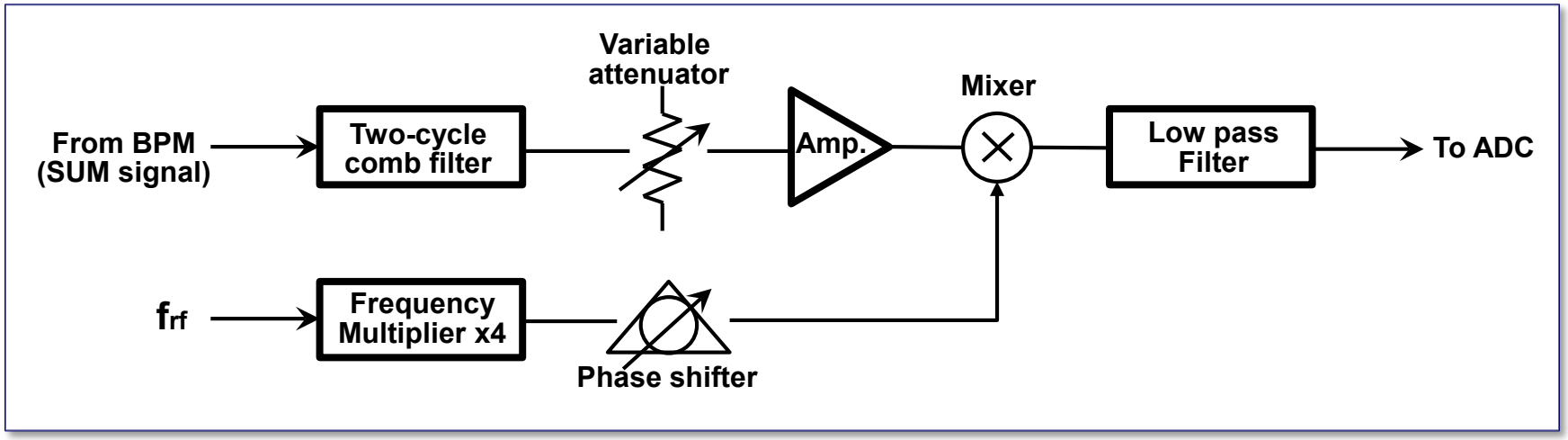




DIMTEL FBE 368L (Front-end)

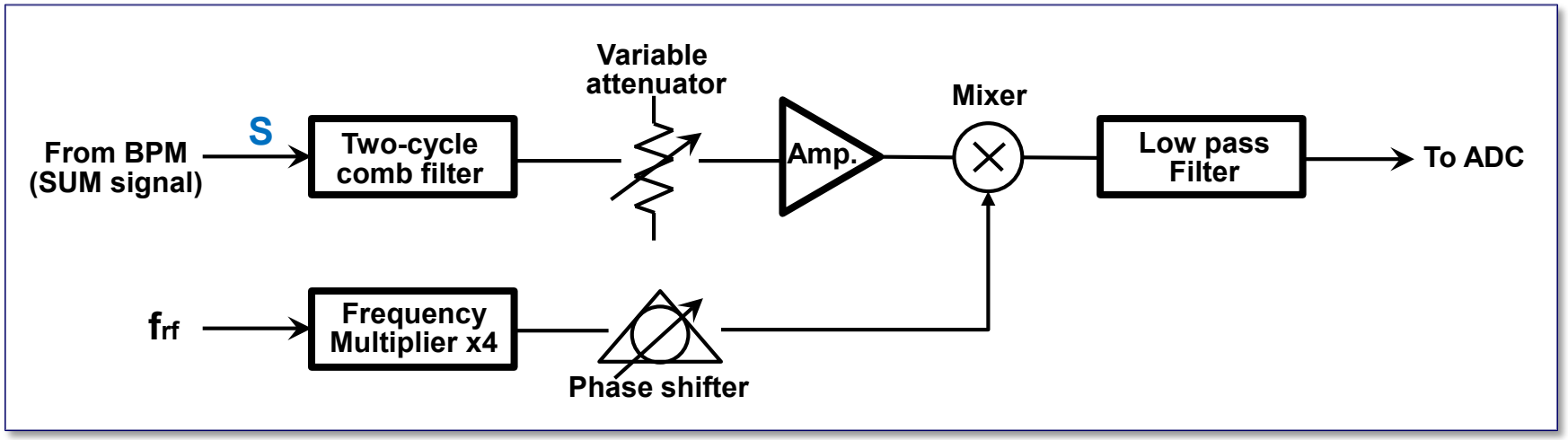


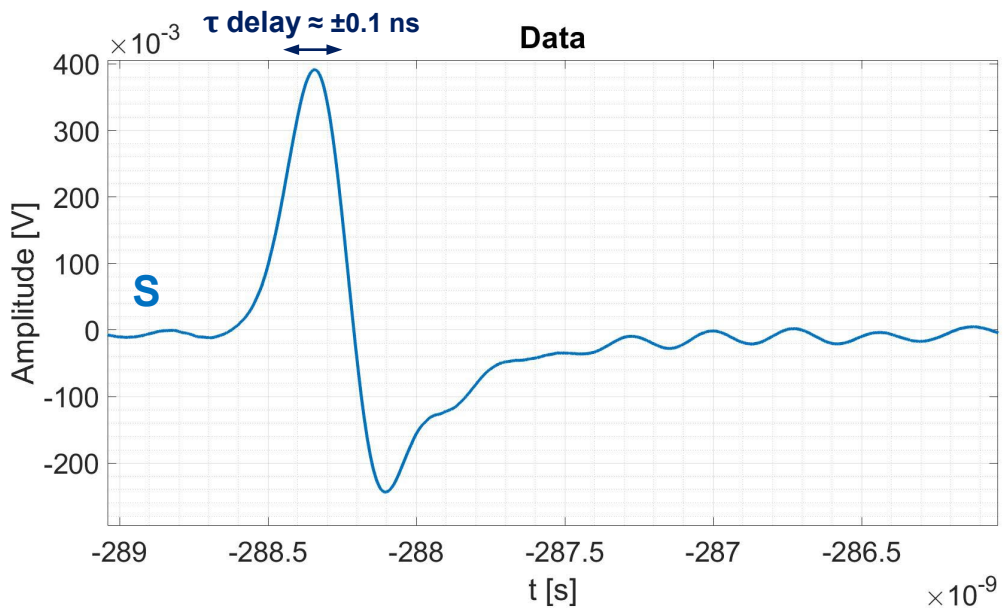
The Front-end main functionality is to transform the phase of the BPM signals into an amplitude signal (to be digitized later on).



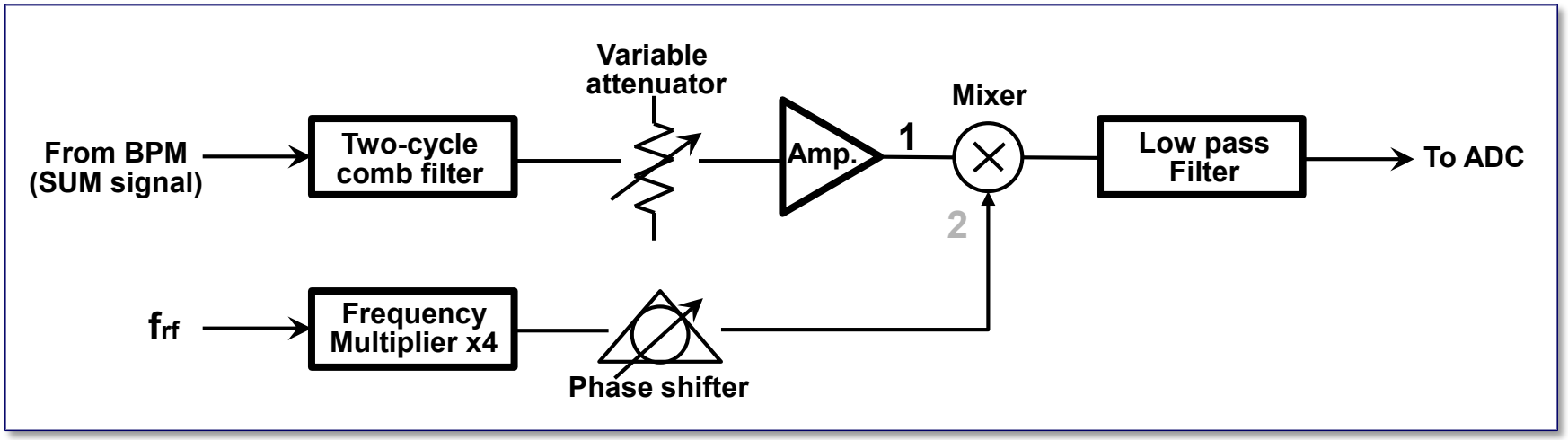
Variable attenuator and phase shifters values are controllable via software.

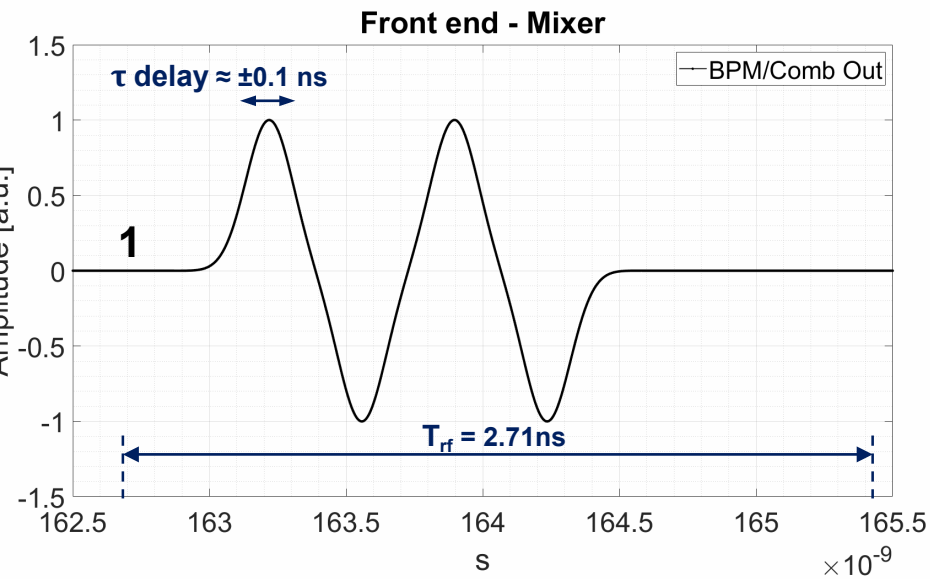
DIMTEL FBE 368L (Front-end)

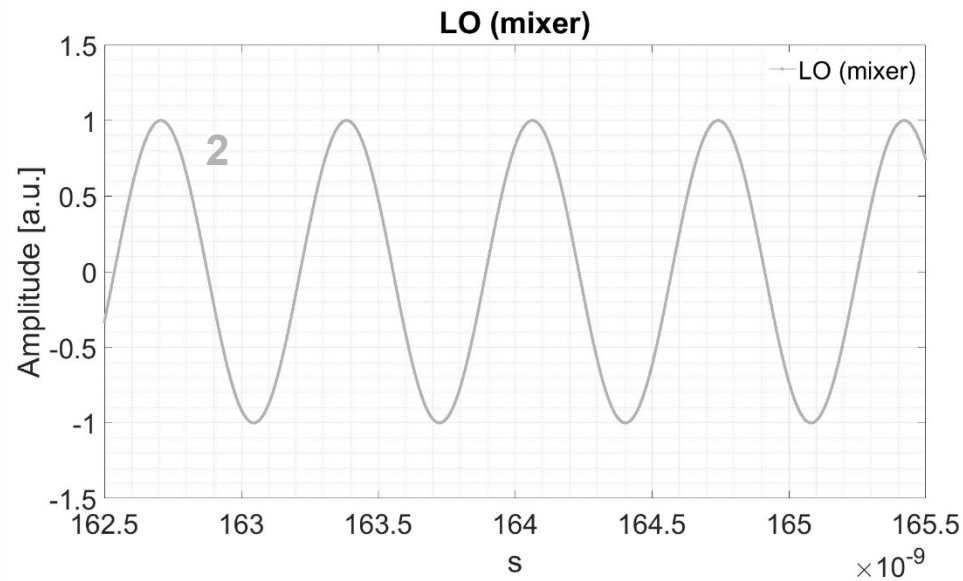




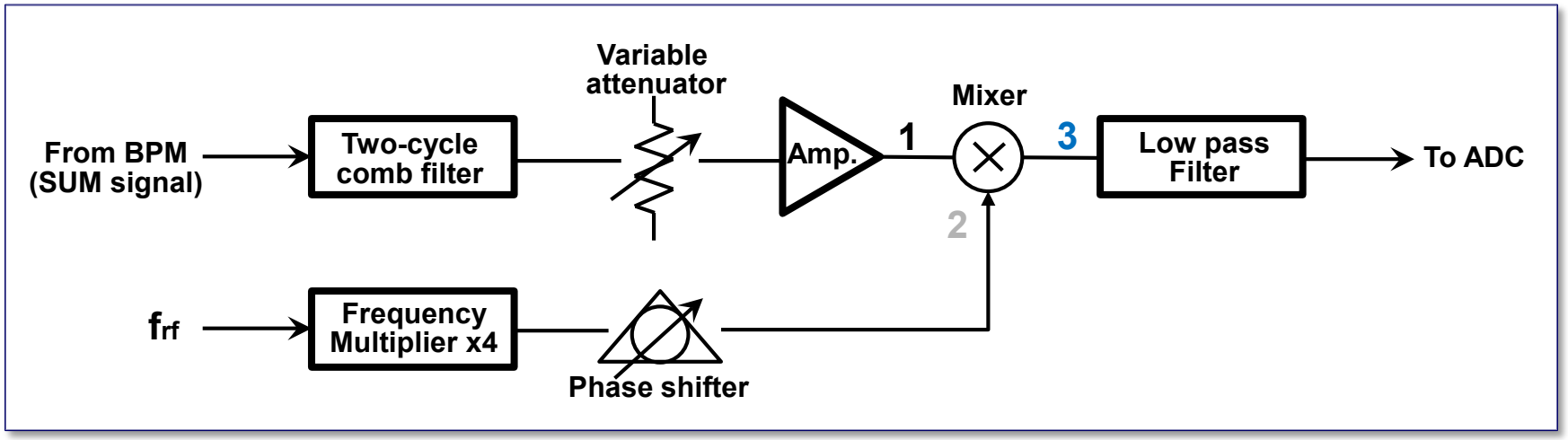
DIMTEL FBE 368L (Front-end)

