STATUS OF THE LASER ELECTRON ACCELERATOR PROJECT*

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A major goal of the Laser Electron Accelerator Project (LEAP) is to perform an experiment that clearly demonstrates laser acceleration in a dielectric loaded vacuum. The experiment is being carried out at the SCA-FEL facility at Stanford University which provides a 30 MeV electron beam that has been propagated through the LEAP line successfully. The energy spectrometer has been calibrated, the laser transport line is near completion and the dielectric accelerator cell is being assembled. We expect to perform our first attempt to observe laser driven acceleration in the summer of 1998. The design of the experiment is discussed and the expected results are presented.

1 Introduction

The subject of laser driven particle acceleration is an ideal example of a classical, quantum-mechanical wave-particle interaction that has generated considerable discussion ranging from its impossibility to its impracticality. Laser driven acceleration in a dielectric loaded vacuum has been discussed in detail in previous papers both for a single cell and for a high-energy accelerator.[1,2] In essence, the three important practical advantages of this scheme are the higher energy gradients that could be achieved compared to conventional RF linear accelerators, the absence of any material that could deteriorate the electron beam quality as in plasma based laser accelerators and the large-scale commercial developments in lasers and integrated circuit technology.

2 Some general Aspects of Particle Acceleration

Because a free, charged particle can't absorb without emission, it should radiate when scattered or accelerated. This suggests a range of peripheral processes that need to be considered when an electron passes through an accelerator cavity or set of boundary conditions such as implied by the Lawson theorem[3] or its variants. Because this is essentially true of any cavity regardless of acceleration, accelerator structure design is important especially at limiting apertures such as the accelerating cavities and their irises. Schwinger was the first one to clearly understand the limitations this imposed on the attainable energy.[4]

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* Supported by U.S. Department of Energy, contracts DE-FG03-97ER41043 & DE-AC03- 76SF00515.
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High energies, bunched beams, "small" apertures and periodic structures all tend to amplify such effects. Thus, even if the characteristic dimensions of a bunch, e.g. the bunch length, are less than those of the cavity there are still coherence effects that have to be considered. Depending on the type of acceleration, examples include transition radiation or aperture radiation that can be generated at the boundaries needed for acceleration. For aperture radiation, the characteristic wavelength must go as a/γ and the radius a must scale as λ_{acc}. Clearly, the characteristics of the accelerator must change according to this basic scaling variable to achieve whatever the required figure of merit is. The feasibility of a high energy, laser-based accelerator satisfying such conditions has been discussed elsewhere.[5]

Classically, one might evaluate the diffraction of an electromagnetic wave passing through the aperture to find the field energy of the bunch that is diffracted i.e. scattered (and possibly absorbed) by the aperture and surrounding cavities. For laser acceleration one source of coupling between the cells comes from leakage fields through the iris openings. Microscopically this may lead to Compton backscattering i.e. deceleration and energy broadening discussed next.

3 Some Quantum Aspects of Laser Particle Acceleration

Because laser acceleration uses real photons having an intensity $I_L = \hbar\omega\rho_L c$ where ρ_L is the number density of the nearly monochromatic photons one expects that this subject is intrinsically quantum mechanical. For ρ_L we have

$$\rho_L = \frac{I_L}{c\ \omega} = \frac{\langle |E_L|^2 \rangle}{Z_o}\frac{1}{c\ \omega} \qquad \text{where } Z_o = 377\ \Omega. \tag{1}$$

For some laser field E_L, an electron will be interacting with a number of photons $n = \rho_L r_o \lambda^2 = I_L r_o \lambda^2 / c\hbar\omega$ where r_o is the classical radius of the electron $e^2/4\pi\varepsilon_o mc^2$. For $E_L = 10^{10}$ V/m, $\lambda = 1\mu$m and $\rho_L = 2.3\times10^{27}/\text{m}^3$ one finds $n \approx 13$. From the expression for Compton scattering we have $\omega_2/\omega_1 \approx 1/4\gamma^2$ for backscattering, i.e. electrons gain at most $\delta\varepsilon = (\varepsilon_1 - \varepsilon_2) \approx \hbar\omega_1$ in any single, free encounter. The probability of an encounter then gives the effective accelerating gradient

$$\begin{aligned} G_L = \frac{\delta\varepsilon}{\delta z} &= \sigma_c\ \omega_1 \rho_L = \frac{8\pi}{3} r_o^2\ \omega_1 \rho_L = 0.3\ \omega \quad \text{eV/m} \\ &= \frac{8\pi}{3c}\frac{\langle |E_L|^2 \rangle}{Z_o} r_o^2 \approx 0.36 \quad \text{eV/m} \end{aligned} \tag{2}$$

