Electrostatic Accelerator Free-Electron Lasers

Avraham Gover[1] and Yosef Pinhasi[2]

[1] Tel Aviv University, School of Engineering, Physical Electronics Dept., Tel-Aviv gover@eng.tau.ac.il
[2] The College of Judea and Samaria, Dept. of Electrical and Electronic Engineering, Ariel yosip@eng.tau.ac.il

1 Introduction

Free-electron lasers (FEL) are high power sources of electromagnetic radiation, utilizing accelerated electrons, which are oscillating transverse to their propagation axis. The name free-electron laser was chosen to distinguish this device from conventional quantum lasers (Light Amplification by Stimulated Emission of Radiation), where the radiation is a consequence of transitions of bound electrons between atomic energy states.

The foundations of FELs go back to the early investigations of stimulated Thomson and Compton scattering carried out by Kapitza and Dirac in 1933 [1]. Motz, at Stanford, in 1951 studied theoretically [2] and experimentally [3] the radiation emitted when an accelerated electron beam passes through a succession of magnetic fields of alternating polarity. This "Synchrotron-Undulator Radiation" is a common source of X-ray and UV radiation in Synchrotron facilities. It is, of course, a spontaneous emission radiation source. The FEL is, in fact, the stimulated emission version of Synchrotron Undulator Radiation.

In 1957 Phillips of the General Electric Microwave Laboratory invented the Ubitron (Undulating Beam Interaction) [4, 5]. This mm-wavelength electron tube may be regarded as the first version of FEL or rather FEM (Free Electron Maser). Both an amplifier and an oscillator versions were built. However, the full potential of this device was not recognized, and the research work was terminated in 1964.

The interest in interaction between an undulating e-beam and electromagnetic fields as related to generation of coherent radiation, arose again when Madey proposed in 1971 his idea [6] of the free-electron laser [7]. Two successive experiments were performed at Stanford in the infrared (IR) regime. First, an amplifier at 10.6 μm was announced in 1976 [8], and laser oscillation at 3.4 μm was obtained the following year [9]. These experiments utilized a relativistic electron beam from a linear accelerator (LINAC).

2 Fundamentals of free-electron laser operation

In principle, a FEL consists of an accelerated electron beam travelling along a periodic undulator structure, which forces the electrons to oscillate in the transverse direction (see Fig. 1). The undulator is usually composed of alternating magnets, equally spaced, with a period λ_W.

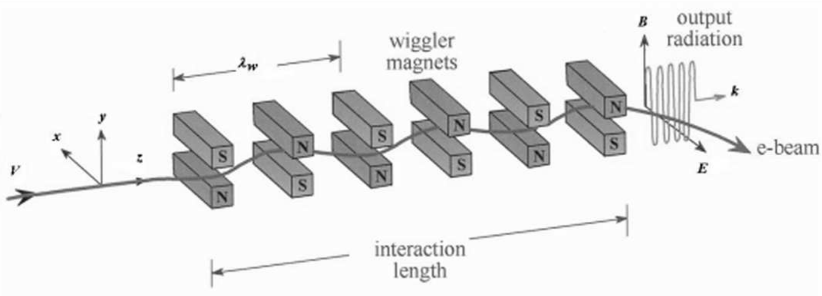

Fig. 1. Electron passing in a wiggler, emitting Undulator Synchrotron Radiation

Each electron is a moving dipole radiator, emitting a Doppler-shifted wave packet of undulator synchrotron radiation [3], which propagates in free-space or in a waveguide. In free space and in an over moded waveguide the wavelength of the radiation is given approximately by:

$$\lambda_S = \frac{\lambda_W}{\beta_z(1+\beta_z)\gamma_z^2} \tag{1}$$

where $\beta_z = v_z/c$ (v_z is the axial electron velocity and c is the speed of light) and $\gamma_z = \frac{1}{\sqrt{1-\beta_z^2}}$ is the axial relativistic Lorentz factor, related to the beam energy E_k and the wiggler parameter $a_W = eB_W/k_W mc$ through the relations:

