Generation and Measurement of 50-fs (rms) Electron Pulses

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(Received 2 June 1994)

An electron source has been developed at the Stanford SUNSHINE facility which can produce electron bunches as short as 50 fs (rms) with $(2\text{–}4.6) \times 10^8 e^-$ per microbunch. This source consists of a 2.6 MeV rf gun with a thermionic cathode and an alpha magnet for bunch compression. Coherent transition radiation emitted at wavelengths equal to the bunch length and longer is used in a Michelson interferometer to determine the bunch length by optical autocorrelation. The experimental setup and results of bunch length measurements are described.

PACS numbers: 29.25.Bx, 06.30.Bp, 42.72.Ai

Progress in experimental techniques with particle beams depends greatly on the ability to reduce the particle distribution in phase space. In this Letter we describe the process of generation and characterization of subpicosecond relativistic electron pulses. Such tight particle compression and its characterization is expected to be of interest for future linear colliders, for free electron lasers, and for direct generation of high intensity coherent radiation in the far infrared regime. To verify successful bunch compression to subpicosecond pulses new bunch length measuring methods must be employed. The signals are too short to be resolved by streak cameras, but optical autocorrelation methods similar to that used to characterize femtosecond laser pulses [1] have been proposed for bunch length measurement [2]. Utilizing the coherence property of the radiation emitted by short electron bunches, a far infrared Michelson interferometer has been assembled at the Stanford SUNSHINE facility [3] to measure subpicosecond electron pulses. Electron bunches of a few picoseconds duration are generally produced from thermionic electron sources by magnetic bunch compression or from photocathodes illuminated with short laser pulses. Both methods are limited due to a finite energy spread in the electron beam or by the shortest available laser pulse powerful enough to generate an electron beam from a photocathode. In long linear accelerators several compression stations could be employed, and the large energy spread introduced in each compression station can be reduced by adiabatic damping during subsequent acceleration to the next compression station. New methods must be applied, however, to reduce the bunch length to less than 1 ps, specifically at low particle beam energies.

Subpicosecond bunch compression at low beam energies requires special equipment which allows generation of an electron beam with an extremely small distribution in energy-time phase space. The combination of an rf gun with a thermionic cathode is such an electron source [4]. Here, the thermionic cathode is immersed into the oscillating rf field of a resonant cavity similar to one of many cells comprising a linear accelerator. In this experiment [3] we use a 6 mm ⌀ thermionic cathode in a $1\frac{1}{2}$ cell rf gun operating at S band or 2856 MHz as shown in Fig. 1.

During the negative cycle of the electric field no electrons can escape the cathode, but as soon as the field turns positive electrons emerging from the cathode become accelerated. The field strength in the rf gun is adjusted such that electrons starting at zero field from the cathode will leave the first $\frac{1}{2}$ cell cavity when the accelerating field again approaches zero after one half period. Any later particle will accumulate less energy, leading to a well defined correlation between energy and time. If the accelerating field or rf power to the gun is chosen too high, the first particles leave the half cell before the field completes a half cycle, and subsequent particles can reach about the same energy as the first particles. The unique correlation between energy and time is thereby destroyed, and the particle bunch cannot be compressed. In this experiment the rf gun is operated at about 2.0 MW for 1.5 μs at a repetition rate of 10 Hz. The thermionic cathode is heated to produce an electron beam current at the gun exit of 700–900 mA over the duration of a useful macropulse of 1 μs or about 3000 microbunches. The electrons reach a maximum energy of

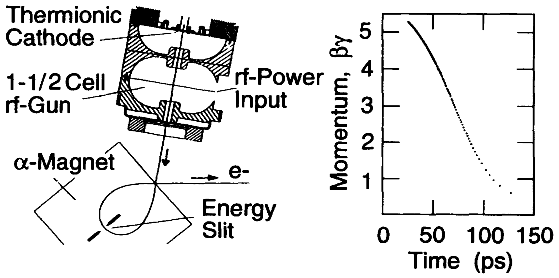

FIG. 1. $1\frac{1}{2}$ cell rf gun with alpha magnet (schematic) and phase space distribution of electrons at the exit of the 2.6 MeV rf gun.