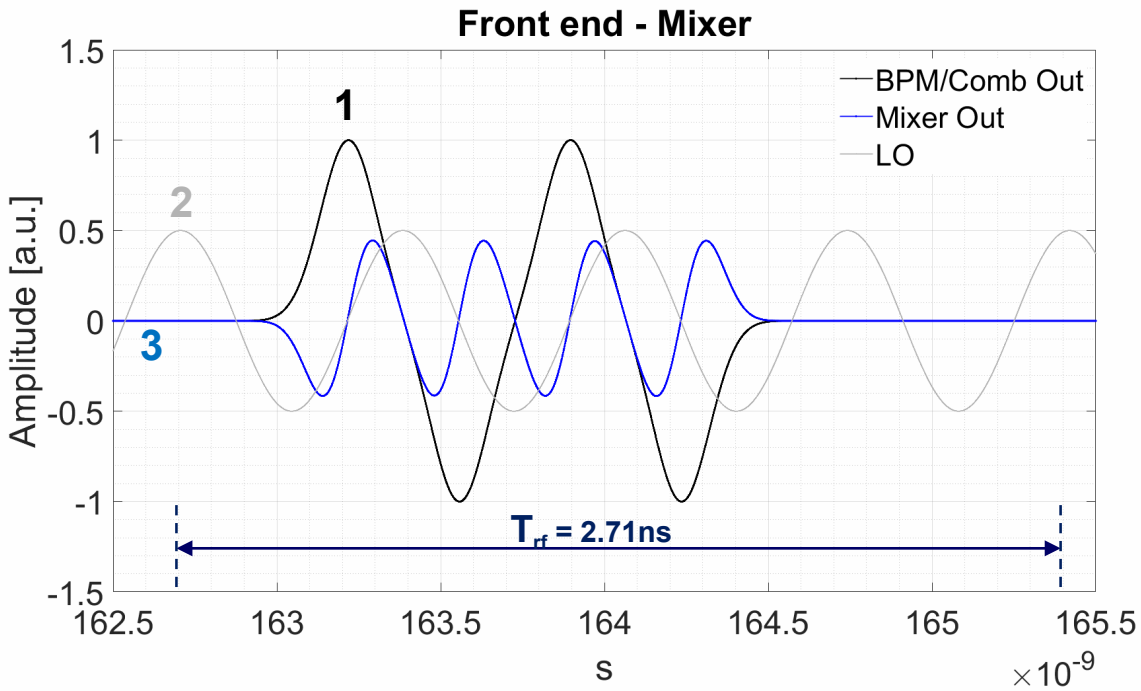






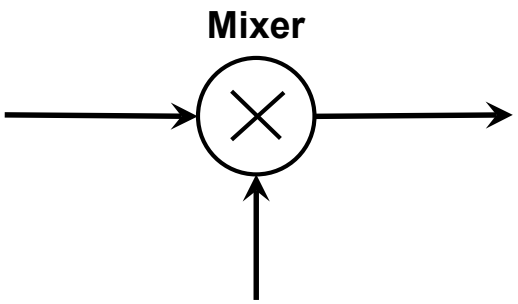
DIMTEL FBE 368L (Front-end)





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

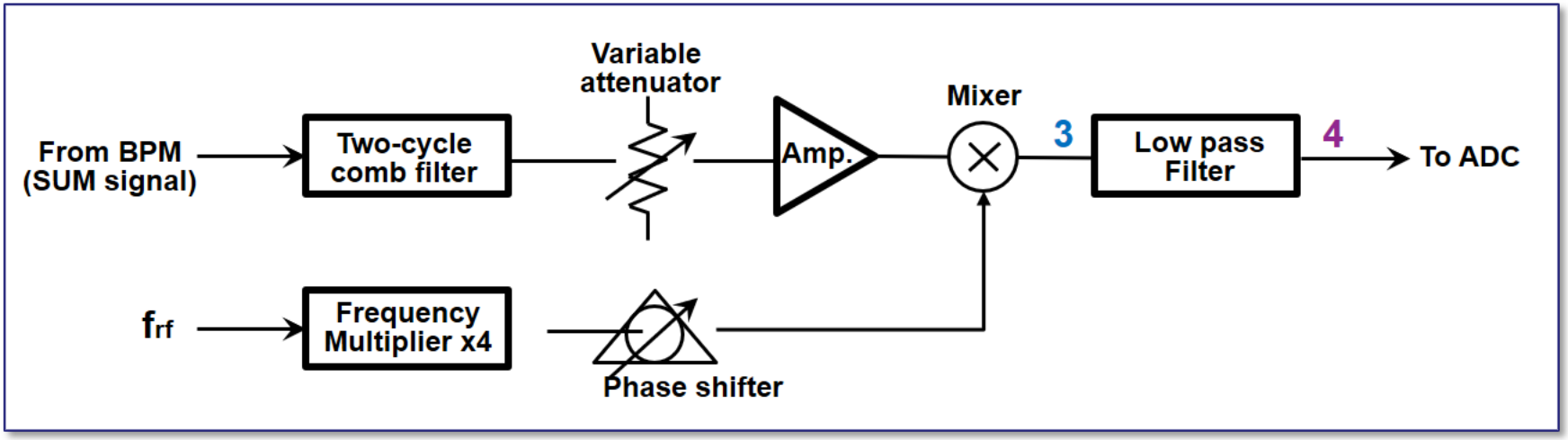
φ_{IN} is what we want to measure
For small angles: $\sin(\varphi_{IN}) \approx \varphi_{IN}$

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

DC component

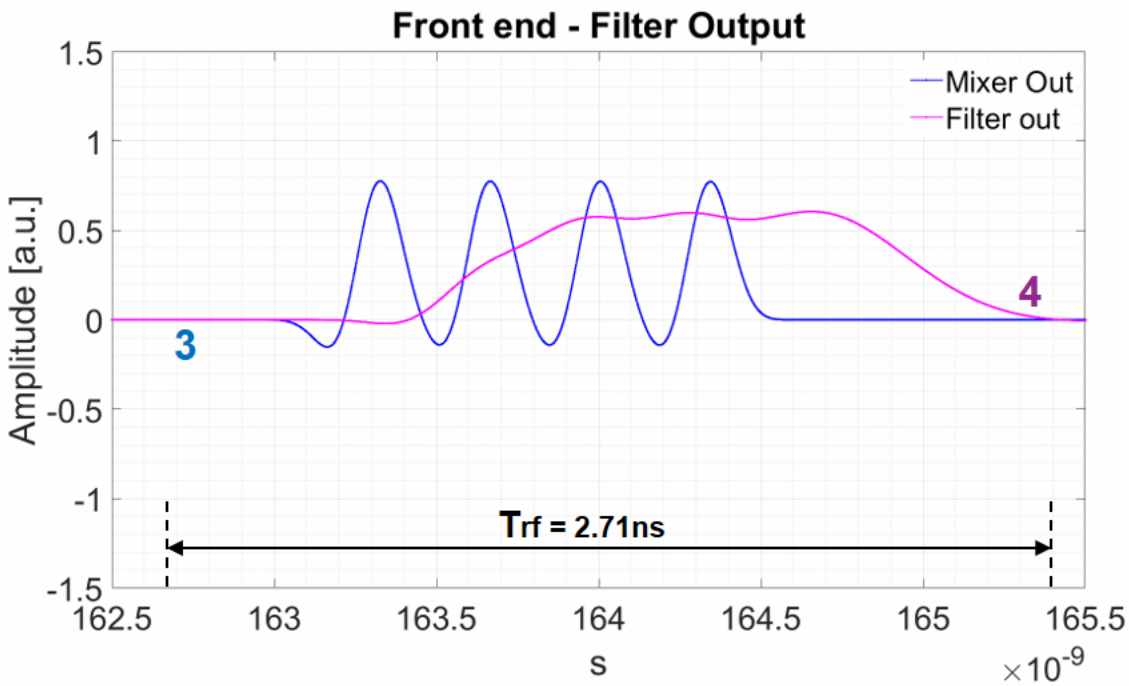
$8 \cdot \omega_{RF}$ component
(it will be filtered out)

DIMTEL FBE 368L (Front-end)

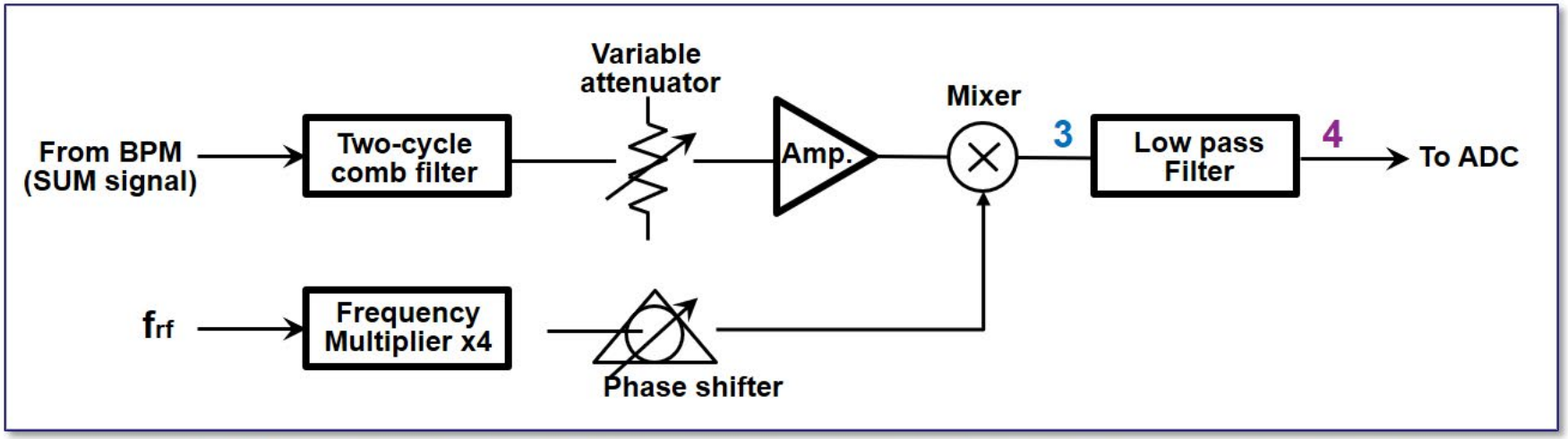


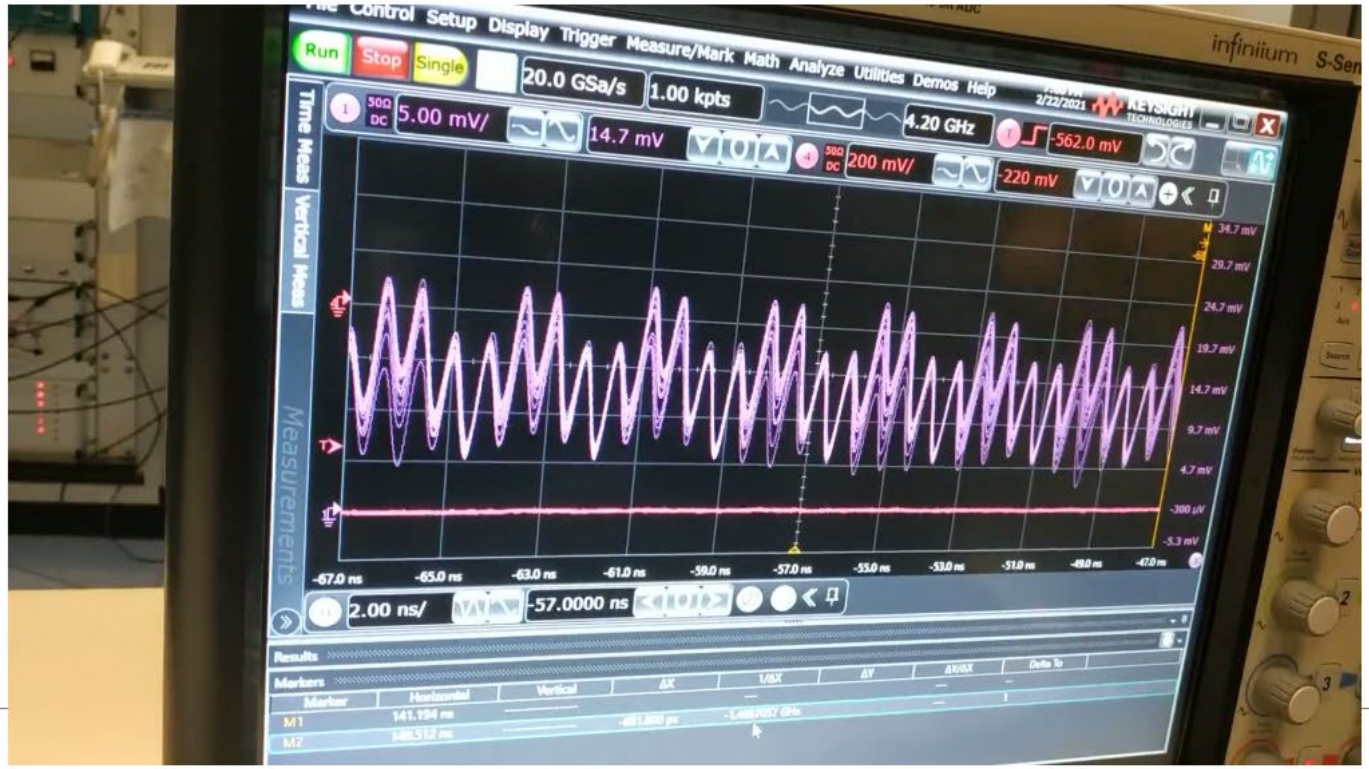
Bessel 4th ord. Low Pass Filter with f_{cut}=1,1 GHz (~3·f_{rf}).

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)





