RF CONTROL SYSTEM FOR THE SC CAVITY OF THE TESLA TEST FACILITY INJECTOR

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Abstract

The superconducting cavity of the TTF injector, which operates in pulsed mode, must accelerate the non relativistic electron beam to an energy of 10 to 15 MeV. Lorentz forces and microphonics detunings are the major sources of cavity field fluctuation. In order to achieve amplitude and phase stabilities much smaller than 10^{-3} and 1 degree, an analog feedback system, mainly based on a self excited loop and I/Q modulators, has been developed. After a description of the RF control module, various measurements without and with beam are reported.

1 INTRODUCTION

The SC cavities in the TESLA Test Facility have to operate in pulsed mode at high gradients, each klystron driving 16 cavities. Although the capture section consists in one single standard 9-cell TESLA cavity, driven by a 300 kW klystron, the main issues for the RF feedback system, namely Lorentz force within the beam pulse detuning, microphonics pulse-to-pulse detuning, except calibration of the vector sum, needed for a multiple cavities RF drive, have been successfully tested with beam, in agreement with the expected dynamic behaviour. It can be shown [1] that the beam energy spread can be kept much below the 10^{-4} level and without excessive extra power, assuming the following precautions have been taken [2]:

1. due to Lorentz forces, the RF generator must track the varying cavity frequency during the filling time, and the cavity must be pre-detuned, such that operating frequency and cavity frequency are approximately equal at half the beam pulse, giving minimal amplitude and phase errors when the loops are opened
2. due to microphonics, the phase feedback loop must be closed during the filling time, following a pre-determined phase law $\phi(t)$, to ensure minimum RF power requirements

Although a digital RF control system is certainly better suited for large scale SC linacs, an analog system was chosen for the capture cavity, because of simplicity for one module and of swiftness to bring into operation.

It is worthwhile noting that for the capture cavity, where the beam is running off-crest, the pre-detuning must be re-adjusted for compensation of the cavity detuning caused by the reactive component of the beam loading. By integration of the dynamics equations in the longitudinal plane, an average phase shift of about -30 degrees with respect to the RF wave is found for an accelerating field of 15 MV/m and an injection energy of 250 keV, resulting in a net beam detuning of almost 200 Hz. Fig. 1 shows for example the development of the field phase error during the RF pulse, when only the amplitude feedback loop is closed. Without beam, the pre-detuning Δf is set to its optimal value +80 Hz for a Lorentz force detuning parameter K = 1 Hz/(MV/m)^2 and a mechanical cavity time constant τ_m = 1 mS. With beam, if Δf is kept to the same value (+80 Hz), the phase error grows continuously and reachs large value at the end of the pulse, leading to non optimal performances once all the loops are closed. Conversely, if Δf is re-adjusted to take into account the off-crest beam effect (+80 -200 = -120 Hz), a small phase error is then recovered. For optimal performance of the capture cavity RF control, we conclude that it is essential to set the proper pre-detuning, sum of the Lorentz force and beam detunings, when the beam is on.

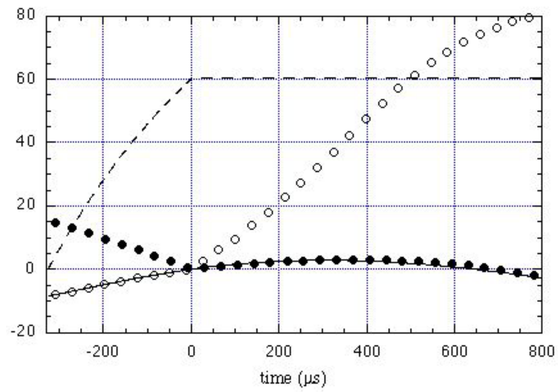

Figure 1 : Cavity phase (in degrees) a)without beam Δf = 80 Hz (solid line), b)with beam Δf = 80 Hz (empty circles), c)with beam Δf = -120 Hz (solid circles)

2 LOOPS DESCRIPTION

The RF control is based upon a self-excited loop, which ensures the cavity frequency tracking during the filling time (see Fig. 2). The attenuator sets the operating field amplitude, whereas the phase-shifter cancels out the phase shifts due to cables and components. The field vector is controlled by means of an I/Q modulator.

