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Polarized Electron Sources for Future e^+/e^- Linear Colliders[*]

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Abstract

Polarized electron beams will play a crucial role in maximizing the physics potential for future e^+/e^- linear colliders. We will review the SLC polarized electron source (PES), present a design for a conventional PES for the Next Linear Collider (NLC), and discuss the physics issues of a polarized RF gun.

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1 INTRODUCTION

Since 1992 the SLC has been operated exclusively with a polarized electron beam. Despite that the Z^0 boson production rate at SLC is nearly two orders of magnitude lower than at LEP, the use of a highly polarized electron beam with a beam polarization approaching 80% has vastly improved the physics luminosity of SLC and rendered it very competitive against LEP in the measurements of important Standard Model parameters such as the weak mixing angle θ_W [1]. For a future e^+/e^- linear collider such as NLC, polarized electron beams will again play a powerful role in its physics programs. The benefits of using a highly polarized electron beam range from simply enhancing the luminosity to effectively extending its physics reach by suppressing backgrounds that would otherwise completely overwhelm the signal that one wishes to measure. Therefore, the development of a high performance PES is of crucial importance to future e^+/e^- linear collider projects.

The successful operation of the SLC PES [2] has established the basic principles for the design, construction, and operation of accelerator-use polarized electron sources. In this paper, we will briefly describe the SLC PES, review its performance parameters and some of the fundamental properties of polarized electron photocathodes. We will then describe a conventional NLC PES design that is based on a DC high voltage photocathode gun similar to the one used in the SLC PES. In particular, we will discuss the necessary improvements in the photocathode design for the realization of an NLC PES. Finally, we will evaluate the feasibility of a polarized electron RF gun for the NLC from the standpoint of photocathode physics considerations.

2 THE SLC PES

At the heart of the SLC PES is a DC high voltage gun that utilizes a thin, *p*-type doped, strained GaAs semiconductor photocathode. The lattice distortion in the cathode induced by the strain removes a degeneracy between the heavy-hole and light-hole valence bands, making it possible for the generation of >50% polarized electrons from GaAs. The surface of the photocathode is treated with Cs and F to lower its workfuction to a so-called negative electron affinity (NEA) state, which enables the cathode to attain a high quantum efficiency and permits the use of photons with just enough energy to excite electrons from the valence band into the conduction band for yielding the highest possible electron beam polarization. The electron gun provides an ultrahigh vacuum environment suitable for prolonged operation of an NEA cathode and a sufficiently high extraction electric field at the cathode surface for the production of a high intensity electron beam. A Ti:sapphire laser system using frequency-doubled Nd:YAG for pumping generates two 2-ns laser pulses which are used to produce electron pulses from the gun, one for the collision beam and the other for the positron target drive beam. A bunching system consisting of two 178.5 MHz subharmonic bunchers (SHB) and one S-band buncher bunches the electron pulses into 20° of 2856 MHz S-band main linac RF. Table 1 lists the important operating parameters of the SLC PES.

An important discovery made during the course of PES R&D at SLAC was the cathode charge limit (CL) phenomenon [3,4]. In short, the CL effect states that, owing to the nature of an NEA semiconductor photocathode, its quantum efficiency (QE) in response to a laser pulse is increasingly suppressed with increasing laser pulse energy and the maximum integrated charge extractable during the pulse is limited to a value determined by the intrinsic properties of the cathode and the extracting field at the surface. The mechanism that appears responsible for the CL effect is the surface photovoltaic effect [5]. In the SLC PES, the maximum CL for a 2-ns pulse from an optimally prepared cathode is about 18×10^{10} electrons, which is a factor of 2.6 higher than the PES's typical operating charge production level.

Some of the fundamental characteristics of the CL effect are summarized as follows. (i) Given an NEA photocathode with fixed operating conditions, the CL in general scales with its linear QE. (ii) The relaxation time for an NEA photocathode to recover from its suppressed QE state caused by the illumination of an intense laser pulse critically depends on the cathode's doping concentration — the relaxation time for the typical doping concentration of 5×10^{18} cm^{-3} used for the SLC PES is on the order of 100 ns whereas for a 2×10^{19} cm^{-3} doping it decreases to about 10 ns. (iii) For long pulse operations, i.e., with the pulse length longer than the cathode's relaxation time, the CL effect manifests itself as a limit in the maximum steady-state emission current from the cathode, and this maximum current is inversely proportional to the CL relaxation time. It is characteristic (iii) that bears the most significant implication for the development of a PES for a future e^+/e^- linear collider such as NLC which requires a long (>100 ns) beam pulse.

