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The High Peak Current Polarized Electron Source of the Stanford Linear Collider*

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Abstract

The Stanford Linear Collider Injector requires two 2 ns pulses of 4.5–5.5 $\times 10^{10}$ electrons, separated by 61 ns at 120 hz, from its source. Since 1992, these currents have been provided by a polarized electron source based on GaAs photocathodes. A beam polarization of 76 ± 4% has been measured at the end of the 50 GeV linac. At low photocathode quantum efficiencies, and for excitation near threshold, the maximum current delivered by the source is constrained, not by the space charge limit of the gun, but by a 'charge limit' of the photocathode. The charge limited current is proportional to the photocathode quantum efficiency, but the proportionality varies for different photocathode types. Experience with high polarization strained GaAs photocathodes on a test beamline and on the SLC is presented.

1. Introduction

Polarized electron beams have been in continuous use for the SLC high energy physics program at SLAC since the spring of 1992 [1,2]. The polarized electrons are generated by the Polarized Electron Source (PES) which consists of an electron gun

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with a GaAs-based photocathode and a laser operated at a wavelength near the semiconductor band gap. In addition to high polarization, the SLC program demands high beam intensities; two 2 ns electron bunches separated by 61 ns with up to 10^{11} electrons in each. The two pulses, the first to collide with positrons at the interaction point and the second to generate a pulse of positrons, are produced at 120 Hz. The gun is operated at 120 kV so that the amount of charge extracted in the space charge limit is 1.1×10^{11} electrons per bunch for a fully illuminated (14 mm diameter) photocathode, which is well above the desired intensity.

If a photocathode responds linearly to the excitation light intensity, then the amount of photoemitted charge will increase proportionally with the light intensity until the space charge limit is reached. In contrast to this expectation, earlier studies [3] indicated that when the quantum efficiency (QE, defined as the ratio of the number of emitted electrons to the number of incident photons) of the cathode drops below a certain level, the total amount of charge extractable within 2 ns from a fully illuminated cathode is limited to a value smaller than the space-charge limited value. This effect is known as Charge Limit (CL).

2. The Electron Gun and Load Lock

The SLC Polarized Electron Gun is of a conventional diode design. The photocathode and cathode electrode are supported by a 10 cm diameter tube which is concentric to, and supported by, a large alumina insulator. The cathode is separated from the ground potential focus anode by about 3 cm. The insulator is capable of holding off a potential of -180 kV. During operation, the cathode potential is held at -120 kV, which gives a space charge limited current of 8.9 amps, or 1.1×10^{11} electrons in a 2 ns long bunch.

The high voltage end of the gun is connected to a load lock system for easy cathode change [4]. The load lock is a vacuum system with a number of manipulators which allows a new photocathode to be installed into the gun without affecting the gun's ultra-high vacuum. The use of the load lock in source operations provides two major advantages over (previous) running without one. First, the photocathode can be introduced into the gun after the gun has been high voltage processed without affecting the high voltage conditioning of the gun. (High voltage processing poisons the photocathode, rendering it unusable.) Without a load lock, the gun must be vented and rebaked to change photocathodes. This degrades the gun's high voltage performance. The second advantage is quick turn around. A photocathode can be changed, activated, and loaded into the gun in a few hours (the full procedure involves the disassembly and reassembly of the high voltage structure and typically takes one day). The photocathode QE may also be improved when introduced through the load lock, as the photocathode is not subjected to the gun bakeout.

The level of vacuum in the gun volume is critical to the photocathode lifetime. Minute levels of CO and CO_2 have been seen to cause a loss in the photocathode QE. The ultra-high vacuum in the gun is maintained by means of nonevaporable getter pumping as well as ion pumping. A residual gas analyzer (RGA) is used to monitor the gun vacuum. During normal operation, the total pressure in the gun is about 1×10^{-11} Torr, and the CO level is about 1×10^{-12} Torr. These levels must be maintained while the high voltage of the gun is on. This limits the allowable dark current, which leads to electron induced gas desorption, to < 50 nA. When a dark current of 100 nA was observed, the partial pressure of CO rose by 10^{-13} Torr, and the QE of the photocathode was irreversibly degraded. Dark currents below 50 nA are routinely maintained.

