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OBSERVATION OF A CHARGE LIMIT FOR PHOTOCATHODE ELECTRON GUNS*

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ABSTRACT

The Photocathode Electron Gun (PEG) at SLAC is required to produce bunch intensities of up to 10^{11} electrons within 2 ns (8 Amps). Operation of PEG has demonstrated a 'Charge Limit' phenomenon, whereby the charge that can be extracted from the gun with an intense laser beam saturates at significantly less than 10^{11} electrons (the expected 'Space Charge Limited' charge) when the photocathode Quantum Efficiency is low. We report studies of this Charge Limit phenomenon observed with a GaAs photocathode.[1]

1. INTRODUCTION

To achieve 10^{11} electrons in a 2 ns bunch, the perveance of PEG requires that its photocathode be at a high voltage, V = 120 kV. This Space Charge Limited current from the gun scales as $V^{3/2}$, and the proportionality constant is the perveance. The perveance of PEG is determined by its electrode geometry and its active photocathode area.

Operation of PEG at the SLAC injector began in November 1991. Operating with a laser at 715 nm, a Charge Limit (CL) phenomenon below the expected Space Charge Limit was observed. This CL was observed to strongly correlate with the photocathode Quantum Efficiency (QE) and did not scale as $V^{3/2}$. Earlier testing of PEG with a laser operating at 532 nm had not shown this effect. This indicates that the CL has a strong wavelength dependence. In contrast to the Space Charge Limit, where the *current* from the gun saturates at high laser intensity, the Charge Limit phenomenon demonstrated *charge* saturation at high laser intensity.

⋆ Work supported by Department of Energy contract DE–AC03–76SF00515 (SLAC).

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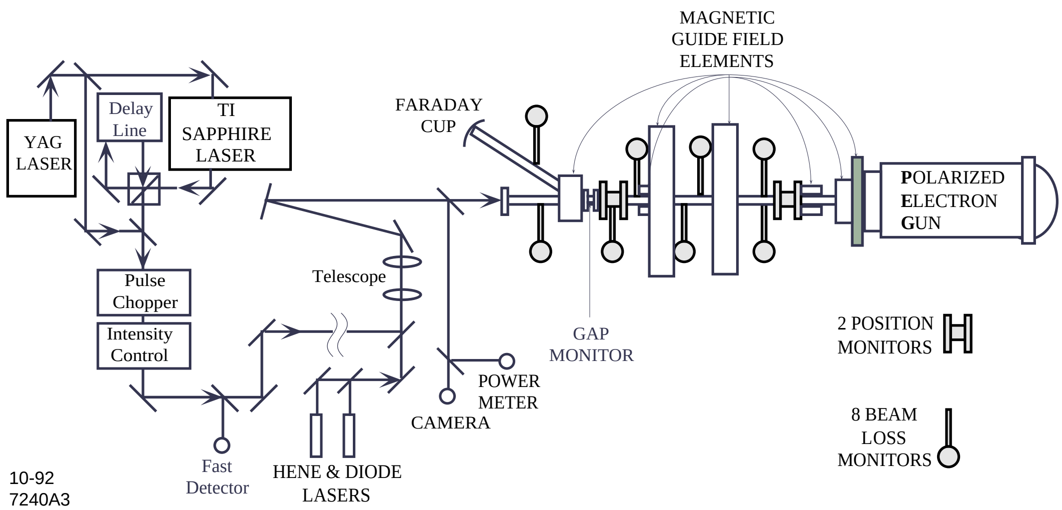

Figure 1. The SLAC Gun Test Facility.

2. EXPERIMENTAL SETUP

The Gun Test Facility used for this experiment is shown in Fig. 1. It consists of the Gun Test Laser System, PEG, and an electron beamline which terminates in a Faraday Cup.

The Laser System allows the cathode to be illuminated with either 765 nm (Ti:Sapphire) or 532 nm (Nd:YAG) pulsed beams, or 633 nm (HeNe) or 750 nm (Diode) cw beams. It provides measurements of the beam intensity, temporal pulse structure, and transverse spatial profile on the photocathode. The Ti:Sapphire beam can be split, with one beam going into a delay line, and then recombined for studies of two closely spaced bunches. The Ti:Sapphire beams and the Nd:YAG beam are combined and pass through a Pulse Chopper Pockels Cell System and an Intensity Control Pockels Cell System. The Pulse Chopper results in laser pulses that are 2.0 ns full width at half maximum (FWHM). The pulsed beams and cw beams are combined and sent to the photocathode, though only one of the 4 laser sources is used at a given time. The spot sizes of the beams on the photocathode are adjusted with a telescope and monitored with a digitizing camera system which looks at a target located the same distance from the telescope as the photocathode. All beams are set up for a nominal spotsize of 10 mm FWHM on the photocathode, and all give near-gaussian transverse profiles there. Laser energy and power measurements are made by calibrated power meters and photodiodes. These measurements have an uncertainty of less than 20%.

