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1. Summary

An ultra-compact Back-Lighted Thyatron (BLT) holds the promise in high voltage (above 30 kV), high current (peak current > 10 kA) switching at high repetition rates (>1 kHz) in a small volume (100 cm³ or less). A helium-filled mini-BLT with the effective electrode volume of 15 cm³ was demonstrated to hold off 40 kV. Novel approaches enabling compact and affordable optical triggering are essential for the development of ultra-compact BLTs. Photocathodes with relatively high quantum efficiencies while still sufficiently robust to survive in a BLT-relevant discharge environment were investigated. Mg was identified to be the most promising metal photocathode material compared to Cu and Mo. Besides the Schottky effect, secondary electron emission due to the formed MgO layer at the surface of the Mg foil was considered to play an important role in the photon-induced discharge initiation process, which results in improved triggering characteristics for Mg photocathodes. In addition, compact optical triggering sources based on intense ultraviolet light emitting diodes (UV LEDs) were assembled for BLT triggering. Although the current version of the light source based on a single UV LED failed to trigger the BLT, approaches combining intense UV LED lamps and novel photocathodes with higher quantum yields would result in compact optical triggering for ultra-compact BLTs.

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2. Introduction

Light-activated pseudospark switches, also called back-lighted thyratrons (BLTs), are low pressure, high voltage (typ. 10~50 kV), high current (typ. 1~100 kA) glow-mode switches. It is of interest to develop BLTs with reliable and practical optical triggering systems for applications of compact pulsed power. The goal of this research is to understand the fundamental physical mechanisms and processes underlying discharge initiation in a compact optically triggered pseudospark switch, and thereby to identify novel approaches for the development of mini-BLTs. This will benefit the development of compact pulse power technology in a variety of AF applications including pulsed power switches for high power microwave (HPM), compact high density electron beam sources for HPM, and pulsed detonation engine technology.

To achieve this end, hydrogen or helium-filled mini-BLTs with an effective electrode volume of 15 cm³ were tested for their hold-off capabilities. Metal photocathodes with relatively high quantum efficiencies while still sufficiently robust to survive in a BLT-relevant discharge environment were investigated. Compact optical triggering sources based on incoherent intense ultraviolet light emitting diodes (UV LEDs) were studied. Approaches attempt to multiply seed electrons for BLT breakdown were discussed.

3. Experimental Setups and Procedures

3.1 Ultra-compact BLTs

An ultra-compact BLT (mini-BLT) with the effective electrode volume of 15 cm³ was engineered [1]. The schematic of the dismountable mini-BLT and its testing circuitry are shown in Figure 1. The electrodes were made of oxygen-free, high conductivity (OFHC) copper tubing capped with molybdenum studs. High voltage capacitors (total capacitance, 16 nF) were axial-symmetrically distributed around the switch. A 2.2 ohm resistor was in series with the switch. A UV laser (Continuum powerlite 8000) or a UV flash lamp (EG&G FX265) was used to trigger the switch.

The mini-BLT filled with helium was integrated into a pulsed power supply, as shown in Figure 2, to generate 60 kV, 100 ns voltage pulses at a 100 ohm load. This pulse generator was able to initiate nanosecond transient plasmas for combustion ignition [1].

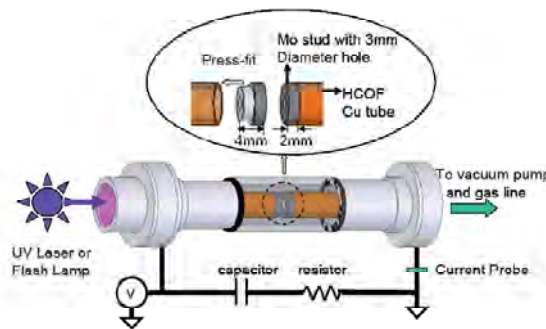


Fig. 1 Mini-BLT and the testing circuitry [1]

