Lasing and radiation-mode dynamics in a Van de Graaff accelerator–free-electron laser with an internal cavity

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(Received 15 July 1997; accepted for publication 30 October 1997)

The lasing of a Van de Graaff electrostatic accelerator–free-electron laser (EA–FEL) with an internal cavity is reported. An EA–FEL employing an internal cavity is a FEL configuration that has a potential to operate at high average power, high frequency, and possibly in a continuous wave (cw) mode. The initial lasing provided a pulsed radiation power of 1 kW at 100.5 GHz frequency. The FEL operated with a 1.4 A, 1.4 MeV electron beam in a recirculation (depressed collector) configuration. It utilizes a high quality ($Q \approx 30\,000$) Talbot effect resonator and a Halbach-type wiggler placed internally in the center of the accelerator tank. Nonlinear features of the oscillation power buildup and decay near saturation and mode hopping were observed and are interpreted. © *1997 American Institute of Physics.* [S0003-6951(97)03952-1]

We report a demonstration of lasing in a tandem Van de Graaff electrostatic accelerator–free-electron laser (EA–FEL) with an internal cavity located at the high-voltage terminal.

The basic structure of the FEL is shown schematically in Fig. 1. The wiggler and the mm-wave resonator are placed in the high-voltage (HV) terminal located at the center of a pressurized insulating gas tank of a tandem Van de Graaff machine. The terminal can be charged to a high-voltage (1–5 MeV) positive potential by means of mechanical transport of static charge by use of rotating belts (symbolically represented in Fig. 1 by current source I_{ch}). Such a structure forms an electrostatic field, which constitutes a conservative system for electrons. Electrons that are injected into the accelerator and transported along the beam line, which includes acceleration, drift, and deceleration sections, exit the beam line with the same kinetic energy in which they are injected. When stimulated emission takes place in the FEL resonator, the electron beam may lose a substantial fraction of its energy by emitting thousands of photons per electron into the radiation field of the resonator.[1] With proper design of the oscillator, the energy, lost in the stimulated emission process, is lower than the initial kinetic energy of the injected electrons, and then the beam still has enough kinetic energy to exit the system after the deceleration section. The energy lost by the e-beam in favor of the radiation field is replenished by the external power supply V_{gun}, and only a small fraction of the beam energy is converted into heat at the collector.

This configuration, based on use of a ''depressed collector'' automatically contains an energy retrieval scheme, which makes the EA–FEL highly efficient. In conventional rf accelerator FELs most of the kinetic energy left in the e-beam after interaction is wasted at a beam dump; energy retrieval schemes are not efficient in such FELs.[1] In an EA–FEL this energy is retrieved from the electrostatic potential energy of electrons in the deceleration field.

The first lasing in an electrostatic accelerator FEL was demonstrated at the University of California Santa Barbara (UCSB).[2] Their EA–FEL operates until now intensively as a user facility, covering the entire infrared to mm-wavelength regimes. However, the UCSB EA–FEL operates with an external cavity configuration, i.e., the electron gun and the collector with their power supplies and associated electronics are placed at the *negatively* charged HV terminal of the pressurized insulating gas tank; the wiggler and the optical resonator are located externally at ground potential. The external cavity configuration has the advantage of easy access to the wiggler and to the resonator. It also has, however, major disadvantages: limitations on the provision of electric power to the terminal, which confines the device to low average power operation. Also, negatively charged electrostatic accelerators cannot operate at high voltage, and therefore, cannot be utilized for development of high-frequency FELs.

It is therefore well recognized now that in order to attain lasing at high average powers, and high frequencies, it is desirable to develop an *internal cavity* EA–FEL with a positively charged HV terminal and a straight electron–optical configuration, as shown in Fig. 1. Only by use of such a configuration can EA–FELs have the potential to radiate average power levels of the order of megawatts. They may, thus, find important applications in industrial processing, tokamak plasma heating, etc.[3] This configuration is, probably, also preferable for realizing the potential for cw operation of an FEL with extremely high coherence.[4]

Development of internal cavity EA-FELs is in progress in a number of laboratories, including UCSB;[5] CREOL, University of S. Florida;[6] FOM, the Netherlands;[7] and KAERI,

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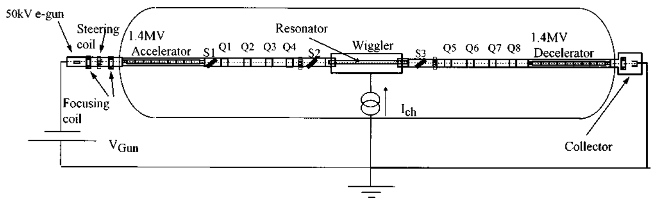

FIG. 1. Schematic illustration of the Israeli electrostatic accelerator–free-electron laser.

