Masing and Single-Mode Locking in a Free-Electron Maser Employing Prebunched Electron Beam

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We report a first demonstration of single-mode selection in a free-electron maser (FEM) using electron-beam prebunching at or near the natural oscillation frequencies of the resonator. The FEM oscillation frequency can be selectively locked to each eigenfrequency of the resonant waveguide cavity within the frequency band of the FEM net gain. When the electron beam is prebunched at a frequency close to an eigenfrequency of the cavity, the oscillation buildup process is sped up and the radiation buildup time is shortened significantly. Measurements are in good agreement with collective (Raman) free-electron laser theory.

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Oscillator frequency selection and locking by means of seed radiation injection or current modulation are well known techniques for enhancing the oscillation buildup process in the oscillator, for determining the oscillation frequency, and for stabilizing it. These techniques have been demonstrated and are being used in microwave tubes [1–4] and in conventional lasers [5–7]. Frequency locking and mode selection of free-electron lasers (FELs), which have important practical and laser theory implications, have not been demonstrated so far.

Frequency locking and mode selection by prebunching of the electron beam, used in the microwave tube art, are somewhat different from seed radiation injection which is more common in laser oscillators. In conventional lasers it would be equivalent to the establishment of phase coherence in the polarization of the amplifying medium (superradiance). Superradiance of short pulses [8–10] and periodic bunching [11–14] in FELs have been the subject of intensive studies recently. This radiative emission is of interest as a fundamental radiation process which is very efficient—proportional to the squared number of electrons [14,15]. By comparison, spontaneous emission, which is the input noise power of conventional laser oscillators, is linearly proportional to the number of oscillating electrons. From the practical point of view, resonator mode seeding by the use of electron-beam prebunching can be performed more easily than by injection of radiation, because it is a unidirectional process, while in the seed radiation process it is impossible to inject the radiation without getting radiation coupled out or contributing insertion losses to the resonator. In this Letter, we report the first demonstration of single-mode selection and seeding in a free-electron maser (FEM) by means of electron-beam prebunching.

A FEL employing a monoenergetic (*cold*) electron beam is a *homogeneously broadened* laser [16]. This means that the different longitudinal modes of the resonator compete with each other for extracting photons from the same electrons in the electron beam in the stimulated emission process. This mode competition process, which takes place during the oscillation buildup period of every FEL oscillator, has been the subject of recent theoretical and experimental investigations [17,18]. In the linear regime all modes for which the gain is larger than the round-trip loss (see Fig. 1) start to grow from noise when oscillation starts. However, as the signal grows and upon entering the nonlinear regime, negative coupling between the longitudinal modes increases the *effective gain* and enhances the buildup of the mode of highest initial power, suppressing the gain of the other modes whose power gets diminished, until single-mode oscillation emerges with extremely high coherence of the omitted radiation [19]. Under certain conditions (of strong pumping) the mode competition process may evolve into chaos and mutifrequency noisy radiation output will emerge out of the oscillator [17].

If the oscillator starts the oscillation buildup process spontaneously (from noise), the single mode that will survive the competition process is the highest gain mode. This is based on the assumption that the initial noise is equally partitioned among the modes. However, such an assumption is limited by the statistical nature of the noise source (shot noise and thermal noise), and if a large number of modes satisfies the oscillation condition, there may be some uncertainty in the prediction of the evolving steady-state oscillation frequency. Such uncertainty also exists if there are other instabilities in the laser parameters (especially beam energy fluctuations).

A way to overcome the uncertainty in the oscillation frequency and to determine it in advance is to inject sufficient initial excess power into the desired oscillator mode. Because of the nonlinear nature of the competition process, this mode will emerge a *winner* even if its linear gain is smaller than the gain of the other modes that satisfy the oscillation condition. The motivation for mode seeding and frequency locking may be a desire to tune to an exact and stable frequency (for particular application or for facilitating coherent coupling of a number of radiation

