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RECENT OPERATIONAL EXPERIENCE WITH THERMIONIC RF GUNS AT THE APS*

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Abstract

The electron beam at the Argonne Advanced Photon Source (APS) is generated from an S-band thermionic RF gun. There are two locations at the frontend of the linac where thermionic RF guns are installed – RG1 and RG2. Three so-called generation-III guns are available, two are installed at RG1 and RG2, one is a spare. In recent years, these guns are showing signs of aging after over a couple of decades of operations. RF trips started to occur, and we had to reduce the nominal operating rf power to alleviate the problem. In addition, beam generated by RG1 suffers from low transportation efficiency from the gun to the linac, and beam trajectory is unstable which results in charge instabilities. Recently, APS obtained a new type of prototype gun and it was beam commissioned in the linac. In this paper, we report our operational experience with these thermionic rf guns including thermionic-cathode beam extraction, gun front-end optimization for maximum charge transmission through the linac, linac lattice setup to match beam for injection into the Particle Accumulator Ring (PAR) and optimization for maximum PAR injection efficiency.

INTRODUCTION

The APS linac [1] is an S-band linac with multiple guns installed at its frontend, including two thermionic rf guns, RG1 and RG2. RG2 provides beam for injection into the PAR [2], booster [3], and finally the APS Storage Ring [4], while RG1 is a hot spare [5]. Three linac sectors, L2, L4 and L5, each composed of four 3-meter long accelerating structures, are available downstream of the thermionic rf guns to boost beam energy to 425 MeV for day-to-day operations. Multiple steering magnets and quadrupoles in the RG1 and RG2 frontend can be used for gun beam tuning. Beam current monitors are installed downstream of the gun, at the entrance of the linac, downstream of the chicane bunch compressor [6], and at the end of the linac. A series of beam profile imaging stations, each includes a YAG screen and an analog camera system, exist throughout the beamline for beam checkout and emittance measurement. Scrapers can be inserted in the beam path either in the RG2 alpha magnet or in the middle of the chicane. A sketch of the linac is shown in Fig. 1.

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EXISITING GEN-III GUNS

Two decades ago, APS acquired three so-called Gen-III thermionic rf guns [7] that have been used to generate the electron beam for APS storage ring operation ever since. The Gen-III gun is an improved version of the SSRL gun design [8–11], operating in $\pi/2$-mode with a side-coupling cell. In recent years, these guns can only run at reduced rf power and current due to frequent rf trips. One of the three guns was cleaned and the interior surface appeared to have improved, however it still can not support 3 MW of rf power without an rf trip. Thus it has been difficult to keep up with 1 nC per rf pulse which used to be the nominal operation condition and will be a requirement for APS-U.

In addition to the rf trips, beam from the RG1 slot has seen large and sudden trajectory jumps up to several mm at the entrance of the linac. An example is shown in Fig. 2. Bunch charge is lost due to the abrupt trajectory motion. Though trajectory feedback has been established that automatically steers the beam to a set of saved beam position monitor readings, it has a slow update interval of 5~10 seconds due to slow power supply response. Thus an instantaneous beam trajectory jump can not be compensated immediately and stable bunch charge can not be maintained at the end of the linac.

The cause of the trajectory jump of RG1 beam is till under investigation, although it was found the trajectory response of the RG1 kicker [11] with ±5 kV step changes resembles closely the trajectory jump pattern as measured, see Fig. 3.

A NEW PROTOTYPE GUN

A prototype gun, operating in π-mode, was designed and fabricated by Radiabeam [12]. The gun was installed in the RG2 slot in Feb. 2021. The gun was rf conditioned, the thermionic cathode was activated, and electron beam was extracted during machine studies. The beam was sent through APS linac, and tuned up to achieve 100% injection efficiency to PAR.

Prior to RF conditioning, the cathode heater power was set to 9 W to keep the cathode warm and clean during the RF conditioning. The RF conditioning went rather smoothly. Gun vacuum was kept below 1x10^{-7} Torr during the conditioning process. In ~70 minutes, the gun was conditioned to 3 MW at 6 Hz repetition rate with an RF pulse length of 1.05 μs rather uneventfully. The forward and reflected RF waveforms of the gun are shown in Fig. 4.