$$\gamma_z = \frac{\gamma}{\sqrt{1+a_W^2/2}} \tag{2}$$

$$\gamma = 1 + \frac{E_k}{m_e c^2} \tag{3}$$

where $k_W = 2\pi/\lambda_W$, B_W is the magnetic field amplitude of the periodic planar wiggler (undulator), m_e is the electron mass. In the relativistic limit $\beta_z \to 1$, the radiation wavelength is approximated by:

$$\lambda_S \approx \frac{\lambda_W}{2\gamma_z^2} = \frac{\lambda_W}{2\gamma^2}(1+a_W^2/2) \tag{4}$$

If a waveguide is used inside the wiggler, (1) and (4) should be modified, and longer wavelength is expected [10].

In the stimulated emission devices (FEL amplifier or oscillator) a radiation wave enters into the undulator collinearly with the e-beam. The beating of the transverse electromagnetic field components of the radiation wave with the wiggler-induced periodic transverse velocity of the electrons, creates a moving "pondermotive force wave", directed in the axial (z) direction. This propagates synchronously with the electrons and modulates their axial velocity, forming density bunching in the beam at the radiation frequency. If the pondermotive wave is slightly slower than the electron velocity, the electrons lose energy to the wave. As a result, the electrons generate radiation by stimulated emission, and amplification occurs.

3 Electrostatic-Accelerator FELs

Free-electron lasers, utilizing a few MeV electrostatic accelerators (EA), normally operate in the mm and IR wavelengths regime. Figure 2 shows a curve of radiation frequency as a function of acceleration voltage of an EA-FEL, assuming free space propagation (1) and a wiggler with λ_W =4.44 cm (Table 1).

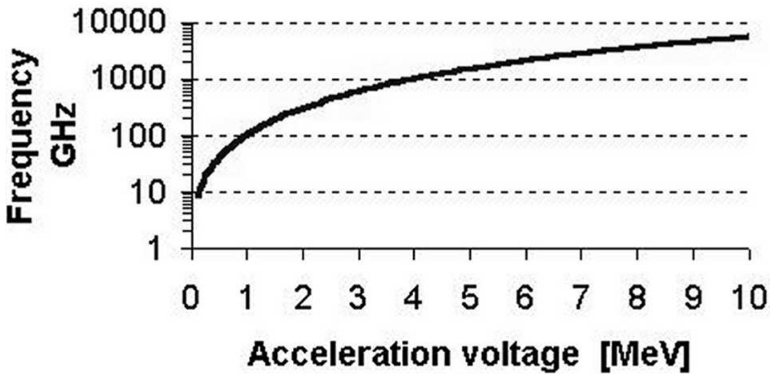

Fig. 2. Frequency vs. acceleration voltage in an EA-FEL

While most FEL facilities are based upon linacs, which produce ultra-short (ps range) electron-beam pulses, a few facilities in the world utilize EA that enable continuous wave (CW) or quasi-CW (long pulse) operation. EA-FELs are also characterized by high average power generation, high energy-conversion efficiency and high spectral purity. The high quality (small emittance and low energy spread) of the electron beam in the electrostatic accelerator is crucial for attaining FEL operation at short wavelengths. The unique features of EA-FELs make them naturally fitted for a variety of applications in the present and in the near future [11].

