SINGLE AND MULTIBUNCH DYNAMICS STUDY DURING THE DAΦNE MAIN RING COMMISSIONING

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Abstract

The Φ-factory DAΦNE is a high luminosity, 510 MeV double ring collider presently in operation at the Frascati laboratories of INFN. The longitudinal and transverse beam dynamics in DAΦNE is a crucial issue, since the strategy chosen to get the required luminosity calls for high values of both single and multibunch currents. Beam measurements (such as bunch lengths in various regimes, beam transfer functions, coupled bunch oscillation growth rates, microwave and head-tail instability thresholds) are reported and the feedback systems aimed to cure or prevent the beam instabilities described. The agreement between the experimental observations and the expected behaviours is emphasized, while the still open problems are discussed.

1 INTRODUCTION

The Frascati Φ-factory DAΦNE [1] is a 510 MeV e^+e^- collider consisting of two separated rings intersecting each other with an horizontal crossing angle in two interaction regions (IRs). The collision energy is tuned on the Φ meson resonance to study the CP violation occurring in the Φ decay into neutral kaons [2]. The statistics needed for an accurate measurement of the CP violation asks for a high luminosity value (of the order of 10^{32} $cm^{-2}s^{-1}$). The main machine design parameters are summarized in Table I.

The strategy adopted to get the required luminosity relies on high values of both single and multibunch currents.

A design single bunch luminosity of ≈ 4 10^{30} $cm^{-2}s^{-1}$ can be obtained with a single bunch current of ≈ 44 mA. Since up to 120 bunches can be stored in each ring, the limit luminosity is of the order of ≈5 10^{32} $cm^{-2}s^{-1}$ with a stored multibunch current as high as 5 A. From these considerations it is clear that single and multibunch longitudinal and transverse dynamics are crucial issues for an effective machine operation.

Table I: DAΦNE design parameters

Energy	E	510.0	MeV
Emittance	ε_x / ε_y	1/0.01	mm·mrad
Beam-beam tune shift	ξ_x / ξ_y	0.04/0.04	
Betatron tune	ν_x / ν_y	5.09/5.07	
RF frequency	f_{rf}	368.263	MHz
Harmonic number	h	120	
Revolution frequency	f_0	3.0688	MHz
Bunch average current	I_0	43.7	mA
Particles per bunch	N	9.0 10^{10}	
Momentum compaction	α_c	0.017	
Natural energy spread	$\sigma_{\varepsilon 0}$ / E	0.000396	
Bunch length	σ_z	2.0 ÷ 3.0	cm
Synchr. radiation loss	U_0	9.3	keV/turn
Damping time	τ_ε / τ_x	17.8/36.0	ms
RF voltage	V_{rf}	100 ÷ 250	kV
Synchrotron tune	ν_s	0.011	
Beta functions at IP	β_x^* / β_y^*	450/4.5	cm
Max. luminosity	L	5.3 10^{32}	cm^{-2} s^{-1}

The commissioning of DAΦNE has begun in autumn 1997 and has been stopped in November 1998 to allow the KLOE [2] detector roll-in. The commissioning interaction regions (the so called "day one" IRs), equipped

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with standard electro-magnetic quadrupoles and abundant diagnostics, have been replaced by the new ones (KLOE and DEAR IRs) and the DAΦNE commissioning with the KLOE detector has restarted in the early spring 1999. The machine is presently in operation, most of the time to deliver luminosity to the experiment. However, some shifts are still dedicated to luminosity tune-up and machine performance optimization.

2 SINGLE BUNCH DYNAMICS

The single bunch dynamics is dominated by the short range wakefields i.e. by the broadband machine impedance. An extensive study aimed to reduce the contribution of every vacuum chamber element to the DAΦNE longitudinal impedance has been carried out at the machine design stage [3]. The overall short-range wake function has been calculated by adding up the contributions of almost all the vacuum chamber discontinuities, that were estimated by analytical calculations or numerical 2D and 3D code (ABCI [4], MAFIA [5]) simulations assuming a 2.5 mm gaussian distribution. The resulting wake function and broadband impedance are shown in Fig. 1.

