SINGLE AND MULTIBUNCH BEAM DYNAMICS IN THE DAΦNE MAIN RINGS

C. Biscari, A. Drago, A. Gallo, A. Ghigo, F. Marcellini, M. Migliorati, M. Preger, F. Sannibale, M. Serio, A. Stella, G. Vignola, M. Zobov, LNF-INFN, Frascati, Italy
J. Fox, S. Prabhakar, D. Teytelman, A. Young, SLAC

Abstract

We describe the results of single bunch measurements and observations of the multibunch beam behavior in the DAΦNE electron-positron collider main rings. In single bunch mode the nominal current of 44 mA has been exceeded, reaching 110 mA in both electron and positron rings without any harmful single bunch instability. We have measured the bunch length as a function of the bunch current at different RF voltages. According to the data the longitudinal normalized impedance is lower than 0.6 Ohm. The estimated transverse broad band impedance is small. This is confirmed by the fact that the head-tail instability threshold without sextupoles is as high as 13 mA. The measured transverse tune shift at the nominal current is a small fraction of the synchrotron tune. The longitudinal feedback systems have been successfully commissioned in both main rings allowing to store routinely high multibunch currents and observe the beam behavior for different multibunch fills. In particular, such observations have helped us to identify some parasitic High Order Modes trapped within vacuum chamber elements and capable to drive rather fast multibunch instabilities, both longitudinal and transverse.

1 INTRODUCTION

The Frascati electron-positron collider DAΦNE is the first Φ-Factory [1,2] in operation. After a total beam time of six months devoted to commissioning without experiments, it is ready to start the operation for physics with the experimental detector KLOE [3]. At the commissioning stage all the machine subsystems such as vacuum, RF, cooling system etc., have been checked and proved to be reliable. Since the final goal of the factory is to achieve a luminosity as high as $5\cdot 10^{32}$ cm^{-2} s^{-1} with 5 A of average current distributed over 120 bunches, several machine shifts have been dedicated to study high current beam dynamics. A separate paper at this conference deals with the luminosity optimisation [4].

In this paper the observations and measurement results obtained in single bunch and multibunch regimes are described and compared with the analytical models and numerical simulations. In particular, Section 2 is dedicated to single bunch dynamics; the bunch lengthening in DAΦNE is discussed, the microwave instability observations are compared with analytical predictions and the broad band impedance is evaluated. Section 3 describes multibunch performance, with emphasis on measures undertaken to damp coupled bunch instabilities. The powerful longitudinal feedback systems have been successfully commissioned in both rings and the experience gained with the system during the DAΦNE multibunch runs is reported in this section. The High Order Mode (HOM) trapped in the injection kicker was also identified as that responsible for coupled bunch vertical oscillations. Special measures, proposed to avoid the transverse instability, are discussed.

2 SINGLE BUNCH DYNAMICS

The DAΦNE Main Rings commissioning started with single bunch. After careful orbit adjustment and chromaticity correction the single bunch current was routinely exceeding 110 mA in both rings. Despite this value is by a factor of 2.5 higher than the nominal project current of 44 mA, no destructive single bunch instability has been observed.

2.1 Bunch lengthening and impedance estimate

A comprehensive study of the longitudinal single bunch dynamics for DAΦNE [5] including numerical simulations, analytical estimates and experimental measurements has been performed. In order to simulate the bunch lengthening process a computer code modelling a large number of macroparticles (up to 600000), interacting through the machine wakefield and tracked over 4 damping times has been used.

The wake potential of a short Gaussian bunch with $\sigma_z = 2.5$ mm (much shorter than the nominal bunch length) has been used as a machine wake function. The wake potential has been calculated with 2D and 3D numerical codes during the machine vacuum chamber design. In addition, all the vacuum chamber components that could give a significant contribution to the DAΦNE impedance and wake potential in the time domain were measured in the laboratory with the wire method.

Below the results of the simulations are compared with the beam measurements.

Bunch length measurements in the DAΦNE positron ring have been performed during single bunch operation at different currents. The bunch signal from a broad band button electrode connected with a low attenuation cable, 8 m long, to a sampling oscilloscope Tektronix 11801A, equipped with a sampling head SD-24 with a rise time of 17 psec and an equivalent bandwidth of 20 GHz, has been analysed. The waveform has been digitized and sent via a GPIB interface to the control system for storage and

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off-line processing. The bunch distribution has been reconstructed by processing the button electrode signal taking into account the button transfer impedance and the cable attenuation. The measurements were performed for different single bunch stored currents in the range from ~ 0 to 48 mA (note that the nominal design current is 44 mA) at RF voltages of 100 kV and 150 kV.