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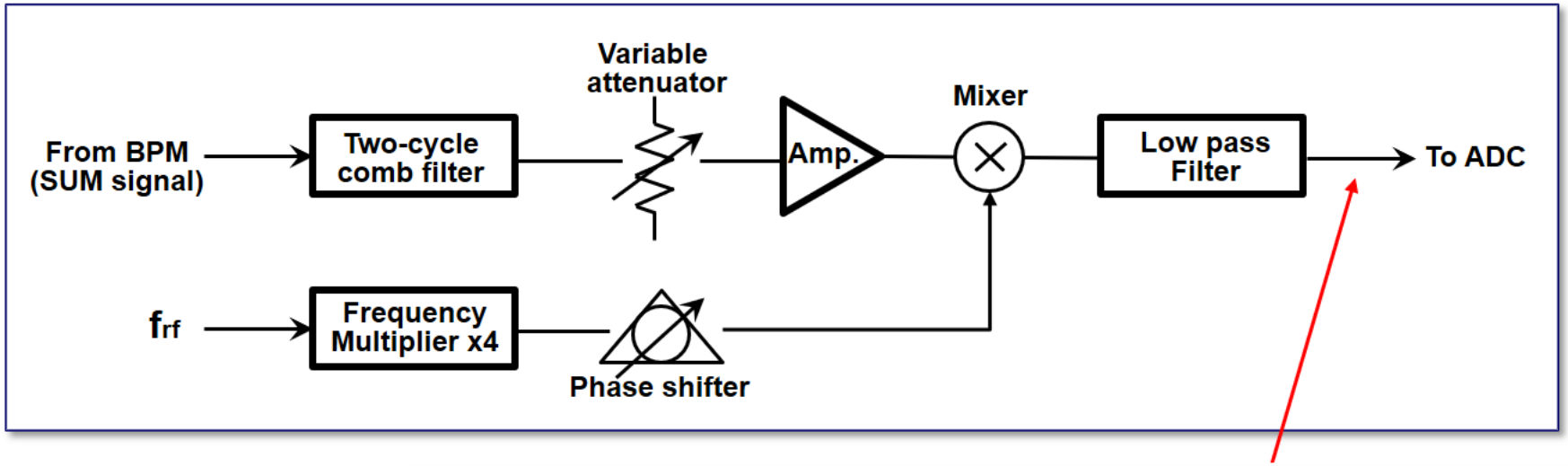
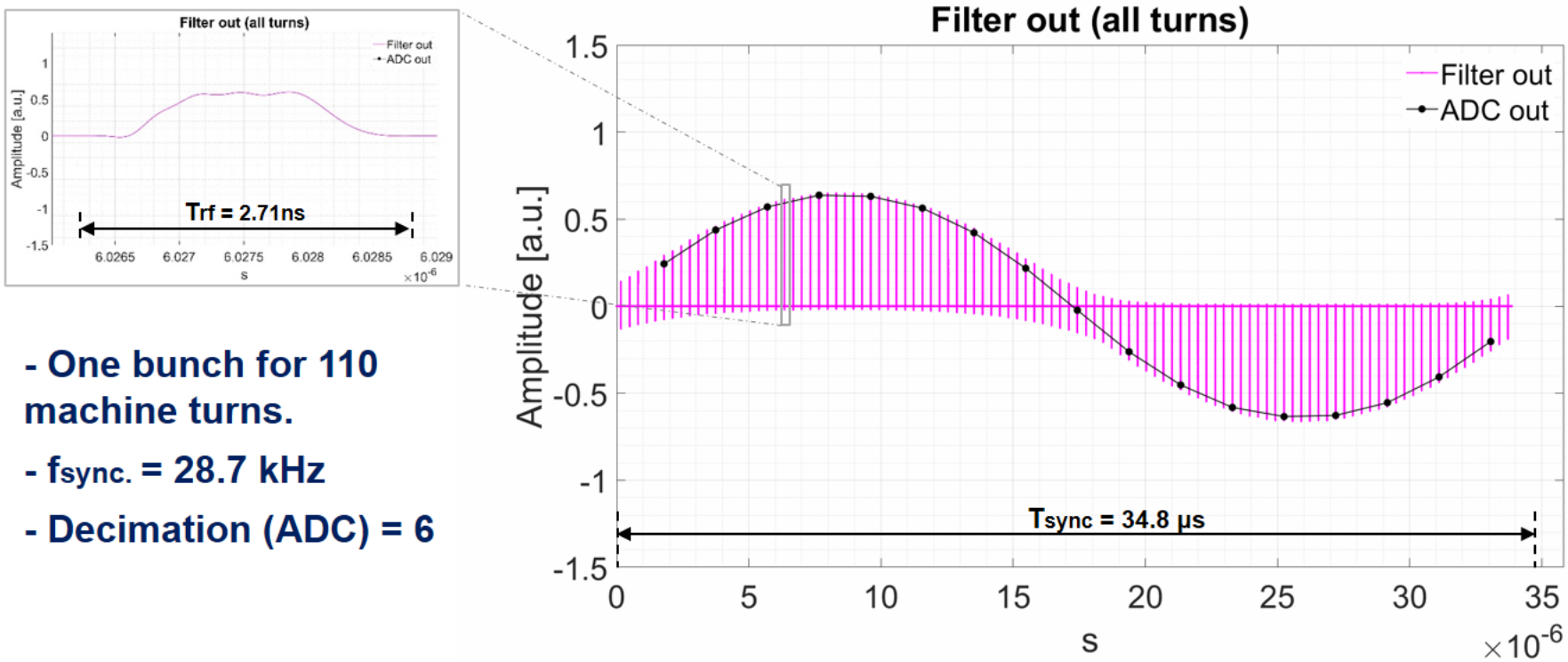
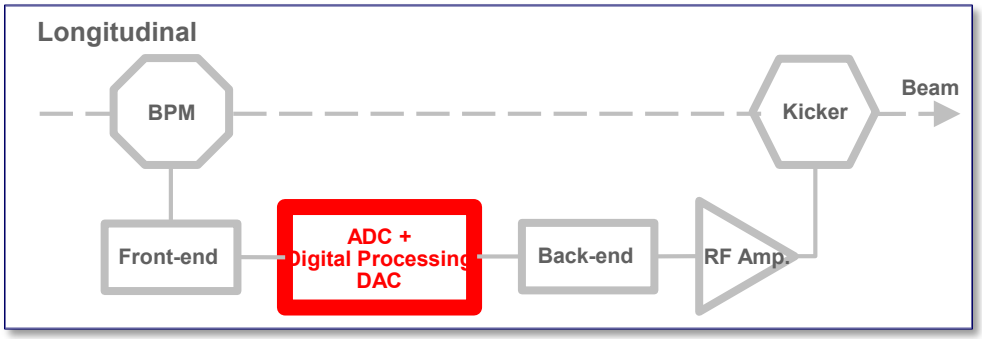




- One bunch for 110 machine turns.
- $f_{sync.}$ = 28.7 kHz
- Decimation (ADC) = 6

DIMTEL iGP-120F

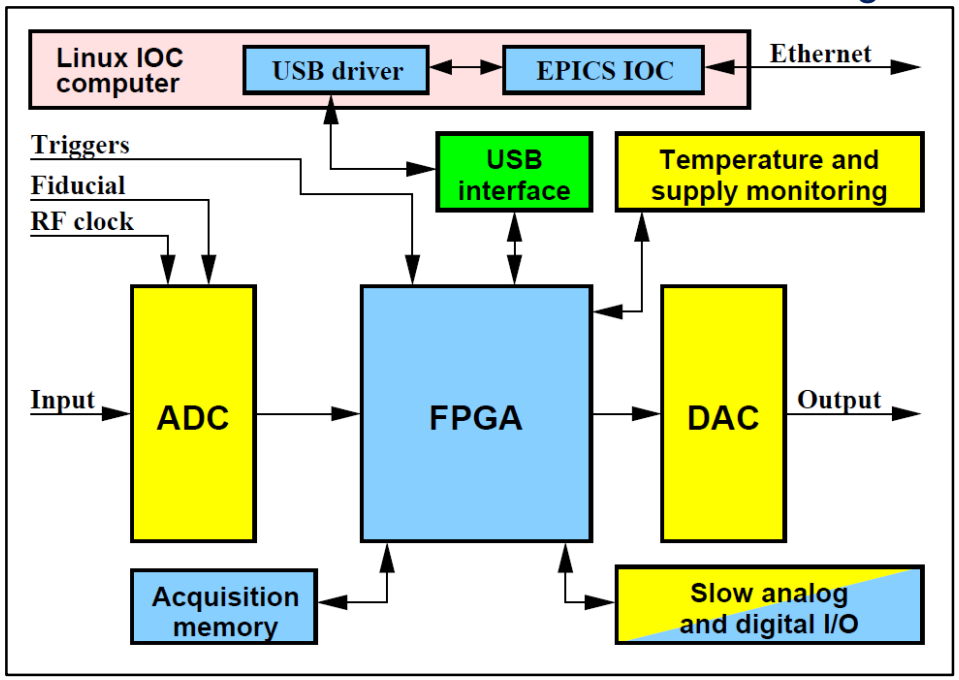


It represents the core of the system. It elaborates the correction signal, based on the phase measurements.

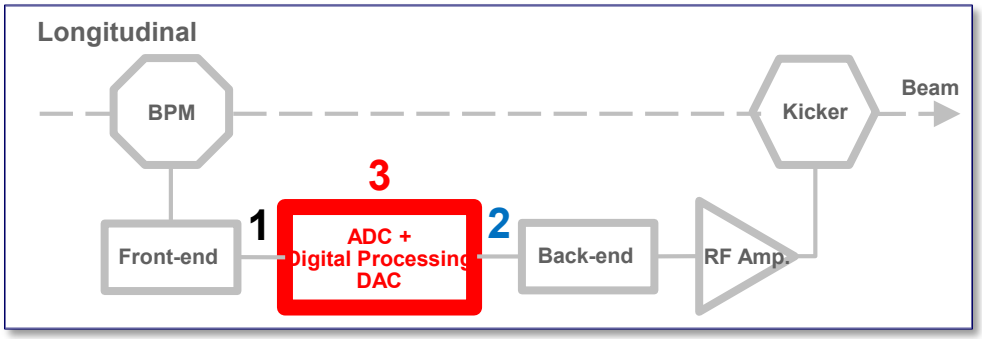
Parameter	Value
Operating Frequency	368 MHz
ADC resolution	8 bits
ADC input bandwidth	1.26 GHz
ADC input Full scale	200 mV_{p-p}
Number of FIR taps	16
Shift Gain (output adjustment)	2^0 - 2^7
DAC resolution	12 bits
DAC rise time (10%-90% FS)	under 250 ps
DAC fall time (90%-10% FS)	under 350 ps
DAC Full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

All the parameters and functionalities are controllable via software.

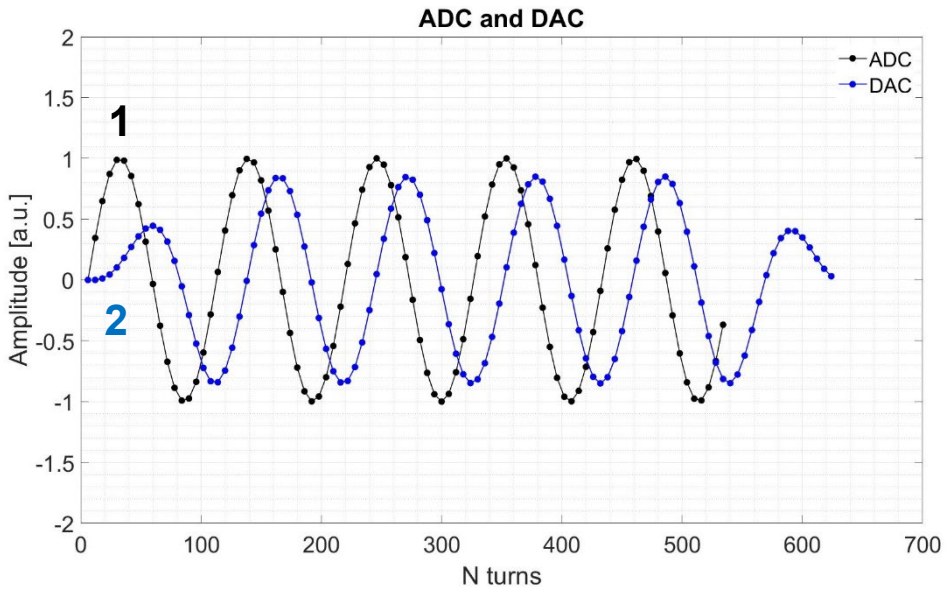
Block Diagram



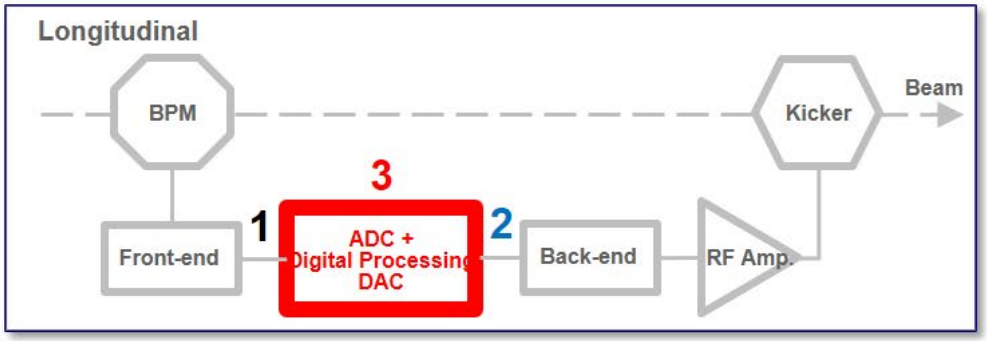
DIMTEL iGP-120F

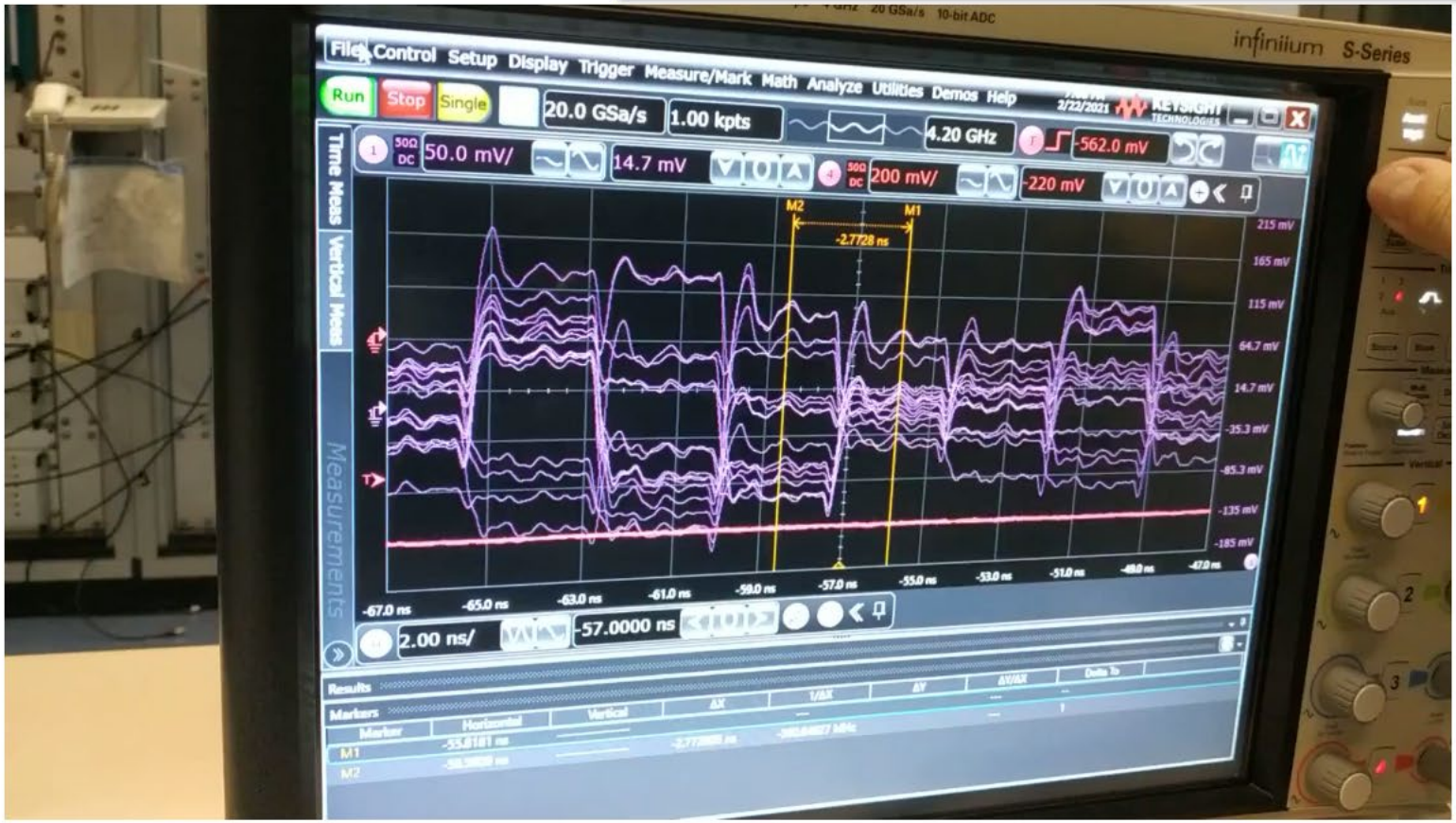


By means of a **sinusoidal digital filters** (16 taps), we obtain the **correction signal** for the n-th bunch. In first approximation, **the filter applies a gain** (user-selectable) and **a phase shift of -π/2** to the digitized signal.

