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Performance of Photocathode RF Gun Electron Accelerators*

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Abstract

In Photo-Injectors (PI) electron guns, electrons are emitted from a photocathode by a short laser pulse and then accelerated by intense RF fields in a resonant cavity. The best known advantage of this technique is the high peak current with a good emittance (high brightness). This is important for short wavelength Free-Electron Lasers and linear colliders. PIs are in operation in many electron accelerator facilities and a large number of new guns are under construction. Some specialized applications have emerged, providing, for example, very high pulse charges. PI have been operated over a wide range of frequencies, from 144 to 3000 MHz (a 17 GHz gun is being developed). An exciting new possibility is the development of superconducting PIs. A significant body of experimental and theoretical work exists by now, indicating the criticality of the accelerator elements that follow the gun for the preservation of the PI's performance as well as possible avenues of improvements in brightness. Considerable research is being done on the laser and photocathode material of the PI, and improvement is expected in this area.

INTRODUCTION

Since the introduction of Photo-Injectors (PIs) [1] about eight years ago, this new field has experienced an exponential growth. It is easy to understand the trend since there is a continuing demand for improved injectors for electron linacs. Free-Electron Lasers (FELs) require high brightness. Linear colliders also require high-charge, low emittance, short pulse bunch trains, either for the accelerated beam or for the generation of rf power. With the rapid growth in the number of projects, the experimental and theoretical results and the diversity of applications, there has been a continued improvement in the performance of these devices. Furthermore, this performance has a considerable influence of the trends in related areas. For example, due to the availability of high-brightness PIs, there is a significant progress in the design of Fourth-Generation Light Sources based on linacs [2]. A number of good recent reviews of microwave guns are available [3,4]

The basic principle of the PI is simple: short bunches of electrons are generated by laser pulses incident on a photocathode located inside an rf accelerating structure. The structure is operated at a high accelerating field to make the electron bunch relativistic in a short distance. Thanks to the combination of the high surface field on the cathode and the high yield of electrons possible by photo emission, a very large current density, $J \sim 10^4$ to 10^5 A/cm^2, is possible. This current density is much larger than that possible by thermionic emission (about 10 A/cm^2). The normalized thermal rms brightness B_n, (for a cathode effective temperature T) is proportional to the current density:

$$B_n \equiv 2I\pi^{-2}\varepsilon_n^{-2} = mc^2 J(2\pi^3 kT)^{-1}.$$

Therefore a PI can deliver a very large brightness. The x-plane normalized rms emittance is defined here as

$$\varepsilon_x \equiv \pi\left[\langle x^2\rangle\langle (p_x/mc)^2\rangle - \langle xp_x/mc\rangle^2\right]^{1/2}.$$

The rapid acceleration also serves to reduce the space-charge induced emittance growth. It also makes the PI a very compact accelerator. For example, the 3 1/2 cell S-band gun designed by a Grumman-BNL collaboration provides 10 MeV electrons in a 20 cm long structure [5].

The mode-locked lasers that drive the PIs provide interesting possibilities. The pulses can be made extremely short (to sub picosecond) and intense (tens of nC at a few ps). The spatial and temporal laser power distributions can be tailored to arbitrary profiles. Particular profiles can lead to the reduction of the emittance of the PI [6]. The pulse format is very flexible and pulse trains of arbitrary length and spacing can be generated.

THE LASER PHOTOCATHODE RF GUN

A 1 1/2 cell PI is shown in Fig. 1. This 'BNL Gun' design [7,8] and somewhat modified versions are in operation at numerous laboratories around the world. It uses a metal photocathode that forms part of the wall of the 1/2 cell. Cathodes can be changed by using the 'choke joint' access port. The rf gun is a resonant π-mode 1½ cell cavity operating at 2856 MHz. The 78.75 mm long cavity is 83.08 mm inner diameter and its beam aperture diameter is 20 mm. It has a Q of 11900 and a shunt impedance of 57 MΩ/m, which corresponds to a beam energy of 4.65 MeV at a structure peak power of 6.1 MW. At this power, the peak surface electric field is 119 MV/m and the cathode field is 100 MV/m. These operating conditions can be achieved after a few days of careful rf conditioning. The rf field contribution to the emittance is minimized in two ways. The first of these uses a choice of an optimal phase of the laser pulses relative to the rf wave for minimum emittance at the gun output. The other involves providing a nearly linear dependence of the transverse fields on beam radius by a suitable cell design. To reduce the non-linear field components, the aperture can be

