DAΦNE TECHNICAL NOTE

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Note: **BM-1**

BUNCH LENGTHENING AND IMPEDANCE MEASUREMENTS AND ANALYSIS IN DAΦNE ACCUMULATOR RING

R. Boni, A. Drago, A. Gallo, A. Ghigo, F. Marcellini, M. Migliorati, F. Sannibale, M. Serio, A. Stella, G. Vignola, M. Zobov

1. Introduction

Two kinds of collective effect measurements, in single bunch mode operation, were performed on the accumulator beam, last December.

The first one is the measurement of the synchronous phase shift versus beam current. This measurement allows to calculate energy losses due to parasitic beam-vacuum chamber interaction and estimate the real part of the machine impedance.

The second one is the measurement of the bunch lengthening. Besides the measurement of the bunch length at different currents, it helps to evaluate the inductive part of the machine impedance, since the inductive impedance is mainly responsible of the bunch lengthening. In turn, the real part of the impedance leads to a bunch shape symmetry distortion. Knowledge of the bunch shape gives a valuable information about the real part of the impedance and parasitic losses.

In this Note we present results of the measurements and their analysis, comparing the results with numerical simulations based on the accumulator ring wake field estimates.

Table 1 lists the accumulator ring parameters relevant for the data analysis.

Table 1. Accumulator ring parameters

Energy, E (MeV)	512
Circumference, $2\pi R$ (m)	32.563
RF peak voltage, $\hat{V}_{rf}$ (kV)	60 (55 - 90)*
RF frequency, f_{rf} (MHz)	73.678
Harmonic number, h	8
Momentum compaction, α_c	0.044
Horizontal tune, Q_x	3.1470
Vertical tune, Q_y	1.1605

* numbers in brackets correspond to bunch length measurements at different RF voltages.

2. Synchronous phase shift measurement

In order to compensate losses due to parasitic interaction of a beam with the surrounding vacuum chamber, besides those due to the synchrotron radiation, an RF system has to provide some extra energy ΔE per turn. For a Gaussian beam ΔE is given [1]:

$$\Delta E = e\hat{V}_{rf} \cos\phi_{s0} \Delta\phi = eI \sum_{p=-\infty}^{+\infty} \mathrm{Re}\{Z(p\omega_0)\} \exp\left\{-\left(\frac{p\omega_0\sigma_z}{c}\right)^2\right\} \tag{1}$$

where:

$\hat{V}_{rf}$	is the peak RF voltage;
ϕ_{s0}	the synchronous phase at zero current;
$\Delta\phi$	the synchronous phase shift;
I	the average beam current;
σ_z	the rms bunch length;
ω_0	the angular revolution frequency;
Re{Z}	the real part of the machine impedance;
c	the speed of light.

As it can be seen from eq.(1), the measurement of the synchronous phase shift allows to determine the parasitic energy losses at a given current and to calculate the sum in (1). However, to get the exact dependence of Re{Z} vs frequency from this kind of measurements is impossible as far as the sum in eq. (1) can be the same for different functions Re{Z(ω)}. Nevertheless, by measuring the energy loss and the bunch length as a function of current, one can imply a simplified impedance model or get an idea of the frequency behavior of the impedance.

A block diagram of the phase shift measurement is shown in Fig. 1.

The synchronous phase shift has been measured with a HP4195 Spectrum/Network Analyzer. A sample of the cavity voltage has been sent to the reference channel R of the instrument, while the longitudinal beam signal, obtained from a stripline pair in the sum mode, bandpass filtered to get the Fourier term at the RF frequency, has been connected to the T channel.

Since the measurement has been taken at constant accelerating voltage ($\hat{V}_{rf}$ = 60 kV), the amplitude of T/R vs. time gives the beam current decay in arbitrary units, while the T/R phase gives a measurement of the synchronous phase shift.

Figure 2 shows the measured average bunch current and corresponding relative synchronous phase shift, for beam current decaying from 58 mA to 11 mA.

