17th Int. Conf. on Acc. and Large Exp. Physics Control Systems ICALEPCS2019, New York, NY, USA JACoW Publishing
ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-WEPHA044

UPGRADE OF THE BUNCH LENGTH AND BUNCH CHARGE CONTROL SYSTEMS FOR THE NEW SLAC FREE ELECTRON LASER*

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Abstract

In 2019 SLAC is building a new linear accelerator based on superconducting niobium cavities. The first one, now called the copper linac, could generate 120 electron bunches per second. The new one, called the superconducting linac, will generate 1 million per second, bringing some challenges to many devices along with the accelerator. Most sensors and actuators in the copper linac are interfaced through a VME-based Platform with its control running in software, with RTEMS as OS. This is feasible for 120 Hz, but not for 1 MHz. The new control hardware is ATCA-based Platform, that has carrier boards with FPGA connected to servers running Embedded real-time Linux OS, forming the High-Performance System (HPS). Instead of having all the new architecture installed at the accelerator and tested on the go, SLAC used the strategy of testing the systems in the copper linac, to have them ready to use in the superconducting linac in what was called the Mission Readiness Program. The Bunch Length System and the Bunch Charge System are examples of devices of this program. Both systems were tested in the copper linac at 120 Hz, with excellent results. The next step is to test them at the superconducting linac, at 1 MHz.

INTRODUCTION

LCLS has two bunch length monitors (BLEN) based on pyroelectric detectors [1] and 13 bunch charge monitors based on Toroids [2], the two types of devices that are in the scope of this upgrade. Beyond these devices, LCLS uses gap diode to measure the bunch length [3] and, to measure the bunch charge, Faraday cups [2] and BPMs [4].

Pyroelectric Detector Bunch Length Structure

LCLS has two bunch compressors (BC). Edge radiation (ER) emitted at the exiting edge of the last bending magnet of each bunch compressor is extracted from the beamline by a mirror at 45 degrees to the beam (see Fig. 1). A hole in the center of the mirror allows the electrons to pass but also emits diffraction radiation (DR) (see Fig. 2). The ER is reflected, split, filtered, and focused by an off-axis parabolic mirror (OAP) onto two pyroelectric detectors [1]. The DR, which is emitted much closer to the OAP, does not image onto the pyroelectric detectors. This light is spread out and produces a little signal.

By using specific optical filters it is possible to measure the difference in the intensity of the signals at the pyroelectric detector output for different lengths of the bunch. Comparing signal intensity for different bunches it is possible to know that one bunch is longer or shorter relative to the other. Calculating the absolute length is only possible when the system is calibrated in advance using invasive methods, like a transverse deflecting cavity. [1]

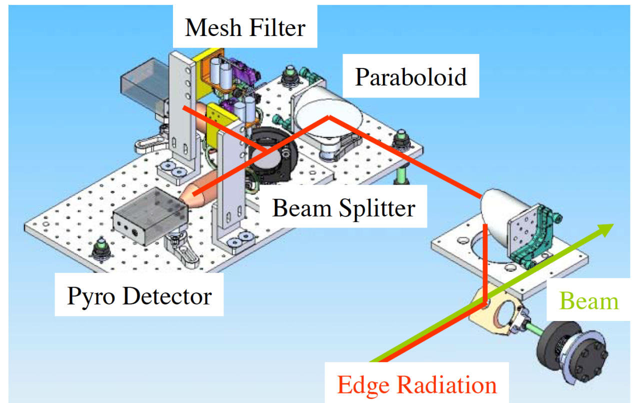

Figure 1: Optical structure of the bunch length system showing how the ER is reflected, split, and filtered before getting to the pyroelectric detectors. Reproduced from [1] with permission from the authors.

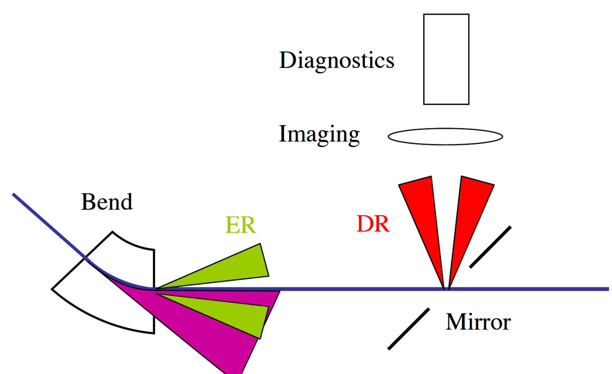

Figure 2: ER from bending magnet generating DR through a hole mirror. Reproduced from [1] with permission from the authors.

