PARMELA SIMULATIONS OF A PWT PHOTOINJECTOR*

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Abstract

Conventional rf guns such as the BNL/SLAC/UCLA 1.6-cell gun require a high operating peak field typically above 120 MV/m. By contrast, the PWT gun can operate at a much lower peak field with excellent beam properties. A 10+2(1/2)-cell PWT photoinjector can achieve an emittance of 0.56 mm-mrad for a 1 nC bunch charge at a peak field of 55 MV/m; and 1.04 mm-mrad for 2 nC at 60 MV/m. By operating the PWT gun at a low peak field, dark current production from back bombardment of electrons emitted elsewhere in the rf cavity is mitigated as the number of electrons which could back stream to hit the photocathode and the cathode holder is significantly curtailed. The quantum efficiency and lifetime of a semiconductor photocathode, such as GaAs are significantly improved if the surface of the cathode is subjected to a lower peak field

PWT PHOTOINJECTOR

A compact, 10-30 MeV, photoelectron linac using the Plane Wave Transformer (PWT) design (Figure 1) has been under development at DULY Research [1] for wide-ranging applications in research, medicine and industry. The PWT photoinjector integrates a photocathode directly into a multicell, standing-wave, π-mode linac, in which the open cells in a large vacuum tank are strongly coupled.
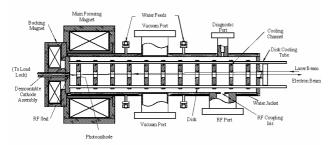

Figure 1: Schematic of a PWT photoinjector.

The beam is focused with emittance compensating solenoids or permanent magnets, and achieves high current with low emittance, producing extremely high brightness.

An S-band PWT prototype was fabricated by DULY Research and installed at UCLA [1]. A higher frequency (X-band) version of the PWT would produce an even brighter beam. In a current DULY/SLAC collaboration, an S-band PWT gun is being developed into a polarized rf gun capable of high vacuum in the 10^{-11} Torr range to support a long GaAs cathode life and a high quantum efficiency [2].

With an integrated photocathode, the PWT has a simple system design which eliminates a separate accelerating section with the associated focusing optics and additional rf feeds as required by a conventional 1.6-cell gun in order to achieve the same energy gain. In addition, the defocusing kick which the beam receives at the exit of the last cell occurs at a significantly higher energy than for a 1.6-cell gun, resulting in less emittance growth.

EMITTANCE CALCULATIONS

We have performed improved, detailed beam dynamics simulations of the PWT photoinjector using the Los Alamos gun code PARMELA, Version 3. With refined space charge mesh and careful optimization, the performance of the PWT gun was evaluated for three illustrative cases. Optimized results of the simulations are shown in Table 1, and in Figure 2.

Table1: Parameters of 0.1 nC, 1 nC and 2 nC operations.

Charge per Bunch (nC)	0.1	1.0	2.0
Frequency (MHz)	2856		
Energy (MeV)	8	17	17.5
Normalized RMS Emittance (mm-mrad, no thermal emit.)	0.36	0.56	1.04
Energy Spread (%)	1.4	1.0	1.3
Bunch Length (rms, ps)	2.2	3.6	3.2
Peak Current (A)	13	80	180
Linac Length (cm)	58		
Beam Size (rms, mm)	1.2	.85	1.62
Peak Magnetic Field (Gauss)	875	1694	1620
Peak Electric Field (MV/m)	27	55	60
Peak Brightness (10^{14} A/m^2-rad^2)	2.0	5.1	3.3

For a given charge per bunch, the initial beam size and bunch length (both flat top) are varied for each case and are optimized for space charge minimization. For a given peak field, the initial injection phase and the solenoidal field are adjusted to give the lowest normalized transverse emittance. A low field of 27 MV/m is sufficient for acceleration of a low emittance beam with a charge of 0.1 nC (see Table 1). The 1-nC case uses a peak field of 55 MV/m, and represents a typical FEL injector (Figure 2). The 2-nC case uses a peak field of 60 MV/m, and represents an injector under NLC-like conditions.