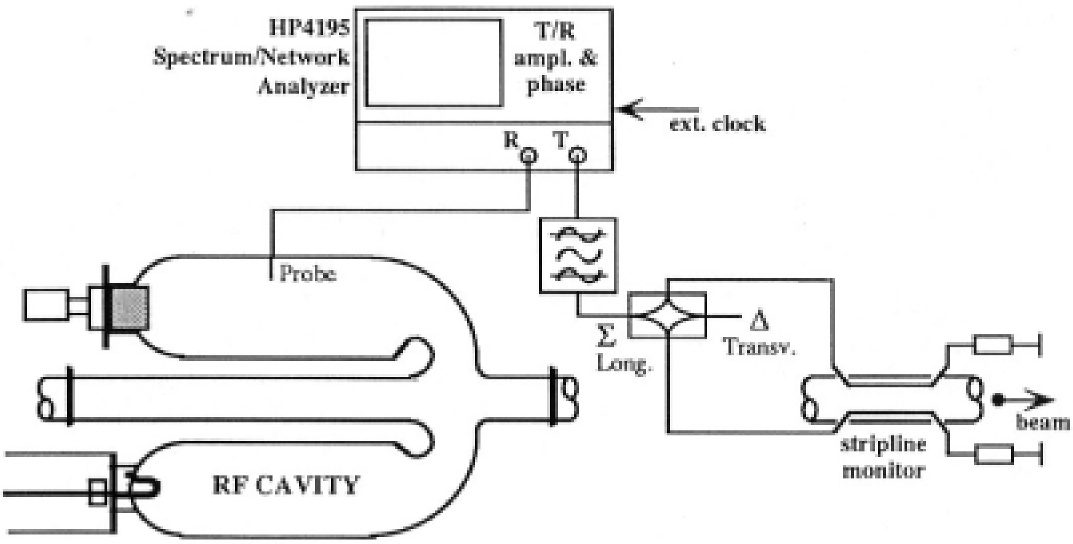

Fig. 1 - Block diagram of phase shift measurement set.

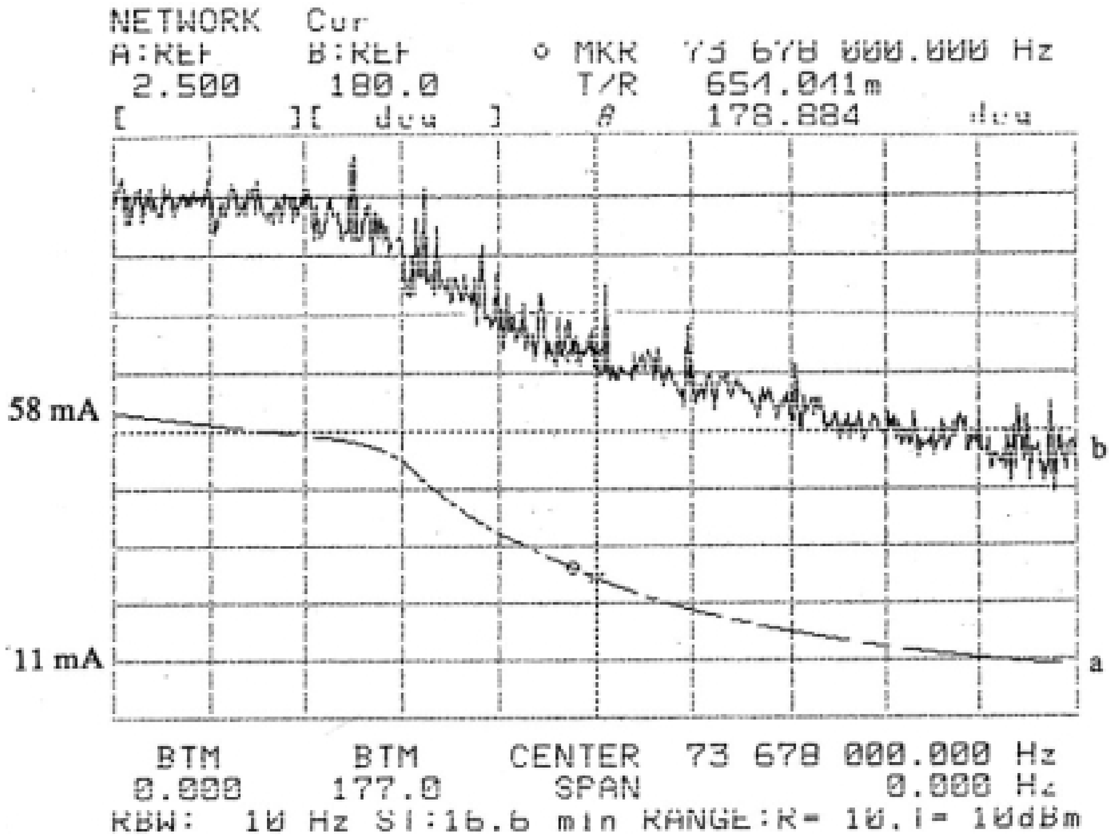

Fig. 2 - Measured average bunch current (a) and relative synchronous phase shift (b)
at $\hat{V}_{rf}$ = 60 kV.

