MINIMIZING RF POWER REQUIREMENT AND IMPROVING AMPLITUDE/PHASE CONTROL FOR HIGH GRADIENT SUPERCONDUCTING CAVITIES

M. Luong, M. Desmons, G. Devanz, A. Mosnier, CEA Saclay, 91191 Gif-sur-Yvette.

Abstract

The search of high gradient in superconducting cavities undertaken by the accelerator community over the last few decades has brought tremendous advances. Henceforth, accelerating gradient of about 35 MV/m can be seriously envisaged in the design for the future accelerators, making use of bulk niobium cavities. Nevertheless, the intrinsic sensitivity of such a technology to the radiation pressure usually known as Lorentz force effects, results in a much higher power requirement to maintain the accelerating field amplitude and phase constant in the cavities. Since the pulsed mode has become practically a common specification for the future linacs, Lorentz force effects can build up into mechanical vibrations. Their consequences in the quality of the RF control has also to be investigated. Based on a detailed analysis of RF-mechanical coupling, different technical solutions including stiffening or active compensation will be compared. Amplitude and phase control performances are simulated with a realistic description for the RF components and subsystems, accounting for delays, bandwidth limitation or quantization.

1 INTRODUCTION

Recent advances in the niobium multi-cells cavity manufacturing and processing point to the possibility of designing accelerating structures with very high gradient up to 35 MV/m for high energy linacs (e.g. TESLA). At such high electromagnetic fields, the wall of a cavity is subjected to mechanical deformations due to the Lorentz force ; this entails a detuning which can exceed several cavity bandwidths. Maintaining amplitude and phase at a constant value then requires an unacceptable extra power as high as 80% even with stiffening rings between each cell. The active compensation by means of piezotranslators appears as a promising solution [1]. However, their implementation in a pulsed linac has not been fully experimented yet. Furthermore, the question of how these piezotranslators could excite some mechanical resonant modes has still to be clarified. The frequency and quality factor of the mechanical modes up to 1 kHz has been measured for the TESLA cavities [1,2], but their contribution to the cavity detuning could not be easily obtained from these measurements. This paper presents a simulation of the performances of a high gradient (35MV/m) 9-cells cavity with regard to amplitude and phase stabilization and power requirement, with or without a piezoelectric active compensation (PZAC), based on a cavity detuning model which accounts for resonant modes dynamics [3].

2 CAVITY, RF FEEDBACK AND PIEZO-COMPENSATION MODELING

All the simulations are carried out in a Matlab-Simulink® environment which offers a wide variety of standard subroutines and blocks for differential equation solving, signal digitizing and filtering, as well as delays management.

2.1 Cavity and RF control

The cavity dynamic is classically modeled with two first order differential equations [2] : one for the in-phase and one for the in-quadrature component. Since the strong Lorentz detuning implies a large excursion of the klystron power, the non-linear saturation effect is accounted with a first-quadrant sine function. Imperfections of the I/Q modulator, like gain unbalance or offsets can also be added to the model. RF bandpass filter for the nearest harmonic modes rejection and low-pass filter for noise filtering in I/Q measurements are simulated with their transfer function.

2.2 Lorentz forces detuning

Instead of the usual first order differential equation parameterized by a static K_L factor and a mechanical time constant τ_m, a second order modal analysis is used [3]:

$$\ddot{\Delta f}_{r,k}(t) + \frac{\omega_k}{Q_k}\dot{\Delta f}_{r,k}(t) + \omega_k^2 \Delta f_{r,k}(t) = -K_{r,k}\,\omega_k^2\, E_{acc}^2(t) \qquad (1)$$

$$\Delta f_{cav}(t) = \sum_k \Delta f_{r,k}(t) \qquad (2)$$

The frequency of eigenmodes ω_k and the coupling factors $K_{r,k}$ for the longitudinal modes, calculated for a 9-cells 1.3 GHz cavity, identical to the TESLA cavity, except the external cells are not asymmetrical, are presented in Figure 1.
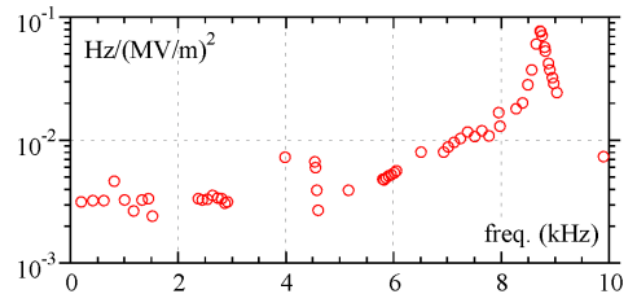

Figure 1 : Distribution of K_r vs. ω for a 9-cells cavity

We can check that the sum of K_r is very close to the usual static Lorentz factor, i.e. $K_L = 0.9$ Hz/(MV/m)².

