Nuclear Instruments and Methods in Physics Research A 393 (1997) 361–365

ELSEVIER

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Performance improvement of FEMs by prebunching of the electron beam

A.L. Eichenbaum*, A. Abramovich, M. Arbel, M. Cohen, L. Gilutin, A. Gover, H. Kleinman, Y. Pinhasi, S. Volkovich, I.M. Yakover

Department of Electrical Engineering and Physical Electronics, Faculty of Engineering, Tel-Aviv University, Tel-Aviv 69978, Israel

Abstract

FEM performance enhancement achieved by use of r.f. prebunching of the e-beam in the FEM developed at TAU was investigated theoretically and experimentally.

For FEM operation as an oscillator, use of e-beam prebunching enables stable, coherent, high output power throughout the r.f. output pulse at any selected oscillator eigenfrequency for which the net gain is above unity. Prebunching enables faster r.f. output power buildup. An eigenfrequency of maximum efficiency and power output can be selected by e-beam prebunching at or near that eigenfrequency. FEM efficiency is thus, considerably improved. By contrast, FEM operation without prebunching leads to saturation in the highest gain mode, giving a lower efficiency. Frequency "hopping" of the FEM r.f. output between various eigenfrequencies is also attainable via prebunching.

FEM operation as a high gain amplifier between the premodulator input and the FEM output is reported for our FEM operating with an e-beam current of only 0.6 A. High FEM gain, broad bandwidth, high power operation possibilities at millimeter waves are also described.

1. Introduction

The primary requirements from a FEM/FEL oscillator are high output power, high efficiency, rapid radiated power buildup, radiation frequency coherence and broad band tunability.

High output power is inherent in FEMs because they employ high voltage, high current e-beams in relatively large resonators.

The basic efficiency of most FELs is less than 10%; by use of multistage depressed collectors and by use of phase velocity or electron velocity tapering one can raise the overall efficiency to the 40% region [1]. To raise the efficiency to an even higher level requires an improvement in basic efficiency [2].

Use of e-beam prebunching enables an increase in FEM efficiency, reduces the power buildup time, provides stable, single eigenfrequency radiation [3] and suppresses the build-up of other modes. The radiated eigenfrequency can be set to various eigenfrequencies by "hopping" of the prebunching frequency [4].

FEM amplifiers typically require a high beam current to obtain appreciable gain in pulsed operation [5]. In our FEM we obtained high gain between the prebuncher input port and the FEM amplifier output port using a relatively low beam current of 0.6 A. A prebunched e-beam FEM is proposed as an efficient mm wave, high power, high gain, broadband FEM amplifier.

* Corresponding author.

2. The prebunched e-beam FEM

The table-top, prebunched e-beam FEM operating at TAU is shown schematically in Fig. 1.

The e-beam is derived from the output of a truncated Traveling Wave Tube (TWT) section. If an r.f. signal is applied to the TWT input, it modulates the e-beam. The r.f. power which builds up on the helix is absorbed near the truncated end of the TWT on internal attenuators; a density modulated e-beam exits from the TWT [6]. By choice of TWT input frequency and power level the e-beam modulation frequency and the density modulation depth can be set and varied.

The overall design of the TAU e-beam prebunched FEM system, [7], and its development are described in Refs. [8,9].

Our FEM resonator [10] is a cavity formed of WR-187 waveguide, propagating only the TE_{01} mode in the 3.2–6 GHz frequency range, The e-beam transport