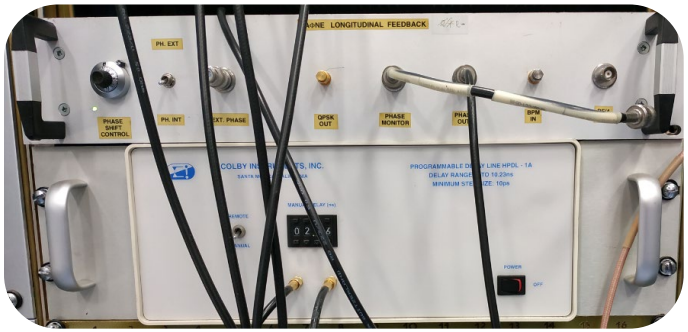


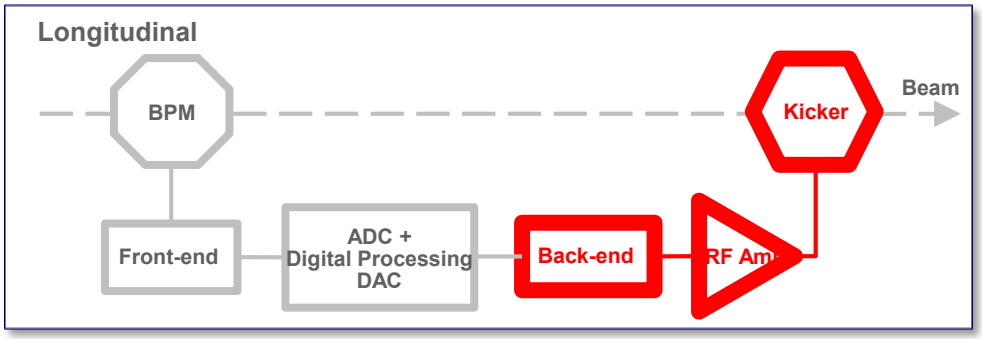
DIMTEL iGP-120F – DAC OUTPUT





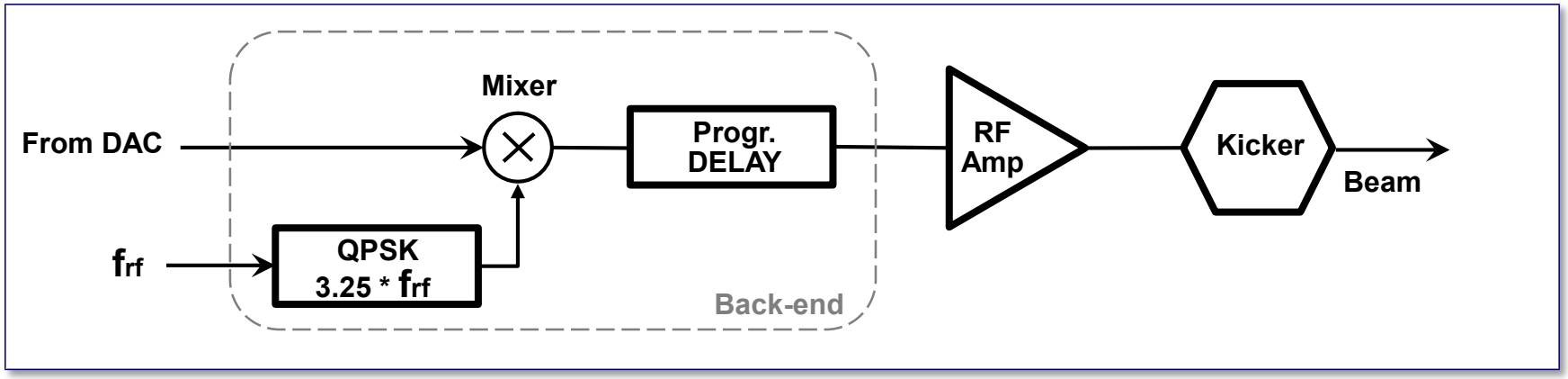
Dafne Long. Feedback (back-end)



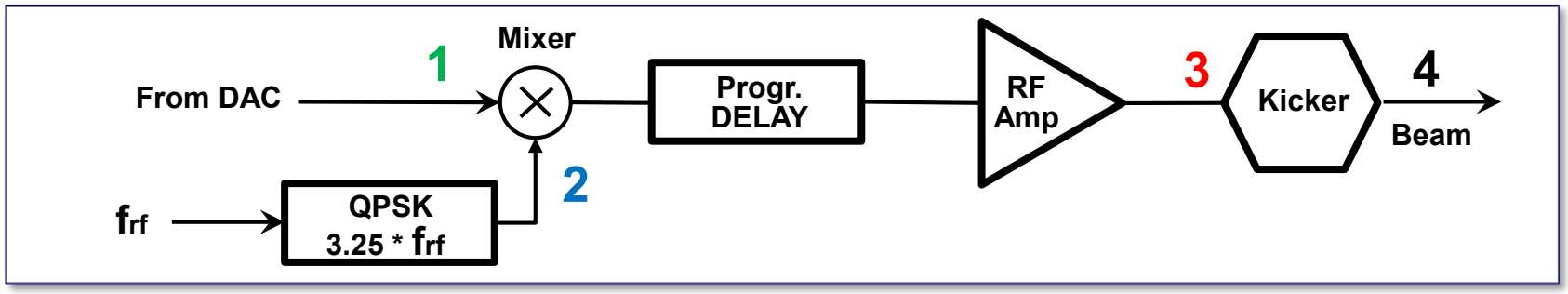


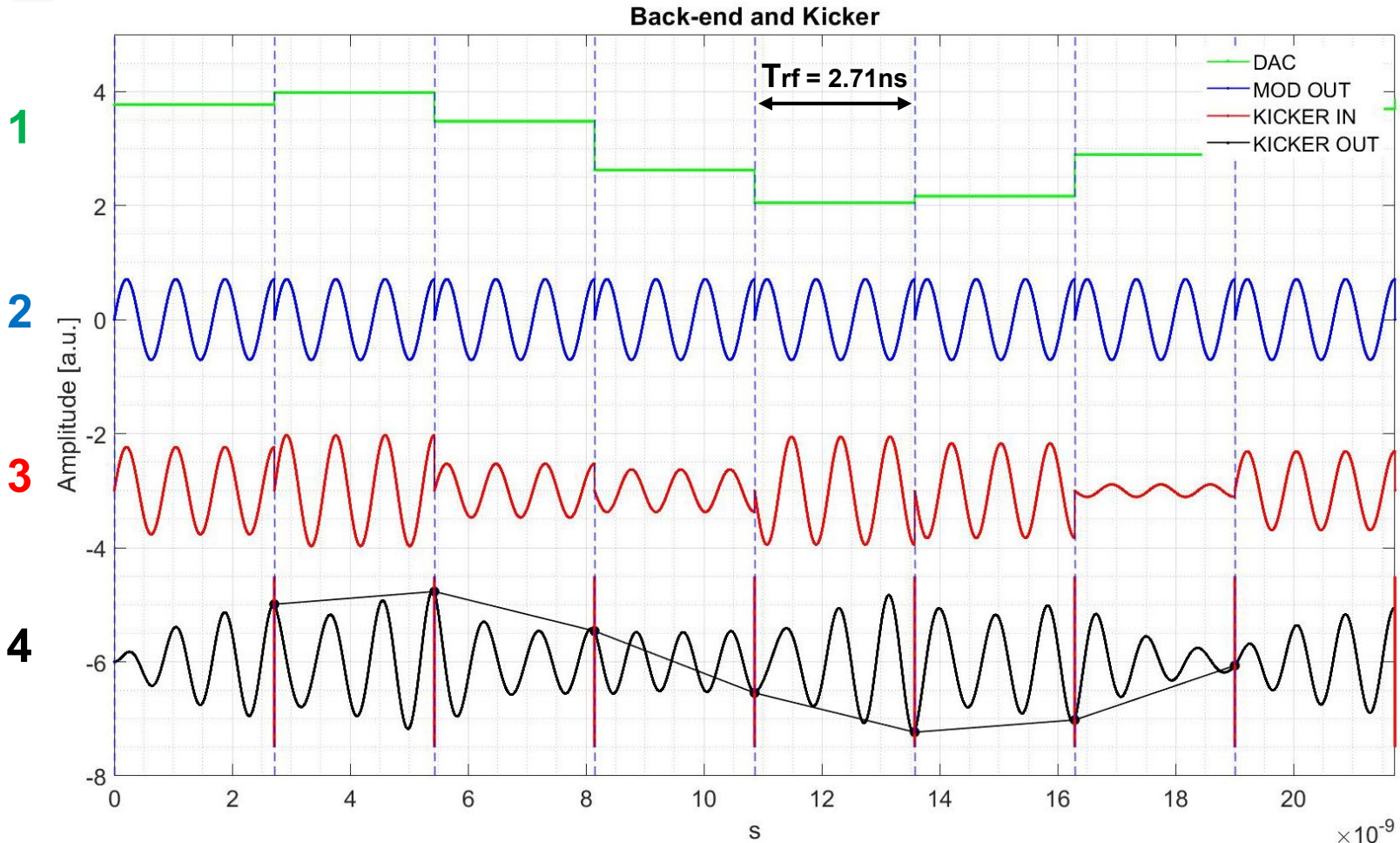
The back-end main functionalities are:

- 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 COLBY HPDL-1A Progr. Delay Line).