Eigenmodes beyond 10 kHz have little contribution since they correspond to small local deformations which tend to cancel each other. Now, any dynamic detuning behavior can be very well described by choosing an appropriate set of Q_k. For example, a first order behavior with $\tau_m = 0.3$ ms corresponds to all $Q = 0.07$ (Figure 2). Eigenmodes with $Q > 0.5$ are referred as resonant modes.
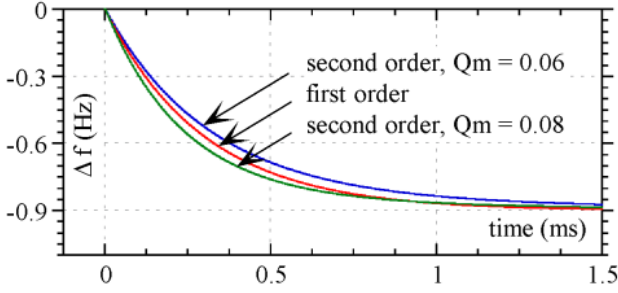

Figure 2 : Step response of 1^{rst} and 2nd order detuning

2.3 Piezotranslator-tuner-cavity modeling

The cavity detuning due to the action of a piezotranslator can be modeled by the same equations 1 and 2 with $K_{r,k}$ replaced by $K_{p,k}$, where "p" refers to the piezotranslator. Assuming a mechanical tuner stiffness of 100 kN/mm, the $K_{p,k}$ are calculated by the same numerical method [3] (Figure 3). Again, one can check that the sum of $K_{p,k}$ over all eigenmodes is equal to K_{pstat}, 520 Hz/µm.
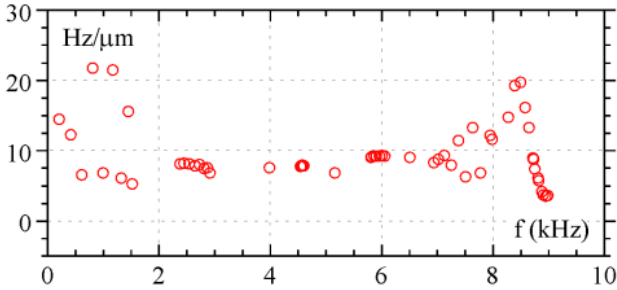

Figure 3 : Distribution of K_p vs. ω for a 9-cells cavity associated with a piezotranslator driven tuner

The conversion of voltage to linear displacement responds as a RC filter since the piezoelectric stack behaves as a capacitor of about tens to hundred nanofarads. The choice of the external resistor will be discussed later on in a next section.

3 RF CONTROL SIMULATIONS

For illustration purpose, we have considered the TESLA 500 case ($Ib_0 = 9.5$ mA, pulse length 950 µs, $\phi_b = -5°$) with an enhanced gradient (35 instead of 23.4 MV/m) to investigate the issues of extra power, active compensation and mechanical mode resonance. For ease of the discussion, the case of one klystron driving one cavity is presented.

