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An Inverse Free Electron Laser Accelerator: Experiment and Theoretical Interpretation

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AN INVERSE FREE ELECTRON LASER ACCELERATOR: EXPERIMENT AND THEORETICAL INTERPRETATION

Jyan-Min Fang

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ABSTRACT

An Inverse Free Electron Laser Accelerator: Experiment and Theoretical Interpretation

Jyan-Min Fang

Experimental and numerical studies of the Inverse Free Electron Laser using a GW-level $10.6\ \mu\text{m}$ CO_2 laser have been carried out at Brookhaven's Accelerator Test Facility. An energy gain of 2.5 % ($\frac{\Delta E}{E}$) on a 40 MeV electron beam has been observed which compares well with theory. The effects on IFEL acceleration with respect to the variation of the laser electric field, the input electron beam energy, and the wiggler magnetic field strength were studied, and show the importance of matching the resonance condition in the IFEL.

The numerical simulations were performed under various conditions and the importance of the electron bunching in the IFEL is shown. The numerical interpretation of our IFEL experimental results was examined. Although good numerical agreement with the experimental results was obtained, there is a discrepancy between the level of the laser power measured in the experiment and used in the simulation, possibly due to the non-Gaussian profile of the input high power laser beam. The electron energy distribution was studied numerically and a smoothing of the energy spectrum by the space charge effect at the location of the spectrometer was found, compared with the spectrum at the exit of the wiggler.

The electron bunching by the IFEL and the possibility of using the IFEL as an electron prebuncher for another laser-driven accelerator were studied numerically. We found that bunching of the electrons at 1 meter downstream from the wiggler can be achieved using the existing facility. The simulation shows that there is a

fundamental difference between the operating conditions for using the IFEL as a high gradient accelerator, and as a prebuncher for another accelerator. For a high gradient accelerator, the IFEL requires the bunching of the electrons inside the wiggler for optimal energy gain, whereas using the IFEL as a prebuncher for another accelerator, a moderate energy gain may be sufficient for the best electron bunching results at a certain distance downstream from the wiggler.

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Chapter 1

Introduction

The term "Free Electron Laser" (FEL) was used by Madey [1] in 1977 to describe an electron beam device he constructed at Stanford which could generate infrared (10.6, 3.4 μm) radiation from a relativistic electron beam as it passed through a periodic transverse magnetostatic field provided by a device known as an "undulator" or "wiggler" [2, 3]. The physics of FEL (generating coherent radiation with an electron beam and an undulator) was actually developed earlier by Motz and others [4] about twenty years previously, but advances in accelerator technology allowed Madey to extend the operating range of the FEL into the infrared. The FEL operates by using an electron beam to amplify radiation via stimulated emission. The cause of the radiation is that the FEL process allows an orderly bunching of electrons to proceed on the beam, and these bunches, when properly phased, result in coherent high power radiation.

The "Inverse Free Electron Laser" (IFEL) on the other hand, uses the principle of stimulated absorption: given a source of high power electromagnetic waves, the electron beam can use this energy to accelerate electrons in a wiggler. The first proposal for IFEL was actually prior to Madey's FEL device. Palmer [5] in 1972 discussed the possibility of using stimulated absorption to accelerate the electrons in a wiggler with a high power laser source, and this idea was examined in theoretical detail by Courant and others [6] in 1985. In recent years, there is a need for a new advanced accelerator technology which will operate at much higher gradients and produce beams of superior quality. While there is some justification for an orderly

progression of existing technology (eg. increase the operating frequency of the rf linac from the present 2.856 GHz to as high as 80 GHz [7]), many "laser accelerator" schemes [8] have been proposed using a short wavelength laser beam as the driving source (Plasma Beat Wave Accelerator [9], Laser Wakefield Accelerator [10], Inverse Cherenkov Accelerator [11, 12], and IFEL [5]). After some study, it is generally concluded that while the IFEL is probably not suitable for a TeV type accelerator, it may be useful as an "injector" or "pre-buncher" for another laser accelerator. It is probably capable of gradients ~ 1 MeV/cm [13].

While the idea of the IFEL has been studied in great detail in theory [6, 14, 15], there were only two reports of a successful IFEL experiment prior to this date [16, 17]. The first was a brief report in the USSR in 1986, which used a $10.6 \mu\text{m}$ CO_2 laser to drive an IFEL using a 7.9 MeV beam of electrons. However, we will show in this thesis that the interpretation of this experiment was questionable and in fact no acceleration could have occurred in this apparatus. The other was a clear demonstration of the IFEL by Wernick in 1992 at Columbia University in an experiment which used a FEL millimeter radiation source to drive an IFEL employing a 800 KeV electron beam. In this experiment, the first FEL stage not only generated radiation as the driving energy for the IFEL but also served as a prebuncher input to the second IFEL stage. So far, the experimental verification of the IFEL has been achieved using the microwave source. In this thesis we will demonstrate the first operation of an IFEL using a $10.6 \mu\text{m}$ CO_2 laser source [18]. An experiment, carried out at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory, has permitted the IFEL theory to be compared with experimental data. In our experiment, laser acceleration proceeds from an unbunched state of the electron beam, which is the typical experimental condition encountered in practice. We use a 40 MeV electron beam generated by a laser-driven rf linac, and the CO_2 laser beam has a power level

of ~ 1 GW; also used is a specially constructed tapered-period wiggler [19] in which the electron beam executes the transverse periodic motion which is necessary for the exchange of energy between the electron beam and the laser waves.

There are three major components in an IFEL: a relativistic electron beam generated by an accelerator, a wiggler or undulator that provides a periodic transverse magnetic field and a high power laser source as the driving energy. Figure 1.1 shows a typical linearly polarized IFEL, where the wiggler is made of individual permanent magnets. In our experiment, the wiggler is a fast excitation electromagnet composed of Vanadium Permendur (VaP) ferromagnetic laminations with copper non-magnetic laminations [19, 20]. Driven by a pulse current (6 KA), it generates a periodic ($\lambda_w \sim 3$ cm) magnetic field ($B_{w\perp} \sim 14$ KG) [21]. A simple linear electron beam propagating in a cylindrical vacuum tube cannot couple to the laser, because the electrons always travel slower than the speed of light in this structure. The reason that continuous exchange of energy between the electron beam and laser beam can take place in an IFEL is the periodic oscillation which is imposed upon the electron beam by the wiggler. The periodic transverse magnetic field of the wiggler induces a periodic oscillation in electron's transverse velocity ($v_{\perp}/c = a_w/\gamma$), where $a_w = eB_{w\perp}\lambda_w/2\pi mc^2$ is the normalized vector potential of the wiggler field, as well as a small spatial transverse

Figure 1.1: Schematic of an inverse free electron laser with a linearly polarized wiggler.

oscillation. This feature permits a continuous interaction to develop between the transverse beam motion and the transverse electromagnetic field of the laser, providing a certain condition (the “resonance condition”) is met: namely, that when the electrons travel forward one wiggler period, the optical wave moves ahead of the electrons by one optical wavelength [22]. Figure 1.2 is an illustration of the “resonance condition”. From this figure, we can see that the electron transverse motion and the electric field of the optical wave will maintain a fixed phase relationship as they travel down the wiggler, and the energy can be transferred from the laser to the electrons or *vice versa*, depending on this phase angle (Ψ).

The resonance condition can be easily derived. In the rest frame of the electrons, the magnetostatic wiggler field is Lorentz transformed into a nearly transverse electromagnetic wave ($\lambda_e = \lambda_w/\gamma$ and $\omega_e = \gamma k_w \beta_{\parallel} c$, the subscript e represents in the electron

Figure 1.2: Relation between the radiation and the electron motion in resonance condition. (from Reference [22] P. 25)

rest frame), which can be considered as a flux of “virtual photons”. These virtual photons Thomson backscatter off the electrons, and the frequency of the backscattered radiations in the laboratory frame can be determined by Lorentz-transforming the frequency of the virtual photons ω_e back to the laboratory frame:

$$\omega_e = \gamma(\omega_s - \mathbf{k}_s \cdot \mathbf{v}) , \quad (1.1)$$

where the subscript s represents the backscattered radiation in the laboratory frame. Since the backscattered radiation is a transverse electromagnetic wave, $k_s = \omega_s/c$ and $\mathbf{k}_s$ is nearly parallel to $\mathbf{v}$ or $\mathbf{v}_{\parallel}$. Equation 1.1 can be rewritten as,

$$\omega_e = \gamma\omega_s(1 - \beta_{\parallel} \cos \theta) , \quad (1.2)$$

where θ is the angle between $\mathbf{k}_s$ and $\mathbf{v}_{\parallel}$ and is small. Therefore, $(1 - \beta_{\parallel} \cos \theta) \simeq (1 - \beta_{\parallel}) \approx 1/2\gamma^2$. With $\lambda_s = 2\pi c/\omega_s$, Eq. 1.2 gives the resonance condition:

$$\lambda_s = \frac{\lambda_w}{2\gamma^2} \quad \text{or} \quad \frac{\lambda_w}{2\gamma^2}(1 + a_w^2) , \quad (1.3)$$

where the relation $\beta_{\perp} = a_w/\gamma$ is used. The resonance condition shows that there is a unique relation between the wiggler, the electron beam and the laser beam. In the IFEL, the laser wavelength is fixed. Therefore, to maintain the resonance condition as the electrons increase their energy along the wiggler, the wiggler has to be programmed to match the resonance condition (by varying either its period or magnetic field strength). This is called the wiggler tapering. The wiggler tapering has been shown to be critical for enhancing the efficiency of the FEL or IFEL [23, 24].

Next, we examine how the energy transfer between the electron beam and the laser beam actually takes place. We first consider a wave which travels with the electron speed, known as the “ponderomotive wave”. The ponderomotive force from the Lorentz interaction between the electron and the magnetic component of the EM wave is $e(\mathbf{v}_{\perp}/c) \times \mathbf{B}_{s\perp}$ and is in the axial (z) direction. In the lab frame, $\mathbf{v}_{\perp}$ is

spatially periodic with the wavenumber $k_w = 2\pi/\lambda_w$ and zero frequency, thus the ponderomotive wave has a phase velocity of $w_s/(k_w + k_s)$. If the phase velocity of the ponderomotive force equals to the electron axial velocity, then the EM wave can continuously interact with the electron beam. The resonance condition can also be derived by setting the phase velocity of the ponderomotive force equal to the electron axial velocity. The importance of the ponderomotive force is that it causes a redistribution of the electron locations which results in the axial bunching of the electron beam so that an average net energy exchange between the electron beam and the EM wave is possible. To appreciate the importance of the bunching of the electrons in the IFEL, we examine Fig. 1.2 again, where the energy transfer (acceleration or deceleration) is shown to be dependent on the phase angle Ψ . In an IFEL that uses the laser beam as the driving force, we will most likely begin with a uniformly distributed electron beam, $-\pi < \Psi_i < \pi$ (the subscript i denotes the individual electron), and even though there will be a modulation in the energy of the electrons at the beginning, no initial average acceleration or deceleration is expected. However, as the electrons travel down the wiggler, the ponderomotive force causes the axial bunching (that is a preferred grouping of electrons near a certain phase, Ψ) of the electrons and this "bunch" of electrons can have its energy increased or decreased. As the interaction is reinforced, further bunching develops and the effect strengthens. As a result, the electron beam becomes bunched on a scale of half a wavelength of the laser, and these bunches readily either emit or absorb radiation by the stimulated process. The exact formula for the energy transfer can be derived by considering the $\mathbf{J}_\perp \cdot \mathbf{E}_{s\perp}$ work term [25] and is expressed as (the derivation will be given in Chapter 2),

$$\frac{d\gamma_i}{dz} = -\frac{a_w a_s \omega}{\gamma_i v_z} \sin \Psi_i, \quad (1.4)$$

where $a_s = eE_s \lambda_s / 2\pi m c^2$ is the normalized vector potential of the laser field. This

equation confirms that, depending on the choice of phase angle Ψ_i , either acceleration or deceleration is possible. This shows the important role played by the ponderomotive force in an IFEL.

