

DEVELOPMENT OF A TANDEM ELECTROSTATIC ACCELERATOR QUASI-CW FEL

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The EN tandem electrostatic accelerator at the Weizmann Institute of Science has been converted into an electron accelerator with beam power recovery. We report on the design and performance of the accelerator as well as on a new approach to stable, long-pulse operation of this class of machines. The long-pulse model of operation offers interesting possibilities for the operation of free electron lasers, in particular the study of high-coherence, single-mode operation.

1. Introduction

As previously proposed [1], an existing EN Van de Graaff tandem accelerator has been converted into a high-intensity electron beam accelerator, capable of accelerating electron beam pulses of 2 A intensity to 5 MeV at the terminal located at the center of the accelerator. This beam, being then decelerated back to ground potential, can therefore be recovered and recirculated. This positive-terminal “straight-geometry” configuration is shown schematically in fig. 1. The charging system (PS1) keeps the high-voltage terminal charged, compensating against leakage current from the electron beam to the high-voltage terminal. The gun power supply (PS2) accelerates the electron beam from the cathode. The collector power supply (PS3) keeps the collector bias positive and also replaces the power radiated in the wiggler.

The straight-geometry tandem accelerator configuration with the wiggler placed in the positively charged terminal and the gun and collector placed at ground potential has a number of important advantages over the alternative configuration (folded-geometry tandem with a negatively charged terminal) used in the first UCSB ES-FEL:

- (1) The straight-geometry electron optics preserves the e-beam quality better and consequently attains higher transport efficiency and higher currents, and

operation at shorter wavelengths is easier to attain (with microwiggler).

- (2) Positively charged terminals are scalable to higher-voltage operation and therefore may be developed in the future for optical-wavelength FELs.
- (3) As will be explained in section 2, the fact that the electron gun is at ground potential leads to diminished droop in the terminal voltage, even when a significant part of the electron-beam current impacts the deceleration tube. This will allow stable, long-pulse operation (milliseconds): pulses two orders of magnitude longer than the present state-

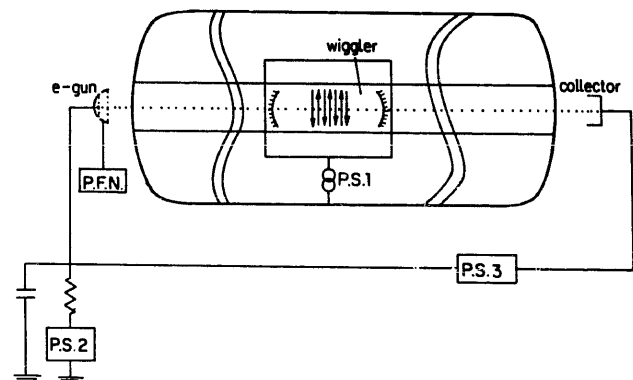


Fig. 1. Schematic diagram of the tandem accelerator including the FEL.

of-the-art will be possible even with poor electron-beam transport.

The long-pulse effect, described in more detail in section 2, was discovered in the course of preliminary tests of the accelerator. This discovery, in addition to other advantages of the straight-geometry tandem configuration, led us to develop a research program aimed towards construction of a quasi-cw FEL and study of radiation coherence, post-saturation dynamics and investigation of stable and unstable multimode operation. This research problem, as it appears in the recent physics literature [3–7] and FEL conference sessions [8], is in the focus of research interest in this field and one of our goals is to provide a machine suitable for studying it experimentally. The details of the FEL research program are described in section 3.

2. Present status of the experiment

2.1. Electron gun

The ion source of the original EN tandem ion accelerator has been removed and its base was transformed into a high-voltage platform, where the electron gun

power supplies and the pulse-forming network have been installed. The platform is at -50 kV potential during the machine operation. The original ion source was replaced with a 2 A electron gun. This gun was designed around a Spectra-mat dispenser cathode in Pierce geometry with a control electrode. The design was based upon the EGUN program of Herrmannsfeldt [9]. The gun design and the Herrmannsfeldt code simulation are shown in fig. 2. The features of the gun are an operating voltage of 50 kV, a control electrode voltage of -6 kV for current cutoff, and $+12$ kV for a current of 1.8 A for best emittance. The agreement between the current output predicted by the program and the measured beam current in the experiment was excellent.

