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MICROWAVE THERMIONIC ELECTRON GUN FOR SYNCHROTRON LIGHT SOURCES*

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Abstract

Thermionic RF guns are the source of electrons used in many practical applications, such as drivers for synchrotron light sources, preferred for their compactness and efficiency. RadiaBeam Systems has developed a new thermionic RF gun for the Advanced Photon Source at Argonne National Laboratory, which would offer substantial improvements in reliable operations with robust interface between the thermionic cathode and the cavity, as well as better RF performance, compared to existing models. This improvement became possible by incorporating new pi-mode electromagnetic design, robust cavity back plate design, and a cooling system that will allow stable operation for up to 1 A of beam current and 100 Hz rep rate at 3.0 µs RF pulse length, and 70 MV/m peak on axis field in the cavity. In this paper we discuss the electromagnetic and engineering design of the cavity and provide the test results of the new gun.

INTRODUCTION

A thermionic RF gun is a compact and efficient source of electrons used in many practical applications. Electron guns are used in electron microscopes, electron beam welders, and as sources for particle accelerators. Thermionic RF electron guns were developed at SLAC/SSRL for the Stanford Positron Electron Accelerating Ring (SPEAR) project [1]. These are thermionic emitters where an electron beam is pulled by RF field from the surface of a heated cathode. Conventional RF guns can offer high average beam current, which is important for synchrotron light and THz radiation sources facilities, as well as for industrial accelerators. Most of the light sources worldwide are storage ring based, and thus rely on thermionic guns for their operation. Unfortunately, they have decades-old thermionic RF gun technology, and are due for an upgrade.

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 [2]. The current RF gun is a 1.6-cell side-coupled structure, operating at 2856 MHz frequency. Typically, the RF gun is powered with ~3.5 MW pulsed power but can sustain up to 7 MW via an end-coupled waveguide. The cathode used is a tungsten dispenser cathode with a diameter of 6 mm. The gun can 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 are ~1µs at a repetition rate of ~15 Hz. More details of the gun parameters may be found in [3].

At the same time, RadiaBeam has developed and demonstrated a compact source of narrow bandwidth free space THz radiation [4] using the actual APS gun at the Injector Test Stand facility. A thermionic injector generates an electron beam, which is compressed in an alpha magnet and propagated through a few cm-long corrugated pipe radiator. A prototype system was commissioned at ANL,and demonstrated a strong signal (> 50 µJ/cm^2), at 500 µm wavelength, in ~ 5% bandwidth. While the initial commissioning of this THz source has so far been very encouraging, pushing the system performance envelope beyond 2 THz also requires an update of the RF gun performance.

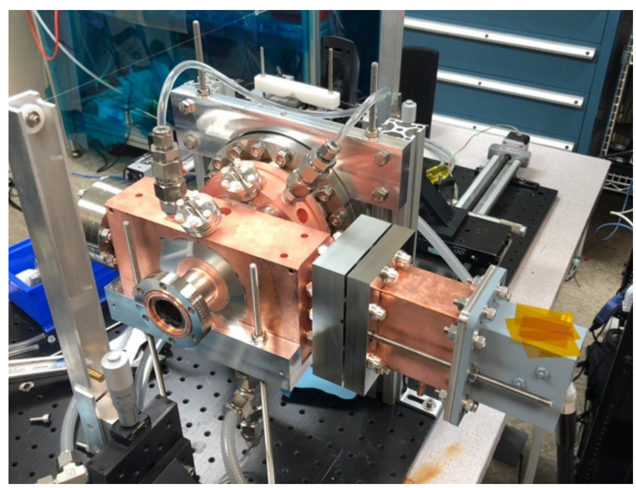

Figure 1: Picture of RadiaBeam's thermionic gun.

The design of a new, more stable and reliable gun with optimized electromagnetic performance, improved thermal engineering and more robust cathode mounting technique is a critical step to improve the performance of existing and future light sources, industrial accelerators, and electron beam driven terahertz sources.

