STATUS OF THE INVERSE FREE ELECTRON LASER EXPERIMENT AT THE NEPTUNE LABORATORY

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Abstract

We report on the status of the Inverse Free Electron Laser accelerator experiment under construction at the UCLA Neptune Laboratory. This experiment will use a 400 GW CO_2 laser to accelerate through a tapered undulator an electron beam from 14.5 MeV up to 55 MeV. The scheme proposed is the diffraction dominated IFEL interaction where the Rayleigh range of the laser beam is 3.5 cm, much shorter than the interaction length (the undulator length is 50 cm). The undulator is strongly tapered in both field and period. The present status of the experiment is reported.

INTRODUCTION

Inverse Free Electron Laser schemes to accelerate particles have been proposed as advanced accelerators for many years [1, 2]. Recent successful proof-of-principle IFEL experiments have shown that along with high gradient acceleration this scheme offers the possibility to strongly manipulate the longitudinal phase space of the output beam [3]. The Inverse Free Electron Laser is in fact, a strong candidate for microbunching and phase-locking electrons at the optical scales. Up to now, though, only modest energy gain has been achieved mostly because of the limitations in the peak radiation power available.

The purpose of the UCLA experiment is to achieve a substantial energy gain and to investigate the longitudinal structure of the electron beam. This experiment addresses problems common to other advanced accelerator schemes like the issue of increasing the interaction length of a laser-driven accelerator dealing with the limitations of radiation diffraction and to increase the final energy gain by tapering of the structure to maintain phase synchronism with the accelerating particles.

At the Neptune Laboratory [4] at UCLA there is the unique opportunity of having a 10.6 μm high power laser and a relativistic high brightness electron beam in the same experimental facility. In the Neptune scheme, the 14.5 MeV electron beam from the split photoinjector linac system, interacts inside an undulator magnet with the high power CO_2 laser focused by a lens (f/25) with focal distance of 2.6 m to a tight spot of few hundreds microns. Because the Rayleigh range of the laser is much shorter than the undulator length, the interaction is diffraction dominated [5]. The fundamental element of the Neptune IFEL experiment is the undulator magnet that provides the coupling between photons and electrons. Strong tapering of both period and magnetic field amplitude is needed for high-gradient acceleration.

In this paper, after a brief status report, we devote a section to the solutions of the problems of spatial alignment and time synchronization of the electron and the photon beam. In the last section we describe the diagnostics setup to analyze the results of the experiment. A Browne-Buechner pole spectrometer is used to get single shot spectrum of accelerated electrons and a Coherent Undulator Radiation based diagnostic to detect microbunching of the electrons down to 3 fs is presented.

INVERSE FREE ELECTRON LASER ACCELERATOR

In the table we summarize the design parameters for the Neptune 10.6 μm IFEL experiment.

Table 1: IFEL at Neptune parameters

Initial beam energy	14.5 MeV
Final beam Energy	55 MeV
Electron beam microbunch size	3 fs
Electron beam emittance	10 μm
Electron beam size at focus	150 μm
Electron beam charge	300 pC

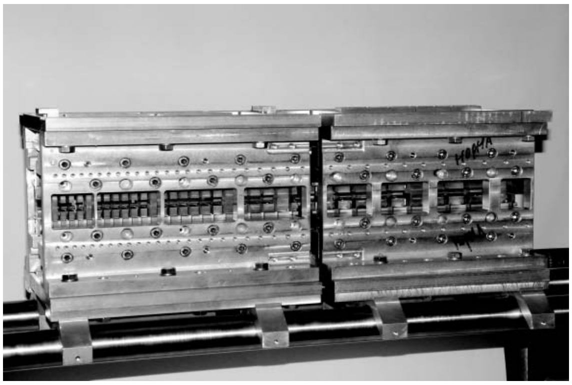

Figure 1: Double tapered 0.5 m long Kurchatov undulator

The undulator is shown in fig.1. It has been designed and built at the Kurchatov Institute of Moscow [6]. In order to

