ACTIVE COMPENSATION OF LORENTZ FORCE DETUNING OF A TTF 9-CELL CAVITY IN CRYHOLAB

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Abstract

Linear colliders and free-electron lasers projects based on the superconducting RF technology require high gradient pulsed operation of superconducting elliptical multicells. The cavities are subject to Lorentz force detuning (LFD) which reflects on an increased RF power consumption when trying to stabilize the accelerating field during the beam passage. This pulsed detuning can be mechanically compensated using a fast piezoelectric tuner. A new tuner with integrated piezoelectric actuators has been developed in the framework of CARE/SRF European program. The tuning system has been tested on a fully equipped 9-cell TTF cavity in the CRYHOLAB horizontal cryostat using the pulsed 1.3 GHz 1.5 MW RF source. In virtue of the high pulse to pulse repeatability of the detuning, the compensation of Lorentz detuning was achieved successfully using a simple feed forward scheme.

INTRODUCTION

Lorentz forces in TESLA-type superconducting cavities operated in pulsed mode generate a time varying detuning which for typical accelerating gradients amounts in hundreds of Hz. Meanwhile, the accelerating field has to be stable 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 if the cavity is run at 35 MV/m without LFD compensation [1]. The dynamic Lorentz detuning is the sum of the contribution of individual mechanical eigenmodes of the cavity. For each of them, one can define a coupling factor to the radiation pressure excitation α_m, a detuning coefficient β_m and a quality factor Q_m such that the steady state amplitude of the cavity detuning is $k_m Q_m = \alpha_m \beta_m Q_m$ if the square of the accelerating field could be sinusoidal modulated at the mode angular frequency ω_m. It is expected from FEM calculations that the fully equipped cavity has seven longitudinal modes below 1 kHz. Measurements show that several of them appear to have a Q_m larger than 100. Therefore the mechanical excitation generated by a 1 or 2 ms long RF pulse can be considered short with respect to mechanical time constants. The actual detuning during the flat top is smaller than the steady state detuning given by $-|k_L|E^2_{acc}$, where k_L is the static Lorentz coefficient and is of the order of 1 $Hz/(MV/m)^2$. A 30 mm long piezoelectric stack integrated in the cold tuning system can in principle change the cavity length and RF frequency on this time scale on a 1 kHz range. The LFD compensation using a fast tuner was achieved at DESY[2] with a modified TTF tuner.

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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 (Fig. 1). The whole system operates in vacuum at liquid He temperature.

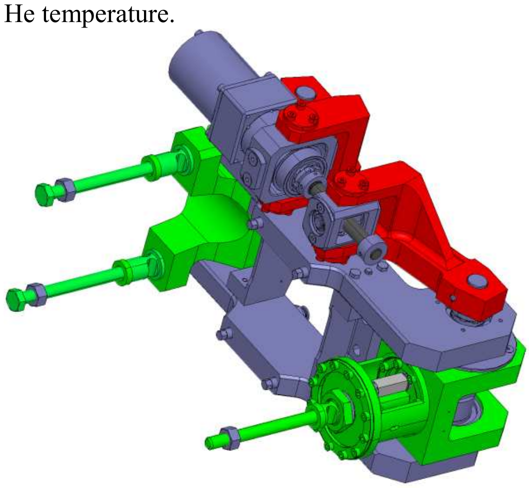

Figure 1: PTS. PZT support in front

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. The piezo support is designed to minimize the shear stress in both PZTs regardless of the static tuning setup. The balance between the two piezos requires tight machining tolerances of the support. In addition, the neutral point of the tuner is outside its operating range to suppress backlash. It is a challenge to control the preload at 1.8 K, and at the present time, it has never been measured in-situ. During cooldown, the preload force on the piezo is expected to decrease due to the difference between the multiple materials thermal contraction. An initial setup at room temperature is necessary, where the cavity is elastically lengthened by 0.75 mm using the zero adjusting screws. At 1.8 K, the cavity has to be stretched using the full tuning range of the CTS to ensure a PZT preload of several hundreds of Newtons.

CW TESTS IN CRYHOLAB

The C45 cavity equipped with a TTF-III fundamental power coupler (FPC) was installed in the CryHoLab horizontal test cryostat [4]. 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 preload. The measured slow tuning full span is 500 kHz at 1.8 K. For the first experiments the tuner was loaded with 30 mm NOLIAC PZT stacks 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 [5]. 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 [6]. The lower frequency part of its amplitude and phase is shown in figure 2. The PZT was harmonically excited with an amplitude of 2 V.

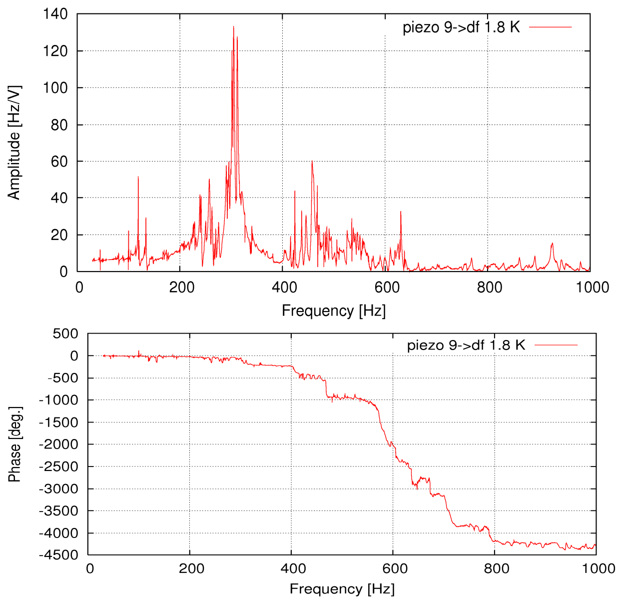

Figure 2: PZT voltage to detuning transfer function., amplitude (top) and phase (bottom).

