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**Advanced R&D
for Electron and Photon Beams
at Brookhaven National Laboratory**

H. G. Kirk
Brookhaven National Laboratory, Upton, NY 11973

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CENTER FOR ACCELERATOR PHYSICS

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ADVANCED R&D FOR ELECTRON AND PHOTON BEAMS
AT BROOKHAVEN NATIONAL LABORATORY

H.G. Kirk

Department of Physics
Brookhaven National Laboratory,
Upton, NY, 11973

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ADVANCED R&D FOR ELECTRON AND PHOTON BEAMS AT BROOKHAVEN NATIONAL LABORATORY

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1 INTRODUCTION

The Brookhaven Accelerator Test Facility consists of a 50-MeV linear accelerator and a laser system capable of generating short (a few picoseconds) laser pulses at both UV (266 nm) and infrared (10 μ m) wavelengths. With these systems in place, the ATF has unique capabilities for the study of fundamental interactions between charged-particle beams and intense electromagnetic radiation.

The principal research goals of the Accelerator Test Facility (ATF) are the following.

- **Laser Acceleration Program:** We will study the principles and techniques of particle acceleration at ultra-high frequencies (up to 30 THz) and with very high acceleration gradients (up to 1 GV/m).
- **Production of Coherent Radiation:** We wish to develop the next generation of photon sources with features like (a) short pulses (picoseconds or less), (b) coherence, and (c) high peak power. All of these attributes can be provided by free-electron lasers.
- **High-brightness sources:** A common denominator for the above programs is the need for electron beams with very small transverse and longitudinal emittances. We will devote a substantial amount of our resources to the production and understanding of electron beams that have these attributes. We will build advanced electron sources such as switched-power devices and rf guns with photocathodes.

Important applications of this line of research include the development of high-luminosity linear colliders and free-electron lasers in the XUV regime.

2 DESCRIPTION OF THE ACCELERATOR TEST FACILITY

The overall layout of the Brookhaven Accelerator Test Facility is given in Fig. 1. The schematic in Fig. 2 shows how the major systems of this facility are linked. The key components of the Brookhaven Accelerator Test Facility are as follows.

- A two-section 2.856-GHz electron linac
- A photocathode-loaded rf gun
- A quadrupled Nd:YAG laser capable of producing 6-ps pulses
- A 100-GW CO₂ laser system producing 6-ps pulses
- Synchronization of the CO₂ and electron-beam pulses

(1a) Injection system and linac sections

(1b) Beam-transport section from linac to experimental hall

(1c) Experimental hall

Fig. 1 The layout of the Brookhaven Accelerator Test Facility

Fig. 2 Schematic of Brookhaven Accelerator Test Facility

The linac consists of two SLAC-type, 3-meter, traveling-wave, S-band accelerator sections built at IHEP in Beijing, China. At present these two sections are serviced by one-half the power from a SLAC XK-5 klystron. This will provide a boost of 45 MeV to the electron beam. The remaining half of the klystron power is available to the rf gun. An eventual upgrade will entail servicing each linac section with its own klystron so that the linear accelerator will be capable of producing electrons with energies > 100 MeV.

The injection of the electron pulses into the accelerating sections is accomplished by means of an rf gun followed by a 180° double bend (see Fig. 3) which allows both magnetic compression of the electron bunches and convenient access to the photocathode by the Nd:YAG laser beam.

Electrons are launched at the photocathode when illuminated by laser light. This system consists of a CW mode-locked Nd:YAG oscillator that provides a chirped seed pulse of about 80 ps in the infrared ($1.06 \mu\text{m}$). This single pulse is then amplified in a Nd:YAG regenerative amplifier¹. The resultant pulse has 10 mJ of energy with a pulse length of 10 ps. After quadrupling, a 6-ps pulse at 266 nm with 100 μJ of energy is available to the photocathode.

The CO_2 laser system has a CW oscillator and a pulse-slicing switching system consisting of two germanium crystals. These crystals either transmit or reflect the CO_2 laser light, depending on whether or not they are exposed to the Nd:YAG-produced laser light, which is the residual infrared light from the first doubling stage (see Fig. 4). This picosecond CO_2 pulse is then sent through a multi-pass, high-pressure CO_2 amplifier that will be used to supply the high power (600 mJ in 6 ps) required by many of the experiments planned at the facility.

Since both the electrons and the CO_2 laser pulses are initiated by the same Nd:YAG laser pulse, the two beams can be synchronized with each other, thus permitting an interesting class of experiments that can be uniquely serviced by the ATF. The key ATF beam parameters are shown in Table 1.

