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THE POLARIZED ELECTRON SOURCE OF THE STANFORD LINEAR ACCELERATOR CENTER*

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Abstract

The Stanford Linear Accelerator has been running with polarized electrons both in the collider (SLC) mode and in the fixed target mode. The accelerator's polarized electron source is based on a thin, strained GaAs photocathode, which is held at a negative high voltage and illuminated by a Titanium Sapphire laser. The reliability of the source was better than 95% during the eight-month-long 1993 SLC run. A beam polarization of 63% was measured by the SLD experiment at the SLC interaction point in the 1993 data run. The fixed-target experiment E143 measured a beam polarization of 85% in its 1993–94 run. These polarization measurements, made at high energy, are in good agreement with measurements made at low energy on a calibrated Mott polarimeter. The higher beam polarization in the fixed target experiment is due to a thinner, more highly strained GaAs photocathode than had been used earlier, and to the experiment's low beam current requirements. The SLC is now running with the high polarization photocathode. Details of the source, and experience with the high polarization strained GaAs photocathodes on the accelerator in the current SLC run, will be presented.

Introduction

Polarized electron beams have been in continuous use for the high-energy physics program at SLAC since the spring of 1992 [1,2]. The polarized electrons are generated by the Polarized Electron Source, consisting of an electron gun with a strained GaAs photocathode and a laser operated at a wavelength near the semiconductor band gap. The source supplies polarized electrons for SLC colliding beam operation and for fixed target experiments. The SLC program demands high beam intensities; two 2 ns electron bunches separated by 61 ns with up to 8×10^{10} electrons in each at the gun. 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. In the 28 GeV beam fixed target mode of operation the source produces one 2-μs-long pulse containing up to 4×10^{11} electrons at 120 Hz. In the upcoming 50 GeV fixed target run the source will be required to produce this charge in 100-ns-long pulses. The high (~6 A) currents needed in SLC

