Section 14. Development of new quantum beams and its application

Femto-second electron pulses from a linear accelerator

H. Wiedemann *, D. Bocek, M. Hernandez, C. Settakorn

Department of Applied Physics, Physics Department and SLAC / SSRL, Bin #69, Stanford University, P.O. Box 4349, Stanford, CA 94309, USA

Abstract

An overview of the research program and recent experimental results from the SUNSHINE (Stanford University short intense electron source) facility will be presented and discussed. This facility consists of an rf-gun and a magnetic bunch compressor followed by a 30 MeV linear accelerator and associated diagnostic instrumentation. The goal of this research activity is to produce sub picosecond electron pulses, study limitations and use those bunches to generate coherent far infrared radiation or for single pass free electron laser development. High intensity electron bunches with a peak current of 298 A at a bunch length of 70 μm rms or 235 fs rms have been produced at a microbunch charge of 0.17 nC while the shortest bunches reached so far last about 100 fs rms at about 10% of maximum intensity. The experimental setup, numerical simulations for bunch compression, sub picosecond bunch length measurements and limitations on achievable short bunches will be discussed. © 1997 Elsevier Science B.V.

1. Introduction

Experimentation with particle beams is greatly influenced by the particle distribution in space, time and energy. Significant progress has been made in the past ten years to reduce transverse beam dimensions in phase space and the beams energy spread while the shortest achievable pulse duration could not be reduced to less than a few picoseconds. Only recently did it become possible to also reduce the pulse length to sub picosecond level with shortest bunches of 100 fs rms [1] achieved so far. Sub picosecond electron pulses are desired for a number of research programs, some of which are discussed by Uesaka [2]. Those applications include direct use of the electron beam in materials research or in high energy physics for linear colliders of the future. Other applications are based on the transformation of short electron pulses into photon pulses by way of free electron lasers (FEL), single pass free electron lasers when no good mirrors for an FEL exist (e.g., X-ray) [3], incoherent X-ray pulses, Compton scatter-

ing or generation of intense, coherent far infrared transition or synchrotron radiation [4–7,1].

Short, sub picosecond electron pulses can be produced in a straight forward way by particle manipulation in interlaced sections of linear accelerators and bunch compressors. In case of a chicane bunch compressor (Fig. 1), a long, relativistic electron bunch with a small energy spread (Fig. 1a) is 'accelerated' in a linear accelerator section at zero-phase such that the head of the bunch loses energy and the particles in the tail gain energy while the energy of particles in the center does not change (Fig. 1b). Because the beam is assumed to be relativistic, all particles travel now with about the same velocity through an asynchronous bend (chicane) where the high energy particles in the bunch tail travel a shorter path than the low energy particles in the bunch head leading to bunch compression. This compression is achieved at the expense of the relative energy spread, $\Delta E/E$, to fulfill Liouville's theorem requiring that the phase space density or in this case the product of the bunch length and energy spread remain constant. Further acceleration of this beam from energy E_0 to E_1 reduces the relative energy spread again by a factor E_1/E_0 due to adiabatic damping. After sufficient further acceleration the energy spread has become small again and a new step of bunch compression can be implemented. This procedure obviously requires a long linear accelerator

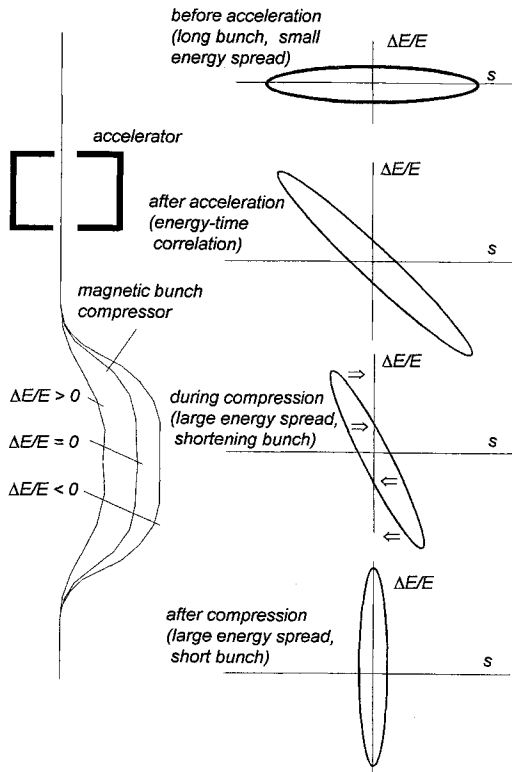* Corresponding author. Tel.: +1-415 926 2305; fax: +1-415 926 4100; e-mail: wiedemann@slac.stanford.edu.

