RF CONTROL REQUIREMENTS FOR THE CEBAF ENERGY UPGRADE CAVITIES*

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Abstract

The 6 GeV CEBAF accelerator at Jefferson Lab is arranged in a five-pass racetrack configuration, with two superconducting radio frequency (SRF) linacs joined by independent magnet transport arcs. It is planned to increase the accelerator energy to eventually support 12 GeV operations. To achieve this, a new 7-cell superconducting cavity is being built to operate at an average accelerating gradient of 12.5 MV/m with an external Q of 2.2 x 10^7. The present RF system, composed of an analog control loop driving a 5 kW klystron, will not easily support the narrower bandwidth cavities at the higher gradients. A new RF control system that may incorporate digital feedback, driving an 8 kW klystron is being proposed. In designing a system it is important to understand the control limitations imposed by the cavity, such as microphonics, Lorentz force detuning and turn-on transients. This paper discusses these limitations and the resulting design constraints for new RF controls.

1 INTRODUCTION

Jefferson Lab is in the midst of developing a new high gradient 7-cell superconducting cavity for the CEBAF and FEL upgrades. From the low-level RF (LLRF) controls perspective higher cavity gradients and cavity detuning associated with background microphonics and turn-on transients are of primary concern. This becomes especially true since the cavity field control specification for the upgrade remains essentially unchanged from the present stringent requirements of 0.13^o and 1.1x10^{-5}, rms phase and amplitude errors respectively. Balancing this is the operational concern of achieving maximum acceleration with as little drive power as possible. By analyzing the needed drive power with the cavity Q_{ext} the optimal Q_{ext} has been determined. The new 7-cell cavity has a higher Q_{ext}, which implies a smaller cavity bandwidth making the cavity more susceptible to microphonic, and Lorentz force detuning. Passive methods and structural additions have been proposed to stiffen the cavities and minimize microphonics and Lorentz detuning. Unfortunately, the extent to which cavity/cryomodule designers can control these effects by adding mechanical stiffening can become impractical because of the implications on the requirements for the mechanical system needed to tune the cavity. Ultimately the solution is to use electronic means to control the microphonics and turn-on transients.

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2 POWER REQUIREMENTS

The power requirements are dictated by the energy content of the cavity at the operating gradient, the power to be transferred to the beam, and the maximum amount of detuning at which the cavity will be able to operate and still maintain phase and amplitude lock. Figure 1 shows the forward RF power at design gradient and beam current as a function of Q_{ext} for several amount of detuning. For an assumed maximum detuning of 25 Hz, the optimal Q_{ext} is 2.2 x 10^7.

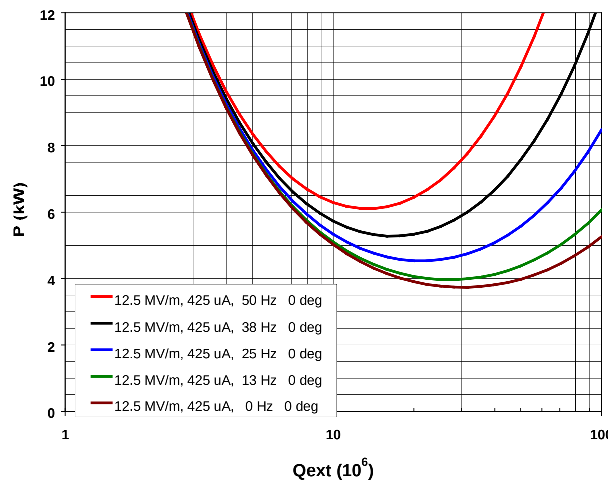

Figure 1. Forward RF power as a function of Q_{ext} at the design operating parameters of the 7-cell cavity for several amount of detuning.

The present CEBAF 5 kW klystrons have been reliably operated at 8 kW using a slightly higher cathode voltage. For the new cavities it is Jefferson Lab's intention to purchase these tubes with a more robust collector and increase the power supply voltage.

3 RESONANCE CONTROL

Because of the high Q_{ext} and small bandwidth, increased constraints are also being placed on the resonance control. The maximum allowable detuning includes a dynamic part (microphonics) and a static or slow-varying part (drift of the average cavity frequency). The latter implies that the average cavity frequency needs to be controlled to 1 to 2 Hz. This will be accomplished by a dual mechanical-piezoelectric system. The coarse mechanical tuner, driven by a stepper motor located outside of the cryomodule similar to what is done presently, will allow tuning to within 5 to 10 Hz of resonance. This mechanical system will be run infrequently. The piezoelectric tuner, with a range of 1 kHz, will allow the cavities to be continuously tuned to within 1 Hz of resonance while operating. Continuous operation of the mechanical tuner is a feature of the present CEBAF system; however the bandwidth is much larger and the tuner-induced microphonics have not been an issue.