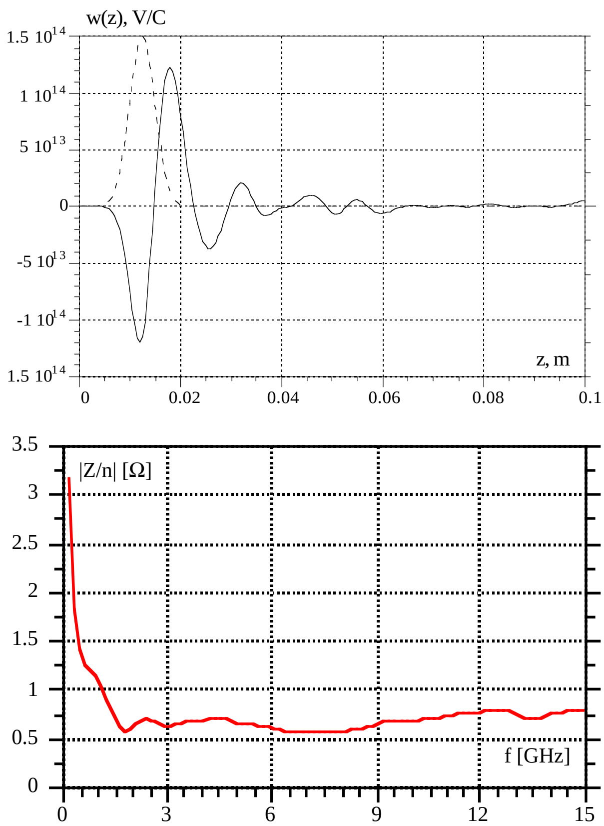


Figure 1: DAΦNE wake potential and broadband impedance of a 2.5 mm Gaussian bunch.

It is noticeable that the $|Z/n|$ value is about 0.6 Ω for frequencies higher than 1.5 GHz. The wake function and impedance of Fig. 1 have been assumed as the basic information to estimate the bunch lengthening process in DAΦNE as well as to evaluate the microwave instability thresholds and analyze the bunch behaviour in the turbolent regime. The results have been compared to the beam measurements.

2.1 Bunch lengthening: simulations

The DAΦNE bunch lengthening has been simulated by means of a tracking code similar to those successfully used to study the same process in the SLC damping rings, SPEAR, PETRA and LEP. This method consists in tracking the motion of N superparticles in the longitudinal phase space over 4 damping times. The turn-by-turn equation of each macroparticle motion includes lattice dispersion, radiation damping, stochastic quantum excitation, interactions with the RF field and with the wake of all the macroparticles ahead [6]. In order to avoid numerical growth of the bunch energy spread, a number of macroparticles larger than 10^5 has to be used to model the bunch.

The bunch physical properties of interest (such as rms length, rms energy spread, bunch centroid shift) are calculated by averaging over the last damping time.

The rms bunch length and energy spread calculated for bunch current from 0 to the nominal value are shown in Figs. 2a) and 2b), while the bunch current distributions for RF voltages of 100 and 250 kV are shown in Fig. 2c.

The distribution centroid in both Fig. 2c plots is delayed by the effect of the resistive part of the impedance.

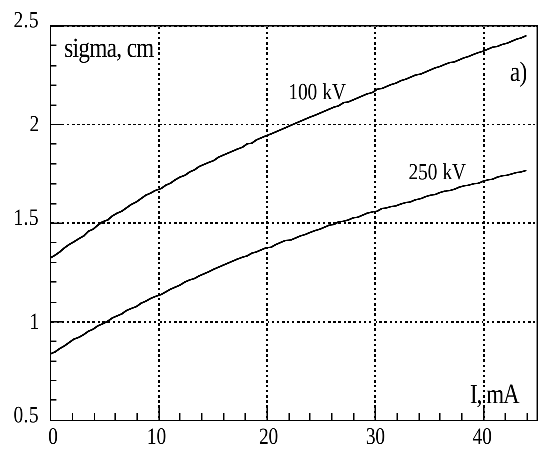


Figure 2a): rms bunch length

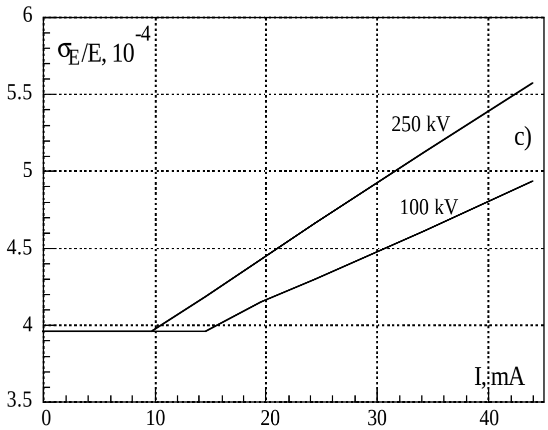


Figure 2b): rms energy spread

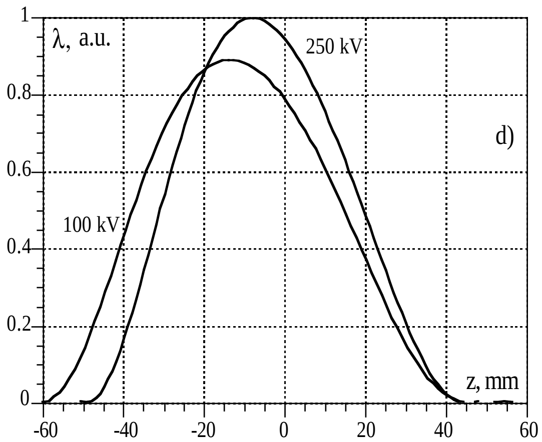


Figure 2c): Current distribution @I_b = 44 mA

It is evident from Fig. 2 that the estimated rms bunch length is always lower than the nominal value of 3 cm, even for RF voltages as low as 100 kV. This result has been confirmed by experimental measurements.

