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Report on first masing and single-mode locking in a prebunched beam FEM oscillator

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Abstract

The effects of electron beam prebunching on the radiation buildup process in a free electron maser oscillator operating in a collective-Raman regime and oscillating in the frequency range of 4 to 5 GHz are studied. An electron beam is prebunched, accelerated to 70 keV, transported through a drift region, and injected into a linearly polarized wiggler in which FEL interaction takes place. Single-frequency selection and locking due to electron beam prebunching is demonstrated; we show that the electron beam prebunching can be used to force the oscillator to achieve steady-state single-mode operation and to select the oscillator frequency to be any of the resonator natural frequencies of the cavity in net gain bandwidth. An appreciable speed-up of the oscillation buildup due to prebunching was also observed.

1. Introduction

In free-electron laser (FEL) oscillator, as in any laser, the radiation may be self-excited and starts to grow spontaneously from noise if the round-trip small-signal gain of the radiation exceeds its round-trip loss [1]. Typically, the gain bandwidth is larger than the spacing in frequency between the natural frequencies of the resonant cavity. This means that a number of different longitudinal modes of the resonator compete with each other for extracting energy from the same electrons in the electron beam in the stimulated emission process. In the linear regime, when the radiation in the oscillator starts to grow, the radiation spectrum may be composed of a large number of different eigen frequencies. However, as the signal grows and enters the nonlinear regime, negative coupling between the longitudinal modes 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 [2] with extremely high coherence of the emitted radiation [3].

In oscillators that start the oscillation buildup process spontaneously from noise, the mode that has the highest gain will generally win in the mode competition process. This conclusion is based on the assumption that the initial noise is equally partitioned among the modes. If a large number of modes satisfy the oscillation condition, there may be some uncertainty in the prediction of the evolving steady-state oscillation frequency. One way to overcome this uncertainty in the oscillation frequency is to inject sufficient initial excess power into the desired oscillator mode. Due to 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. Oscillator frequency selection and single-mode locking by means of seed radiation injection or current modulation are well known techniques [4–7] for enhancing the oscillation buildup process in oscillator resonators, for setting the oscillation frequency and for stabilizing it.

Single mode frequency locking may be used in application where an exact and stable frequency is desired (such as coherent coupling of a number of radiation sources [4]).

2. Free running oscillator

The prebunched FEM scheme was described in our previous publications [8–10]. In this scheme, the electron beam is prebunched, accelerated to 70 keV and transported through a drift section. The electron beam is injected into a planar wiggler consists of 17 periods ($B_w = 300$ G and $\lambda_w = 4.44$ cm). A rectangular waveguide was used for the FEM resonator.

For a rectangular waveguide resonator of dimensions $a < b < L_c$, where a and b are the transverse dimensions and L_c is the length of the resonator, the TE_{10} is the fundamental transverse mode. The parameters of the TE_{10} mode for FEL interaction are given in Table 1. We use the dispersion relation of a waveguide $\omega = \sqrt{c^2k_{zn}^2 + \omega_c^2}$ to determine the eigen frequencies. For any eigen frequency, the mode propagation constant must satisfy $k_{znm} = l\pi/L_c$

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Table 1
Microwave circuit (TE_{10} mode) parameters

Waveguide dimensions	$a \times b = 47.55 \times 22.15\ \mathrm{mm}^2$
Length of resonator	$L_c = 1.05$ m
Cutoff frequency	$f_c = 3.15$ GHz
Frequency (at max. linear gain)	$f_o = 4.535$ GHz
Internal loss (per r.t.)	$L_i = 0.065$ dB
Power filling factor	$A_c/A_{em} = 0.024$

where l is the longitudinal mode number. This condition defines the resonant frequencies of the resonator

$$f_{nml} = c\sqrt{\left(\frac{l}{2L_c}\right)^2 + f_c^2}, \tag{1}$$

where $f_c = c\sqrt{(n/2a)^2 + (m/2b)^2}$ is the cutoff frequency. The frequency spacing between the resonant axial modes of the waveguide resonator is approximately constant and is approximately given by

$$\Delta f = \frac{v_g}{2L_c}, \tag{2}$$

where $v_g = c\sqrt{1 - (f_c/f_o)^2}$ is the group velocity of the radiation. For parameters given in Table 1, $\Delta f \approx 92$–110 MHz and therefore the transit time for one round-trip in the cavity is approximately $T_r = 1/\Delta f \approx 10$ ns. The power emitted from the partially outcoupled end of the waveguide is divided by a power splitter. A calibrated crystal detector is used in one branch to measure the signal power envelope. The other branch is used for frequency heterodyning measurement.

