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Developing Electron Beam Bunching Technology for Improving Light Sources

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Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The goal of this project was to develop a new electron bunch compression technology, experimentally demonstrate subpicosecond compression of bunches with charges on the order of 1 nC, and to theoretically investigate fundamental limitations to electron bunch compression. All of these goals were achieved, and in addition, the compression system built for this project was used to generate 22 nm light in a plasma-radiator light source.

1. Background and Research Objectives

The prospect of advanced accelerator applications has motivated research into developing electron bunches shorter than a picosecond with peak currents in excess of 1 kA. Examples of these applications include linear colliders [1], short wavelength free-electron lasers [2], and plasma wakefield accelerators [3], all of which also require a very low emittance (a low emittance is a measure of a very bright electron beam). Typical design goals for pending machines include compressing 1 nC of charge into 0.25 ps with a final emittance of 1 mm mrad. Previous to this LDRD experiment, the state-of-the-art bunch compression was

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from 10 ps to 0.6 ps at 37 MeV with 0.15 nC, with a transverse normalized emittance of about 25 mm mrad [4]. Also of note is the compression reported using an alpha-magnet and an rf gun [5], which was as low as 0.1 ps, but with charges less than 0.05 nC. These previous results clearly do not meet future advanced accelerator requirements.

The goals of this LDRD project were to demonstrate compression levels relevant to these advanced accelerator applications and to understand the fundamental limits of magnetic compression. There were three thrust areas of research in this project. First, a compression technology based on second order effects in a magnetic chicane was developed. Second, a compressor designed on this principle was built and was used to demonstrate subpicosecond compression of bunch charges up to 1 nC. Third, the two dominant emittance growth mechanisms, the coherent synchrotron radiation force and the noninertial space-charge force, were discovered and analyzed. These emittance growth mechanisms do not preclude the proposed compression results needed for future advanced accelerators, but are important and will lead to constraints on the design of the compressors. In addition, the compressor built for this LDRD project has been used in a collaboration with Northrup-Grumman in which the subpicosecond electron beam was used to excite a neon plasma, which subsequently radiated at 22 nm. No ultraviolet radiation would have been possible without the compressed electron beam, and this experiment demonstrates the impact that this LDRD project will have on advanced light sources.

2. Importance to LANL's Science and Technology Base and National R&D Needs

Compression technology is rapidly emerging as a key technology for advanced accelerator applications, short-wavelength free-electron lasers, and other advanced light sources. As an example, work is progressing on at least four short-wavelength free-electron laser projects worldwide that require subpicosecond compression. Some of these projects are projected to cost in excess of \$2B, and all of these projects will fail if new compression technology is not developed. In the United States alone, there are at least six large projects (short-wavelength free-electron laser, linear collider, high-power free-electron laser, and others) that require advanced bunch compression, some of which will cost in excess of \$1B.

Compression technology, along with nonlinear particle mapping, parametric halo production, and a few other aspects of accelerator physics, are the most active areas of fundamental accelerator research. Because accelerator technology is a core technology base at LANL, it is important that LANL plays a key role in this area both in order to strengthen LANL's core competencies and to ensure that LANL is able to attract sponsors for various future accelerator projects by the virtue of being a recognized world leader in accelerator technology.

3. Scientific Approach and Accomplishments

The project has made significant contributions both experimentally and theoretically. Although these topics are interrelated, we will discuss them separately for clarity.

Experimental Accomplishments

Experimentally demonstrating compression of a 1-nC electron bunch to less than 1 ps (FWHM) was the primary goal of this LDRD project. In previous experiments elsewhere using bunch compressors, the compression took place in pre-existing beamlines within bends originally designed to redirect the electron beam, essentially as an afterthought. As a result, previous compression results were not especially remarkable, and all subpicosecond compression was limited to very low charge. In order to advance the compression state-of-the-art, we planned to design a beamline component especially devoted to compressing the beam, which we planned to install on one of the available electron accelerators available at LANL. We chose to use the photoinjector-driven Extreme Ultra Violet Linac (EUVL), which was being built for a CRADA with Northrup-Grumman to demonstrate a proposed excited-plasma radiation mechanism. We chose the EUVL machine for three main reasons: (1) the open design of the linac would make installation of a chicane easy and compression experiments straight forward to perform, (2) the low beam energy of the EUVL machine (8 MeV) would prevent radio-activation of the compressor (and thus reducing potential complications during the compression experiments), and (3) the compressor would be available for later experiments for exciting the plasma, thereby immediately demonstrating its relevance to advanced light sources. The only disadvantage of using the EUVL machine was the low energy, which as a result constrained the design of the compressor to be as short as possible in order to minimize the effects from the beam's repulsive space-charge forces.

