THE LCLS-II LLRF SYSTEM[#]

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Abstract

The SLAC National Accelerator Laboratory is planning an upgrade (LCLS-II) to the Linear Coherent Light Source with a 4 GeV CW superconducting (SCRF) linac. The SCRF linac consists of 35 ILC style cryomodules (eight cavities each) for a total of 280 cavities. Expected cavity gradients are 16 MV/m with a loaded QL of ~ 4 x 10^7. The RF system will have 3.8 kW solid state amplifiers driving single cavities. To ensure optimum field stability a single source single cavity control system has been chosen. It consists of a precision four channel cavity receiver and two RF stations (Forward, Reflected and Drive signals) each controlling two cavities. In order to regulate the resonant frequency variations of the cavities due to He pressure, the tuning of each cavity is controlled by a Piezo actuator and a slow stepper motor. In addition the system (LLRF-amplifier-cavity) is being modeled and cavity microphonic testing has started. This paper describes the LLRF system under consideration.

INTRODUCTION

In the summer 2013 the LCLS-II project made the decision to build a superconducting electron linac in the first 10 sections of the SLAC tunnel. The new linac is using a TESLA-ILC 1.3 GHz style cryomodule similar to the ones being produced for the European X-FEL. The primary difference being that these cryomodules must support cw operation. The linac consists of an RF gun, buncher cavity, 35 eight cavity cryomodules and two eight cavity 3.9 GHz cryomodules for harmonic linearization. The linac will support cw beam currents up to 100 μA.

The 1.3 GHz cavities are optimized to support 16 MV/m gradients. The loaded Q is relatively high 4 x 10^7, implying a cavity bandwidth of 32 Hz. The Q_L can be adjusted through the coaxial coupler if further optimization is needed. Originally the project had chosen to power multiple cavities off of one large klystron using vector sum control. As the design progressed, the project made the decision to power and control each cavity individually. Therefore each cavity is powered by a 3.8 kW solid state amplifier (SSA). Microphonic detuning is expected to be a maximum of 10 Hz peak detuning (1.5 Hz rms.).

Cavity resonance control is provided by both a slow stepper motor and a fast piezo tuner. Care must be taken in operating both tuners because they are within the insulating vacuum of the cryomodule. For this reason the temperature of the stepper motor is continuously monitored. There are four redundant piezos for each cavity and they are configured to be driven two at a time. The cavity can have up to three of the piezos fail and still be operational.

Cavity field control is specified to be 0.01% and 0.01° for time periods faster than 1 Hz. For time slower than 1 Hz the accelerator must rely on beam based feedback to maintain the proper beam parameters (energy spread and shape). In addition the linac is segmented into four sections each with different beam-phase relationships. Figure 1 shows the linac and these segments. For these slower times phase and amplitude control is greatly relaxed to the 5-10% and 5-10° levels [1].

