THE LLNL/UCLA HIGH GRADIENT INVERSE FREE ELECTRON LASER ACCELERATOR

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Abstract

We describe the Inverse Free Electron Accelerator currently under construction at Lawrence Livermore National Lab. Upon completion of this accelerator, high brightness electrons generated in the photoinjector blowout regime and accelerated to 50 MeV by S-band accelerating sections will interact with $>$ 4 TW peak power Ti:Sapphire laser in a highly tapered 50 cm undulator and experience an acceleration gradient of $>$ 200 MeV/m. We present the final design of the accelerator as well as the results of start to end simulations investigating preservation of beam quality and tolerances involved with this accelerator.

INTRODUCTION

Previous work has shown that acceleration of photoinjector electron beams via an inverse free electron laser interaction is viable both in maximum energy gain and in trapping [1], [2] up to GeV energy. Such as compact accelerator has applications ranging from x ray FEL to inverse Compton scattering. In this interaction a relativistic electron beam is co-propagated through a planar undulator with a high power laser. The undulation of the electron beam allows it to couple to the laser's electric field. The parameters of the undulator can be selected such that a maximum energy exchange between the electron beam and laser field occurs. This resonance condition is:

$$\lambda = \frac{\lambda_u(1+\frac{K^2}{2})}{2\gamma^2} \quad (1)$$

Where λ is the laser wavelength, λ_u is the undulator period, γ is the central energy of the electron beam normalized by the electron rest mass energy, and K is the undulator strength parameter, which a normalized magnetic vector potential and is equal to $eB_w\lambda_u/2\pi mc^2$ where B is the rms magnetic field of the undulator.

Because the energy of the electron beam is increasing during the acceleration process, the undulator is tapered both in field and period such that the trapped electron beam remains on an acceleration curve from an initial energy of 50 MeV to a final energy of 200 MeV. This experiment differs from previous experiments in that it uses a higher peak power and higher repetition rate laser to interact with the electron beam. Previous simulations [3] have shown that the power of the laser must be 4 TW, which is obtained using 500 mJ compressed to 120 fs. Using a short laser makes temporal overlap a significant factor in the experiment and thus a short electron beam must be used in order to get a reasonable amount of electrons trapped and accelerated to 200 MeV. In this paper we describe start to end simulations of the electron beam from the photocathode, through the initial traditional rf accelerating sections up to 50MeV, through compression to 100 fs bunch length, and finally the acceleration. Some accelerator parameters and tolerances are discussed as well as a timing diagnostic to characterize and separate the temporal overlap factor in this experiment.

EXPERIMENTAL LAYOUT

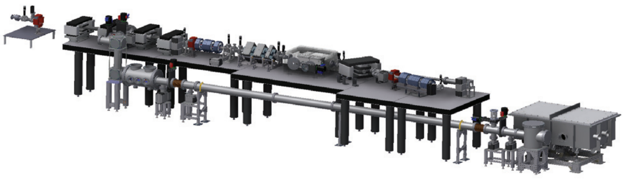

Figure 1: CAD model of the compressor and IFEL region of the LLNL IFEL experiment.

Laser Description

An 800 nm 30 mJ 200 ps laser pulse is split 90/10. Ten percent of the laser power is sent to a third harmonic generation (THG) section using nonlinear crystals and compressed to 100 fs to drive the photocathode and make the electron beam. The remaining 27 mJ is sent through a delay line to a main amplifier to be amplified to 700 mJ. This beam is then compressed to 500 mJ 120 fs in order to get sufficient field for trapping a reasonable 40% of the electron beam in the accelerating bucket. The laser is then sent through a transport in vacuum to a final focus off axis parabolic mirror selected such that the Rayleigh length is 3.5 cm with a spot size at the waist of 100 μm at the center of the undulator.

Electron Beam Description

The electron beam is emitted from a photocathode using the 266 nm generated by THG of the 800 nm. The electron beam is accelerated in a 1.6 Cell BNL/UCLA/SLAC style photogun to approximately 5 MeV. With a charge of 100 pC and initial radial spot size and bunch length of 1 mm and 120 fs, respectively, the electron beam is generated in the photoinjector "blowout" regime. In the blowout regime a rapid space-charge dominated longitudinal expansion transforms the distribution of the beam to one that is approximately a uniformly filled ellipsoid. This reduces the space charge induced emittance growth both transversely and longitudinally at low energy before acceleration.