0168-9002/97/17.00
PII S0168-9002(97)00513-5

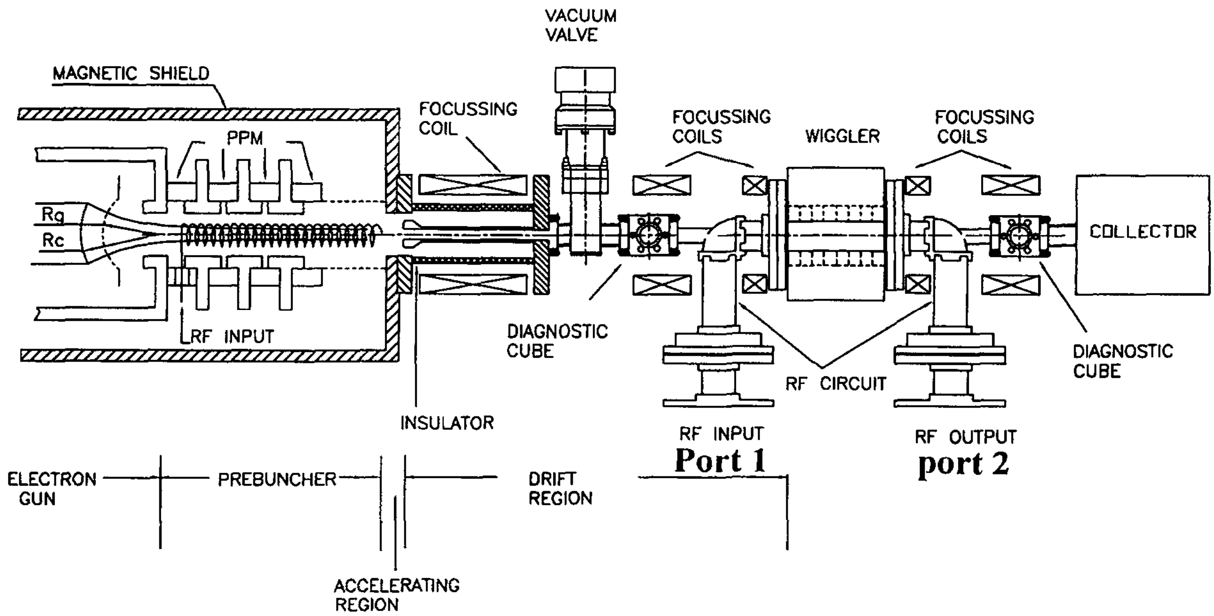

Fig. 1. Schematic of TWT – prebunched FEM.

through the FEM is described in Ref. [9] and in our companion paper [11]. The FEM amplifier (Fig. 1) is operated with a r.f. signal fed into port 1; the amplified signal is obtained at a matched load terminating output port 2. For high-gain FEM operation the input signal is fed to the traveling wave prebuncher input; the amplified signal is obtained at the FEM output port 2.

3. FEM operation as an oscillator (without prebunching)

In the oscillator configuration port 1 is closed by a metal reflecting plate; port 2 is vacuum-sealed by a teflon plate and a metal plate with a round hole in the center is placed adjacent to its permitting r.f. outcoupling. The reflection coefficient R is varied by choice of reflecting plates with different outcoupling holes.

For our waveguide resonator of length L_c operating in the TE_{01} mode (cutoff frequency ω_c) the longitudinal eigenfrequencies ω_l are given by

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

where c is the speed of light, and l is the longitudinal mode number.

For resonator waveguide dimensions are per Table 1 we obtained an intermode free spectral range of

$$\Delta f_{\text{modes}} \cong v_g/2L_c \cong 80\ \text{MHz}, \tag{2}$$

where v_g is the wave group velocity.

A non-linear 3-D code developed at TAU [12,13] was used to predict the behavior of our FEM under conditions of Table 1. Fig. 2 shows the simulation and measured results for small signal gain and the eigenfrequencies as per Eq. (1). The use of the code also correctly predicted the oscillator behavior at saturation. For a reflection coefficient $R = 0.8$ the calculated optimal efficiency without prebunching was 7% for the highest gain eigenfrequency $f = 4.48$ GHz; the calculated maximum power output was 3 kW [14]; these are in good agreement with measurements.

Five eigenfrequencies build up in our FEM as a free running oscillator for $R = 0.8$. The mode evolution and nonlinear mode competition with time was studied with the aid of the multilongitudinal mode MALT 1D code [15].

Simulations showed that the highest gain mode, reaches saturation first and nonlinearly suppresses the buildup of other modes.

Table 1
Set of TAU FEM operating parameters

e-Beam energy	$V_0 = 70$ keV
DC beam current	$I_0 = 0.6$ A
Wiggler period	$\lambda_w = 4.44$ cm
Wiggler length	$L_w = 0.7548$ m
Wiggler field	$B_w = 300$ G
Beam diameter	$d_{\text{beam}} \approx 6$ mm
Waveguide cross-section	$a = 4.755$ cm, $b = 2.215$ cm
Resonator length	$L_c = 1.3$ m

