Breaking the Picosecond Barrier

by HELMUT WIEDEMANN

Graduate students at SUNSHINE design, generate, and measure subpicosecond electron bunches.

MANY OF OUR MAJOR ADVANCES in understanding Nature have resulted from the invention and development of ever more powerful experimental instruments. In particular, particle accelerators and other particle and photon beam devices have made possible striking advances in high energy physics, materials science, biology and medicine, and other fields of scientific research. Today much of the development work in particle-beam and photon-beam research is directed toward producing beams with ever smaller diameters and angular divergences (smaller phase space). Our ability to compress more and more particles into smaller volumes, into the shortest pulse length or the narrowest energy spread, will powerfully affect our future progress in fundamental research that is based on particle beams. An example is the research potential of future linear colliders in high energy physics, which will depend critically on our ability to compress tens of billions of electrons into a tiny pulse with a diameter of only a few tens of nanometers and a pulse duration significantly less than one picosecond. Only then will the head-on collision of two such slugs of particles result in a collision probability for elementary-particle reactions that is large enough to be of interest to high energy physicists. In another application of great scientific significance, the high degree of cooperation among closely spaced electrons (bunch lengths less than about 100 femtoseconds) may make it possible to build a Free Electron Laser (FEL) that can generate, for the first time, coherent X rays at unparalleled brightness for basic research.

Sub-picosecond electron bunches generate coherent, far-infrared radiation pulses at wavelengths of 1 mm and 10 μm.

Developing such electron beams poses a fundamental challenge to beam physicists; this work is presently being pursued at a number of national research laboratories and universities throughout the world. In this article we will concentrate on a particular subset of these developments, the generation of femtosecond electron pulses. Only a few years ago such pulses could not have been produced and could not even have been measured. But great progress has been made recently, and we report here on some of these developments.

WHAT DOES A FEMTO-SECOND ELECTRON BUNCH LOOK LIKE?

First, we try to get some feeling for how short a time interval of, say, 100 femtoseconds actually is. There are 1,000,000,000,000,000 or 10^{15} femtoseconds (fsec) in 1 second. In that one second light can travel a distance equal to seven and a half times around the earth, or almost the distance from earth to the moon. In spite of this incredibly high speed, during a time interval of 100 fsec light would travel only 30 micrometers (or about 1/1000th of an inch). In a 100 fsec electron pulse all the electrons are thus contained in a slug of charge about 1/30th of a millimeter long. The natural repulsion between the electrons caused by their electric charge must be overcome and kept compensated during acceleration and beam transport. Nature helps here in the sense that in relativistic particle beams (where the particles travel at speeds close to the velocity of light), the destructive space-charge forces are compensated as the particle energy increases. This requires that the particle beam be accelerated as rapidly as possible after low-energy bunch compression so that the compressed bunch in effect becomes "frozen." Of course, practical imperfections introduce perturbations in the transport systems of high-density particle beams; the task of beam dynamics physicists and engineers is to detect such sources and to design equipment that will reduce the perturbations to an acceptable level.

WHY DO WE NEED SUCH SHORT PULSES?

As noted earlier, the development of future linear colliders depends critically on the attainment of sub-picosecond (10^{-12} sec) electron bunches with cross sections of only a few tens of nanometers (10^{-9} m). Only such tiny and highly populated electron bunches will provide sufficient collision probabilities (luminosity) to generate the rare high-energy physics events that are the subjects of basic research in this field. Beams with nanometer cross section can be sustained only over a very short distance, which is the reason why electron pulses of less than one picosecond duration (about 300 fsec or less) are needed. Even shorter pulses are required for X-ray free electron lasers (FEL). Such X-ray lasers are the only way to produce coherent X rays at extremely high brightness. They function like ordinary FELs except that the buildup of electromagnetic radiation must occur in a single passage of an electron beam through an undulator magnet. In ordinary FELs the radiation is contained in an optical cavity made of reflecting mirrors, and it interacts many times with the electron beam. This is not possible at X-ray wavelengths where no highly reflective mirrors exist. Extremely high density electron beams are thus required for single-pass X-ray FELs, and the recent developments in beam physics have approached a level of sophistication which suggests that such a laser generator is possible.

An added feature of a single-pass FEL is the fact that its sub-picosecond pulse duration would make it possible to study the dynamics of atomic and molecular systems. Many chemical or biological reactions, for example, occur on a sub-picosecond time scale and often are characterized by one or more intermediate states. Because of the very short time scale, such states cannot as yet be studied.

