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Polarization Developments*

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ABSTRACT

Recent developments in laser-driven photoemission sources of polarized electrons have made prospects for highly polarized electron beams in a future linear collider very promising. This talk discusses the experiences with the SLC polarized electron source, the recent progress with research into gallium arsenide and strained gallium arsenide as a photocathode material, and the suitability of these cathode materials for a future linear collider based on the parameters of the several linear collider designs that exist.

1. Introduction

In high energy e^+e^- storage rings such as LEP, HERA, TRISTAN, and others, the mechanisms which polarize and depolarize the beam compete to establish an equilibrium value. The time to achieve this equilibrium can be tens of minutes to several hours, depending on the details of the design and running conditions. The processes which polarize and depolarize the beam are related to synchrotron emission, a ubiquitous process in these high energy rings. Polarizations have reached 60% in tests at HERA and 20% at LEP, but the tuning of these machines to achieve these levels is somewhat delicate. Polarization is naturally transverse to the plane of the ring. To implement polarization for experimental work, rotation of the transverse spin to a longitudinal orientation is required at the experiments. Designs to do this rotation exist, but to date none have been implemented in a running experiment.

In contrast, linear colliders have an entirely different situation. In the SLC, the beams reside in the linac for 13 μsec and in the damping rings for 8 milliseconds. These times are too short either to polarize or depolarize the beams by the processes at work in storage rings. For linear colliders, the electron beam will be born longitudinally polarized and must be transported and accelerated through the damping ring, through the linear machine, and through the final focus elements while preserving the magnitude of the polarization and restoring the spin orientation to longitudinal at the experiment.

Linear colliders are natural machines for polarized beam work. Recent progress in photoemission sources has made possible the production of longitudinally polarized electrons with intensities sufficient for linear collider needs. In the following sections, this progress will be described.

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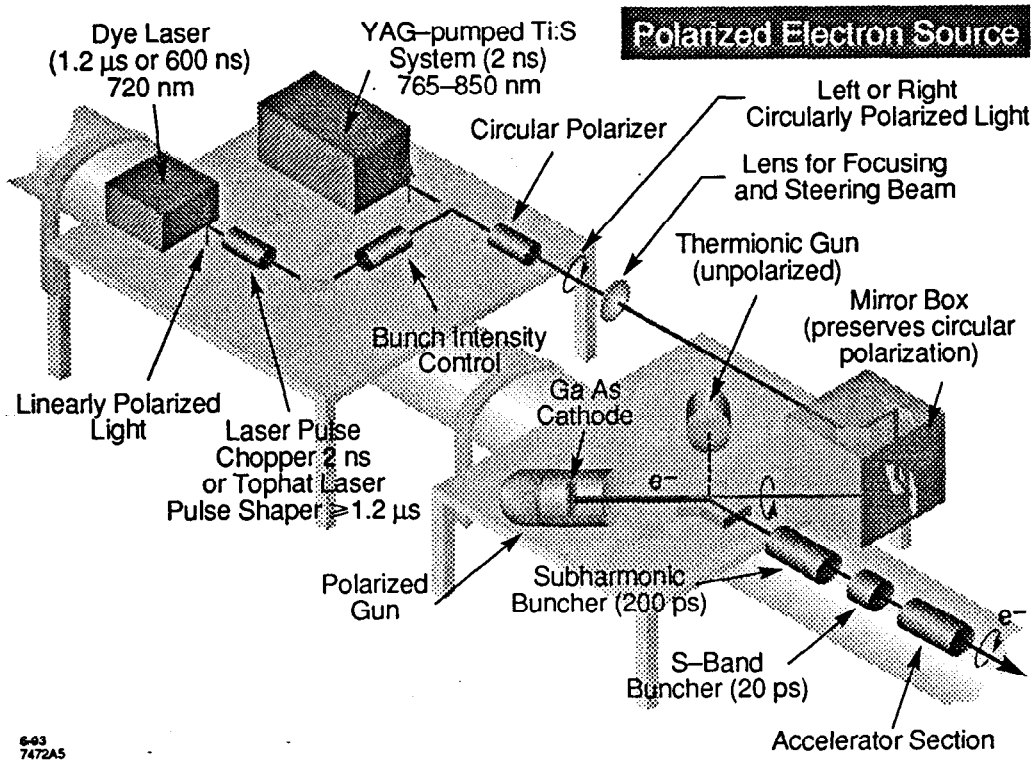

Figure 1. The layout of the lasers and the polarized gun at the SLC injector shown schematically. The SLC runs on the YAG-pumped Ti:sapphire laser tuned to a wavelength of 865 nm. The laser beam passes through an intensity controller, a chopper, a lens box, and mirrors before reaching the gun cathode. Photoemitted electrons are deflected by a bend magnet onto the axis of the accelerator.

