RADIO FREQUENCY CONTROL SYSTEM FOR SUPERCONDUCTING CAVITIES

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Abstract

For beam energy stability, it is important to maintain very stable RF fields in the accelerating superconducting cavities. Field perturbations can be caused by either Lorentz-force detuning or microphonics [1]. A digital RF control system can be put into place to counterbalance these perturbations caused by the changes in the resonant frequency.

INTRODUCTION

A digital RF control system is being developed for Cornell's Energy Recovery Linear–accelerator (ERL). The new digital RF control system is based on a previous generation of control system, which was developed for stabilizing the RF fields in the SRF cavities of the CESR accelerator [2].

With the new RF system, all measurements, calculations, and adjustments are done digitally. The new system is able to quickly and accurately compensate for the field perturbations caused by microphonics and Lorentz-force detuning.

EFFECTS OF LORENTZ-FORCE DETUNING AND MICROPHONICS

Lorentz-force detuning and microphonics change in the cavity's resonant frequency and thereby perturb the RF field in the cavity.

As the field begins to build within the cavity, a force begins to 'pull' and 'push' on the walls of the cavities. These forces are strong enough to deform the shape of the cavity on a nm scale, thereby shifting the resonant frequency of the cavity by many Hz. This is known as Lorentz-force detuning.

Mechanical vibrations in the environment of the cavity can transfer to the cavity and change its resonant frequency. This effect is called cavity microphonics. Several paths exist for the transfer of vibrations to the cavity. Figure 1 displays a several examples of the sources of microphonics and how the vibrations get transferred to the cavity [1].

For the design of the RF and RF control system of a cavity, it is crucial to explore the effects of microphonics and Lorentz-force detuning. It is important to understand up to what levels of both microphonics and Lorentz-force detuning can be handled.

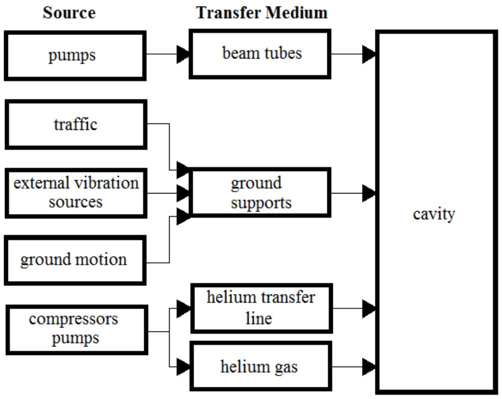

Figure 1: Sources of microphonics and how the vibrations are transferred to the cavity. For example, microphonics caused by traffic is transferred to the cavity through the ground and building supports.

As the loaded quality factor of the cavity increases, its bandwidth decreases. Therefore, the sensitivity for changes in the cavity frequency increases as the quality factor increases. This conclusion can be made based on the following equations [3]:

$$E = \frac{C}{\sqrt{1+\left(\frac{\Delta f}{f_{1/2}}\right)^2}} \quad ,$$

where E is the accelerating electric field amplitude, C is any constant, Δf is the change in frequency which can be found by $\Delta f = f - f_0$. f is the cavity resonance frequency and f_0 is the reference RF frequency, at which the cavity is driven. In the case of this system, the reference signal is 1.3GHz. $f_{1/2}$ is the half bandwidth, which is found from $f_{1/2} = \frac{f_0}{2Q_{load}}$. Q_{load} is the loaded quality factor of the cavity. In the case of the ERL system, Q_{load} is $6.5\text{x}10^7$.

When microphonics or Lorentz-force detuning is introduced to the cavity, the resonance frequency of the cavity becomes time dependent. If the cavity is driven off-resonance ($|\Delta f| > 0.$), more RF power is required to establish a given accelerating field E in the cavity. If the level of microphonics or Lorentz-force detuning is too large, the maximum RF power available to operate the cavity is reached, and the accelerating field in the cavity can no longer be kept constant.

Through a Matlab code, it is possible to predict what levels of microphonics and Lorentz-force detuning can be compensated for by the control system with a limit in RF dive power of 5 kW.