2.2 Bunch lengthening: experimental results

The DAΦNE bunch length has been measured at various RF voltages by acquiring the beam induced signal in a broad band button electrode with a sampling oscilloscope TEKTRONIX 11801A through a low attenuation cable (ANDREW FSJB-50A) about 8 m long.

The oscilloscope was equipped with a sampling head SD-24 with a rise time of 17.5 ps and an equivalent bandwidth of 20 GHz and the acquired waveforms have been stored on a PC through a GP-IB interface for off-line analysis.

The off-line elaboration of the stored waveforms was necessary to take into account the contribution of the button electrode transfer impedance and the cable frequency response. In fact the Fourier transform $V(\omega)$ of the signal $v(t)$ acquired by the oscilloscope is related to the bunch spectrum $I(\omega)$ by:

$$V(\omega) = I(\omega)\, Z_t(\omega)\, \alpha(\omega)$$

where $Z_t(\omega)$ and $\alpha(\omega)$ are the button transfer impedance and the cable frequency response that are both known from previous calibration measurements. Once $V(\omega)$ has been acquired it is easy to reconstruct the bunch current distribution $i(t)$ as the inverse Fourier transform of $I(\omega)$.

The comparison between bunch length measurements (circles) and simulations (solid line) at 100 kV of RF voltage for the positron ring are reported in Fig. 3. The measurements were taken before the KLOE detector roll-in, that means in presence of the temporary day-one interaction regions. The agreement between measurements and simulation is really good for bunch currents larger than 5 mA. The low current disagreement is attributed to the frequency response of the button, that peaks and rolls above the cut-off frequency of the TE11 mode (≈ 5 GHz); short bunches, having a wide spectral contents, produce distorted pulses at the button output, and their original shapes can be hardly recovered.

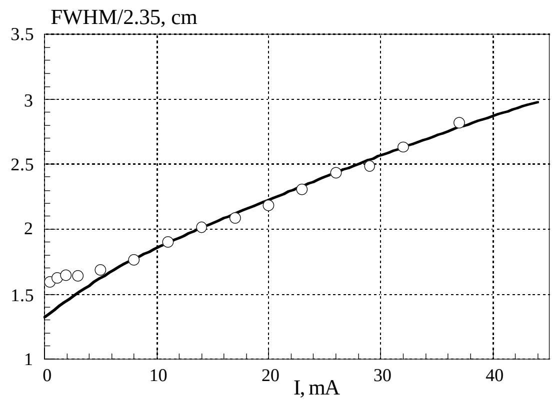


Figure 3: Bunch lengthening (FWHM) at 100 kV RF voltage. Solid line: numerical calculations; circles: measurement results.

The bunch length measurement has been performed also on the electron ring, and has been repeated on both rings after the the detector roll-in, in presence of the new KLOE interaction region.

The measurements have shown that electron bunches, in same conditions, are few percent longer than positron ones. This is probably due to the extra contribution given to the electron ring impedance by several ion clearing electrodes placed along the vacuum chamber.

The measurements taken after the detector roll-in are very similar to those taken before, with the exception that in this case they have been stopped at ≈ 20 mA due to the harmful presence of a quadrupole single-bunch instabilitiy threshold in both ring. This last effect will be discussed in the microwave instability paragraph.

As a conclusion, the very good agreement between the DAΦNE bunch length simulations and measurements shows that the efforts to design a low impedance vacuum chamber and to accurately evaluate the overall machine wake function were successful. Neverthless, it seems that the installation of the new interaction region has given an unexpected contribution to the machine impedance which does not affect significantly the bunch length but which is anyway capable to modify the microwave thresholds by a large amount.

2.3 Microwave instability: analytical evaluations

The coupling between bunch longitudinal coherent modes is the driving source of the microwave instability. Different azimuthal modes may couple if their natural frequencies are shifted by amounts comparable to the synchrotron frequency ("strong" instability), while radial modes having the same azimuthal number may couple already for much smaller frequency shift ("weak" instability). The coherent frequency shift is due to the interaction between the bunch distribution and the machine impedance.

To study the microwave instability for the DAΦNE bunch we assumed again the machine wake function and broadband impedance shown in Fig. 1 and we used the double water-bag analytical method [7]. This consists in approximating the real bunch distribution in the longitudinal phase space by a double water bag. This is one of the simplest methods to take into account the splitting of the azimuthal modes with different radial numbers.

The approximated double water bag bunch distribution is put in the Vlasov equation to obtain, with a normal mode expansion of the distribution perturbation, an eigenvalue system with an infinite number of variables (the angular frequencies $\Omega_{m,k}$ of the coherent modes) and equations, labelled by the azimuthal and radial indexes m and k ($m=1\div\infty$; $k=0,1$). The system can be approximately solved by truncating it at some m_{max}; we limited our analysis to $m_{max} = 9$.

The plot of the calculated coherent mode frequencies $f_{m,k}$ ($m = 1 \div 9$; $k = 0,1$) as a function of the bunch current for 4 different RF voltages (100, 150, 200 and 250 kV) are reported in Fig. 4. The frequencies of the radial modes with the same azimuthal number m are equal at zero current ($f_{m,k} = m\, f_s$), as shown in Fig. 4, while split with increasing current leading to various coupling of modes.

