High gradient rf gun studies of CsBr photocathodes

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CsBr photocathodes have 10 times higher quantum efficiency with only 3 times larger intrinsic transverse emittance than copper. They are robust and can withstand 80 MV/m fields without breaking down or emitting dark current. They can operate in 2×10^{-9} torr vacuum and survive exposure to air. They are well suited for generating high pulse charge in rf guns without a photocathode transfer system.

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I. INTRODUCTION

The chemical identification of materials using standard x-ray absorption techniques is an important problem for homeland security. New techniques are needed that enable the differentiation of liquids, gels, and soft tissues with nearly identical absorption coefficients. Without this, future air travelers will likely continue to be required to remove liquids from their carry-on luggage before boarding.

Materials can be chemically identified based on the real part of their complex index of refraction, often different from unity by an amount on the order of 10^{-8} . X-ray differential phase contrast (DPC) imaging is a technique for this [1,2]. In a typical setup, partially coherent x-rays are generated from an incoherent source using a heavily attenuating transmission grating. The phase and amplitude of x rays after the sample are then measured using a combination of a stationary phase grating and a movable amplitude grating.

A modification to this setup has been proposed [3]. The incoherent x-ray source and first grating can be replaced by a photoelectron x-ray source array (PeXSA). Here a spatially modulated laser illuminates a photocathode, producing a structured beam of electrons. The structure gives rise to a partial coherence when x-rays are generated from a target. The gratings after the sample are fixed and changes to the laser profile provide the variability needed for phase and amplitude measurements. The result is increased sample throughput.

One approach to PeXSA is to use a high gradient rf gun to quickly accelerate the electrons before Coulomb interactions affect them. To a large extent, the success of this

approach depends on the choice of photocathode. Metals have low quantum efficiency and cannot generate high charge at reasonable repetition rates. Semiconductors are not always prompt and are not always vacuum compatible. The best candidates are compounds based on alkali metals bonded either to a pnictogen, chalcogen, or a halogen. Unfortunately they often require specialized guns and photocathode transfer systems.

CsBr is an exception. Even though it has relatively low quantum efficiency, it is robust—surviving even exposure to air. It is also unusual because photons with energy less than the 7.3 eV band gap can produce emission [4,5]. To do so, UV photons must first generate color centers that serve as intragap states. These states are filled with electrons that can excite into the conduction band and emit. The final excitation occurs over a broad range of wavelengths making CsBr attractive for many applications [6].

Building on previous experience [7–9], studies were commissioned to measure the quantum efficiency, lifetime, dark current, and intrinsic transverse emittance of CsBr photocathodes in a high gradient rf gun.

II. METHODS

CsBr photocathodes were studied at the Accelerator Structure Test Area test facility at SLAC National Accelerator Laboratory. The facility contains a replica of the first 1.4 m of the Linac Coherent Light Source injector, including a rf gun and a UV drive laser.

Out of an abundance of precaution, the normally present rf gun was removed and an older “Gun Test Facility” gun was installed. The 1.6 cell 2856 MHz gun was capable of producing fields of up to 120 MV/m and beam energies of up to 6 MeV. The gun was powered by a model 5045 klystron, limited in this case to 4.6 MW peak power, 1.5 μ s rf pulses at 30 Hz.

The UV drive laser consisted of a 68 MHz Ti:sapphire oscillator outputting 6 nJ/pulse at 800 nm. This was stretched and amplified in a Ti:sapphire regen and then

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compressed to generate 3 mJ, 25 fs pulses. Tripling gave 300 μJ pulses at 266 nm. This was expanded and defined by an iris. The iris was imaged on the photocathode with 100 μJ , 700 fs pulses arriving after transport. Rotating a quarter wave plate with respect to a thin film polarizer controlled the pulse energy. Additionally 25 mm of quartz glass could be inserted to stretch the pulses to 1.1 ps. The beam was monitored using beam splitters, a power meter and a virtual photocathode camera. A SPIDER autocorrelator was used to measure the pulse length after the compressor.

The beamline consisted of a gun solenoid and corrector magnets. The beam traversed a YAG crystal 1.4 m downstream of the photocathode before terminating in a Faraday cup. Fluorescence from the YAG was imaged for beam measurements. The Faraday cup was used to collect the charge. Other diagnostics included a camera for imaging the photocathode, thermocouples, rf probes, cold cathode gauges, and RGAs. Additional information on the system is found in [10].

Figure 1 shows an *in situ* optical panorama of a CsBr photocathode deposited on a copper substrate. The CsBr was deposited at 500 °C and 5×10^{-7} torr in a dedicated chamber using standard thermal evaporation techniques. The deposition consisted of a single spot on axis surrounded by three spots off axis in a triangular pattern. Each spot was 5 mm in diameter and 30 nm in thickness. Multiple thin layers were deposited sequentially over several days to reduce the contamination associated with

rising background pressure when the deposition system is used for longer periods of time.