2.2. The electron optical system

The gas stripper tube of the original ion accelerator was removed from the terminal, where the FEL wiggler would be located, and the inclined-field accelerating tube was replaced by a straight-field tube. Four focussing coils were installed, two of them between the electron gun and the accelerating tube and the other two between the decelerating tube and the collector. A set of

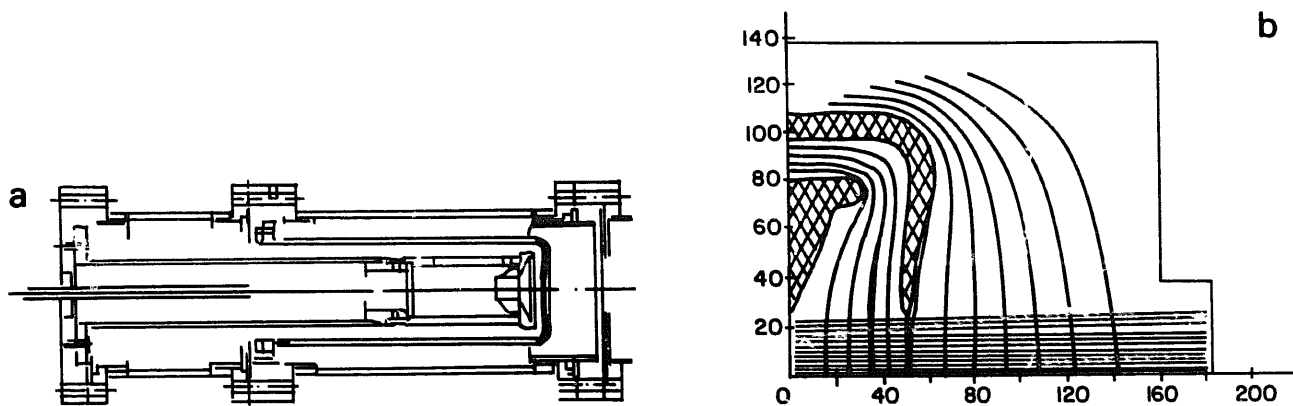


Fig. 2. (a) The injector Pierce gun design; and (b) the Herrmannsfeldt code simulation diagram.

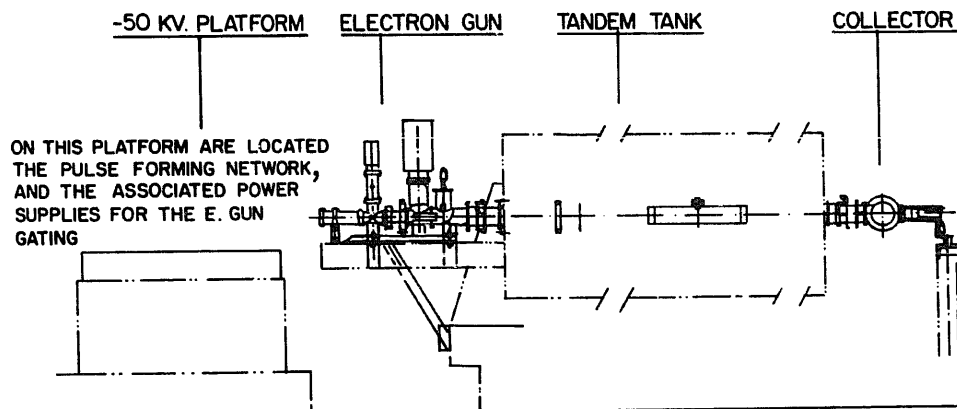


Fig. 3. FEL assembly side view: magnetic lenses.

four electrostatic deflection plates located between the two gun-end focussing coils allows for minor corrections of beam direction and angle. A simplified schematic of the FEL system is shown in fig. 3.

2.3. Diagnostics

Two wire-mesh diagnostic devices, one following the electron gun and the other before the collector, were incorporated in the system. Each wire is electrically isolated, with the outputs of all the wires simultaneously recorded in sample-and-hold circuits, then transferred to a personal computer via analog-to-digital converters and stored in its memory. This information can then be displayed on the computer monitor screen, showing the shape and intensity of the beam.

