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LLRF CONTROLS UPGRADE FOR THE LCLS XTCAV PROJECT AT SLAC*

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Abstract

SLAC's Low Level Radio Frequency (LLRF) controls software for the S-Band deflecting structures needed to be upgraded significantly when a new X-Band transverse deflecting cavity (XTCAV) was installed downstream of the LCLS undulators in Spring 2013 to assist in FEL diagnostics such as characterizing the temporal profile of X-ray pulses that vary shot-to-shot. The unique location of the XTCAV in the beamline posed several challenges. A new design of the Modulator and Klystron control Support Unit (MKSU-II) for interlocking was added at the XTCAV controls station that required new software development. The timing setup was also different from the rest of the Linac. This paper outlines the LLRF controls layout for the XTCAV and discusses the manner in which the challenges were addressed. XTCAV has now become a successful tool for gathering data that enables reconstruction of X-ray FEL power profiles with greater resolution.

XTCAV FOR DIAGNOSTICS

XTCAV is a powerful diagnostic tool for SLAC's Linac Coherent Light Source (LCLS) Free Electron X-ray Laser (FEL). This is a successor to SLAC's historic S-Band TCAV [1], two of which are still used in LCLS for electron beam bunch length measurements. XTCAV provides useful FEL diagnostics without interfering with LCLS operations since it is installed downstream of the LCLS undulators that are the source of the x-ray pulses. XTCAV deflects spent e-beam bunches after they have contributed to the lasing process just after they exit the undulators. Energy spectrometer is then used to capture and analyse in detail the profile of this spent e-beam stream on a bunch-by-bunch basis. Comparison of the longitudinal profile of these electron bunches when they are lasing against when lasing is suppressed allows us to reconstruct not only the longitudinal profile of the incoming electron beam but the time-resolved profile of the X-ray pulses generated during the lasing process. Figure 1 shows the general layout of this diagnostics system.

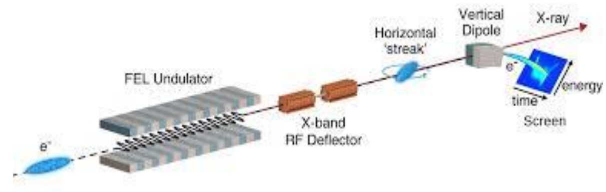

Figure 1: The system includes the transverse deflector "XTCAV", the magnetic spectrometer and the Ce:YAG screen located downstream of the FEL undulators. Horizontal streaking is followed by a vertical-bend dipole magnet for measuring the energy spectrum. A camera captures the transverse images of the electron beam density distribution on the diagnostic screen. (Image: Y.Ding et al., PRSTAB 14, 2011).

XTCAV'S HIGH POWER RF

The SLAC-designed X-Band RF cavity shown in Figure 2 below is powered by SLAC's XL4 50 MW X-Band Klystron that deflects the beam by giving it a 48 MV kick [2]. The Klystron operates at 120 Hz and delivers pulses that can be up to 1.5 uS long. The structure fill time is 200 nS. A legacy 6575 modulator was reused from SLAC, the controls for which were upgraded recently.

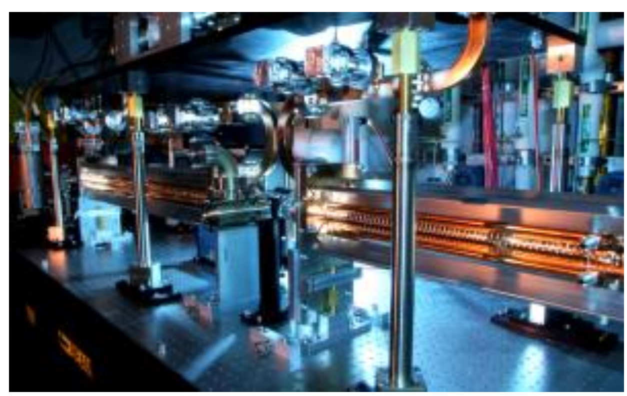

Figure 2: Two one-meter long X-Band RF structures are in the beamline's path towards the e-beam dump. (Image: P.Krejcik/SLAC).

