A COMPACT, NORMAL-CONDUCTING, POLARIZED ELECTRON, L-BAND PWT PHOTOINJECTOR FOR THE ILC*

D. Yu, Y. Luo, A. Smirnov, DULY Research Inc., Rancho Palos Verdes, CA 90275
I. V. Bazarov, Cornell University, R. Fliller, Fermilab, P. Piot, NIU/ Fermilab

Abstract

The International Linear Collider (ILC) needs a polarized electron beam with a low transverse emittance [1]. High spin-polarization is attainable with a GaAs photocathode illuminated by a circularly polarized laser. Low emittance is achievable with an rf photoinjector. DULY Research has been developing an rf photoinjector called the Plane Wave Transformer (PWT) [2] which may be suitable as a polarized electron source for the ILC. A short, 1+2(1/2) cell, L-band PWT photoinjector with a coaxial rf coupler is proposed for testing the survivability of GaAs cathode. It is planned to produce a high-aspect-ratio beam using a round-to-flat-beam transformation [3]. In addition to its large vacuum conductance, the modified PWT has a perforated stainless steel sieve as the cavity wall, making it easy to pump the structure to better than 10^{-11} Torr at the photocathode. An L-band PWT gun can achieve a low emittance with a low operating peak field. A low peak field is beneficial for the survivability of the GaAs photocathode because electron backstreaming is greatly mitigated.

INTRODUCTION

Efforts are currently underway by several collaborations to consider rf photoinjectors as a polarized electron source for the ILC [4]. The successful development of a polarized electron rf photoinjector would provide an alternative to the current ILC baseline design of a dc photoinjector followed by subharmonic bunchers [5]. In addition, if the normalized transverse emittance in one dimension could be made substantially smaller using additional means such as the round-to-flat beam transformation [3], it may be possible to simplify the design of the electron damping ring downstream, thus saving ILC construction and operating costs.

A strained-lattice GaAs photocathode covered with a thin epilayer of activated Cesium has been shown to be the best candidate so far for a polarized electron source. Spin polarization in excess of 85% has been achieved with good quantum efficiency and long life. Stringent conditions, however, must be met in order to maintain the QA and lifetime of the GaAs cathode. These include an ultra high vacuum ($<10^{-11}$ Torr), a clean surface, and no unwanted interference such as that from energetic electrons or ions. In order to use rf photoinjector as a polarized electron source, the design must meet the survivability requirements of the GaAs photocathode, as well as the need to produce a low-emittance polarized electron beam. An earlier experiment [6] showed that a GaAs photcathode needed a specially designed gun to provide an operationally significant lifetime. It is hopeful that better care in the preparation and handling of the GaAs photocathode and improvements in the rf and ultra high vacuum subsystems would eventually demonstrate the feasibility of an rf photoinjector with an activated GaAs cathode.

The Plane-Wave-Transformer (PWT) design (U.S. Patent No. 6,744,226) has been proposed by DULY Research Inc. as an L-band photoinjector for an ILC polarized electron source. We presented an 8-cell PWT design in the Snowmass 2005 conference [2] that requires one or two L-band klystrons, each with a peak power of 10 MW. The required high-power, long-pulse klystrons are being developed by several companies, and in time will be available in the United States. In the meantime, DULY Research Inc. has a DOE SBIR grant to develop a

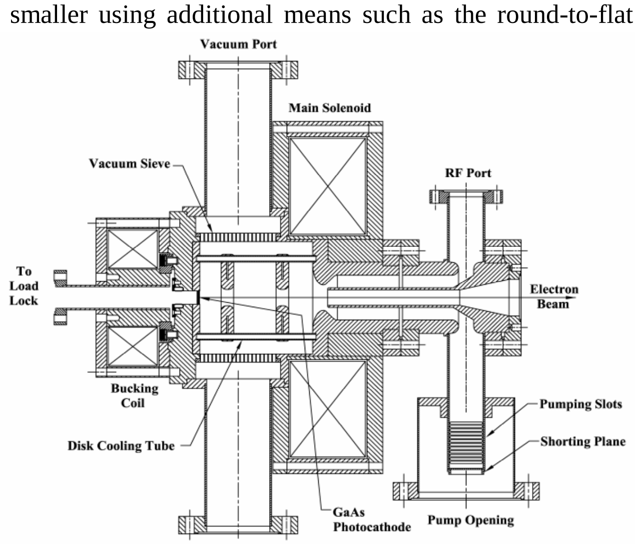

Figure 1a): Schematic of an L-band PWT polarized electron photoinjector with multiple vacuum ports.

