Longitudinal feedback systems at the lepton collider DAFNE

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Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Frascati

UNIVERSITA' degli STUDI di ROMA TOR VERGATA

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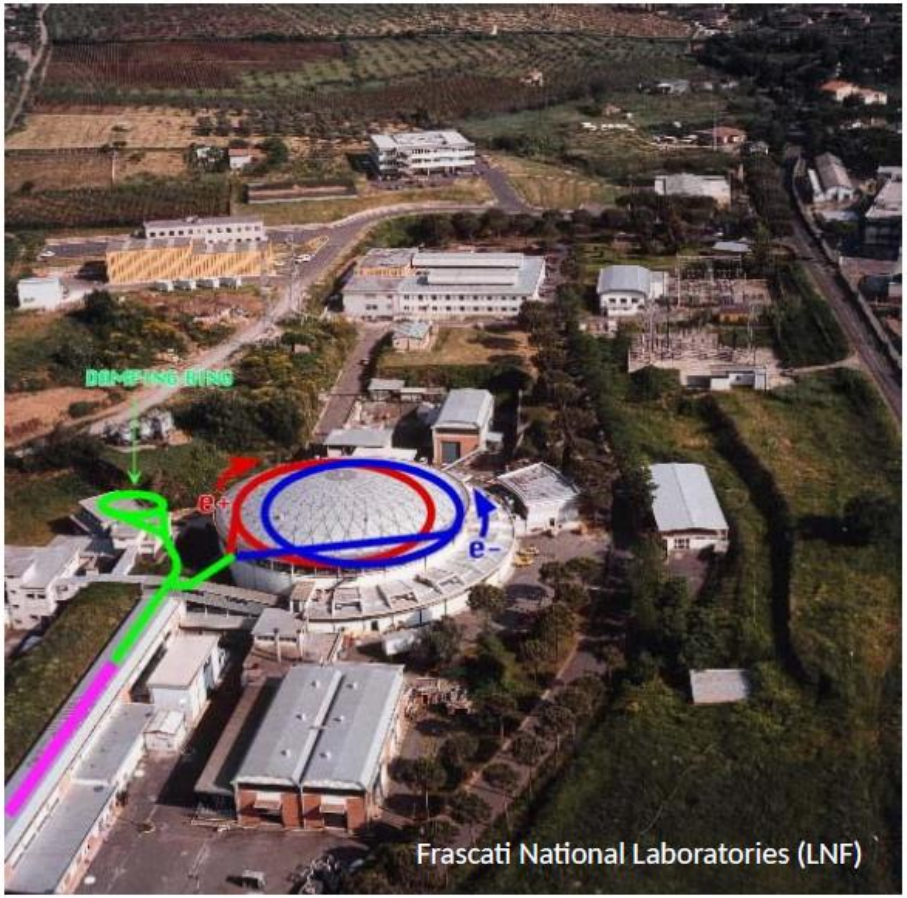
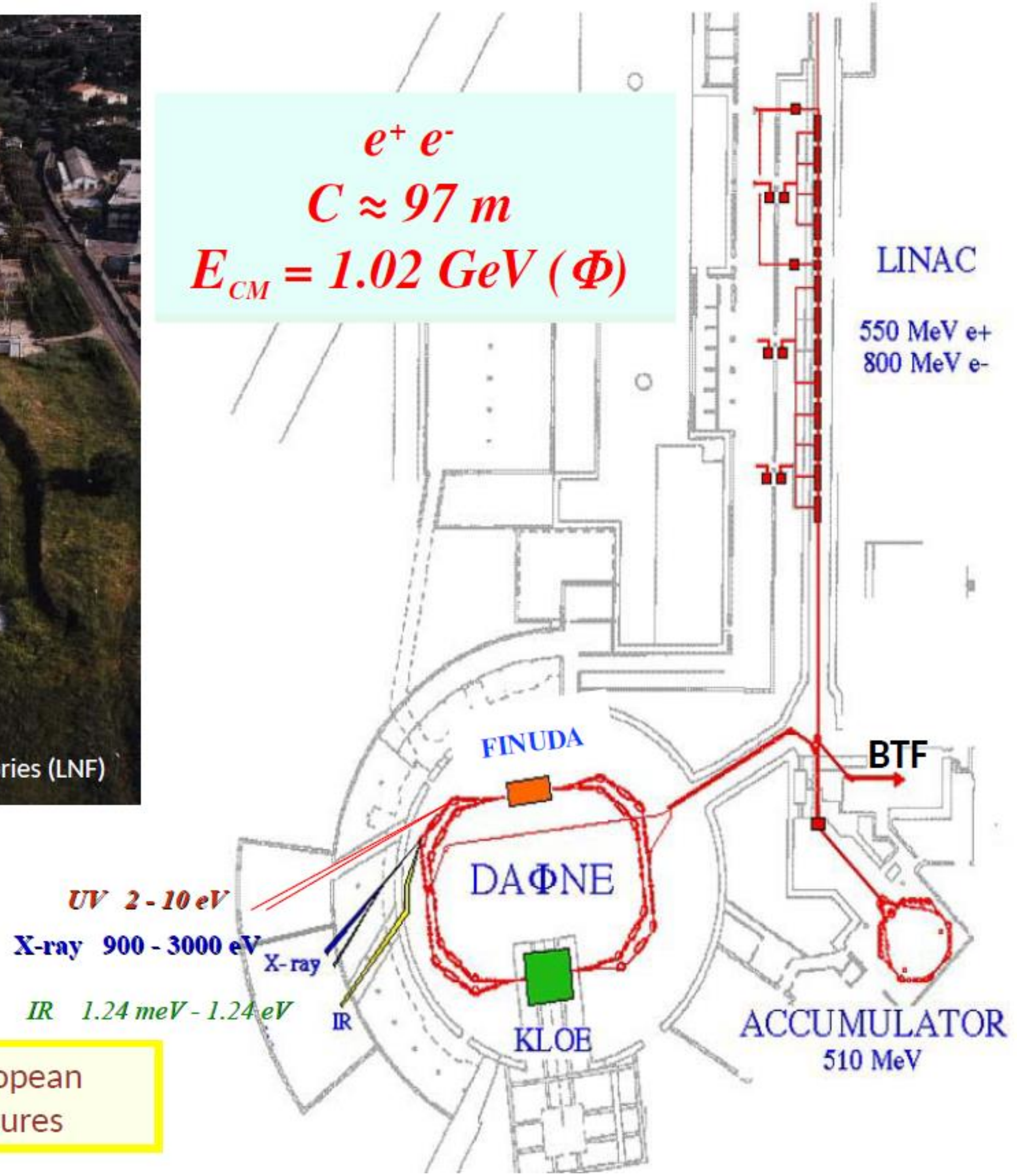
Topics

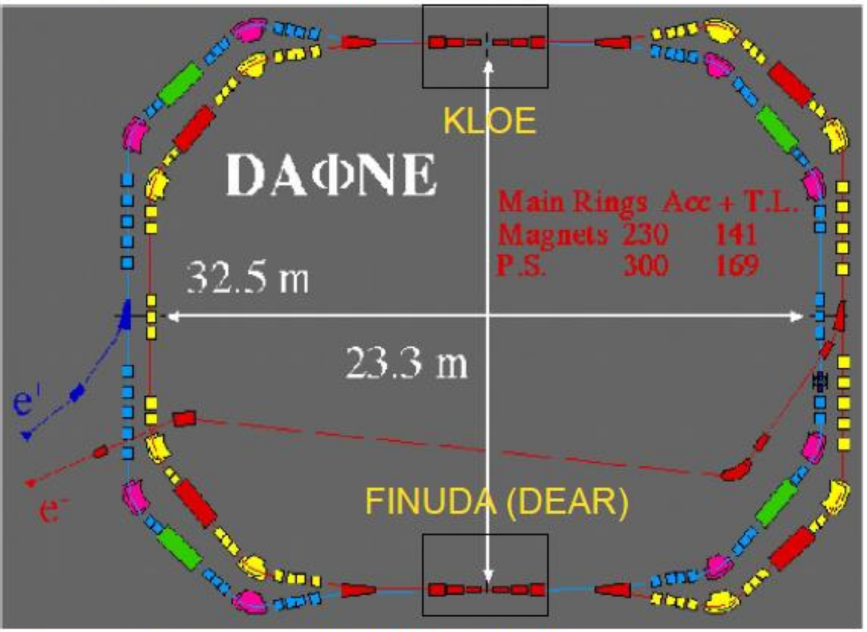
- DAFNE
- Longitudinal bunch-by-bunch feedback collaboration in the 90's
- Frontend
- Backend: Cavity kicker versus stripline kicker
- AM and QPSK modulation
- Longitudinal quadrupole instability control
- Conclusion





LNF are also part of the European synchrotron light Infrastructures

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.