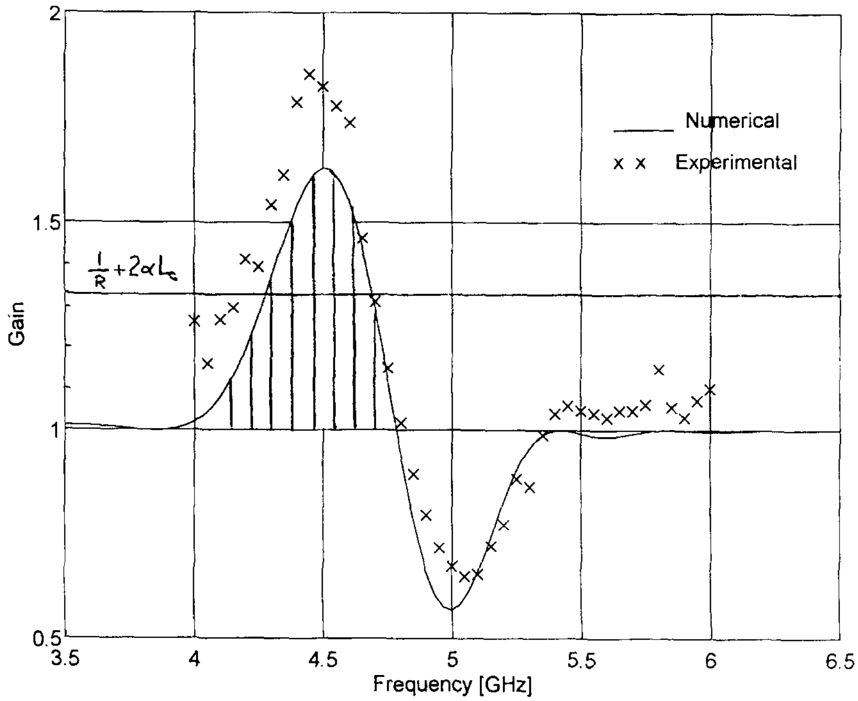

Fig. 2. Small signal gain and eigenfrequencies of gain larger than threshold gain.

If the two highest gain eigenfrequencies are equally spaced on either side of the frequency of maximum gain, the buildup rate of these two modes up to saturation was found experimentally to be nearly equal (neither mode predominates in the competition process and the saturated output power is nearly equally divided in these two modes throughout the radiated pulse duration).

4. FEM oscillator (with e-beam prebunching)

The initial noise power in each mode of our FEM under conditions of Table 1 was estimated to be 0.025 mW [12]. By prebunching of the electron beam at any of the eigenfrequencies ω_i for which the gain is

$$\mathrm{Gain}_i > 1/R_i + \mathrm{Loss}_i \tag{3}$$

we greatly increase the power in that mode and, thus, make it the dominant mode reaching high power saturation [3] much more quickly than other modes. By prebunching at any ω_i at a sufficiently strong power level we:

- operate at one of the five eigenfrequencies satisfying Eq. (3) above, obtaining single mode operation in the detuning range $0 < |\bar{\theta}| < 2\pi$, where $\bar{\theta}$

$$\bar{\theta} = \left(\frac{\omega_i}{v_z} - k_2 - k_w\right) \cdot L_w; \tag{4}$$

- shorten the buildup time considerably. Strong prebunching reduced the time to reach saturation from 1.25 μs to about 0.25 μs.

The mode that dominates at saturation *without prebunching* is the mode of highest gain, lying close to $\bar{\theta} = -2.7$. According to Ref. [16] optimum efficiency of the FEM is obtained for $\bar{\theta} = -5.14$ and for $I/I_{\text{threshold}} \approx 3$, in which case electrons at saturation execute $\frac{1}{2}$ a synchrotron oscillation cycle in the ponderomotive well, falling from maximum energy to minimum energy during one pass through the resonator. The large $\bar{\theta}$ detuning value makes the energy fall proportionally large.

By use of various prebunching frequencies we varied $\bar{\theta}$ nearly over the whole $0 < |\bar{\theta}| < 2\pi$ range. By use of shorting plates with differing outcoupling holes at port 2 of Fig. 1, we varied R ($0.6 \leqslant R \leqslant 0.95$). Our nonlinear 3-D code predicts best efficiency of 10% for $R = 0.775$ and for $\bar{\theta} = -5.6$ [14] The optimal efficiency found experimentally was indeed for $R = 0.775$ but an efficiency of 7% was maintained in going from $\bar{\theta} = -2.7$ to -5.0 (see Fig. 4).

After improvement of e-beam transport [11], we shall again attempt to find the optimum efficiency conditions

