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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

ELSEVIER

Measurements and simulation of the radiation build-up process in a prebunched free-electron maser oscillator

A. Abramovich[a], Y. Pinhasi[a], V. Shterngartz[a], L. Gilutin[a], H. Kleinman[a], A. Eichenbaum[a], I.M. Yakover[a], M. Cohen[a,*], A. Gover[a], B. Levush[b], T.M. Antonsen[b], V.L. Granatstein[b]

[a]*Faculty of Engineering – Physical Electronics, Tel-Aviv University, Ramat Aviv 69978, Israel*
[b]*Institute for Plasma Research, University of Maryland, College Park, MD 20742, USA*

Abstract

Experiments on the radiation build-up process obtained using a prebunched e-beam free-electron maser at Tel-Aviv University (TAU) are compared to results of theoretical studies carried out at TAU and at the University of Maryland (UMD).

Two computer codes were developed and employed for simulation of FEM operation. A non-linear three-dimensional ''amplifier'' code based on a coupled-mode approach was employed for calculations of small-signal gain, extraction efficiency and saturation power. This code (FEM3D) allows simulation of FEL operation taking into account space-charge effects.

The power evolution of several longitudinal modes was also studied numerically using a one-dimensional, multi-frequency simulation code MALT1D; it was also observed in initial experiments.

Numerical calculations of extraction efficiency for the TAU-FEM were made for all resonator eigen-frequencies lying under the FEM net gain curve. It was found that for a constant set of parameters the maximum efficiency is obtained at an eigen-frequency, which differs from the maximum gain frequency. Prebunching of the e-beam provides a unique opportunity to choose any desired oscillator eigen-frequency and thus to select the highest efficiency mode. This makes it possible to obtain efficiency enhancement of the oscillator by a factor of about 2.

1. Introduction

Experimental and theoretical work on free-electron maser (FEM) operating with prebunching [1–5] is under way at Tel Aviv University (TAU). The FEM utilizes a low-energy electron beam, which may be density modulated by a microwave tube. The beam is subsequently accelerated to a mildly relativistic velocity. The FEM can operate in an amplifier or in an oscillator configuration. Pre-modulation of the e-beam enables generation of super-radiant emission in the oscillator cavity at the e-beam bunching frequency. The prebunching enables interference in the oscillator modes competition process and enables selection of longitudinal mode frequencies differing from the free-running frequency (where maximum gain is obtained). The main TAU-FEM parameters are summarized in Table 1.

Table 1
Parameters of the FEM

Accelerator	
Electron beam energy	$E_k = 70$ keV
Beam current	$I_0 = 0.5$–0.8 A
Wiggler	
Magnetic induction	$B_w = 300$–350 G
Period length	$\lambda_w = 4.44$ cm
Number of periods	$N_w = 17$
Waveguide resonator	
Rectangular waveguide	2.215 cm × 4.755 cm
Mode	TE_{01}
Resonator length	$L_c = 130$ cm

Experimental results are compared to numerical simulations obtained by use of non-linear FEL codes. A number of new oscillator dynamic effects where demonstrated; these are also predicted by theory and simulation.

2. The prebunched beam FEM experiment

In the FEM an e-beam obtained from a truncated

* Corresponding author. Tel. +972 3 640 8148, fax +972 3 642 3508, e-mail moshec@eng.tau.ac.il.

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microwave tube (where it can be modulated and prebunched) is accelerated to 70 keV and injected into a magnetostatic planar wiggler [1–5]. The RF cavity is a rectangular waveguide in which the fundamental TE_{01} transverse mode is excited. Higher order modes are at cut-off. The FEM can be configured to operate either as an oscillator (with variable reflectivities R) or as an amplifier (with $R = 0$). The cavity reflection mirror is an aluminum plate with a circular hole in the middle. The hole radius determines the reflection coefficient R.

3. Three-dimensional non-linear FEL simulation code and experimental results

The code FEM3D employed to simulate the FEM operation is a non-linear, single frequency, 3-D code developed at TAU [6,7]. The code is based on modal expansion of the total field in terms of transverse eigenmodes of the waveguide, in which the radiation is excited [7–9]. The interaction of the fields with the e-beam is described by the force equation for the electrons and by a set of excitation equations for the waveguide transverse modes. The model takes into account 3-D effects of the radiation and space-charge fields.

