A FREE ELECTRON LASER EXPERIMENT[†]

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Abstract

An experiment has been performed in which microwaves are generated by the interaction of a helical magnetic wiggler field with an electron beam. This Free Electron Laser can be operated in either the stimulated Raman or stimulated Compton regime by changing the electron beam density. The high repetition rate, and long pulse length of the electron beam facilitate diagnostics and the characterization of the device. To date, the device has been operated in the superradiant and oscillator Raman scattering mode. Preliminary results show an increase of 20 db in the oscillator mode with respect to the superradiant mode. The variations in the spectrum with wiggler field amplitude and electron beam density are shown.

Introduction

A Free Electron Laser (FEL) device is a source of high power, coherent electromagnetic radiation that can be tuned to operate from cm to visible wavelengths. The radiation is generated by scattering an external electromagnetic wave or "pump" from an intense relativistic electron beam. The coherence of the radiation is due in part to the axial self-bunching of the beam in the presence of the pump. The FEL operates in different regimes depending on the magnitude of the macroscopic system parameters. For extremely intense electron beams ($\lambda_D \lesssim \lambda$, where $\lambda_D \equiv$ relativistic Debye length and $\lambda \equiv$ characteristic radiation wavelength), collective effects may play a dominant role in the dynamics of the system [collective regime]. This is to be contrasted for example with the case of extremely energetic, but low intensity electron beams ($\lambda_D \gtrsim \lambda$) where single particle effects dominate the behavior [Compton regime]. Other macroscopic parameters that determine the regime of operation include the electron beam energy spread (ΔE), the pump amplitude (I_p) and wavelength (λ_0), and the length (L) of the system.

We have built an experiment that allows the characterization of the FEL in different regimes. This in turn will permit the optimization of the FEL gain and efficiency. Recent experiments at Stanford[1] and Columbia/NRL[2,3] have shown the feasibility of generating infrared[3], (10.6µ amplifier and 3.4µ oscillator) and millimeter[2] radiation by the free electron laser mechanism. However, each experiment was operated in a different FEL regime, not driven into saturation and at low efficiencies ($\eta < 10^{-3}$). The experiment reported in this paper can operate in both the Compton regime (as the Stanford experiment) and the collective regime (as the Columbia/NRL experiment). It operates in the microwave region and unlike the UBITRON and the Columbia/NRL experiment, it utilizes a helical wiggler as the electromagnetic pump and a solid electron beam of high repetition rate and long pulse length which facilitates diagnostics.

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General Theory

The details of the physical mechanism associated with the FEL interaction are a function of the system parameters that in turn determine the FEL regime of operation. However, the basic mechanism is the same in all regimes. In the presence of the pump, the streaming (say in the $\hat{z}$ direction) beam of electrons oscillates with a transverse velocity $v_{o\perp}$ that is proportional to and in the same direction as the pump field. A longitudinal (along the $\hat{z}$ axis) low frequency Lorentz force is induced by the coupling of the oscillatory velocity $v_{o\perp}$ and the initial high frequency radiation. The induced longitudinal force, also called ponderomotive or radiation pressure force, produces an axial bunching of the beam or a density perturbation. For a sufficiently intense electron beam, collective effects become important and the self-space charge potential set up by a density perturbation influences nearby density perturbations and vice versa creating a periodic oscillating density perturbation or density wave. In any case, the density perturbation couples with the oscillatory velocity $v_{o\perp}$ and induces a current that in turn generates high frequency electromagnetic radiation (stimulated backscattering) that reinforces the initial radiation. The process is then unstable and results in the stimulated emission of high frequency radiation. The intensity of the emission increases with the pump amplitude and it is advantageous to use an external ripple magnetic field (zero frequency pump) instead of an external electromagnetic wave. For example, a 1 kG ripple magnetic field is equivalent to a 300 MW/cm^2, cw external source.

The short and tunable wavelength of the output radiation is due to a double Doppler shift from the pump wavelength. In the case where the pump is a magnetic field of ripple length (incident wavelength) λ_0 and the streaming electron beam velocity is V_b, the lasing frequency ω is given by

$$\omega = \frac{2\pi c}{\lambda_0} \beta\gamma^2 \left(1 - \frac{\omega_p \lambda_0}{2\pi\gamma^{3/2}\beta c}\right)\left(1 + \beta\left(1 - \frac{\omega_{cef}^2 \lambda_0^2}{2\pi c^2}\right)\right)$$

$$\times \ (1 + f(B_r))$$

where

$$\gamma^2 = [1 - \beta^2]^{-1},$$

$$\beta = V_b/c \tag{1}$$

and

$$\omega_{cef}^2 = \frac{\omega_{co}^2}{\beta^2\gamma^2\left[1 - (\omega_p\lambda_0)/(2\pi\gamma^{3/2}\beta c)\right]^2} \tag{2}$$

In Eq. 2, ω_{co} is the waveguide cut-off frequency and ω_p the electron plasma frequency, $f(B_r)$ is a function of the ripple magnetic field amplitude the form of which depends on the regime of operation of the device. Hence, the FEL can be tuned by varying for example the electron beam mean parallel kinetic energy, a large advantage over most other sources of electromagnetic radiation.