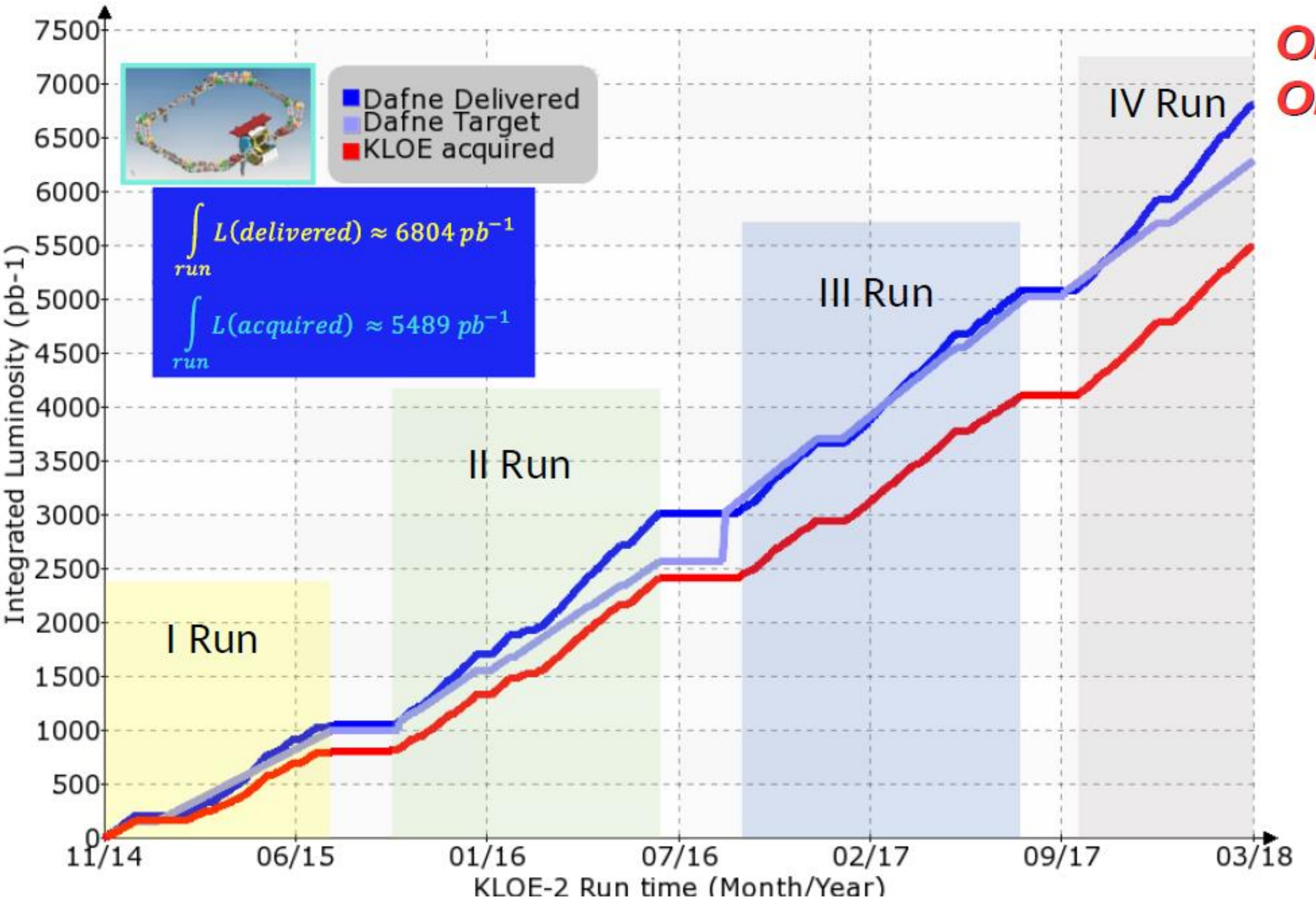


"Proposal for a Φ-factory", LNF-90/031 (IR),1990.

	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_b	120	120

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

KLOE-2 detector runs (2014-2018)



On Time
On Budget

DAΦNE is a collider operating with high currents

Lepton Beam Currents achieved so far

	beam current I [A]	bunch population N_b [10^{11}]	rms bunch length [mm]	bunch spacing [ns]	comment
PEP-II	2.1 (e^-), 3.2 (e^+)	0.5, 0.9	12	4.2	closed
superKEKB	2.62 (e^-), 3.6 (e^+)	0.7, 0.5	7	6	commissioning
DAFNE	**2.4 (e^-), 1.4 (e^+)**	**0.4, 0.3**	**16**	**2.7**	
BEPC-II	0.8	0.4	<15?	8	
CesrTA	0.2	0.2	6.8	4	
VEPP-2000	0.2	1	33	80 (1 b)	
LHC (des)	0.58	1.15	75.5	25	
ESRF	0.2	0.04	6.0	2.8	
APS	0.1	0.02	6.0	2.8	
Spring8	0.1	0.01	4.0	2.0	
SLS	0.4	0.05	9.0	2.0	

Of course so high beam currents have been possible only by using powerful feedback systems

A short look to the basics:

The longitudinal bunch-by-bunch feedback works in time domain by kicking the n-th bunch of particles considered as a rigid body

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

where (see S. Prabhakar, SLAC report-544)

τ_n is the arrival time (time delay) of the n-th bunch relative to the synchronous particle,

d_r is the natural radiation damping,

ω_s is the natural (synchrotron) oscillation frequency,

α_c is the momentum compaction,

E_0 is the nominal energy,

$(e*V_n wk) / T_0$ is the rate of energy loss due to the superposition of the wake forces of the other bunches.

The action of the feedback consists in individual kicks to each bunch increasing the "natural" damping term d_r.

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Feedback acts as anti-impedance term

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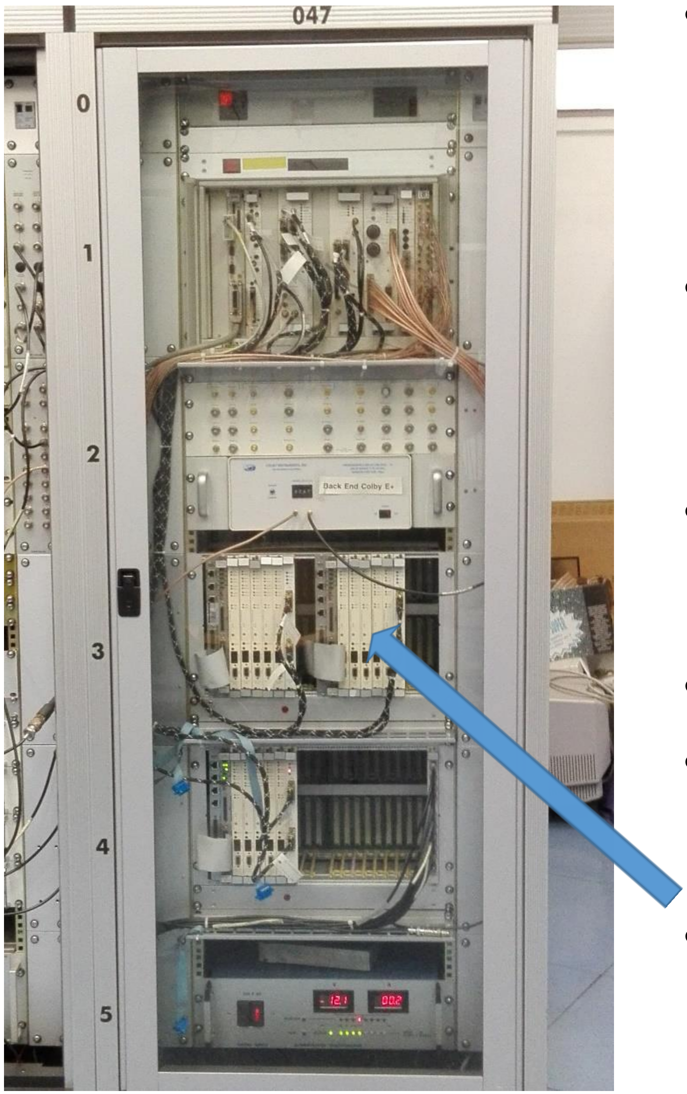
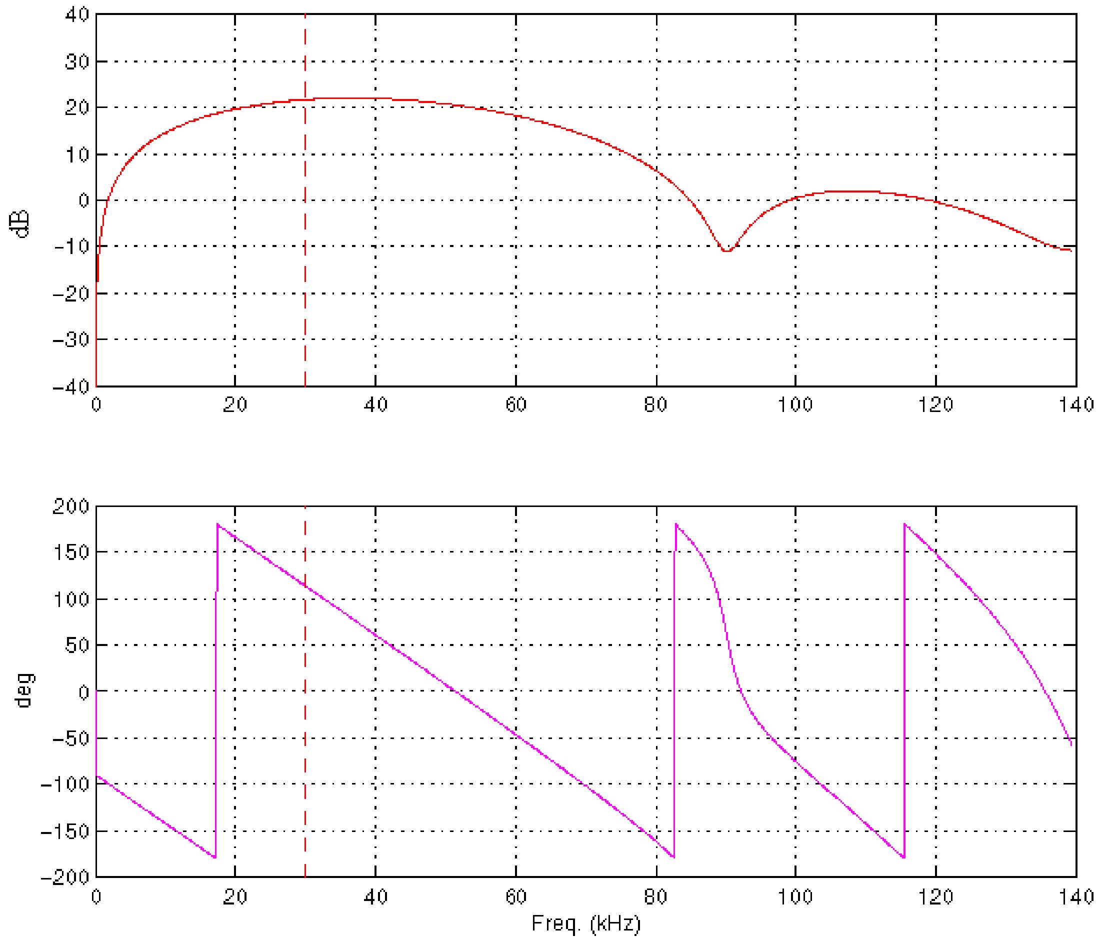
Longitudinal feedback collaboration in the 90's



- The advent of Digital Signal Processor in the audio and telecom market in the 80's opened the chance to develop digital processing feedback system working bunch-by-bunch
- The synchrotron oscillation frequencies were so low (few kHz) to be processed bunch-by-bunch by physical DSP
- First collaboration between SLAC, ALS-Berkeley, DAFNE with some support from CERN (F.Pedersen) and KEK
- First test on a beam at ALS (1994-5)
- In the figure there are 15 boards with 4 DSP each developed at SLAC and installed at DAFNE in 1996
- Each DSP processes only 2 bunches !

