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LCLS-II BEAM CONTAINMENT SYSTEM AVERAGE CURRENT MONITOR*

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Abstract

LCLS-II is a 4th generation light source at the SLAC National Accelerator Laboratory. A new Superconducting Continuous Wave (CW) RF accelerator will be used to accelerate a 30 uA electron beam with a 1 MHz bunch rate. The Average Current Monitor (ACM) is part of the Beam Containment System (BCS) for the LCLS-II accelerator. The Beam Containment System is a safety system that provides paths to safely shut the accelerator beam off under a variety of conditions. The Average Current Monitor is a beam diagnostic within the BCS that is used to verify that the accelerator is producing the appropriate current level and to limit beam power to allowed values to protect the machine and beam dumps. The average beam current is obtained by measuring the power level induced by the beam in a low Q cavity. By knowing the Q, the beta, and the coupling of the cavity, the instantaneous charge can be calculated, then integrated over one millisecond to yield the average current. This paper will discuss progress in the checkout process of the ACM LLRF hardware and firmware leading to LCLS-II commissioning.

INTRODUCTION

The LCLS-II Average Current Monitor (ACM) system uses two redundant normal conducting low Q RF cavities that are installed directly into the beam line downstream of the 100 MeV injector. When the beam may pass through them, it induces an RF field inside the cavities which is measured and used to estimate beam current. The cavities have three RF couplers and feedthroughs, two of which are connected to the measurement electronics to measure the cavity field. The third feedthrough is used to inject an independent, diagnostic signal to continuously evaluate ACM cavity functionality [1].

An independent signal, referred to as the Pilot Tone, is injected into the cavity by the ACM LLRF controller at a frequency that is about 1.3 MHz away from the cavity's 1300 MHz resonant frequency The purpose of the Pilot Tone is to verify the system is still working by maintaining a stable continuous wave signal. Should the measurement electronics fail to detect this signal, then a fault sequence will be initiated which will result in shutting down the accelerator beam operation. The Pilot Tone is also used to verify the cavity has the correct resonant frequency. The mechanism to evaluate proper cavity functionality is discussed in more detail later.

The main purpose of the ACM system is to fault the Beam Containment System (BCS) if the detected beam current surpasses the appropriate limits. These limits can be adjusted to correspond to the level desired by the accelerator operators. As a safety system, the BCS and thus the ACM must be robustly tested and validated for proper functionality. Hardware and firmware processes must work as designed independently without software intervention. Extensive testing of the system has been performed in preparation for LCLS-II commissioning.

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SYSTEM OVERVIEW

ACM Sensors

The ACM system sensors are pillbox cavities installed directly into the beam line that allow for the beam to pass through and induce an RF field inside the cavities. To respond correctly to dark current in the accelerator, with bunch frequencies much greater than 1 MHz, the resonant frequency of the cavities must closely match the 1300 MHz accelerator reference. The cavities are made of stainless steel and have a relatively low loaded Q of about 1200. With an expected maximum bunch frequency of 1 MHz, most of the beam-induced RF from a bunch has decayed by the time of arrival of the next bunch. The loaded Q must also be within a specified range that is determined by the measurement electronics [2].

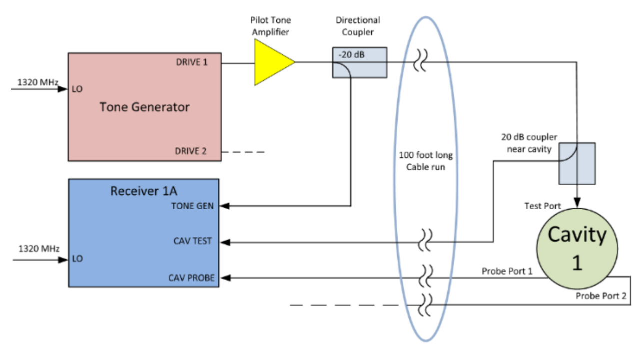

Figure 1: Block diagram showing the connections on one of the cavities. One other receiver connects to Probe Port 2. Drive 2 on the Tone Generator heads to the second cavity which involves the remaining two receivers.

ACM Receivers

The main function of the ACM receivers is to measure the beam-induced field within the cavity. The receivers measure the field of the cavity through the Probe Port (see Fig. 1) which have a coupling of about 0.5 [2]. Through this port, the receiver picks up two distinct signals: the beam-induced RF field and the Pilot Tone. The charge passing through the cavity can be calculated from the measured induced RF field, then integrated over 1 millisecond to obtain an average current. The average current is continuously calculated with a 1 ms moving average [3].

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The receivers will fault by revoking beam permits through the Beam Containment System (BCS) under various conditions. A fast fault occurs if the average current is higher than the permitted beam current threshold. This fault is connected directly to a fast-acting shutoff chassis external to the ACM that will inhibit bunches from electron gun within 10 μs of the fault [4]. Other faults, referred to as slow faults, occur if there are any indications that the ACM is not functioning properly. These faults are reported to a Programmable Logic Controller (PLC) which will respond to the BCS with less urgency. These faults will also shut down the accelerator beam.

