ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-THPOPA23

DIGITAL LLRF SYSTEM DEVELOPMENT AND IMPLEMENTATION AT THE APS LINAC *

Y. Yang†, J. Byrd, G. Fystro, D. Meyer, A. Nassiri, A. Pietryla, T. Smith, Y. Sun,
Advanced Photon Source, Argonne National Lab, Lemont, IL, USA
B. Baricevic, Instrumentation Technologies, Solkan, Slovenia

Abstract

The current analog LLRF systems which have supported the APS linac operation for over 25 years, will be replaced with digital LLRF systems utilizing the latest commercially available electronics technology. A customized LLRF system has been developed as the next-generation APS linac controller. Two systems have been manufactured and delivered to the APS. On-site tests demonstrated they met the APS linac operation requirements with the first system expected to be integrated into APS linac operation this year.

INTRODUCTION

The linac at the Advanced Photon Source (APS) has been operating for over 25 years [1]. The current setup is shown in Fig. 1. It includes a number of S-band travelling-wave (TW) RF structures with two thermionic RF guns, RG1 and RG2. One provides beams for APS injection, while the other is used as backup [2]. Downstream of the RF guns, there are three linac sectors, L2, L4, and L5, each consisting of four TW RF accelerating structures. For each sector, it is powered by an S-band klystron with a SLED power compressor. The beams are accelerated to 425 MeV before injecting into the PAR and then the booster.

To prepare for the next decades of operation with APS-U, the APS linac is undergoing a major refurbishment. One of the main tasks is to develop new digital LLRF systems to replace the existing analog LLRF controllers which are getting obsolete.

RF CONTROL REQUIREMENT

There are five S-band klystrons in the APS linac. The linac operates at 30 Hz. Each klystron needs a new LLRF system. The main specifications are summarized in Table 1. There are three klystrons that are connected to a SLED to compress the RF pulse. As is required by the SLED, the RF pulse signal generated by the new LLRF system must have a phase reversal with a user-specified timing.

The new LLRF system needs to have enough RF monitor channels. The K2, K4, and K5 klystron stations, which power the linac sector downstream, need more RF monitor channels than the K1 and K3 stations. Each RF monitor channel needs to provide time-resolved amplitude and phase waveforms with around 10 ns resolution. Advanced features such as post-mortem buffer and RF stability analyzer should be included. To support the interleaving operation required by the future advanced accelerator study such as the APS LEA [3], all the RF monitor values in the new LLRF system must have a corresponding timestamp with millisecond resolution.

Table 1: LLRF System Main Specifications

Item	Parameter	Specification
RF Drive Out	Amp. Jitter	0.02 %
	Added Phase Noise	10 fs
	Max Power Level	20 dBm
RF Input	Data Rate	119 MHz
	Repetition Rate	30 Hz
	Channel Number	10 and 20
	Timestamp Resolution	1 ms
	Amp. Resolution	0.05 %
	Phase Resolution	0.1 deg

SYSTEM DEVELOPMENT

Over the past several years, the APS team has been collaborating with Instrumentation Technologies on the RF Beam Position Monitor (BPM) for the APS-upgrade [4]. The new digital LLRF system for the APS linac was developed in a similar way on the Libera platform [5]. Figure 2 shows the Libera LLRF system for the APS linac. It consists of two types of units. One is Libera TSRF. the other is the Libera digital processor.

Libera TSRF

Libera TSRF operates as the analog frontend of the LLRF system. It generates the Local Oscillator (LO) and clock (CLK) signals based on the reference 2856 MHz Master Oscillator (MO) signal. The unit converts up to fourteen 2856 MHz RF inputs including the MO signal to 44.6 MHz Intermediate Frequency (IF) signals.

Libera Digital Processor

The Digital Processor is based on MicroTCA.0 standard. There are six AMC slots available in the crate, shown in Fig. 2. Two single-width AMC cards, Vector Modulator (VM) and Timing Control Module (TCM) are installed in the middle. The VM in slot 1 operates as the up-converter to generate RF drive signals. Slot 2 is for the TCM, which distributes the CLK and trigger signals to other modules. It also has a built-in interlock protection function. Four double-width slots from slot 3 to slot 6 are reserved for the

* Work supported by U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.
† yaweiyang@anl.gov