LLRF CONCPETUAL DESIGN

The design is being developed collaboratively between LBNL, FNAL, SLAC and JLAB. The LLRF design builds upon recent design experiences at those laboratories [2, 3, 4]. Figure 2 shows a block diagram of the conceptual LLRF design. Not shown is the second RF station controlling the two other cavities. The layout is designed around the SLAC gallery to cryomodule foot print that the project has settled on; four SSA's/tunnel penetration. Given that footprint the LLRF system for each cryomodule is divided between two penetrations. Four cavities are powered and controlled for each penetration. LLRF control is split between a precision receiver chassis (PRC) which processes four cavity signals and the RF station that processes the forward and reverse power and provides the drive signal to the SSA. Each RF station controls two cavities. For economy and maintainability RF, IF and FPGA hardware are shared between the PRC and the RF stations.
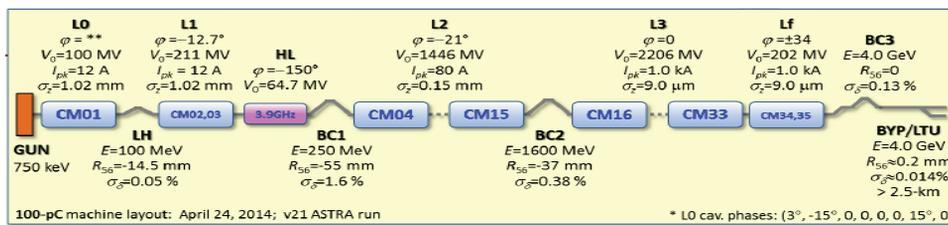
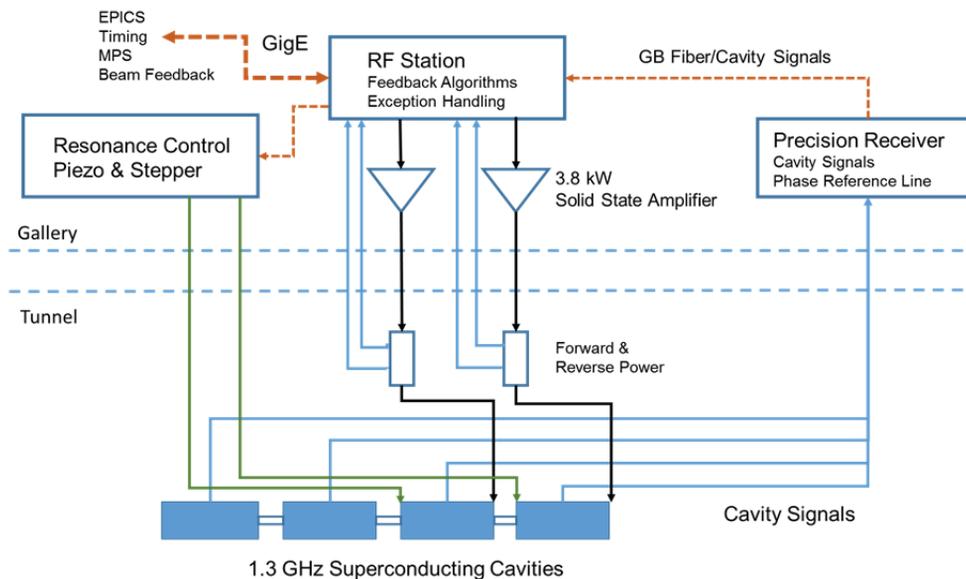Figure 1: LCLS-II Linac segmentation and beam parameters.

Figure 2: LCLS-II LLRF conceptual design.

Precision Receiver Chassis

The key performance parameter for the LLRF system is the very tight phase and amplitude, 0.01^{o} and 0.01% control which the LLRF must maintain for less than 1 second. To reach this level the cavity feedback signal must be representative of the cavity field and have no crosstalk from adjacent channels (typically forward power or the power amplifier drive signal). Simple math says that the channel isolation must be greater than 80 dB. The LCLS-II design achieves this by separating the cavity signals from the less sensitive forward, reverse and drive signals. A precision receiver chassis (PRC) only processes the cavity signals and signals from the phase reference line. The processed signals containing phase and amplitude information are then sent through GB fiber to the RF station. The PRC is located in the bottom half of the LLRF equipment rack where it is temperature controlled to $\pm 2^{o}$C. In addition the rack is located close to the penetration to keep the cavity cables exposed to as little (1 meter) of the gallery environment as possible.

RF Station

The RF stations are network chassis located above the PRC. Two complement each LLRF rack. The RF station is similar to the PRC, but also includes transmit signals and an up-converter. The fiber optically transmitted phase and amplitude signals are processed in the feedback algorithm and a drive signal is sent to the SSA to correct for microphonic perturbations. Resonance (detuning information) control is also determined in the RF station by comparing the forward power to the cavity signals. Each RF station will have an interface to the timing, beam based feedback and the machine protection systems.

Common Hardware

The PRC and the RF station will share common hardware including an eight channel down converter 1300 MHz to 20 MHz, an eight/two (ADC/DAC) channel IF processor and an FPGA board that will interface to the EPICs controls and other LLRF chassis.