S. Korea.[8] The Dutch project is aimed towards attainment of a record level radiation power (1 MW cw) at 1–2 mm wavelengths for plasma heating applications.[7] The Korean project recently demonstrated laser action with a low potential Cockcroft–Walton accelerator with open air insulation ($V=430$ kV, $\lambda=10$ mm).[8]

Our EA-FEL is based on a converted 6 MeV tandem Van de Graaff ion accelerator.[9,10] The ion source was replaced by an electron injection system using a 50 kV parallel flow Pierce-type e-gun followed by focusing and steering coils (see Fig. 1). The parallel flow electron gun produces a high-quality electron beam. In a pepper-pot experiment we measured that the injector e-beam has a normalized emittance of $\epsilon_n \leqslant 10\pi$ mm mrad.[10]

The permanent magnet wiggler is arranged in a Halbach planar configuration;[11] it has the following basic parameters: magnetic induction $B_w=2$ kGs, period length $\lambda_w=4.44$ cm, and the interaction length 88.9 cm (20 periods). Two long magnets were used, one on each side of the wiggler to focus the e-beam in the lateral (wiggling) plane by means of a lateral magnetic-field gradient, which they produce on the wiggler axis.[12] The rf resonator utilizes curved parallel plates as a waveguide structure and has two quasioptical Talbot effect reflectors (wave splitters), one at each resonator end, which enable e-beam passage into and out of the resonator.[7,13] This type of resonator is characterized by very small Ohmic and radiation losses of about 8%, as determined by loss measurements[13] prior to the installation of the resonator in the HV terminal.

To attain the goal of cw operation in an EA-FEL one must satisfy the condition of zero net discharge of the HV terminal:

$$I_{\mathrm{ch}}=I_{\mathrm{leak}}=I_0(1-\eta), \tag{1}$$

where I_{leak} is the leakage current of the electron beam to the terminal and the acceleration tubes, I_0 is the electron-beam current, and η is the transport efficiency of the electron beam from the e gun to the collector.

If this condition is not satisfied, the terminal voltage drops in accordance to the net discharge rate and the capacitance C of the terminal relative to the tank walls:

$$\frac{dV}{dt}=-(I_{\mathrm{leak}}-I_{\mathrm{ch}})/C. \tag{2}$$

The FEL is, therefore, limited to operate in a pulsed energy mode, where the pulse duration is short enough to avoid excessive terminal voltage droop, which diminishes the gain of the electromagnetic mode excited in the cavity below the round-trip loss level of the resonator. A rough estimate for this allowed voltage droop ΔV (for the case of low losses) is half the voltage bandwidth of the gain curve

$$\Delta V=V_0/4N_w, \tag{3}$$

where V_0 is the terminal voltage and N_w is the number of wiggler periods.

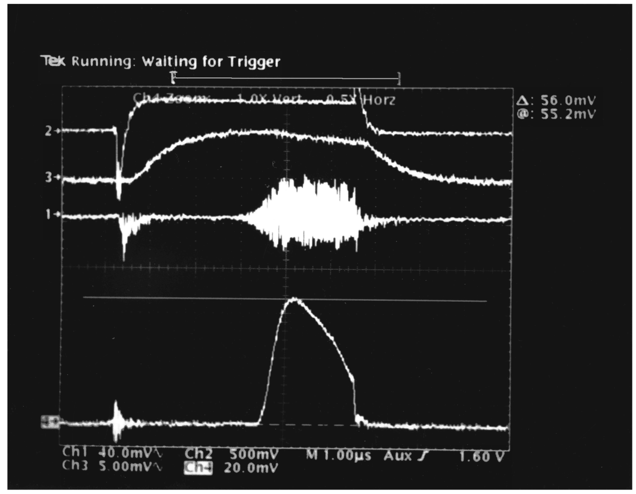

FIG. 2. Radiation measurement results: (1), signal obtained from the IF output of the mixer; (2), e-beam current pulse at the cathode; (3), e-beam current measured at the exit of the wiggler; and (4), radiated power.

For the parameters of our experiment: $I_0=1.4$ A, $I_{\mathrm{ch}}=225$ μA, we obtain from Eq. (1) $\eta_{\mathrm{cw}}=99.98\%$. In the initial experiments, we did not obtain such a high transport efficiency. Hence, the EA-FEL was operated in a pulsed mode by providing pulses to a control electrode of the e-gun, which produced 5 μs e-beam current pulses.

