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OBSERVATION OF A CHARGE LIMIT FOR SEMICONDUCTOR PHOTOCATHODES*

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ABSTRACT

The Stanford Linear Accelerator Center is currently operating with a Photocathode Electron Gun (PEG) to produce polarized electrons for its experimental program. Bunch intensities of up to 10^{11} electrons within 2 ns (8 A) are required from the electron gun. 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.

INTRODUCTION

The Stanford Linear Accelerator Center (SLAC) is currently operating the SLAC Linear Collider (SLC)[1] for its Z^0 physics program. A major goal of this program is a precision test of the Standard Model of Electroweak Interactions from a measurement of the left-right asymmetry, A_{LR}, at the Z^0 resonance.[2]

This measurement requires a polarized electron beam, which is achieved with a Photocathode Electron Gun (PEG).[3] The cathode used is GaAs,[4] and its band structure is shown in Fig. 1. The relative probabilities for transitions from the valence band to the conduction band are indicated in Fig. 1b. Incident laser light in a pure helicity state with photon energies between 1.5 eV and 1.8 eV can produce an electron beam with 50% polarization $[(3-1)/(3+1) = 50\%]$.[5] Operation of PEG for SLC running requires it to produce two electron bunches separated by about 60 ns with up to 10^{11} electrons per bunch. The first bunch is used for collisions with positrons produced by the second bunch. Each of the two bunches has a Full Width at Half Maximum (FWHM) of 2 ns, and this time structure is repeated at 120 Hz.

To achieve 10^{11} electrons in a 2 ns bunch (8 A), the perveance of PEG requires it to operate with its photocathode at a high voltage, V, of 120 kV.[6] This Space Charge Limited current[7] 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.

First operation of PEG on the SLC 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 correlate strongly with the photocathode Quantum Efficiency (QE) and to not scale as $V^{3/2}$. Earlier testing of PEG with a laser operating at 532 nm had not shown this effect, thus indicating that the CL had 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.

The CL has been observed when PEG is operated with high intensity pulsed lasers at 715 nm (1.7 eV) and 765 nm (1.6 eV), but not when operated with a high intensity pulsed laser at 532 nm (2.3 eV). The CL has been observed for three different p-type GaAs photocathodes, and in this paper we report CL studies with one of these. This work was done in SLAC's Gun Test Facility, which is a duplicate of the first few meters of the SLC Injector.

EXPERIMENTAL SETUP

The Gun Test Facility used for this experiment is shown in Fig. 2. It consists of the Gun Test Laser System, PEG, and an electron beamline that terminates into a Faraday Cup. The electron beamline is a duplicate of the beamline on the SLC Injector through the first Bend magnet.

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 Nd:YAG Laser produces 30 mJ of frequency doubled 532 nm laser light in 6 ns FWHM pulses at a repetition rate of 60 Hz. The Ti:Sapphire laser[8] is pumped by the Nd:YAG laser and uses a Pockels Cell cavity dump to produce 400 μJ of 765 nm laser light in 3ns FWHM pulses at 60 Hz. The Ti:Sapphire beam can be split, with one beam into a delay line, and then recombined to duplicate the bunch time structure required for SLC operation. 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 FWHM. These are measured with a fast (less than 60 ps rise and fall time) photodiode and a fast 30 GHz sampling scope. The pulse widths for the resulting Ti:Sapphire and Nd:YAG beams are very similar, though the Nd:YAG beam temporal structure exhibits high frequency longitudinal mode beating. The pulsed beams and cw beams are combined and sent to the photocathode, though only one of the four 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 at 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 four beams 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 anode electrode (through which both the laser beam and electron beam pass) is 3 cm in front of the cathode and has a hole diameter of 19 mm. The GaAs photocathode is heat-cleaned and activated with Cs and NF_3 to achieve a Negative Electron Affinity (NEA) surface.[3] PEG is operated at 120 kV.[3,6]The electron beam from the gun is focused and steered into a Faraday Cup by a series of magnets. An ultra-high vacuum of better than 10^{-11} Torr is maintained in the gun,[3,9] and is monitored with a Residual Gas Analyzer. 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. SLC 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. 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. Beamline setup is optimized experimentally after initial set up, with a configuration determined by simulations with the programs EGUN, CONDOR, and PARMELA.[6,10] Measurements of the electron bunch intensities have an uncertainty of less than 5%.

