NEW MICROWAVE THERMIONIC ELECTRON GUN FOR APS UPGRADE: TEST RESULTS AND OPERATION EXPERIENCE*

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Abstract

Recently, RadiaBeam has designed and built a robust thermionic RF gun with optimized electromagnetic performance, improved thermal engineering, and a robust cathode mounting technique. This gun allows to improve the performance of existing and future light sources, industrial accelerators, and electron beam driven terahertz sources. Unlike conventional electrically or side-coupled RF guns, this new gun operates in π-mode with the help of magnetic coupling holes. Such a design allows operation at longer pulses and has negligible dipole and quadrupole components. The gun prototype was built, then installed and tested at the Advanced Photon Source (APS) injector. This paper presents the results of high power and beam tests of this RF gun, and operational experience at APS to this moment.

INTRODUCTION

The Advanced Photon Source (APS) at Argonne National Laboratory (ANL) is a national synchrotron-radiation light source research facility that utilizes a thermionic cathode RF gun system capable of providing beam to the APS linac [1]. The previously used RF gun was a 1.6-cell side-coupled structure operating at 2856 MHz frequency. Typically, the RF gun was powered with ~3.0 MW pulsed power but could sustain up to 7 MW via an end-coupled waveguide. The cathode used was a barium-tungsten dispenser cathode with a diameter of 6 mm. The gun could produce peak beam kinetic energies of up to 4.5 MeV and peak macro pulse currents of up to 1.3 A. Normal operating RF pulse parameters were ~1 μs at a repetition rate up to 30 Hz. More details of the previous gun parameters may be found in [2]. Three generations of RF guns have been used as injectors at the APS since 1997.

APS procured three RF guns in 2001 [3] and recorded a mixed experience with these systems' performance. Two RF guns failed in 2010 due to excess reflected power. Further failures of the last spare gun would limit capabilities and suspend APS operations. Inspection of the RF gun design revealed that most of the problems came from the distortion of the mating surfaces of the gun back plate and the cathode.

To solve these problems, RadiaBeam has developed and built a new reliable and robust thermionic RF gun with the parameters specified in Table 1. This RF gun for synchrotron light sources offers substantial improvements over existing thermionic RF guns and allow stable operation with up to 1 A of beam peak current at a 100 Hz pulse repetition at 3μs RF pulse length rate and up to 5 μs at a reduced repetition rate. More details about the gun design can be found in [4-6].

Table 1: Comparison of the Developed and Existing Thermionic RF Guns Parameters

Gun	**Old**	**New**
Mode	$\pi/2$	π
Mode separation, MHz	48	22
Shunt impedance (β=0.999), MΩ/m	62.5	60
Q-factor	16000	15000
Max pulse length, μs	1.5	3.0
Max repetition rate, Hz	10	100

The gun prototype was installed at the APS injector in February 2021. The gun was RF conditioned, the thermionic cathode activated, and electron beam extracted. The beam was sent through the APS linac and tuned to achieve 100% injection efficiency to the Particle Accumulator Ring (PAR). The gun has been running well supporting APS operations since then with a 150 mA current in the past 15 months.

RF CONDITIONING

After the gun was installed, the water temperature was set to 111 °F per the LLRF measurement of resonate temperature, performed at APS. This is different from design resonant temperature which is 105°F due to a minor detuning. The water station set up for the RF gun is shown in Fig. 1. Prior to the RF conditioning, the cathode heater was set to 9.2 W at equilibrium to keep the cathode warm and clean during the RF conditioning. As the heater is turned on, a gun vacuum spike is observed as expected.

The RF conditioning went smoothly. Gun vacuum was kept below 1×10^{-7} torr during the conditioning process. Over 70 minutes, the gun was conditioned to 3 MW at 6 Hz repetition rate with an RF pulse length of 1.05 μs. The forward and reflected RF waveform of the gun are plotted in Fig. 2.