2. The SLC Gun Performance

The polarized gun for SLC has been under development at SLAC for several years and began first operations during the 1992 run cycle for SLC.[1] Figure 1 shows the layout of the injector section of the SLC. Presently, two lasers exist, and both have been used. A flashlamp pumped dye laser was used for a duration of 6 months for the 1992 SLC run. It operated at a wavelength of 720 nanometers and at a pulse rate of 120 Hz, producing a 600 nanosecond-long pulse which was chopped into two 2.8 nanosecond-long pulses spaced by 61 nanoseconds, with 10 μJ of energy in each pulse. For the 1993 SLC run, that laser was superceded by a YAG-pumped Ti:sapphire laser operating at 120 Hz with two separate cavities each producing a pulse having energy up to 100 μJ. The wavelength of the first pulse is 865 nm, while the second pulse (used for positron production) is set to 765 nm and follows the first by 61 nanoseconds.

The SLC lasers are well integrated into the SLC operations. They are instrumented with intensity controls, a light chopper (for the 2.8 nanosecond FWHM pulse length), a circular polarizer consisting of a linear polarizer and a Pockels cell, and a

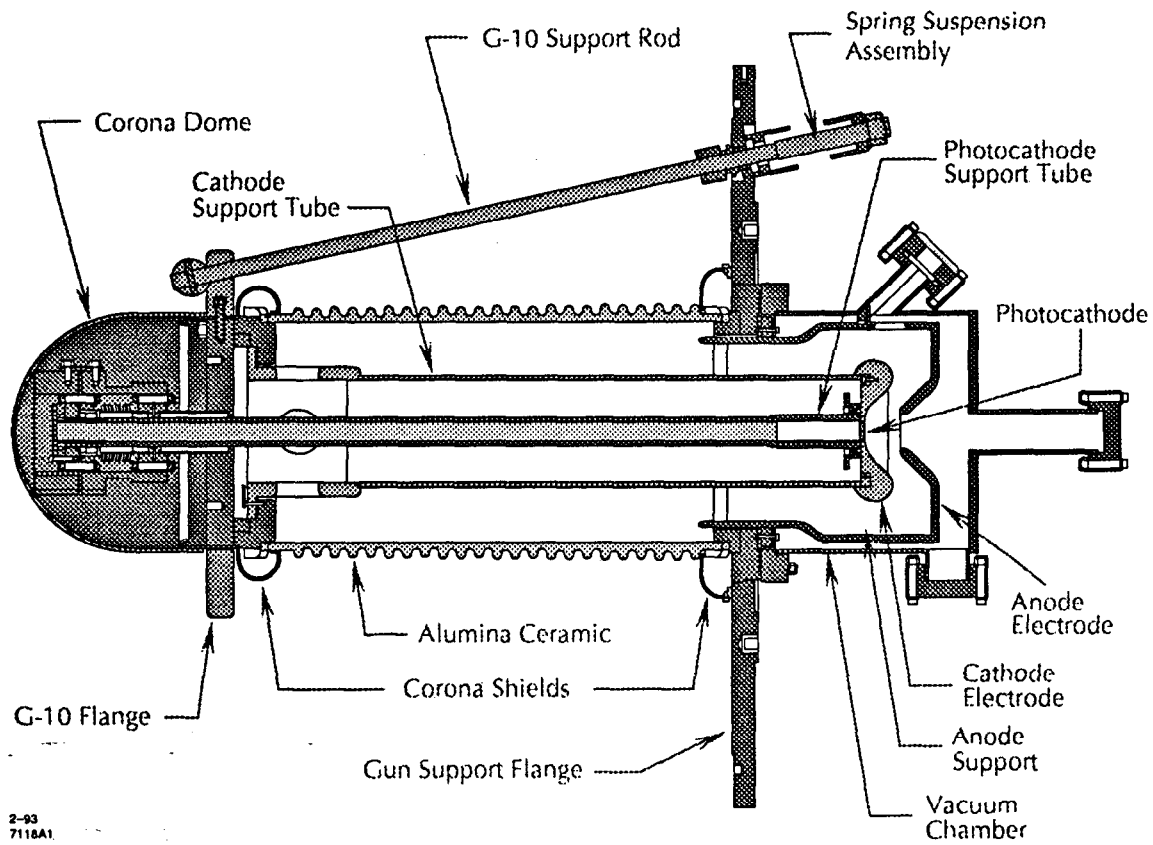

Figure 2. The polarized gun structure consists of a high voltage electrode (at -120 KV), a ceramic insulator, and a ground electrode. The photocathode sits on the end of its own support tube, centered in the high voltage electrode. Photoemitted electrons accelerate across the 3 cm gap between the cathode and the anode, and leave the gun through the front port.

lens box for focussing and steering. The laser intensity and focussing are controlled with feedback to stabilize the laser performance. The output beam passes through a mirror box, and into the exit port of the polarized gun, where it falls onto the photoactive cathode. Photoemitted electrons accelerate across a 3 cm wide gap, leave the gun, and are deflected by a magnet onto the linac injector axis where they enter bunchers and the first accelerator section.

Figure 2 shows the SLC gun structure. It is a diode structure, operating between -120 KV and ground. The photoemission cathode (a gallium arsenide wafer) is held on a cylindrical tube, the emitter tube, which sits in the center of the cathode electrode. The field gradient at the surface of the gallium arsenide is 2.4 MV/m, and the photoemitted electrons are accelerated to 120 KV kinetic energy in the 3 cm gap. The gallium arsenide cathode is an 18 mm diameter, .020 inch thick disc with an exposed surface 14 mm in diameter. It is clamped to the outside on the end of the emitter tube by a tantalum ring which captures the cathode and crimps it down to

