RF CONTROL OF HIGH Q_L SUPERCONDUCTING CAVITIES*

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Abstract

In the last 20 years the requirements for RF Control have increased as the target use has broadened from electron/ion accelerators for Nuclear and Particle Physics to light sources such as Free Electron Lasers. The increasing requirement of cavity field control to meet the spectral and jitter performance specifications for light sources has led system designers to a more rigorous approach in designing the RF controls. Design attention must be applied not only to the hardware and control algorithms but also to the overall accelerating system to meet performance and cost requirements. As an example, cavity Q_L in Energy Recovery Linacs (ERL) must be optimized such that the RF controls can accommodate the lowest possible RF power given the background cavity microphonics. This paper presents the status and future directions of high Q_L superconducting RF control systems.

INTRODUCTION

Recent proposals for energy recovering linacs (ERLs) at Cornell, Daresbury and Argonne have challenged the RF community to meet the field control requirements of the higher Q_L cavities. It should be noted the operation of high Q_L cavities is not new. Superconducting (sc) accelerating structures such as the types used in proton and ion accelerators have always operated with $Q_L > 10^7$. The difference is that beam requirements to meet the optical frequencies and line widths require them to be on the order of < 0.1° and 10^{-4} amplitude stability. Some of the techniques (Self Excited Loop) for operating these cavities can be applied to the ERLs. In addition to field control sc cavities can have large Lorentz coefficients making turn on or cavity recovery difficult. Fortunately, advances in electronics have made developing and designing RF control systems easier, where the designs have shifted from fairly rigid analog-centric hardware 20 years ago to a more flexible digital-centric software design.

RF control design starts at the beginning of the accelerator design. Depending on the application, energy spread and jitter specifications will directly correlate to the required cavity field control. Once this is known, the designer can begin modeling the receiver and feedback necessary to meet the field control requirement. Next, one must optimize the cavity Q_L for the application. If the Linac is pulsed, some form of Lorentz detuning compensation must be considered. Other control considerations include: multiple cavity control (i.e. vector sum) vs. single cavity control and Generator Driven Resonator (GDR) vs. Self Excited Loop (SEL).

OPTIMIZING CAVITY Q_L

The RF system must be optimized for minimum power which ultimately sets the cavities loaded Q. The optimum coupling (β_{opt}) to a cavity can be derived from the steady state cavity equations and is given by

$$\beta_{opt} = \sqrt{(b+1)^2 + \left[\frac{2\delta f}{\Delta f_o}\right]^2} \qquad (1)$$

$$\text{where} \quad b = \frac{I_o (R/Q) Q_o}{V} \cos\phi$$

V is the cavity voltage, I_o is beam current, R/Q is the shunt impedance, Q_o is the cavity quality factor, ϕ is the beam phase, f_o is the cavity frequency, δf is the cavity detuning, and Δf_o is the cavity bandwidth [1]. In the limit where the $Q_o >> Q_L$, one can make the approximation that $\beta \sim Q_o/Q_L$. In the case of a heavy beam loaded cavity such as one might find in an injector, the optimized loaded Q is driven by beam loading (i.e. $b >> 1$) and eq. (1) reduces to

$$Q_{Lopt} \cong V / I_o (R/Q) \qquad (2)$$

In the case of an ERL where the vector sum of the two beams results in a net current that is less than a few tens of micro-amps, there is an incentive to increase the Q_L [2]. Q_L is limited by the amount of microphonic detuning the cavity exhibits under normal operating conditions (i.e. $2\delta f/\Delta f_o >> b+1$). In this case Q_{Lopt} is given by

$$Q_{Lopt} \cong f_o / 2\delta f \qquad (3)$$

Figure 1 shows the optimizations on generator power for different beam loads.

If the cavity power requirement is driven by the microphonics, some consideration to cavity stiffening is necessary. At Jefferson Lab, we have operated both stiffened and un-stiffened cavities. The stiffening rings can have an effect on roughly similar cell shapes. Table 1 shows the microphonic detuning of elliptical cavities with and without stiffening. Included in the table is the klystron power required for the Q_{Lopt} given the 6σ microphonic detuning.

