COMPENSATION OF LORENTZ FORCE DETUNING OF A TTF 9-CELL CAVITY WITH A NEW INTEGRATED PIEZO TUNER

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Abstract

The high gradient operation of superconducting elliptical multicells in pulsed mode is required for linear colliders or free-electron lasers based on the superconducting technology. Such an operation is limited by dynamic Lorentz force detuning if no compensation for this effect is attempted. The RF power headroom required for accelerating field amplitude and phase stabilisation by low-level RF control techniques solely would be too costly. A new active tuner with integrated piezo actuators has been developped in the framework of the european CARE/SRF program to solve this issue. The design is based on the lever-arm concept of the Saclay tuner already installed on running TTF cavities. We have carried out integrated tests of the 9-cell cavity equipped with the piezo tuner and power coupler in the CryHoLab horizontal test cryostat. Characterisation of the electromechanical system consisting of the cavity and piezo-tuner assembly and full power pulsed tests will be presented.

INTRODUCTION

Lorentz forces in TESLA-type superconducting cavities operated above 20 MV/m in pulsed mode can generate a detuning larger than one cavity bandwidth during a typical 1-2 ms pulse duration. Since the accelerating field amplitude variations have to be kept within a few 10^{-4}, and the RF driving frequency is fixed, the power overhead for the RF source would typically be of the order of the nominal power. Therefore, a fast tuner is necessary to operate a cavity at even higher gradients at 35 MV/m [1] . The dynamics of the Lorentz detuning is dominated by the mechanical time constants of the cavity, of the order of 1 ms. For a 1 or 2 ms long RF pulse, the mechanical steady state is not reached, therefore the quality factors Q_m of the mechanical eigenmodes of the structure, especially those of the low frequency modes are very important parameters of the system. A piezo stack integrated in the cold tuning system can in principle change the cavity length on this time scale. Readily available piezoelectric stacks exhibit a resonant behaviour above 20 kHz, it is thus safe to use them with driving frequencies of the order of 1kHz, which matches the cavity dynamics. The RF frequency correction should be of the order of 1 kHz, which corresponds to 3 microns variations in the cavity length in steady state. Considering the 10 fold reduction in the displacement at maximum driving voltage of the piezo elements at 2K compared to room temperature, long piezo stacks are needed. The piezo stroke has to be transferred into cavity length with maximum efficiency. The first experimental compensation of Lorentz force detuning using a fast tuner was carried out at DESY[2] with a modified TTF tuner.

CTS MECHANICAL DESIGN

The new Piezo Tuning System (PTS) is based on the lever arm design already used for the current Saclay tuner which is operating at TTF since 10 years. The static tuning is obtained with the combination of the lever arm and a screw which is driven by a stepper motor and a gear box. Like the SOLEIL/Super 3HC tuning system [3], the new PTS uses a symmetric lever arm action. One of the link to the He tank is equipped with two piezoelectric elements (PZTs) which provide for the fast tuning. The whole system operates in vacuum at liquid He temperature. The tuner is designed to lengthen the cavity only. The cavity is acting as a spring on the PTS in order to generate a compression force on the piezo elements, which is mandatory to maintain their mechanical integrity during operation. In addition, the neutral point of the tuner is outside its operating range to suppress backlash. During cooldown, the preload force on the piezo is expected to decrease due to the difference between the multiple materials thermal contraction. Therefore, an initial setup at room temperature is necessary, where the cavity is elastically lengthened by 0.75 mm using the zero adjusting screws.

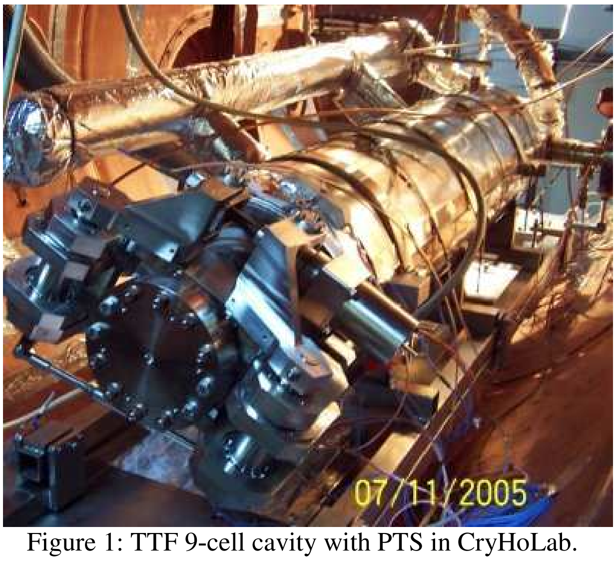

Figure 1: TTF 9-cell cavity with PTS in CryHoLab.