Table 1. Parameters of the EA-FEL

Accelerator	
Electron beam energy	$E_k = (1-3)$ MeV
Beam current	$I_0 = (1-2)$ A
Undulator	
Type	Magneto-static planar wiggler
Magnetic induction	B_W=0.2 T
Period length	λ_W=4.444 cm
Number of periods	N_W=20
Resonator	
Waveguide	Curved parallel
Transverse mode	TE_{01}
Round trip length	L_C=2.62 m
Out-coupling coefficient	T=7%
Total round tripe reflectivity	R=65%

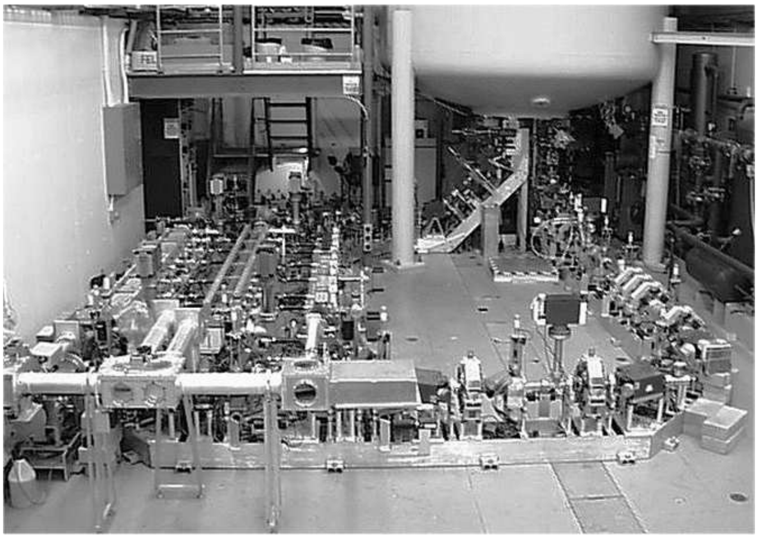

Fig. 3. The UCSB 6MV FEL Laboratory (http://sbfel3.ucsb.edu/fel_lab.html)

The first demonstration of EA-FEL, operating at the far IR-band, was made at the University of California Santa Barbara (UCSB) in 1984 [12–14]. The experiment employed a 6 MV Pelletron accelerator, and produced 10 kW over the range of (390-1000) μm. Subsequently the FEL was upgraded to cover the entire wavelengths range from 2.5 mm to 30 μm by adding two more wigglers of shorter period. Figure 3 shows a photograph of the UCSB FEL laboratory. The electron beam originates from a 2A Pierce type electron gun located in the negatively-charged High-Voltage (HV) terminal inside the accelerator tank (top-right part of Fig. 3). The high current beam is transported down the acceleration tube into the Beam-Switchyard room (Fig. 4) where it can be directed at choice to pass through any of the three wigglers (mm-wave, FIR and 30 μm). The used e-beam is then bent and directed back into the accelerator terminal by means of low dispersion bending magnets and a vertical deceleration tube, which goes parallel to the acceleration tube inside the tank. The beam is then collected by a multi-stage collector closing the high current beam electrical circuit at the HV terminal. The UCSB FEL has been operating for almost two decades as a Radiation User Center.

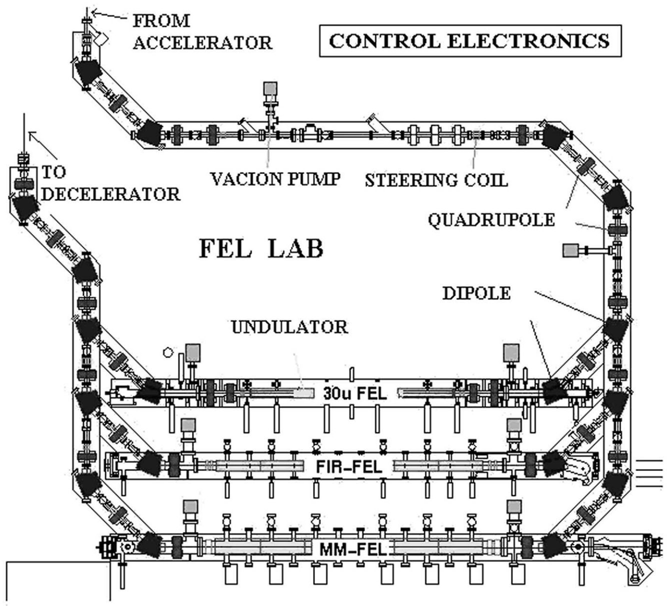

Fig. 4. The UCSB 6MV Beam Switchyard (http://sbfel3.ucsb.edu/6mv/6mv_swtchyd.html)

