Lorentz Force Compensation of Pulsed SRF Cavities

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Abstract

Significant progress on the issues of pulsed operation of superconducting cavities at high gradients has been made at the TESLA Test Facility at DESY. Meanwhile several pulsed accelerators under construction (SNS) or in planning (TESLA, the Joint Project JAERI/KEK, SPS) will employ this technology. Dynamic detuning of the SRF cavities due to Lorentz force induced mechanical excitation is a critical concern since the magnitude can approach the cavity bandwidth and require significant additional rf power for field control. While passive stiffening of the cavities is already applied to the cavity designs, the further reduction of the Lorentz force detuning is necessary for most projects. Presently under study at various labs is a piezotranslator based active compensation scheme for the time varying Lorentz force detuning which if successful will reduce RF power requirements considerably and provide improved field stability.

1 INTRODUCTION

Lorentz force detuning in superconducting cavities has been observed in the early years of the development of superconducting resonators for heavy ion accelerators [1] and has been studied in great detail since then. Since all of these accelerator are operating in a continuous wave mode (cw) the issue of Lorentz force detuning is only relevant during the turn-on of the cavities. Only in systems where one klystron has been driving multiple cavities (LEP) the dynamic ponderomotive instability has been observed while in systems with individual cavity control, the instability has not been observed due to sufficient feedback gain.

Table 1: Accelerators employing pulsed superconducting rf cavities

Accelerator / Parameter	TESLA/TTF	SNS	Joint Project JAERI/KEK	CONCERT	SPL
frequency [MHz]	1300	805	972	704	352
gradient [MV/m]	23.4(35)/15	10.2/	9.9/10.5	10.3/12.4	3.5/5/9/7.5
cavity beta	1	0.61/0.81	0.73/0.77	0.68/0.86	0.52/0.7/0.8/1
number of cavities / klystron	36/32	1	2	1	1/1/4/6
rf /beam pulse duration [ms]	1.4/0.95	1.17/1.04	<1.0/0.5	1.13/1.0	<4.2/2.2
repetition rate [Hz]	5/10	60	50	50	75
av. beam current in macro pulse [mA]	9.5/8.0	27.7	28	75	11
chopper on/off time [n/ns] or %	n/a	546/295(68%)	54%	360/240	40%
beam energy spread at linac end [%]	0.01	0.2	0.2 (0.1)	0.1	0.2
phase/ampl. stab. requ. [+-deg./+-%]	0.5/ 0.02 (rms)	0.5/0.5	1.0/ 1.0	0.5/ 0.5	0.5/ 0.5
loaded Q [1e6]	3/3	0.73/0.70	~0.7	0.43/0.38	2/2.5/3/2
cavity bandwidth HWHM [Hz]	220	550/500	~600	1600/1800	~60
expected microphonics [Hz] (rms)	3-7	100 (6σ)	20	100	20
Lor. force det. const. [Hz/(MV/m)^2]	1	2.9/0.7	1.6/1.4	8/4[a]	0.75[a] (β=1)
frequency (Q) of dominant mech. mode	280(20)	280/2200	122(60)[b]	40-60(100)	~100 (~40)[a]

a. assumption made for simulation
b. measured at 600 MHz

The issues of the dynamics of Lorentz force detuning came up again during the design of the pulsed linacs for the TESLA linear collider. Meanwhile the TESLA Test Facility has demonstrated the feasibility of pulsed operation of superconducting cavities at high gradients [ref]. Following the encouraging results at the TTF, several new projects employ superconducting cavities in pulsed mode [Table 1].

Despite the success at TTF, future works has to be performed in the area of very high gradients (35 MV/m for TESLA), the low beta structures with large Lorentz force detuning constants, and the possibility of exciting mechanical resonances with high quality factor. In these cases the peak cavity detuning may exceed one cavity bandwidth leading to excessive power requirements.

2 LORENTZ FORCE DETUNING

The electric and magnetic field on the cavitz surface induce small surface forces known as Lorentz forces. These pressures are proportional to the square of the surface electric and magnetic fields as:

$$P = \frac{1}{2} \cdot (\mu_0 |H|^2 - \varepsilon_0 |E|^2)$$

The forces act inward near the cell equator and outward near the cell bore. The resulting static cavity detuning is therefore propotional to the accelerating field squared:

$$\Delta f = -K \cdot E_{acc}$$

with typical Lorentz force detuning constant K of the order of a few $((MV)/m)^2$ (see table 1). The factor K depends on the mechanical stability and is directly affected by the wall thickness and the geometry of the cavity. Stiffening rings as applied to the TESLA cavities can ireduce static and dynamic detuning considerably as can be done with thermal or plasma spraying of a copper layer onto the bulk niobium cavities [ref]. This techniques are limited to a K of around 0.7 $((MV)/m)^2$ for β=1 cavities if applied with reasonable effort. Excessive stiffness would also prohibit the use of a mechanical frequency tuner.