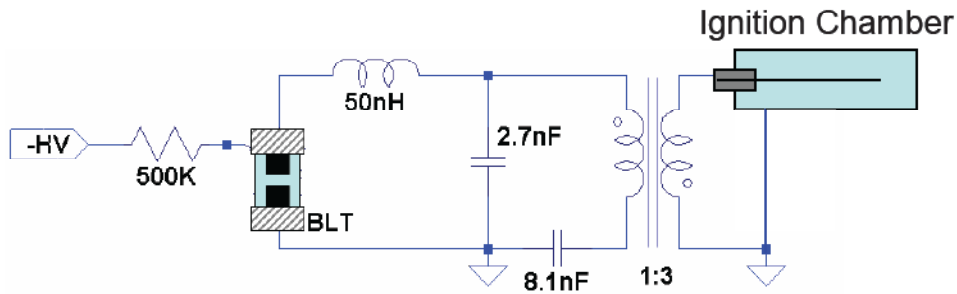


Fig. 2 Schematic of a mini-BLT-switched pulsed power generation circuitry for plasma assisted combustion ignition [1]

3.2 Quantum efficiency measurement of metal photocathodes and a 2D electrostatic simulation of the Electric field distribution in a BLT

Extensive literature research was conducted to identify potential photocathodes for BLT applications. Metal photocathodes were considered to be the most promising candidates due to their relatively high quantum efficiencies while still sufficiently robust to survive in a BLT-relevant discharge environment [2]. Table 1 lists the reported quantum efficiencies (QE's) of magnesium, copper, and molybdenum [2]. The QE's of the three metal photocathodes were measured and compared. The experimental setup is shown in Figure 3a,b. The setup consists of a measurement chamber, a vacuum pumping system, pressure gauges, a UV laser (as the light source), and other electronics system for electrical diagnostics, as shown in Figure 3a. A high vacuum up to 10^{-7} Torr was obtained in the chamber as the base pressure. Inside the chamber, photocathode samples were placed on a 45 degree holder facing the incident laser beam. A 9.5 mm diameter, 12.7 mm long cylindrical Faraday cup, was placed ~ 10 mm above the sample. The measurement circuit, in a high pass filter layout, records the fast photoelectric current excited by the 5 ns (FWHM) laser pulse at 266 nm. A frequency quadrupled Nd:YAG laser (Continuum 8000 powerlite) was used as the light source. The average incident energy per pulse on the cathode is 54.9 μ J. The laser beam was directed into the chamber without any focusing. The spot diameter on the sample surface was measured to be 3 mm.

A 2D electrostatic simulation of the electric field distribution in the BLT before breakdown was conducted [2]. The simulation work is to understand the electric field-posed effects, if any, on photocathodes in a typical BLT geometry. A 2D finite-element, electrostatic code, EStat¹ was performed for a typical BLT switch geometry. A cylindrically symmetric geometry is used for simulation purposes, and the dimensions on the figure are in mm. A 30 kV potential difference is applied across the hollow cathode and anode which are assumed to be perfect conductors (Dirichlet boundary condition). Each electrode has a 3 mm diameter central hole, and the electrode spacing is 3 mm. All corners are rounded with a 0.1 mm radius in order to limit field enhancement due to sharp edges. The figure shows only a portion of the simulation space in order to see details at the electrode surfaces; the actual simulation included the entire geometry of the switch to include the insulating outer wall (Nuemann boundary condition).

¹ Simulations were performed using finite-element electrostatic software available from Field Precision, Albuquerque, NM (see <http://www.fieldp.com/>).

Table 1. Reported quantum efficiencies of Mg, Cu and Mo. The measurement vacuum condition and the applied electric field on the surface of the sample were indicated.