4 PRESENT LLRF

The present LLRF system was designed for gradients of 5 MV/m and a Q_{ext} of 6.6 x 10^6 [1]. It uses a traditional analog phase and amplitude controller. It has an open loop bandwidth of 1 MHz with close in (< 200 Hz) loop gain boost for the cavity microphonics (both phase and amplitude). Amplitude control is accomplished with a fast analog multiplier. Phase control uses an analog vector modulator that also provides additional amplitude control. A limitation of the phase control is its inherent control range of +/- 45^o. This is not presently a problem with the 5-cell cavities because rarely do we operate in an area that the Lorentz force or microphonics detunes the cavity beyond a bandwidth. For the 7-cell cavity the operational environment is quite different and the present LLRF system will not control these cavities at design gradient without extensive modification.

The new 7-cell cavity will have an average accelerating gradient of 12.5 MV/m and have a Q_{ext} of 2.2 x 10^7. This implies a rather narrow cavity bandwidth of ~75 Hz. Considering operational gradients in excess of 12 MV/m, the Lorentz detuning at turn-on alone will pose a problem for the present LLRF controller. Solutions such as a gradient ramp at turn-on using a fast (~100 Hz) tuner have been considered. In addition, there is a question of stability (with our present phase amplitude controls) when the resonance folds over under the Lorentz detuning and the system becomes multi-valued. Lastly there is no easy way to integrate the piezoelectric (fast) tuner into the present LLRF system.

5 CAVITY MICROPHONICS

Cavity microphonics are one of the most important aspects that one needs to consider for field control of a superconducting cavity. The level of microphonics and the cavity Q_{ext} ultimately will drive the amount of loop gain needed to meet the field control specification. The microphonics, along with resonance control, also drive the amount of amplifier power needed to control the cavity, which should be kept to a minimum.

The 5-cell CEBAF cavities have an rms microphonic detuning of ~ 2Hz and a peak-to-peak average of 20 Hz. Depending on cavity location within the machine this can vary a small amount. Some cryomodules seem noisier than others, and in certain cases vibrations have been driven by vacuum pumps.

Recently a 7-cell cavity was tested in the Jefferson Lab cryomodule test facility. Figure 2 shows the measured microphonic background of the 7-cell cavity. The observed cavity microphonics were 2 Hz rms and 25 Hz peak-to-peak. The frequency component at 33.7 Hz is a real cavity mechanical resonance while the higher frequency component at 54.7 Hz is believed to be from a cryogenic pump. This is comparable to the 5-cell cavity but the impact of the higher Q_{ext} will increase the amount of loop gain needed to control the field.

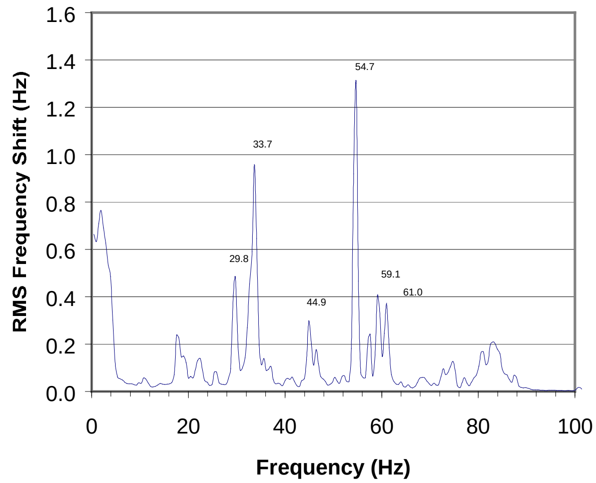

Figure 2. Actual 7-cell cavity microphonics baseline.

The results of this test are encouraging but more extensive tests are needed with the final cryomodule design to verify the level of the microphonics.

6 LORENTZ DETUNING & STABILITY

A concern with increasing the gradient in a superconducting cavity is the effect of the Lorentz detuning. The Lorentz force shifts the resonance frequency of the cavity by $\Delta f = K V_c^2$, where K is typically ~ 2 for unstiffened elliptical cavities (it can vary anywhere from 1.5 to 3 in CEBAF). Applying this to the cavity transfer function results in a folding of the curve as the gradient is increased. Figure 3 shows the expected resonance curve for the 7-cell cavity at design gradient and for a typical 5-cell cavity operating in CEBAF. The folding can lead to what is known as the monotonic ponderomotive instability, [2,3] which has been a common feature in cavities for low-velocity, low-current beams and also for some high-Q_{ext} elliptical cavities. This has been dealt with effectively by electronic control [4-7].

