DAΦNE BROADBAND IMPEDANCE

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Abstract

Beam dynamics is one of the most challeging issues of DAΦNE, due to the high single bunch current involved. The single bunch dynamics is dominated by the short range wakefields, that are usually expressed in terms of machine broad band impedance. Measurements of bunch lengthening and betatron tunes as functions of bunch currents have been performed on both rings to evaluate the longitudinal and transverse broadband impedances. Results are compared with calculations and impedance differences between the two rings are discussed.

1 INTRODUCTION

The Φ–factory DAΦNE is a e^+e^- collider at the energy of the Φ resonance (1020 MeV in the center of mass) designed and built in Frascati National Laboratories of INFN [1]. It is aimed at producing a very high luminosity in the 10^{32} $cm^{-2}s^{-1}$ range. Longitudinal and transverse beam dynamics in DAΦNE are crucial, since the strategy chosen to get the required high luminosity calls for high values of both single and multibunch currents. At present, the design single bunch current of 44 mA has been largely exceeded in both collider rings: about 200 mA have been stored in a single bunch without observing harmful instabilities. In the multibunch regime more than 2 A of average current have been stored in the electron storage ring and about 1.3 A in the positron one. In this paper we discuss the single bunch dynamics, while multibunch dynamics aspects are considered elsewhere [2]. In particular, we study the machine broadband coupling impedance describing parasitic interaction of a bunch with the surrounding vacuum chamber. In the longitudinal plane this can be done by measuring and analyzing bunch lengthening and microwave instability. These issues are very important for the low energy collider DAΦNE since the lifetime, dominated by the Touschek effect, grows proportionally to the bunch length. On the other hand, an excessive bunch lengthening may lead to luminosity performance limitation due to the "hour-glass" effect. In turn, in the microwave regime, unstable internal bunch oscillation modes can worsen injection and create new destroying resonances in beam-beam collisions. In the transverse plane, short range wake fields cause betatron tune shift and, in the worst case, can result in the turbulent mode coupling instability, putting severe restriction on the bunch current. Section 2 of this paper describes the experimental set up for the bunch length measurements, while the experimental results, longitudinal broad band impedance estimates and comparison with analytical calculations and numerical simulations are given in Section 3.

In Section 4 we summarise the results of the transverse broad band impedance measurements.

2 MEASUREMENT SETUP

DAΦNE synchrotron light in the visible range of the radiation, emitted by the electrons and the positrons in dipole magnets symmetrically placed in the two rings, is transported to an external laboratory through two 25 m long optical lines. In this configuration, with the identical length of the two optical lines, simultaneous measurements on the two beams (also during interaction) are feasible without any change of the experimental set-up.

In each line a water-cooled Al mirror extracts the radiation from the antechamber of the vacuum pipe through a fused silica vacuum window. The light passes a 2 mm aperture slit which limits the source path to 3 mm in order to have temporal resolution better than 10 ps. Two large aperture achromatic lenses and a series of glass mirrors with surface metallization transport the light up to the optical bench outside the DAΦNE hall in which the measurement systems are installed.

The bunch length is measured with a Streak Camera Hamamatsu C5680 with 1.5 ps resolution. The camera operates in synchroscan mode, in which the fast sweep is triggered by an internal RF signal locked to the machine RF. In order to use a Hamamatsu commercially available circuit we trigger with the fourth sub-harmonic of the master oscillator (368/4 = 92 MHz). The single bunch longitudinal distribution is recorded with variable integration time (1-100ms) depending on the bunch current. The incoming trigger jitter, which can affect the measurements overestimating the bunch length, has been measured: its rms value is less than 4.5 ps. During the measurements the stability of the longitudinal position of the bunch has been verified by monitoring an electromagnetic pickup signal with a spectrum analyser. The streak camera signals are stored in a PC and analysed initial-time with a Hamamatsu software to give the full width at half maximum value of the pulse length. More complete analysis is performed extracting the pulse profiles data and fitting them off-line.

3 BUNCH LENGTH AND IMPEDANCE MEASUREMENTS

We have performed bunch length measurements at different RF voltages V_{RF} and varying the momentum compaction α_c. Figures 1 and 2 shows the bunch length σ_z for the positron and electron rings, respectively. The RF voltages and momentum compactions for each set of measurements are indicated in the corresponding plot legends. In these plots we note that above certain current thresholds bunch lengthening no longer depends on the momentum compaction and can be described by simple scaling laws:

$$\sigma_z[cm] = 4.36 \times \left(\frac{I[mA]}{V[kV]} \right)^{1/3} ;\ for \quad positron \quad ring$$

$$\sigma_z[cm] = 5.50 \times \left(\frac{I[mA]}{V[kV]} \right)^{1/3} ;\ for \quad electron \quad ring$$

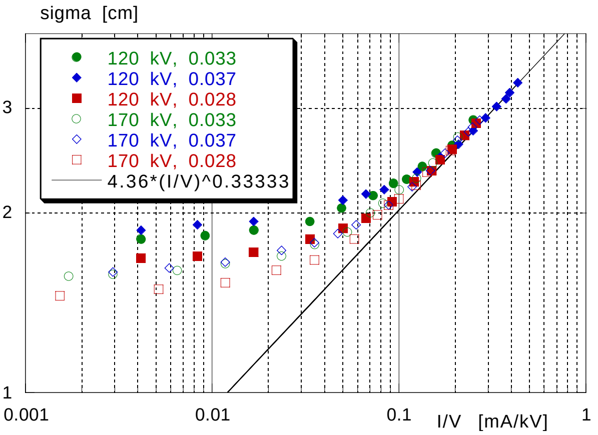

Figure 1: Bunch lengthening in e$^+$ ring.

