TITLE THE LOS ALAMOS HIGH-BRIGHTNESS PHOTOINJECTOR

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The Los Alamos High-Brightness Photoinjector

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ABSTRACT

For a number of years Los Alamos National Laboratory has been developing photocathode RF guns for high-brightness electron beam applications such as free-electron lasers (FELs). Previously thermionic high-voltage guns have been the source of choice for the electron accelerators used to drive FELs. The performance of such FELs is severely limited by the emittance growth produced by the subharmonic bunching process and also by the low peak current of the source. In a photoinjector, a laser driven photocathode is placed directly in a high-gradient RF accelerating cavity. A photocathode allows unsurpassed control over the current, and the spatial and temporal profile of the beam. In addition the "electrodeless emission" avoids many of the difficulties associated with multi-electrode guns, i.e. the electrons are accelerated very rapidly to relativistic energies, and there are no electrodes to distort the accelerating fields. For the past two years we have been integrating a photocathode into our existing FEL facility by replacing our thermionic gun and subharmonic bunchers with a high-gradient 1.3 GHz photoinjector. The photoinjector, which is approximately 0.6 m in length, produces 6 MeV, 300 A, 15 ps long electron micropulses at a 22 MHz rep. rate. The beam is then injected into an RF linac, and accelerated to a final energy of 40 MeV. We have recently begun lasing at wavelengths near 3 μ m.

INTRODUCTION

The efficient conversion of electron energy into photon energy requires low emittance, high-brightness beams¹. Free-electron laser oscillators operating at high power and short wavelength (λ_0) require high-current, low-emittance (ϵ_n) electron beams. The gain of an FEL increases with beam current subject to the constraint that

$$\lambda_0 > \frac{\epsilon_n}{4\pi\beta\gamma} \quad (1)$$

where $\epsilon_n = 4\pi\beta\gamma(\langle x^2 \rangle \langle x'^2 \rangle - \langle x \cdot x' \rangle^2)^{1/2}$ is the normalized emittance. In this context high current implies $I \gg 100$ A and low emittance implies $\epsilon_n \ll 100 \pi$ mm-mrad. Very low emittance allows the possibility of accessing short optical wavelengths at low beam energy, by lasing on harmonics of the fundamental FEL wavelength. The FEL resonance condition is given by:

$$\lambda_o = \frac{\lambda_w}{2N\gamma^2}(1 + K^2) \quad (2)$$

where: K is the wiggler parameter typically of order 1, γ is the relativistic energy parameter, λ_w is the wiggler period, N is the harmonic number with $N = 1, 3, 5, \dots$. If the emittance satisfies the constraint of eqn. 1, then harmonic lasing may be possible at short wavelengths. The electron beam energy required to produce a given wavelength scales as $\frac{1}{\sqrt{N}}$, and produces a corresponding saving in the size and cost of the accelerator required.

There are two issues of importance here. The first is the intrinsic brightness of the source and the second is the ability to transport the beam with minimal emittance growth through the linac.

Previously high brightness beams have been produced by thermionic high-voltage guns, with emittances near the source thermal limit. We can define the normalized emittance for a source in terms of the cathode radius (r_c) and temperature (T)²:

$$\epsilon_n = 2\pi r_c \sqrt{\frac{kT}{mc^2}} \quad (3)$$

and the normalized brightness in terms of the current density J :

$$B_n = \frac{2I}{|\epsilon_n|^2} = \frac{mc^2 J}{2\pi kT} \quad (4)$$

Table 1 shows a comparison between the best thermionic cathode and photocathode sources for RF linacs³.

Table 1. Comparison of thermionic cathode and photocathode

Cathode	Thermionic	Photocathode
T: Effective temp. (eV)	0.1	0.2
J: Current density (A/cm ²)	10	600
Brightness (A/(m-rad) ²)	1 x 10 ¹¹	2 x 10 ¹²

Photocathode has intrinsically higher brightness and reduced emittance growth in transport through the linac. The design of an integrated photoinjector linac removes the requirement for subharmonic RF bunching at non relativistic energies and of

magnetic bunching common in linacs with thermionic sources, thereby removing many of the emittance growth opportunities.