Dynamic behavior

In the case of pulsed accelerators, the time varying Lorentz force results in a time varying cavity detuning. The situation is complicated by the fact, that the cavity as a mechanical system exhibits its own dynamics. Therefore the mechanical properties of the cavities must be considered when modelling the time-varying detuning of the cavity. While a single mechanical mode is described by:

$$\ddot{\Delta f} + \frac{\omega_m}{Q_m}\dot{\Delta f} + \omega_m \Delta f = -k_m \omega_m^2 E^2{}_{acc}$$

the total cavity detuning is described by the sum detuning of all individual modes:

$$\Delta f = \sum_{m=1}^{N} \Delta f_m$$

For control system analyses the system of second order equation is converted to the state space equation.

Power requirements

If the cavity fields - in presence of time varying Lorentz force detuning - are controlled purely by the incident wave to cavity, the generator power required is given by:

$$P_g = P_{g0}\left(1 + 0{,}25 \cdot \left(\frac{\Delta f}{f_{12}}\right)^2\right)$$

where Δf is the cavity detuning and f_{12} the cavity bandwidth (HWHM). The equation is simplified for the case of matched coupling to the beam accelerated on crest. In addition the system must be close to steady state which is the case for TESLA and SNS operation.

For one bandwidth detuning the extra power needed is 25%. Since the dynamic detuning of the TESLA cavities reaches only 2/3 of the steady state value during the flat-top, a K of 1Hz/(MV/m)^2, would lead to $\pm$1 bandwidth detuning from which only 50% occurs during the flat-top portion. For a gradient of 35 MV/m the dynamic detuning would increase by a factor of 2, demanding 4 times the extra power. This is unacceptable so that another solution must be found which reduces the peak cavity detuning.

Measurement of cavity detuning

The time varying Lorentz force detuning can be measured by operating the cavity in a self-excited loop (or a VCO system in a phase locked loop configuration) and measuring phase between cavity field and a fixed frequency oscillator (or the VCO control signal). Another approach is based on system identification where forward, reflected and probe signal are measured in open or closed loop configuration (even with beam if current and phase are known). Using a parameterized model, namely the differential equation, the time varying detuning can be extracted. A third method uses a state estimator which provides a real time update of best estimate for the cavity detuning during the rf pulse. The state estimator can be used in sophisticated control algorithms for fast control of cavity field and/or the cavity resonance frequency.

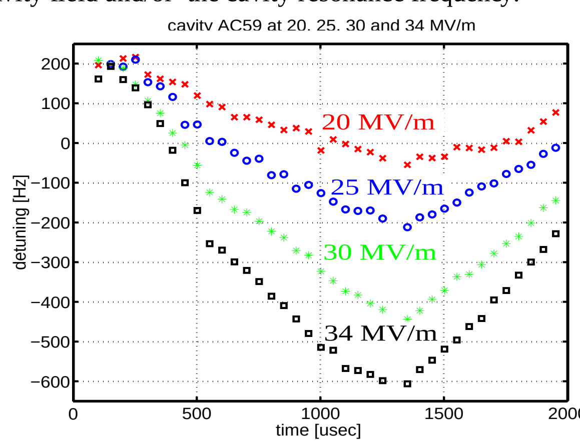

Figure 1. Detuning measured at TTF

3 ACTIVE LORENTZ FORCE COMPENSATION

The time varying detuning $\Delta f(t)$ of the superconducting cavities induced by the Lorentz force $(F(t) = -K \cdot E^2_{acc}(t))$ 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 $\Delta f_c(t) = -\Delta f(t)$. 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.

4 FEEDFORWARD CONTROL

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 actuator (piezotranslator or PZT) which applies a programmable time varying force to the cavity is integral part of the motor controlled 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 $\dot{x}$, 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 stated using matrix B.

The system is controllable if the controllability matrix $C_0 = \left[B \ AB \ A^2B \ ... \ A^{n-1}B\right]$ which has n rows and nm columns has full rank n.

Feedforward Algorithm

An adaptive feedforward scheme similar to that applied for RF control at the Tesla Test facility can 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 defines 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.

5 ACTUATOR REQUIREMENTS

Piezotranslators operated at cryogenic temperatures can provide sufficient force (several 10 N) at a travel range of several µm combined with a fast response (<100 µs). Typical failure modes during pulsed operation at cryogenic temperartures 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 at the TTF have shown that a linear ramp with 100µs 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 beome brittle at cryogenic temperatures leading to disintegration of the piezostack. Meanwhile industry has develeped sintered piezostacks for operation at high frequencies and maximum stroke. The application for the piezo actuator model from EPCOS is for the fuel injection of diesel engines implying rough environmental conditions. Tests at cryogenic temperatures will be conducted to verify this hypothesis.