XTCAV CONTROLS

The Controls hardware for XTCAV is located in a service building above the cavity in the tunnel. In addition to the klystron, this building houses the modulator, LLRF controls hardware, power supplies, waveguides, vacuum, temperature and water controls. The LLRF phase reference is derived from the 476 MHz Linac Reference via a heliax cable from the tunnel. Timing and trigger generation for controls is obtained with an Event Receiver

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module which receives precisely timed event codes from the LCLS Event Generator (EVG) on optical fibre links. Networking and serial communication devices are also located in this building. An upgraded model of the MKSU-II keeps the HPRF devices safe by interlocking the whole system with fault detection and protection.

XTCAV LLRF CONTROLS LAYOUT AND ITS CHALLENGES

Implementing the controls for the XTCAV station posed several challenges due to the unique nature of its location in the beamline. It was a structure that was added later to LCLS which meant that the supporting infrastructure needed for this add-on device did not exist when the upgrade project began.

XTCAV Location

While most of the LCLS RF controls are located either in the temperature controlled RF Hut or in the RF stations along the Linac's gallery, the XTCAV RF controls are located in a service support building farthest away from the rest of RF stations towards the end of the Linac.

This resulted in several key differences in the way the XTCAV station is setup as opposed to the other LCLS RF stations.

All other RF stations use the 476 MHz Phase Reference and other X-Band or S-Band RF signals that are distributed from a central location, amplified or boosted and synchronized locally as needed along the Linac. The XTCAV is located close to the end of the beam line and much beyond where the last of the RF stations end in Sector 30 of the Linac. This necessitated that the phase reference and other RF signals needed for the XTCAV station be derived locally. This problem was overcome by sharing the phase-stabilized 476 MHz Reference line from the tunnel that was used for the beam phase monitor in the vicinity of XTCAV. This Phase Reference was brought up to the service building via low-noise heliax cables. A local frequency generator used this reference to derive X-Band LO, Clock and all other RF which were then amplified and distributed locally.

LLRF Controls

In general, LCLS LLRF controls for each RF station comprises of an S-Band or X-Band Phase and Amplitude Controller (PAC), a Phase and Amplitude Detector (PAD) and an MKSU for modulator and klystron fault detection and protection. It may have an additional diagnostics PAD for monitoring the RF output from the PAC and the klystron forward and reflected power. A Master Controller controls a group of PACs and PADs at several stations to provide local or beam-based feedback. Figure 3 is a block diagram of the LLRF controls in service building B921.

Temperature and Feedback

The phase and amplitude stability provided by the closed loop LLRF feedback controls is tied very closely to the temperature of both the structure as well as the LLRF hardware. Unlike the rest of the Linac where the key feedback PAD digitizer is located in a temperature controlled environment to guarantee phase and amplitude stability within the tolerance limits, the XTCAV feedback PAD is located in s service building that is not temperature controlled and thus prone to ambient diurnal temperature variations. The X-Band PAC and PAD's temperature is regulated with water which minimizes this issue. Improvements to feedback algorithm further improved stability. The behaviour of feedback is also closely related to the overall accuracy of timing at the station which will be discussed next.

XTCAV TIMING

The PAC and PAD are controlled by an EPICS IOC running in a PowerPC based CPU board in a VME crate.

XTCAV was the first and is still the only LCLS RF station that has all EPICS controls and the new MKSU-II. This station does not have any of the older SCP, CAMAC or PIOP related controls that are used in combination with EPICS in several portions of the Linac. This minimized XTCAV station setup complexity but at the same time posed newer system integration challenges and some training challenges for the operators.

Unlike the rest of the LCLS controls which use just an EVR module, the XTCAV VME crate has the EVR-RF module for timing. This board has an event clock that is divided from the externally input 119 MHz RF signal. This 119 MHz RF signal is derived directly from the same 476 MHz Phase Reference which was used to derive locally all LLRF RF signals and clock for the PACs and PADs as discussed earlier. This special setup with the EVR-RF module ensures the best possible synchronization between local RF and timing system and provides accurate timing and triggers for all HPRF and LLRF components at the station. This is paramount for keeping the phase and amplitude of the very narrow X-band pulses stable since the XTCAV is located near the beam dump where tolerances for reference phase deviations may not be as stringent as in the rest of the beamline in the Linac.