Figure 3 to 5 display the effects of microphonics on a cavity while Lorentz-force detuning is also occurring. The frequency of microphonics is set to 100Hz while the amplitude of the microphonics is changed. These simulations include modeling the feedback control by the digital control system to stabilize the accelerating field.

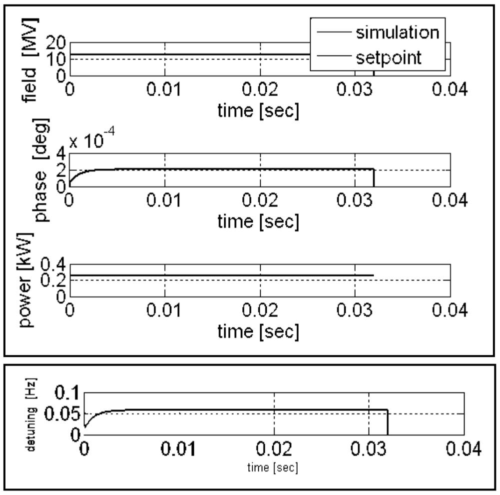

Figure 2: The above series of graphs displays what is happening to the cavity field, cavity RF phase, RF power, and detuning of the cavity with 0Hz of microphonics. The field, phase and power are stable.

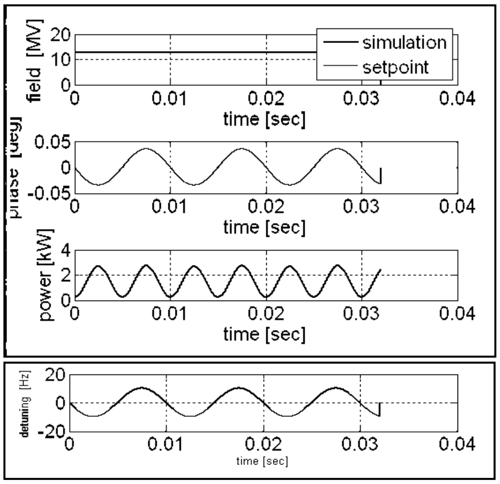

Figure 3: The effect that 10Hz of microphonics amplitude has on the cavity field, cavity RF phase, RF power and detuning of the cavity. While the power and phase begin to oscillate, the field remains relatively stable.

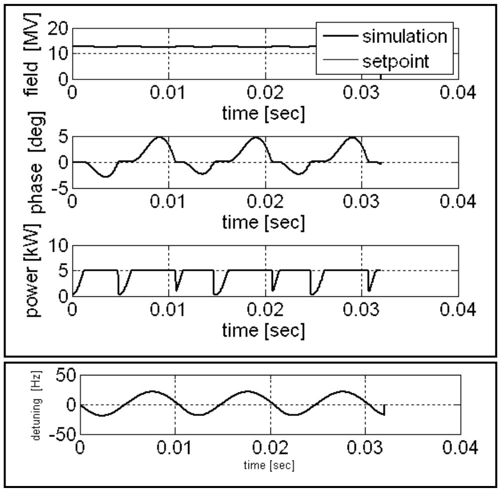

Figure 4: The effect that 10Hz of microphonics amplitude has on the cavity field, cavity RF phase, RF power and detuning of the cavity. The power is beginning to reach its maximum, and the phase begins to fluctuate more strongly. However, the field amplitude is still relatively stable.

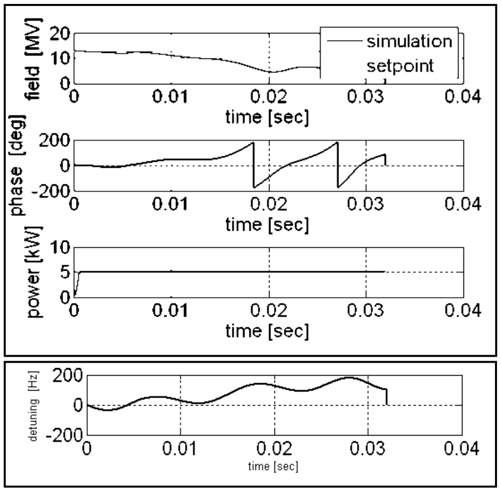

Figure 5: At 40Hz of microphonics, the RF power is no longer sufficient to maintain the cavity field.