Material	Φ (eV)	λ (nm)	QE	Pressure (Torr)	E Field (MV/m)
Cu	4.5	308	2×10^{-6} [12]	1×10^{-7}	~ 0.3
		222	5×10^{-5} [12]		
		266	1×10^{-5} [17]	1×10^{-8}	100
		266	5×10^{-4} [18]	$< 1 \times 10^{-7}$	130
Mg	3.66	266	$> 3 \times 10^{-4}$ [8]	$< 1 \times 10^{-8}$	> 4
		266	2×10^{-3} [6]	$< 1 \times 10^{-9}$	> 3
		266	1.5×10^{-5} [7]	7.5×10^{-9}	1
		266	1.7×10^{-3} [19]	7.5×10^{-9}	1
		262	1.0×10^{-3} [9]	2.25×10^{-8}	57
Mo	4.3-4.6	222	2.07×10^{-5} [20]	1×10^{-7}	0.3

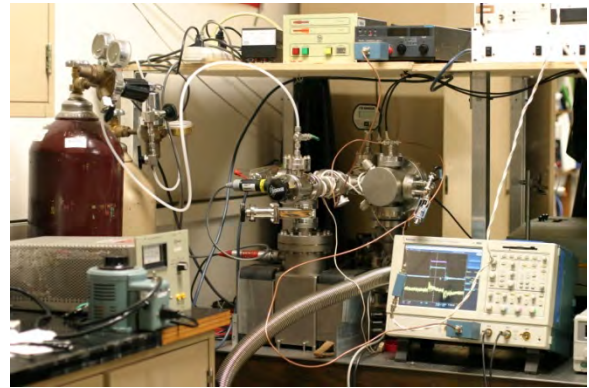
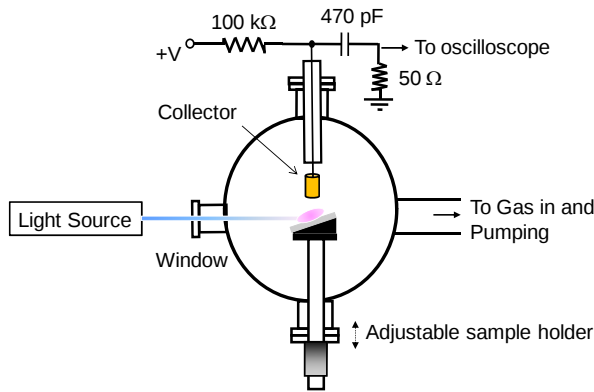


Fig. 3 Experimental Setup of the quantum efficiency measurement for metal photocathodes: (a) the schematic, and (b) a picture of the setup (the light source is not shown).

3.3 Mg-based photocathodes for BLTs

Mg-based photocathodes for potentially improving BLT switching or triggering characteristics were investigated. The switch delay and jitter, hold-off voltage, and maximum pulsed current were measured and compared for the BLT system with and without the application of Mg [3]. The experimental setup is shown in Figure 4a,b. When the Mg foil was applied, a 250 μm thick

Mg foil was placed against the back surface of the hollow-cathode that was made of oxygen-free Cu, as shown in Figure 4a. 3 mJ, 5 ns laser pulse at 266 nm was incident on the back surface of the Cu cathode or the inserted Mg foil. The optical pulse was generated by a frequency-quadrupled Nd:YAG laser (Continuum Minilite II). A standard sample cleaning protocol was always followed to ensure the repeatable condition of the Mg foil surface. The Mg foil (purchased from Alfa easer.com) was polished with 1200 grit SiC sand paper, followed by 30 min ultrasonic cleaning in hexane bath. Laser cleaning for 20 min at 10 Hz were applied after placing the sample in the hollow cathode, prior to taking the experimental measurements.