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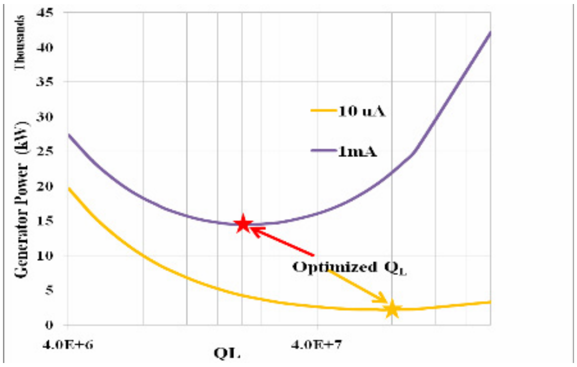


Figure 1: Forward power at 10 Hz detuning for a non-beam loaded and beam loaded sc cavity operating at 20 MV/m.

In the case of an ERL with complete energy recovery and improved microphonic damping, it may be possible to optimize the power to below 1 kW. For large installations (100+ cavities) where it is not beam current driven there is an incentive to keep the klystron power low for energy savings.

Table 1: Microphonic Detuning

Microphonic Detuning	Renascence	C100 (Upgrade)
RMS (Hz)	1.98	3.65
6 σ (Hz)	11.9	21.9
Stiffened	Yes	No
Power$_{OPT}$ (20 MV/m and 100 μA)	3.3 kW	5.3 kW

LORENTZ DETUNING

A concern with the increasing gradient and Q_L in a superconducting cavity is the effect of the Lorentz detuning. Lorentz detuning is caused by the radiation pressure exerted on the cavity walls by an electromagnetic wave. The Lorentz force shifts the resonance frequency of the cavity by $\Delta f = -K E_c^2$, where the Lorentz coefficient, K, is typically ~ 2 for un-stiffened 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 2 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, which has been a common feature in cavities for low-velocity, low-current beams and also for some high Q_L elliptical cavities [4, 5]. This can be dealt with effectively by electronic control.

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 control system may have trouble reaching gradient without some fast tuner or slow gradient ramp (slow enough for the tuner to track the Lorentz detuning). In CW accelerators where the cavities trip off on the occasional arc or vacuum event, the system cannot always rely on electronic feedback (klystron power) to compensate for the turn on transient. An example of how large this detuning can be is the CEBAF 12 GeV upgrade cavities. They have a typical Lorentz detuning value, K, of ~ 2. At the required gradient of 20 MV/m this leads to a detuning of 800 Hz. Coupled with the large Q_L (3.3×10^7), this is 18 bandwidths away!

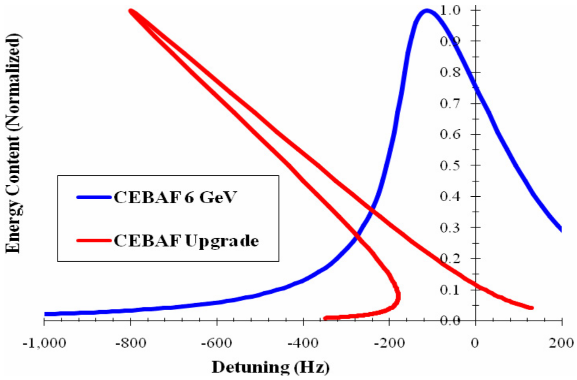


Figure 2: Resonance curves for a typical 5-cell cavity operating in CEBAF at 7.5 MV/m and Q_L of 5×10^6 and for the 7-cell upgrade cavity at design gradient of 20 MV/m and Q_L of 2.2×10^7.

RF MODEL

Once the acceleration system (RF amplifier, distribution, and cavity) is specified, the RF control system can be modeled for the application. More often than not, control system models use Matlab/Simulink. At Jefferson lab we used a simple dc model. In this case the complex cavity representation as well as beam is simplified to quadrature components. The cavity can then be described by a low pass filter. Lorentz Force detuning, microphonics and tuners are incorporated as frequency modulators [6]. In addition to Jefferson Lab very good models exist for the cavity control [7, 8]. Whether to model in I and Q or phase and amplitude must be chosen and each has their advantages. While one can investigate many control algorithms (and they have), the simple Proportional, Integral, Derivative (PID) controller is often sufficient. From the background microphonics and required cavity field control, the feedback gain can be determined. This will drive the system latency (delay) requirement. Knowing that the klystron and distribution delay is set for the system, the only flexibility is in the signal processing and control algorithm.

CAVITY CONTROL ALGORITHMS

There are two control algorithms now employed in high Q_L operation; Generator Driven Resonator (GDR) and Self Excited Loop (SEL). In the case of the GDR, an external source drives the cavity, and control is maintained by comparing phase and amplitude to a reference. The cavity must be kept near the source frequency (within a few Hz) to keep the drive amplifier from saturating. Field control can be maintained using I and Q or its transformed companion, phase and amplitude. Presently CEBAF (old systems), XFEL, SNS and the proposed Cornell ERL use or intend to use the GDR method [2]. The advantage is that for pulsed systems the cavities are at a defined phase. GDR's are conceptually a traditional feedback system and therefore easier to model. Disadvantages are the cavity needs to be near resonance, and the system requires an automated search feature to find a detuned cavity.