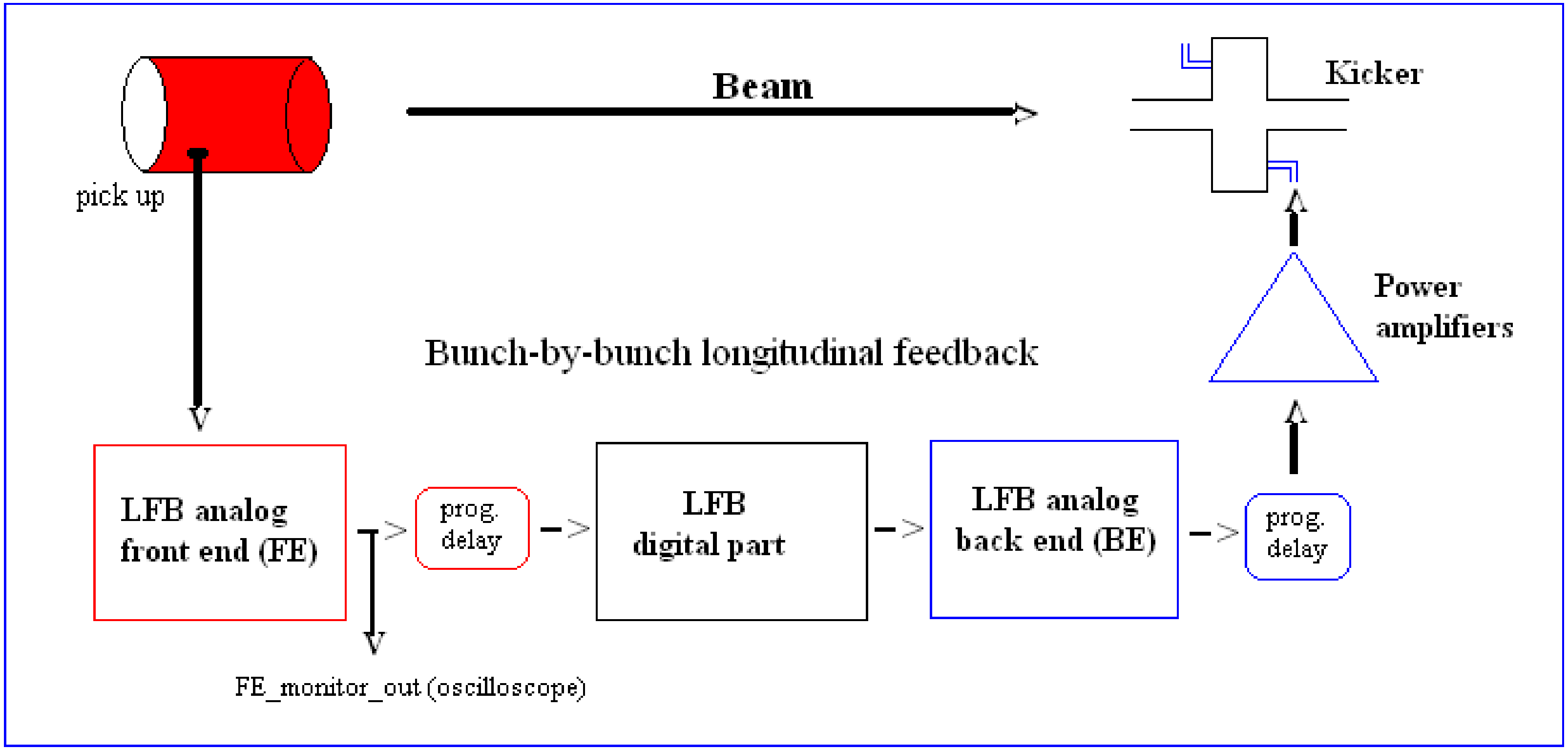
- The goal of the DSP is to implement in real time a FIR or IIR finite or infinite impulse response to produce the “right” correction signal for each bunch based on the last n input data acquired.
- As it is well known, the phase (in theory -90 degree in the equation) of the filter transfer function is extremely important to be able to damp the bunch oscillation
- Downsampling is useful to optimize the number of DSP having low frequency signals and high number of bunches



Longitudinal feedback after the year 2000

- As it is well known with the inception of powerful models of FPGA including inside enough DSP’s, it was possible by Dmitry and others researchers and companies to implement very compact versions of the feedback systems

Looking to the longitudinal feedback main blocks

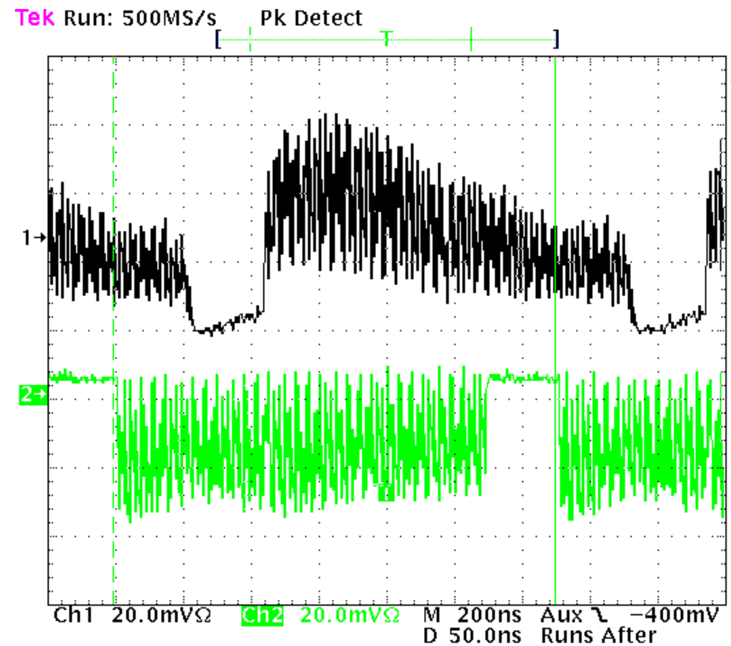


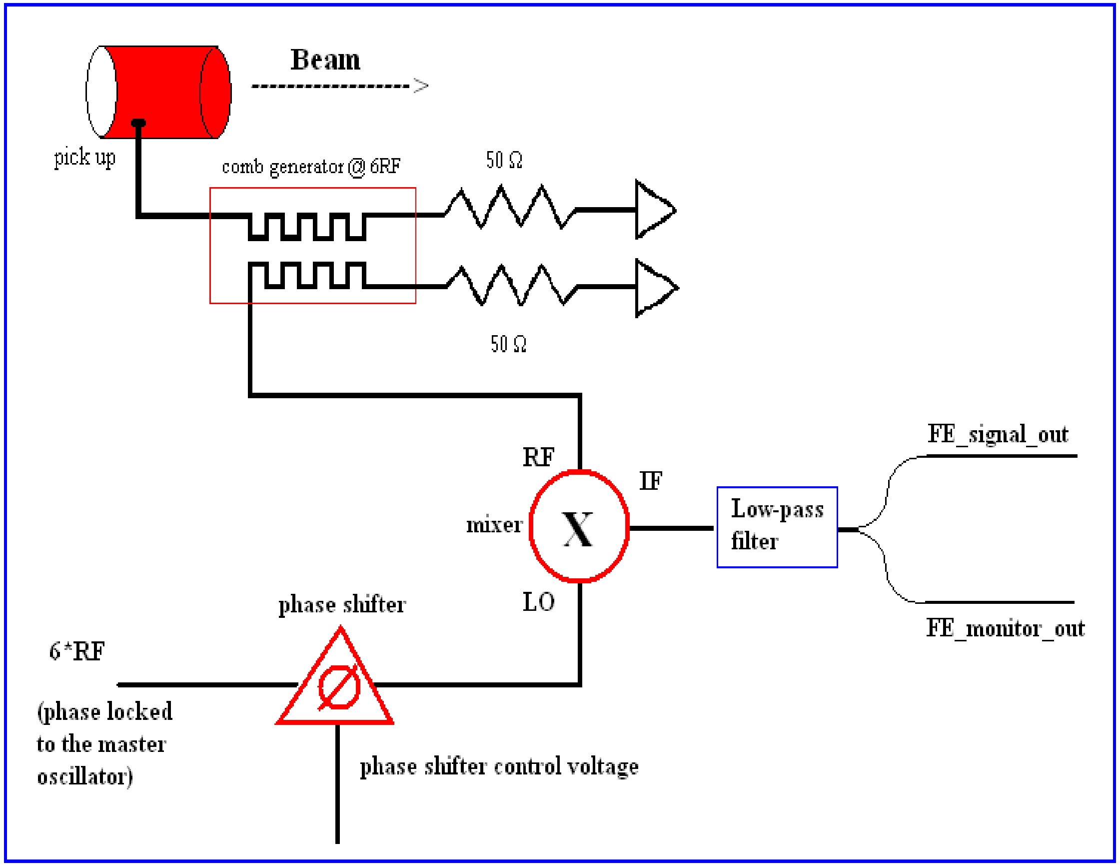
However the analog parts (front-end and back-end) needed specific studies

- Front-end
- Necessary to acquire for each bunch the longitudinal oscillations respect to the synchronous phase
- Basically a phase detector

- Back-end
- Necessary to apply the correction signal to the bunch
- How ?
- The first idea was to use a simple stripline kicker but it was a problematic solution
- With the risk to have a cure producing some collateral effects (instabilities) if used in the longitudinal plane

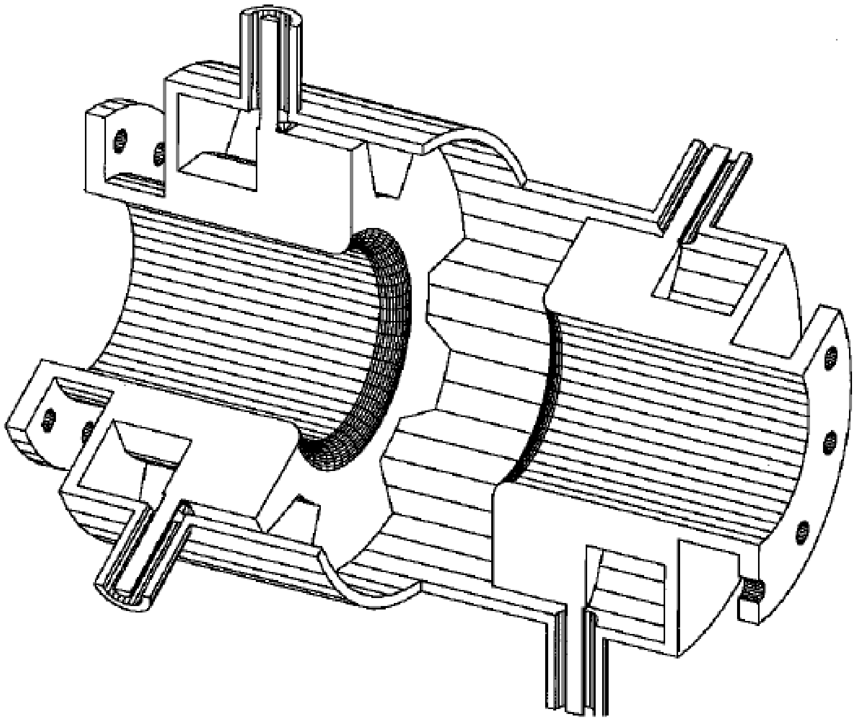
Front-end module based on a comb filter/generator (used to minimize the noise and tuned at 6*RF) and a mixer used as phase detector