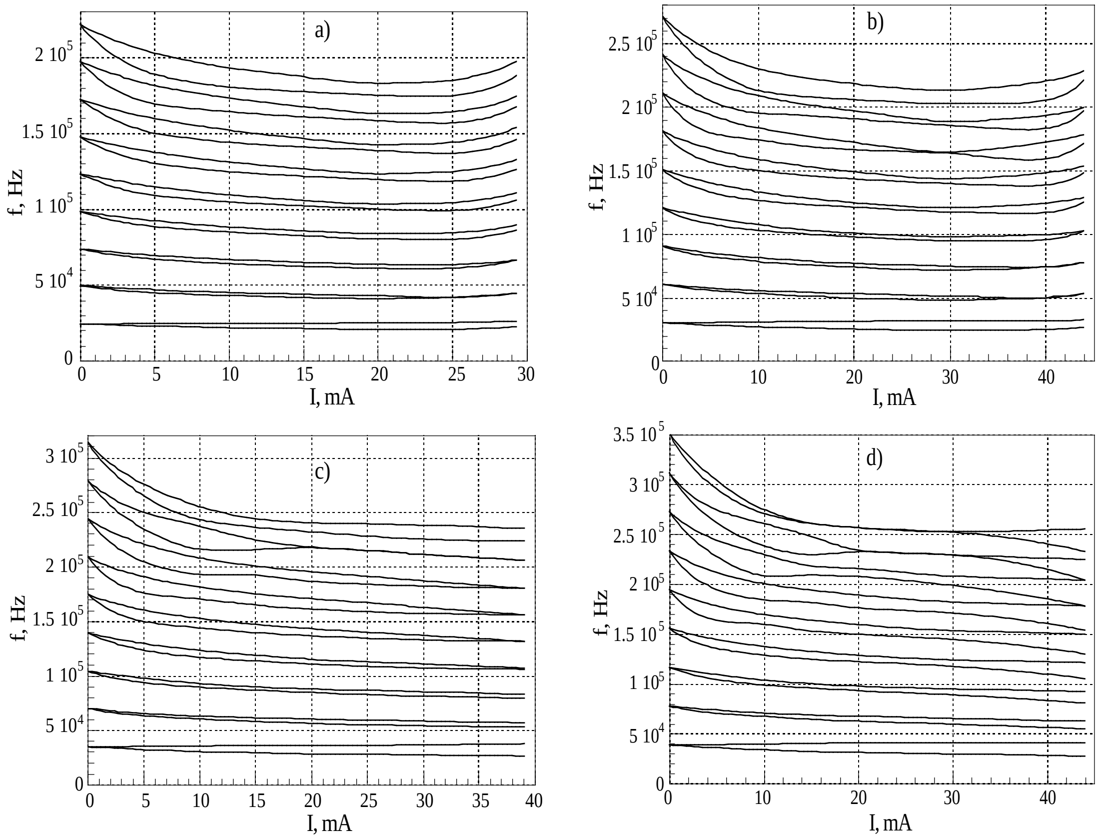


Figure 4: Longitudinal coherent mode coupling at different RF voltages
a) - 100 kV; b) - 150 kV; c) - 200 kV; d) - 250 kV

Accordingly to these results, the microwave instability at low RF voltages is driven by the coupling of radial modes with low azimuthal index. For instance, at V_{RF} = 100 kV the lowest thresholds are given by the coupling of the radial quadrupole modes (@ $I_b \approx$ 24 mA) and sextupole modes (@ $I_b \approx$ 28 mA). At higher RF voltages the microwave instability is driven by the coupling of modes with high azimuthal index.

Since the excitation of coherent longitudinal modes produce a bunch length modulation, which can in turn excite beam-beam resonances, the turbulent regime may affect seriously the collider luminosity. From this point of view a high RF voltage operation seems to be preferable since unstable high order coherent modes drive high order beam-beam resonances which are much less harmful for the beam-beam interaction.

2.4 Microwave instability: experimental observations

In spite of the fact that the nominal DAΦNE single bunch current of ≈44 mA is already a quite large value, in the first commissioning stage before the detector roll-in we managed to store routinely single bunch currents of 110 mA in both rings, about a factor 2.5 above the nominal value, with no evidence of destructive single bunch instabilities.

Indeed, we also got a good agreement with the analytical calculation since we observed, during the bunch length measurements at V_{RF}=100 kV, the presence of pure quadrupole and dipole thresholds at $I_b \approx$ 26 mA and $I_b \approx$ 35 mA respectively. By increasing the RF voltage to 150 kV, the quadrupole threshold was shifted to ≈ 38 mA and the dipole one was pushed beyond the nominal single bunch value. The observed thresholds correspond precisely to those predicted for the low azimuthal mode coupling by the double water bag method and shown in the Fig. 4 plots.

At higher RF voltage we got no evidence of instability, even for single bunch currents much larger than nominal value. This probably means that high azimuthal mode coupling is Landau damped, or, more likely, that the mode coupling analytical predictions are much less accurate for high azimuthal indexes as a consequence of the eigenvalue equation system truncation.

