ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-THPB007

PROGRESS UPDATE ON THE RF SYSTEM REFURBISHMENT AT THE APS LINAC*

Y. Yang†, N. DiMonte, G. Fystro, D. Meyer, A. Nassiri, T. Smith, Y. Sun, S. G. Wang
Advanced Photon Source, Argonne National Lab, Lemont, IL, USA

Abstract

A new storage ring, which utilizes a multi-bend achromat (MBA) lattice, has been built at the Advanced Photon Source. Currently, the commissioning process is ongoing in order to bring beamlines back into operation. The APS linac consists of two S-band thermionic cathode guns, one photo-cathode gun at the front end, and thirteen S-band traveling-wave RF structures, all powered by five klystrons. A significant refurbishment is underway to upgrade the RF system in the APS linac. This includes the replacement of the high power modulators and klystrons with a newly designed solid-state switching modulator RF system. In addition, the RF control and diagnostic systems are being upgraded to the new digital LLRF systems. To date, one RF station has been successfully replaced, commissioned, and has been in operation for almost two years. The RF stability, and power efficiency at this station is notably improved compared to the other stations.

INTRODUCTION

The Advanced Photon Source has been successfully upgraded after a year-long shutdown. The original storage ring has been replaced with a new ring using a multi-bend achromat (MBA) lattice. The new storage ring has been successfully commissioned. We are currently in the process of bringing each of the 71 beamlines around the ring into operation [1]. The upgraded X-ray, generated by the new storage ring will be up to 500 times brighter.

The APS linac needs to operate between 400 MeV and 500 MeV with high reliability for the new machine [2]. The linac setup is shown in Fig. 1. The electron beam is generated by one of two thermionic cathode guns (RG1 and RG2) and accelerated by three sectors of S-band traveling wave RF structures (L2, L4, and L5). Each sector consists of four linac structures powered by a klystron and a SLED power compressor. Currently, the APS linac has five operating RF stations (K1 through K5). K6 is used as a SLED test stand [3]. Each station uses a pulse-forming network (PFN) type pulse modulator to supply power to a Thales-35/45 MW klystron [4]. The original LLRF systems for the APS linac have been in operation for around 30 years, and it's challenging to find spare components and replace them when needed.

* 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

RF STATION DEVELOPMENT

A new RF station has been developed for the APS linac. It includes a Cannon S-band klystron, a Scandinova solid-state modulator, and a Libera LLRF system.

Solid State Modulator and Klystron

The solid-state pulsed power modulator technology has been implemented globally to replace conventional klystron modulators. In contrast to a PFN-type modulator, which uses a thyratron tube as the high-power switch, a solid-state pulse modulator uses semiconductor switches such as the Insulated Gate Bipolar Transistor (IGBT). Each IGBT is powered by a DC power supply. A pulse transformer steps up the voltages from the IGBT to the high power level for the klystron. This technology offers significant improvements in power efficiency, compact footprint, pulse flatness and DC stability for RF stations used in accelerators [5].

We have selected the K400 solid-state modulator, developed by Scandinova Systems, for the new RF station. The modulator consists of two Capacitor Charging Power Supply (CCPS) units and twelve IGBT switch units. Each CCPS unit converts a three-phase AC power line to DC voltage, which charges six IGBT units to a primary voltage of around 1 kV. An external trigger gates the charged IGBT switches to discharge, generating a high-power pulse of around 350 kV through the pulse transformer. This high-power pulse is capable of powering an S-band klystron to generate RF pulses with a peak power up to 60 MW and 4.5-µs width.

The APS linac currently utilizes Thales TH2128 klystrons, capable of generating a peak power of 35 MW. However, it is incompatible with the K400 modulator. Therefore, the Canon (Sumitomo) E3712 klystron was chosen as the new klystron to work with the new modulator.

To conduct the site acceptance test, a dedicated utility shed was developed. The first system was delivered to ANL in 2021, and a comprehensive site test was carried out in the shed. Figure 2 shows the first installed system in the utility shed. During the test, we collaborated closely with the vendor to resolve the identified issues and developed operation and maintenance procedures. Eventually, the klystron output power reached 60 MW during the test.

Digital LLRF System

A customized digital LLRF system has been developed by Instrumentation Technologies to control the APS linac RF station [6]. This system has 22 RF monitor inputs, with each input capable of providing amplitude and phase waveforms with 8 ns resolution. A customized LLRF software has been developed to extract average and peak information from

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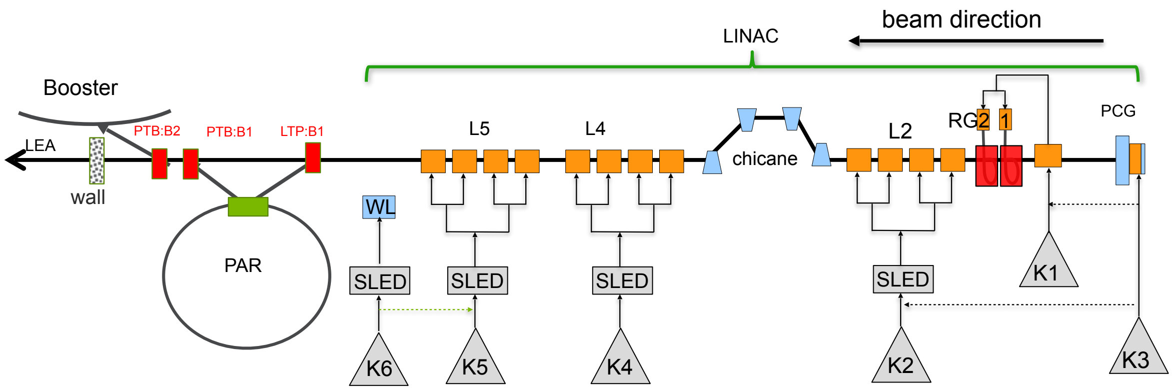

Figure 1: The APS Linac has five operational RF stations, which are called K1 through K5. RF stations K2, K4, and K5 drive the linac sectors L2, L4, and L5. Each of these sectors consists of four TW linac structures. K1 powers the thermionic gun, while K3 can be used to power the photo-cathode gun or serve as a backup RF station for K1 or K2. Additionally, K6 is a test station that will be connected to L5 during the K5 upgrade.