The analysis of the above data has shown that the dependence of the relative synchronous phase shift on the bunch current can be satisfactory fit by a straight line with a slope:

$$\frac{d\left(\Delta\phi_s\right)}{dI} = 0.0267\frac{\deg}{mA} \tag{2}$$

According to eq.(1) and remembering that the measurement was performed at $\hat{V}_{rf}$ = 60 kV:

$$\frac{d(\Delta E)}{dI} = e\hat{V}_{rf}\cos\phi_{s0}\frac{d\left(\Delta\phi_s\right)}{dI} = 29.7\frac{eV}{mA} \tag{3}$$

The linearity of the dependence implies that the energy loss depends linearly on the average current, but does not depend on the bunch length. It means that the sum in eq. (1) must be constant despite, as we will see later, the bunch length changes by a factor of 2 in the above mentioned current range.

There are some possibilities in which the above condition can be fulfilled:

1) smooth broad band impedance with the real part inversely proportional to the frequency (~1/ω): one can convince himself by changing the sum in eq. (1) by an integral and performing the integration;
2) the impedance is composed by narrow peaks and the spectrum lines couple to those peaks for which the exponential roll-off factor is close to unity, i. e. peaks at low frequencies.

In general, one can invent other dependencies of the impedance on the frequency satisfying the condition. However, the situation 2) seems to be more probable since at $\hat{V}_{rf}$ = 60 kV the bunch is rather long and most of its power spectrum lies below the beam pipe cut-off. The impedance in this frequency region exhibits numerous HOMs of the RF cavity and injection-extraction kickers.

3. Measurement of bunch lengthening

3.1 Preliminary theoretical considerations

When the real part of the impedance consists of narrow HOM peaks, small changes of the working conditions (ambient temperature, tuner position in the RF cavity etc.) can substantially change coupling of the beam power spectrum lines to the HOMs, i. e. the effective real part of the machine impedance and parasitic losses can vary in a wide range. This means that any broad band impedance model is not quite appropriate in this case.

On the other hand, the imaginary part of the impedance is a continuous and smooth function of frequency. This implies that the effective imaginary impedance does not depend strongly on the HOM positions. If numerical simulations or analytical impedance estimates are made correctly, the effective inductive part of the impedance will be known rather precisely.

In our case, the inductive part is mostly responsible of the bunch lengthening, while the real part of the impedance breaks the bunch distribution symmetry without notable lengthening. As an example of this, Fig. 3 demonstrates the bunch lengthening effect for purely inductive (a,c) and purely resistive impedance (b,d). The graphs were obtained by solving the Haissinski equation [2] at $\hat{V}_{rf}$ = 60 kV for $Z(\omega)$ = 600 Ω and $Z(\omega)(\Omega) = j * 6.2E\text{-}08 * \omega$, respectively. These values correspond to the R-L impedance model which we have got by fitting the measured bunch shape (see 3.2, Fig. 9).

