Efficiency enhancement of free electron Maser oscillator by mode selection with a prebunched electron beam

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We present a method for enhancing the efficiency of a Free Electron Laser Maser oscillator by locking it to a preferred resonator mode. This is done by prebunching of the e beam before injection into the wiggler. In a free running oscillator, the longitudinal mode that dominates the mode competition process during the oscillation buildup period is usually the highest gain mode. However, this mode does not extract the highest energy from the e beam. Lower eigenfrequency modes would provide a higher efficiency if they could dominate the mode competition process. By prebunching the e beam at a frequency near any one of the longitudinal eigenfrequencies of the resonator (having a gain>1), we can make that mode dominant at saturation. The eigenfrequency for which the maximum efficiency is obtained is the lowest eigenfrequency of the resonator for which the net small signal gain is greater than 1. Employing an experimental setup of a prebunched beam Free Electron Maser, we demonstrated efficiency enhancement of 30% for this lowest eigenfrequency mode (as compared to the highest gain mode). Simulation results predict an efficiency enhancement of up to 50%. © *2000 American Institute of Physics.*
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Free Electron Lasers and Masers (FEL, FEM) are inherently highly efficient radiation sources. High energy conversion efficiency is a particularly important feature in electrostatic accelerator FELs. These FELs (FEMs) have the potential to operate at very high average power for such applications as plasma heating in thermonuclear fusion and industrial processes.[1–3] Operation at very high conversion efficiency is a paramount requirement for the realization of such devices and applications. We have demonstrated experimentally a method for significant enhancement of the conversion efficiency of FEM. This method is based on preferential resonator mode selection by means of prebunching the electron beam at the desired mode frequency.[4]

Mode selection either by seed radiation injection or by e-beam modulation (prebunching), have been used before for enhancing the buildup process and for avoiding multimode operation in microwave tubes and in FEMs.[4,5] Here we demonstrate the effectiveness of the mode selection technique for enhancing the radiative energy extraction of the radiation source. Mode selection by e-beam prebunching is preferred, since it can be accomplished without any degradation of the resonator quality.

The eigenmodes of an FEM oscillator, which can normally build up from noise, are the longitudinal modes located under the net gain curve (see Fig. 1). In a waveguide resonator the eigenfrequencies of these modes are apart a free-spectral range (FSR):[4]

$$\Delta f_{\mathrm{FSR}} \cong \frac{\nu_g}{2L_c}, \tag{1}$$

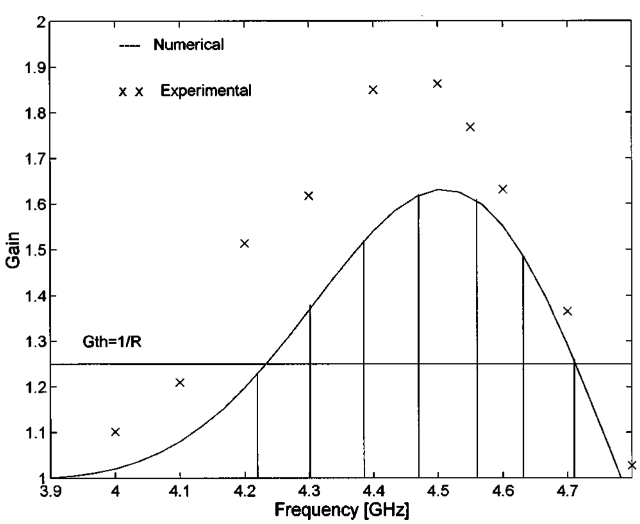

FIG. 1. Five net gain. >1 eigenfrequencies of the TAU FEM oscillator, theoretica gain curve of the FEM (solid line), measured gain curve (marked with ''x'').

