# 7TH HARMONIC BUNCHER EXPERIMENT AT THE UCLA NEPTUNE LABORATORY

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*Abstract*

Since typically FEL undulator magnets have period length in the cm range, and the normalized magnetic field strength K is usually close to unity to guarantee a good coupling, a very high energy electron beam is needed to access the UV and x-ray region of the electromagnetic spectrum. One way to reduce the beam energy necessary for short wavelength light sources consists of exploiting the FEL harmonic interaction. An experiment aimed at demonstrating the efficiency of harmonically coupled schemes is proposed for the Neptune Laboratory at UCLA. We plan to inject the 12.4 MeV beam from the split photoinjector in an already available undulator with period = 3.3 cm and K = 1.8. The FEL resonant wavelength with these parameters is 74.2 μm. A copropagating high power 10.6 μm CO2 laser bunches the beam via 7th harmonic FEL/IFEL interaction. Preliminary calculations show that even though the interaction is weakened by the high harmonic number, only 5 -10 MW of laser power are required in order to induce full bunching on the beam in the 10 period long undulator.

## INTRODUCTION

Free-electron laser (FEL) amplifiers operating at short wavelengths (<100 nm) are undoubtedly one of the top research fields nowadays because of the new possibilities opened by generation of powerful, short pulses in a range of the electromagnetic spectrum important for material science, biology and chemistry. The lasing wavelength of an FEL depends primarily on the undulator magnet characteristics --period and field amplitude-- and on the electron energy. Since the undulator magnet has typically period lengths in the cm range, and the normalized magnetic field strength $K$ is usually close to unity to guarantee an efficient coupling, a very high energy electron beam is needed to access the UV and x-ray region of the electromagnetic spectrum.

One way to reduce the necessary beam energy is to utilize the FEL harmonic interaction[1-5]. The FEL resonance condition, i.e. the condition for efficient energy exchange between the transverse EM wave and the electrons, takes place at electron energies such that the wiggling induced by the laser field has the same frequency as the wiggling induced by the undulator in the electron rest frame. However, a planar undulator resonance can also occur when the laser frequency is a multiple of the undulator wiggling frequency and electrons of a given energy interact with the fundamental radiation frequency and with its higher harmonics[6]. In some cases, when the laser frequency is constrained by the source availability and the energy of the beam is so low that in order to design an FEL at the resonant condition the undulator parameters are unfeasible or the normalized vector potential $K$ has to be very small to reduce the magnetic amplitude induced frequency red-shifting, harmonic coupling becomes the only viable solution to ensure a strong interaction.

Even for FEL cascade schemes, one of the factors limiting the frequency multiplication of all cascade schemes is related to the necessity of operating all the stages of the cascade with the same electron beam energy. The change in the resonant wavelength for the different sections must be compensated by variations of the undulator period and $K$ parameter. Using the conventional techniques for undulator magnet construction, the span of these variations is limited and harmonic coupling has been considered as a possible solution [7].

Here we propose and discuss an experiment to be carried out at the UCLA Neptune Laboratory to test the efficiency and feasibility of a high order harmonic FEL/IFEL interaction. For this purpose an existing short undulator with a period of 3.3 cm and K = 1.8, for which the resonant wavelength with a 12.4 MeV electron beam is 74.2 μm, will be seeded with a CO2 laser radiation. This will allow to study the microbunching obtained by 7th harmonic FEL/IFEL interaction, since 10.6 x7=74.2μm.

## EXPERIMENTAL LAYOUT

Table 1: Parameters for Neptune 7th harmonic interaction experiment

| | |
|---|---|
| Beam energy | 12.4 MeV |
| Beam energy spread | < 0.2 % |
| Emittance | 5 mm-mrad |
| Current | 100 A |
| Laser wavelength | 10.6 μm |
| Laser seed Power | 10 MW |
| Laser size (at focus) | 650 μm |
| Undulator period | 3.3 cm |
| Undulator $K$ | 1.8 |
| Undulator length | 33 cm |