The first FEL theory developed by Madey was fully quantum-mechanical [1, 26], but it was later shown that a classical theory is sufficient to describe the FEL [25]. In 1977, Colson showed that the dynamics for the FEL can be modeled by the pendulum equation [27]. As a result, one can easily demonstrate the electron motion in the phase space. First, the “closed” region (the separatrix) in the phase space for a pendulum equation defines the motion of the pendulum. For the FEL, this “closed” region corresponds to the size of the ponderomotive bucket, which depends on the amplitude of the wiggler field and the radiation field. When the electrons fall inside this “closed” region, they will be trapped in the potential well of the ponderomotive wave, resulting in the bunching. As the radiation field gets larger, the “closed” region gets larger too and more electrons are trapped and bunched in the ponderomotive wave. When the electrons fall outside of the “closed” region, they will undergo unbounded motion and are untrapped by the ponderomotive wave.

In the thesis we study the effect of the IFEL using a $10.6\ \mu\text{m}$ CO_2 laser both experimentally and theoretically. In Chapter 2, we give a brief overview of the IFEL theory. The basic dynamical equations are derived and we benchmark our simulation code based on these equations for various conditions. The experimental setup for the ATF IFEL experiment is described in detail in Chapter 3. Also discussed is the critical issue of the diagnostics for the system. The experimental results are presented and discussed in Chapter 4. In Chapter 5, we present the numerical interpretation of the experimental results based on our simulation code. Also presented is the numerical investigation of the bunching of the electrons induced by the IFEL. Discussion and conclusion is presented at the end of the thesis.

Chapter 2

IFEL Theory

In this chapter, we present a brief review of the FEL theory. The equations that describe the interaction between the electrons in a filamentary beam and the electromagnetic wave inside the magnetostatic wiggler are derived. We also present the numerical results, showing the electron energy spectrum and its spatial distribution in the course of the IFEL interaction.

2.1 FEL Equations

The equations presented here were first derived for the low current density case by Kroll, Morton and Rosenbluth [28], and later modified by S.Y. Cai [29] and T.B. Zhang to include the electron space charge effect. The space charge term was first introduced by Tang and Sprangle [30]. The IFEL equations consist of two first order differential equations for the electron motion in the phase space of the γ and phase variable and a wave equation for the radiation with the electron beam as the current source.

In the FEL, a relativistic electron beam enters a wiggler and the wiggler magnetic field induces a periodic transverse motion of the electron beam. This transverse motion is in the same plane as the electric field of the EM wave and the exchange of energy between the electrons and the radiation occurs through the vector product $\mathbf{J}_\perp \cdot \mathbf{E}_\perp$ of the electron transverse velocity and the electric force acting on it. Although the vector potential of the radiation is small compared with that of the

wiggler, the radiation magnetic field is important in that its cross product with the electron transverse velocity $-(e/c)\mathbf{v}_\perp \times \mathbf{B}_{s\perp}$ produces an axial force called the "Ponderomotive Force". This force causes an axial bunching of the electron beam so that an average net energy exchange between the electron beam and the radiation field becomes possible. As the bunching develops, a "coherent" enhancement in the interaction between the electrons and the wave develops.

For a helically polarized wiggler, the vector potential can be expressed as,

$$\mathbf{A}_w(z) = -\frac{mc^2}{e}a_w(z) \left[\hat{x} \cos\left(\int_0^z dz' k_w(z')\right) + \hat{y} \sin\left(\int_0^z dz' k_w(z')\right) \right] \quad (2.1)$$

where $m, -e$ are the rest mass and charge of electron, c is the speed of light, $a_w = eB_w/(k_w mc^2)$ is the normalized vector potential, $k_w = 2\pi/\lambda_w$ is the wavenumber of the wiggler and the wiggler axis is along the $\hat{z}$ axis. In Eq. (2.1), a_w and k_w are expressed as functions of z for the wiggler tapering. The transverse dependence of the wiggler vector potential has been ignored, since the electron beam diameter and the amplitude of its transverse wiggles $r_b = a_w/(k_w \gamma)$ are much smaller than the wiggler period λ_w .

The vector potential of a circularly-polarized radiation wave propagating along the wiggler axis can be expressed as,

$$\mathbf{A}_s(\vec{r}, t) = \frac{mc^2}{e}a_s(\vec{r}, t) \{ \hat{x} \cos[k_s z - \omega t + \phi(\vec{r}, t)] - \hat{y} \sin[k_s z - \omega t + \phi(\vec{r}, t)] \} \quad (2.2)$$

where $a_s = eB_s/(k_s mc^2)$ is the normalized vector potential, $k_s = 2\pi/\lambda_s = \omega/c$ is the wavenumber of the radiation, ω is the wave frequency and ϕ is the phase shift of the wave.

We define a phase angle Ψ which describes the phase of the electron relative to the wavefront of the radiation wave,

$$\Psi = \int_0^z [k_s + k_w(z')] dz' - \omega t + \phi \quad (2.3)$$

where ϕ is the phase of the radiation wave.

The phase equation of the electron motion is obtained by taking a derivative of Ψ with respect to z ,

$$\frac{d\Psi_j}{dz} = k_w + k_s - \frac{\omega}{v_{zj}} + \frac{\partial\phi}{\partial z} \quad (2.4)$$

where the subscript "j" is the index for the j'th electron, $v_z = dz/dt$ is the electron axial velocity and can be determined from the conservation of the transverse canonical momentum $P_\perp = \gamma m v_\perp - eA/c$ of the electron moving in the EM fields of Eq. (2.1)–(2.2). With an initial transverse canonical momentum of zero (a good approximation for a low energy spread and low emittance beam), we have,

$$\frac{v_z}{c} = \sqrt{1 - \frac{1}{\gamma^2} - \left(\frac{e}{mc^2}\right)^2 \frac{A^2}{\gamma^2}} \quad (2.5)$$

and Eq. (2.4) can be rewritten as,

$$\frac{d\Psi_j}{dz} = k_w + k_s - \frac{\omega}{c} \left[1 - \frac{1 + a_w^2 + a_s^2 - 2a_w a_s \cos \Psi_j}{\gamma_j^2} \right]^{-1/2} + \frac{\partial\phi}{\partial z} \quad (2.6)$$

The energy equation of the electron motion is obtained from the energy conservation law,

$$\frac{d}{dt}(\gamma m c^2) = -e \mathbf{v} \cdot \mathbf{E} \quad (2.7)$$

where $\mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{A}}{\partial t} - \nabla \Phi$ is the total electric field. Φ is the electric potential of an electrostatic plasma wave excited by the electron beam under the influence of the wiggler and the radiation wave and is assumed to be a 1-D plane wave. The electrostatic plasma wave accounts for the space charge effect. The energy equation can be expressed as

$$\frac{d\gamma_j}{dz} = -\frac{a_w a_s \omega}{\gamma_j v_z} \sin \Psi_j + \frac{2\omega_p^2 v_z}{\omega c^2} [\langle \cos \Psi \rangle \sin \Psi_j - \langle \sin \Psi \rangle \cos \Psi_j] \quad (2.8)$$

where $\omega_p = \sqrt{\frac{4\pi n_0 e^2}{m}}$ is the plasma frequency, n_0 is the electron beam current density, and the angular bracket indicates an ensemble average over all the electrons. The

first term on the right hand side of Eq. (2.8) comes from the ponderomotive force and the second term comes from the electrostatic force (eE_z) of the plasma wave for the space charge effect which is important in the Raman FEL or when the electrons are highly bunched by the ponderomotive force.

Finally the equation for the radiation wave is derived from the Maxwell equation with the electron beam as the current source. The wave equation for the vector potential of the radiation wave is

$$\nabla^2 A_s - \frac{1}{c^2} \frac{\partial^2 A_s}{\partial t^2} = -\frac{4\pi}{c} J + \frac{1}{c} \nabla \frac{\partial \Phi}{\partial t} \quad (2.9)$$

where the current density J is given by

$$J = -e \int \frac{P}{m\gamma} f(z, P, t) d^3P,$$

with f being the electron distribution function. Φ is assumed to be a 1-D plane wave and can be dropped, since A_s is a transverse field. The radiation equation is then obtained by substituting J and Eq. (2.2) in Eq. (2.9) and integrating it over one wave period,

$$(\nabla_{\perp}^2 + 2ik_s \frac{\partial}{\partial z} + 2i \frac{w}{c^2} \frac{\partial}{\partial t}) u(r, t) = -\frac{\omega_p^2 a_w}{c^2} \left\langle \frac{e^{-i(\Psi - \phi)}}{\gamma} \right\rangle \quad (2.10)$$

where $u(r, t) = a_s(r, t)e^{i\phi(r, t)}$ is the complex field amplitude of the radiation wave. We have made the slowly varying ("eikonal") approximation for the complex field amplitude, therefore the second derivative terms with respect to z and t are neglected. Also worth noting is the time derivative term on the LHS of Eq. (2.10). This term represent the slippage effect in the FEL, where the electron trails the radiation one radiation wavelength over one wiggler period. Slippage can be important in the FEL as it contributes to the sideband instability [31] and spiking phenomena [32, 33, 34].

The three equations (2.6), (2.8) and (2.10) constitute the basic FEL equations with a helically polarized wiggler and a circularly polarized radiation wave. For the

linearly polarized wiggler and linearly polarized radiation wave, which is the case in the ATF IFEL experiment, these equations become [35],

$$\frac{d\Psi_j}{dz} = k_w + k_s - \frac{\omega}{c} \left[1 - \frac{1 + a_w^2 + a_s^2 - 2a_w a_s f_B \cos \Psi_j}{\gamma_j^2} \right]^{-1/2} + \frac{\partial \phi}{\partial z}, \quad (2.11)$$

$$\frac{d\gamma_j}{dz} = -\frac{f_B a_w a_s \omega}{\gamma_j v_z} \sin \Psi_j + \frac{2\omega_p^2 v_z}{\omega c^2} [\langle \cos \Psi \rangle \sin \Psi_j - \langle \sin \Psi \rangle \cos \Psi_j] \quad (2.12)$$

and

$$(\nabla_\perp^2 + 2ik_s \frac{\partial}{\partial z} + 2i \frac{w}{c^2} \frac{\partial}{\partial t}) u(r, t) = -\frac{f_B \omega_p^2 a_w}{c^2} \left\langle \frac{e^{-i(\Psi - \phi)}}{\gamma} \right\rangle \quad (2.13)$$

where $f_B = J_0(\chi) - J_1(\chi)$, $\chi = a_w^2/2(1 + a_w^2)$ and J_0 and J_1 are the zeroth and first order Bessel function. The factor f_B comes from the fact that the wiggler magnetic field is not constant along the electron transverse wiggles axis.