For a number of years we have been developing photocathode RF guns for high-brightness electron beam applications⁴. In a photoinjector, a laser driven photocathode is placed directly in a high-gradient RF accelerating cavity (see fig. 1). This system allows unsurpassed control over the spatial and temporal profiles, and current of the beam. In addition the "electrodeless emission" avoids many of the difficulties associated with multi-electrode guns, i.e. the electrons are accelerated very rapidly to relativistic energies, and there are no electrodes to distort the accelerating fields.

Fig 1 Photoinjector schematic

Drive Laser and Photocathode

There have been a number of approaches proposed for the photocathode/drive laser combination necessary for a photoinjector. These approaches are divided into two classes: Low quantum efficiency and high quantum efficiency. (Quantum efficiency, Q , is defined as the number of free electrons produced off the cathode per incident photon). Low Quantum efficiency cathodes ($Q < 0.1\%$) have typically the following characteristics⁵⁻⁷:

- metal or LaB_6 cathode
- long cathode lifetime
- very high drive laser power required in ultra-violet (e.g. quadrupled Nd:YAG)
- not readily scalable to high rep. rate or duty factor.

High Quantum Efficiency Cathodes ($Q > 1\%$) are characterized by³:

- multi-alkali(e.g. CsK₂Sb)
- short cathode lifetimes (days)
- high Q in the visible
- scalable to high duty factor

Following from the definition of quantum efficiency above, we can readily obtain the fundamental relationship between drive-laser wavelength (λ_{DL}), and pulse energy (E), photocathode quantum efficiency (Q) and charge (C) per pulse is given by:

$$C = \left[\frac{e}{hc} \right] QE \lambda_{DL} \quad (5)$$

An alternative formulation of this equation is in terms of current (I) from the cathode and drive laser power (P):

$$I = \left[\frac{e}{hc} \right] Q P \lambda_{DL} \quad (6)$$

Equation (6) is only valid for the case of prompt electron emission from the cathode i.e. the emission time is much less than the drive laser pulse length. Equation (6) may be re written in practical units:

$$I(A) = 8.08 \times Q(\%) \times P(kW) \times \lambda_{DL}(\mu m) \quad (7)$$

In the case of the Los Alamos experiment $I = 0.1$ A (macropulse average), $Q = 6\%$ and $\lambda_{DL} = 0.527$ μm (doubled Nd:YLF), then $P = 4$ W. For low quantum efficiency cathodes $Q < 0.01\%$, at $\lambda_{DL} = 0.26$ μm (quadrupled Nd:YAG), then $P = 4800$ W for the same 0.1 A macropulse average current. Note that this is the drive laser power actually delivered to the cathode. The low quantum efficiency cathodes do not appear practical for high average current applications because of the high drive laser power required.

At Los Alamos we have chosen a high Q material CsK₂Sb. Typically Q is greater than 6% at the start of an accelerator run. However such cathodes are sensitive to contamination in poor vacuum. Typically the vacuum in the operating photocathode cell is less than 1×10^{-9} torr. The 1/e lifetime for decay of Q is greater than 10 hrs when the accelerator is operating. Our design requirement is to produce 5 nC per 10 ps micropulse at the cathode, in which case we need to maintain our $Q \times E$ product greater than 1.1 % μJ for effective operation. Since our drive laser can deliver up to 6 μJ to the cathode we can operate with Q as low as 0.2 %.

The performance of our FEL depends critically on our photocathode and its drive laser. Phase and amplitude jitter in the drive laser result in energy and current jitter

in the electron beam. We require the phase and amplitude jitter to be <1 ps and <1 % respectively. Table 2 gives the measured performance of the drive laser and photocathode.

To improve our operating time on a single cathode we are endeavoring to a) reduce the quantum efficiency decay rate; and b) increase the energy delivered by the drive laser to the photocathode.