An SEL uses the cavities own resonance in the same way an oscillator uses a tank circuit [5]. In this way it naturally tracks the cavity frequency (see Figure 3). Amplitude control is obtained by limiting the feedback amplitude, and then, providing an external set point which can be compared to the cavity signal. The circuit can be phase-locked to a reference (near the cavity frequency) by comparing the cavity signal to the reference. Optimally, for RF power reasons, this is less than half a cavity bandwidth. Heavy ion and electron accelerators have used analog versions of the SEL successfully for many years. The advantages for the SEL is that it can quickly energize a cavity regardless of frequency, which is useful at turn on where the Lorentz detuning can be large, minimizes or eliminating the need to use PZT devices on start up. The disadvantage is that for pulsed systems phase is arbitrary until locked to the reference. For cw machines this is not an issue, and the SEL should be considered for cavity recovery.

Digital Self Excited Loop

At Jefferson Lab, we have developed a Digital SEL algorithm that can be configured in a modern FPGA based RF control system [9]. The idea of building a digital SEL has been around for some years. The Jefferson Lab system fully incorporates the SEL algorithm in a digital format. All algorithmic processing occurs at a multiple of the clock frequency, 56 MHz. Figure 4 shows a block diagram of the control logic. The control logic can be switched quickly, and various operational modes can be obtained (tone, SEL, and GDR).

The SEL algorithm was tested on numerous sc cavities including the 12 GeV upgrade cavity. In SEL mode, the system quickly (~ 10 ms) found (off to on) the cavity resonance with cavities detuned as much as 50 kHz away from the reference. The effective capture range of the SEL is only limited by the receivers digital filtering (typically > 100 kHz). Field control has been tested with both a microphonic compensation scheme and with traditional proportional feedback. Turning on the compensator and adjusting the proportional gain allowed us to reduce the phase error from 0.75^{o} rms to 0.11^{o} rms error. The utility of the digital SEL has not yet been fully realized. At the higher gradients (+20 MV/m) like those needed for future cw electron LINACs, the Lorentz detuning makes cavity turn-on (fault recovery) problematic without some tuner based compensation or other algorithmic solution. The digital SEL solves this problem.

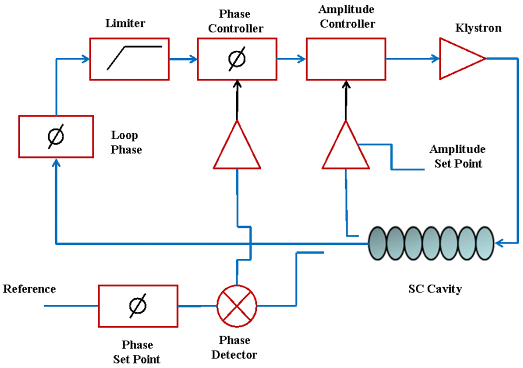


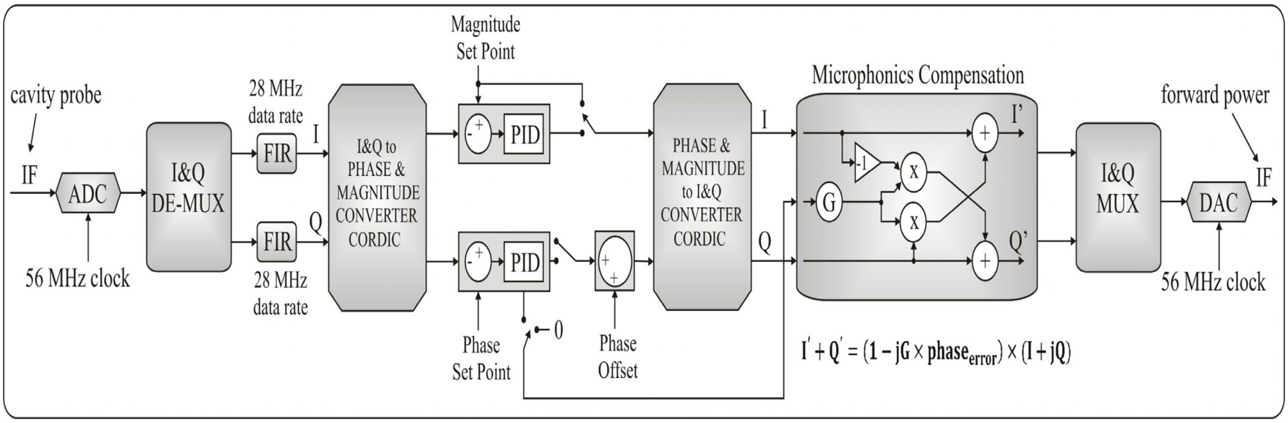
Figure 3: SEL block diagram.