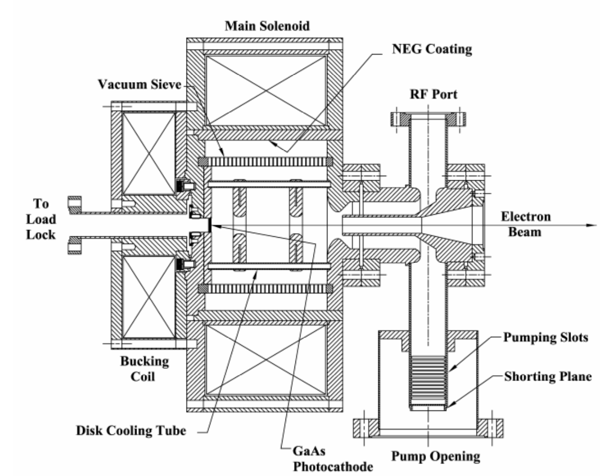

Figure 1b): Schematic of an L-band PWT polarized electron photoinjector with SNEG.

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1+2(1/2)-cell, L-band PWT that requires less peak power to achieve the needed peak field. This work is being performed by DULY Research in collaboration with Fermilab and Northern Illinois University (NIU).

SHORT PWT WITH COAX RF COUPLER

Two designs of a 1+2(1/2)-cell PWT photoinjector using a coaxial rf coupler are shown in Fig. 1a and 1b. At critical coupling, $Q_{external} = Q_{unloaded}$. Using the Kroll-Yu method [7] we calculate the value of $Q_{external}$ and the resonance frequency of the structure by varying the length of the shorted coax transmission line. The condition for critical coupling is achieved by adjusting the dimensions at the cavity-to-coax junction. Due to the strong cell-to-cell coupling, the PWT is a robust rf structure and has a large frequency separation between the operating TM01-like mode and the nearest higher order mode. If 4 (or 6) cooling rods are used to support the 2 disks, the shunt impedance with the 3D code GdfidL is 9.6 MΩ/m (13.6 MΩ/m), the average gradient is 10.2 MV/m (12.1 MV/m), and the peak field on axis is 19.6 MV/m (23.4 MV/m) with an input rf power of 2.5 MW. These parameters are obtained for a PWT with Cu disks and a SS cylindrical tank without perforation in the wall.

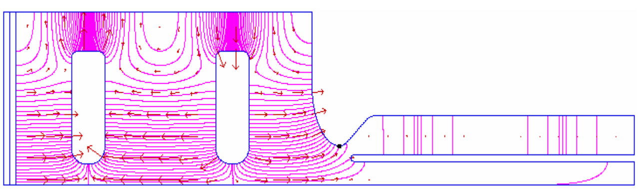

Figure 2: Field plot of a coax-coupled, B-mode, PWT cavity in the operating TM_{010} mode.

ULTRA HIGH VACUUM

The PWT tank includes a perforated section, or "vacuum sieve" (Fig. 3), inside the pumping chamber. Open pumping paths through the sieve, as well as between the disks and the tank, also contribute to the PWT's large vacuum conductance. Out-gassing rates are minimized by use of a stainless steel tank and Class I OFHC disks and rods, careful cleaning procedures and high-temperature bake-out. With several NEG pumps or an SNEG (Sputtered Non-Evaporative Getter) coated vessel providing a high pumping speed at low pressure, the vacuum pressure at the GaAs photocathode can be as low as 10^{-12} Torr, up to 2 orders better than a conventional L-band 1.6-cell gun. A specially designed load lock system allows transport, manipulation and reactivation of the GaAs cathode without a vacuum break to the PWT.

