LEAP Phase II, Net Energy Gain From Laser Fields In Vacuum

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Abstract. The current Laser Electron Acceleration Program (LEAP) seeks to modulate the energy of an electron bunch by interaction of the electrons with a copropagating pair of crossed laser beams at 800 nm. We present an optical injector design for a LEAP cell so that it can be used to give net energy gain to an electron bunch. Unique features of the design are discussed which will allow this net energy gain and which will also provide a robust signature for the LEAP interaction.

INTRODUCTION

Modern Terawatt lasers have fluences 13 orders of magnitude greater than those produced by SLAC klystrons and other radiowave sources. This indicates great promise for the production of intense electric fields and for high gradient acceleration. Many schemes for using these large fields directly in a dielectric structure have been proposed [1,2]. STELLA and STELLA-II at Brookhaven have also demonstrated acceleration of electrons using Inverse Free Electron Lasers [3]. The LEAP program, a collaboration between Stanford University and SLAC, seeks to accelerate electrons with the electric field of intense laser light in vacuum by crossing two lasers with opposite phase such that there is a longitudinal component to the field propagating with the electrons [4].

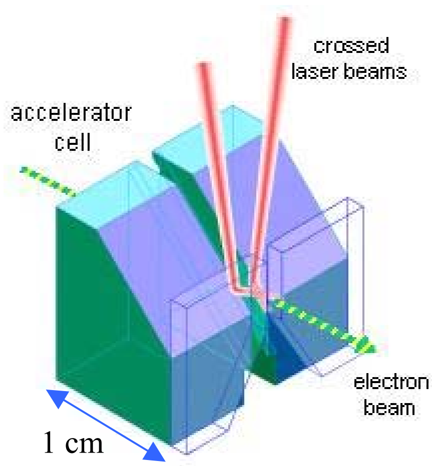

FIGURE 1. The LEAP Cell as used in recent experimental runs.

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In Phase I of LEAP, we seek to modulate the energy of electrons in a bunch produced by a conventional rf accelerator [5,6]. This involves a single interaction between the laser beams and the electrons. Because the electrons cover all phases of the laser field, some particles will be accelerated and others decelerated.

At the SCA-FEL center located at Stanford University, the laser produces regeneratively amplified 800 nm radiation with 1 mJ in two picoseconds. The peak electric field is 1 GV/m, and we have a crossing angle between the two laser beams of 32 mrad. Because the laser phase velocity is greater than c, the 30 MeV electrons slip by π radians in a distance of 1.5 mm, the length of the interaction in a LEAP cell. Energy modulation of 20 keV is thus achieved with one cell.

For Phase II, we will move to the NLCTA facility at SLAC. There we will bunch the electrons at our optical frequency in order to give net energy to the electrons. This article presents the results of detailed simulations showing how to create and preserve femtosecond structure on our electron beam for long enough to accelerate. Demonstration of an optical injector and net energy gain is our goal.

TABLE 1. HEPL and NLCTA Electron Beam Parameters.

Parameter	**HEPL Value**	**NLCTA Value**
Electron Energy	30 MeV	60 MeV
Energy Spread	15-20 keV	20 keV
Beam Charge	1 pC	50 pC
Normalized Emittances	8 π mm·mrad	2 π mm·mrad
Laser Power (Wiggler)	-	40 MW
Laser Power (LEAP Cell)	20 MW	50 MW

PROPOSED EXPERIMENTAL SETUP

Below is a schematic of the layout for our proposed experiment, showing the three main components. First is an IFEL for energy modulation, second is a chicane for optical bunch formation, and last is the LEAP cell where we accelerate:

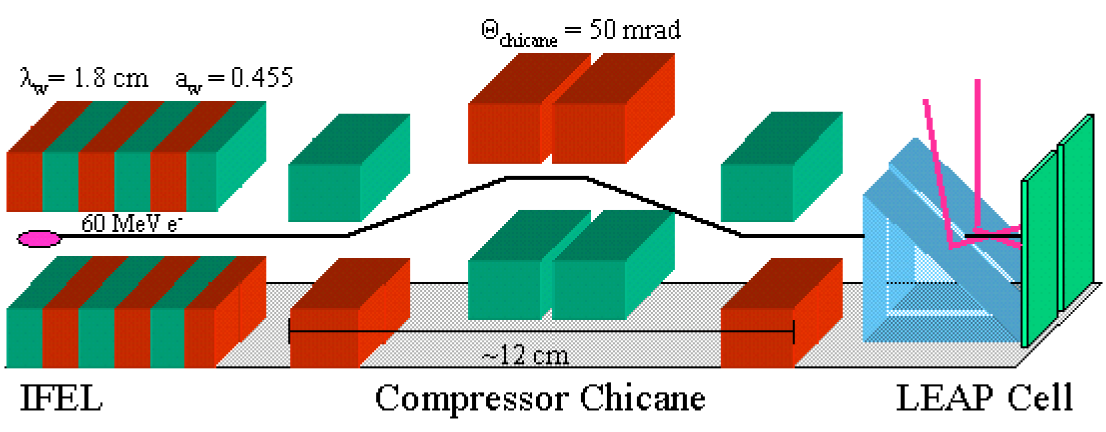

FIGURE 2. Schematic of Phase II. The wiggler period is 1.8 cm and normalized strength is 0.455. The Compressor Chicane deflection angle is 50 mrad.

The Inverse Free Electron Laser (IFEL) modulates the energy of the incoming electron bunch at the wavelength of the drive laser, here 800 nm. After the IFEL modulates the energy of the electrons, travel through the Compressor Chicane converts the energy modulation into phase bunching.

As our original electron bunches from the X-band accelerator are 1 picosecond long, there are expected to be approximately 300 optical bunches produced. The second laser pulse goes to the LEAP cell and accelerates this bunch train.

To gain insight and refine our design, we used a start-to-finish simulation of the NLCTA facility, including proposed additions to it required for Phase II.

SIMULATION

We used PARMELA [7] from the gun through the first accelerator section, as it provides accuracy when the electrons are not highly relativistic. For increased speed, ELEGANT [8] was used to model the rest of the linac to the LEAP interaction area. This article focuses on the simulations of the LEAP cell region to the end. To model the IFEL, GENESIS 1.3 [9] was used, with a few modifications to allow it to share data with ELEGANT. This code is a particle tracking FEL code, where transverse variables are pushed using transfer matrices and the longitudinal motions are given by fourth order Runge-Kutta solutions to the standard FEL equations.

After the IFEL, the propagation to the LEAP cell through the small chicane was again modeled with ELEGANT. For the LEAP interaction and calculation of spectrometer images, a MATLAB code was used.

Figure 3 shows longitudinal phase spaces as the electron bunch propagates through our experiment from the end of the NLCTA main accelerator. The first plot shows the electron bunch produced by the NLCTA, the second shows one cycle of energy modulation after the IFEL. The third phase space plot shows one optical bunch after the chicane, and the last phase space is what is expected after the LEAP interaction.

