Femtosecond Microbunching of Electron Beam in a 7th Harmonic Coupled IFEL

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Abstract. We report the results of studying electron beam microbunching in a 7th order IFEL interaction using coherent transition radiation emitted by the bunched beam as a diagnostic. The resonant wavelength for the undulator with a period of 3.3 cm and K=1.8 is 74.2 μm, but it was seeded by a CO₂ laser with a seven times shorter wavelength of 10.6 μm. The ~12.3 MeV electrons were efficiently bunched longitudinally inside a ten period long undulator producing the first, second, and third harmonics in a CTR spectrum. It is shown that in the case of approximately equal sizes of the electron and the seed radiation beams, the IFEL interaction results in transverse variation of bunching which significantly affects the CTR harmonic content. The measurements were compared to the predictions of IFEL simulations. These experimental results demonstrate for the first time feasibility of using very high order harmonic coupling for efficient IFEL/IFEL interactions.

1. INTRODUCTION

Seeded IFEL/IFELs have proved to be very useful techniques for longitudinal modulation of a relativistic electron beam (microbunching) on the scale of the optical radiation wavelength. An electron beam tightly microbunched on the optical time scale (few femtoseconds) can be used either for matched injection in a laser/plasma accelerator [1] or for driving a plasma wakefield accelerator [2]. In a collinear IFEL interaction in a planar undulator, the electron beam may exchange energy with a seed radiation not only at the fundamental resonant frequency but also at its odd harmonics if the normalized undulator parameter K ≥ 1 [3]. In some cases, when the laser frequency is constrained by the source availability or the energy of the beam is too low for designing an IFEL undulator at the resonant condition, coupling to high-order harmonics may be the only viable approach to microbunch the beam.

The high-order IFEL interactions have been considered theoretically [4] and observed experimentally when undulators were seeded by 10 μm [5] and 0.8 μm radiation pulses [6] at a laser intensity of 2x10^{14} W/cm² and 2.6x10^{12} W/cm², respectively. However, both studies [5,6] measured the energy modulation in a high-order harmonic interaction without characterizing microbunching of the electron beam inside the undulator. Beam microbunching is induced by longitudinal motion of the particles in the periodic ponderomotive potential with a period of \lambda_{mb}=λ_s formed by the interaction of the radiation with a wavelength of λ_s with the undulator magnetic field. Characterization of
the electron microbunching in the undulator yields directly a measure of the strength of 
the beam-radiation coupling [7,8]. A tightly microbunched beam has a nonsinusoidal 
wave form and therefore can have a significant harmonic content at \( \lambda_{\text{me}}/h \), where \( h = 1,2,3, \) etc is the harmonic number. Observation of harmonic components in the beam 
spectrum can then serve as a unique indicator of the strength of the beam-radiation 
coupling for the high-order IFEL/IFEL interactions.

Here we report on the 7th order IFEL interaction when the undulator designed for a 
resonant wavelength of 74.2 \( \mu \text{m} \) is seeded by a CO\(_2\) laser fulfilling the condition 
10.6x7=74.2 \( \mu \text{m} \). Using coherent radiation (CTR) emitted by the bunched 12.3 
MeV beam as a diagnostic, strong microbunching of the beam is inferred from the 
observation of CTR at the first, second, and third harmonics of the seed 10 \( \mu \text{m} \) radiation. 
We compare the measured ratio between the CTR harmonics with that extracted from the 
3D IFEL simulations.

2. 7th HARMONIC IFEL MICROBUNCHING EXPERIMENT

For a planar IFEL undulator the resonant condition and the energy gained by electrons 
in an \( n \)-th order interaction (\( n=1,3,5,7, \ldots \)) can be written as [3]:

\[
\lambda_{\text{seed}} = \frac{\lambda_u}{2\gamma^2 n} \left(1 + \frac{K^2}{2}\right) \quad \text{and} \quad \frac{\partial \gamma}{\partial z} = \frac{k_u a_0 K}{\gamma} \sum_n J_{2n}\sin(\psi + k_u z(n - 1))
\]  

(1)

where \( K = e B_0 / m c k_u \) is the dimensionless undulator parameter, \( \gamma \) is the electron Lorentz 
factor, \( \lambda_u \) the undulator wavelength, \( k_u \) the undulator wavenumber, \( B_0 \) the undulator 
magnetic field, \( k_0 \) is the seed radiation wavenumber, \( a_0 \) is the normalized laser electric field 
amplitude (eV/m), \( \psi \) is the phase of coupling between the wiggling motion and the 
EM wave, and \( J_{2n} \) is the IFEL coupling coefficient, which is a function of \( K \). The 
effective coupling strength of the IFEL interaction from Eq. 1 is proportional to \( K J_{2n}(K) \). 
In Fig. 1, for an undulator period of 3.3 cm and \( K = 1.8 \), we plot the coupling coefficients 
and the coupling strength for the first odd harmonics of the fundamental. It is remarkable 
that even at \( a_0 = 0.1 \) the \( n=7-11 \) IFEL resonances can be very efficient and the coupling 
strength reaches 50 \% of that at the fundamental frequency (\( n=1 \)).