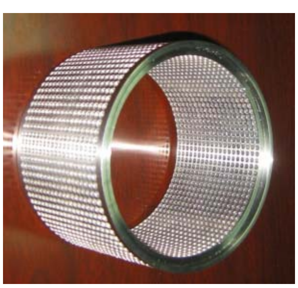

Figure 3: PWT tank vacuum sieve located inside the pumping box.

LOW TRANSVERSE EMITTANCE

The emittance-compensating magnetic focusing system for the normal-conducting PWT comprises a main solenoid placed at the nearest available location to the photocathode and a small bucking coil placed behind the cathode. The main coil yoke is designed to shape the field concentration, first to focus the space charge dominated beam near the cathode, and also to compensate for the rf kick at the gun exit. Using Cornell's multivariate optimizer APISA [8], the normalized transverse emittance is minimized by varying beam parameters, and intensities of the magnetic field profiled in Fig. 4 (from POISSON) and the cavity electric field calculated from SUPERFISH. The simulation results for an *unmagnetized*, round beam of 0.8 nC and 3.2 nC charge, from an L-band 1+2(1/2) cell PWT (Fig. 1a) followed by four TESLA cavities, are compared in Table 1, and illustrated in Figures 5a,b.

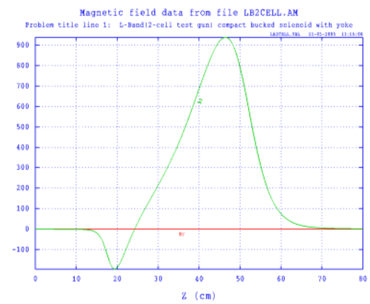

Figure 4: Axial magnetic field profile associated with the configuration of solenoids shown in Fig. 1a. The cathode is located at 24 cm, where the B-field vanishes.

Table 1: APISA/ASTRA simulation results for an L-band 1+2(1/2) cell PWTand four 9-cell TESLA cavities

Charge per Bunch (nC)	0.8	3.2
Frequency (MHz)	1300	1300
Energy (MeV)	47	51
Normalized rms Emittance (mm-mrad, including thermal emittance)	0.45	1.6
Energy Spread (%)	0.36	0.71
Bunch Length (rms, ps)	10	13
Peak Current (A)	23.1	71.1
Active Linac Length (cm)	26	26
Transverse Beam Size (rms, mm)	0.8	1.6
Peak Magnetic Field (Gauss)	1256	1234
Peak PWT Electric Field (MV/m)	23.4	23.4
Peak TESLA Electric Field (MV/m)	20.3	22.2

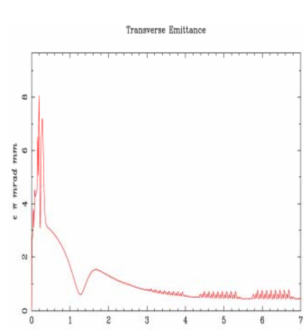

Figure 5a: RMS transverse emittance (mm-mrad) vs z (m).

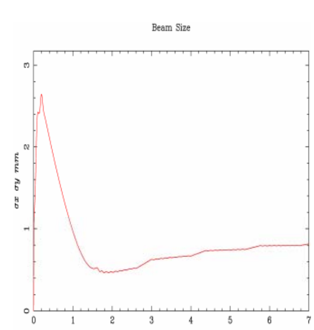

Figure 5b: RMS transverse beam size (mm) vs z (m).

As we have reported earlier [9], it is significant to note that the relatively low peak field needed to achieve the low transverse emittance is beneficial to the survivability of GaAs cathode. A low peak field reduces the numbers of backstreaming electrons reaching the cathode.

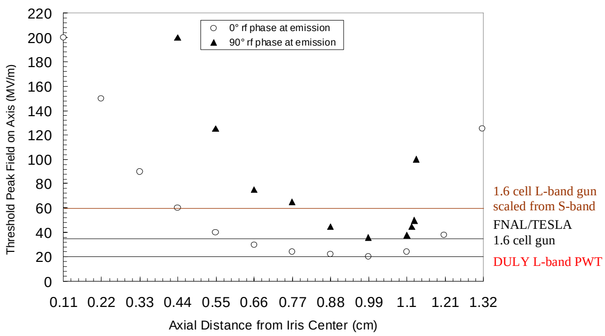

Figure 6: Peak field threshold for backstreaming secondary electrons emitted from first iris hitting the GaAs cathode vs emitter location.