Since an annular sapphire tube is used to confine the radiation wave in the ATF IFEL experiment, the transverse fields of the radiation field are nearly constant over the beam cross section, and so the transverse dependence in the radiation equation (i.e. ∇^2 term) can be dropped and Eq. (2.13) becomes,

$$(ik_s \frac{\partial}{\partial z} + i \frac{w}{c^2} \frac{\partial}{\partial t}) u(r, t) = -\frac{f_B \omega_p^2 a_w}{2c^2} \left\langle \frac{e^{-i(\Psi - \phi)}}{\gamma} \right\rangle. \quad (2.14)$$

Equations (2.11), (2.12) and (2.14) form the basis for the numerical analysis in this thesis.

The electron motion equations (2.6) and (2.8) can be derived alternatively using a Hamiltonian formalism [36],

$$H = \frac{k_w}{\gamma_r} (\delta\gamma)^2 + \delta\gamma \frac{\partial \phi}{\partial z} + F(\Psi) \quad (2.15)$$

where $\delta\gamma = \gamma - \gamma_r$ and γ_r is the resonant energy, defined as

$$\gamma_r^2 = \frac{k_s}{2k_w} (1 + a_w^2) \quad (2.16)$$

The function F is called the ponderomotive potential and given as,

$$F(\Psi) = \frac{k_s a_s a_w}{\gamma_r} [\cos \Psi + \Psi \sin \Psi_r] + \frac{2\omega_p^2 v_z}{\omega c^2} [\langle \cos \Psi \rangle \cos \Psi + \langle \sin \Psi \rangle \sin \Psi], \quad (2.17)$$

whereas Ψ_r is the resonant phase, defined as

$$\frac{d\gamma_r}{dz} = -\frac{k_s a_s a_w}{\gamma_r} \sin \Psi_r \quad (2.18)$$

When (2.16) and (2.18) define γ_r and Ψ_r with a known wiggler setting (k_w and a_w) and radiation parameters (k_s and a_s), another point of view is to consider these as the design equations for the wiggler parameters k_w and a_w such that the system will achieve the desired functions γ_r , Ψ_r and a_s . Therefore, γ_r and Ψ_r specify the wiggler tapering.

The ponderomotive potential forms a series of potential wells along the wiggler and, with a sufficiently large a_s , these potential wells can trap a substantial number of the electrons, i.e. bunching. The position of these potential wells or “buckets” depends on the resonant energy γ_r . By slowly changing this resonance energy along the wiggler (by tapering the wiggler field and/or period), we can assure that the electrons will stay inside the bucket and continue to participate in the FEL or IFEL interaction along the wiggler. Figure 2.1 shows the ponderomotive potential for an IFEL tapering (stimulated absorption). The rise of the centers of the buckets along the wiggler maintains the resonance condition as the electrons gain energy from the radiation. For the FEL (stimulated emission), the centers of the buckets descend and the electrons trapped inside the bucket lose their energy to the radiation. Overall, the tapering of the wiggler will enhance FEL or IFEL efficiency greatly.

2.2 Simulation Scheme and Results

In this section we will first give a description of the simulation scheme implemented to solve Eqs. (2.11), (2.12) and (2.14), then we present the numerical simulation results of various cases, with an emphasis on the effect of bunching by the ponderomotive force on the IFEL acceleration. Three different cases are presented: (1) the initial ATF

Figure 2.1: Ponderomotive potential for an IFEL tapering

IFEL design, (2) the design for the current ATF IFEL run and (3) an early Russian IFEL experimental result. The detailed comparison of the numerical simulation and the experiment results is separately given in Chapter 5.

2.2.1 Simulation Scheme

We will first describe the simulation scheme we implemented for Eqs. (2.11), (2.12) and (2.14), and then summarize how to generate the initial electron distribution. The simulation code was initially developed by T.B. Zhang [37, 38] for various FEL studies and was later modified by the author to include the space charge effect and the energy spread for the input electron beam. It also has been modified to allow comparison between the results with and without the slippage effect.

In solving the IFEL equations, it is worth mentioning that the calculation can be

greatly simplified by integrating along the equations' characteristic lines. Thus, the following variable transformations,

$$X = \frac{ct - z}{L_w(c/v_z - 1)}, \quad Y = \frac{z - v_z t}{L_w(c/v_z - 1)\beta_z} \quad (2.19)$$

are introduced. Then Eqs. (2.11), (2.12) and (2.14) transform to,

$$\frac{\partial \Psi_j}{\partial X} = L_w \left(k_w + k_s - \frac{\omega}{c} \left[1 - \frac{1 + a_w^2 + a_s^2 - 2a_w a_s f_B \cos \Psi_j}{\gamma_j^2} \right]^{-1/2} + \frac{\partial \phi}{\partial X} \right), \quad (2.20)$$

$$\frac{\partial \gamma_j}{\partial X} = -\frac{L_w f_B a_w a_s \omega}{\gamma_j v_z} \sin \Psi_j + \frac{2L_w \omega_p^2 v_z}{\omega c^2} [\langle \cos \Psi \rangle \sin \Psi_j - \langle \sin \Psi \rangle \cos \Psi_j], \quad (2.21)$$

and

$$\frac{\partial u}{\partial Y} = i \frac{L_w f_B \omega_p^2 a_w}{2k_s c^2} \left\langle \frac{e^{-i(\Psi - \phi)}}{\gamma} \right\rangle. \quad (2.22)$$

These equations are then solved in the domain illustrated in Fig. 2.2. The two solid diagonal lines represent the entrance and the exit of the wiggler. The electron Eqs. (2.20) and (2.21) are integrated along the horizontal ($Y = \text{constant}$) solid line, while the radiation Eq. (2.22) along the vertical ($X = \text{constant}$) dotted line. The slippage effect is embedded in this integration scheme automatically. We can see, as the radiation being integrated "upward" along the wiggler, it catches the electrons that were initially ahead (notice the time arrow direction). These equations are then solved self consistently, using the Adams-Bashford predictor-corrector method.

The initial electrons distribution is implemented in the following way. The electrons are initially divided into 150 or 300 groups (from a to b in Fig. 2.2), with each group spanning one radiation wavelength $10.6 \mu m$ (150 and 300 groups correspond to 5 and 10 ps lengths respectively, which is the typical electron beam pulse length at ATF). Each group is further divided into 5 or 10 subgroups, with each subgroup

Figure 2.2: Domain of integration for the IFEL equations in X and Y transform variables. The electrons are distributed from a to b , and the radiation from a to c . The scale is arbitrary to illustrate the advance of the electrons and the radiation in the wiggler.

containing 100 test electrons. The electrons inside the subgroup are uniformly distributed over the phase space, from $-\pi$ to π . A random number generator with a weighted Gaussian distribution is used to generate their initial energy with appropriate energy spread. Since the resonance condition states that the electrons trail the radiation by one optical wavelength when traveling over one wiggler period, we choose the integration step size to be $1/5$ or $1/10$ of the wiggler period (depending on the number of subgroups in each group), thus assuring that the slippage effect is treated correctly.

2.2.2 Initial ATF IFEL Design

The initial design of the ATF IFEL experiment was intended to demonstrate that the IFEL can have potential for a new mode of electron acceleration and a high accelerating gradient of ~ 90 MV/m could be achieved [13]. The initial design parameters to achieve this accelerating gradient target are listed in Table 2.1. In the original design, both 1-D and 3-D simulations codes were used. The 1-D code was used to define the optimal wiggler tapering for a given input laser power, resonant energy and phase and peak wiggler field. The 3-D code was modified from the multiparticle simulation Linac code PARMELA (Phase And Radial Motion in Electron Linear Accelerators) to study the full 3-D aspects of the IFEL interaction. In this simulation result, approximately 40 % of the initial particles were trapped in the ponderomotive well and were accelerated to ~ 90 MeV.

Using their design parameters, we benchmarked our simulation result against the 3D code. Fig. 2.3 are our simulation results. Fig. 2.3(a) is the electron energy spectrum at the entrance (solid line) and the exit (dotted line) of the wiggler. Fig. 2.3(b) and 2.3(c) are the axial particle distribution and the phase space particle distribution at the exit of the wiggler, respectively. Our simulation results are in good agreement with the prior simulation results; this gives us confidence in using our code as the numerical analysis basis in this thesis.

Figure 2.3(a) shows that the accelerated and unaccelerated electrons are clearly separated. The unaccelerated electrons fall out of the resonance condition from the beginning and are left behind in the IFEL interaction, drifting along the wiggler with the initial energy. We can see, in Fig. 2.3(c), that the unaccelerated electrons are distributed nearly uniformly in the phase space, and are not trapped and bunched at all inside the “ponderomotive” bucket. On the other hand, the accelerated particles are trapped and bunched inside the buckets right from the beginning. Fig. 2.4 is

Table 2.1: Parameters for the initial ATF IFEL experiment design [13]

Electron Beam	
Injection energy	48.9 MeV
Exit energy	87.95 MeV
Mean accelerating field	89 MV/m
Current, nominal	5 mA
$N_e(\text{bunch})$	$6 \times 10^9 e^-$
$I(\text{max})$	100 A
$\Delta E/E$ (one σ)	$\pm 3 \times 10^{-3}$
Emittance (one σ)	7×10^{-8} m rad
Beam radius	0.3 mm
Wiggler Parameters	
Wiggler length	0.47 m
Section length	0.6 m
period length	2.86–4.32 cm
Gap	4 mm
Field max. (Const. B mode)	1.25 T
Beam oscillation, $a_{1/2}$	0.17–0.22 mm
Laser Parameters	
Power, $P(\text{laser})$	200 GW
Wavelength, λ	10.6 μm
Max. field	1.36×10^4 MV/m
Dielectric guide loss par., α	$0.025 m^{-1}$
Field attenuation/section	0.13 dB
Pulse length (FWHM)	6 psec

the electrons longitudinal distribution in the middle of the wiggler, which shows the bunching of the electrons already occurs inside the wiggler. This group of electrons

(a)

(b)

(c)

Figure 2.3: The simulation result of the initial ATF IFEL design. (a): the energy spectrum, (b): the longitudinal phase distribution and (c): the phase distribution, at the exit of the wiggler

Figure 2.4: The longitudinal phase distribution of the electrons at the middle of the wiggler for the initial ATF IFEL design

closely maintains the resonance condition and stays inside the bucket as it propagates down the wiggler and is accelerated up to ~ 90 MeV. In our simulation, about 40 % of the electrons are trapped and accelerated, which also agrees with the previous simulation results. The initial ATF IFEL design reveals that bunching plays an important role in IFEL performance.

