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Dynamic Lorentz Force Compensation with a Fast Piezoelectric Tuner

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Abstract

Superconducting cavities are highly susceptible to small changes in resonance frequency due to their narrow bandwidth. At the proposed linac for the TESLA Linear Collider [1] the frequency changes resulting from mechanical deformations caused by Lorentz force detuning of the pulsed cavities will be of the order of the cavity bandwidth at the design operating gradient close to 25 MV/m. The additional power required for field control is of the order of 10 % and will be intolerably high for the planned upgrade to 35 MV/m which appears to be feasible in the near future. While passive stiffening of the cavities is already applied to the present cavity design, the further reduction of the Lorentz force detuning constant is technically challenging. Therefore we propose an active scheme which reduces the timevarying Lorentz force detuning to much less than one cavity bandwidth. If successful, the scheme will improve the power efficiency of the TESLA linac significantly.

1 INTRODUCTION

The time varying detuning $\Delta f_l(t)$ of the superconducting cavities induced by the Lorentz force $F_l(t) \propto E_{acc}^2(t)$ can - at least from a theoretical viewpoint - be compensated by a time varying force in opposite direction. Since the Lorentz force is distributed over the large surface of all cavity cells it is technically not feasible to generate an equal distribution of counteracting forces which cancel at all locations of the cavity surface. It seems however feasible to locally apply a force $F_c(t)$ which generates a time varying cavity detuning $\Delta f_c(t)$ which cancels the Lorentz force detuning such that $\Delta f_c(t) = -\Delta f_l(t)$. In this case the cavity geometry and therefore the cavity field will be slightly different from that of the unperturbed case but the difference is negligible for the effective accelerating field.

The local force can be applied by a piezotranslator which is incorporated in the support rods of the mechanical motor driven frequency tuner. Since piezotranslators can also be used for measuring forces (generated voltage is proportional to force) and therefore indirectly the cavity resonance frequency, one can imagine to use one piezotranslator for control while a second piezotranslator measures the cavity resonance frequency. Feedback control is however not feasible since the high bandwidths required (several kHz) cannot be realized due to lower frequency mechanical resonances of the cavity-tuning frame assembly. Feedforward compensation must instead be applied which relies on the high repetitive characteristics of the Lorentz force detuning of pulsed cavities.

2 LORENTZ FORCE DETUNING

The static detuning of a resonator due to the action of Lorentz forces is proportional to the square of the accelerating field: $\Delta f = -K \cdot E_{acc}^2$

However, in the linac of the TESLA Test Facility, the 9-cell cavities are operated in pulsed mode. In this case the mechanical properties of the cavities must be considered when modelling the time-varying detuning of the cavity. The dynamics of the cavity detuning is described by the state space equation:

$$\begin{bmatrix} \Delta\dot{\omega}_1 \\ \Delta\ddot{\omega}_1 \\ \vdots \\ \Delta\dot{\omega}_N \\ \Delta\ddot{\omega}_N \end{bmatrix} = \begin{bmatrix} 0 & 1 & \dots & 0 & 0 \\ -\omega_1^2 & -\frac{1}{\tau_1} & \dots & 0 & 0 \\ & & \vdots & & \\ 0 & 0 & \dots & 0 & 1 \\ 0 & 0 & \dots & -\omega_N^2 & -\frac{1}{\tau_N} \end{bmatrix} \cdot \begin{bmatrix} \Delta\omega_1 \\ \Delta\dot{\omega}_1 \\ \vdots \\ \Delta\omega_N \\ \Delta\dot{\omega}_N \end{bmatrix} + 2\pi \begin{bmatrix} 0 \\ -K_1\omega_1^2 \\ \vdots \\ 0 \\ -K_N\omega_N^2 \end{bmatrix} \cdot \left[V_{acc}^2 \right]$$

where $\Delta\omega_m$: detuning of mode *m*, V_{acc} : accelerating voltage, τ_m : mechanical time constant of mode *m* and K_m : Lorentz force detuning constant of mode *m*.

The total detuning is given by: $\Delta\omega = \sum \Delta\omega_m$. The typical Lorentz force detuning measured for different gradients is shown in Fig. 1.

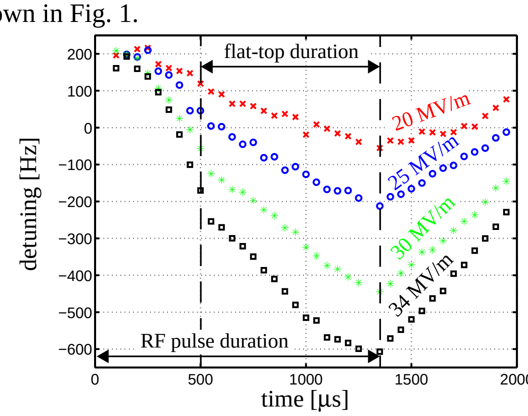

Fig. 1: Typical Lorentz force detuning during pulsed operation of a TTF 9-cell cavity at different flat-top gradients.