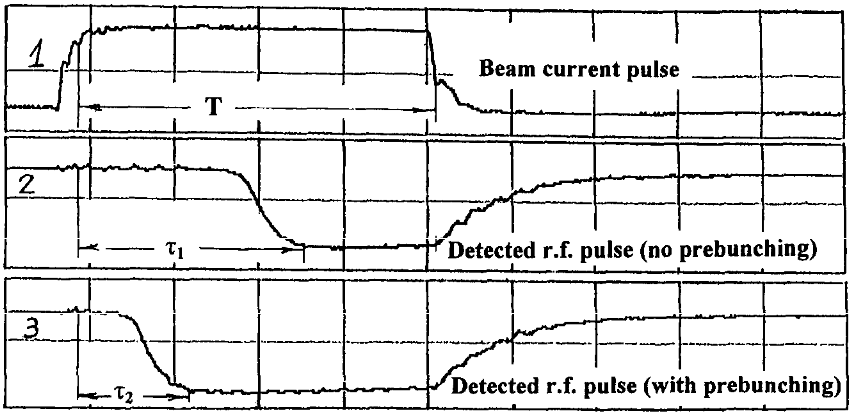

Fig. 3. Beam current pulse and radiated energy pulse (time scale is 0.5 μs/division): 1. beam current pulse, 2. detected r.f. power pulse (no prebunching) and 3. detected r.f. power pulse (with prebunching).

experimentally by operating at various $\bar{\theta}$, R values and at various prebunching frequencies and power levels.

5. Energy efficiency improvement due to prebunching in pulsed FEMs

In a CW coherent oscillator the basic device efficiency η_b can be defined by

$$\eta_b = \frac{P_{em}}{P_{dc}}. \tag{5}$$

Here P_{em} is electromagnetic output power and P_{DC} is the input DC power (mainly beam power $I_0 V_0$).

For pulsed devices in which the radiated power buildup time τ is an appreciable fraction of the current pulse time T *an energy efficiency* concept is more appropriate.

The frequency purity aspect is even more important; simulations and experiments indicate [16] that single mode establishment time can be as large as the current pulse time (in some cases hundreds of microseconds). Therefore, for pulsed devices it is appropriate to speak of energy conversion efficiency η'_{be} defined by

$$\eta'_{be} = \frac{\int_0^T \left[\int_{f_0-\Delta f/2}^{f_0+\Delta f/2} P'_{em}\,\mathrm{d}f \right] \mathrm{d}t}{\int_0^T P_{DC}\,\mathrm{d}t} \tag{6}$$

Here P'_{em} is the spectral output power density and Δf is the bandwidth of interest around f_0, T is the duration of the e-beam pulse current. Fig. 3 illustrates the time dependence of the current pulse and of the radiated output power; τ is the radiation power buildup time up to saturation. The time τ, or number of roundtrips N, required in the resonator to reach saturation depends on the initial power level in the resonator [14] which is due to noise (for τ_1) or to prebunching radiation (for τ_2) in Fig. 3. If after $t = \tau$ the saturated output power is constant and is within the desired Δf bandwidth, the energy conversion efficiency η_{be} is given by

$$\eta_{be} = \frac{P_{em}(T-\tau)}{P_{DC} \cdot T} = \eta_b \left(1 - \frac{\tau}{T}\right). \tag{7}$$

Use of strong prebunching greatly reduces τ and concentrates P'_{em} around f_0. The "energy conversion efficiency" for our FEM (using 2 μs current pulses) was, thus, improved by a factor of 3.

The advantages of prebunching may be summarized as follows:

1. It enables operation at a desired detuning value (near $\bar{\theta} = -5$) and at a selected single eigenfrequency, leading to optimum power efficiency (Fig. 4).

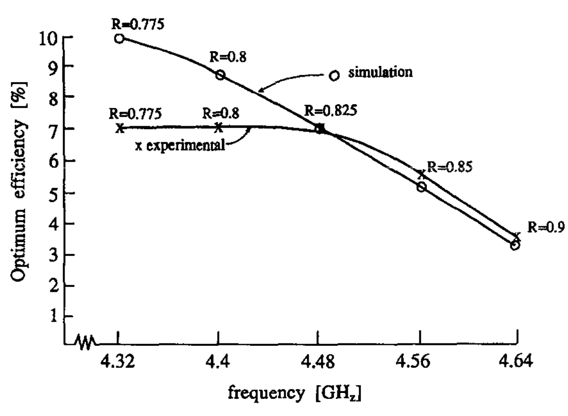

Fig. 4. Measured and calculated maximum efficiency of prebunched FEM versus eigenfrequency (or θ) [the reflection coefficient is optimized for each frequency].

2. The radiated pulse duration $T - \tau$ is only slightly shorter than the beam pulse duration T, improving the basic energy efficiency.
3. It enables attainment of a high spectral power density near the desired output frequency, increasing the "useful output energy efficiency".

As pointed out by Kosmahl [2] the highest device efficiency (using a multistage depressed collector) is obtained only if the basic efficiency is high. The prebunched FEM is, therefore, a candidate for attainment of high overall efficiency.

