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The SLAC Polarized Electron Source*

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Abstract. Since 1992, the SLAC 3-km linac has operated exclusively with *polarized* electrons. The polarized electron source is highly reliable, remotely operated and monitored, and able to produce a variety of electron bunch profiles for high-energy physics experiments. The source and its operating characteristics are described. Some implications drawn from the operating experience are discussed.

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INTRODUCTION

Polarized electrons were first accelerated to high energy in 1974[1] using the SLAC 3-km linac and a Li atomic-beam source.[2] The source had a relatively high polarization, but the peak currents were low and the stability of the beam was marginal. Following a proposal first made in 1974,[3] a polarized electron source[4] based on photoemission from GaAs was developed at SLAC and operated successfully for a high-energy experiment in 1978.

Development of a high peak-current GaAs source matched to the needs of the future SLC was undertaken at SLAC in the early 1980s in parallel with research to find higher-polarization photocathodes. The SLC requires two electron bunches each with a charge in the linac of 5×10^{10} e^- in single S-band buckets, the two bunches separated by 60 ns and repeated at a rate of 120 Hz.

Because of the high charge density, the source was designed to produce 2-ns bunches at >100 kV that would then be rf compressed and accelerated. The rf compression is in two stages utilizing 2 cells at the 16th subharmonic followed by 4 cells at S-band. Compression is completed in the first S-band accelerator section. Because capture plus transmission through this system is limited to about 70%, the gun has to be able to produce up to 10^{11} e^- per 2-ns bunch.

PHYSICS OF GaAs PHOTOCATHODES

Direct band-gap III-V semiconductors, with gaps on the order of 1.5 eV, have long been known as efficient photoemitters into the infrared regime.[5] When highly p-doped, the Fermi level is near the valence band maximum (VBM) while the

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energy bands at the surface are bent downward by as much as half the band gap due to the presence of positive charge at the surface. Using the technique of adding an alkali plus an oxide to the surface, the work function can be lowered from 4 eV to below the conduction band minimum (CBM) in the bulk, creating a negative electron affinity (NEA) surface. Cesium is the most effective alkali, and at SLAC NF_3 is used as the oxide carrier. The process of cleaning the crystal surface and then adding the alkali plus oxide is known as *activating* the surface.

The quantum efficiency (QE) in the red for bulk (i.e., thick unstrained) GaAs is particularly high because the optical absorption length and electron diffusion length for doping concentrations in the mid-range of 10^{18} cm^{-3} are both on the order of 1 μm at room temperature.

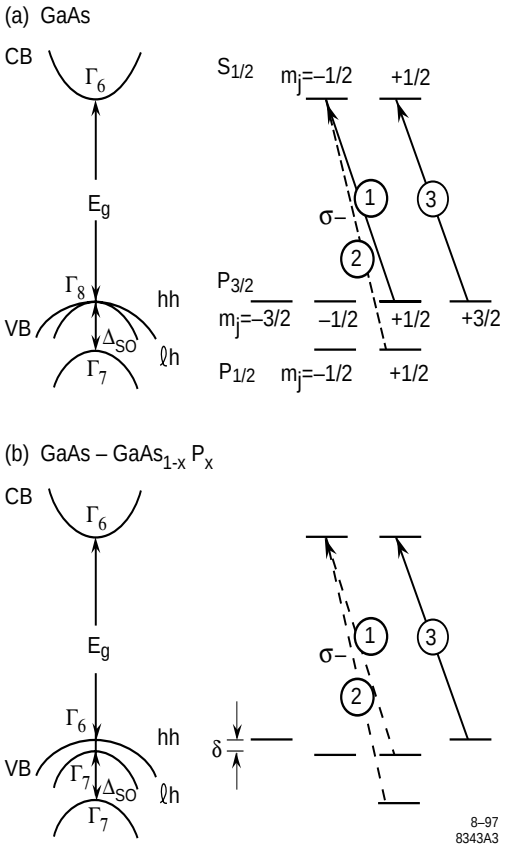

FIGURE 1. Energy level diagram and transition probabilities at the Γ point. Only the transitions for left circularly polarized light are shown. (a) For GaAs, the solid-line transitions are for $E < h\nu < \left(E_g + \Delta\right)$. (b) For GaAs-$GaAs_{1-x}P_x$, the solid-line transitions are for $E < h\nu < \left(E_g + \delta\right)$.

