Experimental observation of high-brightness microbunching in a photocathode rf electron gun

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We report the measurement of very short, high-brightness bunches of electrons produced in a photocathode rf gun with no magnetic compression. The electron beam bunch length and the charge distribution along the bunch were measured by passing the energy chirped the electron beam through a momentum selection slit while varying the phase of the rf linac. The bunch compression as a function of rf gun phase and electric field at the cathode were investigated. The shortest measured bunch is 370 ± 100 fs (at 95% of the charge) with 2.5×10^{8} electrons (170 A peak current); the normalized rms emittance of this beam was measured to be 0.5π mm mrad and the energy spread is 0.15%. [S1063-651X(96)51110-4]

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Femtosecond electron bunches that contain a large number of electrons and have small dimensions in the six-dimensional phase space have emerged as a powerful tool for the investigation of transient effects. Extremely short, low emittance electron pulses are of interest to a number of disciplines. A few examples are the study of the dynamics of isolated molecular structures using ultrafast electron diffraction [1], condensed matter studies of phase transformation and superheating [2], or as time-resolved surface-lattice temperature probes [3]. Femtosecond pulses of x ray can be produced by a 90° Thomson scattering geometry of laser light from an electron bunch [4]. Such radiation is the most effective probe of structural dynamics of materials on the time scale of the motion of atoms. The best coherence and intensity of the produced x rays requires electrons with a high density in six-dimensional phase space. The beam physics related topics are the injection into future linear colliders or laser accelerators and the generation of powerful broadband radiation in the millimeter to far-infrared (FIR) wavelength [5]. In all of these applications the high transverse brightness of the electron beam is as important as the shortness of the bunch. Consequently, interest in the generation and measurement of extremely short electron pulses by a thermionic rf gun [6] and photocathode rf gun [7–9] is increasing. Electron beams produced by laser photocathode rf guns are much brighter than those of thermionic guns and their synchronization to the laser expedites pump-probe experiments. To maintain the high brightness it is desirable to avoid magnetic bunch compression.

We report the measurement of extremely short, high-brightness electron bunches with a photocathode rf gun *without* the use of magnetic compression leading to an extremely high density in six-dimensional phase space. Our results are comprised of three parts. First, we present a systematic experimental study of the bunch charge distribution as a function of the gun phase, the bunch length as a function of phase and peak field of the gun, and emittance as a function of phase. The second result is a single measurement of a very high-brightness electron bunch where the measurement has been pushed to an extreme. Finally, we briefly present a calculation showing that the bunching can be understood theoretically and that short bunches are to be expected under the experiment's conditions.

The measurements we report in this Rapid Communication were performed at Brookhaven National Laboratory's Accelerator Test Facility (ATF) using an *S*-band (2856 MHz) one-and-a-half cell photocathode rf gun [10]. The ATF accelerator system consists of a photocathode rf gun with a pair of solenoid magnets positioned symmetrically along the rf gun's axis, and two sections of SLAC type linac as shown in Fig. 1. The electrons are generated by photoemission from a copper cathode using a frequency quadrupled neodymium:yttrium aluminum garnet (Nd:YAG) laser system. The frequency doubled Nd:YAG laser pulse was measured to be 14 ps full width at half maximum (FWHM) using a streak camera. The additional frequency doubling reduces the laser pulse length to 10 ps (FWHM). There is a Faraday cup and a beam profile monitor mounted on the

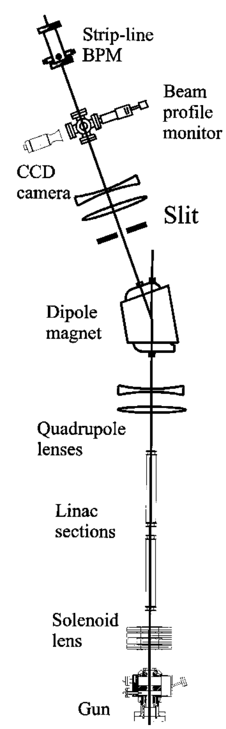

FIG. 1. A schematic drawing of the ATF injector and linac system.

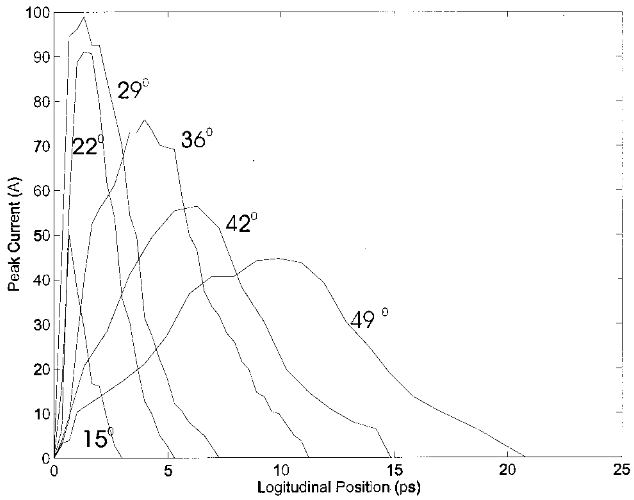

FIG. 2. Photoelectron charge distribution within the bunch for six different rf gun phases: 15°, 22°, 29°, 36°, 42°, and 49°.