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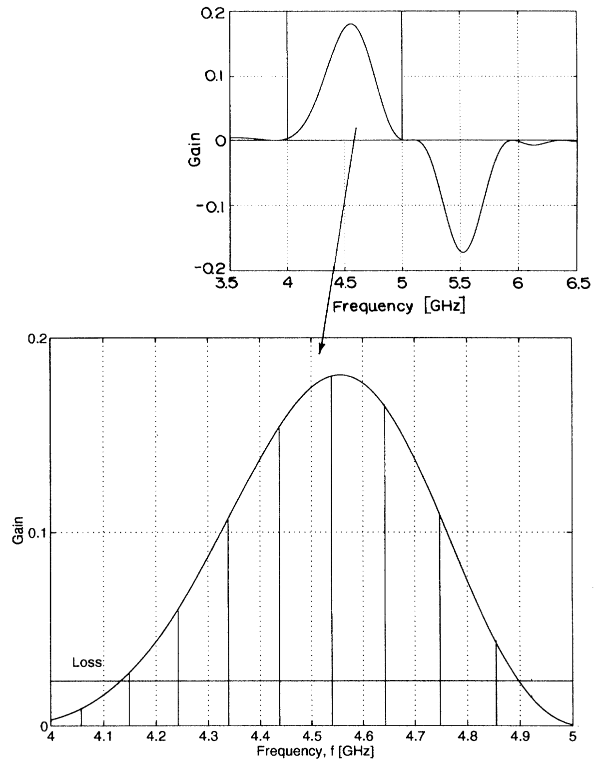

FIG. 1. FEM gain vs the signal frequency. The maximum gain is achieved at 4.539 GHz. The round-trip loss was estimated from the decay constant of the energy in the resonator and found to be 2.3% (Q factor is about 11 000).

sources [2]). Furthermore, as shown in [17] the highest gain mode is not necessarily the one which extracts the highest power from gain medium (the electron beam) at saturation and yields the highest oscillator power. It is usually desirable to excite a mode with a larger *detuning value* (which can be done by mode seeding) in order to operate the FEL at the highest energy extraction efficiency.

Using a linear gain model [20,21] the small signal gain of a FEM in the low gain collective (Raman) regime is described analytically by the following approximate expression:

$$G(L) \equiv \Delta P(L)/P(0) = \kappa \mathcal{F} \theta_p^2 L_W^3 F(\overline{\theta}, \overline{\theta}_{p_r}), \qquad (1)$$

where $\kappa = \frac{1}{4}(\overline{v}_W/v_{0z})^2(\omega/c)^2/k_z$ is the coupling parameter, $\overline{v}_W$ is the rms wiggling velocity, v_{0z} is the axial velocity of the electron beam, and ω and k_z are the frequency and the axial wave number of the radiation, respectively; $\mathcal{F} \equiv A_e/A_{\rm EM}$ is the power filling factor which describes the overlap of the electron beam with radiation field in the transverse plane; $\theta_p = \omega_{\rm pl}/v_{0z}$ is the relativistic electron-beam plasma wave number; and L_W is the wiggler length. The gain function $F(\overline{\theta}, \overline{\theta}_{p_r})$ is defined by [21]

$$F(\overline{\theta}, \overline{\theta}_{p_r}) = \frac{1}{2\overline{\theta}_{p_r}} \left\{ \frac{\sin^2[(\overline{\theta} + \overline{\theta}_{p_r})/2]}{[(\overline{\theta} + \overline{\theta}_{p_r})/2]^2} - \frac{\sin^2[(\overline{\theta} - \overline{\theta}_{p_r})/2]}{[(\overline{\theta} - \overline{\theta}_{p_r})/2]^2} \right\}, \qquad (2)$$

where $\overline{\theta}_{p_r} = r\theta_p L_W$ is the plasma wave number modified by a geometric reduction factor r [22] and normalized to the wiggler length, $\overline{\theta}(\omega) = [\omega/v_{0z} - k_W - k_z(\omega)]L_W$ is the normalized detuning parameter and k_W is the wiggler wave number.

The two terms in Eq. (2) correspond to FEL interaction with the slow (negative energy) and fast (positive energy) Langmuir beam plasma waves, respectively. The gain and loss curves of the two plasma waves are well separated in the collective (Raman) regime ($\overline{\theta}_{p_r} \gg \pi$) as is the case in the presently reported experiment (see Fig. 1). For the regime ($\overline{\theta}_{p_r} \ll \pi$) the gain curve reduces to the well known S-shaped curve of the Compton regime [21].

In a FEL oscillator, as in any laser, the condition for oscillation is that at least one of the resonant modes of the laser resonator must have a round-trip (in FEL single path) small signal gain larger than its round-trip loss [16]. For our FEM which employs a rectangular waveguide resonator the eigenmode frequencies are given by

$$\omega_\ell = \sqrt{(c\ell\pi/L_c)^2 + \omega_c^2}, \qquad (3)$$

where ℓ is the longitudinal mode number, $\omega_c = c\sqrt{(n\pi/a)^2 + (m\pi/b)^2}$ are the cutoff frequencies of the waveguide of a rectangular cross section $a \times b$, and L_c is the resonator length. The resonator modes falling under the gain curve (as calculated numerically) are shown in Fig. 1 (for the parameters of our FEM oscillator given in Table I). The resonant frequencies under the gain curve are longitudinal modes of the transverse mode TE_{10}. The frequency spacing between these modes is nearly constant. In our experiment eight longitudinal modes satisfied the oscillation condition.

