Low Emittance High Energy Gain Inverse Free Electron Laser Using a Waveguided Helical Undulator

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Abstract

Free electron lasers (FEL) are capable of producing high brightness X-ray radiation but require a high current and low emittance electron beam. Work is underway at the UCLA Neptune laboratory to produce such a beam using an inverse free electron laser (IFEL). Producing a high energy gain IFEL requires a high power laser. Due to the power limitations of the optics, the near-TW CO_2 laser implemented by UCLA provides the needed power at the cost of a short Rayleigh length. After several modifications, including the addition of a waveguide to control the highly divergent laser beam, the helical undulator design has been completed. This design is expected, from 1-D electron dynamic simulations, to produce a 100 MeV electron beam with a trapping fraction of 63% and a normalized emittance of 5 mm-mrad.

Introduction

The FEL is a versatile laser with applications in a wide range of fields. Its high power, at a wide range of wavelengths from millimeters to X-rays, makes it the prime candidate for antimissile defense systems. Imaging of nanostructures is also possible with this extraordinary laser due to its short wavelengths and picosecond laser pulses that are able to image an object without destruction [1]. None of the characteristics that make the FEL so versatile would be possible without a highly energetic, low emittance, electron beam. In fact, the advancement of the FEL is strongly dependent on the development of superior electron accelerators.

Advancements of the FEL have mainly occurred over the past decade with higher energy accelerators becoming more common. The first FEL developed by Dr. Madey in 1976, five years after he created the FEL theory, only amplified a 10 μm laser beam by a small amount. It took scientists nearly another two decades and a half a billion dollars from the government, who wanted to use the FEL as an antimissile defense system during the Cold War, to produce a sixth of the power of a standard light bulb (11 W). Powerful FELs could not be created because technology had not yet caught up with the physics. It was not until accelerators reached higher energies that true advancements in FELs began.

Although accelerators have been rapidly increasing in energy, the majority are large and expensive making them impractical for producing FEL. However, the IFEL is a new form of accelerator that promises to produce a high acceleration gradient while remaining smaller than its counterparts. Generating such a gradient with an IFEL requires a powerful laser and a strong undulating magnetic field. The final design, along with the IFEL theory, the design process of the undulator, including problems, simulations and modifications are presented in this paper [2].

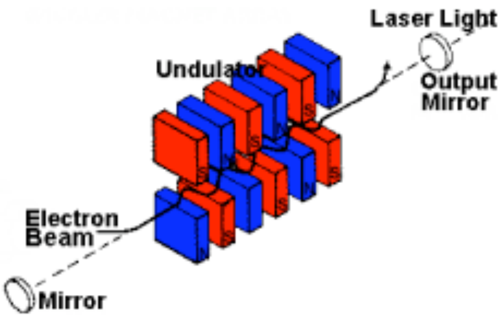

Figure 1: *Diagram of the major components of the FEL in the oscillation scheme. Two mirrors form an optical resonator with a planar undulator in the middle. The electron beam travels down the length of the undulator producing radiation that forms the laser light.*

FEL Theory

Free electron lasers consist of two main components; a relativistic electron beam and an undulator. An undulator is a series of magnets that form a sinusoidal magnetic field. Due to the Lorenz force the electron beam begins to wiggle as it is injected into the undulator (Figure 1). This up and down motion, as seen in the electrons frame, produces dipole radiation because the electrons are accelerating charged particles. This radiation is then Doppler shifted to higher frequencies or shorter wavelengths into the laboratory frame. The wavelength of the radiation that is produced is dependent on the energy of the electron beam, magnetic field of the undulator (B_u), and undulator period (λ_u) [3].

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

Where

$$K = \frac{eB_u\lambda_u}{2\pi mc} = 0.093B_u(KGauss)\lambda_u(cm)$$

The FEL can operate in three different lasing schemes: amplification, oscillation, and self amplified spontaneous emission (SASE). High power laser light in the X-ray wavelengths can only be created through operation in the SASE scheme. Operation in the other modes is not possible because X-ray seeding lasers do not exist (amplification) and mirrors do not reflect X-ray wavelength light which are needed to form the optical resonator of the oscillation scheme. In the SASE scheme a long undulator is used. Radiation is produced in the first section of the undulator and is then amplified as it progresses along the remaining length. To produce short X-ray wavelengths in this scheme the emittance (ε) of the electron beam must follow this inequality [4].

$$\varepsilon < 4\beta\gamma\lambda$$

So by producing a low emittance electron beam it is possible to obtain short wavelength X-rays without large expensive high energy accelerators.