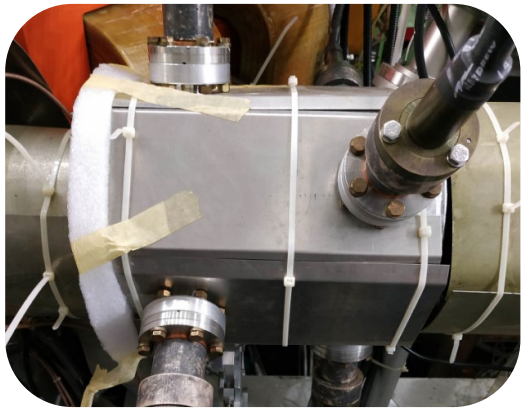


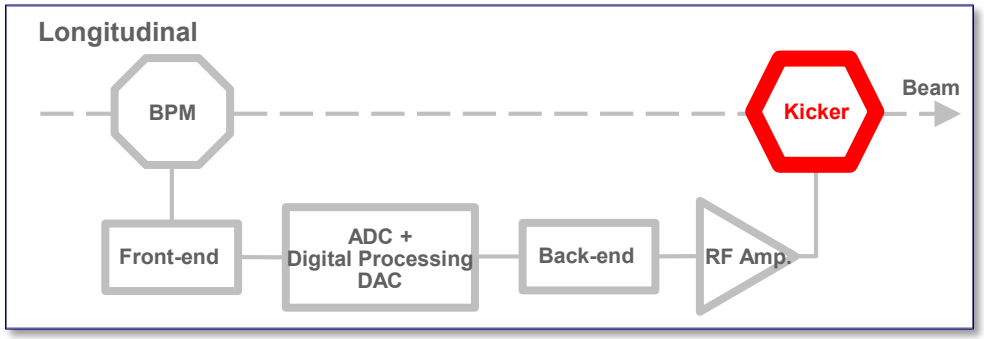
Longitudinal Feedback Back-end

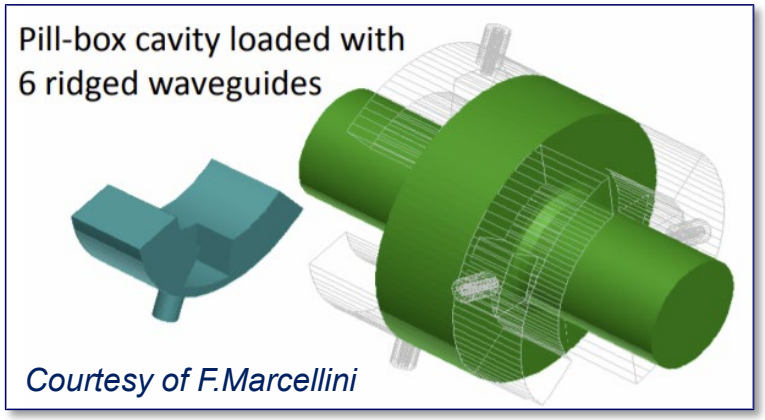




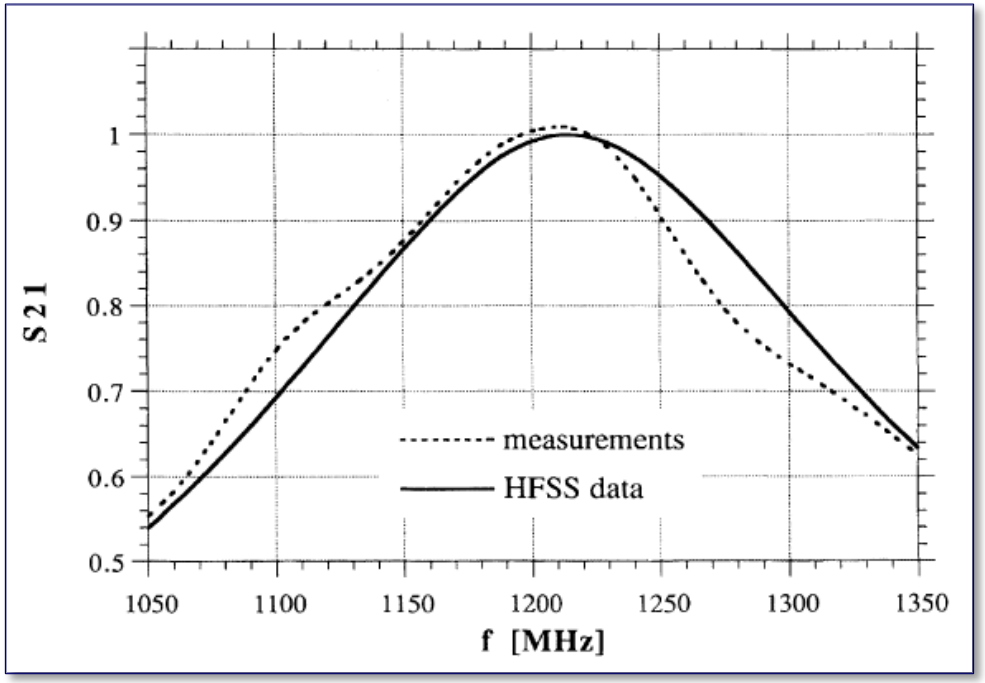
Longitudinal Feedback Kicker







Transmission coefficient



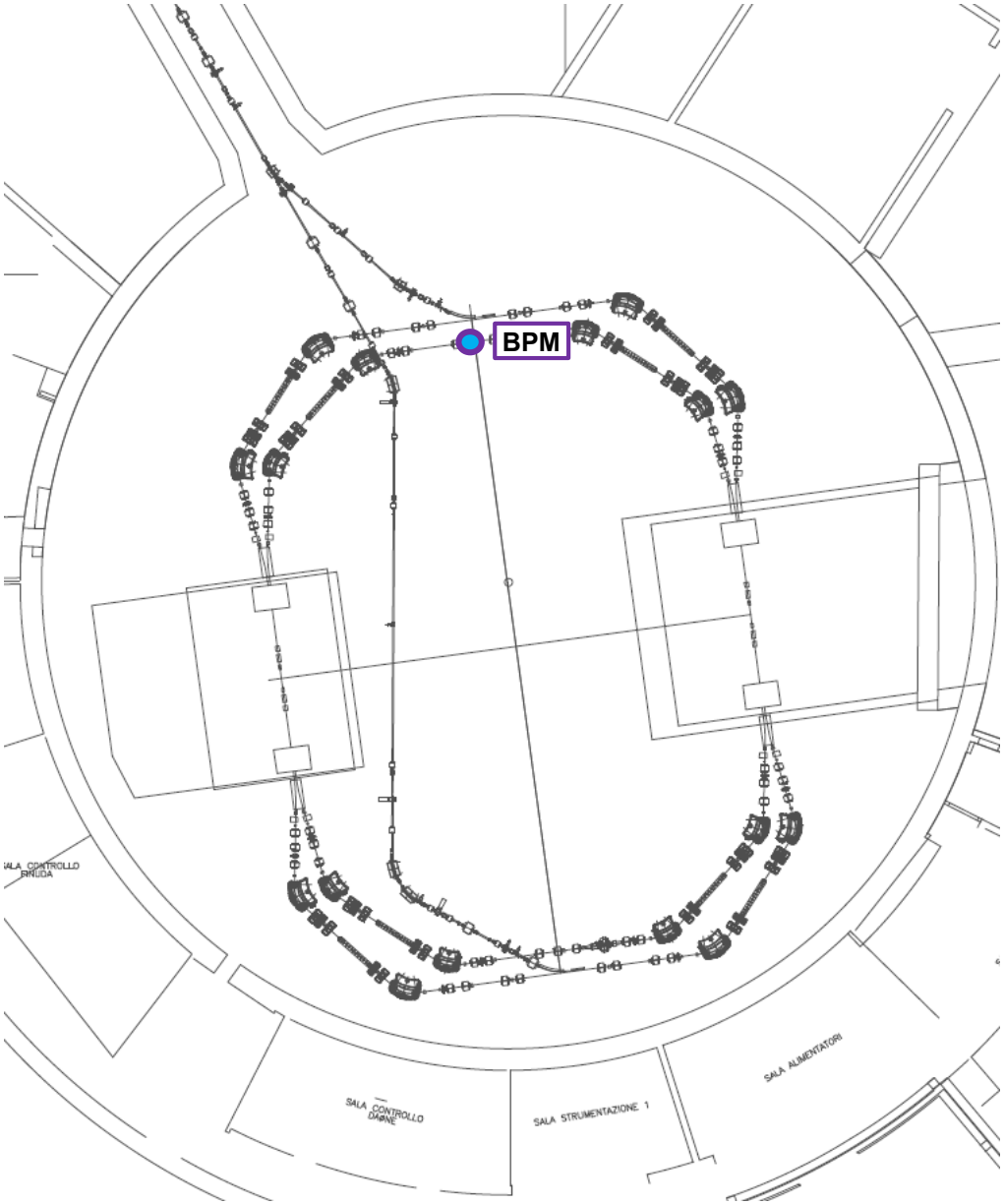
TM010 (main mode):

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

BW ~220 MHz

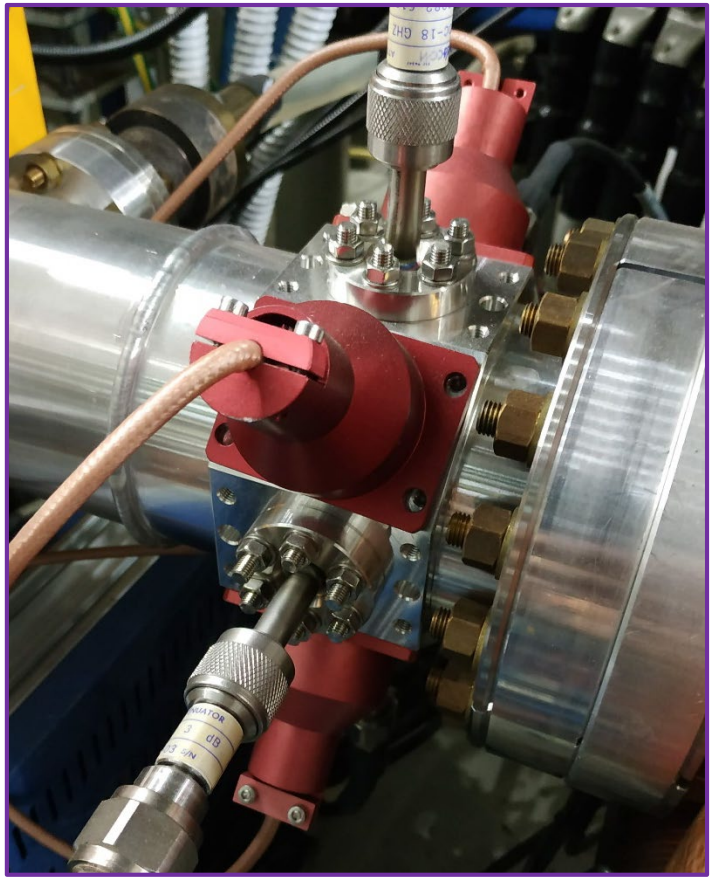
(see: A Waveguide overloaded Cavity as Longitudinal Kicker for the DAFNE Bunch-by-bunch feedback system. R.Boni, A.Gallo, A.Ghigo, F.Marcellini, M.Serio, M.Zobov. Particle Accelerators, 1996, Vol.52, pp 95-113)

Longitudinal e- Feedback

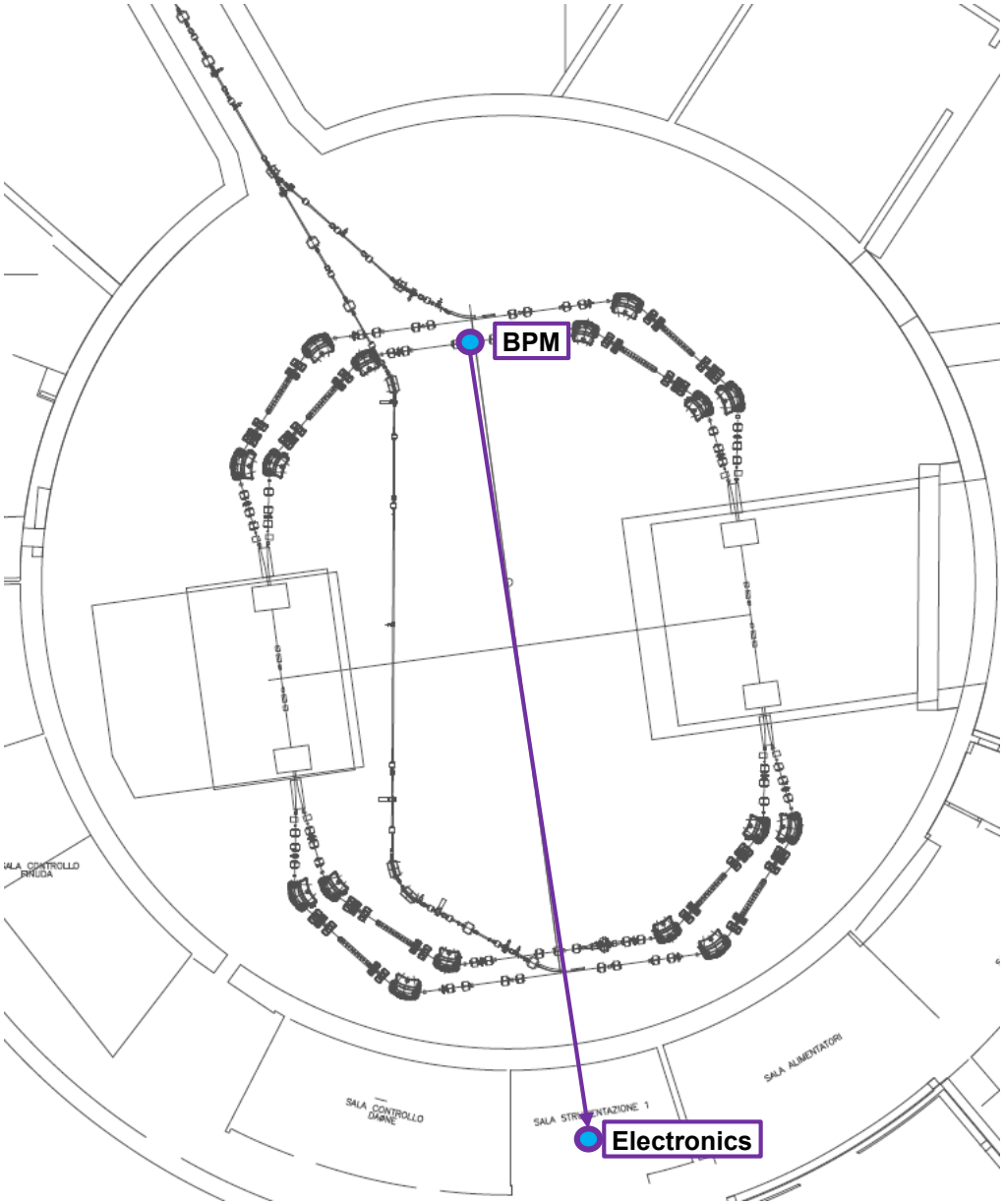


- BPM (BPBES 108)

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



Longitudinal e- Feedback

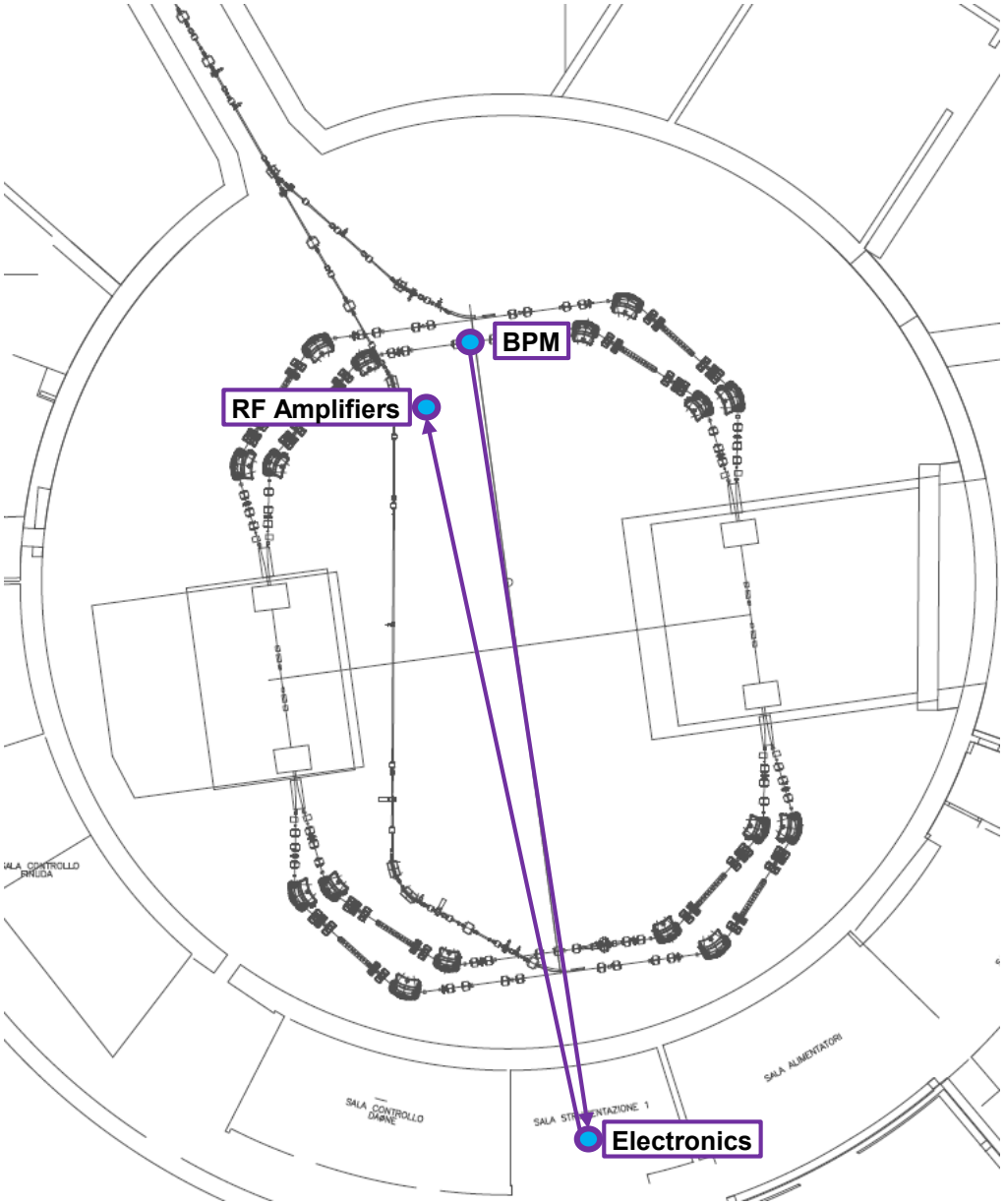


- ELECTRONICS

(instr. room – Rack 46 - multiple devices)

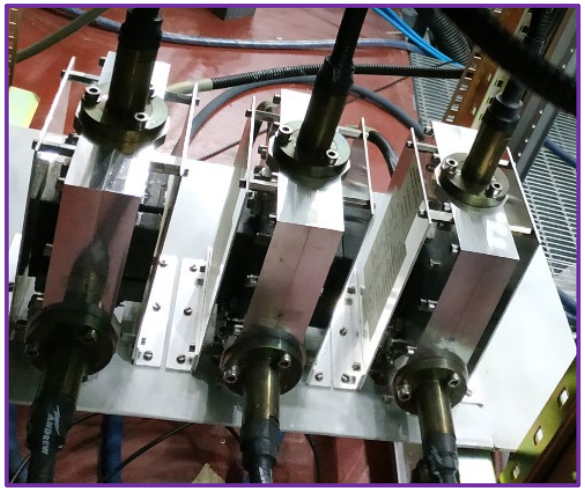
The analogue signal is adjusted (front-end) and digitized (ADC). The correction signal is calculated, transformed in an analogue signal (DAC), adjusted (back-end + delay unit) and sent to the RF amplifiers.

