RESONANCE CONTROL SYSTEM FOR THE CEBAF SEPARATOR UGRADE*

T. Plawski, R. Bachimanchi, B. Bevins, L. Farrish, C. Hovater, G. Lahti, M. Wissmann
Jefferson Lab, Newport News, VA, USA

Abstract

The Continuous Electron Beam Accelerator Facility (CEBAF) energy upgrade from 6 GeV to 12 GeV includes the installation of four new 748.5 MHz normal conducting deflecting cavities in the 5th pass extraction region. The RF system employs two digital LLRF systems controlling four normal conducting cavities in a vector sum configuration. Cavity tune information of the individual cavities is obtained using a multiplexing scheme of the forward and reflected RF signals. Water systems equipped with heaters and valves are used to control resonance. A new FPGA-based hardware and EPICS-based predictive control algorithm has been developed to support reliable operation of the beam extraction process. This paper presents the architecture design of the existing hardware and software as well as a plan to develop a model predictive control system.

INTRODUCTION

The fifth pass CEBAF Separator System consists of four normal conducting, two-cell, deflecting cavities operating at 748.5 MHz as shown in Fig. 1.

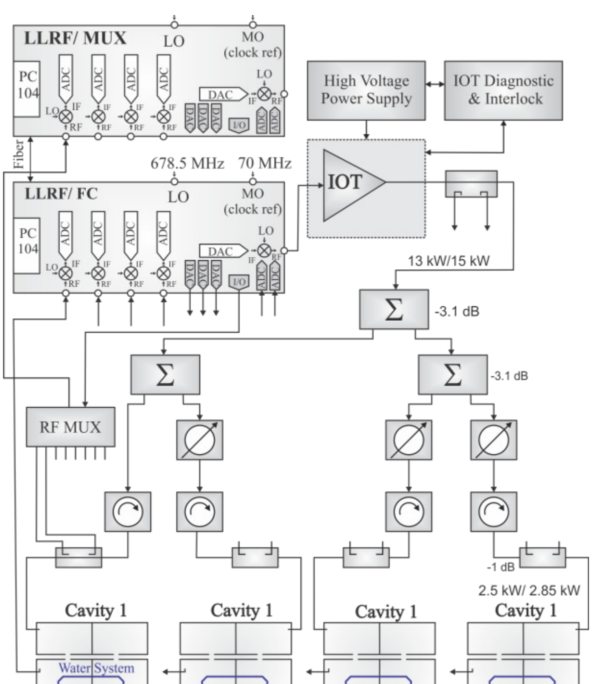

Figure 1: CEBAF 5th pass RF system.

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The cavity design parameters and specification can be found in [1] [2]. The cavities are water-cooled and the average resonance frequency shift is around 12 kHz per °C. One high power amplifier (IOT) powers all four cavities; therefore the system employs a vector sum configuration. To minimize the cost of the control system, an FPGA based digital LLRF system developed previously for a one cavity/one amplifier configuration has been adapted to perform vector sum control. The LLRF module has only four receivers available thus it was necessary to adopt an RF multiplexer for signals other than cavity probe. A detailed description of the CEBAF Separator LLRF can be found in [3].

THE RESONANCE CONTROL WATER SYSTEM

Figure 2 shows a simplified diagram of the water system designed to keep the cavity at resonance as well as prevent the resonator from overheating.

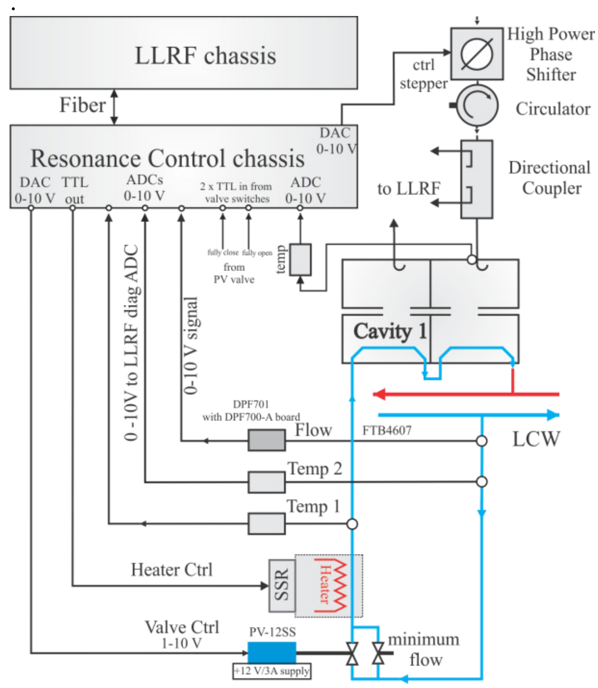

Figure 2: Separator Water System.