Unfortunately, the well consistent scenario described above appeared to be modified after the insertion of the detector interaction region. Although we did not expect sizeable contributions to the machine wake function and impedance by the new IR, an harmful quadrupole instability has appeared in both rings. The typical dependence of the single bunch threshold on the RF voltage for both e^+ and e^- beams is shown in Fig. 5. The first noticeable effect is the threshold reduction at higher RF voltage. This behaviuor, on one hand, is opposite to that observed in the early commissioning stage, and, on the other hand, forced us to operate the RF system at lower voltage (≈100 kV) which is certainly not beneficial for the beam lifetime and the RF beam loading.

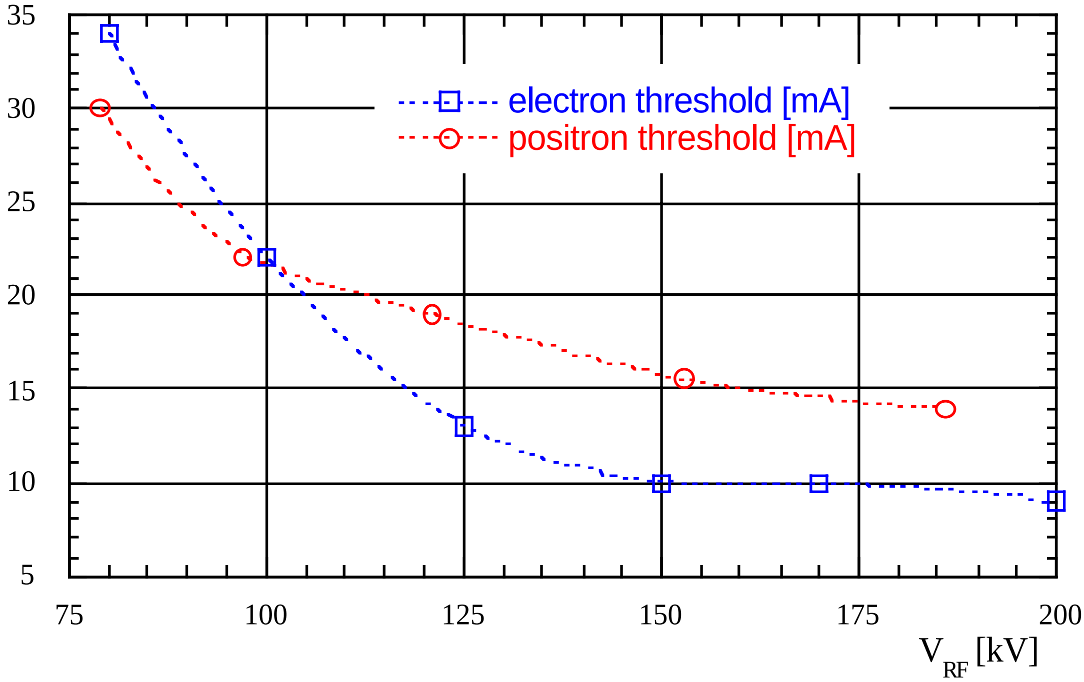


Figure 5: Single bunch current thresholds of the quadrupole mode for the DAΦNE e^+ and e^- beams.

The threshold dependence on the RF voltage can be explained by the bunch lengthening effect which reduces the effective impedance at low RF voltages. This interpretation has been confirmed by measuring the treshold tendency with the ring momentum compaction α_C at fixed RF voltage: the results show that, by lengthening the bunch through an α_C increase, the quadrupole thresholds shift up. This can also explain why the measured thresholds of Fig. 5 were different for the two rings: in fact we know that the α_C values of the two lattices were not equal during that measurements.

Being the quadrupole thresholds so sensitive to the bunch length, we can conclude that something has been modified in the high frequency part of both ring impedances during the machine stop of last winter. The source of this modification is situated with high probability in one common part of the rings, that means in one of the two IRs, where some delicate devices are located (some shielded bellows, the KLOE shielded vacuum chamber, ...). At this time we are not able to formulate a more accurate hypothesis.

Anyway, since the bunch length control has been demonstrated to be effective in pushing up the instabilty thresholds, and since the measured bunch length is still lower than the nominal value, we are planning to install an high harmonic RF cavity to contro the bunch length. This should allow us not only to freely control the bunch length, but also to add substantial Landau damping.

2.5 Transverse single bunch dynamics

So far we did not carry out measurements especially dedicated to single bunch transverse dynamics, but some observations have shown that the DAΦNE broadband transverse impedance is small.

First, an head-tail instability threshold as high as 13 mA with sextupoles off has been achieved after an accurate orbit correction; second, the observed vertical tune shift is a small fraction of the synchrotron tune in the whole current range from 0 to the nominal value, indicating that the DAΦNE operation is quite far from the transverse mode coupling threshold.

3 MULTI-BUNCH DYNAMICS

The multibunch dynamics is dominated by the long range machine wakefields, that means by the resonant fields trapped in various regions of the machine vacuum chamber.