Longitudinal e- Feedback

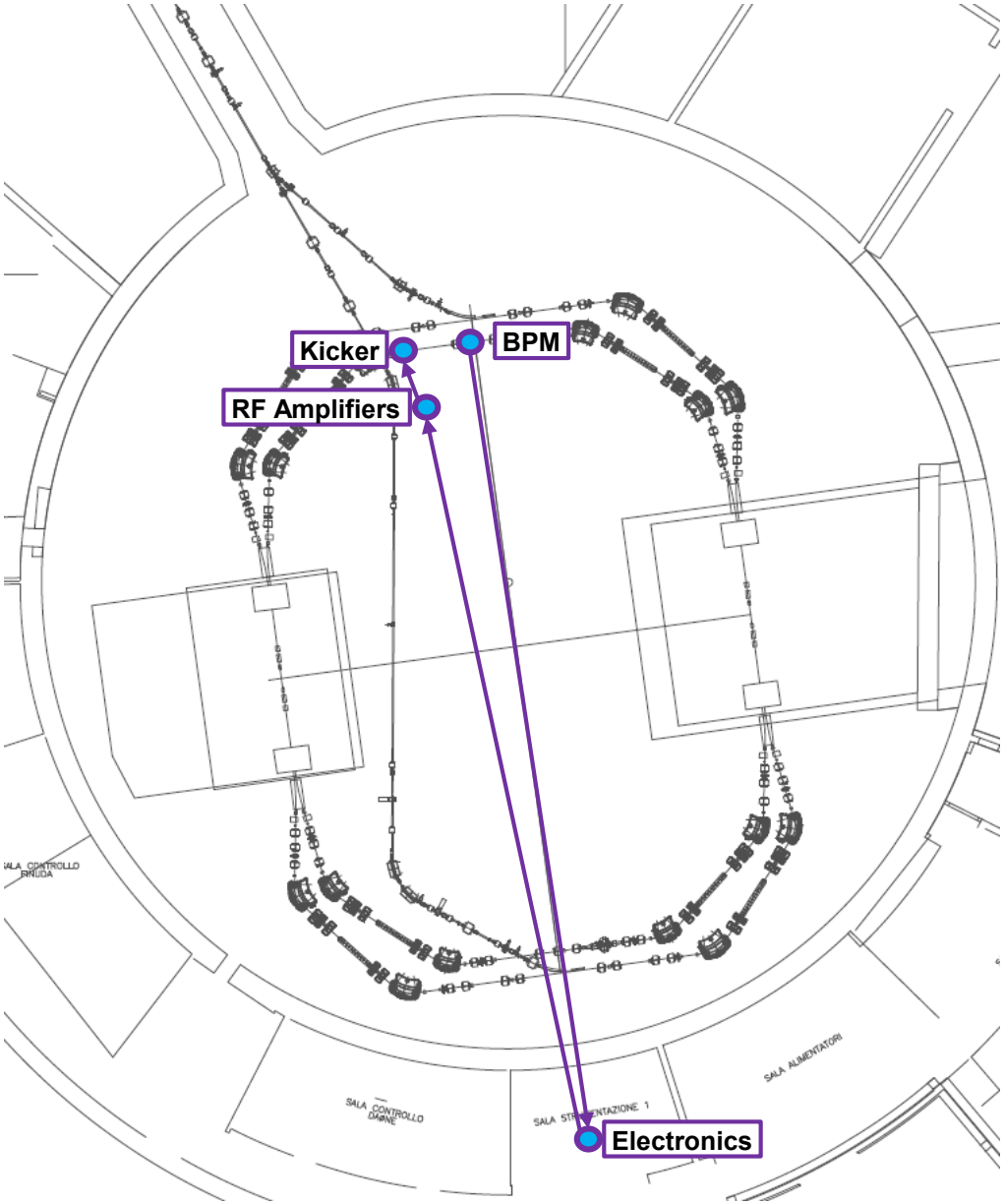


- RF AMPLIFIERS
(Rack 54 - Three units)

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

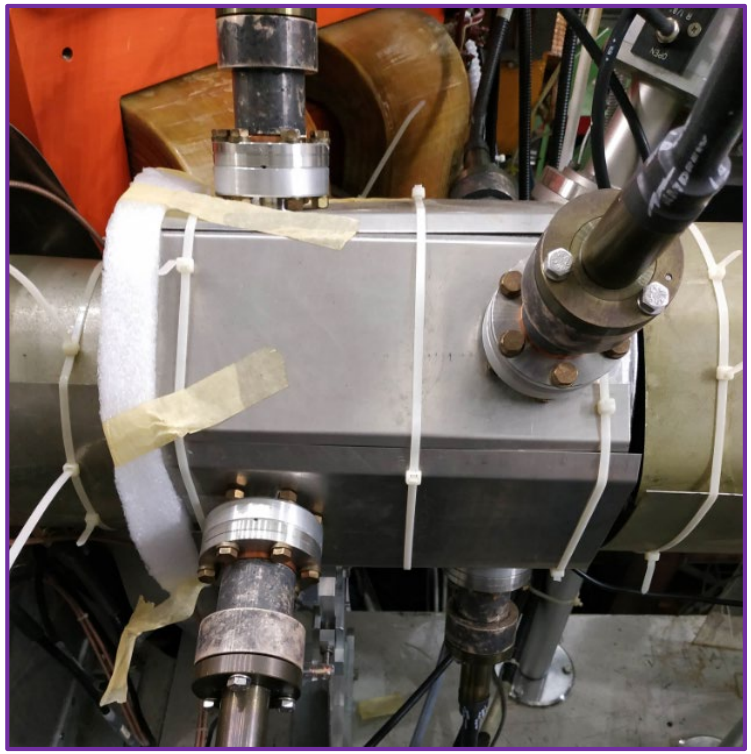


Longitudinal e- Feedback

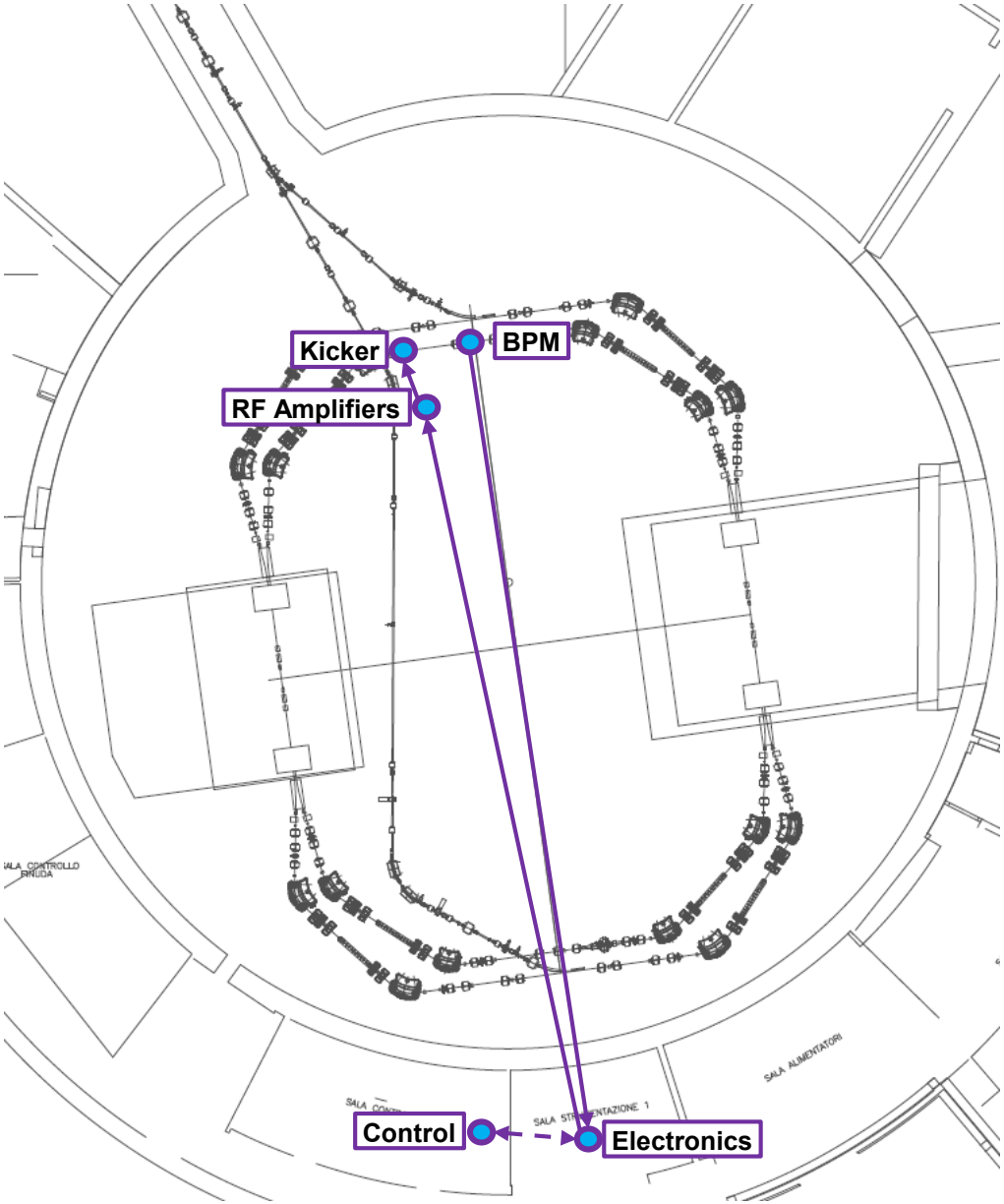


- KICKER

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.

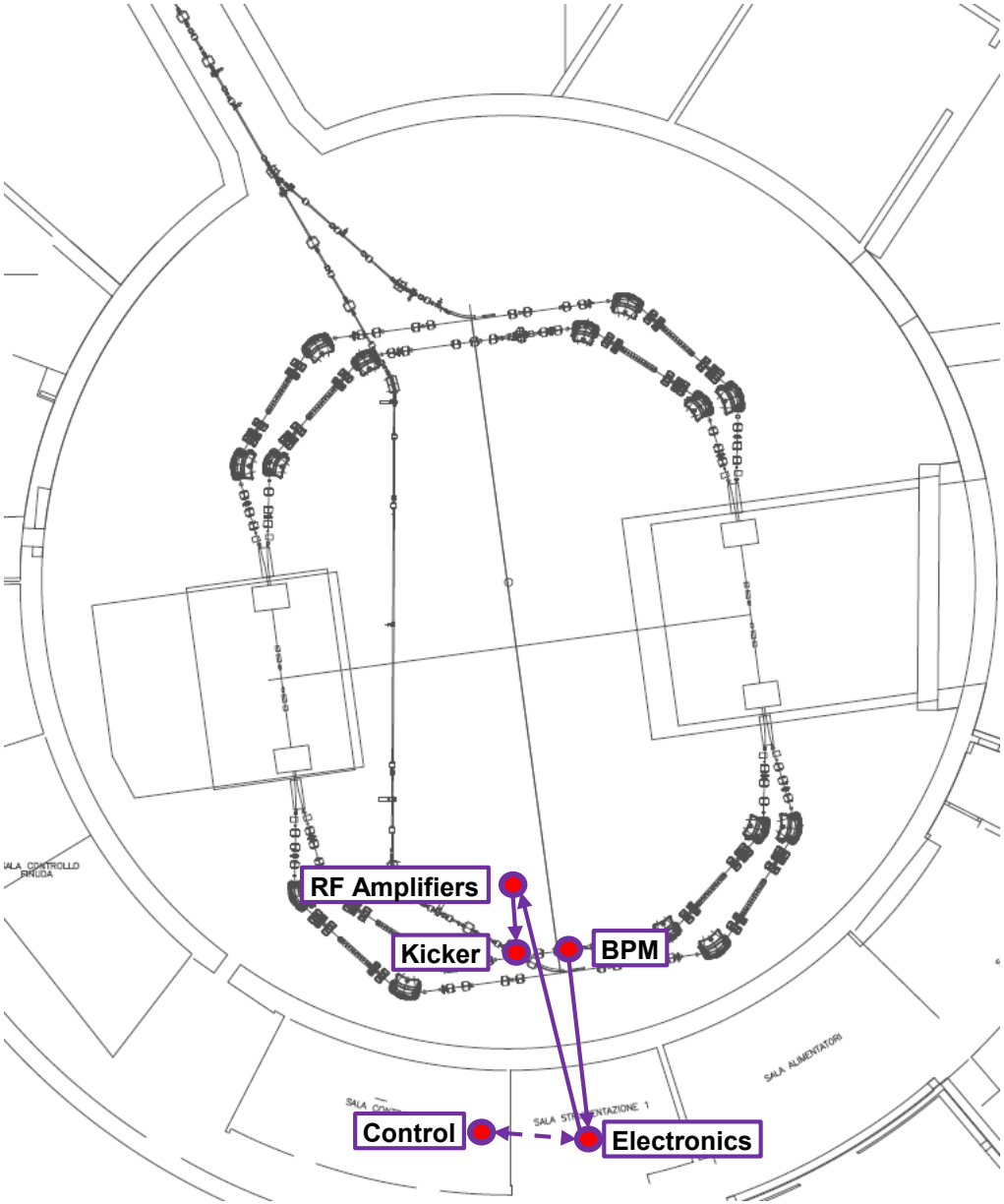
- RF AMPLIFIERS
(Rack 54 - Three units)

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.

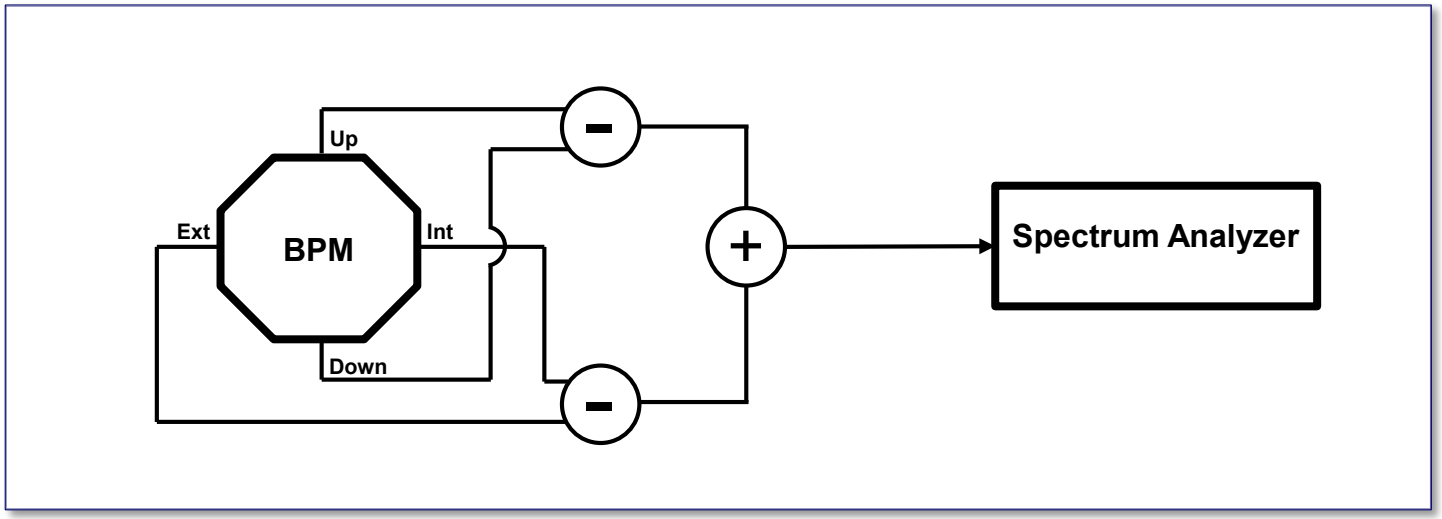
- RF AMPLIFIERS
(Rack 51 - Three units)