the emitter tube surface.

The emitter tube itself is vacuum tight with a flat end. The outside of the emitter tube is exposed to the gun vacuum (typically 1×10^{-12} torr on the CO species). The inside volume of the tube opens to the atmosphere, allowing a heater to be inserted from behind. Gas (nitrogen) flows in this space, and upon application of electric power, the end of the tube is driven to 620°C for an hour, heating the gallium arsenide surface to approximately this temperature. Following cooldown to room temperature, cesium and fluorine at low pressures (the flourine is in the form of NF_3) are added while white light illuminates the surface. The light photoemits electrons in a steady current which grows as the surface quantum efficiency increases due to the adhesion of cesium and flourine. The process is allowed to proceed until the photocurrent reaches a maximum and begins to decline, at which point the cesium and NF_3 supplies are shut off. The heater is removed before high voltage is applied to the gun. This process ("activation") has been studied a great deal, and much is written about the subject.

In our cathodes, we achieve a quantum efficiency (the probability that a photon ejects a free electron from the surface) of up to 10% at $\lambda = 765$ nm. We routinely operate the cathodes at SLC up to 8% and can operate with values as low as 1%. Quantum efficiency is seen to decay in our gun at a rate that requires reprocessing about once per week . The simplest reprocessing was found to be the addition of more cesium without fluorine ("re-cesiation"). However, after a number of re-cesiations, a full cleaning cycle was needed, so the full re-activation would be done. During SLC running in 1992, re-activation occurred about once a month and re-cesiation about once a week.

These periodic maintenance activities for the cathode were essential, but the timing of the maintenance could be scheduled one to two days ahead, allowing other essential maintenance activities to be done at the same time. The fraction of the overall calendar time during 1992 for which the electron beam was available was 94%. This figure represents a very dependable performance for a technical system involving lasers, high voltage, ultra-high vacuum, and photoactive cathodes.

In a subsequent two month long run for the fixed target program at SLAC, the uptime of the source was 96%, and in the first two months of the 1993 SLC running, it was 95%. The polarized gun and associated systems have become a routine and reliable component of the SLC.

