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Title:

APT LLRF CONTROL SYSTEM FUNCTIONALITY AND ARCHITECTURE

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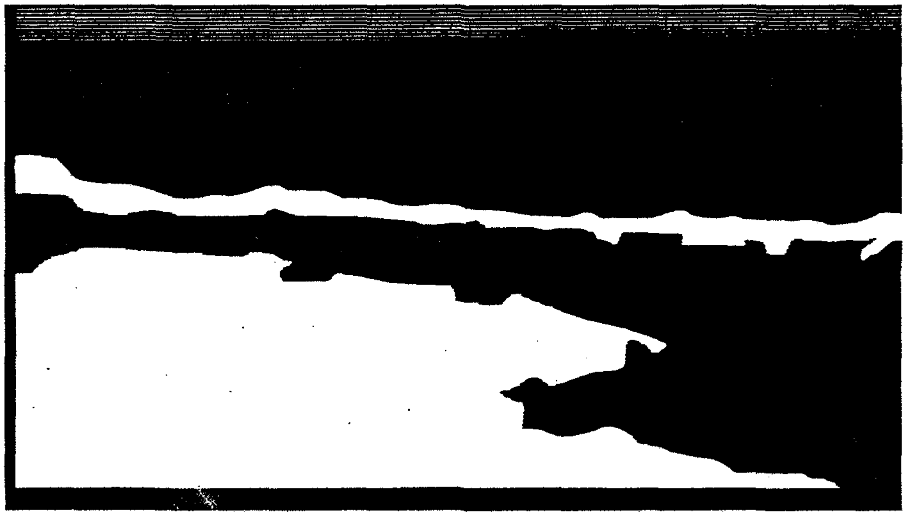

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APT LLRF Control System Functionality and Architecture

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Abstract

The low-level RF (LLRF) control system for the Accelerator Production of Tritium (APT) will perform various functions. Foremost is the feedback control of the accelerating fields within the cavity in order to maintain field stability within ±1% amplitude and 1° phase. The feedback control system requires a phase-stable RF reference subsystem signal to correctly phase each cavity. Also, instead of a single klystron RF source for individual accelerating cavities, multiple klystrons will drive a string of resonantly coupled cavities, based on input from a single LLRF feedback control system. To achieve maximum source efficiency, we will be employing single fast feedback controls around individual klystrons such that the gain and phase characteristics of each will be "identical." In addition, resonance control is performed by providing a proper drive signal to structure cooling water valves in order to keep the cavity resonant during operation. To quickly respond to RF shutdowns, and hence rapid accelerating cavity cool-down, due to RF fault conditions, drive frequency agility in the main feedback control subsystem will also be incorporated. Top level block diagrams will be presented and described for each of the aforementioned subsystems as they will first be developed and demonstrated on the Low Energy Demonstrator Accelerator (LEDA).

Resonance Control

Resonance control of each accelerator cavity is required in order to control the shift of the cavity's resonant frequency due to RF heating, beam loading, ... During normal operation of room temperature copper structures, the resonance condition of the cavities will be measured and the structure cooling water temperature will be maintained to optimize match. In the superconducting case, a magnetostrictive loop will be used to change the cavity's shape in response to resonant frequency shifts.

Because large amounts of cooling water will be running through the room temperature accelerating structures to accommodate RF heating, a fast shutdown of the RF will cause the cavity to cool down dramatically and cause a large shift in resonant frequency. Rather than rely on the cooling water system to bring the cavity back on resonance, we intend to employ a frequency agile system which will drive the klystron at the cavity's resonant frequency and slowly bring that drive frequency in to the nominal beam-required resonant frequency. In this manner we can quickly bring a cavity back on to resonance. This frequency agile function, based on direct digital synthesis, will be utilized only when the cavity is far from nominal resonance, not during normal operation.

Amplifier Regulation

For the room temperature linac, multiple klystrons will be driven by a single LLRF control system as shown in Figure 1. There is concern that by driving a group of klystrons, the overall LLRF control system will be attempting to compensate all of the klystrons for errors introduced by the "worst" one. Therefore in order to achieve maximum source efficiency, we intend to measure the amplitude and phase across each klystron and maintain a predetermined transfer function by applying local feedback control. This is used to linearize multiple klystrons driving a single accelerator cavity, to negate phase drifts in those klystrons, and to reject power supply ripple.