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2.6 MeV in the $1\frac{1}{2}$ cell rf gun, and the simulated phase space distribution of particles at the exit of the rf gun is shown in Fig. 1 for one of about 3000 microbunches separated by 350 ps. Most particles are concentrated in the first few picoseconds of each microbunch, and we may select this highly populated part of the whole bunch with an appropriate energy filter. The area occupied by this bunch in phase space is very small, and it is this property that can be exploited by phase space manipulation to produce an electron bunch of extremely short duration.

Bunch compression is accomplished by guiding the electron beam coming from the rf gun through an alpha magnet [5] in which particles with a higher energy follow a longer path than particles with a lower energy. Since high-energy particles are emitted from the rf gun first, followed by lower energy particles, the characteristics of the trajectories in an alpha magnet are well suited for bunch compression. The effect of this compression process is shown in Fig. 2 where the strength of the alpha magnet is adjusted so as to overcompress the microbunch (a) whereby now lower energy particles emerge first and are followed by higher energy electrons. This distribution together with the slight variation of velocities results in the shortest possible bunch (b) at the location where coherent radiation is produced downstream from the alpha magnet. We note an instability of the particle distribution which limits the compression of the bunch at high intensities, and to reach short electron bunches it is therefore important to avoid excessive particle intensities as long as the beam is nonrelativistic.

The radiation spectrum from short electron bunches is the Fourier transform of the particle distribution [6], and extends therefore to wavelengths equal to the bunch length and longer. For the bunches produced in this experiment the wavelength range is in the far infrared regime. Measurement of this spectrum allows the determination of the particle bunch length by reverse Fourier transformation. Coherent radiation can be generated from such bunches, for example, in form of Cherenkov, synchrotron, or transition radiation. In this experiment the compressed electron bunches are first accelerated to 32 MeV by a 3 m single linac section downstream of the alpha magnet. After acceleration, coherent transition radiation is generated while the electron beam passes through a 25.4 μm Al foil as shown in Fig. 3. The Al foil is rotated by 45° with respect to the particle beam, causing the backward radiation to be emitted normal to the beam path for easy extraction from the vacuum chamber through a 1-mm-thick high-density polyethylene window of 19 mm ⌀. The total collected radiation energy per macro pulse outside the window is about 400 μJ [3]. To create a small source size the electron beam is focused by quadrupole magnets to a focal point at the Al foil of 1 mm ⌀ or less.

The divergent far infrared radiation emerging from the polyethylene window is focused by a parabolic mirror into a parallel beam and enters a Michelson interferometer, which (Fig. 3) consists of a 12.7 μm Mylar beam splitter, a fixed and a movable first surface mirror, and a room temperature pyroelectric bolometer (Molectron P1-65 with preamplifier). An ideal beam splitter would provide equal transmission (T) and reflection (R) intensity at all frequencies, while the far infrared suitable beam splitter used here has frequency-dependent transmission and reflection. This is mainly due to the interference of light reflected from both surfaces of the Mylar foil and is equivalent to thin film interference. The efficiency of the beam splitter, which is defined as the product of transmission and reflection (TR), increases from zero at zero frequency to the maximum value of 0.17 at a wave number of 116.3 cm^{-1} and then drops again to zero at the first singularity for a wave number of 232.6 cm^{-1} when the light reflected from both surfaces of the Mylar foil forms destructive interference. Typical bolometer signals of about 300 mV are recorded for the total radiation entering the Michelson interferometer of which only a small fraction reaches the bolometer due to the limited efficiency of the beam splitter. These signals are to be compared with a noise level of less than 50 μV. The bunch length information is contained in the spectral distribution of the radiation and following the technique of Fourier transform spectroscopy [7] we measure the signal on the bolometer as a function of the location of the movable mirror.

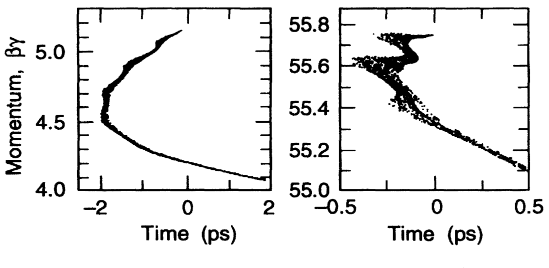

FIG. 2. Phase space distribution of electrons after compression at the exit of the alpha magnet (left) and at the radiation source (right) downstream from the alpha magnet.