Figure 3 shows the polarization as measured at the SLD experiment during a 15-day period in March and April 1993. The polarization is seen to increase steadily to its present value of 62-63%. The increasing polarization during this period can be attributed to the improving quality of the beam. Tuning of the linac, improvements in the linac stability, improvements in the linac emittance, and reducing the energy spread, all contribute to lowering the depolarizing effects in SLC. Early in April 1993, the laser wavelength was increased from 855 to 865 nm to increase the source polarization. This led to the jump in polarization seen in the April data. The SLC has continued to deliver a beam polarization near 63% to the SLD from that time to the present.

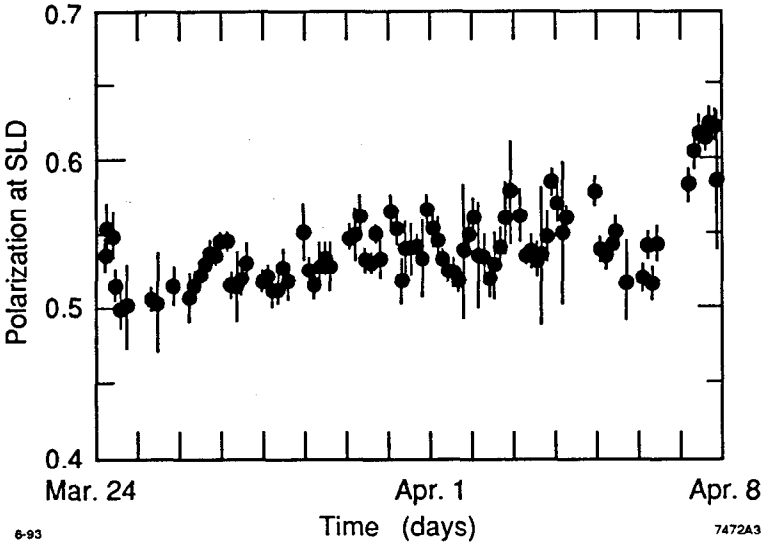

Figure 3. Recent measurements of beam polarization from the Compton polarimeter at the SLD detector show short term and long term variations. The period shown covers March 24, 1993 to April 8, 1993, a period of 15 days. During this period, steady improvement in the SLC running conditions contributed to increasing polarization. An intentional change of laser wavelength from 855 nm to 865 nm on April 6 led to a jump in polarization to 62%, as seen in the data.

3. The Strained Gallium Arsenide Photoemission Cathodes

The use of GaAs as a photoemission material of high quantum efficiency has been in practice since the 1960's when the principles and techniques were investigated for commercial applications (photo-multiplier tubes, night vision devices, etc.). Use of these materials for polarized electrons was first proposed in 1974 by E. Garwin, H. C. Seigmann, and D. Pierce.[2] The technique was limited to 50% polarization, but promised to provide high currents. Experimental demonstration of the polarization of photoemitted electrons from gallium arsenide first occurred at low intensities at Zürich[3] and later at high intensities at SLAC.[4] During the period from 1974-1977, searches for higher polarization in solid state cathodes began, and among the ideas considered was that of strained gallium arsenide. To test this idea, an experiment was performed at SLAC in which a gallium arsenide crystal was strained by a mechanical system, and the bulk sample was illuminated with 100% circularly polarized light. To measure the polarization of the internal conduction-band electrons, the recombination light was analyzed for its circular polarization. A value of 71% for the polarization of the conduction-band electrons was deduced from the circular polarization of the recombination light.[5]

During the 1980's, the molecular beam epitaxy process (MBE) was developed and commercialized by industry.[6] With the proper MBE equipment, layered gallium arsenide structures could be created, and experimentation with these layered structures began. To pursue the GaAs line of work, in 1990 a group from SLAC, Wisconsin,