These simulations assume that the microphonics is caused by constant source of vibration (i.e. a pump working). The simulations show that for the cavity and RF parameters chosen, detuning amplitudes below 20 Hz can be compensated for. If the detuning reaches values above 20 Hz, even for a short time, constant RF field can no longer be maintained since only insufficient RF power is available. The RF system needs to be designed such that sufficient RF power is installed with a realistic safety factor to support cavity operation during maximum level of detuning encountered.

DIGITAL RF CONTROL SYSTEM

The RF and RF control system consists our of several components: master oscillator, RF synthesizer, vector modulator, high power amplifier (HPA), circulator, waveguide, superconducting cavity, mixer, RF load, DSP board, RF monitor and interlock and the LVDS timing device. Figure 6 shows a block diagram of the system.

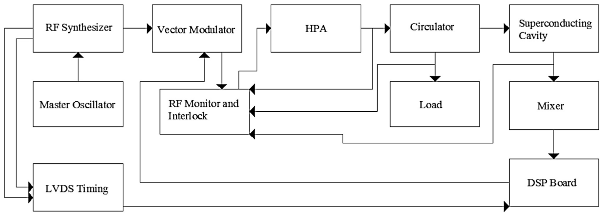

Figure 6: A block layout of the ERL RF system. The arrows indicate the direction the signal is travelling, starting at the master oscillator. Even though the waveguide is not shown in this diagram, it is a crucial component of the system and is explained later on.

The RF system is broken into two parts: components inside of the control rack and components outside of the rack.

INSIDE THE CONTROL RACK

Figure 7 illustrates the layout of the control rack. The lines drawn between components shows how each element is connected to the next.

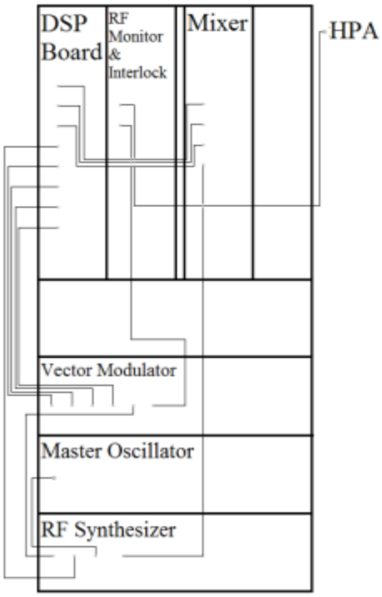

Figure 7: A block layout of the control rack. The lines represent the cables that connect the components together.

The contents of the control tower include: master oscillator, RF synthesizer, vector modulator, RF monitor and interlock, DSP Board and LVDS timing device.

Master Oscillator

The *Master Oscillator* creates and sends a 1.3GHz reference signal to the *Radio Frequency (RF) Synthesizer.*

RF Synthesizer

The *RF Synthesizer* receives the 1.3GHz reference signal from the *Master Oscillator.* The *RF Synthesizer* references this signal and creates four phase locked signals from it. A 1.3GHz signal is sent to the *Vector Modulator*, a 1.2875GHz signal is sent to the *Mixer.* Two signals are sent to the *LVDS Timing* device. One signal is at 12.5MHz and the second is at 50MHz.

Because all four signals are created from one reference signal, the signals are phase locked to one another. This is crucial in achieving a stable RF phase of the accelerating field of the cavity with respect to the reference signal and the pulsed particle beam to be accelerated.

Vector Modulator:

The *Vector Modulator* receives the 1.3GHz signal from the *RF Synthesizer,* modifies it in amplitude and phase, and then passes it on to the *RF monitor and interlock.*

The digital controller running on the *DSP Board* generates analog control signals (refer to Figure 6) to adjusted the output signal from *Vector Modulator* in amplitude and phase. The control of amplitude and phase is done by adjusting the so-called I and Q components of the RF field vector (IQ control).

