PERFORMANCE OF THE PHOTOINJECTOR ACCELERATOR FOR THE LOS ALAMOS FREE-ELECTRON LASER

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Abstract

The Los Alamos free-electron laser (FEL) facility has been modified by the replacement of the thermionic electron gun and bunchers with a 1300 MHz RF photoinjector. Two more accelerator tanks have been added to increase the beam energy to 40 MeV. Preliminary studies at 15 MeV have demonstrated excellent beam quality with a normalized emittance of 40 π mm-mrad. The beam quality is now sufficient to allow harmonic lasing in the visible. At present we are beginning FEL experiments at a wavelength near 3 μm. In this paper we report on the performance of our photoinjector accelerator.

I. Introduction

Free-electron laser oscillators operating at high power and short wavelength (λ) require high-current, low-emittance (ε_n) electron beams. The gain of an FEL increases with beam current subject to the constraint that

$$\varepsilon_n < 4\beta\gamma\lambda.$$

In this context high current implies I»100A and low emittance implies $\varepsilon_n \ll 100\,\pi$ mm-mrad (normalized). Very low emittance allows the possibility of accessing short optical wavelengths at low beam energy, by lasing on harmonics of the fundamental FEL wavelength.

High quality electron beams must not only be generated, but must also be transported to the wiggler without loss of beam quality. Previously such beams have been produced by thermionic high-voltage guns, with emittances near the source thermal limit. Before being accelerated in an RF linac the beam is typically passed through subharmonic bunching cavities at nonrelativistic energies. Nonlinear forces from space-charge and RF fields of the bunchers generally cause emittance growth and result in diminished FEL performance.

For a number of years we have been developing photocathode RF guns for high-brightness electron beam applications [1]. In a photoinjector, a laser driven photocathode is placed directly in a high-gradient RF accelerating cavity. 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.

We have installed and tested a high-gradient (26 MV/m at the cathode) 1300 MHz, π/2-mode photoinjector, that is 0.6 m long and produces 6 MeV, 300 A, 15 ps electron pulses at a 22 MHz rep. rate. Figure 1 shows a cutaway view of the photoinjector. Table 1 gives the specifications for the photoinjector.

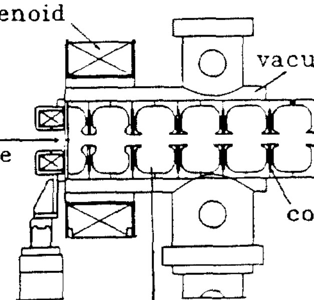

Figure 1. Photoinjector

Table 1 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 MΩ/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 μs
Macropulse rep. rate	1 Hz
Macropulse ave. current	0.1 A
Emittance (4rms, normalized)	< 50 π mm-mrad

Following the photoinjector the 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) [2]-[4] configuration as shown in figure 2. Resonator optics are often the limiting factor in high average power FELs. In the SAMOPA concept

Work performed under the auspices of the Department of Energy for the United States Army.

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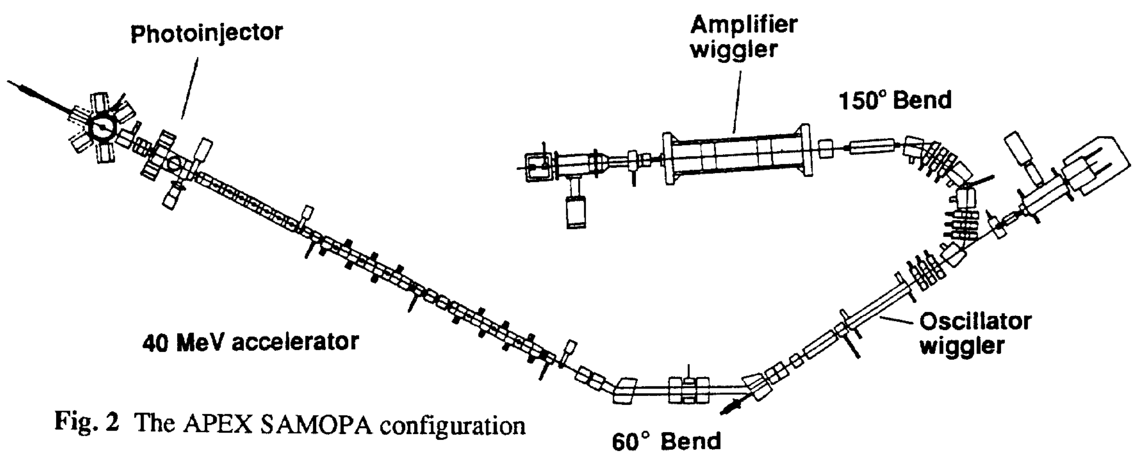

Fig. 2 The APEX SAMOPA configuration

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.