3.1. Small-signal gain

The 3-D amplifier code was used to compare the simulation results with the measured FEM small-signal gain curve of the FEM in an amplifier configuration. In Fig. 1, experimental and numerical calculation results of the small-signal gain vs. frequency are shown. It may be noted that the small-signal gain obtained from the code, shows good agreement with experimental results. The small-signal gain curve shows that a maximum gain of $G \cong 1.63$ is obtained at a frequency of $f_0 \cong 4.5$ GHz. The measured small-signal gain curve is marked with "x". The bandwidth of the gain curve (FWHM) is $\Delta f_{\mathrm{Gain}}/f_0 \cong 10\%$.

The frequencies of the waveguide resonator longitudinal modes are given by:

$$\omega_l = \sqrt{\left(l \frac{\pi c}{L_c}\right)^2 - \omega_c^2}, \qquad (1)$$

where l is the longitudinal mode number, $\omega_c = c\sqrt{(n\pi/a)^2 + (m\pi/b)^2}$ is the cut-off frequency of the waveguide with rectangular cross section ab, and L_c is the length of the resonator. The free spectral range between the modes is given approximately by $\Delta f_{\mathrm{modes}} \cong v_g/2L_c = 80$ MHz, where v_g is the group velocity of the electromagnetic wave. In the oscillator configuration only, longitudinal resonator eigen-modes that have a single-pass gain larger than their round-trip loss will be excited. Fig. 2 shows five longitudinal modes that lie within the gain curve and satisfy the oscillation condition. The longitudinal mode having a resonant frequency nearest to the frequency of maximum gain is expected to win the mode competition process in a free running oscillator.

3.2. Oscillator simulation and the optimal resonator outcoupling

In oscillator simulation, the amplified signal obtained at the end of the FEM amplifier section is reflected back to the FEM input by the feedback mirror having a reflectivity R. The single frequency amplifier code was augmented with a feedback algorithm that simulates the oscillator build-up process (many round trips in succession) by starting with some low initial power P_i circulating in the cavity. We start our simulation with an initial power $P_i = 1$ W which is low enough to assure initial operation in

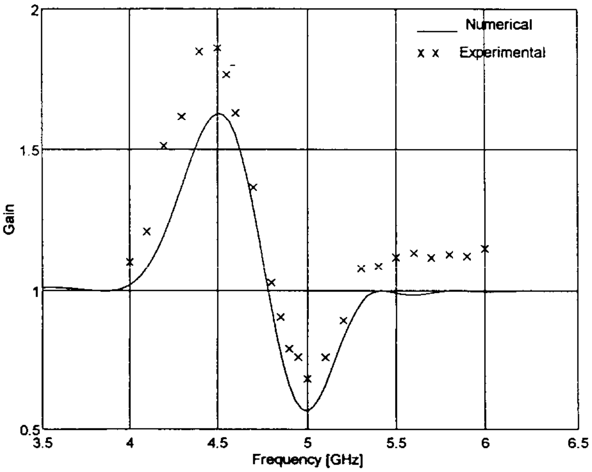

Fig. 1. Small-signal gain curve of the FEM.

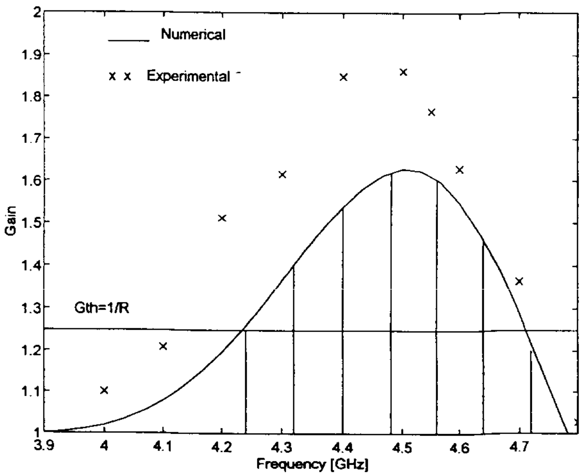

Fig. 2. Eigen-frequencies of the FEM resonator under the gain curve.

the linear gain regime, and high enough to avoid tedious computation in the linear gain regime. We also assume that the longitudinal mode having its eigen-frequency nearest to the maximum gain frequency will win the mode competition process, and survive at steady state. Operating the code with those parameters, we skip the spontaneous emission process and the mode competition process, but presumably arrive at the same steady-state result.