2.4. Beam current transmission

We are using an electron gun delivering 1.8 A of beam current, the intensity of which while passing through the differential pumping tube and the beam scraper is reduced to about 1.0 A entering the accelerating tube. This current passes undisturbed through the whole length of the accelerating tube, the terminal and 2/3 of the decelerating tube. About 75% of the beam reaches the collector, and we believe that with more careful choice of the beam-optics parameters we shall increase the recovery rate substantially.

2.5. The long-pulse effect

The long-pulse mode of operation offers interesting possibilities for the operation of free electron lasers, in particular it makes our facility uniquely suited to the study of high-coherence, single-mode operation, mode competition and nonlinear-regime (saturation) dynamics.

Thanks to the pioneering work of the Santa Barbara group [3], it is an accepted fact that an electron beam which passes the whole path of an electrostatic accelerator with beam energy recovery without interception does not cause any change in the terminal voltage. However, a beam recovery system with absolutely no interception of any fraction of the beam is yet to be achieved. Thus we observe that the terminal voltage of the Santa Barbara FEL exhibits a droop. The voltage promptly starts decreasing as soon as the beam current is switched on. The difference between the gun output and the collector input acts as a direct current load on the terminal (both gun and collector are situated inside the terminal). As long as this current load exceeds the terminal charging current, the terminal experiences a net discharging current resulting in the voltage droop. This droop is unfortunate since it changes the synchronism condition of the FEL during operation and re-

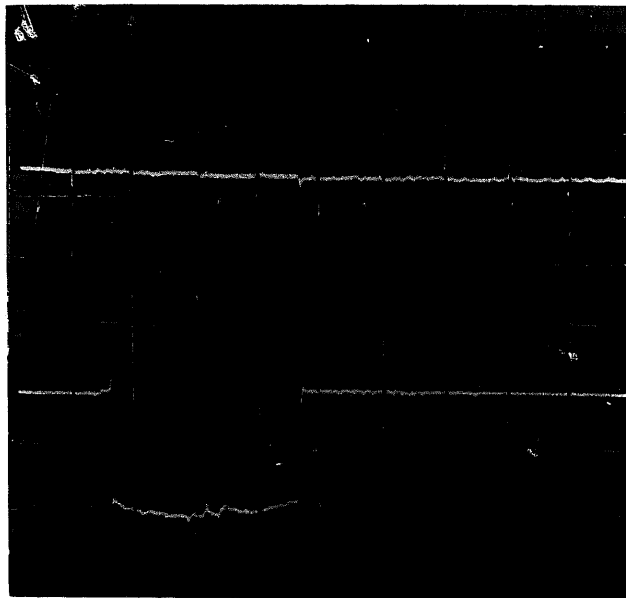


Fig. 4. The terminal-voltage behaviour as a result of a short (65 μ s) beam pulse (upper trace); $V_0 = 2.7$ MV; vertical scale = 6.4 kV/box; horizontal scale = 20 μ s/box. The lower trace represents the collector current; vertical scale = 100 mA/box.

duces the effective time available for mode competition at a given wavelength.

When operating our tandem electron accelerator, we have noticed that the charging effect of the beam hitting the last third of the decelerating tube does not effect the terminal voltage. In other words, the terminal voltage remains stable for at least milliseconds, as long as one does not hit the terminal directly. Fig. 4 displays the collector current (lower trace) and the terminal voltage (upper trace) measured recently with a newly installed e-gun pulser which turns the e-gun current on for a period of 65 μ s. In this experiment the terminal voltage was 2.7 MV. The measured collector current was 200 mA, while the current entering the accelerator was measured to be 400 mA; i.e. 200 mA (50%) of the current was incident internally, probably on the deceleration tubes. Despite the length of the current pulse and the high leakage current, there was no observable droop of the terminal voltage. This sets a low upper limit value on the voltage droop of the terminal, $\Delta V_T/V_T < 3 \times 10^{-4}$, set only by the measuring accuracy of the voltage terminal.