Experimental Device

The experimental arrangement is illustrated in Fig. (1). The electron source is the cathode and anode assembly taken from a commercial high power klystron. The heated cathode is 5.7 cm in diameter and produces up to 60 A at 100 kV. The electron beam is pulsed at up to 60 pps and the pulsewidth is 1.6μs. A converging magnetic field designed to produce Brillouin flow, guides the electrons through a hole in the anode into the interaction region. The resulting instantaneous axial energy spread of the beam, $\Delta E_{\parallel}/E_{\parallel}$, is expected to be of the order of 10^{-5}.
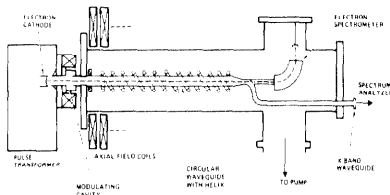

Figure 1. Schematic of X-band FEL Experiment

The interaction region consists of a circular waveguide, 1 m long and 2.54 cm in diameter, along the axis of which the electron beam propagates. On the outside of the waveguide is wound a double helical coil which produces the perpendicular magnetic field perturbations with a wavelength λ_0 = 2.5 cm. This helical coil is powered by a pulsed power supply and is capable of producing a perpendicular magnetic field on axis in excess of 1000 gauss, with 10 kA in the coil.

The whole assembly is contained in a vacuum vessel which is surrounded by 24 large pancake coils. These coils produce an axial solenoidal magnetic field up to 6 kG which confine the electron beam to <5 mm diameter.

Downstream from the interaction region, waveguides extract the electromagnetic radiation produced, while the electron beam is analyzed with a magnetic spectrometer.

At 100 keV, and with a helical field wavelength λ_0 = 2.5 cm, the electromagnetic radiation is in the X-band regime of around 10 GHz. The emission can therefore be analyzed using standard microwave receiver techniques. A heterodyne receiver was assembled from a magic T, a mixer diode and a sweep local oscillator. It permits the detailed analysis of the emission frequency spectra. Using a box-car averager, the spectra can be time resolved within the duration of the electron beam.

Experimental Results

Typical spectra of the microwave radiation generated by the interaction of the rippled magnetic field and the electron beam are shown in Fig. 2. It should be noted that each frequency f_0 appears at

$f_0 = f_{LO} \pm f_{IF}$ where f_{LO} is the local oscillator and f_{IF} the intermediate frequency of the receiver. The parameters of Fig. 2 are: beam voltage 90 kV, beam current 12 A, beam density 1.2×10^{10} cm^{-3}, and external magnetic field 2.1 kG. By increasing the helix current to a certain value I_0, a narrow band mode is excited. At 0.9 I_0, no microwave power was observed while at 1.2 I_0 several modes are present with down

shifted frequencies. Both the onset and frequency shift with the pump field is predicted by theory. A threshold pump field is necessary to obtain a positive growth rate and the frequency shift is evident from the last term of Eq. (1). The helix current in these measurements is typically in the kA range. The corresponding wiggler field has not yet been measured but is expected to be several hundred gauss.
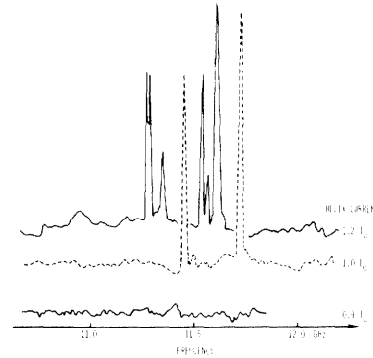

Figure 2. Frequency spectrum of electromagnetic power output as a function of helical magnetic field.

The high operating density in excess of 10^{10} cm^{-3} lets the interaction take place in the collective regime. This regime has a significantly larger growth rate compared to the single particle interaction. Correspondingly, the superradiant excitation of microwaves was observed for beam densities larger than 5×10^9 cm^{-3} only.

The system was also operated as an oscillator. To this end, the experiment was modified as shown in Fig. 3. At the beam input end of the wiggler-waveguide combination, an aperture was inserted that allows the beam to pass but reflects microwaves. The opposite end of the waveguide is terminated by a movable short in the rectangular waveguide section. The lower part of Fig. 4 shows the mode spectrum as observed with a relative short position of 1.00 cm. Operating conditions are the same as in Fig. 2, except the helix current is 1.3 I_0. By changing the short position by 1.00 cm, corresponding to one quarter of the guide wavelength, one single mode can be selected. Simultaneously, the power in this mode is increased by about a factor 100 indicating that the operation of this system as an oscillator is indeed possible.
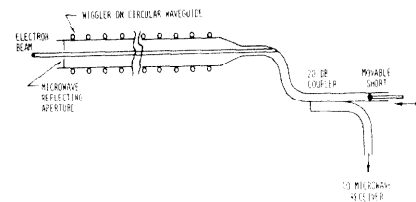

Figure 3. Schematic showing FEL oscillator configuration. The reflecting elements of the oscillator are the upstream aperture, and the movable waveguide short. Intracavity power is outcoupled using a 20 db coupler.
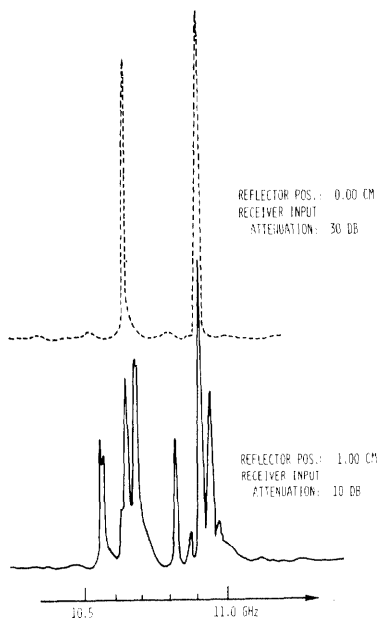
Figure 4. Frequency spectra of the oscillator emission as a function of the position of the movable short.

The data reported here are of a preliminary nature only. A thorough parameter study of the interaction will be made. Specifically, the dependence of wave spectrum amplitude, and system gain on beam and pump characteristics will be studied. This includes the determination and intentional modification of the beam distribution function which will help to determine the saturation mechanism.

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