An alternative configuration of an EA-FEL was developed in Israel by a consortium headed by Tel-Aviv University, based on the 6 MV EN-Tandem accelerator of the Weizmann Institute (shown in Fig. 5) [15, 16]. In this configuration the wiggler (and resonator) is placed at the positively charged HV-terminal, and the electron gun and collector are external to the tank at ground potential (see Fig. 6). The accelerator, originally an ion accelerator, was converted into an electron accelerator and its internal transport system was modified (two out of four acceleration tube sections removed) to accommodate a magneto-static wiggler and electron-optics focusing, steering and diagnostic elements (see Fig. 6). First lasing and high-coherence single mode operation was demonstrated in 1997 [16,17]. In 2001 the FEL was relocated to Ariel to a dedicated radiation-users building, and has returned just recently to operation in a new configuration. In the present FEL, the mm-wave radiation, generated in the resonator, is separated from the electron beam by means of a perforated Talbot effect bent reflector [18]. A quasi-optic delivery system, composed of overmoded corrugated wave guides and dielectric lenses, transmits the out-coupled power through a window in the pressurized gas accelerator tank and into the radiation-users room, across a 1.3 m radiation protection concrete wall (see horizontal aluminum waveguide tube at the top-right corner of Fig. 5). The Israeli FEL was built to serve as a Radiation-User Facility. In recent experiments [19] 0.5kW rf power at 100 GHz was delivered to the users rooms. It is now being further developed to operate at high average power (1kW) in the range of (70-130) GHz.

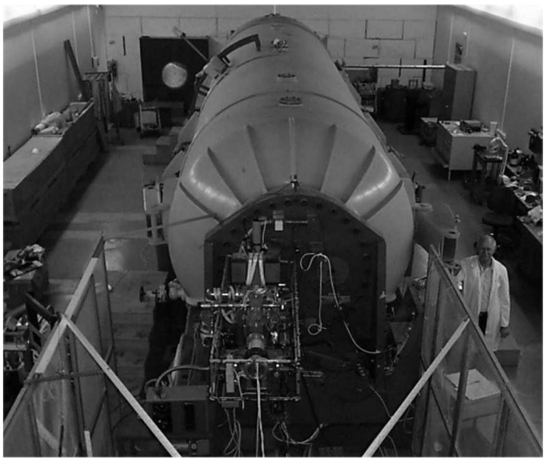

Fig. 5. The Israeli Electrostatic-Accelerator FEL

The capability of the EA-FEL to produce almost continuous high average power at μm wavelengths with wide range tunability (by varying the beam energy) aroused interest in applying it for Electron Cyclotron Resonance Heating (ECRH) of magnetically confined plasma for controlled thermonuclear fusion. Such a FEM was suggested and constructed by the Dutch FOM-Institute for Plasma Physics [20,21], and attained record high power of 730 kW in a few μs

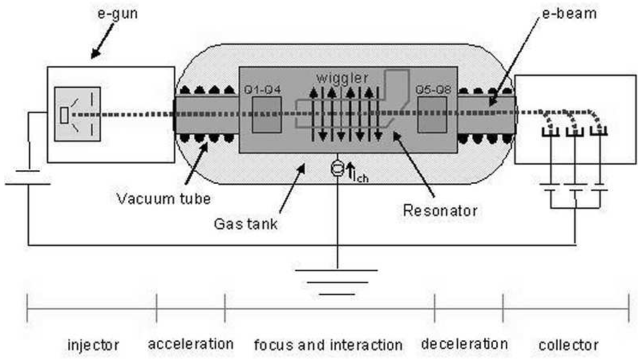

Fig. 6. The internal-cavity straight transport line EA-FEL scheme

at 206 GHz and tens of μs long pulses of 80 kW in the (200-300) GHz range. The accelerator used in this case was charged by a 2 MV 20 mA Insulated Core Transformer HV power supply.