- From the front end signal we implement a synchronous phase monitor placed in the DAFNE control room to evaluate different type of instabilities

RF-17
DAFNE technical note
8 June 1995



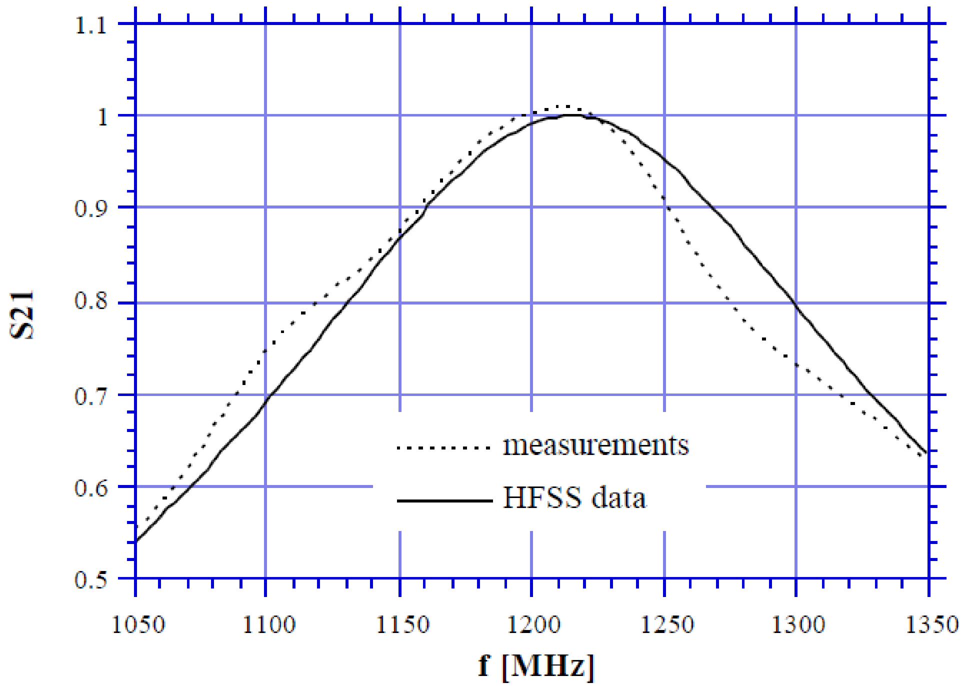


Fig. 7: Kicker frequency response.

For the back-end, to avoid instabilities given by a stripline device, an overdamped cavity kicker with 3 +3 ports was proposed and designed at LNF.

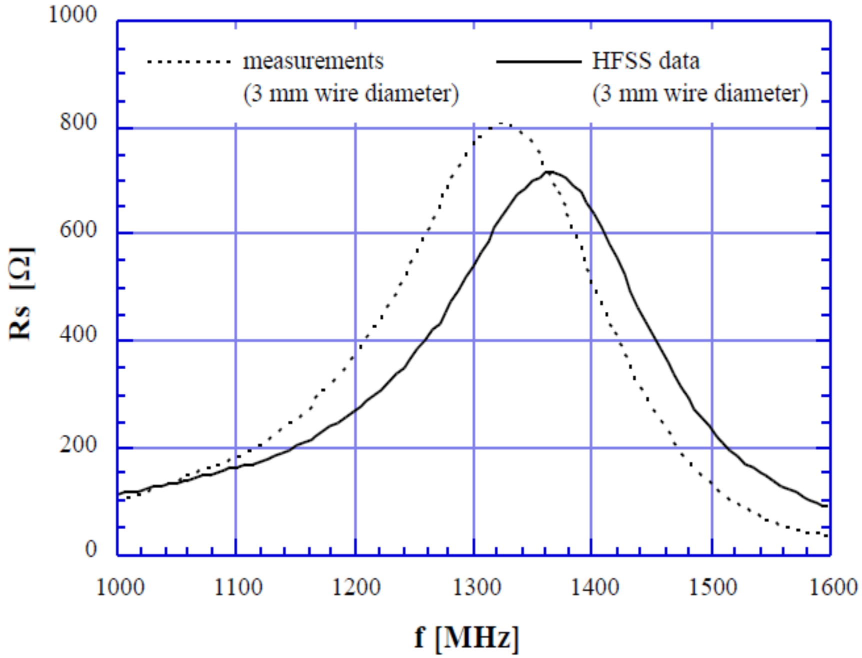


Fig. 15: Kicker shunt impedance obtained with the wire method.

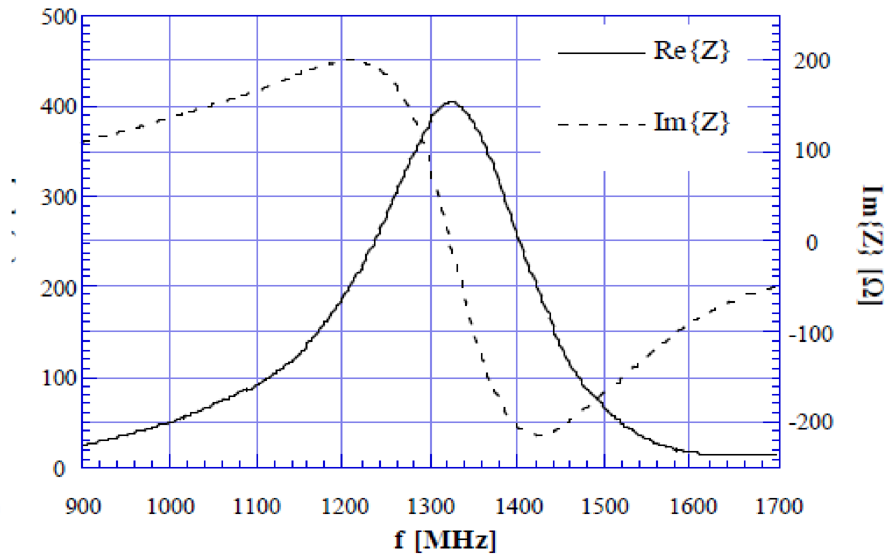
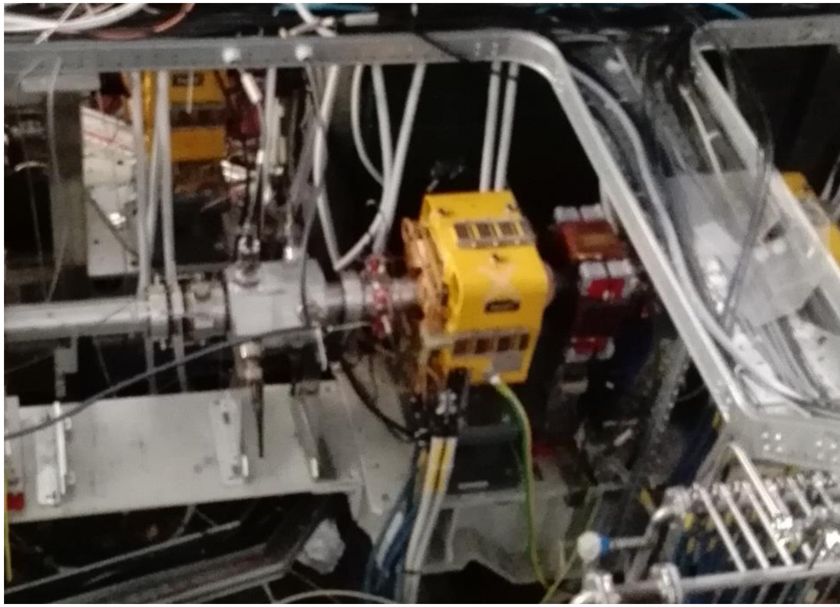
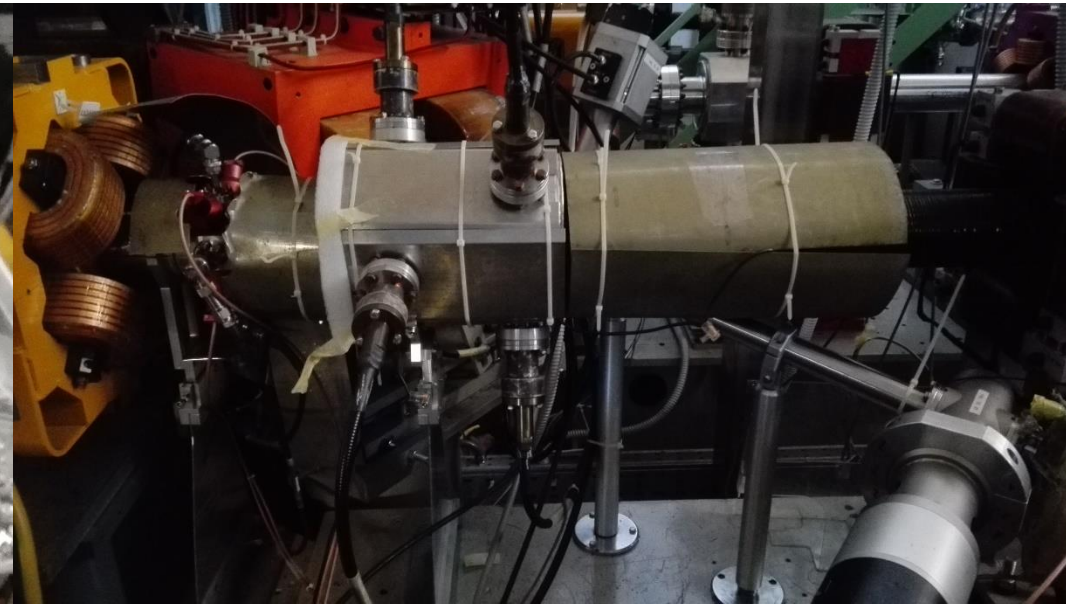


Fig. 14: Beam coupling impedance measured on the kicker prototype.

