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HIGH-POWER TEST OF A HIGHLY OVER-COUPLED X-BAND RF GUN DRIVEN BY SHORT RF PULSES*

J. Shao†, P. Piot[1], X. Lu[1], S. Doran, W. Liu, J. Power, C. Whiteford, E. Wisniewski
Argonne National Laboratory, Lemont, IL, USA
S. Kuzikov, C. Jing, Euclid Techlabs LLC, Bolingbrook, IL, USA
W. H. Tan, Northern Illinois University, DeKalb, IL, USA
[1]also at Northern Illinois University, DeKalb, IL, USA

Abstract

Beam brightness, a key figure of merit of RF photocathode guns, can be improved by increasing the cathode surface field which suppresses emittance growth from space charge. The surface field in normal-conducting structures is mainly limited by RF breakdown and it has been experimentally discovered that RF breakdown rate exponentially depends on RF pulse length. A highly over-coupled 1.5-cell X-band photocathode gun has been developed to be powered by 9 ns RF pulses with 3 ns rising time, 3 ns flat-top, and 3 ns falling time generated by an X-band metallic power extractor. In the recent experiment at Argonne Wakefield Accelerator facility, cathode surface field up to ~350 MV/m with a low breakdown rate has been obtained under ~250 MW input power. Strong beam loading from dark current was observed during RF conditioning and quickly recovered to a negligible level after the gun reached the maximum gradient. Detailed high-power test results and data analysis will be reported in this manuscript.

INTRODUCTION

High-brightness photocathode RF gun is the enabling tool for many high-impact scientific machines, such as free-electron laser, ultrafast electron diffraction/imaging, and wakefield accelerator [1]. The development of these machines poses demanding requirements for next-generation photocathode RF guns. In general, high cathode surface field is favorable to mitigate emittance growth from space charge, but it is usually limited by RF breakdown, dark current beam loading, and average heat management in normal conducting structures.

We have proposed a new type of RF photocathode gun based on ns-scale pulse technology [2]. The pulse length is at least 2-3 orders of magnitude shorter than the ones used in current guns. Compared with state-of-the-art guns, higher gradient is expected by using ns-scale pulses according to the extensive research of RF breakdown in normal conducting structures [3]. With the same average cooling capacity, the gun may also operate at higher repetition rate as pulse heating reduces with pulse length. In this manuscript, we present the high-power test of the first prototype that successfully achieved ~350 MV/m cathode field.

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† shaojiahang2021@outlook.com

STRUCTURE OVERVIEW

The first prototype is designed to be driven by a metallic disk-loaded X-band power extractor at the Argonne Wakefield Accelerator facility (AWA) [4]. The 1.5-cell gun works at π-mode with four magnetic slots between cells to ensure large mode separation. A coaxial coupler is used to couple the input RF power with high coupling factor so as to reduce the loaded quality factor and the filling time, as illustrated in Fig. 1. The main RF parameters of the gun are summarized in Table 1 and more details can be found in Ref. [2].

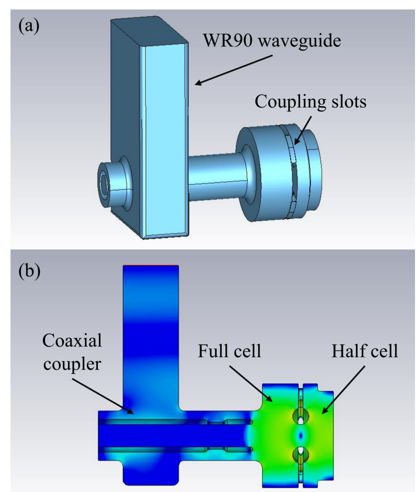

Figure 1: (a) Layout of the X-band RF photocathode gun. (b) Electric field distribution.

Table 1: RF Parameters of the Photocathode Gun

Parameter	Value
Frequency	11.7 GHz
Q_{load}	180
Mode separation	250 MHz
RF pulse length	9 ns (3 ns flat-top)
Maximum input power	250 MW
Corresponding cathode field	470 MV/m

COLD TEST

The cavity transient response is critical to determine the cathode surface field with short RF pulses. After brazing, the measured S-parameter of the gun shows good agreement

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with CST simulation, as illustrated in Fig. 2. Therefore, the simulated transient response of the cathode field is used in the following analysis. Figure 3 presents the comparison of cathode field when the gun is driven by long (100 ns flat-top) and short (3 ns flat-top) RF pulses. It can be seen that the maximum cathode field in the short pulse case can reach 67% of the steady status since the gun is not fully filled.

