IFEL EXPERIMENT AT THE NEPTUNE LAB

Pietro Musumeci

Department of Physics and Astronomy, University of California at Los Angeles, 405 Hilgard Avenue, Los Angeles, CA, 90095-1547

Abstract. We present a two stage Inverse Free Electron Laser accelerator proposed for construction at the UCLA Neptune Lab. Proof-of-principle experiments on the IFEL scheme have been carried out successfully. This experiment is intended to achieve a 100 MeV energy gain, staging two IFEL modules. It will use a 16 MeV electron beam, a 1 TW CO2 laser and two different tapered helical undulators. The problem of refocusing both laser and electron beam is analysed in detail. A preliminary beam-line layout and numerical simulation are presented.

INTRODUCTION

One of the most appealing possibilities for the acceleration of charged particle is to make them interact with the very large high electric fields easily available in today’s high power lasers. One important advantage of far field accelerator with respect to other advanced accelerator scheme, is that the acceleration takes place in vacuum and the interaction does not require the presence of a plasma or other media at a wavelength distance from the beam, thus avoiding problems of electrical breakdown, beam intensity limitations due to electromagnetic interaction with material boundary, and beam quality degradation due to the interaction with a plasma. In principle every reverse process of a charged particle radiation can be used for acceleration. In this paper we study the inverse process of the Free Electron Laser, namely the interaction of a quasi monochromatic electromagnetic wave, with a relativistic electron beam inside an oscillating static magnetic field.

This idea has been proposed initially by Palmer [1] and then extensively explored by CPZ [2] and others [3-4]. Proof-of-principle Inverse Free Electron Laser experiments have already been carried out successfully and recently also the possibility of staging of different IFEL modules has been proved [5]. In particular a system with many accelerating regions can be obtained either by using a number of laser beams each focused only once, or by multiple focusing of one laser beam. In the first case the main problem is to keep the phase coherence of the different laser beams so that the particles remain in step with the accelerating field [6]. We explore the second case, where the main problem is the transport and focusing of a high power laser beam.

The goal of the proposed experiment is to realise an IFEL accelerator raising the beam energy from about 14 MeV, to about 100 MeV, and to test the feasibility of a staging scheme using only one laser beam.
Table 1. Initial parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam energy</td>
<td>14 MeV</td>
</tr>
<tr>
<td>Electron beam pulse length</td>
<td>6 ps</td>
</tr>
<tr>
<td>Electron beam emittance</td>
<td>5 mm-mrad</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>10.6 µ</td>
</tr>
<tr>
<td>Laser energy</td>
<td>100 J</td>
</tr>
<tr>
<td>Laser pulse duration</td>
<td>100 ps</td>
</tr>
</tbody>
</table>

The Neptune Laboratory at UCLA has already a high brightness split photoinjector [6], and the high power MARS laser. The initial parameters of the IFEL are given in the table.

In the first part of this paper it is proposed a solution to the problem of focusing and transporting a laser pulse with 3-4 order of magnitude more energy respect to other IFEL experiments. A particular study of the IFEL interaction including the effect of the laser diffraction is also presented. The Guoy phase shift that a gaussian beam experiences going through a waist, is compensated by a gap between two half-undulators to allow re-phasing of electrons and photons. With this new scheme it is particularly important to control the effect of the wigglers in the transverse beam dynamics. At the end we present the results of 3 dimensional simulation of the beam phase space dynamics.

DEALING WITH TERAWATT LASER

We describe the laser beam with a gaussian approximation:

\[
E, B \propto e^{-\frac{\left(x^2 + y^2\right)}{w(z)^2} + i \left(kz - \omega t + \varphi_0 + \frac{k}{2R(z)} \arctan\left(\frac{z-w}{zr}\right)\right)}
\]

The best possible optical configuration for an IFEL application would be a laser beam focused at the center of the undulator to a spot size such that the Raleigh range is comparable with the length of the interaction region, that is the undulator length. To reach this optimum situation is complicated by the limit set by the damage threshold of the materials used in the transport system (2J/cm²) [6]. In fact the spot size on the focusing lens cannot be smaller than 50 cm² and the focal distance is limited by the fact that for practical space reasons, the lens cannot be more than 2-3 m away from the waist point. Plugging in these numbers in the relation valid for Gaussian beams:

\[
f = \frac{\pi w_0 w_f}{\lambda}
\]

it is immediate that the final spot size \( w_f \) is about 0.25 mm, and the associated Raleigh range about 2 cm. Focusing 1 TW of CO₂ laser beam to this small spot size will result in
electric field at the waist as high as 60 GV/m, but because the Raleigh range is much shorter than the undulator length, it is important to include the effect of diffraction in the analysis of the Inverse Free Electron Laser interaction.