A cavity kicker for the DAΦNE bunch-by-bunch longitudinal feedback system based on a pill-box loaded by six waveguides has been designed and a full-scale aluminium prototype has been fabricated at LNF. Both simulations and measurements have shown a peak shunt impedance of about 750 Ω and a bandwidth of about 220 MHz. The large shunt impedance allows to economise on the costly feedback power. Moreover the damping waveguides drastically reduce the device HOM longitudinal and transverse impedances.

The electron (left) and the positron (right) cavity kicker.

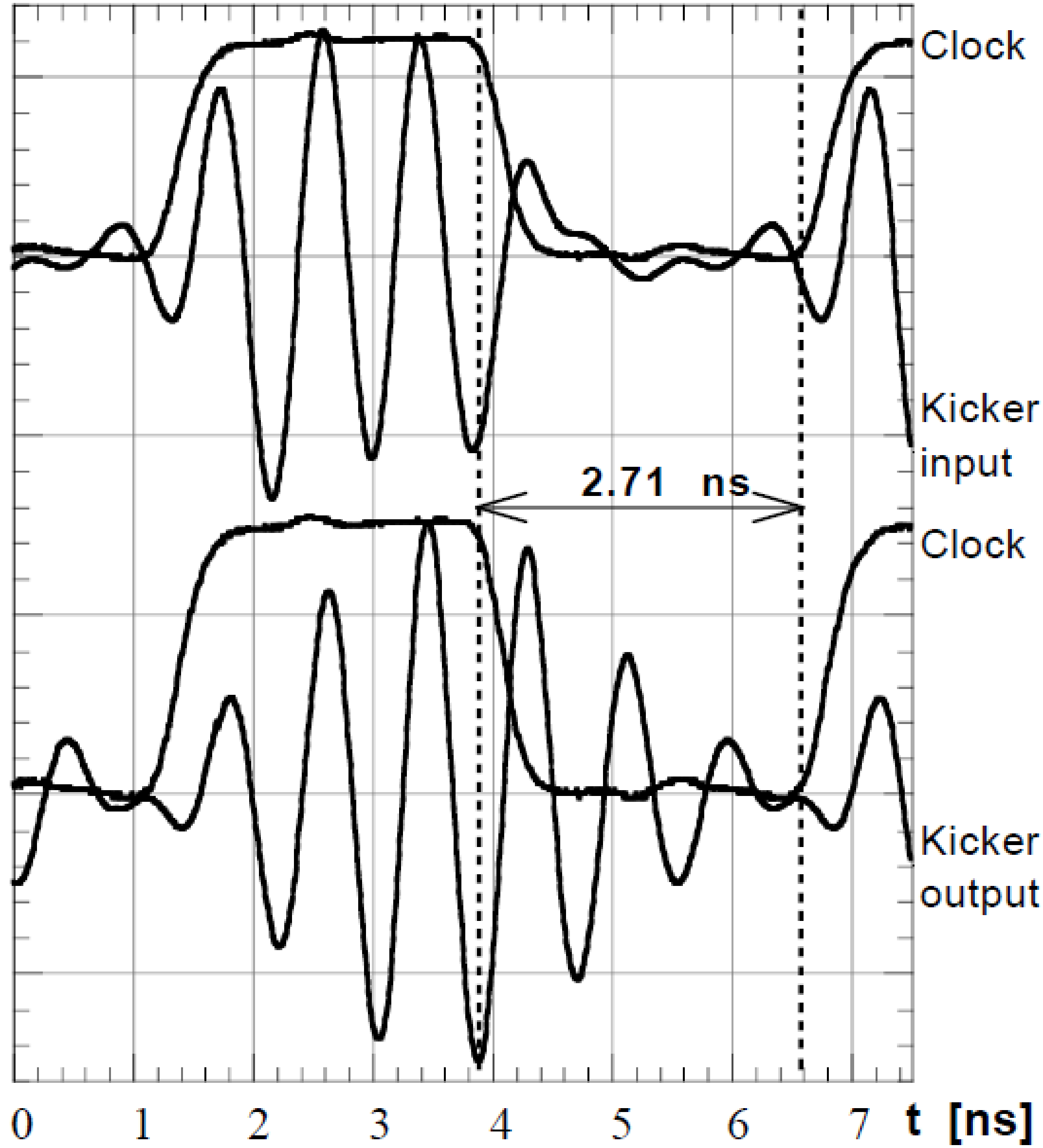
The positron cavity needs to be heavily shielded to avoid noise from the electron injection.

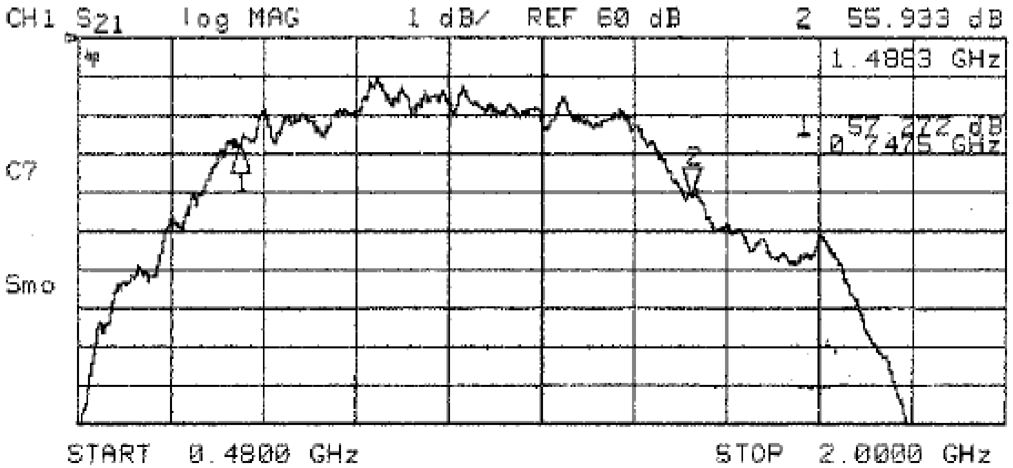
Note that the e- vacuum chamber passes below the cavity.

Note that the cavity kickers do not need any cooling.

In the side figure Kicker input signal and output signal are shown in time domain.

As it is shown in the plot some crosstalk between adjacent bunches is possible if the correction signal is not perfectly timed with the bunch passage in the kicker





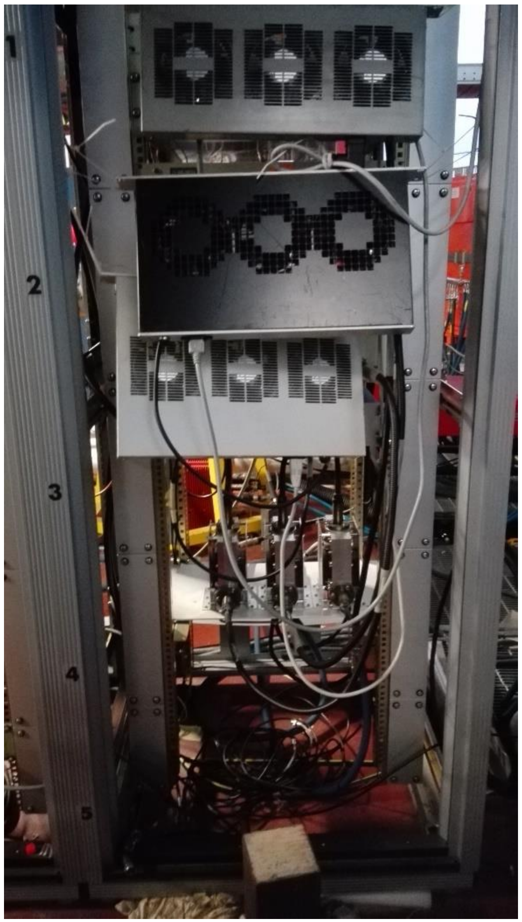
The choice of the power amplifier has been based on the two considerations:

a) The bandwidth have to be as requested by the cavity kicker. In the figure the magnitude (dB) vs. frequency response is shown.

b) Rise time must be < 2 ns to manage a pulsed signal without crosstalk

In total 750W power is installed (3 x 250W amplifiers) for each ring.

To protect the power amplifiers from the beam loss damages, 3+3 custom RF circulators have been bought and placed under the amplifiers

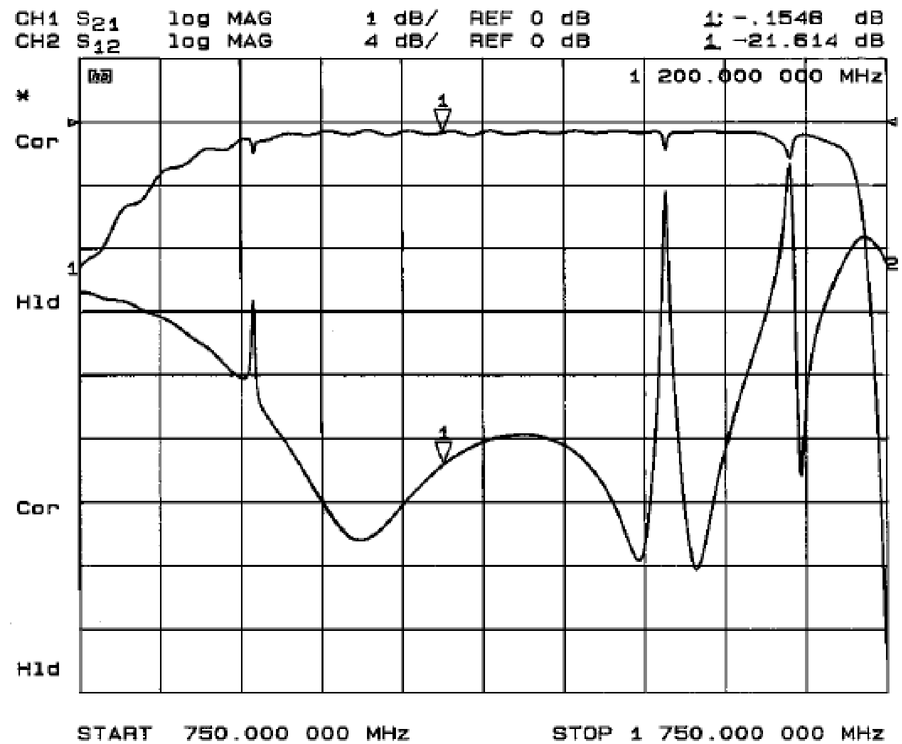


A lot of fans to cool the amplifiers

The RF circulators are cooled by water. Along more than 20 years they had only two failures for water leakages.

