A Polarized Electron PWT Photoinjector for the ILC

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In order to provide maximum physics benefits, the International Linear Collider (ILC) must have a highly polarized electron beam with a low emittance. High electron spin-polarization (>85%) is attainable with a modern GaAs photocathode illuminated by a circularly polarized laser. Low emittance is achievable with an rf photoinjector. DULY Research has been developing an rf photoelectron injector called the Plane Wave Transformer (PWT) which may be particularly suitable as a polarized electron injector for the ILC. A round-beam transverse emittance of 1.7 mm-mrad for 3.2 nC, and 0.6 mm-mrad for 0.8 nC charge is achievable with a 7+2/2 cell PWT rf photoinjector; and the vertical emittance can be further reduced with a round-to-flat beam transformation. A unique feature of the PWT is that it has a much larger vacuum conductance than conventional rf guns, which makes it possible to easily pump the structure to a vacuum level better than 10^{-11} Torr at the photocathode. In contrast with other L-band gun designs which require operation at a high peak field (≥35MV/m) in order to achieve a low normalized transverse emittance, an L-band PWT gun can achieve a low emittance at a lower operating peak field (≈20MV/m). The low peak field in the PWT gun is beneficial for the survivability of the GaAs photocathode because electron backstreaming is greatly mitigated.

1. INTRODUCTION

Currently a dc-gun based polarized electron source [1] may provide the low beam emittance required by the ILC [2], but only with a complicated and expensive damping ring [3]. DC guns are also prone to ion back-bombardment, which is extremely harmful to the GaAs cathode. An L-band, Plane Wave Transformer (PWT) electron photoinjector with an activated Gallium Arsenide (GaAs) cathode has been proposed by DULY Research Inc. (U.S. Patent No. 6,744,226) as a possible polarized electron source for the International Linear Collider [4]. The normal-conducting PWT photoinjector (Fig. 1), comprising a “quasi-open” multi-cell, π-mode, standing-wave structure, can operate in a high vacuum and a relative low peak field, both important for maintaining long lifetime of the GaAs photocathode. The L-band PWT can achieve a much lower transverse emittance than a polarized electron photoinjector design based on a dc-gun and sub-harmonic bunchers, while operating at a lower peak field than other rf guns. In addition, the cells in the PWT structure are strongly coupled, thus relaxing fabrication tolerances while providing a large frequency separation between the operating mode and the nearest mode. Some, though not all, of the PWT features may be separately achievable with either dc-based guns or other rf guns. However, the combination of all the features that are essential for the ILC polarized electron source may be unique for the PWT photoinjector. The simplicity of the PWT construction and its operation would also help increase reliability of the polarized electron injector.

In order to demonstrate the feasibility of the PWT photoinjector as a polarized electron gun for the ILC, two critical experiments are needed. The first is to show that an activated GaAs photocathode could indeed survive in the rf cavity. The high vacuum and the low peak field in the PWT should drastically improve results of an earlier measurement [5] in which the GaAs cathode became unusable after just a few rf cycles in a conventional rf gun. The second is to show that an ultra-low vertical emittance could be achieved for a high-aspect-ratio beam from the PWT after a round-to-flat-beam transformation [6]. This would reinforce and amplify the recent success at the Fermilab/NICADD Photoinjector Laboratory where a 100-to-1 aspect-ratio beam was demonstrated experimentally with a conventional L-band, 1.6-cell gun using the flat-beam transformation [7]. Prior to a flat-beam transformation, however, it is important that a round electron beam has sufficiently small transverse emittances that are angular-momentum correlated. We show in this paper that an L-band PWT rf gun can in principal achieve such a condition. Future work will consider a round-to-flat-beam transformation to further minimize the vertical emittance for the PWT to meet the ILC requirements.

2. CHARACTERIZATION OF THE PWT PHOTOINJECTOR

2.1. Ultra High Vacuum

A 4-wavelength long version [4] of the L-band PWT gun comprises 7+2/2 cells, *i.e.* a first half cell, followed by 7 full cells, and finally another half cell (Fig. 1). It has enough room for 1 or 2 side-coupled rf port(s) and a pumping chamber, as well as a primary focusing coil surrounding the PWT tank. The PWT cells are formed between copper circular disks supported by pipes parallel to the beam axis, carrying water to disk internal cooling channels. The PWT disk assembly is suspended with 6 pipes and the end plates inside a large stainless steel cylindrical tank. The DULY design of the PWT tank includes a perforated section (or "sieve") (Fig. 2) inside the pumping chamber. Open pumping paths through the sieve, as well as between the disks and the tank, contribute to the PWT's large vacuum conductance. Out-gassing rates are minimized by a careful choice of materials, 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 (Fig. 3) allows transport, manipulation and reactivation of the GaAs cathode without a vacuum break to the PWT.