Fig. 1. Principle of magnetic bunch compression.

Fig. 2. Rf-gun (schematic) with α-magnet.

available only in high energy physics facilities and is not of practical interest for laboratory experimentation.

Sub-picosecond electron bunches can be produced in a much smaller facility from an rf-gun with a thermionic cathode and a magnetic bunch compression system. In the SUNSHINE facility [7,8] at Stanford University a train of 2000 to 3000 microbunches of 100 to 235 fs rms duration and separated by 350 ps are produced in each pulse. Installation of a beam chopper would allow the generation of single or few such bunches at desired time intervals.

2. Electron source and beam characteristics

To produce sub-picosecond electron bunches we use an rf-gun with a thermionic cathode [9–11] and a magnetic compression system in the form of an α-magnet [12]. The rf-gun, fed by 3 MW of rf-power from a klystron at 2856 MHz, consists of 1 1/2 S-band cavities and a thermionic cathode attached to one wall of the first 1/2-cell. Fig. 2 shows a schematic cross-section of the rf-gun and α-magnet installed at the SUNSHINE. Electrons emerging from the cathode are instantly exposed to a high accelerating field of 27 MV/m to minimize detrimental effects of space charge forces which would lengthen the pulse irre-
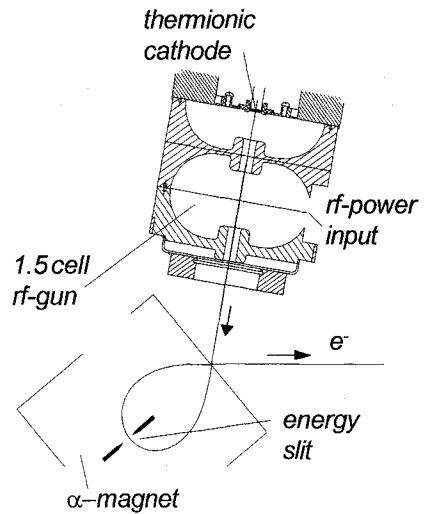
versibly. In the second cell the field is increased even more to reach 85 MV/m.

Fig. 3 shows the phase-space distribution of the particle beam at the exit of the gun. We note the uniform momentum-time correlation of the particle distribution in phase space which is the prerequisite for successful magnetic bunch compression. The distribution shown in Fig. 3 has been obtained by numerical simulations with the particle-in-cell code MASK [13]. This code allows to simulate the evolution of an electron beam emerging from a cathode through an rf-field in a self-consistent way including space charge forces and beam loading. The fast acceleration in the rf-gun to relativistic energies of 2.6 MeV diminishes emittance-diluting effects of space-charge forces and results in a particularly small distribution in energy-time phase space. This small phase space can be exploited by appropriate particle manipulation to achieve very short bunches. RF-gun and associated beam parameters are compiled in Table 1.