Figure 1 shows the bunch length measurements together with the numerical calculation results for an RF voltage of 100 kV. The agreement is good except at low current (< 5 mA). This small discrepancy is due to the fact that for short bunches, with length comparable to the button size, the bunch spectrum covers a frequency range where the button transfer impedance undergoes cutoff and the measurement are no longer reliable. The measurements will be repeated with a fast fotodiode (25 GHz bandwidth), which should resolve short longitudinal bunch dimensions. In Figure 2 the measured bunch current distribution at an RF voltage of 100 kV is compared with the numerical simulations for a current of 26 mA.

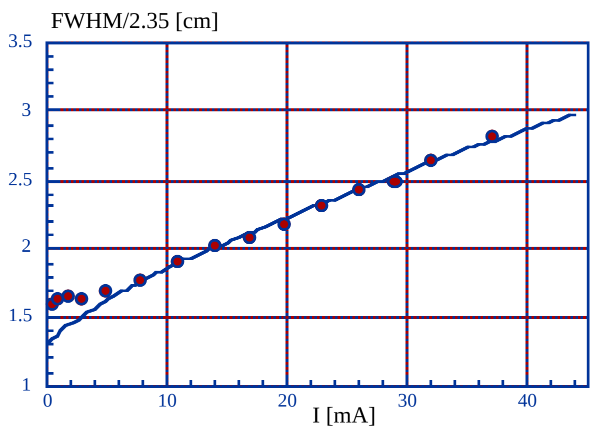

Figure 1: Bunch length at 100 kV RF voltage. Solid line - numerical calculations; circles - measurement results.

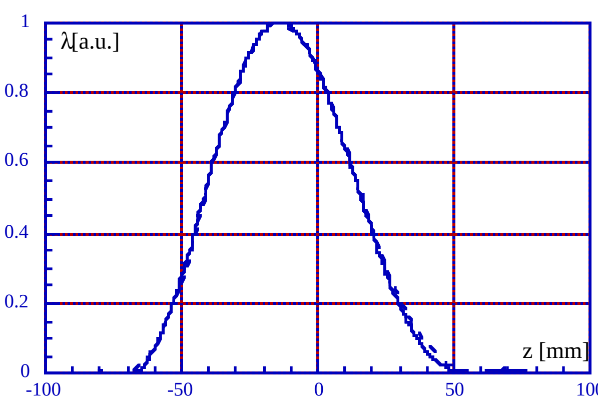

Figure 2: Bunch current distribution at 100 kV (I = 26 mA). Solid line - measured signal; dotted line - simulation.

The bunch distribution is wider than a Gaussian one due to the interaction with the imaginary part (mainly inductive) of the impedance. The bunch centroid is shifted and the distribution is slightly distorted because of the power loss. The normalized coupling impedance |Z/n| has been evaluated by making the Fourier transform of the machine wake field. In the frequency range up to 20 GHz the absolute value of the impedance does not exceed 0.6 Ω.

2.2 Microwave instability

The microwave instability is caused by the bunch longitudinal coherent mode coupling. The instability can manifest itself either through the coupling among the azimuthal modes or the radial ones having the same azimuthal number. A double water bag distribution model [6] which allows to treat analytically the mode coupling taking into account splitting of each azimuthal mode in two radial modes has been applied.

So far the theoretical model predictions of the longitudinal mode coupling coincide well with experimental observations. According to the model, at lower voltages (V_{RF} = 100 kV for DAΦNE) the microwave instability is driven by the radial mode coupling of the quadrupole (m = 2) and sextupole (m = 3) azimuthal modes. At higher RF voltages the instability arises from coupling of the higher azimuthal modes. The conclusion is that an RF voltage higher than 150 kV would be preferable for DAΦNE operation in order to avoid the radial mode coupling of the lowest azimuthal modes (dipole, quadrupole, sextupole) which could lead to a strong bunch shape modulations harmful for beam-beam interactions.

Indeed, experimentally, at V_{RF} = 100 kV an appearance of pure quadrupole synchrotron sidebands has been detected at stored current of ~25 mA, while the onset of the dipole mode was observed only at about 35 mA. Increasing the RF voltage to 150 kV, the quadrupole mode threshold shifted to 38 mA while the dipole mode was stable up to the nominal bunch current. For higher RF voltages the coupling of the low coherent modes has not been observed below the nominal value. Exactly the same threshold current were calculated by applying the above theoretical model.

2.3 Transverse single bunch dynamics

No special measurements have been so far dedicated to transverse single bunch dynamics but some indirect observations have shown that the transverse impedance is small. The following possible single bunch transverse instabilities do not seem to be dangerous for DAΦNE:

a) Head tail instability without sextupoles: a very high current has been stored in the single bunch without sextupoles when the orbit is corrected in the machine. A maximum value of 13 mA, that is almost 1/3 of the nominal bunch current, has been achieved. The instability threshold decreases rapidly by changing the orbit.

b) Transverse mode coupling instability: when the chromaticity is corrected, the observed vertical tune shift versus stored current is a small fraction of the synchrotron tune. In the range from ~ 0 to 80 mA the frequency shift was ~ 9 kHz compared to a synchrotron frequency of 35 kHz, demonstrating that DAΦNE is far from the transverse mode coupling threshold.