EXPERIMENTAL RESULTS

When the photocathode was illuminated by the high intensity Nd:YAG Laser, a saturated charge of $13.3 \cdot 10^{10}$ electrons per bunch (with PEG at 120 kV) was measured with the Gun Current Meter. This is in good agreement with the Space Charge Limit expected from computer simulations.[6] 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 [see Fig. 3(a) for the electron bunch temporal shape recorded by the Gap Monitor] for Gun voltages from 60 kV to 120 kV. This data was then normalized to the Gun Current Meter measurement at 120 kV and is plotted in Fig. 4. The data fits very well to a $V^{3/2}$ scaling, as expected.

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. 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 with the 750 nm Diode Laser and with PEG operating at 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.[11] Figure 5 shows our measurements of QE versus PEG HV for several data sets corresponding to different surface conditions of the photocathode.

When the photocathode was illuminated with the Ti:Sapphire Laser, we obtained the *Saturation Curves* shown in Fig. 6. 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 Limt*. 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. 7. 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 Nd:YAG illumination and Ti:Sapphire illumination. The results are shown in Fig. 3. With Nd:YAG illumination, the electron bunch shows a flattop of about 2ns as one would expect for Space Charge Limited operation. In contrast, no flattop is seen for Ti:Sapphire illumination. For Ti:Sapphire Laser illumination, our observations are that the electron pulse gets narrower as the QE decreases.

With the Ti:Sapphire 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 bunch for a time separation of 60 ns (the nominal SLC bunch spacing), 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.

Lastly, we found no difference in the Saturation Curves (with Ti:Sapphire Laser excitation) for circular polarized light versus linear polarized light. If the CL were due to a band filling effect, one would have expected to see an earlier onset of saturation for circular polarized light. (To understand this, note that positive helicity laser light will fill the electron band with m_J=-1/2 three times faster than the m_J=1/2 band. The m_J=-1/2 band might therefore be expected to saturate at lower laser intensities if the incident laser light had positive helicity as opposed to no helicity or negative helicity. While the CL at high laser intensity would be the same for all incident polarization states, the shape of the Saturation Curve could be different. However, we observed the Saturation Curves to be independent of the laser polarization.)

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. In this paper, we do not propose an explanation for why high carrier densities increase the Work Function.[12]

For a GaAs cathode, τ_e is expected to be about 1 ns for a doping level of $2 \cdot 10^{19}$ cm^{-3}.[13] Our measurement of the effect of one electron bunch on a closely spaced second bunch supports $\tau_{\Delta_{WF}}$ being less than a few nanoseconds, 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. Our observations of the electron temporal pulse shape in the CL regime are that as the laser power is increased, the electron pulse gets narrower. We observe *charge* saturation, *not current* saturation. We expect that laser pulses shorter than τ_e will give similar or somewhat lower CL densities to what we present in Fig. 7. For laser pulses significantly longer than τ_e, higher CL densities should be possible since Δ_{WF} has time to decay. We expect it is only for laser pulse lengths comparable to or shorter than τ_e, for which the CL saturation truly behaves as a *Charge* Limit.

Let us 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 can have a much greater probability of being photoemitted; and 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 photoelectrons produced by 532 nm photons being hotter than photoelectrons 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. This suggests that the sole relevant parameter may be the QE measured at the excitation laser wavelength. For the reasons stated above, the QE is much higher for 532 nm photons than for 765 nm photons. Using the CL dependence on QE shown in Fig. 7, 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. In Fig. 1a, 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.[14] 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 to be photoemitted due to their higher energy. Their higher energy also makes them less sensitive to the CL.

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 does not appear to be due to a bandfilling phenomenon. It 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 SLC operations 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. It is desired to achieve high electron polarization (80%) with photocathodes that have inherently low QE (about 0.1%),[15] and the CL may present a significant obstacle. We plan to extend our studies of the CL to other GaAs-based photocathodes, and in particular to the high polarization photocathodes. We also plan to study more carefully the wavelength dependence of the CL.

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[2] M. L. Swartz, Proc. 1987 SLAC Summer Inst. Particle Physics; SLAC–PUB–4656 (1988).

[3] D. Schultz et al., Proc. EPAC '92 Conf., Berlin; SLAC–PUB–5768 (1992).

[4] SLAC's GaAs photocathodes are obtained from American Crystal Technology, and are grown by the Vertical Gradient Freeze method. These photocathodes are p-type (doped with Zinc) and have a (100) orientation. The doping concentration for the studies reported here is $2 \cdot 10^{19}$ cm^{-3}.

[5] See, for example, T. Maruyama et al., Appl. Phys. Lett. **55**, 1686 (1989).