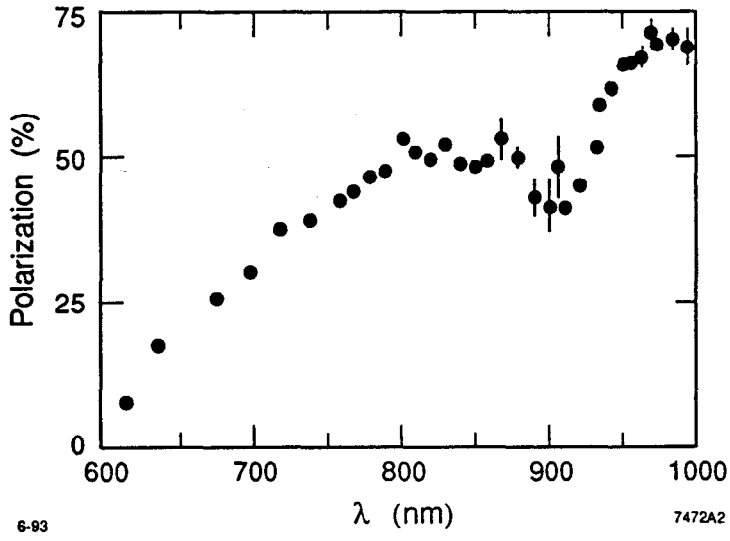

Figure 4. Polarization of photoemitted electrons versus wavelength of the (circularly polarized) laser light for a 0.10 μm thick layer of InGaAs, on a substrate of GaAs. The rise in polarization at wavelengths above 900 nm is due to the strain induced by the lattice mismatch in the heterostructure. This measurement was the first observation of high polarization for electrons photoemitted from strained cathodes.[7]

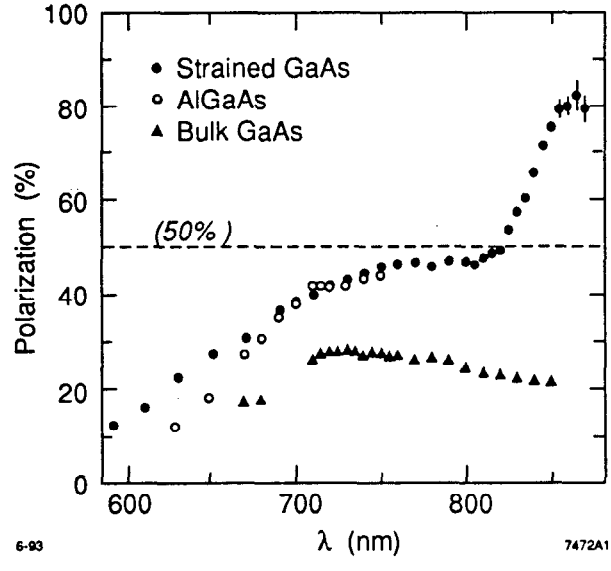

Figure 5. A comparison of polarization versus wavelength for three different cathodes that have run on the SLAC accelerator. The bulk GaAs cathode delivered beam to the SLC in 1992. The AlGaAs cathode was used for a fixed target experiment in 1992. The strained GaAs cathode is presently running on the SLC (1993).

and Berkeley collaborated on the fabrication of a device consisting of InGaAs grown on a substrate of GaAs. The introduction of indium (In) into the GaAs lattice changes the lattice spacing by about 1%, but otherwise leaves the basic band structure unchanged. Placing a thin layer of InGaAs on the GaAs substrate significantly strains the thin layer. Internal electric fields are induced by this strain, and a degeneracy in the valence band is broken. Some transitions from the valence band to the conduction band which participate in the 50% polarization are not excited at the longest wavelength, and a value of 100% polarization becomes theoretically possible.

Following fabrication of the material at Berkeley, the SLAC-Wisconsin-Berkeley group measured the electron spin polarization versus wavelength for this strained InGaAs material.[7] Figure 4 shows the rise in polarization at long wavelengths, reaching 71% at $\lambda = 865$ nm. These results were the first demonstration of a strained cathode material for high ($\geq 50\%$) polarization for electron accelerators.

A group at Nagoya University in Japan had been working independently on superlattice and strained GaAs materials, and shortly after the SLAC-Wisconsin-Berkeley group reported their results, the Nagoya group published results from strained GaAs on a GaAsP substrate. They achieved a polarization of 86% at $\lambda = 860$ nm.[8] The shorter wavelength and higher polarization they achieved relative to InGaAs is an advantage and an improvement. Today the cathode materials under study mostly involve the GaAs/GaAsP system, but future advances with variations on these materials seem possible.

The recent successes with strained GaAs stem from a world-wide effort to provide highly polarized electrons from solid-state materials. Beyond the works mentioned here, there have been many studies of the GaAs system and other materials for cathodes at accelerator labs and other labs around the world. These include KEK, CEBAF, Mainz, MIT-Bates, to name a few, and these activities have been supported by a series of international workshops.