This energy gain results from a completely random or spontaneous Compton single scattering process. In the limit where the scattering may be said to be coherent and stimulated, the potential energy gain of the electron is the energy of the photons of the laser field inside the classical volume of the electron. This is equal[6] to $n \cdot \omega_1 / r_o$ or more than 10^6 GeV/m. This shows that the forward scattering always causes acceleration, even at 0°, and the importance and possibility of stimulated absorption. Any particular result is expected to lie somewhere within this large range. We note that the coupling between charged particle and field can be described by dimensionless classical (η) and quantal (Υ) invariants involving the photon wavelength and electron Compton wavelength:

$$\eta = \frac{e}{m}\left[-\frac{\left(F_{\mu\nu}\cdot p_1^{\nu}\right)^2}{\left(p_1\cdot k_1\right)^2}\right]^{1/2} \rightarrow \frac{e\sqrt{\langle A_\mu A^\mu\rangle}}{m} = \frac{e\langle E_L\rangle}{m}\lambda\!\!\!^{-} = \Upsilon\,\frac{m^2}{2\;\;\omega_1\varepsilon_1} \qquad (3)$$

where c=1 and the arrow implies *head-on* collisions. η =1 (Υ =1) corresponds to an energy gain of one electron mass over one photon (Compton) reduced wavelength.[7] The expression for eF_μ / m^2 when the beams are copropagating is one reason for some skepticism regarding laser acceleration.[8]

4 Experimental Setup

4.1 Overview

The LEAP experiment is located in the SCA-FEL facility, which provides a 30 MeV electron beam and a Ti:sapphire regenerative laser amplifier that delivers 1psec pulses of 1 mJ energy at a repetition rate of 1 kHz. The laser beam has to travel from a FEL laboratory room a total distance of 400 ft. to reach the site of the laser accelerator cell in the SCA tunnel. The laser accelerator cell is not placed directly in the main electron beam line but is located in a secondary line to which single electron bunches from the main beam line can be directed by a fast kicker. An energy spectrometer is placed behind the experimental accelerator cell to measure the effects caused by the test cell on the energy of the electron beam.

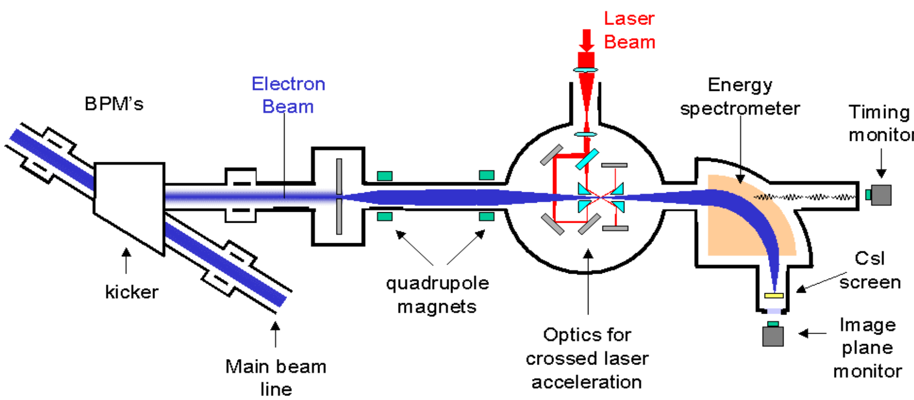

Fig. 1
Schematic of the LEAP experimental setup at the SCA facility

4.2 The electron beam transport line

The SCA-FEL facility provides an electron beam of about 30MeV in electron bunches with a charge of 16 pC per pulse, separated by 85 nsec and 1 to 3 psec in duration. The pulse train is not continuous but comes in macro pulses of 2 msec duration at a typical repetition rate of 10 Hz.