Toroid Bunch Charge Monitor (BCM) Structure

A toroid is placed around the accelerator beamline so that the electron beam passes through its hole, inducing a current in the turns. This current is conditioned and digitized. By measuring the peak of the conditioned signal, the system can calculate the bunch charge. For an explanation of the theory, please refer to [5].

The Mission Readiness Program

The goal of the SLAC Mission Readiness Program is to implement improvements in the present to guarantee that the laboratory will comply with its mission in the future and

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maintain it in the long-term [6]. The upgrade of the control system for LCLS is part of this broader program.

As the description of the previous Bunch Length and Bunch Charge Systems will show in the next sections, before the LCLS upgrade signal processing was done by software running in RTEMS OS. Since we were in a condition where the minimum distance between the bunches was 8.33 ms, it was feasible to let the software running in a real-time OS take care of all the processing. The new XFEL, though, will operate at a maximum of 1 MHz frequency, which reduces the time between bunches to 1 µs. For this time range, another architecture is needed [7, 8].

To work with high-processing speed, SLAC has chosen to use FPGAs. The architecture of choice to have the FPGAs on board was ATCA [9, 10].

The Mission Readiness Program substituted VME for the ATCA-based architecture, while still retaining the 120-Hz rate. The goal was to verify if the copper linac would still operate as before after the control hardware was changed.

BUNCH LENGTH SYSTEM

The pyroelectric detectors signal is digitized, processed by an equation that results in the length of the bunch, and timestamped to log a correspondence between the result and the electron bunch throughout the accelerator systems. In the next two sections, we will show the architecture of the previous VME-based system and how it was upgraded to an ATCA-based architecture.

VME-based Architecture

Figure 3 shows the high-level process of the original bunch length system.

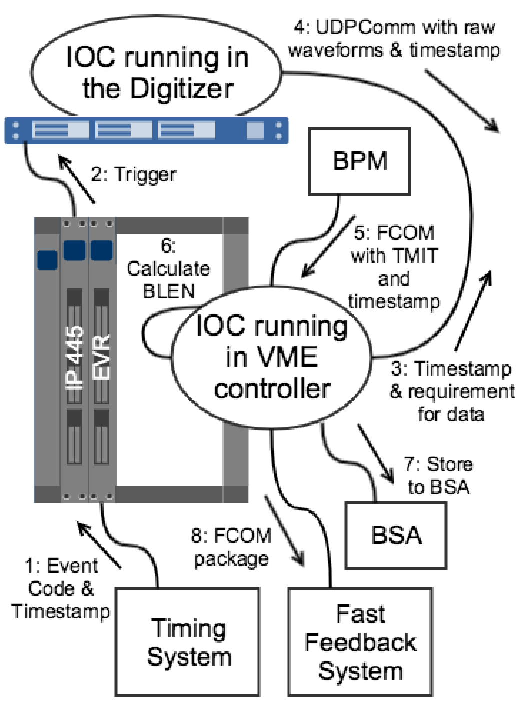

Figure 3: The original (before the upgrade) bunch length system process.

1. The timing system sends a packet containing the timing pattern with event codes and the timestamp. The EVR in the VME crate receives this data. The IOC running in VME waits for a specific event code. When it arrives, the timestamp is registered.
2. Using the IP 445 module, the IOC running in VME sends a trigger to the digitizer, telling it to start collecting data from the pyroelectric detector.
3. The IOC running in VME tells the IOC running in the Digitizer that it is waiting for data as soon as the digitization is complete. The VME IOC also sends a timestamp that will be used by the Digitizer IOC as a data label.
4. After digitization, the Digitizer IOC sends an UDPComm packet to the VME IOC with the digitized data containing one raw waveform for each pyroelectric detector. The data is labeled with the timestamp previously sent by the VME IOC.
5. Parallel to the communication with the Digitizer IOC the VME IOC receives the charge of the bunch (TMIT), sent by the BPM system through an FCOM packet.
6. The VME IOC compares the timestamps from the EVR, the Digitizer, and the BPM system. If they match, the VME IOC calculates the bunch length.
7. The result of the calculation is recorded in the many EPICS records that are part of the BSA system.
8. The VME IOC sends an FCOM package to the Fast Feedback System, containing the calculated bunch length.