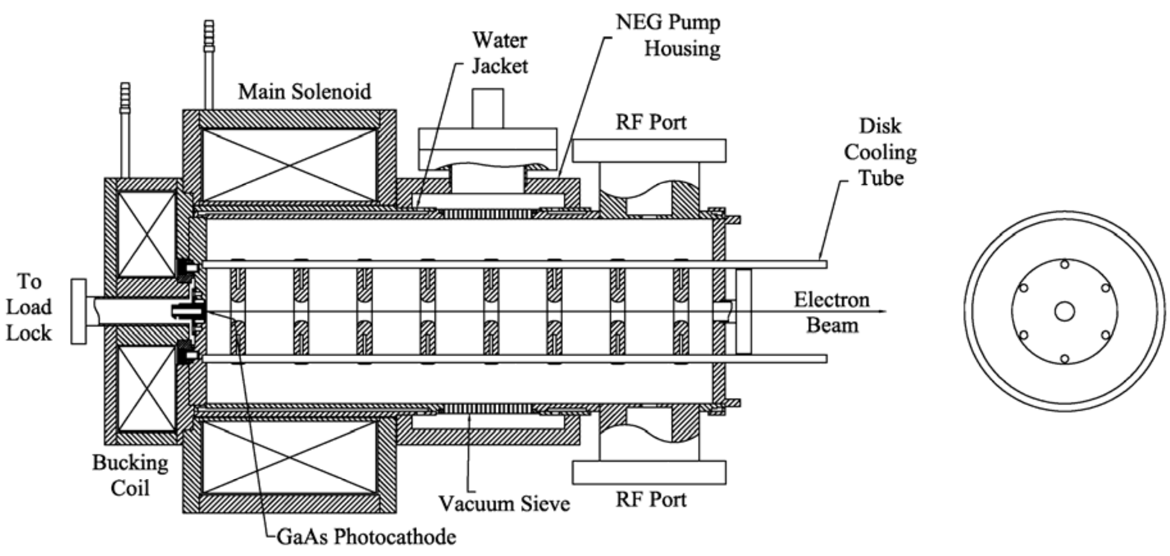

Fig. 1: Schematic of an L-band PWT polarized electron photoinjector.

2.2. Low Transverse Emittance

The emittance compensating focusing system of the PWT comprises a pair of solenoids. In addition to the main coil outside the PWT tank, there is a small bucking coil surrounding the cathode assembly. The currents in the main and bucking coils are easily adjustable to provide either a magnetic null on the cathode surface for an uncorrelated beam, or in the case of flat beam transformation [7], a non-zero longitudinal magnetic field on the cathode for the generation of an angular-momentum-dominated beam. This design gives large flexibility in the operation of the PWT to achieve an ultra-low transverse emittance. Using a set of 3 skewed quadrupoles to transform an initially angular-momentum-dominated round beam into a flat beam with a high aspect ratio, the vertical transverse emittance can be further reduced possibly by two orders of magnitude or more [6].

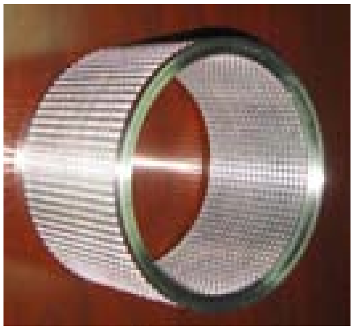

Fig. 2: PWT tank sieve inside the pumping box.

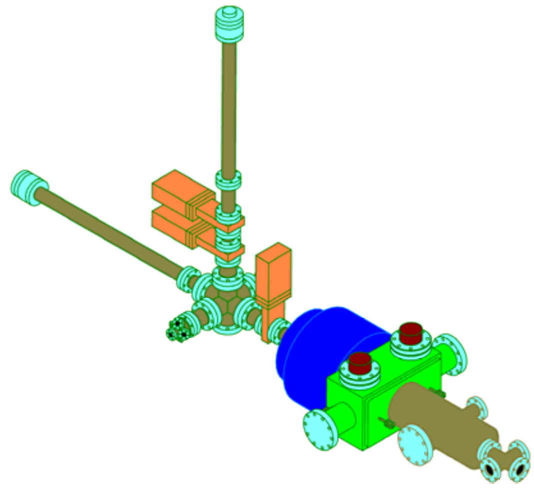

Fig. 3: DULY load lock mounted on a PWT gun.