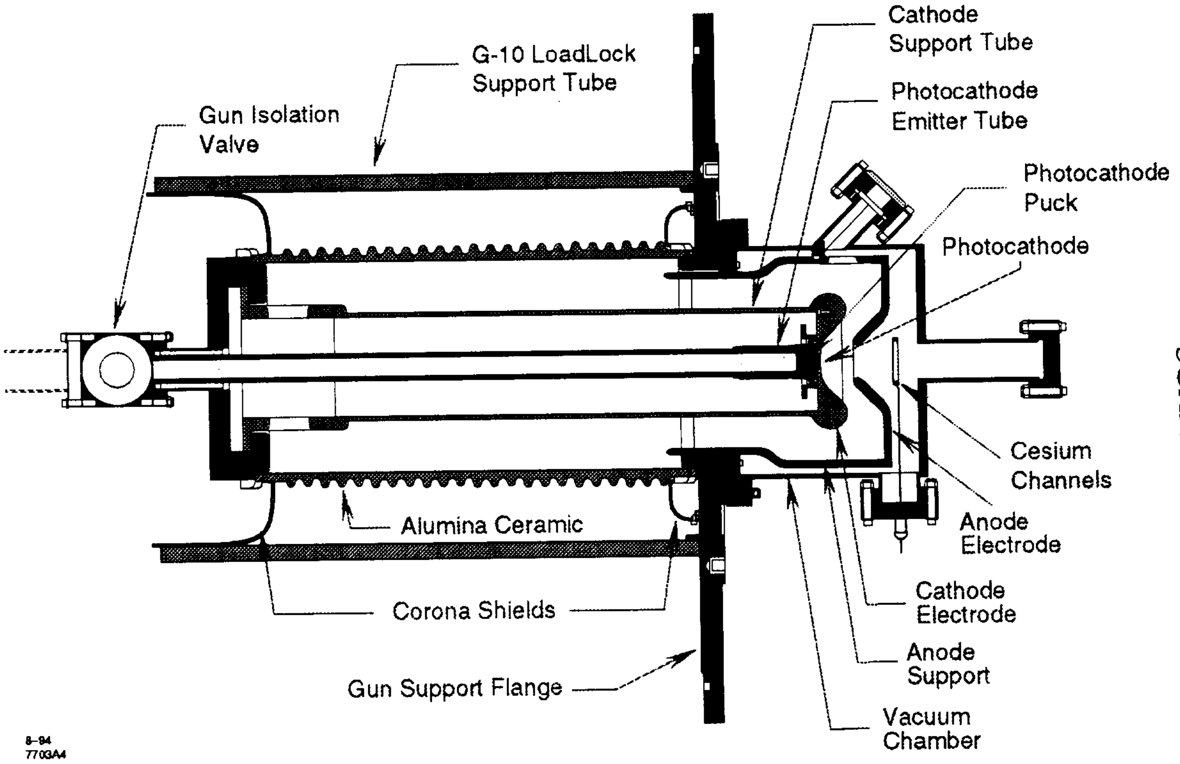

Fig. 1. The SLC Polarized Electron Gun.

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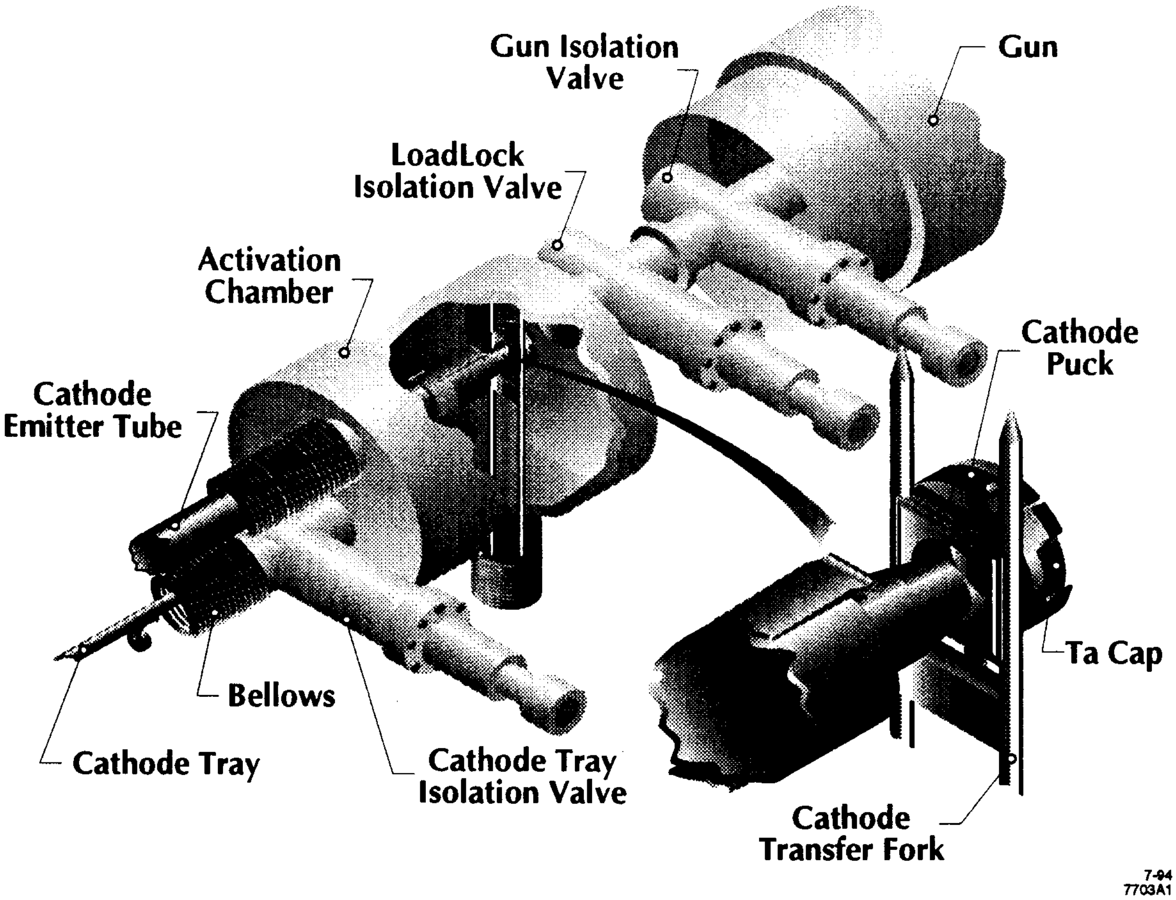

Fig. 2. The load lock of the electron gun.

operations, compared to the low (1–600 mA) currents of the fixed target running, place different restrictions on the operation of the polarized electron source.