Following deposition, the photocathode was installed in the gun. The installation began with the deposition chamber being opened inside of a plastic bag filled with argon. The photocathode was extracted and transferred in air to another plastic bag filled with nitrogen that enclosed the gun. Even though the bag-to-bag transfer time was less than 1 min, the time from opening the deposition chamber to evacuating the gun was still several hours. Furthermore the photocathode was exposed to air several more times because the gun had a leak that required venting to fix. As expected, the CsBr survived these exposures [11], illustrating that CsBr photocathodes are well suited for rf guns that do not contain a photocathode transfer system.

Following installation the gun was rf processed to 80 MV/m fields at 2×10^{-9} torr vacuum. Radio-frequency breakdown occurred above this level. There was approximately one event every 10 min. at 100 MV/m with events being much more frequent at 120 MV/m. No dark current was measured until the fields exceeded 100 MV/m. The origin of the breakdown was not clear. It may have been due to surface roughness rather than to the presence of CsBr. The data from the two RGAs suggested that CsBr was not being ablated. They recorded similar spectrum even though one was located a few cm from the photocathode and the other was located 1 m downstream. It was concluded that CsBr is compatible with a high gradient rf environment, up to 80 MV/m fields and maybe more.

The CsBr did not have high quantum efficiency initially. Rather the quantum efficiency had to be activated. For this, several methods were tried. Using low photon flux to slowly activate the film over time was not effective; neither was using a kV electron flood gun. The only successful method was to focus the laser spot down such that the dose received was large. At this point the quantum efficiency quickly saturated and no further gains were observed. The quantum efficiency would decay slowly over time but could be regenerated using the same technique.

During the experiment sub-ps laser pulses were used. Because of nonlinear self-focusing in the optics, the laser profile was dominated by hot spots. These hot spots were beneficial for increasing the intensity but difficult to control. They also prevented quantification of the minimum intensity necessary to activate high quantum efficiency. Much time was spent stabilizing the laser beam profile. Fortunately no damage was observed, either to the photocathode or to any of the optics.

Schottky scans are a plot of the emitted charge as a function of rf field strength (Fig. 2). They were routinely used to verify the offset between the laser and rf pulse arrival times. The offset was calibrated such that there was no emission beyond the zero phase crossing, with the phase of the electric field decreasing from left to right. Typical operation for generating high charge or high quantum

FIG. 1. Optical panorama of the CsBr photocathode installed in the gun. Red circles indicate the spots where CsBr was deposited and higher quantum efficiency was recorded. The blue circle indicates a spot where CsBr was deposited too far off axis for a beam to exit the gun. The green square indicates the area of the quantum efficiency map shown in Fig. 3. The bright area is a reflection from a lamp used to illuminate the photocathode during imaging.

FIG. 2. Schottky scan from CsBr taken at 80 MV/m field showing a maximum charge extracted of 0.9 nC at -65° phase.

efficiency was at -60° phase. Typical operation for minimizing emittance was at -15° phase. The residual emission beyond the zero phase crossing may be attributed to a ghost reflection illuminating the photocathode later in time or it may be a phenomenon inherent to the emission from CsBr.

Measuring the rotation angle of the beam as it traversed the gun solenoid was used to determine the beam energy. At -15° rf phase and with a solenoid strength of 0.3070 kG-m, the rotation angle was 69° and the beam energy was determined to be 3.85 MeV.

III. RESULTS

The maximum quantum efficiency observed was 6×10^{-4} at 300 pC of charge, -60° rf phase, 80 MV/m field. The nominal quantum efficiency was 3×10^{-4} at 300 pC of charge, -60° rf phase, 80 MV/m field. For comparison, copper at 266 nm typically has a quantum efficiency of 3×10^{-5} and even with special processing rarely exceeds 1×10^{-4} . The quantum efficiency from CsBr was up to an order of magnitude higher than that of copper.

The highest charge density extracted exceeded 10 nC/mm^2 at 80 MV/m. From this it is predicted that CsBr is able to emit up to the space charge limit for a given field. This makes CsBr an attractive candidate for high pulse charge applications. Because the charge density was larger than expected it is hypothesized that the emitted bunch length is significantly longer than the drive laser pulses. This hints at the emission process in CsBr being slower than in metals and more in line with other semiconductor photocathodes—a claim that needs to be verified in future experiments.

Little difference in quantum efficiency was observed between 700 fs and 1.1 ps laser pulse lengths. It is possible that the quantum efficiency was marginally higher, $<10\%$, at the longer pulse length but not significantly so.

FIG. 3. Quantum efficiency map from CsBr following activation taken at -60° rf phase, 80 MV/m field, 5 uJ laser pulse energy. The 5 mm CsBr disk on axis is clearly resolved and shows an order of magnitude higher quantum efficiency than that of the surrounding copper.

Figure 3 is a quantum efficiency map following activation. The 5 mm CsBr disk on axis is clearly resolved from the surrounding copper. Two of the three CsBr spots off axis are also resolved but they were too far off axis for emitted beams to exit the gun properly. The quantum efficiency from the CsBr was $2\text{--}4 \times 10^{-4}$ while the quantum efficiency of the surrounding copper was $1\text{--}3 \times 10^{-5}$, demonstrating the order of magnitude difference between the two. Feedback scripts controlled the corrector magnets and the quarter wave plate to maintain maximum beam collection efficiency and constant laser pulse energy during this measurement. The pulse energy was set such that the maximum charge emitted was 300 pC. The spatial resolution was approximately $300 \mu\text{m}$, determined by a convolution of the mirror step size and the laser profile.

