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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

First operation of the Israeli Tandem Electrostatic Accelerator Free-Electron Laser

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Abstract

Results of first operation of the Israeli Electrostatic-Accelerator Tandem Free-Electron Laser (EA-FEL) are reported. This EA-FEL utilizes a 1.4 A electron beam obtained from a parallel flow Pierce-type electron gun. The e-beam is transported into a resonator located inside a planar Halbach configuration wiggler, which is at a potential of 1.4 MeV with respect to the cathode. A resonator utilizing two curved parallel plates as a waveguide and two Talbot effect quasioptical reflectors (wave splitters) provides a quality factor $Q \approx 30\,000$. Millimeter wave radiation pulses of 2 μs duration were obtained at a frequency of 100.5 GHz, as predicted, at a power level above 1 kW.

1. Introduction

We report a first demonstration of lasing in our EA-FEL which utilizes a tandem Van de Graaff electrostatic accelerator and a wiggler located at the positively charged high voltage (HV) terminal.

First lasing in an Electrostatic Accelerator FEL was demonstrated at the University of California Santa Barbara (UCSB) [1–3]. This EA-FEL operates intensively up to this date as a user facility, covering the entire IR to mm-wavelength regimes. However, the UCSB EA-FEL operates with a negatively charged HV terminal configuration. The electron gun and the collector with their power supplies and associated electronics are placed at the HV terminal of the pressurized insulating gas tank; the wiggler and the optical resonator are located externally at ground potential. This configuration has some important disadvantages: difficult access to the electronics in the HV terminal; limitation on raising the accelerator potential to very high voltages (and the consequent limitation on operating the FEL at higher frequencies); and most important, the limitation on electric power provision to the terminal which floats at high voltage and limits device operation to low average power levels.

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It was recognized in the early stages of EA-FEL development that in order to attain lasing at high average powers (possibly CW operation), and at high frequencies, it is desirable to develop EA-FELs using a positively charged HV terminal and a straight electron-optical configuration, as shown in Fig. 1.Only by use of such a configuration EA-FELs have the potential to operate at megawatts average power levels. They may thus find important applications in industrial processing, tokamak plasma heating, etc. [4]. Development of such EA-FELs is in progress in a number of laboratories, including UCSB [5], CREOL-Univ. of S. Florida [6], FOM-the Netherlands [7,8] and KAERI-S. Korea [9]. The Dutch project is aimed towards attainment of record level radiation power (1 MW CW) at 1–2 mm wavelengths for plasma heating applications [7,8]. The Korean project recently demonstrated laser action with a low potential Cockcroft-Walton accelerator with open air insulation ($V = 430$ kV, $\lambda = 10$ mm) [9].

2. FEL design

The TAU EA-FEL is based on a 1–6 MeV Tandem Van de Graaff accelerator, which was originally designed as an ion accelerator for nuclear physics experiments. It was converted into a high current electron beam accelerator, and it was modified so as to enable the insertion of a magnetostatic wiggler containing a mm-wave resonator and electron-optical focusing elements in the positively charged HV terminal [10–13].

Fig. 1 shows the layout of the electron beam line along the FEL. The electron optics of this FEL is based on a straight line geometry and a positive HV terminal. The electron injection system is based on a 50 kV Pierce-type e-gun and employs focusing and steering coils after the anode. The parallel flow electron gun produces a high quality electron beam. A pepper-pot experiment performed on the e-beam yielded a normalized emittance of $\varepsilon_n \leqslant 10\pi$ mm mrad [12].

The other sections of the beam line are located inside of a steel tank pressurized to 15 atm with Nitrogen and CO_2 gas. An e-beam acceleration tube is followed by four quadrupole lenses (Q1–Q4), which are used to control the e-beam and to inject it into the wiggler entrance under controlled, near-optimal conditions. The wiggler and the mm-wave resonator, forming the FEL interaction region, are installed inside the positively charged high voltage terminal, located at the center of the tank along the symmetry axis. The quadrupoles Q5, Q6, Q7 and Q8 collimate the e-beam into the accelerator deceleration tube prior to collection by a depressed collector, which provides e-beam energy recuperation. Three diagnostic screens: S1, S2, S3 as shown in Fig. 1 were used for monitoring of the e-beam transport.

The wiggler of the permanent magnet type is arranged in a Halbach planar configuration [14] as illustrated in Fig. 2. Two long magnets were used on the sides of the wiggler to focus the e-beam in the lateral (wiggling) plane by means of a lateral magnetic gradient which they produce on the wiggler axis [15]. The RF resonator (see Fig. 3) 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 [8,16]. This type of resonator is characterized by very small ohmic and radiation losses of about 8%, as determined by loss measurements [16] prior to the installation of the resonator in the HV terminal. The parameters of the accelerator, wiggler and resonator comprising the FEL are summarized in Table 1.

