Field Stabilization in a Superconducting Cavity Powered in Pulsed Mode

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Abstract

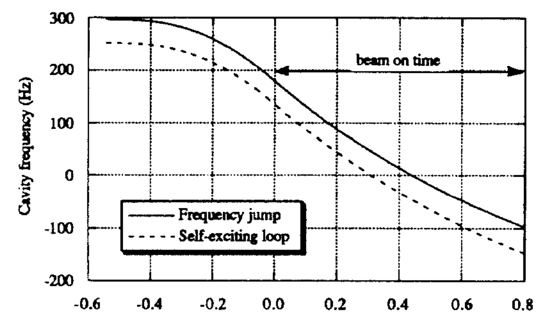
The Lorentz forces (also called "radiation pressure") and microphonics, by shifting the cavity frequency, are the main bunch-to-bunch energy spread sources. With superconducting cavities operating in pulsed mode, the Lorentz Forces problem arises from the wall deformation response time [1] . The cavity frequency goes on to shift after the field rise time, whereas the beam is passing through the cavity. After a brieve review of the two methods [2,3] coping with the Lorentz forces detuning when one cavity only is fed by one klystron, the effect of parameters spreads is studied when several cavities are fed by one klystron. External feedback loops to minimize the residual amplitude and phase errors are then added and the loop gains are determined. The influence of a spread in external Qs (from coupler tolerances or on purpose for having different fields from cavity to cavity) is analysed and the extra power needed to stabilize the total accelerating voltage is given after an optimization of the beam injection time. Finally, microphonics effects, which can increase dramatically the field errors, are considered and a remedy, allowing to alleviate the problem, is proposed [4].

1. INTRODUCTION

The beam energy spread at the exit the TESLA linac must be below the energy acceptance of the final focus but also small enough to limit the emittance dilution due to chromatic and dispersive effects. The intra-bunch energy spread, resulting from the rf sinusoidal wave and the induced bunch wake potential, can be reduced to about 5.10^{-4}, by running properly the bunch off the crest of the accelerating wave [5]. Any cavity field fluctuation, in phase and in amplitude, during the beam pulse will generate some bunch-to-bunch energy spread. It would be desirable to keep this energy spread below the intra-bunch energy spread in order to assure that the bunch-to-bunch chromatic effects will be no worse than the single bunch ones.

2. DESCRIPTION OF METHODS

During the field rise time, the generator frequency must be locked in any case on the cavity frequency which is shifting because of the Lorentz forces. The phase lock can be provided by a voltage controlled oscillator (VCO) or a self-excited loop. In the first method the generator frequency is then suddenly switched to the reference frequeny (1300 MHz) as soon as the beam is injected into the cavity, leading to a frequency jump at the beam injection time. The secong method uses the self-exciting loop principle during the field rise time and during the beam pulse, without any frequency jump. To minimize the phase shift for both methods during the beam traversal, the cavity frequency must be higher at the beginning (positive phase slope) and lower (negative phase slope) at the end than the reference frequency. The figure 1 gives the cavity frequency shifts (relative to the reference frequency) and the phase errors evolutions for the TESLA cavity parameters when the initial phase and the initial cavity frequency have been adjusted to cancel the phase deviation when the beam is injected and to minimize the phase error during the beam pulse.



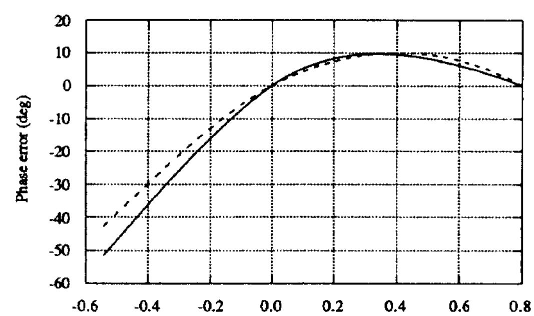


Figure 1 : Relative cavity frequency and phase error for both methods

The TESLA and TTF parameters and the resulting amplitude and phase errors, assuming one cavity driven by one generator, are listed in the table below for comparison.

	TESLA	TTF
Accelerating Gradient	25 MV/m	15 MV/m
Beam current	8 mA	8 mA
electric time constant τ_e	0.78 ms	0.78 ms
mechan. time constant τ_m	1 ms	1 ms
beam injection time $\tau_e \ln 2$	0.54 ms	0.54 ms
beam pulse duration	0.8 ms	0.8 ms
detuning parameter K	1 Hz/(MV/m)^2	1 Hz/(MV/m)^2
Amplitude error	5-6 10^{-3}	0.7 10^{-3}
Phase error	10 deg	3.5 deg

Without stiffening system, the static Lorentz forces detuning has been estimated to be slightly higher than 1000 Hz for a field gradient of 25 MV/m. With the stiffening system, the detuning reduces to 400 or 600 Hz according to the rigidity of the tuning system. A detuning parameter of 1 $Hz/(MV/m)^2$ has been conservatively retained. The mechanical time constant, which parametrizes the dynamic wall deformation response, has been measured on a 5-cell cavity at 1.5 GHz, and is assumed to be of the same order of magnitude.

