PROPOSAL OF AN EXPERIMENT ON BUNCH LENGTH MODULATION IN DAΦNE

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Abstract

Obtaining very short bunches is an issue especially for colliders but also for CSR sources. The modulation of the bunch length in a strong rf focusing regime had been proposed, corresponding to a high value of the synchrotron tune. A ring structure where the function R56 along the ring oscillates between large positive and negative values will produce bunch length modulation. The synchrotron frequency can be tuned both by the rf power and by the integral of the function R_{56}, up to the limit of zero value corresponding to the isochronicity condition. The proposal of a bunch length modulation along the ring in DAΦNE is here described. DAΦNE lattice can be tuned to positive or negative momentum compaction values, or to structures in which the two arcs are respectively set to positive/negative integrals of the R56 function. With the installation of an extra rf system at 1.3 GHz, experiments on bunch length modulation both in the regime of high and low synchrotron tune can be realized.

INTRODUCTION

Short bunches are interesting for both e+e- circular colliders and synchrotron light source storage, the first to overcome the luminosity degradation due to the hourglass effect at very low β*, the second to produce in a controlled way Coherent Synchrotron Radiation (CSR). All factory upgrades use minimization of the bunch length by high rf voltages as an essential feature of their projects, while CSR sources base the feasibility of very short bunches on the isochronicity regime.

In the framework of superfactories studies the strong rf focusing regime (SRFF) [1] was used as one of the principles for a Φ factory design. This regime is based on a high rf voltage and a high momentum compaction (α_c) ring lattice which together produce a bunch length modulation along the ring. The microwave instability effects on the bunch lengthening in principle can be controlled by placing the high impedance objects in the ring zones corresponding to the longer bunch, with the collision point placed at the shorter bunch position.

An evolution of the SRFF principle has been recently proposed[2]: a ring structure where the dependence of the longitudinal position of a particle on its energy oscillates between large positive and negative values along the ring can also produce a bunch length modulation. The synchrotron frequency can be controlled by means of the rf voltage and the momentum compaction. This regime overcomes one of the critical points of the SRFF principle, where due to the large synchrotron tune Q_s both the dynamic aperture and beam-beam effect depend critically on the 3D working point choice[3].

No storage ring has been so far operated in such a regime. The DAΦNE magnetic structure can be tuned both on the high and low synchrotron tune regimes, and with a new rf system at 1.3 GHz[4] the bunch length modulation can be enhanced. This paper will be focused mainly on the beam dynamics aspects of the experiment, referring the reader to [4,5] for hardware details.

PRINCIPLE FOR THE BUNCH LENGTH MODULATION

In a ring with one rf cavity placed at s_{rf} (peak voltage V, wavelength λ_{rf},) whose gradient is given by:

$$U = \frac{2\pi}{E}\frac{V}{\lambda_{rf}} \tag{1}$$

where E is the beam energy, the general expressions of the generalised longitudinal Twiss parameters are[1,2]:

$$\begin{aligned} \cos\mu &= 1 - \frac{\alpha_C L}{2} U \\ \beta_L(s) &= \frac{1}{\sin\mu}\left(\alpha_C L - R_1(s) R_2(s) U\right) \\ \gamma_L &= \frac{U}{\sin\mu} \end{aligned} \tag{2}$$

where μ is the longitudinal ring phase advance, L the closed orbit length and $R_i(s)$ the longitudinal drift functions defined as:

$$R_1(s) = \int_s^{s_{rf}} \frac{D(s')}{\rho(s')} ds' \quad \text{and} \quad R_2(s) = \alpha_c L - R_1(s) \tag{3}$$

D is the dispersion function and ρ the dipole bending radius. Notice that $R_1(L) = \alpha_c L$, and therefore the function β_L is periodic in L. The beam energy spread, proportional to γ_L, is constant along the ring:

$$\left(\frac{\sigma_E}{E}\right)^2 = \frac{\gamma_L}{2} C_L \frac{\gamma^5}{L\alpha_\parallel} \int \frac{\beta_L(s)}{\left|\rho(s)\right|^3} ds \tag{4}$$

with C_L = 2.15 10^{-19} m^3 sec^{-1}, and $\alpha_{\|}$ the longitudinal damping costant. The longitudinal emittance ε_L is:

$$\varepsilon_L = \frac{1}{\gamma_L}\left(\frac{\sigma_E}{E}\right)^2 \qquad (5)$$

and the bunch length is $\sigma_L(s) = \sqrt{\varepsilon_L \beta_L(s)}$. The modulation in β_L and bunch length becomes not negligible if U is high and the drift functions large. Two regimes can be used:

a) the function $R_1(s)$ is *monotonic* in s, corresponding to the SRFF regime[1], with a large synchrotron tune Q_s.

b) $R_1(s)$ is *non-monotonic*, and has a large derivative with opposite signs in two different zones of the ring[2]. As $R_1(L)$ tends to zero the ring becomes isochronous. Most storage rings lattices are not flexible enough to reach the necessary $R_1(L)$ variation, and/or do not have the necessary powerful and concentrated rf system.