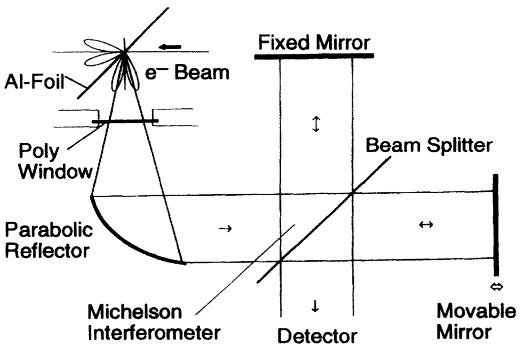

FIG. 3. Transition radiation source and Michelson interferometer for bunch length measurement.

For an ideal beam splitter the incoming radiation is split 50:50, and a monochromatic wave of wavelength λ would produce a bolometer signal $S(x) = I(k)(1 + \cos kx)$, where $I(k)$ is the intensity of the incoming radiation at $k = 2\pi/\lambda$, and x is the path difference between both arms of the Michelson interferometer. For a finite spectrum this is replaced by the signal $S(x) = \int_0^\infty I(k)(1 + \cos kx)\, dk = S_0 + \int_0^\infty I(k) \cos kx\, d$, where $S_0 = \int I(k)\, dk$ is the signal for large path differences x. The function $S(x) - S_0$ is called the interferogram. For a short bunch we would expect a constant signal S_0 rising to twice that when the pulses from both arms of the interferometer overlap at $x \approx 0$. The width of the main peak in the interferogram at half maximum is equal to the bunch length for a rectangular particle distribution. For a Gaussian distribution the FWHM of the interferogram is equal to $(2.35/\sqrt{2})\,\sigma_z$ or the equivalent bunch length is given by $\sqrt{2\pi}\sigma_z = 1.5$ FWHM. From simulation and observations of the radiation spectrum we conclude that the particle distribution is not Gaussian but is deformed toward a rectangular distribution. The actual equivalent bunch length is therefore between 100% and 150% of the FWHM of the main peak in the interferogram. Figure 4 shows a typical interferogram exhibiting the sharp rise in signal when pulses from both arms of the interferometer overlap.

A beam splitter thickness of 12.7 μm has been chosen to include the whole expected spectrum below the first interference singularity which occurs at a wavelength of 43 μm. The measurement of the bolometer signal as a function of the position of the movable mirror was performed through the LABVIEW control environment implemented on a PC. The total translation of the mirror was typically 20 mm, resulting in a spectral resolution of 0.5 cm^{-1}. Each measurement point resembles the average reading for several beam pulses containing 3000 microbunches each. To record the distribution of the main peak takes about 30 sec, and the bunch length measurement therefore involves about 10^6 microbunches.

A typical radiation spectrum for this measurement is shown in Fig. 5. The lower (uncorrected) curve shows the raw data from the bolometer, which must be corrected due to the thin film interference effects discussed earlier. As a consequence of the correction procedure, an artificial spike appears at the first singularity of the beam splitter in the corrected spectrum indicating a significant error due to the large correction necessary at the interference singularity. The use of a 12.7 μm Mylar beam splitter limits the measurement of the spectrum to a range between zero wave number and 232.6 cm^{-1}. To push the first singularity to shorter wavelength a thinner Mylar foil with the drawback of further reduced efficiency must be used. For the measurements presented here we considered a single 12.7 μm beam splitter sufficient to cover the required spectrum for an accurate representation of the bunch length.

The multitude of absorption lines in the spectrum of Fig. 5 can be identified as water absorption lines [7] since the Michelson interferometer had not yet been protected from ambient air with finite humidity. Below 10 cm^{-1} the spectrum is believed to be contaminated by slow drifts of beam parameters during the half hour measurement of a 20-mm-wide interferogram, causing slight variations in the intensity. At wave numbers above about 50 cm^{-1} we note a logarithmic decay of the spectrum which is consistent with an electron micropulse shape closer to a rectangular particle distribution rather than a Gaussian distribution. This is also expected from simulation of magnetic bunch compression.

Utilizing results from interferograms we optimized operating parameters for the rf gun, alpha magnet, and focusing to reach the shortest bunch length. Figure 6 shows the main peak of the interferogram for the most compressed bunch obtained so far averaged over the duration of the measurement. The electron beam intensity has been recorded with a current transformer to be between 2×10^8 and 4.6×10^8 electrons depending on operating conditions. At present the transmission of the electron beam through the linear accelerator is compromised by strong vertical focusing in the alpha magnet and lack of focusing along the 10-ft-long accelerator structure.