For optimum bunch compression we must adjust the field in the first 1/2-cell such that the particle beam at the
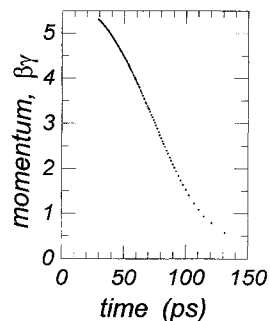

Fig. 3. Particle distribution in phase space at gun exit.

exit of the gun displays the unique relationship of particle momentum with time in phase space as mentioned earlier. This is achieved in the following way. During the negative cycle of the electrical field no electrons are accelerated. Just when the field turns positive, however, electrons emerging from the cathode can be accelerated. The field strength is chosen by design such that these first particles sample the full half-cycle of the accelerating field before they vanish into the field-free channel between the first and the second cell. Later particles will not be able to accumulate the same amount of acceleration, since they do not reach the end of the first cell before the field turns negative again. In the design of the SUNSHINE cavity, the field in the first cell is therefore only about one third of that in the second cell. If higher fields were used, particles would need less than one half-cycle to travel through the first cell. Consequently, particles emerging from the cathode at a little later time can still accumulate similar amounts of energy without experiencing negative fields before they leave the first cell. In this case, the energy gain would be about the same for the first few picoseconds in a microbunch, thus eliminating a unique correlation between momentum and time. Such a bunch cannot be readily compressed although this is the preferred mode of operation for FEL's where a monochromatic particle beam is desired. The optimum rf-field amplitude in the first half-cell can be determined for a particular rf-gun design with the computer code MASK.

An optimized situation for the electron beam at the exit of the rf-gun is shown in the phase-space diagram of Fig. 3 for the SUNSHINE experiment. Most particles are concentrated at the high energy end of the microbunch while lower energy particles form a long tail which will be discarded in the energy filter in the α-magnet. The small distribution of the beam in phase-space is obvious, and use of an energy filter in the α-magnet allows the selection of those particles only which can be compressed effectively. The situation as shown in Fig. 3 is true for small beam currents only. As the cathode temperature and beam intensity are increased, an instability occurs which limits ultimately how short a pulse can be achieved. This instability, which we call the shock-wave instability [11], is caused by space-charge forces originating from steep variations of the charge density which occurs specifically at the begin-

Table 1
RF-gun and beam parameters

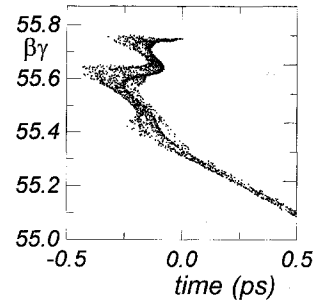| Energy	3.0	MeV
Pulse current	1.3	A
Beam pulse width	1.0	μs
Pulse rep. rate <	30	1/s
RF power to gun	~ 3	MW
RF pulse duration	2.5	μs
Acc. field/1st cell	27	MV/m
Acc. field/2nd cell	85	MV/m

Fig. 4. Phase space distribution of particles after compression and acceleration. On this time scale the effect of the shock wave instability becomes apparent.

ning of the microbunches in the rf-gun. The effect is an oscillatory appearance of density variations, as shown in Fig. 4. This dilution of phase-space ultimately limits how short an electron bunch can be obtained at a given beam intensity. For the simulation shown in Fig. 4 a beam current of 3.4 A emitted from a 6 mm diameter cathode was used.

3. Magnetic bunch compression

To compress electron bunches from about 20–30 ps to less than one ps, an α-magnet [12] is used. This magnet has the shape of the left or right half of a quadruple with a mirror plate terminating the fields across the vertical midplane. Unlike a beam passing through a quadruple along the axis, the beam enters the α-magnet at an angle of 49.29° with respect to the axis, as indicated in Fig. 2. Particles entering at this angle follow a closed loop similar to the letter α and exit the magnet exactly at the entrance point independent of the particle momentum. This makes an α-magnet a convenient and simple bunch compressor allowing one to change the magnet strength and thereby the compression without changing the geometry of the beam path outside the α-magnet. The beam dynamics in an α-magnet has been worked out in detail in [10] and the momentum dependent path length s_o is given as a function of field strength by

$$s_o(m) = 0.192\sqrt{\frac{\beta\gamma}{g(T/m)}}, \qquad (1)$$

where g is the field gradient of the α-magnet. In Fig. 4, the numerically simulated particle distribution of Fig. 3 is shown after compression and after acceleration to 28 MeV. In the SUNSHINE experiment, the beam is further accelerated after exiting the α-magnet by a linear accelerator which is not required for successful bunch compression but facilitates the generation of well collimated, coherent FIR radiation. Setting the energy slit in the α-magnet appropriately, one can filter out that part of the beam

which represents the shortest bunch length, for example the range $55.5 < \beta\gamma < 55.8$ in Fig. 4.