Although bulk GaAs is an efficient photoemitter, the polarization of the photoemitted electrons is limited to 50%. As shown in Fig. 1(a), there is a two-fold degeneracy in the energy band at the VBM at Γ_8. This band has a $P_{3/2}$ symmetry while the CBM at Γ_6 has an $S_{1/2}$ symmetry. Transitions between these bands are governed by the $\Delta m_j = \pm 1$ selection rule. Because the transition rates from the $m_j = \pm 3/2$ sub-states are 3 times that from the $\pm 1/2$ substates, illumination of the crystal with circularly polarized light will preferentially fill one of the 2 possible conduction band states. The conduction band electrons that then diffuse to a negatively-biased NEA surface will be emitted into vacuum with a theoretical polarization (for the case of left-circularly polarized light) of

$$P_e = \frac{N_+ - N_-}{N_+ - N_-} = \frac{3-1}{3+1} = 0.5.$$

The measured polarizations from bulk GaAs using 100% polarized light vary between 0.25 and very close to 0.5 depending on the experimental conditions.

A major achievement in the early 1990s was the discovery that the energy-band degeneracy at Γ_8 could be lifted by directly growing a thin epitaxial layer of the desired III-V material on a substrate with a slightly different lattice constant. This was done first by a SLAC/Wisconsin/Berkeley collaboration[6] using a thin layer of InGaAs MBE-grown on a GaAs substrate, producing a uniaxial compressive strain along the growth direction. However, compared to GaAs, InGaAs has a significantly smaller band gap that is outside the range of high-power tunable laser systems and also results in a lower QE. A better combination was soon found in which a thin layer of GaAs was MOCVD-grown on a GaAsP substrate[7] producing a tensile strain. The cathodes used in the SLAC source since 1993 are of this latter type.[8]

Fig. 1(b) illustrates the allowed transitions for the strained-layer cathodes. If the splitting of the $P_{3/2}$ states at the top of the valence band is larger than the bandwidth (about 25 meV at room temperature), then a narrow-line tunable laser can be adjusted to pump only from the $m_j = \pm 3/2$ substates, resulting in a theoretical polarization of 100%. In practice polarizations of 0.75 to 0.85 are achieved with the SLAC source, depending primarily on the QE. It is interesting that the maximum experimental polarization achieved for strained-lattice GaAs is approximately twice that for thin, unstrained GaAs (both at room temperature).