As one can see the Low Conductivity Water (LCW), due to construction constraints, runs in an open-loop configuration rather than closed-loop, making the system more vulnerable to fluctuations of the supply LCW temperature and reducing the control loop dynamics. Temperature sensors installed in the system

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are for monitoring purposes only, while the detuning information is obtained from the angle between cavity field probe and forward signal vectors.

The FPGA based system Resonance Control Chassis (RCC) equipped with multichannel ADCs and DACs as well as digital I/O-s has been designed and built exclusively to control resonance for all four cavities. There are two controllable water system variables, flow and temperature. A COTS stepper motor controlled valve regulates the LCW flow with a relatively coarse step size resulting in temperature fluctuations due to large changes in flow. The surge of LCW causes radical drops of the temperature and therefore cannot provide precise regulation. The LCW heater on the other hand allows very precise regulation, but because the latency of the water transport line is on the order of eighty seconds (large distance between heater and cavity) and the cavity thermal time constant is about five minutes, the control loop bandwidth is greatly reduced. Because of the long dead time, a Smith predictor is used to enhance a digital PI controller to provide a delay-free prediction of the response of the system (assuming adequate model accuracy).

The Resonance Control System needs to overcome an additional challenge when transitioning from RF off to steady state. At maximum electric water heater output of 5.2 kW/per cavity but without applied RF power, all cavities are still considerably detuned ("too cold") and significant RF power is needed (~35% of nominal power) to get the cavities on resonance. Once the nominal field (imposed by required deflection angle) is established in the cavity, RF power entering the cavity is typically 2.5 kW, and the cavity becomes detuned ("too hot"). Because the water heater cannot compensate for the added RF heat, the LCW flow needs to be increased. This is also a reason why measured temperatures are not practical to control the cavity resonance. These operational limitations are accounted for in a special automated cavity turn-on procedure described further in this paper.

SYSTEM MODELING

The thermodynamic model of the water system (see Fig. 3) includes delays from water flow, a dynamic model of the electrical heater as well as the dynamic behaviour of the separator cavity due to RF power dissipation. Since the presented model replicates cavity temperature rather than detuning, the coefficient of linear thermal expansion of copper (cavity rods) is used to calculate the change in the angle. LCW flow, regulated by voltage control valve, affects both cavity temperature and the time delays therefore variable time delays have been used in the model.

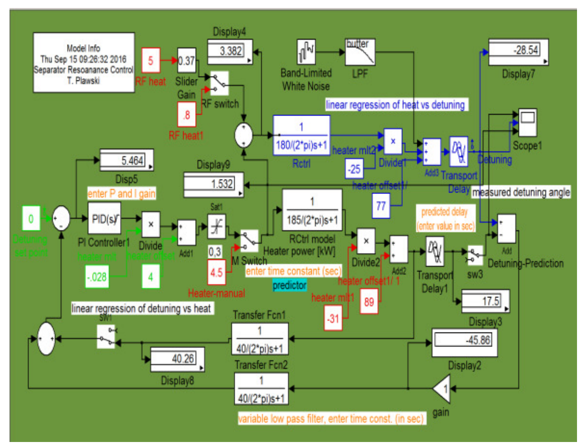

Figure 3: Simulink model of PI & Smith Predictor.

There is noteworthy simplification of the RF power dissipated on the cavity surface: zero RF signal reflection is assumed hence 100% of this power turns into heat. Fig. 3 shows the structure of the controller PI + Smith Predictor and Fig. 4 the whole model of the cavity water system.