PEG's photocathode is circular with an active diameter of 14 mm. The electron beam from the gun is focused and steered into a Faraday Cup by a series of magnets. The average electron beam current is measured by the Gun Current Meter between the PEG photocathode and its HV power supply, and a current meter on the Faraday Cup. Beam Position Monitors are used to measure beam position and intensity, and provide diagnostics on steering. A ceramic Gap Monitor is used to measure the electron beam temporal profile, and scintillation counters are used to monitor beam losses. Beam steering and focusing is done by maximizing current transmission to the Faraday Cup and by minimizing scintillator signals. Measurements of the electron bunch intensities have an uncertainty of less than 5%.

3. EXPERIMENTAL RESULTS

Illuminating the photocathode by the high intensity 532 nm laser produced a saturated charge of $13.3 \cdot 10^{10}$ electrons per bunch (with PEG at 120 kV) as measured by the Gun Current Meter. This is in good agreement with the Space Charge Limit predicted by computer simulations. Space Charge Limited operation should give saturated *current* proportional to $V^{3/2}$. Using the Gap Monitor to record the electron bunch temporal shape, we measured the electron current amplitude at the flattop of the pulse for Gun voltages from 60 kV to 120 kV. The saturated current amplitude was observed to fit very well to a $V^{3/2}$ scaling as expected.

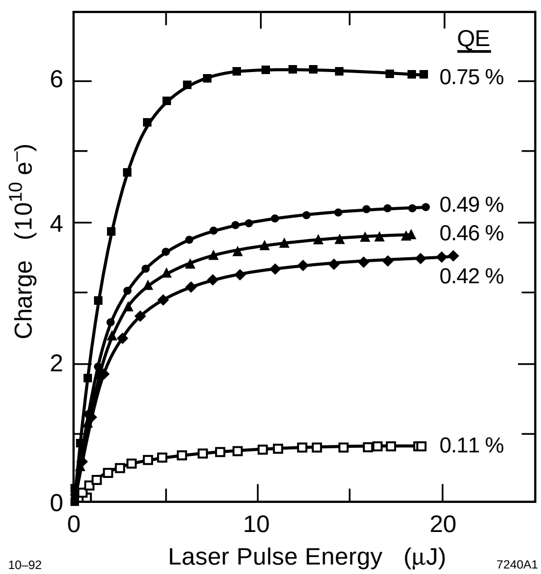

Figure 2. Electron intensity vs Laser intensity at different QE.

The photocathode QE was measured to be 0.3% for this data. This value was measured with the 750 nm cw Diode Laser and with PEG operating at 120 kV. Since the QE can have a strong dependence on both wavelength and electric field at the photocathode, all QE measurements quoted in this paper are measured at 750 nm and 120 kV. When the QE is lower than 1%, the electric field at the photocathode has an appreciable effect on the measured QE due to the Schottky effect.

When the photocathode was illuminated with the 765 nm laser, we obtained the 'Saturation Curves' shown in Fig. 2. We were not able to achieve the expected Space Charge Limited electron intensity. For these Saturation Curves, we define the saturated charge at high laser intensity to be the 'Charge Limit.' This Charge Limit (CL) can be normalized to the active photocathode area (1.5 cm^2 for PEG) to give a CL density. Using the Gun Current Meter to measure the electron charge at high laser intensity, we determine the CL density and plot it against QE in Fig. 3. It is observed to scale linearly with QE. We also find that the CL does not scale as $V^{3/2}$, though it has some dependence on HV which appears consistent with the Schottky Effect and the observed dependence of the CL on QE.

To further explore the CL phenomenon, we studied its temporal behaviour. The electron bunch temporal profile, as measured with the Gap Monitor, was measured for both 532 nm illumination and 765 nm illumination. With 532 nm illumination, the electron bunch

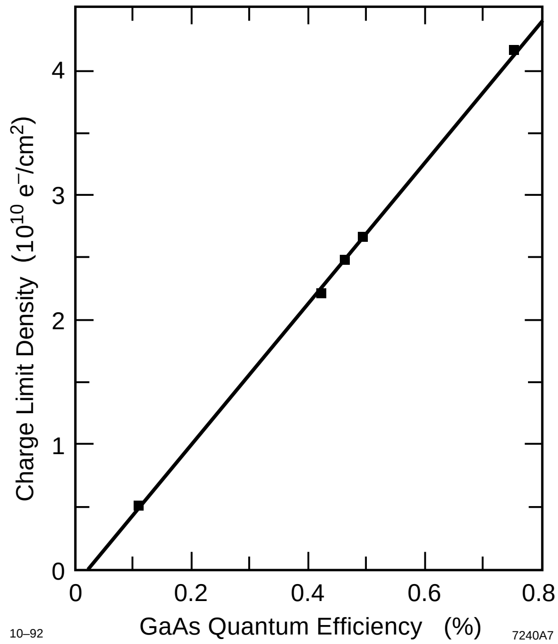

Figure 3. Charge Limit density vs QE at 765 nm.

shows a flattop of about 2 ns as one would expect for Space Charge Limited operation. In contrast, no flattop is seen for 765 nm illumination. For 765 nm laser illumination, we observed that the electron pulse narrowed as the QE decreased.