Figure 3 displays the e-beam and radiation pulse traces recorded in the initial experiments. The radiation pulse duration is 2 μs, and its peak corresponds to about 1.1 kW of output power radiated from the FEL cavity. The FEL radiation frequency was determined by heterodyning part of the FEL radiation power with a local oscillator (LO) signal in a mm-wave mixer. Trace 1 is the intermediate frequency (IF) output signal from the mixer corresponding to a LO frequency of 100.55 GHz. The IF frequency, determined from this trace (about 20 MHz), finds the radiation frequency at 100.55±02 GHz.

Important information concerning the TAU FEL performances was obtained by analyzing the rising and the decaying portions of the detected radiation pulses (trace 4 of Fig. 3). The radiation decay time found from Fig. 3 is $\tau_c \approx 50$ ns, corresponding to a loaded Q factor of $Q=2\pi\tau_c f \approx 30\,000$. The total round-trip losses are, thus, estimated to be $1-R=2\pi L_c/\lambda Q=0.09$, where R is the equivalent round-trip power reflectivity of the resonator, and λ is the radiation wavelength. This loss level is close to the loss obtained from cold measurements of the resonator.[13]

Analysis of the initial rising part of trace 4 in Fig. 2 gives an estimate of the single path FEL gain value $G=1.18$. This is an underestimated value of the small-signal gain since nonlinear effects are already prevalent in that portion of the detected pulse, reducing the gain at the measured power level. The dynamic range of the detector was not large enough to measure the gain at lower power levels corre-

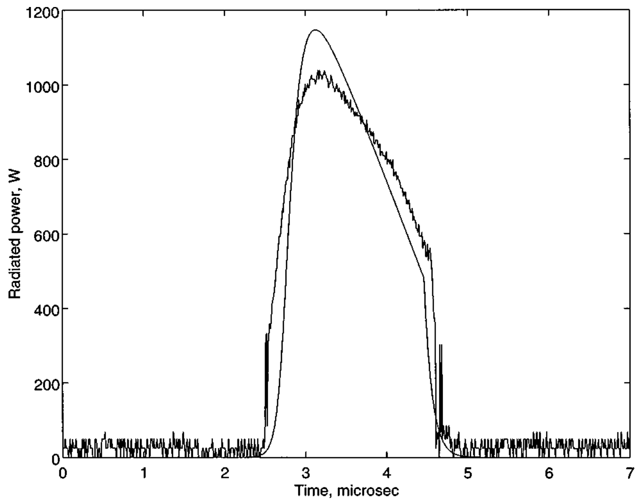

FIG. 3. Comparison of experimental and theoretical results.

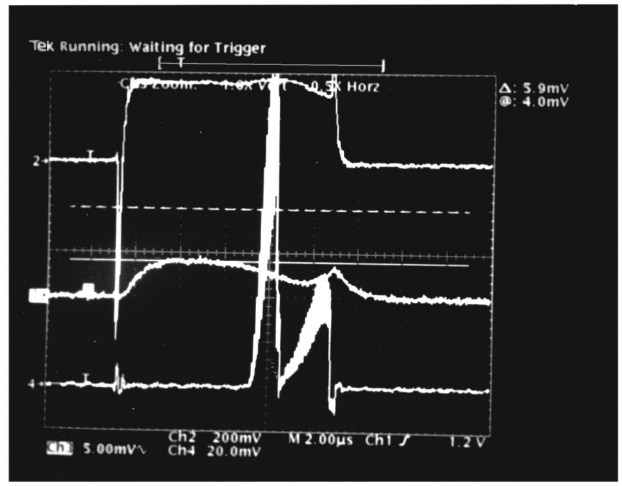

FIG. 4. Effect of mode hopping.

sponding to the linear regime. Consequently, we conclude that the small-signal differential gain G_0-1 exceeds the estimate $G-1=18\%$.

One can note from trace 4 of Fig. 2 that our FEL does not reach steady-state operation and that the radiated power decay begins long before the e-beam current interrupts. The reason for this effect is that the HV terminal voltage droops because of interception of electrons by apertures of an e-beam transport line. The droop in the voltage of the terminal (and resonator) reduces the gain per pass in the resonator continuously until that gain equals the resonator losses (at which point no net gain is obtained). The power output gradually reduces as the gain becomes even lower than the losses, and, thus, the maximum power output does not correspond to saturation. For our experimental parameters, Eq. (3) gives an allowed voltage drop of about 17.5 kV until the net gain diminishes to zero. The value of the measured voltage droop rate is 9 kV/μs; a voltage drop of 17.5 kV, therefore, corresponds to a pulse duration of 2 μs, which is in good agreement with the experiment.