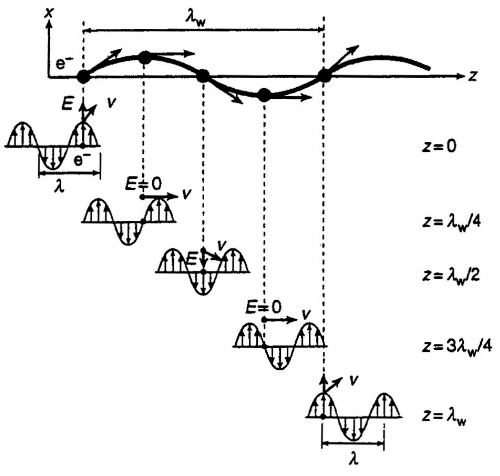

Figure 2: *Snapshots of the electron and electric field of the laser as they progress along the length of an undulator. This diagram is of a FEL since the wiggle velocity of the electron is in the same direction as the electric field of the laser. For an IFEL the electron wiggle velocity will be in the opposite direction.*

IFEL Theory

The inverse free electron laser, as the name implies, operates in the FEL laser amplification scheme but in reverse. In the FEL laser amplification scheme, a seeding laser is injected along with the electron beam into the undulator. If the electron wiggle velocity is in the same direction as the electric field of the laser (Figure 2) then energy is transferred from the kinetic energy of the electron beam to the laser, and the laser is amplified. However, if the electric field and electron velocity are in opposite direction then energy is transferred from the laser to the electrons, causing the electrons to accelerate. So the IFEL is a FEL operating in the laser amplification scheme with the electron beam 180 degrees out of phase. Net acceleration occurs when [5]:

$$\lambda_r = \frac{\lambda_u}{\beta^2}(1 + K^2)$$

The radiation wavelength (λ_r) is the wavelength of light that is being used as the seeding laser. So the undulator period (λ_u) and magnetic field (B_u) must be chosen to satisfy the above condition.

Design

UCLA's IFEL is unique in the high power laser that it employs. High acceleration gradients can be created using the 10.6 μm CO_2 laser able to produce 0.3-0.6 TW of power. A short Rayleigh length is the cost of this high power. Large mirrors, with small f/#, are required since the intensity of the light would destroy smaller mirrors. The highly divergent laser beam, due to the short Rayleigh range, caused the laser and electron beam to be mismatched and prevented ideal electron acceleration in the previous designs. In the new IFEL design a waveguide is used to control the divergent laser beam.

Research has been conducted at UCLA to find the optimum waveguide for this situation. To maintain the high acceleration gradient throughout the undulator the waveguide must not significantly attenuate the laser. Capillary waveguides, hollow conducting cylinders, are the simplest form of waveguides. The power loss in these waveguides is caused by the power dissipated in the conducting walls from the induced currents created by the magnetic field of the electromagnetic wave. The power loss in lower order modes for a copper waveguide is quite small. However, these waveguides can excite higher modes, in turn destroying the ideal electron acceleration scheme. An Open Iris-Loaded waveguide Structure (OILS) has been found to be the ideal waveguide for this situation. The OILS is a cylindrical pipe with a series of irises along its length. In this structure the laser beam is kept from diverging and has little interaction with the walls of the waveguide. Small amounts of attenuation along with no excitation of higher modes makes this waveguide perfect for the UCLA IFEL.

Producing a high acceleration gradient also requires a strong precise magnetic field inside the undulator. If the magnetic field is slightly flawed the electrons will not obtain the appropriate trajectory and peak acceleration will not occur. UCLA's undulator design allows the individual magnets to be adjusted to create a nearly flawless field. Designing the undulator to have a strong but tunable magnetic field is challenging because the magnets are created of Neodymium Iron Boron (NdFeB), which is a fairly brittle material. As such, the magnets themselves can not be threaded to be adjusted by a screw. Instead a holder must be created for the magnets that will allow them to be adjusted. Several problems were encountered in the design of this holder. The holder itself must be of simple design so it will be easy to machine. It must be able to constrain the magnet from shear forces. It must be designed so that the magnetic field remains as strong as possible by keeping the magnets close together.

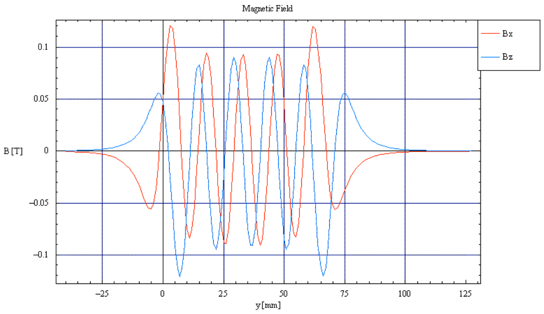

Figure 3: *Simulation of the magnetic field of the UCLA undulator using Radia. The red plot is the magnetic field in the x-direction and the blue is the magnetic field in the z-direction. The strength of the magnetic field is the 0.1 T that is required for ideal electron acceleration.*