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

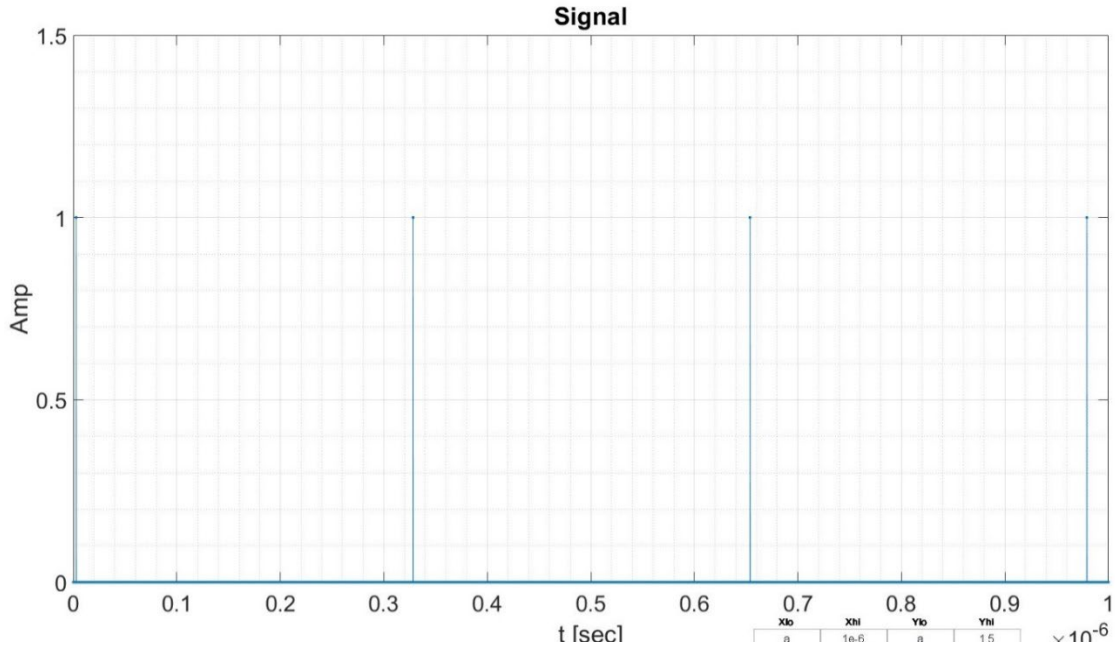
- KICKER

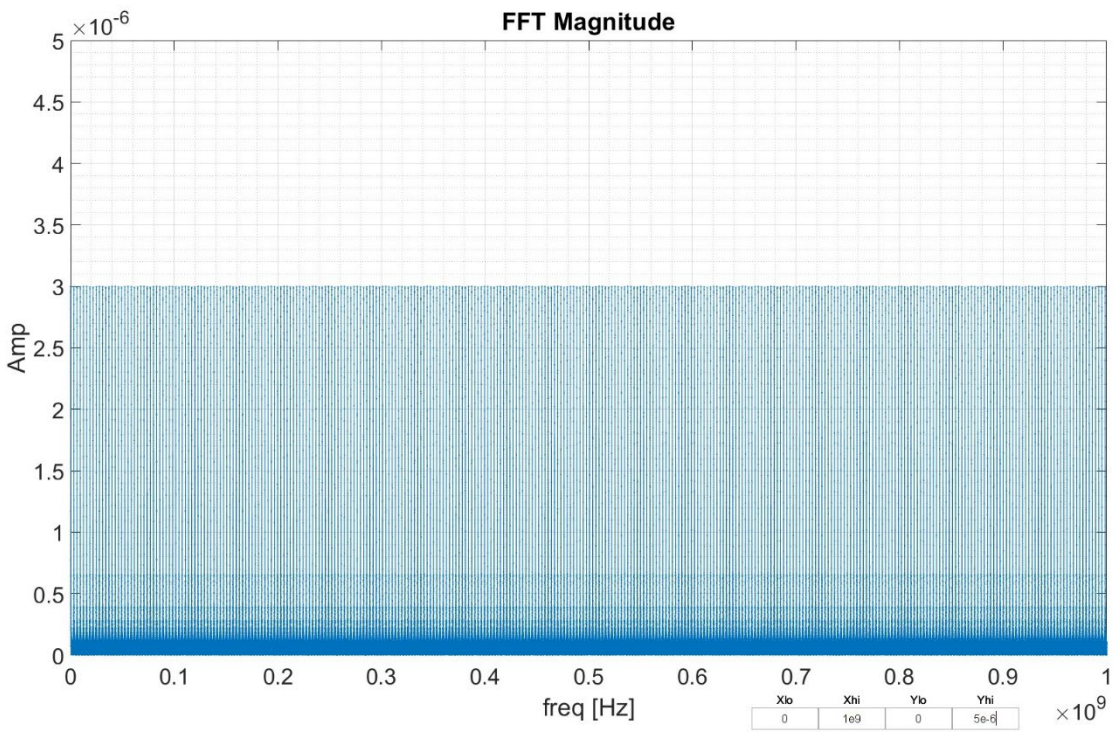
The correction signal is applied to the bunches with a longitudinal kicker (RF resonator).

Beam Spectrum

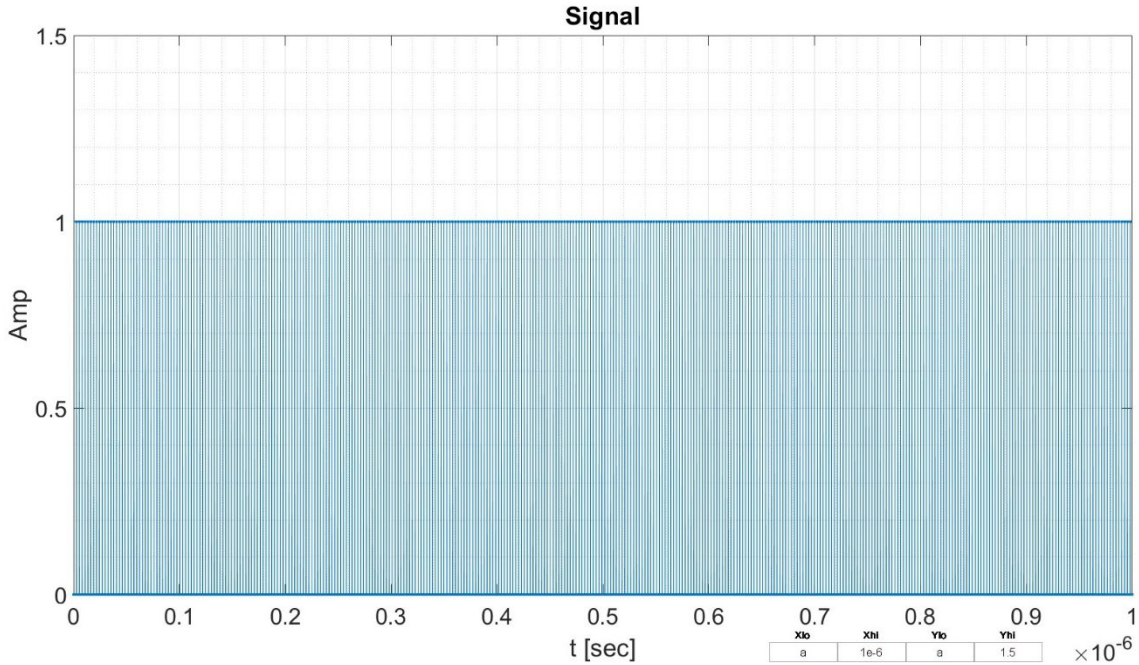


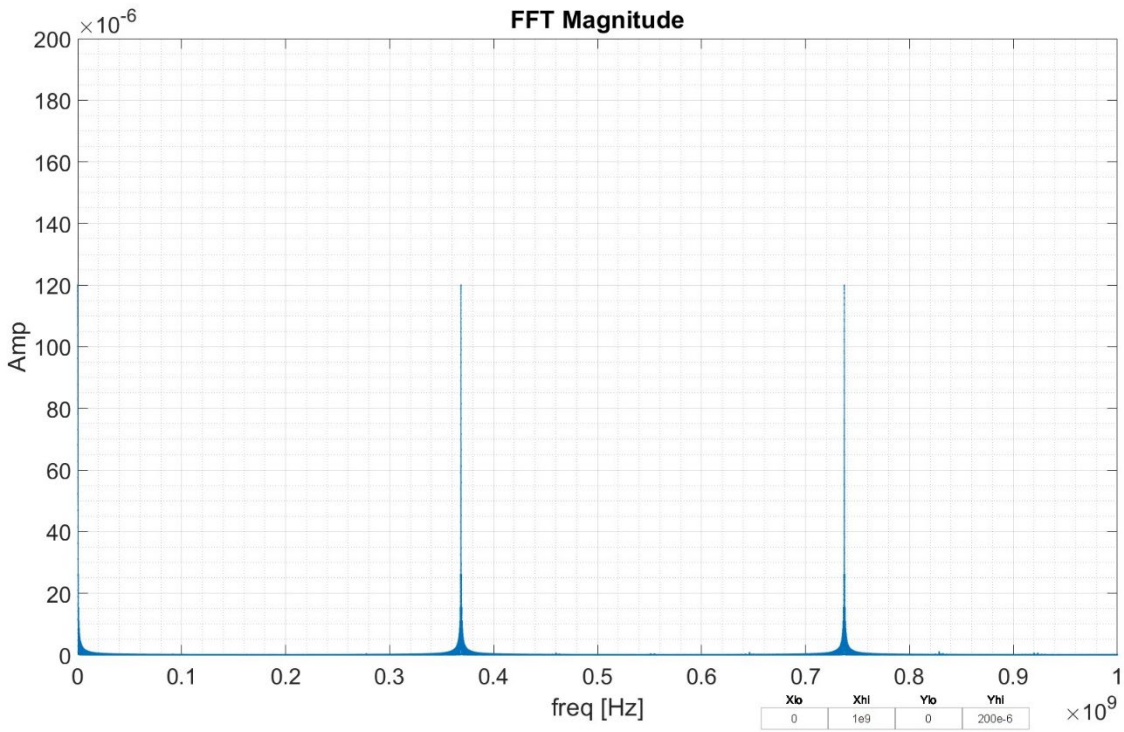
- In order to observe beam instabilities during operations, beam spectrum is measured from the combination of signals (V_{up} - V_{down}) + (V_{left} - V_{right}) from one BPM.
- This is an independent measurement system from the feedback, but it is a useful tool to diagnose instabilities and feedback behaviours.



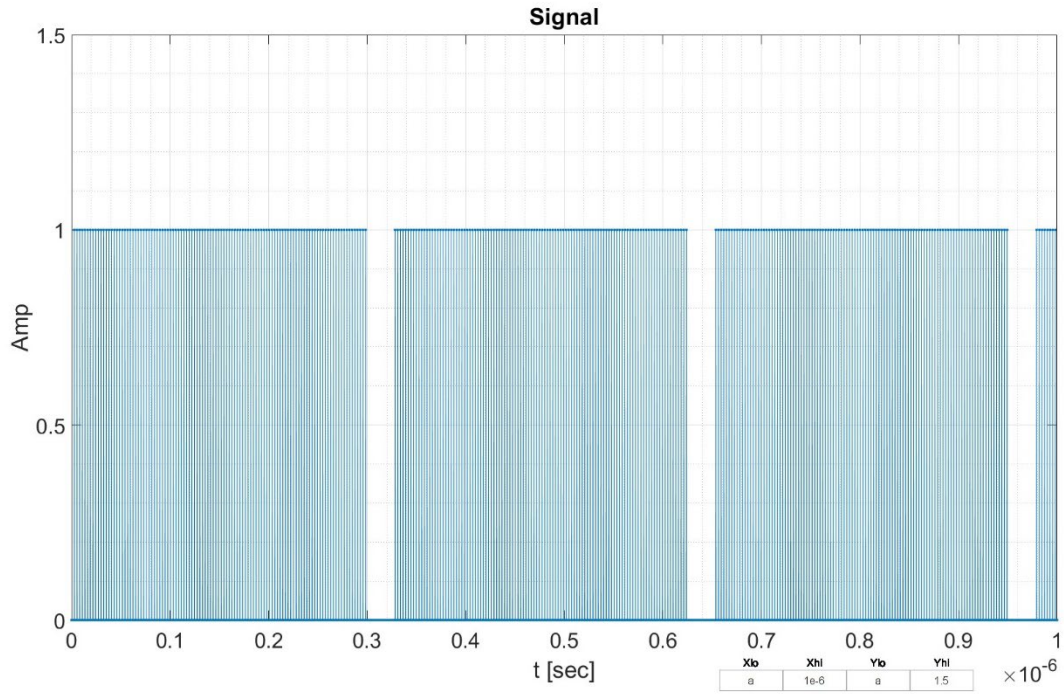


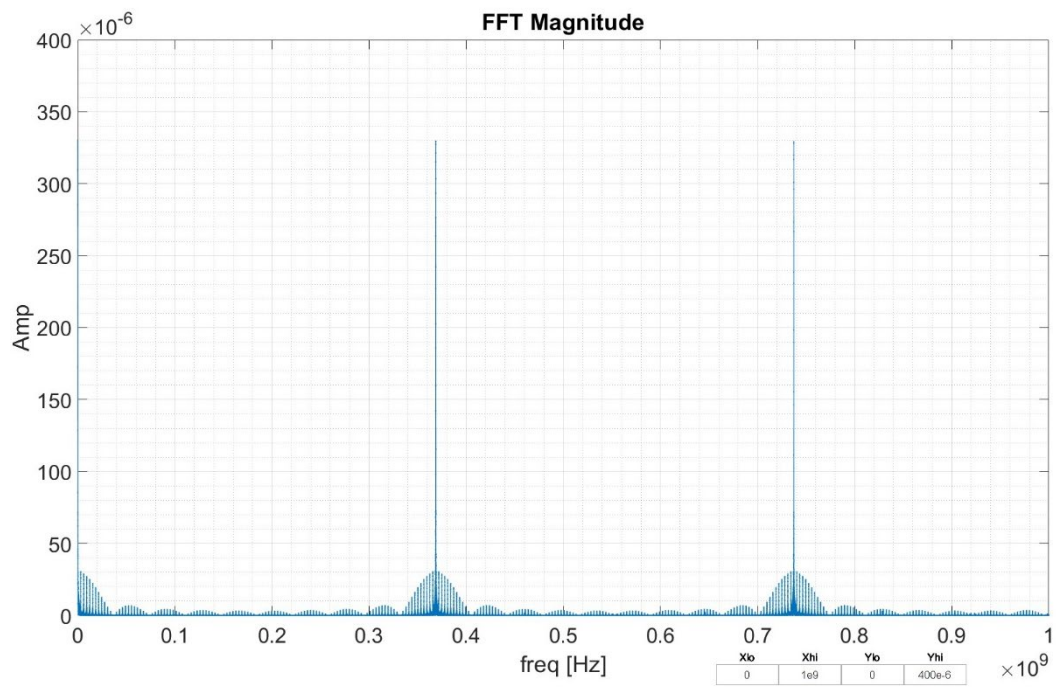
- Single bunch
- T_{rev}= 325 ns
- f_{rev}= 3.0722 MHz