3. The Laser System

The polarized electron source for the SLAC linac uses a semiconductor photocathode illuminated by circularly polarized laser light. For the 1992 physics run, a flashlamp pumped dye laser was used [5]. The new high polarization strained-lattice cathodes [6] intended for the 1993 run required higher optical pulse energies and longer wavelengths than the dye laser could deliver. The requirements for the new laser were:

Operating wavelength	760–870 nm
Pulse energy at cathode	>50 μJ
Pulse length	2.0 ns
Timing jitter	<50 ps RMS
Pulse structure	2 pulses, 61 ns apart
Repetition rate	120 Hz
Energy stability	<3% RMS
Pointing stability	<5 μR RMS
Reliability	>95% uptime
System Lifetime	>10,000 Hours

No commercial lasers which could meet these parameters were available, so a system was developed at SLAC.

Titanium doped sapphire ($Ti^{+3}:Al_2O_3$) [7] is the only commercially available solid state laser material which can operate over the required wavelength range at the required powers and repetition rates. Frequency doubled YAG was chosen as the most practical pump source for Ti:Sapphire.

We decided to use two Ti:Sapphire cavities to produce the first and second pulses. This allowed independent control of pulse timing and intensity. Commercial YAG lasers with the required output energy (5 mJ at 532 nm) were not available with repetition rates greater than 60 Hz. This necessitated the use of two YAG lasers operating interleaved to pump each of the Ti:Sapphire cavities. Figure 1 shows the overall system layout.

The Ti:Sapphire cavities are Q-switched [8] and cavity dumped [9] with an intra-cavity Pockels cell and polarizer (fig. 2). When high voltage is applied to the Pockels cell, the polarization of the light in the cavity is rotated, and lasing is inhibited. Removing the high voltage allows build-up of light in the cavity to begin. When the intra-cavity optical power reaches maximum, a fast high voltage edge is applied to the Pockels cell causing the circulating light to be extracted through one of the cavity polarizers. This produces a pulse whose length is the round trip length of the optical cavity.

A Pockels cell with a fast (150 psec rise and fall time) avalanche transistor driver chops the output pulse to the required 2 ns width. An additional Pockels cell after each cavity is used to control the output intensity.

A pair of feedback loops stabilize the output energy from each of the YAG lasers. A photodetector monitors the output energy and adjusts the flashlamp high voltage. Drifts in the YAG output beam steering are removed by optics which image the YAG rods onto the Ti:Sapphire crystals.

The primary source of intensity jitter in the Ti:Sapphire cavities is variations in the optical gain which cause the timing of the Q-switched pulse to change. As the cavity dump time is fixed by the accelerator timing, these variations in build-up time cause variations in output intensity. Feedback loops which measure the build-up time of the light and control the stop time of the Q-switch pulse are used to maintain the cavity-dump time at the peak of the optical pulse. The gain variations due to changes in each of the YAG lasers on each of the Ti:Sapphire cavities are independent, so four separate timing feedback loops are used. Without the timing stabilization, the output intensity jitter from the Ti:Sapphire lasers is approximately 12% RMS. The feedbacks reduce this to approximately 5% RMS.

The output power from the Ti:Sapphire cavities is stabilized by intensity feedbacks which read the optical energy and control the high voltage to a Pockels cell. Separate feedbacks are used for pulses generated by each of the pump lasers.

After the slow timing feedbacks have removed drifts in the build-up time of the optical power, the major remaining source of jitter is pulse to pulse fluctuations in gain due to intensity jitter in the pump YAG lasers. A "fast feedforward" system is used to eliminate this effect to first order. The fast feedforward measures the YAG output energy, and on the same pulse, adjusts the stop time for the Ti:Sapphire Q-switch to reduce the build-up time jitter. The fast feedforward reduces the output jitter from the Ti:Sapphire cavities to <3% RMS.

A Pockels cell also controls the circular polarization of the laser light. The polarization is changed in a random order on a pulse-by-pulse basis. Both the first and second pulses go through the circular polarization system, although the polarization of the second pulse is not important. The first pulse has a wavelength of 865 nm, near the bandgap of the strained GaAs photocathode maximizing electron spin polarization. The second pulse has a wavelength of 770 nm, chosen to match the 865 nm wavelength of the first pulse in the gain of the Ti:Sapphire cavity.