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shaped to approximate the idealized prescription [8] near the aperture:

$r = \left[a^2 - (4d/\pi)^2 \log(\sin \pi z/2d)\right]^{1/2}$ where a is the aperture radius and d is the length of the cell. We have verified that this prescription does indeed significantly reduce the non-linear transverse fields [5] but not the (space-charge

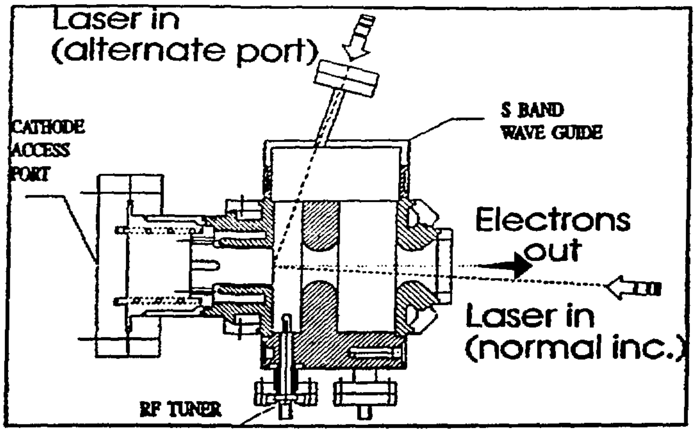

Fig. 1. Cross section of a 2.856 GHz, 1 1/2 cell PI.

dominated) emittance. With the advent of emittance correction schemes this prescription may become more important.

THE PHOTOCATHODE AND LASER

These subjects are fundamental to the performance of the PI, however they are too vast to be covered here. The ideal photocathode material would have high emission efficiency (for drive laser cost containment) and high ruggedness. A study of various materials [9] for the photocathode has shown that certain metals have a good combination of quantum efficiency, high damage thresholds, and good mechanical and chemical stability. Copper and yttrium metal cathodes proved particularly robust. Yttrium has a work function of about 3.1 eV and a quantum efficiency (QE) of up to 10^{-3} at 266 nm. Copper's work function is 4.3 eV and it has a QE of up to 10^{-4}. Semiconductor cathodes such as Cs_3Sb or CsK_2Sb offers a much higher QE, up to several percent at 532 nm [10], but require a much better vacuum and have short lifetimes, a few days at best. Other researchers [11] work on the improvement of the QE of rugged materials such as LaB_6, achieving QE of up to 7 10^{-4} at 355 nm. The laser power required to drive the PI increases as the QE becomes lower, but also as the wavelength used is shorter due to the inefficiency of frequency multiplication (~0.5, ≥ 0.3 to ≥0.2 for 2,3 and 4th harmonics of the ~1μm respectively in routine operation). It is reasonable to expect that new materials will emerge with significantly higher quantum efficiencies as well as ruggedness. Furthermore, an increase of the efficiency by a factor of 3 has been observed in a PI using an illumination angle of 70° [12].

The laser plays a significant role in the performance of the PI. High power, short pulse lasers are complicated systems and require considerable attention. Fortunately the state-of-the-art of lasers has been advancing very rapidly. Diode pumped Nd:YLF or Nd:YAG lasers provide short pulses with a considerable power at costs of about $200k. CW pumped Nd:YLF amplifiers can provide 2 to 4 mJ/pulse in the IR and better than 0.4 mJ/pulse quadrupled (σ_b about 2 ps) at repetition rates of multi kHz. Other laser systems are based on a Ti:sapphire oscillator followed by various amplifiers, such as Ti:sapphire, alexandrite or excimer. While these systems are generally more expensive, they provide several advantages such as higher repetition rates and the possibility of shaping the temporal intensity of the laser.