A DIFFRACTION-DOMINATED IFEL INTERACTION

The Resonant Acceleration

To describe a diffraction-dominated Inverse Free Electron Laser interaction we modify the classical IFEL equations [12] to include the diffraction effects, in particular the dependence of the electric field from the spot size, and the Guoy phase shift effect.

\[
\begin{align*}
\frac{\partial \gamma}{\partial z} &= \frac{e E_0}{mc^2} K \frac{1}{\sqrt{1 + \left(\frac{z-z_w}{z_r}\right)^2}} \sin(\psi) \\
\frac{\partial \psi}{\partial z} &= k_w + k - \frac{k}{\beta_z z_r} - \frac{1}{z_r (1 + \left(\frac{z-z_w}{z_r}\right)^2)}
\end{align*}
\]

valid for helical geometry with constant undulator parameter K. We assume the laser wave function not to be a dynamical variable of the problem. If the undulator is properly tapered electrons and photons can maintain a definite phase relationship and there can be an energy transfer from the wave to the electrons[2].

\[\text{FIGURE 1. Energy and wavelength along a constant K optimally tapered undulator}\]
Stability Of Acceleration

Fig.2 shows the longitudinal phase space of the electrons. It is evident that going through the laser waist, the change in parameters, in particular the fast 180º phase shift is not adiabatic, and the accelerating bucket concept, useful in describing the dynamics for slowly changing Hamiltonian [12] is not valid anymore. The accelerating bucket disappears the end of the second half-undulator.

Solution Of The Guoy Phase Shift Problem

To avoid this problem we can insert in the region around the laser waist, a gap in the undulator magnetic field such that electrons and photons have the right accelerating phase at the entrance of the second undulator section. The laser phase shift is of 180º and if the length of the gap is given by:

$$\Delta z = \lambda \gamma^2 \approx 4 \text{ cm}$$

the electrons slip other 180º respect of the electromagnetic wave and the resonant
phase is preserved. 1 dimensional simulations confirm that with this scheme, the bucket is preserved at the end of the accelerating region.

Fig.3 clearly shows what happens in the critical region: the resonant phase slips $2\pi$ at the laser waist and the energy starts to grow again when the particle enter the second half-undulator.

**UNDULATOR DESIGN**

The undulator parameters are in Table 2. The helical geometry is convenient because the Inverse Free Electron laser interaction is always “turned on”. The choice of keeping constant $K$ is made for convenience. A crucial concern for the undulator design is the period tapering. The best tapering function is shown in Fig.1. To simplify the undulator design though, a linear approximation is made to this function in each half-undulator. The value of $K$ is also increased going from the first interaction region to the next one. In the first half-undulator $K$ has to be as low as possible to meet the resonant condition for a 15 MeV electron beam. Then, when the electrons have been already accelerated, the value of the undulator parameter can be raised to give even bigger accelerating gradient.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1st half-undulator</th>
<th>2nd half-undulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial $\lambda_w$</td>
<td>1.5 cm</td>
<td>1.5 cm</td>
</tr>
<tr>
<td>$K$</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>$B$</td>
<td>0.2 T</td>
<td>0.6 T</td>
</tr>
<tr>
<td>Undulator length</td>
<td>0.27 m</td>
<td>0.27 m</td>
</tr>
<tr>
<td>Linear tapering coefficient</td>
<td>0.08</td>
<td>0.14</td>
</tr>
</tbody>
</table>

The undulator parameters can be achieved in different ways. Either hybrid design with permanent magnet and iron, or an electromagnetic undulator appear to have satisfying performances. As a first step towards undulator design, in order to study the particle evolution, a 3 dimensional magnetic field map form RADIA [10] was generated for two bifilar helical undulators with dipole kickers at the entrance and exit to compensate for the transverse kick due to the undulator magnetic fields.
FIGURE 4. Field map for the first half undulator. B(T) vs. z(mm). Note the linear period tapering. Note that in the bifilar design the radius of the winding helices was increased to decrease the field amplitude to maintain constant K.

3D SIMULATION

TREDI [11], a Lienard-Wiechert based, particle tracking code, using 4th order Runge-Kutta, was used to follow the particles in the RADIA 3d map, and the gaussian laser field (1). The results are compatible with 1d simulations.

Figure 5. Histogram plots of the normalized energy of the particles at the end of first half-undulator (on the left) and at the end of second half-undulator (right).

The variation of the percentage of captured particles with electron beam size and transverse initial displacement of the position of the bunch centroid (fig. 6) can be explained observing that because of the gap around the waist is about 2 Raleigh range, the smallest laser beam size that the electrons see inside the undulator is about 0.4 mm.
CONCLUSION

The results of the initial study of the Inverse Free Electron Laser Accelerator at the Neptune Lab at UCLA are summarised in Table 3.

<table>
<thead>
<tr>
<th>Table 3. IFEL parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial energy</td>
<td>15 MeV</td>
</tr>
<tr>
<td>Final energy</td>
<td>75 MeV</td>
</tr>
<tr>
<td>Averaged energy gradient</td>
<td>100 MeV/m</td>
</tr>
<tr>
<td>Microbunch length</td>
<td>10 fs</td>
</tr>
</tbody>
</table>

The proposed solution to the problem of focusing and transporting the high power laser is not the only one possible. Laser waveguides, or the optical properties of an already ionized medium can also solve the problem and we will study them in the future. The initial calculations and the simulation result though, show that interesting results can be obtained in this diffraction-dominated configuration.

REFERENCES

6. W.Kimura These Proceedings