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 is dictated by the capacity of the cryogenic which can handle additional 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 CERN Report 75-18 this should not impose a problem since mild damage is expected at a total dose >100 MGy.

Integrated SystemTest

The performance of the piezotranslator in a radiation environment (Co^{60} source, 1.4 kGy/h) during pulsed operation (at 100 Hz) at 77K (liquid nitrogen dewar) has been evaluated. The fixture contains 2 piezoelements in series where one element is pulsed at 100 Hz with a pulse structure consisting of a 100µs ramp from -20 to +80 V, 1 ms flat-top duration followed by a 100µs ramp from +80V to -20V. The second element is used as a sensor to detect the force created by the first sensor. During a 1 year test we have evaluated 3.1e9 pulses (at 100 Hz) comparable to almost 20 years of operation of TESLA at 5 Hz. The total does has been 4 MGy without performance degradation.

5 EXPERIMENTAL RESULTS

Meanwhile experimental results for Lorentz force detuning and compensation are available for TESLA and SNS cavities, cavities for the JAERI/KEK Joint Project, and a 500 MHz low beta cavity study for ESS.

TESLA cavities

The excitation of mechanical resonances through Lorentz force detuning and a piezo actuator has been studied at the TTF. The main group of resonances have been found around 300 Hz and 450 Hz with a Q factor close to 100. Other frequencies are excited only weakly for the standard TESLA rf pulse structure and a trapezoidal pulse on the piezo actuator as described above. The Lorentz force detuning characteristic is highly repeatable and no build-up of mechanical resonances is observed. The result of the Lorentz force compensation with a trapezoidal waveform on the piezo actuator is shown in Figure 2.

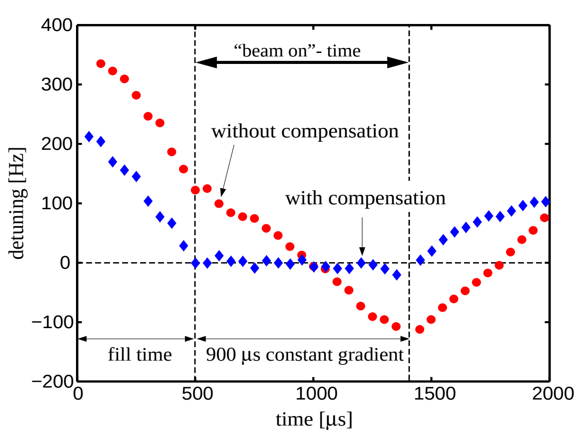

Figure 2. Lorentz force compensation at the TTF

SNS cavities

Measurements performed at an SNS (β=0.61) their main resonances excited by Lorentz force detuning around 200 Hz and 300 Hz and 2200 Hz. The coupling of Lorentz force and piezo actuator to the cavity mechanical resonances are quite different. Nevertheless a first attempt to reduce Lorenz force detuning with a piezo actuator has led to a reduction by a factor of 2 without further optimization as shown in Figure 3. Due to the repetitive nature of the Lorentz force detuning further optimization should lead to a significant improvement in error reduction.

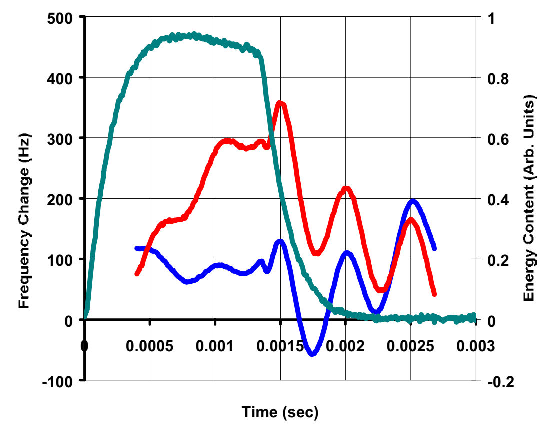

Figure 3. Lorentz force compensation at SNS cavity

6 CONCLUSION

Dynamic Lorentz force detuning as been major concern in the development of pulsed superconducting accelerator since the resulting time-varying cavity detuning can requires additional power for field control. The power can become excessive in the case a mechanical resonance enhances the detuning especially at high gradients. Meanwhile a solution has been found which makes use of a fast piezoelectric tuner to compensate the Lorentz force detuning. Several Labs have now demonstrated the successful compensation of Lorentz force detuning.

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