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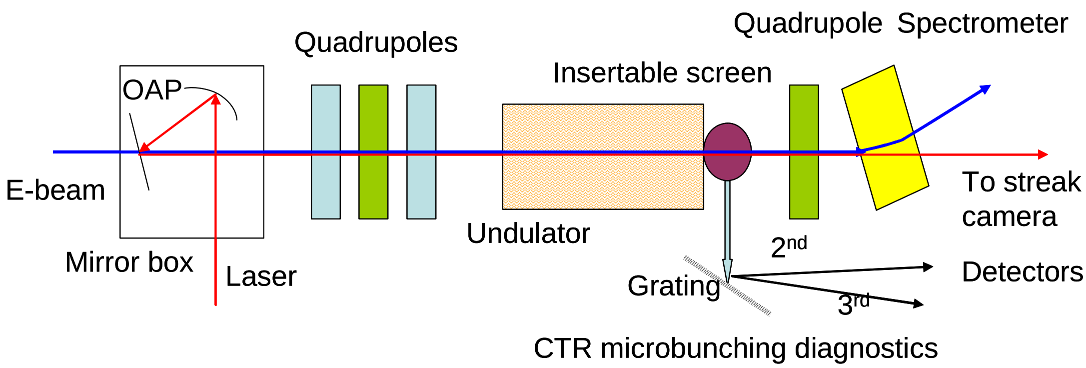


Figure 1: A simplified experimental layout for the 7th harmonic buncher experiment.

The Neptune laboratory hosts a split rf photoinjector capable of producing 10-14 MeV beam with a peak current in excess of 100 A and an emittance as low as 5 mm-mrad.

The $CO_2$ laser system, which has been reported in detail elsewhere[8], has the capability of producing 1 TW mid-infrared laser pulses. However, the repetition rate at this high power is limited to one shot per few minutes by the main discharge capacitor cooling time. Recently a new high-pressure CO2 laser amplifier was installed which is capable to produce ~1mJ at 1 Hz. By shortening the seed pulses to <100 ps in principle up to 10 MW of drive $CO_2$ laser power is available to drive the interaction. Such a power level, as will be shown below, is sufficient to bunch the electron beam. At the same time the high pulse repetition rate allows parametric studies of the system which would be otherwise very difficult in a single-shot experiment.

A conceptual design of the experiment is shown in Fig. 1. A laser beam is focused by an off-axis parabolic mirror (F/50 scheme). After the FEL interaction in the undulator the electron beam is sent to a high resolution spectrometer (horizontally focusing quadrupole + bending dipole) to detect the energy modulation imparted by the laser. Electron microbunching at 10.6 μm is observed by measuring the coherent transition radiation spectrum from a foil screen inserted at 25 cm from the exit of the undulator. Because of the background noise due to the high drive laser power, detection of the harmonics is suggested as a way to measure the beam microbunching. A diffraction grating separates the different wavelength content in the beam generated radiation and MCT detectors are placed at the angles corresponding to the $2^{nd}$ and $3^{rd}$ harmonic of the $CO_2$ laser line. The main $CO_2$ laser beam is sent to a streak camera to enable temporally resolved diagnostic.

## FEASIBILITY OF THE $7^{TH}$ HARMONIC BUNCHING

It can be shown that in planar geometries the coupling between the beam electrons and an electromagnetic wave at a harmonic of the resonant undulator frequency is actually very strong and comparable to the fundamental coupling if the normalized magnetic field amplitude $K$ is larger than 1. The coupling coefficients can be written as:

$$JJ_n = J_{n-1/2}(n \cdot \xi(K)) - J_{n+1/2}(n \cdot \xi(K))$$

for n = 1,3,5,7…where $\xi(K) = K^2/4 + 2K^2$.
Moreover, for a given laser frequency and electron beam energy one has to maintain the resonant condition so the undulator $K$ changes as the square root of the harmonic number. The effective interaction coupling strength is $KJJ_n(K)$.

In Fig. 2, assuming an undulator period of 3.3 cm, we plot the coupling coefficients for different $K$ values and the coupling strengths for the first odd harmonics. The normalized vector potential $K$ to obtain resonance at the fundamental is only 0.1. If the coupling is on the $7^{th}$ harmonic, $K$ = 1.8 and the effective coupling strength is 2 times higher. This example illustrates the main advantages of choosing an harmonic coupling when designing an undulator/beam interaction.