4. The Photocathode

The photocathode used in the SLC source in 1993 is a strained GaAs photocathode. The layer structure of the photocathode, shown in fig. 3, was grown by MOCVD techniques by Spire Corp.[10]. The 0.3 μm thick active layer is grown on a 2.5 μm thick $GaAs_{(.76)}P_{(.24)}$ underlayer. The lattice constant of the underlayer is smaller than that of the active GaAs layer. The strain induced by the lattice mismatch causes the degeneracy in the $P_{3/2}$ top valence band to be lifted. This allows photoelectrons, excited from the material with circularly polarized light having energy near the bandgap, to have spin polarization greater than the 50% limit of normal GaAs.

The cathodes are activated to high QE by heating to 610 °C for one hour, cooling to room temperature, applying Cs until the photocurrent peaks, followed by codeposition of Cs and NF_3. The 0.3 μm thickness of the active layer is much less than the absorption depth for light with energy near the bandgap, so the QE of this material is lower than that of thicker photocathodes, and higher energy is required in the laser pulses.

This photocathode material has been measured in the lab [6] to give 82% polarization at 860 nm, while other similar, thinner active layer (lower QE), strained GaAs photocathodes have been shown to produce polarizations in excess of 90%. The photocathode in use in the SLC source was measured with a Møller polarimeter at the end of the linear portion of the SLC to give 76 ± 4% polarization at a laser wavelength of 864 nm. Significant polarization losses in the SLC arcs reduce the polarization to 63 ± 1% at the interaction point.

5. The Charge Limit

Experiments on charge limit have been performed using the Gun Test Facility at SLAC which is essentially a duplicate of the first few meters of the SLC injector [11]. The facility consists of a polarized electron gun with a loadlock system for easy cathode change, a YAG-pumped pulsed Ti:Sapphire laser tunable between 750 nm and 870 nm [12], and an electron beam line with a beam position monitor, a fast gap monitor and a Faraday cup. A large number of III-V semiconductor photocathodes were studied including: 0.3 μm strained lattice (high polarization)

$GaAs/GaAs_{(.76)}P_{(.24)}$; 0.3 μm, 1 μm, and bulk GaAs; and 0.3 μm $Al_{(.12)}Ga_{(.88)}As$, where the thicknesses refer to the active layer, all doped with either Be or Zn to a concentration of $5x10^{18}$ to $2x10^{19}/cm^3$. Two continuous wave diode lasers of wavelengths 750 nm and 833 nm operating at low power (< 1 mW) were used for QE measurements. Unless otherwise stated, the cathode temperature was 0°C. All of the data presented below were obtained from the 0.3 μm strained GaAs cathode, whose results are qualitatively representative of those of the other cathodes.

Figure 4 shows the charge versus laser pulse energy data, or saturation curve, for the 0.3 μm strained GaAs cathode. The Ti:Sapphire laser was tuned to a wavelength of 850 nm for the measurement. The QE is 1.51% and .57% at 750 nm and 833 nm, respectively, measured with the laser spot fully illuminating the cathode area. The difference in the QE measured at the two wavelengths can primarily be attributed to the different number of photons actually absorbed by the 0.3 μm thick cathode for an equal number of incident photons at the two wavelengths. The figure shows clearly that for low laser intensities, the amount of emitted charge per pulse is linearly proportional to the laser pulse energy. However, the dependence quickly becomes nonlinear for higher energies, and the amount of emitted charge eventually saturates to a limit of $7x10^{10}$ electrons/pulse. This is well below the inherent space charge limit of the gun, which permits $1.1x10^{11}$ electrons/pulse. This behavior is consistent with the results reported in ref. [3]. As the QE drops with time, the charge limit decreases almost proportionally.

The nature of the charge limit is more clearly elucidated in the time resolved electron intensity measurement with the gap monitor. Two temporal profiles of the electron bunch with low and high intensity laser illumination, corresponding to non-charge-limited and charge-limited cases, respectively, are shown in fig. 5. At low laser energy, the electron pulse shape is symmetric and closely resembles that of the laser pulse, indicating that the cathode response to the laser illumination is approximately linear. At high laser energy, when the charge limit is reached, the electron pulse becomes asymmetric and peaks at a significantly earlier time than the light pulse. This behavior is very different from the space charge limit manifested by a flat-topped symmetric pulse with the flat top amplitude determined by the space charge limit effect.