A system for coupling the generated high power radiation from the resonator out of the pressurized tank has not been installed as yet. FEL output power was monitored by measuring a fraction of the emitted radiation that passes through a 2″ diameter glass window at the collector end of the vacuum tube. This aperture transmits a small fraction of the FEL radiation emitted from the resonator reflector opening which radiates with a divergence angle of about 20° in the main radiation lobe. A transmission coefficient of -42 dB from the resonator exit to a receiving horn antenna with detector placed next to the glass window outside the tank was measured. The calibration was made a-priori using a solid state mm-wave source at 101 GHz as a source of radiated power.

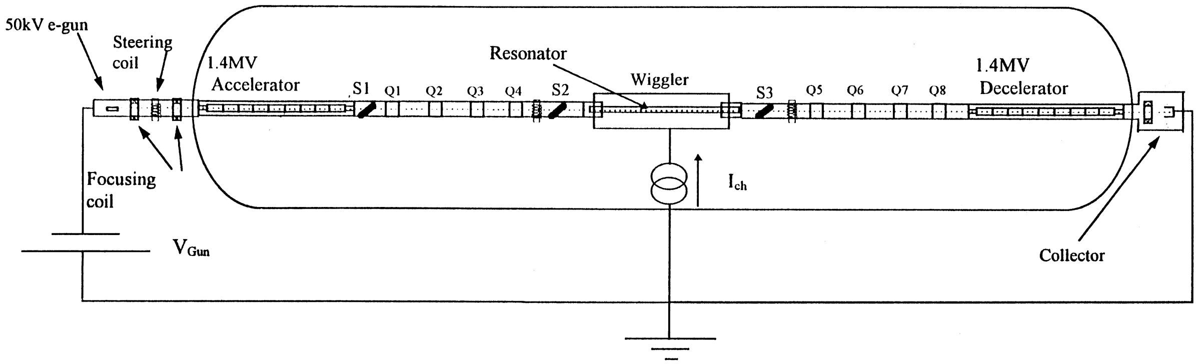

Fig. 1. Schematic illustration of the Israeli Electrostatic Accelerator Free Electron Laser.

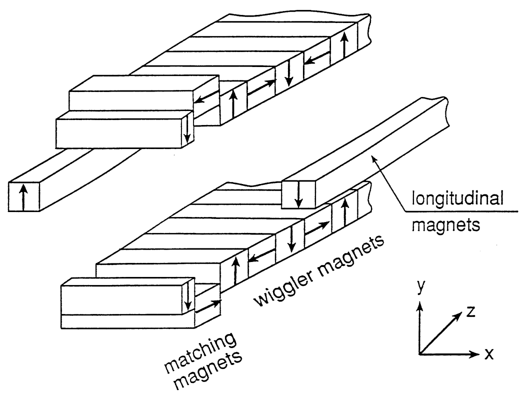

Fig. 2. Magnets arrangement in the magnetostatic planar wiggler including longitudinal focusing magnets.

Table 1
Parameters of the tandem FEL

Accelerator:	
Electron beam energy	$E_k = 1.3$–$1.5\,\mathrm{MeV}$
Cathode e-beam current	$I_0 = 1.4\,\mathrm{A}$
Wiggler:	
Magnetic induction	$B_w = 2$ kGs
Period length	$\lambda_w = 4.44$ cm
Number of periods	$N_w = 26$
Waveguide resonator:	
Type	Curved parallel plate waveguide
Mode	TE_{01}
Interaction length	$L_w = 88.9$ cm
Resonator length	$L_c = 131$ cm
Q-factor	$> 30\,000$
Power round trip losses	$1 - R < 10\%$

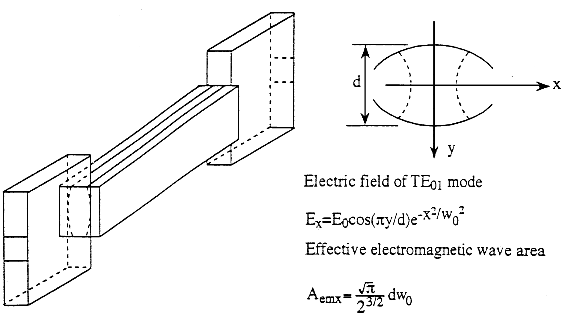

Fig. 3. The mm-wave resonator based on a curved parallel plates waveguide and two wave splitters.

The expected FEL performance was investigated using a nonlinear simulation code "FEL3D" [17]. This code is based on a modal expansion of the total fields (radiation and space charge) in terms of transverse waveguide eigenmodes [18]. The code was utilized to simulate FEL operation in the linear and non-linear saturation regimes. Simulations predict maximum small-signal gain at a frequency of 101 GHz for an e-beam energy of 1.4 MeV. The threshold current required for excitation and buildup of oscillations in the cavity was found to be about 150 mA for a 10% power round trip loss in the resonator.

3. Experimental results

The FEL radiation diagnostic setup is shown in Fig. 4. Power measurements were made using detector D1. Frequency measurements were made, using mixer M1, a mm-wave source, detector D2 and a frequency meter. Variable attenuator A1 provides optimal conditions for detector D1; attenuator A2 adjusts the local oscillator signal amplitude to a value for which the IF output signal from the mixer is proportional to the FEL radiation field amplitude.