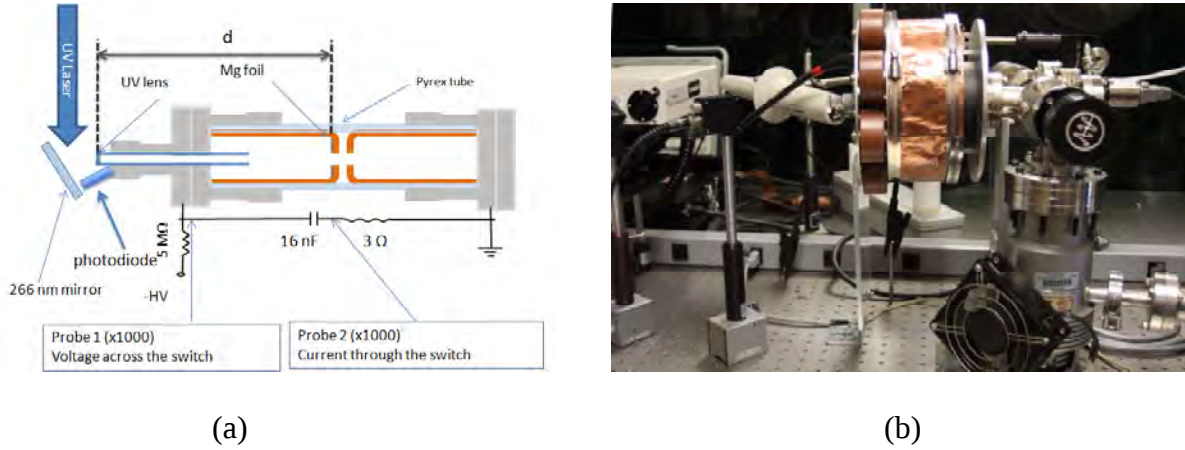


Fig. 4 Experimental setup of application of Mg-based photocathodes for BLTs: (a) The schematic including the testing circuitry. The distance between the lens and the Mg foil is 13 cm. (b) The setup picture.

3.4 Investigation of the feasibility of utilization of intense UV LEDs as compact optical light sources for BLT triggering

A UV LED was obtained from Sensor Electronic.com. A pulse generator was designed and assembled to drive the LED, which emits at 270 nm with the FWHM of 10 nm. The LED emission was recorded with a photodetector (Thorlabs DET 25K), as shown in Figure 5a. The CW power of the UV LED was compared with the pulsed power, as shown in Figure 5b. Maximum pulsed optical power of 2.5 mW was measured at 120 mA when the LED was driven with 500 ns pulses at 10 kHz [4].

In order to determine the minimum number of photoelectrons needed to trigger a BLT, a positively biased coaxial probe was inserted from the hollow anode side into the switch. The experimental setup is shown in Figure 6. The energy of incident light pulse was adjusted such that the switch was barely triggered. In this case, 5 ns, 55 μ J per pulse energy, generated by a Nd:YAG frequency quadrupled laser (Continuum Minilite II), was used for the measurement. The measurement circuit consisted of a current limiting resistor and a high-pass filter scheme to record the photocurrent.

The resulted optical energy per pulse, 1 nJ, is at least 3 fold less than that of the previously used incoherent UV light sources capable of triggering BLTs. Seed electrons in the order of 10^7 were estimated as the critical number of electrons for reliable BLT triggering. This also suggests that UV optical triggering with 3 fold higher intensity than the output of the UV LED is needed [4]. The use of UV LED lamps which integrate up to 100 UV LEDs can increase the optical output intensity to 1-2 folds. The application of novel photocathodes such as Mg and MgO-based cathodes will be able to reduce the intensity requirement for BLT triggering. We are in the process of combining the two schemes therefore to develop compact BLT with compact optical triggering.

