IFEL EXPERIMENT AT NEPTUNE LAB

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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 simulations are presented.

1 INTRODUCTION

One of the most appealing possibilities of scheme 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 laser. One important advantage of far field accelerators with respect to other advanced accelerator schemes, 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 of the beam 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 quasimonochromatic 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]. Proof-of-principle Inverse Free Electron Laser experiments have already been carried out successfully[4-5] and recently also the possibility of staging of different IFEL modules has been proved[6]. 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 amplified laser beams so that the particles remain in step with the accelerating field. 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 beeam energy from about 14 to about 100 MeV, and to test the feasibility of a staging scheme using only one laser beam.

The Neptune Laboratory at UCLA has already a high-brightness split-integrated photoinjector[7] and the high power MARS laser. The initial parameters of the IFEL are given in the table.

Table 1: Initial Parameters

Electron beam energy	14 MeV
Electron beam pulse length	6 ps
Electron beam emittance	5 mm-mrad
Laser wavelength	10.6 µ
Laser power	1 TW
Laser pulse duration	100 ps

In the first part of this paper we described the proposed solution for focusing and transporting a laser pulse with 3-4 orders of magnitude more energy respect to other IFEL experiments. A particular approach to the problem of the laser diffraction is also presented. The Guoy phase shift that a gaussian beam experience going through a waist is compensated by a gap between two half-undulators to allow the re-phasing of electrons and photons. With this new scheme particular interest is in 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.

2 DEALING WITH TERAWATT LASER

We describe the laser beam with a gaussian approximation:

$$\mathbf{E}_l, \mathbf{B}_l \propto \frac{e^{-\frac{\left(x^2+y^2\right)}{w(z)^2}+i\left(kz-\omega t+\varphi_0+\frac{k\left(x^2+y^2\right)}{2R(z)}+arctg\left(\frac{z-z_w}{z_r}\right)\right)}}{\sqrt{1+\left(\frac{z-z_w}{z_r}\right)^2}} \qquad (1)$$

The best possible optics 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 due to the damage threshold of the materials used in the transport system, avout 2J/cm^2 [8]. In fact the spot size on the focusing lens cannot be smaller that 50 cm^2 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. Using these number in the relation valid for gaussian beams[9]:

$$f = \pi w_0 w_f / \lambda \qquad (2)$$

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

3 A DIFFRACTION-DOMINATED IFEL INTERACTION

3.1 The resonant acceleration

To describe a diffraction dominated Inverse Free Electron Laser interaction we modify the IFEL equations[2] to include the diffraction effects, in particular the dependence of the electric field from the spot size, and the Guoy phase shift effect.

$$\begin{cases} \dfrac{\partial \gamma}{\partial z} = \dfrac{eE_0}{mc^2} K \dfrac{1}{\sqrt{1 + \dfrac{(z - z_w)^2}{z_r^2}}} \sin(\psi) \\ \dfrac{\partial \psi}{\partial z} = k_w + k - \dfrac{k}{\beta_z} - \dfrac{1}{z_r \left(1 + \dfrac{(z - z_w)^2}{z_r^2}\right)} \end{cases} \qquad (3)$$

valid for a helical geometry with constant undulator parameter K.

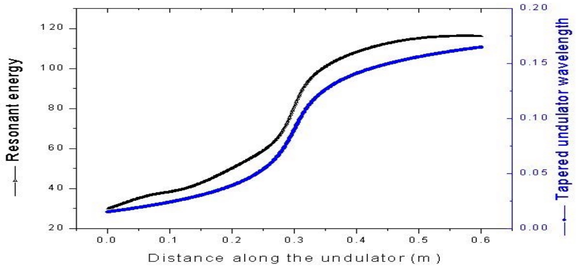

Fig. 1: Energy and wavelength along the tapered undulator

If the undulator is tapered, electrons and photons can maintain a definite phase relationship and there could be an energy transfer from the wave to the electrons[1] (see Fig.1).