The trigger setup complexity is minimized in the XTCAV station. Unlike the rest of the RF stations where a number of different triggers from a variety of sources provide discrete triggers for the modulator, PACs and PADs, and whose delays have to be setup up carefully in careful coordination, the XTCAV station takes in a single trigger output from the EVR and fans this out to all the LLRF HW via the MKSU-II that automatically routes the appropriate trigger based on the station's operating mode which can either be beam 'Accelerate' or 'Standby'.

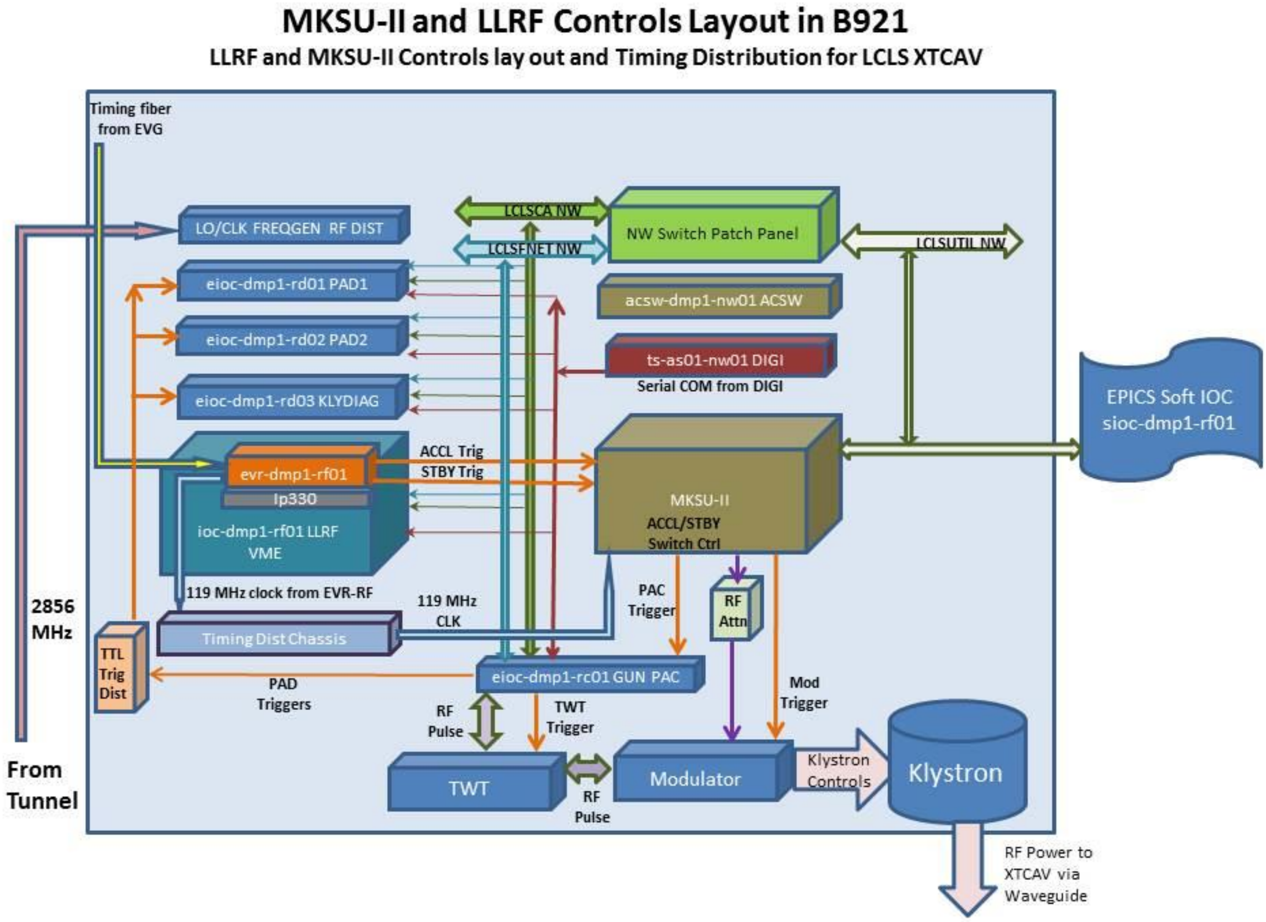

Figure 3: Block diagram of LLRF and HPRF controls layout in XTCAV service building.