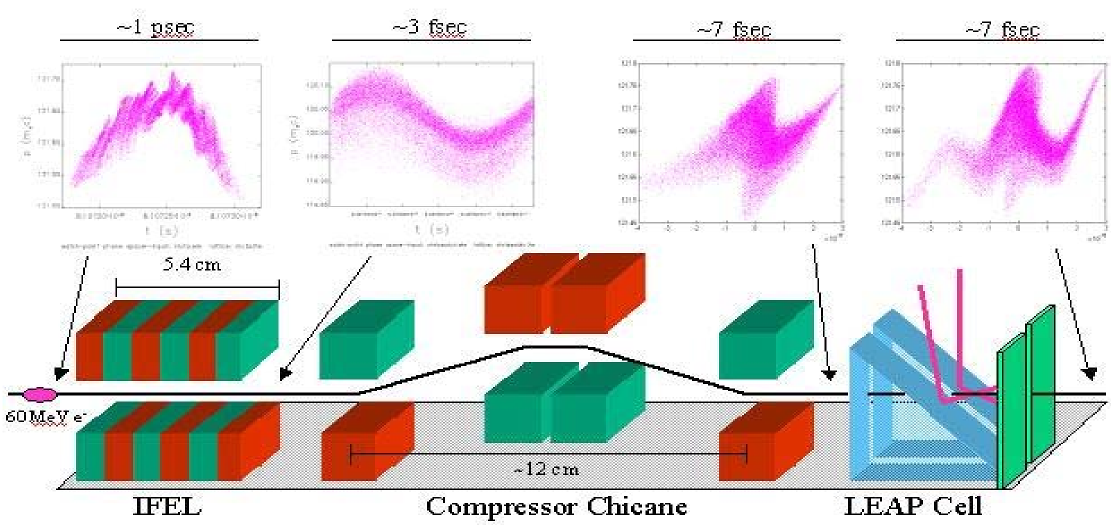

FIGURE 3. Phase space progression through LEAP Phase II experiment

Design Considerations

Because bunching requires that electrons only change phase by as much as one quarter of a wavelength longitudinally, the bunch structure must be preserved to a tolerance of better than 200 nanometers. Path length differences represent a significant condition, in that particles taking extreme trajectories through a focusing system will travel further than the reference particle by more than 200 nanometers unless care is taken.

The desire to minimize path length differences requires that the entire experimental setup be placed near the final focus used to make the electron beam narrow enough to pass through the ~10 μ slit of the LEAP cell.

Thus the IFEL must be as short as practical, while giving sufficient energy modulation to bunch. As the intrinsic energy spread of the beam is of order 20 keV, one can achieve bunching with energy modulations in the IFEL that are not much greater than this value. Our 40 MW of laser power in a 3 period wiggler gives about 70 keV of energy modulation peak-to-peak. Although larger energy modulation allows stronger bunching, it also makes detection of the LEAP interaction's accelerating effect hard to see, driving the design to smaller modulation.

For velocity bunching, these small energy spreads are not sufficient to bunch the electrons in less than 2 meters of drift distance, because the particles are highly relativistic. Fortunately, use of a chicane allows bunching to occur in a much shorter distance. With a deflection of 50 mrad, the electrons achieve maximum bunching in a chicane 12 cm long. Thus, even allowing several centimeters of open space for beam diagnostics, one can bunch the electrons optically in a distance of only 20 cm.

For comparison, STELLA's second stage gives large energy gain, so they can see signal even after inducing large energy spreads to bunch the beam with only a drift space. Also, the bunching at the CO_2 wavelength has a much larger longitudinal scale, so the transverse path effects of refocusing the beam are much less of a concern.

ANTICIPATED RESULTS

As we cannot observe longitudinal phase spaces directly, we simulate what can be observed in the real experiment, namely spectra of the electron bunches. Because the optical frequency bunching is not perfect, significant numbers of electrons will be decelerated even as the majority gain energy.

Below is a simulated scan where the relative phase between the IFEL and LEAP cell is varied over 5 periods. Averaged spectra are taken at 90 degree intervals showing the different effects on the electron beam as the relative phase changes.