Figure 1 shows the PTS and its mounting position on the He tank. The piezo support is designed in order to

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minimize the shear stress in both PZTs regardless of the static tuning setup. The computed cavity elongation over piezo stroke ratio is 0.22. The balance between the two piezos requires tight machining tolerances of the support. Figure 2 shows the piezo support loaded with NOLIAC 30 mm stack actuators. The stiffness of the tuner was measured using a pneumatic jack. The experimental value is 70 kN/mm.

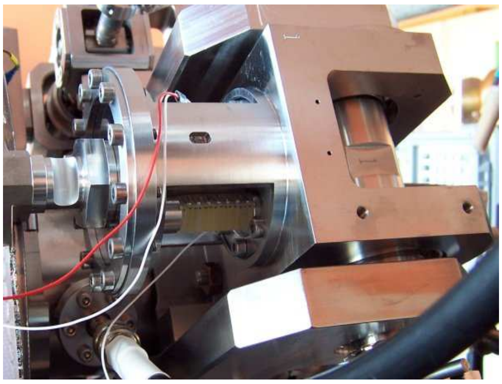

Figure 2: PZT actuators support

LOW POWER TESTS IN CRYHOLAB

The C45 cavity was equipped with a TTF-III power coupler and installed in the CryHoLab horizontal test cryostat [4]. The measured external Q is $1.34\ 10^6$, corresponding to a 3 dB bandwidth of 970 Hz. For a faster cooldown of the tuner, copper braids were connected between the PTS and a LHe circuit. Once the cold mass had reached 4.2 K, the slow tuner was brought to the maximal cavity extension in order to provide the piezo preloading. The measured slow tuning full span is 500 kHz at 1.8 K. The static detuning generated by one PZTs is 800 Hz for a driving voltage of 100 V DC, which is safely below the maximum driving voltage of 200 V. The recorded temperature of the PZTs is between 20 and 30 K, which is favourable in terms of piezo stroke compared to the case of a fully thermalized system at 1.8 K. The transfer function between the two piezos was measured with a sinusoidal signal generator to drive one PZT and a lock-in amplifier to measure the response of the other PZT. The harmonic scan is a slow but accurate method to identify sharp mechanical resonances. The PZT to PZT transfer function at 4.2 K is shown on figure 3.

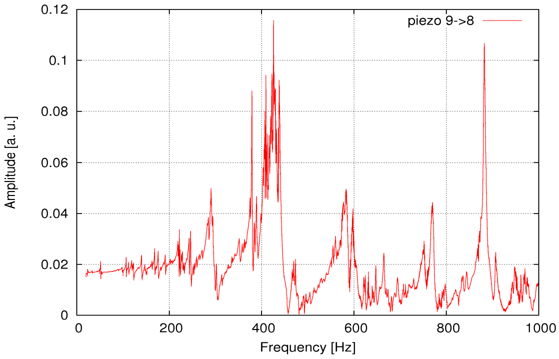

Figure 3: piezo to piezo transfer function.

The piezo voltage to detuning (Δf) transfer function has been measured at 1.8 K using a phase demodulation rack and a setup described in [5]. The lower frequency part of its amplitude and phase is shown in figure 4.

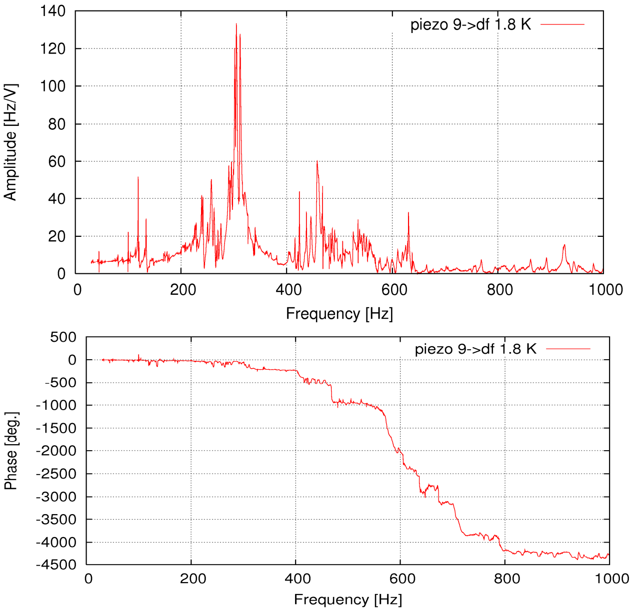

Figure 4: Piezo voltage to detuning transfer function., amplitude (top) and phase (bottom).

It exhibits a large number of resonances which cannot be identified as purely longitudinal modes of the cavity. The PTS is likely to couple longitudinal and transverse modes of the cavity since its principle is to transform a transverse displacement of the two arms into longitudinal displacement. The comparison between the two pictured transfer functions reveals a strong discrepancy concerning the position of the main resonant peaks. Most likely, the piezo to piezo transfer function is dominated by modes which are localized in the piezo support and are weakly coupled to the cavity. The analysis of the phase behaviour of the piezo to Δf transfer function is compatible with a mechanical delay of the order of 400 µs.