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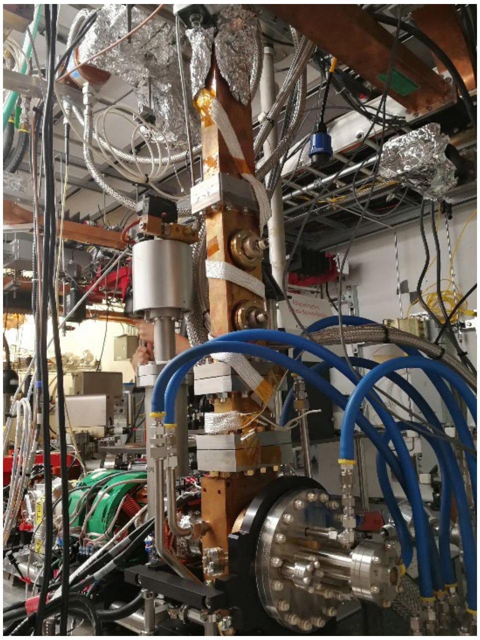

Figure 1: Thermionic gun prototype installed at Injector Test Facility at APS.

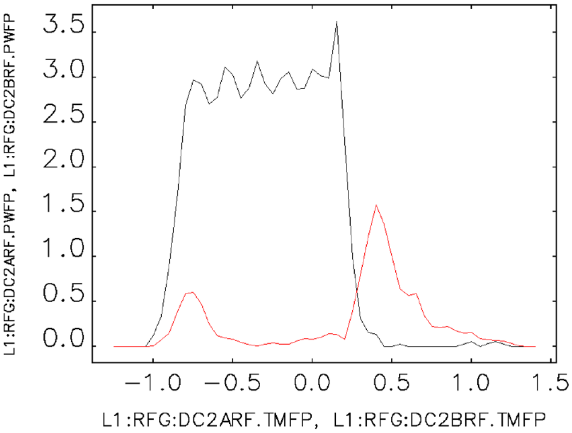

Figure 2: RF gun forward (black) and reflected (red) power waveforms.

CATHODE ACTIVATION AND BEAM EXTRACTION

After the gun was conditioned to 3 MW, the next step was to activate the cathode. During the gun installation the cathode has been heated at 25 W for several hours, however from past experience that does not guarantee that beam can be extracted without causing a gun RF trip, therefore additional processing was required.

Without any RF power directed to the gun, the cathode heater power was set to 30 W overnight. As the gun RF power was off, gun vacuum was under 1×10^{-8} torr despite the cathode heater power being set so high. After heating up the cathode at 30 W for 13 hours without RF power in the gun, the cathode was ready for beam extraction. The cathode heater power was reduced to 10 W to bring in RF power to the gun. Once RF power reached 3 MW, the cathode heater power was slowly increased to extract electron beam. At 25 W, 180 mA beam current was measured on the gun current monitor downstream of the alpha magnet, corresponding to a bunch charge of 1.8 nC. A bright beam spot was also seen on the first profile monitor, as shown in Fig. 3, left.

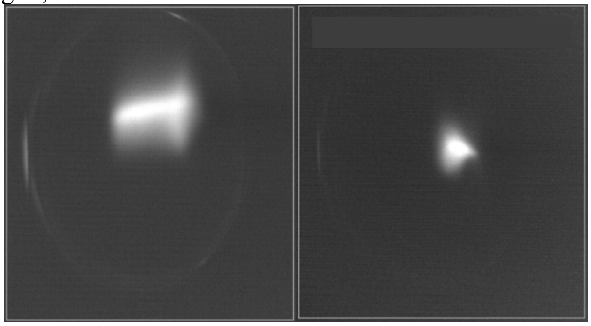

Figure 3: First observed beam with 1.8 nC bunch charge (left) and after being centered by adjusting frontend steering.

BEAM TUNING

At 180 mA gun current, the beam trajectory and linac RF phase were adjusted. With 2.4 nC measured by the current monitor at the entrance of the linac, 1.4 nC bunch charge was obtained at the linac end. The first attempt to inject beam into PAR found an injection efficiency around 70%. With this initial configuration, RCDS and simplex optimization of the front-end quadrupoles and steering magnets was performed. The simplex optimization led to a modest bunch charge increase after the chicane to 1.5 nC.

After the optimization, front-end steering elements were manually adjusted to get beam centered with a triangular profile as shown in Fig. 3, right. Subsequently, the beam entrance position and angle into the linac were adjusted and the beam was steered to the end of linac with a good trajectory while minimizing steering magnet current.

