9 HARMONIC CONTENT OF THE HGHG

As discussed in Chapter 6, the electron beam energy modulation, as measured in the electron energy spectrometer, is an indicator for the strength of the HGHG interaction. In this section we will use the energy modulation as a parameter to study the harmonic content of the FEL.

In the HGHG process, energy modulation of the electron beam is generated in two ways: (1) through the initial interaction of the seed laser and electron beams in the modulator; and (2) through the HGHG FEL interaction itself in the radiator. Usually the energy modulation produced in the radiator dominates. The electron beam images after the spectrometer (a) with CO_2 laser on, and (b) with the CO_2 laser off, are shown in Figure 9-1. With the CO_2 laser on, the energy modulation is seen to be 2.5%.

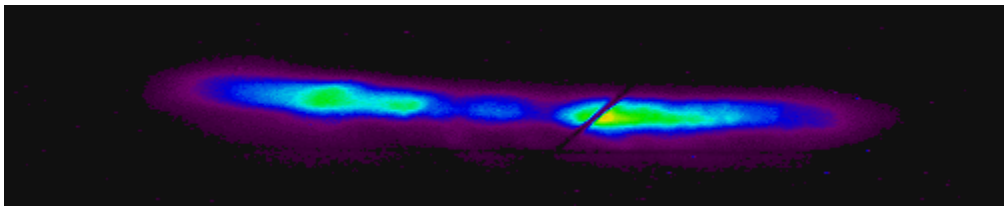

Figure 9-1 (a) Electron beam with CO_2 laser on, horizontal axis shows the energy modulation, and vertical axis is the beam size.

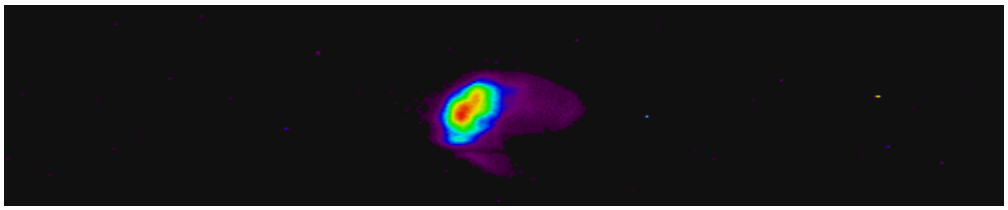

Figure 9-1(b) Electron beam with CO_2 laser off, horizontal axis shows the energy modulation, and vertical axis is the beam size.

The double peak observed in Figure 9-1 (a) is consistent with the theoretical plot shown in Figure 6-4. The projection of the plot in Figure 6-4 onto the energy axis gives a similar double band. The center of mass of the whole beam shifts to the right by 14 pixels (see Figure 9-2), which means overall electrons lose energy by 0.167 %. For a 41.3 MeV electron beam this loss is 67 keV. Assuming the current is 120 Amp the energy loss would correspond to 50 μJ, which is typical energy of HGHG output indicating the energy conservation.

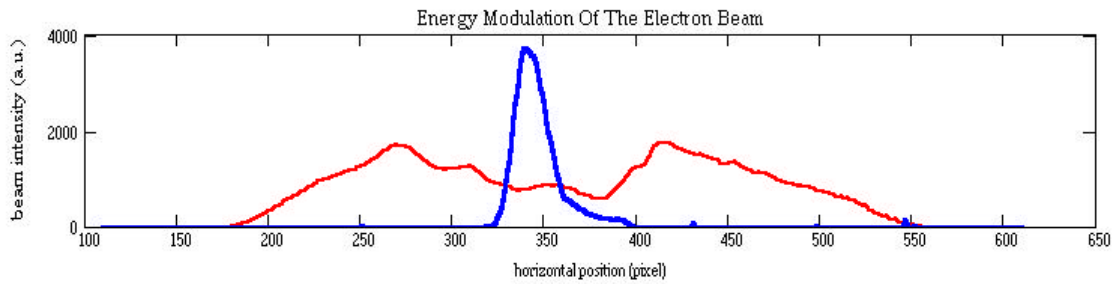

Figure 9-2 Intensity plot of the modulated and unmodulated electron beams as a function of horizontal position which corresponds to energy of the electrons

The theory of higher harmonic emission has been studied in refs. [46-49]. Here, we measured the fundamental (5.3 μm), second (2.65 μm), and third (1.77 μm) harmonics relative to the radiator as a function of electron energy modulation. We used the In-Sb detector in conjunction with appropriate bandpass and neutral density filters, to select the various wavelengths and generate comparable signal levels in the detector. According to the manufacturer's data, the responsivity of the In-Sb detector is a factor of 0.67 less at 2.65 μm and a factor of 0.5 less at 1.77 μm as compared to the responsivity at 5.3 μm. A 100-nm bandpass filter with 80% transmission through this band and 1×10^6 attenuation were used at the fundamental (5.3 μm). For the second harmonic, (2.65 μm), we used a 35-nm bandpass filter with 75% band transmission and 1×10^3 attenuation. For the third harmonic (1.77 μm), a 35-nm bandpass filter with 60% band transmission was used with 1×10^4 attenuation.