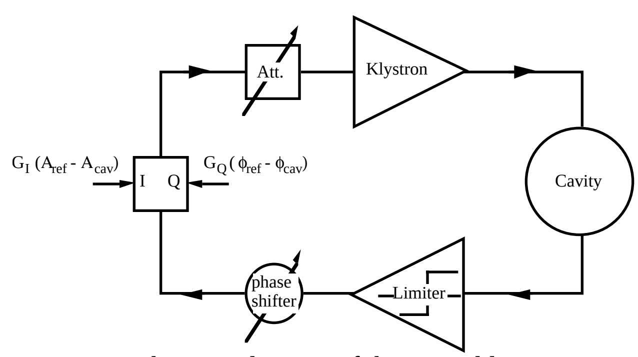

Figure 2 : Schematic drawing of the control loops.

Since the main perturbations come from cavity detuning (Lorentz forces, microphonics), the injection of an out-of-phase signal by the modulator will compensate automatically phase and amplitude of the field. The starting phase of the self oscillator is fixed by simply injecting a very low level reference signal. A klystron phase loop (not drawn on the figure), including a phase modulator, has been added to compensate any phase shift of the klystron. While the in-phase loop is closed just before the beam pulse, the out-of-phase loop is closed from the beginning of the RF pulse, otherwise the pulse to pulse detuning due to microphonics would give rise to large phase jitter, just when the beam is coming. The phase setting is of course a time varying signal, which is fixed to the average of previous measurements during the cavity filling and to zero during the beam pulse.

3 HARDWARE

The low level RF system has to fulfill different purposes:

- to set up the RF field in the resonator
- to stabilize amplitude and phase of the field by means of feedback loops
- to provide different informations, as reflected and transmitted power, field errors, etc

The gain cross-over frequency is about 25 kHz of the open loop transfer functions, mainly determined by the pole of the cavity. The bandpass RF filter and video notch filter (damping the nearest parasitic mode) contribute to a phase shift of 10°. Besides the resonator pole, the higher frequency poles (BW>1MHz RF components, cables, error amplifiers) give the minimal phase shift at the gain cross-over frequency. For the desired specifications of steady state error magnitude and degree of stability during the beam time, loops gain is held higher than 40 dB with a phase margin of 80° (Fig. 3).

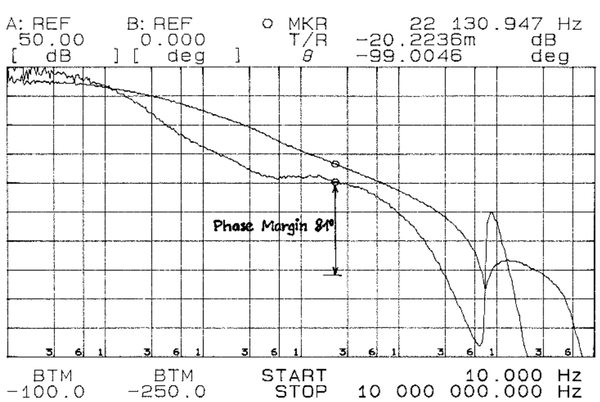

Figure 3 : Open-loop transfer function

The most important RF component is the CPM (Complex Phase Modulator), which has three different applications in this low level RF system :

- to provide continuous 360° unambiguous phase shifts for the self excited loop, for the phase setting of the RF field at the beginning of the pulse and for the global phase setting with respect to the beam.

- to control the cavity field through the I and Q ports. The I-ports behaves as a constant phase amplitude modulator (Fig. 4), while the Q-port behaves as a variable amplitude modulator (Fig. 5), ensuring a nearly total decoupling between the two feedback loops.