An important issue is the phase lock stability between the laser and the rf system of the gun (and linac). Sub picosecond phase lock systems are available commercially for Nd:YAG and Nd:YLF lasers. Recently there have been reports of similar or better performance in Ti:sapphire lasers. A technique of direct phase measurement of the rf to laser radiation is being tested [13]. This method may solve the problem of long-term phase drift due to temperature or barometric pressure changes.

THEORETICAL FRAMEWORK

An analytical model developed by K-J. Kim [14] provides scaling laws that provide insight into the relationship of some of the design parameters of PIs. Using practical units, we have:

$$\varepsilon_{sc} \approx 3.8\ 10^3 q (2\sigma_x + \sigma_b)^{-1} (E_0 Sin\phi_0)^{-1}$$

$$\varepsilon_{rf} \approx 2.7\ 10^{-5} E_0 f^2 \sigma_x^2 \sigma_b^2$$

where the normalized rms emittance contribution due to rf fields ε_{rf} and that due to space charge forces ε_{sc} are expressed in π mm mrad, E_0 is the cathode peak electric field in MV/m, f is the gun frequency in GHz, q is the charge in nC, related to the peak current by $I=q/(2\pi)^{.5}\sigma_b$, where σ_b is the rms bunch length in ps and σ_x is the rms transverse size in mm. ϕ_0 is the launch phase, typically 50° to 60°.

For a given cathode electric field, charge and beam size, the emittance is optimized by:

$$f_{opt} = 1.2 \times 10^4 (\sigma_b \sigma_x E_0 Sin\phi_0)^{-1} q^{1/2} (\sigma_b + 2\sigma_x)^{-1/2},$$

and then the optimized total emittance (neglecting correlations as well as thermal emittance) is:

$$\varepsilon_{min} \approx \left[\varepsilon_{rf}^2 + \varepsilon_{sc}^2\right]^{1/2} \approx 5.4 \times 10^3 q (E_0 Sin\phi_0)^{-1} (\sigma_b + 2\sigma_x)^{-1}$$

Since the minimum emittance is proportional to the charge q (and thus to the peak current), the highest brightness is not necessarily associated with the highest charge. Since we have left out the thermal emittance in these expressions, one should not conclude that the brightness is maximized for a vanishingly small charge.

The minimum emittance (using the given optimized frequency) is inversely proportional to the electric field. Thus clearly for a given set of beam parameters (charge, bunch size), we would like to apply the highest possible electric field. As we increase the field (ceteris paribus) the optimal frequency is lowered. However, for a number of practical reasons the technically achievable field is smaller at lower frequencies. At some field and frequency the PI will operate at the limit of breakdown or available rf power. Once we cross that limit the assumptions of the optimization break down and one can not apply these results.

The beam of a PI has significant correlations of the longitudinal position and transverse phase space. This is the key to 'emittance correction' schemes (discussed later on). When one uses an emittance correction scheme of one sort or another, the space charge emittance is reduced. This will invalidate the conditions of the calculation presented above, pushing the optimum towards lower frequencies, lower electric fields and smaller beam size.

It is instructive to compare the Kim model with beam dynamics modeling. There are a number of codes in use, e.g., PARMELA [15] and MAGIC [16]. The comparison, shown in Fig. 2, has been done with the MAGIC particle-in-cell code [5]. The simulation is for a 3 1/2 cell PI operating at 2856 MHz, E_0=100 MV/m, σ_x=4 mm and σ_b=2 ps. The output energy is 10 MeV. This code includes the effect of image currents, space charge, and wakefields. The MAGIC simulation was done with truncated Gaussian distributions in r and t. This was compared to Kim's model with a full Gaussian distribution. The emittance is sesitive to the distribution details, thus the somewhat better emittance of the simulation is not surprizing.

