POLARIZED ELECTRON SOURCES FOR LINEAR COLLIDERS*

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ABSTRACT
Linear colliders require high peak current beams with low duty factors. Several methods to produce polarized e⁻ beams for accelerators have been developed. The SLC, the first linear collider, utilizes a photocathode gun with a GaAs cathode. Although photocathode sources are probably the only practical alternative for the next generation of linear colliders, several problems remain to be solved, including high voltage breakdown which poisons the cathode, charge limitations that are associated with the condition of the semiconductor cathode, and a relatively low polarization of ≤50%. Methods to solve or at least greatly reduce the impact of each of these problems are at hand.

1 COLLIDER REQUIREMENTS AND POLARIZED SOURCES

The accelerator of choice for pushing higher the energy frontier for electron-positron collisions is the linear collider [1]. The linear collider concept has been demonstrated with the SLC, and already the designs of the next generation linear colliders are well underway. A comparison of electron source parameters for several new collider designs is given in Table 1 along with the SLC source parameters. The KEK, DESY, and SLAC designs require a electron source similar to that employed by the SLC but with a macropulse structure consisting of a string of micro-bunches whose total charge is somewhat larger than that of the SLC source.

A variety of methods for externally generating polarized electron beams for linear accelerators have been developed and successfully used or tested. These methods include photoionization of state-selected alkali atoms [3], photoionization of high-Z alkali atoms by circularly polarized light (the Fano effect) [4], optical pumping of a flowing helium afterglow [5], and photoemission from *III-V* semiconductors [6]. Although other methods have been proposed--such as pair-production from gammas produced at high-energy (>100 GeV) for VLEPP [7]--only the semiconductor photocathode source, as demonstrated with the SLC, has so far met the low duty factor, high peak current source requirements of linear colliders. Consequently, this paper will concentrate on the SLC photocathode source as the model for the next generation of linear colliders.

The application of polarized-electron photocathode sources for accelerators began with the SLAC parity-violating experiments in the late 1970's [8]. The SLAC linac injector at that time required a gun pulse that was 1.6 μs long with a peak current of about 100 mA. The SLC polarized electron source utilizes the principles and much of the technology of the original SLAC photocathode source, but is designed to meet the SLC specification of 10 A peak current in a 2-ns bunch [9]. Two of these bunches, separated by 60 ns, are required for each RF pulse. Although this pulse structure was easily and quickly attained with the SLC injector utilizing a thermionic gun [10], it has only recently been achieved with the photocathode gun.

2 INJECTION

With the exception of RF guns [11], electron sources must utilize RF bunching systems to compress the gun pulse sufficiently to match the longitudinal phase space acceptance of the injector accelerating structure. The impediment to producing high intensity pulses directly from the gun lies with the space-charge forces within the resulting e⁻ beam which dilute both the longitudinal and transverse emittances during transport of a low-energy, high intensity bunch from the gun to the injector . Space-charge forces are reduced by increasing the potential at which the electrons are initially collected from the cathode. RF guns solve this problem by accelerating a very short pulse from the cathode immediately to relativistic energies before space charge can significantly affect beam size. Unfortunately the vacuum environment of RF guns as so far developed is not compatible with GaAs-type photocathodes.

The injector RF bunching system can employ one or more subharmonic RF cavities (not necessarily each at the same frequency) separated by appropriate drift lengths. Axial magnetic fields are usually employed for containing the beam transverse size. The transverse emittance of the bunched beam, which is too large for direct injection and acceleration in the main linac of a linear collider, will have to be reduced in a damping ring.

Although the emittance characteristics of the source will be somewhat isolated from the collider by one or more damping rings, several critical parameters associated with photo

* Work supported by Department of Energy contract DE-AC03-76SF00515.

Contributed to the 15th International Conference on High Energy Accelerator (HEACC '92), Hamburg, Germany, July 20-24, 1992

Table 1. Electron Source Parameters for Linear Colliders [2]

PARAMETER	SLC[a]	NLC	JLC	DESY	CLIC (main)	VLEPP
f (Hz)	120	180	150	50	1700	150
N_{linac} (10^{10} e^-/bunch)	5 {3}	0.7	2	2.1	0.5	20
N_{source} (10^{10} e^-/bunch)	12 {6}	0.9	3	4	1.5	-
Bunches	2	90	20	172	1-10	1
Spacing (ns)	60	1.4	1.4	10.7	0.33	-
Total charge at source: (10^{10} e^-/RF pulse)	24 {12}	80	60	688	15	20
(10^{10} e^-/s)	2880	15000	9000	34400	25500	3000
I_{souce} (A)	10 {5}	1.0[b]	3.5[b]	0.6[b]	7.2[b]	-
Duty Factor (10^{-6})	0.2	2	4	90	0.6-6	-

a The SLC e^- source generates 2 bunches. One bunch gets converted to positrons, so that at the final focus, the electron and positron beams have only 1 bunch each. Present SLC operating parameters are shown in braces.

b The source current is here the average within a macropulse.

cathode guns are still marginal. Chief among these are intensity and position stability, high voltage limitations, total available charge, lifetime, and the degree of polarization.