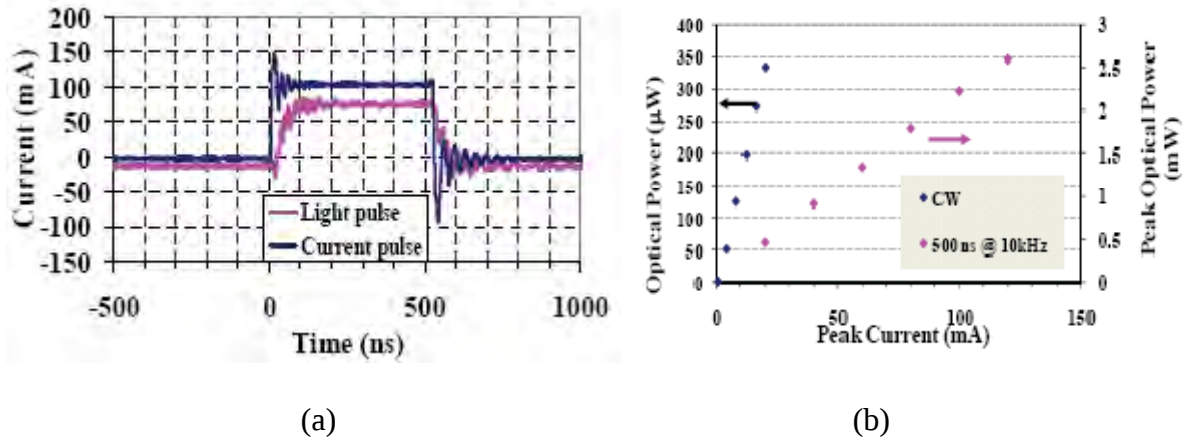


Fig. 5 (a) Output waveforms of a UV LED (UVTOP-270), driven by a customized pulse generator; and (b) the output pulse power with respect to the pulse current when the LED was driven by 500 ns, 100 mA current pulse at a repetition rate of 10 kHz. The optical output of the LED operating at continuous mode was also plotted for comparison. [4]

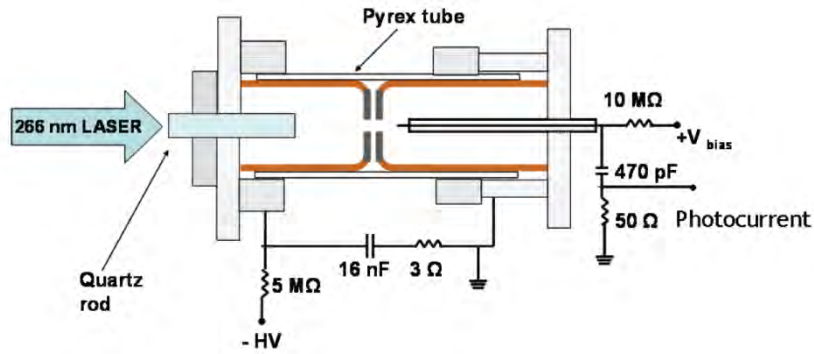


Fig. 6 Experimental setup for the photoelectron measurement [4]

3.5 Investigation of electron multiplication channels to increase the photon-induced seed electrons for BLT breakdown

Several electron multiplication schemes were proposed to amplify the photoelectrons from the primary photoelectric emission. A gaseous electron multiplier (GEM) was proposed as a try-and-

error practice [5]. The GEM depends on gaseous ionization within high-field millimeter or sub-millimeter in dimension channels. For the preliminary test, a single-stage GEM made of PCB board was attached to a collector electrode in a stainless steel chamber filled with Ar at a mini-BLT-relevant pressure (e.g. 800 mTorr), as shown in Figure 7. The primary electrons were generated by the photoelectron emission from a magnesium foil surface with the incidence of an incoherent light pulse. An electron multiplication up to 1000 was obtained when a bias voltage of 100 V was applied [5].

Although the electron gain of the tested GEM indicated sufficient multiplication of electrons in a BLT-relevant discharge environment, the electric circuitry required for the GEM would pose complicated electrode configurations for the BLT, which will compromise the advantageous characteristics of BLTs including optical insulation, simplicity, and compact housekeeping. For these considerations, research efforts were consequently focused on application of secondary electron emitter materials for BLT electrodes to achieve the same and more reliable multiplication of electrons.