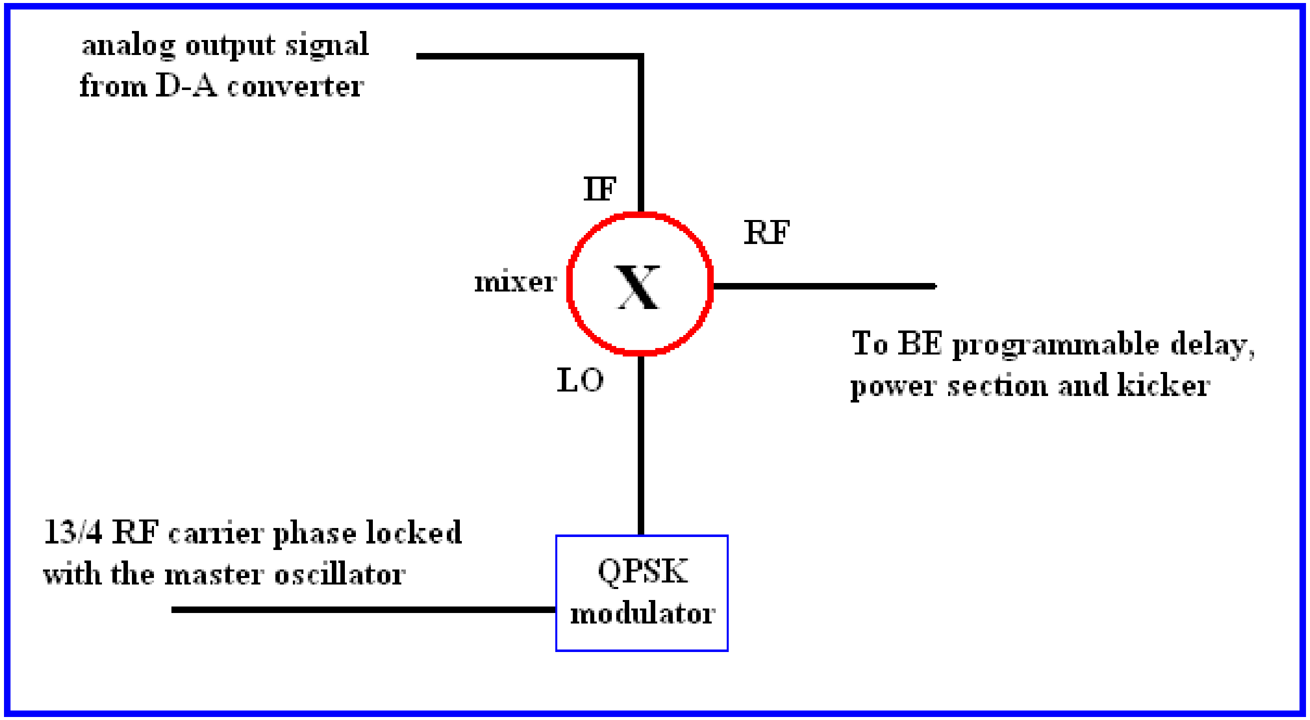
RF circulators performance

- The transmission (S21) and isolation (S12) frequency responses of the RF circulator.
- The beam reverse power entering in the power amplifier from circulator should not be more than 15 W (this value was foreseen by the calculations).



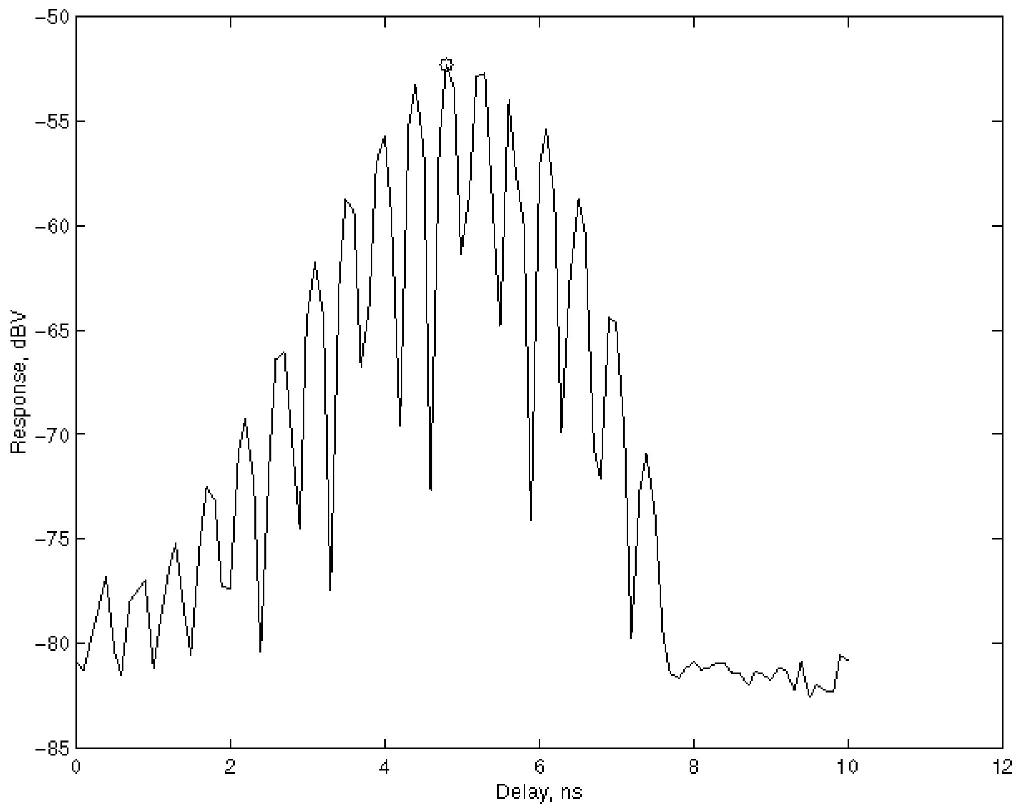
In reality to have the best efficiency in the back end if using a cavity kicker the QPSK modulation is recommended after the necessary amplitude modulation. This makes more complicate the timing procedure

Bucket delay and fine delay for the baseband correction signal (they are digital)



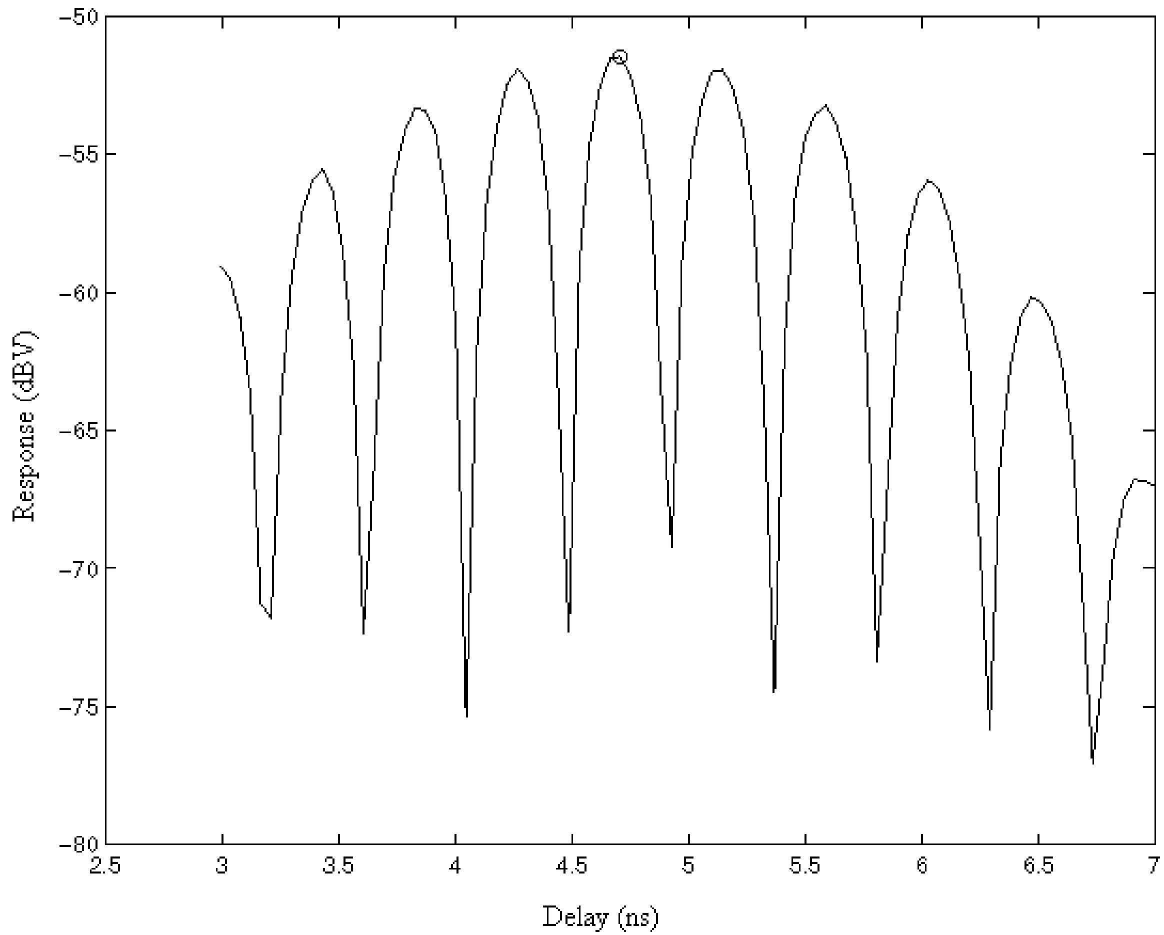
The last delay is an analog delay line even if digitally controlled

By using the QPSK modulation the backend timing procedure can be very complicated