Shown in Table 1 are the calculated normalized emittance of 0.56 mm-mrad (1 nC) and 1.04 mm-mrad (2 nC), which are lower than earlier simulation results [1]. Thermal emittance is not included. From Figure 2, it is interesting to note that the energy spread and bunch length decrease with drift distance. It appears that a negative

chirp is introduced by the gun, in this case allowing for longitudinal focusing of the bunch. In all cases, the beam brightness, defined as twice the peak current divided by the transverse emittance squared, well exceeds 10^{14} A/(m-rad)². From Table 1 and Figure 2, it is clear that the integrated PWT design produces excellent beam quality over a wide range of input parameters.
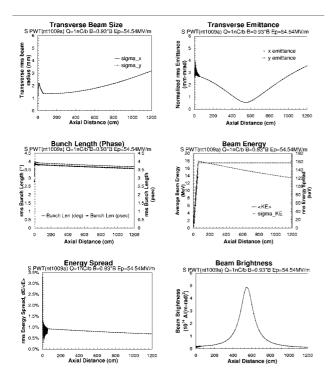

Figure 2: PWT beam parameters for 1 nC bunch charge.

Figure 2 indicates that the transverse emittance and beam size go through their respective minima and then grow as the beam continues on after leaving the PWT. This is a result of the energy (about 17 MeV) not being high enough to overcome space charge effects. The beam must be matched into an additional accelerator. The standard way to do this with a 1.6-cell gun is to position the input of the accelerator at a laminar beam waist. The emittance will then be preserved if the proper accelerating gradient is chosen. Two solutions have been found with 1.6-cell guns for achieving an emittance minimum after acceleration. The first is to adjust the gun solenoid so the waist coincides with the emittance minimum without the accelerator. Utilizing the fact that the emittance undergoes a plasma oscillation, the second solution is to adjust the solenoid so that the waist coincides with the immediately following emittance maximum. These strategies can also be applied to the PWT.

A peak field of 55 MV/m in an S-band PWT gun is considerably lower than an operating peak field of 120-140 MV/m in a conventional 1.6-cell gun. The lower peak field at the photocathode is particularly beneficial for the survivability of an activated GaAs cathode in a polarized rf gun, and also, as we shall see below, for

mitigation of dark current and electrical breakdown due to field emission and electron back bombardment.

For comparison with the 1.6-cell gun [3], we also calculated the tranverse emittance for a PWT gun in which the length of the first cell is 0.625 of a normal cell of a half wavelength, instead of a 0.5 cell as in the present design. Figure 3 shows the normalized transverse emittance versus magnetic field (varying the injection phase at a given peak field) for these two cases.
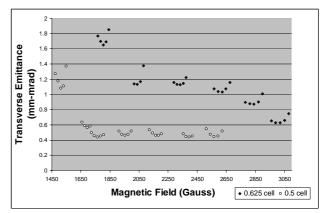

Figure 3: Emittance vs magnetic field for 1 nC bunch. The solid diamonds are for a 0.625 first cell at a peak field of 60, 80, 100, 120, 140 and 160 MV/m, and the open circles are for a 0.5 first cell at 45, 55, 73, 91, 109, 127 and 145 MV/m.

The simulations show that an S-band, π-mode, integrated PWT photoinjector with the first cavity of 0.5 cell is better than the first cavity of 0.625 cell. They both can achieve very low emittance. But performance is different for these two cases. For the 0.5 cell case, the normalized transverse emittance is 1.08 mm-mrad at 45 MV/m (Bz = 1.5 kG). It decreases to 0.56 mm-mrad as the peak field increases to 55 MV/m (Bz = 1.7 kG). From 73 to 145 MV/m, the emittance stays very close to 0.4 mm-mrad. For the 0.625 cell case, the emittance decreases as the field gradient increases, but always remains higher than the 0.5 cell case. The normalized transverse emittance is 1.6 mm-mrad at 60 MV/m (Bz = 1.8 kG) and is 0.63 mm-mrad at 160 MV/m (Bz = 3.0 kG). Unlike the BNL/SLAC/UCLA 1.6-cell gun, the PWT electron beam is only minimally affected by the exit rf kick.