The prebunched FEM scheme used in our experiments is shown in Fig. 2. The electron beam is prebunched by a microwave-tube section operated at 10 kV, 1.2 A. The electromagnetic wave is absorbed at the end of the prebuncher while the prebunched beam exits. The frequency and the level of prebunching are controlled by the rf input signal to the prebuncher. The e beam is accelerated to 70 keV in a short acceleration gap, trans-

TABLE I. Parameters of the TAU free-electron maser.

Electron beam energy (spread)	$\mathcal{E} = 70$ keV	$(\sigma_{\mathcal{E}}/\mathcal{E}) \approx 0.5\%)$
Beam current	$I_0 = 1.0$ A	
Wiggler field	$B_W = 300$ G	$(a_W = 0.12)$
Wiggler period	$\lambda_W = 4.4$ cm	
Wiggler length	$L_W = 0.748$ m	
Waveguide dimensions	$a \times b = 47.55 \times 22.15$ mm^2	

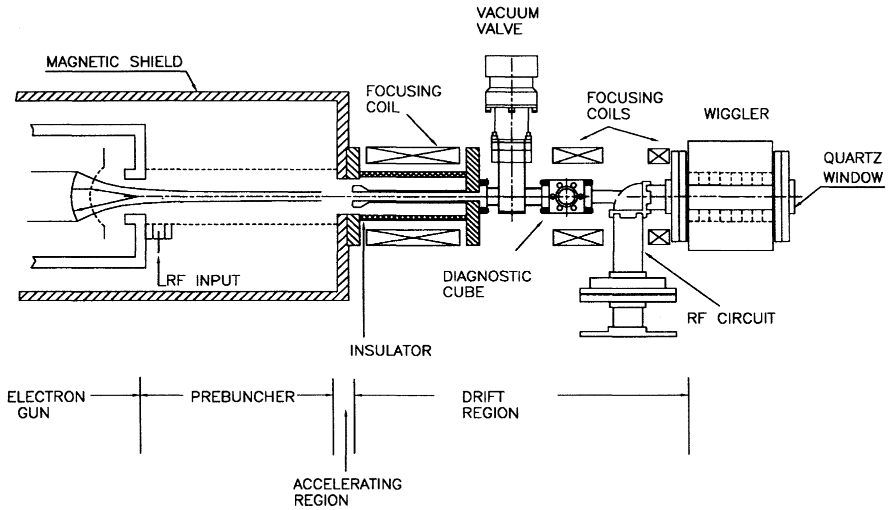

FIG. 2. Schematic of the prebunched beam FEM experiment at TAU.

ported through a drift section, focused by a solenoidal magnetic field, and injected into a planar wiggler. Since the electron-beam energy is moderate and the current density in the beam is relatively high, the space-charge forces tend to spread the *e* beam inside the wiggler. A new scheme for horizontal focusing based on the use of two long permanent magnets at the sides of the wiggler, which create at the electron-beam axis a lateral gradient of the magnetic field, was used [13].

A rectangular waveguide with a cross section of $47.55 \times 22.15\ \text{mm}^2$ is used for the FEM resonator. Synchronous interaction between the *e* beam and the radiation field takes place only in the TE_{10} transverse mode. In the frequency range of 4–6 GHz all higher order modes are cut off. The end of the bent waveguide section and the front end are terminated with reflectors in order to produce resonator configuration. The output signal was coupled out through a quartz window. The beam is injected into and out of the resonator through nonradiative holes in the waveguide bends which produce no rf power coupling out of the resonator and cause internal rf power reflections of less than 5% [23].

The detected power envelope and the frequency of the output signal were measured using a setup shown in Fig 3. A crystal diode detector is used to measure the signal power, and the frequency is measured by heterodyning.

In Fig. 4 we display the wave forms of the electron-beam current pulse [trace (1)] and the detected power of the resonator output signal [trace (2)]. When a current pulse without premodulation passes through the resonator it causes initially an exponential buildup of the rf power in the resonator, starting from an initial noise level. The radiation buildup process continues until the circulating power reaches saturation; at steady-state level the single pass saturated FEM gain just equals the total round-trip cavity losses. The oscillation buildup time as shown in the oscilloscope trace (2) is about $\tau_b = 1200$ ns.