Mixer

The Mixer takes the 1.2875GHz signal from the RF Synthesizer and multiplies it with one of the RF signals from the cavity: a probe signal of the RF power sent to the cavity (forward power), a probe signal of the power reflected by the cavity (reflected power) and the power picked up from the cavity, (transmitted power); each one is multiplied separately in a mixer with the 1.2875GHz signal. The 1.2875GHz signal is labeled as the local oscillator (LO) input while the other RF input signal is labeled as the radio frequency (RF) input; see Figure 8. When the LO signal and the RF signal are multiplied in the mixer, the result, which is then sent to the *DSP board,* is labeled intermediate frequency (IF).

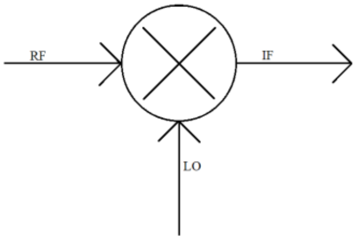

Figure 8: RF mixer. The RF and LO signal are the two imports. These two signals are multiplied together, and then passed through a low pass filter to create the IF output signal.

The LO signal and RF signal are combined in such a way that the frequency of the IF signal is the difference between the LO and RF frequencies, which is 12.5MHz in our case. As the RF signal and the LO signal enter the mixer, their signals are initially multiplied together.

The RF signal can be represented by $f_{RF} = A_{RF}\sin(\omega_{RF}t + \varphi_{RF})$ and the LO signal by $f_{LO} = A_{LO}\sin(\omega_{LO}t + \varphi_{LO})$. When these equations are multiplied, the result is:

$$f_{IF} = f_{RF} \cdot f_{LO} = A_{RF}A_{LO}\sin(\omega_{LO}t + \varphi_{LO})\sin(\omega_{RF}t + \varphi_{RF})$$

Through the use of trigonometric identities, this resulting equation simplifies to:

$$f_{IF} = \frac{1}{2}A_{RF}A_{LO}\cos\big((\omega_{LO} - \omega_{RF})t + (\varphi_{LO} - \varphi_{RF})\big) - \frac{1}{2}A_{RF}A_{LO}\cos\big((\omega_{LO} + \omega_{RF})t + (\varphi_{LO} + \varphi_{RF})\big)$$

The multiplied signal is passed through a low pass filter, removing the high frequency term in the above equation. Therefore, the final IF output signal is represented by:

$$f_{IF} = \frac{1}{2}A_{RF}A_{LO}\cos\big((\omega_{LO} - \omega_{RF})t + (\varphi_{LO} - \varphi_{RF})\big)$$

Notice that the signal still contains the amplitude and phase information for the original input RF signals.

RF Monitor and Interlock

Like the *mixer,* the *RF Monitor and Interlock* samples the power forwarded to the cavity, reflected by the cavity, and transmitted by the cavity. For hardware protection, the amplitudes of these probe signals are compared with maximum allowable values. If signal amplitude is above the maximum value, the *RF Monitor and Interlock* will trip the system, in other words, turn off the RF drive power to the cavity.

LVDS Timing Device

The low-voltage differential signal (LVDS) timing device is located in the *DSP Board.* It receives two signals from the *RF synthesizer*, one at a frequency of 50MHz and another at 12.5MHz. The 50MHz sets the sampling rate of the Analog to Digital Converters (ADC), which convert the IF signals of the forward power, reflected power, and transmitted power from an analog signal to a digital signal. The 12.5MHz is the control loop cycle frequency for the XILINX chip, also located in the *DSP board*. It is crucial that the XILINX chip is operating at ¼ the rate of the sampling time.

Digital Signal Processor (DSP) Board

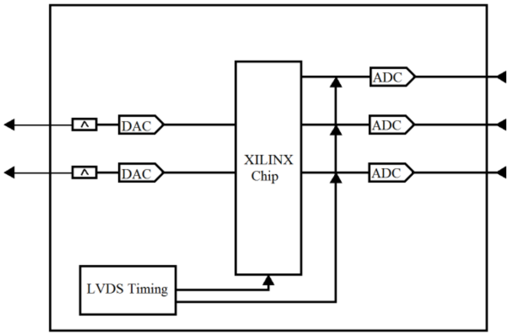

Figure 9: The DSP board is one of the most complicated and important components within the control loop. It is responsible for sampling the cavity field signal to be stabilized and creating a new control signal to keep the field in the cavity stable.