From work on a previous project [6], we decided that a chicane geometry (Fig. 1) would be the best for this experiment. In a chicane, four identical dipole magnets are used (all with parallel edges), and the beam is deflected in a shallow “u” geometry (inverted in Fig. 1). A particle with a higher energy would be deflected less, and have a shorter path length. A particle with a lower energy would be deflected more, and have a longer path length. Since at these relativistic energies, all particles travel very close to the speed of light, this means that a particle with lower energy would take a longer time to traverse the chicane than a particle with higher energy. Thus, an electron bunch could be compressed if the bunch is prepared in such a way that the particles at the front of the bunch have lower energy than the particles at the rear of the bunch. The chicane geometry was partly picked because the parallel edge geometry of the dipoles makes it especially easy to preserve the beam brightness during compression.

Another important aspect of the chicane is that by increasing the beam angle θ , it is possible to introduce any desired amount of nonlinear dispersion, which refers to the path length difference between particles that depends on the square of the difference of the particles’ energies.

The first aspect of this project we worked on was to understand the electron bunch energy and brightness distribution that is produced by the rf photoinjector in the EUVL machine. The electron bunch space-charge forces induce a large emittance growth in the bunch, which dominates the phase-space distributions. This work was published in the journal Particle Accelerators [publication 1]. Simulations using the particle-tracking code PARMELA [7] indicated that at large charges (on the order of 1 nC) there was a large nonlinear correlation between a particle’s energy and its longitudinal position in the bunch, mostly due to the longitudinal wakefields the bunch induces in the accelerating cavities. This nonlinear correlation could be corrected by properly adjusting the nonlinear dispersion of the chicane. We show this effect in Fig. 2, where linear dispersion is adequate for a low bunch charge, but quadratic dispersion is required for a large bunch charge. The horizontal axes in Fig. 2 are phases relative to the rf frequency of the linac (at our operating frequency of 1.3

GHz, a phase of 2 mrad is about $1/4$ of a picosecond). A paper describing this principle of nonlinear compression has been accepted for publication by the journal Nuclear Instruments and Methods in Physics Research A [publication 7]. Some form of nonlinear compression is required for all future compressors trying to compress charges on the order of 1 nC, or more, to lengths of 1 ps or less.

A final consideration of the chicane design was to minimize the longitudinal wakefields within the chicane itself. This was done by using a beam-box within the chicane that had an elliptical cross section, and that would concentrate the bunch's image charges above and below the bunch. In Fig. 3 we see the chicane and beam-box configuration. Detailed simulations of this compressor geometry predicted that bunches with low charges should be compressed to a FWHM of about $1/4$ ps, bunches with about 1 nC should be compressed to about $1/2$ ps, and bunches with even as high charges as 3 nC could be compressed to about 1 ps.

Compression experiments using the chicane and the EUVL machine verified the second-order compression technique, and compressed bunch lengths of no more than 0.25 ps were measured for low bunch charges (about 0.1 nC), and compressed bunch lengths of 0.7 ps for high bunch charges (about 1.1 nC). These results were presented both in an invited talk at the first international compression workshop [publication 3] and in Physical Review E [publication 5]. We measured the bunch length at low charges by transversely spreading out the bunch with an rf cavity and looking at the bunch's transverse size on a downstream screen, shown in Fig. 4 (the amount of transverse spreading is proportional to the bunch length). At high charges, we pioneered a new technique to measure the bunch length, based on measuring the energy spread induced in the beam after compression.

The final experimental accomplishment of this project has been to develop a new emittance measuring technique, based on nonintercepting beam-position-monitors. Although this technique was first proposed in principle in 1983 [8], we have recently been able to modify this technique to reduce the noise and to make reliable emittance measurements.

Subsequent experimental work on the extreme ultraviolet light production CRADA has demonstrated that a 1-ps, 1-kA electron beam is essential for the production of very short wavelength light from a neon plasma, which is excited by the wakefield interaction with a short electron beam. Wavelengths as low as 22 nm (a Ne^{+3} line) were measured. This experiment has already demonstrated the usefulness of this compression technology for advanced light sources.