It should be noted that no long-term "afterpulse" of terminal voltage droop was observed in the recent experiment in a time scale of 1 s after the pulse. An improvement of the e-gun pulser electronic design eliminated the delayed voltage droop (after 20 ms) which was observed by us in earlier reported experiments.

We explain the high stability of the terminal in the positive-terminal mode of operation of the tandem

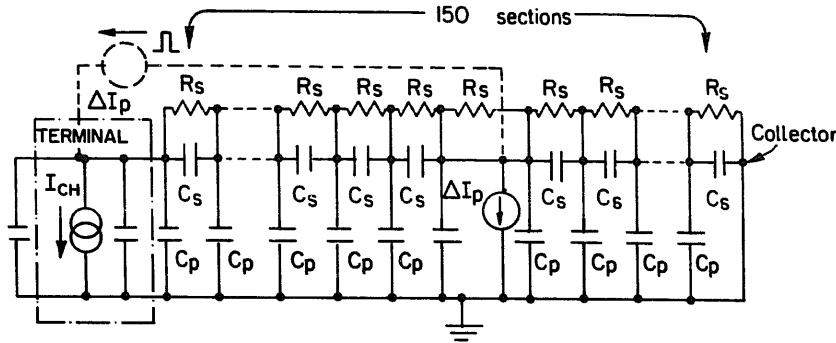


Fig. 5. The electronic equivalent circuit of the accelerator.

accelerator on the basis of the electronic equivalent circuit of the machine shown in fig. 5. According to this model, the capacitances between the electrode sections along the accelerating tubes and between these electrodes and the tank form a capacitance network which attenuates the voltage drop at the terminal due to charging of a remote capacitance section along the tube by incident beam leakage current. The continuous capacitive voltage divider network produces an attenuated terminal voltage drop given by

$$\Delta V_T = - \frac{\Delta I_p t}{2\sqrt{C_p C_s}} \left(1 - \sqrt{\frac{C_p}{C_s}} \right)^n, \quad (1)$$

where ΔI_p is the leakage current assumed in this model to impinge and charge a localized area on the deceleration tube n sections away from the terminal.

For the present configuration we assume $C_s = 110$ pF, $C_p = 1.3$ pF, $\Delta I_p = 0.2$ A, $n = 75$ (assumption of localized incidence of the beam leakage current at the center of the deceleration tube) and $V_T = 2.5$ MV. With these assumptions $\Delta V_T/V_T = 5 \times 10^{-5}$ for $t = 100$ μ s. The voltage drop will be small enough ($\Delta V_T/V_T = 5 \times 10^{-4}$) even with a long pulse of $t = 1$ ms.



Fig. 6. Typical picture of the wiggler magnetic field measured using the pulsed-wire method.

2.6. Wiggler testing and installation

We use a wiggler made of permanent magnets in a Halbach [11] arrangement, with $\lambda_w = 4.4$ cm; the individual magnets were selected using a Hall probe and assembled in a 75 cm long unit. We are presently in the process of adjusting the magnetic field profile, using the pulsed-wire method [12,13] and shimming the individual magnets accordingly. Fig. 6 shows a typical picture of the magnetic field measured by this method. This technique enables us to measure instantly the field integral of the whole wiggler along its z -axis (the relevant information) and it will be indispensable for measuring pulsed electromagnetic wigglers which we intend to use in the future. We are constructing the terminal section of the vacuum system which will contain the wiggler, resonator, beam diagnostics and associated mechanical adjustment systems. The pertinent electronics will be located inside the terminal and the control signals will be transmitted through fiber optics.

3. The proposed FEL research program

The main experimental effort will be directed towards the study of single-mode operation of FELs, mode competition dynamics, the saturation process and efficiency enhancement, multimode operation and the route to chaos. These aspects of FEL operation physics are the subject of extensive theoretical investigations with little experimental study. There is still debate on the conditions necessary for single-mode operation and whether single mode operation was unequivocally demonstrated in the only experiment attempted so far in UCSB [3]. The potential of the tandem electrostatic accelerator to operate with a long pulse duration (perhaps 100 μ s to 10 ms), which was explained in the previous section, makes it possible to launch a research program which will put the existing theory to test and will allow us to demonstrate unequivocally single-mode operation, to study the mode competition and satura-

tion process, and go further to study multimode and chaotic operation.