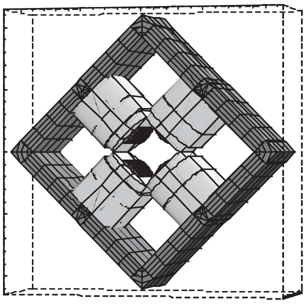

Figure 2: 2.5 inches gap quadrupole magnet. Maximum gradient at 10 amps excitation current = 6.5 T/m

maintain phase synchronicity and preserve the accelerating bucket along the accelerator, the undulator is strongly (non adiabatically) tapered in period (from initial 1.5 cm to final 6 cm) and magnetic field amplitude (from 0.1 T to 0.6 T). It is 50 cm long and has a constant gap of 12 mm. The construction phase has been completed and the installation in the beamline is scheduled for the next month.

A TW CO_2 laser system capable of generating 100 J in 100 ps pulse is used in the experiment. To match into the 0.5 m long 12 mm gap undulator with the 10.6 μm beam the f/25 geometry will be used. The spot size at the focus has $w_0 \simeq 350$ μm so that the Rayleigh range is 3.5 cm is matching the tapering design. To ensure clipping-free propagation of the focused beam in the vacuum pipe (diameter of the pipe larger than $4w_0$), we designed new quadrupole magnets with large aperture. These magnets have a gap $\geq$ 2.5 inches and tapered coils to maintain the field gradient ($\simeq$ 6.5 T/m) required to focus the electron beam to 150 μm spot size. They have been designed with the help of the 3D magnetostatic code RADIA [7] (fig.2).

The energy of the NEPTUNE LINAC has been upgraded to the design value 14.5 MeV replacing the old klystron. The available S-band RF power is now 22 MW. To improve the high power handling capabilities of the dielectric filled waveguide, a recycling system for the SF_6 is being implemented to purify the gas after any breakdown occurred. Also, the electric field gradient inside the 1.6 cell gun has been limited in the past by severe arcing inside the standing wave cavity. For this reason, a new 1.6 cell gun has recently been installed and it is now in the conditioning stage.

INPUT DIAGNOSTIC

We describe in this section the experimental setup to ensure the spatial and temporal overlapping of the photon and electron beam inside the undulator.

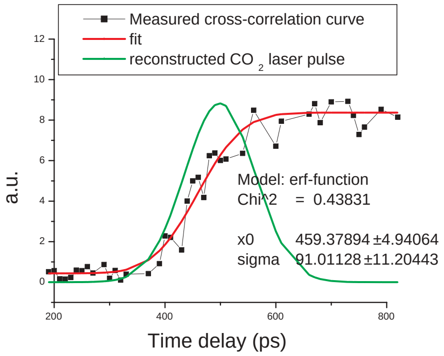

Figure 3: Cross correlation of CO_2 pulse and electron beam.

Spatial alignment

To ensure overlapping of the photon and electron beam inside the undulator the alignment is performed on a screen in the middle of the undulator at the common waist. A phosphorous screen fluorescent to the electrons and with a graphite layer coating so that unamplified CO_2 pulse can produce a visible spark, will be used for the alignment of the two beams. A combination of two such screens separated by $\sim$ 0.5 m provides a very small angle misalignment ($\sim$ 1 mrad). The precision of the alignment is limited by the spot sizes and the spatial jitters of the two beams to 50 μm. The acceptance window of the IFEL accelerator has been estimated with the help of three dimensional simulations [**?**] to be 2 mrad and 100 μm well above the expected values of alignment errors.

Temporal synchronization

A deterministic synchronization of 10 μm and e-bunches is possible because the same 1 μm laser pulse is used for the production of electrons on the photocathode (after frequency quadrupling) and to switch the short CO_2 laser pulse. A first order temporal synchronization is reached by synchronizing at the ns level, the photocathode drive laser and the CO_2 laser system using fast photodiodes. To break the barrier of ns resolution, optical techniques have to be used. The effect we exploit is the electron-beam-controlled transmission of 10 μm radiation in semiconductors [9]. A cross correlation timing technique based on this effect, has already been successfully applied at the Neptune laboratory in the context of the Plasma Beat Wave accelerator [10]. One of the cross-correlation curves is shown in fig. 3.

