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Efficiency enhancement of a pre-bunched free-electron maser oscillator by locking to a single eigen frequency of the resonator

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Abstract

We present simulations results and experimental evidence of radiation energy extraction efficiency enhancement by use of pre-bunching in a free electron maser (FEM). This enhancement is attained by locking the oscillator to operate at a distinct resonator eigen frequency (longitudinal mode) which is different from the maximum-gain frequency of the free running oscillator. The mode selection is accomplished by means of pre-bunching at the desired eigen frequency. It was shown that maximum extraction efficiency is obtained if the dominant resonator mode (obtained by pre-bunching at that frequency) is the one having the lowest eigen frequency under the net gain larger than unity curve (which is below the maximum gain eigen-frequency mode that would normally dominate in a free running oscillator). The numerical simulations predict that it should be possible to obtain a basic extraction efficiency enhancement of the oscillator of 50%. Experimental results so far have shown an improvement of about 30%.

Keywords: Eigen frequency; Maser; e-beam

1. Introduction

Selection and operation of oscillators at a desired frequency by using seed radiation or modulation of the e-beam is a well-known technique for enhancing the build-up process and for avoiding multimode operation in microwave tubes and in FEMs [1–4]. Mode locking by pre-bunching is different from seed radiation since no RF radiation is introduced into the FEM cavity. Pre-bunching of the e-beam is preferable over seed radiation injection into the cavity because pre-bunching is unidirectional while insertion of RF seed radiation may cause RF outcoupling from the cavity and thus increases total resonator losses. In a FEM with a resonator there are several longitudinal modes (eigen frequencies) under the net gain larger than one curve competing with each other and deriving their energy from the e-beam, until the mode having the highest gain wins and the growth of other modes is suppressed. Pre-bunching of the e-beam provides a unique handle for interfering in the mode competition process by injecting an e-beam prebunched at a desired eigen frequency of the resonator. This interference can shorten the mode competition process time, in particular if the

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pre-bunching frequency is equal to one of the eigen frequencies of the FEM resonator that satisfy the oscillation condition. On the other hand, the mode competition process can become longer if the pre-bunching frequency is between two eigen frequencies of the FEM resonator that satisfy the oscillation condition [5]. In this work we present a new method of efficiency enhancement by locking the FEM oscillator to an eigen frequency having a large detuning parameter θ, which enables attainment of greater energy extraction from the e-beam [6,7], than that which would be attained if the largest gain eigen frequency prevailed at saturation (as in a free running FEM).

2. Experimental setup

The experimental setup is shown in Fig. 1. The e-beam passes a pre-bunching region which is a traveling wave tube interaction section and enters the FEM interaction region, which is a waveguide resonator located inside of a planar magnetic wiggler. As we reported in a previous publication [3] it is possible to select and make dominant in the resonator, at will, any one of the 5 eigenmodes of the FEL oscillator that have a net gain greater than unity. This is accomplished by choosing an RF-buncher frequency close to the desired resonator eigen frequency, with a bunching RF power input high enough to give the desired mode a sufficient head start in the mode competition process. Several milliwatts of RF input to the buncher were sufficient to select a desired mode and win the mode competition against the other (possibly higher gain) modes. The process always resulted in single mode operation. A radiation diagnostic system described in Fig. 1 was used to sample the power that was obtained in each selected mode and in order to verify its frequency and spectral purity. These measurements were repeated for each mode using various reflectivities of the resonator output coupler. The radiation was coupled out through a hole in a copper plate placed beyond a Teflon window at the end of the resonator waveguide. By using reflectors with different holes we were able to change their reflectivity from 60% to 100%. By changing the reflectivity we controle the I/I_{trh} parameter where, I is the e-beam current and I_{trh} is the oscillator threshold current of the FEM [6,7]. An RF sampler prior to the load provides information on power evolution with time for all modes existing in the resonator.

A power splitter divides the sampled power; part of it is fed to a diode detector and another part to a mixer. The detector output and the IF output of the mixer are monitored and recorded with the aid

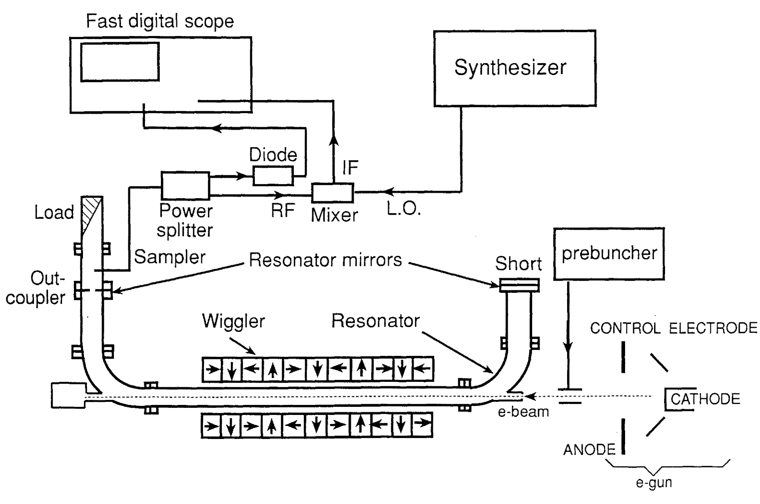

Fig. 1. Experimental setup of the FEM.