The strategy adopted to optimize the machine design for multibunch operations was based on three guidelines:

- reduction of the number of trapped modes by smoothing the geometry of the vacuum chamber components and shielding the resonant volumes;

- damping of the residual trapped modes by means of broadband waveguides (RF cavities, longitudinal feedback kickers) or dedicated probes (transverse kickers, injection kickers);

- development of fast and efficient feedback systems (bunch-by-bunch longitudinal feedback, 0-mode feedback) to actively cure the coupled bunch instabilities.

3.1 Longitudinal Multi-bunch dynamics

The bunch-by-bunch longitudinal feedback systems [8] have been succesfully commissioned on both rings (July '98 for electrons, September '98 for positrons). With the temporary day-one IRs, a maximum current of ≈ 550 mA in 30 bunches configuration has been obtained in both rings, limited by the poor IR vacuum. Recently, about ≈ 700 mA have been stored in 120 bunches in both rings with the longitudinal feedback turned off; this indicates that the machine vacuum has been substantially improved by the new IRs.

The bunch-by-bunch longitudinal feedback systems have been developed in the frame of an international collaboration involving the PEP II (SLAC), ALS (LBNL) and DAΦNE (INFN-LNF) groups. Many other machines in the world are presently implementing similar systems.

The basic architecture of this systems is shown in Fig. 6. The longitudinal position of each bunch is tracked by the front-end electronics which consists in a broadband phase detector followed by a fast digitizer. The digitized signal is downampled and sent to a DSP farm where, through a wide choice of possible digital filters, the longitudinal oscillation of each bunch is shifted by $\pi/2$ to generate a proper out-of-phase kick. The correction signals are recombined in a single channel by a hold buffer, and the individual kicks are transferred to the bunches by broadband kickers driven by pure class A solid state amplifiers, providing damping of the oscillations. The longitudinal kickers are waveguide overloaded cavities that have been designed for DAΦNE to optimize the shunt impedance and reduce the HOM content [9].

A plot of the beam spectrum around a revolution harmonic with feedback off and on is reported in Fig. 7 giving a glance of the system effectiveness in damping dipole coupled bunch oscillations. A damping time shorter than ≈ 200 μs has been measured under various conditions.

The feedback system is also a very powerful diagnostics tool when used to perform the so called "grow-damp" measurements [10]. In this modality the feedback gain is inverted or set to 0 for a time long enough to let the instability amplitudes grow to a measurable level, then turned again in the standard operation mode restoring beam control.

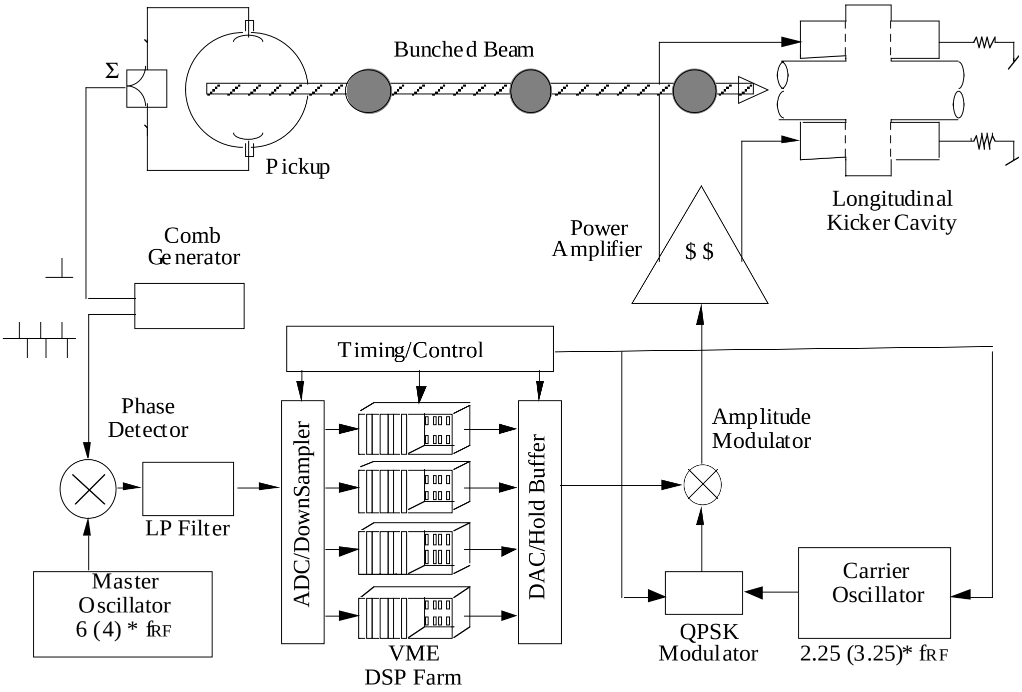
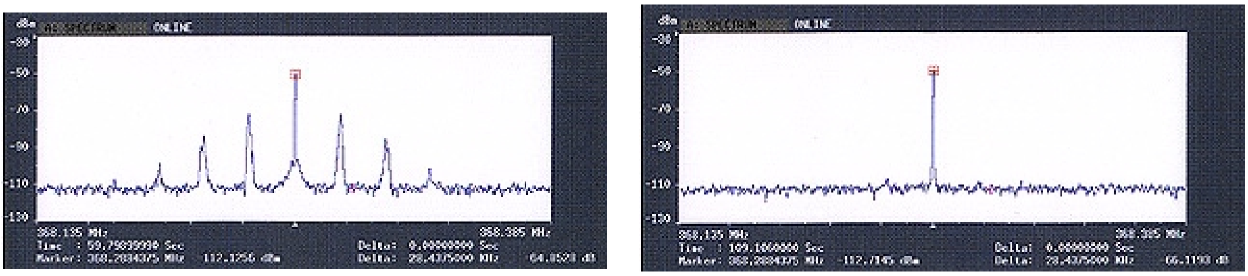