[6] K. R. Eppley, T. L. Lavine et al., Proc. 1991 IEEE Part. Accel. Conf., SLAC–PUB–5453 (1991).

[7] Space Charge Limited current occurs when the electric field at the cathode goes to zero. This happens when the electric field produced by the space charge of the electron beam cancels the electric field produced by the cathode bias.

[8] J. Frisch et al., "A Ti:Sapphire Laser for the New SLAC Polarized Electron Source," Proc. Linac '92 Conf., Ottawa.

[9] T. Lavine et al., Proc. 1991 IEEE Part. Accel. Conf.; SLAC–PUB–5454 (1991).

[10] A. D. Yeremian et al., Proc. Linac '92 Conf., Ottawa, SLAC-PUB-5885 (1992).

[11] See, for example, J. S. Escher in *Semiconductors and Semimetals,* R. K. Willardson and A. C. Beer, eds., Vol. 15, *Contacts, Junctions, Emitters* Academic Press, 1981, p. 257.

[12] For a possible explanation of this effect, see M. Zolotorev, SLAC-PUB-5896 (1992).

[13] R. J. Nelson and R. G. Sobers, Appl. Phys. **49**, 6103 (1978).

[14] See Ref. 11, p. 238.

[15] See, for example, T. Maruyama et al., Phys. Rev. **B46**, 4261 (1992).

[16] This figure is taken from S. M. Sze, *Physics of Semiconductor Devices,* John Wiley&Sons, 1981, p. 646.

[17] This figure is taken from D. T. Pierce and F. Meier, Phys. Rev. **B13,** 5486.

FIGURE CAPTIONS

1. (a) shows the energy structure of the conduction and valence bands for GaAs,[16] and (b) shows the spin structure of the conduction band and the upper two valence bands. The relative probabilities of the allowed transitions for positive and negative helicity photons are indicated by the circled numbers.[17]

2. The Gun Test Facility includes several pulsed and cw laser sources, PEG, and an electron beamline which is a duplicate of the SLC Injector through the first bend magnet.

3. (a) shows the electron bunch pulse shape as measured by the Gap Monitor for Nd:YAG Laser illumination, and (b) shows the corresponding electron bunch pulse shape for Ti:Sapphire Laser illumination. The difference in pulse shapes is due to the Charge Limit as explained in the text. (For this data, the laser bunch energy was about 8 μJ. The QE, at 120 kV and 750 nm, was 0.3% for the Nd:YAG data and 0.2% for the Ti:Sapphire data. The time scale is 2 ns/division in Fig. 3(a) and 1ns/division in Fig. 3(b). Different attenuation was used for the scope traces shown in Figs. 3(a),(b), and so the relative amplitude scale is arbitrary.)

4. Saturated Current as a function of PEG HV for Nd:YAG Laser illumination. The Gun Gap was used to measure the relative peak electron current at different PEG Voltages, and the data was normalized to the Gun Current Meter measurement of the electron charge at 120 kV. The Saturated Current is observed to scale as $V^{3/2}$, as expected for Space Charge Limited operation (the line drawn is a linear fit of the Saturated Current to $V^{3/2}$). For this

data set, the incident laser intensity was 8 μJ, and the QE at 750 nm and 120 kV was 0.3%.

5. QE as a function of PEG HV for several data sets corresponding to different conditions of the photocathode surface. This data is obtained with a 750 nm, low power, cw Diode Laser.

6. Electron intensity as a function of Laser intensity at 765 nm, with PEG operating at 120 kV. Five sets of data obtained for different values of cathode QE are shown. (The electron charge is measured with an ADC readout of the Faraday Cup signal. Cathode QE is measured at 750 nm and 120 kV with a low power cw diode laser.)