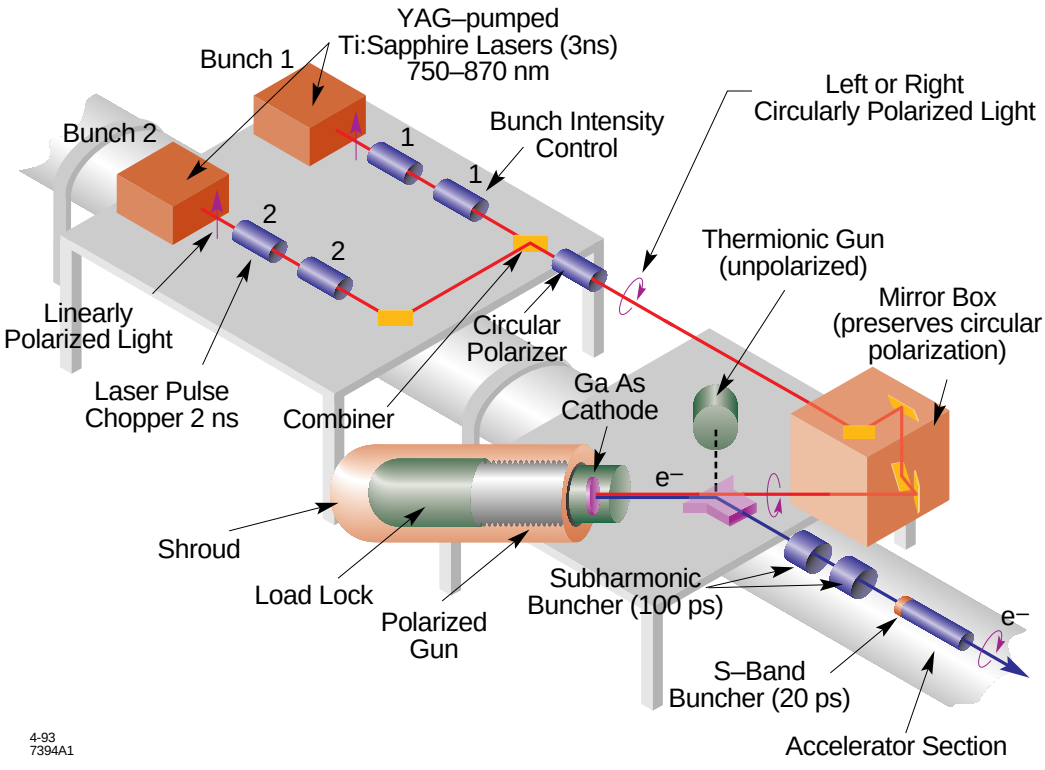

FIGURE 2. The SLAC polarized electron source configured for SLC.

DESCRIPTION OF THE SOURCE

The overall layout of the SLAC polarized electron source[9] is shown in Fig. 2. The gun follows the conventional design for thermionic-cathode guns in which the cathode at high voltage (HV) is supported by a large ceramic insulator which also forms a major part of the vacuum wall. For reliability and ease of operation, the HV is DC. (Pulsed HV would significantly reduce the field emission current.) The Pierce-type electrodes, shown in Fig. 3, were designed[10] using the SLAC Electron Trajectory Program.[11] Special care was taken to minimize the electric field at large radii.[12] The electrodes were fabricated from stainless steel having a very low carbon content and low inclusion density. After machining, they were diamond-paste polished to a 1-μm finish. The gun was assembled in a Class-100 clean room only after a close microscopic inspection of 100% of the electrodes' surfaces showed no remaining contamination or defects >1 μm.

The vacuum for the gun is provided by a 120-l/s ion pump and a 200-l/s non-evaporable getter (NEG) pump. To isolate the gun vacuum system from the 10^{-9} Torr pressure of the rf bunchers, a differential-pumping section follows the gun. It is equipped with a 220-l/s ion pump and a closely-coupled 500-l/s NEG pump. As the RGA spectrum in Fig. 4 shows, the total pressure in the gun is about 10^{-11} Torr, dominated by H_2. The RGA spectrum is not affected by turning either the HV or the beam on or off.

A grounded gas vessel (shroud), which is attached to the rear of the

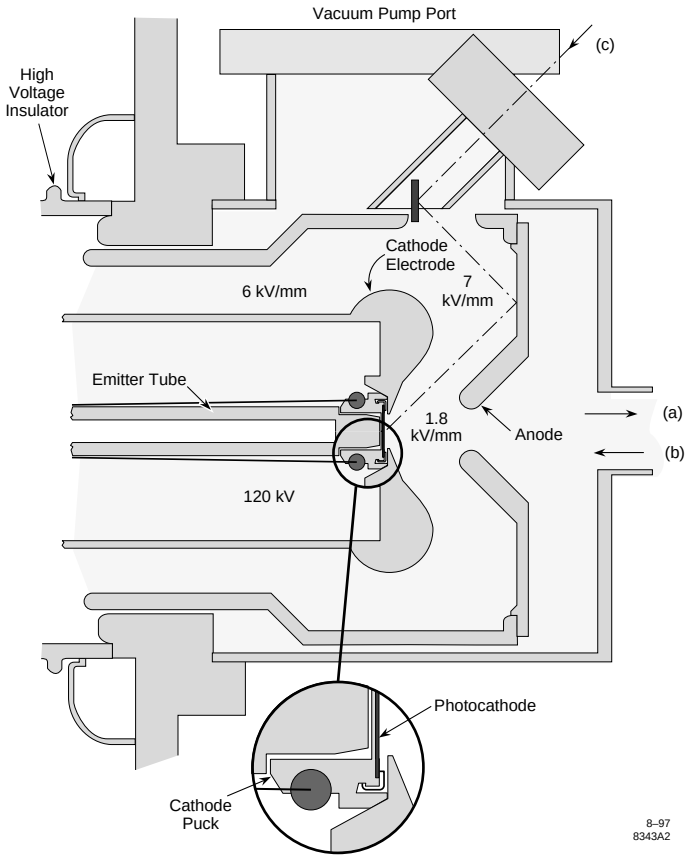

FIGURE 3. Cross section of the gun electrodes. The arrows indicate directions of (a) e- beam, (b) Ti:sapphire laser beam, and (c) beam from diode laser monitoring QE.

