# DEMONSTRATION OF EFFICIENT ELECTRON-RADIATION INTERACTION IN A 7TH HARMONIC IFEL EXPERIMENT

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*Abstract*

Many proposals and ongoing national projects exist worldwide to build a single-pass X-ray FEL amplifier in which a high-brightness, multi-GeV electron beam has a resonant energy exchange with radiation in an undulator. Because of the practical limit on the undulator period, the electron beam energy represents one of constraints on the shortest reachable wavelength. Recently the high-order harmonic FEL/IFEL interactions were considered theoretically as a technique that would allow the reduction of the beam energy without corresponding decrease in the undulator period and the magnetic field strength. We demonstrate microbunching of the 12.3 MeV electrons in a $7^{th}$ order IFEL interaction, where the seed radiation frequency is seven times higher then the fundamental frequency. Strong longitudinal modulation of the beam is inferred from the observation of the first, second and third harmonics of the seed radiation in a Coherent Transition Radiation spectrum. The level of seed power is comparable to that required for microbunching at the fundamental frequency of the ten-period-long undulator. The implications of these results for the next generation of FELs will be explored.

## INTRODUCTION

The high-intensity ultrashort coherent X-ray FELs promise to enable numerous scientific experiments in solid-state physics, biology and material science [1]. Many proposals and several ongoing national projects exist worldwide to build a single-pass X-ray FEL amplifier in which a high-brightness, multi-GeV electron beam produced by a several km long LINAC has a resonant energy exchange with radiation in a ~100-m long undulator tuned to a fundamental frequency.

Planar undulator FELs allow resonant interactions with radiation fields of wavelength $\lambda_{rad}=\lambda_u(1+K_u^2/2)/2n\gamma^2$, where n=1 is the fundamental with odd harmonics n=3,5,7,…, $\lambda_u$ is the undulator period, $\gamma$ is the electron beam energy, and $K_u=eB_u\lambda_u/2\pi mc^2$ is the normalized undulator parameter whith the magnetic field $B_u$. Because of the practical limit on the tunability of undulator magnets, which all have periods in the cm range, the electron beam energy represents one of the main constraints on the shortest reachable wavelength. Recently several groups proposed and considered theoretically a use of the high-order FEL interactions in order to reduce the energy of the drive beam without sacrificing strength of the magnetic field [2]. This approach can potentially decrease the size and price of short wavelength FEL amplifiers significantly. This is only one example among many other applications which will benefit from the use of the efficient high-order FEL/IFEL interactions on equal footage with the interactions at the fundamental frequency of the undulator.

High-order electron-radiation interactions have been observed in proof-of-principle experiments when an undulator was seeded by 10 μm [3] and 0.8 μm [4] radiation pulses at a laser intensity of $2x10^{14}$ W/cm$^2$ and $2.6x10^{12}$ W/cm$^2$, respectively. These studies have shown that high-order interactions do occur by observing energy modulation of the electrons whenever the beam energy, undulator parameters and laser wavelength satisfy the resonant condition. However, lack of longitudinal current modulation (microbunching) of the electron beam inside the undulator left questions of the coupling efficiency and the applicability of the high-order interactions in future FEL and IFEL schemes unanswered.

We report efficient coupling between the seed radiation and the electron beam in a $7^{th}$ order IFEL interaction by measuring longitudinal current modulation (microbunching) in the undulator. Here the undulator designed for a resonant wavelength of 74.2 μm is seeded by a $CO_2$ laser fulfilling the condition 10.6x7=74.2 μm (n=7). At a modest seed power the beam is modulated so strongly that we observed harmonics of the longitudinally bunched beam in a Coherent Transition Radiation (CTR) spectrum produced by the beam. Altogether it made possible a direct comparison between the measured longitudinal structure of a bunched beam as deduced from the CTR harmonic analysis and the 3-D simulated longitudinal phase space distribution of the electron beam in a high-order IFEL interaction.