ELECTROMAGNETIC DESIGN

RadiaBeam in collaboration with APS have developed a new reliable and robust thermionic RF gun (see Figure 1) with the parameters specified in Table 1. This RF gun for synchrotron light sources would offer substantial improvements over existing thermionic RF guns and allow stable operation with up to 1A of beam peak current at a 100 Hz pulse repetition rate and a 3.0 µs RF pulse length.

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

Gun	Current	New
Mode	$\pi/2$	π
Number of cells	1.6	
Frequency, MHz	2856	
Max. field E_1, MV/m	70.0	
Cells field ratio $E_1/E_{1/2}$	1.63	
Modes separation, MHz	48	22
Shunt impedance, MΩ/m	62.5	60
Q-factor	16000	15000
Peak surface E-field, MV/m	145	142
Max pulse length, μs	1.5	>3.0
Peak surface H-field, kA/m	~450	363
Peak heating @3μs pulse , K	~75	48.9

Conventional thermionic RF gun design implements a side coupling cell [5]. This cell is required to tune the field ratio between main cells and to increase frequency mode separation in the cavity. However, such design has several significant drawbacks. First, an additional cell complicates the engineering design and fabrication process. Second, it breaks the symmetry of the structure. Finally, due to the sharp edges in the area where accelerating cells connect to the coupling cell, the peak surface magnetic field can be strong in this area. Strong magnetic field increases the pulsed heating temperature gradient and limits the performance of the RF gun both by reducing the maximum gradient and by limiting the pulse length [6].

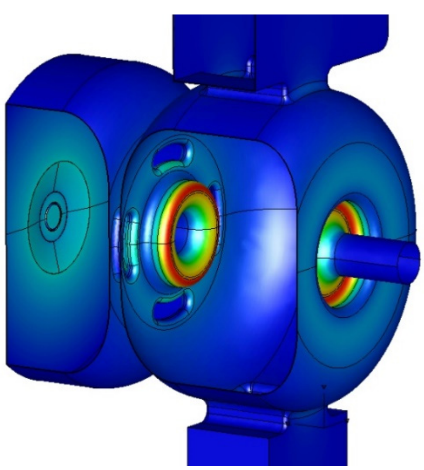

Figure 2: Electromagnetic design of the thermionic gun: surface electric field distribution.

In our design, we have removed the coupling cell and added magnetic coupling holes to the iris between the cells to provide required mode separation and similar dimensional sensitivity without any change to the electrodes shape (see Figure 2). In this case, the structure operates in π-mode, and magnetic field will provide the coupling. Pin tuners in each cell will allow the tuning of the field ratio.

The magnetic coupling holes cause the longitudinal field asymmetry in the full cell. To compensate this effect, we reduced the blending radius of one side of the cavity.

The beam dynamics simulation results demonstrate that the π-mode gun design produces the symmetric beam with no transverse deflection due to the absence of non-symmetric dipole field component from the coupling cell in the original $\pi/2$ design as shown in Figure 3. The transverse emittance of the modified gun is smaller than one of the original, while the energy chirp is preserved. The detailed study of the dipole and quadrupole impedances of the original and modified guns with the attached RF couplers was performed according to [7]. The results confirmed the elimination reduction in the dipole asymmetry without any increase of the quadrupole component.

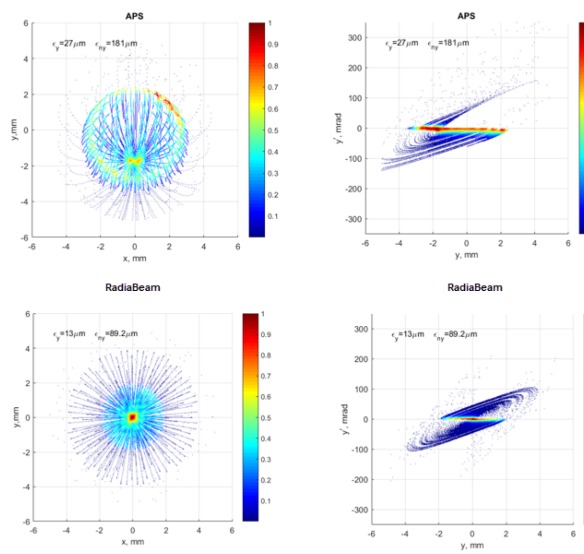

Figure 3: Comparison of beam profile (left) and transverse phase space (right) of the existing APS (top) and developed RadiaBeam (bottom) thermionic guns.