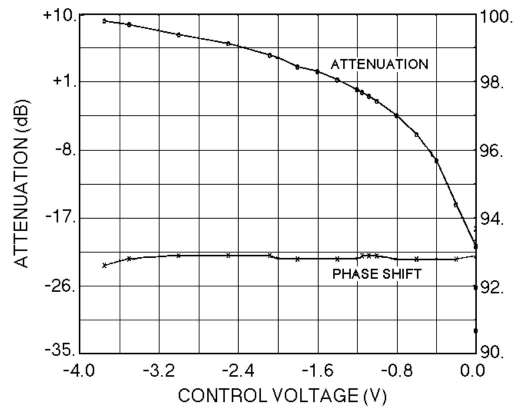

Figure 4 : CPM port I control

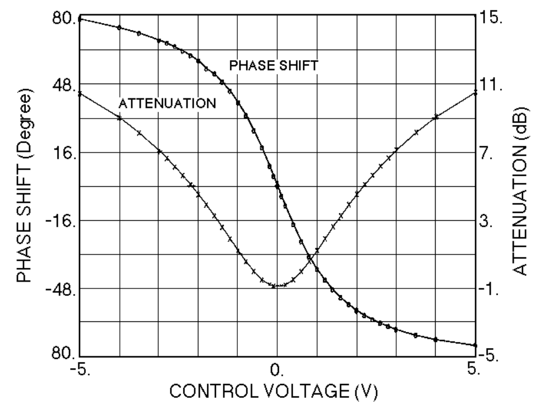

Figure 5 : CPM port I control

In order to suppress the strong modulation, which can be generated through the self excited loop by the $8\pi/9$ mode of the cavity, a RF bandpass filter (centered on 1302 MHz with a BW of ±2 Mhz) has been inserted at the cavity output and audio notch filters have been added in the feedback loops, giving a total attenuation of this parasitic mode of 43 dB. The reactive RF peak power has also been limited, in order to avoid high RF power peaks and over-oscillations for equivalent phase errors of 25°.

4 SOFTWARE

The operation of the RF feedback system is controlled by EPICS routines. The first goal is to tune correctly the different loops : to search for the right phase of the self excited loop while keeping klystron phase shift constant during the RF pulse, to search for the minimum error between the reference and the field amplitude, to reduce the field phase error at the beam injection time and to adjust the phase setting during the cavity filling. They have also to insure a survey while the system is running : monitoring of the control voltages of the loops, and re-adjustment, if necessary, of the frequency of the cavity, by minimizing the reactive RF power. All parameters and measurements, needed for remote-control, can be reached from a main control panel (Fig. 6).

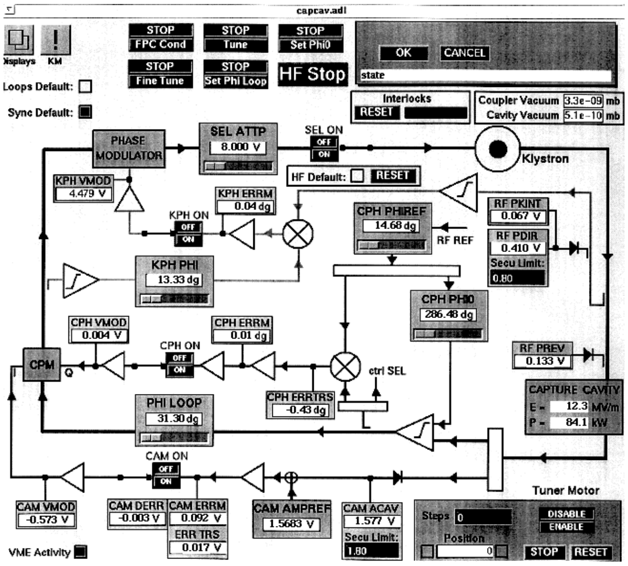

Figure 6 : Main control panel open to operators

5 RESULTS

Most of the tests at DESY in February 1997 on the TTF capture cavity have been performed at an accelerating gradient of 12.5 MV/m, first without beam and last with a beam current of 6 mA.