Two other noteworthy experiments were carried out in Korea and at CREOL (University of Central Florida). In 2001 the Korean FEM demonstrated first lasing in a straight-line transport, positively charged terminal configuration. No accelerator was used, rather an open-air insulation transport system, based on a 500 kV power supply and e-gun, were used to demonstrate lasing at 35 GHz at rf power of 1 kW [22]. In CREOL, a compact FEL based on a mini-wiggler (λ_W=8 mm) and a Pelletron accelerator has been developed [23]. In 2000 it was first time demonstrated lasing in the FIR region (λ=400 μm, P=100 W). This FEL was transported recently to University of Hawaii and is being reassembled there.

4 EA-FEL Design Considerations

The EA-FEL is inherently an energy retrieval (current recirculation) device. This means that the entire high current (Ib) of the accelerated electron beam (in the order of amperes), except for a small interception current I_{int}, must be transported after passing the wiggler (where it transfers part of its kinetic energy to the radiation field), and decelerated down to the moderate (tens of kV) voltages of the collector high-current power supplies. Through the collector power supplies the e-beam electric circuit closes back to the electron gun. Because the electron beam energy distribution spreads out during the interaction with the radiation wave inside the wiggler, it is desirable to collect the decelerated electrons with a multiple-electrodes collector. This means that each electron beam energy-class hits the corresponding collector electrode with minimal kinetic energy, and consequently minimal heat waste and secondary electrons emission. This technology of "multi-stage depressed collector" was developed before in the microwave tubes art.

The beam current recirculation scheme makes the EA-FEL a potentially high efficiency high average power radiation source. However, its primary benefit is making it possible to transport high beam current (order of amperes is needed to surpass the FEL lasing threshold) in an electrostatic accelerator, that can supply to the HV terminal only very low charging current I_{ch} (order of mA in electrostatic accelerators and tens of mA in high voltage electrodynamic accelerators). The current recirculation scheme makes it possible to maintain passage of a high current beam through the wiggler, because this current is not supplied through the terminal charging circuit. However, in order to maintain steady state voltage of the terminal, the transport efficiency from the e-gun to the collector $\eta_{trans} = 1 - I_{int}/I_b$ (I_{int} is the e-beam current intercepted along the acceleration- deceleration transport line) must be high enough to keep the current balance:

$$I_{ch} = I_L + \langle I_{int} \rangle \tag{5}$$

where I_L is the constant leakage current (Corona discharge and bleeding series-resistors current). Typically, transport efficiency in excess of η_{trans}=99.9% ($\langle I_{int} \rangle / I_b$ <10^{-3}) is required to maintain condition (5) for steady state lasing (CW) operation.

Attaining high transport efficiency is difficult, and therefore all present EA-FELs are operated in a (long) pulse operating mode. In this mode the pulsed e-beam intercepted current I_{int}=(1-η_{trans})I_b exceeds the net terminal charging current $I_{ch} - I_L$, and therefore the terminal voltage drops during the pulse duration τ_p according to

$$\Delta V_T = I_{int} \tau_p / C_T \tag{6}$$

where C_T is the HV-terminal capacitance relative to the tank enclosure. The terminal voltage drop causes decrease in the e-beam kinetic energy $\Delta E_k = mc^2 \Delta\gamma = e\Delta V_T$, which down-shifts the synchronism wavelength (4). If the e-beam pulse is long enough to enable oscillation build-up in the FEL oscillator up to saturation, and consequently establishment of monochromatic stored radiation-field in the resonator, then as the terminal voltage continues to drop, the oscillator stored radiation field gets out of synchronism with the slowing down beam, and the FEL gain drops. Because of the finite bandwidth of the FEL gain curve, only a relative energy drop of

$$\frac{\Delta\gamma}{\gamma} = \frac{1}{2N_W} \tag{7}$$

(N_W - the number of wiggler periods) shifts the gain curve out of the frequency of the stored radiation, and causes it to stop lasing and decay. Thus, the consideration of (6) and (7), using (3), determines the maximum single