The decreased photoemission in the latter part of the pulse, as revealed by the time profile in fig. 5, is characteristic of the charge limit effect. In the deep charge limit regime, the suppression of photoemission after the electron pulse peaks can be so strong that the electron pulse becomes significantly shorter than the light pulse. These results suggest that as a large number of electrons are excited from the valence band into the conduction band in the cathode, the work function at the cathode surface increases and reduces the escape probability of the excited electrons. Several models have been proposed to account for the induced work function increase [13]. From these data it is unclear which model is correct, and it is possible that more than one mechanism may be responsible. However, a strong argument can be made for the photovoltaic effect [14] as the dominant cause for the charge limit effect [11].

4. Source Operations

The laser light is steered onto the photocathode by a telescope system which has remote controlled X and Y motion. Both of the two laser pulses are dynamically corrected to hit the center of the photocathode. The remote controlled Z motion of the laser telescope controls the laser spot size on the photocathode. The laser energy per pulse is held at a high enough value so as to saturate (in the charge limit) the current density from the illuminated part of the photocathode, thus minimizing electron beam intensity jitter. No effect in beam polarization, due to operating in the charge limit, has been observed.

After the activation of the photocathode, the QE drops slowly with time. As the QE decreases, the charge limited current density decreases. The laser spot size is automatically increased through a feedback system which maintains the desired electron beam intensity. Eventually the charge limit falls to a level such that the fully illuminated photocathode cannot deliver the desired beam intensity. At this point, the QE of the photocathode must be refreshed. This is accomplished by a brief deposition of additional cesium on the surface of the photocathode. This recesiation is performed by remote control and takes a total of 20 mins. There is a gradual decrease in photocathode performance with each recesiation, and after many (10–30) recesiations the photocathode must be heat cleaned and reactivated.

5. Conclusion

The Stanford Linear Collider at SLAC has been operating with a spin polarized electron source based on a strained GaAs photocathode. The source employs a Ti:Sapphire laser system to generate two 2 ns long pulses at 120 Hz. The gun operates at a potential of -120 kV to generate the 4.5×10^{10} electrons per pulse required by the accelerator. The polarization from the source has been measured at $76 \pm 4\%$ at the end of the linac, and the polarization at the interaction point has been $63 \pm 1\%$. The source has been reliable, available for operations >95% of the time.

6. References

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[14] Photovoltaic effect refers to the reduction in the band bending due to the photoexcitation-induced accumulation of charges at the surface of opposite sign (electrons in our case) to that of the original surface charges (positively charged ions in our case) which leads to a reduction in the net amount of surface charges. A. Herrera, W. Spicer, Stanford University, private communication.

Figure Captions

Figure 1. SLC Polarized Electron Source laser system layout

Figure 2. TI:Sapphire laser cavity layout.

Figure 3. The layer structure of the strained GaAs photocathode.

Figure 4. The photoemitted charge versus laser pulse energy at a wavelength of 850 nm, for the 0.3 μm strained GaAs cathode.

Figure 5. Two temporal profiles of the electron bunch with low and high intensity laser illumination corresponding to non-charge-limited and charge-limited cases, respectively.