![Coupling coefficients and coupling strength for the high-order IFEL interaction.](image-url)

**FIGURE 1.** Coupling coefficients and coupling strength for the high-order IFEL interaction.
2.1. Experimental Apparatus

Parameters of the 7th order IFEL microbunching experiment, carried out at the Neptune Laboratory at UCLA, are summarized in Table 1. The Neptune rf photoinjector provided a ~12.3 MeV electron beam with a pulse length of 10 ps (FWHM). The beam was injected into a 33 cm long planar permanent magnet undulator with a period of 3.3 cm and K=1.8. The beam was typically focused to a rms spot size of ~350 μm at the exit plane of the undulator where an insertable probe for a CTR screen was placed. The probe was also used for spatial alignment and temporal synchronization between the CO2 laser and the electron beam. The CO2 laser beam was focused to a spot size of 650 μm (1/e2) in the middle of the undulator using a 2.5 m focal length NaCl lens. This F100 focusing provided an almost constant laser field intensity over the entire length of the undulator. A 100 ps long CO2 laser pulse generated by a master oscillator-power amplifier laser chain [9] was used in the experiment. The beams were aligned in the middle and at the exit of the undulator with a spatial accuracy of 100 μm and an angular alignment of better than 1 mrad. After the undulator, the electron beam was sent to a high-resolution spectrometer to measure the energy spread.

<table>
<thead>
<tr>
<th>Energy</th>
<th>12.3 MeV</th>
<th>Beam size 250-350 μm</th>
<th>Wavelength 10.6 μm</th>
<th>Period 3.3 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>500 pC</td>
<td>Length ~10 ps</td>
<td>Seed power ~34 MW</td>
<td>K 1.8</td>
</tr>
<tr>
<td>Transverse emittance</td>
<td>5-6 mm-mrad</td>
<td>Pulse Length ~100 ps</td>
<td>Length 33 cm</td>
<td></td>
</tr>
</tbody>
</table>

The microbunching diagnostic consisted of a CTR screen made of an 8 μm thick Al foil, a movable mirror to transport the forward emitted CTR outside the vacuum chamber, a focusing off-axis parabolic mirror, a set of broadband-pass filters (Δλ~1 μm) centered around the first (10.6 μm), the second (5.3 μm), and the third (3.5 μm) harmonic wavelengths, and a liquid nitrogen cooled Mercury Cadmium Telluride (MCT) detector. Even though the light-tight CTR screen was used to dump the pump laser beam, separation of the weak CTR component from the strong stray 10 μm radiation was a critical issue. Two main measures were undertaken: first, the CTR foil screen was made larger than the undulator gap size and second, a 6 mm diaphragm was placed in front of the pick-up transport mirror limiting the field of view to the CTR radiation only. Together, these measures provided a rejection of the pump by a factor of 5x10^9 reducing the leakage-background to ~0.5 pJ. The CTR detector with a known spectral sensitivity was absolutely calibrated using the 10 μm radiation pulse.

3. RESULTS AND DISCUSSION

The theory of CTR and its application to longitudinal microbunching measurements of electron beams has been extensively studied [7,8]. These authors predict that the number of beam radiated photons scales as square of the bunch population N and the angular spectrum is narrowed when the microbunching period is small compared to the
transverse beam size, $\sigma_{x,y}$ or $\sigma_x \sigma_y/\gamma \gg 1$. For a given CTR harmonic, the energy emitted forward at a normal incidence to the conducting surface is given by:

$$U_n = \frac{N^2 e^2 b_n^2}{4\sqrt{\pi} \sigma_t} \left( \frac{\gamma}{\hbar k_t} \right)^4 \left( \frac{1}{\sigma_{x,y}} \right)^4 \quad (2)$$

where $b_n = 1/N \sum e^{i\theta_k z_i}$ is the bunching factor for the $h$th harmonic, $\sigma_{x,y}$ and $\sigma_t$ are the rms transverse and longitudinal beam sizes, and $z_i$ is a longitudinal position of particles. Predictions from Eq. (2) will be compared to the experimentally measured ratios between the CTR harmonics and simulations when determining the microbunching factors $b_n$.