ATCA-based Architecture

Figure 4 shows how the new architecture was applied to the Bunch Length System of the copper linac. Here we don't show the complete ATCA architecture for the sake of simplicity, but the detailed description can be found in [9, 11].

1. Similarly to the VME system, the timing system sends a packet containing the timing pattern with event codes and the timestamp, but now the ATCA RTM receives this information and sends it to the Carrier Board.
2. The FPGA firmware triggers the digitizer and waits for the array of data to arrive.
3. The same as in the VME system, the IOC running in the CPU receives the charge of the bunch (TMIT) sent by the BPM system, through an FCOM packet.
4. The IOC sends the TMIT and timestamp to the FPGA firmware as an input for the bunch length calculation.
5. The firmware calculates the bunch length.
6. The result of the calculation is sent to the CPU.
7. The result of the calculation is recorded in the many EPICS records that are part of the BSA system.
8. The VME IOC sends an FCOM package to the Fast Feedback System, containing the calculated bunch length.

The steps related to external systems (1, 3, 7, and 8) were kept the same since these systems will not be changed.

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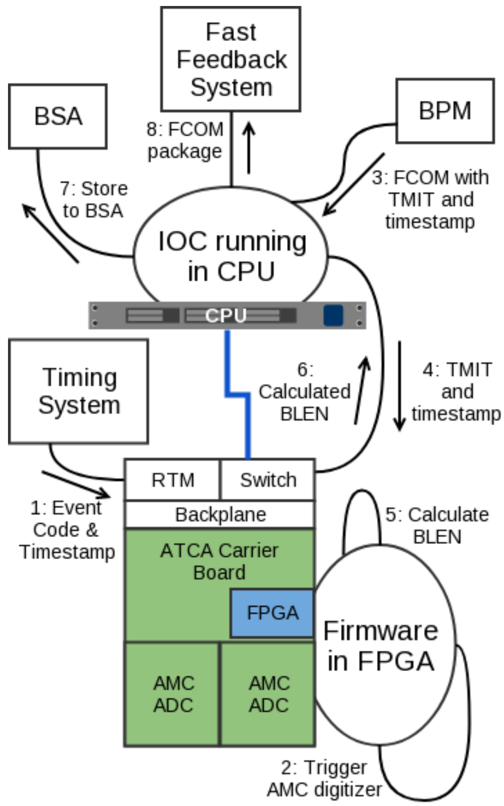

Figure 4: The upgraded bunch length system process.

BUNCH CHARGE SYSTEM

The conditioned signal of the toroid is digitized, processed by an equation that results in the charge of the bunch, and timestamped to log a correspondence between the result and the electron bunch throughout the accelerator systems. In the next two sections, we will show the architecture of the previous VME-based system and how it was upgraded to an ATCA-based architecture.

VME-based Architecture

Figure 5 shows the high-level process of the original bunch charge system.

1. The signal conditioner that receives the short current pulse from multiple toroids is constantly comparing the signals between them and, when a bad condition is measured, it changes the digital signals connected to the Machine Protection System (MPS).
2. The timing system sends a packet containing the timing pattern with event codes and the timestamp. The EVR in the VME crate receives this data.
3. The IP 300 module digitizes the conditioned signal and the IOC reads its value.
4. The IOC calculates the bunch charge.
5. The IOC takes the bunch charge and the timestamp read in step 2 and stores it in BSA.