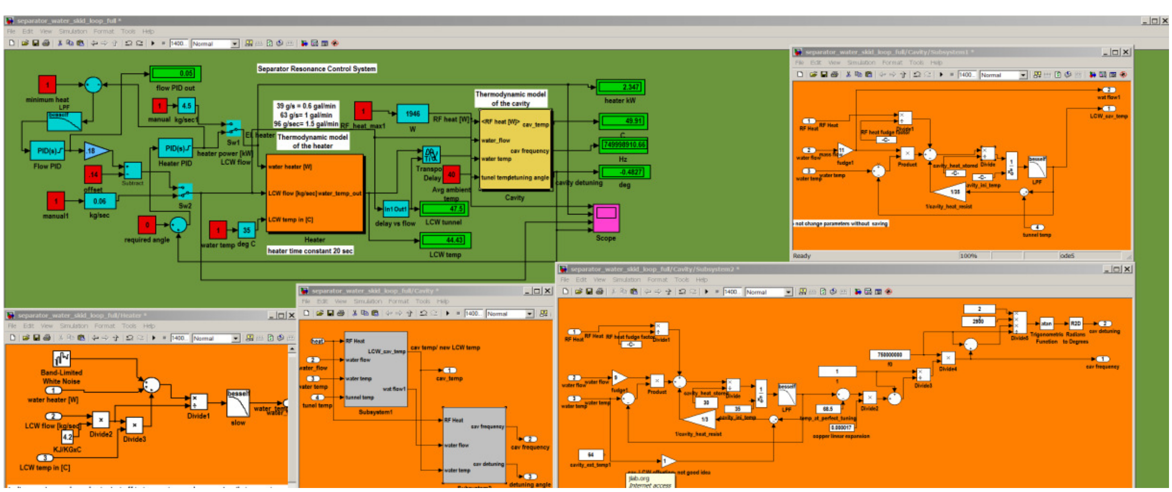

Figure 4: Simulink model of the Separator Water System.

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Careful selection of controller parameters allows the system to run in a stable and relatively robust manner as shown in Fig. 5.

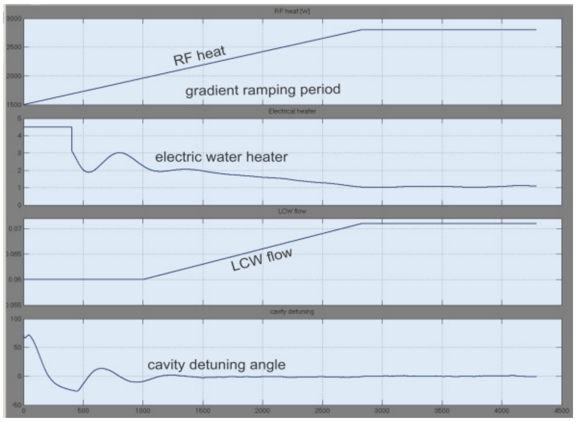

Figure 5: Simulated RF turn-on procedure.

OPERATIONAL EXPERIENCE

The presented separation system has been intensively tested, commissioned and operated for several weeks. Unfortunately, the extraction system (beam transport and separators combined) could not deliver the designed beam separation initially, and the system has been modified [4] to ensure it can deliver the required separation. Most importantly, the power of IOT has been increased up to 16 kW by modification of the high voltage power supply, and subsequently cavities have been pre-detuned farther from resonance frequency making the turn–on procedure more difficult. The PI gains and predictor parameters have been updated, and recent test shows stable and event-free operation. Fig. 6 shows data from the accelerator archiver recorded during RF turn-on procedure for the final system.

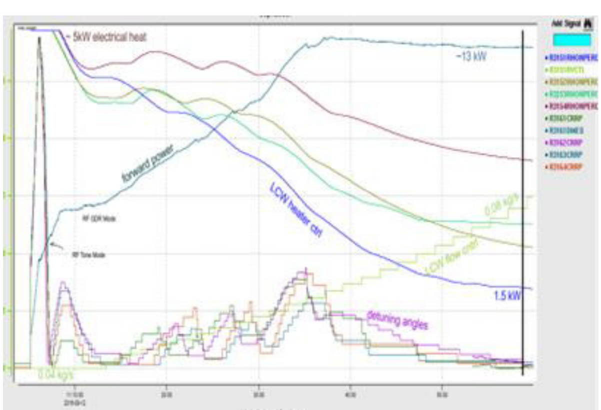

Figure 6: Recorded data from 5th Pass Separator turn on procedure.

The turn-on process:

- runs the electrical heater at maximum power and reduces LCW flow to a safe minimum
- turns RF ON in Tone Mode (no RF feedback) and gradually increases the power until the cavities are coarsely tuned
- engages the PI-Smith regulators
- switches from Tone Mode to GDR (Generator Driven Resonator) Mode
- gradually increases the cavity gradients and increases LCW flow to the requested values

The cavity field reaches the required level ~35 minutes after start, and the system is ready to separate beams at this point. Notice the system is still far from thermal equilibrium and PI-Smith Predictor controllers continue to reduce electrical heat in order to minimize individual detuning angles. This process usually takes more than two hours to reach steady state. Additionally in order to maintain a reasonable electrical heat level and consequently preserve the system from zero-limit, LCW flow is gradually increased.

CONCLUSION

The fifth pass Separation system has been tested for 24 h at 13 kW of total RF power demonstrating stable and reliable operation. Physical separation of the nearly 12 GeV beams will take place in October 2016.

Because the system has multiple controllable variables as well as long and variable time constants, it would be wise to replace the PI-Smith Predictor controller with a Model Predictive one (MPC). MPC has the ability to forecast the future of the controlled process based on an internal model, takes into account process variable constraints, and provides optimal control by optimizing a cost function. Such a controller could reduce RF turn-on time and be more robust in the event of larger than normal LCW pressure/temperature fluctuations.

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