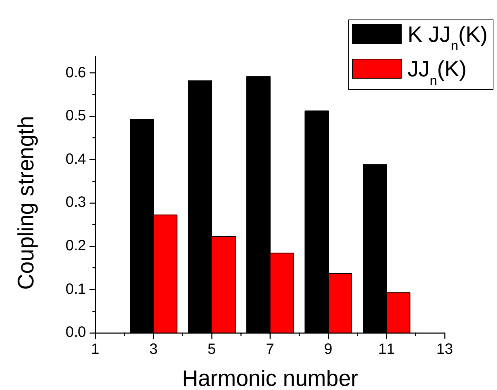


Figure 2: Coupling coefficients and coupling strength.

Fundamental parameters of the interaction like the energy width of the ponderomotive bucket and the synchrotron oscillation frequency depend on the coupling strength. A simple estimate of the power required to bunch the beam can be obtained requesting that ¼ synchrotron oscillation is obtained during the undulator length. The synchrotron period is given by:

$$z_s = \frac{\lambda_w}{n} \frac{\sqrt{1+K^2/2}}{\sqrt{2KK_r JJ_n}}$$

where $K_r = eE_0\lambda_0 / 2\pi m_0 c^2$ is the normalized electric field associated with the radiation. With the request that along the undulator particles would perform ¼ of synchrotron oscillation i.e.

$$z_s / 4 = L_u$$

we can solve for the minimum electric field to achieve microbunching. With the parameters of the short undulator available at Neptune, reported in Table 1, we obtain $K_r$ = 1.2e-4, and $E_0$= 40 MV/m which corresponds to a laser intensity of $I$ = 0.2 GW/cm$^2$. The estimate reported here shows that even though the interaction is weakened by the high harmonic number, it is required to use only modest levels of power to induce full bunching on the beam using the 10-periods long undulator.

The amplitude of the ponderomotive bucket in the energy plane is given by:

$$\frac{\delta\gamma}{\gamma} = \sqrt{\frac{2KJJ_n K_r}{1+K^2/2}}$$

which for our parameters is very small ( ~ 0.5 %) and imposes an important experimental constraint on the quality of the input beam. Thus the energy spread of the electron beam must be well below 0.5 % rms.

Another important constraint in the design is imposed by the amplitude of the beam wiggling oscillations. As shown in Fig.3, the focused CO2 laser beam must cover the entire trajectory of the wiggling electron beam in order to achieve the same acceleration gradient for particles at different distances from the axis. To maintain the required laser intensity level with a spot size of 650 µm at the focus and a relative Rayleigh range of 10 cm, a minimum drive laser power of ~3 MW is required.

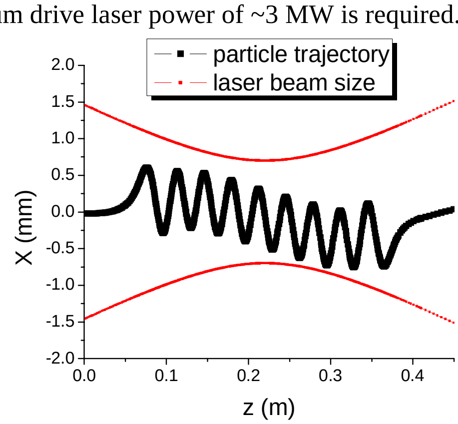


Figure 3: Particle trajectory and laser beam size inside the undulator.

## 7$^{TH}$ HARMONIC BUNCHER SIMULATIONS

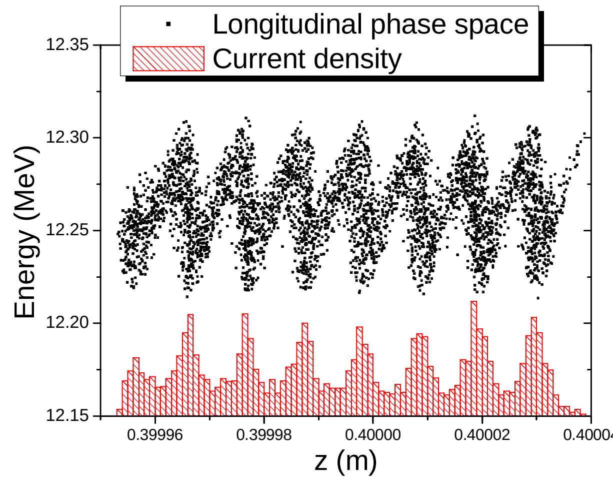


Figure 4: Longitudinal phase space at the undulator exit for 10 MW input CO2 power and initial e-beam energy spread of 0.2 %.