2.2.3 Current ATF IFEL Design

The initial ATF IFEL design assumed a CO_2 laser power of 200 GW, which is beyond the capability of the current ATF CO_2 laser system [39, 40]. Therefore, when the IFEL run started in October of 1995, the design was modified to match the available CO_2 laser power, which was believed to be a few GW. The main modification was the tapering of the wiggler, which changed from the initial design of 2.86–4.32 cm period to 2.89–3.14 cm. The initial idea of choosing this new taper for the wiggler, besides to match the CO_2 laser power, was that simulations showed it should work well for an initial electron beam energy of 35, 40 and 45 MeV and 3–5 GW laser power [41], by the changing of the wiggler field strength between 8.5 and 11.5 KG. Table 2.2 is

Table 2.2: Design parameters for the current ATF IFEL run

Electron Beam	
Injection energy	40.0 MeV
Exit energy	42.3 MeV
Mean accelerating field	4.9 MV/m
Current, nominal	5 mA
$N_e(\text{bunch})$	$10^9 e^-$
$I(\text{max})$	30 A
$\Delta E/E$ (one σ)	$\pm 3 \times 10^{-3}$
Emittance (one σ)	7×10^{-8} m rad
Beam radius	0.3 mm
Wiggler Parameters	
Wiggler length	0.47 m
Section length	0.6 m
period length	2.89–3.14 cm
Gap	4 mm
Field max. (Const. B mode)	1.0–1.024 T
Beam oscillation, $a_{1/2}$	0.16–0.19 mm
Laser Parameters	
Power, $P(\text{laser})$	1 GW
Wavelength, λ	$10.6 \mu\text{m}$
Max. field	0.78×10^3 MV/m
Dielectric guide loss par., α	0.05 m^{-1}
Field attenuation/section	0.26 dB
Pulse length (FWHM)	200–300 psec
Norm. field A^1	$1.53 \times 10^3 \text{ m}^{-1}$

¹The parameter A is defined as $\frac{e}{mc^2} \frac{(\pi W_l Z_0)^{1/2}}{R_0}$, where $Z_0 = 377\Omega$, is the vacuum impedance and R_0 is the waveguide radius.

the design parameters for a 40 MeV electron beam and 1 GW laser power with this wiggler setting [18].

We simulated the IFEL using this set of parameters with our code. Figure 2.5 is our simulation results, showing the electron energy spectrum, the longitudinal particle distribution and the phase space distribution at the exit of the wiggler, respectively. Figure 2.5(a) shows a maximum energy increase of ~ 2.5 MeV, which agrees reasonably with the design parameters in Table 2.2. However, unlike the initial ATF IFEL design, the accelerated and unaccelerated electrons are not separated here. The cause for this behavior is that, while the accelerated electrons satisfy the resonance condition at the entrance of the wiggler, their energy increase using a 1 GW laser power is unable to match the resonance condition along the wiggler (the wiggler is designed for 3–5 GW laser power). As a result, they are accelerated only for a portion of length in the wiggler, and then fall out of resonance quickly and stay unaccelerated after that. The continuity in the energy spectrum is due to the fact that the electrons are uniformly distributed in the phase space initially. Figure 2.5(b) and 2.5(c) show the trapping and bunching of the electrons in the “ponderomotive” well. As expected, the bunching of the electrons is not as good as the initial ATF IFEL design. We presented 1 GW laser power case here, since we found out during the experimental run that it is closer to the actual laser power measured.

2.2.4 Early Russian IFEL

A Russian IFEL experiment was done in 1987 by A. Amatuni, *et. al.* [16]. Like the ATF IFEL experiment, they used a CO_2 laser as a radiation source to accelerate the electrons. The electron beam is generated by a microtron accelerator. The experimental parameters are listed in Table 2.3.

Their experimental result yielded a 10 KeV energy increase on the center energy.

(a)

(b)

(c)

Figure 2.5: The simulation result of the current ATF IFEL design. (a): the energy spectrum, (b): the longitudinal phase distribution and (c): the phase distribution, at the exit of the wiggler

Table 2.3: Experimental parameters for the Russian IFEL experiment

Electron beam energy	7.9 MeV
Electron beam energy spread	150 KeV
Electron beam diameter	4 mm
undulator period	5.25 mm
undulator length	20 cm
undulator magnetic field on axis	750 G
Minimum laser power	10 MW

Figure 2.6 shows the energy spectrum, the longitudinal particle distribution and the phase space distribution at the exit of their wiggler from our simulation using the parameters in Table 2.3. In our simulation, we find the bunching of the electrons never occurred throughout the wiggler, as indicated in Fig. 2.6(b), where the solid, dashed and dotted curves represent the electron longitudinal distribution at the entrance, middle and exit positions of the wiggler, respectively. As a result of no significant bunching of the electrons, the energy increase between the input beam and the output beam is not observed in Fig. 2.6(a).

We have presented three different IFEL cases here. For the initial ATF IFEL cases, the bunching of the electrons is observed in the simulation, and these particles are able to participate the IFEL interaction throughout the wiggler and achieve substantial energy gain. For the current ATF IFEL design case, due to the mismatch of the laser power, some partial bunching occurred and there is some modest energy gain. For the early Russian IFEL, the bunching did not occur and, as a result, no energy gain is to be expected. The importance of the electron bunching to the IFEL interaction is clear and should be one of the main considerations in designing an "excellent" IFEL machine, where the accelerated electrons are trapped and bunched

(a)

(b)

(c)

Figure 2.6: The simulation result of the early Russian IFEL. (a): the energy spectrum, (b): the longitudinal phase distribution and (c): the phase distribution, at the exit of the wiggler

in the "ponderomotive" well, so as to maintain the resonance condition and increase their energy throughout the wiggler. Finally, our simulation results agree well with the original ATF IFEL simulation results, which gives us confidence to use it as the numerical basis in this thesis.

Chapter 3

Experimental Apparatus

In this chapter, the basic experimental apparatus for Brookhaven ATF's IFEL experiment is discussed. The main apparatus can be separated into 5 parts: (1) the Nd:YAG pulse laser system, (2) the linear accelerator system, (3) the picosecond high power CO_2 laser system, (4) the magnetic wiggler and (5) the electron beam energy diagnostic system. A 10 ps Nd:YAG laser pulse is frequency quadrupled to UV (266 nm) to drive the photocathode RF gun. The emitted electrons from the RF gun pass through two traveling wave linac sections to increase their energy to 40 MeV (maximum 70 MeV) and are sent to an IFEL interaction region (wiggler) in the experimental hall. A high power CO_2 laser pulse (GW, a few hundred picoseconds) is sent into a sapphire tube located inside the wiggler to interact with the electron beam. The energy profile of the electron beam is analyzed by a beam energy spectrometer, consisting of a magnetic dipole and several quadrupole magnets. Fig. 3.1 is the overview of the facility.

3.1 Nd:YAG Pulse Laser System

The Nd:YAG pulse laser system [42] serves two purposes, to produce the electron emission for the RF gun and to power the picosecond semiconductor switch for the CO_2 laser system. Figure 3.2 is the schematic of the Nd:YAG pulse laser system. A diode-pumped, actively mode-locked Nd:YAG oscillator (Lightwave, Model 131), controlled by a 81.6 MHz pulse generator (SRS, Model DG535), produces train of

Accelerator Test Facility

Figure 3.1: The overview of Accelerator Test Facility

Figure 3.2: Nd:YAG laser system

20 ps FWHM pulses spaced 24.5 ns apart at 1.06 μm at a repetition rate of 1.5 or 3 Hz.

The SRS pulse generator also controls two klystrons (at its 35th harmonic) which provide the RF power to the electron gun and the two traveling wave linac sections for electron acceleration. The use of this pulse generator allows the Nd:YAG laser pulses to be phase locked with the RF power so that there is a stable relationship between the pulse of emitted electrons and the accelerating field. The phase jitter between the optical pulse train and the RF power is less than 1 ps with the use of a timing stabilizer circuit which controls the piezoelectric cavity length tuning. For the IFEL experiment, a Pockels cell and a polarizer are used to limit the number of pulses inside the train to just 2. The leading pulse is for the picosecond semiconductor switch of the high power CO_2 laser and the trailing one to drive the RF gun. The need for two separate pulses is due to the synchronization requirement for the CO_2 pulse and the electron beam inside the wiggler.

The pulses generated by the oscillator pass through two stages of flashlamp-pumped amplifiers (a 4-pass preamplifier and a 2-pass amplifier) to increase their energies to 12 mJ in the leading pulse and 8 mJ in the trailing pulse, respectively. A low vacuum spatial filter cleans out the higher order mode contents of the pulses. A 66 % transmission beamsplitter splits the pulses. The transmitted beam of the leading pulse (8 mJ) is sent to the CO_2 laser area to activate the picosecond semiconductor switch. The reflected beam of the trailing pulse ~ 2.5 mJ goes through two doubling crystals to first convert to green with an energy of 600 μJ and a pulse duration of 14 ps, and then to UV (266 nm) with an energy of 200 μJ and a pulse duration of 10 ps. The UV pulse is transported to the RF gun area through a 20 meter long low-vacuum tube. In the RF gun hutch, optics of limiting aperture and cylindrical lenses are arranged to allow the laser spot size to be varied between 0.5 to

1.5 mm diameter at the photocathode at an oblique incidence angle of 72° . Since the whole system is more than 20 meters long, the beam quality and position stability is a critical concern. To insure a stable laser pulse at the photocathode, a Fourier relay imaging scheme is used throughout the system to transport the laser pulse. This scheme utilizes Keplerian telescopes with aperture located at the Fourier transform plane. The apertures allow passage of a diffraction free beam, but block most of the higher order modes generated by scattering or diffraction in the system. Figure. 3.3 is the schematic of this Fourier relay imaging system.

Figure 3.3: The Fourier relay imaging scheme

3.2 Linear Accelerator System

The ATF linear accelerator system [43, 44] consists of a laser-driven RF gun injector, a 70 MeV linac section and the transport system with 3 separate experimental beamlines. Fig. 3.4 is the experimental hall. The IFEL experiment is located in the middle beamline.

THE EXPERIMENT HALL OF THE BNL ACCELERATOR TEST FACILITY

Figure 3.4: The experimental hall

The RF gun injector consists of, in sequence, a one-and-half cell, S-band, laser-driven copper RF gun, a pair of solenoid magnets for emittance compensation, a 45° mirror mounted on an actuator in a six-way cross for laser beam profile monitoring at the photocathode, and a copper block for the charge measurement and electron beam profile and position monitoring via the coated phosphor.

The RF gun is powered by a XK-5 klystron. The klystron, controlled by the SRS pulse generator, delivers a 12 MW, 2.5 μ s RF pulse at a frequency of 2.856 GHz. A 3db divider to reduce the RF power by 2 is needed to prevent the arcing of the gun by the excess RF power. The gun sustains an accelerating gradient of 100 MV/m. The highest quantum efficiency of the gun was measured to be 0.05 %. The high quantum

efficiency of the gun is a result of the following factors: the oblique incidence gives a factor of 2 improvement over normal incidence because of polarization optimization; the accelerating gradient of 100 MV/m gives a factor of 2 improvement by the schottky effect. The typical charge generated by a 50 μJ UV pulse with a 1.5 mm spot size is 0.5 nC. The beam energy output is typically 5 MeV with a 0.5 % energy spread and 1-2 mm mrad normalized rms emittance. One of the problems with the system is that the output of the klystron may drift due to various reasons, e.g. temperature heatup. An RF Phase shifter and amplitude attenuator allow the tuning of the RF power into the gun, in the event of RF drifting.

