DESIGN STATUS OF A HIGH HARMONIC RF SYSTEM FOR DAΦNE

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Abstract

The Φ-Factory DAΦNE, a 1 GeV c.m. high luminosity double ring collider, is presently in operation at the Frascati Laboratories of INFN. The study and the design of a high harmonic RF system, aimed to increase the bunch length and to add Landau damping through the broadening of the synchrotron tune spread, is in progress. The bunch lengthening will provide better beam lifetime (which is Touschek dominated at the DA ΦNE energy) and will decrease the interaction between the beam and the high-frequency part of the machine impedance. A larger Landau damping is also expected to contribute to the stabilization of the beam dynamics. In this paper we report the beam dynamics study in the presence of the harmonic RF system, with special attention to the impact on the performances of the bunch-by-bunch longitudinal feedback system. Comparison between the passive and active mode of operation is also presented.

1 INTRODUCTION

The need for a harmonic RF system in the DAΦNE main rings has become evident during the luminosity tune-up of the machine [1]. To increase the single bunch luminosity the coupling factor in both rings has been decreased, thus reducing the beam lifetime.

The best values of single bunch luminosity have been obtained typically with 10÷15 mA per bunch, with a bunch length of 2÷2.5 cm and a RF voltage of 120 kV. Since the nominal bunch length value is 3 cm, we have a margin to increase both the bunch length and the acceptance by rising the main RF voltage and adding a harmonic voltage with an opposite slope on the bunch. In this case the bunch length can be kept always at about its nominal value, with the maximum energy acceptance available. An improvement of the Touschek lifetime is expected, and the gain factors for different scenarios have been calculated and are reported in this paper.

The bunch lengthening and the Landau damping due to the increased synchrotron tune spread are also expected to give a beneficial contribution to the machine dynamics, in particular concerning the microwave regime [2, 3].

On the other hand, the harmonic voltage significantly perturbs the longitudinal beam dynamics, the most concerning issues being the shift of the coupled-bunch mode “0”, “1” and “N-1” coherent frequencies (N is the number of regularly spaced bunches) and the synchronous phase spread along a bunch train with a gap.The expected performance of the high harmonic system is discussed and a comparison of the various options is given in the paper.

2 DESIGN PARAMETERS

The aim of the harmonic system is to keep the rms bunch length at $\sigma_z \approx 3$ cm. Since the short-range wakefields always contributes to the bunch lengthening, the harmonic system has been designed to work with a natural bunch length of $\sigma_{z0} \approx 2$cm. The harmonic voltage necessary to get the required bunch length is obtained by solving the Haissinski equation. In Table 1 the voltages required to have $\sigma_{z0} \approx 2$ cm for RF harmonic number 2, 3 and 4 are shown, together with the expected synchrotron frequency values and their variation for oscillations of 1 σ_{z0} amplitude. The RF voltage is V_{RF}= 200 kV, the momentum compaction is $\alpha_c = 0.02$, and the harmonic voltage is assumed to be 90° out of phase with respect to the harmonic of the beam current, in order to have only pure reactive beam loading on the harmonic RF system.

Table 1: Basic Parameters

n of RF harmonic	2	3	4
f_{RF_H} [MHz]	736.53	1104.8	1473.1
V_{RF_H} [kV]	81	57	45
f_S [kHz]	15.15	13.42	10.6
$\Delta f_S(@\sigma_{z0})$ [kHz]	0.54	1.63	3.55

The harmonic voltages reported in Table 1 do not scale exactly as 1/n, and the synchrotron frequency (i.e. the slope of the overall RF voltage) is not constant for different harmonic choices. This is due to the non-linearity of the harmonic voltage over the bunch length.

The required harmonic voltage can be obtained by powering a cavity with an external RF source (active option) or by letting the beam current interact with the harmonic cavity fundamental mode impedance (passive option). In the latter case the cavity has to be progressively detuned upward as the current increases in order to keep the harmonic voltage constant.

The passive option is more attractive since it is much simpler and cheaper. On the other hand, the active option is already effective at zero current, and allows single bunch measurements in lengthening regime.

3 COHERENT FREQUENCY SHIFT

The shift of the coherent synchrotron frequencies of the coupled bunch (CB) dipole modes is given by [4]:

$$j(\omega_c - \omega_s) \approx \frac{I_b \alpha_c \; p\omega_0^2 \exp\left(-p^2\omega_0^2\sigma_t^2\right)}{4\pi \; \omega_s \; E/e} Z_L\left(p\omega_0 + \omega_s\right) \quad (1)$$

where $p = kN + M$, M designates the CB mode, ω_0 is the revolution angular frequency, ω_c and ω_s are the coherent and incoherent synchrotron angular frequencies, σ_t is the bunch rms duration, E/e is the beam energy , and Z_L is the longitudinal coupling impedance. This formula, which is accurate only for small shifts, indicates that the imaginary part of Z_L changes the frequency of the CB coherent oscillations. Too large shifts are not tolerable for the bunch-by-bunch longitudinal feedback system [5] (LFB) which damps coherent oscillations in a limited band around the unperturbed synchrotron frequency.