Theoretical Accomplishments

The fundamental limitation to the compression technology is the energy spread and emittance growth induced in the compressed bunch by space-charge forces while the bunch is in circular motion. For straight-line motion, the space-charge forces in the bunch decrease as the square of the beam energy. This has led designers to naively assume that if bunch compression takes place at a high enough energy, no induced energy spread or emittance growth from the space-charge forces will occur. However, for circular motion, there are two components of the space-charge force that are in fact independent of beam energy, which are called the coherent synchrotron radiation force and the noninertial space-charge force. Both of these forces can significantly degrade the beam emittance to a point beyond that tolerable for advanced accelerator applications.

The coherent synchrotron radiation force leads to a net loss of energy from the electron bunch, which can be thought of as a coherent synchrotron radiation. In the far-field, the radiation consists of wavelengths longer than the bunch length. This force is long range, and a given electron only feels the force from electrons behind it. This force is particularly dangerous, because, for a fixed bend angle, the emittance growth actually increases as the bend radius is increased, as would happen as the beam energy increases. The noninertial space-charge force is a short-range, nonradiative effect.

The noninertial space-charge force was first proposed in a paper published in Physical Review E [publication 2]. Coherent synchrotron radiation was suggested by J.

Schwinger as far back as 1946; the emittance growth from that effect as well as from the noninertial space-charge force was first calculated using a retarded Green's function technique in a paper published in Physical Review E [publication 6]. In Fig. 5, we show the emittance growths from these two effects for a nominal 1-nC, 1-ps electron, 1-mm-radius bunch traveling through a 5° dogleg as a function of the bend radius. It is very clear that these emittance growths exceed the target emittances for many future accelerators.

From this theoretical work, we have learned that the emittance growth scales roughly linearly with both beam radius and angle, and inversely as the square of the bunch length. Since the average beam radius decreases as the beam energy is increased, this means that bunch compression and the transport of compressed bunches must be done at extremely high energies, with only small angle bends. These scaling laws will have a major impact on the design of compressors and transports for future advanced accelerators.

In short-wavelength free-electron lasers, the circular wiggling motion of the electrons in the wiggler itself is enough to generate a large degradation in the bunch's brightness. The coherent synchrotron radiation force is suppressed by the wiggling motion, but the short-range noninertial space-charge force is not; a recent paper submitted to the journal Nuclear Instruments and Methods in Physics Research A [publication 9] argues that for present short wavelength free-electron laser designs, the energy spread induced by this effect is large enough to prevent the laser from saturating. The only apparent way to overcome this effect is to roughly double the energy of the electron beam for planned short-wavelength free-electron lasers.

A final theoretical accomplishment was to predict the amount of compression of a bunch with a very small charge in the first cell of a photoinjector. The compression occurs because in an rf photoinjector, the front of the electron bunch is accelerated by a somewhat lower electric field than the rear of the bunch, and as a result, the rear of the bunch begins to catch up with the front. For sufficiently low charges, compressed bunch lengths of 10-20% of the initial bunch length are possible. A paper describing this work was accepted for publication in Particle Accelerators [publication 8]

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Figure 1. Particle trajectory in a four-dipole chicane.

Figure 2. Longitudinal phase space for an initially 17.5-ps bunch. (a) Before compression - low charge. (b) After compression, using just linear dispersion - low charge. (c) After compression, including the nonlinear dispersion for a 40° chicane bend angle - low charge. (d) Before compression - moderate charge. (e) After compression with purely linear dispersion - moderate charge. (f) After compression with matched linear and quadratic dispersions - moderate charge.

Figure 3. Chicane dipoles and beam-box configuration.

(a)

(b)

(c)

Figure 4. Images of a low-charge electron bunch transversely streaked by an rf cavity. (a) RF cavity turned off, to determine resolution. (b) RF cavity turned on, poor bunch compression - bunch width corresponds to a bunch length of about 4 ps. (c) RF cavity turned on, better bunch compression - bunch width corresponds to a bunch length of about 0.9 ps.

Figure 5. Emittance growth for a 1-ps, 1-kA, 1-mm-radius, 400-MeV bunch in a 5° dogleg as a function of the bend radius. The emittance growth from the noninertial space-charge force is shown as a solid line and the emittance growth from the coherent synchrotron radiation force is shown as a dashed line.