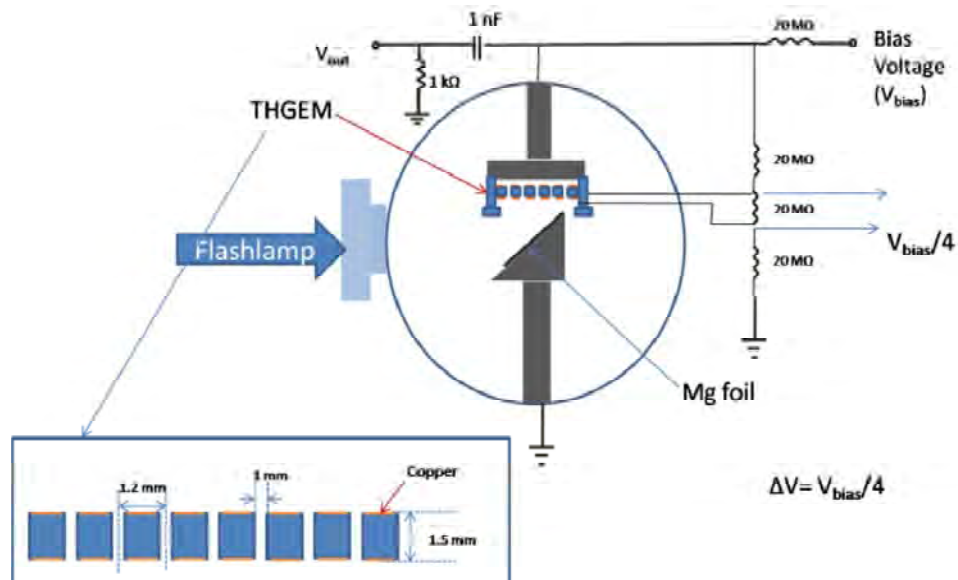


Fig. 7 Gaseous electron multiplier test bed, inset shows the dimensions of the multiplier [5].

4. Experimental Results/accomplishments

4.1 Performance of the mini-BLT [1]

Hold-off voltages greater than 40 kV were obtained in both helium and hydrogen. The switch holds off higher voltages in helium at the same pressure compared to that in hydrogen, as shown in Figure 8. As high as 4.5 kA peak current with a current rise rate of 10^{11} A/s was achieved when the 16 nF capacitor bank was charged with 40 kV. It was observed that higher switch operation pressure resulted in shorter dV/dt and less jitter and delay. Smaller switch volume enables the switch to operate at relatively high pressure while still maintaining high hold-off.

Minimum delay of $30 \text{ ns} \pm 2 \text{ ns}$ was achieved when a 355 nm laser pulse ($>70 \text{ mJ/pulse}$) incident at the back surface of the cathode, as shown in Figure 9. Higher energy optical pulses produced more photoelectrons during the 5-7 ns optical pulse duration and resulted in shorter delay and jitter. A flash lamp (EG&G FX265) was also used to trigger the BLT, but the delay and jitter were in the range of several hundreds of nanoseconds and several microseconds. As low as $50 \mu\text{J/pulse}$ optical energy from the flash lamp was observed to trigger the BLT.

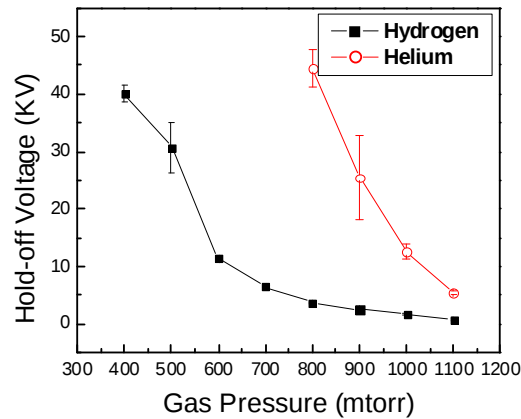


Fig. 8 Pressure dependence of the hold-off voltage for the mini-BLT filled with helium or hydrogen. Each data point was averaged over 30 samples. For the hold-off voltage less than 10 kV, which corresponds to $>1100 \text{ mTorr}$ for the helium-fill or $>600 \text{ mTorr}$ for the hydrogen-fill, 10% variation of the mean was recorded. [1]

