HIGH-HARMONIC INVERSE FREE-ELECTRON-LASER INTERACTION AT 800 NM

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Abstract

The inverse Free Electron Laser (IFEL) interaction has recently been proposed and used as a short wavelength modulator for micro bunching of beams for laser acceleration experiments [1,2]. These experiments utilized the fundamental of the interaction between the laser field and electron bunch. In the current experiment, we explore the higher order resonances of the IFEL interaction from a 3 period, 1.8 centimeter wavelength undulator with a picosecond, 0.5 mJ/pulse laser at 800nm. The resonances are observed by adjusting the gap of the undulator while keeping the beam energy constant. We also compare the experimental results to a simple analytic model that describes coupling to high order harmonics of the interaction.

INTRODUCTION

Current RF injectors can produce electron beams of a few hundred femtoseconds length [3]. This is much larger than the sub-femtosecond pulse lengths needed for laser acceleration research [1,2,4,5]. To obtain net acceleration, an electron pulse from an RF linac must be bunched at the optical wavelength. Previous experiments [1,2] have employed an inverse FEL to modulate the beam and a chicane to convert this modulation into a density modulation. In this paper we extend the technique to utilize high harmonics of the interaction.

$$n = \frac{\lambda_w}{2\lambda_L \gamma^2}\left(1 + a_w^2\right) \quad (1)$$

From the Lorentz equations one can derive the resonance condition for FELs (eq 1). Here, n is the harmonic number, N the number of periods, and a_w the normalized undulator field strength. The amplitude of the interaction requires a more in depth analysis than is typically performed in FEL literature [6]. For instance, assuming a sinusoidal electron trajectory and a plane wave optical field, the electrons will only couple at odd harmonics of the resonance equation. If, however, the electron has an additional net transverse motion the electrons can couple to even harmonics as well [7]. The coupling coefficient is given by equation 2:

$$JJ_n = \sum_{m=-\infty}^{\infty} J_m(n\xi)\left[J_{2m+n+1}(nZ) + J_{2m+n-1}(nZ)\right]$$
$$\xi = \frac{a_w^{\ 2}}{1+2a_w^{\ 2}+\gamma^2\theta^2} \qquad Z = \frac{4a_w\gamma\theta}{1+2a_w^{\ 2}+\gamma^2\theta^2} \quad (2)$$

Here θ is the angle of the electron net motion. For this experiment, we de-tune the undulator end fields to introduce a net transverse motion to the electrons. Figure 1a shows the centroid trajectory, giving θ=15 mrad. By solving eq 1 for a_w and substituting into equation 2 we can obtain the coupling coefficients for values of n expected in the experiment. These are shown in figure 1b. The beam energy is 30 MeV.

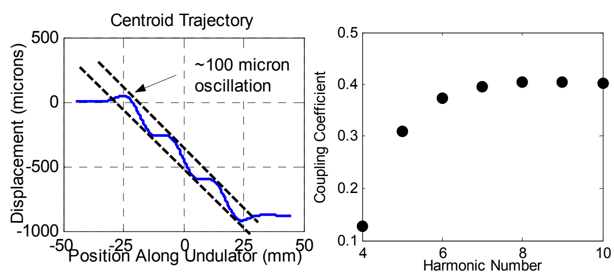

Figure 1: a) Centroid trajectory of electron bunch through undulator. b) Coupling coefficients from eq 2.

Further complications make the analysis of [6] and eq 2 less useful for estimating the interaction strength for each harmonics. This includes strong focusing of both the electron and laser beams, and further non-uniformities of the electron motion due to the short undulator. Also, to simplify the experiment, the laser angle was not adjusted to keep track with the changing electron angle depending on a_w. Instead of further analytic efforts, the experimental results are compared to simulations using a particle tracking code and magnetic field profiles obtained from Radia [8].

EXPERIMENTAL DESCRIPTION

The experiment was performed at the Stanford HEPL-SCA facility. An overview of experimental parameters is given in table 1. Both beams were focused at the middle of the undulator. This allows for a peak electric field for a strong interaction while maintaining good overlap between beams. The beams are aligned using two phosophors located immediately fore and aft of the undulator. Downstream of the undulator the electrons entered a high resolution 90° spectrometer. Data is collected in runs of several hundred laser shots. The laser is scanned past the electron beam temporally in 20-30

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picosecond windows, creating a correlation signal in offset time versus electron energy spread from which we obtain the IFEL modulation strength.

Table 1: Experimental parameters. The electron beam pulse length and transverse size were measured using the IFEL data.