3.1 Multiple resonance modes, without PZAC

We first assume that the first 20 modes (up to 4.5 kHz) and 3 highest K_m modes around 8.7 kHz exhibit a Q of

100. Even if this assumption may appear very pessimistic, it fits well to a first order model approximation with $\tau_m = 0.18$ ms, which agrees with some measurements on the TESLA cavity [2]. Figure 4 shows amplitude and phase stabilization with an ideal proportional RF feedback : analog signal with very short delay. The nominal open loop gain was set to 80, and the klystron had a power budget of 100%.
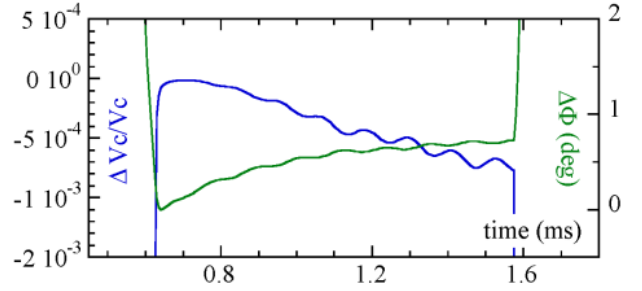

Figure 4 : Amplitude and phase stabilization without PZAC at 35 MV/m (stiffening rings only)

The Figure 5 gives the corresponding detuning and power requirement (nominal power amounts to 344 kW).
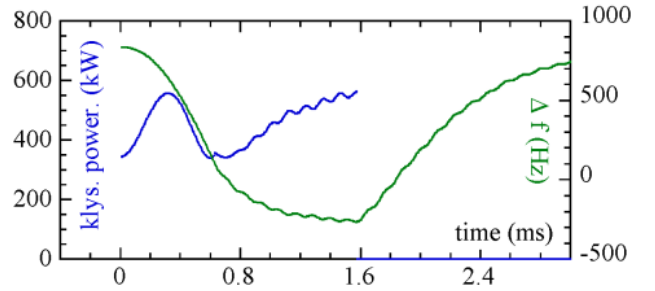

Figure 5 : Power requirement and cavity detuning without PZAC at 35 MV/m (stiffening rings only)

3.2 Multiple resonance modes, with PZAC

The higher value of K_r at higher frequencies versus K_p indicates an intrinsically faster cavity detuning due to radiation pressure than piezotranslator action. When multiple resonance occurs, especially at high frequencies, a slow compensation with a RC filter cutoff frequency set to 200 Hz is recommended. With a 2.5 V of amplitude square driving signal (assuming a static sensitivity of 1 µm/V) delayed by 165 µs with respect to the RF pulse and switched off at its end, a partial but nevertheless satisfying compensation is obtained (Figure 6 and 7).
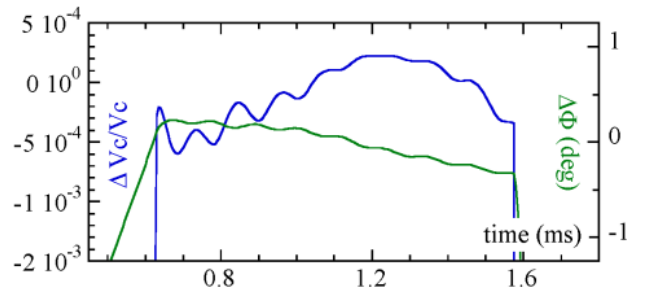

Figure 6 : Amplitude and phase stabilization with a partial active compensation at 35 MV/m

In this situation, the active compensation does not improve nor degrade significantly the amplitude and phase stability, but the extra power is reduced from 65% to 15% (Figure 7).
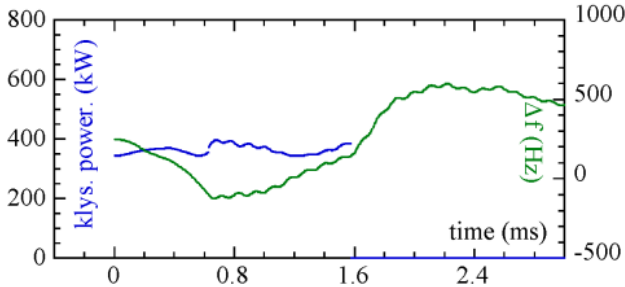

Figure 7 : Power requirement and cavity detuning with a partial active compensation at 35 MV/m

3.3 Only 2 low frequency resonant modes

Experimental investigations have shown that only few lower frequency modes had a significant Q of the order of 100. We assume a case where Q = 100 for the first two modes and 0.07 for the other modes, then a fast piezotranslator with a cutoff frequency of 3 kHz can be used. The response of the active compensation system is well approximated by a first order transfer function :

$$\frac{\Delta f(s)}{V_p(s)} = K_{pstat} \frac{1 + (\tau_p / 20)s}{1 + \tau_p s}, \text{ with } \tau_p = 0.55 \text{ ms.}$$