Figure 6: Basic architecture of the bunch-by-bunch longitudinal feedback system



a) feedback off

b) feedback on

Figure 7: Longitudinal pick-up signal spectrum of 30 bunches

The output data of the system front-end during both "grow" and "damp" phases are acquired and post-processed. The amplitude vs. time of any possible coupled-bunch mode can be singled out allowing to determine the most dangerous coupled bunch modes, their growth rates, where they are probably located in the frequency spectrum, how much they are damped by the feedback system. An example of grow-damp measurements on the DAΦNE electron ring with 30 bunches is shown in Fig. 8. The time evolution of the bunch oscillation amplitudes, the time evolutions of the coupled bunch mode amplitudes, the mode growth rates and damping rates pre and post breakpoint are reported.

The modes #6 and #11 are the most unstable ones (with rise times of ≈ .8 ms and ≈ 1.3 ms respectively), and they are efficiently damped by the feedback system (damping times ≈ 200 μs and ≈ 300 μs respectively).

As explained in section 1.4 we have been recently forced to operate the RF systems at a lower voltage (V_{RF} ≈ 100 kV). The negative shift of the synchrotron frequency of the beam barycentric oscillation (the coupled bunch mode "0") with beam loading is emphasized under this conditions.

The longitudinal feedback system got in some trouble when dealing with low synchrotron frequency lines located out of the digital filter band. To avoid such kind of malfunctioning we decide to increase the damping of the 0-mode by adding a dedicated analog feedback acting on the RF low-level controls. It consists of an RF phase modulation π/2 out of phase with respect to the longitudinal barycentric oscillation detected by the beating between a sample of the cavity voltage and the beam-induced signal on a longitudinal monitor [11]. The π/2 phase shift is produced by an analog AC coupled integrator circuit simply based on OP-AMPs. The calculated damping time provided by this system is roughly proportional to the integrator bandwith, and is ≈ 50 μs for a 6 kHz bandwidth.