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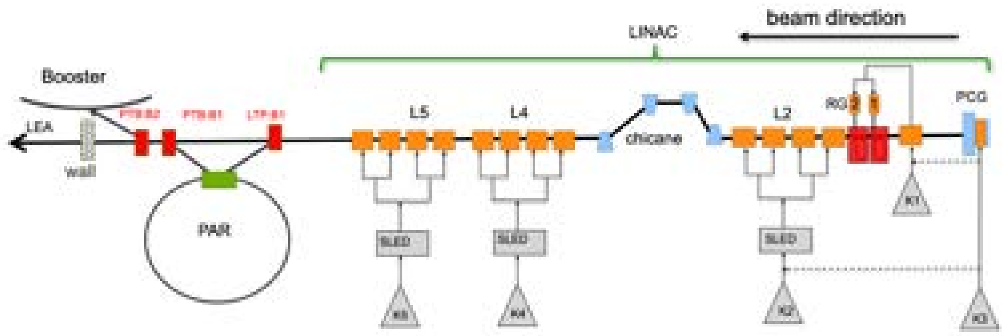

Figure 1: The APS Linac setup. There are five klystrons from K1 to K5. Three of them, K2, K4, and K5, are connected with a SLED to power the linac sectors L2, L4, and L5. Each sector consists of four TW linac structures.

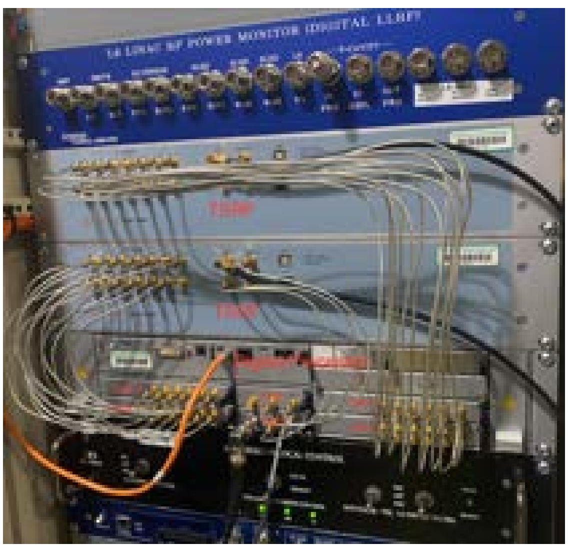

Figure 2: The first Libera LLRF system delivered to the APS. It consists of two TSRF units and one digital processor unit. Six AMC slots are marked in the photo.

KADC modules, two on the left side and two on the right side. Each KADC module has six channels. The FPGA chips of the AMC boards have been upgraded to Xilinx Kintex Ultrascale+. The A/D converters we have chosen are dual-channel 16-bit LTC2185 and D/A converters are AD9117.

Software Development

The IOC software was upgraded to the EPICS7 interface. New features were developed including SLED timing control, stability analyzer, and interlock postmortem buffer. Three types of timestamps were added to all the RF monitor values, including an ADC clock synchronized with an external MO signal, a CPU clock synchronized with an absolute time reference server over the network, and a trigger counter that can be synchronized with other instruments.

System Setup

To meet the APS linac operation requirement, two kinds of system setups were developed. One has 22 RF input channels and the other has 11 input channels. The 22-input setup needs two TSRF units and one Digital Processor unit, as is shown in Fig. 2. Four ADC boards are installed in the Digital Processor, each has six ADC channels. Two of the 24 ADC channels are reserved for reference signal processing from the MO signal. Thus the number of RF input channels is 22. The 11-input setup only needs one TSRF unit and two ADC boards in the Digital Processor instead of four.

The APS linac has five klystron stations as shown in Fig.1. The LLRF system with 22 RF input channels will be installed at the three stations that have a SLED and four TW linacs downstream. And for the remaining two stations, the 11-input system will be installed.

DELIVERY AND ON-SITE TESTS

Two 22-channel LLRF systems have been manufactured and delivered to the APS. Due to the Covid travel restrictions, the factory acceptance tests were performed over video conferences.

After delivery at the APS, the bench tests were repeated, which verified the specifications have been met including RF drive level, amplitude and phase error, spectrum, ADC channel gain difference, noise level, and crosstalk. Several software bugs were identified and fixed during the acceptance test.

At the APS linac, a spare klystron K6, which has a SLED and a water load downstream, was used for on-site acceptance tests. The test purpose was to demonstrate that the new LLRF system meets the APS linac operation requirement and demonstrate its integration into the APS control system.