After the gun was conditioned, the cathode was activated by setting the cathode heater power to 30 W for 13 hours (overnight) without rf power in the gun. The gun vacuum

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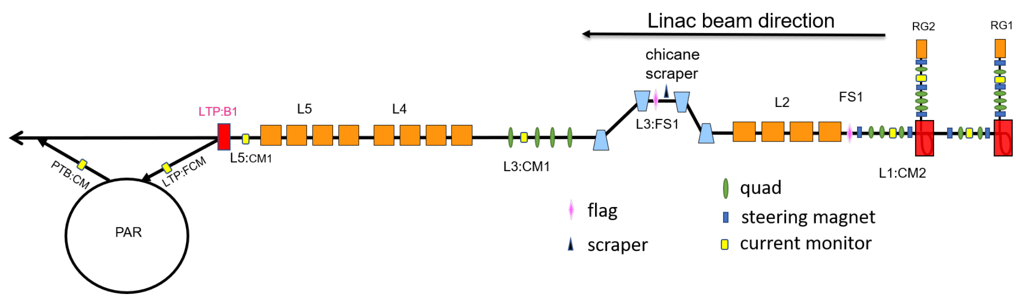

Figure 1: A sketch of the APS linac beamline. Two slots, RG1 and RG2, at the front of the linac, are available for the installation of thermionic rf guns.

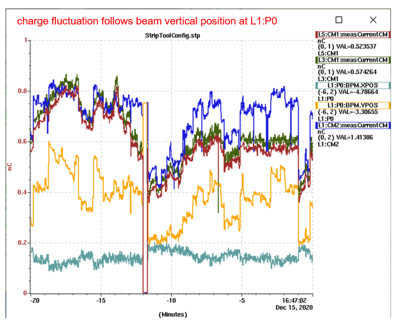

Figure 2: Sudden beam trajectory jumps result in charge loss.

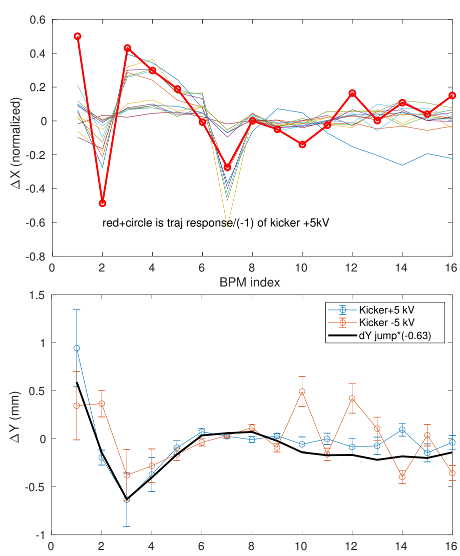

Figure 3: Measured trajectory response of RG1 kicker with ± 5kV step changes resembles the trajectory jump pattern measured.

stayed under 1x10^{-8} Torr during the activation process despite the high cathode heater power.

To extract beam from the cathode, RF power is required. The cathode heater power was reduced to 10 W to start bringing in RF power to the gun. Once the rf power reached 3 MW, the cathode heater power was slowly increased. At 25 W, 180 mA beam current was measured on the gun current monitor (though current was not yet at equilibrium), as shown in Fig. 5.

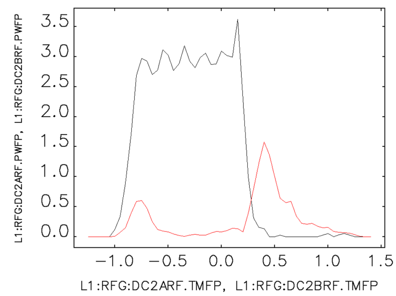

Figure 4: Prototype gun forward (black) and reflected (red) RF waveform.

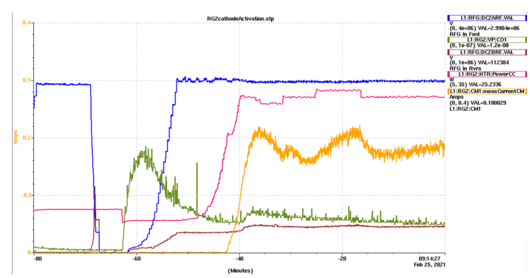

Figure 5: 180 mA gun current was extracted with cathode heater power at 25 W and gun rf power at 3 MW.

With 180 mA gun current, beam trajectory and linac rf phase were adjusted. RG2 and L1 front end magnets (quadrupoles and steering magnets) were optimized to maximize charge transmission through the linac [13–15]. The optimization resulted in a bunch charge of 1.5 nC per rf pulse downstream of the chicane at L3:CM1, with gun kicker voltage set to 13.5 kV.

After the charge optimization, beam images on flags were checked out. RG2 front end steering was manually adjusted to get beam centered on FS1 with a up-down symmetric, triangular appearance that results from second-order x-y coupling in the alpha magnet [9]; see Fig. 6. Subsequently, beam entrance position and angle into the linac were adjusted. Beam was steered through the end of linac with a good trajectory, requiring minimal steering magent currents.