The down converter and IF processor are based on designs from FNAL and LBNL. Those designs have demonstrated channel isolations above 85 dB.

A common FPGA board is shared between the PRC and the RF station. Besides algorithms for feedback and resonance control, it will interface to the EPICs and other accelerator systems (timing, mps etc.).

Resonance Control

The LLRF system also provides tuning control for the cryomodule. Each resonance control chassis will have eight piezo amplifiers and four stepper drivers. The coarse tuner is a Phytron stepper motor which is contained within the insulating vacuum space of the cryomodule [5]. The stepper will only be used for startup tuning and to re-center the piezo. There is concern that the stepper will induce mircophonics if used continuously, therefore it will be off most of the time. For this reason the cryomodule will rely primarily on the piezo tuner for resonance control.

The piezo tuner assembly consists of 4 piezo-stacks that will be used to control the cavity [5]. Maximum piezo voltage is 120V, but we intend operate the piezos differentially with no more than 50 volts to ground. This is being done both for safety reasons and to prevent premature failure of the piezo stacks. The amplifier will also be slew rate limited to protect the piezos. For each cavity, two amplifiers will drive two piezo stacks in parallel. The amplifier will be designed such that it has the bandwidth to control not just slow He pressure variations (< 1 Hz), but also acoustic microphonic fluctuations (up to couple 100 Hz).

PHASE REFERENCE LINE

The phase reference line (PRL) will be installed in the tunnel, sending a 1.3 GHz phase reference signal to the precision receiver chassis. Through the PRC, the cavity signals are phase synchronized to the master reference. The PRL is divided up into three segments to support different requirements for field control. In the front end of the linac (L0/L1 and L2/3.9) the PRL will use a phase averaging scheme to minimize drifts. In the final linac section, L3, the PRL will float freely with the tunnel temperature, which we expect to be on the order of ± 1 C degree. Figure 3 shows a block diagram of the phase averaging portion of the PRL.

Phase averaging reference lines have been demonstrated at both SLAC and FNAL [6, 7]. The concept is to lock the phase reference system back on itself like a phase-lock-loop. Then at each tap compare the forward and the reverse signals to effectively eliminate phase drifts. In our case this will be done in each PRC. The only drawback to this concept is that as taps are added it becomes increasingly harder to

overcome the VWSR ripple from the taps. This is perfect for the linac sections L0/L1 and L2 but not so much for L3 where 20 cryomodules are installed.

A low phase noise local oscillator signal, 1320 MHz, will be distributed upstairs in the gallery to both the RF
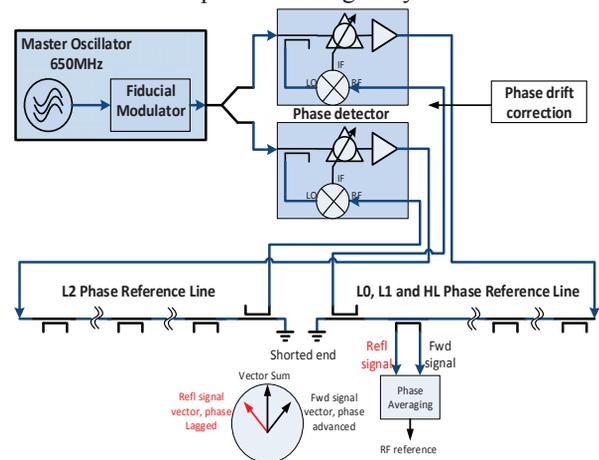

Figure 3: LCLS-II Phase Averaging Scheme

stations and the PRC. In this case we are not concerned about drifts because each cavity signal is referenced back to the PRL.

SUMMARY

The LCLS-II LLRF and phase reference designs build upon reliable operating systems. The key performance parameter, field control, has been mitigated by ensuring a system that can meet the high channel isolation needed for 0.01° and 0.01% cavity regulation. A prototype system is being developed with the goal of testing on a full LCLS-II cryomodule in later half 2016.

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