EXPERIMENTAL TESTS OF THE DAΦNE RF FEEDBACK SYSTEM

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Abstract

The Φ-Factory DAΦNE is a high current, multibunch e^+e^- double ring collider in construction at INFN Frascati Laboratories. The operating current has to reach 5 Amps to get the ultimate luminosity, while the required gap voltage per ring is quite small (250 kV). For this reasons the beam loading effect is really emphasised in the machine. A fast RF feedback system has been implemented to prevent the beam loading instability, and a prototype of the control circuit has been tested in a real environment, including the RF cavity, the high power klystron and the rest of the RF servo loops. A general description of the system and the experimental results are reported in this paper together with some considerations on the effects of the beam-cavity interaction on the whole RF control electronics.

1 INTRODUCTION

The main characteristics of the DAΦNE [1] RF system are summarized in Table I.

Table I: DAΦNE RF system parameters

f_{RF}	RF frequency (MHz)	368.32
V_c	Cavity voltage (kV)	250
Q_0	Cavity unloaded quality factor	33,000
R_s	Cavity shunt impedance (MΩ)	2
β	Cavity input coupling factor	2.5
P_{MAX}	Max klystron RF power (kW)	150
E_r	Energy loss / turn (keV)	15
f_s	Synchrotron freq. (@V_c=250kV) (kHz)	42
h	Harmonic number	120
I_b	Max beam current (Amps)	5

The interaction between the cavity accelerating mode and the beam is the primary source of the coupled-bunch, rigid-mode instability (sometimes called "center-of-mass" instability) in multibunch storage rings [2]. As the stored current increases the synchrotron equation parameters, i.e. the damping constant α and the synchrotron angular frequency Ω_s, are not lattice constants anymore, but they are affected by other variables such as the beam current itself and the cavity tuning angle.

Under certain conditions the damping constant α can get negative giving anti-damped rigid-mode oscillations (the so called "Robinson instability"), while above a certain current threshold the synchrotron angular frequency Ω_s, i.e. the longitudinal focusing force, is reduced to zero, getting the beam suddenly lost (beam loading instability).

More specifically, considering the perturbation induced by the beam-cavity interaction on the synchrotron equation, the beam loading current limit is given by:

$$I_b = - \frac{V_c \sin(\varphi_s)}{2\, Z_i\, (j\omega_{RF})} \tag{1}$$

where V_c is the cavity accelerating peak voltage, φ_s is the synchronous phase and $Z_i(j\omega_{RF})$ is the cavity impedance imaginary part as seen by the beam at the frequency of the RF master generator.

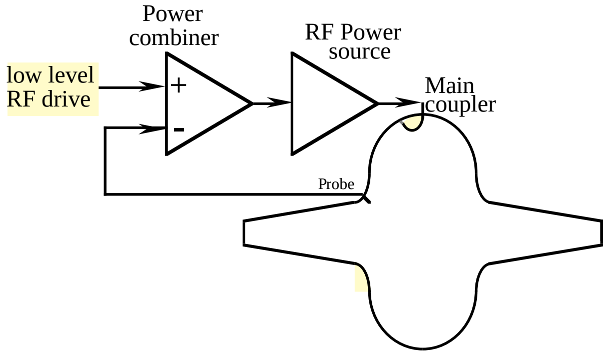

Figure 1: RF feedback general scheme.

The RF feedback scheme, reported in Fig. 1, is a cure of the beam loading instability and consists in adding out-of-phase a sample of the cavity voltage to the RF master source. In this case the impedance seen by the beam $Z(j\omega)$ is that of the cavity accelerating mode reduced by the open loop gain $H(j\omega)$, accordingly to:

$$Z(j\omega) = \frac{Z_c(j\omega)}{1+H(j\omega)} \tag{2}$$

and the impedance dynamic reduction pushes the beam loading instability current limit toward higher values.

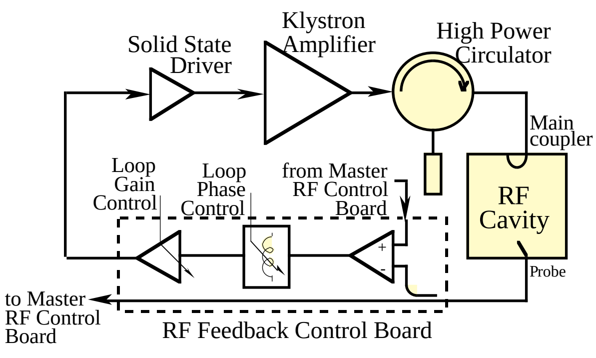

Figure 2: DAΦNE RF feedback system schematics.