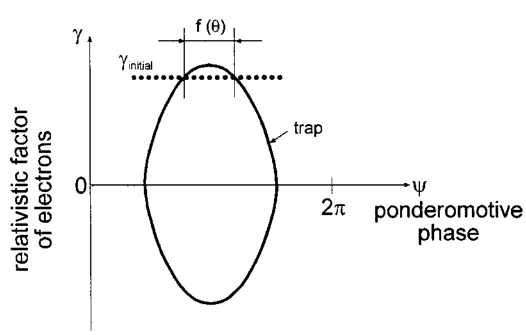

FIG. 2. A description of the trapping fraction $f(\theta)$.

TABLE I. Parameters of the experimental FEM.

Accelerator:	
Electron beam energy	$E_k = 70$ keV
Beam current	$I_0 = 0.9$ A
Wiggler:	
Magnetic induction	$B = 320$ Gauss
Period length	$\lambda_w = 4.44$ cm
Number of periods	$N_w = 17$
Waveguide resonator:	
Rectangular waveguide cavity	2.21 cm×4.75 cm
Mode	TE_{01}
Frequency	4.5 GHz
Resonator length	$L_c = 138$ cm
Output power	$P = 3$ kW

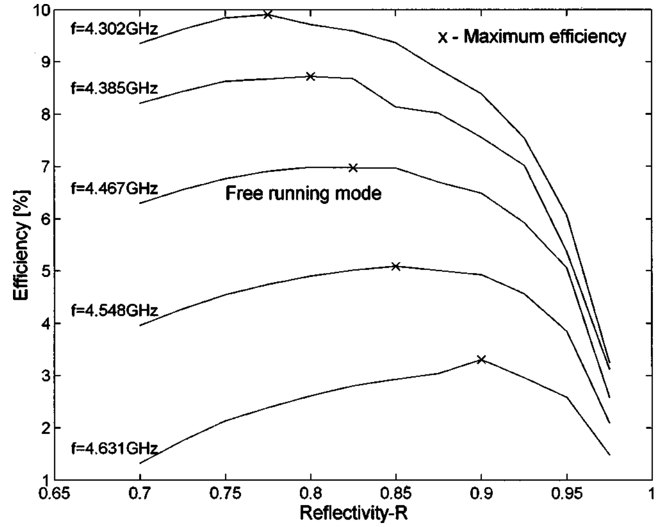

FIG. 3. FEL3D simulation code prediction of efficiency for each of the five net gain>1 eigenfrequencies of our FEM oscillator.

where ν_g is the wave group velocity in the resonator cavity and L_c is the resonator length. The eigenfrequencies compete with each other during the power buildup process as all of them derive their energy from the e beam. The mode having the highest gain, normally wins in the mode competition process, and the gain of the other modes is suppressed in the nonlinear regime and at saturation. By prebunching the e beam at a frequency which is equal to or near to one of the eigenfrequencies of the FEM resonator, we can shorten the time of the oscillation buildup process and cause a desired eigenmode to become dominant at saturation.[4] The radiation energy extraction efficiency η_{ext} is given in terms of the detuning parameter θ by[6]

$$\eta_{\text{ext}} = -\frac{\gamma_0}{\gamma_{z0}-1}\gamma_{z0}^2\beta_{z0}^2\frac{\nu_{z0}}{\omega}\theta\frac{f(\theta)}{2\pi}, \tag{2}$$

where $\theta \equiv \omega/\nu_{z0} - (k_z + k_w)$, $f(\theta)/2\pi$ is the "trapping fraction" (see Fig. 2), γ_0 is the relativistic Lorenz factor, γ_{z0} is the relativistic Lorenz factor in the z direction, $\beta_{z0} = \nu_{z0}/c$, ν_{z0} is the e-beam velocity in the z direction, and c is the speed of light. According to Eq. (2) operation of a FEM oscillator at an eigenfrequency having a large detuning parameter θ results in high extraction efficiency, i.e., large extracted power from the electron beam [as long as the trapping fraction $f(\theta)$ is stile substantial—see Fig. 2]. Locking the oscillator to operation in a low eigenfrequency mode, can be accomplished by e-beam prebunching. Efficiency enhancement in FEM oscillators, by selection of the eigenfrequency with the largest detuning parameter under the net small signal curve was predicted by us previously using the FEL3D simulation code.[7,8]

We applied the FEL3D code to an FEM operating in an oscillator mode for the FEM parameters given in Table I. In order to find the optimal power output that can be extracted from the FEM we ran the code for different values of mirror reflectivity. Simulation results of the predicted efficiency in the prebunched FEM oscillator are shown in Fig. 3. An efficiency enhancement of 50% is predicted by the FEL3D code for the eigenfrequency having the largest θ under the net small signal gain curve (compared to the efficiency at the highest gain eigenfrequency).