CO2 laser pulses and 10-ps electron bunches (FWHM) can be deterministically synchronized with a total uncertainty of $\sim$ 20 ps. The tolerance on the error on the temporal synchronization for the IFEL accelerator depends on the laser pulse length. The accelerator performances seriously degrade when the peak power driving the interaction falls below a threshold value. In the Neptune case, the window of acceptance is 30 ps.

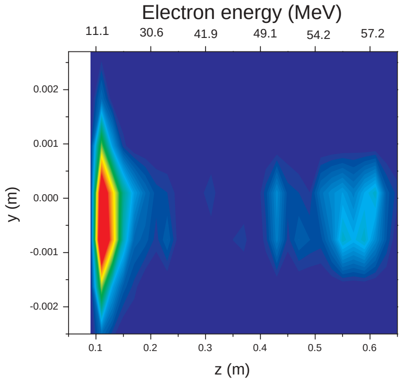

Figure 4: Simulated image at the output slit of the Browne Buechner spectrometer.

OUTPUT DIAGNOSTICS

Browne-Buechner spectrometer

The electron spectrometer consists of a pair of pole pieces energized by a ”C-shaped” water-cooled electromagnet and a vacuum box[11]. The gap between the pole pieces is set to 1.5” by the requirement of dumping the high power CO_2 beam after the interaction. Browne-Buechner [12] pole pieces are chosen to maximize the dispersion and the energy coverage. An additional edge entrance angle of 10 degrees provides additional vertical focusing. The tilted exit plane of the vacuum box is made so that the different energies are in focus along the length of the exit plane. The radius of the circular boundary of the magnetic field is 9.3 cm and with 40 amp excitation in the main coils of the spectrometer, the field inside the gap is 1.1 T. With this magnetic field amplitude, electrons of energy up to 65 MeV can be focused on the output slit the spectrometer. The electron beam dynamics through the spectrometer has been simulated with the three dimensional code TREDI [8]. In the fig. 4, we show the image on the output slit of the spectrometer obtained from a ”start-to-end” simulation of the Inverse Free Electron Laser accelerator.

Coherent undulator radiation bunching diagnostics

The output beam is microbunched with 10.6 μm period so that any radiation generated by the beam has a spectrum peaked at this wavelength [13]. On the other hand it is not possible to distinguish between beam generated radiation and the driving high power CO_2 laser beam. Moreover a transition radiation screen cannot be inserted in the beam line too close to the exit of the undulator because it would be damaged by the high power driving laser. The proposed solution to detect the microbunching is to look at coherent undulator radiation harmonics. Debunching of the electrons in the drift space following the accelerator is not important, because the radiation source is inside the undulator where the bunching reaches the maximum. The light can be collected few meters downstream with the advantage that the fluence level of the high power CO_2 beam is strongly reduced by diffraction. To further attenuate 10.6 μm light with respect to the harmonics level a SF_6 damping cell can be inserted. SF_6 has a peak in the absorption spectrum at 10.6 μm but it is transparent at the harmonics 5.3 μm and 3.15 μm. An optical grating can then disperse the different wavelengths to selectively measure the power in the radiation harmonics. For 300 pC bunch charge, we calculated an energy of 10 nJ at 3.15 μm in a 3 mrad collection cone, 3 m downstream of the exit of the undulator. Studying how the power radiated in the harmonics changes as a function of the electron charge injected in the accelerator should give a quantitative measurement of the beam bunching [14].

ACKNOWLEDGEMENTS

The authors wish to thank S. Telfer for the help in designing the large aperture quadrupole magnets and C. Clayton for a number of fruitful discussion. This work is supported by U.S. Dept. of Energy grant DE-FG03-92ER40693

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