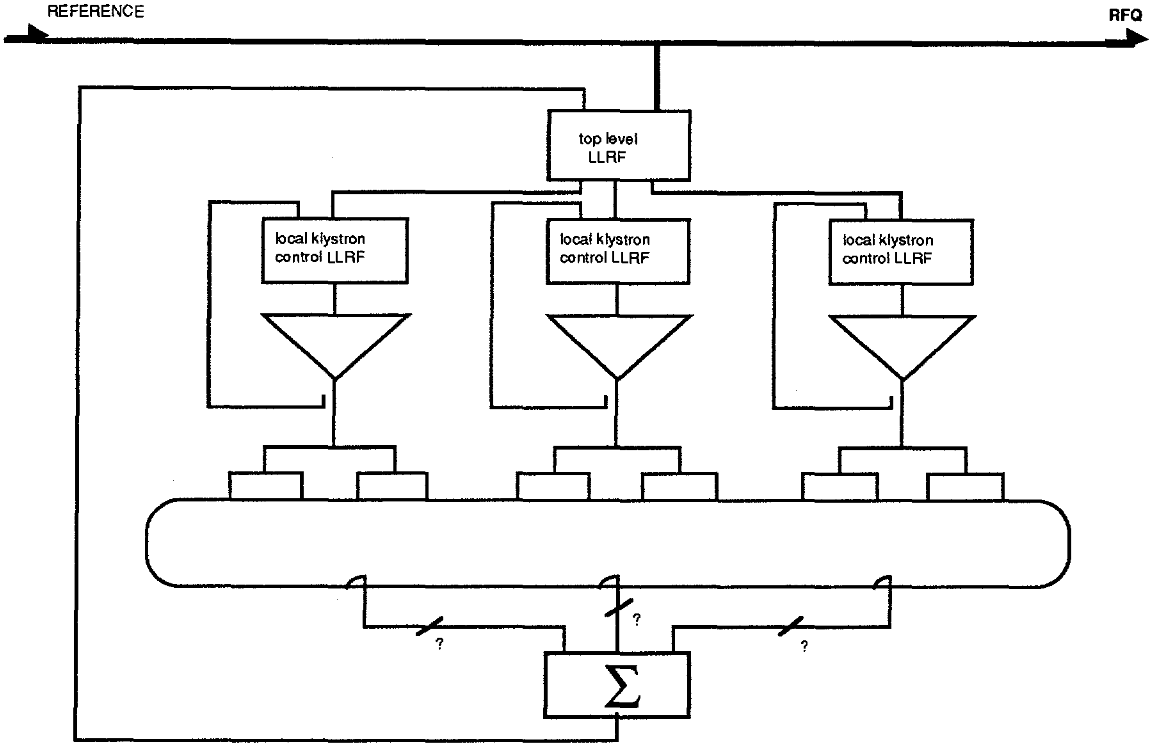
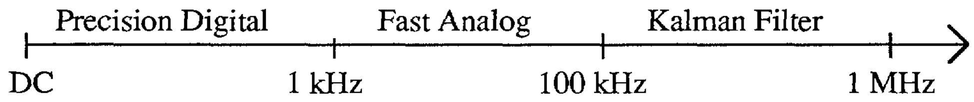


Figure 1. Block diagram of feedback control system for multiple klystrons.

For the superconducting portion of the linac, we anticipate driving four linked cavities within a single cryomodule with a single LLRF control system and one klystron split four ways. Control of the fields in these 4 cavities is based on an arithmetic average of the field probes within each of the cavities fed back to the LLRF system. The concern with this system is that should one cavity become dramatically detuned, or loaded relative to its 3 companions, we will be compensating the drive to all 4 to really only take care of problems in the 1. Hence, we also intend to have individual cavity control to compensate for any individual cavity errors as well. The overall LLRF feedback loop will be identical to that of the room temperature structure. Individual cavity control will be comprised of magnetostrictive tuning for high frequency tuning and a mechanical servo-driven tuner for low frequency compensation. Combining the overall loop with individual cavity control should provide us with the ability to control the fields in the cavity well within the required ±1°, 1% for the gang of 4, or ±3°, 5% individually.