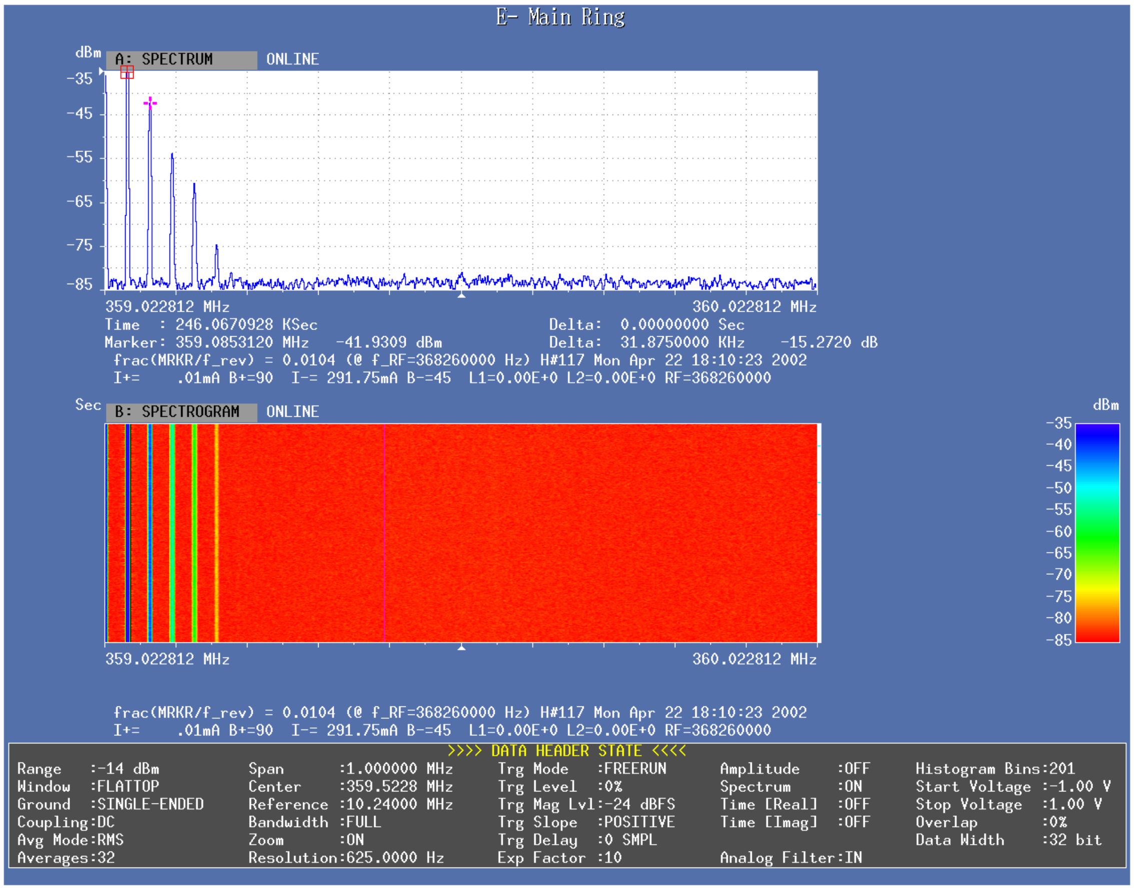


This is the longitudinal backend response versus delay done by kicking with a sinusoidal signal (at the synchrotron frequency) a single bunch stored in the ring.
The bunch passage should be synchronized with the center of the highest lobe to exploit the most of the power.
Each lobe is 418 ps, so the peaks are small

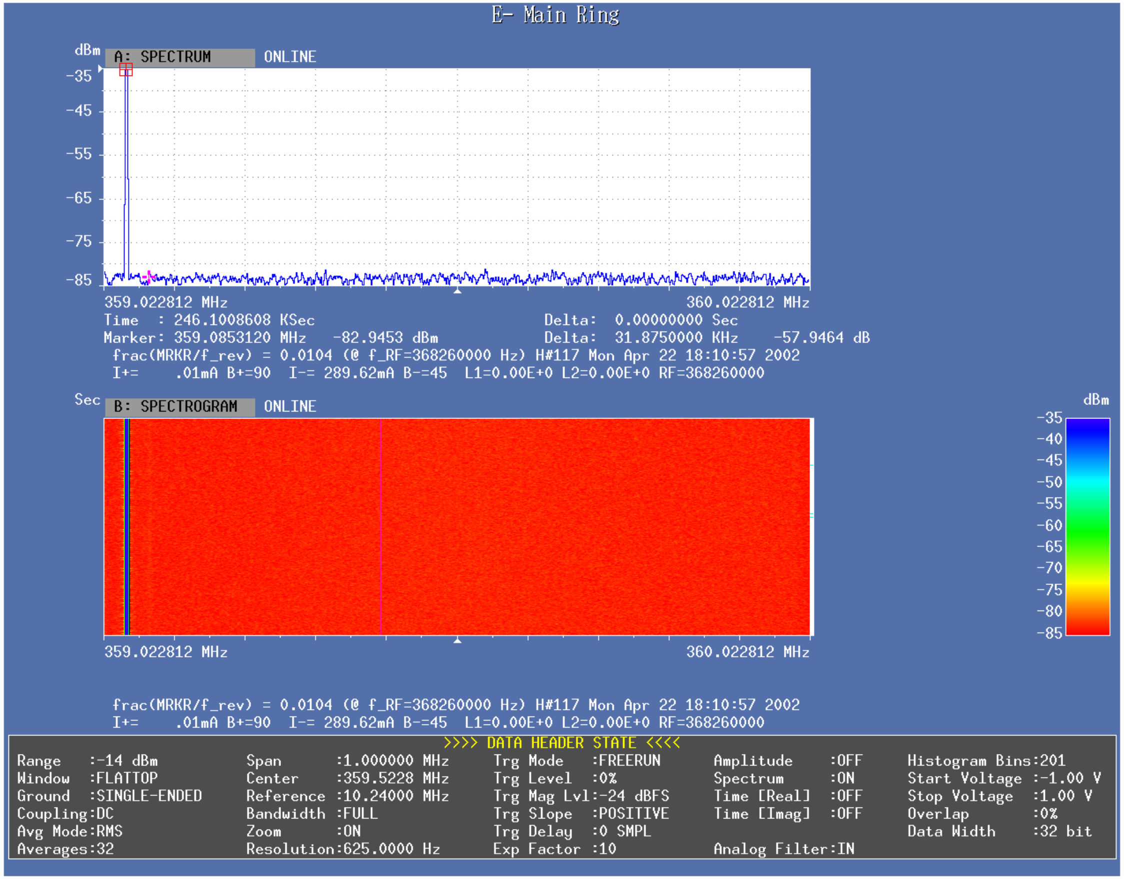
This is a more clean acquired record



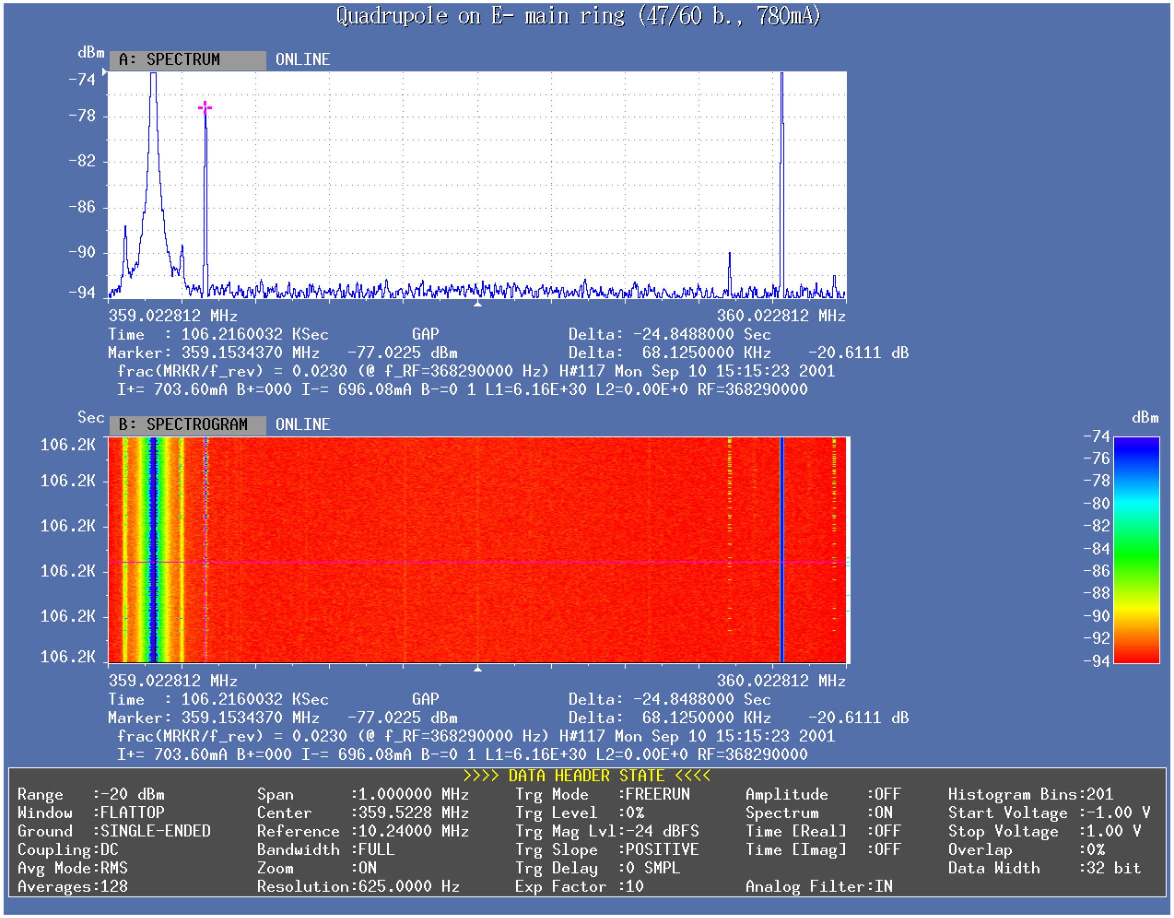
Beam behavior with longitudinal feedback off



Beam behavior with longitudinal feedback on



New problems: a broken bellow creates a longitudinal quadrupole instability (shape oscillations, not rigid body). Of course the feedback system has been designed only to damp longitudinal dipolar motions.