Table 2 Drive laser and photocathode performance

Drive laser:	Doubled Nd-YLF
Wavelength	527 nm
Micropulse width	7-15 ps
Micropulse rep. rate	21.7 MHz
Micropulse energy	12 μ J (5-6 μ J at cathode)
Macropulse length	0-200 μ s
Phase jitter	< 1 ps
Amplitude jitter	< 1 %
Photocathode:	CsK ₂ Sb
Radius	4 -5 mm
Peak quantum efficiency	8 %
1/e lifetime in operating accelerator	10-15 hrs at 2×10^{-9} Torr

Reducing the decay rate of Q implies improving the vacuum conditions in the accelerator. Studies have shown that CO₂ and H₂O can contaminate the cathode and reduce its effective lifetime⁸. Since a standard bake at 250-350°C imparts ≈ 1 eV to surface adsorbed molecules, it is not effective in removing those adsorbed gases that are bound with binding energies $\gg 1$ eV. In the non-operating accelerator (no RF, no beam) such a bake produces a vacuum of 5×10^{-10} torr. In the operating accelerator there are many electrons with energies $\gg 1$ eV that induce electron stimulated desorption (ESD) of gases from the cavity walls and cause the pressure to rise to the mid 10^{-9} torr range. To improve this situation we have initiated an RF generated glow discharge cleaning technique⁹. Using 200 W CW 1.3 GHz RF, fed into the photoinjector cavity through the waveguide, we generated a glow discharge with approximately 10^{-2} torr of hydrogen. By varying the RF frequency (1.3-10.03 GHz) the glow could be initiated in one or more cells of the photoinjector. During the discharge the photoinjector was maintained at a temperature of 130 °C. The

discharge was run for 48 hours, followed by a 24 hour bake at only 130 °C. The immediate result was to reduce the pressure to 1×10^{-10} torr at room temperature. Preliminary results indicate that the pressure during high power RF operation has been reduced to the low 10^{-9} torr range.

We have implemented a drive laser upgrade which has increased the deliverable optical energy to the photocathode from 1 to 6 μ J per micropulse. At present we have a single cathode which must be refurbished when its Q falls below allowable limits. This refurbishment process involves retraction of the cathode into a preparation chamber and the bake-off of the residual cathode material that is only a few tens of nanometers thick, followed by the redeposition of the cathode material. This process takes about 3 hours. So as to reduce this downtime we plan to replace the single cathode system with a six-cathode cassette. These cathodes will be fabricated away from the accelerator and brought to the accelerator in a portable vacuum chamber. When this system is in place we will not need a preparation chamber attached to the accelerator. The accelerator runtime between cassette changes should be in excess of a week.

The APEX Photoinjector

We have installed and tested a high-gradient (26 MV/m at the cathode) 1300 MHz, $\pi/2$ -mode photoinjector, that is 0.6 m long and produces 6 MeV, 300 A, 15 ps electron pulses at a 22 MHz rep. rate¹⁰ Figure 2 shows a cutaway view of the actual Los Alamos 6 MeV photoinjector. Table 3 gives the specifications for the photoinjector. The photocathode cell is a half cell, followed by five full accelerating cells. The RF feed is through the sixth cell. The accelerating cells are coupled by on axis coupling cells. The RF structure is enclosed in a stainless steel vacuum jacket, to which are attached a titanium sublimation pump and an ion pump. Pumping from the accelerating cells into the vacuum manifold is achieved through 16 longitudinal slots per cell, giving an effective pumping speed of approximately 170 l/s per cell. The resultant pressure at the photocathode is typically less than 10^{-9} torr. The photocathode itself is on a molybdenum plug that is attached to an actuator. The cathode can be retracted from the accelerator into the photocathode preparation chamber.

Following the photoinjector electron beam is accelerated to 40 MeV by three additional side-coupled linac tanks. RF power is provided by Thomson CSF klystrons (TH2095A), with one klystron per accelerator tank. The FEL configuration is a single-accelerator master-oscillator power-amplifier (SAMOPA)¹¹⁻¹³ configuration. Resonator optics are often the limiting factor in high average power FELs. In the SAMOPA concept the electrons first pass through a low power oscillator and then through a high gain amplifier. The light from the oscillator is fed into the amplifier. Since the power in the oscillator is low, and there are no resonator optics in the amplifier, the optical damage difficulty is removed. We are studying the physics issues associated with SAMOPA operation as part of

the Boeing/Los Alamos collaboration to build the Average Power Laser Experiment (APLE). Los Alamos will perform the APLE prototype experiments and will be known by the acronym APEX.