Based on the FEM3D code mentioned above, we studied the power evolution in our FEM operating as an oscillator from the 1 W level up to steady state. Power extraction efficiency vs. reflectivity were also found using this code. The calculated energy extraction efficiency η is given by:

$$\eta = \frac{P_{\mathrm{out}}}{V_{\mathrm{k}} I_0} = (1 - R)\frac{P(L_{\mathrm{w}})}{V_{\mathrm{k}} I_0}, \tag{2}$$

where V_{k} is the accelerating voltage, P_{out} is the output power of the FEM, $P(L_{\mathrm{w}})$ is the power in the resonator at the output end and I_0 is the beam current.

The longitudinal mode competition process is neglected in this code and we assume operation at a single mode, single frequency ($f_0 = 4.48$ GHz), where maximum gain is obtained. A graph of the numerically computed FEM energy extraction efficiency as a function of the round-trip number is shown in Fig. 3 for different mirror reflectivities R. The optimal mirror reflectivity is found to be $R \cong 80\%$ giving a maximum oscillator output power. In that case, the efficiency obtained at steady-state is approximately 7%. The oscillator output power at steady state is shown in Fig. 4 for simulation and experimental results as a function of the round-trip reflectivity. The simulation results are close to the experimental results and the maximum power is obtained in both cases for $R \cong 0.8$.

3.3. The radiation oscillation build-up time

In order to calculate the oscillation buildup time from noise to saturation, an analytical calculation based on exponential growth from spontaneous emission level and up to $P_{\mathrm{i}} = 1$ W (from which we started our simulation) was made. We used the expression for shot-noise power in a waveguide [6] and found that the total spontaneous emission power in our FEM gain bandwidth is $P_{\mathrm{sp}} \cong 0.2$ μW. In order to estimate the noise power in each longitudinal mode, we divided P_{sp} by the total number of longitudinal modes within the small-signal gain bandwidth. Thus, the spontaneous emission power of each mode is $P_{\mathrm{sp}_{\mathrm{mode}}} = 0.025$ μW [9′]. The number of round-trips N_{i} in the resonator until power of $P_{\mathrm{i}} = 1$ W is reached in the linear regime is determined from the small-signal round trip net gain RG according to:

$$N_{\mathrm{i}} = \frac{\log(P_{\mathrm{i}}/p_{\mathrm{sp}_{\mathrm{mode}}})}{\log(RG)}. \tag{3}$$

For the case of optimal coupling $R = 0.8$ and with $G = 1.63$ we found that $N_{\mathrm{i}} \cong 60$ round trips to arrive at power $P_{\mathrm{i}} = 1$ W. According to Fig. 3 an additional $N_2 \cong 40$ round-trips are required to arrive to saturation. The radiation build-up time from noise to saturation is therefore approximately $(N_{\mathrm{i}} + N_2)(2L_{\mathrm{c}})/v_{\mathrm{g}} \cong 1$ μs. Fig. 5 illustrates on a semilog scale the full self-excitation oscillation build-up curve. The analytical calculations are given by the dotted line; it is compared to experimental results and found to be in good agreement.