The ATF linac section consists of two $2\pi/3$ mode, disc loaded, 3.05 meters long, SLAC type traveling wave sections. It is powered by a separate XK-5 klystron controlled also by the SRS pulse generator. The klystron can deliver up to 20 MW RF power at 2.856 GHz to both sections, which will give final electron beam energy of 70 MeV. For IFEL experiment, we usually run at 8 MW for a 40 MeV beam. Again, the phase shifter and amplitude attenuator are available for the RF tuning.

The transport system following the linac consists of various quadrupole magnets used for emittance measurement or beam matching for the experiment. A 20° bending dipole magnet deflects the electron beam into the experimental hall and a phosphor coated momentum slit that follows the dipole is used for the energy spread measurement and the selection of the beam energy. Further downstream, because of the straight injection of the CO_2 laser pulse, another 20° bending dipole is needed to bring the electron beam into the straight wiggler section of the IFEL.

3.3 Magnetic Wiggler

Figure 3.5 is a schematic of the magnetic wiggler which uses a novel design invented by Arie van Steenberg [19]. The design goals for an IFEL wiggler are that it should be easy for us to vary its period to satisfy the resonant condition under various experimental conditions, and it should be able to generate a high magnetic field to maximize the acceleration. With this goal in mind, the conventional way of using permanent magnetic material or a fixed yoke with winding circuit was abandoned because it would be impossible to adjust the geometry of the wiggler once it is built.

Figure 3.5: The fast excitation magnetic wiggler

The wiggler is built by alternative stacking of Vanadium Permanganite (VaP) ferromagnetic laminations with conductive, nonmagnetic laminations (Cu) [19, 20, 45]. The use of these easily restackable laminations of a thickness of 0.254 mm makes varying the wiggler geometry possible. The wiggler period for the current experimental run is 2.89 cm step-tapered in 5 increments to 3.14 cm at the end of the wiggler. Each increment is about 10 cm long and the period increase between increments is about 0.5 mm. The conductive, nonmagnetic laminations acts as an eddy current induced "field reflector", which enhance the magnetic field strength by approximately a factor

Figure 3.6: The magnetic field profile of the wiggler

of 2. The wiggler is energized by 4 KA current, and with a gap of 4 mm a magnetic field of 10 KG is obtained. The maximum magnetic field of the wiggler is 1.25 T and the pole-to-pole field variation is approximately 0.2 % [21]. Figure 3.6 shows the magnetic field profile of the wiggler (the wiggler was an early prototype and had a different setting than the current one) [45, 13]. The whole assembly is 60 cm long, when the wiggler itself is 47 cm long.

3.4 CO_2 Laser System

Figure. 3.7 is the schematic of the CO_2 laser system [39, 40]. The IFEL experiment requires a gigawatt level $10\ \mu m$ laser pulse precisely synchronized with the electron

Figure 3.7: CO_2 laser system

beam. To meet this requirement, the CO_2 laser system is designed as a combination of three different components: the oscillator for the $10\ \mu m$ radiation source, the slicing system to reduce the pulse duration, and the amplifier to achieve the high peak power.

3.4.1 Oscillator

Figure 3.8 is the schematic of the CO_2 laser oscillator. The hybrid oscillator consists of a TEA (Transverse Electric discharge Atmosphere pressure) main discharge cell and low pressure smoothing tube. The main discharge cell is an open system where a mixture of $N_2 : CO_2 : He$ at ratio of 1 : 1.3 : 0.3 continuously flow through. The main discharge is UV preionized and is energized by a 40 KV capacitor bank. The maximum discharge rate of the capacitor bank is 1/3 Hz. The smoothing tube, operated at 20 torr, is energized by a separate high voltage source before the firing

Figure 3.8: CO_2 oscillator

of the main discharge to provide a narrow gain spectrum. The operation of the smoothing tube, coupled with the piezoelectric tuning of the oscillator cavity length, allows a single longitudinal mode operation. The cavity length is approximately 1.5 m. The outcoupler is a dielectric coated 1.5 m focal length convex germanium mirror and the back reflector is a flat copper mirror. The beam spot size is controlled by two intracavity iris that produce a nearly Gaussian beam. Typical output of the oscillator ranges from 50–300 mJ energy in a 50–75 ns main pulse with a 200 ns tail containing 1/3 of the total energy.

3.4.2 Picosecond Slicing System

Figure 3.9 is the schematic of the picosecond semiconductor switch slicing system. The switch is achieved by optically modulating the transmission and reflection of the germanium plates at $10.6\ \mu\text{m}$ with the 20 ps Nd:YAG laser. Germanium has a band gap energy above the photon energy of the CO_2 laser and is transparent at $10.6\ \mu\text{m}$, but it absorbs and reflects the Nd:YAG laser, as the photon energy of $1.06\ \mu\text{m}$ is higher than its band gap energy. When the Nd:YAG laser illuminates the germanium plates, free charge carriers are formed near the surfaces of the plates, making it essentially a metal at $10.6\ \mu\text{m}$. These free charge carriers have a diffusion rate of 150 ps, and their recombination rate is much longer than $\sim 50\ \text{ns}$. The germanium will act as a reflector for the CO_2 laser until the free carriers diffuse into the bulk of the plate. Thus, we are able to control the optical property of the germanium plates with the Nd:YAG laser.

The first stage of the system operates as follows: the $10.6\ \mu\text{m}$ light pulse is transmitted through the plate until the $1.06\ \mu\text{m}$ 20 ps pulse hits the plate. The reflected $10.6\ \mu\text{m}$ light from this switch has a rise time of 20 ps and a fall time of 300 ps, because of the diffusion of the free carriers into the bulk.

REFLECTION SWITCHING

TRANSMISSION SWITCHING

Figure 3.9: Schematic of the slicing system

In the second switch, the reflected light at both wavelengths is redirected to the second germanium plate. A prism on the $1.06\ \mu\text{m}$ light path creates the time-delay between the light wavelengths; the delay can be varied from 0–300 ps. The $10.6\ \mu\text{m}$ light is transmitted for this variable delay period until the $1.06\ \mu\text{m}$ pulse arrives, after which the $10.6\ \mu\text{m}$ light is reflected. The transmitted light is then amplified. Figure 3.10 is the setup of the slicing system.

Figure 3.10: Setup of the slicing system

Since a common source, the Nd:YAG laser, is used, both the high power CO_2 laser pulse and the electron beam are synchronized to the Nd:YAG laser pulse. The first synchronization adjustment between the electron beam and the CO_2 beam is done by measuring the stripline signal of the electron beam and the fast photodiode signal of the CO_2 beam near the wiggler with a fast oscilloscope and by adjusting the optical path length of the Nd:YAG pulse into the CO_2 room; this synchronizes them within 1 ns of each other. The optical path length of the Nd:YAG pulse is adjusted by the repositioning of a prism located on the ceiling (the adjusted range allowed is more than 24.5 ns). The final adjustment is also done by adjusting the

arrival of the Nd:YAG pulse into the CO_2 room, but through a motorized translation stage with the prism located on top. The translation stage allows a time delay range of 1.33 ns and a subpicosecond precision. The final adjustment was confirmed during the experimental run by directly observing the evidence of acceleration.

3.4.3 CO_2 Laser Amplifier

Figure 3.11 is the schematic of the CO_2 laser amplifier, a multi-atmospheric UV pre-ionized transverse electric discharge amplifier. The discharge cell, bounded by two sets of serially-placed brass electrodes, has a dimensions of $2 \times 5 \times 120\text{ cm}^3$ and is filled with a 3 ATM mixture of CO_2 , N_2 and He at a ratio of 1.0 : 0.5 : 8.0, respectively. The amplifier cell is situated on an oil tank containing the high voltage pulse-forming circuit. Two two-stage 140 KV Marx generators provide the high voltage pulses to

Figure 3.11: CO_2 amplifier

the main discharge. The high voltage pulse is about 400 ns long. The small signal gain under these parameters is 2.4 %/cm at 10.6 μm and lasts for 250–300 ns. This time duration is determined by the decay rate of the excited nitrogen gas. To amplify the sliced beam (~ 0.5 MW) up to $\sim$ multi-gigawatt level, a multipass configuration is built. The system allows up to eight passes of amplification. The repetition rate of the system is once every 30 seconds or longer and the lifetime is about 3–6 hours, depending on the condition of the gases. The typical energy in an amplified beam is a few tenths of Joules to 2 Joules.

3.4.4 CO_2 Optical Beam Transport and Measurement

The amplified CO_2 laser pulse is transported into the experimental hall where a telescope system allows the choice of the desired beam spot size at the entrance of the wiggler. The telescope system consists of a plano-convex lens of 90 cm focal length and a plano-concave lens of -110 cm or -130 cm focal length made of ZnSe. The beam spot size available is between 0.7 mm to 1.4 mm $1/e^2$ Gaussian beam radius at the entrance of the wiggler. Two remotely controlled step-motorized mirrors allow the alignment of the amplified beam through a 2.8 mm ID, 3.8 mm OD hollow sapphire tube located on the axis of the wiggler during the experimental run. The sapphire tube is needed to confine the CO_2 beam spot to maintain a high intensity along the wiggler.

The choice of the sapphire tube to confine the high power CO_2 laser is based on the result of a low power CW CO_2 beam measurement done with three different guiding systems: the annular sapphire tube, a stainless steel rectangular guide, and a germanium-coated stainless steel guide. The sapphire tube has an inner diameter of 2.8 mm and lengths of 33, 66 and 100 cm were studied. The stainless steel rectangular guide has a width of 2.8 mm and lengths of 5, 10, 20 inches. The rectangular guides

Figure 3.12: CO_2 transmission, input beam radius (a): 1.0 mm, (b): 1.3 mm

Figure 3.13: Low power CO_2 beam profile at the exit of the guide. (a): 33 cm sapphire tube, (b): 15 in. germanium coated stainless steel guide, (c): 15 in. stainless steel guide. The scale of the figure is 5.2 mm in both directions.

can be assembled together to a length of 35 inches. The transmission properties of these structures are shown in Fig. 3.12 with an input CO_2 beam radius of 1.0 mm and 1.3 mm. In both cases, the circular sapphire tube shows better transmission than the others. Fig. 3.13 is the beam profile taken at the exit of the guides (within 0.5 cm) with an input beam radius of 1.0 mm. The beam profile at the exit of the sapphire tube is more uniform than the others, which indicates a stronger fundamental mode content which is desirable for the IFEL acceleration.

