AN ISRAELI FREE ELECTRON LASER PROJECT*

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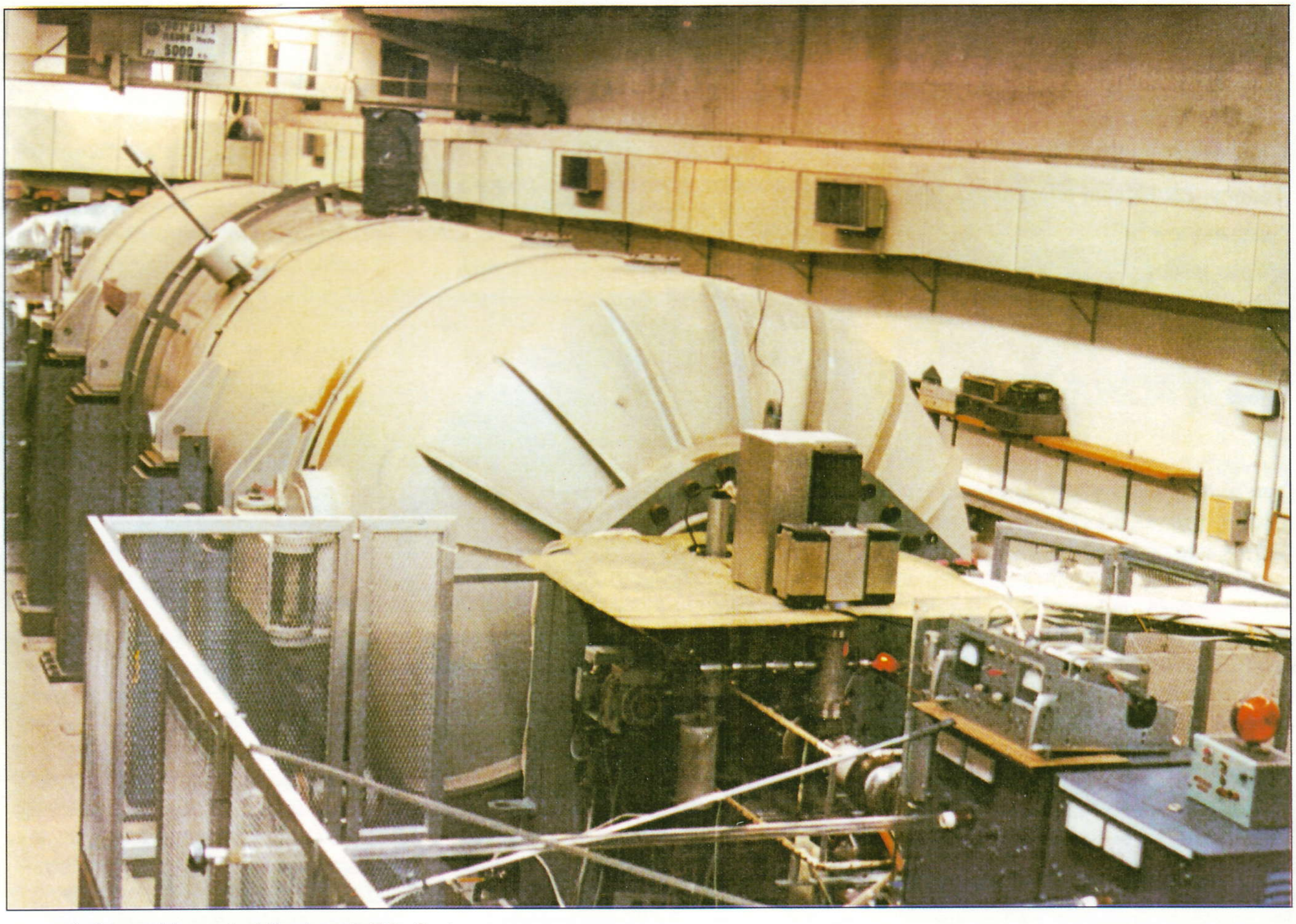

Fig. 1: A General Layout of the Israeli FEL System.