DEDICATED DAΦNE STRUCTURE

The dispersion in DAΦNE can be tuned on a wide range thanks to the independently powered quadrupoles, while the rf system is dimensioned for the usual collider operation: the present U parameter must be increased at least one order of magnitude to reach a measurable bunch length modulation. An extra SC rf cavity at 1.3 GHz, with a maximum voltage of 10 MV[4] can be installed in either of the two Interaction Regions (IRs), serving both rings. The IRs are usually occupied by different experiments[6], and since vacuum aperture is needed to install the rf cavity, our proposed accelerator physics experiment can be scheduled between two physics runs, using a detuned optics for both IRs, without low-beta insertions.

The maximum α_c value and $R_j(s)$ variation are limited by the physical and dynamic aperture of the ring. Three different structures are considered: structure A) in *monotonic* regime, where the contributions of all dipoles to the drift function is positive, as shown with black ; in Fig. 1, which shows the $R_1(s)$ behaviour for all three cases; α_c is 0.073, about three times larger than the present one. With high values of V, Q_s approaches the half integer, as shown in Fig.2. Structure B) (violet empty dot in figures) corresponds to *non-monotonic* regime with negative dispersion in two of the short arc dipoles, and a value of α_c similar to the present one (0.02). Structure C) (blue full dot in figures) is also *non-monotonic* but with a much lower value of α_c (0.004).

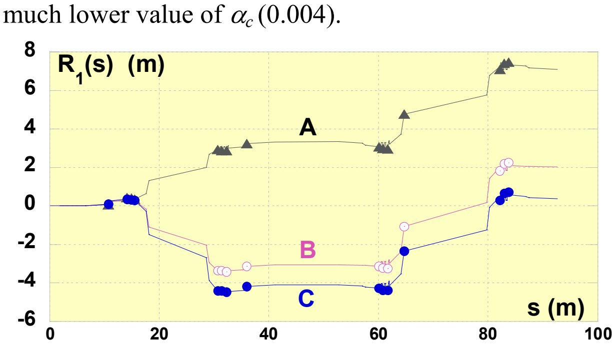
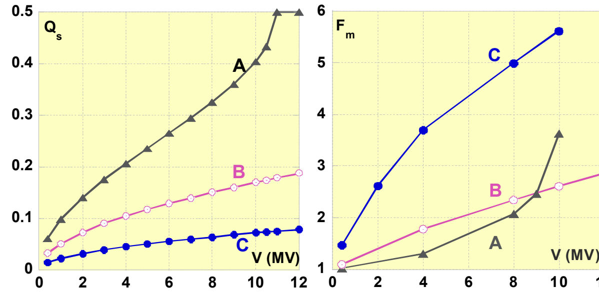


Figure 1 : Behaviour of R1(s) along the ring with $s_{rf} = 0$.

The main goal of the experiment is to measure the bunch length modulation factor, $F_m = \sigma_{Lmax}/\sigma_{Lmin}$. For structure A) F_m becomes noticeably larger than unity for high V (see fig.3), when μ approaches π. In structure B) F_m is measurable also with low rf voltage. In C) F_m is larger since it is enhanced when approaching isochronicity.



Figures 2-3 : Q_s and F_m as a function of V.

In the *monotonic* case (A) the minimum bunch length is in the IR opposite to the cavity position, since it occurs in the point where $R_1(s) = \alpha_c L/2$ [1,2], while in B) and C) it is near the rf cavity position. In the whole range the bunch length is of the order of few mm, as shown in Fig 4, which represents σ_{Lmax} and σ_{Lmin} for the three structures.

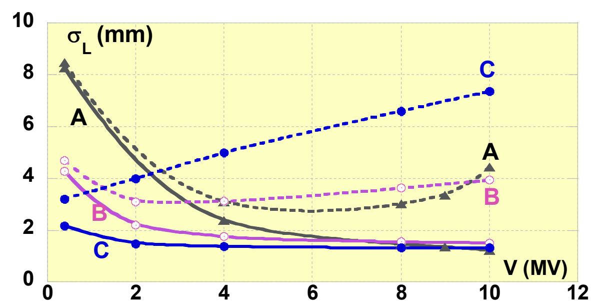


Figure 4 – σ_{Lmin} (full) and σ_{Lmax} (dashed) on V

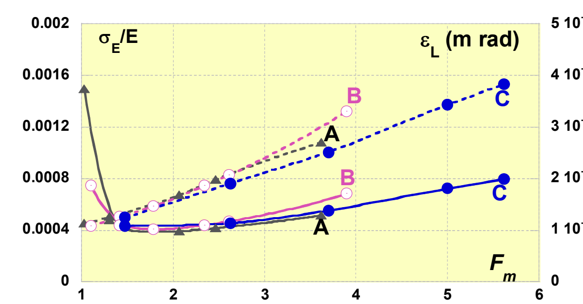


Figure 5 – σ_E/E (dashed) and ε_L (full) as functions of F_m.