Interestingly not all of the data collected was completely understood. An unexpected variation in quantum efficiency with respect to the laser pulse energy was observed (Fig. 4). In each curve the quantum efficiency increased from near zero to a maximum before rolling off. The roll off is understandable due to space charge effects; however, the increase from zero is not. According to the Spicer 3-step emission model, the quantum efficiency should be constant along the green lines shown for low charge. Furthermore, as the laser energy was changed the resulting quantum efficiency depended on whether the laser energy was increasing or decreasing. These effects are thought to derive from a balance between a fast activation and a slower decay of emission from CsBr. In practice, high quantum efficiency had to be maintained with sufficient photon flux that these processes balanced.

Transverse emittance is the product of an electron beam size and its divergence angle. Transverse emittance measurements were made using the solenoid scan technique, which varies the magnet strength around its optimum focus and fits measurements of the beam size to a transport

FIG. 4. Unusual dependence of charge extracted from CsBr on laser pulse energy for two different laser spot sizes, each taken at 80 MV/m field, -60° rf-laser phase. Data from the smaller spot are colored red and the larger spot are colored blue. Lines of constant quantum efficiency are colored green.

equation. The result at 80 MV/m field and -15° rf-laser phase was

$$\left(\frac{E}{mc^2}\right)\epsilon = 2.63 \frac{\mu\text{m}}{\text{mm}}\sigma + 0.03 \frac{\mu\text{m}}{\text{pC}}\chi$$

where σ is the rms beam size and χ is the charge emitted. The intrinsic transverse emittance is given by setting the charge to zero. The result is $2.63 \mu\text{m}/\text{mm}$, which is 3 times larger than the standard $0.9 \mu\text{m}/\text{mm}$ from copper [12]. The result is not surprising considering the order of magnitude gain in quantum efficiency and the presumed quartic relationship between the two. Including the Schottky effect, the value is larger than what was inferred in previous work [13] so it may be best to think of it as an upper bound due to the rf gun used. Even so it is not too large for many applications. These measurements and a fit to them are shown in Fig. 5.

FIG. 5. Dependence of transverse emittance from CsBr on extracted charge and laser spot size taken at 80 MV/m field, -15° rf-laser phase. An empirical plane of best fit is shown in grey. Data above the fit are colored increasingly red. Data below the fit are colored increasingly blue. Data that match the fit are colored green.

FIG. 6. 24 hr of continuous operation of a CsBr photocathode. The charge extracted is colored blue, the laser pulse energy is colored red and the quantum efficiency is colored green.

Finally, 24 hr of continuous operation extracting 0.5 nC of charge from a 1.6 mm diameter laser spot were successfully completed. In total 2.6×10^6 pulses or 1.3 mC were extracted. The data are shown in Fig. 6. The laser pulse energy varied during this time due to ambient temperature effects and nonlinearities in the optical system as well as the observed balance between the fast activation and slow decay of emission from CsBr. As a result the quantum efficiency evolved as shown. The decrease over the first 6 hr is attributed to insufficient photon flux to sustain full activation. After 6 hr equilibrium was established. The results show that CsBr is capable of continuous operation, at least on the order of days. If the lifetime were shorter than this the 24-hr time evolution would show a more pronounced decline. Moreover the photocathode operated intermittently over a period of weeks so it is reasonable to expect even longer lifetimes.

IV. CONCLUSIONS

CsBr photocathodes are well suited for generating high pulse charge in rf guns without a photocathode transfer system. They are robust. They can operate in 2×10^{-9} torr vacuum and survive being transferred in air. They can withstand 80 MV/m fields without breaking down or emitting dark current. They have a nominal quantum efficiency of 3×10^{-4} at 266 nm, an order of magnitude higher than copper. Similarly they have intrinsic transverse emittance of $2.63 \mu\text{m}/\text{mm}$, a factor of 3 times larger than copper. Charge densities exceeding $10 \text{ nC}/\text{mm}^2$ have been extracted. Unusual emission characteristics are attributed to a balance between activation and decay processes.

Future work will continue to evaluate CsBr photocathodes for application to PeXSA. Several improvements will be made. The first will be to use a different rf gun capable of higher fields, more symmetrical fields, and higher repetition rates. The second will be to modify the laser

to improve the profile uniformity, to stabilize the pulse energy and to illuminate the photocathode with sub 100 fs pulses. The third will be to add electron beam diagnostics that allow for the verification of prompt emission and the measurement of femtosecond electron bunch lengths. This will allow for better evaluation of ultrashort x-ray pulse generation for PeXSA. Future experiments will also focus on verifying emission at 400 nm, which has the potential to simplify drive laser systems and will provide compatibility with other DPC experiments being performed at Stanford.

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