The beam is accelerated by two SLAC style accelerating sections to 50 MeV and a negative chirp is induced on the beam so that it can be compressed in a chicane. The beam is compressed to an rms time value of 60 fs and drifts to a final focus quadrupole triplet section to match into the undulator with a spot size of 25 μm with the waist at the center of the undulator.

After acceleration the beam is sent to a dipole spectrometer designed to measure entire energy range from 50 MeV to 200 MeV. The spectrometer's fluorescent screen can be extracted enough to allow the 200 MeV electrons to escape to a downstream quadrupole triplet and diagnostic screen where the emittance of the accelerated part of the beam can be measured via a quadrupole scan technique.

A computer assisted design (CAD) model drawing for the end of the LLNL/UCLA IFEL experiment is shown in Fig. 1. On the right the main laser compressor as well as the transport to the left where the focusing OAP mirror and injection of the laser into the center of the chicane occurs. The electron beam approaches from the left after being accelerated to 50 MeV and acquire chirp from the SLAC style accelerating sections (not shown) is compressed in the chicane, runs through a timing diagnostic section and is focused to be matched into the undulator with the laser. Finally the spectrometer and quadrupole section can be seen on the right end of the optical table.

START TO END SIMULATION

To model the electron beam's interaction a cross platform simulation set was used. At low energy where space charge is important, the beam is modeled using Parmela [4]. Parmela tracks the particles through the conventional acceleration to 50 MeV and the application of the chirp on the beam. During this section two quadrupole triplet sections keep the beam round and roughly collimated around a mm RMS. Elegant is then used to perform the simulations through the compression in the chicane. The embedded Saladin/Stupakov models for CSR are used to model the electron beam through the chicane and drift after, as well as the two final focus quadrupole triplets that match the beam into the undulator [5]. Finally the distribution is placed into cbeam [3], a particle tracking code developed by S. Anderson that tracks the particles through the undulator and IFEL interaction. Cbeam has an option for with higher order Laguerre-Gaussian "supergaussian" modes, which are a more realistic representation of the applied laser as some saturation occurs during the amplification process transversely in the lasing medium.

A sample longitudinal phase space plot resulting from the start to end simulation is shown in Fig. 2. Clearly acceleration of a part of the beam can be seen, as well as some structure due to particles slipping out of the accelerating bucket and falling into another. A histogram of the energy of the beam is shown in Fig. 3. This should closely match the image obtained on the spectrometer screen. This simulation is performed using the optimized parameters reported in Table 1. To understand what we will likely observe during the experiment parameters were varied around to this operating point to determine tolerances for the accelerator.

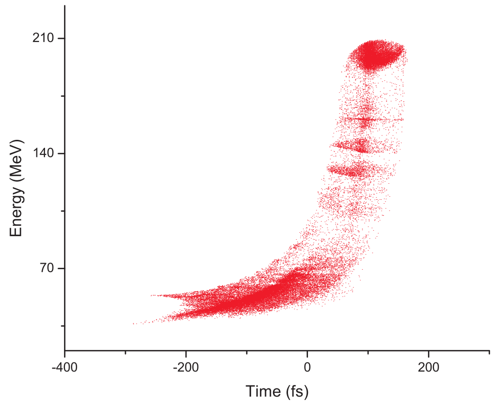

Figure 2: Longitudinal phase space plot of beam after acceleration.

Table 1: Operating Point Parameters

Operating Point Parameters	
Initial Energy	50 MeV
Final Energy	200 MeV
Normalized Emittance	.6 mm-mrad
Charge	100 pC
Undulator Parameters	
λ_{u0}	1.5 cm
λ_{uf}	5.0 cm
$K_{initial}$	0.2
K_{final}	2.8
L_u	50 cm

TOLERANCING AND TIMING DIAGNOSTIC

Tolerance Studies

Tolerance studies were performed by varying parameters such as charge, initial transverse spatial offset into the beginning of the chicane, and time of arrival at the undulator. The figure of merit for these studies is the percentage of electrons captured and accelerated to 200 MeV. The results of these studies can be seen in Fig. 4.