3 DESIGN OF THE NLC PES

In contrast to SLC which operates in a single bunch mode, the NLC is designed to collide 90 bunches of closely spaced e^+ and e^- beams per pulse [6]. While the required single-bunch charge for the NLC is less than that of an SLC bunch, the integrated charge per beam pulse is more than an order of magnitude greater. Using the SLC PES as a design basis, we have completed a design of a conventional PES for the NLC [6]. The design includes a slightly modified SLC-type DC high voltage gun with a thin, improved strained layer GaAs cathode, a more complicated Ti:sapphire laser system with an additional stage for power amplification to produce the required high-power long pulse trains, and a subharmonic bunching system consisting of two 714 MHz SHBs and an S-band buncher. The design parameters for NLC-II, namely the 1.0 TeV center-of-mass energy machine, are summarized in Table 1, along side those of the SLC PES.

The single most challenging issue for materializing such a PES design lies with the photocathode technology. For this reason, we shall not concern ourselves with other issues, such as the laser system or the bunching system, for which there are no significant technological obstacles to overcome. The present generation of SLC strained GaAs cathodes have a CL or QE relaxation time of on the order 100 ns and a maximum steady-state emission current of about 0.7 A, which is only about 20% of the design value of the average pulse beam current for the NLC PES. To overcome this deficiency, improved photocathode charge performance is the key.

Table 1: Operating Parameters of the SLC PES and Design Parameters of the NLC PES

Parameters	SLC	NLC-II
Gun vacuum (Torr)	$<10^{-11}$	$<10^{-11}$
Cathode bias (kV)	–120	–120
Dark current (nA)	<25	<25
Extraction field (MV/m)	1.8	2.0
Photocathode area (cm^2)	3.1	3.1
Space charge limit (A)	15.5	13
No. bunches per pulse	2	90
Bunch spacing at gun (ns)	62	1.4
Bunch FWHM at gun (ns)	2	0.7
Bunch charge (10^{10} e^-)	7	2.8
Peak current (A)	5.6	6.4
Average pulse current (A)	0.4	3.2
Beam polarization	~80%	~80%
Laser oscillator	Ti:sapphire	
Pulse energy (μJ)	100	90×20
Repetition rate (Hz)	120	120
No. of SHB's	2	2
SHB frequency (MHz)	178.5	714
rms $\gamma\varepsilon$ at 80 MeV (mm-mrad)	~100	46

Cathode CL studies on a variety of photocathodes have shown that a 100 nm 2×10^{19} cm^{-3} doped strained GaAs photocathode, which differs from a standard SLC PES photocathode only in doping concentration (i.e., four times higher) appears capable of producing the required steady-state emission current for the NLC PES [6,7]. However, due to the increased doping density, the cathode's polarization performance is degraded significantly to the 60 – 65% range. To meet both the polarization and charge specifications of the NLC PES, the so-called graded doping scheme will be essential. By selectively doping a thin (~10 nm) surface layer of a 100 nm properly strained GaAs photocathode to a high concentration, e.g., 2×10^{19} cm^{-3}, while leaving the remainder of the cathode (~90 nm) at low doping, e.g., 1×10^{18} cm^{-3} would be a good choice, high polarization and high charge production that meet the NLC requirements should be simultaneously achievable.

The charge performance of a GaAs photocathode may be further improved if the atomic cleanliness of the cathode surface can be preserved prior to an NEA activation. A thick As cap layer on the order of a few microns thick grown on top of the cathode at the end of growth by the manufacturer should accomplish this purpose adequately. As a result, a two-fold increase in the cathode's QE should be possible following an NEA activation, which should lead to a proportional increase in the charge production capability for the cathode. In addition, future R&D efforts will likely lead to further advancement in both photocathode and gun technologies. It is safe to conclude that our conventional NLC PES design is sound. If the bunch spacing is doubled, a major design change now under serious consideration, then, the required average pulse current will be halved, rendering our design even more feasible.

4 POLARIZED RF GUN CONSIDERATIONS

Because of the low beam emittance that an RF gun promises and a simplified injector design, i.e., without the need for a bunching system, a polarized RF gun utilizing an NEA GaAs photocathode is a very compelling idea. However, major technological breakthroughs are required towards the realization of a polarized RF gun, the most outstanding being attaining a $<10^{-11}$ Torr vacuum in an RF gun under operation so that an NEA cathode may have a reasonable lifetime. Technological difficulties aside, the physics of photoemission from NEA cathodes will play a deciding role as to whether the idea of an S-band polarized electron RF gun is a viable one in the first place. In the following we will address the main physics issues related to this question and show that there are no apparent fundamental problems with the RF gun idea.