The longitudinal particle distribution is affected by the transverse dynamics along the beam line. Some particles at the edge of the beam undergo large amplitude oscillations in the focusing field of quadrupoles and thus contribute to bunch lengthening. A crude estimate

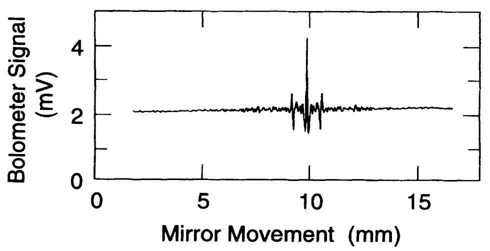

FIG. 4. Typical interferogram for radiation from a short electron pulse.

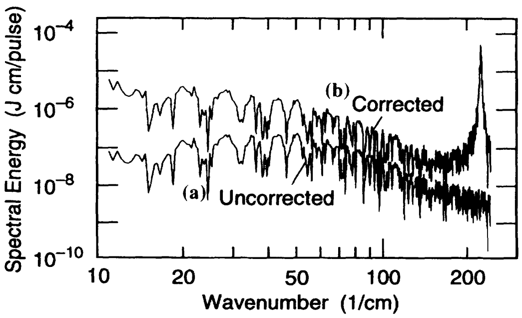

FIG. 5. Radiation spectrum derived from an interferogram. Trace (a) is the uncorrected spectrum, and trace (b) shows the spectrum corrected for the beam splitter efficiency.

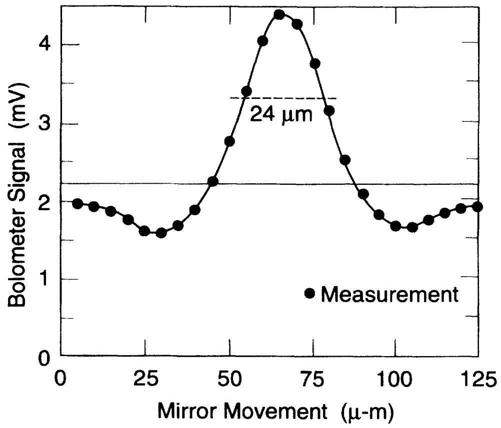

FIG. 6. Main peak of the interferogram for the shortest electron bunch length obtained so far. The effective average bunch length in this case is $\sqrt{2\pi}\sigma_z = 36\ \mu\mathrm{m}$ or $\sqrt{2\pi}\sigma_t = 120$ fs.

indicates that this effect may add about 40 and 10 μm to the path length from horizontal and vertical oscillations, respectively. From simulations of the transverse particle distribution, however, only a small fraction of the beam is expected to contribute to this bunch lengthening which scales quadratically with oscillation amplitude. A halolike bunch lengthening increases the low frequency spectrum while preserving the concentration of most particles in a short length as demonstrated by the narrow width of the interferogram. Accurate reconstruction of the particle distribution from the interferogram or spectrum would be highly desirable but is not possible because the phase information is lost when the radiation intensity is measured.

In summary, a system to produce and characterize subpicosecond electron bunches has been developed and described. The combination of a thermionic cathode in an rf gun and a magnetic compression system can be used to produce subpicosecond electron bunches, and passing the compressed electron through a thin Al foil produces coherent transition radiation in the far infrared regime. Utilizing the coherence property of the radiation, a Michelson interferometer, optimized for far infrared radiation, can be employed to conveniently measure by optical autocorrelation the durations of subpicosecond electron bunches. Since this method is based on optical rather than electronic processes, the resolution is of optical dimensions and is applicable to any short bunch length one can hope to produce in the foreseeable future. The Michelson interferometer fits on a 20 by 30 cm^2 breadboard and is easily transportable to be used as a diagnostic instrument. The radiation intensity is proportional to the square of the number of electrons per microbunch and is therefore sufficiently intense to allow the use of a room-temperature bolometer.

The authors gladly acknowledge the expert technical support by M. Baltay, C. Chavez, D. Day, J. Haydon, G. Husak, and many others during the assembly of the facility. We also appreciate the useful introduction to techniques of far infrared experimentation received from P. Richards. For the use of some critical measurement equipment we are thankful to A. Schwettman and T. Smith. This work was supported in part by the Department of Energy, Basic Energy Sciences Contract No. DE-AC03-76SF00515 and the Office of Naval Research Contract No. N00014-91-C-0170.

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