gun, prevents discharges from the HV gun terminal to nearby ground level components in the crowded source area. Inside the shroud, a load-lock chamber[13] is attached to the HV end of the gun. It permits the exchangeof cathode crystals without backfilling the gun. The cathodes are mounted on Mo pucks allowing them to be activated and then tested at HV in the laboratory for polarization and QE before transferring them to the accelerator gun in a portable vacuum vessel. The operational benefits of a load-lock system will be discussed later.

The cathode temperature and voltage, gun vacuum, leakage current, and dark current, along with the beam current and orbits are monitored using the SLC control system. The beam emittance can be measured using wire scanners at 40 MeV. The energy and energy spread can be measured using a spectrometer at 200 MeV. The principal maintenance activity is to recesiate the cathode every few days. The cesiation is computer controlled, but initiated by the SLC operators. Each cesiation takes about 30 minutes, mostly to run the HV supply down and then back up.

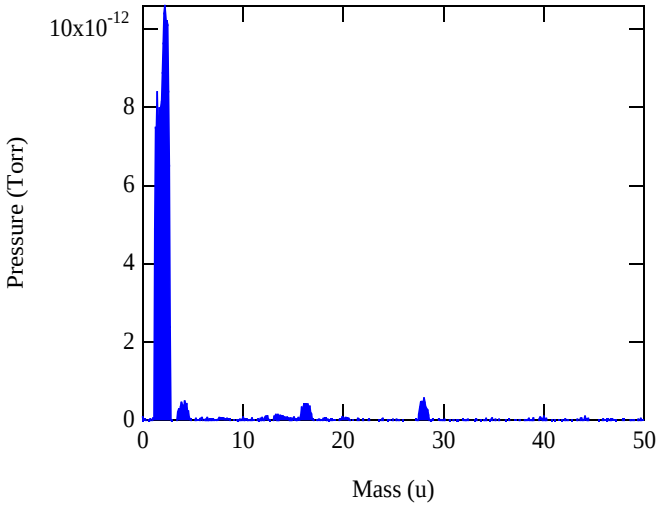

FIGURE 4. RGA spectrum of the gun vacuum during 1997 operation.

A SLAC-built Ti:-sapphire laser system that can be tuned to the band gap energy of most III-V semi-conductors was com-missioned in 1993 and is still in oper-ation. Two com-mercial flashlamp-pumped Nb:YAG lasers each operating at 60 Hz are combined to provide 120-Hz pumping. The combined YAG output is split to pump two separate Ti:sapphire cavities, one cavity for each of the 2 required SLC pulses. The Ti:sapphire cavities are each Q switched and cavity dumped, the timing of which is adjusted to provide the desired 60-ns separation. Pulsed Pockels cells with crossed polarizers are used to chop out the desired 2-ns pulse and to control the intensity of the pulses from the first cavity (the *production* cavity[14]) independently of the intensity of the pulses from the second cavity (the *scavenger* cavity[15]). Ten feed-back and 4 feed-forward systems are used to stabilize the laser itself for SLC operation. Over 100 μJ of energy at the cathode can be provided in each laser pulse. The system is remotely

monitored and controlled from the SLC main control center via the SLC computer control program with oversight by system physicists. Routine maintenance includes changing the flashlamps every couple months.

For fixed target experiments, a SLAC-built flashlamp-pumped Ti:sapphire laser system has been used.[16] It has provided up to about 75 μJ at the cathode in a 1-2 μs pulse or more recently, with improved reflectors, a similar energy was provided in a 200-300 ns pulse. The flashlamps for this system were changed every 2 weeks to preclude any chance of lamp explosions.