PULSED POWER TESTS IN CRYHOLAB

The high power pulsed RF source is able to deliver a maximum power of 1.5 MW for 1ms at maximum repetition rate of 6.25 Hz. Most of the pulsed experiments on the cavity have been carried out at 0.87 Hz to reduce He consumption. The power coupler (FPC) was conditioned at room temperature and at 4.2 K, connected to the cavity at all times, ramping the incident power from 50 kW to 800 kW. In order to simulate the flat-top operation of the cavity within 1ms,we have used a 220 µs pre-pulse with $4xP_{flat}$ peak power followed by 780 µs at P_{flat}. The klystron is equipped with an amplitude regulation, but no phase feedback. With such a setup, the pre-pulse operation generates a fast phase shift during the 4xP/P switching, that has to be compensated by inserting a synchronized voltage controlled phase shifter between the RF synthesizer and the klystron preamplifier. The residual klystron phase shift during the pulse is about 5 degrees. The frequency of the RF generator is fixed, Lorentz detuning can be diagnosed by amplitude and phase modulation of the transmitted signal.

The maximum operational accelerating field of 25 MV/m was obtained. Above this value, noticeable X-ray emission starts and dissipations in the cavity become excessive. At 25 MV/m the phase of the cavity shifts by 30 degrees during the flat top as seen on figure 5. The frequency shift of -240 Hz was not measured directly, but was derived using a numerical model of the cavity and fitting the measured phase and amplitude evolution of the cavity voltage. This rather low value for the detuning can be explained by the reduced length of the RF pulse. The compensation was obtained by feeding a simple pulse shape to the piezo driver amplifier and minimizing the phase excursion during the flat top. Although good results were obtained with a square pulse, it was thought a better solution to avoid exciting the higher frequencies of the mechanical system. A trapezoidal pulse with three parameters, pre-delay, rise time and amplitude was a good candidate. The compensation was achieved with a moderate driving voltage of 42 V, a pre-delay of 500 µs and a rise time of 200 µs. The phase excursion during the flat top is 3 degrees in the compensated case.

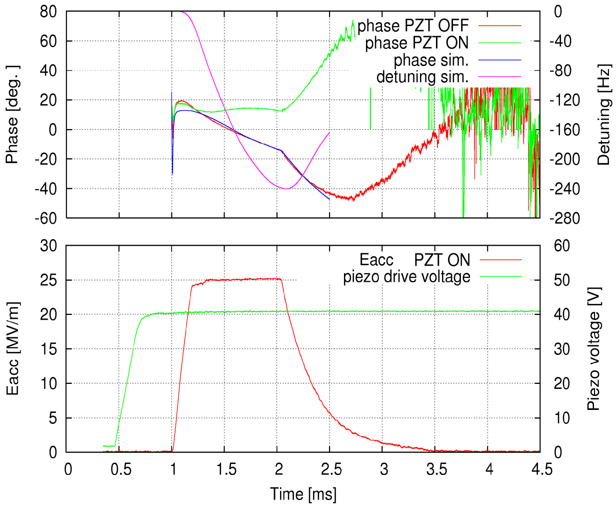

Figure 5: Pulsed operation at 25MV/m. Phase and detuning evolution (top). Accelerating field and piezo driving pulse (bottom).

The pre-delay is compatible with the 400 µs delay derived from the piezo voltage to detuning transfer function. Another way to investigate the mechanical delay is to measure the signal on one of the PZTs used as a sensor. The radiation pressure generates a deformation of the cavity which propagates to the PZTs. As shown on figure 6, the delay between the beginning of the Rf pulse and the reaction of the piezo sensor is about 400 µs. The other PZT is not used in this case, therefore the effect of the detuning can be observed on the accelerating field.

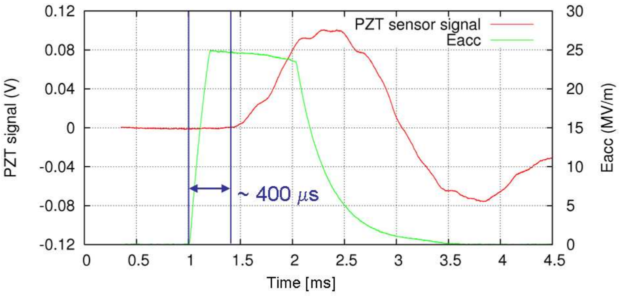

Figure 6: Signal on PZT sensor due to Lorentz force.

DISCUSSION

The Lorentz force detuning compensation on a TTF 9-cell cavity at 25 MV/m was achieved with the new integrated PTS tuner. The driving voltage employed is less than a quarter of the maximum admissible voltage of the NOLIAC actuators. The access to higher accelerating gradients was prevented by electronic activity in the cavity. Assuming a linear behaviour of the PTS, it could in principle achieve the compensation at any accelerating field level envisaged for a TESLA type cavity, for a 1 ms RF pulse.

During a period of 6 month a total of 13 million full steps have been sent to the cold stepping motor without any flaw.

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