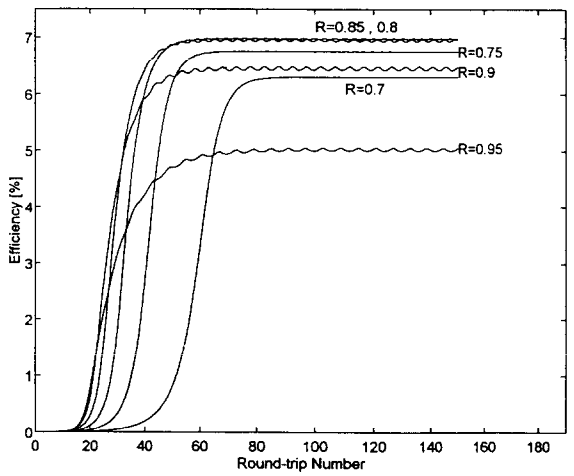

Fig. 3. FEM efficiency as a function of round-trip number for various mirror reflectivities R.

3.4. Enhancement of efficiency by prebunching

The radiation frequency of a free running oscillator at steady state is near the resonance frequency of the longitudinal mode having the highest round trip gain (which is 4.48 GHz in our experiment). This is however, not the

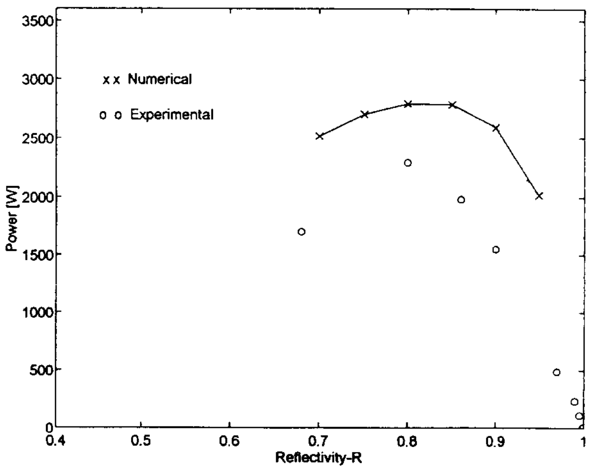

Fig. 4. Steady-state power of the FEM oscillator as a function of mirror reflectivities R.

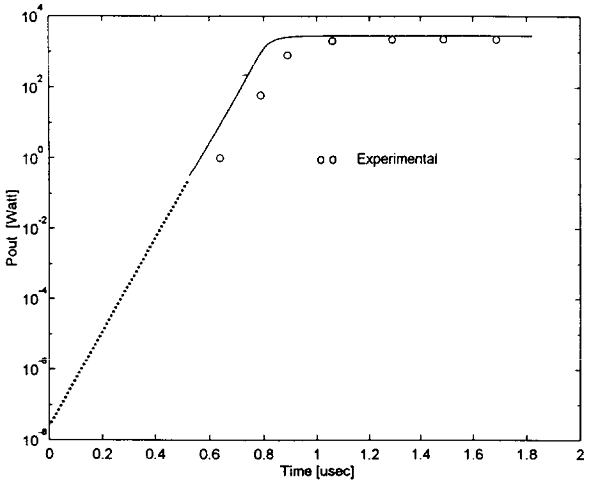

Fig. 5. Curve of power build-up from noise for optical reflectivity $R = 0.8$.

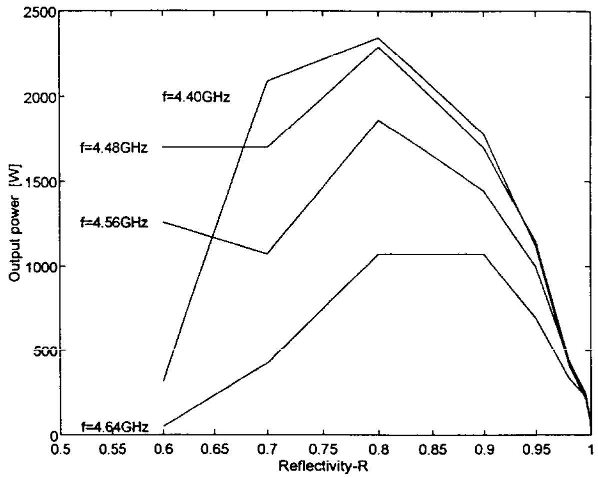

Fig. 7. Output power measurements of the FEM eigen-frequency.