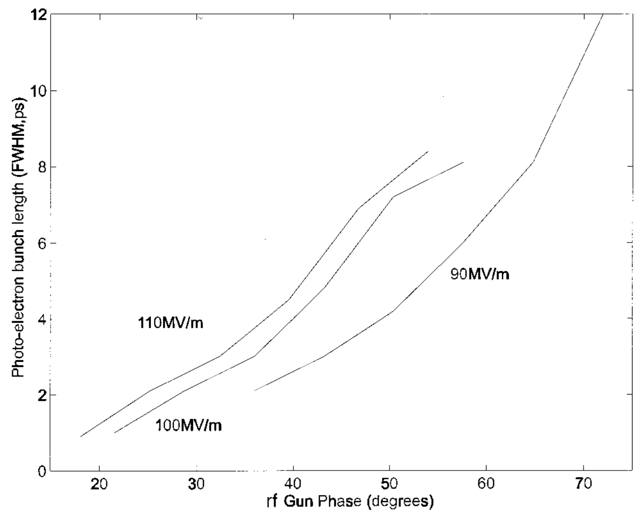

FIG. 3. Photoelectron beam bunch length (FWHM) dependence on the rf gun phase for peak cathode electric fields of 90, 100, and 110 MV m.

actuator located before the linac for electron beam diagnostics. The rf phases of the rf gun and two linac sections can be varied independently. The rf phase of the second section linac relative to the first section is controlled by a motorized, high-power, waveguide phase shifter. Downstream of the linac, quadrupole magnets, a 20° dipole magnet, momentum selection slit, and several beam profile monitors and stripline beam position monitors (BPM) provide control and measurement of the electron beam. The front surface of the momentum slit is phosphor coated and monitored by a charge-coupled device camera to measure the electron beam profile and slit opening. The sum signal of the BPM located after the slit was used to measure the charge past the slit.

Our technique for measuring electron beam bunch length and charge distribution within the bunch is particularly effective for the low emittance beams of the ATF. For each rf gun phase, the linac rf power and phase was adjusted to produce a 52 MeV electron beam. The second linac section was dephased 30° off crest. This produced an energy chirp of 0.44% per ps within the electron beam. The electron beam was transported to the momentum slit; the horizontal beam size observed on the momentum slit is given by

$$x=\sqrt{\frac{\beta\varepsilon_x}{\gamma}+D^2\left[\left(\frac{\Delta\gamma_i}{\gamma}\right)^2+\left(\frac{\Delta\gamma_t}{\gamma}\right)^2\right]}, \tag{1}$$

where β is the Courant-Snyder β function, ε_x is the normalized horizontal emittance, $D=5.4$ mm % is the dispersion function at the momentum slit, $\Delta\gamma_i/\gamma$ and $\Delta\gamma_t/\gamma$ are the intrinsic and bunch length induced relative energy spreads, respectively. To perform the electron beam energy spread measurement and selection, the dispersive term must be larger than the emittance term. This was accomplished by tuning the quadrupole magnets upstream of the dipole magnet to produce a small value of the β function. The opening of the slit was set to $\Delta\gamma/\gamma=0.5\%$ for scans with about 1 ps resolution. The electron beam bunch length and the charge distribution within the bunch were measured by varying the second section linac rf phase (1° corresponds to 970 fs) and measuring the charge past the momentum slit.

The charge variation with the rf gun phase is dominated by the Schottky effect in the strong electric field at the cathode [11]. Figure 2 presents the charge distribution within the bunch for several rf gun phases at the cathode field of 110 MV m. As the electron bunch length becomes shorter, the distribution of the electrons within the bunch becomes more asymmetric. In this measurement, the maximum peak current measured was 98 A with total charge of about 0.4 nC. The electron beam bunch compression was measured for peak electric fields on the cathode (fields at 90°) of 90, 100, and 110 MV m (Fig. 3).

The phase convention in Fig. 3 is zero degree corresponding to zero field, and the electron acceleration increases with the phase. Figure 3 shows that with higher field, we were able to observe more electron beam bunch compression since the charge increases with the electric field, as a result of the Schottky effect. However, the compression reduces with the

TABLE I. Bunch width following the tun, the 80 cm drift space, and the linac, for a few gun to laser phases. The gun phase is in degrees, the bunch width is rms in ps. The gun field is 100 MV m; the linac is 6 m long with an energy gain of 45 MeV. The laser power distribution is Gaussian with a 4 ps standard deviation.