CST PIC solver was used for simulation of the beam back bombardment effect. Average heat values for 3μs and 100 Hz repetition rate are the following: back-plate – 7.4W, cathode – 13.3 W. Most of the energy dissipated on the back-plate is distributed inside a ring.

ENGINEERING DESIGN

The cathode backplate is one of the most critical parts of the thermionic gun. It must provide thermal isolation of the hot cathode to exclude the field distortions due to the plate deformation. Also, the electrical contact of the cathode and the back plate should be provided, so that RF fields do not get into the gap between the cathode and the back plate and therefore damage the structure.

We have designed the indirect cooling scheme to provide active cooling of a removable gun backplate, along with thermal sensors to monitor the backplate temperature and direct water cooling of the main coupler body. The indirectly cooled detachable backplate was chosen as it permitted flexibility of back plate modifications and experimen-

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tation. Thermionic gun integration involved mounting directly to the cathode plate to allow the best alignment of the gun on the backplate.

RF contact is maintained via a toroid spring inside the cathode assembly. We have chosen to use the Heatwave 61280 commercial cathode for its proven operation history and availability. The cathode was modified to fit the modified electrode thickness. A viewport was added to measure the temperature of the cathode, along with RF probes placed within each cell on the structure.

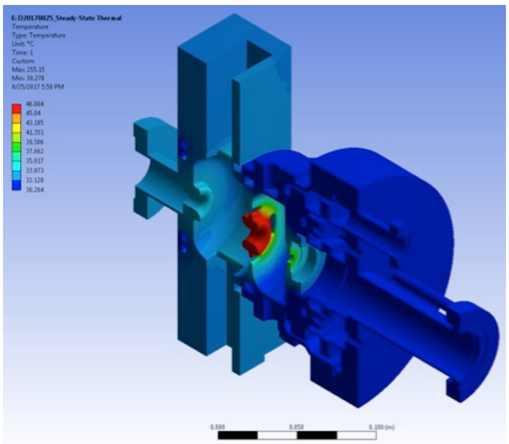

Figure 4: ANSYS thermal simulation of the gun.

The model of full assembly was used for thermal analysis (Figure 4). Comparing with the test assembly, the cavity geometry is different, a number of water cooling channels becomes three instead of two. The results of this analysis suggest that the temperature difference within the cavity body is less than 17° C. Since the cathode structure is identical to the test assembly, the heat loads from the hot cathode are the same. However, the RF heat load is different from the test assembly. With the temperature profile, the profile of thermal deformation can be obtained as well, which is less than 21 μm within the cavity.

FABRICATION AND TESTS

The manufacturing approach of this gun followed typical RadiaBeam recipes for high gradient normal conducting RF devices. Gloved handling is employed in all machining operations, sulphurized and chlorinated cutting fluids are never utilized, copper specific cutting tools and only brass or stainless steel fixtures are used for part holding. The surface finishes obtained on the cavity interior range from 2 microinches to 6 microinches. The device part dimensions were validated by Coordinate Measuring Machine (CMM) measurement. The device components were cleaned utilizing a modified version of the SLAC etching formulary.

The final brazing of the device was performed and the device passed He leak testing below the measurable limit of our Pfeiffer ASM340D with no observable signal below 10^{-10} STD-cc/s.

The measurements of the resonant frequency, coupling coefficient, Q-factor and field profile were taken before the brazing cycles (structure was clamped) and right after brazing. The structure performance is in good accordance with 3D EM simulations; noticeable deviations from nominal characteristics can be removed with further tuning. Measured post-braze frequency was 2855.45 MHz with 24.88 MHz mode separation, coupling of 1.91, and Q-factor of 14200. at 25°C, 1 atm pressure.