### 3.1. CTR Measurements in the IFEL Microbuncher

To prove the resonant character of interaction between the laser and the electron beam, we measured the CTR signal for different energies of the electron beam. The CTR output peaked at 12.5 MeV (a FWHM ~0.3 MeV), which was, within an absolute energy measurement error, in agreement with the 12.34 MeV resonant energy for the 7th order IFEL interaction obtained from Eq. (1). In Fig. 2a we present the CTR signal dependence upon the beam charge. Note that we recorded the CTR signal, the laser power and the electron beam charge for each interaction event and each data point represents the mean value for 12 measurements with its standard deviation. In the experiment we varied the charge from 80 to 450 pC and observed a clear nonlinear increase in the 10 μm CTR signal by a factor of 10, which was weaker than the one anticipated from $N^2$ scaling. This was mainly attributed to the worsening of the focusing ability for high charge beams; therefore, the CTR level will be significantly reduced due to the increase in the beam size on the foil screen. Indeed, as shown in Fig.2b, for a fixed charge of ~300 pC we measured a factor of 3.2 decrease in the CTR level when the rms spot size $\sigma_{x,y}$ for the axisymmetric beam was increased from 220 to 300 μm. The $(1/\sigma_{x,y})^2$ scaling from Eq. (2), shown by a solid line in Fig.2b, predicts a decrease by a factor of 3.5.

**FIGURE 2.** CTR signal as a function of the electron beam charge (a) and the transverse spot size $\sigma_{x,y}$ (b).
The results of CTR energy measurements for the first, $U_1$ ($\lambda_{mb}=\lambda_{se}$), and the second, $U_2$ ($\lambda_{mb}=\lambda_{se}/2$), harmonic components as a function of the laser power are presented in Fig. 3. As seen in Fig. 3, at a low laser power of 3-19 MW only the 10 $\mu$m CTR signal was detected. Higher laser power caused microbunching at the first harmonic to occur earlier in the undulator giving rise to the second harmonic CTR component for powers above 19 MW. A further increase in power speeded up the bunching process even more and for powers above 28 MW, we observed a third harmonic component. The measured ratios between the harmonic energy for the bunched beam were $U_1/U_2 \approx 17$, $U_1/U_3 \approx 70$.

**FIGURE 3.** CTR energy on the first harmonic and the second harmonic of the seed radiation as a function of the laser power for a $\sim$400 pC electron beam charge.

### 3.2 3D Simulations of the IFEL Microbunching

To compare these CTR measurements to a microscopic model of the beam, the 3D code TREDI [10] was used to model the $7^{th}$ order IFEL interaction. While this code provides the bunching factor for all the harmonic components, it does not take into account the space charge force. To study a possible contribution of the space charge force on a $\sim$12.3 MeV beam, we analyzed the IFEL interaction for the same experimental conditions using another 3D code GENESIS [11]. Fig. 4a plots the bunching factor for the first harmonic with and without the space charge force contribution for a laser power of 34 MW. It is apparent that for the electrons bunched longitudinally on the 10.6 $\mu$m scale the effect of the space charge force on the beam is very small.

In an attempt to explain the observed ratios of the second and third harmonic to the first harmonic in the CTR spectrum, we used the bunching factor for each harmonic generated in the TREDI simulations in Eq. (2). When the bunching on harmonics was taken for the whole beam, the simulations produced $U_1/U_2=64$ and $U_1/U_3=2025$. However, the physical picture is more complicated: analysis of phase space distribution of electrons at the exit of the undulator indicated that there was a significant transverse variation in bunching and particles on axis were better bunched than the particles off axis. The laser beam size in the experiment was approximately equal to the electron beam envelope size including the wiggling motion. In terms of the IFEL interaction, this represented a case where the off-axis particles saw a smaller laser power, and were therefore bunched more weakly. Fig. 4b shows radial distribution of the normalized bunching factor $b_1$, $b_2$, and $b_3$ for the first, second, and third harmonic components,
respectively. The rms effective beam size derived from Fig 4b are 380 \( \mu \text{m} \) for the first, 335 \( \mu \text{m} \) for the second, and 295 \( \mu \text{m} \) for the third harmonics. This 3D effect significantly affects the measured harmonic ratios in the CTR spectrum. For the on-axis values of \( b_1=0.6, b_2=0.5 \) and \( b_3=0.45 \) and the above mentioned rms effective beam sizes, Eq. (2) predicts \( U_1/U_2=14 \) and \( U_1/U_3=53 \), which is in close agreement with the measurements presented in Fig.3.

![Diagram](image)

**FIGURE 4.** Dependence of the bunching factor \( b_1 \) along the undulator for different beam charges (a) and normalized bunching factor for the first, second, and third harmonics of the microbunched beam at the exit of the undulator as a function of the electron beam radius.

### 4. SUMMARY

This experiment has shown microbunching of an electron beam at the seventh order resonance from an IFEL. The electrons are efficiently bunched longitudinally inside a ten period long undulator producing the first, second, and third harmonics in a CTR spectrum. Observation of the tightly bunched beam at a modest intensity of \( \sim 10^9 \text{ W/cm}^2 \) demonstrates for the first time feasibility of using very high-order harmonics for efficient IFEL/FEL interactions. With the inclusion of the \( n \geq 3 \) IFEL/FEL interactions on equal footage with the \( n=1 \) case, a significant flexibility can be gained in designing undulators.

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### REFERENCES