3 ELECTRON BEAM STABILITY

The stability of an e^- beam produced by a photocathode source is governed primarily by the properties of the associated laser system. With the advent of pulsed, high-power, solid-state, tunable lasers, questions of laser power at the desired wavelength, reliability, and efficiency are largely solved. However, for a given beam intensity, I, and beam size, $s \approx 10\,\mathrm{cm}$, collider injectors require intensity and position stability on the order of $\sigma_I/I \approx \sigma_x/s \approx 1\%$. Although these parameters are beyond the capability of today's lasers by a factor of 2 or so, adaptive optics could presumably be designed to meet the collider requirements. An additional improvement in stability can be made by operating the cathode in a charge saturation regime.

4 HIGH VOLTAGE LIMITATIONS

High voltage (HV) breakdown problems have been a major barrier to increasing the electric field gradient on the cathode and thus the extracted charge from a practical photocathode gun. Cesium, used to activate the GaAs cathodes, eventually migrates to most of the electrode surfaces, resulting in field emission (FE) sites being generated at field gradients as low as a few MV/m. FE can result in direct metal deposition from the anode onto the cathode or in desorption of molecules from exposed surfaces, which in turn poisons the cathode. The HV threshold for FE can be raised by careful choice of electrode material, by judicious use of Cs, and by careful cleaning and processing of electrodes. It is also possible to decrease the voltage and/or the gradient. For a given cathode-anode gap, the maximum current that can be extracted from the cathode is given by $kV^{3/2}$ (Child's law), where k, the perveance, is given by the geometry of the gun. The SLC gun, designed with a perveance of 0.16 μpervs, would require 160 kV to extract 10 A. Since k varies as $(r/d)^2$, the minimum required voltage for a given current can be decreased if the ratio of cathode radius, r, to the gap separation, d, is increased. Since FE is driven by the field gradients, it is preferable to increase r. Finally, pulsed instead of dc HV, although perhaps more complex to produce, can be used to bias the cathode in order to reduce the probability of HV breakdown.

5 CHARGE LIMITATIONS

Recently at SLAC [9] it was discovered that the maximum charge in a short pulse that can be extracted from a GaAs cathode near the bandgap threshold can be less than the space charge limit established by the gradient at the cathode. This charge limit is proportional to the quantum efficiency (QE) but is independent of the laser power density [12]. For p-doping concentrations on the order of 2×10^{19} cm^{-3}, a QE > 2% is required for the SLC gun to generate a charge of 6×10^{10} e^-/bunch, whereas the corresponding space charge limit at 120 kV is 10^{11} e^-/bunch. With lower doping levels, the minimum required QE is increased. QEs significantly >2% can reliably be achieved by introducing the cathode into the vacuum system after baking [13].

For impurity doping of 2×10^{19} cm^{-3}, the charge limit relaxation time, τ, is reduced to a few ns. For bunch spacing that is $\lesssim\tau$, the charge limit, q_{max}, can be considered a current limit, $I_{max} \approx q_{max}/\tau$. Other mitigating factors for collider design: the current density can be reduced while maintaining the same charge by designing a gun for a larger diameter cathode as discussed earlier. A factor of 10 increase in the gun emittance, which grows as r^2, can probably be accommodated by the SLC injector without increasing the acceptance of the accelerator.

6 LIFETIME

The lifetime of a photocathode source is very system dependent. Besides selection of materials, and fabrication and handling techniques, all of which affect the lowest pressure that can be achieved, there are such indeterminate factors as the basic cathode material, its preparation prior to insertion into the gun, and the cathode activation process itself. These factors are discussed elsewhere [14]. The SLC gun operates with a total pressure $<10^{-10}$ Torr and with a partial pressure of CO of about 2×10^{-12} Torr. The dark current drawn by the gun at 120 kV with the laser off is about 40 nA, which indicates a very low level of HV vacuum activity. Thus the fall off in QE with time, which is about 1% per day with the cathode cooled to 0° C, does not increase when the HV is on. Likewise, by limiting interception of the e^- beam in the first couple meters of the transport system to <0.1% of the total charge, the presence of the e^- beam is found to have no effect on the lifetime.

7 HIGH POLARIZATION POSSIBILITIES

The theoretical and practical upper limit for the e^- polarization that can be achieved with a GaAs cathode is 50% [15]. Recently, studies of strained-lattice cathodes consisting of a thin layer of MBE grown GaAs on GaAsP have resulted in polarization as high as 90% [16]. The high polarization cathodes developed to date all have QEs of 0.1% [17] or less. This low QE is due in part to the thinness (typically 100 nm) of the active layer required to achieve the higher polarization in comparison to the photon absorption length which is about 1 μm. Until these cathodes have been tested at high voltage and with an intense laser beam, there is considerable concern that for similar cathode doping concentrations, the maximum charge limit will also be lower by a factor of 5 - 10 than for bulk materials. A reduced charge limit would have an immediate impact on plans to increase the polarization in the SLC but can most likely be accommodated in a future gun design through the use of larger area cathodes and additional materials engineering.

8 CONCLUSION

Polarized beams for the next generation of linear colliders will most likely be generated by a modified version of the SLC source and injector. For the requirements of the new colliders, the present performance of the SLC source is marginal, but a means to address each of the critical factors in this performance is at hand.

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10 / 8 / 92