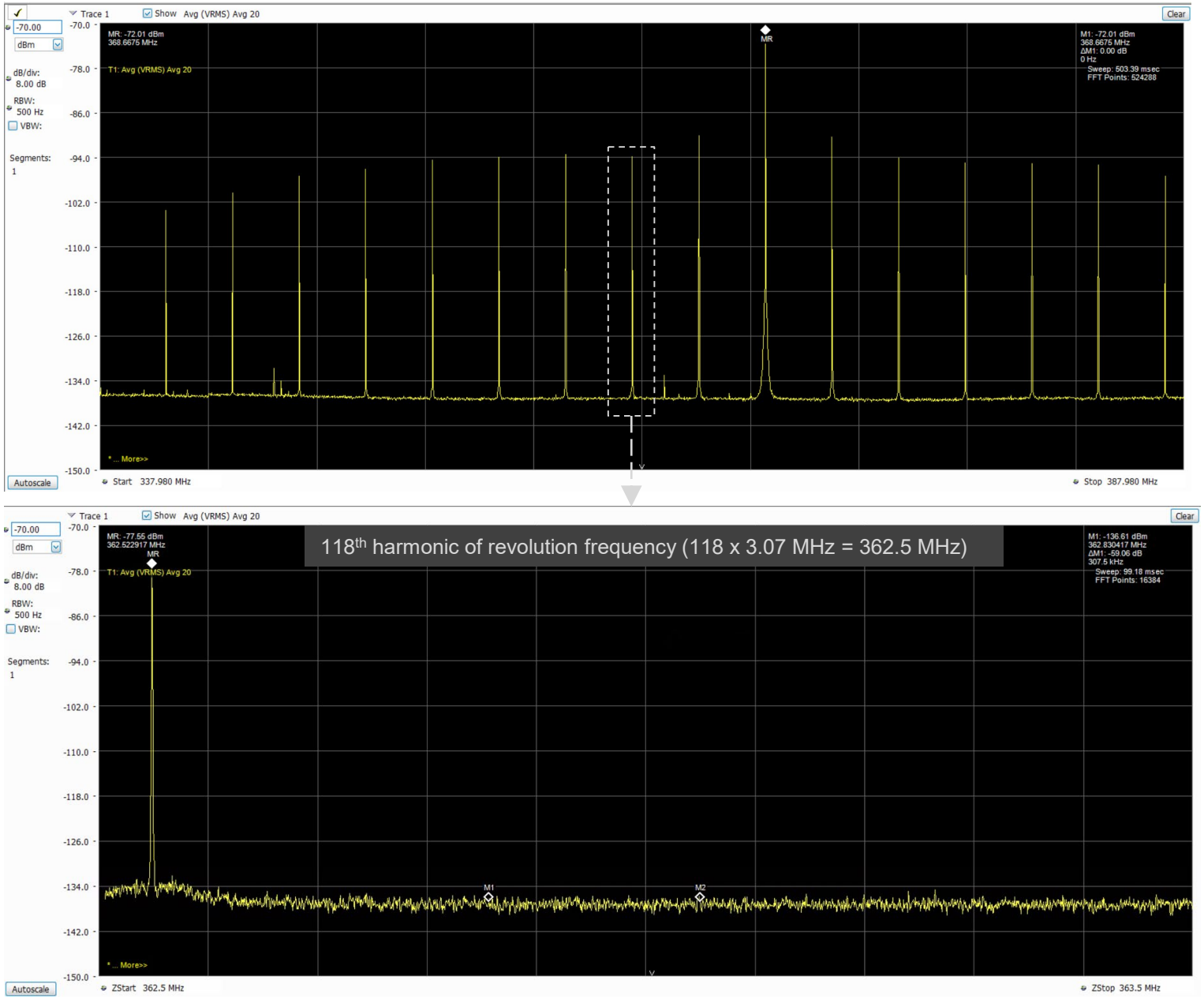


- 120 bunches
- T_{rf}= 2.7 ns
- f_{rf}= 368.667 MHz





- 100 bunches
- T_{rf}= 2.7 ns
- f_{rf}= 368.667 MHz
- T_{rev}= 0.325 μs
- f_{rev}= 3.0722 MHz



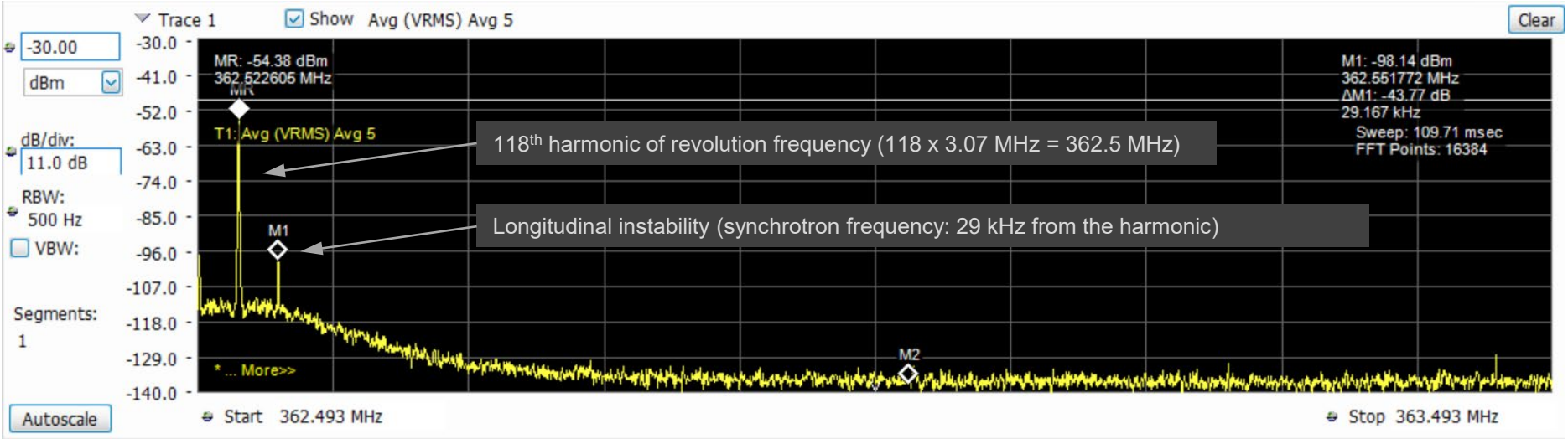
118th harmonic of revolution frequency (118 x 3.07 MHz = 362.5 MHz)

Beam Spectrum

- 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.

In this example (positrons):

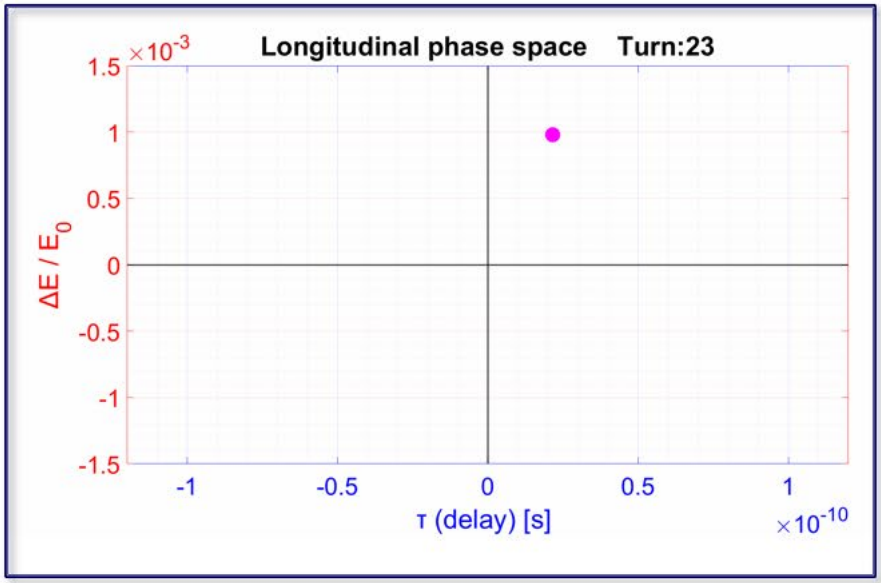
- revolution frequency (f_{rev}) = 3.072 MHz
- synchrotron frequency (f_s) = 29.2 kHz
- synchrotron tune (Q_s) = fs/frev = 0.0095
- Number of revolutions to complete one synchrotron oscillation: 105.2

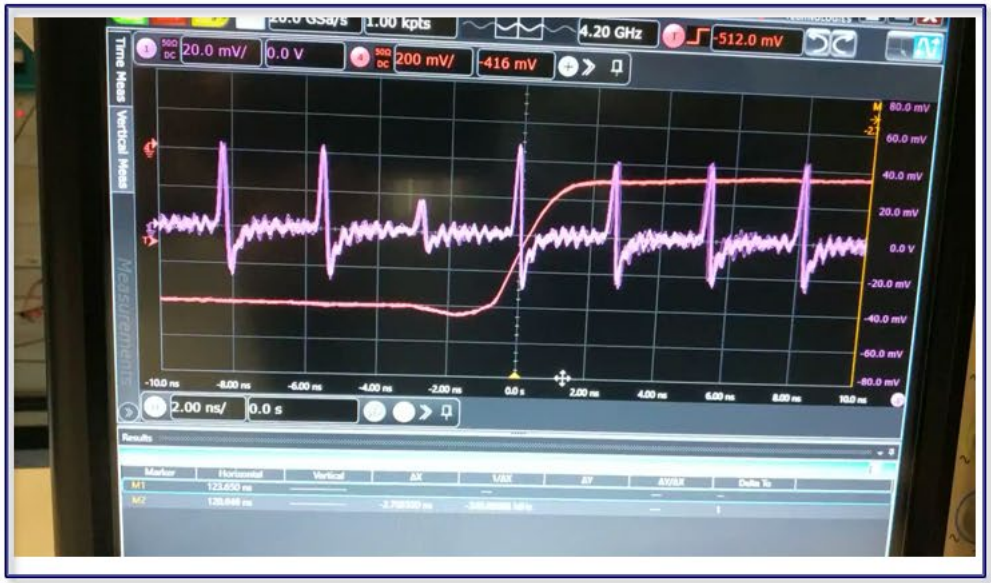


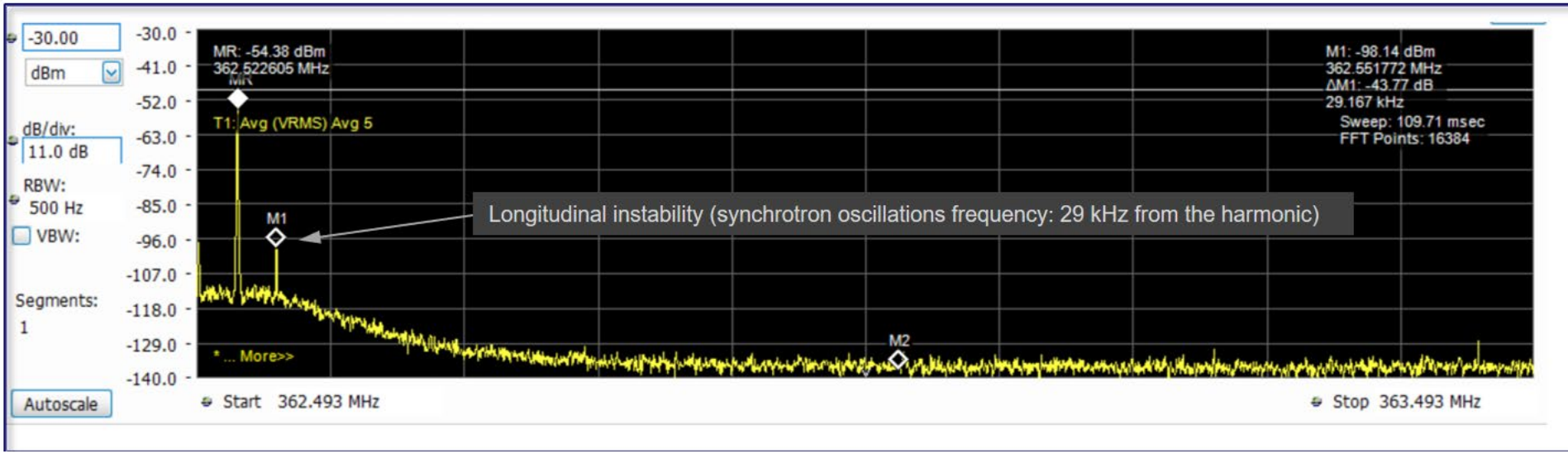
Example of beam spectrum with Positron beam (100 bunches) with I_{avg} = 150 mA. Long. feedback turned off.

Longitudinal oscillations

- Longitudinal oscillations from different perspectives



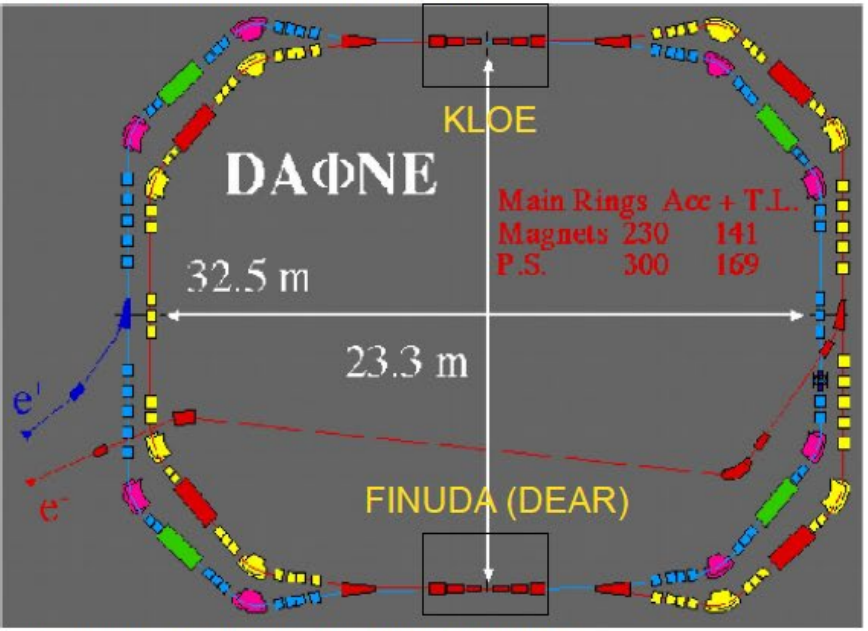




Thank you for your attention.

Spares

P. Raimondi , *2° SuperB Workshop, March 2006,*
P.Raimondi, D.Shatilov, M.Zobov, physics/0702033,
C. Milardi et al., Int.J.Mod.Phys.A24, 2009.

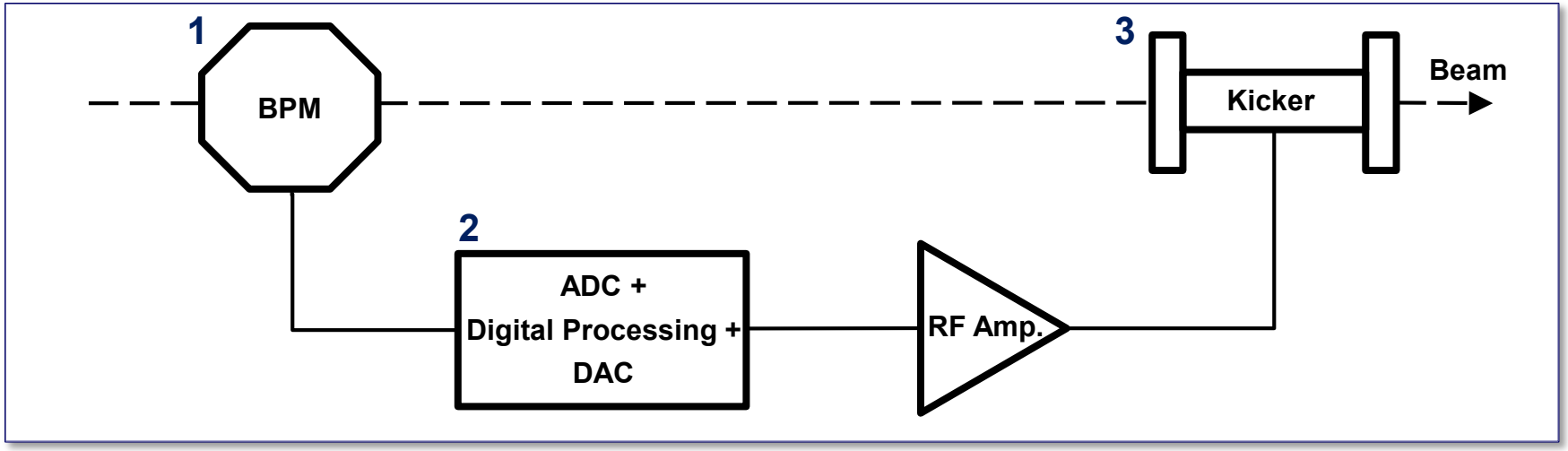


"Proposal for a Φ-factory", LNF-90/031 (IR),1990.

	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_h	120	120

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

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 Feedback Back-end