INTRODUCTION

Free Electron Lasers (FEL) are the high power lasers which were the prime candidates to produce the intense laser beams intended to destroy attacking balistic missiles in the "star wars" program. This veteran of the cold war has made a vocational conversion in the post coldwar era. Presently it is being used mostly as a very flexible tuneable source of coherent radiation for scientific, technological and medical research which is conducted in big user facilities. This application does not really take full advantage of the high operating power capabilities of the device.

Quite natural applications for it lay in the industrial and energy related areas.

At the present time there are more than 50 FEL facilities in operation and

* Reprinted from ***Israel Energy News***, Summer 1993, pp. 6-10.

development all over the world - primarily in the U.S., Europe and Japan. The Israeli FEL is one out of three projects in the world which are based on electrostatic accelerators. Only such devices can operate with a continuous wave (cw) or in a quasi-cw (long pulse) mode. All other FELs, are based on pulsed accelerators and can produce, therefore, only a pulsed waveform. Electrostatic Accelerator FELs (EA-FEL) are also characterized by potential for high average power, high energy conversion efficiency and high spectral purity (narrow linewidth). These special features are summarized in Table 1.

Wavelength range:	IR to mm waves
Average Power:	$\gtrsim$ 1 MWatt
Energy conversion efficiency:	> 50%
Linewidth:	$< 10^{-5}$
Wave form:	pSec to continuous wave

Table 1: Potential characteristics of EA-FEL

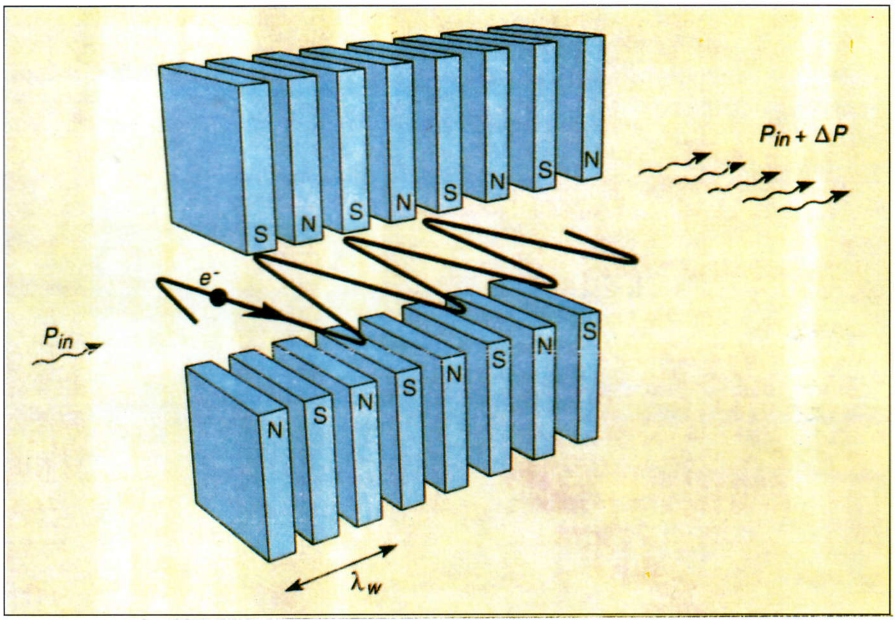

Fig. 2a: FEL Lases when Free Electrons Interact with Magnetostatic Wiggler Field.