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

II. Drive Laser and Photocathode

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.

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 μJ (5-6 μJ at cathode)
Macropulse length	0-200 μs
Phase jitter	< 1 ps
Amplitude jitter	< 1%
Photocathode:	CsK_2Sb
Radius	4 -5 mm
Peak quantum efficiency	8 %
1/e lifetime in operating accelerator	10-15 hrs at 2 x 10^{-9} Torr

The fundamental relationship between drive laser micropulse energy (**E**), photocathode quantum efficiency (**Q**) and charge (**C**) per micropulse is given by:

$$C\ (nC) = 4.5[Q\ (\%) \times E(\mu J)]$$

Since the type of cathode material used (CsK_2Sb) produces prompt electrons, the current may be approximately calculated by multiplying the charge by the laser pulse FWHM. Typically **Q** is greater than 6% at the start of an accelerator run. The 1/e lifetime is greater than 10 hrs when the accelerator is operating. Since our design value of **C** is 5 nC, we require our **QxE** product to be greater than 1.1 for effective operation.

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.

Reducing the decay rate of **Q** implies improving the vacuum conditions in the accelerator. Studies have shown that CO_2 and H_2O can contaminate the cathode and reduce its effective lifetime [5]. 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 » 1 eV. In the non-operating accelerator (no RF, no beam) such a bake produces a vacuum of 5 x 10^{-10} torr. In the operating accelerator there are many electrons with energies » 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 technique [6]. 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 ±0.03 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 x 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. Because we are now recommissioning the accelerator after a long shutdown, we do not yet have data on enhanced photocathode lifetimes

We have implemented a drive laser upgrade which has increased the deliverable optical energy to the photocathode from 1 to 5 μJ per micropulse. This will allow the nominal 5 nC per micropulse to be produced with a Q as low as 0.22 %

III. 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-feedback [7]. 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-μs macropulse on the photoinjector.

Table 3 RF phase and amplitude stability

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

We will be testing the effectiveness of the feedback system on all four accelerator tanks shortly.

IV. 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 are presented elsewhere in these proceedings [8].

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 as indicated in table 4.

Table 4 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

A visual example of our beam quality is shown in fig. 3. The letters **FEL** were cut from a mask that was placed in the drive laser beam. The **FEL** was then imaged on the cathode with a dimension of 2x3 mm. The electron beam (in the shape of **FEL**) was accelerated to 15 MeV, focused on an insertable screen 7 m downstream of the cathode, and imaged by optical transition radiation. The letters **FEL** were clearly visible on the screen.

There were three unanticipated effects observed during operation of the photoinjector:

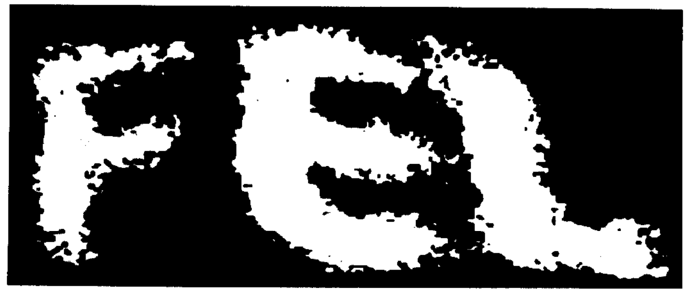

Fig 3. Electrons make an "FEL"

1)Multipactoring in one or more coupling cells produced coherent 7 MHz oscillations in both phase (±1°) and amplitude (±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 crossection 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 problem is being partially corrected by placing a small quadrupole magnet between the photoinjector and the next tank. For more detail see ref. [8].

3) A small field-emission electron current (~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. [9].

V. Present Status

We are at present commissioning the complete 40 MeV linac and the oscillator leg of the SAMOPA. We have successfully accelerated beam to 40 MeV and transported it around the 60° bend to the beam dump beyond the oscillator. Later this year we will install the 150° bend and amplifier legs of the system.

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