Field Control

The cavity field control functionality is divided into three separate compensators working in parallel. Each of these compensators has a frequency range over which it is most effective.



The Precision Digital compensator provides extremely accurate DC and low-frequency measurements by employing quadrature sampling and digital signal processing (DSP) techniques. Its bandwidth is limited to about 1 kHz by the digital throughput of the ADCs and DSPs. The Fast Analog compensator is implemented in high-bandwidth RF and analog circuitry to maximize the closed-loop bandwidth (limited to approximately 100 kHz by the group delay through the other components of the RF system. Transmission delay of up to 700 ns precludes feedback compensation for more than a couple hundred kilohertz). This type of fast analog electronics is susceptible to DC offsets and drifts and should have its low frequency gain reduced for those frequencies where the Precision Digital compensator is most effective. In order to extend the control bandwidth of the system, we intend to add-on an optimal state-variable Kalman Filter. The Kalman Filter uses statistical processing (and perhaps other complicated digital algorithms) to predict and correct the high-frequency errors. The Kalman filter will require a beam current signal, and possibly a cathode voltage, in addition to the RF field and drive signals, to perform its statistical processing and correction. The Precision Digital and Fast Analog compensators will be designed to allow independent or joint operation, while the Kalman Filter will be an add-on to improve performance.

The cavity field control system is based on the I/Q control functionality originally developed for the Ground Test Accelerator. It will consist of a four module VXIbus set: a Clock Module, a Resonance Module, a RF module, and a DSP module. All RF and IF signals will be transmitted between modules using front-panel coaxial connectors. All of the baseband and digital signals will be transmitted over the VXIbus backplane. The Clock Module receives a 10 MHz reference and produces LO (650 MHz and 300 MHz), IF (50 MHz), and ADC (40 MHz) frequencies needed for downconversion and I/Q sampling. The RF module contains all of the RF electronics for the entire control system. The DSP Module is primarily a digital module that performs two functions: the high-precision I/Q detection and control, and the modern control algorithms that extend the control bandwidth. The Resonance Module performs three basic functions: provides a resonance control signal to the water temperature controller that maintains resonance; provides an open-loop I/Q control signal that can adjust the LLRF output amplitude, phase, and frequency; and performs the calculation for amplitude and phase equalization needed to balance the three klystrons.

Samples of the RF field inside the accelerating structure, the drive from the klystrons, and reflected power signals are all fed back to the LLRF control system located near the multiple klystrons it drives. (This "supermodule"/multiple klystron concept is described in [1]). See figure 1. The field, drive, and reflected RF signals are mixed with a local oscillator locked to the master oscillator RF reference in order to produce IF signals (50 MHz) for quadrature and digital sampling. In addition the field IF signals are downconverted a second time to produce baseband I/Q signals. These baseband signals are processed in the following order: (1) Error correction, phase rotation, and scaling of the filed I/Q signals is accomplished by a 2-by-2 multiplier. (2) Error signals are provided by subtracting the measured filed I/Q signals from the I/Q setpoints. (3) The error signals are applied to the baseband control filter. (4) The baseband I/Q control signals from the DSP module are added to the filter-compensated signals. (5) A 4:2 multiplexer selects either these closed-loop control signals or the open-loop drive signals generated by the Resonance Module as the signals that define the LLRF output. (6) The baseband control signals are split three ways and processed by three 2-by-2 multipliers that provide the phase and amplitude equalization for the three klystrons driving the single accelerator cavity. (7) The three resulting baseband I/Q signals are double-upconverted back to the RF frequency. An overall block diagram of the LLRF control system is given in figure 2.

Figure 2. Block diagram of the LLRF control system.

Summary

The required functions and their implementations for the APT low-level RF control system have been described. Presently we are modeling the various components, and schematics and breadboarding are on-going.

LOW-LEVEL RF CONTROL SYSTEM