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. A mechanical delay of the order of 400 µs is derived from the slope of the phase of the piezo to Δf transfer function at low frequency.

DYNAMIC LDF COMPENSATION

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 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. The measured external Q is $1.34\ 10^6$, corresponding to a 3 dB bandwidth of 970 Hz. The RF frequency was set 1 MHz above the cavity resonant frequency during the processing to prevent high power pulses from quenching the cavity. 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 stabilization loop, but no phase feedback. The pre-pulse operation generates a fast phase shift during the 4xP/P switching, compensated using a synchronized voltage controlled phase shifter in front of 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 3. 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. The compensation was obtained by feeding a simple pulse shape to the piezo driver amplifier and minimizing the phase excursion during the flat top. Good results were obtained with a square pulse. However a trapezoidal pulse with three parameters, pre-delay, rise time and amplitude is better suited to avoid exciting the higher frequencies of the mechanical system. 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. The numerical simulation of the compensation using the experimental parameters was also carried out which is in agreement with the phase excursion. The deduced detuning of the cavity during the flat top is 20 Hz peak-peak. However, the PZT voltage amplitude had to be reduced to 36 V in the simulation which uses the transfer function of figure 2. This could be explained by a non-linear behaviour of the PTS: preliminary experiments at 1.8 K have shown that the harmonic response of the cavity detuning was not linear with respect to the PZT driving amplitude in several frequency ranges, most notably in the 300 to 350 Hz region. The lower span from DC to 250 Hz is not affected by this non-linearity. This preliminary study covers PZT voltages ranging from 2 V to 16 V only.

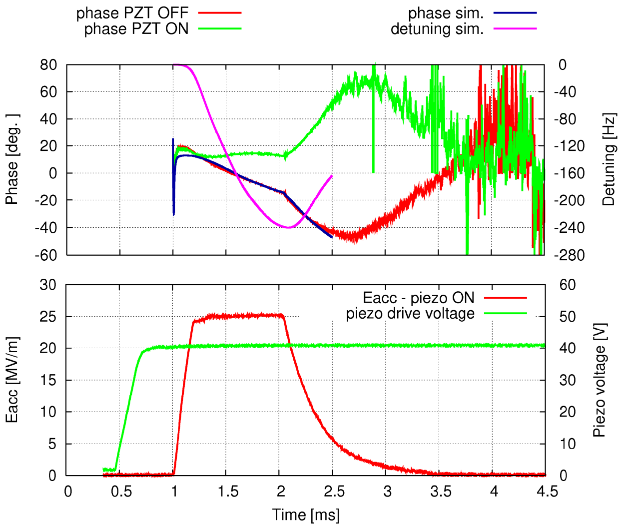

Figure 3: Pulsed operation at 25MV/m. Phase and detuning evolution (top). Accelerating field and piezo driving pulse (bottom).

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 4, 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.

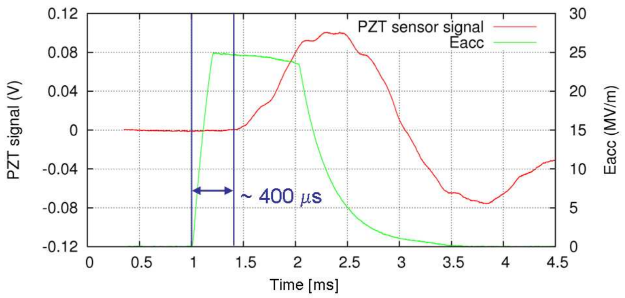

Figure 4: Signal on PZT sensor due to Lorentz force.

A second series of experiments was carried out replacing the NOLIAC piezo by PICMA 36 mm piezo stacks. The main screw of the tuner was also replaced by a longer one in order to reach a wider range of PZT preload. At 1.8 K the cavity was progressively stretched using the slow tuner. The PZT temperature, initially around 50 K dropped to 20-30 K. The upper piezo experienced this drop at one third of the tuning range, the lower piezo at two thirds. It is a clear indication that the initial preload is so weak at 1.8 K that the thermal link between the PZTs and their support is affected. Moreover, the load is not balanced equally among the PZTs although the support is symmetrical. For LFD compensation experiments, the upper piezo with the higher preload was used as an actuator. Equally good results were obtained with PICMA and NOLIAC PZTs. In order to check the sensitivity of the preload on the piezo actuator, a LFD compensation experiment was carried out at an intermediate position of the slow tuner, just above 2/3 of the extension to prevent the lower PZTs from getting loose. The compensation was achieved with the same parameters for the PZT driving pulse.

CONCLUSION

The Lorentz force detuning compensation on a TTF 9-cell cavity at 25 MV/m was achieved with the new integrated piezo tuning system. Both NOLIAC and PICMA PZTs performed equally well The driving voltage employed is less than a quarter of the maximum admissible voltage for the NOLIAC actuators and one third for the PICMA PZTs. 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. This still has to be demonstrated since a non linear behaviour of the detuning has been observed with respect to the PZT driving voltage in dynamic operation.

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