Beam Loading in DAΦNE Cavities

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Abstract

The beam-cavity interaction is a fundamental topic in high current storage rings and it strongly affects the RF system design in order to avoid coherent instabilities.

In this paper we present some considerations on the DAΦNE beam stability at the RF accelerating mode, according to analytical and numerical evaluations.

Transient and stationary regime results are shown, including the effect of RF amplitude and tuning servo loops.

1. INTRODUCTION

Due to the very high current value foreseen for DAΦNE operation [1] - 1.3 Amps/ring into 30 bunches as short term goal, up to 5.5 Amps/ring into 120 bunches for the highest luminosity - the longitudinal beam stability is among the most challenging task of the project.

The interaction between the beam and cavity spectra can drive any kind of multibunch instability; the rigid mode is a particular multibunch oscillation that arises from the interaction to the cavity accelerating mode. In fact, over some current thresholds, the beam center of mass may be longitudinally unstable as effect of either anti-damping (Robinson limit) [2] or repulsive force (Sands limit) [3].

The aim of this paper is to present some considerations on this topic using two different approaches: a frequency domain analytical method and a time domain code simulation.

The first is a stationary regime analysis based on a simple circuital model representing the beam as a current source at RF frequency [4]. This method allows to predict how much current one can adiabatically store with a given configuration of the RF parameters, but it does not give information on the transient behaviour of the system.

The second is a numerical approach based on a tracking code especially developed to study the beam to cavity fundamental mode interactions in the time domain. The code follows the bunches in the phase space for a selected number of turns starting from the injection, and it describes the transient regime behaviour of the system including the non-linearity of the accelerating field.

2. STATIONARY REGIME ANALYSIS

The main parameters of the DAΦNE RF system are listed in Table I , where Z/n is the machine broadband impedance.

We made our estimations by solving the circuit of Fig. 1 that represents a model of the RF system, including the RF source, the transmission line, the cavity and the beam [4].

Table I
DAΦNE RF System main parameters

RF Frequency	368.25 MHz
Harmonic number	120
RF Peak Voltage	130 kV (@ Z/n=1Ω)
	260 kV (@ Z/n=2Ω)
Bunch Current	43.75 mA
Max Beam Current	5.5 A/120 bunches (@ Z/n=1Ω)
	2.75 A/60 bunches (@ Z/n=2Ω)
Total Losses	16.3 keV/turn (@ Z/n=1Ω)
	23.3 keV/turn (@ Z/n=2Ω)
Cavity Shunt Impedance	2.25 MΩ
Unloaded Cavity Q	30,000
Max Available RF Power	150 kW

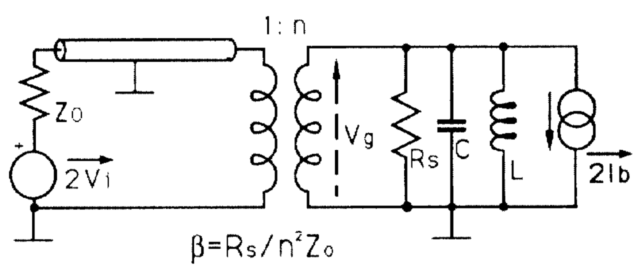

Figure 1. Circuital Model of DAΦNE RF System

This model explicitly takes into account the generator to cavity coupling coefficient β and it gives direct information on the incident power required in the various configurations of the system.

The beam center of mass is stable as long as the cavity tuning angle (the phase of the cavity impedance) is negative [2], and the phase between the bunch and the gap voltage due to the RF generator alone (Sands phase) is positive [3].

These parameters have been calculated at any beam current value using the equivalent circuit of Fig. 1. The gap voltage and the overall tuning angle (including the beam) have been taken as independent variables in the calculations because they are parameters directly controlled by the RF servo loops. Typical results are reported in Figs. 2 and 3. They represents the working point loci of the RF system plotted in a plane having the normalized beam current $Y = 2I_bR_{SL}/Vg$ on the vertical axis [5], where R_{SL} is the loaded cavity shunt impedance, and the overall tuning angle ϕ_L on the horizontal one.

Shaded areas are the forbidden regions due to Sands and Robinson limits, together with RF main power limitation.

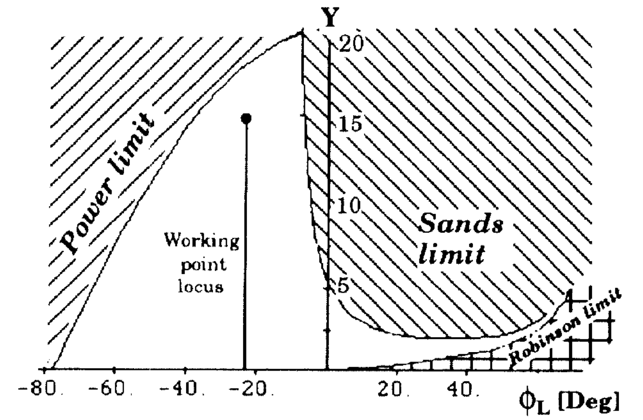

Figure 2. Working Point Locus (@ 130 kV)

The curves have been calculated for a beam current from 0 to 2.7 Amps, equivalent to 60 bunches stored in the Z/n=2Ω case. The coupling coefficient β has been set to 5 to well match the full beam current.
The gap peak voltage has been set to the minimum value (130 kV) in Fig. 2 , which is the worst operating situation for the center of mass stability, and to the nominal value (260 kV) in Fig. 3. The working point paths are vertical segments because the overall tuning angle is kept constant at any current by the dedicated servo loop.