The Electron Gun and Load Lock

The SLC Polarized Electron Gun is of a conventional diode design as shown in Fig. 1. 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 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 level of vacuum in the gun volume is critical to the photocathode lifetime. Minute increases in the levels of CO and CO_2 (the levels are coupled) have been seen to be correlated with a degradation of the photocathode quantum efficiency (QE, defined here as the ratio of the number of electrons in the beam pulse to the number of photons entering the gun vacuum, with all measurements done at 833 nm). The ultra-high vacuum in the gun is maintained by means of nonevaporable getter pumping as well as ion pumping. These pumps, not shown in Fig. 1, are located on the vacuum chamber near the electrodes so that the vacuum conductance to the photocathode is high. 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. 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 slightly but irreversibly degraded. Dark currents below 50 nA at 120 kV are routinely maintained.

The high voltage end of the gun is connected at the gun isolation valve to a load lock system to facilitate photocathode change [3]. The load lock, shown in Fig. 2, 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 photocathode is mounted on a Molybdenum puck using a Tantalum cap. The puck is held on the end of the cathode emitter tube and inserted through two isolation valves into the gun. Photocathode heat cleaning and activation are performed in the load lock vacuum chamber. Two additional pucks with photocathodes can be stored under vacuum in the load lock cathode tray. The weight of the load lock is supported by a G-10 tube which is attached to the gun support flange.

The use of the load lock provides two major advantages to source operations over (previous) running

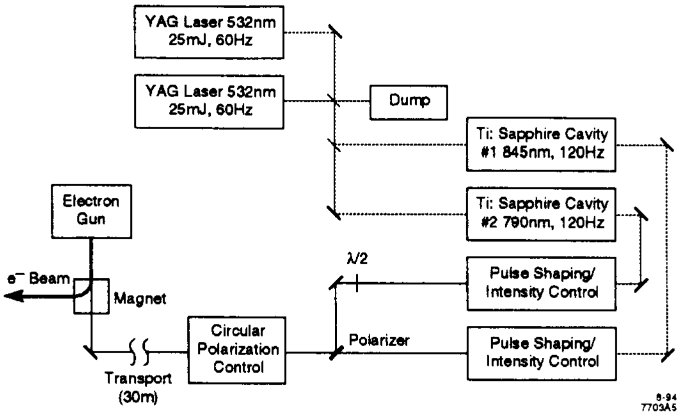

Fig. 3. The SLC Ti:Sapphire laser system.

without one. The first of these is that 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 to change photocathodes and rebaked, and 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 performance may also be improved when introduced through the load lock, as the photocathode is not subjected to the gun bakeout.

The Laser Systems

The photocathode is illuminated with circularly polarized light from a Titanium-doped Sapphire laser system at a wavelength chosen to maximize polarization [4]. The different time structures of the electron beam for SLC and fixed target operation requires two separate laser systems.

For SLC operations, two Ti:Sapphire crystals, pumped by doubled YAG beams, are used to produce two pulses. This allows 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 2 YAG lasers operating interleaved to pump each of the Ti:Sapphire cavities. One of the two crystals is in a cavity tuned to 844 nm, and used to generate the electron pulse sent to the interaction point. The second crystal is in a cavity tuned to 790 nm (the peak of the gain curve), and is used to generate the electron pulse for positron generation. Pockels cells with fast avalanche transistor drivers chop the output pulses to the required 2 ns width. An additional Pockels cell after each cavity is used to control the output intensity. This laser system is capable of producing energies of more than 100 μJ in the 2-ns-long pulses at the photocathode. Figure 3 shows the overall system layout. 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 primary source of intensity jitter in the Ti:Sapphire cavities is variations in the optical gain causing 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 3% rms. The major remaining source of jitter is pulse-to-pulse fluctuations in gain due to intensity jitter in the pump YAG lasers. A feedforward system is used to minimize this effect. The feedforward measures the YAG output energy and adjusts the stop time for each Ti:Sapphire Q-switch to reduce the build-up time jitter. This feedforward has been improved over the SLC '93 version, and reduces the output jitter from the Ti:Sapphire cavities to < 1.5% rms.