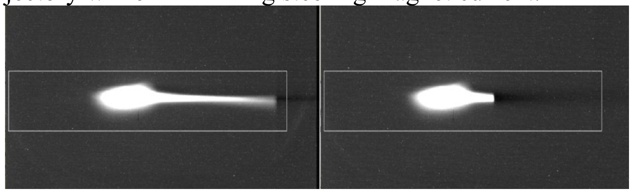

Figure 4: Beam in the middle of chicane with horizontal direction indicating energy: with scraper out (left) and in (right).

RF phase was adjusted to have minimum energy spread in the middle of chicane. The chicane's low energy scraper was inserted to remove the low energy tail as shown in Fig. 4. With the scraper inserted, charge transmission efficiency was reduced from 90% to 70%. Some beam jitter was observed, and the RF phase was fine-tuned (lowered by 4°) to avoid large charge jitter as the low energy chicane scraper was inserted. Subsequently, RF phase was set to achieve minimum energy spread at the end of linac.

A few iterations of three-screen emittance measurement and lattice correction downstream of the chicane were performed. Beam normalized horizontal emittance was measured to be 24 µm and vertical 9 µm for a 1 nC bunch at

125 MeV. Beam images on the three high-resolution emittance measurement are shown in Fig. 5.

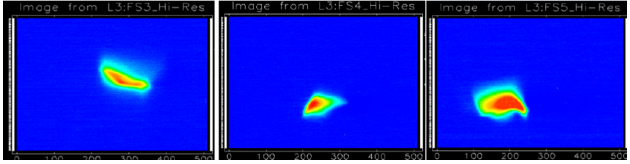

Figure 5: Beam images on the three emittance measurement flags.

INJECTION TO ACCUMULATOR RING/BOOSTER AND TOP-UP TEST RUN

After sending the beam down from the linac to PAR (LTP), we adjusted the linac beam entering angle to the LTP, the LTP steering magnet current, and fine tuning of beam energy, 90% injection efficiency was obtained. A fine tuning of gun kicker timing further increased the injection efficiency to the PAR to 100%; see Fig. 6. The linac was conditioned and a stable beam with 1 nC per bunch was confirmed with 100% injection efficiency. This charge is sufficient to support APS and future APS Upgrade operations and the new gun design has been proven to be a success.

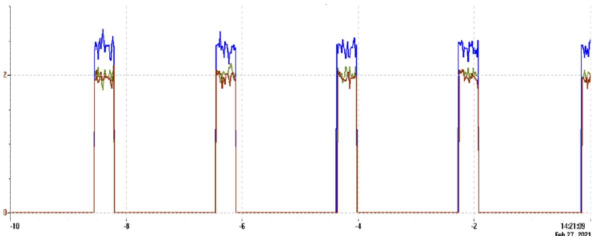

Figure 6: Top-up test run with two linac pulses, 2 nC at the main ring and over 95% linac to PAR injection efficiency. Green – Linac-to-PAR (LTP)bunch charge, brown – PAR-to-Booster (PTB) charge, blue – Linac to PAR injection efficiency.

Since the RF gun was commissioned during injector studies and the storage ring was operating in 324-bunch mode with only two injections are required per day, additional performance verification was required. To verify the gun performance for other modes, a top-up test was conducted during the injector study. During this test, the gun to booster pulsed magnets were enabled every two minutes and the beam was injected to the PAR as in 24-bunch mode top-up operation.

Under nominal operation conditions with 150 mA gun current, 13.5 kV gun kicker voltage, and 3 MW RF power, the gun was able to provide 2 nC to the PTB with two linac pulses over an accumulated 8 hours of top-up with over 95% injection efficiency as shown in Fig. 6.

SUMMARY

The new RF gun was commissioned at the APS in February 2021. The new gun design is confirmed to be suitable for APS and future APS-U operation with 1 nC per pulse delivered to the accumulator ring with 100% efficiency. The gun has been proven to be a reliable electron source and has been used to provide beam for the APS storage ring operation for the 15 months since its beam commissioning.

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