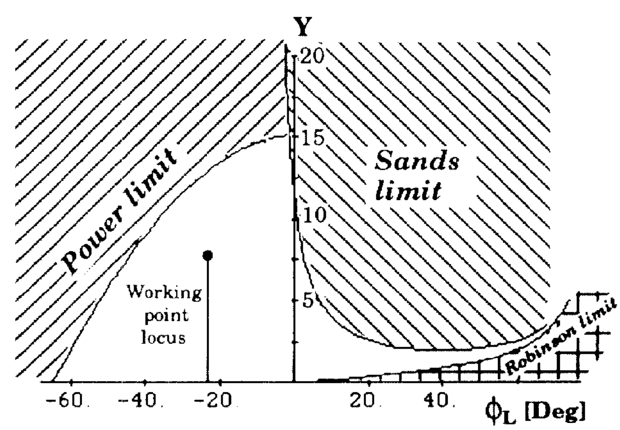

Figure 3. Working Point Locus (@ 260 kV)

The plots of Figs. 2 and 3 show that positive values of ϕ_L lead the system to Robinson instability at low current and to Sands instability at high current. The "compensate case" ϕ_L = 0 becomes unstable crossing the Sands limit at high current for any gap voltage lower than the nominal value (260 kV).

A fully stable configuration is achieved setting a negative ϕ_L value (ex. : ϕ_L = - 23 Deg). In this case the working point lays roughly in the middle of stability region between Sands and power limits.

However these fully stable configurations of the RF system have a rather small stability margin. The possibility to install a fast RF feedback chain to lower as much as possible the apparent beam loading should be considered [5].

3. THE TIME DOMAIN TRACKING CODE

Transient effects are not included in the previous results. Nevertheless they are not negligible and they have to be studied carefully both because the stability margin is always small and the injection of a whole bunch in a single shot can not be considered adiabatic. A Time Domain Tracking Code has been developed to take them into account.

A schematic flow chart of the code is shown in Fig. 4.

The code simulates the injection of the Nth bunch with a certain phase and energy errors while the other N-1 are in the equilibrium position on the synchronous phase. Each bunch interacts to the cavity and evolves in the machine turn by turn accordingly to its own instantaneous phase and energy errors, while the wakefields left in the cavity are responsible for the coherent motion. So the code follows each bunch in the longitudinal phase space.

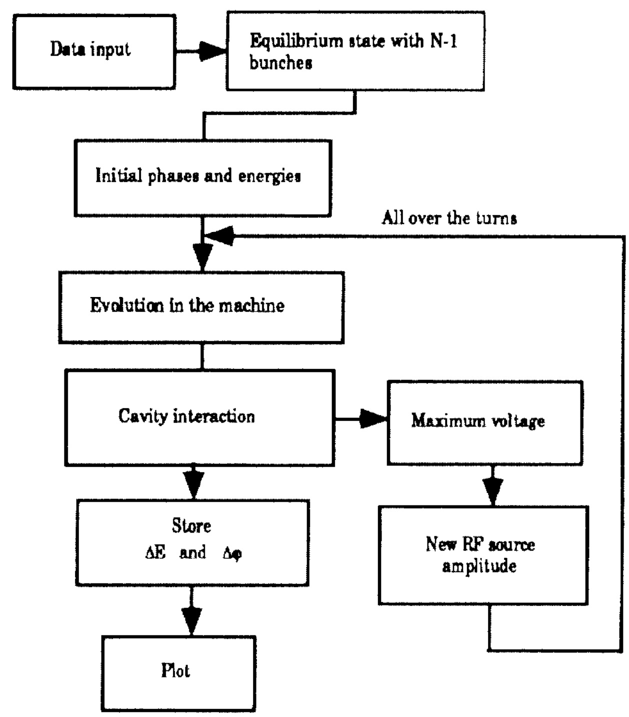

Figure 4. Tracking Code Flow Chart

The schematic model for the bunch to cavity interaction together with the RF supply and the RF amplitude feedback circuit are shown in Fig. 5.

The bunches are treated as macroparticles and any internal charge distribution is neglected. They are represented by impulsive current sources (Dirac-δ like) in the schematic circuit. The cavity is treated again as an RLC resonator supplied by an RF generator, suddenly discharged by the impulsive current and left to evolve freely between bunch passages [7].