We have performed some preliminary simulations using ASTRA and HOMDYN, and calculated the transverse emittance (including the GaAs thermal emittance) associated with a round beam generated by an L-band PWT gun, and subsequently accelerated by four 9-cell TESLA cavities. Given this configuration, the beamline was optimized with ASTRA using the optimizer in Ref [8] and the generic optimizer SDDS [9]. The results of this optimization for two cases of bunch charges are presented. In Figs. 4 and 5 we present the evolution of the normalized transverse emittance along the beamline for a bunch charge of 3.2 nC (PWT peak field at 23 MV/m), and 0.8 nC (PWT peak field at 21 MV/m), respectively. At the exit of the last TESLA cavity (z≈10 m), the normalized transverse emittance is 1.7 microns and 0.6 microns, respectively, for these two cases. Iterative design of the PWT injector is likely to improve the normalized transverse emittance to reach the goal of 0.4 microns for a round beam [10].

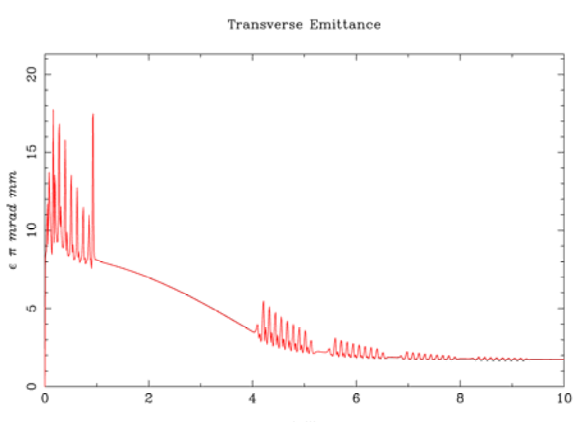

Fig. 4: Transverse emittance *vs* distance for 3.2 nC

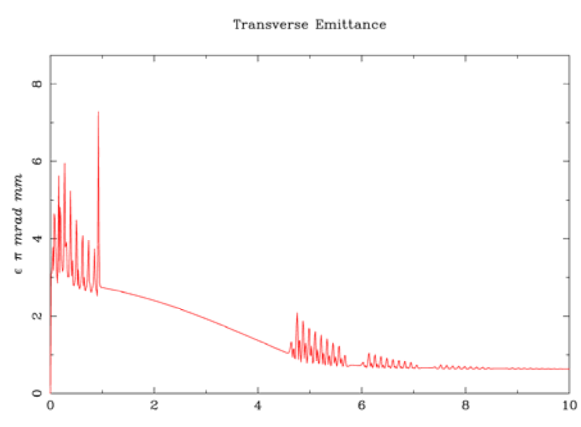

Fig. 5: Transverse emittance *vs* distance for 0.8 nC

2.3. Low Operating Peak Field

Fig. 6 shows the normalized transverse emittance at the end of simulation (z≈10 m) *vs* peak longitudinal electric field at the cathode for an L-band PWT for a bunch charge of 3.2 nC. At very low peak fields (<18 MV/m), capture of the electron bunch into the rf bucket with a low transverse emittance is difficult due to the space charge effect. However, because of the superior emittance compensation design of the PWT, the beam is effectively focused at a peak field ≈21-23 MV/m, and the low transverse emittance improves little as peak field increases further. A low operating peak field of the PWT would keep many of the backstreaming electrons from hitting the photocathode. Fig. 7 shows the threshold peak electric field for backstreaming secondary electrons that are emitted from the first PWT iris and reaching the cathode, at rf phases of 0 and 90 degrees at the time of emission [11]. These results were obtained with PARMELA, using the full electric and magnetic field maps from SUPERFISH and POISSON. It is seen that operating the gun at 20 MV/m, none of the secondary electrons emitted from the first iris reaches the cathode. By contrast if the gun were operated at say, 35 MV/m, many secondary electrons would hit the cathode. Simulations were also performed with PARMELA for electrons emitted from the cathode holder and streaming back toward the cathode. In this case, at very large initial rf phases (150-180 degrees) some slow electrons would hit the cathode after the field direction reverses.

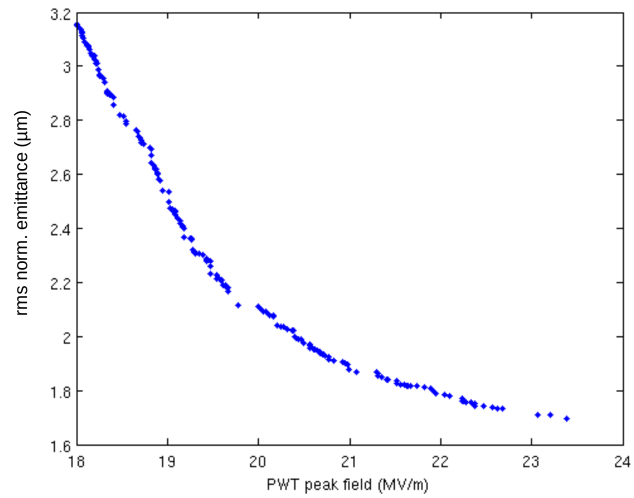

Fig. 6: Normalized transverse emittance *vs* peak field of an L-band PWT (7+2/2 cell, 3.2 nC).