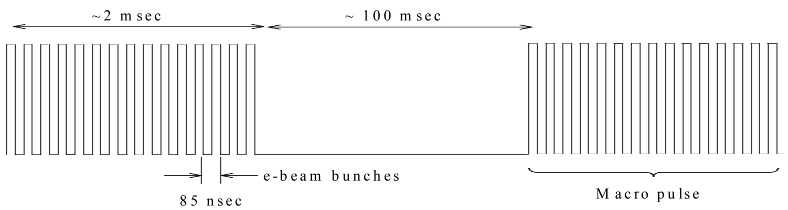

Fig 2
Schematic representation of the beam duty cycle at the SCA-FEL facility

The ability to send individual electron bunches from the main line rather than the full beam is crucial for the success of the experiment, since only one out of every several thousand electron bunches would overlap with a laser pulse. A fast kicker located in the main line gives a 4 mrad deflection (E<70 MeV) to a selected electron beam bunch in the main line, and a permanent sextupole situated downstream amplifies the horizontal kick, sending the desired pulse into the LEAP line. A quadrupole doublet at the beginning of the LEAP line matches the incident beam to the triplet that brings it to a tight focus in the accelerator region, where there is an insertable screen. Another screen for measuring the energy profile of the electron beam is located at the image plane behind the spectrometer.

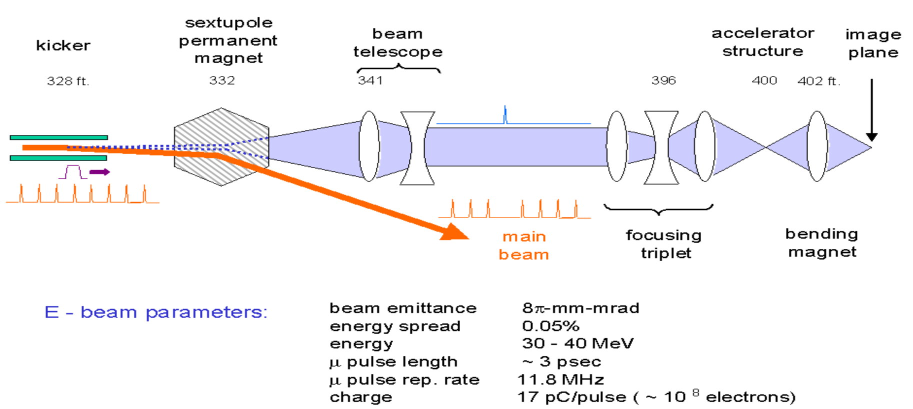

Fig. 3
For clarity the LEAP line was drawn as the undeflected Beam line. Actually the main beam line goes straight and the LEAP line is deflected at the permanent sextupole.

4.3 The laser beam optics

The laser is ~ 400 ft. away from the interaction region. A telescoping scheme is necessary to transport the beam over that distance. To minimize the phase distortion effects from air the transport line is under vacuum. Inside the transport line the beam has a diameter of about 1cm. Small optics have to be used in order to fit them inside the interaction chamber, hence the beam is telescoped down to a spot of 2 mm diameter. A third telescope focuses the beam into the interaction region.