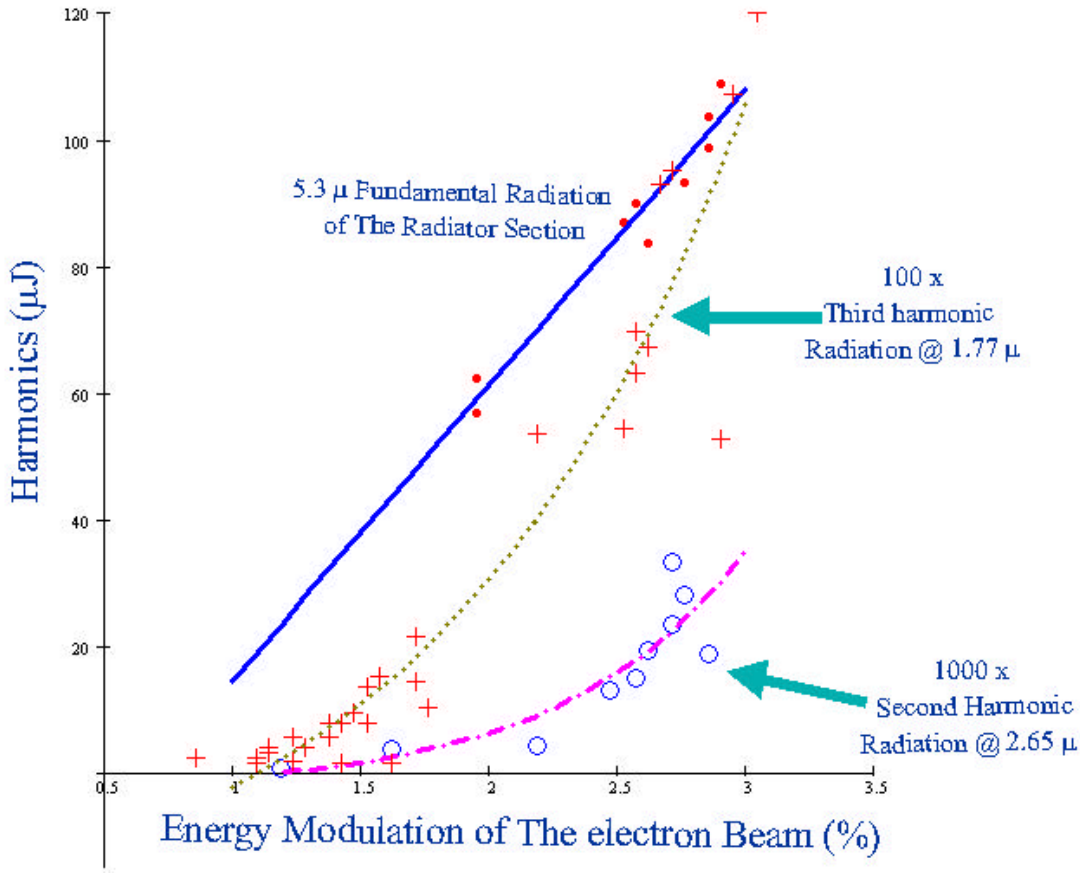

Figure 9-3 Harmonic content of the HGHG vs. energy modulation. Various harmonics of the fundamental are plotted as function of modulation. The blue line is linear fit to the fundamental data, brown and pink curves are the exponential fits to the harmonic data.

The results of the measurements are presented in Figure 9-3, where we plot the harmonic contents (μJ) of the first three harmonics as a function of the electron beam energy modulation (%). The rapid increase of the harmonic intensities at 2.65 μm and 1.77 μm as the electron energy modulation approaches 2.5% is strong evidence of saturation. In Table 9-1, the theoretical predictions and experimental measurements of the ratios of the harmonic-to-fundamental energies are presented for a 2.5% electron beam energy modulation. The agreement between experiment and simulation is reasonable.

Wavelength	Simulation	Experiment
2.65 μm	6×10^{-4}	2×10^{-4}
1.77 μm	1×10^{-2}	0.8×10^{-2}

Table 9-1 The theoretical and experimentally measured harmonic-to-fundamental ratios

Another result of this measurement is the linear dependence between the fundamental output and the energy modulation. This relation shows that most of the modulation comes from the FEL interaction. If it originated from the CO_2 interaction it would have been a nonlinear dependence as mentioned in Chapter 6.

Also the amount of modulation, as well as the strength of the higher harmonics, indicates that saturation or near-saturation has been reached [44].