The basic theory of mode competition in an FEL oscillator is almost independent of the operation wavelength. However, the parameters which affect the physics of the mode competition process are dependent on the operating wavelength as well as on the technological capabilities, which are also dependent on wavelength. By applying various wiggler and optical resonator technologies and varying the accelerator energy, we have the possibility to operate an FEL in the entire mid-IR, far-IR and mm-wavelength regimes. Three schematic designs corresponding to operation at 3 mm, 300 μm and 15 μm wavelengths are described in the subsequent subsections and compared in table 1. We have determined from considering both minimizing the technical difficulties and attaining optimal parameters for studying the mode competition process, that it is preferable to start the experimental work at long wavelengths. However, in order to study the physical problem comprehensively it is desirable to perform additional experiments, changing the operating wavelength and other parameters of the FEL.

3.1. Planned experiments of spectral analysis for study of mode competition

We base our estimates of mode competition parameters on the theory of Antonsen and Levush (AL) [7]. The main necessary condition that must be satisfied in order to attain single-mode operation (assuming the oscillation threshold current is exceeded) is that the mode competition time is long enough to assure establishment of a single dominant mode. This time is estimated by

$$t_{\text{sm}} \sim \frac{1}{\epsilon^2} t_c, \quad (2)$$

where t_c is the cavity decay time $t_c = Q/\omega$ (Q is the quality factor of the resonator). The slippage parameter

ϵ is defined as the ratio between the slippage time and half of the round-trip time:

$$\epsilon = \frac{2L_w/v_{z0} - L_w/v_g}{t_{\text{rt}}}, \quad (3)$$

where v_{z0} is the axial velocity of the electron beam, v_g is the group velocity of the radiation (in an open resonator $v_g = c$, but in a waveguide $v_g < c$), t_{rt} is the round-trip time of a radiation wave packet inside the cavity (in an open resonator $t_{\text{rt}} = 2L_c/c$).

This criterion is in debate, and was not satisfied in the UCSB FEL experiment. Being able to satisfy this criterion in some of the experiment will allow us to determine the validity of the AL theory, and gives credence to our expectation to be able to demonstrate unequivocal single-mode operation. One might add that, if the condition $t > t_{\text{sm}}$ [eq. (2)] cannot be satisfied in some experiments, it may still be possible to enhance the mode competition process and single-mode establishment by special schemes like seed radiation injection.

To resolve the debate whether single-mode operation can take place before the condition $t > t_{\text{sm}}$ [eq. (2)] is satisfied, or that the laser operates then at a phase-locked multimode condition [7], one can use quite routine experimental equipment. Since according to the AL theory the entire spectral region of net FEL gain ($\Delta\omega/\omega \sim N_w^{-1}$) oscillates during this period, a simple grating spectrometer with resolving power N_{grating} suffices, provided that

$$N_{\text{grating}} > N_w. \quad (4)$$

This condition can be easily satisfied considering that in practice $N_w < 100$ and $N_{\text{grating}} > 100$ are typical.

In order to resolve between the different longitudinal modes, higher resolution may be necessary corresponding to the spacing between the modes

$$\frac{\Delta\omega}{\omega} < \frac{1}{N_w} \epsilon. \quad (5)$$

Since $\epsilon \ll 1$ one may have in some cases difficulties to

Table 1
FEL experiments with the tandem FEL

Experiment	Type of FEL	E [MeV]	λ_w [cm]	λ	Gain [%]	Loss [%]	Net [%]
(1) mm	Internal waveguide resonator	5	4.4	3 mm	100	20	80
(2) FIR	Internal waveguide resonator	5.5	4.4	300 μm	45	15	30
(3) MIR	External open resonator, optical klystron	5.5	0.4	15 μm	70	5	65

Table 2
Mode competition parameters of FEL experiments

Experiment	χ	$1/\epsilon$	$1/\epsilon^2$	t_c	t_{coh}	t_{SM}
(1) mm	1–5	–17	278	3–12 ns	51–200 ns	0.8–3.3 μ s
(2) FIR	1–3	147	2.1×10^4	5–15 ns	0.7–2.2 μ s	100–300 μ s
(3) MIR	1–14	1875	3.5×10^6	43–600 ns	0.08–1.1 ms	0.15–2.1 s

resolve single modes during the oscillation buildup process. However, in steady-state operation, homodyne and heterodyne techniques will make such measurements possible.