5.1 Without beam

The optimal cavity tuning, giving minimal phase error fluctuation during 800 µs after the filling time, was first searched. The time varying phase reference was then adjusted, in order to match the cavity phase variation during the filling time. Fig. 7 shows the different relevant signals, recorded from a digital oscilloscope. The incident RF power decreases suddenly after the filling time to about one quarter of its initial value, because there is no beam load. The field amplitude and the time varying phase reference, reversed signal of the cavity phase can also be seen. Only a small amount of extra RF power was needed to stabilize the cavity phase. The loop gains have been set to 200 for the I-loop and to 100 for the Q-loop, with a sufficient phase margin of 80°. Fig. 8 shows a zoom on the phase error, which looks well behaved when the pre-detuning has been properly set. With 0.6° per square, we deduce a phase fluctuation lower than ± 0.1° , while the amplitude fluctuation was measured lower than $\pm 4\ 10^{-4}$ during the flat top.

5.2 With beam

The same measurements were made with an accelerated beam current of about 6 mA. Unfortunately, the pre-detuning was not corrected to take into account the beam detuning effect. A zoom on the field phase (Fig. 9) reveals clearly the incorrect cavity tuning. Nevertheless, and thanks to the efficiency of the feedback loops, amplitude and phase errors are found about identical to the previous ones, without beam : $\pm 4\ 10^{-4}$ peak-to-peak, for the amplitude and ± 0.1° peak-to-peak for the phase. These fluctuations come mainly from high frequency noise, which would be uncorrelated from cavity to cavity and then would result in much lower beam energy spread.

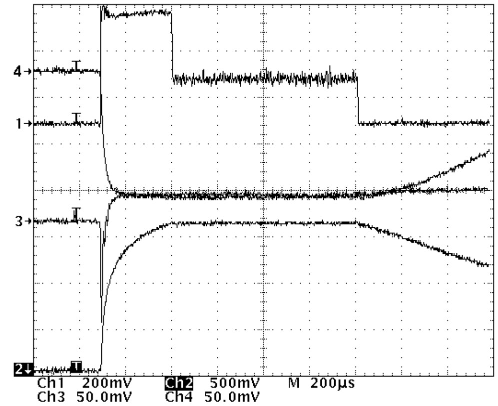

Figure 7 : Without beam, incident power (trace 1), field amplitude (2), field phase (3), phase reference (4)

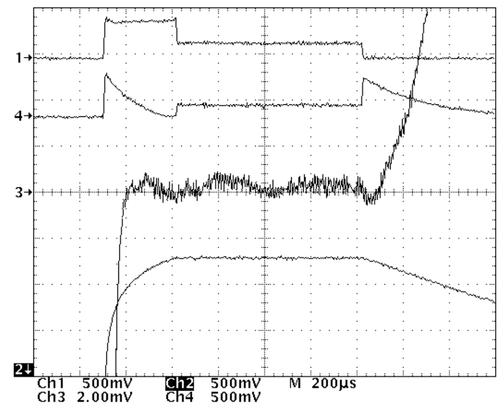

Figure 8 : Without beam, incident power (trace 1), field amplitude (2), field phase (3), reflected power (4)

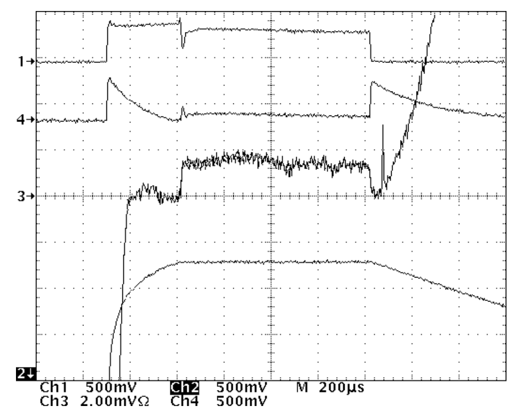

Figure 9 : With beam, incident power (trace 1), field amplitude (2), field phase (3), reflected power (4)

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[1] ‘Stabilisation de champ dans des cavités supraconductrices en régime pulsé’, J.-M. Tessier, Ph-D thesis, 1996.

[2] ‘Energy Spread Sources in TESLA and TTF’, A. Mosnier and J.-M. Tessier, TESLA report 95-5

[3] ‘Design of the Digital RF Control System for the TESLA Test Facility’, S. Simrock et al., Proc. of the 1996 European Part. Acc. Conf., Sitges.