The measurement of the CO_2 laser energy during the experimental run is done

in two steps. First, prior to the run, we measured the overall transmission of the system, from the exit of the amplifier to the end of the sapphire tube. A 10 % reflection beamsplitter near the exit of the amplifier extracts part of the beam and its energy is measured with a pyroelectric detector, which measures the total energy in the pulse in the millisecond time scale. The laser energy at the end of the sapphire tube is measured using a 45° copper mirror and with the same pyroelectric detector. We maximize the transmission of the system. During the experimental run, we measured the energy of the 10 % reflected beam together with the transmission obtained to determine the total amount of CO_2 laser energy passing through the sapphire tube. Since the pyroelectric detector can only measure the integrated energy on the millisecond time scale, a fast detector is needed to determine the time structure of the CO_2 laser output during the high gain period (250–300 ns) of the amplifier. The amplifier not only amplifies the picosecond sliced beam for the IFEL interaction, but also produces other CO_2 pulses via various mechanisms during this time frame. Therefore, a fast detector is needed to distinguish the picosecond sliced beam from others.

There are two mechanisms that cause the amplifier to produce the CO_2 pulse. First, due to the high gain of the amplifier, self-lasing can occur, which produces a long CO_2 pulse of 250–300 ns. The self-lasing pulse can have up to one Joule of total energy. Second, there is leakage through some optical components on the beam path which is fed into the amplifier, resulting in a multipulsed output. We have observed up to 4 CO_2 pulses within the high gain period. These pulses have sub-nanosecond pulse duration and energy comparable to the picosecond sliced beam.

The fast detector measures the scattered light from the surface of the pyroelectric detector and an oscilloscope displays its signal during the high gain period. For the self-lasing pulse, the scattered light from the pyroelectric detector surface has a

power level that is only in the noise level of the fast detector, and therefore can't be observed. We have observed, in some occasions, that the slow detector showed one Joule of energy output, but the fast detector had no output at all. Thus, we conclude that the self-lasing pulse has up to one Joule of total energy. For the picosecond sliced beam and the leakage pulses, their scattered light can be detected by the fast detector, which allows us to determine the portion of the energy contained within the picosecond sliced beam, assuming that there is no self-lasing pulse and the total energy detected by the slow detector is solely from the sliced beam and the leakage pulses. The contribution of the self-lasing pulse to the total energy measured with the slow detector gives an uncertainty in the determination of the picosecond sliced beam energy.

The pulse duration of the picosecond sliced beam is determined by observing the IFEL effect (next chapter) while varying the time delay between the sliced beam and the electron beam; this, together with the energy measured, determines the CO_2 laser pulse power. The overall transmission from the amplifier through the IFEL is between 20–60 %. The wide range in the overall transmission and relatively low transmission compared to the low power measurement are due to the fact that the amplified CO_2 beam is sensitive to the alignment of the system and contain a various high order transverse modes. Fig. 3.14 is the amplified beam profile taken at a distance equivalent to the entrance of the sapphire tube. Due to the physical constraint of the system, the amplified beam profile at the exit of the sapphire tube can't be taken. Although the low power beam profile shows close to Gaussian distribution at the exit of the sapphire tube, we should keep in mind that the low power beam is purely Gaussian too before entering the sapphire tube. Since the high power beam in Fig. 3.14 shows a non-uniform distribution, in which most of the energy appears near the outer part and less energy in the center, before entering the sapphire tube, it is possible that

Figure 3.14: Amplified CO_2 beam profile at the entrance of the sapphire tube. The scale of the figure is 5.2 mm in both directions.

the field distribution inside the sapphire tube is not uniform too, especially near the center of the tube where the electrons will execute the wiggle motion, it may have less energy than a normal Gaussian beam does. In summary, we can only determine the amplified CO_2 pulse loosely. Its power ranges between less than 0.1 GW to greater than 1 GW and the electric field amplitude is in hundreds of MV/m .

3.5 Electron Energy Diagnostic System

The electron beam energy diagnostic system consists of an energy spectrometer, a phosphor screen, a CCD camera and an image-grabbing unit, Spiricon. The energy spectrometer consists of a 20° bent dipole magnet and series of quadrupole magnets. The quadrupoles allow the change of the system's β function and dispersion function. The electron beam size is equal to $\beta\epsilon + \eta\frac{\Delta p}{p}$, where β is the beta function, ϵ the emittance, η the dispersion function and $\frac{\Delta p}{p}$ the momentum spread. For the IFEL measurement, the spectrometer is tuned to have the $\eta\frac{\Delta p}{p} \gg \beta\epsilon$ condition at the phosphor screen, so that the reading of the electron beam size on the phosphor screen is a sole function of the electron beam energy. The typical dispersion function used in this experiment is a few tenths of a meter to a few meters. The spectrometer is benchmarked against the phosphor coated momentum slit mentioned earlier. The

phosphor screen has a diameter of $\sim$ an inch, which defines the dynamic range of the spectrometer to be a few percent. The fluorescence generated on the phosphor screen by the electron beam is captured by a CCD camera and a image-grabbing unit, Spiricon, grabs the signal from the CCD. The use of the Spiricon allows a quick precise reading of the energy increase from the IFEL interaction to within one tenth of a percent.

Chapter 4

Experimental Results

In this chapter, we present the experimental results of the Brookhaven IFEL experiment. First, we show typical raw data from the Spiricon which gives the energy spectra of the electron beam downstream from the IFEL; the CO_2 laser on and off conditions are presented for different best representative experimental conditions. Then, the dependence of IFEL acceleration upon wiggler magnetic field, input electron beam energy, and CO_2 laser electric field are summarized, respectively.

4.1 Evidence of IFEL Acceleration

We first observed the evidence of IFEL acceleration in October 1995, obtaining an energy gain of 0.2 %. Figure 4.1 is the electron beam energy spectrum of that observation, (a) with CO_2 laser on and (b) with CO_2 off. The energy indication is on the horizontal axis with high energy toward the left of the figure. The energy range ($\Delta p/p$) covers ~ 1.2 % over the axis. The 0.2 % energy gain is measured between the highest energy edges of both figures. The video gain of the Spiricon was set to its maximum value to allow the easy reading of the edge. The faint ring in the figure is the boundary of the phosphor screen. The input unaccelerated beam is positioned near the edge of it, therefore only the accelerated electrons are observed here. Fig. 4.2 is the resulting energy distribution. The energy distribution is obtained by summing the pixel values along the vertical axis over the portion where electrons are recorded and then subtracting the background. The input energy is defined at the peak of the

Figure 4.1: Spiricon image from Oct. 1995 run. (a): laser on, (b): laser off

Figure 4.2: Energy distribution of Figure 4.1, (a): dashed line, (b): solid line

input unaccelerated beam. Since a major portion of the unaccelerated beam signal was saturated, due to the high video gain of the Spiricon, one must be careful in using these distributions to compare with the simulation results later. The parameters for this figure were, 40 MeV electron beam, 10 KG wiggler magnetic field, and laser energy of 0.2 J. The transmission of the system was 33 %. Prior to the experiment, we observed a vacuum pressure increase, from 2×10^{-8} torr to 2×10^{-7} torr, in front

of the wiggler during the CO_2 laser firing and, as a precaution, a 10 times attenuation filter was placed in front of the beamline entrance port to reduce the laser energy.

After the first observation of IFEL acceleration, effort was devoted to increase this effect by adjusting the delay between the electron beam and the CO_2 laser pulse; we observed 2 % energy gain by November 1995. Fig. 4.3 and Fig. 4.4 are the Spiricon

Figure 4.3: Spiricon image from Nov. 1995 run. (a): laser on, (b): laser off

Figure 4.4: Energy distribution of Figure 4.3, (a): dashed line, (b): solid line

images and corresponding energy distributions from this date. This image covers $\sim 3\%$ of energy and an energy gain of 2.1% was observed. High video gain again caused the saturation of the images. The parameters were: 40 MeV electron beam, 10 KG wiggler magnetic field and laser energy of 0.85 J. The transmission was 25% on this day and a 2.43 times attenuation filter is used to reduce the pressure rise in the beamline when CO_2 laser is firing.

In Fig. 4.5, we show the energy gain vs. the delay between the electron beam, and the CO_2 laser pulse. The energy gain shown has been normalized to a common CO_2 laser electric field. The experimental parameters are: 40 MeV electron beam, 10 KG wiggler magnetic field and laser energy between 0.4 Joules and 1.2 Joules. Although it shows only a portion of the full delay, a peak can still be reasonably defined and, from this, we conclude that the laser pulse fullwidth is $\simeq 500ps$ long. The cause for only a portion of delay recorded is caused by that the positioning of the prism assembly which controls the delay prior to the experiment being slightly off from the desired position (there are two experiments, IFEL and ICA, sharing the same CO_2 laser transport system. Since the timing requirement is different for both

Figure 4.5: Energy gain vs. the time delay

experiments, the prism assembly was placed at a compromised position that would work for both experiments.)

4.2 Data Summary

In this section, the effect of IFEL acceleration is summarized with respect to the CO_2 laser radiation field, the input electron beam energy and the wiggler magnetic field. We first discuss how the individual raw data, the energy spectrum images taken by the Spiricon, were assembled and the criteria of data selection is given.

4.2.1 Data Handling and Selection

During the running of the experiment, it was clear that whereas the wiggler magnetic field and electron beam energy can be easily characterized and controlled, the measurement of the CO_2 laser power poses the most serious difficulty in comparing each individual data point. Therefore, the data handling and selection are mainly concerned with the CO_2 laser pulse power.

From the IFEL equations, we know that the energy gain in an IFEL depends on the CO_2 laser power and is linearly proportional to the radiation field in the first order approximation (assuming that the source term in the energy equation stays constant along the wiggler). Since the CO_2 laser output varies between a few tenths of a Joule to 2 Joules and contains one to four pulses, the energy gains observed are normalized to a common radiation field before comparison. In order to normalize the energy gain to a common radiation field, we assume that the CO_2 laser pulse duration is the same during the data collection, thus the CO_2 laser energy measured is directly proportional to its power, i.e. the square of the radiation field (the transverse intensity distribution is the same, since the sapphire tube is used to confined the laser).

We summarize criteria for data selection for inclusion of IFEL data into an admissible set:

1. Only the data from the same day are compared. This is due to the fact that the maximum CO_2 transmission measured varies from day to day, indicating a change in its mode content and in its coupling into the sapphire tube. Comparing only the data from the same day allows us to eliminate the dependence on the variation of the CO_2 mode content and coupling.
2. The picosecond sliced CO_2 pulse energy must be reasonably determined. The CO_2 laser firing which shows substantial energy in the slow detector, but zero or near zero signal in the fast detector, especially for the picosecond sliced beam signal, has to be discounted. Some data in which we changed the opening of an aperture along the CO_2 beam path, aren't included in the summary either, since the transmission was never measured for those occasions (the transmission was measured with the aperture fully open).
3. The input electron beam energy has to remain nearly constant during the data collection for a specific input energy. In case of RF drifting which causes an energy shift, the electron beam energy has to be tuned back to its specified value, before taking any further data. A shot has to be discounted, if the input beam spectrum following it changes and is different from the one prior to it.
4. The energy gain has to be large enough to distinguish itself from the electron beam energy jitter. The electron beam energy jitter from the ATF Linac is less than 0.1 %; therefore, only energy gain greater than that can be safely characterized as a result of IFEL acceleration. Also note, the electron beam energy jitter depends on the stability of the Linac and the klystrons, and can vary from day to day.