In the following subsections we detail the design considerations of the three different experiments. The technical parameters and the parameters of the mode competition theory are summarized in a comparative way in tables 1 and 2. We note that the parameter examples of tables 1 and 2 do not represent an optimal choice. A detailed design and parameter optimization study still needs to be done as part of the research program. However, the examples serve the purpose of proving the possibility of obtaining desirable and interesting experimental parameters even before a design optimization step was deployed.

3.2. Millimeter-wave experiment

The first experiments are proposed to be carried out in the mm wavelength regime. The operating parameters of an FEL experiment at $\lambda = 3$ mm are listed in line 1 of table 1, and the corresponding mode competition parameters of this experiment are listed in line 1 of table 2.

Since at this long wavelength the diffraction effect is substantial, we chose to design the optical resonator as a closed (waveguide) internal resonator (namely, the entire resonator is placed inside the HV-terminal and its length is about the length of the wiggler, $L_c \approx L_w$). Operating in a waveguide results in some very interesting features from the points of view of FEL design and FEL physics, and particularly the physics of mode competition. The operating wavelength in a waveguide FEL is determined by the intersection of the waveguide mode dispersion curve and the “wiggler-momentum-shifted” e-beam dispersion line (fig. 7). For each transverse mode there can be two solutions [14]

$$\lambda_{1,2} = \frac{\lambda_w}{\beta_z \gamma_z^2} \left[1 \pm \sqrt{\beta_z^2 - \left(\frac{\lambda_w}{\gamma_z \lambda_{co}} \right)^2} \right]^{-1}, \quad (6)$$

where λ_{co} is the cutoff wavelength of the transverse mode.

We have examined various kinds of waveguides, including parallel (curved) plates, circular and rectangular waveguides and a variety of modes. The gain and

loss (including mirror loss) values are typical values calculated for an $L_w = 75$ cm long wiggler, copper waveguide and $\bar{a}_w = 0.5$. The nature of the waveguide FEL wavelength expression (6) allows flexibility in design. With the presently available wiggler of period $\lambda_w = 4.4$ cm, operating the FEL at $\lambda = 3$ mm is possible at the higher-intersection solution of fig. 7 with a low-energy beam ($E \approx 2$ MeV) and high-cutoff mode, or at the lower intersection with a high-energy beam ($E \approx 5$ MeV) and a low-cutoff mode. Because of the difficulty of transporting the e-beam at lower energy (when the emittance is larger), the second choice would be usually preferable.

The mode competition parameters of table 2, line 1, were calculated assuming operation at the lower intersection with a 5 mm radius circular-waveguide mode TM_{11} . The higher energy required for operating at this point is a technical advantage, because the e-beam transport through the accelerator is better at higher energy. In addition to the technical advantage, this solution is of particular interest from the point of view of the physics of mode competition and coherence development. At the lower intersection the group velocity of the radiation is smaller than the speed of the

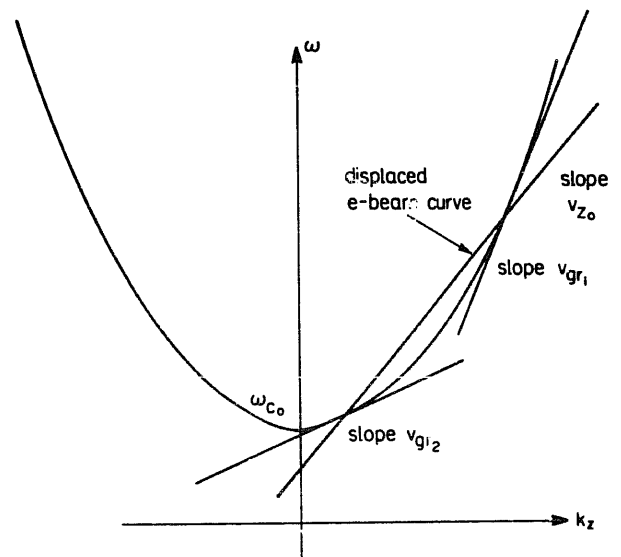


Fig. 7. Intersection of the dispersion curve of the electromagnetic mode with the wiggler momentum-shifted e-beam line $k_z = \omega/v_z - k_w$.