In an active RF harmonic system the cavity is always tuned nearby $n\omega_{RF}$, and the imaginary part of the fundamental mode impedance interacts only with the CB mode "0" (the beam barycentric motion). In this case the interaction between the beam and the fundamental mode impedance can be reduced by means of active feedback techniques including the RF power source [6].

In the case of a passive harmonic cavity the situation is quite different since the fundamental mode impedance, depending on the beam current, is tuned in between $n\omega_{RF}$ and $n\omega_{RF}+\omega_0$, and its imaginary part interacts also with the CB modes "1" and "N-1". An existing time-domain tracking code [7] has been adapted to study the CB dynamics in presence of a passive harmonic cavity. The code tracks the motion of macroparticles in the longitudinal phase space in the presence of longitudinal resonant modes and includes radiation damping and realistic models for the RF and the LFB systems.

4 SIMULATIONS OF UNIFORM BEAMS

To study the CB dynamics related to the shift of the coherent synchrotron frequencies, the motion of uniformly filled beam has been simulated in the time domain. The frequency of the coherent CB modes is obtained by FFT transforming the output of the tracking code.

The frequency of the coherent CB modes as a function of the beam current is shown in Fig. 1 in the case of .a passive 4th harmonic cavity.

Modes different from "0","1" and "N-1" do not show significant frequency shift since there are no resonant impedances interacting with them in the simulations. The CB mode "0" interacts with both main and harmonic cavity impedances and its coherent frequency , according to the simulations, is largely shifted up. The agreement with eq. 1 is not very good, since in this case the shift is a result of two very large contributions of opposite signs, while eq. 1 is valid only for small frequency shifts. Anyway, although the LFB system is not effective on it, the "0" mode motion is stabilized by Robinson damping.

The CB modes "1" and "N-1" interact with the harmonic cavity and their coherent frequency decreases. In this case, which is less peculiar with respect to that of mode "0", the agreement with eq. 1 is much better. The frequency decreases only by ≈ 35% for a beam current increase from 0 to 1.2 A, and the LFB system can be tuned in such a way that it will be effective for all CB modes (except the mode"0") in that current range.

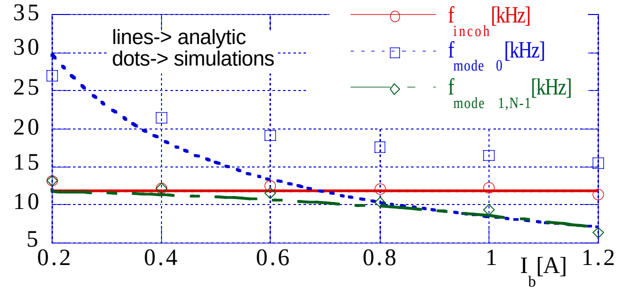

Figure 1: Shift of the CB mode coherent frequencies.

The harmonic cavity R/Q value plays a crucial role in the previous results. The larger it is, the more the cavity has to be detuned to keep the voltage constant, and the larger is the frequency shift of the modes "1" and "N-1". A large R/Q, which is desirable for an active cavity, may be very unsuitable for a passive cavity.

According to both simulations and eq. 1, the coherent frequency shift of CB modes 1" and "N-1" is less critic for lower harmonic numbers (n=2,3).

5 SIMULATIONS OF BEAMS WITH GAP

The operational configuration of the DAΦNE beam consists in a bunch train with ≈30% gap to avoid ion trapping in the e$^-$ ring.

The presence of the gap substantially complicates the analytical approach of the CB motion, since the concept of CB spatial mode has to be deeply revised. We follow a numerical approach in this case, which consists in running the time-domain tracking code and interpreting the output results by means of physical arguments.

It is well known that different bunches in a train with a gap are subject to different long-range wakefields, resulting in different values of the energy loss per turn or, in other words, in a parasitic loss spread along the train. If the train interacts mainly with imaginary impedance, the average of this spread is zero.

The parasitic loss spread is converted in a synchronous phase spread along the train, since every bunch is positioned at the RF phase corresponding to its energy loss per turn. The primary effect of the harmonic cavity on that is to produce a large magnification of the synchronous phase spread since the local slope of the total RF voltage at the bunch position is lowered by the harmonic component. The parasitic loss spread is also increased by the contribution of the harmonic cavity impedance to the long-range wakefields. Because of the harmonic voltage non-linearity, each bunch acquires its own synchrotron frequency, shape, length and lifetime.

The bunch train distribution over the total RF voltage, the synchrotron frequency and the natural length of the bunches along the train and the charge distribution in the first, central and last bunches are shown in Fig. 2, in the case of a 3rd harmonic cavity for a current of 1.2 A in a 40 bunch train filling 2/3 of the ring.