Finally, due to the limitation on the CO_2 amplifier lifetime (a few hours only), it is likely that the mode quality of the amplified CO_2 laser pulse gradually deteriorates and its transmission and coupling into the sapphire tube changes during the course of data collection. Also, the repetition rate of the amplifier is low (once every 30 seconds or longer); so there is a limit on how many data points can be taken at each point for a meaningful comparison. We usually collected 3 or 5 data points for each position, depending on the condition of the amplifier output.

4.2.2 IFEL Effect Summary

We first present the energy gain vs. the CO_2 laser electric field in Fig. 4.6 and 4.7. The electron beam energy is 35 MeV and the wiggler magnetic field is 8.5 KG in Fig. 4.6, and 40 MeV and 10 KG in Fig. 4.7. Both figures show that the energy gain is approximately linearly proportional to the CO_2 laser electric field, which justifies our assumption in data handling of normalizing the energy gain to a common electric field before comparison for its dependence on the input electron beam energy and the wiggler magnetic field. The scattering of the data points on both figures indicates the instability of the CO_2 laser output. The solid curves are from the numerical simulation using the IFEL equations in chapter 2 and will be discussed in the next chapter.

Figure 4.8 shows the effect of IFEL acceleration vs. the electron beam input energy. The wiggler magnetic field strength is 9.5 KG. The data was averaged over 5 shots and the error bar indicates the standard deviation. The figure indicates a maximum energy gain with the input electron beam energy near 38.5 MeV and is in reasonable agreement with the IFEL resonant condition. The resonant energy for wiggler magnetic field of 9.5 KG is ~ 38.4 MeV at the entrance of wiggler. This figure shows the importance of matching the electron beam energy to the resonance

energy for the IFEL acceleration. The half width of this figure is roughly 10 % of the resonance energy. This can be explained by considering the width of the “closed” region in the phase space. The width of the “closed” region is expressed as [46, 22],

$$\frac{\gamma - \gamma_r}{\gamma_r} = 2\sqrt{a_s a_w}$$

where a_s is $\sim 1.15 \times 10^{-3}$ for one GW laser power, assuming that the laser is uniformly distributed across the aperture of the sapphire tube, and a_w is 1.8 at the entrance of the wiggler for 9.5 KG field strength. This yields the width of the “closed” region of 9.1 %. When the input electron beam energy is outside of the “closed” region in phase space, the electrons will undergo unbounded motion inside the wiggler and no trapping or bunching occurs, i.e. no energy gain for these electrons. The width of the “closed” region in phase space agrees reasonably well with the 10 % width we observed in this figure. The solid curve is from the numerical simulation and will be discussed in the next chapter.

We next show the effect of IFEL acceleration vs. the wiggler field strength in Figure 4.9 and 4.10. The input electron beam energy is 35 MeV in Fig. 4.9 and 40 MeV in Fig. 4.10. During the taking of these data, the CO_2 amplifier system behaved unstably. As a result, we were limited in the amount of usable data collected and we are unable to plot the error bar for each point. However, we can still loosely determine the position of the wiggler field at which the maximum energy gain occurs for both figures. For Fig. 4.9, the maximum energy gain occurs near 8.5 KG, and it is in good agreement with the resonance condition at the entrance of the wiggler. The wiggler field required for a 35 MeV resonance energy at the entrance of the wiggler is ~ 8.39 KG. For Fig. 4.10, the maximum energy gain is near 10 KG and the wiggler field for a 40 MeV resonance energy is ~ 10 KG: this agrees well too. Therefore, both figures, like Fig. 4.8, show the importance of matching the resonance condition for the IFEL acceleration.

Figure 4.6: Energy gain vs. CO_2 laser electric field: electron beam energy 35 MeV and wiggler magnetic field 8.5 KG

Figure 4.7: Energy gain vs. CO_2 laser electric field: electron beam energy 40 MeV and wiggler magnetic field 10 KG

Figure 4.8: Energy gain vs. electron beam input energy. 9.5 KG wiggler magnetic field

Figure 4.9: Energy gain vs. the wiggler field strength with 35 MeV electron beam energy

Figure 4.10: Energy gain vs. the wiggler field strength with 40 MeV electron beam energy

Chapter 5

Numerical Interpretation

In this chapter, we compare the observed IFEL acceleration results with the numerical results using the IFEL equations described in Chapter 2. We first summarize the numerical simulation results for the observed IFEL effect given in section 4.2.2. Then, we present the electron energy distributions and compare them with the Spiricon image. Finally, we present the numerical result of the electron bunching under various conditions and discuss the possibility of using the bunched beam as a source for other acceleration schemes.

5.1 Numerical Simulation of the IFEL Effect

The IFEL acceleration effect with respect to the CO_2 laser radiation field, the input electron beam energy and the wiggler field strength is presented in section 4.2.2 and we can see, in Fig. 4.6–4.10, that the numerical simulation (the solid lines) shows good agreement with the experimental results in each case. Next, we will discuss how we obtained those results and the parameters used for those calculations.

As we mentioned in section 4.1, the energy gain was measured between the highest energy edge of the energy spectra when the CO_2 laser is on and off. Therefore, for the simulation results, we calculate the highest energy edge as the mean energy of the top 1 % of the highest energy electrons, and the energy gain is taken to be the difference between this “mean” maximum energy at the entrance and the exit of the wiggler. We’ve also used other choices, like the top 0.1 %, to calculate this “maximum” energy

and we found this does not change the interpretation.

During simulation, the main parameter we vary to match the experiment results is the laser power, since it is the only parameter in the experiment that cannot be unambiguously determined. For the parameters of the electron beam and the wiggler, we use the actual experiment values for the simulation. Also, we set the energy spread of the injected electrons at 0.2 % (half width, rms) for all the calculations, just for the sake of simplicity. The energy spread was set by the momentum slit (Chapter 3 in experiment. The power level used in Fig. 4.6 is from 0.01 to 0.25 GW, in Fig. 4.7 from 0.01 to 0.15 GW and in Fig. 4.8–4.10 0.1 GW. This laser power level used in the simulation is much smaller than what we estimated during the experiment, which was believed to be ~ 1 GW (a few tenths of Joules of energy measured and 500 ps in pulse duration estimated). The causes for this significant difference is not clear so far, although the discussion on p. 45 offers a possible explanation. It could be that the laser energy measured is mainly from the self-lasing of the amplifier and the picosecond amplified CO_2 pulse power is only at 0.1 GW level. Further study is needed to resolve the discrepancy on the laser power.

5.2 Energy Distribution

In the IFEL experiment, we are mainly interested in the accelerated electrons, thus, for most of the time, we place the input electron beam at the edge of the phosphor screen to maximize the dynamic range of the high energy tail. However, it is also very useful for understanding the IFEL effect to study the details of the full electron energy distribution, i.e., observing both the accelerated and decelerated electrons at the same time. We have recorded several of these images and Figure 5.1 is one example. Figure 5.2 is its energy distribution.

Figure 5.1: Spiricon image showing both the accelerated and decelerated electrons.
(a): laser on, (b): laser off

Figure 5.2: Energy distribution of Figure 5.1, (a): dashed line, (b): solid line

We can see that the electron energy distribution gets spread out in both the high energy and low energy directions, indicating that acceleration, as well as deceleration, occurs, after undergoing the IFEL interaction. This results in a broadening of the energy spectrum. Also, it is worth noting that the center energy stays nearly unchanged in this case. Most of the Spiricon images that cover both acceleration and

deceleration show the similar features in their respective energy distributions.

However, we should point out that not all the Spiricon images show these features (broadening of the spectrum and the center energy unchanged). One of these examples is Fig. 4.3 and Fig. 4.4 which we show again as Fig. 5.3. We can see in this figure that the accelerated electrons distribution is almost separated from the initial energy distribution and its center energy is at 40.5 MeV. Also, there are not many electrons left at the initial energy now. Since this image doesn't cover the low energy end, we can't see the details of the decelerated electron distribution. Nevertheless, a general picture can still be drawn. The full energy distribution should look like two piles of electrons at both extremes of energy with a valley between them. This example indicates that the details of the electron energy distribution can be complicated and vary considerably under different conditions.

Figure 5.3: Energy distribution of Figure 4.3, (a): dashed line, (b): solid line

We next show the simulation result of the electron energy distributions under various conditions in Figure 5.4. The parameters are 40 MeV electron beam, 10 KG wiggler field and the CO_2 laser power at 0.01, 0.05, 0.1 and 0.2 GW. This figure shows that when the laser energy is small, the electron energy distribution appears

Figure 5.4: The electron energy distribution at the exit of wiggler for 40 MeV electron beam and 10 KG wiggler field. The laser powers are, (a): 0.01 GW, (b): 0.05 GW, (c): 0.1 GW and (d): 0.2 GW. Solid line: at the entrance and dotted line: at the exit of wiggler.

to broaden, and the separation between the accelerated and decelerated electrons is not clear. As the laser power gets higher, the energy gain increases and there appear two peaks at the high energy and low energy end, as seen in Fig. 5.4 (b)–(d). The clear separation of the accelerated and decelerated electrons is not seen here, since the laser power is low compared to the ideal laser power (3–5 GW) for this wiggler, thus there is a continuity in electron distribution from the low energy to high energy.

Also notice that, although the high energy peaks in Fig. 5.4 (b)–(d) appear to shift higher as the laser power gets higher, the low energy peaks appear to stay put at the same position, unrelated to the laser power. The reason for this different behavior is that the resonance condition of the wiggler is intended for IFEL acceleration. Thus, even though the laser power levels in Fig. 5.4 (b)–(d) can't maintain the resonance condition throughout the wiggler, the position at which the accelerated electrons fall out of resonance depends on the laser power. The higher the laser power is, the longer the electrons stay in resonance inside the wiggler and the higher the energy gain will be. For the low energy peak, the decelerated electrons lose energy to the radiation from the very beginning and fall out of the resonance very quickly. The position at which the decelerated electrons fall out of the resonance mainly depends on the wiggler setting, not on the laser power, thus the low energy peaks appear at the same position even when the laser power is different.

Although the energy distribution of Fig. 5.4 (a) shows the similar feature of energy spectral broadening as Fig. 5.2, its energy gain is smaller. As we increase the laser power (Fig. 5.4 (b)) to reach the energy gain comparable with Fig. 5.2, the simulated energy distribution starts to show the two-peak feature which doesn't show in Fig. 5.2. While Fig. 5.3 may indicate a similar two-peak feature, the absence of the low energy distribution in this figure makes it difficult to compare with the numerical result of the spectrum.