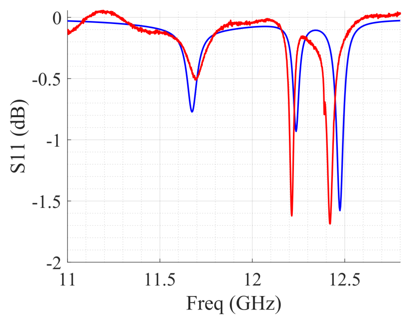

Figure 2: Comparison of S11 of the gun between CST simulation (blue) and cold test (red).

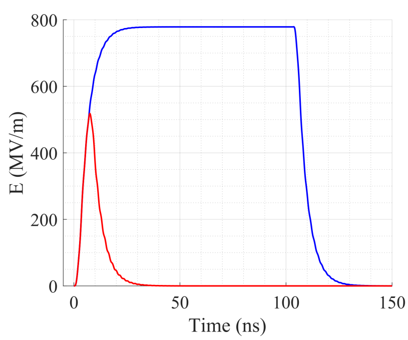

Figure 3: Comparison of the transient cathode gradient when driven by long (blue) and short (red) pulse. In both cases, the input power is fixed at 300 MW and the rising/falling edge is fixed at 3 ns.

HIGH-POWER TEST SETUP

The high-power test setup at AWA is illustrated in Fig. 4. The generated RF pulses from the power extractor were transferred to the gun by a WR90 waveguide. The reflected power from the gun moved back along the power extractor and was absorbed by a RF load at the drive beam entrance upstream. A calibrated directional coupler was installed between the power extractor and the gun to monitor the incident and the reflected pulse. A YAG screen was installed at the gun exit to monitor dark current. More details of the drive beamline configuration and diagnostics can be found in Ref. [5].

HIGH-POWER TEST RESULTS

RF conditioning of the X-band photocathode gun took ~11.5 hours at 2 Hz repetition rate and accumulated ~82800 pulses. Limited by the data acquisition program as well as the beamline tuning, the RF signals of 5765 pulses were recorded by a 12 GHz, 50 GS/s oscilloscope.

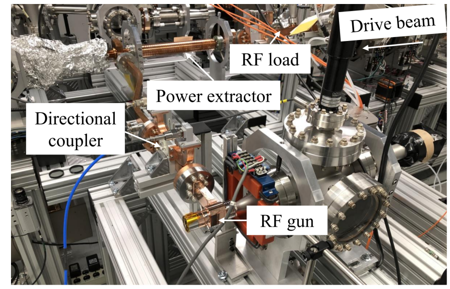

Figure 4: Experimental layout of the photocathode RF gun high-power test at AWA.

The number of drive bunches was fixed to eight and the typical RF pulse shapes are illustrated in Fig. 5. Due to the non-ideal charge balance of the drive bunch train, the flat-top of the forward pulse was shorter than 3 ns. The corresponding cathode field has similar transient shape as the ideal case shown in Fig. 3 (red curve), but its peak value is ~25% lower (i.e. ~350 MV/m with 250 MW input power). Under normal operation with no RF breakdown and negligible dark current beam loading, the reflected pulse shape can be predicted by convoluting the incident pulse shape and S11 from cold test, which usually shows good agreement with the measurement. We define R as the peak amplitude ratio between prediction and measurement.

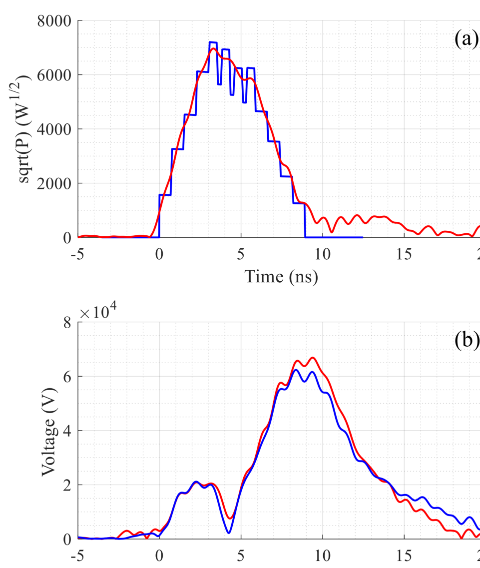

Figure 5: Typical incident (a) and reflected (b) RF pulse. The red curves represent measurement. The blue curve in (a) represents the predicted shape based on wakefield properties of the power extractor (no coupler included) and the realistic charge balance. The blue curve in (b) represents the convoluted result of the incident pulse and the cold test S11.