A schematic of the prebunched FEM used in our efficiency enhancement experiments is shown in Fig. 4. The e beam is prebunched in a traveling wave tube section[9] operated at 10 kV with an e-beam current of 1.2 A. The frequency and level of prebunching are controlled by the radio-frequency (rf) input signal to the prebuncher. Following the prebunching step the e beam is accelerated to 70 kV, transported in a drift region where it is magnetically confined, and subsequently injected into the interaction region. The interaction region is a rectangular waveguide resonator located on the axis of a planar magnetic wiggler. The prebunched FEM parameters are summarized in Table I. By use of a rf prebuncher frequency close to a desired resonator eigenfrequency, it is possible to assure radiation from the resonator at

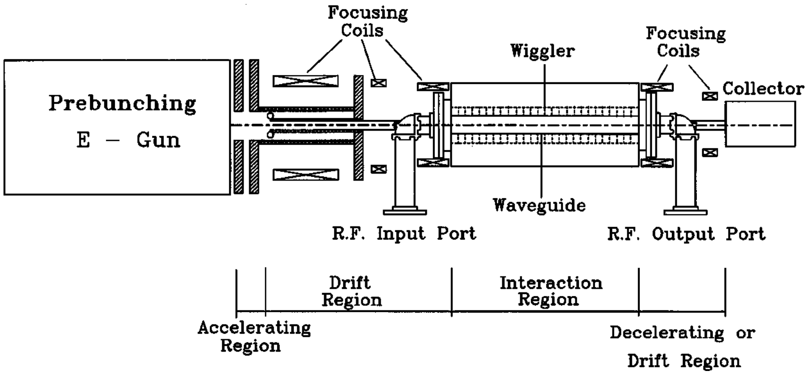

FIG. 4. Schematic of the TAU prebunched beam FEM oscillator experiment.

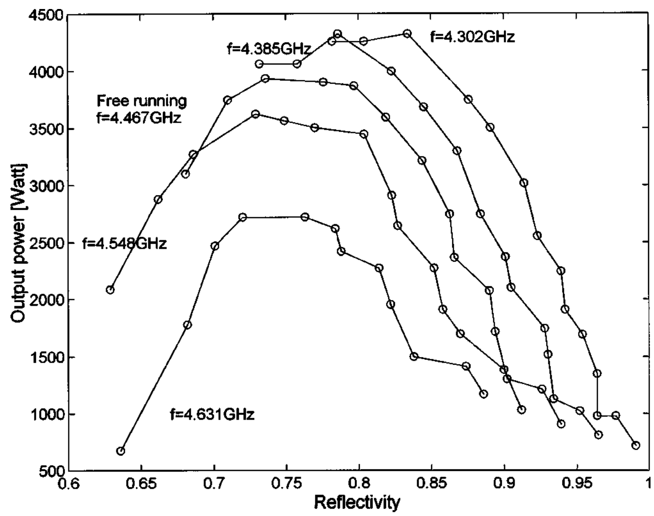

FIG. 5. Experimental results: efficiency for each of the five net gain>1 eigenfrequencies of the FEM oscillator. (The efficiency of the lowest eigenfrequency mode which is made dominant by prebunching is 30% higher than the maximum gain eigenfrequency).