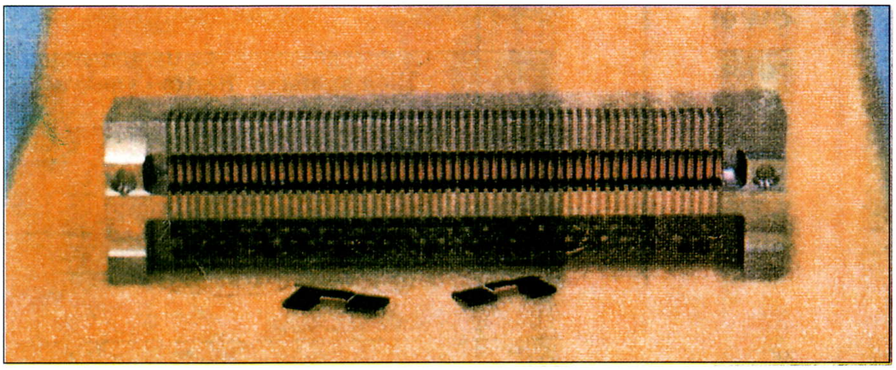

Fig. 2b: Electromagnet Microwiggler with Period λw = 2.4mm (Demonstration Model of MIT/Odetics, Ref. 5).

THE PRINCIPLE OF EA-FEL OPERATION

Contrary to conventional lasers where the active medium which provides the optical gain is matter, the active medium and source of energy in FEL are accelerated electrons transported in vacuum. The FEL operates in principle as a DC to optical frequency power converter, converting efficiently a big fraction of the large kinetic energy of the electrons into radiated power. Operation in vacuum eliminates the power limitations which in conventional lasers are due to material damage, heating and non-linear optical effects. This explains the high operating power capabilities of the device.

The operating principles of EA-FEL are illustrated in Fig. 1. A high current electron-gun ($I \gtrsim 1$ Amp) injects an electron beam into the acceleration tube of a van de Graff accelerator. The electron beam is accelerated through the tube up to the voltage of the High Voltage (HV) terminal which is kept at a level of few million volts by the charging belts of the van de Graff accelerator. The high energy electron beam then goes at very high speed through a periodic magnetic structure called a "wiggler" which is placed inside the terminal. The wiggler causes the electrons to oscillate (wiggle) along the wiggler length, and consequently emit electromagnetic radiation like every oscillating charge (Fig.2). The emission frequency depends on the electrons speed and the "wiggler" period. This frequency may be very high (optical frequency) because of the Doppler effect which increases the forward emission frequency of a moving oscillator.

Because the radiation wavelength is determined only by the electron velocity and the wiggler period, any wavelength of operation can be attained by proper choice of FEL parameters, and tuning can be carried out by varying the e-beam energy (velocity). This is a fundamental difference from conventional lasers where the emission frequencies are usually discrete, and are determined by the naturally occuring quantum energy level of the active medium material. Thus the FEL may provide radiation energy in wide ranges of wavelengths where no other coherent radiation sources exist, predominantly in the IR-mm wave region. The virtual power of the electron beam at the HV terminal is very high. A beam of average current I of a few amperes accelerated to voltage V of a few million Volts carries a power $P = V \cdot I$ of many Megawatts. In a FEL oscillator the radiation emitted by the e-beam in the

wiggler is trapped inside the laser resonator. When the radiative power stored between the resonator reflectors is high enough a big fraction (few percent) of the e-beam power is extracted upon passage through the resonator and turned into radiative power by the process of stimulated emission. At saturation each electron which traverses the wiggler emits millions of photons. This is again fundamentally different from the emission process in conventional lasers (where each excited electron emits a single photon) and provides another explanation for the high power capability of FEL. The electrons lose a few percents of their energy during passage through the wiggler, and transform it into radiative energy. However, the e-beam still keeps most of its kinetic energy at this stage. In most conventional FELs the e-beam is dumped right after the wiggler and most of its energy is wasted (turned into heat). Not so in EA-FEL. As shown in Fig. 1 the wasted electrons exiting from the wiggler are decelerated through the deceleration tube (in an energy conservative system) and are slowed down almost to zero velocity.
The beam is then collected externally by a multi-stage collector with little heat generation. This scheme called "depressed collector" or "energy retrieval" scheme enables the FEL to operate with very high energy conversion efficiency. In fact if the entire electron beam is transported along the accelerator without interception then the dominant consumer of electric power in the FEL system is the collector power supply. The power it provides is transferred almost entirely into radiative power. This explains the high total (wall plug) conversior efficiency of EA-FEL as opposed to conventional FEL (see Table 1).