The *Digital Signal* Processor (*DSP) Board* is the heart of the system; it is the element that computes the control loop stabilizing the field in the cavity.

The analog IF signals coming from the *mixers* are passed through analog to digital converters (ADCs) on the *DSP Board,* converting them to digital signals. The digital signals are then sent to the XILINX chip*,* which runs any diagnostics, performs all necessary data acquisitions, and runs the digital LLRF control loop stabilizing the field in the SRF cavity.

The digital control signals of the control loop pass through digital to analog converters (DACs) and are converted back to analog control signals. The two control signals represent the in-phase (I) and quadrature (Q) coordinate components of a vector in complex notation [2]. The (I) and (Q) are similar to (x) and (y) in Cartesian coordinates, respectively. The 'I' and 'Q' control signals are then sent to the *vector modulator.*

OUTSIDE THE CONTROL TOWER

High-Power Amplifier (HPA):

Figure 10: Simplified diagram of the *HPA*. On the left, the three RF power slices are indicated with circles representing the RF outputs. Here, thick RF cables are connected which send the power to the RF power combiner.

The *high-power amplifier (HPA)* takes the drive signal received from the *RF monitor and interlock* and amplifies it. The maximum RF output power of the HPA is 5kW. The 5kW is the combined maximum power of three separate solid-state amplifier slices.

The three slices within the *HPA* produce approximately 1.67kW each. The power output from each of these slices is passed through to the *waveguide,* where the outputs are combined.

Waveguide:

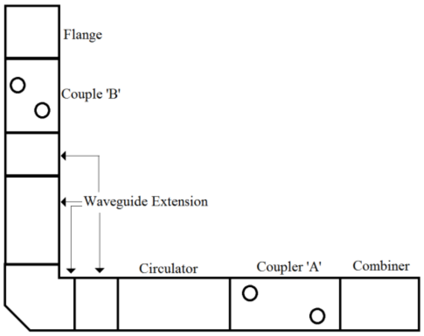

Figure 11: The waveguide is guiding the RF power from the HPA to the RF input coupler on the SRF cavity. The waveguide consist out of several components.

The *waveguide* itself has several components. It consists of a combiner, two couplers, four waveguide extensions and a flange.

The combiner is responsible for taking the output power from each of the three slices in the *HPA* and combining them into one 5kW source.

The first coupler, in the diagram, labeled as 'Coupler 'A'', allows for two probes to be put into place to measure the forwarded power to the circulator and the power reflected by the circulator, which should be very small under normal operation.

The waveguide extensions are used to redirect the RF signal after leaving the circulator.

At the second coupler, two probes are connected to measure the forward power to the cavity and the reflected power from the cavity.

The final flange connects the waveguide to the input RF power coupler of the cavity.

Circulator:

The *circulator* is the component preventing any reflected power from the cavity from reaching the *HPA,* since it could damage the HPA. The circulator is redirects any power reflected by the cavity to a RF load.

Load:

The *load* is attached to circulator. The load is made up of a ferrite material that absorbs any RF power reflected by the cavity, protecting the *HPA.*

Superconducting Cavity:

The superconducting cavity for this system is a seven-cell, niobium cavity.

CONCLUSION

Microphonics and Lorentz-force detuning can cause strong field perturbation in narrow bandwidth SRF cavities. However, new simulations can be used to predict the behavior of the cavity and a powerful digital control system is now available, which is capable of stabilizing the accelerating field even in the presence of strong cavity detuning.

The new control system allows for regulation of the phase and amplitude of the field within a superconducting cavity with larger gains and bandwidth than previous systems. While each component in the system plays an important role in the regulation, the main digital control loop runs in the XILINX chip on the DSP board.

With its performance, the new control system meets specification for the Cornell University's Energy Recovery Linac (ERL). If placed into the ERL, the control system will be responsible for stabilizing the RF accelerating field of 384 cavities.

ACKNOWLEDGMENTS

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