Figure 2: The first K400 modulator being tested in the utility shed with the Canon E3712 Klystron. There are two CCPS units and twelve IGBT switch units in the system.

these waveforms, and calculate amplitude and phase jitter. The software can also save all waveforms whenever the RF drive is tripped by interlocks for further investigation.

In the APS linac, the SLEDs require the RF drive to have a phase reversal at an appropriate timing to extract the stored energy and generate a compressed RF pulse. The LLRF software encodes the SLED phase reversal into an RF drive waveform stored in the FPGA chip. The chip contains two arbitrary RF drive waveforms that can be swapped within several milliseconds. The waveform swapping will be used for the future Linac Extension Area experiments [7].

System Integration

The solid-state modulator and LLRF units are both equipped with machine protection interlocks which need to be integrated into the existing interlock systems [8]. A new ACIS interface chassis has been developed to prevent the RF system from powering up when tunnel access is enabled. Additionally, a new protection chassis with a new arc

Figure 3: The Libera LLRF Systems are installed in the LLRF rack, with the new ACIS interface and protection chassis connected.

detector is developed, which will turn off the RF drive when any INTLK signals are triggered or when waveguide arc is detected. Figure 3 shows the LLRF system and new chassis.

New EPICS IOC databases have been developed for the new modulator and LLRF units. New control screens have been added and updated. The LLRF systems are configured to boot from a network server, making software maintenance a lot easier.

INSTALLATION AND OPERATION

The removal, installation, and commissioning of a new station will take at least several months. To ensure the RF system installation and operation are successful without affecting the APS operation schedule, a backup RF station is required to provide the RF power for the linac sector during the process.

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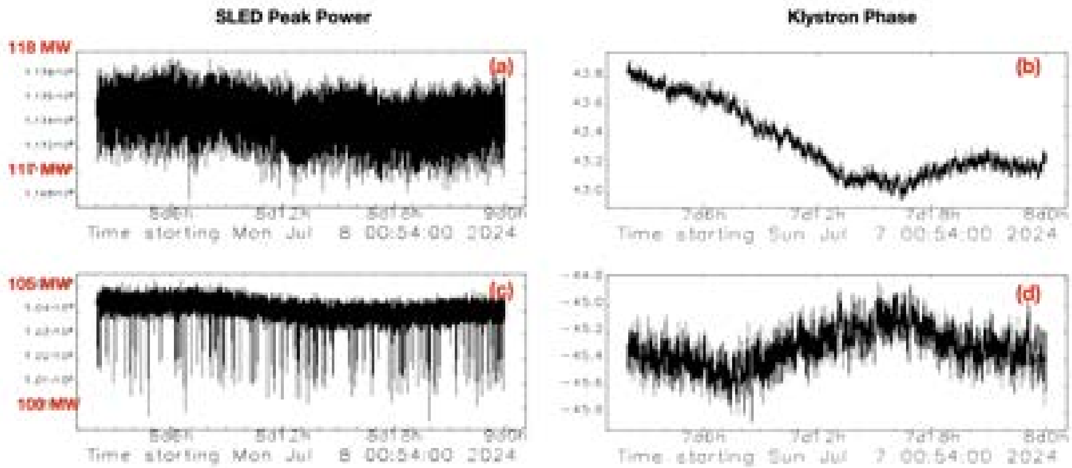

Figure 4: The SLED peak power (a) and klystron phase (b) with the new RF station demonstrated improved stability compared to the results from the old RF station (c) (d).

The first RF system we installed in the APS linac was at the K2 station. During the installation and commissioning process, K3 was the backup, providing RF power to the L2 sector through RF switches. The new RF station was initially connected to a water load during the commissioning phase. After being fully commissioned, the new RF station was connected back to provide power to the L2 sector.

The new K2 RF station has been operational since September 2022, and has proven to be reliable. Currently, the RF power to sector L2 shows much lower power and phase jitter levels compared to other RF stations. An example of this improvement can be seen in Fig. 4, which compared the new station with an old one in open loop mode on a given day. The improvement is mainly due to the better pulse flatness and stability of the new K400 modulator, as well as the encoding of phase reversal in the FPGA chip, which eliminates SLED reversal timing jitters. Additionally, the new RF station's AC power consumption was reduced by over 60 percent within one day.

The remaining stations will be gradually replaced with the new RF stations in the coming years. We will soon begin the process of removing and installing of a new RF station at K5. During this process, K6 will be connected to L5 via waveguides and will operate as the RF station for the L5 sector.

ACKNOWLEDGEMENTS

The authors would like to thank W. Berg, M. Douell, A. Grelick, R. Hong, J. Hoyt, D. Jefferson, A. Johnson, T. Jonasson, J. Lenner, M. Martens, L. Martinez, A. Pietryla, A. Thurman, M. Westbrook, and R. Wright for their support during the design, assembly, site-acceptance testing, installation, and system commissioning of the new RF station.

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