3. MEASUREMENTS ON A 1.5 GHZ CAVITY

In order to prove the validity of the methods, they were tested on existing 5-cell cavities at Saclay. Since the Lorentz forces detuning is much stronger on these non-stiffened cavities (a factor 3.6 higher), the same static detuning of about 230 Hz was obtained with a lower accelerating gradient (8 MV/m instead of 15 MV/m). In addition, the beam current was simulated by injecting a rf signal in phase with the beam. The plots 2 show the amplitude and phase errors for the self-exciting loop arrangement during the field rise time and the beam pulse with different initial tunings of the cavity. The phase error was set to zero at the beginning of the beam pulse by readjusting the initial phase for each tuning value. For optimal initial tuning (200 Hz higher than the reference frequency), the amplitude and phase fluctuations are minimum, whereas the amplitude is growing with the time when the cavity is not correctly tuned and the phase slope is positive (negative) just after the field rise time when the tuning frequency is too high (low).

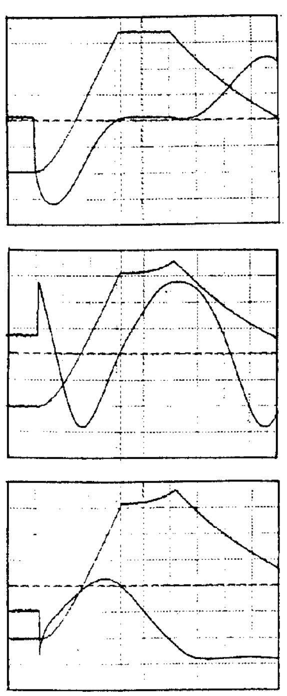


Figure 2 : Measured field amplitude and phase error for optimal (top) too high (center) and too low tunings (bottom) for the self-exciting loop arrangement

4. EFFECTS OF PARAMETERS SPREADS

In the aim to reduce the cost of the power sources, two 8-cavity modules are powered by one 5 MW klystron. Since the rf and mechanical parameters of the cavities are expected to be not identical, the effects of a spread in the different parameters have been studied. During the field rise time, the generator frequency has to be locked on the varying cavity frequency. Since the cavities cannot be initially perfectly tuned, the frequency tracking must be carried out by using the phase signal from the vectorial sum of all cavity voltages and not from a single cavity voltage. With this arrangement, there is no dramatic performance degradation when a spread in the initial cavity tuning or a spread in the detuning parameter K and mechanical time constant are introduced. The figure 3 shows the histograms of the errors for a gradient of 15 MV/m and with 1000 different simulations, where the initial tuning of the 16 cavities has been randomly varied between ± 40 Hz (corresponding to a tuning angle error of 10°).

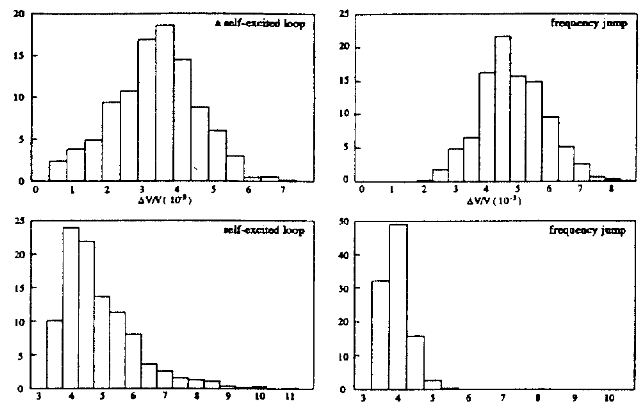


Figure 3 : amplitude (top) and phase (bottom) histograms with static cavity tuning errors for self-excited loop (left) and frequency jump (right) methods

In the same way, the histograms of the errors for a simultaneous spread of 20 % in the detuning parameter K and the mechanical time constant, are showed on the figure 4, for 1000 simulations.

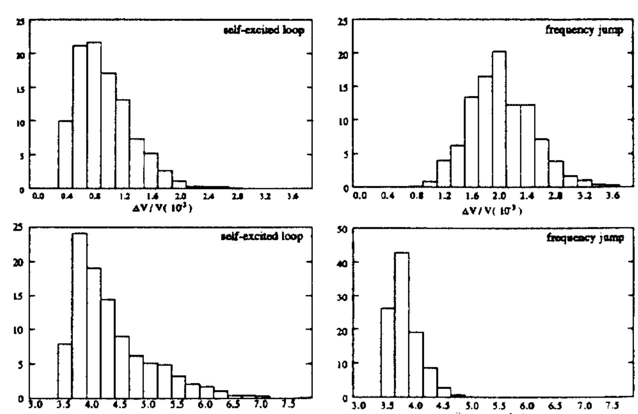


Figure 4: amplitude (top) and phase (bottom) histograms with K and τ_m spreads for self-excited loop (left) and frequency jump (right) methods