ELECTRON BACKBOMBARDMENT SIMULATIONS

Electron Backstreaming from the PWT Iris to the Photocathode

A GaAs photocathode is prone to dark current emission when bombarded by electrons or ions. Since electrons have a smaller mass and are hence more mobile, field-emitted electrons in the rf cavity can potentially reach the cathode, damaging the activated layer. We have

performed PARMELA simulations to assess the effects of electron backstreaming from the first PWT iris to the photocathode. A thin ring electron bunch, initially with essentially zero velocity, is placed at a given location on the surface of the iris. The model includes a drift tube at the center of the endplate. The aperture of the drift tube is chosen to be that of the photocathode and its support plug (0.5 inch). Field emitted electrons move under the rf field and external magnetic field of the PWT. The number of electrons which can reach the photocathode depends on the initial location of the ring bunch, the rf phase and the peak rf field. At certain locations the rf field on the PWT iris surface may be as high as 1.17 times the maximum peak field on axis. The maximum number of electrons that can reach the cathode occurs at such locations when the rf field magnitude exceeds a threshold value and when the initial rf phase at the iris at the time the electrons are emitted is near zero. Figure 4 shows the dependence of the field threshold on the iris location at which electrons are emitted. Figure 5b is an example of snapshots of electrons emitted from the surface of the first iris and backstream toward the cathode plane under the rf and magnetic fields in the PWT. No electrons would reach the cathode below the field threshold. The beneficial effect of operating the PWT at a lower peak field (55 MV/m) than conventional rf guns (>120 MV/m) is evident from Figure 4.
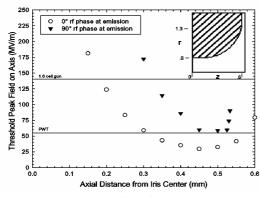

Figure 4: Threshold peak field for electrons emitted from the first PWT iris reaching the cathode surface. The insert shows the iris geometry.

In the PWT gun, backstreaming electrons emitted at an initial rf phase of 90° from the first iris never reach the cathode at a peak field (on axis) of 55 MV/m; and at an initial phase of 0°, only a small fraction of the electrons would reach the cathode. By contrast if the gun were to operate at a peak field (120MV/m) comparable to that in a conventional, BNL-type, 1.6-cell gun, then a large number of electrons emitted from the iris surface would hit the cathode. Since field emission is likely to be most abundant when the surface field is at its maximum (i.e. 90° rf phase); by operating the PWT at a peak field much lower than conventional rf guns, it is expected that dark current emission from the GaAs and its support structure would be considerably mitigated.

Back Bombardment of Electrons Emitted from the Cathode Holder

Another PARMELA simulation was performed to evaluate the possible back bombardment of electrons which were first emitted near the PWT end plate and cathode support. The model puts a ring of electrons initially around the cathode and tracks their trajectories under the rf field and the solenoidal field. At a sufficiently high peak electric field around 15 MV/m or higher, all electrons emitted near the cathode would either go through the first iris or hit the disk (see Figure 5a). At very low peak fields electrons would oscillate near the cathode surface. The low field resonance-like condition could send electrons back to the GaAs cathode surface and contaminate it. The lower the peak field, the longer the "trapped" electrons would stay near the cathode surface. Therefore in order to prevent electrons emitted from the cathode or the cathode holder from hitting the photocathode in an rf gun, the operating voltage should not be too low. The operating peak field chosen for the proposed polarized PWT gun appears to be optimum in that it is low enough to discourage back bombardment of electrons from the iris, and yet high enough to avoid back bombardment of electrons from the cathode holder. During rf conditioning, however, it is important that the GaAs cathode is not exposed to low fields. For that reason, we will be using a sacrificial cathode during rf conditioning and replacing it with a freshly activated cathode via the load lock.
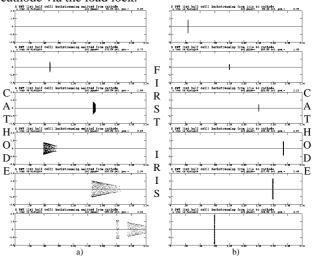

Figure 5: Examples of snapshots (projected onto an x-y plane) of backstreaming electrons emitted (a) from the cathode holder, and (b) from the first iris.

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[3] M. Ferrario et al., Proc. 2nd ICFA Adv. Accel. Workshop on the Physics of High Brightness Beams, Nov. 1999, p.534.