any selected eigenfrequency out of the five eigenmodes of the FEL oscillator whose net gain is greater than 1 (Fig. 1). The prebuncher input power must be high enough to give the desired mode a sufficient head start in the mode competition process. In our FEM one watt of prebuncher input power was sufficient to select any mode and to win the mode competition against the other (possibly higher gain) modes and result in single-mode operation. A diagnostic system sampled the radiation power, that was obtained from the FEM versus frequency. These measurements were made at each of the eigenfrequencies and for different values of reflectivity of the resonator output coupler. The radiation coupled out of the cavity through a hole in a copper plate placed beyond a Teflon window at the end of the resonator waveguide. The reflectivity was changed by use of reflector plates having different central holes. The reflectivity determines the I_0/I_{th} parameter where I_0 is the e-beam direct-current (dc) and I_{th} is the oscillator threshold current for FEM oscillation.[10,11]

Antonsen and Levush[10,11] predicted that optimum efficiency and stable operation are obtained for a certain set of θ and I_0/I_{th} values. Experimentally, the main handle on the FEM parameters is the resonator mirror reflectivity, which determines the Q factor of the resonator and consequently the parameter I_0/I_{th}. Normally the θ parameter cannot be controlled and the oscillator settles at steady state at the parameters of the free running oscillator mode (which is the mode of maximum linear gain for which $-\theta \approx 2.7/L_w$ (L_w is the wiggler length). In our experiment we can vary θ by selecting the mode frequency of operation by prebunching the e beam at that frequency and we can vary I_0/I_{th} by changing the mirror reflectivity.

We adjusted the rf input frequency of the prebuncher to each of the five eigenfrequencies of the FEM resonator shown in Fig. 1. For each eigenfrequency we operated the FEM with various out coupling mirrors having reflectivities from 60% to 95% and measured the out-coupled power from the FEM resonator. The efficiency (the output rf power fraction of the beam power) versus mirror reflectivity that was measured for the eigenfrequencies of the FEM oscillator are shown in Fig. 5. The experimental results show clearly that the highest efficiency is obtained for the lowest eigenfrequency mode ($f = 4.302\,\mathrm{GHz}$) for reflectivities above $\mathcal{R} = 0.8$ (in good agreement with the simulation results). The highest efficiency of the FEM is about 8% for the lowest eigenfrequency of 4.302 GHz; it is about 5.5% for the free running (highest gain) mode of 4.467 GHz. For a mirror reflectivity below $\mathcal{R} = 0.8$ the lowest eigenfrequency did not build up sufficiently due to the high out-coupling loss and the low value of small signal gain of this eigenfrequency.

In conclusion, a method for improving the efficiency of FEM oscillators by at least 30% was demonstrated experimentally by prebunching of the e beam at the eigenfrequency having the largest detuning parameter θ under the net gain curve of the FEM. These results are in good agreement with our theoretical predictions and numerical simulations.

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[1] L. R. Elias, G. Ramian, R. J. Hu, and A. Amir, Phys. Rev. Lett. **57**, 424 (1986).
[2] W. H. Urbanus *et al.* Nucl. Instrum. Methods Phys. Res. A **331**, 231 (1997).
[3] A. Abramovich, Y. Pinhasi, M. Cantor, A. Gover, and Y. M. Yakover, Phys. Rev. Lett. **82**, 5257 (1999).
[4] M. Cohen, A. Eichenbaum, H. Kleinman, D. Chairman, and A. Gover, Phys. Rev. Lett. **74**, 3812 (1995).
[5] R. P. Fischer, A. W. Fliflet, W. M. Manhimer, B. Levush, M. Antonsen, and V. L. Granatstein, Phys. Rev. Lett. **72**, 2395 (1994).
[6] A. Gover and P. Sprangle, IEEE J. Quantum Electron. **QE17**, 1796 (1981).
[7] Y. Pinhasi, M. Cohen, and A. Gover, Int. J. Electron. **78**, 581 (1995).
[8] Y. Pinhasi and A. Gover, Phys. Rev. E **54**, 6774 (1996).
[9] A. Eichenbaum, IEEE Trans. Plasma Sci. **27**, 568 (1999).
[10] T. M. Antonsen and B. Levush, Phys. Rev. Lett. **62**, 1488 (1989).
[11] T. M. Antonsen and B. Levush, Phys. Fluids B **1**, 1097 (1989).