Table 1
Parameters of the Mini FEM

Accelerator:	
Electron beam energy	$E_k = 70$ keV
Beam current	$I_0 = 0.9$ A
Wiggler:	
Magnetic induction	$B = 320$ G
Period length	$\lambda_w = 4.44$ cm
Number of periods	$N_w = 17$
Waveguide resonator:	
Rectangular waveguide cavity	2.21 cm $\times$ 4.75 cm
Mode	TE_{01}
Frequency	4.5 GHz
Resonator length	$L_c = 138$ cm
Output power	$P = 3.5$ KW

of a fast digital scope. The fast digital scope has a 1000 MHz bandwidth and a sample rate of 4 Gsample/s. These scope parameters enable simultaneous recording of 5 longitudinal modes (which are the modes that satisfy the oscillation condition [3]); the frequency difference between adjacent modes is about 80 MHz and the net gain greater than unity bandwidth is about 400 MHz [3]. The main operation parameters of the FEM are given in Table 1.

3. Simulations, experimental results and discussion

Simulations of FEM operation were made using the FEL3D code developed in our research group [8,9]. Fig. 2 shows simulation results of efficiency for each of our FEM for the five resonator modes having a net gain greater than one as a function of the reflectivity of the rear reflector. The simulations predict an efficiency of about 10% for an eigen frequency of 4.302 GHz, while the highest gain eigen frequency of 4.466 GHz (which is normally dominant in a free running operation of the FEM) has an expected efficiency below 7%. These results were obtained using the FEL3D code, which was used independently for each of the net gain eigen frequencies of the resonator.

Pre-bunching of the e-beam (see Fig. 1) enables interference in the mode competition process and determines which of the five longitudinal modes of the resonator will become dominant in FEM operation. Fig. 3 shows experimental results of efficiency enhancement due to mode selection by

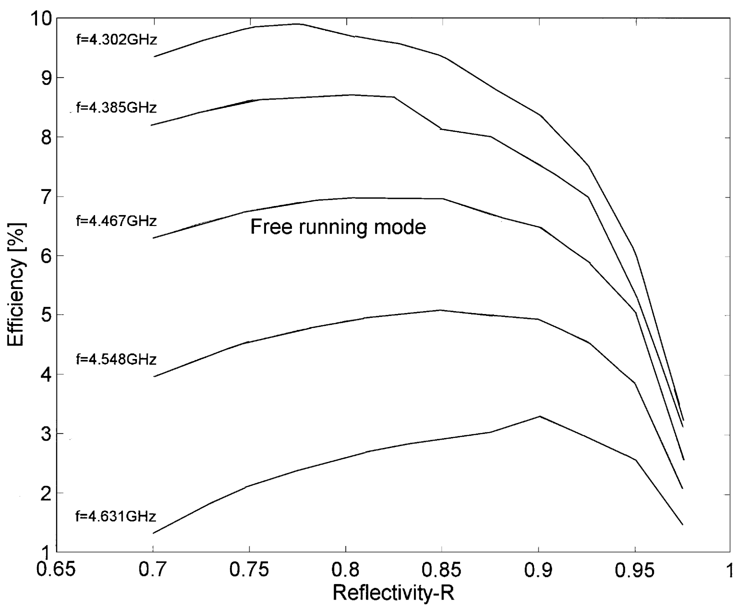

Fig. 2. Simulation prediction of efficiency for the five net gain greater than one eigen frequencies of FEM.

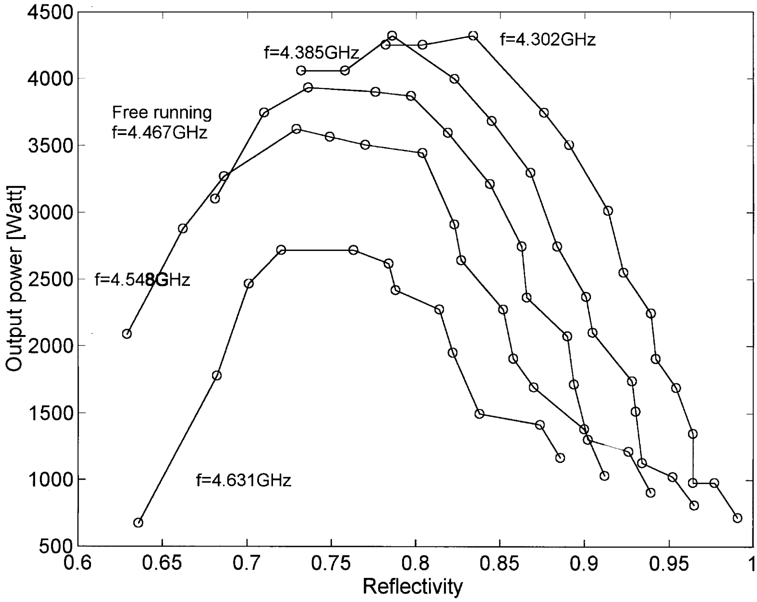

Fig. 3. Experimental obtained efficiency for each of the five eigen frequencies of the FEM having a gain greater than one (modes selected by pre-bunching).

pre-bunching in FEM operation. The experimental results show clearly a higher efficiency for the lowest eigen-frequency mode ($f = 4.302$ GHz) for reflectivities above $R = 0.8$ in good agreement with the simulation results. Under these conditions the efficiency is about 8% for the lowest eigen frequency of 4.302 GHz; it is about 5.5% for the free running mode of 4.467 GHz. For reflectivities below $R = 0.8$ the lowest eigen frequency did not build-up sufficiently, probably due to greater out-coupling loss and a low small signal gain.

In this work we have demonstrated a new method of significant radiation efficiency enhancement of FEMs by mode selection via pre-bunching of the e-beam. The experimental set-up enables us to select the mode with the largest detuning parameter θ (out of the 5 modes having net small signal gain greater than one). Our simulation code FEL3D predicts that this mode will be the most efficient. This prediction was confirmed by our experimental results as given in Fig. 3.

Acknowledgements

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