6. Prebunched FEM as a high gain amplifier and a frequency agile power source

A gain of 14 db between the TWT input port and the output port 2 (Fig. 1) of the FEM was measured near 4.5 GHz. The use of a high gain TWT prebuncher can increase the overall hybrid prebuncher–FEM gain to the 50 db range. This can result in a high gain, high power device in which the high gain and modulation possibilities are provided by the low voltage TWT prebuncher and the high power is provided by the high voltage FEM interaction section (a power booster). The combination of a wide band, high gain TWT premodulator with a broadband FEM interaction structure, based on a non-dispersive transmission line [17] may enable the development of an efficient, broadband, high gain, power amplifier for mm waves. The modulation and frequency agility capabilities of such a prebunched FEM were described [4]. Research on modulation possibilities, mode competition and efficiency studies in prebunched FEMs are continuing.

Acknowledgements

The authors wish to express their appreciation to Mr. M. Draznin, Mr. A. Kugel and Mr. David Ben-Chaim for their contributions in the design and development of the TAU FEM.

References

[1] W.H. Urbanus, R.W.B. Best, W.A. Bongers, A.H. van Inden, P. Manintvelt, A.S. Sterk, A.G.A. Verhoeven, M.J. van der Wield, M. Caplan, V.B. Bratman, G.G. Denisov, A.A. Varfolomeev, A.S. Khlebnikov, Nucl. Instr. Meth. Phys. Res. A 331 (1993) 235.

[2] H.G. Kosmahl, Proc. IEEE 70, (1982) 1325.

[3] M. Cohen, A.L. Eichenbaum, M. Arbel, D. Ben-Chaim, H. Kleinman, M. Draznin, A. Kugel, I.M. Yakover, A. Gover, Phys. Rev. Lett. 74 (1995) 3812.

[4] A.L. Eichenbaum, M. Cohen, H. Kleinman, D. Ben-Chaim, A. Kugel, D. Chairman, I. Ronin, M. Arbel, M. Draznin, Y. Pinhasi, I.M. Yakover, A. Gover, A novel free electron maser as a high power microwave source of sophisticated signals, in: Proc. 18th National Conv. of IEEE in Israel, 95th 8044 (1995) 4.4.4.

[5] D.E. Pershing, R.D. Seeley, R.H. Jackson, H.P. Freund, Amplifier performance of the NRL Ubitron, 16th Int. FEL Conf., Stanford, 1994.

[6] A.L. Eichenbaum, Proposed use of a TWT prebuncher for a FEM, TAU Research proposal, 1990.

[7] A. Eichenbaum, H. Kleinman, M. Cohen, Mini FEL for the study of microwave radiation from r.f. prebunched electron beams' Mini-Symp. on FEL, FOM Institute, The NETHERLANDS, 1991, pp. 20–24.

[8] M. Arbel, Electron optics for a FEL, TAU Master Thesis, 1995.

[9] M. Cohen, An analysis of a prebunched beam free electron laser, Ph.D. thesis, Tel-Aviv University, 1995.

[10] D. Ben-Chaim, A microwave system for a free-electron masers, M.Sc. thesis, Tel-Aviv University, 1994.

[11] A. Abramovich, M. Arbel, L. Gilutin, H. Klienman, A.L. Eichenbaum, I.M. Yakover, Y. Pinhasi, A. Gover, these Proceedings (18th Free Electron Laser Conf., Rome, Italy, 1996) Nucl. Instr. and Meth. A 393 (1997) 419.

[12] Y. Pinhasi, Analysis of super-radiance effects and of transverse mode excitation and coupling in FELs, Ph.D. thesis, Tel-Aviv University, 1995.

[13] Y. Pinhasi, A. Gover, Three-dimensional coupled-mode theory for FEL in the collective regime, Phys. Rev. E 51 (1995) 2472.

[14] A. Abramovich, Y. Pinhasi, V. Shterngratz, L. Gilutin, H. Kleinman, A.L. Eichenbaum, I.M. Yakover, M. Cohen, A. Gover, B. Lavush, T.M. Antonsen, V.L. Granatstein, Nucl. Instr. and Meth. A 375 (1996) 164.

[15] T.M. Antonsen, M. Caplan, B. Levush, V.L. Granatstein MALT-ID multilongitudinal mode code for simulation of power buildup in FEL, private communication.

[16] T.A. Antonson, Jr., B. Levush, Mode competition and control in FEL oscillators, Phys. Rev. Lett. 62 (13) (1989) 1488.

[17] I.M. Yakover, Y. Pinhasi, A. Gover, Theoretical investigation of a FEM operating with a TEM transmission line, IEEE Trans. on Microwave Theory and Techniques, 44 (4) (1996) 607.