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Low Emittance Guns for the ILC Polarized Electron Beam *

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Abstract

Polarized electron beams generated by DC guns are routinely available at several accelerators including JLAB, Mainz and SLAC. These guns operate with a cathode bias on the order of -100 kV. To minimize space charge effects, relatively long bunches are generated at the gun and then compressed longitudinally external to the gun just before and during initial acceleration. For linear colliders, this compression is accomplished using a combination of rf bunchers. For the basic design of the International Linear Collider (ILC)[1], a 120 kV DC photocathode gun is used to produce a series of nanosecond bunches that are each compressed by two sub-harmonic bunchers (SHBs) followed by an L-band buncher and capture section. The longitudinal bunching process results in a significantly higher emittance than produced by the gun alone. While high-energy experiments using polarized beams are not generally sensitive to the source emittance, there are several benefits to a lower source emittance including a simpler more efficient injector system and a lower radiation load during transport especially at bends as at the damping ring. For the ILC, the SHBs could be eliminated if the voltage of the gun is raised sufficiently. Simulations using the General Particle Tracer (GPT) package indicate that a cathode bias voltage of ≥200 kV should allow both SHBs to be operated at 433 or even 650 MHz, while ≥500 kV would be required to eliminate the SHBs altogether. Simulations can be used to determine the minimum emittance possible if the injector is designed for a given increased voltage. A possible alternative to the DC gun is an rf gun. Emittance compensation, routinely used with rf guns, is discussed for higher-voltage DC guns.

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[1] See *Electron Source* at http://www.linearcollider.org/wiki/doku.php?id=bcd:bcd_home .

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Keywords: electron gun, low emittance, polarized electrons.
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INTRODUCTION

Low emittance beams produced at the electron source present several fairly obvious advantages for high-energy linacs including: (1) they allow a simpler, more efficient injection system; (2) in the injection and acceleration systems prior to the damping ring, they present a lower radiation load, which is especially relevant at the bends; and (3) they reduce gas desorption near the cathode, which may be critical for certain types of photocathodes, particularly for GaAs.

The beam parameters for the ILC are in some respect less stringent than for the SLC. The charge per bunch at the gun is assumed to be 6.4 nC (twice the charge required at the IP) compared to 16 nC for SLC, and the spacing between microbunches

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[1] See *Electron Source* at http://www.linearcollider.org/wiki/doku.php?id=bcd:bcd_home .

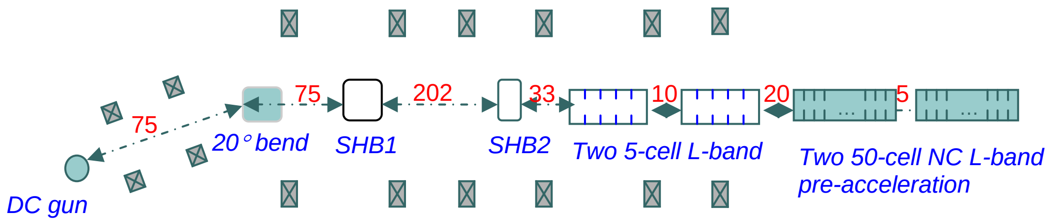

FIGURE 1. Layout of the ILC injector. All dimensions are in cm.

is significantly larger. The magnitude of the cathode bias for the SLC gun was limited by dark current and HV breakdown to 120 kV. To avoid the surface charge limit at the cathode and to avoid bunch lengthening due to space charge in the following drift section, the laser spot hard radius was 1 cm and the bunch length was typically 2 ns. The normalized rms transverse emittance of the SLC gun at 120 kV, calculated using EGUN, is 15 mm-mrad for the SLC charge and about 20 mm-mrad for the ILC charge. EGUN calculates only the correlated emittance. The thermal, i.e., uncorrelated, emittance for the electron beam from a fully activated GaAs photocathode has been measured to be ~0.15 mm-mrad per mm hard radius[2] or 1.5 mm-mrad in this case.

EMITTANCE AND THE ILC INJECTOR

Only a preliminary non-detailed study of the ILC L-band injector exists. It presently consists of 2 subharmonic bunchers (SHB) (108 and 433 MHz) followed by 2 room temperature, 5-cell, β=1, L-band SW bunchers [1]. This conceptual design is shown in Fig. 1. The drift between the gun and SHB1 is a duplicate of the SLC drift, which includes 2 vacuum isolation valves and a differential pumping region as well as a 20° bend. This drift distance can potentially be shortened when a detailed design is done. PARMELA is used to calculate the emittance after the bunchers. As shown in Table 1, the bunch length is reduced to 14 ps (6.8° L-band), but because of the radial forces in the L-band bunchers, the emittance is now ~40 mm-mrad. These radial forces vary with the phase of the rf. Thus the bunch particles at different phases experience the radial forces for different lengths of time, resulting in a large emittance. The emittance

TABLE 1. PARMELA results.