For fixed target operations, a single Ti:Sapphire crystal is pumped directly by two flashlamps in a cavity tuned to 845 nm [5]. For running during the '93–'94 fixed target experiment, E143, the light pulse was chopped to a 2 μs width and the power controlled by a feedback system which held the beam current constant. For the upcoming 50 GeV fixed target run higher laser power will be needed in a 100-ns-long pulse. A new flashlamp-pumped Q-switched Ti:Sapphire laser is being developed to stably provide > 10 kW.

The Photocathode

The polarized electron source is based on a thin, strained GaAs photocathode grown by MOCVD techniques by Spire Corp. [6]. The 100-nm-thick GaAs active layer is strained due to a lattice mismatch with the $GaAs_{(.72)}P_{(.28)}$ layer upon which it is grown. This strain lifts the degeneracy in the $P_{3/2}$ valence band allowing photoelectrons, excited from the material with circularly polarized light having energy near the bandgap, to have spin polarization higher than the 50% limit of unstrained GaAs.

The photocathodes are activated to high quantum efficiency by heating to 610°C for one hour, cooling to room temperature, applying Cesium until the photocurrent peaks, followed by codeposition of Cs and NF_3. The quantum efficiency decreases with time and must be periodically recovered with a brief application of

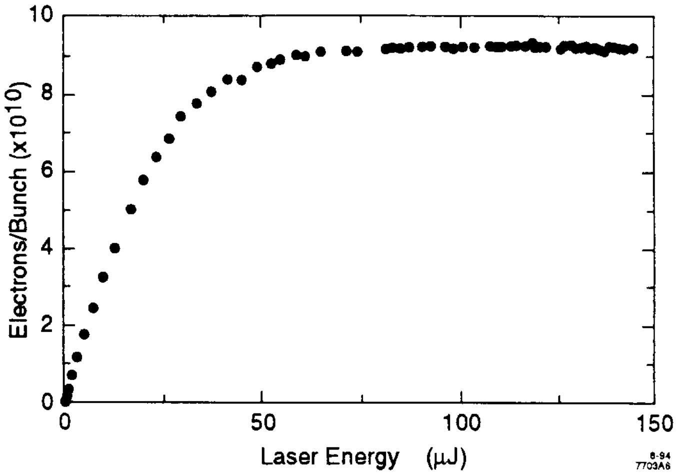

Fig. 4 The photoemitted charge versus laser pulse energy, at a wavelength of 844 nm, for the 0.1 μm strained GaAs cathode.

Cs. This recesiation is done in situ, using Cesium channels located beyond the anode.

The quantum efficiency must be maintained at a high value for SLC running, not only to lower the power required from the laser system but to keep the beam current above the *charge limit*. The charge limit effect temporarily extinguishes the quantum efficiency as current is drawn from the photocathode. The amount of charge which can be extracted in a 2 ns pulse is limited as the current in the first few hundred ps of the electron bunch decreases the quantum efficiency for the rest of the pulse. Figure 4 shows the charge delivered in a 2-ns-long electron pulse versus the laser energy incident on the photocathode for the 0.1-μm-thick strained GaAs cathode. The Ti:Sapphire laser was tuned to a wavelength of 844 nm for the measurement. The QE of the photocathode was 0.27%, measured at 833 nm with the laser spot fully illuminating the cathode area. The figure shows 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 9×10^{10} electrons/pulse. This is below the inherent space charge limit of the gun, which permits 1.1×10^{11} electrons/pulse. In the deep charge limit regime, the suppression of photoemission in the latter part of the electron pulse can be so strong that the electron pulse becomes significantly shorter than the light pulse. This is the reason for the decrease in charge, shown in Fig. 4, above 120 μJ laser energy. This effect becomes more pronounced as the surface of the photocathode becomes contaminated and the low-current quantum efficiency decreases. Several models have been proposed to account for the induced work function increase [7, 8, 9]. The 5×10^{18} cm^3 doped photocathode recovers from the effects of the 2 ns pulse after a few tens of ns.