Sub-picosecond electron bunches can also be used directly to generate high brightness, coherent, far-infrared radiation pulses in a spectral regime between wavelengths of 1 millimeter and 10 micrometers where so far only very few high brightness FELs exist. The extreme compression of electrons into sub-picosecond pulses causes them to "cooperate" with each other in the generation of coherent far-infrared radiation. In an electron pulse that is long compared to the wavelength of the radiation emitted, each electron radiates independently from all others; in contrast, the radiation intensity emitted from a bunch that is short compared to the wavelength is greatly enhanced. More explicitly, in a long bunch, the radiation intensity from two electrons is twice that of one electron, while the radiation intensity of two electrons very close together is four times that of a single electron. Putting N electrons into close proximity results in a radiation intensity proportional to N^2 instead of N, and this can result in a total increase of radiation intensity by a factor of 10^8 or more for short pulses compared to long pulses. Furthermore, this radiation is coherent, polarized, and comes in very short pulses.

Far infrared radiation is produced whenever an electron beam passes, for example, through a magnetic field (synchrotron radiation), a dielectric material (transition radiation, Cherenkov radiation) or travels close to a periodically corrugated surface (Smith-Purcell radiation). A wealth of physics is waiting for such sources in areas such as surface physics, high-temperature superconductors, and the dynamics of large biomolecules.

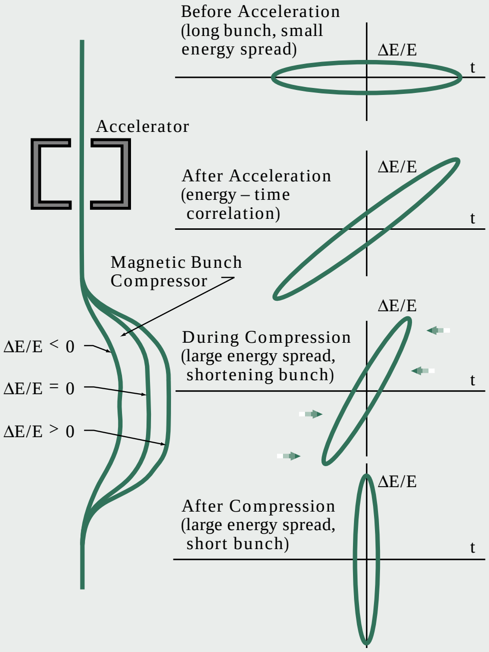
BUNCH COMPRESSION

There are no known methods for directly producing sub-picosecond electron pulses of sufficient intensity. While femtosecond lasers together with photocathodes can in fact be used to produce short pulses, the achievable intensities are insufficient for the desired applications. The only way to create intense sub-picosecond pulses known so far is first to produce pulses with the desired intensity but longer duration, and then to apply some sort of bunch compression. That is possible if the electrons have different properties as a function of their location along the bunch. Exploiting this, one can cause electrons with different properties to respond differently to external forces and thereby rearrange their position along the bunch. For example, if the electron energy changes monotonically from lower values in the head of the bunch to an ideal design energy in the center and to higher values in the tail of a bunch, one can exploit this beam property for bunch compression in a magnetic chicane.

This energy variation along the bunch can be generated by fast cycling radiofrequency fields in an accelerating section (see box on the right). Consider an electron beam arriving at the accelerating section just when the field is about to change its sign but is still negative. Electrons in the head of the bunch then would be decelerated. By the time the center of the bunch arrives the field has reached the zero point, and then increases monotonically to accelerate the electrons behind the bunch center. As the figure shows, the more energetic electrons at the back of the bunch travel along a shorter path through the chicane because they are deflected less than the electrons in the bunch center, and thus start to catch up with them. Conversely, the less energetic electrons in the head of the bunch are deflected along a

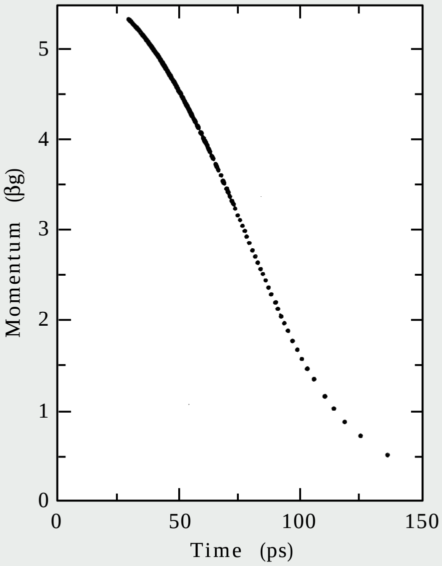
Bunch Compression

IN THE CASE OF A CHICANE-TYPE bunch compressor (see figure below), a long, relativistic electron bunch with small energy spread is "accelerated" in a linear accelerator section at zero phase so that the particles in the head of the bunch lose energy, those in the tail gain energy, and those in the center are unaffected. The beam is assumed to be relativistic (all particles travel close to the velocity of light) and passes through an asynchronous bend (chicane), where the higher energy particles in the bunch tail travel a shorter path than the lower energy particles in the head, thus leading to bunch compression. This compression is achieved at the expense of the relative energy spread, $\Delta E/E$, to fulfill Liouville's theorem.