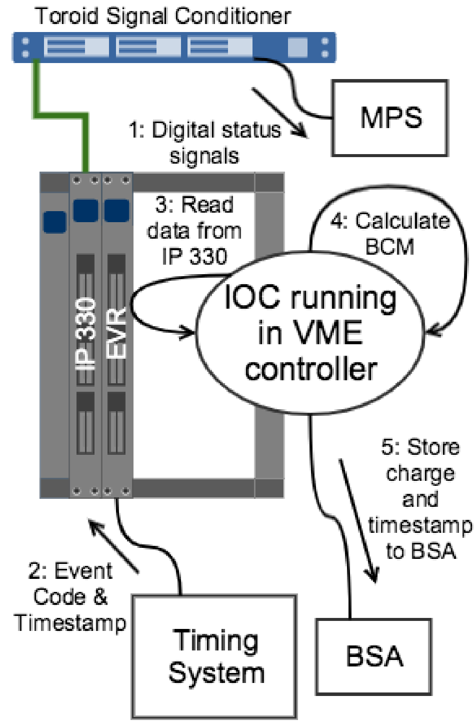

Figure 5: The original (before the upgrade) bunch charge system process.

ATCA-based Architecture

Figure 6 shows how the new architecture was applied to the Bunch Charge System of the copper linac. Here we don't show the complete ATCA architecture for the sake of simplicity, but the detailed description can be found in [9, 11].

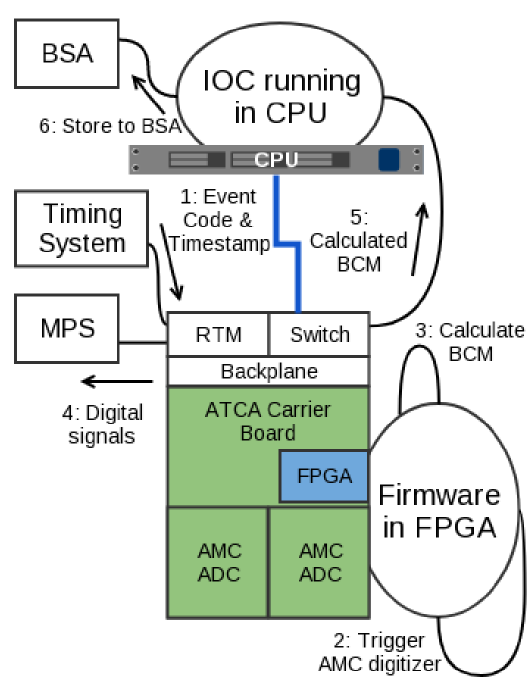

Figure 6: The upgraded bunch charge system process.

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1. Similarly to the VME system, the timing system sends a packet containing the timing pattern with event codes and the timestamp, but now the ATCA RTM receives this information and sends it to the Carrier Board.
2. The FPGA firmware triggers the digitizer and waits for the array of data to arrive.
3. The firmware calculates the bunch charge.
4. One Carrier Board is connected to many toroids. The firmware calculates the charge based on all of them and sets RTM digital signals according to the comparison of the results. These digital signals are received by the MPS, which reacts when a bad condition raises.
5. The result of the calculation is sent to the CPU.
6. The result of the calculation is recorded in the many EPICS records that are part of the BSA system.

As with the BLEN, the interfaces to the external systems were not changed.

RESULTS AND DISCUSSION

Bunch Length

As seen in Fig. 1, the BLEN system uses two pyroelectric detectors. To test the new system, one of them was connected to the digitizer in the ATCA. The accelerator was run with both systems operating at the same time. A positive test result should provide the same scalar number for the BLEN at the same beam pulse in both systems.

Both pyroelectric detector BLEN systems, one in sector 21, after Bunch Compressor (BC) 1, and one in sector 24 after BC 2 were tested.

The test was performed for many different lengths. A correlation of 1 should be observed when we plot the measurement of one system against the other. Figure 7 shows the scattering with the VME system on the x-axis and the ATCA system on the y-axis. The linear regression result shows that the correlation is close to 1, confirming that the new system provides the expected results.

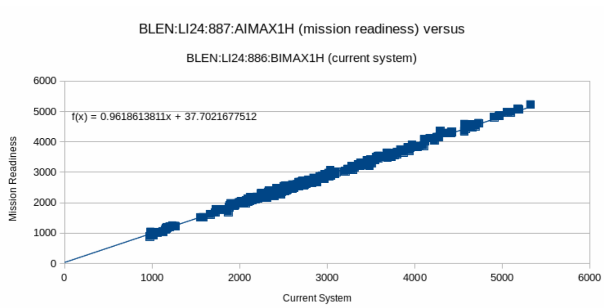

Figure 7: Measured bunch length correlation between the ATCA (Mission Readiness) and the VME (Current) system in sector 24.