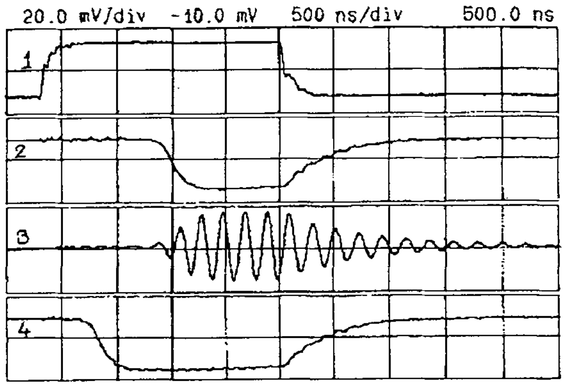

Fig. 1. The electron beam current pulse and the FEM output signals evolution in time are shown. Trace no. (1) is the electron beam current pulse. Trace no. (2) is the rf output signal without prebunching the electron beam. Trace no. (3) is the if-signal at a frequency of 4.75 MHz while the local oscillator frequency is 4.540 GHz. Trace no. (4) is the rf output signal corresponding to the electron beam bunching frequency which is close to the free-running oscillator frequency.

In Fig. 1 we display the wave forms of the electron-beam current pulse [trace (1)] and the detected power envelope of the resonator output signal [trace (2)]. The current pulse without prebunching 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. The oscillation buildup time as shown by trace (2) is about $\tau_b = 1200$ ns which corresponds to $N = \tau_b/T_r \approx 120$ round-trips. Then if signal is shown as trace (3) of Fig. 1. The local oscillator frequency is $f_{lo} = 4.540$ GHz and the if signal frequency if $f_{if} = 4.75$ MHz. These frequencies correspond to a free-running oscillator frequency of $f_o = 4.53525$ GHz.

The total loss per round-trip, L, for the loaded waveguide resonator is $L = 0.1$ dB. We deduce that the power reflection coefficient is $R = 99.2\%$. The output power measured on a calibrated crystal diode in this limit is about 250 mW. It should be possible to obtain kW power levels with optimal coupling.

3. Single-pass small-signal gain

We calculate the small-signal single-pass gain as a function of the radiation frequency. The resonant frequencies under the gain curve are nearly equispaced longitudinal modes determined by Eq. (1). We found that seven longitudinal modes satisfied the oscillation condition [9].

The small-signal gain calculation shows that the present FEM experiment is operated in the low-gain Raman regime (i.e., $\bar{\theta}_{p_r} = 8.5 > \pi$). At this regime, the gain and attenuation regions of the two plasma waves, are well separated. The frequency of the mode with the maximum gain agrees with the measured frequency of the free running oscillator.

4. Single-frequency evolution

We investigated whether the FEM oscillator oscillates only in a single mode and at a single frequency, or in many modes at once. The axial cavity mode whose frequency is located closest to the center of the FEM gain curve corresponds to the highest gain, and thus normally will be the one which will emerge from the competition with other modes as the single surviving mode. One factor that may prevent the single-frequency is that not enough time has elapsed during the pulse duration to complete the mode competition process.