The gun was RF conditioned by gradually increasing the drive beam charge. The shot-to-shot cathode field variation can be as large as ±20% due to the charge fluctuation. The conditioning history of the RF photocathode gun is illus-

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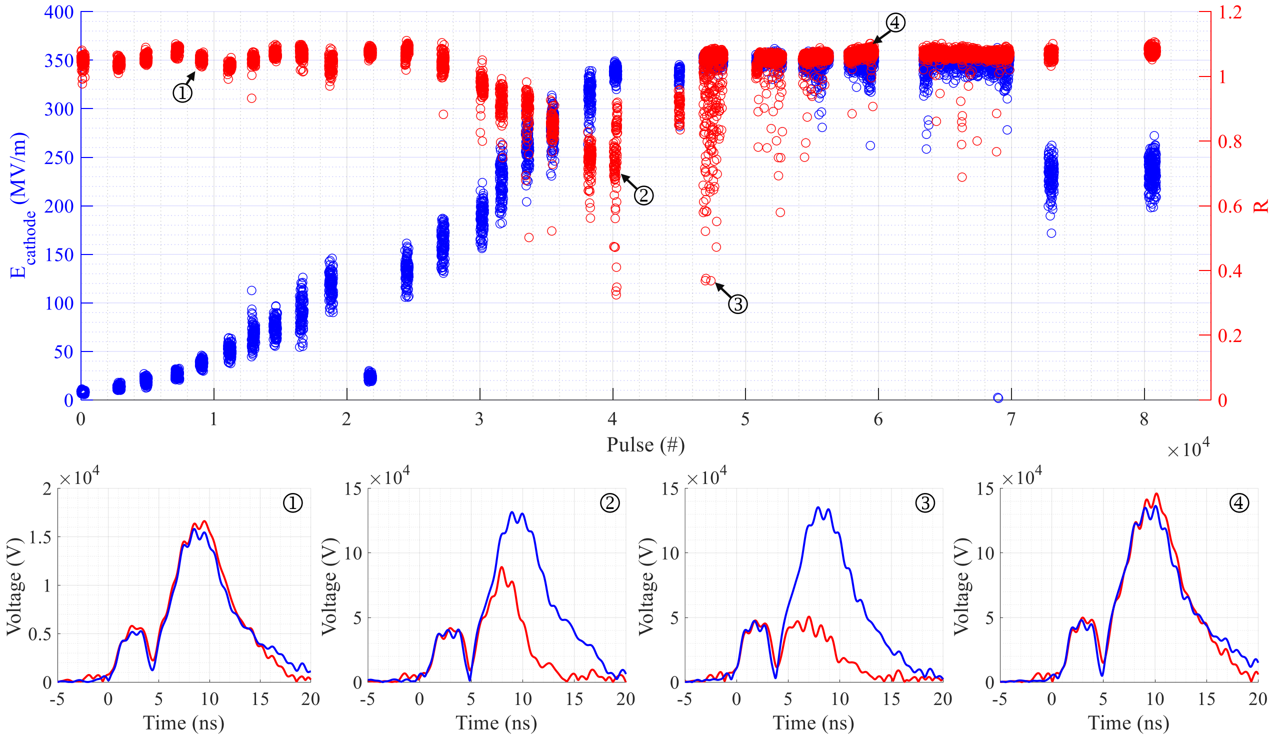

Figure 6: Conditioning history of the X-band photocathode gun. The blue dots represent the calculated cathode gradient and the red ones represent R. The data between vertical groups was not recorded. The typical pulse shapes during conditioning are illustrated in the bottom indexed figures.

trated in Fig. 6, including the calculated cathode field (by convoluting the simulated transient response and the incident pulse shape) together with the parameter R.

The conditioning history can be divided into four periods according to the structure behavior. When the cathode gradient was lower than 200 MV/m, R was close to 1, indicating normal operation. As the field was pushed to 350 MV/m, R dropped continuously and bright spots could be seen on the YAG screen at the gun exit. We suspect such behavior was caused by beam loading from field emission current. A circuit model that could match the measured pulse shape will be needed to fully understand the dark current amplitude and pulse duration. After reaching ~350 MV/m, R quickly recovered to 1 but there were abrupt and separated drops, which could be caused by RF breakdowns. After staying at the maximum gradient, the possibility of abnormal R significantly reduced to the order of 1×10^{-2}. The measured reflected pulse shape also shows good agreement with prediction after conditioning.

CONCLUSION

A highly over-coupled X-band photocathode gun has been developed to reach high cathode surface gradient. The gun is designed to be driven by ns-scale short RF pulses generated from a power extractor. ~350 MV/m surface gradient has been achieved with negligible dark current in the high-power test of the first prototype at AWA. The second prototype is currently under test for photoelectron generation and characterization.

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