Parameter	Units	At gun exit	After bunchers
Charge	nC	6.4	6.2
Bunch length (FWHM)	ps Deg. L-band	2000 932	14 6.8
Energy/Energy spread	MeV	0.12	9.5/0.09(0.95%)
Normalized rms emittance	mm-mrad	n/a	43

[2] A *beer can* charge distribution at the cathode is assumed.

can be minimized by keeping the bunch radius and field strength in the L-band bunchers small and by capturing the bunch close to the RF crest and away from the longitudinal field null[3] [2]. The low bunching efficiency can be tolerated if the initial bunch length is shortened.

The GPT simulation code has been used to estimate the bunch lengthening due to space charge in the drift section following the gun[2]. At 120 kV, the bunch length at 1.5 m is increased by only ~10% if the initial length is 2-ns FWHM, which is still comfortably less than a half period (4.6 ns) of the 108-MHz SHB1 RF. As shown in Table 2, if the initial bunch length is decreased, the percentage growth at 1.5 m increases rapidly so that the minimum bunch length is only 1.3 ns, achieved with an initial bunch length at z=0 of ~750 ps. For comparison, the minimum bunch length at 200 kV is 750 ps, achieved with an initial 500 ps, which is short enough to be directly injected into a 433-MHz SHB (half period 1.1 ns) or possibly even a 650-MHz SHB. At ≥500 kV, direct injection into an L-band buncher becomes a possibility.

EMITTANCE OPTIMIZATION

A DC polarized electron gun has been successfully operated in the laboratory at the University of Nagoya with a cathode bias of 200 kV, while the electron gun for the Jefferson Lab FEL operates at 350 kV with a GaAs cathode[4]. In addition, there has been much progress in overcoming the cathode surface charge limit, which allows a much higher current density to be extracted from the cathode. In fact peak current densities >200 mA/mm^2 for excitation by nanosecond laser pulses have recently been reported [3]. Consequently the laser spot size on the cathode as well as the bunch length for the ILC design can be reduced if desired. These advances will allow an optimization of the gun parameters—initial radius, bunch length and energy, drift distances and SHB frequencies—to minimize the emittance out of the L-band buncher while keeping the bunching effective. For example, the emittance after bunching a 4.5 nC beam with an initial bunch length of 700 ps and drift of 30 cm has been shown to be a factor of 2 lower than with 2 ns and 75 cm [4]. A complete optimization may result in an even lower emittance.

TABLE 2. Minimum bunch length at entrance to first SHB.

Δt @z=0 m	**Δt @z=1.5 m (ps)**		
(ps)	**120 kV**	**200 kV**	**500 kV**
2000	2172	2000	
1000	1333	1000	
500	1333	766	500
250	1562	780	312
125	1722	833	250

[3] These steps simultaneously result in less efficient bunching.
[4] Since polarization is not required for the FEL, the laser excitation can be done at shorter wavelength than the band gap, which generally enhances cathode operation in the presence of dark current or HV breakdown.

As the emittance contribution of the bunchers is lowered, the emittance of the beam at the gun becomes more important. Some decrease in gun emittance can be expected if a careful study of electrode shape as well as bunch radius and length is made as a function of cathode bias.

FUTURE PROSPECTS

There are at least 2 ways the beam emittance at the injector L-band accelerator might be lowered even more. If activated GaAs photocathodes can be shown to survive in an operating RF gun, then both the SHB and L-band bunchers can be eliminated. RF guns operating with emittance compensation have demonstrated beam emittances <2 mm-mrad for a charge of 1 nC. The emittance grows as about 1.4 mm-mrad/nC [5], so for the ILC, one would expect a normalized rms emittance at high energy on the order of 10 mm-mrad.

The performance of rf guns described above is achieved using a technique called *emittance compensation* in which a solenoidal field just after the cathode is used to temporarily reverse the angular spread of the electrons in a given bunch so that at a defined point downstream, the correlated emittance is minimized at a value near zero. To be useful, this minimization must occur just as the bunch reaches a velocity of $\beta=1$. It has been suggested that emittance compensation would work with a bunch produced by a DC gun if the bunching process used is linear [6]. It is proposed here that a shorter bunch length with respect to the buncher rf will reduce the non-linear radial forces on the bunch, resulting in less emittance growth.

SUMMARY

Minimizing the emittance for the bunched beam out of the ILC injector will result in superior performance and less radiation damage. With a modest increase in the cathode bias, the injector parameters can be optimized to significantly reduce the beam emittance. For very high DC cathode bias, or by using an rf gun, the emittance can be lowered even more. Emittance compensation might be successfully applied to a higher voltage DC gun operating with a short bunch length.

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