An additional constraint placed on any LLRF system is the Lorentz detuning of the cavity at turn-on. If the Lorentz detuning is beyond a bandwidth, a traditional phase and amplitude system or an I&Q system may have trouble-reaching gradient without some fast tuner or slow gradient ramp (slow enough for the tuner to track the Lorentz detuning).

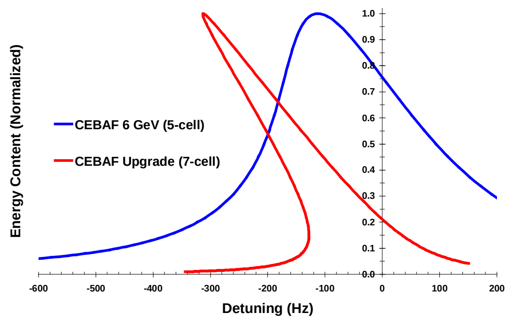

Figure 3. Resonance curves for a typical 5-cell cavity operating in CEBAF at 7.5 MV/m and Q_{ext} of 5 x 10^6 and for the 7-cell upgrade cavity at design gradient of 12.5 MV/m and Q_{ext} of 2.2 x 10^7.

Comparing the Lorentz detuning of the 5-cell cavity at 5 MV/m, which is a ¼ of a bandwidth to the new 7-cell cavities at 12.5 MV/m, which is 4 bandwidths, it is easy to see the difficulty the LLRF might have at turn-on. The brute force method would use the amplifier power to compensate for the detuning. As shown in Figure 4, this requires considerably more power to reach design gradient than is needed to operate at that gradient. Some gradient ramp-up with a tracking tuner would be desirable in this last case. In the case of a large installation of superconducting cavities, however, this method of slowly ramping the gradient and tracking the frequency after an RF trip could substantially reduce beam delivery time.

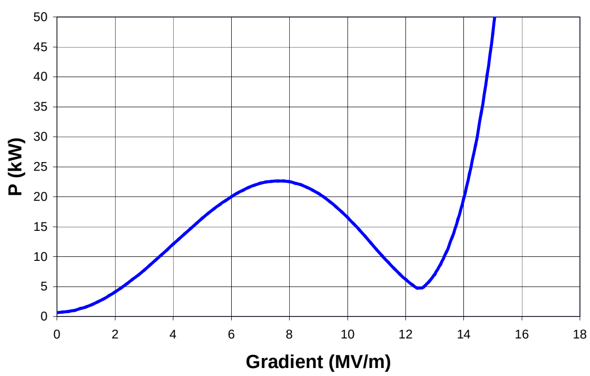

Figure 4. RF power as a function of gradient for the design parameters of the 7-cell cavity. The cavity frequency has been tuned so the cavity will be on resonance at operating field.

6 SUMMARY

In order to achieve the CEBAF upgrade goal of 12 GeV a new 7-cell cavity and cryomodule are under development. This goal can be achieved only if the cavities can be stabilized at operating gradient by the LLRF control system. The present LLRF control is over 10 years old and relies on many obsolete components. In addition, given the new requirements it would be costly to modify the present LLRF system to allow it to reach the gradients the new 7-cell cavities are capable.

The requirements are challenging. The upgraded LLRF will have to be able to control the cavity to ~1 Hz of resonance in order to keep the power requirements reasonable. The microphonic effects will be higher than in the present cavities due to the higher Q_{ext} and hence smaller cavity bandwidth. Finally the turn-on transients, most notably the Lorentz detuning, will move the resonance more than few bandwidths making field control difficult.

All these problems can be alleviated by the use of self-excited loops (SEL), which has been the common method of controlling high-Q_{ext} cavities in the past, and we expect the LLRF upgrade to use this method. The CEBAF upgrade will bring a new feature that has not been present until now: while the beam loading will not be dominant, as it is at present in CEBAF, neither will it be negligible, as it is in other low-current accelerators using SEL. This intermediate region is the most interesting, and challenging, and has already been investigated analytically [8].

Presently Jefferson Lab is completing the top-level requirements for the upgraded LLRF system. We plan to begin conceptual design and prototyping of a digital LLRF system in the next year.

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