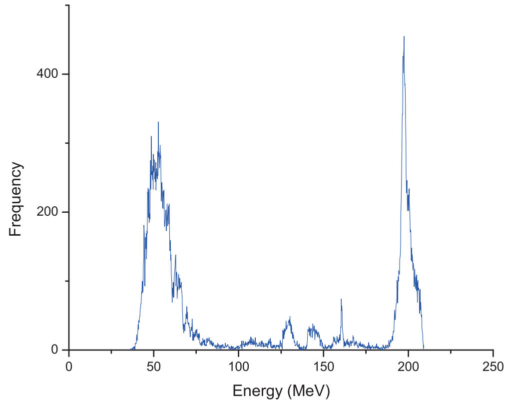

Figure 3: Histogram of Energy of beam at accelerator operating point. The accelerated beam is roughly 40% of the total beam can be seen as a spike at 200 MeV.

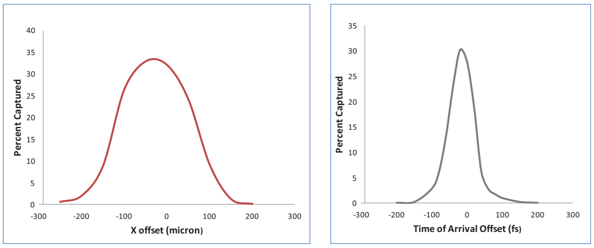

Figure 4: Spatial and TOA Tolerance Studies.

Timing Diagnostic

As mentioned earlier, to keep the trapped electrons on the acceleration curve from 50 MeV to 200 MeV set by the undulator tapering profile, the electric field of the laser must be such that the laser's peak power is 4 TW, and the laser pulse length must be 120 fs. As can be seen from the tolerance studies the time of arrival (TOA) sensitivity is on the order of 100 fs. With this level of sensitivity an online time of arrival diagnostic is useful in characterizing and understanding the accelerator's behavior.

Recent work done at UCLA has shown that spatially encoded electro-optic sampling (EOS) can act as a relative TOA diagnostic with a temporal resolution of 100 fs [6]. In that work a ZnTe crystal was placed 5 mm above the electron beam and a the polarization of a laser traveling perpendicularly to the electron beam path is modulated by electron beam's field. By using crossed polarizers and a camera the spatial information of the electron beam's field is mapped in onto the transverse profile of the laser detected at the camera. This field map has the shape of a line set at the Cerenkov angle. If a lineout is taken longitudinally, the centroid can be measured. The change in the centroid of this lineout shot-to-shot gives information about the relative time of arrival of the electron beam. This measurement is non destructive and thus can be taken every shot at the standard repetition rate of the laser (10 Hz) while the accelerator is being operator. Thus the time of arrival can be directly correlated with the spectrometer measurements and accelerator can be characterized with respect to the time of arrival.

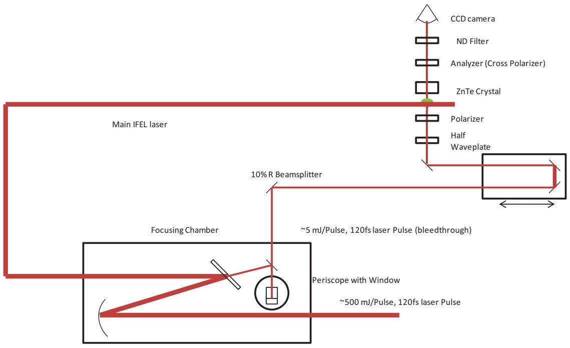

Figure 5: Timing Diagnostic Layout. Bleedthrough of one of the mirrors in the focusing chamber for 500 mJ laser yields a beam of roughly 1% of the power. This laser s transported through a delay stage to a cross polarizer setup where the field profile of the electron beam modulates its polarization. The transmission through the analyzer maps out the field of the electron beam. The centroid of the signal presents a relative time of arrival shot-to-shot.

CONCLUSION AND OUTLOOK

The laser installation for the experiment will be complete by the end of May 2012. First attempts at acceleration are scheduled for June 2012. Possibilities of inverse Compton scattering or x-ray FEL light source can happen as early as next year.

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