SLAC Ti: Sapphire Polarized Source Laser System Layout

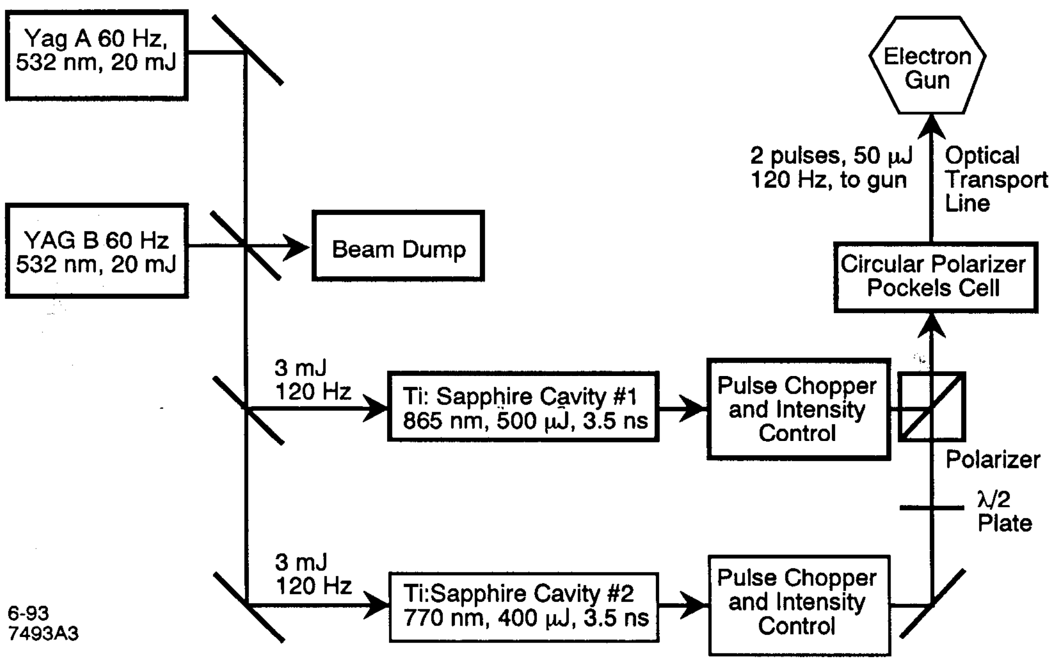

Fig. 1

SLAC Polarized Source Ti: Sapphire Cavity

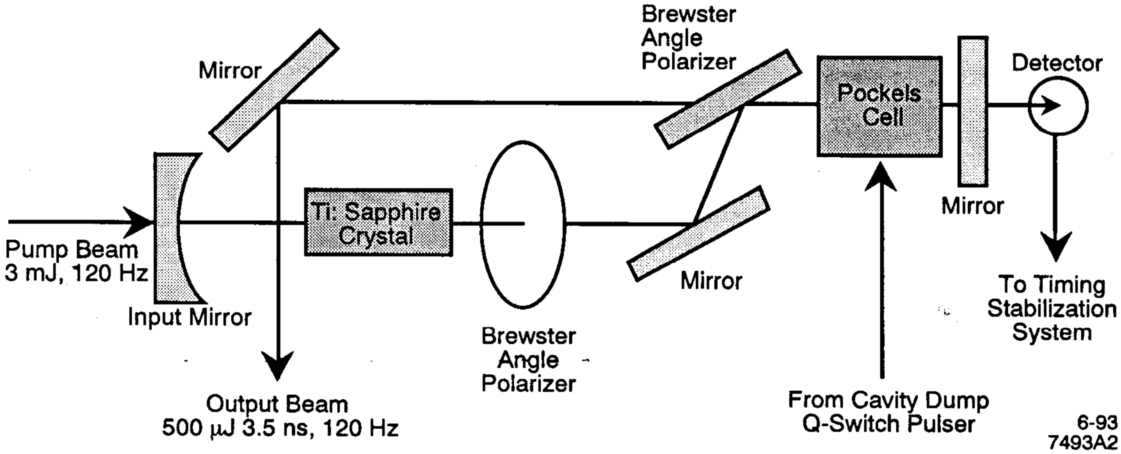

Fig. 2

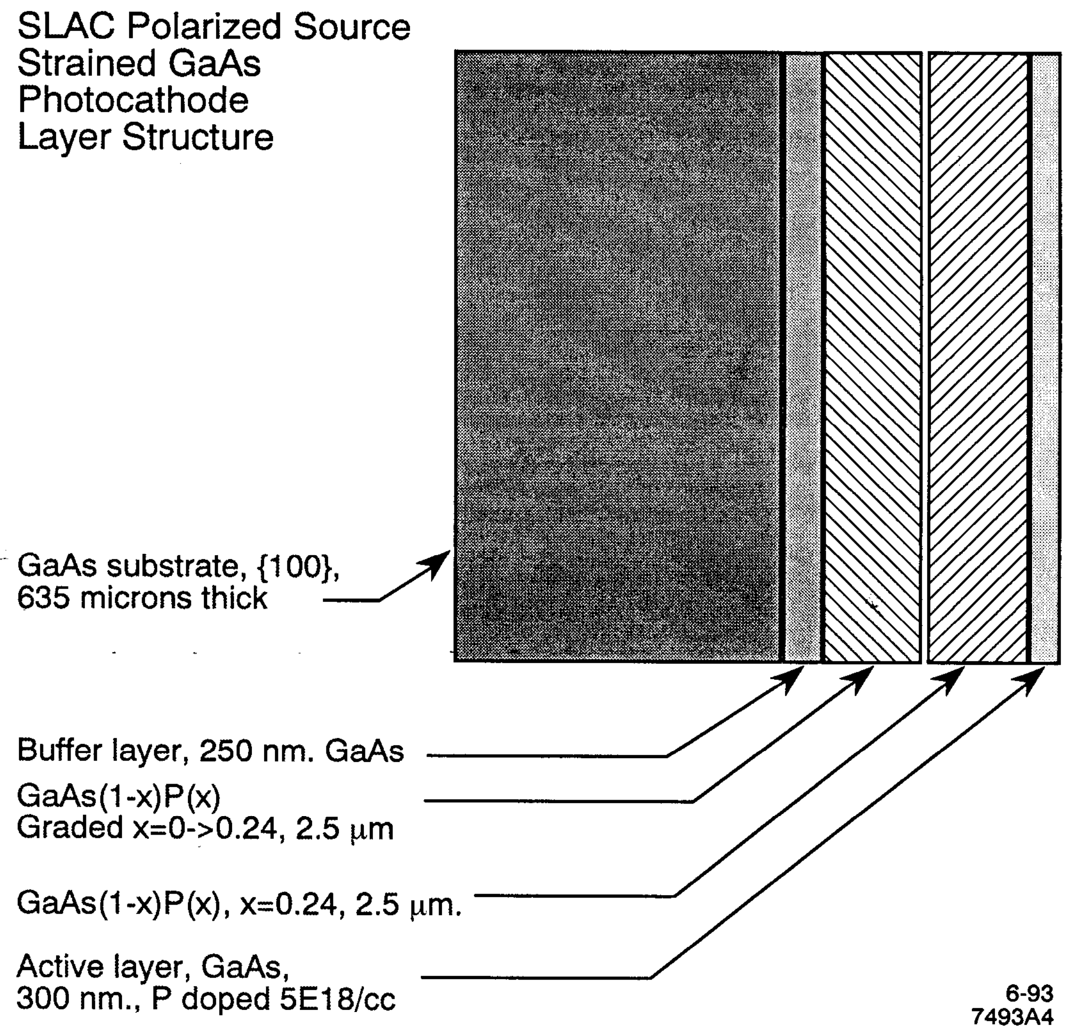
SLAC Polarized Source
Strained GaAs
Photocathode
Layer Structure
GaAs substrate, {100},
635 microns thick
Buffer layer, 250 nm. GaAs
GaAs(1-x)P(x)
Graded x=0->0.24, 2.5 μm
GaAs(1-x)P(x), x=0.24, 2.5 μm.
Active layer, GaAs,
300 nm., P doped 5E18/cc
6-93
7493A4