5. FEEDBACK LOOPS

Feedback loops have to stabilize the field fluctuations, which are induced mainly either by Lorentz forces or by microphonics detunings, while keeping the needed extra rf power (peak and average) within a reasonable level. In order to reduce the coupling between amplitude and phase feedback, the feedback loops must use a vectoriel modulator, in which an in phase signal, proportional to the amplitude error and an out of phase signal, proportional to the phase error are added to the main drive signal. Loop gains of 50 for the phase and 100 for the amplitude are a good compromise between the extra needed rf power and the resulting amplitude and phase errors. Taking into account the perturbation due to the Lorentz forces only, the resulting energy spread is of the order of 10^{-5} for an increase of the rf powers of about 10% peak and 4 % average.

6. Q-SPREAD EFFECTS

In order to make the best possible use of the SC gradient capability, it would be advantageous to operate each cavity at its maximum field. Since the cavity tuning is not allowed to play with (see previous study), the easiest way of varying the cavity gradients in a chain fed by one klystron, is to change the external Qs from cavity to cavity. Even without Lorentz forces detuning however, a spread in external Qs, resulting from coupler tolerances or on purpose for having different cavity fields, will affect dramatically the amplitude error of the total voltage, because the source is not any more matched to the beam loads. This error must therefore be minimized first by means of the incident power (P_g) and of the beam injection time (t_0), before attempting to close the feedback loops, which would result to a huge extra rf power. Assuming for example a uniform spread in accelerating field around 25 MV/m of a string of 16 cavities, the figure 5 gives the required source power in kW as a function of the total voltage fluctuation for different widths of the gradient spread (10, 15 and 20 %). About 230 kW per cavity (instead of 200 kW) are needed to reach amplitude errors of the order of 10^{-4} for a gradient spread of ± 20 %.

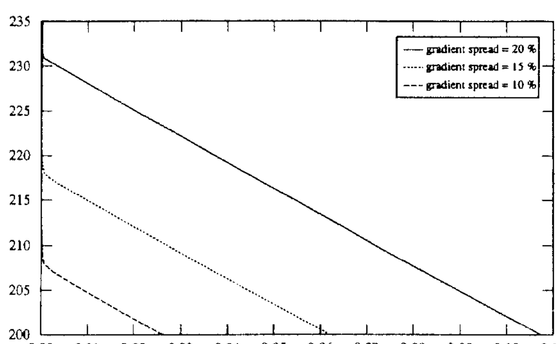


Figure 5: Needed source power (in kW) vs. the fluctuation level of the total voltage

If the Lorentz forces effects are included, the final energy spread is of the order of 2 10^{-4} with the gains of 100 and 50 for the amplitude and phase loops. The net additional powers to be delivered by the source are finally 30 % peak and and 20 % average with a Q-spread of ± 20 %.

7. MICROPHONICS EFFECTS

The main effect of microphonics, because they change the cavity frequency, is to displace the rf phase with respect to the beam, assuming that the initial phase is fixed. The demand of rf power from the feedback loops would then be huge. Instead of having a fixed initial phase, we could think of a feedback system acting on this initial phase to recover a vanishing phase shift when the beam is coming. Unfortunately the frequencies of mechanical vibrations are expected to be around and above the TESLA repetition rate of 10 Hz, making a direct feedback unefficient. Instead of having fixed phase and amplitude references of the feedback loops, floating references following the actual phase and amplitude at the beginning of the beam pulse (by means of a tracking-and-hold circuits), can solve the microphonics problem in case of too large mechanical vibrations. The beam energy is then constant within a beam pulse but could slightly fluctuate from pulse to pulse. This is not harmful for a long machine like TESLA because the errors coming from the Lorentz forces detuning are correlated whereas the errors coming from the microphonics detuning (jitter) are essentially uncorrelated. The figure 6 shows for example the phase error curves during the beam pulse for 3 cavity tunings, including the Lorentz forces effects : the optimal one and with a shift of ± 50 Hz around due to microphonics, giving moderate extra powers (20% peak and 6% average), with amplitude and phase loop gains of 100 and 50.

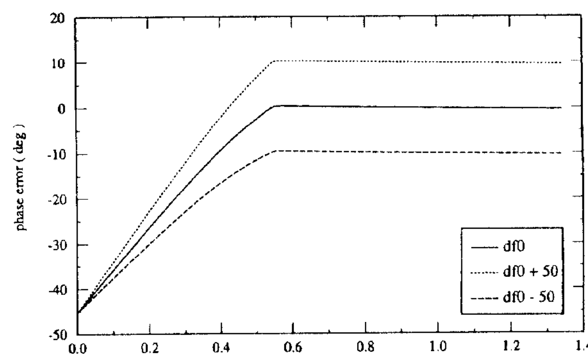


Figure 6: Phase profiles for the optimal initial tuning and ± 50 Hz around

8. REFERENCES

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