A second, further acceleration of this beam from energy E_0 to E_1 could reduce the relative energy spread again by a factor E_0/E_1 due to adiabatic damping. After sufficient acceleration the energy spread would become small again, and a new step of bunch compression could be implemented. This procedure would obviously require a long linear accelerator of the sort available only in high energy physics facilities like SLAC and is not of practical interest for laboratory experimentation.

RF Gun and Beam Properties

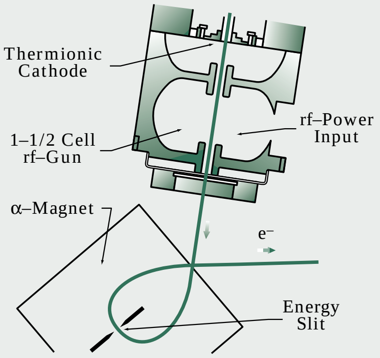


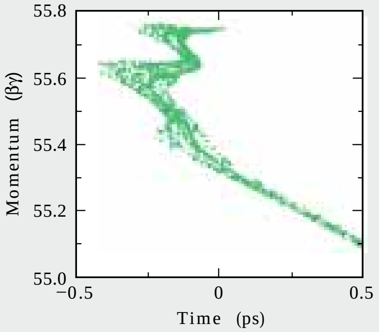
SUB-PICOSECOND ELECTRON BUNCHES can be produced from a radiofrequency (rf) gun with a thermionic cathode and a magnetic bunch-compression system. The rf gun at SUNSHINE consists of 1-1/2 cells of an S-band linear accelerator and produces a train of 2000 to 3000 microbunches separated by 350 psec in each main pulse. The illustration on the left shows the phase-space distribution for one microbunch at the exit of the gun. The uniform momentum-time correlation of the particle distribution shown is a prerequisite for successful magnetic bunch compression. Fast acceleration in the rf gun to relativistic energies of 2.6 MeV diminishes the emittance-diluting effects of space-charge forces and results in a particularly small distribution in energy-time phase space.

To compress the electron bunches from 20 to 30 picoseconds to less than one picosecond, an α-magnet 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 quadrupole along the axis, the beam enters the α-magnet at an angle of 49.29 degrees with respect to the axis, as indicated in the figure on the right. 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. The beam dynamics in an α-magnet have been worked out in detail; the momentum-dependent path length s_0 is given as a function of field strength by

$$s_0\ (\text{cm}) = 19.2\sqrt{\frac{\beta\gamma}{g(\text{T/m})}},$$

where g is the field gradient of the α-magnet. In the illustration on the right, the numerically simulated particle distribution of the previous graph is shown after compression and acceleration to 28 MeV. 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 $55.5 < \beta\gamma < 55.8$.





longer path and then start to fall back toward the center of the bunch. The bunch would reach its shortest length at the exit point of a correctly designed magnetic bunch compressor. From there on the bunch length would be “frozen in” for highly relativistic particles traveling with almost the speed of light, and assuming that we ignore any perturbations.

The shortest electron bunches achieved so far, about 100 fsec rms, have been generated at SUNSHINE (the Stanford UNiversity SHort INtense Electron source), which is an accelerator research facility operated by Stanford graduate students. Here, the electron source is a radiofrequency electron gun that directly generates the monotonic energy variation along the pulse that is required for bunch compression. This differs from the previous technique in that the higher energy particles are in the head of the bunch, and the bunch compressor is an alpha magnet in which the higher energy electrons follow a longer path than those of lower energy particles (see box on the left).

Performing bunch compression is relatively straightforward once the particle beam has been prepared properly. Preserving an ultra-short bunch over longer distances is a much more difficult matter. The shortest bunch length achievable at SUNSHINE is limited by the transverse motion of the electrons. On a femtosecond time scale, a finite divergence of the particles of only a fraction of a degree can cause considerable bunch lengthening because the particles traveling at an angle with respect to the beam axis must be refocused again and again, resulting in an oscillatory path. Such a path is obviously longer than that of a particle following the beam axis, and as a consequence particles traveling along at an angle with respect to the beam axis fall behind, and the bunch is thereby lengthened. The degree of collimation that can be achieved on the transverse beam divergence of the particle beam ultimately determines the shortest bunch length that can be preserved along a beam transport line.