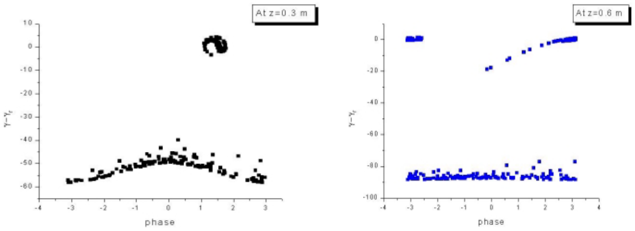

Fig.2: longitudinal phase space

3.1 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 the parameters, in particular the fast 180° phase shift, is too fast, and not adiabatic and the accelerating bucket concept, useful in describing the dynamic for slowly changing Hamiltonian is not valid anymore. The accelerating bucket disappears at the end of the undulator.

3.2 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 180° and if the length of the gap is given by

$$\Delta z = \lambda \gamma^2 \approx 4\,cm \qquad (4)$$

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

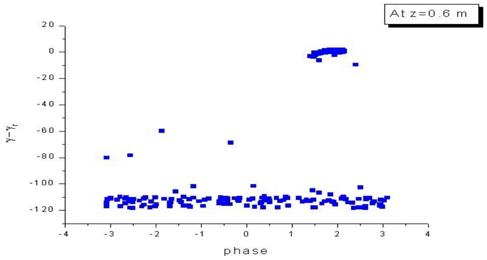

Fig.3: Phase space with a gap around the laser waist

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[1] We assume the laser wave not to be a dynamical variable of the problem.

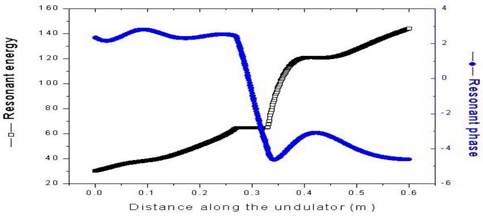

Fig.4: Resonant energy and resonant phase

Fig.4 clearly shows what happen in the critical region: the resonant phase slips 2π at the laser waist, and the energy starts growing again when the particles enter the second half-undulator.

4 UNDULATOR DESIGN AND 3D SIMULATIONS

The undulator parameters are in table 2. The helical geometry is convenient because the Inverse Free Electron Laser interaction is always "turned on". The linear period tapering[2] is a good approximation to the best tapering function (see Fig.1) and can satisfy the resonant condition throughout the undulator. The choice of keeping constant K is made for convenience.

Table 2: Undulators parameters

Parameters	1st half-undulator	2nd half-undulator
Initial λ_w	1.5 cm	1.5 cm
K	0.5	1.5
B(T)	0.2 T	0.6 T
Linear tapering coefficient	0.08	0.14

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 particles evolution a 3d magnetic field map from 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.

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. The variation of the percentage of captured particles with electron beam size and transverse initial displacement of the position of the bunch can be explained observing that because of the 2 Raleigh ranges gap, the smallest laser beam size that the electrons see inside the undulator is about 0.4 mm.

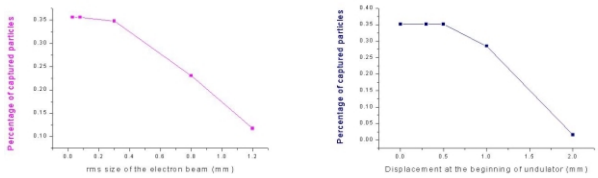

Fig.5: 3d effects on percentage of captured particle

5 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 3: IFEL parameters

Initial energy	15 MeV
Final Energy	75 MeV
Avg. Energy gradient	100 Mev/m
Microbunches length	10 fs

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 results though, show that interesting results can be obtained in this diffraction-dominated configuration.

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[2] Linear period tapering: $\lambda_\omega(z)= \lambda_\omega(0)+A\cdot z$