The code GENESIS 1.3 has been used to simulate the three dimensional interaction between the electrons and the laser pulse in the undulator. The code has been recently upgraded to be able to simulate the interaction of the particles with the harmonic of the fundamental field [9]. In Fig. 4 one can see that electrons at the exit of the undulator are fully bunched when a 10 MW CO2 laser is used as a seed.

Along with the goal of first experimental demonstration of the 7$^{th}$ harmonic interaction of a relativistic electron beam and a laser in an undulator, the proposed experiment addresses a couple of other important issues.

For a 0.5 mJ, 100 ps long laser pulse interacting with a 10 ps long electron beam, the energy of the laser available for the electrons to absorb corresponds to 50 µJ of IR power. This energy is the amount required to accelerate a 500 pC beam by 0.1 MeV.

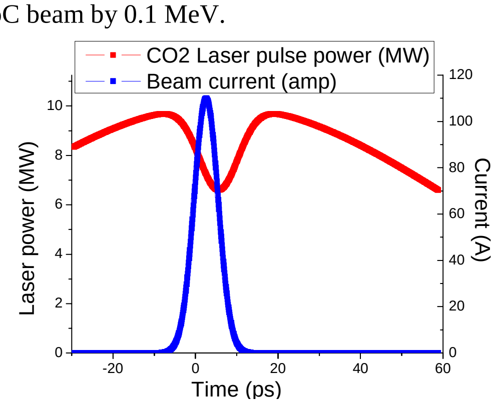


Figure 5: Beam loading in the 7th harmonic IFEL accelerator for a 100 Amp beam current and 12.3 MeV input energy. The beam current longitudinal profile is also shown.

Detuning slightly the input electron beam energy and injecting the beam 100 KeV below resonance, the particles will extract energy from the laser via 7th harmonic interaction. With a temporally resolved diagnostics of the infrared power, one could observe the pump depletion (beam loading) of the laser wave. Up to 30 % of power can be absorbed from the laser as it is shown in the time domain simulation reported in Fig. 5.

Finally, the 10.6 μm buncher running at 1 Hz will allow a detailed study of various microbunching diagnostics [10]. The coherent transition radiation foil has to be located as close as possible to the undulator exit, since the beam debunches quickly due to its low energy and strong longitudinal space charge forces. At 20 cm from the output the bunching factor is still greater than 0.3 and any radiation emitted by the beam (via transition or Cherenkov mechanisms) will be enhanced by the coherent form factor at the bunching wavelength 10.6 μm and the relative harmonics. In Fig. 6 we show the evolution of the bunching coefficients at the 10.6 μm, and its second and third harmonic along the undulator. Because of the strong space charge force and of the low beam energy, debunching quickly takes place after the particles leave the interaction region.

The effect of the finite transverse beam size on the radiation emission is particularly interesting when the emission mechanism has a preferred angular direction as it is the case of a Cherenkov radiator.

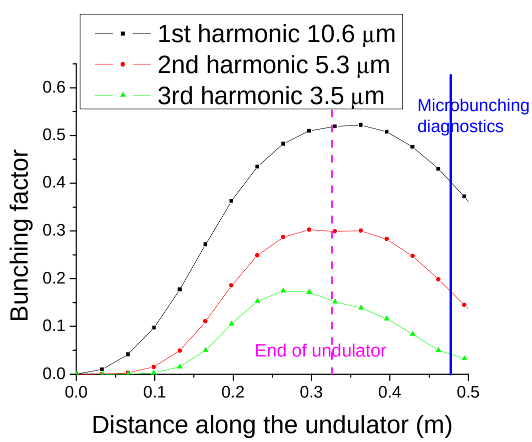


Figure 6: Bunching coefficients at the drive laser frequency and relative harmonics.

## CONCLUSIONS

We have proposed and discussed here an experiment to be carried out at the UCLA Neptune Laboratory with the goal to measure the efficiency of a high order harmonic FEL/IFEL coupling. The experiment also addresses important issues like the development of diagnostics for longitudinal microbunching and the beam loading in a vacuum laser accelerator. The implementation costs are very low since most of the hardware is in house (undulator already installed on the beamline after a previous experiment [11]). Some experimental efforts are needed to set up the microbunching diagnostics, however for the relevant wavelengths — harmonics of $CO_2$ laser frequency — a number of components, optical elements and detectors are already available in the Neptune laboratory.

## ACKNOWLEDGEMENTS

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