With the 765 nm laser we also studied the effect of one electron bunch on a closely spaced second bunch. For this study, the QE was 0.1%, and each laser bunch energy was 3.5 μJ. We observed no effect of the first bunch on the second for a time separation of 60 ns, but found that the presence of the first bunch reduced the charge in the second bunch by 25% when the bunch separation was 7 ns.

4. DISCUSSION

Our studies of the CL phenomenon lead us to the following model. At high incident laser intensities, the resulting high density of carrier electrons causes an increase in the Work Function, Δ_{WF}. The Δ_{WF} decays with a characteristic time constant, $\tau_{\Delta_{WF}}$, equal to the carrier electron recombination time, τ_e.

For a GaAs cathode, τ_e is expected to be about 1 ns for a doping level of $2 \cdot 10^{19}$ cm^{-3}. Our measurement of the effect of one electron bunch on a closely spaced second bunch supports $\tau_{\Delta_{WF}}$ being less than a few ns, consistent with the expected electron recombination time. However, we do not attempt a more precise determination of $\tau_{\Delta_{WF}}$, since determining this will be model-dependent and will require a more quantitative understanding of the Charge Limit.

The laser pulse length for the studies described above was 2.0 ns FWHM, which is comparable to τ_e. In our observations of the electron temporal pulse shape in the CL regime, we noted that as laser power is increased, the electron pulse gets narrower, and we observed *charge* saturation, *not current* saturation. We expect that laser pulses shorter than τ_e will give similar or somewhat lower CL densities than those presented in Fig. 3. For laser pulses significantly longer than τ_e, higher CL densities should be possible since Δ_{WF} will have time to decay. We expect it is only for laser pulse lengths comparable to or shorter than τ_e, that the CL saturation truly behaves as a *Charge* Limit.

We now give a possible explanation for the observed wavelength dependence of the CL. Electrons excited into the conduction band quickly thermalize by phonon exchange with the lattice; however, electrons can diffuse to the cathode surface before reaching thermal equilibrium. These hot electrons have a much greater probability of being photoemitted; we note that electrons produced by 532 nm photons are hotter than electrons produced by 765 nm photons. Additionally, 532 nm photons have a significantly shorter absorption depth than 765 nm photons, and photoelectrons produced by them will diffuse to the surface more quickly, resulting in less time to thermalize with the lattice and a greater photoemission probability. Thus, incomplete thermalization and the wavelength dependence of the absorption depth result in the photoelectrons produced by 532 nm photons being hotter than those produced by 765 nm photons. The hotter photoelectrons will be less sensitive to changes in the Work Function and therefore less sensitive to the CL phenomenon. We note that the QE is much higher for 532 nm photons than for 765 nm photons. From the CL dependence on QE shown in Fig. 3, it can be speculated that the CL may not have been observed in our 532 nm data because the QE at 532 nm was greater than 1%.

Another possible explanation for the wavelength dependence of the CL results from examining the band structure of GaAs in the conduction band. The conduction band exhibits an L minimum 0.3 eV above the Γ minimum. While the L minimum is not accessible by direct transitions from the valence band to the conduction band, carrier electrons in the conduction band can scatter into this region if they are energetic enough. Carrier electrons produced by 715 nm photons or 765 nm photons will not be energetic enough to reach the L minimum. However, carrier electrons produced by 532 nm photons are energetic enough, and some will scatter into the L minimum and become trapped there. When these trapped electrons diffuse to the cathode surface, they will have a higher probability of being photoemitted due to their higher energy. Their higher energy also makes them less sensitive to the CL.

5. CONCLUSIONS

We have observed a Charge Limit for Photocathode Electron Guns using GaAs. The CL is observed to scale linearly with QE for QEs lower than 1%. We believe the CL results from an increase in the cathode Work Function due to high carrier densities, and we observe the temporal aspects of the CL to be consistent with this. The CL has a strong wavelength dependence, and is observed for 715 nm and 765 nm incident photons, but not for 532 nm incident photons. We suggest two possible explanations for the wavelength dependence. First, it may result from the QE for 532 nm photons having been sufficiently high during our measurements that the CL at 532 nm was greater than the Space Charge Limit for PEG. Second, it may result from the structure of the GaAs conduction band. The CL has significant implications for PEG at SLAC and for other high intensity photocathode electron guns, such as are planned for the next generation of Linear Colliders. These accelerators are using or plan to use photocathodes for the production of intense polarized electron beams. They wish to achieve high electron polarization (80%) with photocathodes that have inherently low QE (about 0.1%). The CL may present a significant obstacle. We plan to extend our studies of the CL to other GaAs-based photocathodes, in particular, to high polarization photocathodes. We also plan to study more carefully the wavelength dependence of the CL.

6. REFERENCES

1. A more complete description of this work can be found in M. Woods et. al., SLAC-PUB-5894 (1992); submitted to J. Appl. Phys.