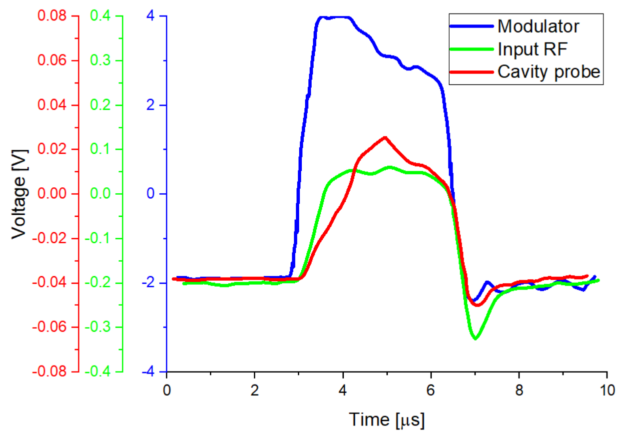

Figure 5: Measured RF signals during the conditioning: modulator RF pulse (blue), input RF power (green) and RF field envelope inside the structure (red).

Conditioning of the gun was completed with 4 μs RF pulse width at 100 Hz repetition rate, and a peak power of about 3.16 MW. The gun was also conditioned up to 3MW peak power with a 5 μs pulse width and 10 Hz repetition rate. Vacuum stayed in the range of $2.0 \cdot 10^{-8}$ torr during con-ditioning (Figure 5). However, with no RF power, the pressure reached $6.0 \cdot 10^{-9}$.

SUMMARY

This RF gun for synchrotron light sources offers substantial improvements over existing thermionic RF guns and incorporates the following innovations:

- Improved RF design that can operate at longer pulses and has negligible dipole and quadrupole components;
- Robust cavity back plate that eliminated the thermally induced detuning that plagued the previous design;
- Indirect cooling scheme to provide active cooling of a removable gun backplate, along with thermal sensors to monitor the backplate temperature;
- Cathode seating and alignment provisions along with vacuum considerations were integrated into the design;
- Back plate geometry allowing easy cathode exchange capability;
- Viewport added to measure the temperature of the cathode along with the RF probes placed at two different cells to measure the field profile;
- Pin tuners in each cell provide the tuning of the field ratio and frequency;
- Use of commercially available Heatwave 61280 cathode, assures proven operation history and availability.

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REFERENCES

[1] E. Tanabe *et. al.*, "A 2-MeV Microwave Thermionic Gun", SLAC, Melno Park, CA, USA, Rep. SLAC-PUB-5054, Jul. 1998.

[2] J.W. Lewellen *et al.*, “Operation of the APS RF Gun”, in *Proc. XIX International Linac Conference (Linac’98),* Chicago, IL, USA, Aug. 1998, paper TH4042, pp. 863-865.

[3] M. Borland, “Cavity Design and Beam Simulations for the APS RF Gun”, *APS Light Source Note*, Chicago, IL, USA, Rep. LS-186, Nov. 1991.

[4] A. V. Smirnov *et al.*, “Observation of a variable sub-THz radiation driven by a low energy electron beam from a thermionic RF electron gun”, *Phys. Rev. ST AB* 18, 090703, 2015. doi: 10.1103/PhysRevSTAB.18.090703

[5] K. Beczek, J.W. Lewellen, A. Nassiri, E. Tanabe, “A Rationalized Approach to Thermionic RF Gun Design”, in *Proc. 2001 Particle Accelerator Conference (PAC’01),* Chicago, IL, USA, Jun. 2001, paper WPAH052, pp. 2206-2208.

[6] D.P. Pritzkau, “RF Pulsed heating”, Ph.D. thesis, Dept. Appl. Phys., Stanford University, Stanford, CA, USA, 2001.

[7] [A. D. Cahill, M. Dal Forno, and V. A. Dolgashev, “TM01 Mode Launcher for Use in High Brightness Photoguns”, in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 491-493. doi:10.18429/JACoW-IPAC2016-MOPMW039