ROUND-TO-FLAT-BEAM TRANSFORMATION

Following recent work of DESY and Fermilab [10], we consider the possibility of producing a large-aspect-ratio flat beam with a very low transverse emittance in one dimension by re-partitionning the transverse emittances associated with an angular-momentum-dominated beam using a set of three skewed quadrupoles [11]. In this case the round beam is produced by the PWT with its cathode immersed in an axial magnetic field. In practice, this is easily achieved by reversing the current in the bucking coil. Although not included in this preliminary APISA/ASTRA simulation, additional solenoids can be placed in the beam line to improve results. The goal is first to minimize the normalized x-y *uncorrelated* transverse emittance of the rotating round beam, which is related to the correlated transverse emittance as follows:

$$\varepsilon_u = \sqrt{\langle x^2\rangle\langle x_u'^2\rangle - \langle x x_u'\rangle^2} = \sqrt{\varepsilon_{corr}{}^2 - \varepsilon_B{}^2}$$

For an angular-momentum-dominated round beam,

$$x_i \equiv r_i \cos\theta_i \qquad x_i' \equiv x_{ui}' - y_i \omega_L / v_z$$

$$\omega_L \equiv \dot{\theta} \qquad x_{ui}' \equiv r_i' \cos\theta_i$$

and the “magnetic” or Lamor/Busch’s emittance is given by:

$$\varepsilon_B = \frac{e|B_o|\sigma_{ro}{}^2}{4\gamma m_o \beta_z c}, \quad \sigma_{ro}{}^2 = \langle r^2\rangle = 2\langle x^2\rangle.$$

During the phase space transformation, there are two basic invariants through the dispersionless transport channels [12]. These are the 4D emittance ε_{4D} and the generalized emittance ε_g defined respectively by:

$$\varepsilon_{4D}{}^2 \equiv \det\begin{pmatrix} x^2 & xx' & xy & xy' \\ xx' & x'^2 & x'y & x'y' \\ xy & x'y & y^2 & yy' \\ xy' & yy' & yy' & y'^2 \end{pmatrix} = const$$

and

$$\varepsilon_g{}^2 \equiv \varepsilon_x{}^2 + \varepsilon_y{}^2 + 2\varepsilon_{x\&y}{}^2 = const$$

where

$$\varepsilon_{x\&y}{}^2 = \det\begin{pmatrix} xy & xy' \\ x'y & x'y' \end{pmatrix}.$$

Thus the various emittances before and after the transformation are related as shown below:

Beam	4D emit. $\varepsilon_{4D}{}^2$	$\varepsilon_{x\&y}$	Gen. emit. $\varepsilon_g{}^2$
Round	$\varepsilon_{corr}{}^2 - \varepsilon_B{}^2$	ε_B	$2(\varepsilon_{corr}{}^2 + \varepsilon_B{}^2)$
Flat	$\varepsilon_x \varepsilon_y$	0	$\varepsilon_x{}^2 + \varepsilon_y{}^2$

It follows directly that the normalized transverse emittances of the flat beam are given by the round beam uncorrelated emittance and the Larmor emittance:

$$\varepsilon_x >> \varepsilon_y : \qquad \varepsilon_y \approx \frac{\varepsilon_u{}^2}{2\varepsilon_B}, \qquad \frac{\varepsilon_x}{\varepsilon_y} \approx \frac{4\varepsilon_B{}^2}{\varepsilon_u{}^2}.$$

From the above equations it is clear that in order to achieve the lowest possible value of the normalized transverse vertical emittance ε_y and the largest emittance ratio $\varepsilon_x / \varepsilon_y$, we need to maximize the magnetic flux at the cathode *and* minimize the x-y uncorrelated, round-beam transverse emittance ε_u. While the transverse emittance for a round beam from the short PWT gun with no field at the cathode has achieved a very low value, the results we have obtained so far with the standard PWT coils have not yet achieved these flat beam objectives. Work is in progress to optimize the focusing system by adding solenoids after the PWT exit to improve the flat beam results.

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