The time dependence of the Lorentz force detuning is almost linear during the flat-top i.e. during the beam pulse and changes by approximately +-130 Hz at 25 MV/m. It is important to note that the time-varying cavity detuning is reproduced very accurately from pulse to pulse and is only slightly (up to +-10 Hz) modulated by microphonics. The additional power needed for control is given by $\Delta P / P = 0.25 \cdot (\Delta f / f_{1/2})^2$, where $f_{1/2}$ is the half cavity bandwidth. Combined with the quadratic dependence of the cavity detuning with the accelerating field the power requirements become excessive at high gradients.

3 COMPENSATION OF LORENTZ FORCE DETUNING

The objective of the active Lorentz force compensation is achieved if the cavity detuning can be maintained constant and close to zero (<< 1 bandwidth) during the whole rf pulse or at least during the flat-top duration of 800 μs.

Compensation Mechanism

The piezotranslator (PZT) which applies a programmable time varying force to the cavity, is integral part of the motor controlled frequency tuner as shown in Fig. 2.

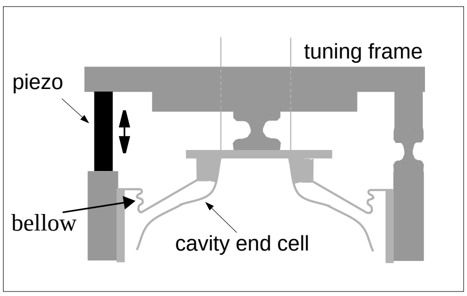

Fig.2: Experimental set-up of PZT integrated with mechanical motor driven frequency tuner.

In contrast to the Lorentz force the PZT acts only locally on the cavity walls which results in a different coupling factor to the various mechanical modes as compared to the Lorentz force. The dynamics of the frequency control of the cavity can be described as state space equation:

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du \ , D = 0$$

with cavity detuning vector x covering all contributing modes, system dynamics matrix A (nxn), input matrix B (nxm), and control input u. The measurement of the cavity detuning is given by y which is derived from the measured state using matrix C.

The system is controllable if the controllability matrix $C_0 = [B \ AB \ A^2B \ ... \ A^{n-1}B]$ which has n rows and nm columns has full rank n. This is equivalent to a linear independent finite coupling of the PZT to each relevant mechanical mode. For practical purposes the coupling factors should be of the same order of magnitude. This can always be guaranteed by use of multiple PZTs. First measurements indicate that one PZT will be sufficient for the TESLA 9-cell cavities.

Feedforward Algorithm

An adaptive feedforward scheme similar to that applied for RF control at the Tesla Test facility will be used to obtain the correction signal. The response of the detuning curve to a small step input which will be shifted in time in discrete steps will be determined and define a response matrix. This matrix can be inverted to determine the appropriate signal to the piezo actuator needed to compensate the Lorentz force detuning. Slow drifts in operating parameters require regular update of the feedforward tables.

4 PIEZOTRANSLATOR ISSUES

Piezotranslators operated at cryogenic temperatures can provide sufficient force (several 100 N) at a travel range of several μm combined with a fast response (<100 μs). Typical failure modes during pulsed operation at cryogenic temperatures include cracks resulting in electrical breakdown and subsequent electrical shortening of the piezo stacks.

Time Response of Piezotranslators

Fast response is one of the desirable features of piezo actuators. A rapid drive voltage change results in a rapid position change. A PZT can reach its nominal displacement in approximately 1/3 of the period of the resonant frequency with significant overshoot. For example, a piezo translator with a typical resonance frequency of 10 kHz can reach its nominal displacement within 30 μs. The experimental result have shown that a linear ramp with 100 μs rise time will be sufficient for the compensation of the dynamic Lorentz force detuning.

Pulsed Operation at 2 K

Traditionally piezostacks are produced by use of an elastic glue which combines many piezoelectric elements in series. This glue can become brittle at cryogenic temperatures leading to disintegration of the piezostack. Meanwhile industry has developed sintered piezostacks for operation at high frequencies and maximum stroke. A typical application for this type of PZT is the fuel injection of diesel engines implying rough environmental conditions. Tests at cryogenic temperatures will be conducted to verify that this reliability is also true at low temperatures.

Radiation Hardness

The piezotranslators will be integral part of the cavity tuning mechanism and will therefore be exposed to the γ-radiation generated by field emission in the cavities (dark currents) and occasional beam loss in the accelerator. The upper limit for the average dose rate for TESLA is dictated by the capacity of the cryogenics which can handle an additional heat load of 0.1W/m corresponding to a dose rate of 10 Gy/h. Assuming a lifetime of the accelerator of 20 years this correspond to a maximum total dose of 2 MGy. According to [2] this should not impose a problem since mild damage is expected at a total dose >100 MGy.