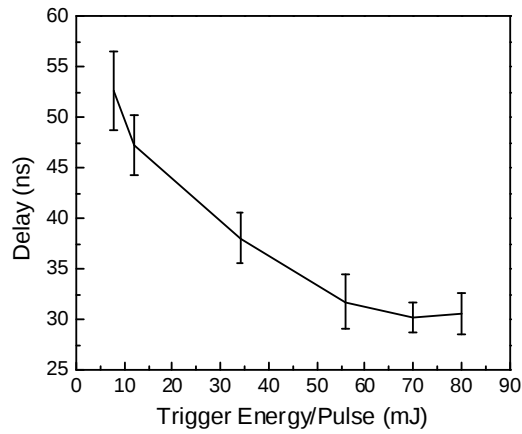


Fig. 9 Delay and jitter of the mini-BLT, filled with He at 800 mTorr, as a function of the pulsed laser triggering energy (5 ns at 355 nm). Each data point was the average of 20 measurements. [1]

4.2 Quantum efficiencies of metal photocathodes for BLTs [2]

The quantum efficiencies of Mg, Cu and Mo in a range of helium pressure of 3×10^{-7} to 0.1 Torr were measured and compared, as shown in Figure 10. Under 0.1 Torr helium – a typical operation pressure for BLTs but much higher than other reported high vacuum conditions for photocathodes, Mg and Cu photocathodes indicated QE's of 50% more than that of Mo. After all, Magnesium has the highest quantum efficiency among all three samples, up to 1.5×10^{-5} at 0.1 Torr. Strong dependence of the QE's of the photocathodes on the electric field at the sample surface was observed, and was contributed to the Schottky effect.

The 2D electrostatic simulation results indicated high to low electric field regions, mapped with color contours, as shown in Figure 11. The strong electric field region is around the electrodes at the gap, as shown in Figure 11a, where is well known for its high erosion rate. As the erosion rate is one of the major limitations of switch lifetime, the medium E-field region (Figure 11b) may be a better location for photocathode material implementation where the quantum efficiency of the photocathode will be enhanced while the erosion rate stays at an acceptable level.

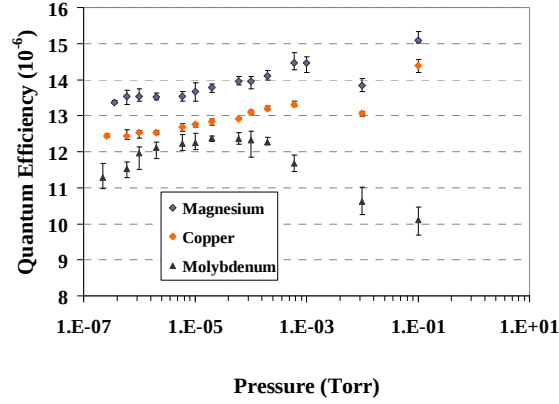


Fig. 10 Pressure dependence of the quantum efficiency for Mg, Cu and Mo. The collector was biased at 550 V for the measurements [2].

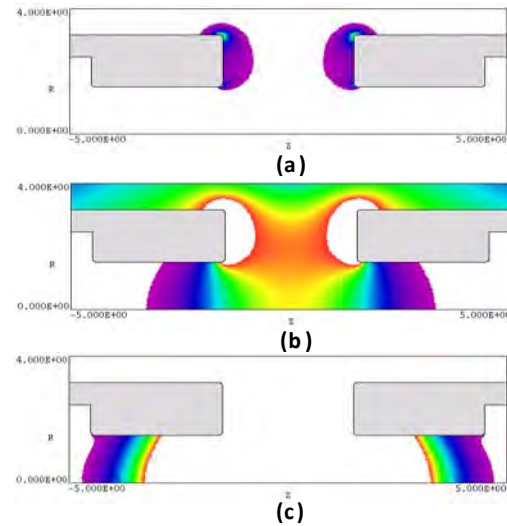


Fig. 11 Electric field distribution indicated in color contours for (a) the strong electric field region for a field strength between 100 (purple) and 300 (red) kV/cm, (b) the medium field region where the colored area corresponds to a field strength between 5 (purple) and 100 (red) kV/cm, and (c) the modest field region where the colored area corresponds to a field strength between 500 (purple) and 5,000 (red) V/cm [2].