Besides transient effects, the code accounts for the nonlinearity of the accelerating fields and for any dynamic interactions between the beam synchrotron motion and the RF amplitude feedback. Furthermore, by simply adding a multimodal cavity circuit, the code can be upgraded to check the system stability at any multibunch mode [6].

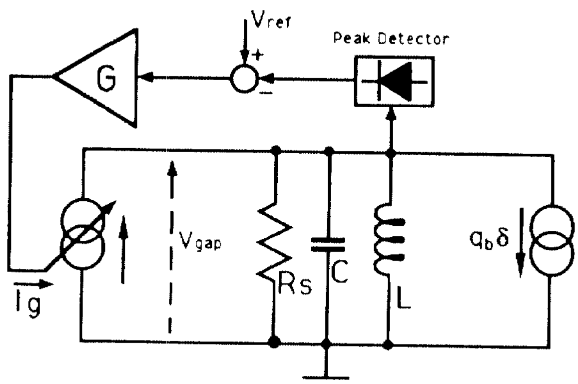

Figure 5. Equivalent Circuit for the Tracking Code

A typical simulation result is reported in Figs. 6 and 7. It represents the injection of the 30th bunch in the machine filled with other equal and stable 29 bunches previously stored. A 260 kV accelerating voltage has been set together with a - 75 Deg cavity tuning angle to match the current of the 29 bunches. A moderate bandwidth of the RF amplitude feedback has been chosen (less than 1 KHz) because other simulations showed that a too large bandwidth can couple the feedback to the synchrotron motion and get the beam to be unstable.

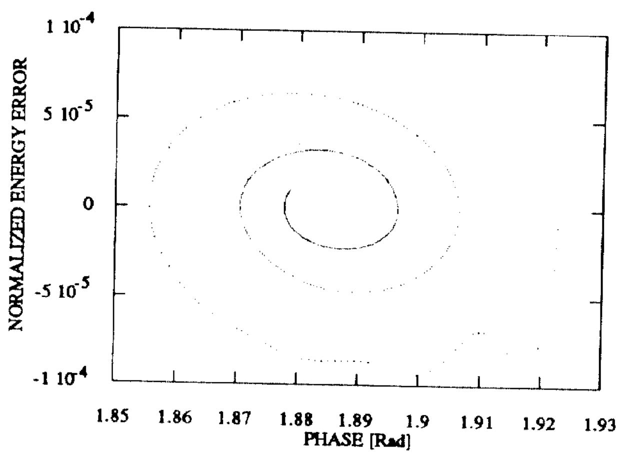

Figure 6. Bunch Phase Space Trajectory

The path of the 30th bunch in its own longitudinal phase space for the first 500 machine turns is reported in Fig. 6. The phase and energy errors at injection decrease turn by turn and the bunch tends to reach its stable equilibrium position with a characteristic damping time that is given by the machine natural damping plus the extra Robinson damping due to the cavity detuning [2].

The amplitude of the RF accelerating voltage for the first 500 turns is reported in Fig. 7.

The perturbation caused by the injection of the 30th bunch is damped with the feedback characteristic time. As the feedback bandwidth is much smaller than synchrotron frequency, the transient synchrotron oscillations can modulate the RF amplitude, as clearly shown in Fig. 7.

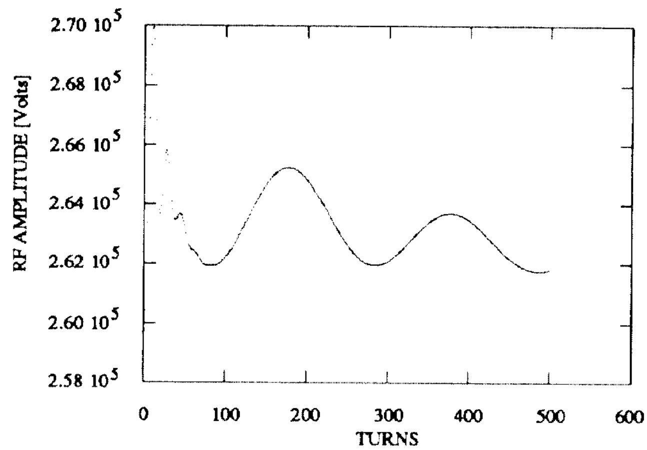

Figure 7. Envelope of the RF Accelerating Voltage

4. CONCLUSIONS

The previous results show that in principle any beam current in the DAΦNE operating range can be stored avoiding both transient and stationary beam center of mass instability conditions, providing that RF system parameters were properly set. The cavity tuning angle is the most crucial variable to be controlled to prevent beam instability, but also the gain and the bandwidth of dc feedback loops has to be chosen carefully.

Nevertheless, at high current values, the stability region around the working point is rather small and the system behaviour could be negatively affected by any cavity phase perturbations, such as large tuning system oscillations.

A fast RF feedback seems to be a possible solution to lower the apparent beam loading and then to broaden the stability region around the working point. The simulation code can be easily upgraded to implement such a feedback and a cross check between analytical and numerical consideration can be performed again for this new arrangement of the RF system.

5. REFERENCES

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