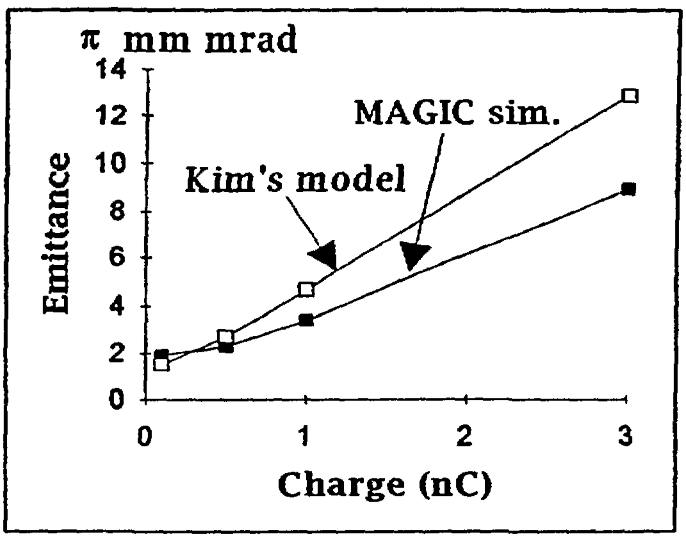

Fig. 2. Normalized rms emittance vs. charge comparing the MAGIC code to Kim's model.

The axisymmetric gun geometry (2-D) was modeled with the exact gun fields. This is accomplished by prescribing the magnetic field for the fundamental TM_{01} cylindrical cavity mode and allowing the cavity to ring while numerically damping out higher order modes. The fields are then stored and used for later runs with particles. The damping of higher order modes is turned off for the particle runs.

The advantage of using the MAGIC codes is that the field components at the cavity apertures and beam exit are continuous, the method of calculating the space charge forces is inherently more stable and wake fields are included. In the computation the numerical grid for calculating the fields is made very fine near the emission spot and the time steps are small enough to avoid plasma frequency and grid type instabilities, and to properly resolve the temporal behavior of the wakefields. The agreement between simulation and model is quite good for such a closed-form simple model. Thus we may use the model for initial parameter choice. The thermal emittance was left out of the model (but included in the MAGIC calculation). The thermal emittance contribution is difficult to estimate. The effective energy E_e of the photoemitted electrons is not well determined and may be anywhere between the cathode temperature and the excess energy of the photon relative to the work function modified by the Schottky effect modified. The thermal emittance is given by

$\varepsilon_n = \sigma_r \left[2E_e \left(3mc^2 \right)^{-1} \right]^{1/2}$. The cathode spot size is set to optimize the total emittance and thus depends on the charge. Experimental results from PIs indicate that the thermal emittance can be neglected at charges larger than 1 nC.

DESIGN CONSIDERATIONS

In designing a PI one must remember that it is but one component of a larger complex machine including an rf source, laser, diagnostics, beam transport system and an accelerator. In certain designs there is also a cathode preparation system and an UHV system or a cryogenic system. To design a PI one must make use of accelerator physics, laser technology, rf cavity design and more. The objective is not always a high brightness beam, but may be high charge pulses or high duty factor. All of these considerations influence the PI design. The high brightness of the PI will be diluted by any one of a large collection of effects: Wake fields, beam transport aberrations, space charge induced emittance growth (both linear and non-linear), skew quadrupoles and more. For example, ambient magnetic field B on the cathode (from magnetic lenses or ion pumps), produces an emittance increase given by

$\varepsilon_n \approx \left[\varepsilon_{n0}^2 + e^2 B^2 \sigma_r^4 m^{-2} c^{-2} \right]^{1/2}$. Thus fields of the order of 10 gauss may be detrimental.

The phase space beam parameters of a PI electron bunch are highly correlated, leading to emittance growth on one hand but to emittance correction possibilities on the other. Space-charge forces produce an energy spread in the bunch. This energy spread may appear in the middle of a magnetic transport system designed to be achromatic and defeat the achromaticity. Good design practices call for a rapid acceleration of the beam to a few tens of MeV before applying dipole fields. Thus, magnetic pulse-compression is better done above, say, 70 MeV. Pulse-compression has always been part of conventional electron gun technology. Although the beam pulses of a PI start out short, the brightness can be further increased by magnetic pulse-compression. A PARMELA simulation of the magnetic pulse-compression at about 80 MeV, the peak current of a 7 ps long, 2.5 nC bunch was increased by a factor of 3 to 800 amp. The emittance, about 4 π mm mrad before compression, increased to 6 π mm mrad in the bending plane and unchanged off the bending plane [17]. The accepted estimate of the emittance increase due to magnetic compression is $\Delta\varepsilon_n \approx 5I\gamma^{-2}$. This is much smaller than the simulation result, suggesting that some improvement may be made in the magnetic compressor optics.