During a few tests, the Fast-Feedback system received data from the ATCA system. The accelerator operated normally, as before.

The filters were moved to verify the readback from the limit switches, with positive results.

Bunch Charge

The toroids in sector 24 and 25 were tested, following the procedure below. The input toroid is the upstream toroid in sector 24, closer to the electron gun. The output toroid is downstream in sector 25.

1. The MPS was configured to ignore alerts from the toroids being tested.
2. Still using the VME system for both toroids, we measured the correlation between the input and the output toroids to make sure that it was 1.
3. We physically switched the input toroid cable to the ATCA system and measured the correlation with the output toroid still running through VME. Calibrating the ATCA system parameters, we could get a 1 correlation.
4. We switched the input toroid cable back to the VME system and connected the output toroid to ATCA. Again, adjusting the ATCA system parameters we've got a 1 correlation.
5. Finally, we put both toroids in the ATCA system and measured successfully a correlation of 1.

Figure 8 shows the result when the input toroid was switched to the ATCA-based system. The correlation is close to 1 as expected.

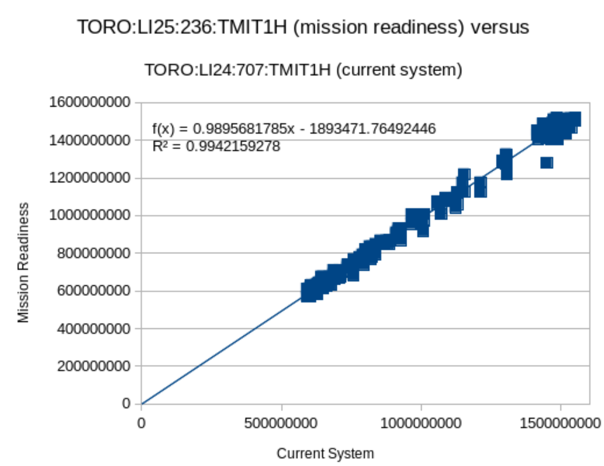

Figure 8: Measured bunch charge correlation between the ATCA (Mission Readiness) and the VME (Current) system in sectors 24 and 25.

Once both toroids were running in the ATCA system, we connected the digital signals to the MPS and activated it. With the accelerator running, no signal tripped the MPS. We forced both systems to generate alerts to the MPS, which reacted by blocking the injector, as expected.

Tests couldn't be done in sector 21 because the cables were too short to reach the new rack and there was no time slot before the start of the long 1-year downtime to install new cables.

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CONCLUSION

Given the successful test results, the ATCA-based Bunch Length system is ready to replace the VME-based system in both sectors 21 and 24.

The ATCA-based Bunch Charge system is ready in sector 24 but will require calibration for the 6 toroids in sector 21 and tests with the MPS before the replacement takes place.

The Mission Readiness Program goal was achieved for BLEN and BCM systems, as it was proven that the ATCA-based systems could make the copper linac operate correctly at 120 Hz together with all other sub-systems and operator interfaces.

In the next step, final measurements and the switchover to ATCA will take place on the copper linac when operations resume at the end of 2019. Commissioning of the superconducting linac will begin in 2021.

ACKNOWLEDGMENTS

Many people contributed to the success of this project. The authors would like to acknowledge Bryce Jacobson, Carolina Bianchini, Charles Granieri, Chris Ford, Ernest Williams, Hugo Slepicka, Jeremy Mock, Jesus Stanescu, Kenneth Brobeck, Kristi Luchini, Kukhee Kim, Luciano Piccoli, Maria Urbina, Matt Gibbs, Richard Truong, Shawn Alverson, Sonya Hoobler, Thuy Vu, Till Straumann, and Timothy Maxwell.

We acknowledge Josef Frisch and Juhao Wu for authorizing the use of the figures explaining the Bunch Length structure.

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