4.3 A Mg foil-based photocathodes for BLT triggering improvement [3]

Application of a Mg foil at the back surface of the cathode significantly improved the switch triggering characteristics; the delay and jitter were at least three times reduced when the Mg foil photocathode was employed in a 0.4 – 1 Torr helium-filled BLT, as shown in Figure 12 . In the mean time, the hold-off voltage and the peak current of the switch showed negligible difference with or without application of the Mg foil, as shown in Figure 13. These findings demonstrate great potential of Mg-based photocathodes for improving BLT performance with reduced switch

delay and jitter, and imply that the trigger energy criteria may be reduced due to higher quantum yield of such cathodes. Additional experiments are under progress to understand the electron emission processes contributing to the delay and jitter reduction.

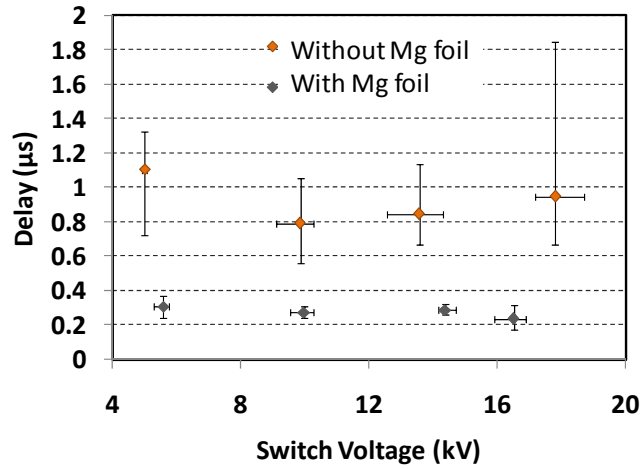


Fig. 12 Trigger delay with respect to the switch voltage for the helium-filled BLT with and without inserting Mg foil as the photocathode.

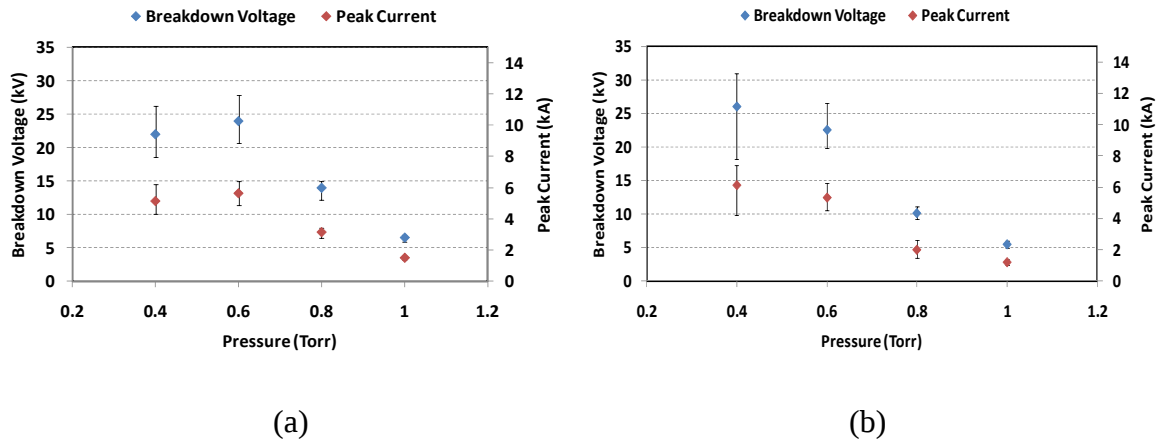


Fig. 13 Switch hold-off with respect to the helium pressure of the switch: (a) with and (b) without the Mg-foil as the photocathode

5. References

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