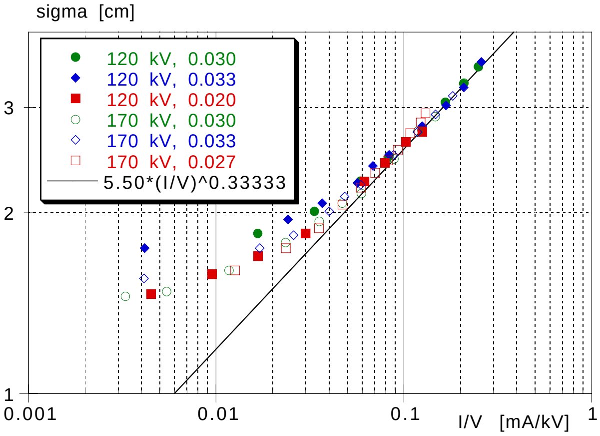

Figure 2: Bunch lengthening in e$^-$ ring.

As it has been shown [3], for a given storage ring, the bunch length satisfies the following scaling property above the microwave instability threshold:

$$\sigma_z = f(\xi)$$

where the scaling parameter ξ does not depend on momentum compaction:

$$\xi = \frac{\alpha_c I}{\nu_s^2 E} = \frac{2\pi I}{heV_{RF} \cos\varphi_s}$$

Here E is the storage ring energy; h the harmonic number; ν_s the coherent synchrotron tune; ϕ_s the synchronous frequency and e the electron charge.

The fact that in our case the bunch length scales as

$$\sigma_z \propto \xi^{1/3}$$

shows that the effective longitudinal coupling impedance is practically purely inductive. This is not a surprise since the bunch in DAΦNE is relatively long at the nominal current and the effective impedance "seen" by the bunch is dominated by the low frequency inductive impedance of the vacuum chamber. From the above scaling laws the impedance is evaluated to be 0.53 Ω for the positron ring and 1.1 Ω for the electron one. The significant difference between the impedances of the two rings (by a factor 2) can be explained, in our opinion, by the presence of 40 ion clearing electrodes in the electron ring. Figure 3 shows the measured bunch distribution profiles at low current and at the nominal current for the electron ring. As it can be observed, the bunch gets much broader due to interaction with the inductive impedance and slightly asymmetric due to the real part of the impedance. The shift of the bunch center corresponds to the synchronous phase shift due to small, but not negligible parasitic energy losses.

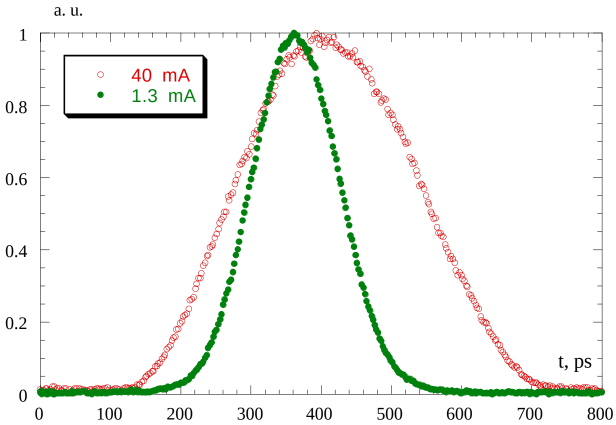

Figure 3: Bunch density profiles at low and high current.

Yet another observation is that the bunch enters the turbulent regime (see points reaching the straight lines in Figs. 1, 2) at higher currents for lower RF voltages and higher momentum compactions. This is in agreement with Boussard's criterion on the higher instability thresholds for lower peak currents. The microwave instability does not seem to be harmful to beam dynamics. In the worst case we observe unstable quadrupole oscillations on the spectrum analyzer at high currents per bunch that can be damped by lowering the RF voltage.