In that moment it was not possible to open the vacuum chamber because DAFNE was running for KLOE data taking but a solution was found to use the system to control both motions, the dipolar and the quadrupolar one

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Longitudinal quadrupole instability and control in the Frascati DAΦNE electron ring

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(Received 14 January 2003; published 7 May 2003)

A longitudinal quadrupole (q-pole) instability was limiting the maximum stable current in the DAΦNE e^- ring at a level of ~700–800 mA. In order to investigate the phenomenon, the instability threshold has been measured as a function of various machine parameters as radio frequency voltage ($V_{\rm rf}$), momentum compaction (α_c), number of bunches, fill pattern, etc. An unexpected interaction with the longitudinal feedback system, built to control the dipole motion, has been found and a proper feedback tuning has allowed increasing the threshold. The maximum stable beam current has now exceeded 1.80 A and it is no longer limited by the quadrupole instability.

DOI: 10.1103/PhysRevSTAB.6.052801 PACS numbers: 29.27.Bd

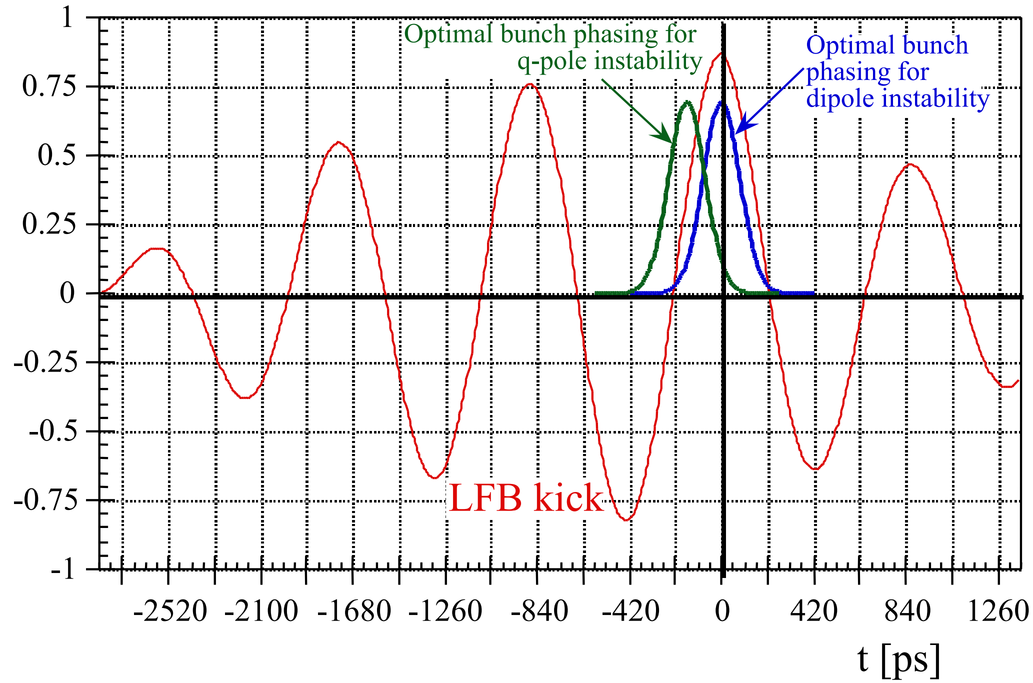
The solution is based on three steps

a) Detect quadrupole motion in the analog front end (*too easy to do ! Indeed there are risks of signal saturation)*

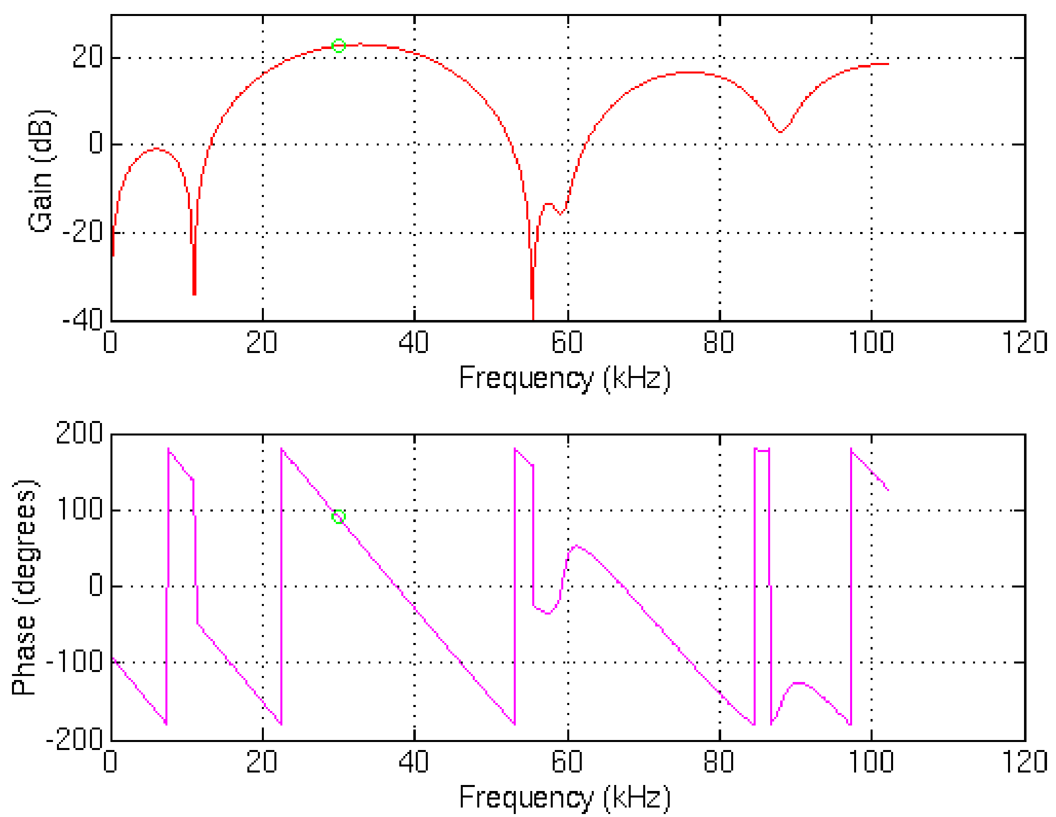
b) Play with software FIR filter to have the "right" phase response both at the dipole and quadrupole frequency. This can be done in at least two ways:
   a) designing a precise filter with two lobes and with peaks and phases tailored for dipole and quadrupole frequencies
   b) or simply implementing a filter with an enough slow phase slope (*both medium difficulty: note that physicists in the control room usually play with the RF voltage to make longer or shorter the bunch and increase the luminosity*)

c) Detuning the correction kick as shown in the next slide (*not so difficult to do, but difficult to know if perfectly optimized*)

Detuning the kick



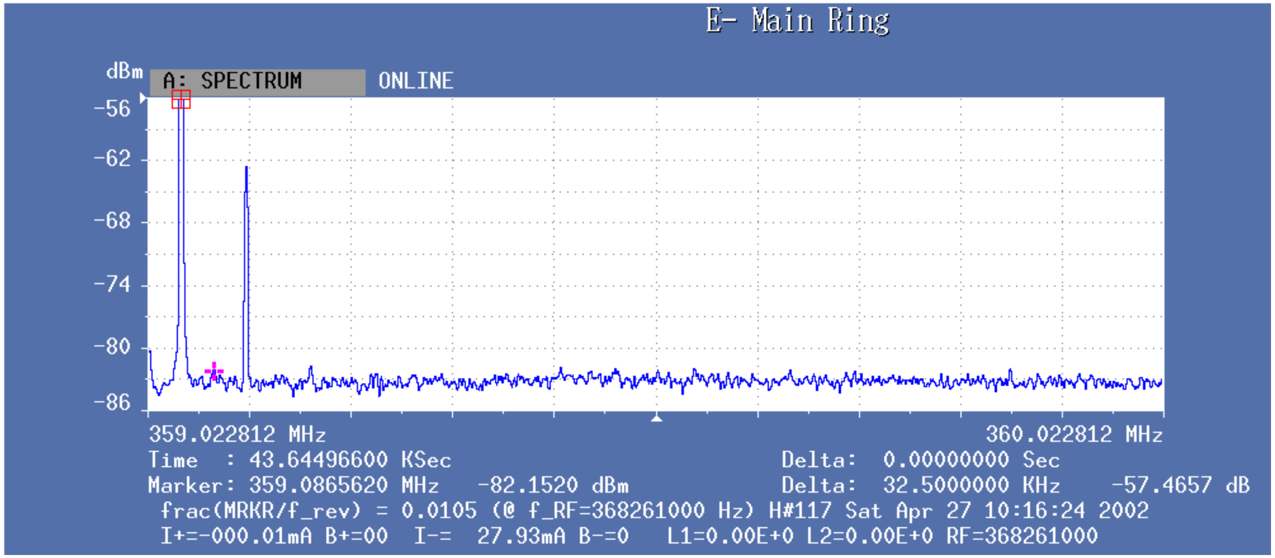
- To have the best dipole kick, the timing setup should align the peak of the signal (qpsk modulated) with the bunch peak
- To have the best quadrupole kick, the timing setup should align the zero crossing of the signal with the bunch peak. Note that only one of the two zero crossing (falling or growing slope) is able to damp the head tail motion, the other works as excitation signal.
- To have both, the best dipole and quadrupole kick, the timing setup should align the peak of the bunch at half way between the two strategies



Amplitude and phase response versus frequency response of a FIR filter with a peak at 30 kHz (synchrotron frequency) and a notch at 56 kHz (q-pole frequency) . Implementing this filter the quadrupole motion remains.
This fact has been interpreted as a definitive proof that the longitudinal quadrupole instability is not generated by the longitudinal feedback.
The instability is self-excited, i.e. the LFB itself does not create it.
In our opinion, the machine impedance must be the source of the instability.

Just to prove that it is not all a fiction, in this plot we choose a back end timing that damps the dipole oscillations and excites the quadrupole motions because it is placed toward the “wrong” zero-crossing side.

Indeed, a counterproof was performed: turning on the LFB, injecting single bunch with Vrf = 120 kV, and current > 26 mA, and decreasing by 150 ps from the peak the LFB backend delay, a q-pole motion has been excited (note that this happens also in the e+ rings at higher currents), as shown in the figure below.



Conclusion

- DAFNE cannot work as collider without longitudinal feedback systems
- The overdamped cavity kicker has been designed in the 1995 and it did not have any problem until now.
- A broken bellow in the year 2002 caused a longitudinal quadrupole instability has required new solution to damp it
- In the last two years, even if DAFNE has not more broken bellows in the vacuum chamber, it is necessary to use both dipole and quadrupole damping feedback to avoid small quadrupole motions that, at very high beam currents (> 1.5 A), can bring feedback input in saturation
- During the present DAFNE shutdown, a new faster back end timing control is in progress