The receivers have three RF input ports referred to as: the "Cav Probe" port, the "Cav Test" port and the "Tone Gen" port. At the Cav Probe port input, the receiver is connected to the probe port on the cavity through a "long haul" heliax. This port is used to directly measure the field within the ACM cavity. Under normal operation, the field within the cavity will be a combination of two distinct signals: the Pilot Tone and the beam-induced signal.

The Cav Test port on the receivers observes a coupled reference of the Pilot Tone just before the Pilot Tone enters the cavity. This enables a differential measurement by comparing the signal that passes through the cavity, and the Test Tone that does not. This differential signal is used to determine if any changes have occurred in the cavity after a baseline characterization is established.

The Tone Gen port on the receivers looks at yet another version of the Pilot Tone that is coupled from the Pilot tone before it leaves the LLRF rack. The Gen Pilot tone is compared with the Test Tone and the difference is used to see the effect of the cables that lead to the cavity.

ACM Tone Generator

The main function of the tone generator is to produce the Pilot Tone. The tone generator produces two identical Pilot Tones with one sent to the Test Port of each cavity. The frequency of the Pilot Tone was chosen to be 1,298.66050808 MHz, to minimize the interaction of the Pilot Tone and beam signal harmonics of the planned bunch repetition frequencies. As a test for the system, the tone generator can also produce a second signal at 1300 MHz, which is the same frequency as the beam. This second signal, referred to as the confidence tone, will be turned on at regular test intervals by accelerator operators to simulate a larger current than the fast fault trip threshold. The test is considered a success if the receivers properly trip the fast fault and inform the shutoff chassis.

SYSTEM TESTING

As part of the requirements set by the safety standards at SLAC National Accelerator Laboratory there must be two unique firmware versions (referred to as 'Chain A' and 'Chain B') developed by two separate engineers. Along with the two redundant cavities, the two firmware versions create another level of redundancy in the ACM system. Each of the cavities have one Chain A receiver and one Chain B receiver.

The hardware and firmware development and testing were a major portion of the ACM project. Based on the design requirements, the hardware must be tested and shown to work as designed and the testing methods must be rigorous and reliable. Firmware testing was performed using a test stand which can simulate beam-pulses and include all aspects of the system (Fig. 2).

Figure 2: ACM test stand with one receiver, one tone generator, and one cavity (not visible).

Firmware testing was done in a test stand which is set up with its own cavity that is temperature regulated just like those in the field. The RF cable connections are also the same as those in the field, except that the lengths are a meter or less versus thirty meters or so. The test stand can produce its own 1300 MHz beam-like signal using a pulse generator connected to an RF switch to simulate the beam-induced signal. This setup was used to study the interactions between the Pilot Tone and the beam current measurements (Fig. 3).

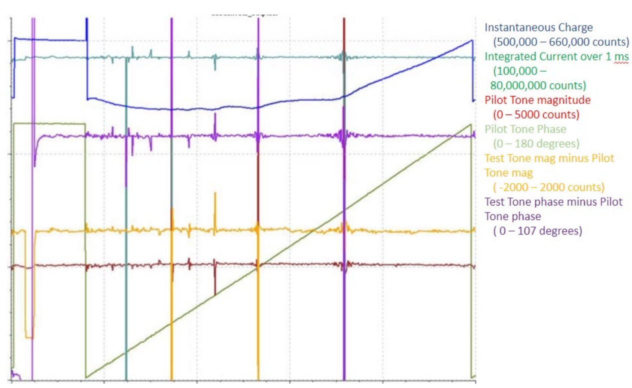

Figure 3: Test to show increasing beam repetition rate's influence on other signals collected by the receivers. Certain beam repetition rates are shown to cause interference with other signals; however, these repetition rates will not be used in LCLS-II.