An S-band RF gun is required to produce a beam with a bunch length less than ~20 ps, thus placing an upper limit on the cathode response time at about 10 ps. For an NEA photocathode, the photoemission response time is determined by the minority carrier (i.e., excited electron) diffusion coefficient and the thickness of the active layer, which is taken to be 100 nm as appropriate for an optimally performing strained GaAs cathode. Assuming a bulk doping density of 1×10^{18} cm^{-3} for a graded doping GaAs cathode, the diffusion coefficient at room temperature is approximately 75 cm^2/s [8]. Then, on the average it will take about 1.3 ps for an excited electron to diffuse through the 100 nm thick active layer along the normal direction. Of course, most electrons will diffuse along off-normal directions and will take longer times to reach the surface (perhaps 2 ns on the average). More importantly, once an electron reaches the cathode surface it has a rather small probability (as small as a few percent as one study suggested [9]) of escaping at once. It will likely be reflected back into the cathode interior, bounce back and forth via interactions with the lattice and the backside surface, and need multiple emission attempts before finally escaping [10]. Taking all factors into account, we may place an estimated upper limit of 10 ps on the response time for our proposed GaAs cathode.

Recent measurements by Hartmann et al. using a 150 nm, 5×10^{18} cm^{-3} doping, strained $GaAs_{0.95}P_{0.05}$ cathode yielded a response time of 10 ps [11]. We note that the QE of this cathode was about ten times below the operating level required for NLC PES applications. A higher QE will lead to a slower response time. On the other hand, the thickness of the cathode we propose to use is 100 nm instead of 150 nm, and the response time scales quadratically with thickness. In addition, at a doping level of 1×10^{18} cm^{-3} the response time should be a factor of 2 faster due to an increased diffusion coefficient. Thus, the estimated ≤10 ps response time for our proposed cathode seems quite reasonable.

The other issue is whether an NEA cathode can produce the required single-bunch charge in an RF gun. The bunch charge requirement at the RF gun is 2.2×10^{10} electrons (or 3.6 nC), which is taken to be 80% of the design value of the proposed conventional NLC PES as allowance for beam loss in the bunching process is no longer needed. Though this requirement is less than that in the conventional design, the charge must be extracted from the cathode within a much smaller area, e.g., ~2 mm (rms) radius, in order to generate a beam with a normalized rms emittance close to the desired mm-mrad level. This area is an order of magnitude smaller than the corresponding value chosen for the conventional design. Thus, the CL per unit area in the RF gun needs to be an order of magnitude higher than in an SLC-type gun.

Before proceeding to address this important question, it is advatangeous to clarify a few other issues which otherwise might complicate our discussion. (i) With an extraction electric field of >100 MV/m in an RF gun, which is nearly two orders of magnitude higher than that in an SLC-type gun, the space charge limit should not be a problem. Indeed, experiments with an S-band RF gun have demonstrated an order of magnitude higher charge production than required for the NLC for an emission area of 5 mm (rms) radius [12]. (ii) The CL on a much shorter time scale, i.e., 20 ps, should not be grossly different from the CL on a time scale of 2 ns, as in the case of SLC. The only reason that the CL should depend on the pulse length at all is because it has been defined, with a good reason, as the maximum extracted charge instead of the saturated charge when the laser pulse energy approaches "infinity". To first order, the saturated charge should not depend on the pulse length and is therefore a purely intrinsic parameter of the cathode itself. The CL as defined is attained in a transient state while the cathode is undergoing through a change from the initial low-intensity linear response state to the saturated (or constant yield) state and does indeed depend on the pulse length, albeit weakly. Based on the available 2-ns CL data, a good estimate on the CL for a 20 ps pulse would be about half the CL for a 2 ns pulse. (iii) Multiple bunch charge production should be much less of a problem for a cathode operated in an RF gun than in an SLC-type gun in the conventional design so long as single bunch charge production is adequate.

With everything else kept the same, the CL has been shown to scale almost linearly with the extraction field within a range from 0.15 to 1.8 MV/m [4]. If this scaling law remains valid up to the 100 MV/m field range typical for an S-band RF gun, then, the CL for a similar NEA cathode with a CL of 18×10^{10} electrons in an SLC gun will be about 45×10^{10} electrons in an RF gun with a pulse length of 20 ps and an emission area of 2 mm (rms) radius. This value is more than an order of magnitude greater than the single-bunch charge specification for the RF gun design, suggesting that the CL will not be a problem. While this conclusion is very encouraging, the linear scaling with extraction field is most questionable as this behavior is not satisfactorily understood. It is quite possible that the field dependence of the CL may deviate significantly from linear in an extended field range. If any deviation occurs, the dependence can only become weaker, which would make our estimate too optimistic, but unlikely off by an order of magnitue. Thus, it is fair to state that the above conclusion appears well justified.

4 REFERENCES

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