A Tektronix fast digitizer oscilloscope with a bandwidth of 0.5 GHz was used to observe a wide frequency range from the output radiation pulse spectrum. The FEM output signal is mixed with a local oscillator signal that is tuned

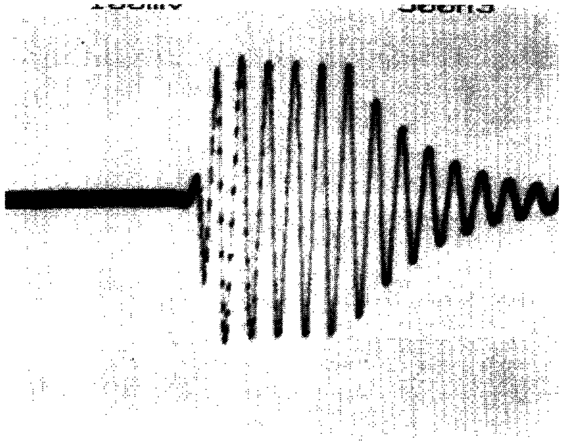

Fig. 2. FEM output signal evolution in time without prebunching the electron beam. Oscilloscope trace is an if-signal at a frequency of 3.75 MH where the local oscillator frequency is 4.539 GHz. The time full range is 5 μs.

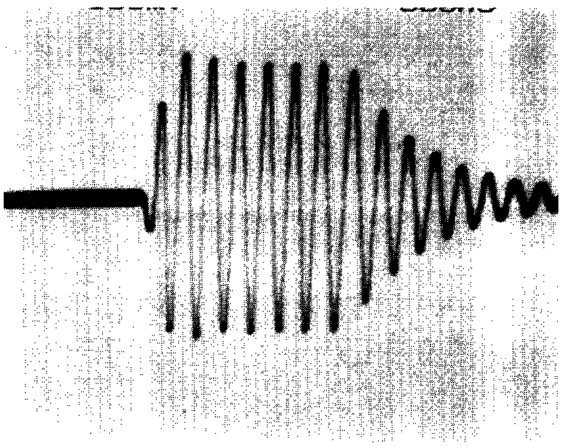

Fig. 3. FEM output signal evolution in time with prebunched electron beam. Trace is an if-signal at a frequency of 3.75 MHz where the local oscillator frequency is 4.539 GHz. The time full range is 5 μs.

to a frequency close to the free running oscillator frequency. The amplitude of the FEM output signal at if frequency as it evolves in time is shown in Fig. 2. The nonlinear competition of at least two axial modes is shown. One can note that single-frequency oscillation is achieved about 800 ns after saturation is reached. This steady-state is attained after a mode competition process, in which the mode that corresponds to the free-running oscillator mode and has the highest linear growth rate is accompanied by at least one adjacent axial mode with relatively small amplitude.

5. The effects of electron beam prebunching

If enough power can be induced into one of the modes (in comparison with the spontaneous power), by prebunching of the electron beam at the frequency of one of the resonator modes, one may interfere in the mode competition process and thus dictate the oscillator eigen-frequency. In Fig. 3 we present the FEM oscillator output (if signal) for the case where the electron beam is prebunched at the frequency of the mode of highest gain. The rf input power to the prebuncher is about 10 mW.

Single mode priming by prebunching of the electron beam enhances the oscillation buildup rate of radiation in the cavity. When oscillation starts from initial spontaneous-emission noise the radiation builds up exponentially and reaches a saturation power level 1200 ns after start of the electron beam current pulse, as shown by traces (1) and (2) of Figs. 1 and 2. As we tune the prebuncher rf frequency of to the free-running oscillator frequency, the oscillation buildup time is shortened significantly. The buildup time in the experiments reported in trace no. (4) of Figs. 1 and 3 and is about 500 ns (for a prebuncher rf input power of 10 mW) [11].

6. Oscillator mode selection

Prebunching of the electron beam can be performed at any frequency in the FEM gain bandwidth. The prebuncher rf frequency was scanned through the net gain bandwidth to demonstrate single frequency locking and mode selection. When the prebunching frequency is close to one of the eigen frequencies of the resonator, we observe single-frequency oscillation. This effect is observed at all resonantor eigen frequencies in the gain bandwidth. Furthermore, the oscillation buildup time shortens significantly relative to the free-running oscillation buildup time. By scanning the buncher rf premodulation frequency, it was found that the prebunched electron beam causes the seven different longitudinal modes to be excited with a spacing of about 100 MHz in agreement with Eq. (2). We noted that even a weak input signal to the prebuncher was sufficient to turn the selected axial mode into the dominant one in the cavity.

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