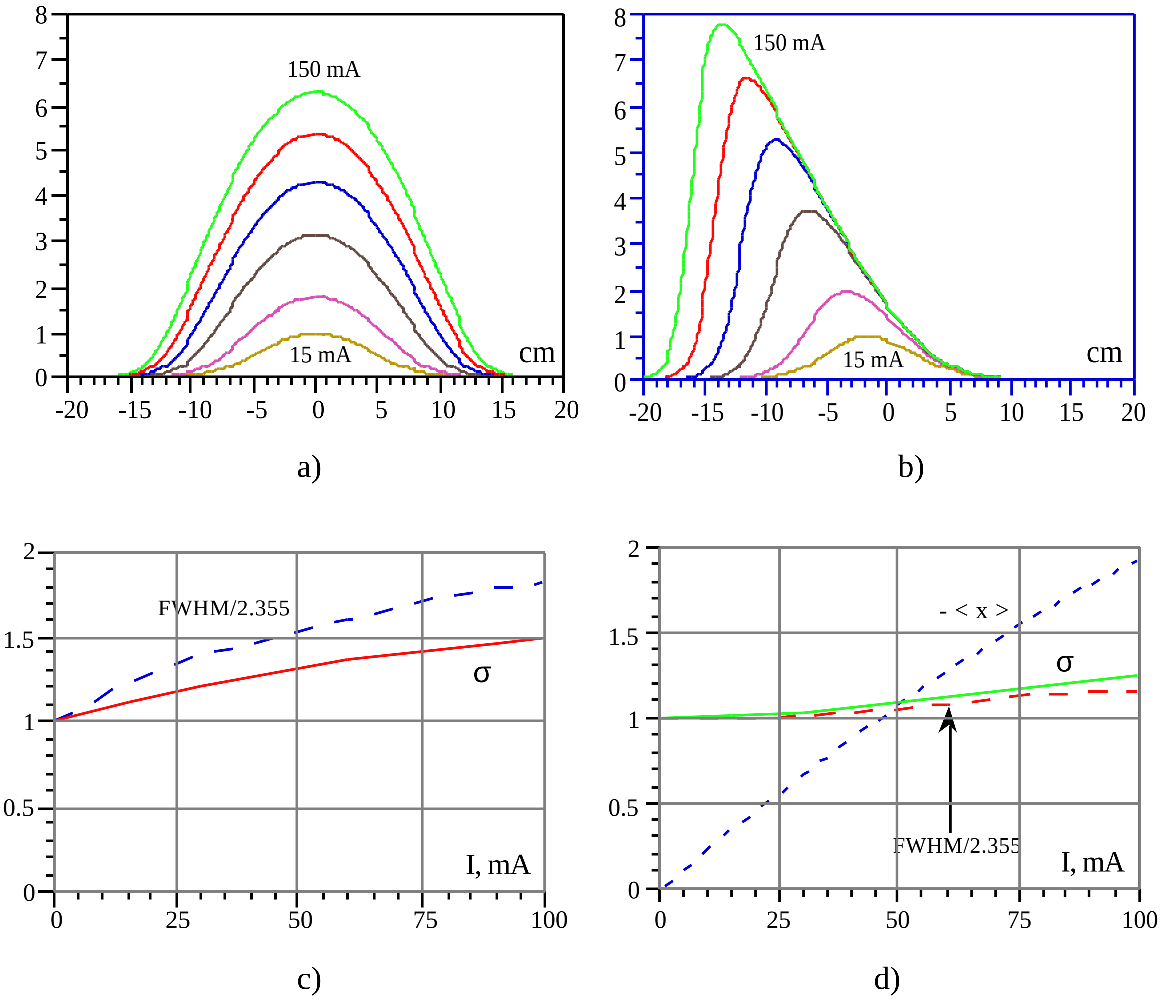

Fig. 3 - Examples of bunch shape and relative bunch lengthening for purely inductive (a, c) and purely resistive (b, d) impedance: solid line - rms bunch length; long-dashed line - full width at half maximum; short-dashed line - shift of bunch center of mass.

The impedance of the DAΦNE accumulator ring has been estimated well in advance prior to the bunch length measurements. Figure 4 shows the wake field of a 5 mm Gaussian bunch, which was taken as the Green function in numerical simulations of the bunch lengthening.

Note that this is the single passage wake field, since existing numerical codes do not calculate a multiturn effect. It means that we neglect the discrete nature of the beam power spectrum and this does not guarantee an exact reproduction of the effective real part of the impedance in the simulations.