Fig. 3 The ATF injection system

Fig. 4 Schematic of the ATF laser systems

Table 1 ATF Beam Parameters

	<i>Low Emittance</i>	<i>High Current</i>
Energy, MeV	50	50
Bunches/macropulse	1	100
Macropulse duration, μ s	1.25	1.25
Micropulse length (FWHM), ps	6	6
Peak current, A	.006	160
$\epsilon_N = \gamma\sigma_x\sigma_{x'}$, π mm-mrad	.03	7
Energy spread, (1σ) , %	0.3	0.3
CO ₂ laser energy/pulse, J	0.1 to 0.6	0.1 to 0.6
CO ₂ laser pulse length (FWHM), ps	6	6
Linac Rep. Rate, Hz	1	6

3. THE EXPERIMENTAL PROGRAM

First-round experiments have been approved. They include (1) a study of the acceleration of charged particles with grating-like surfaces exposed to 10 μ m coherent radiation,²(2) the construction of a 500-nm free-electron laser,³(3) a study of nonlinear Compton scattering⁴; and (4) the acceleration of charged particles utilizing the inverse Čerenkov effect.⁵

These experiments fall roughly into three classes.

Laser Acceleration Experiments

Both the laser grating and the inverse-Čerenkov effect experiments attempt to accelerate electrons directly with the 10- μ m laser light. In the former, the laser light will be brought to bear on various open structures⁶ with the intent of establishing strong accelerating gradients up to 1 GV/m. This experiment is particularly challenging due because of the small geometric emittances required of the electron beam so that it will pass through the micro-structures needed to create accelerating electric fields directly from the 10- μ m laser light.

The inverse-Čerenkov acceleration experiment seeks to pass the electron beam through a vessel filled with 1.8 atm hydrogen and couple it with circularly polarized CO₂ laser light impinging at 20 mrad thus accelerating the beam. Acceleration gradients of 100 MV/m over a 20-cm interaction region are expected for 25 GW of delivered laser power.

Coherent Radiation Sources

This experiment takes advantage of the brightness of the ATF's electron source. A superconducting microwiggler⁷(8.8-mm period, 60-cm length, K=0.35) will be configured inside an optical cavity to permit the generation of visible (500-nm) light. This work will constitute the basis of an experimental program which eventually will explore the generation of coherent x-ray radiation.

Fundamental Electromagnetic Interactions

This experiment will probe the nonlinear Compton scattering regime induced by very high intensity ($> 10^{15}$ watts/cm²) electromagnetic pulses interacting with free electrons. With such intensities, one can expect multiple-photon absorption before a single photon is emitted by the electrons. In addition, the shift of the effective mass of the electron after absorption of a single photon will be observed.

In addition further experiments have been announced in the form of letters of intent. These include the following.

- Inverse free-electron laser acceleration—a proposal to build a 1.5-T, 60-cm long undulator which, when coupled with 200 GW of CO₂ laser radiation, will provide an energy boost of 53 MeV to the electron beam.

- Switched-power acceleration—a scheme to compress a high-voltage pulse radially, which can, in principle, lead to accelerating gradients of 3 GV/m.³ This high gradient can be especially important in a switched-power gun, where the strategy employed is to boost the electrons as quickly as possible to high values of gamma ($\gamma = E/mc^2$) in order to minimize emittance blowup due to self-fields within the beam.

4 DESCRIPTION OF THE BNL RF GUN

The Brookhaven rf gun is a $1\frac{1}{2}$ cell, side-coupled structure operating at 2.856 GHz (see Fig. 5). The ultimate aim of this device is to provide a source of electrons which will have as high a brightness as possible. Beam brightness is defined as the ratio of the beam peak current to the product of the horizontal and vertical normalized rms emittances:

$$B = \frac{I_p}{\varepsilon_{N,x}\varepsilon_{N,y}} .$$

Clearly, a substantial gain in beam brightness can be realized if the beam emittance can be minimized. Two effects dominate to cause growth in emittance beyond the thermal emittance of the electrons at the photocathode itself. These effects are the dynamics of the interaction of the electrons with the rf fields in the rf gun and the emittance growth caused by the self-fields of the electrons.

Emittance growth due to the rf dynamics can be controlled by ensuring that nonlinear transverse components of the rf fields are minimized. This is accomplished by placing relatively thick disks between cells and adjusting the diameter of the apertures so as to approximate the ideal shape, which does not allow nonlinear transverse components. Note that since we use a π -mode for acceleration, the rf fields are near a minimum when the particles traverse through the apertures.

The strategy used to control emittance growth due to the self-fields of the electrons is to operate the gun so that the electrons are launched in a high-gradient accelerating field. Once the electrons are relativistic, emittance growth due to space charge becomes more manageable. The BNL rf gun has been designed to operate with a 100-MV/m peak accelerating gradient at the cathode. Three design features ensure this: (1) the 2.856-GHz operating frequency, (2) the relatively low peak-wall field to peak-axial field ratio (1.18 to 1), and (3) an initial $\frac{1}{2}$ cell to ensure that the particles are launched near peak accelerating gradients.

Fig. 5 The Brookhaven 1½ cell gun

The rf gun has a photocathode installed on the back plane of the half cell. At Brookhaven, we are concentrating our photocathode R&D on metals, such as yttrium, samarium, and copper because we think that metals will provide the robustness necessary for continuous operations over long operating periods.