In this simulation of bunch compression we have ignored the effect of transverse beam size. In a beam of finite transverse dimensions some of the particles follow, under the forces of focusing elements, oscillatory trajectories about the ideal beam axis. Such trajectories are longer than the on-axis path leading to a longitudinal spread of the particle distribution or bunch lengthening. This effect turns out to be stronger than the shock wave instability limiting the shortest achievable bunch length at SUN-SHINE to 235 fs rms for a high beam intensity of 1.1×10^9 electrons or 0.17 nC per microbunch. Shorter bunches can be obtained at reduced intensity by eliminating particles with large transverse oscillation amplitudes. Reducing the transverse beam sizes and beam divergence will make it possible to further reduce bunch lengths to the limit given by the shock-wave instability.

To quantify progress in bunch reduction reliable instrumentation for sub picosecond bunch length measurement must be available. Since conventional time-domain instrumentation like a streak camera for bunch length measurements of 350 fs or less a new way of determining electron pulse length had to be developed. This new method works in the frequency domain and relies on the frequency spectrum of coherent radiation emitted by sub picosecond electron bunches.

4. Generation of coherent far infrared radiation

The possibility of generating intense, coherent FIR radiation from sub-picosecond electron bunches was first pointed out by Motz [14]. The intensity enhancement comes from the fact that the radiation field scales linearly with the number of radiating particles and the intensity is therefore proportional to the square of the beam intensity. The degree and spectrum of coherence depends greatly on the particle distribution. Consider the radiation field $E_k = E_0 \exp[i(\omega t - \varphi_k)]$ generated by a single electron k, which we normalize for simplicity to unity ($E_0 = 1$), and where $\varphi_k = 2\pi z_k/\lambda$ with z_k the position of electron k with respect to the bunch center and λ the radiation wavelength. The total spectral radiation power from all N_e electrons is then given by

$$P(\omega) \propto \sum_{k,j=1}^{N_e} E_k E_j^* \propto \sum_{k,j=1}^{N_e} e^{i(\varphi_k - \varphi_j)}$$

$$= N_e + \sum_{k,j \neq 1}^{N_e} e^{i(\varphi_k - \varphi_j)}. \tag{2}$$

The first term on the right hand-side represents the incoherent radiation scaling linearly with particle intensity and the second term is the coherent part which is determined

by the longitudinal particle distribution. Considering in one extreme all particles to be located at the same place, then $\varphi_k - \varphi_j = 0$ and the double sum would add up to $N_e(N_e - 1)$. In reality, particles are distributed over a finite length, and the sums in Eq. (2) must be replaced by integrals folding the exponential factor with the longitudinal particle distribution function $\Psi(\varphi)$. For an arbitrary distribution Eq. (2) becomes then

$$P(\omega) = p(\omega)\left[N_e + N_e(N_e - 1)g^2(l)\right], \tag{3}$$

where $p(\omega)$ is the spectral radiation power from a single electron, $g^2(l)$ is the form factor of the particle distribution depending on the effective bunch length l. For a Gaussian distribution $l = (2\pi)^{1/2}\sigma$ and $g^2(s) = \exp(-4\pi^2\sigma^2/\lambda^2)$ while for a rect-angular distribution $g^2(l) = (\sin(x)/x)^2$ where $x = \pi l/\lambda$. Coherent radiation occurs for long wavelengths $\lambda \geq 1.35\, l$ and the spectral radiation power is enhanced above incoherent radiation by the number of coherently radiating particles or by a factor of $N_e = 10^8$ and more at SUNSHINE. To be precise, the coherent enhancement occurs over a frequency range which is the Fourier transform of the longitudinal particle distribution. Measuring the coherent frequency spectrum allows the determination of the electron bunch length.