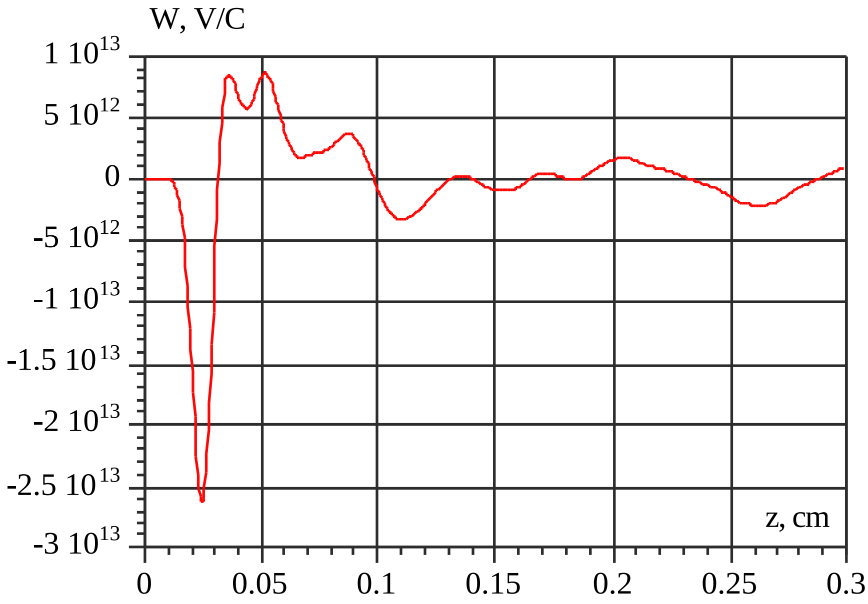

Fig. 4 - Accumulator ring wake potential for 5 mm Gaussian bunch.

3.2 Measurement results.

The bunch lengthening measurements were performed twice during the December '96 shifts. First, the bunch length was measured at different currents and by changing the RF voltage in a such way to avoid a multiturn instability. A day later, the measurements were made at the constant RF voltage of 60 kV with the current changing in 0 - 60 mA range.

In order to measure the bunch shape, a beam signal has been picked up from one of the 50 Ω bidirectional striplines normally used as beam shaker in the tune measurement system. The strip length of 0.5 m is such that the back-reflected pulse, typical of such kind of pick-up, is well separated from the first induced pulse (see Fig. 5), which is the one zoomed-in and analyzed.

The stripline signal was digitized by a sampling oscilloscope Tektronix 11801A, equipped with a sampling head SD-24, with a rise time of 17.5 ps and an equivalent bandwidth of 20 GHz. The signal was split by means of a large bandwidth resistive divider and one part was used as trigger. In this way we could get a stable waveform even in the presence of longitudinal oscillations. A Macintosh IIx provided the real time acquisition via high speed National GPIB interface.

The measuring set-up has been placed immediately outside the radiation shielding area, to allow the access. At the same time the length of the measuring cable (Andrew FSJ4-50B, low attenuation) could be kept as short as ~6 m, resulting in negligible signal distortion, as confirmed by the predicted natural radiation length and gaussian shape measured at very low current.

Figure 6 shows a comparison of the measurement and simulation results obtained at different RF voltages, while Fig. 7 demonstrates the results at $\hat{V}_{rf}$ = 60 kV. The agreement is very satisfactory.