To monitor the QE of the photocathode during accelerator operations, an 833-nm cw diode laser, modulated at 1.5 Hz but gated off during beam time, is rigidly attached to a vacuum window near the cathode as shown in Fig. 3. An optically-powered nanoammeter (at HV) transmits the current drawn from the cathode to a lock-in amplifier via an optical fibre. The modulated signal is detected and continuously recorded by the SLC control system with appropriate conversion constants for the diode laser power. This system is calibrated by a second diode laser whose output can be substituted for the Ti:sapphire's. Finally, the SLC control system periodically runs the Ti:sapphire laser beam through its full energy range using 20 accelerator pulses in succession. For this, the cathode current is measured in the normal manner. The laser beam energy is monitored from pickoff light using calibrated photodiodes. The peak current is recorded online while all the data is saved to an offline disk.

OPERATIONAL CHARACTERISTICS

The gun was originally built without a load-lock chamber. This required the photocathode to be inserted into the gun when it was at atmospheric pressure. The gun then had to be evacuated and baked before the cathode could be activated and tested. Often following a bake the cathode could not be successfully activated. The original design called for the gun to be operated at 150 kV. The gun could be HV processed either before or after the cathode was initially activated, but the processing generally poisoned the cathode requiring reactivation which in turn required addition processing, etc. No matter how much care was taken, this cycle was only rarely broken by production of a fully processed and activated cathode. One such occasion was at the beginning of the 1992 SLC run.

The load-lock, which was built during the 1992 SLC run, completely solved the problem above, but also provided other benefits, including:

a) Experience at SLAC indicates that cathodes which undergo a complete gun bake do not activate as well as cathodes which are not baked.[17] The SLAC load-lock system incorporates a cathode activation system. The load-lock/activation-chamber is itself initially baked after which it is continuously maintained under

vacuum. Cathodes are introduced into the load-lock chamber either from air (requiring activation in the load-lock chamber) or from a portable vacuum chamber (if already activated, the cathode may only need to have a little Cs/NF_3 added in the load-lock chamber). When activated cathodes are introduced into a baked gun that has already been HV processed, no additional HV processing is required.[18] With the addition of the load-lock system, activations (but not cesiations) in the gun itself have been eliminated.

b) Load-lock systems permit QE lifetimes to be longer. This is probably due to the constantly-improving gun vacuum. The influence of vacuum on lifetime will be discussed in more detail later. The gun presently in use for SLC has been maintained under continuous UHV conditions since the spring of 1993 and now routinely produces lifetimes in excess of 1000 h.

c) When the gun is not backfilled, it needn't be baked. This virtually eliminates vacuum leaks once the gun is initially evacuated and successfully baked. Consequently the system reliability vastly improves.

d) The benefits of electron scrubbing--from the beam and due to field emission from vacuum components operated at HV--continuously accrue in favor of better vacuum and thus also of longer lifetimes.

e) As a consequence of long lifetimes, the cathodes can more readily be operated with a QE that is close to the minimum needed to produce the charge required by a given experiment. Since the polarization is weakly and inversely dependent on QE, this permits some slight improvement in average polarization.

f) For experiments using polarized electron beams, it is important to know the beam polarization. A constant polarization from the source--which requires a constant QE, i.e., a long lifetime--can reduce the integrated error of polarization measurements.

The cathode is normally operated at 120 kV and 0ºC. Immediately after a cesiation the QE (833 nm) is typically 0.005.[19] At the polarization peak, which is typically at ~850 nm, the QE (120 kV) is approximately a factor of 2 lower. The QE decreases with time. It can usually be restored to its original value by adding a small amount of Cs (additional oxide not necessary). For the SLAC source, these cesiations are done discretely since the HV is first lowered to 1 kV, disrupting the beam. If the cesium supply is turned off before (after) the peak in the photoyield is reached, it is called an under- (over-) cesiation.

The time in which the QE decreases by a factor of e is defined as the QE lifetime. Lifetimes computed following each cesiation during the SLC 1994-95 run are shown in Fig. 5. The QE lifetimes are significantly longer when over-cesiation is employed. This is confirmed by the lifetimes associated with the maximum charge.[20]

Although the maximum charge that can be extracted from a semiconductor photocathode appears to be independent of the thickness of the epilayer, for a given cathode it varies linearly with the low-charge QE (measured near the band gap) up to the gun space-charge limit. Lifetimes derived from measurements of maximum charge are also displayed in Fig. 5. The most likely reason the maximum-charge lifetimes appear to be longer than the corresponding QE lifetimes is that at high QE the maximum charge is depressed by the space-charge limit.