7. Charge Limit Density as a function of QE for excitation by 765 nm laser light.

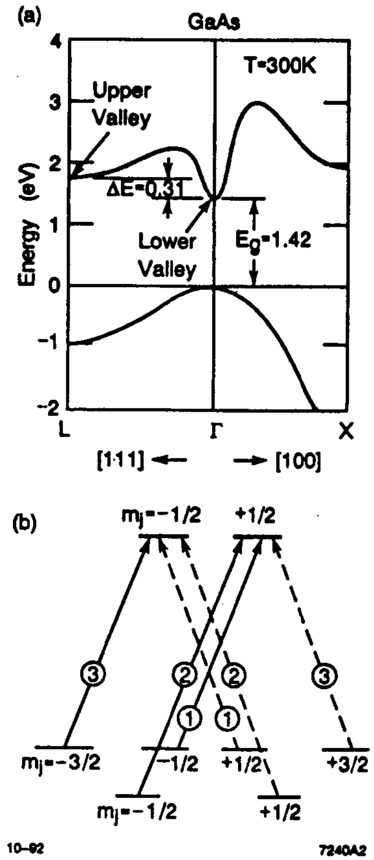

(a)
GaAs
T=300K
Upper Valley
ΔE=0.31
Lower Valley
Eg=1.42
Energy (eV)
L
Γ
X
[111]
[100]
(b)
mj=−1/2
+1/2
mj=−3/2
−1/2
+1/2
+3/2
mj=−1/2
+1/2
10-92
7240A2

Fig. 1

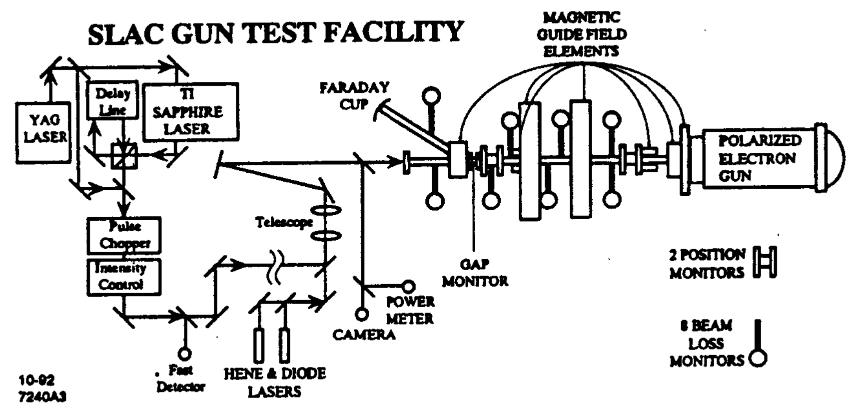
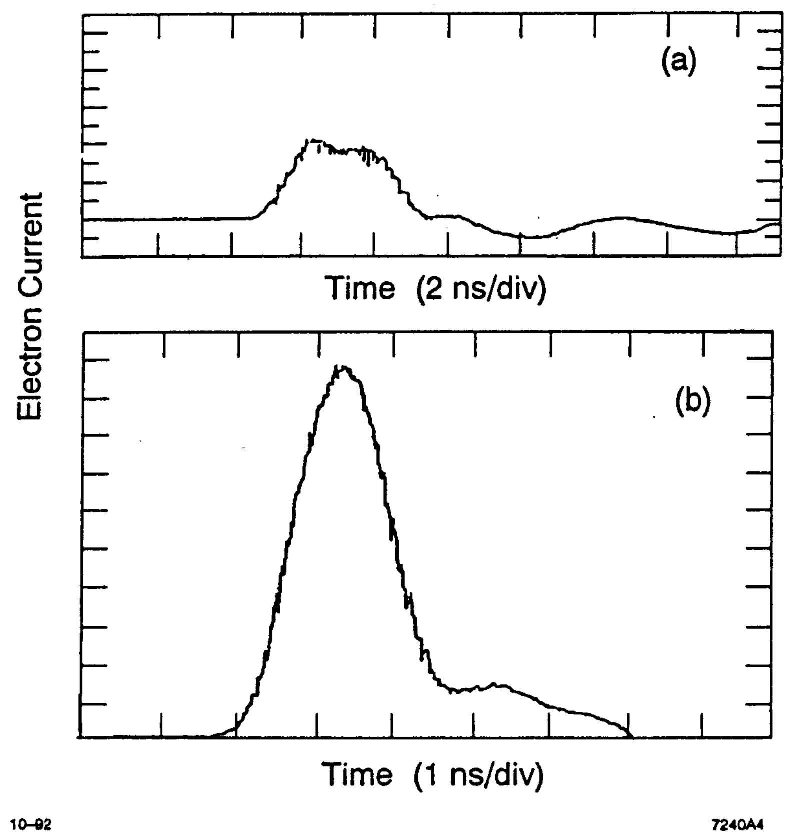
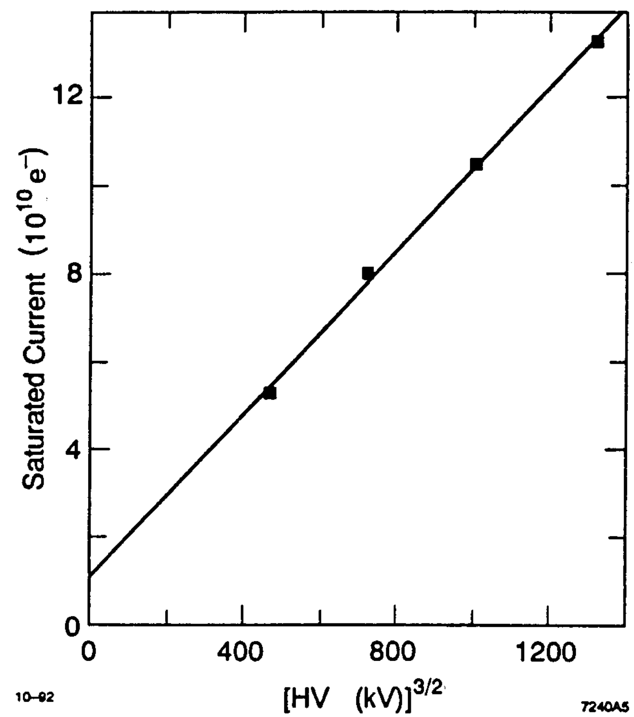