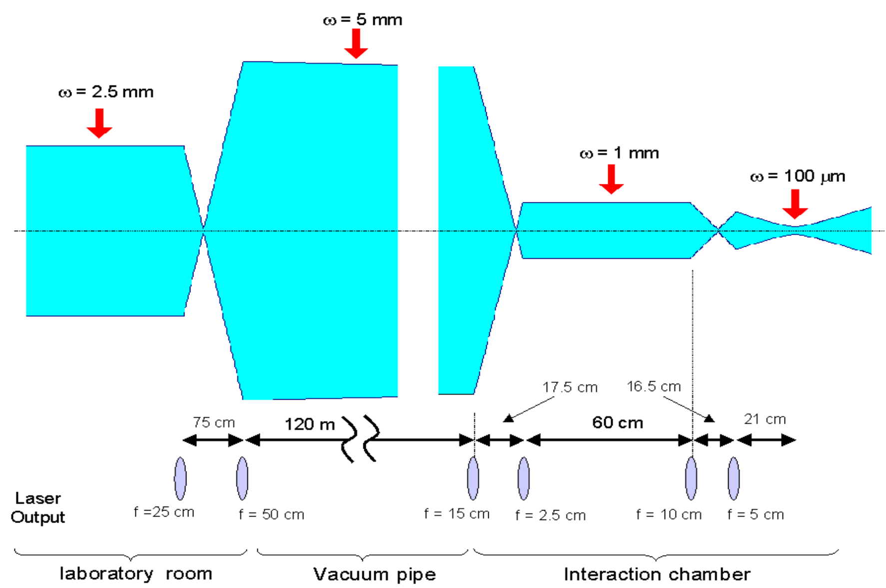

Fig. 4: The laser telescoping scheme and beam line

2.4 The accelerator cell

The accelerator structure is made from dielectric components which are arranged such that a electron beam travelling through the cell is combined with a pair of laser beams that cross inside the accelerator cell. The effect of the length of the interaction inside the accelerator cell, the angle of crossing between the laser beams, and the laser beam intensity on the energy gain of the electron beam will be studied. A maximum energy gain of about 300 keV is expected. For the interaction region we chose to employ four prisms arranged in such a way that they form a slit which allows the e-beam to pass the structure. Two laser beams travel above the plane of the e-beam and are deflected down by a prism into the accelerator cell.

The top prism is attached to a vertical translation stage. The two blocks that support the prisms of the accelerator cell are mounted on two horizontal translation stages. This gives a control of the lateral position and width of the slit trough which the electrons have to pass to transverse the accelerator cell.

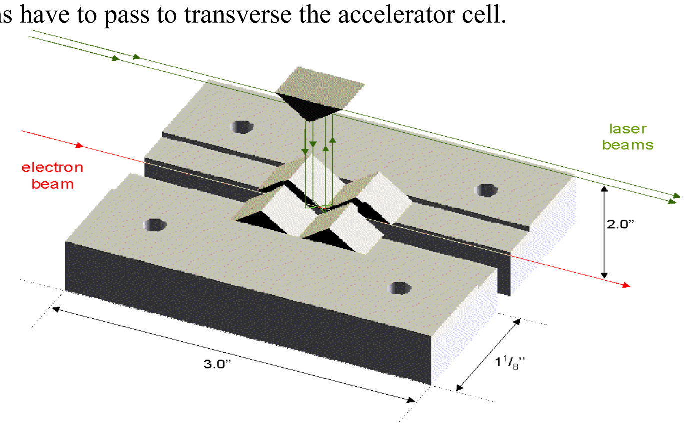

Fig.5: The accelerator cell

In order to reach the 1/3 MeV energy gain that we want to observe we need ~1/20 mJ per pulse if we use 100 fsec pulses focused to about 25 µm. If we use 3 psec pulses we will need about 1 mJ per pulse, which is the maximum output power from the laser source which is a regenerative amplifier from Positive Light.

5 Results

5.1 The energy spectrometer

The energy of the SCA-FEL electron beam could be determined from the precise value of the wavelength at which the FEL was lasing. The SCA-FEL facility monitors the wavelength of the FEL continuously, and corrects for any drift in a closed loop operation. The conversion between FEL wavelength and the electron beam energy is

$$\lambda_{FEL} = \frac{\Lambda}{2 \cdot \gamma^2}\left(1 + \tfrac{1}{2}K^2\right) \tag{4}$$

Where λ_{FEL} is the wavelength at which the FEL is lasing, Λ the period of the wiggler, γ the time dilatation constant for moving particle, and K the strength of the wiggler. The value of K was specified to be K^2 = 0.69, and the wiggler period Λ = 2.9 cm. The energy spectrometer is a dipole sector magnet designed to bend the beam by 90 degrees in a radius of ~1/2 m. The first order resolving power R is

$$R = \sqrt{\left\langle \frac{P}{\Delta P} \right\rangle^2} = \frac{\eta_x}{\sigma_x} = \frac{1.12 \quad m}{30 \quad \mu m} = 4 \cdot 10^4 \tag{5}$$

where η_x is the dispersion and σ_x is the monochromatic spot size at the focal plane. σ_x is defined in terms of the transverse emittance and the beta function as $\sqrt{\beta_x \cdot \varepsilon_x}$.