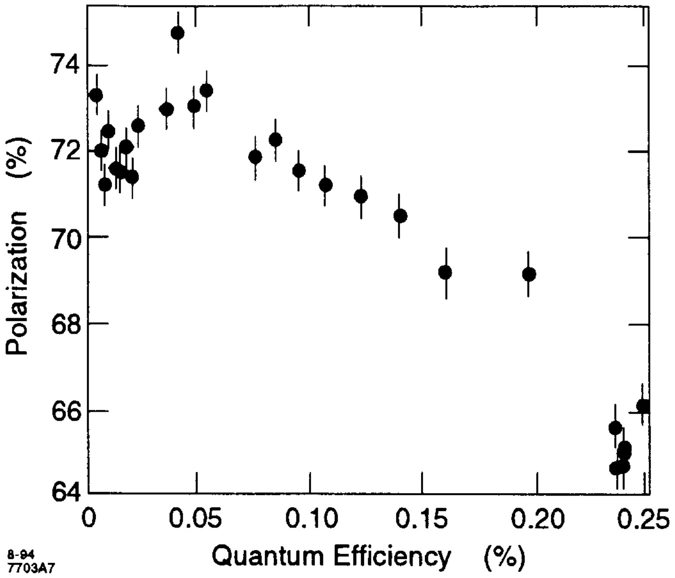

Fig. 5 The polarization of the electron from a 0.1 μm strained GaAs photocathode measured with decreasing quantum efficiency.

Polarization

After the activation of the photocathode, the QE drops slowly with time. As the QE decreases the charge-limited current density decreases. The laser power is increased through a feedback system which maintains the desired electron beam intensity from the source. 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 SLC operators with computer control, and interrupts the beam a total of 20 min. 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.

The requirement of high quantum efficiency is at odds with the desire for maximum polarization; the polarization measured just following recesiation is low, and the polarization increases as the quantum efficiency decreases. Figure 5 shows polarization measurements made at different quantum efficiencies on a 100-nm-thick, strained GaAs photocathode similar to those used in the polarized source. The data were taken at low current and low energy on a calibrated Mott polarimeter in the SLAC cathode test system [10]. In these data the quantum efficiency was forced down by NF_3 gas, and polarization was measured periodically. The peak polarization of this test sample, 73%, is lower than the 85% peak polarization observed with other, similar, photocathodes. This may be due to a partial relaxation in the strain in the active layer of this particular photocathode. Figure 5 shows a substantial increase in polarization as the quantum efficiency falls.

In the current SLC '94 run the peak quantum efficiency is about 0.3%. When the quantum efficiency drops (over several days) to just below 0.2% the charge limit falls below the 7.5×10^{10} electrons per pulse now required from the source. The beam polarization, which is approximately 15% higher than that shown in Fig. 5, drops by ~5% (relative) over the quantum efficiency cycle, consistent with the data shown in Fig. 5. The average polarization could be improved by maintaining the quantum efficiency at the minimum allowable level instead of fully recovering the peak QE during recesiation. This could be accomplished by the more frequent application of less Cesium during recesiation than has been practiced, or by continuously applying a small amount of Cesium. These procedures are being tested prior to use on the accelerator.

For fixed target operations, where the photocathode current is much lower, the charge limit is not observed, and the quantum efficiency can be allowed to drop to the lowest value allowed by the laser power limit. The low quantum efficiency enhances the beam polarization. The fixed target experiment, E143, measured a beam polarization of 85% in its 1993–94 run [11] (~15% higher than that shown in Fig. 5). In this run the 100-nm-thick strained photocathode was also used. The quantum efficiency of the photocathode was allowed to fall from a maximum value of 0.3% to 0.05%, and was maintained in the range 0.05–0.007% by periodic limited recesiation.

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 7.5×10^{10} electrons per pulse required by the accelerator. Using a 100-nm-thick strained GaAs photocathode, beam polarizations of 85% have been measured at low beam intensities. For high intensity beams the photocathode quantum efficiency must be maintained near its maximum value. The high quantum efficiency results in lower polarization.

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