SLAC GUN TEST FACILITY
MAGNETIC GUIDE FIELD ELEMENTS
YAG LASER
Delay Line
Ti SAPPHIRE LASER
FARADAY CUP
POLARIZED ELECTRON GUN
Telescope
Pulse Chopper
Intensity Control
GAP MONITOR
2 POSITION MONITORS
POWER METER
CAMERA
8 BEAM LOSS MONITORS
Fast Detector
HENE & DIODE LASERS
10-92
7240A3

Fig. 2



(a)
Time (2 ns/div)
(b)
Time (1 ns/div)
Electron Current
10-92
7240A4

Fig. 3



0
4
8
12
0
400
800
1200
Saturated Current (10^10 e^-)
[HV (kV)]^3/2
10-92
7240A5

Fig. 4

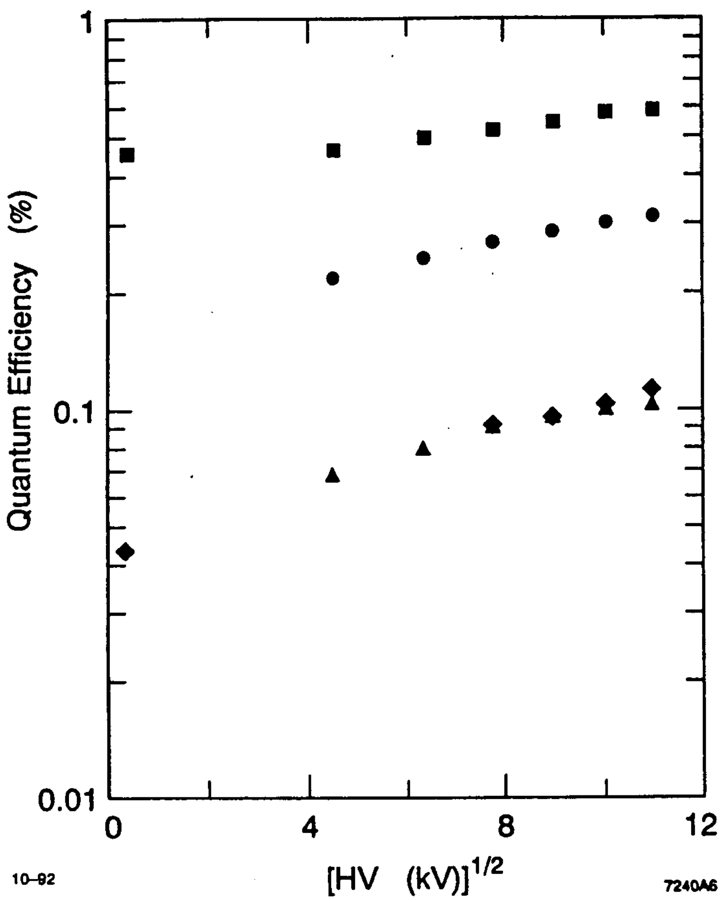

1
0.1
0.01
0
4
8
12
Quantum Efficiency (%)
[HV (kV)]^1/2
10-92
7240A6

Fig. 5

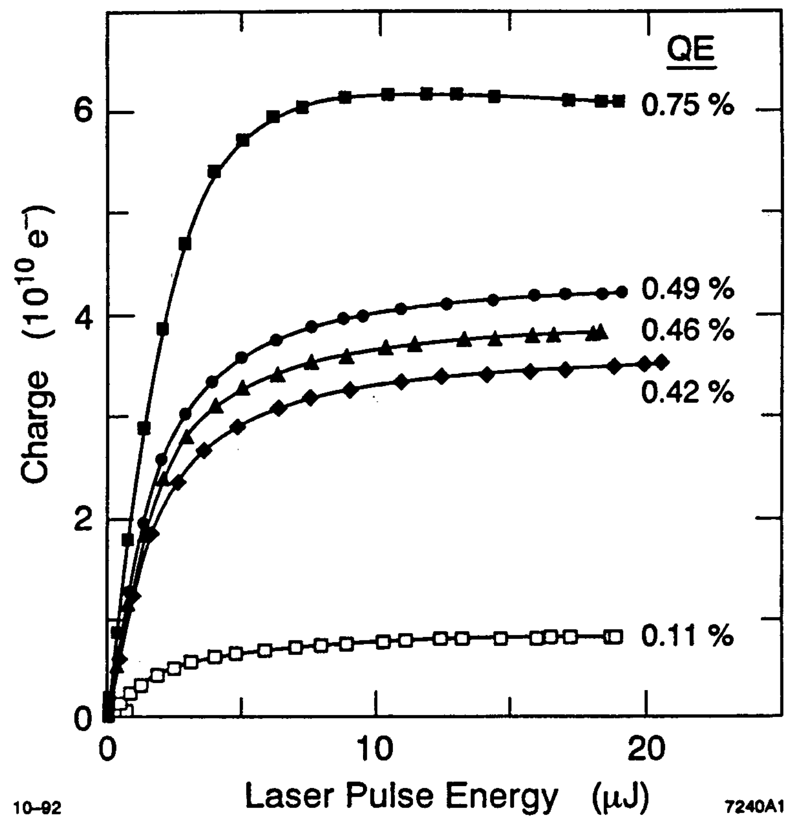
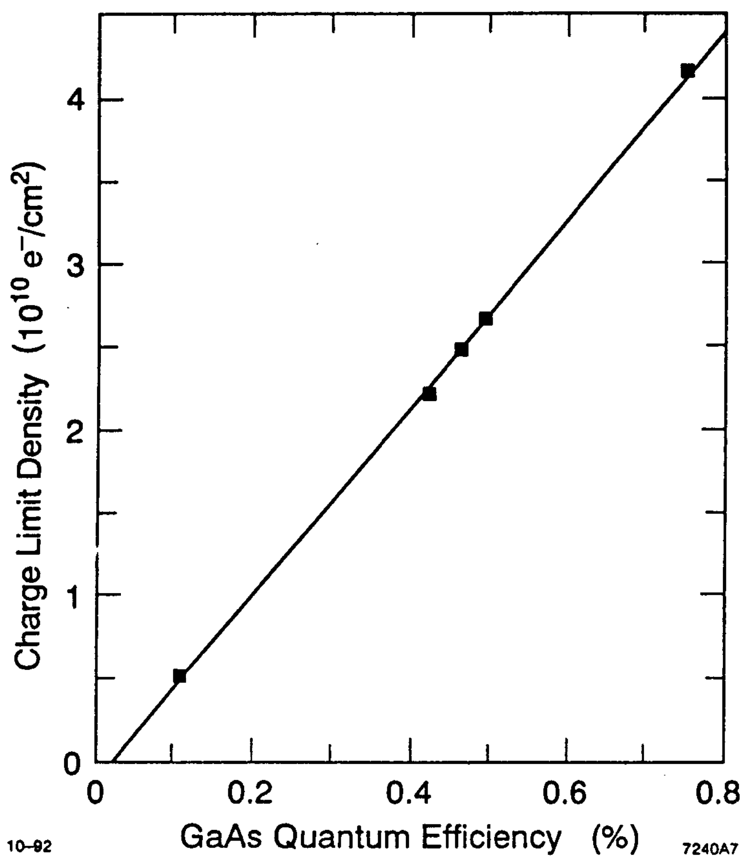

QE
0.75 %
0.49 %
0.46 %
0.42 %
0.11 %
0
2
4
6
10
20
Charge (10^10 e^-)
Laser Pulse Energy (μJ)
10-92
7240A1

Fig. 6



Charge Limit Density (10^10 e⁻/cm²)
0
1
2
3
4
0
0.2
0.4
0.6
0.8
GaAs Quantum Efficiency (%)
10-92
7240A7

Fig. 7