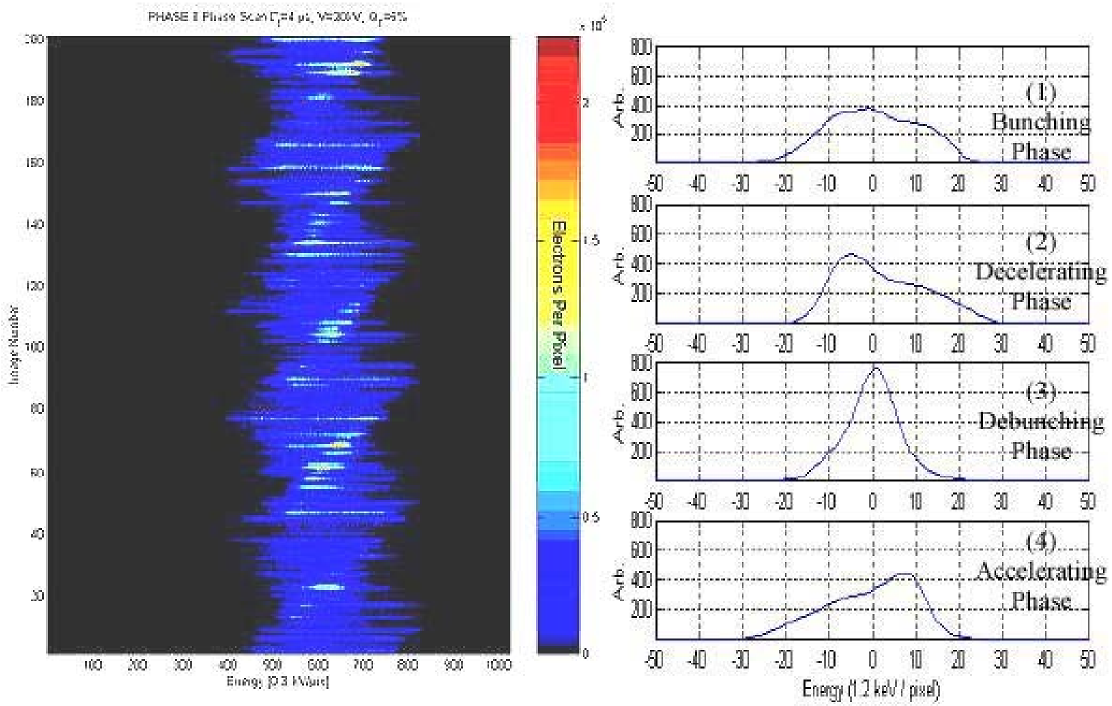

FIGURE 4. Simulated phase scan with jitter covering five cycles of relative phase between IFEL and LEAP cell. On the right are averaged spectra taken each 90 degrees apart, showing the distinctive behavior which provides the robust signature we seek.

These electron bunch spectra change markedly as we scan the relative laser phase between the IFEL and LEAP cell. This behavior, although not ideal for a future practical accelerator, gives a specific signature, allowing ready detection of even a weak LEAP interaction. For a practical accelerator, a superior bunching system would involve larger energy modulations. The current goal is to demonstrate optical bunching at 800 nm, and to detect the LEAP cell's effect unambiguously.

Practical Issues

Based upon experience from Phase I, spatial and temporal overlap of the laser and electron pulses is a significant concern. Both are 1-2 picoseconds long and will be less than 100 microns in RMS transversely.

Care must also be taken to control the phase of the laser beams driving the IFEL and LEAP cells. We will use feedback with delay lines and piezo actuators to ensure repeatable relative laser phase.

Intrinsic energy spread of the electron beam is a consideration, as it directly affects the bunching. The photoinjector proposed for the NLCTA does not have sufficient stability, so we use a chicane and energy collimator to constrain the energy spread and jitter. Studies indicate that as few as 5% of our linac pulses will make it to the LEAP cell, so data taking will be slow.

Fortunately, there are several parameters which have relaxed tolerances. The energy of the electron beam, and equivalently the IFEL wiggler's strength, can vary by several percent without significantly degrading the electron bunching. The chicane similarly can have strength errors of up to 5%. Since the IFEL and chicane will be made with permanent magnets, this insensitivity is helpful.

Such things as electron focusing and position errors will affect the brightness of our images or the data taking rate, but do not affect the signature shapes for which we are searching.

CONCLUSION

LEAP Phase II presents a number of technical challenges, but is very promising. It will demonstrate optical injection for future laser based accelerators, and will show energy gain to electrons in a vacuum using laser radiation.

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