The cavity accelerating mode tail may also couple to the sidebands of multibunch instability modes other than the rigid one, especially when the beam loading causes the cavity to be largely detuned toward lower frequencies. The RF feedback is a cure also for this kind of instabilities. Anyway, only long machines, having low revolution frequencies, are affected by this phenomenon [3]. This is not the DAΦNE case.

2 DAΦNE RF SYSTEM AND RF FEEDBACK CONTROL ELECTRONICS

The DAΦNE RF system schematics, including the RF feedback control board, is shown in Fig. 2.

The loop group delay value τ in a span of ≈ 2 MHz around the cavity resonant frequency f_c is the parameter determining the maximum achievable loop gain G for a given phase margin φ_m accordingly to:

$$G = \frac{(\pi/2 - \varphi_m)\, Q_0}{\pi\, \tau\, f_c\, (1+\beta)} \tag{3}$$

where Q_0 is the cavity unloaded quality factor and β is the generator-to-cavity coupling factor. As a safety measure, the loop operational phase margin should always exceed $\pi/4$.

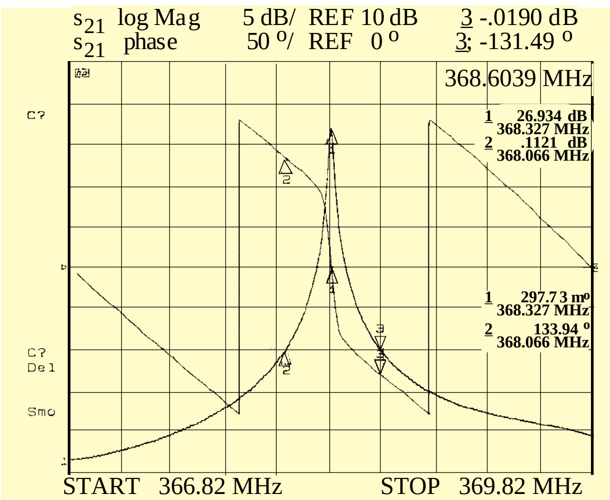

Figure 3 : Measured open loop gain.

The loop group delay is mainly made of two contributions: the "physical" delay due to the cable lengths, the control electronics and the solid state amplifiers (τ_l) and the group delay of the DAΦNE klystron TH2145 related to the tube frequency response (τ_k). The compactness of the RF power plant, obtained locating the klystron amplifiers in the machine hall and connecting them to the cavities through only a ≈15 m long transmission line, is beneficial for the minimization of the "physical" delay τ_l ; on the other hand a great care has been taken in the klystron tuning operation in order to enlarge the tube bandwidth and minimize its contribution to the loop group delay.

3 EXPERIMENTAL TESTS

Recently the first DAΦNE cavity has been high power tested [4] in the LNF RF test hall in a layout configuration very similar to that of the DAΦNE machine hall where the RF system will be finally located. A special session of the power tests has been dedicated to set up and operate the RF feedback system with a control electronics prototype board.

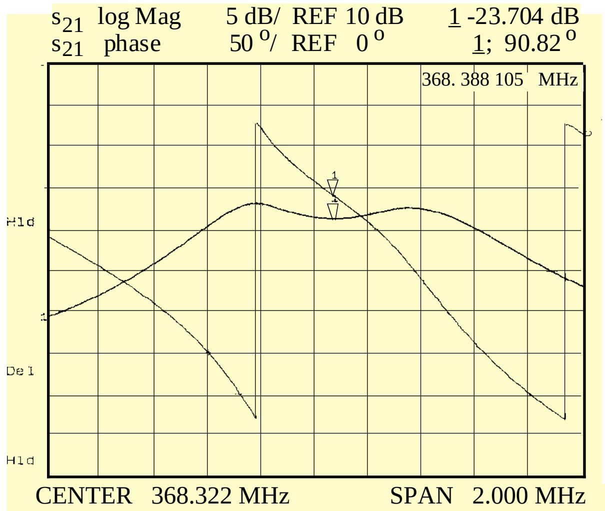

Figure 4: Measured closed loop gain.

No special criticality has been found in setting-up and operating the feedback system, and the presence of a klystron tube in the loop does not distort too much the overall frequency response.

The open and closed loop frequency responses of the system measured with a vector network analyzer are shown in Figs. 3 and 4 respectively. By adjusting the loop gain amplitude and phase a $\pi/4$ phase margin stable configuration with a ≈27 dB maximum gain G has been obtained, while the loop group delay, given by the slope of the phase plot of Fig. 3 in the region external to the cavity bandwidth, is τ ≈ 500 nsec.