XTCAV LLRF SOFTWARE UPGRADES

The XTCAV station was the first RF station that adopted a new LLRF Software model that overcame several limitations and issues in the existing design. The PAD was designed primarily to down-mix and digitize the raw LLRF signals such that I and Q can be derived from the raw waveforms for phase and amplitude feedback control. In the original software, the IQ calculations were performed within the PAD which faced several limitations and issues due to the low processing power of the PAD CPU at higher trigger rates. To overcome this limitation, a new software model was implemented where the PAD was relegated to its primary role of digitizing the raw signal and all CPU-intensive calculations were offloaded to the master VME controller. This vastly improved the performance of LLRF controls software. This upgraded software model was first tried out at the XTCAV station since it was considered a diagnostics device, thus not invasive to the beam and was not expected to interfere with LCLS operations. Following the success of this new LLRF software design at XTCAV, the same model was used to upgrade all other EPICS-controlled LCLS RF stations.

MKSU-II

The XTCAV is the only LCLS station that has an upgraded Modulator Klystron Support Unit called as the MKSU-II. This chassis protects the Klystron by monitoring various sensors and removing high power pulse to the klystron when the system is compromised. The MKSU-II hardware and firmware were modified specifically for the LCLS XTCAV project. A new driver and accompanying business logic were written for it with a new user interface. The new UI mimicked the chassis front panel and provided a remote view of the current status of HPRF at the station. Among several other new features, the MKSU-II supports continuous monitoring of fast waveforms such as the klystron beam voltage and current and forward and reflected power. The MKSU-II chassis front panel, its user interface and fast waveforms are shown in Figure 4. XTCAV's new MKSU-II was clearly a big improvement in RF station fault detection and protection albeit the transition to this new hardware in a station that already differed from the rest of the RF stations in several aspects posed some challenges for operations. Training has improved adaptation.

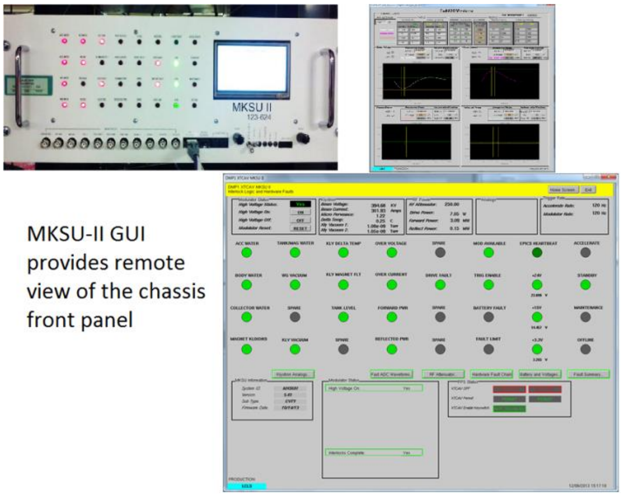

Figure 4: MKSU-II chassis front panel, user interface and fast waveform panel.

CONCLUSION

Commissioning of the controls for XTCAV came with its own set of unique challenges as outlined in this paper but each one of them were overcome in a manner that actually set the path for improvements in LLRF controls for the rest of the Linac. Ever since it was commissioned in May 2013, the XTCAV has become a successful tool in gathering data that enables reconstruction of X-ray FEL profiles with greater resolution. Its success has called for further experimental upgrades which are already underway with the installation of a new SLED cavity at the station that is expected to double the peak power at the structure with longer RF pulses.

ACKNOWLEDGMENT

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REFERENCES

[1] “New Tool to Measure X-ray Pulses Borrows from SLAC History”, SLAC Today News, June 25, 2013.

[2] P.Krejcik et al., “Engineering design of the new LCLS X-BAND Transverse Deflecting Cavity”, Proceedings of IBIC2013, Oxford, UK; http://ibic2013.org/prepress/papers/mopc41.pdf