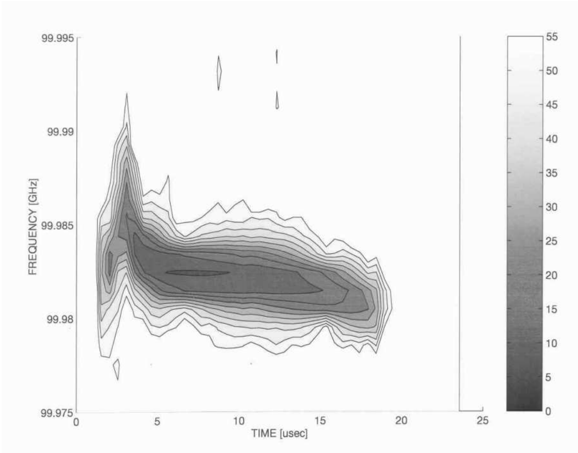

Fig. 7. Spectrum of the coherent single mode radiation emitted from the Tandem EA-FEL [17]. The FWHM bandwidth is Δf=1 MHz (the intensity scale is logarithmic)

frequency lasing pulse τ_p duration permissible. Typical pulse durations in an EA-FEL are tens of μs.

The possibility to obtain long pulse operation (and potentially CW operation) brings into expression an important feature of EA-FEL - high temporal coherence. Because the FEL is essentially an homogeneously broadened laser, the modes competition process in the resonator during the oscillation build-up period winds up with single mode operation [14, 17, 24]. Figure 7 shows the spectrum of the single mode radiation measured out of the Israeli FEL [17]. It shows FWHM emission bandwidth of Δf=1 MHz that corresponds to a relative linewidth of $\Delta f/f \cong 10^{-5}$, still Fourier transform limited by the finite pulse duration (τ_p=20 μS).

The saturation radiative extraction-power in the FEL is given by:

$$\Delta P_{ext} = \eta_{ext} E_k I_b / e \tag{8}$$

where the extraction efficiency, $\eta_{extr} \cong 1/2\mathrm{N}_W$, can be understood as a result of the electrons getting out of synchronism due to their energy loss in the resonator (compare (7)). The power coupled out of the resonator at saturation depends on the power transmission T of the out-coupling mirror and the total round trip loss factor 1-R (R is the resonator round trip reflectivity):

$$P_{out} = \frac{T}{1-R} \Delta P_{ext} \tag{9}$$

As in any laser, there is always an optimal transmission factor T, for which P_{out} is maximized. Its determination requires numerical solution of the FEL equations in the nonlinear (saturation) regime [25].

The resonator design is a difficult part in EA-FEL design. Because of the long wavelength of operation, diffraction is significant, and usually an over-moded waveguide resonator is used. If the electron beam can be bent into and out of the resonator axis (as in [13, 23] then slit out-coupling can be used in the output mirror. In [17, 19, 21] the Talbot-effect reflector configurations [18] were used, enabling out-coupling of the radiation aside of the resonator axis. The e-beam is injected, then entering and leaving the resonator through holes in the mirrors keeping a straight trajectory along the co-axial accelerator and resonator.

An example of EA-FEL construction parameters based on the Israeli EA-FEL is given in Table 1. For these parameters, extraction efficiency of η_{extr}=2.5% and output power of P_{out}/I_b=7 kW/A are expected at saturation, according to (8) and (9). So far P_{out}=5 kW (0.5 kW at the users room) was measured in this device at I_b=1.8 A, yet before saturation.