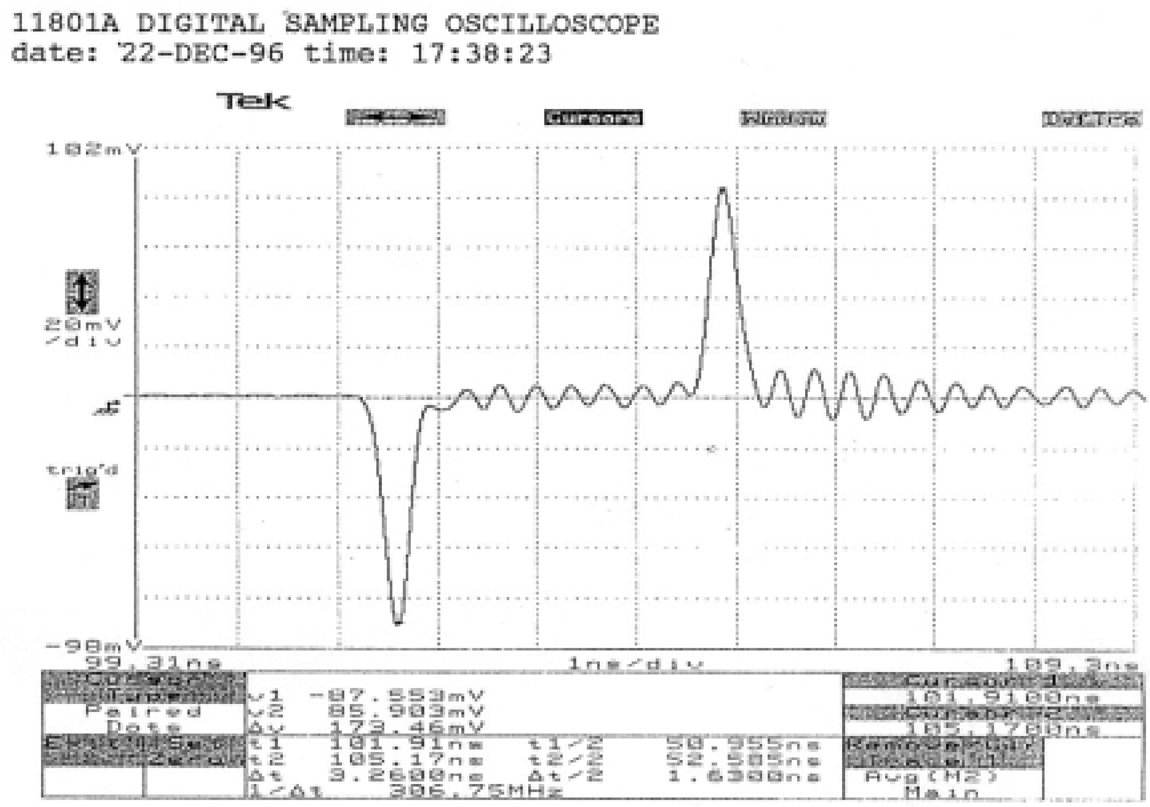

Fig. 5 - Typical stripline response at low-current. The small superimposed oscillation occurs at the first TM waveguide mode in the round beam pipe (Ø ~ 86 mm).

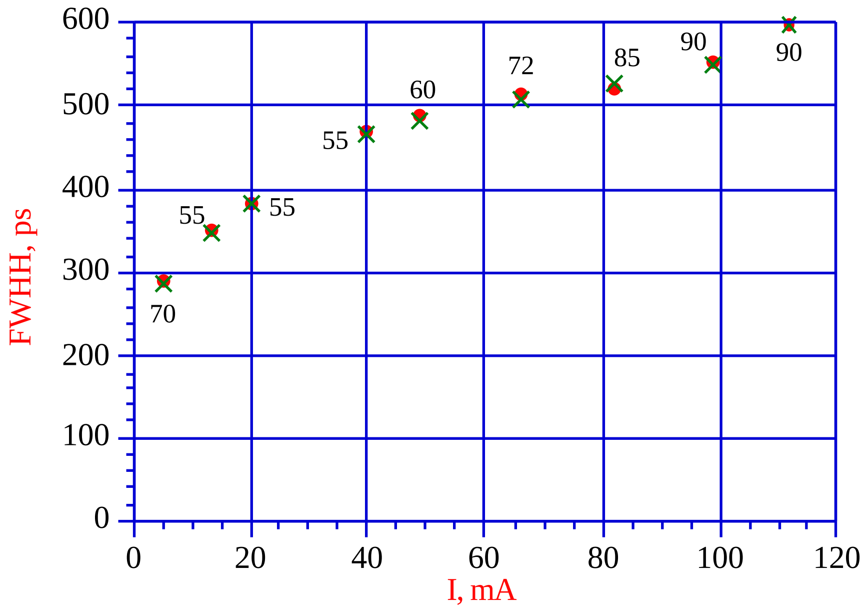

Fig. 6 - Bunch length at different voltages (full width at half maximum): dots - measurement results; crosses - numerical simulation; numbers - RF voltage.