5.2 The electron-beam images behind the spectrometer

A CsI screen behind the spectrometer was monitored with a CCD camera. The calibration of the dispersion observed by the CCD was performed by measuring the displacement of the image for a known change in the magnet current. The spectrometer is well suited to measure the energy profile of any electron bunch in the pulse train that drives the FEL.

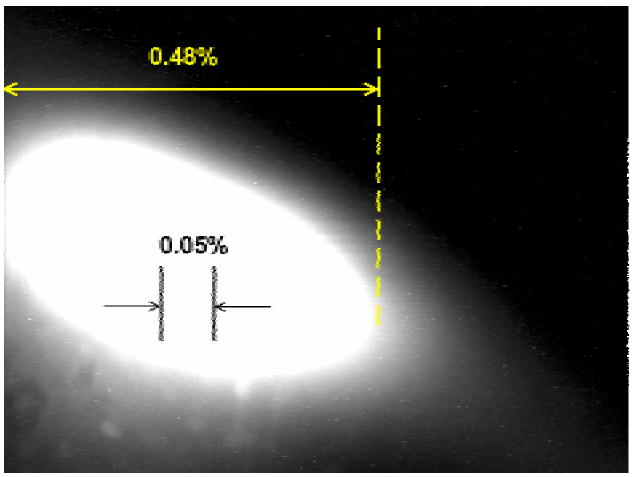

Fig. 6
Image of the full electron beam when the FEL in not lasing. The observed spot is formed from about 20 thousand micro-bunches.

These images were taken with the full electron beam and the bright areas were clearly saturated. This may be part of the reason why the spot in the image above is larger than the expected 0.05% energy spread. Assuming that the image was optimally focused and that there was no blooming the observed 0.48% corresponds to a ~140 keV full energy spread at the base.

With the FEL lasing the energy spread in the beam was so large that an image could only be formed by taking several pictures at different spectrometer magnet current strengths. When the FEL is lasing weakly a faint tail of lower energy is seen to appear along with the bright spot that appears alone when the FEL is off.

When lasing strongly, the whole distribution of the electron beam shifts toward the lower energy end, implying an average deceleration for the electrons due to the FEL.

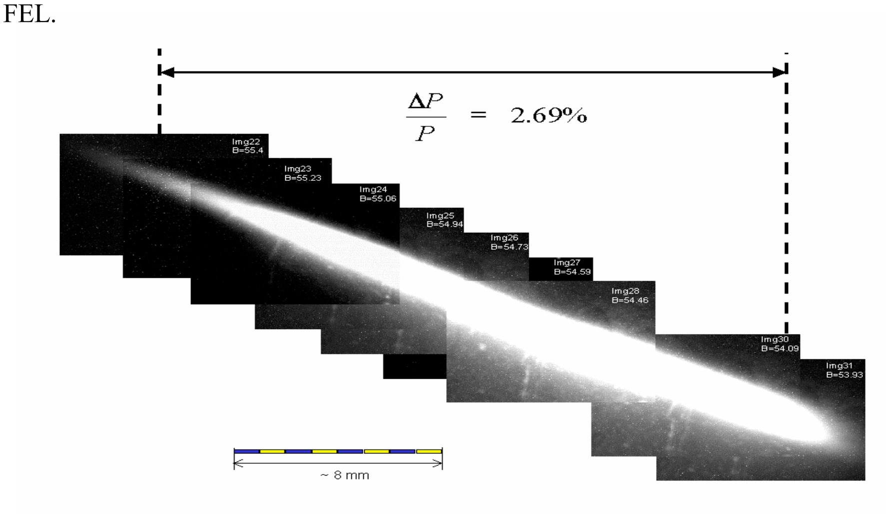

Fig. 7
Image of the electron beam energy spread when the FEL is lasing strongly. The low energy end is clearly brighter.