In conclusion of the design considerations, an important note should be made concerning the choice of accelerator polarity and configuration. The external resonator and wiggler configuration is advantageous for application in a radiation-users facility, mostly because it leaves room for extended and multiple wigglers-resonators design, and the radiation can be coupled easily out of the resonator directly into the user rooms (see the horizontal aluminum pipe in the bottom-left corner of Fig. 3). However, for future specific short-wavelength and high power applications, the internal cavity configuration is advantageous. Because of voltage-breakdown considerations, it is possible to build high voltage electrostatic accelerators (needed for short wavelength operation) only with a positive polarity terminal. Furthermore, in this configuration the e-gun and collector power supplies are placed at ground potential. At the high average power levels (order of MW) at which EA-FELs can potentially operate, it would be inconceivable to place the large power supplies in the terminal and transfer the grid power to them mechanically, as it is done in the negative polarity terminal configuration. In addition, the simple straight geometry of the electron beam transport in the internal cavity configuration (Fig. 6) promises better transport efficiency and consequently higher average power operation.

5 EA-FEL Applications

The main application of EA-FEL at present (as most other kinds of FELs) is as a radiation-user facility for scientific studies. In this connection the main feature taken advantage of, is the wide range tunability in a wavelength region (from mm-wave to IR), which is deficient with tunable sources. For some studies also the high power and narrow spectrum of the radiation source are important characteristics. Figure 8 depicts a conceptual design of radiation exposure stations in a radiation user facility based on EA-FEL [29].

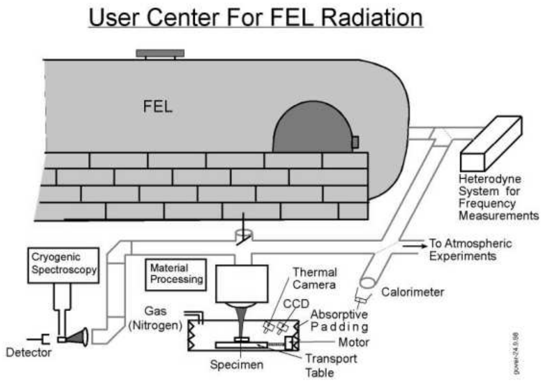

Fig. 8. Conceptual scheme of Radiation User Facility based on EA-FEL

The EA-FEL as an intense tunable FIR source is a useful study tool in condensed-matter physics research. It has been used in linear and non-linear spectroscopy of elementary excitations in material: phonons, magnons, excitons and shallow impurity levels in semiconductors, small energy-gap materials as High-Temperature Super-Conductors (HTSC), quantum wells, superlattice, and various mesoscopic semiconductor structures and devices [26]. In biological research such a source can be useful in spectroscopic investigation of vibrational levels in proteins and DNA molecules. It can be used also for studies of damage or therapeutic effects of mm-wave or FIR radiation interacting with biological tissues.

The high average power and high efficiency potential of EA-FEL holds promise for development of energy related industrial and commercial applications. The MW level design and partial demonstration of operation of the FOM FEL, indicate that such high power applications are feasible with further investment in technological development. The fusion application (ECRH heating of magnetically confined plasma in tokamaks) requires few MW power at short mm-wavelengths, 35% step tunable in time scale of seconds. More moderate average power levels (kW to tens of kW) are required for applications in thermal material processing (ceramic sintering, surface treatments, cutting, curing, drying etc.) [27]. Interesting applications and schematic designs have been proposed for compact EA-FEL systems used in free space atmospheric beam propagation. These include concepts of radiative energy transmission to atmospheric or ionospheric Unmanned Air-borne Vehicles at atmospheric transmission windows (35 GHz, 94 GHz) [28, 29]. Other such applications include Extremely High Frequency (30-300 GHz) mm-wave radars and high resolution imaging systems, communication (to satellite) systems, and remote sensing of gases and aerosols in the atmosphere [29].

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