At SUNSHINE we use coherent transition radiation to measure the bunch length. Charged particles emit radiation as they pass through the transition between two media of different dielectric constants. We collect this radiation by guiding the 28 MeV electron beam through a thin aluminum foil. Rotating this foil by 45° the backward radiation is emitted normal to the beam axis through a polyethylene window into open air as shown in Fig. 5. The production of coherent transition radiation is particularly simple and serves as a convenient source of coherent radiation for bunch length measurements. The incoherent
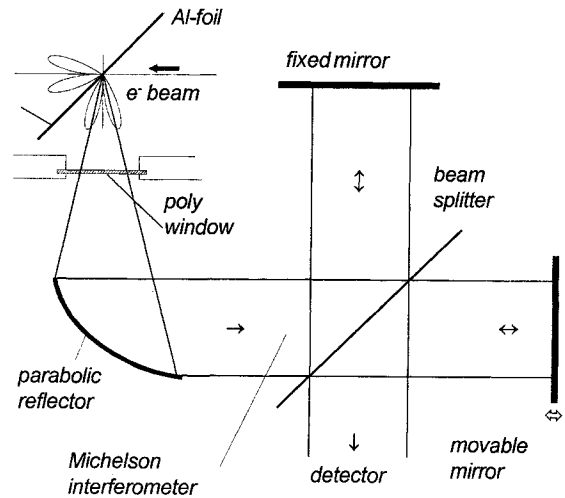

Fig. 5. FIR transition radiator and Michelson interferometer.

transition–radiation spectrum is frequency independent for long wavelengths and the coherent enhancement represents therefore directly the Fourier transform of the particle bunch.

5. Bunch length measurement

Independent measurement of the bunch length is highly desirable but cannot be performed for sub-picosecond pulses by time-resolved methods like a streak camera. A frequency-resolved autocorrelation method has been proposed [15] based on coherent transition radiation. At SUNSHINE, a FIR Michelson interferometer has been developed making it possible for the first time to measure particle pulse lengths as short as 100 fs rms [1,6]. In this setup (Fig. 5) the electron beam passes through a thin aluminum foil to produce transition radiation. Measuring the radiation intensity with a room-temperature pyroelectric bolometer (Molectron P1-65) as a function of the path length difference in both arms of the Michelson interferometer, we obtain an interferogram (Fig. 6) which is the Fourier transform of the radiation spectrum [1]. Since the spectrum is the Fourier transform of the particle distribution, we have a direct measurement of the bunch length in the form of the interferogram.

The full width at half maximum of the central peak above the baseline in the interferogram is nearly equal to the bunch length. However, since the beam splitter can introduce frequency dependent effects due to interference of reflected radiation from both surfaces, some corrections may have to be applied to obtain the actual bunch length. The degree of required correction depends on the thickness of the beam splitter compared to the bunch length. A
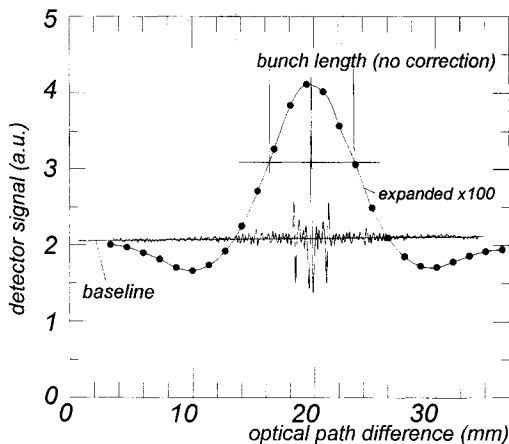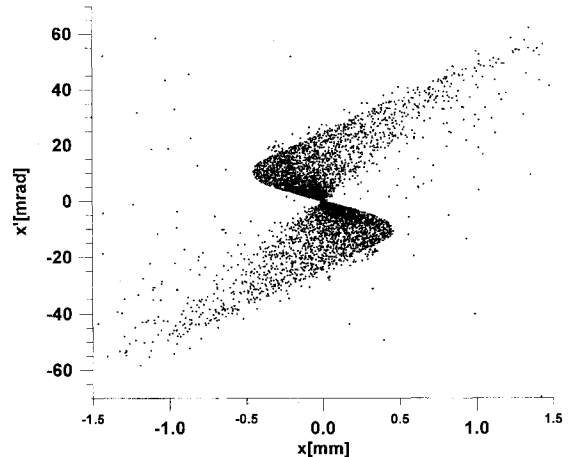