3 MULTIBUNCH BEAM DYNAMICS

During the DAΦNE commissioning several shifts were dedicated to the multibunch operation. A current of 540 mA has been stored in 30 bunches configuration in both electron and positron rings without transverse feedback installed. Despite some coherent multibunch oscillations have been observed they were not limiting the current. The poor vacuum in the temporary Day-One interaction regions is the main current limiting factor.

3.1 Longitudinal

A very high current in many bunches must be stored in each ring. Special cares have been undertaken while designing the RF cavity and other vacuum chamber elements to damp the HOMs capable to drive unstable coupled bunch oscillations. Their effectiveness have been confirmed by the measurements on prototypes. Nevertheless, residual low impedance HOMs couple the bunches and a rise time faster than the radiation damping time can occur. The rise time during injection transients can be very fast. A very powerful longitudinal feedback capable to damp all the coupled bunch instabilities has been developed. A bunch-by-bunch feedback scheme in which any bunch is kicked proportionally to the time derivative of its longitudinal position error has been adopted [7].

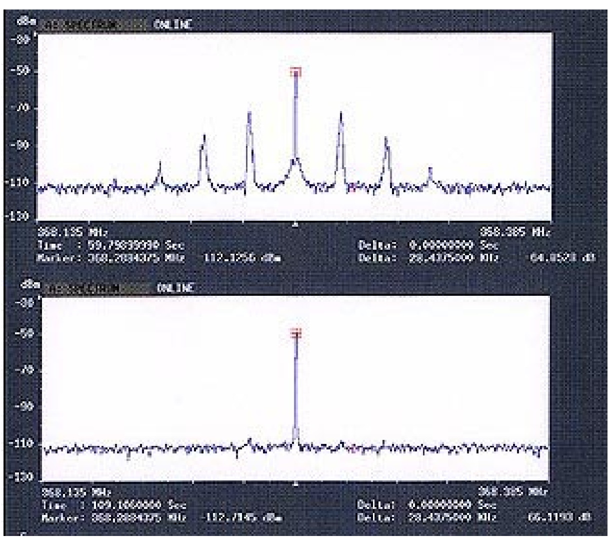

Figure 3: Longitudinal pick-up signal spectrum of 30 bunches with feedback off - feedback on.

In this system a time gated phase detector measures the bunch position; a bank of parallel filters produce the correction kick signals; a broad band power amplifier transfers the correction kick to the bunch by means of a broad band kicker [8]. The synchronization with the bunches (better than 50 psec), in particular of the back end part, has been accurately set in order to kick the bunches with the maximum efficiency. Sinusoidal digital filters with different downsampling factor have been tested and the optimum filter uses 6 taps to reconstruct the signal and with proper regulation of the gain, the system was able to manage up to 120 injected bunches.

In the commissioning phase the longitudinal feedback systems have been successfully commissioned allowing to store in both electron and positron ring routinely high current in any filling configuration. A damping time of ~ 200 μs has been achieved.

A current larger than 540 mA has been stored in each ring in 30 bunches configuration without any significant longitudinal oscillations. At these current levels the feedback is not yet saturated. Figure 3 shows that the synchrotron sidebands disappear with the feedback on.

3.2 Transverse

The first transverse multibunch instability has been observed while tuning the machine to a working point with fractional part close to the integer (5.09,5.07). The beam transverse motion was studied by digitizing a beam position monitor signal with the front end of the longitudinal feedback of the other ring and storing the turn by turn motion of each bunch in its memory. The off-line analysis of the bunch motion, consisting in the Fourier analysis of the time domain bunch signal, permitted to identify the mode 55 as the one responsible for the instability.

In order to understand where the dangerous mode is trapped, local orbit displacements (bumps) were made around suspected HOMs sources: RF cavity, transverse kickers, injection kickers. We have found a clear dependence of the transverse multibunch instability threshold on a bump localized in one of the injection kickers. Indeed, the unstable line of mode 55 coincides with the frequency of the HOM (1304 MHz) trapped in the injection kicker, that was found both in the simulations and bench transverse impedance measurements. To overcome the problem, the present working point has been moved elsewhere thus shifting the mode line away from the HOM frequency. For the future a transverse feedback system has been envisaged and a study to damp the incriminated mode by inserting an antenna has been performed. Impedance measurements confirm the successful HOM damping.

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