## EXPERIMENTAL LAYOUT

The schematic of the experiment, carried out at the Neptune Laboratory at UCLA, is shown in Fig.1. The Neptune rf photoinjector provides a ~12.3 MeV electron beam with a charge up to 500 pC, a normalized emittance of 6 mm•mrad, and a pulse length of 10 ps (FWHM). The beam is injected into a 33 cm long planar permanent magnet undulator with a period of 3.3 cm and $K_u$=1.8. The beam is typically focused to a spot size of ~350 μm (rms) at the exit plane of the undulator where an insertable probe for a CTR screen is placed. The probe is also used for spatial alignment and temporal synchronization between the $CO_2$ laser and the electron beam. The 10.6 µm $CO_2$ laser beam is focused to a spot size of 650 µm ($1/e^2$) in the middle of the undulator using a 2.5 m focal length NaCl lens. This F/100 focusing provides an almost constant laser field intensity over the entire undulator length. A 100 ps long $CO_2$ laser pulse is used to seed the undulator with a peak power up to 34 MW ($2x10^9$ W/cm$^2$). After the undulator, the electron beam is sent to a high-resolution spectrometer to measure the energy spread.

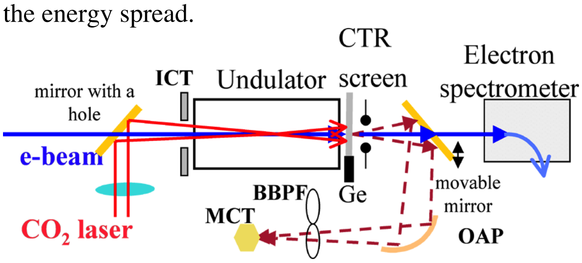


Figure1: A schematic of the experiment. ICT is an integrating current transformer, BBPF - a broadband-pass filter, MCT - a Mercury Cadmium Telluride detector.

The microbunching diagnostic consists 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 through a NaCl window, a focusing off-axis parabolic mirror, a set of broadband-pass filters ($\Delta\lambda$~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 detector. The signal-to-nose ratio of 25 at 10.6 µm, 3 (5 µm) and 1.6 (3.5 µm) are reached in the CTR measurements. More details on the experimental arrangement can be found elsewhere [5].

## RESULTS AND DISCUSSION

The theory of CTR and its application to longitudinal microbunching measurements of electron beams has been extensively studied [6,7]. 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 $hk_s\sigma_{x,y}/\gamma \gg 1$. For a given CTR harmonic, the energy emitted forward at a normal incidence to the conducting surface is given by:

$$U_h \approx \frac{N^2 e^2 b_h^2}{4\sqrt{\pi}\sigma_z}\left(\frac{\gamma}{hk_s}\right)^4\left(\frac{1}{\sigma_{x,y}}\right)^4 \qquad (1)$$

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

To prove the resonant character of interaction between the laser and the electron beam, we recorde the 10-µm CTR signal for different energies of the electron beam and observe a maximum for the CTR signal at 12.5 MeV (width ~0.3 MeV), in agreement with the 7$^{th}$ order IFEL interaction. Fig. 2 shows the CTR energy measurements for the first, $U_1$ ($\lambda_{mb}=\lambda_s$), the second, $U_2$ ($\lambda_{mb}=\lambda_s/2$) and the third, $U_3$ ($\lambda_{mb}=\lambda_s/3$) harmonic components as a function of the laser power for the electron beam charge of ~400 pC. Note that for all data points here the background, which is proportional to the laser power, is subtracted. As seen in Fig. 2, at a low laser power of 3-19 MW only the 10 µm CTR signal is detected. It is important that this seed laser power is comparable to that required for microbunching using the same undulator at the fundamental resonance. Higher laser power causes bunching at the first harmonic to occur earlier in the undulator giving rise to the second harmonic component for powers above 19 MW. A further increase in power speeds up the bunching process even more and for powers above 28 MW, the beam at the exit of the undulator has a third harmonic component. The measured ratios between the harmonic energy for the bunched beam are U1/U2≈17; U1/U3≈70.