6 Important aspects of the experiment

6.1 Optimized laser pulse duration

The maximum expected energy gain from the single accelerator stage is about 300 keV. In our first experiment the electron beam is not optically bunched to match the optical cycles of the laser. The laser optical cycle is $\sim 1\mu$m whereas an e-beam pulse of 1 ps is about 1 mm long. It can be assumed that the electrons are equally distributed over all the optical phases of the laser beam. Therefore, rather than a discrete shift in energy a certain energy distribution about the initial e-beam energy is expected. Since the probability for gaining energy is equal to that for losing the same amount of energy the distribution is expected to be symmetric.

For an ideal monoenergetic beam this distribution shows a sharp acceleration and deceleration peak. When the initial energy spread of the e-beam is taken into account the sharp peaks smear out as fig. 8 illustrates. For the SCA beam, if the energy spread is 0.05%, the ΔE ~ 15 keV and the acceleration and deceleration peaks would be clearly visible. For 0.5%, which is what we observed with the FEL off, ΔE ~150keV, and this would roughly correspond to line 3 in Fig 8.

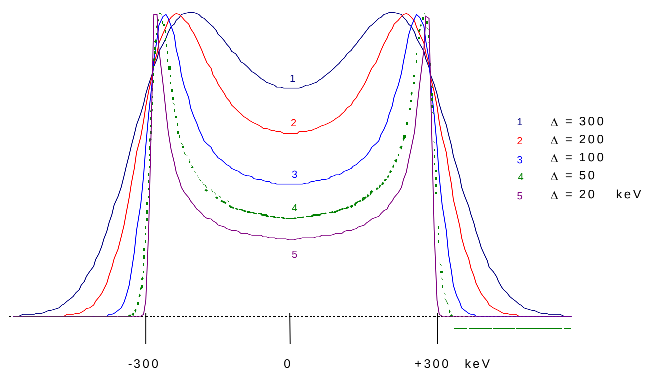

Fig. 8
Energy profile for a maximum acceleration of 300 keV at various initial beam energy spreads

The relative duration of the laser pulse to the electron pulse plays an important role in the energy distribution of the e-beam. If the laser pulse is much longer than the e-beam pulse a distribution like the one in the previous graph is expected, where the laser intensity was kept constant but the phase was random. If the laser and the e-beam pulses have the same time duration less electrons see the maximum possible acceleration. In the limit where the laser beam is very short compared to the e-beam most electrons experience no change in energy. The effect of finite time duration of a laser beam of fixed energy per pulse is illustrated in fig. 9.

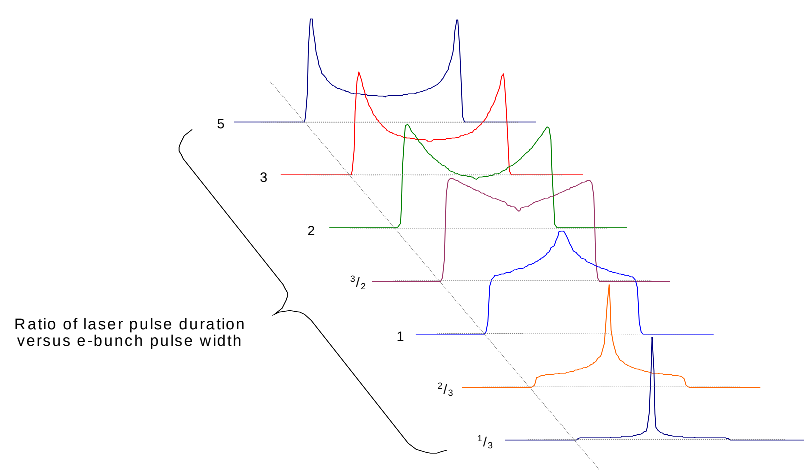

Fig. 9
Effect of the laser pulse duration. To display the relative intensity between the center and the sides of the energy histograms, each curve was normalized to have a maximum peak height of 1.