electrons (which is the reason for the negative sign of ϵ). This means that the radiation wave packets emitted by the electrons propagate backwards relative to the electrons which generate them, so that the phase-locking process is opposite to the regular case. This can be demonstrated, for instance, by injecting a short pulse of seed radiation and observing its coherent widening and backdrift in a negative time direction relative to the leading original pulse.

We expect that the AL theory should apply to the $\epsilon < 0$ case, but careful examination of the implications of this case is advisable. The more interesting case, where the two solutions of the dispersion equation coincide and degenerate into one single double solution (the e-beam line is tangential to the radiation curve in fig. 7) requires reformulation of the theoretical model. In this interesting case, the radiation group velocity equals the electron velocity $v_g = v_z$ and $\epsilon = 0$. Consequently, any information about the oscillation phase cannot be propagated from one electron to the others. A neutral-stability situation may evolve in which the coherence of the oscillator will be determined only by the initial conditions (possible injection) and by the spontaneous-emission radiation. Another interesting aspect of the existence of a double solution in the FEL dispersion equation in a waveguide is the possible competition between the waves that correspond to these two solutions. Choice of parameters and discriminative losses can make it possible to produce above threshold conditions for both solutions. Whether they can both exist stably and the nature of the physics of their competition is an open theoretical problem. Two frequencies operation is also interesting for some scientific applications.

The mode competition parameters of table 2 are quite favourable for the mm wavelength experiment. The coherence establishment time t_{coh} and the single-mode establishment time t_{sm} are in the submicrosecond and microsecond time ranges. The coherence time t_{coh} is the lower limit of the time it takes the phase information (established for example by momentary seed radiation injection) to propagate and dictate its value to the fields in the entire cavity. The single-mode time t_{sm} is the estimated time for a single mode to dominate over other modes developed in the cavity. Both times can be experimentally measured and are substantially shorter than the pulse duration (100 μs –10 ms) expected to be possible in the proposed experimental setup.

3.3. FIR experiment

The far-infrared (FIR) regime is a natural operating regime for an FEL based on an accelerator with $E \approx 5$ MeV. However, the gain levels that can be obtained (table 1) and the mode competition parameters (table 2) are also less favourable than in the millimeter wavelength. For this reason the FIR experiment is planned

to be carried out only after operating at the mm wavelengths.

Little has to be changed in the accelerator, wiggler and resonator in order to operate the FEL in the FIR regime. Indeed, the same configuration assumed in experiment 1 (TM₁₁ mode in a 5 mm radius circular waveguide, $E = 5$ MeV, $\bar{a}_w = 0.5$) can operate also at $\lambda = 300 \mu\text{m}$. This is simply the higher-frequency solution of eq. (6) (the upper intersection in fig. 7). It may be possible to operate the FEL at two wavelengths (300 μm and 3 mm), though it is not clear if such dual oscillation is stable.

The gain and mode competition parameters of experiment 2 were calculated assuming a parallel (curved) plates waveguide of 4 mm \times 6 mm cross section, $L_w = 75$ cm, $\bar{a}_w = 1$ and $I_0 = 1$ A. Since the wavelength is shorter than in the previous example, diffraction effects are less important and it may be possible to design an open-resonator experiment, or a weakly guiding resonator. At this short wavelength the waveguide will be highly overmoded and mode competition between the transverse modes may be a substantial effect which requires experimental study and theoretical understanding.

The coherence time t_{coh} and single-mode establishment time in this example are still below the millisecond range and therefore substantial mode competition studies can be carried out in this wavelength.