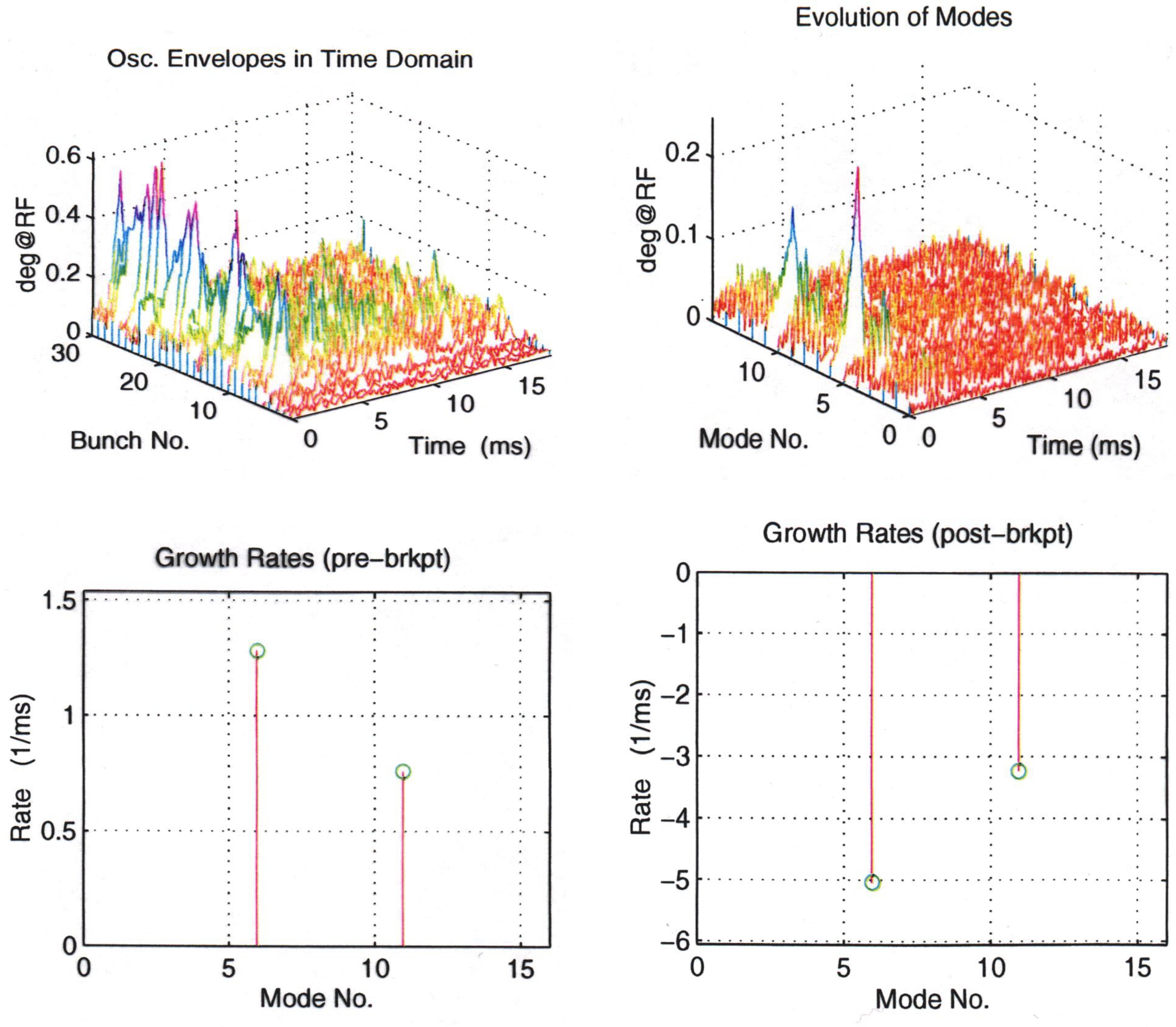


Figure 8: Example of multibunch "grow-damp" measurement on the electron beam

The implementation of the 0-mode feedback systems was successful in preventing the anomalies in the longitudinal feedback system operations. At present, the multi-bunch current limits are set only by the quadrupole single bunch threshold or by the machine vacuum, which is still improving due to the beam conditioning.

3.2 Transverse Multi-bunch dynamics

During the early commissioning phase we observed the presence of a coupled-bunch vertical instability limiting the total positron current. At beginning the transverse instability has been studied by simply analyzing the spectrum of the signal induced by the unstable beam on a vertical position monitor. The frequency location of the highest betatron lines gave us information on what were the most excited coupled bunch modes. We also noticed that the vertical oscillations would start as soon as the longitudinal feedback was turned on, while almost only longitudinal oscillations were present with the feedback turned off. Moreover, the vertical instability could be damped by increasing the strength of the magnetic sextupoles, that means by overcorrecting the ring chromaticity.

More accurate measurements have been made on the positron beam by digitizing the signal from a transverse BPM using the front-end electronics of the longitudinal feedback system of the electron ring. The transverse motion of the bunches has been acquired and off-line processed to extract information on the dynamics.

The most unstable coupled bunch mode was found to be the number 55 in 120 bunch operation. The instability source has been identified as a 1304 MHz mode trapped in the injection kicker that was found by bench impedance measurements performed before the machine assembling. Its resonant frequency is located very near to an unstable sideband of the transverse coupled bunch mode 55;

moreover, the instability threshold is clearly correlated to the vertical orbit in the injection kickers, as it has been experimentally demonstrated by setting local orbit bumps in all the vacuum chamber regions considered potentially dangerous for the transverse dynamics.

Once the betatron tunes have been changed (from 5.11/5.08, close to the design values, to 5.15/5.21) to operate the machine at a less critic, farther from the integer working point[12], the driving mode has been detuned with respect to the unstable line, and the vertical instability almost disappeared. Anyway, since the HOMs trapped in the injection kickers are potential source of both longitudinal and transverse multibunch instabilities, we have designed special HOM dampers based on capacitive coupling of the resonant fields[13]. A full set of new injection kickers equipped with HOM dampers is presently in fabrication, and we plan to install them on the rings in the next machine shutdown.

4 CONCLUSIONS

The dynamics measurements made during the DAΦNE commissioning are globally in good agreement with the expected beam behaviour. The very good agreement between the bunch length measurements and simulations indicates that the computed machine wake function and impedance are quite realistic, and the measured values of the single bunch thresholds (microwave, head-tail, ..) show that the design efforts aimed to reduce the longitudinal and transverse broadband impedances were successful.

The longitudinal multibunch dynamics is kept under control by the feedback systems, which means that the natural growth rates due to the resonant modes of the vacuum chamber are not too large. The installation of the new damped injection kickers should improve the transverse multibunch dynamics, which however has not limited the machine performances so far.

Presently, the only beam dynamics serious issue is represented by a pure quadrupole longitudinal instability limiting the single bunch current to ≈15 mA. This is probably a microwave threshold caused by an unexpected contribution to the high frequency part of the machine broadband impedance given by some element in the new interaction regions. Although the efforts to overcome this problem were ineffective so far, we are quite confident that the installation of an high harmonic RF system is the right solution to the problem since we have experimental evidence that the instability threshold raises with the bunch length; moreover we can also expect in this case a beneficial contribution from the Landau damping coming from the double RF system operating in the lengthening regime.

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