Both the laser pulse and the e-beam pulse are assumed to have a gaussian temporal profile. In order to obtain clear acceleration/ deceleration peaks the laser pulse should be at least three times longer than the e-beam pulse. For 3 psec e-beam bunches, laser pulses of ~10 psec time duration should be used.The ability to vary the laser pulse duration and timing accurately provides a measure of the energy distribution along the electron bunch and its length.

4.2 Effect of finite gamma

The finite gamma factor reduces the distance required for the electron beam to become out of phase with respect to an optical cycle of the laser beam. This effect reduces the distance useful for acceleration. For a 35 MeV electron beam the effect is reasonably small provided the interaction length is less than 1 mm.

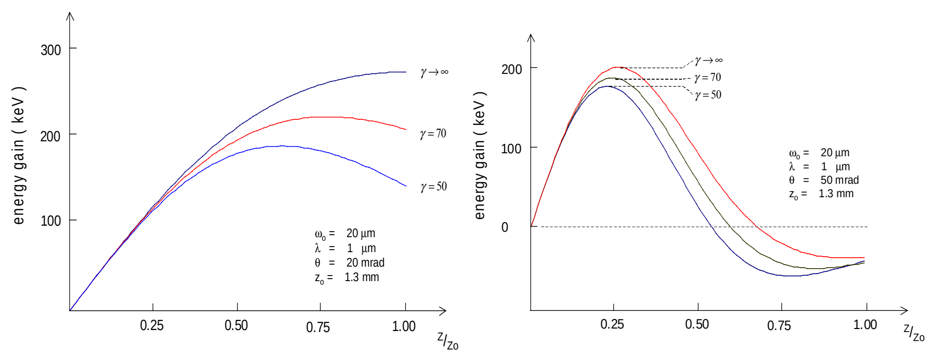

Fig. 10: The expected energy gain for θ = 20 mrad and θ = 50 mrad crossing angles

5 Conclusions and future plans

Armed with a high resolution, high sensitivity energy spectrometer and a bright source of photons LEAP is capable of measuring radiative effects in a regime where the corresponding forward emitted photons are difficult to discriminate. The LEAP experiment can be extended with few modifications to study scattering effects other than acceleration such as the Compton effect that has a *K* analogous to the FEL. The effect of the length of the accelerator cell is interesting in this regard because it allows to observe the effects of the different boundaries, for example halving the acceleration discussed above or introducing a net deceleration. The ultimate goal for LEAP is to understand how such radiative effects depend on the accelerator structure design in order to devise an accelerator structure optimized for keeping a clean electron beam emittance while optimizing the acceleration gradient.

During the summer 1998 efforts will focus on obtaining the minimum possible timing jitter between the laser beam and the electron beam. We expect to carry out our first attempts for observing laser driven particle acceleration before the end of summer 1998. We will measure the electron energy distribution as a function of

- laser beam intensity
- the effective laser-electron beam interaction length
- the angle of crossing of the laser beam pair
- polarization of the laser beam
- position and size of the electron beam
- micro-bunch location in the macro pulse train (FEL on/off)

Acknowledgements

The authors thank Pisin Chen for a fine conference as well as Roger Route, Kellie Koucky, Jim Schmidt, Simon Larochelle, Chris Barnes, An-Chung Chiang, Dennis Palmer, Bill Smith, Dieter Walz and professors R.H. Pantell and H.A. Schwettman.

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6. The number-phase relation $\delta n \cdot \delta\phi \geq ½$ implies we should use $n^{½}$ rather than *n*. The scattering in the forward direction is coherent but with a classical phase uncertainty.
7. The electron effective mass in the laser field is easily shown to be $m\sqrt{1+\eta^2}$ so that $m\eta^2/2$ can be identified as the ponderomotive potential in the equivalent Hamiltonian for the electron in the laser field.
8. When the *E*- and *B*- fields are equal and orthogonal as in a plane wave the coupling goes to zero as the particle velocity v approaches *c* for copropagating beams. This is one reason why we cross a pair of laser beams at an angle with respect to the particle beam. This also eliminates any transverse acceleration and its larger radiative effects. Body self fields cancel but external B-fields, imposed for better synchronism, require radiative corrections that are seldom discussed. This is one reason why we don't use external B-fields. Other technical objections[3] such as reduced beam intensities are discussed in Ref.5.