An interesting PI subject is emittance correction. We define the 'slice-emittance' as the transverse emittance measured for a short longitudinal slice of the bunch. It has been observed [18,19] that the slice-emittance is considerably smaller than the total emittance (that is integrated over the full length of the bunch). This effect is due to the variation of the space-charge force as a function of longitudinal position in the bunch. Carlsten [18] proposed a simple scheme of reducing the total emittance by using the space-charge force to compensate its own effect. The method employs a lens set to produce a beam size extremum with no cross-over. The electrons 'reflect' relative to the beam axis due to space-charge forces. This condition, that can restore the effects of the linear space-charge force, has been verified in experiments (see next section). It has been assumed that to produce this emittance correction a solenoid lens must be placed in proximity to the cathode and the cathode field must not exceed a certain limit. This assumption has been proven wrong [17,20]. A PARMELA simulation and an analytic-approximate model show that this correction can be applied to a 1 1/2 cell BNL gun operating at 100 MV/m with a solenoid placed at the exit of the gun. A drift space and accelerating structure follow the lens. The acceleration 'freezes' the corrected emittance against further space-charge effects.

The Carlsten technique corrects linear space-charge effects. Other correction schemes have been proposed [6,19,21] to produce the same correction by laser pulse shaping, Radio Frequency Quadrupoles and asymmetric rf cavities, respectively. However the Carlsten scheme is simple and has been tested experimentally. Other correction schemes have been proposed to correct rf time dependent effects [22] and non-linear space-charge effects [21,23]. Finally, a correction scheme for ultra-short, disk-like bunches using an optimized charge distribution has been proposed by Serafini [24].

The emittance correction techniques are expected to exert a significant influence on the design of future PIs. The optimization strategy described above leads a choice of frequency and cathode field. When an emittance correction scheme is in use the optimal frequency will be lower and the usable bunch length longer. Alternately the same gun parameters may be used to produce a higher charge. At the higher charges, more attention will be necessary to non-linear space-charge effects and it is expected that non-linear correction techniques will be necessary.

Another interesting line of R&D is the super-conducting PI [25]. This device holds the promise of cw operation at very low rf power. Since the rf power is the largest cost item in a PI, superconducting devices also hold the promise of lower system cost.

MEASURED PERFORMANCE

By now there have been many experimental results of PI performance. In general, careful experiments are in agreement with the simulation codes, thus it can be concluded that the better computer codes have been benchmarked.

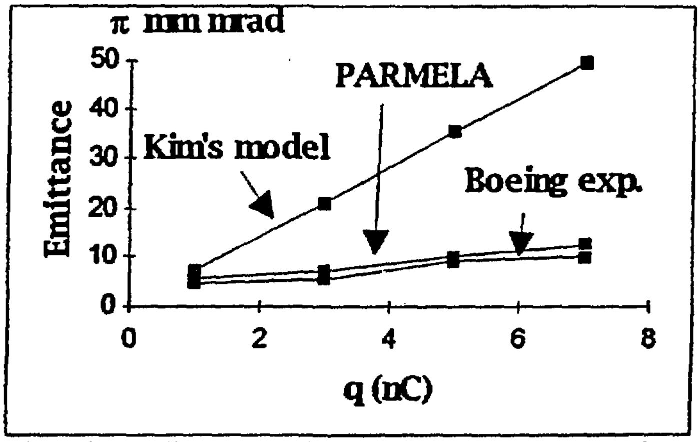

Fig. 3. Normalized rms emittance vs. charge for a the Boeing PI compared to Kim's model.