Figure 5 shows the polarization versus wavelength for three cathodes that have recently run on the accelerator at SLAC. The cathode used in the 1992 SLC run was bulk GaAs, giving a polarization of 28% at λ =720 nm. This cathode was removed and replaced by an aluminum-gallium-arsenide (AlGaAs) cathode and used for a two-month long run for fixed target work in November-December 1992. It provided a polarization of 40% at 720 nm. In January 1993, in preparation for the 1993 SLC, run a strained GaAs cathode was installed. This cathode, operating at 865 nm, provides 75% to 80% from the source, and is the one running on the SLC today.

Work is proceeding on strained GaAs materials to optimize the cathode parameters for future SLC runs. The important parameters which affect polarization and current are: (i) the phosphorus concentration in the GaAsP substrate; (ii) the thickness of the epilayer (strain relaxes as this layer becomes too thick); and (iii) the level of zinc doping in the strained material. Figure 6 shows polarization versus λ for strained material where some of these parameters have been varied.[9] Work is in progress to fully characterize these materials, with the primary goal of achieving up to 90% polarization at the SLC source.

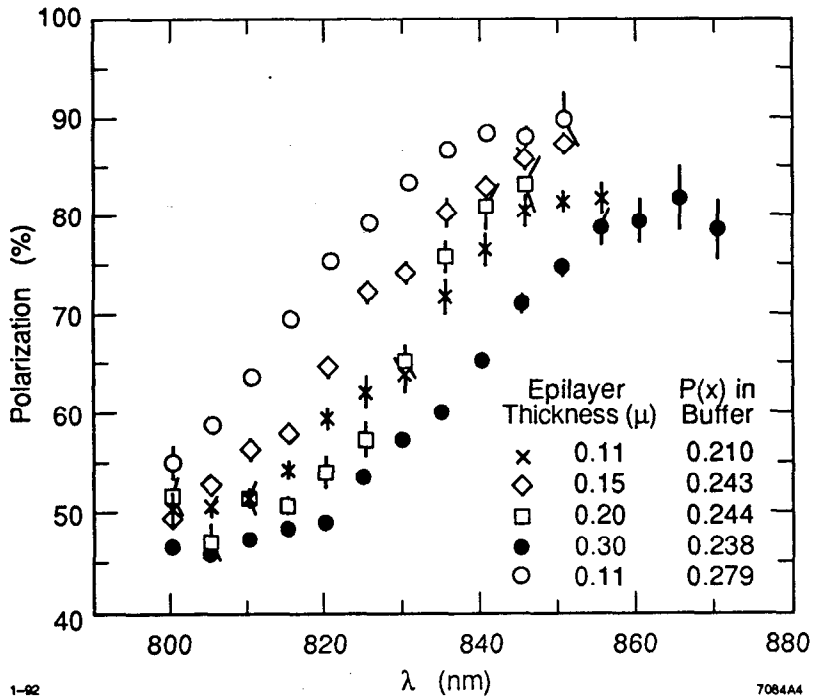

Figure 6. Comparison of GaAs cathode materials in which thickness of the epilayer and strain (as determined by the phosphorus concentration in the substrate (GaAsP)) have been varied. The black dots correspond to a sample of material like that running presently on the SLC (1993). The open circles are for a newer sample which has the thinnest epilayer (0.11 μm) and the highest strain.

4. Charge Limits

GaAs was originally proposed as a source of 50% polarized electrons at high currents. The properties of the solid state (as compared to polarized electrons from ionized gases or atomic beams) promised large currents would be available. The tests at SLAC in 1977 confirmed that such materials indeed provided the desired high currents. Also at that time, it was conjectured that these materials would demonstrate some current limitations limited not by the number of available electrons, but by properties of the semiconductor material. Although there were indications of limitations from earlier work, the question *"How much charge can one extract from the cathode?"* basically remained unanswered until March 92, when measurements were made with a high peak power laser.[10]

Figure 7 shows the observed saturation in a sample of bulk GaAs as the laser power increases. The tests were performed in the SLC gun, in which the space charge limit is well above the observed saturation values. The family of curves shows charge versus laser energy (in a 2.8 nanosecond-long pulse at $\lambda = 765$ nm) for several values of the quantum efficiency (QE) as measured at low power. A saturation of the charge is clearly seen, and is seen to depend on the value of QE. Since the SLC demands greater than 6×10^{10} e^-s per pulse, one conclusion is that high QE is desirable.