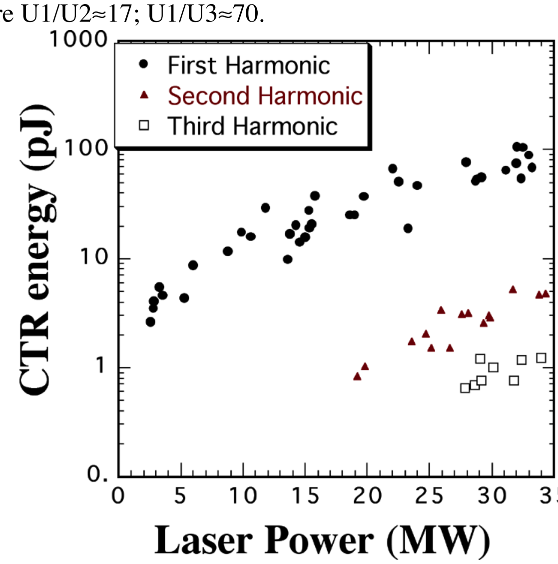


Figure 2: CTR energy for the first, second, and third harmonics as a function of $CO_2$ laser power for the 12.3 MeV beam.

To compare these CTR measurements to a simulated longitudinal phase space of the beam, the 3D code TREDI [8] is 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 ~12.3 MeV beam, we analyze the IFEL interaction for the same experimental conditions using another 3D code GENESIS

[9]. Fig. 3a 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 µm scale the effect of the space charge force on the beam is very small.

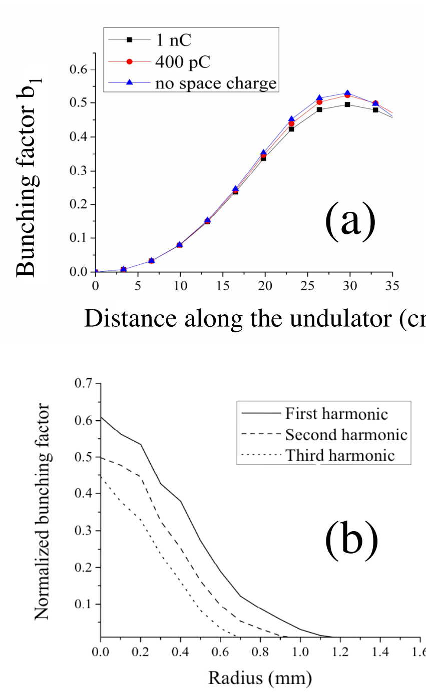


Figure 3: 3-D simulations. Dependence of the bunching factor $b_1$ along the undulator for different beam charges (a) and normalized bunching factor for the first, second, and third harmonic of the microbunched beam at the exit of the undulator versus the electron beam radius (b).

In an attempt to explain the observed ratios of the second and third harmonic to the first harmonic in the CTR spectrum, we use the bunching factor for each harmonic generated in the TREDI simulations in Eq. (1). When the bunching on harmonics is taken for the whole beam, the simulations produce U1/U2=64 and U1/U3=2025. However, the physical picture is more complicated: analysis of phase space distribution of electrons at the exit of the undulator indicates that there is a significant transverse variation in bunching and particles on axis are better bunched than the particles off axis. The laser beam size in the experiment is approximately equal to the electron beam envelope size including the wiggling motion. In terms of the IFEL interaction, this represents a case where the off-axis particles see a smaller laser power, and are therefore bunched more weakly. Fig. 3b 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 3b are 380 µm for the first, 335 µm for the second, and 295 µm 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. (1) predicts U1/U2=14 and U1/U3=53, which is in close agreement with the measurements presented in Fig.2.

## CONCLUSIONS

In conclusion, this experiment has shown microbunching of the electrons at the $7^{th}$ order resonance from an IFEL. The electrons are efficiently bunched longitudinally inside a ten period long undulator producing the first, the second, and the third harmonics in a CTR spectrum. Observation of the tightly bunched beam at a modest seed intensity of ~$10^9$ W/cm$^2$ demonstrates for the first time feasibility of using very-high-order harmonics for efficient IFEL/FEL interactions. It is shown that in the case of approximately equal sizes of the electron and the seed radiation beams, the IFEL interactions result in transverse variation of bunching that significantly affects the CTR harmonic content. Note that in practically all seeded IFEL/FELs, 3D effects in beam matching may play a similar role and should be considered in CTR analysis. With the inclusion of the high-order IFEL/FEL interactions (n≥3) on equal footage with the n=1 case, a significant flexibility can be gained in designing UV/X-ray FELs [2].

## ACNOWELEDGEMENTS

This work was supported by US. Department of Energy contracts DE-FG03-92ER40727 and DE-FG03-92ER40693.

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