The on-site tests verified that the new LLRF system could generate and control phase-reversal signals to trigger the SLED. Figure 3 shows an example. The phase reversal could be seen in the klystron output before the SLED, which was generated by the new LLRF system. This reversal would trigger the SLED to extract its stored energy to generate a very narrow and rapidly decayed compressed pulse, as is shown in the klystron output. Compared with the existing analog switch, which is triggered by an extra fiber-transmitted signal, the timing jitters of the SLED trigger were avoided because the phase reversal signal was digitally coded into

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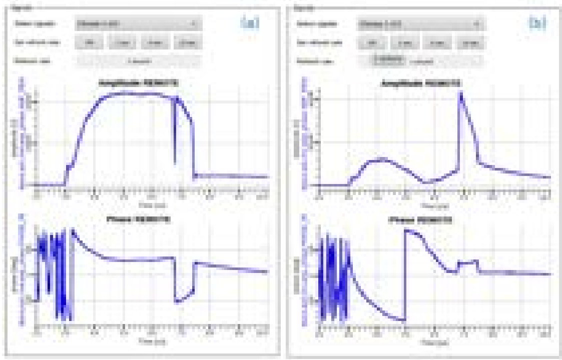

Figure 3: Amplitude and phase curves of klystron output (a) and SLED output (b)

the RF drive waveform in the FPGA chip. And we expect the linac beam stability would be improved due to that.

The long-term stability of the test klystron was investigated with the new software features provided by the new LLRF system. Figure 4 shows the result of a three-day test, where the pulse-by-pulse amplitude and phase values from different RF monitor channels were compared. Those values were averaged within a user-specified window in the RF pulse. The result showed that there were significant RF amplitude and phase variations due to temperature and humidity drift. And the klystron and SLED output have stronger instabilities than the other channels, which was mainly caused by the klystron PFN modulator. As another major task of the APS linac refurbishment, the PFN modulators are being replaced with the latest solid-state modulators, which will significantly reduce the RF instability once complete.

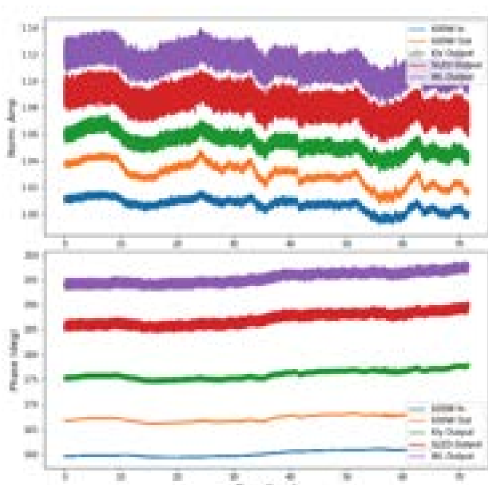

Figure 4: Long-term stability of normalized amplitude and phase values at different spots.

In the current operation scheme of the APS linac, all the klystron stations are running in open-loop mode. The new digital LLRF system provides pulse-by-pulse feedback. And we have demonstrated this feedback feature, as is shown in Fig. 5. When there was no feedback, the RF phase of the SLED output pulse varied with the water temperature cycle. And this variation of the SLED output pulse could be reduced with the feedback loop on. This feedback will be further investigated for the future APS LEA operation when strict requirements are imposed on beam stability.

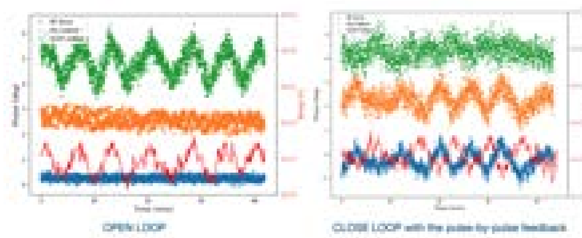

Figure 5: RF signal phases at different spots vs SLED water temperature (red curve) when there is no feedback (open-loop) and when the pulse-by-pulse feedback is on.

CONCLUSION

A new customized digital LLRF system has been developed for the APS linac under a collaboration between Argonne National Lab and Instrumentation Technologies. Two systems have been manufactured and delivered to the APS. The on-site tests have demonstrated that they meet the APS operation requirements. The systems are being integrated into the APS control system, with the first system expected to be installed and operate in the APS linac by the end of this year.

ACKNOWLEDGEMENTS

The authors would like to thank the engineering team of Instrumentation Technologies for the system development, assembly, and delivery of the new LLRF system under challenging circumstances. The authors also would like to thank D. Jefferson, M. Dowell, and A. Grelick for their efforts in the system commission and installation. Their support is critical to project completion.

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