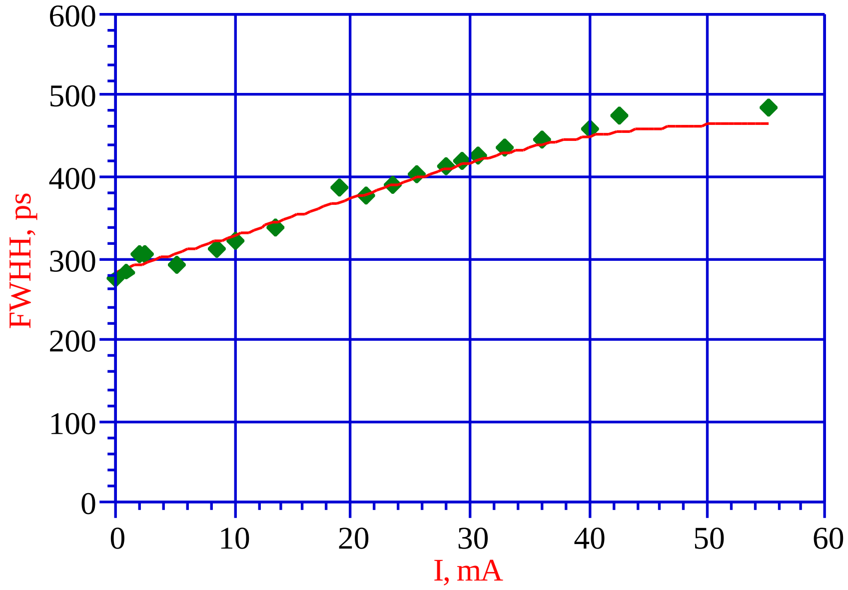

Fig. 7 - Bunch lengthening in the accumulator ring (full width at half maximum): dots -measurement results; solid line - numerical simulation.

The bunch shape was also recorded for different bunch currents (see Fig. 8). The bunch shape is clearly distorted indicating not negligible parasitic losses.

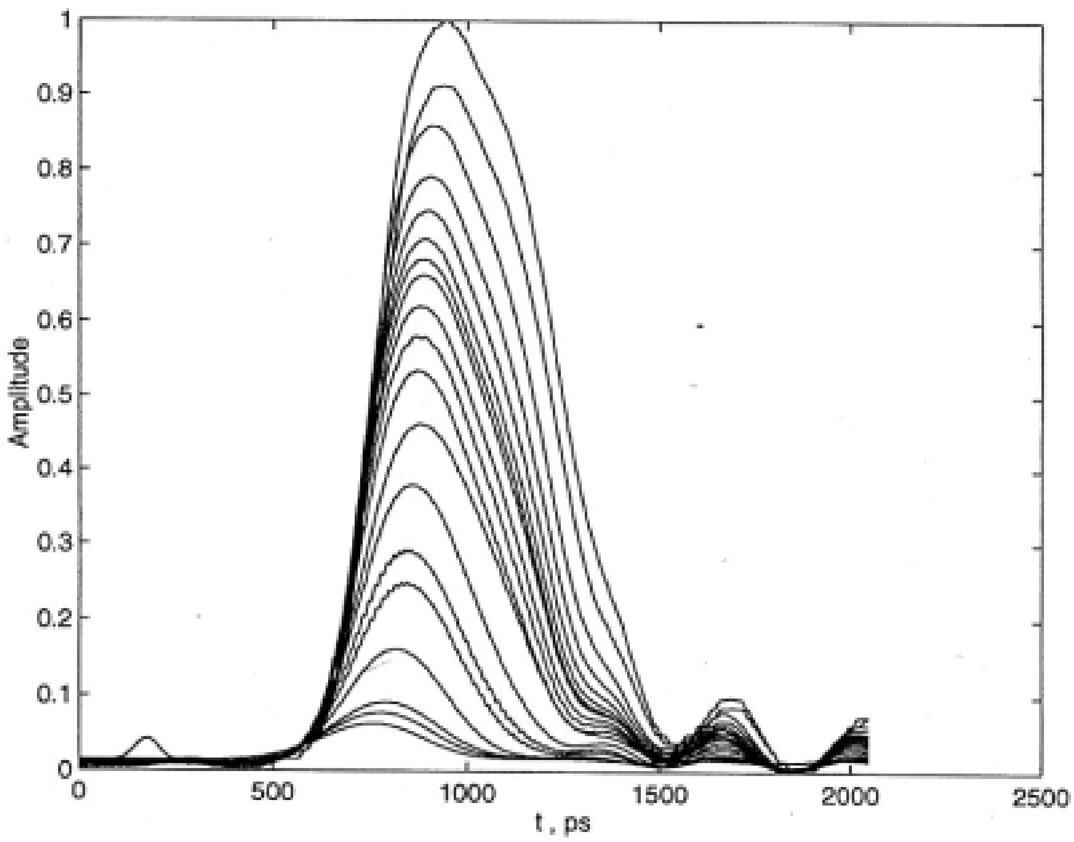

Fig. 8 - Bunch shape for different average bunch currents

In order to estimate the parasitic losses at a given current, one can try to find the best fit of the bunch shape by solving the Haissinski equation for a certain impedance model. Then, a convolution of a real part of the model impedance over the bunch power spectrum will give the corresponding loss factor.