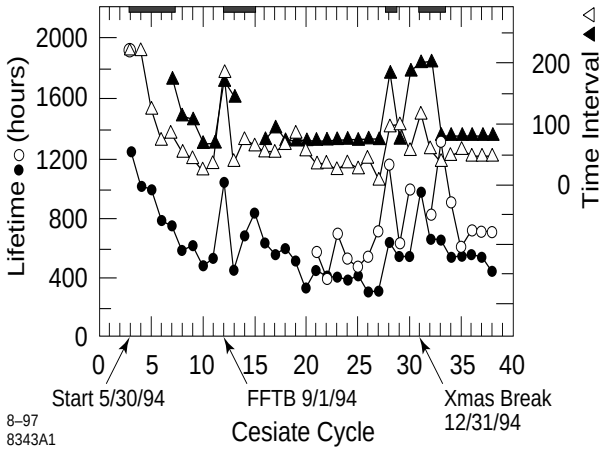

FIGURE 5. Lifetime data for the SLC 1994-95 run as a function of cesiation cycle. The closed (open) circles represent QE (maximum-charge) lifetime, the closed and open triangles represent the cesiation time (in seconds) and days in a cesiation cycle (x10) respectively. The heavy bars at the top represent periods of over-cesiation whereas under-cesiation was otherwise employed.

For SLC, the QE is kept as low as possible since this slightly increases the average beam polarization. During the SLC 1994-95 run, the cathode was typically under-cesiated every 5 days with about 0.1 monolayer of cesium,[21] corresponding to an average Cs disposition rate of 1.4×10^{8} atoms cm^{-2} s^{-1}. The minimum partial pressure, P_{min}, of an oxidizing background gas that would be required if the added cesium is continuously oxidized by it alone is given in Table 1. The 1994 RGA pressures are also shown. Clearly O_2 and CO_2 cannot alone be responsible for oxidizing the added Cs. CO_2 is also ruled out because it has been found not to permit complete restoration of the QE,[22] and O_2 is unlikely since the activations at SLAC are made with NF_3 and in a separate chamber. CO has been found to have little or no effect on the QE.[22] Excluding the effect of H*, this leaves water as the most likely oxidizer in the SLAC source causing the QE to decrease. Water molecules are presumably slowly scrubbed from the vacuum walls by a combination of beam interception and field emission from components held at HV.

Table 1. Calculated and Measured Partial Pressures of Oxidizing Gas Species

Gas Species	P_{min} (Torr)	P_{RGA} (Torr)
H_2O	3×10^{-13}	2×10^{-13}
CO	4×10^{-13}	2×10^{-12}
O_2	4×10^{-13}	2×10^{-14}
CO_2	5×10^{-13}	1×10^{-14}

Since the SLAC source is operated above 100 kV, it is possible

to minimize beam interception as the beam exits the gun by detecting and minimizing the associated x-rays. Field emission is more difficult to eliminate. Following the introduction in late 1992 of the procedures for preparing and assembling electrodes outlined earlier, it was still found necessary to reduce the gun voltage to about 120 kV in order to consistently achieve a dark current of <50 nA and thus eliminate any gross effect of the HV operation on the QE lifetime. Subsequently the dark current has dropped below 20 nA.[23]

A single strained-layer cathode has been operated in the SLAC source for as long as 0.015 A-h cm^{-2} (equivalent to 1-h of operation of a 10-μA cw beam having a diameter of 0.3 mm) with no obvious sign of permanent cathode damage.[24]

The rms intensity stability of the electron beam out of the source is generally <1% for SLC and about 2% for long pulse operation. This performance depends primarily on the laser stability. The large peak currents required for SLC operation necessitate operating the strained-layer cathodes near their charge saturating limit, thus mitigating the effects of laser jitter. With the laser feed-back/-forward loops operating, the Nb:YAG-pumped Ti:sapphire system has an rms energy stability of 1-2%, while the best achieved from the flashlamp-pumped Ti:sapphire system was about 2%. A highly-stable Nd:YAG pumping laser could probably be designed that would reduce the Ti:sapphire laser jitter to <1%.

Long term stability is ensured not only by additional feed-back loops that keep the electron beam intensity and orbits constant, but also by maintaining the laser-room temperature and humidity to within ±0.2ºC and ±5% respectively.