POTENTIAL ENERGY - RELATED APPLICATIONS

The outstanding charactersitics of EA-FEL displayed in Table 1 and on the other hand its large dimensions and cost determine the range of applications that can be ascribed to this unique radiation source[2]. The high average power capability of the device makes it naturally fitting for energy related applications. A number of attractive future applications were identified, and are briefly described in this section. Most of them require long range development programs and international cooperation.

A. Heating Magnetically Confined Plasma in Thermonuclear Fusion Reactors

Thermonuclear power reactors are the "environmentally clean" future power reactors, which like "little suns" use Hydrogen isotopes as the fuel for power production instead of the radioactive heavy elements used in nuclear reactors. Recently a scientific break-even demonstration took place in the JET (Joint European Tokomak) Labs in England and gave a great impetus to the pursuit of this energy source of the future. Nevertheless, despite this success, a continuous engineering, technological and scientific development effort for tens of years will be required to achieve commercial realization of this concept. To ignite the plasma in the fusion reactor, it has to be heated to high temperatures which only exist in the sun. One of the schemes, suggested for heating the plasma and controlling its density profile, requires radiation sources with total power of 20 MWatt which operate quasi-CW at wavelength λ = 1 - 2mm and are tuneable.
A battery of a few Free Electron Masers (FEM) seems to be an excellent candidate to perform this function.
A development project of a 1MWatt FEM for fusion research application is now under way in FOM Institute for Plasma Physics in Nieuweigen, Nederlands. The Dutch project relies on wide international collaboration, and the Israeli FEL group participates in making contributions to its conceptual design.

B. Energy Transmission in Free Space

The high average power and high energy conversion efficiency of FEL (see Table 1) gives hope to an old dream of energy transmission by means of "radiation beams" propagating freely in the open atmosphere or in outer space. Options of microwave and optical energy beaming from ground to satellite and vice versa were considered for various schemes like solar energy utilization, satellite powering and energy redistribution on land. More easily applicable schemes may be short range wireless energy transmission links to inaccessible energy consumers beyond natural obstacles, or catastrophy zones (e.g. earthquake or pollution striken areas). State of the art of large transmitting and receiving mirrors permits transmission of collimated laser beams to distances of kms to hundred thousands kms depending of the wavelength. For atmospheric transmission the tunability of FEL is an advantage, making it possible to choose an atmospheric transmission window in the frequency domain.

C. Isotope Separation

The high spectral purity and tunability of EA-FELs are their most important property in this application which relies on the small difference in the IR absorption lines of molecules composed of different isotopes. This, combined with the high average power and energy efficiency of EA-FEL makes it a well fitted source for molecular laser isotop seperation schemes for effcient production of nuclear fuels.

D. Study, Detection and Removal of Air Pollutants

In the combustion process of fossil fuel, various polluting by-products (as SO_X and NOx gaseous compounds) are released into the air. The molecules of these gases have characteristic vibrational resonances which determine their IR absorption spectrum. As in the previous application, the high spectral purity and tuneability of EA-FEL make it a good tool for investigating and monitoring the combustion products.
If efficient schemes will be developed for breaking the molecular bonds of undesirable combustion gases by resonant multiphoton excitation, then EA-FEL will have the advantages of high fluence (average power) and high energy efficiency necessary for this application.