frequency where highest extraction efficiency is obtained [14]. It should be possible to obtain higher efficiency if the oscillator is forced to oscillate at a resonance frequency lower than the frequency of maximum gain, corresponding to a larger gain detuning parameter. That frequency must still be within the small-signal gain curve (Fig. 2) satisfying $RG > 1$. By prebunching of the e-beam we can select a mode having an output frequency of the FEM, which differs from the mode of maximum gain frequency. If we prebunch the e-beam at a eigen-frequency lower than 4.48 GHz, we should get a higher efficiency. Fig. 6 shows simulation of the FEM efficiency for various longitudinal modes of the FEM indicating that the eigen-frequency giving maximum power and efficiency is lower than the eigen-frequency of maximum gain. Preliminary experimental results for several eigenfrequencies are given in Fig. 7. Note that for an eigen-frequency lower than the maximum gain eigen-frequency a higher extraction power is obtained as predicted by the theory. The experimental work on this effect is being refined.

4. Mode competition simulation

Multimode analysis of low gain/pass FEM have been carried out in the past [10–14]. In our work we used a high gain/pass multimode model [15]. Specifically, we employed a recently developed code MALT1D [16]. This code is a one-dimensional multi-longitudinal mode nonlinear code which simulates the mode competition process taking place in FEM oscillators. Fig. 8 shows the results of simulation of temporal power evolution of the longitudinal

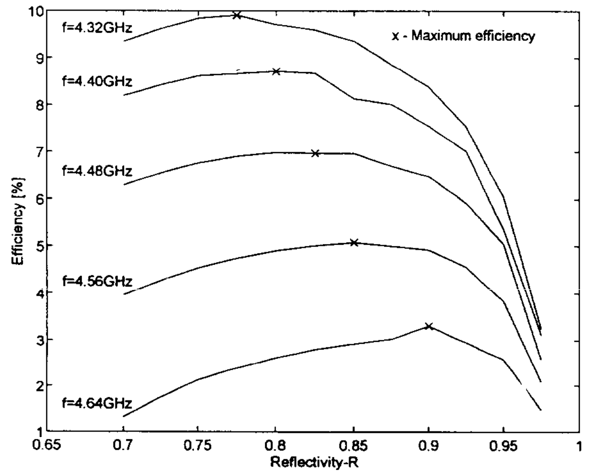

Fig. 6. Efficiency of the FEM for various longitudinal mode frequencies.

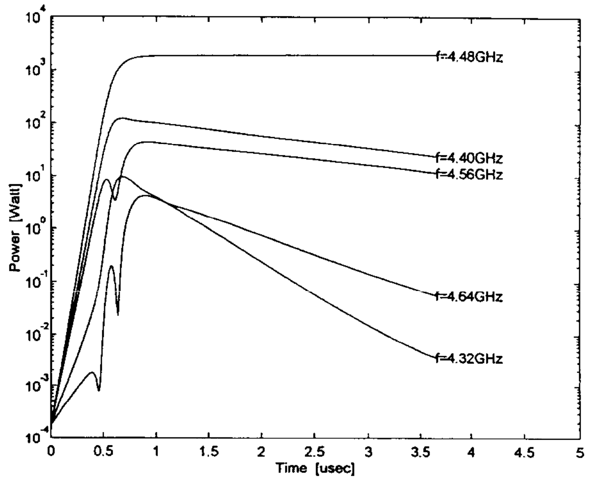

Fig. 8. Results of multi-frequency longitudinal mode-competition simulation.

modes excited in our FEM using that code. The simulation was carried out assuming an optimal mirror reflectivity of $R = 0.8$. Oscillation is established at the longitudinal mode with a resonance frequency (4.48 GHz in our case) nearest the frequency of maximum gain, while the other modes are decaying. Oscillations in several modes are excited and evolve simultaneously up to and beyond the saturation of the dominant longitudinal mode of highest gain at 4.48 GHz. However the power of the two adjacent competing modes (at 4.40 and 4.56 GHz) after saturation of the dominant mode is established is lower by more than an order of magnitude as compared to the dominant mode. The power in modes further removed from the highest gain mode is much lower. Such behavior was found to take place also in traveling wave tube recirculating amplifiers oscillators [17].

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