In the IFEL experimental setup, the spectrometer is actually located at 8 meters downstream from the wiggler. As we will see in the next section, the bunching of the electrons can occur either within or after the wiggler. As the electron bunching develops, the space charge effect becomes significant and can result in a modification of the electron energy distribution. To simulate this 8 meter drift distance with the space charge effect, we set the wiggler field to zero in the IFEL equations. Figure 5.5

Figure 5.5: The electron energy distribution at the spectrometer for 40 MeV electron beam and 10 KG wiggler field. The laser powers are, (a): 0.05 GW, (b): 0.1 GW. Solid line: at the entrance and dotted line: at the spectrometer.

shows the energy distribution at the spectrometer for a 40 MeV electron beam, 10 KG wiggler field and 0.05 and 0.1 GW laser power respectively. We can see that the energy distribution at the high energy end is smoothed out at the spectrometer and the high energy peak that appears at the exit of the wiggler in Fig. 5.4 is no longer there. Even though the energy distribution in Fig. 5.5 doesn't perfectly match the details of the measured distribution in Fig. 5.2, it does show that both the energy gain and the absence of the two-peak feature agree well with the experiment. For a better understanding of the details of the electron energy distribution, more data are needed from the experiment.

5.3 The Bunching of the Electrons

While IFEL has the potential to provide a high accelerating gradient for electron acceleration, another possible use of the IFEL is that it can serve as an electron energy modulator to produce a well bunched beam for other laser-driven accelerators, such as

the ICA (Inverse Cherenkov Accelerator) or another stage of IFEL. In fact, study of the electron microbunching has just begun in ATF for a joint ICA-IFEL experiment [47, 48]. In this section, we will present various bunching results (simulation only) and discuss the viability of using the IFEL as an electron buncher for another accelerator. But first we will discuss the main difference between running the IFEL as a high gradient accelerator and using it as an electron buncher for another accelerator.

We know from the simulation in chapter 2 that electron bunching is essential to achieve a high energy gain for an IFEL accelerator, since it will allow the electrons to maintain the resonance condition and participate in the IFEL interaction throughout the wiggler. Therefore, for an ideal IFEL accelerator, we would like to have the bunching of the electrons occur inside the wiggler. However, when we use the IFEL as an electron buncher for another accelerator, it is obvious that the best result would be to have the bunching occur at the next accelerator position, which would be a few meters downstream from the IFEL wiggler (the space is needed to refocus the electron beam out of the IFEL wiggler and into the next accelerator module). Thus, there is a big difference in using the IFEL as an accelerator or as an electron buncher for another accelerator.

Figure 5.6 shows the longitudinal distribution and the phase space distributions of the electrons. The parameters are: 40 MeV electron beam, 10 KG and 0.1 GW laser power. We can see that the electrons show very good bunching at the exit of the wiggler, where close to $2/3$ of the electrons are bunched within 1 radian of phase ($\sim 1/6$ of $10.59 \mu m$). However, at the 100 cm downstream of the wiggler, the electron bunching is very weak. It is also instructive to examine the phase space distributions at various positions. At the middle of the wiggler (Fig. 5.6 (c)), we see that the the electrons at the front have lower energy than the electrons at the back, and eventually, the electrons at the back catch up with the electrons in front

Figure 5.6: (a): the longitudinal distribution of the electrons, solid line: at the entrance of wiggler, dashed line: at the exit of wiggler and dotted line: 100 cm downstream of wiggler. (b), (c) and (d) are the phase space distributions at the exit of wiggler, middle of wiggler and 100 cm downstream of wiggler, respectively. 40 MeV electron beam, 10 KG and 0.1 GW CO_2 laser power.

at the exit of the wiggler, resulting in bunching of the electrons (Fig. 5.6 (b)). As the electrons travel farther down the beamline, the wide energy spread (due to the IFEL interaction) results in a deterioration of the electron bunching (Fig. 5.6 (d)). It is clear that the conditions of Fig. 5.6 are not favorable as an electron buncher for another accelerator. We have also investigated the bunching with larger laser

power (0.15–0.25 GW) and our simulation shows that as the laser power gets larger, the bunching improves. However, the electron bunching will now occur inside the wiggler.

Figure 5.7 shows another example for electron bunching. The parameters are 40 MeV electron beam, 10 KG wiggler field and 0.01 GW. The electron bunching in

Figure 5.7: (a): the longitudinal distribution of the electrons, solid line: at the entrance of wiggler, dashed line: at the exit of wiggler and dotted line: 100 cm downstream of wiggler. (b), (c) and (d) are the phase space distributions at the exit of wiggler, 100 cm and 200 cm downstream of wiggler, respectively. 40 MeV electron beam, 10 KG and 0.01 GW CO_2 laser power.

this figure is not as good as the previous case. Here, about 50 % of the electrons are bunched within 2 radians of phase (from -0.5 to 1.5). Also, due to the low laser power, the energy modulation on the electrons is small, therefore, the bunching doesn't deteriorate as fast as the previous case. We can see that the level of the electron bunching is very similar at the exit and 100 cm downstream from the wiggler. For laser power between 0.01 and 0.1 GW, our simulation shows that the bunching would occur somewhere between the wiggler exit and 100 cm downstream from the wiggler, and as the power gets larger, the bunching will get better too. The conditions of Figure 5.7 could be used as an IFEL electron buncher for another accelerator.

Although Fig. 5.7 can be a candidate for an electron buncher, its bunching isn't as good as Fig. 5.6 shown at the exit of the wiggler. Therefore, we further investigated the possibility of achieving good bunching downstream from the wiggler. We show another example in Figure 5.8. The parameters are 40MeV electron beam, 9.5 KG wiggler field and 0.1 GW laser power. The key difference from the previous two cases is that the electron beam energy doesn't match the resonance energy at the entrance of the wiggler. We can see that it shows very good bunching at 100 cm downstream from the wiggler, where about 2/3 of the electrons are bunched within 1 radian of phase; however not much bunching exists at the wiggler exit and 200 cm downstream from the wiggler; thus Fig. 5.8 can be a good candidate for the electron buncher.

We have presented three cases of the electron bunching by IFEL. It is clear that beam bunching on an optical scale can occur using the IFEL. Figure 5.6 and 5.7 show us that when large laser power is used, good electron bunching can occur, but at a position near or even inside the wiggler, which is not suitable as an electron buncher for another accelerator. When the laser power is low, good electron bunching can occur at 100 cm downstream from the wiggler, which is suitable as an electron buncher. However, the bunching is not as good as when using high laser power. An alterna-

Figure 5.8: (a): the longitudinal distribution of the electrons, solid line: at the entrance of wiggler, dashed line: at the exit of wiggler, dotted line: 100 cm downstream of wiggler and dash-dotted line: 200 cm downstream. (b), (c) and (d) are the phase space distributions at the exit of wiggler, 100 cm and 200 cm downstream of wiggler, respectively. 40 MeV electron beam, 9.5 KG and 0.1 GW CO_2 laser power.

tive is to run the IFEL at off-resonance conditions (Fig. 5.8), where good electron bunching occurs at 100 cm downstream from the wiggler. However, we should keep it mind that the position at which the electron bunching occurs depends strongly on the laser power, the electron beam energy and the wiggler field. Therefore, when using IFEL as an electron buncher for another accelerator, the Linac, the wiggler and, most

importantly, the CO_2 laser system, must be very stable. Finally, using the IFEL as a high gradient accelerator or as an electron buncher for another accelerator requires different operating conditions. A moderate energy gain IFEL may be sufficient for the best electron bunching results.

Chapter 6

Conclusion

The acceleration of electrons using the principle of IFEL and a high power laser source has been confirmed. An Energy gain of 2.5 % ($\frac{\Delta E}{E}$) on a 40 MeV electron beam using a 1 GW CO_2 laser and a tapered wiggler with a peak field on axis of 10 KG has been observed. The effects on IFEL acceleration with respect to the variation of the laser electric field, the input electron beam energy and the wiggler magnetic field strength were studied, and show the importance in the IFEL of maintaining the resonance condition throughout the wiggler, thus insuring the continuous participation of the electrons in the IFEL interaction.

A Numerical study has been carried out to interpret the experimental results. First, our simulation code was benchmarked against the initial ATF IFEL design and shows very good agreement against the prior result. The simulation of an early Russian IFEL experiment report shows that no acceleration could exist under such condition, since no trapping and bunching of the electrons can have taken place in this apparatus. Numerical simulations were performed under various conditions and the importance of the bunching of the electrons by the ponderomotive force in an IFEL is clearly shown.

The numerical interpretation of our experimental results was examined. First, the effect of IFEL acceleration with respect to the laser electric field, the input electron beam energy and the wiggler magnetic field strength were modeled, but to obtain good numerical agreement with the experimental results, there is a discrepancy between the level of the laser power used in the experiment and in the simulation, possibly due

to the non-Gaussian profile of the input high power laser beam. In the simulations that match the experimental results, only 0.1 GW of laser power is needed, whereas the estimated laser power is believed to be ~ 1 GW in the experiment. However, we pointed out in Chapter 3 that the determination of laser power is the most difficult task in this experiment, and due to the instability of the CO_2 laser amplifier system, it is possible that there is a large uncertainty in our estimation of the CO_2 laser power that actually reaches the electrons.

Next, the comparison of the electron energy distribution between the experiment and the simulation is made. Due to the limitation of the electron energy spectrometer and our main interest in studying mainly the accelerated electrons, most of the energy spectrum images were focused on only the high energy portion, thus we are limited on the number of the experimental data for this comparison. In the few energy spectrum images where both the accelerated and decelerated electrons are shown, a broadening of the energy spectrum is observed. For the simulation result, when the laser power is low, the electron energy distribution also appears to broaden as in the experiment. However, the energy gain at this power level in the simulation does not match the energy gain observed in experiment. As the laser power gets higher, the simulation shows that two peaks appear at the high and low energy ends of the spectrum, which was not found in the experiment. However, by running the simulation to the actual axial location of the spectrometer, we find there is a smoothing of the energy spectrum by the space charge effect which is significant because of the bunching of the electrons by the ponderomotive force.

The bunching of the electrons by the IFEL and the possibility of using the IFEL as an electron prebuncher for another laser-driven accelerator is studied numerically. We find that bunching of the electrons at 1 meter downstream from the wiggler can be achieved and this enables the IFEL to be used as a prebuncher for another accelerator.

The simulation also shows that there is a difference between the operating conditions for using the IFEL as a high gradient accelerator, and as a prebuncher for another accelerator. For a high gradient accelerator, the IFEL requires the bunching of the electrons in the wiggler to insure the best energy gain. For a prebuncher for another accelerator, a moderate energy gain IFEL may be sufficient for the best electron bunching results at a distance downstream from the wiggler.

In summary, we have observed the IFEL acceleration of an electron beam using a $10.6\ \mu\text{m}$ CO_2 laser and a tapered wiggler. The dependence of the IFEL effect upon the laser electric field, the input electron beam energy and the wiggler magnetic field has been validated. The simulation results show agreement with data, but a difficulty in the accurate laser power measurement needs to be resolved. The comparison of the predicted electron energy distribution with data is attempted, but is limited by the scarcity of the experiment data. The bunching of the electrons is studied numerically and shows the potential of the IFEL as an electron prebuncher for another laser-driven accelerator. At present, an experiment at Brookhaven is in progress to measure the bunching of the electrons produced by this IFEL, using a coherent transition radiation diagnostic [47]. A scaling-up of IFEL acceleration to $\sim 100\ \text{MeV/m}$ requires CO_2 laser power $> 200\ \text{GW}$, which will be available for IFEL experiment in the future.

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