Figure 2. The APEX photoinjector

Table 3 Photoinjector specifications

Frequency	1300 MHz
Accelerating gradients:	
cell 1	26.0 MV/m
cell 2	14.4 MV/m
cell 3-6	10.0 MV/m
Measured Q	18500
Shunt impedance	35 M Ω /m
Copper power	1.8 MW
Output energy	6 MeV
Micropulse length	15 ps
Micro pulse charge	5nC
Micropulse rep. rate	21.7 MHz
Peak current	300 A
Macropulse length	100 μ s
Macropulse rep. rate	1 Hz
Macropulse ave. current	0.1 A
Emittance (4rms, normalized)	< 50 π mm-mrad

In 1990 we completed experiments that characterized the photoinjector operation and beam transport through one additional accelerator tank at an energy of 15 MeV

RF Controls

The stability of the RF phase and amplitude is as critical to the FEL performance as is that of the drive laser. We have replaced our old RF feedback control system with a novel system using state-feedback¹⁴. The system in its present form is significantly smaller and produces better RF stability than our old system. Table 3 gives the performance of the state-feedback system over a 100- μ s macropulse on the photoinjector.

Table 4 RF phase and amplitude stability

	Amplitude (%)	Phase (ps)
Jitter	0.03	0.1
Slew	0.25	1

We have recently testing the effectiveness of the feedback system on all four accelerator tanks.

Operational Experience

Measurements on the electron beam produced by the photoinjector have been made after post acceleration to 14 MeV by an additional side coupled tank. Of particular interest has been the comparison between the design code (INEX) predictions and actual performance. Details of the comparison between INEX and measurements have been presented elsewhere¹⁵.

The performance of the photoinjector has proven to be excellent in the areas of most importance to FEL operation, i.e. reduced emittance and reduced energy spread and increased brightness as indicated in table 5.

Table 5 Comparison of the performance of the old vs. new injector at the Los Alamos FEL

Electron source	Thermionic gun	Photoinjector
Emittance	160 π mm-mrad	40 π mm-mrad
Energy spread	0.5%	0.3%
Charge per bunch	5 nC	5 nC
Peak Current	300 A	300 A

Brightness	$2.4 \times 10^9 \text{ A/(m-rad)}^2$	$4 \times 10^{10} \text{ A/(m-rad)}^2$
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There were three unanticipated effects observed during operation of the photoinjector:

1) Multipactoring in one or more coupling cells produced coherent 7 MHz oscillations in both phase ($\pm 1^\circ$) and amplitude ($\pm 1\%$) of the RF in the tank. The problem was solved by detuning the photocathode cell (the end wall was pulled by a couple of tenths of mm) so as to raise the fields in the coupling cells above the multipactoring limit.

2) The electron beam was observed to have an elliptical crosssection before passing through any quadrupole magnets. The source of this effect was RF quadrupole focusing resulting from the number and location of the coupling slots in the accelerator. This has caused an emittance growth of approximately $10 \pi \text{ mm-rad}$. This problem is being partially corrected by placing a small quadrupole magnet between the photoinjector and the next tank. Future photoinjector designs will have a modified coupling slot arrangement which will eliminate this emittance growth problem. For more details see ref. 15.

3) A small field-emission electron current (0.1 mA) was observed with the drive laser off. The intensity of this field emission current is not sufficient to significantly affect our operation. For more details see ref. 16

Present Status

The commissioning of the complete 40 MeV linac with the integrated photoinjector is complete. On June 21, 1991 first lasing was observed at a wavelength of $3.5 \mu\text{m}$ with an extraction efficiency of 0.6% over a 40 μs macropulse. We are continuing to characterize the accelerator and FEL performance. Details of the designed performance of the FEL system are given in ref. 3.

Conclusion

We have shown in practice that photocathodes integrated into RF linac in the form of photoinjectors are a viable and practical alternative to thermionic sources. In the Los Alamos case replacing the thermionic gun and subharmonic bunchers with a photoinjector has increased the electron beam brightness by a factor of 20. We believe that high quantum efficiency cathodes are the only practical choice for high average current electron accelerators because the drive laser power is prohibitively high for low quantum efficiency sources. The present disadvantage of high quantum efficiency sources is the relatively short cathode lifetime. We have made significant progress in understanding the cathode decay processes and in improving the lifetime. We continue to work on more advanced cathode designs that will lead us to both high quantum efficiency and long lifetimes. Based on our experience with the APEX

photoinjector we are constructing new 20 MeV photoinjector as part of the Advanced FEL (AFEL) project. The electron beam from the AFEL accelerator should be an order of magnitude brighter than that of APEX.

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