Gun Phase (deg)	10	20	30	40	50	60	70	80	90
After gun (ps)	1.2	2.0	2.6	3.0	3.3	3.6	3.9	4.2	4.7
After drift (ps)	0.48	1.1	1.8	2.4	3.0	3.6	4.3	5.2	6.7
After linac (ps)	0.28	0.82	1.5	2.2	2.9	3.6	4.4	5.4	7.2

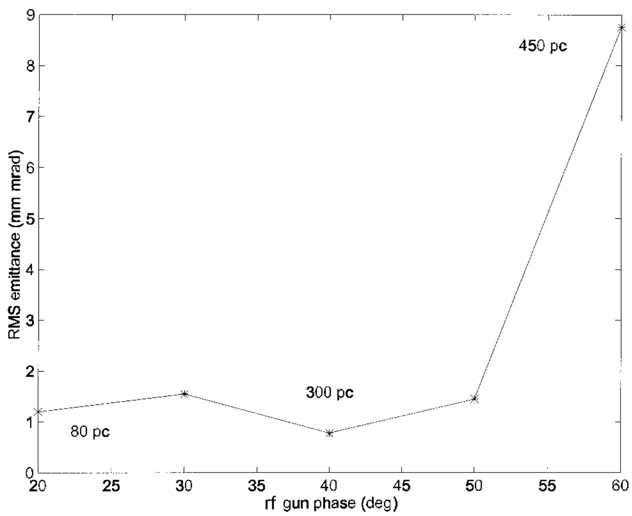

FIG. 4. The transverse normalized rms emittance as a function of rf gun phase for a constant laser energy. The charge is indicated at several phases.

increased field at a given rf phase as the beam becomes relativistic in a shorter time.

The transverse emittance of the photoelectron beam was measured after the linac using the two-beam-profile method with 20% error. The transverse normalized rms emittance as a function of the rf gun phase for a constant laser energy is shown in Fig. 4. The bunch charge is also indicated in the figure. The emittance is dominated by the rf induced emittance growth in the higher phases, where the bunch is long. Space charge primarily contributes at the lower rf phases. The optimum phase for transverse emittance is about 40°. The time resolution of our measurement at the present time was limited by the betatron beam size, local energy spread, and the timing jitters between the laser and rf system, to about 0.5 ps.

In our second result, i.e., the production of the shortest, highest-brightness electron bunch with a 40 pC charge (2.5×10^8 electrons), the laser spot size on the cathode was reduced from 1 mm diameter to 0.4 mm diameter. The calculated β function was set to 3 m at the momentum slit. The slit opening was set to the equivalent of 500 fs. With this setting, better than 95% of the charge, or 40 pC, passed through the slit. A normalized rms emittance measurement was done for this bunch yielding 0.5π mm mrad and the intrinsic energy spread of the beam was $\Delta\gamma_i/\gamma=0.15\%$ full width. This energy spread is measured by observing the spot size of the beam on the momentum slit with both linac sections in phase. The emittance contribution to the beam size [see Eq. (1)] is negligible, but the intrinsic energy spread contributes nearly half of the beam size on the momentum slit. Therefore the estimated bunch length (95% charge) is 370 fs. The corresponding peak current is 170 A.

For a one-dimensional (1D) model of the bunching we integrate the equations of motion [12] for the energy γ and the phase ϕ and a function of longitudinal position z in the $3\lambda/4$ long gun (where λ is the rf wavelength),

$$\frac{\partial\phi}{\partial z}=\frac{k\gamma}{\sqrt{\gamma^2-1}}-k, \tag{2}$$

$$\frac{\partial\gamma}{\partial z}=k\alpha[\sin\phi+\sin(\phi+2kz)], \tag{3}$$

where $\alpha=E_0/(2mc^2k)$, $k=2\pi/\lambda$, and E_0 is the peak electric field in the gun.

The result of the integration for a set of initial phases ϕ_0 results in a mapping from input phase to output phase. The electron charge distribution emitted from the cathode is given by the laser power distribution, multiplied by the emission function of the cathode [11]. The electron distribution following the gun is derived by applying the mapping to the initial distribution. Similarly, the mapping can be extended to the drift space and the linac, where analytical expressions for the mapping are straightforward. The calculated rms estimate of the bunch width is given in Table I. The drift space provides a significant degree of bunch compression even though the electrons are quite relativistic. Some compression may take place in the linac. The 1D model results are in reasonable agreement with the measured results.

The six-dimensional charge density of the electrons in the bunch can be defined as

$$\mathcal{B}\equiv\frac{eN/\Delta t}{4\pi^2\varepsilon_x\varepsilon_y(\Delta\gamma/\gamma)}=\frac{I}{4\pi^2\varepsilon_x\varepsilon_y(\Delta\gamma/\gamma)}. \tag{4}$$

$\mathcal{B}$ is related to the normalized transverse brightness $B_t=I/4\pi^2\varepsilon_x\varepsilon_y$ by $\mathcal{B}=B_t\gamma/\Delta\gamma$ and to the spectral brightness of a 6D photon beam [13]. Our result of $\mathcal{B}=114$ A (mm^2 mrad^2 %) is, to the best of our knowledge, a record 6D phase space density in an electron bunch.

Coherent transition radiation produced by the short bunches was observed [14]; the full quadratic dependence of the radiation intensity on the beam current shows that the radiation is coherent and the electron bunch length is much shorter than the detector spectral response (under 7 ps).

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