Since 1992, all electron beams for the 3-km linac have been produced by the polarized source. It operates for weeks at a time without any intervention for maintenance or adjustment. The principal operating parameters for the source are shown in Table 2. Note that the total operating time is equivalent to over 3 years of continuous operation. The availability of the polarized source has routinely been ~99%.

Table 2. Source Operating Parameters

Parameter	**SLC**	**Fixed target**
Total operating hours	~20,000	~7,000
e^- polarization	0.75 to 0.80	0.80 to 0.85
No. e^-/bunch at source	~6×10^{10}	4×10^{9} to 10^{11}
Bunch length at source (ns)	2	200 to 2000
Cathode bias (kV)	-120	-120
Cathode temperature (ºC)	0	0

CONCLUSION

The stellar performance of the SLAC polarized electron source over the past 5 years invites speculation as to why. Some of the more interesting possibilities are discussed here. Like the SLC itself, this source has proven to be a very important prototype for future linear colliders.

REFERENCES

[1] P.S. Cooper et al., Phys. Rev. Lett. 34, 1589 (1975).

[2] M.J. Alguard et al., Nucl. Instrum. and Meth. 163, 29 (1979).

[3] E.L. Garwin et al., Helv. Phys. Acta 47, 393 (1974).

[4] C.K. Sinclair et al., AIP Conf. Proc. 35, 424 (1976).

[5] R.L. Bell, *Negative Electron Affinity Devices*, Oxford: Clarendon Press, Oxford, 1973.

[6] T. Maruyama et al., Phys. Rev. Lett. 66, 2376 (1991).

[7] T. Nakanishi et al., Phys. Lett. A 158, 345 (1991).

[8] Since 1994, a 100-nm epilayer has been used. The cathode design is similar to sample (3) found in T. Maruyama et al., Phys Rev. B 46, 4261 (1992). The cathodes are cut from 2-inch wafers MOCVD-grown by SPIRE Corporation, One Patriots Park, Bedford, MA 01730.

[9] R. Alley et al., Nucl. Instrum. and Meth. A 365, 1 (1995).

[10] The final design is based on an early design by R. Miller (SLAC). See C.K. Sinclair and R.H. Miller, IEEE Trans. on Nucl. Sci. NS-28, 2649 (1981).

[11] W. Herrmannsfeldt, SLAC Report 331 (1988).

[12] W. Hermannsfeldt (SLAC), private communication.

[13] R.E. Kirby et al., *Procedings of the 1993 Particle Accelerator Conference*, 1993, p. 3039.

[14] The electron bunch it produces will be the electron bunch at the SLC interaction point (IP).

[15] The associated electron bunch goes to the SLC conversion target to generate the positron bunch destined for the IP.

[16] K.H. Witte, *Proceedings of the International Conference on Lasers '93*, 1994, p. 638.

[17] Note that whether or not a given cathode is baked, at SLAC the activation process always includes heating the cathode to about 600ºC for about 1 hour.

[18] This may not prove true for guns designed to operate with significantly higher rf fields, such as rf guns.

[19] In cooling from room temperature to 0ºC, the QE (833 nm) for these cathodes (close to the band gap energy) at 120 kV decreases by 2×10^{-5} per ºC. See P. Sáez, SLAC-R-501 (1997), Fig. 4.7. At low voltage (no Schottky effect) the rate of decrease is about twice this value.

[20] During the commissioning of the SLAC source for the 1992 SLC run, it was discovered that as the laser energy was increased to very high values, the charge that could be extracted saturated at a value well below the space charge limit. For details, see reference (9) and references therein.

[21] A monolayer of Cs is taken to be 6×10^{14} cm^{-2}. A sticking coefficient of 1 was assumed. Calibration of the SAES Cs-dispenser channels was made by R. Kirby (SLAC) using a thermally-stabilized quartz-crystal oscillator.

[22] T. Wada et al., Jpn. J. Appl. Phys. 29, 2087 (1990).

[23] Future polarized sources operating with much higher electric fields may require much more elaborate material selection and preparation. For progress in this area, see H. Matsumoto, *Proceedings of the XVIII International Linear Accelerator Conference*, 1996, p. 626.

[24] Although at the end of use of a given cathode the QE remains fully restorable with the addition of Cs, in some cases a change in the QE profile across the cathode surface has been seen that may be permanent.