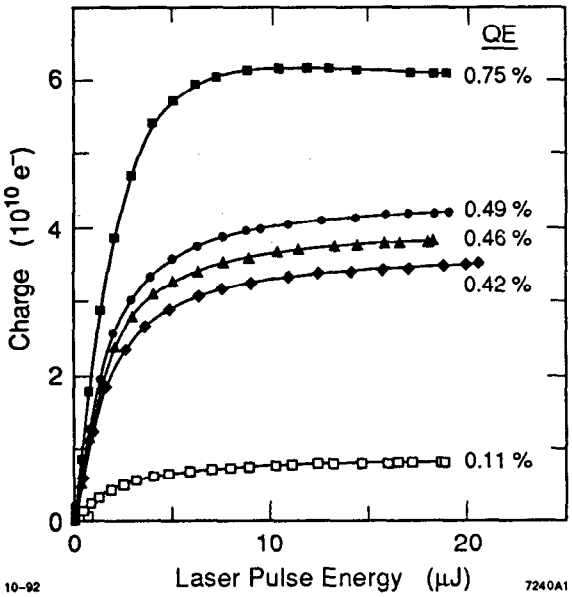

Figure 7. Charge versus laser pulse energy (at a wavelength of 765 nm, in a 2.8 nanosecond long pulse) is shown for a 14 mm diameter bulk GaAs cathode for several values of quantum efficiency (QE) as measured at low power. The SLC requires that more than 6×10^{10} e$^-$'s be delivered from the cathode. These curves show that QE greater than 0.75% are needed for this specific material.

What is the mechanism for this saturation? Bill Spicer (Stanford) tells us that it is the photovoltaic effect operating in our material. Electrons are first pumped into the conduction band by the laser. Those electrons near the surface migrate to the surface, and some pass over (or through) the surface potential barrier and are emitted (the preparation of the surface with cesium and flourine serves to lower this barrier sufficiently for good photoemission efficiency). Some electrons, however, become trapped in surface states, and as this trapping occurs, the surface potential barrier rises. The increasing barrier extinguishes the further flow of current. This process is dynamic and depends on the time constants in the laser and in the photoemission process. Oscilloscope traces of the laser waveform and the photoemitted currents seem to confirm this picture.

Although charge saturation curves were first observed in bulk GaAs material, it was assumed that strained GaAs would not necessarily behave the same. The measurement of charge limits in strained GaAs came nearly a year later, delayed by the need for a special gun designed to handle the strained cathode material. Figure 8 shows the charge limit (QMAX) versus the gun high voltage (KV) for the 0.3 μm thick strained GaAs (on GaAsP) cathode. The charge limit was seen to increase linearly with the surface field (reaching 2.4 MV/m at the 120 KV operating voltage), and to reach 9×10^{10}e$^-$'s/pulse. This observed linear behavior of QMAX versus KV was a surprise (it was expected to be quite non-linear) and today is unexplained.

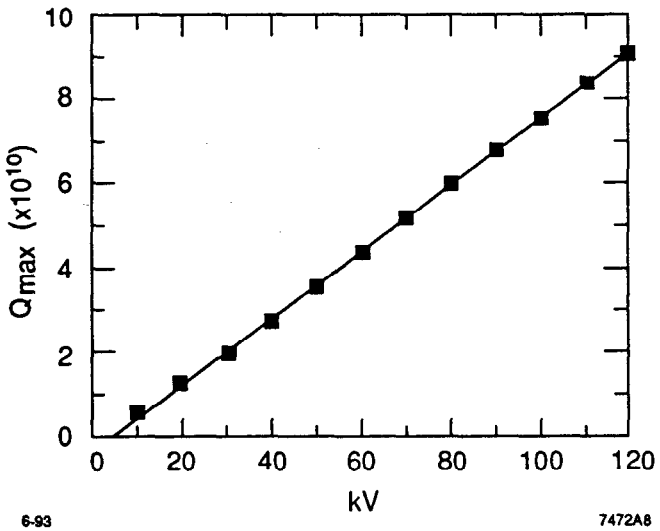

Figure 8. The saturated current (QMAX) versus gun high voltage (KV) for a sample of 0.3 μm thick strained GaAs. These results in January 1993 showed that at the gun operating voltage (120 KV), the strained material could deliver enough charge to operate the SLC ($9 \times 10^{10} e^{-}s$)

Nevertheless, the charge limit at $9 \times 10^{10} e^{-}s$/pulse is high enough for the SLC to operate, and this cathode was chosen for the 1993 SLC run.