Fig. 7. Particle distribution in transverse phase space at the gun exit.

detailed analysis of sub-picosecond bunch length measurement including beam splitter correction is given in Ref. [1].

6. Bunch length and peak current

As the bunch length is reduced one would expect the peak beam current to increase proportionally and be limited only by the shock-wave instability. This is only partially true. Closer study of the beam dynamics at SUNSHINE revealed that the shortest bunch length is limited by beam divergence as a consequence of strong focusing from rf-fields in the gun. In Fig. 7 the transverse phase-space distribution of the beam emerging from the gun is shown. Particles with large angles follow a longer path than particles close to the beam axis. This path length spread is further enhanced by strong quadruple focusing, especially between gun and α-magnet. To obtain the shortest electron bunches in SUNSHINE as it is presently configured one must scrape off particles which undergo large betatron oscillations. That obviously can be done only at a loss of intensity. Micro-bunch lengths as short as 100 fs rms have been measured and a maximum beam peak current of 298 A has been achieved for a bunch length of 235 fs rms. For the shortest bunch length of 100 fs rms the peak current is reduced to about 30 A.

7. High intensity FIR radiation source

The primary goal of research and development at the SUNSHINE facility has been to generate high intensity coherent FIR sources where so far only black-body radia-

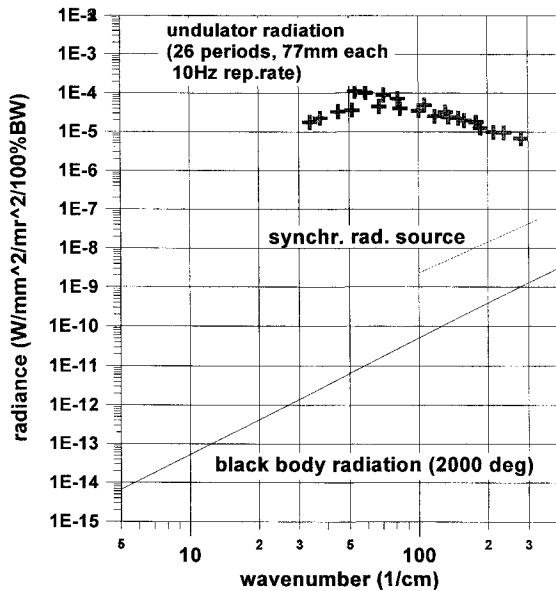Fig. 6. Typical interferogram.

Fig. 8. FIR radiance from sub-picosecond electron bunches compared with black body radiation and synchrotron radiation.

tors and a few synchrotron radiation sources are available. As shown in Fig. 8, high intensity FIR can be produced with university style instrumentation from sub-picosecond bunches. The radiation is coherent, well collimated and polarized. The highest radiation pulse energy obtained so far from undulator radiation is 2.6 mJ/pulse and 0.45 mJ/pulse from transition radiation. At the expense of some collimation, similar intensities can be obtained at much lower beam energies since the total radiation intensity is determined primarily by the bunch length. A low energy FIR radiation source is conceivable consisting of only a magnetron-driven 3 to 4 MeV rf-gun and an α-magnet. To produce undulator radiation under such conditions the period length would have to be reduced to one cm or less, which is well within present-day technology.

Acknowledgements

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