In order to confirm our interpretation for the mode decay dynamics, we applied our FEL simulation code FEL 3D,[14] which is based on a modal expansion of the total fields (radiation and space charge) in terms of transverse eigenmodes of a waveguide.[15] This code was modified to update the beam energy after every round-trip traversal of the wave in the resonator in accordance with the measured voltage droop. Numerical results, obtained for a beam current of 200 mA transported through the resonator and a starting terminal voltage of 1.425 MV with the measured voltage droop of 9 kV/μs and a resonator quality factor of $Q=30\,000$, simulate well the experimental results, as shown in Fig. 3 (the time is counted from the e-beam pulse start).

For some e-beam pulses, for which the starting voltage and the e-beam current passing through the resonator were smaller than those of Fig. 2, an effect of mode hopping was observed, in which a lower-frequency resonator eigenmode was excited after the initial mode was suppressed [see Fig. 4]. This mode transition process was confirmed qualitatively by the simulation results which reproduced the temporal behavior of Fig. 4 for successively excited modes at frequencies $f=100.55$ and $f=98.6$ GHz.

In conclusion, development of internal cavity EA-FELs is presently being pursued in a number of laboratories in the world.[5–7] The demonstration of lasing, using this configuration in the Israeli tandem FEL, is an important milestone in the pursuit of the desirable goal of operating such devices with high average power and possibly in a cw mode.

This work was supported by the Israeli Ministries of Energy and Science, the Israel Academy of Sciences, U.S.–Isreal Binational Science Foundation, and the Meyer Fund.

[1] C. Brau, *Free Electron Lasers* (Academic, Boston, 1990).

[2] L. R. Elias, G. Ramian, R. J. Hu, and A. Amir, Phys. Rev. Lett. **57**, 424 (1986).

[3] A. Gover, A. Friedman, and A. Drobot, *Laser Focus World* 95, October 1995.

[4] A. Gover, A. Amir, and L. R. Elias, Phys. Rev. A **35**, 164 (1987).

[5] G. Ramian, The 17th International FEL Conference, New York, NY, August 21–25, 1995.

[6] I. Kimel and L. R. Elias, Nucl. Instrum. Methods Phys. Res. A **358**, 186 (1995).

[7] W. H. Urbanus, R. W. B. Best, W. A. Bongers, A. M. van Ingen, P. Manintveld, A. B. Sterk, A. G. A. Verhoeven, M. J. van der Wiel, M. Caplan, V. L. Bratman, G. G. Denisov, A. A. Varfolomeev, and A. S. Khlebnikov, Nucl. Instrum. Methods Phys. Res. A **331**, 235 (1993).

[8] B. C. Lee, S. K. Kim, Y. U. Jeong, S. O. Cho, B. H. Cha, and J. Lee, Nucl. Instrum. Methods Phys. Res. A **375**, 28 (1996).

[9] E. Jerby, A. Gover, S. Rushin, H. Kleinman, I. Ben-Zvi, J. S. Sokolowski, S. Eckhouse, Y. Goren, and Y. Shiloh, Nucl. Instrum. Methods Phys. Res. A **259**, 119 (1987).

[10] A. Arensburg, A. Abramovich, D. Chairman, M. Cohen, M. Draznin, A. Gover, H. Kleinman, Y. Pinhasi, J. S. Sokolowski, V. Shterngartz, I. M. Yakover, L. A. Levin, O. Shahal, A. Rosenberg, J. Shiloh, and I. Schnitzer, Nucl. Instrum. Methods Phys. Res. A **375**, 1 (1996).

[11] K. Halbach, Nucl. Instrum. Methods Phys. Res. A **169**, 1 (1980).

[12] M. Cohen, A. Eichenbaum, H. Kleinman, D. Chairman, and A. Gover, Phys. Rev. E **54**, 4178 (1996).

[13] I. M. Yakover, Y. Pinhasi, and A. Gover, Nucl. Instrum. Methods Phys. Res. A **358**, 323 (1995).

[14] Y. Pinhasi, V. Shterngartz, and A. Gover, Phys. Rev. E **54**, 6774 (1996).

[15] Y. Pinhasi and A. Gover, Phys. Rev. E **51**, 2472 (1995).