Fig. 3

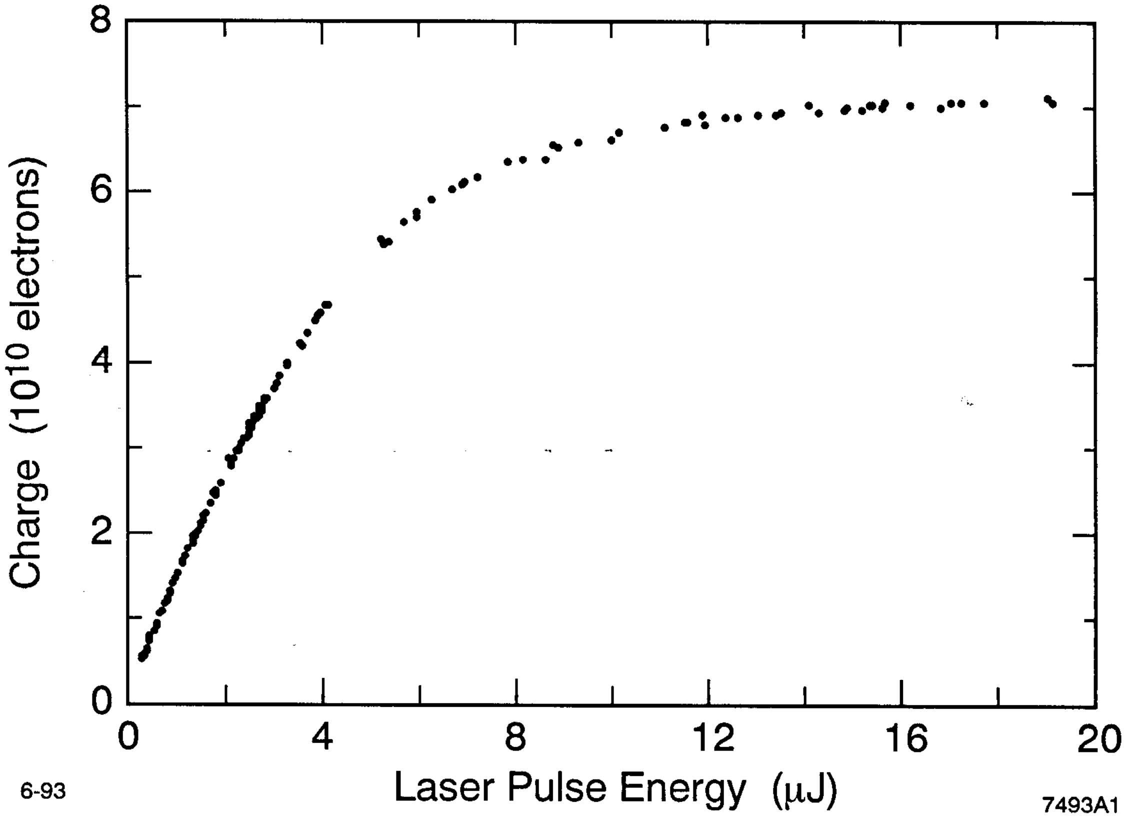

Fig. 4

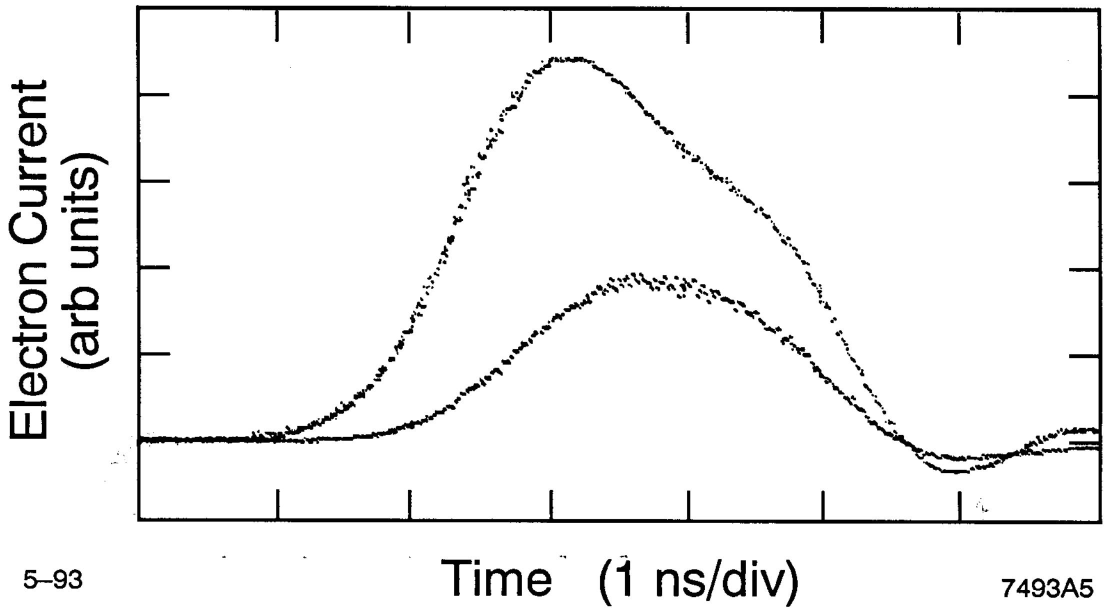

Fig. 5