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. The experimentally observed e-beam current from the cathode vs time is shown as trace 2 in Fig. 5. The observed e-beam current vs time at the resonator exit is shown as trace 3 in that figure. Trace 4 represents the radiation power observed at

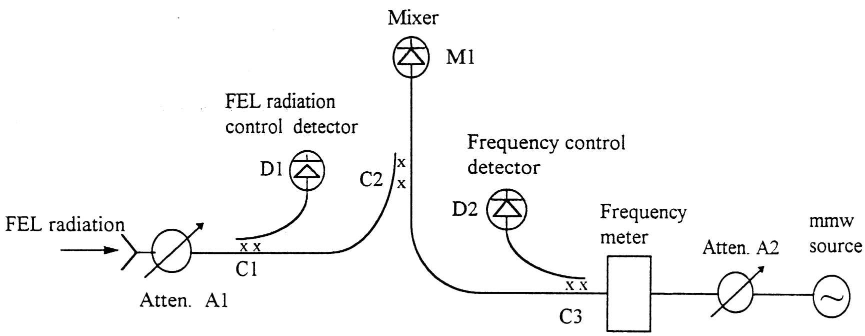

Fig. 4. Radiation diagnostics setup.

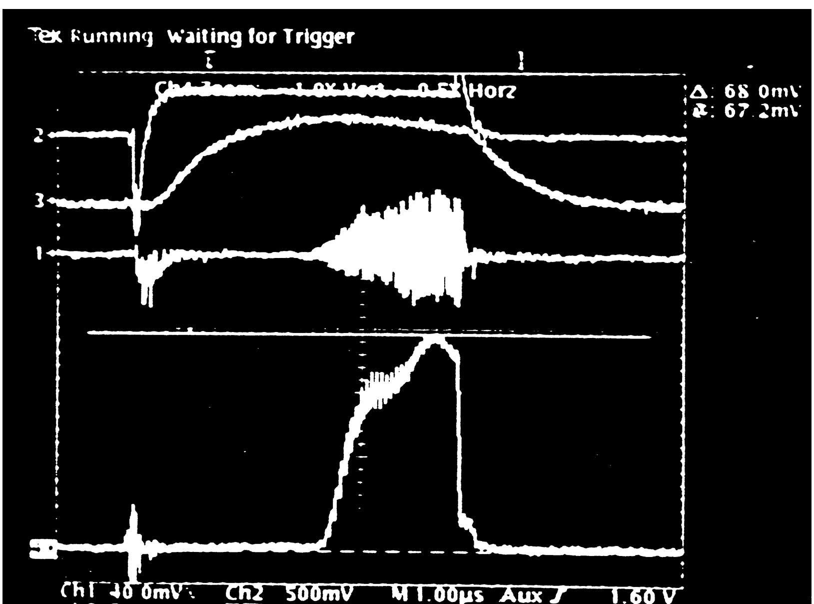

Fig. 5. Radiation measurement results: 1 – signal obtained from the IF output of the mixer, 2 – e-beam current pulse at the cathode, 3 – e-beam current measured at the exit of the wiggler, 4 – radiation power.

detector D1. The radiation pulse duration is 2 μs, and the peak detector voltage output is 140 mV. This voltage corresponds to a power level of 70 mW at the input to the mm-wave diagnostic assembly and is equivalent to about 1.1 kW of output power from the FEL cavity. The FEL radiation frequency was determined by heterodyning using mixer M1. The local oscillator (LO) frequency was changed from pulse to pulse until the IF frequency was low enough so as to be within the minimum resolvable range of the frequency meter (tens of MHz). Trace 1 is the IF output signal from the mixer corresponding to a LO frequency of 100.55 GHz. The IF frequency, determined from this trace, is about 20 MHz; the difference between the FEL radiation frequency and the LO frequency is below this 20 MHz value.

4. Analysis of obtained results

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. 5). The radiation decay time found from Fig. 5 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 (including internal cavity diffraction and ohmic losses and the radiation out-coupling from resonator) 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 number is close to the loss obtained from cold measurements of the resonator [16].

Analysis of the initial part of the rising part of trace 4 in Fig. 5 gives an estimate of the single path FEL gain value $G = 1.075/R = 1.18$. However, it should be clear that even this gain value is low as it exhibits some nonlinear regime gain reduction effect. The dynamic range of the detector was not large enough to detect lower power levels corresponding to the linear regime. Consequently, we can only determine that the small signal differential gain $G_0 - 1$ exceeds $G - 1 = 18\%$.

5. Conclusions

Demonstration of lasing in the Israeli Tandem FEL is an important milestone in the development effort aimed at operating positively charged EA-FELs at high average power and possibly in a CW mode. These goals are being pursued in on-going projects in the Netherlands [7,8], in the USA [5,6] and in Israel.

Acknowledgements

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