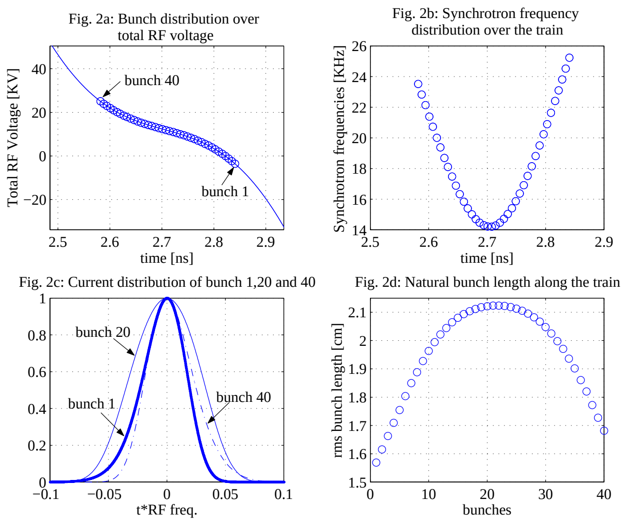

Figure 2: Effects of the gap on the bunch characteristics.

The spread of the synchrotron frequencies produces a decoherence in the CB motion acting as a sort of bunch-by-bunch Landau damping. We observe this effect in the simulations. In fact, the simulated CB dynamics looks more critical in the 2nd harmonic case, where the total RF voltage is linear on a wider phase range.

Anyway, large values of synchronous phase spread may change the interaction point (IP) position leading to luminosity degradation. They affect also the synchronism of the LFB front-end and back-end, limiting the system performances. We believe that these effects set the ultimate operational limits to the RF harmonic system. From this point of view the active and passive options are equivalent, with the annotation that low R/Q cavities give smaller contributions to the synchronous phase spread.

6 BUNCH LENGTHENING AND LIFETIME

The short range wakefields tends to reduce the differences in length and Touschek lifetime from bunch to bunch in trains with a gap. In order to study the single bunch dynamics including the higher harmonic cavity, we have adapted a single bunch tracking code already used to estimate the DAΦNE bunch length [3].

The results of the simulations are shown in Fig. 3. The solid line represents the bunch length as a function of the bunch number for a 3rd harmonic cavity with a current of 1.2 A in a 40 bunch train with a gap of 1/3rd of the ring. The σ_z values vary from 2.4 cm of the last bunch, which has an almost triangular shape (see Fig. 4) to 2.8 cm of the central one, having a more symmetrical shape.

The longitudinal charge distribution $\rho(z)$ given by the code and the RF acceptance of each bunch have been considered to calculate its own Touschek lifetime [8].

In Fig. 3 the dotted line represents the expected gain in Touschek lifetime with respect to a routinely DAΦNE operating configuration, where the RF voltage is typically set to 120 kV.

The calculated improvement is in the 35÷60% range depending on the bunch position over the train, and is due mainly to the bunch lengthening since the limited physical aperture of the acceptance increase vacuum chamber reduces the gain due to the RF.

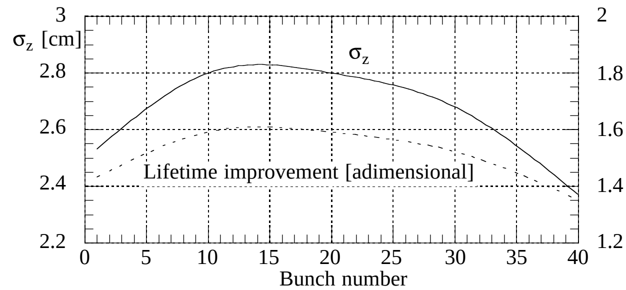

Figure 3: σ_z and lifetime gain for different bunches.

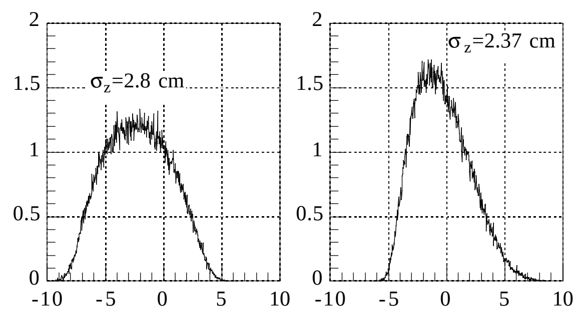

Figure 4: shapes of two different bunches (right: last bunch, left: central bunch).

CONCLUSIONS

The most important issue related to the implementation of a high harmonic RF system is the large synchronous phase spread of the bunches along intense trains with a gap. From this point of view active cavities, with high R/Q, are worse with respect to passive ones.

The coherent frequency shift of the CB modes “1” and “N-1” is relevant, but not destructive, in the passive option and it is less critic for low harmonic number (n=2,3), while it is not an issue in the active option.

Simulations of the CB dynamics of bunch trains filling 2/3 of the ring show that a 1.2 A is still stable when considering passive 3rd and 4th harmonic cavities.

We believe that a passive 3rd harmonic cavity is a simple and effective option.

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