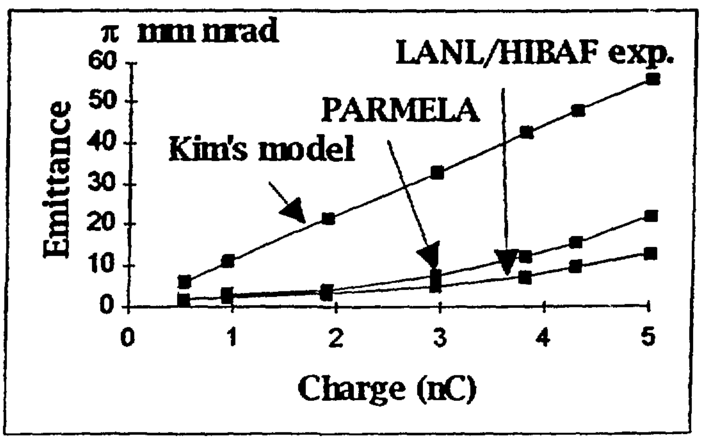

Fig. 4. Normalized rms emittance vs. charge for the LANL/HIBAF PI compared to PARMELA (with wake field) simulation and Kim's model.

Of the most recent results, the Boeing [26] and Los Alamos [27,28] results are noteworthy. The Boeing two cell PI is impressive not only in its emittance results, shown in Fig. 3, but also in its duty factor of 25%. Such a PI would be ideally suitable for very high average power FELs and perhaps linear colliders. It operates at a frequency of 0.433 GHz, a cathode field of 26 MV/m a radial bunch size of σ_x=2 mm and longitudinal size of σ_b=20 ps. The final energy is 5 MeV. A focussing solenoid is placed between the two cells. From the comparison to Kim's model clearly the emittance correction used in the experiment is very effective. The PARMELA simulation (using the 90% beam emittance) is in good agreement with the experiment.

The Los Alamos gun design has been evolving from the original, single cell design to the six cell HIBAF injector [10] to the 11 cell AFEL integrated gun/linac design [28]. The HIBAF emittance measurements[27] are shown in Fig. 4. This six cell 1.3 GHz PI operated at E_0=24.5 MV/m, σ_x=3-5 mm, σ_b=6.6 ps. The emittance is measured after acceleration to 36 MeV. This PI has been the first to use the Carlsten emittance correction technique. Fig. 4 shows clearly the correction relative to Kim's model prediction for an uncorrected emittance. The measurement is bracketed by two PARMELA simulations. One, which includes wake-field effects (shown in Fig. 4) predicts a somewhat larger emittance. The other (not shown) predicts a slightly better emittance. Both show clearly the emittance correction at work.

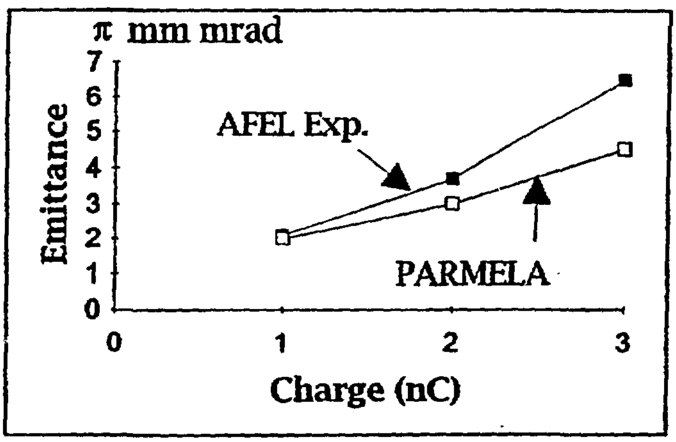

Fig. 5. Normalized rms emittance vs. charge for the LANL/AFEL PI experiment and PARMELA simulation.

The best performance in terms of emittance at a given charge belongs to the LANL AFEL PI [28], shown in Fig. 5. This 11 cell gun operates at E_0=20MV/m with a $C_sK_2S_b$ cathode, final energy 12 MeV. The laser FWHM pulse width is 9 ps. The thermal emittance calculated for the 4 mm radius cathode spot-size is 1.25 π mm mrad, assuming thermalized photoelectrons. The design final energy is 20 MeV. A better brightness is expected at that energy.

The PARMELA simulation suggests that we may expect even better experimental results from this PI.

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