BUNCH LENGTH MEASUREMENT

How do we know just how short is "short"? Conventional time-domain methods of measuring short pulses are simply not adequate to resolve pulse lengths in the femtosecond domain. Traditionally, one would use a streak camera to observe very fast events. In such a camera, a light pulse derived from the electron pulse to be measured strikes a photosensitive screen. Using the photoelectric effect, low energy electrons are released with a temporal distribution that resemble the original electron pulse to be measured. The low energy electron beam is then deflected transversely by rapidly varying electric fields and thereby inscribes a transverse trace on a fluorescent screen. In this way, the longitudinal position of any electron is transformed into a transverse position which can be measured on the screen. The pulse length can be deduced from the transverse width of the trace on the screen. The advantage of this instrument is that the detailed particle distribution of a single bunch can be observed. The disadvantage is its high cost, complexity of operation, and most significant its limitation to pulses of the order of one picosecond. Faster streak cameras are under development by industry, but these developments have not kept pace with the growing ability to generate femtosecond electron pulses.

Hung-chi Lihn built the first far infrared Michelson interferometer optimized to measure electron bunches as short as 100 fsec rms at SUNSHINE.

The alternative to time-domain bunch-length measurements with streak cameras is frequency-domain methods designed to measure subpicosecond pulse durations. In particular, an autocorrelation method that is widely used in the femtosecond laser community is also applicable to subpicosecond electron pulses. The application to particle beams is based on the observation that the coherent part of the radiation emitted by short electron bunches in the form of, for example, transition radiation has a spectrum that is the Fourier transform of the particle distribution. Thus any system that can measure the coherent radiation spectrum can be used for bunch-length measurements. The time-resolution problem has been eliminated—independent of how short the bunch might be—because the radiation spectrum is derived directly from the particle distribution. The only limitations that occur are related to possible spectral changes in the properties of the optical components (windows, mirrors, gratings, beam splitters, and detectors) used in the measuring apparatus. Different kinds of optical spectrometers can be used, depending on the expected bunch length and frequency spectrum. This frequency-domain bunch-length measuring system was proposed by Walter Berry; Hung-chi Lihn built the first far infrared Michelson interferometer optimized to measure electron bunches as short as 100 fsec rms at SUNSHINE. Berry and Lihn shared the 1996 Faraday Cup Award for this development.

Transition radiation is emitted when the electron beam passes through a thin metal foil (see sidebar on the next page). This radiation is guided into a Michelson interferometer, where it is split by a far-infrared beam splitter into two equal parts, each representing the temporal distribution of the particle beam. One part is reflected from a fixed mirror, and its intensity distribution represents the particle distribution to be measured. The other part of the radiation is reflected from a movable mirror and is used to probe the radiation pulse from the fixed mirror. In order to measure any length dimensions, we need a yardstick at the scale of the object to be measured. In this instrument, one part of the split radiation pulse is used as the yardstick to measure the other part. After splitting, each pulse follows a different path through the interferometer towards the detector. By changing the position of the movable mirror, the path legngth of one of the pulses is changed, and the two pulses may arrive at the detector about the same time or completely separated in time. The detector signal is sensitive to the arrival times of the two pulses. It gives one signal amplitude when both pulses arrive at different times and an increasing amplitude as both pulses partially or completely overlap in time at the detector. Observing the increase and decrease of this signal as the mirror is moved allows one to measure the bunch length, which is directly proportional to the movement of the mirror. This method of splitting a pulse and using one part to probe the other is called an autocorrelation measurement.

OUTLOOK

The short bunches that are needed for the next linear colliders or for X-ray FELs have not yet been obtained at the required particle intensity. However, the present state of our understanding and experimentation has brought such potential research tools much closer to realistic projects which may well become possible within the next few years. Coherent, polarized far infrared radiation can already be derived from state of the art short bunches at relatively low cost over a large wavelength range between 40 µm and 1 mm with high brightness comparable to that of FELs, and greatly exceeding that of black body radiation and synchrotron radiation. Having reached a solid foothold on this time scale, beam physics will begin again to question the limits and prepare for the next step.

Michelson Interferometer

COHERENT ENHANCEMENT OF RADIATION occurs over a frequency range which is the Fourier transform of the longitudinal particle distribution; measurement of the electron bunch length is therefore reduced to the observation of the coherent frequency spectrum. At SUNSHINE, a far-infrared Michelson interferometer developed to measure the frequency spectrum has made it possible for the first time to measure particle pulses as short as 100 fsec rms. As shown in the figure on the left, the electron beam passes through a thin aluminum foil to produce transition radiation. By measuring the radiation intensity with a room-temperature pyroelectric bolometer (Molectron Pl-65) as a function of the path-length difference in both arms of the Michelson interferometer, an interferogram (see figure below) is obtained which is the Fourier transform of the radiation spectrum. 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 Michelson interferometer actually performs the Fourier transform of the spectrum automatically 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 introduces frequency-dependent effects caused by the interference of reflected radiation from both surfaces, some corrections 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.