3.4. Mid-IR experiment

Experiment number 3 (mid-IR: $\lambda \approx 15 \mu\text{m}$) is based on an open external resonator. Since the wavelength is short enough to minimize diffraction effects, the optical beam may remain narrow enough along the entire accelerator length. Consequently, the open-resonator mirrors can be placed at ground potential at the ends of the accelerator (see fig. 8). This provides a substantial design and control advantage. Alignment and radiation outcoupling are simple. Furthermore, operation at this wavelength regime can be aided by available mid-IR optics, detectors, sources and other components.

Realization of the mid-IR FEL requires development and integration of two new technologies, namely the

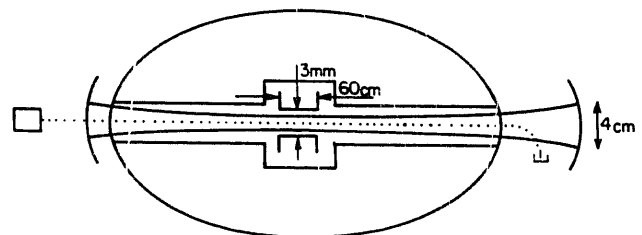


Fig. 8. Schematic diagram of the mid-IR FEL optical resonator.

microwiggler and the optical klystron. Furthermore, line 3 of table 2 indicates its limitations for studying single-mode operation. In particular, we do not know if pulses as long as $t_{sm} \approx 1$ s will ever become available. On the other hand, this system provides some new features for the study of mode competition and saturation effects. Theory development will be required to analyze this case of optical klystron which is different from FEL. Consequently, there is also great uncertainty to what extent the parameters calculated from the existing theory are indicative.

The basic design parameters of the mid-IR FEL are as follows:

Beam energy $E = 5\text{--}6$ MeV ($\gamma = 11\text{--}13$),

Microwiggler period $\lambda_w = 4$ mm,

Microwiggler field $\bar{B}_w = 1$ kG,

Dispersive magnet field $B_d = 6$ kG,

Optical-klystron total length $L = 60$ cm.

These parameters result in an operating-wavelength range of $12\text{--}17$ μm (for $E = 5\text{--}6$ MeV; see table 1).

The parameters listed above result in an FEL single-path incremental gain of

$$G^{\text{FEL}} - 1 = 1.21\%/A.$$

Using an optical-klystron design with bunching, dispersion and radiation section length ratio 1:3:1, a gain enhancement factor of $\times 60$ is possible with the design parameters listed above and the same total length. This results in gain values

$$G^{\text{OK}} - 1 = 72\%/A.$$

which leaves a wide margin for optimal FEL system design.

3.5. Long-range future experiments

The spectral feature of the straight-geometry tandem FEL configuration (high-quality e-beam, quasi-cw operation, high average power and efficiency) make our facility an interesting subject for future FEL research development and applications. Future FEL experiments and FEL applications are under consideration as a follow-up to the main experimental program of coherence and mode competition studies.

The expected high-coherence and quasi-cw operation may bring about specialized spectroscopic applications of the FEL facility in the IR regime. Use of photocathode emitter guns (not limited in pulse duration and repetition rate as in rf-linacs) may extend the applicability of this facility.

Laser-pumped FELs, which were proposed by a number of groups, require very high-quality electron beams. To the extent that technological developments will make this concept realizable, it can be argued that straight-geometry tandem accelerators (possibly with photocathode emitters) can provide the highest elec-

tron-beam quality and therefore would be the preferable choice for the development of such devices. An FEL based on a 6 MeV tandem accelerator with a CO₂ laser (10.6 μm) or Nd-Yag laser (1.06 μm) would operate in the UV-soft-X-ray regime if sufficient pump intensity and beam quality can be reached.

Finally, we contemplate operating future experiments at the high-gain collective regime. This can be made possible by eliminating one accelerator tube section on each side of the HV terminal of the accelerator. This will cut down the accelerator voltage to 3 MV but will provide room for a long wiggler, up to 6 m long.

Acknowledgements

It is our pleasure to thank the Reuben Meyer Fund of Singapore for the generous financial support of our project. The Israeli Ministry of Science contribution is also gratefully acknowledged. Barry Freedman of Brandeis University, who spent the summer with us, was extremely helpful in our recent experimental and computer simulation efforts.

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