5. Recovery from Saturation

The model of the photovoltaic effect as an explanation for charge saturation implies that the recovery from saturation will be controlled by currents in the semiconductor. Electrons trapped in surface states can flow away. The mechanism is believed to be due to holes migrating to the surface and combining with the electrons. The currents should be increased by increasing the concentration of the p-dopant, zinc. Present cathodes have a p-dopant concentration of $6 \times 10^{18}/cm^3$, and materials with p-doping levels up to $2 \times 10^{19}/cm^3$ have been studied. Information available at present is sketchy, but preliminary tests show that recovery occurs with a time constant in the 10-20 nanosecond range.

For the SLC, the laser generates two nearly equal pulses 61 nanoseconds apart. The first pulse provides the polarized electrons for physics collisions, while the second is used to generate positrons for the next machine pulse. At 61 nanoseconds, there remains a residual effect of the first pulse on the second (when the first pulse is adjusted, SLC observes a small effect on the second).

The recovery from saturation is not a serious problem for SLC. However, looking ahead at linear collider designs, the present cathode performance may not satisfy the needs, depending on which linear collider design is considered. Table I lists a set of parameters for the SLC and for the several linear collider designs presented at LC92 in Garmisch.[11] In the table, three linear colliders already can be satisfied by the present

Table I. Bunch Parameters for Linear Collider Designs.

Machine	RF freq.(GHz)	N/bunch ($\times 10^{10}$)	no. of bunches	bunch sep. (nsec)
SLC	2.856	5.	2	61
TESLA	1.3	5.15	800	1000
DLC	3	2.1	172	10.66
JLC-I(S)	2.8	1.3	55	5.6
JLC-I(C)	5.7	1.0	72	2.8
JLC-I(X)	11.4	0.63	90	1.4
NLC	11.4	0.65	90	1.4
VLEPP	14	20	1	-
CLIC	30	0.6	1-4	0.33

cathode performance, the SLC, TESLA, and CLIC. The SLC operates at 6×10^{10}, and 61 nanosecond spacing (two bunches). TESLA operates at 5.15×10^{10}e$^-$s/bunch and 1000 nanosecond (800 bunches). The long time between bunches in the TESLA bunch structure allows recharging of strained GaAs cathodes. The CLIC design calls for 0.6×10^{10}e$^-$s/bunch (one to 4 bunches), which also appears to fall into the range achieved by these cathodes.

The DLC design has 2.1×10^{10}e$^-$s/bunch spaced at 10.66 nanosecond (172) bunches. This is close to, but presently beyond, the ability demonstrated by the present strained cathodes. VLEPP needs 20×10^{10} e$^-$s (but only one bunch), also beyond what has presently been achieved. It seems that with modest improvements, the existing cathodes could satisfy the needs for a DLC or VLEPP type design.

The linear collider designs that presently imply a need for more cathode development work are the JLC (three versions) and the NLC. These designs have pulse trains with bunches spaced at 5.6 to 1.4 nanoseconds. Improved charge recovery times or increased charge delivery capability may need to be developed for polarized beams to work in these latter cases.

6. Summary

Strained GaAs cathodes have made beams of highly polarized electrons for linear colliders practical. The SLC has been running since April 1992 with polarizations up to 63% and full SLC currents. The availability of the SLC source has been 94-96% of the calendar time, and the reliability has been excellent. There is considerable work in progress to fully characterize the performance of the strained GaAs cathode materials, and to optimize the parameters for linear collider use. Some of the linear collider designs have parameters well within the capabilities provided by the strained cathodes. The SLC needs have already been met. The TESLA and CLIC design parameters appear easy to satisfy; the VLEPP and DLC designs appear close to being satisfied; while the JLC and the NLC designs may need more work. Overall, the picture looks very promising for highly polarized electron beams in the next linear collider.

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