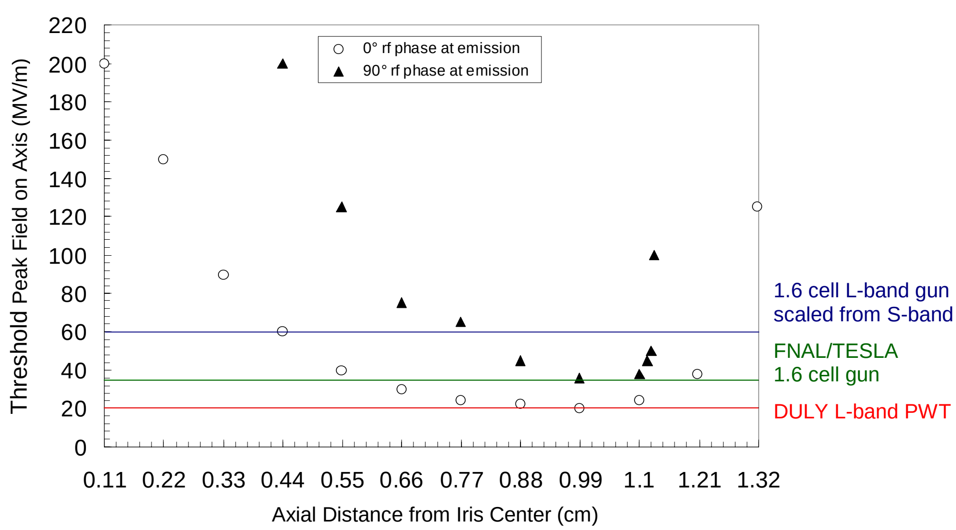

Fig. 7: Peak field threshold for electron back bombardment on cathode (see Ref [11]).

3. L-BAND PWT PHOTOINJECTOR DESIGNS

The L-band design of a 7+2/2 cell PWT with 6 cooling pipes and a stainless steel cylindrical tank depicted in Fig. 1 has been shown by simulations with the GdfidL/Gd1 code to achieve a peak field [12] of 25 MV/m at 10 MW of rf power. Further details of this design including a thermal hydraulic analysis under ILC parameters are described in Ref. [4].

Based on the present work in this paper and Ref [4], DULY Research has proposed a short, 1+2/2 cell version of the L-band PWT photoinjector with a coaxial rf coupler for testing the survivability of a GaAs cathode at Fermilab. This PWT is designed to have >20MV/m peak field using a long-pulse modulator/klystron system capable of providing 2.5-5 MW of rf power. It is also planned to produce a high-emittance-ratio beam with a round-to-flat beam transformation.

The primary goal of an L-band PWT electron photoinjector and a flat-beam transformation is that, after a polarized electron beam from the PWT is accelerated to 5 GeV, a beam with an ultra low vertical emittance would be ready to be injected into the ILC main linac without having to first go through a large electron damping ring. A secondary goal is that, in case the primary goal proves too ambitious, a polarized round electron beam from an L-band PWT photoinjector with a very small transverse emittance would significantly simplify the electron damping ring design.

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[9] H. Shang *et al*., Proc. of 2003 Particle Accelerator Conference, p. 3470 (2003).
[10] Current ILC specification (Ref. 2) requires a vertical emittance (εv) of 0.02 mm-mrad and a horizontal emittance (εh) of 8 mm-mrad at the exit of the damping ring. Therefore if the damping ring were to be replaced by an rf gun, the round-beam transverse emittance $\varepsilon r = (\varepsilon v \bullet \varepsilon h)^{1/2}$, *before* the flat-beam transformation should be 0.4 mm-mrad for a bunch charge of 3.2 nC.
[11] Y. Luo *et al*., Proc. of 2003 Particle Accelerator Conference, p. 2126 (2003).
[12] Note, in Ref. 4 the average gradient was mislabeled as E_{peak} or E_{ampl}. For a 6-rod PWT standing-wave cavity operating in the π-mode, the peak field is 1.87 times the average gradient. As usual, the rf power is equal to the square of the voltage (or average gradient times accelerator length) divided by the shunt impedance.