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Linac trajectory control law set points were updated and turned on.

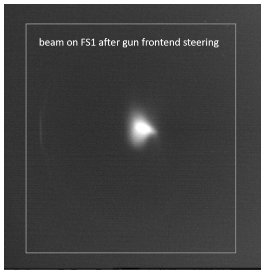

Figure 6: Beam centered on FS1 by adjusting RG2 frontend steering.

L2 sector RF phase was adjusted for minimum energy spread in the middle of chicane by observing beam on L3:FS1. The chicane low energy scraper was inserted to remove the low energy tail; see Fig. 7. With the scraper inserted, charge transmission efficiency from L1:CM2 to L3:CM1 was reduced from 90% to 70%.

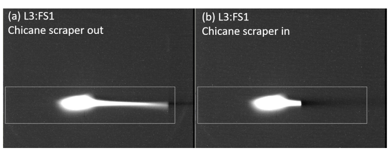

Figure 7: Beam in the middle of of chicane on L3:FS1 with horizontal plane indicates energy: (a) with scraper out and (b) with scraper in.

Some jitter in beam energy was observed in the middle of the chicane on the flag L3:FS1. The L2 sector rf phase was fine tuned (lowered by 4°) to avoid large charge jitter when the scraper was inserted. The beam position on L3:FS1 before and after L2 phase adjustment are shown in Fig. 8. Subsequently, L4 and L5 sector RF phase were set to achieve minimum energy spread at end of linac. Linac RF phase control law set point are updated and turned on.

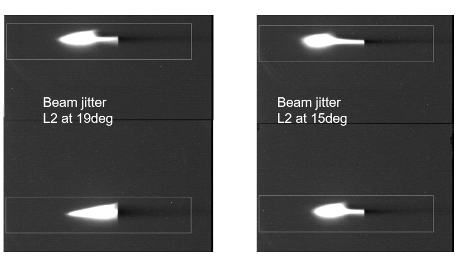

Figure 8: Energy jitter in the middle of of chicane as observed on L3:FS1 with horizontal plane indicates energy: (a) jitter before fine phase tuning and (b) jitter after fine phase tuning.

A few iterations of three-screen emittance measurement and lattice correction using four quadrupoles downstream of the chicane were performed. Beam normalized horizontal emittance was measured to be 24 µm and vertical 9 µm for the 1 nC bunch at 125 MeV. Sending linac beam down to PAR, 90% injection efficiency was obtained. A fine tuning of beam arrival time increased the injection efficiency to PAR to 100%; see Fig. 9.

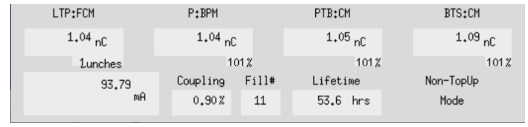

Figure 9: Beam from the prototype gun at RG2 slot is injected to PAR and booster with 100% efficiency.

After saving the configuration, linac magnets were conditioned to the saved values for verification. Under nominal operation conditions, i.e., 13.5 kV gun kicker voltage and 150 mA gun current,1 nC per linac rf pulse was confirmed with 100% PAR injection efficiency. A top-up [16] test was conducted during machine studies, and the gun was able to provide 2 nC to PTB with two linac pulses over an accumulated 8 hours, with PAR injection every two minutes with an efficiency over 95%; see Fig. 10. The prototype gun has been providing beam for APS operations since Feb. 2021.

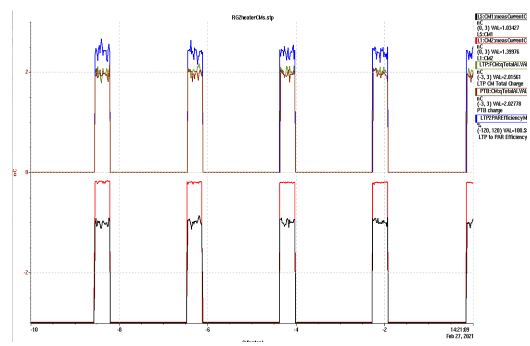

Figure 10: Topup test run with two linac pulses and 2 nC at PTB and 100% linac to PAR injection efficiency.

SUMMARY

After two decades of operation, the existing Gen-III guns are no longer able to meet the charge requirement for APS-U. A new prototype gun was commissioned successfully in the RG2 slot in Feb. 2021, confirming that the new design is suitable for APS and future APS-U operation with 1 nC per pulse delivered to PAR with 100% linac-to-PAR injection efficiency. The gun has been proven to be a reliable electron source and is now the primary source of beam for APS storage ring operation. A new version of the prototype gun design is being finalized.

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