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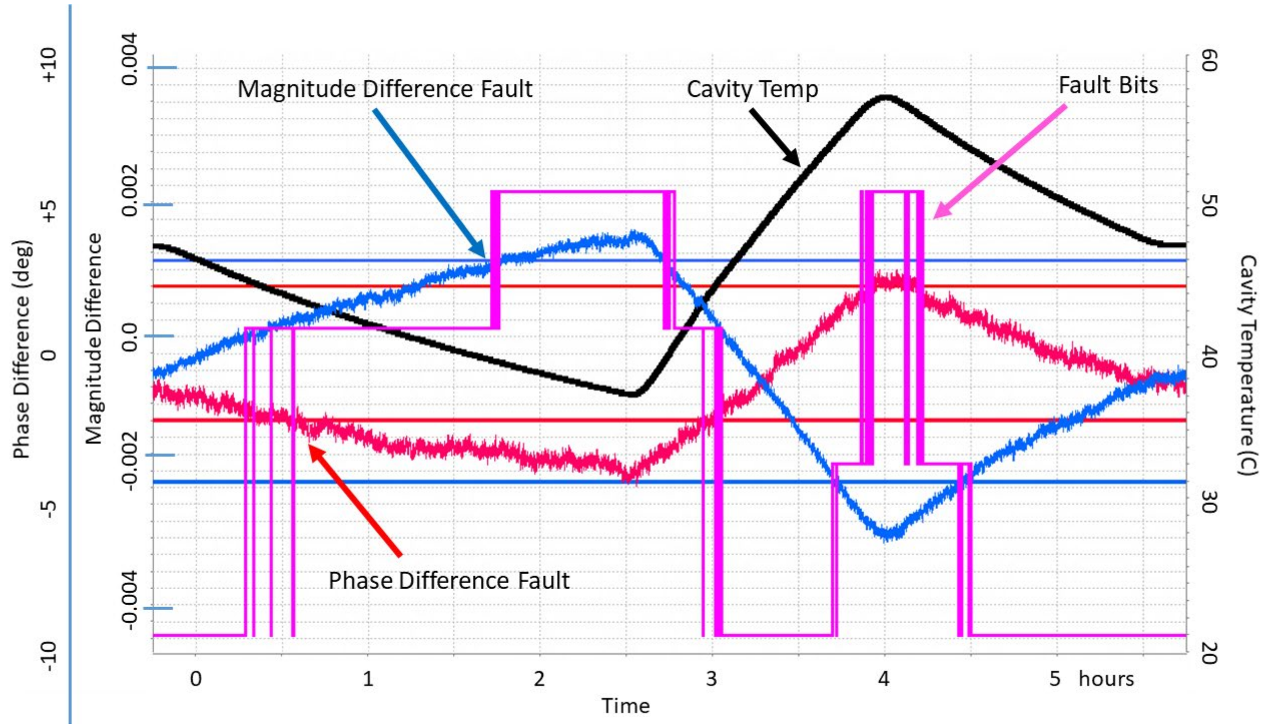

Figure 4: Plot of slow fault test. The cavity was allowed to cool which shifted the resonant frequency of the cavity closer to the Pilot Tone until it grew too strong and tripped the system. Then, the cavity was heated to test the fault in the other direction.

COMMISSIONING

Commissioning of the ACM system is planned in two parts. First, the pre-beam Initial Acceptance Test (IAT) and a with-beam IAT. At the time of this paper, the ACM system has passed the pre-beam IAT and is ready to begin the with-beam IAT once other aspects of the accelerator are also ready.

During the pre-beam IAT, the ACM system was shown to properly trip under all fault scenarios and communicate with fast fault hardware and the PLC. The resonant frequency of the cavity is verified to be in the acceptable range near 1300 MHz. Mechanical tuning of the cavity was done for coarse frequency adjustment and the temperature regulation setpoint of the cavity was adjusted to fine tune the resonant frequency [5].

Calibration was performed to account for loses in cables, attenuators, and variations in receiver sensitivity and to properly scale the digital values reported by the receivers and the actual beam current. This was done using a calibrated signal sent through the Probe Port cable at the cavity up to its receiver and recording the receiver response. Once the cavity tuning and calibration are completed, the RF cables should not be touched, otherwise the calibration must be re-done [6]. Based on the values obtained from the calibration, the trip thresholds for the various receiver faults should be set to encompass the current values (Table 1).

There are several slow faults in the system that have been shown to function correctly. The firmware constantly monitors the Pilot Tone and should fault if its amplitude through the cavity is too low or too high (see Fig. 4). This could be caused by a failure of the Pilot Tone system or by a change the resonant frequency of the cavity. This was tested by intentionally changing the cavity temperature as shown in Fig. 4.

Table 1: Samples of ACM Calibration

Current (uA)	ProbeBeam	Charge (pC)	Probe-BeamMag
0	98,955	0	44
0.1	133,050	0.1	148
1	894,886	1	1,435
10	9,034,193	10	14,541
300	274,417,024	300	422,289

Testing each receiver one at a time, all four must be shown to properly relay the fault to the shutoff chassis, the network, and the PLC.

After each of the four receivers are shown to pass all tests involved in the IAT and all firmware checksums are verified in the safety database, the ACM system is now qualified to begin the with-beam IAT [5].

SUMMARY

In summary, the ACM system is part of the Beam Containment System which is a safety system for the LCLS-II accelerator at SLAC National Laboratory. There are specific requirements that must be followed in accordance with SLAC safety standards which include: redundancy and robustness. With successful completion of the pre-beam IAT, the ACM system will soon be involved in the with-beam IAT for the Beam Containment System.

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