These values are consistent with eq. 3 considering that the generator-to-cavity coupling factor β has been temporarily set to 1.4 to decrease the input line VSWR during these very first high power tests. Therefore restoring the operational β value of 2.5 should decrease the maximum achievable gain by ≈ 3.3 dB.

By excluding the klystron from the loop layout, a physical delay τ_l ≈ 320 nsec has been measured, so that a τ_k ≈ 180 nsec klystron contribution has been estimated. It is possible to further reduce the τ_l value; we estimated that using faster, air-dielectric cables and shortening them to the minimum in the DAΦNE hall, a physical delay as low as 170 nsec can be achieved, corresponding to a total delay τ ≈ 350 nsec.

The delay reduction will allow to recover ≈ 3 dB in the loop gain.

A phase margin φ_m value lower than $\pi/3$ produces an impedance frequency dependence similar to that of Fig. 4 plot, showing a local minimum corresponding to the cavity resonant frequency. This cause the beam to be Robinson unstable, with an estimated minimum rise time as low as 2.5 msec in the DAΦNE case, that has to be cured by the DAΦNE bunch-by-bunch feedback system [5] or by a dedicated feedback system based on fast cavity phase modulation.

4 BEAM LOADING INSTABILITY CURRENT LIMIT

With the reported experimental data it is possible to realistically estimate the RF feedback performances in terms of instability threshold current.

An useful representation of the RF system status is the Y/φ_L plot [6], where Y is a beam loading parameter related to the beam current I_b accordingly to:

$$Y = \frac{2\, I_b\, R_S}{(1+\beta)V_c} \tag{4}$$

while φ_L is the phase of the load seen from the RF input coupler, including the cavity and the beam.

The Y/φ_L plot for the DAΦNE RF system is shown in Fig. 5.

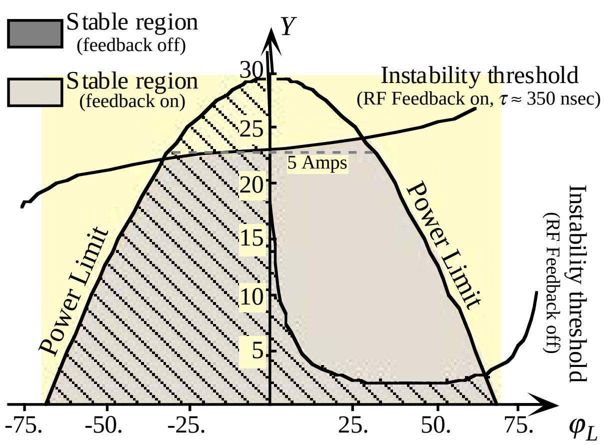

Figure 5: DAΦNE RF system Y/φ_L plot.

The curves on the plane represent the power limits and the instability thresholds with and without the RF feedback system. It is clear from the plot that in principle the system can operate up to 5 Amps even without the RF feedback by setting a working point with a small negative φ_L value. Anyway, this would not be a safe choice being the operation close to the instability limit too critical and sensitive to any phase oscillation. On the other hand the RF feedback system operation allows to approach the maximum current being the working point φ_L value limited only by the available RF power and not by instability thresholds.

The situation is a little more worrying if, in order to lengthen the bunches or for any other reason, the system should be operated at a lower cavity voltage level. Let us consider, for instance, a 150 kV cavity voltage. In this case the expected cavity detuning is much wider, and the beam loading effects are really emphasised. By recomputing the Y/φ_L plot with V_c =150 kV, an instability current threshold of ≈3 Amps has been obtained, well below the DAΦNE maximum beam current. In order to operate the system up to the maximum current even in this case, a sophisticated equalization of the loop frequency response, to decrease the group delay and increase the loop gain, is required.

5 CONCLUSIONS

The DAΦNE RF feedback system has been tested during a high power conditioning session of the first DAΦNE RF cavity. The cavity has been powered well beyond the nominal voltage (250 kV) in the feedback configuration and no special difficulties have been encountered while operating the system.

A total group delay of ≈500 nsec has been measured, an acceptable value that can be further reduced to 350 nsec by optimizing the cable layout in the DAΦNE hall. The DAΦNE RF feedback performances are sufficient to allow a safe and stable operation of the RF system up to the maximum beam current (5 Amps) at the nominal cavity voltage (250 kV), while not trivial system improvements are required to approach the maximum beam current at voltages significantly lower than nominal value.

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