The energy spread increases with F_m, as can be deduced from eq.(4). ε_L is large for low V, decreases up to a minimum, and then increases again. An interesting result is that the behaviour of σ_E/E and ε_L with F_m is very similar for all the structures (see Fig.5).

Dynamic aperture

The horizontal and longitudinal planes in the bunch length modulation regime are strongly coupled. Also on-energy particles, due to the coupling non-linear terms, oscillate with large amplitudes in the longitudinal plane.

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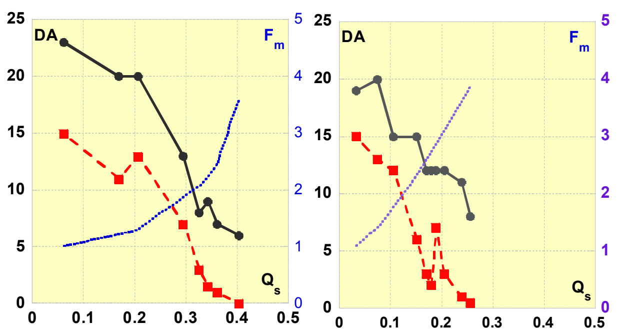
The dynamic aperture (DA) for the *monotonic* structure A (Q_x = 4.82, Q_y = 5.21, ε_x = 0.54 mm mrad) and the *non-monotonic* B (Q_x = 5.81, Q_y = 5.15, ε_x = 0.6 mm mrad) has been computed with the MAD8 code, after a first optimisation of the sextupole configurations for chromaticity correction. Figures 6 and 7 represent the horizontal dynamic aperture in terms of σ_x on energy (black) and at $6\sigma_E/E$ (red) as functions of Q_s. Since σ_E/E increases with Q_s (see eq(4) and Fig,5), each point in the red line corresponds to a different off-energy absolute value. In the figures also F_m has been represented (right vertical scale): for the same value of F_m the *non-monotonic* regime has a wider DA.



Figures 6-7 – Horizontal DA for structures A-B on energy (black dots) and at 6 σ_E/E (red squares) as Q_s functions, and corresponding F_m (blue right scale).

There are different effects affecting the aperture as Q_s changes: the stronger longitudinal kick, the corresponding increase in the value of σ_E/E, and the resonances: in the curves the effect of Q_s = 0.166 and 0.33 is evident. The typical island representation to which we are used in the transverse planes, appears now also in the longitudinal phase plane, as in the example of Fig.8 corresponding to Q_s near 0.33 (structure A, V = 8 MV).

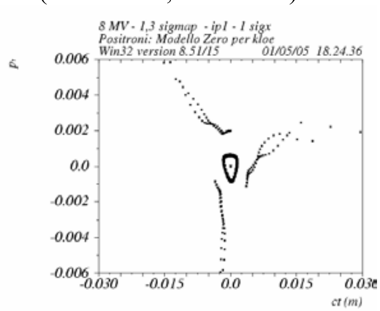


Figure 8 - Longitudinal phase plane with Q_s = 0.33

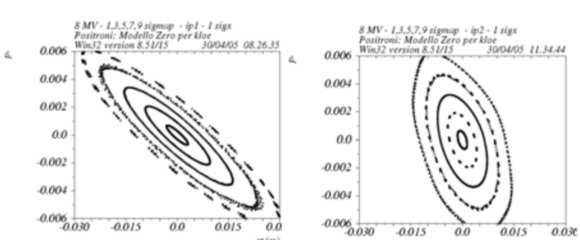


Figure 9 – Longitudinal phase plane at IP_2 and IP_1 for structure B, V = 8MV.

Figure 9 represents the longitudinal phase plane at the cavity position (IP_2) and in the opposite side (IP_1) of the ring for structure B with V = 8 MV. The ellipse projection on the horizontal axis is proportional to the bunch length, and there is about a factor 2 between the two points. Results show that the experiment is feasible, but give a special warning on the sensitivity of the working point choice, specially for the *monotonic* case.

CONCLUSIONS

We propose an accelerator physics experiment in DAΦNE to test the bunch length modulation regime in storage rings. It is not meant for increasing the collider performances with the present design, since a luminosity increase would need a different IR, a stronger variation of the drift functions, more radiation damping and a lower impedance, specially on the e- ring [6].

The experiment offers anyway a wide range of different results. The measurement of the modulation factor is the first and essential aim of the experiment, and can be done even at very low current, single bunch operation. The high synchrotron frequency (above the MHz for case A) which can be reached with these structures asks for feedback system modification to test multibunch operation at high currents.

Other results of the experiment are:

- The measurement of the microwave instability threshold in different regimes with very short bunches. In fact the two DAΦNE rings have different impedances due to the presence in the e-ring of ion clearing electrodes. The two IRs will have also different impedance since one will house the new rf cavity, and the bunch length is minimum in IR_1 or IR_2 according to which of the two regimes are used.
- The Touschek effect observation as a function of the bunch length modulation.
- Beam dynamics and dynamic aperture with high synchrotron frequency.
- Localized production of stable CSR and comparison with the distributed production along the ring.

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