Fortunately, for the accumulator ring the simplest R-L impedance model:

$$Z(\omega) = j\omega L + R \tag{4}$$

suits very well. The energy loss in this case is given by:

$$\Delta E = \frac{ek_l I}{f_0} \quad \textit{with} \quad k_l = \frac{Rc}{2\sqrt{\pi}\sigma_z} \tag{5}$$

As an example, the bunch shape at I = 28 mA and the corresponding fit are presented in Fig. 9.

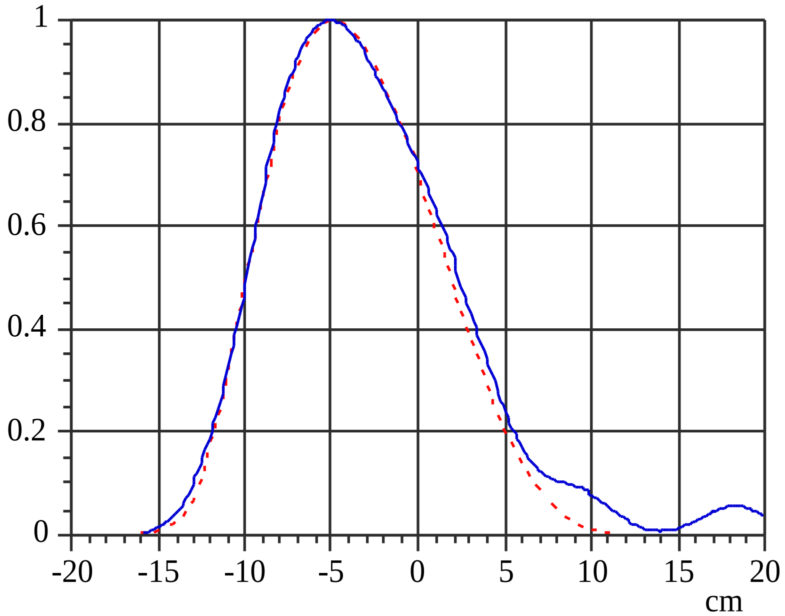

Fig. 9- Bunch shape at I = 28 mA: solid line - measurement; dotted line - fit with $Z(\omega) = (600 + j6.2e-08\omega)\Omega$

Application of eq.(5) gives 3.086 keV energy loss for I = 28 mA. The value could be compared to that obtained applying eq.(3) if all the working conditions in both sets of measurements were the same. This gives 1.015 keV of parasitic losses at the current of 28 mA, i.e. different by a factor of 3. In our opinion, this discrepancy can be accounted for by the shift of the HOMs with respect to beam spectrum lines, as was discussed above. Indeed, during the phase shift measurement the bunch was stable for all currents, while the bunch lengthening measurements were performed later in time and the bunch was unstable for currents between 5 mA and 23 mA. Presumably, the ambient temperature change resulted in some HOM shift in the RF cavity.

Conclusions

The first measurements of the synchronous phase shift and bunch lengthening have been carried out. A comparison of the simulation and measurement results has shown that the numerically calculated wake-field is suitable to predict bunch length for different working conditions (voltage, beam current, momentum compaction etc.). In addition, the parasitic losses and bunch shape distortion depend much on the actual HOM positions with respect to the beam power spectrum lines. Both phase shift measurements and a fit of the bunch shape with the R-L impedance model can be used for the loss estimates in the accumulator ring.

Further study of the bunch lengthening, first of all measurements of the energy spread versus current, would be useful in order to find the microwave instability threshold and compare it with analytical predictions [3].

References

[1] J. L. Laclare, "Bunched Beam Coherent Instabilities", CERN 87-03, 21 April 1987.

[2] J. Haissinski, Il Nuovo Cimento, Vol. 18B, N. 1, p. 72, 1973.

[3] M. Migliorati, L. Palumbo, M. Zobov, "Study of Microwave Instability for DAΦNE accumulator ring", DAΦNE Technical Note: G-44, Frascati, January 17, 1997.