Integrated System Test

It is planned to evaluate the performance of the piezotranslator in a radiation environment (Co^{60} source, 1.4 kGy/h) during pulsed operation (> 100 Hz) at 77K (liquid nitrogen dewar). The fixture will contain 2 piezoelements in series were one element is pulsed at 100 Hz with a pulse structure consisting of a 100 µs ramp from -60 to +160 V, 1 ms flat-top duration followed by a 100 µs ramp from +160V to -60V. The second element is used as a sensor to detect the force created by the first element. During a 1 month test we will evaluate $2.6 \cdot 10^{10}$ pulses (at 100 Hz) comparable to almost 2 years of operation of TESLA at 5 Hz. The total does will be about 1 MGy. During the test the voltage and current to the piezo under test will be recorded as well as the signal from the second piezo used as sensor. Small deviation in current-voltage characteristics can be detected and used as an indicator of performance degradation.

5 EXPERIMENTAL RESULTS

For a proof of principle the tuning frame of a TTF 9-cell cavity has been equipped with a PZT-element, see Fig. 2. During pulsed operation of the cavity at high gradients the voltage induced in the PZT by mechanical excitation has been monitored. As shown in Fig. 3, the resonant excitation still exists at the begin of the next pulse (pulsed operation at 10 Hz). The corresponding frequency spectrum (Fig. 4) indicates mechanical resonances around 300 Hz and 450 Hz.

In the next step the piezo-element has been used as an actuator to compensate the dynamic Lorentz force detuning. The amplitude and rise time of the piezo drive signal have been adjusted to maintain the cavity on resonance within a few Hz during the whole flat-top duration of the RF pulse. A comparison of the cavity detuning with and without compensation is presented in Fig. 5. The compensation scheme has been reproducible and stable for long periods of time.

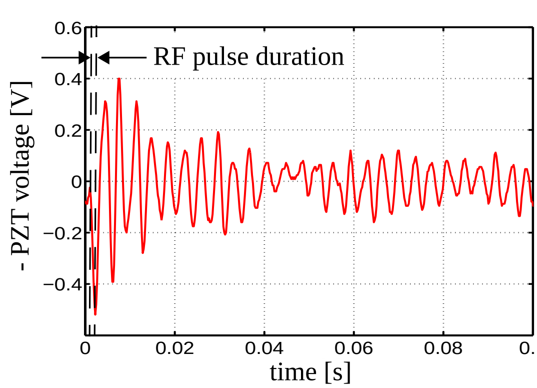

Fig. 3: Lorentz force excitation of mechanical modes during pulsed operation of a TTF 9-cell cavity, measured with the piezo-element (30 MV/m flat-top gradient 10 Hz repetition rate).

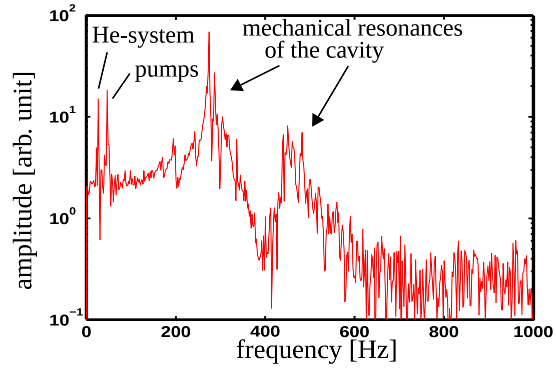

Fig. 4: Frequency spectrum of the Lorentz force excitation shown in Fig. 3.

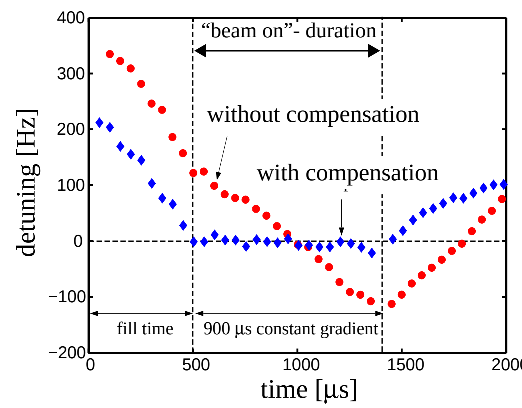

Fig. 5: Demonstration of active Lorentz force compensation with a PZT driven tuner (TTF 9-cell cavity at 23.5 MV/m flat-top gradient).

6 CONCLUSION

Initial experiments with a piezoelectric tuner have demonstrated the successful control of the cavity resonance during pulsed operation of superconducting cavities at high gradients. The measurements have shown similar coupling of the Lorentz forces and the piezoelectric tuner to the relevant mechanical modes.

The use of the PZT as a vibration sensor has been a valuable tool to study the mechanical resonances excited by Lorentz forces. Therefore we envision the combination of actuator and sensor for more detailed investigations and future resonance control designs.

REFERENCES

[1] TESLA Technical Design Report, DESY 2001-011, 2001

[2] S. Battisti et al., CERN Report 75-18, Geneva, 1975