Since the cavity detuning due to the Lorentz forces is predicted with 1^{rst} or 2nd order model, one can derive the electric drive signal to be applied to the piezotranslator in order to attempt an optimal compensation, using the inverse z-transform (Figure 8).
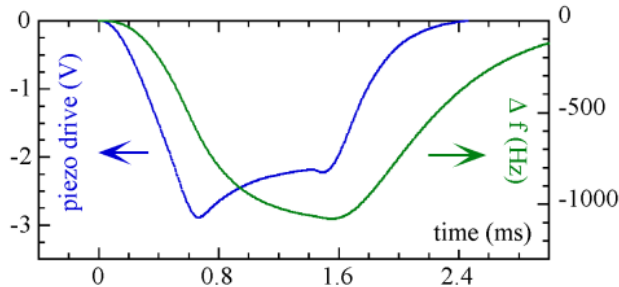

Figure 8 : Piezotranslator drive signal and Lorentz forces detuning to be compensated

One can notice the fast rising front and the overshoot of the drive signal as expected from the K distribution in Figure 1 and 3. With two resonant modes, this approach ensures an improvement of the relative amplitude stability to 5 10^{-4} and the phase stability to 0.15° (Figure 9) while only 6% of extra power is required for an accelerating gradient of 35 MV/m (Figure 10). The residual cavity detuning (~60 Hz) is due to the fact that the drive signal was derived from an approximation of the piezoelectric compensation by a first order model. The dotted curves

correspond to a more realistic feedback loop with 2 µs of delay and a 14 bits analog to digital conversion.
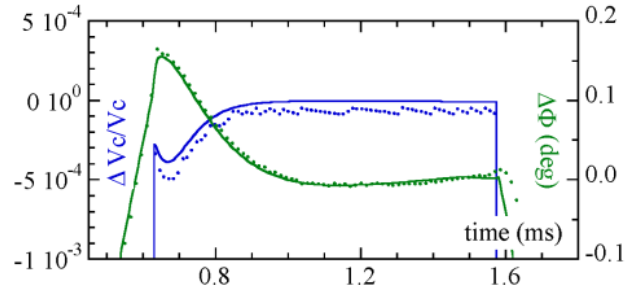

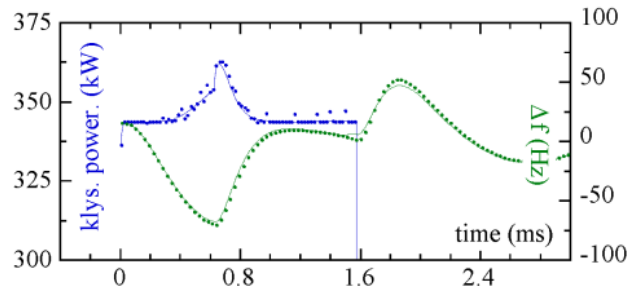Figure 9 : Amplitude and phase stabilization with a optimal active compensation at 35 MV/m

Figure 10 : Power requirement and cavity detuning with a optimal active compensation at 35 MV/m

4 CONCLUSION

The dynamic Lorentz force detuning and piezoelectric detuning are characterized by 2 sets of K parameters, each of them forms a coherent basis to describe dynamic and static detuning. Their values for the longitudinal modes of a TESLA-type 9-cells cavity are calculated by numerical simulations (CASTEM-SUPERFISH). These parameters, particularly low at low frequencies provided a stiff enough tuner (100 kN/mm), serve as inputs for RF low level control simulations. The simulations showed that the piezoelectric active compensation performs very efficiently even in the presence of singular or multiple resonance, at least for the considered 9-cells cavity. No resonance enhancement is observed at a repetition rate of 5 Hz in pulsed operation.

5 REFERENCES

[1] M. Liepe et al, "Dynamic Lorentz Force Compensation with a Fast Piezoelectric Tuner", Proc. of Part. Accel. Conf., Chicago, 2001
[2] T. Schilcher, "Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities", TESLA 98-20
[3] G. Devanz et al, "Numerical Simulations of Dynamic Lorentz Detuning", these Proceedings