After three design modifications the magnet holder design is complete. Simulations were conducted on the static magnetic field that this design creates using a program called Radia, created by the European Synchrotron Radiation Facility (ESRF). From 1-D electron dynamic simulations it has been found that to achieve strong bunching and a high acceleration gradient the magnetic field of the undulator needs to be around 0.1 T. By increasing the size of the magnets from the previous design to 11 x 11 x 3.6 mm the desired strength of the magnetic field is achieved, figure 3 is a graph of the simulated magnetic field. The magnet design was then improved upon further. Instead of using rectangular magnets the magnets were slightly tapered on one end. This barely affects the strength of the magnetic field, but allows the magnets to be moved closer together, increasing the field.

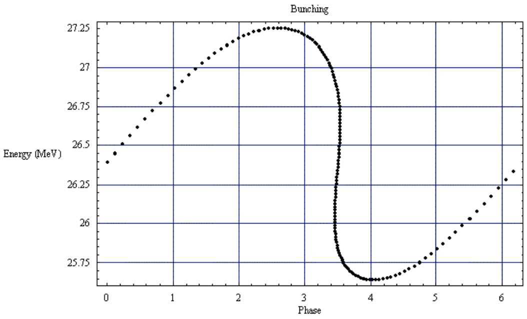

Figure 4: *Ideal bunching of the electron beam after it travels through the undulator. Simulation produced using helical IFEL dynamic equations.*

Using Mathematica, a Wolfram Research program, the bunching of the electron beam was investigated for the adjustable IFEL design parameters. In this design the laser intensity, magnetic field strength, and electron beam injection energy can all be slightly modified. If for some reason the bunching of the electron beam is not what we expect these parameters will be adjusted to remedy the situation. The Mathematica program simulates the electron dynamics as the beam progresses through the undulator. Figure 4 is a plot of the ideal bunching of the electron beam. By adjusting the parameters in the program it is possible to investigate how the bunching is affected (Table 1).

- Increase in Bunching
    - Increase in Laser Intensity
    - Increase in Electron Energy
- Decrease in Bunching
    - Undulator Period
    - Decrease in Laser Intensity
    - Decrease in Electron Energy

Table 1: *Affects of IFEL parameters on the bunching of the electron beam, using 1-D*

electron dynamic simulations.

The undulator that is now being constructed is a smaller design of the 100 MeV. This design will not produce electrons with energies of 100 MeV but will test the type of acceleration gradient and bunching we should expect. The final design will be about eight times longer (80 cm) with a tapered period so that as the electrons increase in energy they will remain in phase with the lasers electric field. From 1-D simulations of this design we are expecting an electron beam with a high energy and low emittance. The exact beam characteristic that the simulation predicted is presented in Table 2.

Normalized emittance (ε)	5 mm-mrad
Matched rms beam size (σ)	175μm
Injection energy	14.5 MeV
Extraction energy	100 MeV
Trapping fraction	~ 63%

Table 2: *Characteristics of the electron beam, found through 1-D electron dynamic simulations, after exiting the UCLA 100 MeV IFEL.*

Conclusion

In the next few months the prototype of the UCLA IFEL will be constructed and tested. This test will demonstrate the acceleration gradient and bunching that the final design should produce. If the results of these tests are promising then the final design will be constructed that should produce a 100 MeV low emittance electron beam.

Acknowledgements

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References

1. "DESY's free-electron laser FLASH illuminates the nano-world." Photon Science. 19 Jan 2007. HASYLAB. 11 Sep 2007 <hasylab.desy.de/news__events>.
2. Gover, Avraham. "Lasers: Free Electron Lasers."Encyclopedia of Modern Optics. 2005.
3. Pellegrini, Claudio. "Design considerations for a SASE X-ray FEL." Nuclear Instruments and Methods in Physics Research (20001): 1-12.
4. O'Shea, P.G., S.C. Bender, B.E. Carlsten, J. W. Early, D.W. Feldman, R.B. Feldman, W. J.D. Johnson, A.H. Lumpkin, R.L. Sheffield, R.W. Springer, W.E. Stein, L.M. Young. "Performance Of The Photoinjector Accelerator For The Los Alamos Free-Electron Laser." IEEE (1991): 1-3.
5. Murphy, Ryan. "Guiding of a Pulsed, Infrared CO2 Laser With an Open Iris-Loaded Waveguide Structure." 1-6.
6. Rosenzweig, J., N. Bodzin, P. Frigola, C. Joshi, P. Musumeci, C. Pellegrini, S. Tochitsky, and G. Travish. "A Helical Undulator Wave-guide Inverse Free-Electron Laser." 1-8.