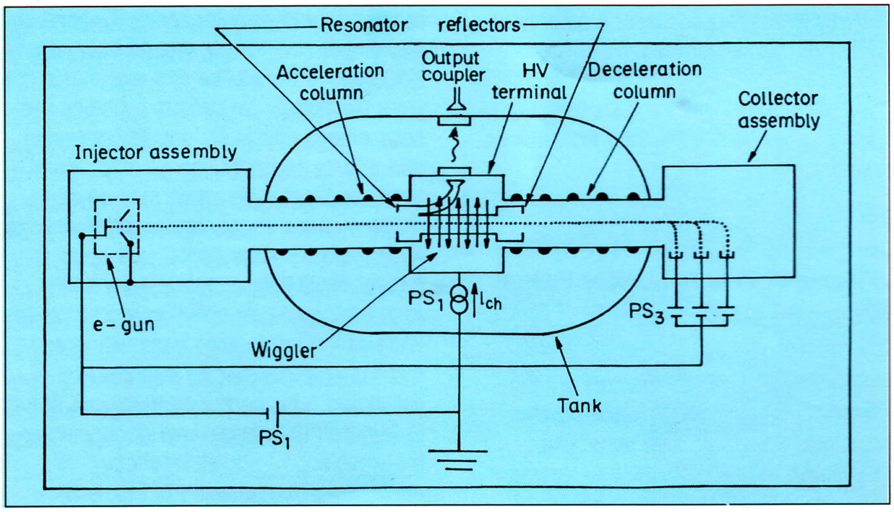

Fig. 3: Overview of the Experimental Setup.

THE ISRAELI FEL PROJECT

The Israeli FEL project is based on a 2-6 MeV EN-Tandem van de Graff accelerator which was used before as an ion accelerator for nuclear physics experiments. The Weizmann Institute (Dannie Heinemann Accelerator Lab) is permitting the FEL collaboration to convert the machine into a high current electron accelerator and demonstrate its use in an FEL experiment. The accelerator development work and the subsequent FEL experiment are funded by Israeli Minstry of Energy and Infrastructure, Ministry of Science and Ministry of Defence, the Israel Academy of Science, U.S.- Israel B.S.F., and the Meyer Foundation .The configuration of the planned FEL is shown in Fig. 1. This is an improved scheme relative to the only previous EA-FEL which was demonstrated at the Univ. of Cal. Santa-Barbara(3). Contrary to the previous experiment, this scheme uses straight geometry for the electron optics and keeps the electron gun and collector power supplies out of the accelerator. It is therefore the only scheme that can be conceiveably developed for future high average power applications.Fig. 3 shows an overview of the experiment, including the accelerator, the electron beam injector and the associated H.V. electronics. The source of the electron beam is a 50kV 2 Amp electron gun seen at the front end of the accelerator. The high current electron beam is partially scraped and then injected into the accelerator by means of solenoid focusing lenses.

The 5MegaVolt energy of the EN-Tandem accelerator corresponds to possible FEL lasing wavelengths in the entire milimeter and Far-Infrared range (100 μm to 10 mm with conventional wigglers and down to 10 μm with microwigglers). The present goal of the project is to demonstrate the feasibility of a 3mm wavelength FEM operating at accelerator voltage of 2.5 MegaVolt with power levels of the order of KWatts.

This requires efficient transport (better than 90%) of a high current electron beam (at least a few hundreds milliAmp) through the entire accelerator system.Up to now, the FEL group scientists succeeded to transport through the bare accelerator system 200mAmp at high transport efficiency and 0.5Amp at low transport efficiency. The group is engaged this year in major internal modifications of the accelerator, installing inside the H.V. terminal magnetic lenses and fiber-optic linked control electronics which will enable focusing and steering of the electron beam through the acceleration tube, wiggler and deceleration tubes (see Fig. 1) without loss of electrons on the way. Beyond the technical demonstration of lasing in a straight geometry Tandem configuration the FEL team has a scientific interest mostly in the study of the limits of coherence (monochromaticity) of the FEL light and the dynamics of coherence establishment. The high coherence properties of FEL is not only of practical importance but also gives rise to scientific research problems of quite fundamental nature in laser physics (4).

The expected long electron beam pulse duration of the Israeli FEL experiment will provide a unique set-up for studying and improving the EA-FEL coherence properties.

CONCLUSION

The Electrostatic Accelerator FEL project is one of the major fundamental research and technology projects in Israel concerning future energy-related technologies and advanced concepts. In a spirit of international scientific cooperation, the Israeli research team strives to make its contribution to the world-wide development effort of the science and technology of FELs. The unique experimental set-up of the group, based on a converted EN-tandem van de Graff, will help to advance the concept of high efficiency high power EA-FEL, and study its high coherence property.

References

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