RF CONTROL HARDWARE

As has been presented in prior conferences, RF control has been simplified in the last 10 years to an embedded algorithm in a processor or a Field Programmable Gate Array (FPGA) [10]. The flexibility of having the algorithm programmed in the logic or software and being able to reconfigure quickly is a very desirable feature. Typical hardware consists of an RF receiver using a super heterodyne scheme (frequency mixer) to down convert the cavity signal down to a manageable intermediate frequency (IF). IF's are typically between 10 and 100 MHz. This is driven by the ADC's degrading S/N as the clock is increased. The IF is then digitized using a fast ADC clocked at quadrature (or near quadrature). A large FPGA then performs the necessary digital signal processing, and finally a control algorithm is applied to the signal. The feed forward portion is then processed similarly through a fast DAC, up converted through a mixer, applied to a power amplifier and finally driving the cavity.

Depending on the application, the basic system can take on various forms. For high Q_L cw systems such as ERLs and nuclear physics accelerators, needed field control dictates one cavity/amplifier. In the case of the ILC or FLASH, where the footprint is multiple cavities/power amplifier, the receiver needs to have multiple cavity receiver channels [11].

Overall field control is ultimately determined by the front end receiver (mixer/LO, amplifiers, ADC/clock) and the reference jitter. This assumes delay and gain bandwidth are such that they do not interfere with the feedback controls. Figure 5 shows a receiver block diagram with pertinent information (S/N, Linearity) of the CEBAF Upgrade RF receiver. The selection of linear components (mixer, amplifiers) also plays into the design. Components that contribute to distortion can affect field control, especially if designing over a large gradient dynamic range. Amplitude control is driven by the cavities residual amplitude error requirement (~ 10^{-4} for light sources). Therefore the S/N must be better than this over the control bandwidth. It is possible to improve upon S/N digitally with processing gain (i.e. oversampling), but at the expense of either gain or stability margin [12].



$$I' + Q' = (1 - jG \times \mathrm{phase}_{error}) \times (I + jQ)$$

Figure 4: SEL algorithm logic block diagram.

Figure 6 shows the amplitude error of a digital receiver (14 bit) while controlling a superconducting cavity. In this case the receiver's S/N (Fig. 5.) has been improved by large over sampling (i.e. the receivers quantization noise has been improved by oversampling ~ $N^{1/2}$).

Cavity phase error largely depends on the reference jitter (phase noise), receiver components (mixer, amplifiers), the ADC aperture jitter, the PC board level clock/distribution, and loop gains [13, 14]. Therefore, the system needs to have a jitter budget from the master oscillator to the RF controller and ultimately to the beam. Clock circuitry and designing circuit boards to minimize sources of jitter is critical to meet the demands of light sources (< 0.1° residual phase noise). AM to PM contributions (component nonlinearities) can add to the phase uncertainty and some thought should be given to choosing linear receiver components. In addition, one can also use near quadrature sampling to improve the ADC linearity [15]

Digital Signal Processing

With the conversion to all digital systems, signal processing becomes a large focus of the design. Modern digital communications has put filter, receiver designs, and DSP tricks at our finger tips. A typical front end receiver would consist of the I and Q muxing logic, followed by a digital filter such as a Cascaded-Integrator Comb (CIC) filter. Other filters and decimation may be added depending on the application. The feedback algorithm at this point is embedded in the process. Finally the output I and Q stream is demuxed and then applied to a DAC.

As simple as it sounds, it does require some thought. The latency between the ADC and DAC is really the only flexibility a designer has in the feedback. Sloppy, inefficient logic or poor filter choice can reduce the system stability by increased latency. Fortunately, FPGA tools can help synthesize and test the design.

Excitation of another cavity pass-band mode has always plagued RF control systems. In some cases the modes can be 1 MHz or less away from the accelerating mode. The made-to-order solution is a digital filter. One can potentially use creative ways of a digital filter's null to eliminate the need for a separate filter.