The if (intermediate frequency) signal is shown as trace (3) of Fig. 4. The local oscillator frequency is 4.540 GHz, and the if signal frequency is 4.75 MHz. These frequencies correspond to an accurately measured free-running oscillator frequency of 4.53525 GHz. The free-running oscillator frequency result agrees with the theoretical frequency (3) of the maximum gain mode presented in Fig. 1 (4.539 GHz) within 0.1% accuracy (the inaccuracy is due to the inaccurate determination of the resonator effective length L_c).

The frequency spacing between the resonant modes of the waveguide cavity is given approximately by

$$\Delta f = v_g / 2L_c \,, \qquad (4)$$

where v_g is the group velocity of the radiation. For parameters given in Table I, $\Delta f \approx 92–110$ MHz for the excited modes shown in Fig. 1, and therefore the transit time for one round-trip in the cavity is approximately $T_r =$

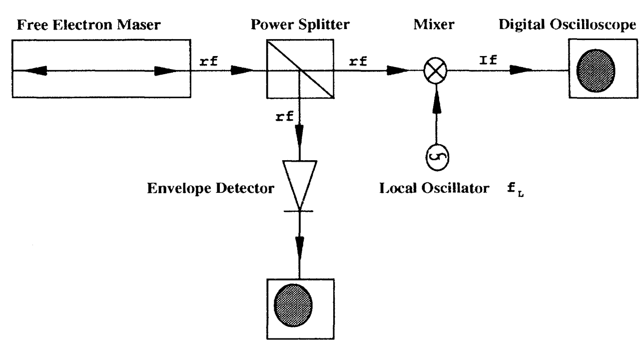

FIG. 3. A block diagram for measuring the power and the frequency of the FEM signal output.

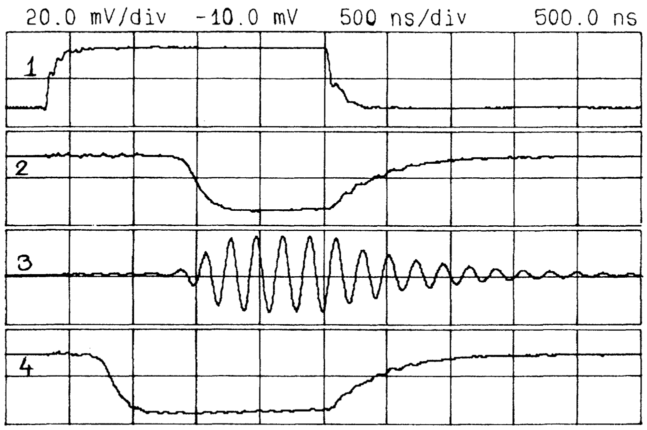

FIG. 4. The electron-beam current pulse and the FEM output signals evolution in time are shown. Trace (1) is the electron-beam current pulse. Trace (2) is the power of the rf output signal without prebunching of the electron beam. Trace (3) is the if signal at frequency of 4.75 MHz. Trace (4) is the detected rf output signal obtained with an electron-beam prebunching frequency close to the free-running oscillator frequency.

$1/\Delta f \approx 10$ ns. A constant output signal is obtained after $N = \tau_b/T_r \approx 100$ round-trips. This number of round-trips is relatively small, corresponding to an appreciable net linear gain per path.

The prebuncher used enables prebunching of the e beam at any frequency in the FEM gain bandwidth as described above. We observed in the experiment single-mode locking effect at all resonator natural frequencies in the gain bandwidth. As we tune the rf source of the buncher to one of the eigenfrequencies of the resonator the oscillation buildup time shortens significantly relative to the free-running oscillation buildup time (see Fig. 4). The buildup time for the case of a mode-seeded oscillator [trace (4)] is about 500 ns (for a prebuncher rf input power of 10 mW); powers in the μW level were sufficient in order to lock the axial mode. By scanning the buncher rf modulation frequency it was found that the eight different longitudinal modes were selectively excited with a spacing of about 100 MHz in agreement with Eq. (4) and the mode map of Fig. 1. The resonator locking range around each eigenfrequency was about 5 MHz at each side of the eigenfrequency. This corresponds to half of one rf period slippage between the prebunching signal and the resonator mode frequencies in a time period of 100 ns—ten resonator round-trip transversal times. The physical significance of this is that the mode growth in ten round-trips was large enough so that it is not depressed by the prebunched beam, which then slips out of phase with the radiation signal.

In summary, FEM oscillations in the deep collective regime and single-mode seeding and selection of FEM by e beam prebunching were first demonstrated in the present experiment. Good agreement between theory and measurements was found. The FEM frequency can be locked to each of the resonant eigenfrequencies for which gain is higher than the loss of the resonator; the oscillation buildup time was shortened significantly due to the prebunching.

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