Parameter	Value
E-beam energy	30 MeV
E-beam initial energy spread (rms)	30 keV (typ.)
E-beam charge	2 pC
E-beam pulselength (rms)	1 ps
E-beam normalized emittance	2 π-mm-mrad
E-beam focused vertical width (FWHM)	40 µm
E-beam focused horizontal width (FWHM)	210 µm
Laser pulselength (FWHM)	2 ps
Laser wavelength	800 nm
Laser energy	0.5 mJ
Laser focused spotsize (FWHM)	110 µm

GAP SCAN RESULTS

For the gap scan, the gap is held constant during each run, and changed by small increments between runs. The laser trajectory is also held constant, meaning that as the gap is changed, thus changing the electron trajectory, the overlap between the beams worsens. The alignment was optimized for a gap of 6.3 mm. The full scan consists of 164 separate runs (figure 2). The vertical error bars come from estimating the peak modulation from the correlation signal and are dominated by particle statistics near the peak. The 5^{th} and 6^{th} harmonics are clearly present in the data, the 4^{th} is obvious enough once comparison is made to simulation. The 4^{th} order peak is stretched in the plot since at large gap heights, the rate of change of the magnetic field is less as the gap is adjusted.

Comparison to simulation is complicated by the fact that the overlap diagnostics do not give the absolute position of either beam with respect to the undulator. The distance of the electron beam off of the bottom pole tips is not well known. Since the field of an undulator varies as the hyperbolic cosine of the vertical position, the field strength is in turn not well known. However, using the height of the beams as a free parameter in simulation, a best match can be found. Figure 2 gives the best match of simulation to the data where the height of the electrons off of the bottom pole tips is 2.5 mm. The overall amplitude of the simulation is some 50% greater than the raw data, reaching a peak of 50 keV on the 5^{th} harmonic. Other scans done during the experiment did reach this expected interaction strength [9]. Many factors can cause an overall drop in interaction amplitude though the most likely is transverse alignment error since the alignment process is accurate to ~25 µm.

With the inclusion of higher harmonics the IFEL can interact over a broad range of parameters. It is worth noting that the 5^{th} and 6^{th} harmonics are comparable in intensity, the IFEL interaction does not necessarily decrease with harmonic number. This is also evident in the analytic description shown in figure 1b. The analytic

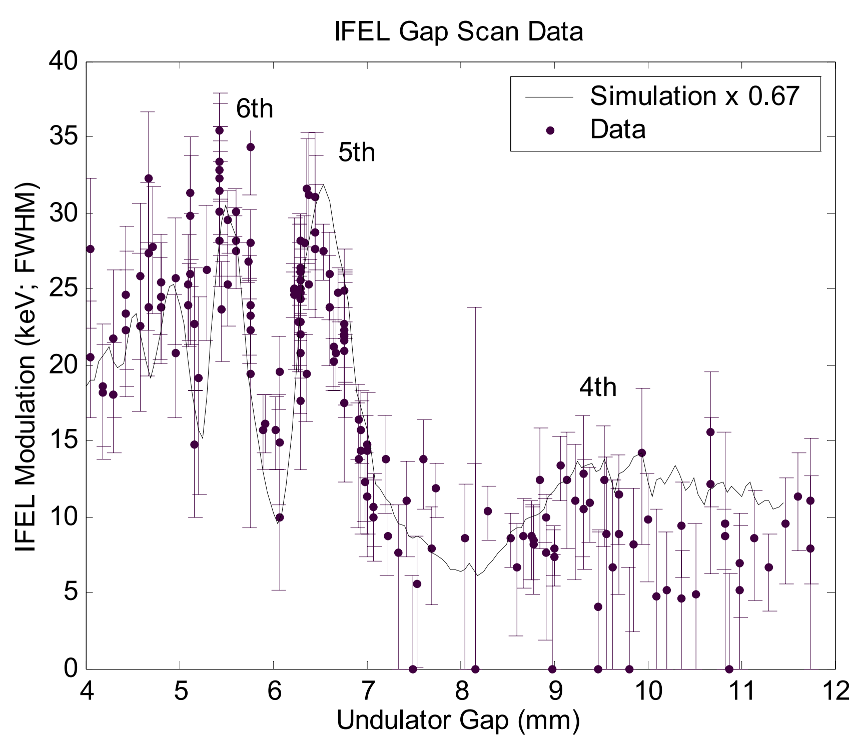

Figure 2: IFEL gap scan da, 164 runs total. Comparison to simulation (solid line) shows very good agreement to the shape and spacing of resonance peaks. The harmonic numbers are given next to each peak. Simulation has been rescaled vertically by 0.67 to better visualize overlap.

and simulation results compare fairly well, especially when we recall that the beam overlap falls off at smaller gap heights. This would result in the decrease in amplitude seen in the simulation for the 7^{th}, 8^{th}, and 9^{th} harmonics. The data itself is too noisy at these small gap heights to distinguish the peaks.

This experiment has successfully demonstrated the interaction of an 800 nm laser with electrons via the IFEL interaction and observed multiple resonances. There are multiple clearly distinguished peaks in the gap scan data. The relative peak amplitudes and spacing agree quite well with simulation. By adjusting the laser-electron angle back to zero and adding a chicane the IFEL can be used to microbunch beams on the optical scale.

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