Resonance Control

A subset of field control is the control of the cavities resonance frequency. In High Q_L cavities, it is extremely important to keep the cavity near resonance (< ½ bandwidth). The RF system is optimized such that the power amplifier operates with a limited amount

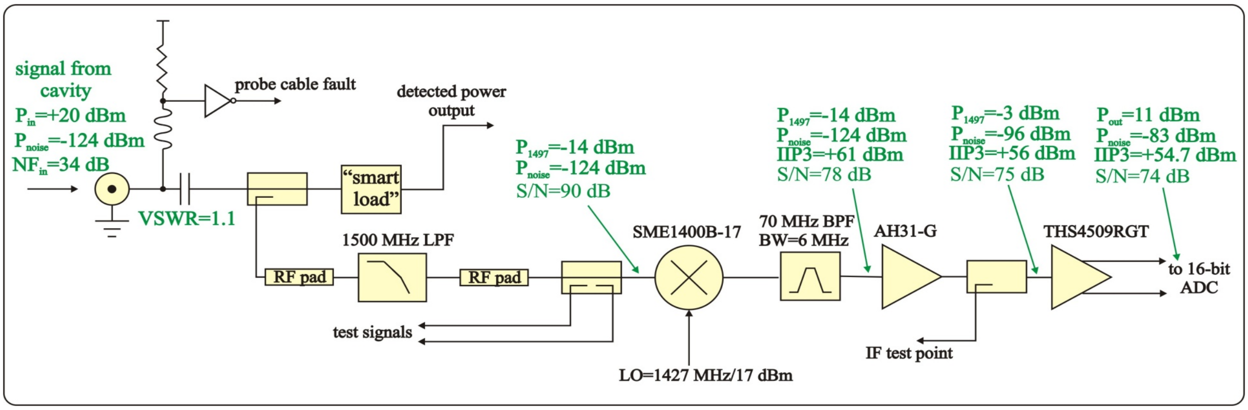


Figure 5: CEBAF upgrade receiver.

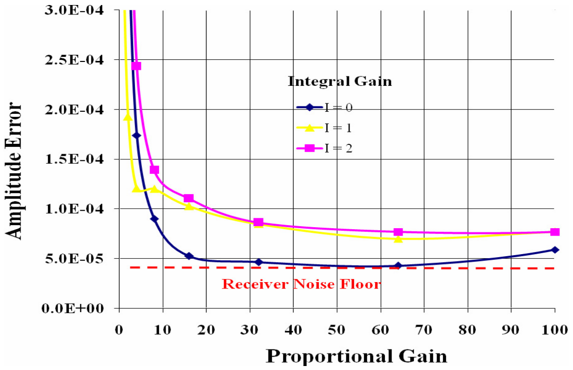


Figure 6: Measured amplitude error vs. proportional gain for a digital receiver (14 bit).

of control margin. In addition to the cw case, the pulsed (or during cavity recovery) system must account for Lorentz detuning. At the extreme, the detuning can be over 18 bandwidths between 0 and full gradient. For a pulsed accelerator to be practical, it needs a fast tuner to compensate for Lorentz detuning. Typically an accelerator will utilize both a slow and fast tuner. Some form (the actual mechanical mechanism can vary) of stepper motor is used. The CEBAF cryomodules have continuously used stepper motors for over 15 years with minimal down time. In this application, with Q_L's ~ 6x10^6 and average gradients around 7 MV/m, Lorentz effects on cavity recovery are small and can be handled by the klystron overhead.

For fast-finer control stepper motors are not adequate. For this, the accelerator community has turned to piezoelectric devices for tuning (PZT). The industrial utilization for Piezo devices is large, with many finding their way into fuel injectors and copiers/printers. PZT's were successfully demonstrated at DESY supporting the TESLA project [16]. In this application, the PZT was compensating the Lorentz detuning during each pulse. For the CEBAF upgrade, PZT's are intended to reduce detuning fluctuations due to He pressure in the cryo system. In addition to CEBAF, PZT's have been installed in the production cavities of the SNS [17] and are planned for the ILC and XFEL [11].

SUMMARY

Operation of the next generation high Q_L superconducting cavities will require precise RF control. The LLRF community has by in large answered this challenge using commercial solutions (modern digital receiver technology, Piezoelectric devices etc.) and novel methods (Digital Signal Processing) to meet the requirements. As more accelerators come on line, new control challenges, we are only now beginning to understand, such as ERLs with incomplete energy recovery [18] and light sources with tighter field control specifications, will have to be addressed. Given the flexibility of the digital RF systems, this will only be an increase in RF power and an algorithm change in the logic!

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