It is worth mentioning that the measured impedance is in a good agreement with analytical calculations and numerical simulations carried out much prior to DAΦNE commissioning. At the very early stage of the vacuum chamber design the applied broadband impedance model [4] predicted for DAΦNE had the following frequency dependent impedance:

$$\frac{Z}{n} = \left\{ \begin{aligned} & -i0.26 + \frac{24.8}{n} + \frac{(1 - i\,\mathrm{sgn}(n))2.89\sqrt{|n|}}{n} + \\ & + \frac{(1 + i\,\mathrm{sgn}(n))274.42}{n\sqrt{|n|}} \end{aligned} \right\} \Omega$$

The estimate of the impedance at the bunch spectrum roll-off frequency for the nominal bunch length of 3 cm gives |Z/n| = 0.41 Ω, close to the measured positron ring impedance. Later, the overall short range wake function was calculated numerically by adding up contributions of almost all the vacuum chamber discontinuities [5] assuming a 2.5 mm gaussian bunch. The resulting wake function and the broadband impedance (Fourier transform of the above wake field) are shown in Fig. 4 and Fig. 5, respectively. It can be pointed out that the |Z/n| value is about 0.6 Ω for almost all the 2.5 mm bunch frequency spectrum. The results of bunch lengthening process simulations based on the given wake function have already shown a good agreement with previous measurement results in the positron ring performed by detecting and elaborating the beam signal induced in a broadband button electrode [6].

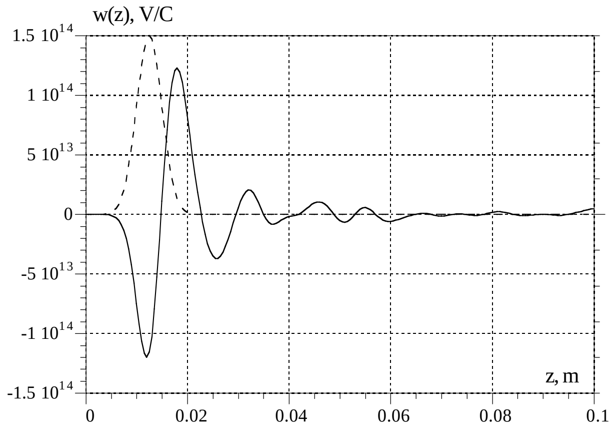

Figure 4: Wake field of a 2.5 mm Gaussian bunch.

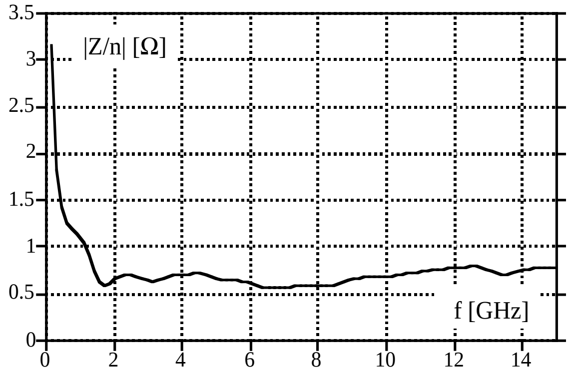

Figure 5: Normalized impedance estimated numerically.

4 TRANSVERSE IMPEDANCE

We estimated the transverse effective impedance Z^{eff} by measuring the dependence of the coherent betaron frequency of the dipole mode (m = 0) on the bunch current. The imaginary part of the impedance is proportional to the measured current dependent betatron frequency shift Δf:

$$\mathrm{Im}\left\{Z_{\perp}^{eff}\right\} = \frac{\Delta f \sigma_z}{I} \frac{32\pi^2 f_0 Q(E/e)}{c^2}$$

where Q is the betatron tune (either vertical or horizontal); f_0 the revolution frequency; and$c$ the speed of light.

Figure 6 shows the betatron frequency shifts as a function of the bunch current measured in the electron ring (empty circles) and in the positron one (full circles). The two upper curves correspond to the frequency shift in the horizontal plane while the lower ones show the results of the vertical frequency shift measurements. Due to the shape of the vacuum chamber, the vertical tune shift is higher than the horizontal one for both rings. The vertical frequency shift curves are similar for the two rings, but the transverse impedances are different since the bunch is longer in the electron ring. For the nominal bunch current of 40 mA, the effective impedances are evaluated to be equal to 165 kΩ/m and 130 kΩ/m for the electron and positron rings, respectively. It is noteworthy that the vertical impedance of the electron ring is by a factor of 4 higher than the horizontal one, while in the case of the positron it is only 2. This difference is still to be understood.

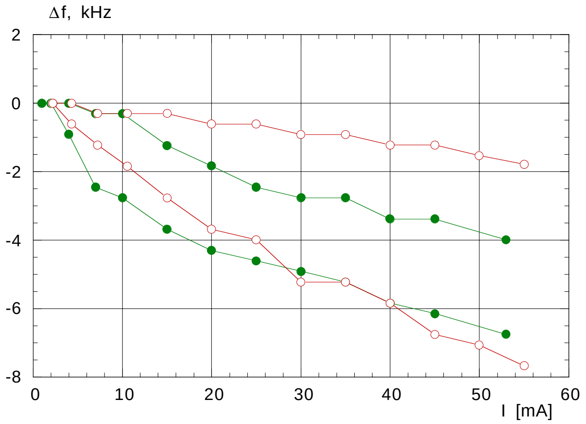

Figure 6: Measured betatron tune shifts vs. bunch current.

We also can conclude that we are safely far from the transverse turbulent microwave instability threshold, since the measured frequency shifts at the nominal bunch current are much smaller than the synchrotron frequency, which varies in the range 25÷40 kHz depending on applied RF voltages and momentum compaction.

5 REFERENCES

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