The quantum efficiencies of yttrium and samarium at a wavelength of 266 nm can be 10^{-3} and that of copper can be 10^{-4} . Thus, with the $100 \mu\text{J}$ of UV light available, we can expect up to 10 nC of electrons to be ejected from the cathode surface. Our design operating conditions call for a 1-nC charged micro-pulse with a 6-ps pulse length, thus yielding a peak current of 160 A. If we elect to illuminate a 3-mm-radius spot on the cathode material, this corresponds to 560 A/cm^2 issuing from the surface, well within the capabilities of these photocathode materials.⁹

5 OPERATION OF THE RF GUN

A principal rf characteristic of an accelerating cell is its shunt impedance, which is a measure of the cell's intrinsic ability to transform input power into accelerating gradients. It is conveniently expressed as

$$(\Delta E)^2 = ZT^2P ,$$

where ΔE is the energy gain per meter in the cell, P is the power per meter dissipated, Z is the shunt impedance, and T^2 is the overall transit time factor on the axis of the cell.

Figure 6 shows results of measuring the energy of the electrons ejected from the rf gun as a function of the input rf power. The measured shunt impedance is $50 \text{ M}\Omega/\text{m}$

(without transit time) compared to a SUPERFISH predicted value of 57 MΩ/m. The peak momentum achieved to date is 4.6 MeV/c. This was obtained when we put 6.2 MW of rf power into the gun. This output momentum corresponds to a peak-axial electric field in the rf gun of 98 MV/m, which is nearly our design value of 100 MV/m.

Fig. 6 The square of the energy boost to the electrons as a function of input power from the BNL RF gun

The measurement of the transverse emittance of the electron beam is done at either profile monitors 1 and 2 for the momentum-dispersed beam (see Fig. 3) or profile monitors 3 and 4 for the momentum-recombined beam. For the case of the momentum-dispersed beam at monitors 1 and 2, we have access only to the vertical emittance. These results, however, more nearly represent the emittance of the beam as produced by the gun, whereas measurements at monitors 3 and 4 include growth in the transverse emittance which the injection system may contribute to the beam.

The transverse emittance is analysed by one of two methods. The quadrupole variation method entails varying a quadrupole before an individual profile monitor and observing the corresponding variations in the spot size on that monitor. Figure 7 shows an example of data collected in this manner.

An alternative method consists of focusing the beam on one profile monitor, measuring the resulting spot size of the focused beam, and then observing the beam spot on the companion monitor without readjusting the beam optics. The emittance is obtained by

$$\sigma_y^2 = \sigma_y^{0^2} + L_{\text{drift}}^2 \sigma_{y'}^2, \quad \text{and} \quad \epsilon_n = \gamma \sigma_y \sigma_{y'},$$

where the measured quantities σ_y^0 and σ_y are respectively the focused and unfocused rms profile widths; $\sigma_{y'}$ is the inferred divergence of the beam and L_{drift} is the known drift distance between the two profile monitor screens. Note that the roles of the two companion monitors can be reversed thus giving two independent measurements of

Fig. 7 The vertical projections of the electron beam on a profile monitor as a function of quadrupole current

the emittance. The measurement also has the convenient property of being free of interpretation in that knowledge of the characteristics of the quadrupoles in the beam line is not required in order to extract the emittance from the measurements. Figure 8 shows an example of profiles obtained with the two profile monitor method.

The longitudinal structure of the electron pulse is an important beam parameter which, along with the charge, determines the peak current of the beam. This longitudinal profile is measured by means of rf cavities. An rf kicker has been installed before the first dipole (see Fig. 3) to measure the length of the electron pulses as they leave the rf gun. This kicker operates at 2856 MHz and provides a vertical displacement proportional to time which can be observed at either the momentum slit (located between elements Q4 and Q5) or profile monitor 1. The resolution of this measurement system approaches 1 ps.

Bunch length compression around the double bend can be measured by varying the phase of the two linac sections following the double bend. This measurement technique, in effect, uses the two linear accelerating sections as longitudinal rf kickers. By adjusting the rf phase of the linac sections, it is possible to vary the accelerating gradient significantly along the longitudinal dimensions of the electron bunch. We can then infer the bunch length by observing the resulting dp/p of the electron beam in the post-linac line.

Table 2 shows the results of the most recent measurements of the parameters of the electron beam issuing from the rf gun. Both the peak current and the beam brightness are the results of measurements taken at one occasion and are not obtained using best results for the other parameters.

Fig. 8 The vertical projections of the electron beam on both profile monitors when the beam is focused on monitor 1

Table 2 BNL RF Gun Results to Date

	Design	Achieved
Energy, MeV	4.6	4.6
Repetition rate, Hz	6	6
Electron pulse charge, nC	1.0	2.0
Electron pulse length, rms, ps	2.5	4.9
Peak Current, A	160	106
Energy spread, rms, %	0.3	0.4
Emittance ($\gamma\sigma_x\sigma_{x'}$), m-rad	7×10^{-6}	4×10^{-6}
Beam Brightness, A/m ²	3×10^{12}	7×10^{12}

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