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STATUS OF THE REHOVOT EN TANDEM ACCELERATOR FREE ELECTRON LASER

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The EN tandem electrostatic accelerator at the Weizmann Institute of Science has been converted into an electron accelerator with a source intensity of 2 A and with beam current recovery. The tandem FEL configuration, in which the wiggler is located in the high voltage terminal, allows for stable, long pulse operation. Two wire-mesh diagnostic systems for monitoring of the beam shape have been installed; one between the electron gun and the entrance to the accelerating tube, the other between the exit from the decelerating tube and the beam collector. We believe to be able to operate our machine with pulse lengths of the order of 1 ms without terminal voltage droop during such a pulse. At present, when operating with 5 μs pulses, only after 10–20 ms there is a noticeable terminal voltage droop. A beam current of 0.8–1.0 A enters the acceleration tube and 75% of it can be presently recovered at the collector. We expect to improve on this figure considerably. The long pulse operation mode, for which we are striving, offers interesting possibilities for the operation of free electron lasers, in particular demonstrating high coherence, single mode operation. A three year FEL experimental study program based on the tandem accelerator was recently proposed.

1. Introduction

The model EN tandem electrostatic accelerator is ideally suited for transformation into a free electron laser. The 2 MV up to 6 MV standard operation range is appropriate for an FEL with our present wiggler and for the wavelength at which we plan to operate it initially (the mm regime). This range of operation was chosen mainly for practical reasons; we have diagnostic equipment in this range available, we can operate the machine with a short ($l = 75$ cm) wiggler and no drastic changes in the accelerator structure are needed. At a later stage we would like to proceed into the mid-IR range, using probably a microwiggler; a possibility of operating with shorter accelerating tubes, in order to increase the terminal length and thus accommodate a longer wiggler, is being also considered.

We have followed quite closely our original proposal [1] and the design [2] presented at the Berlin conference. The accelerator originally designed for ion beam currents of microamperes was converted into a high current (1.0 A) electron accelerator operating in the depressed collector mode.

In the course of preliminary tests it was observed that the accelerator could operate in high current mode with stable HV terminal voltage for periods as long as milliseconds independent of the transport efficiency of the electron beam. This would make our pulse two orders of magnitude longer than the present state of the art of pulsed FELs. In addition to offering important advantages, this particular feature distinguishes the proposed tandem electrostatic accelerator FEL scheme, from the only other ES-FEL experiment demonstrated so far (in UCSB), which was based on a different configuration. This long pulse feature makes it possible to propose the construction of a quasi-CW FEL and the 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 in FEL conference

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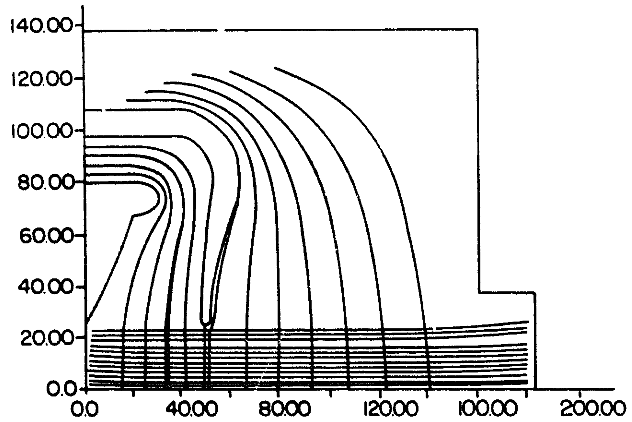

Fig. 1. The Herrmannsfeldt code simulation diagram.

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.

2. Electron gun

The ion source 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 Herrmannsfeldt code simulation is shown in fig. 1. The features of the gun are: an operating voltage of 50 kV, the control electrode voltage of −6 kV for current cut-off 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.

3. Tandem machine modifications

The gas stripper tube 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 focusing coils were installed, two of them (see fig. 2) between the electron gun and the accelerating tube and the other two between the decelerating tube and the collector (fig. 3). A set of 4 electrostatic deflection plates located between the two gun-end focusing coils allows for minor corrections of beam direction and angle. A simplified schematic of the FEL system is shown in fig. 4.

4. Diagnostics

Two wire-mesh diagnostic devices, one following the electron gun and the other before the collector, were

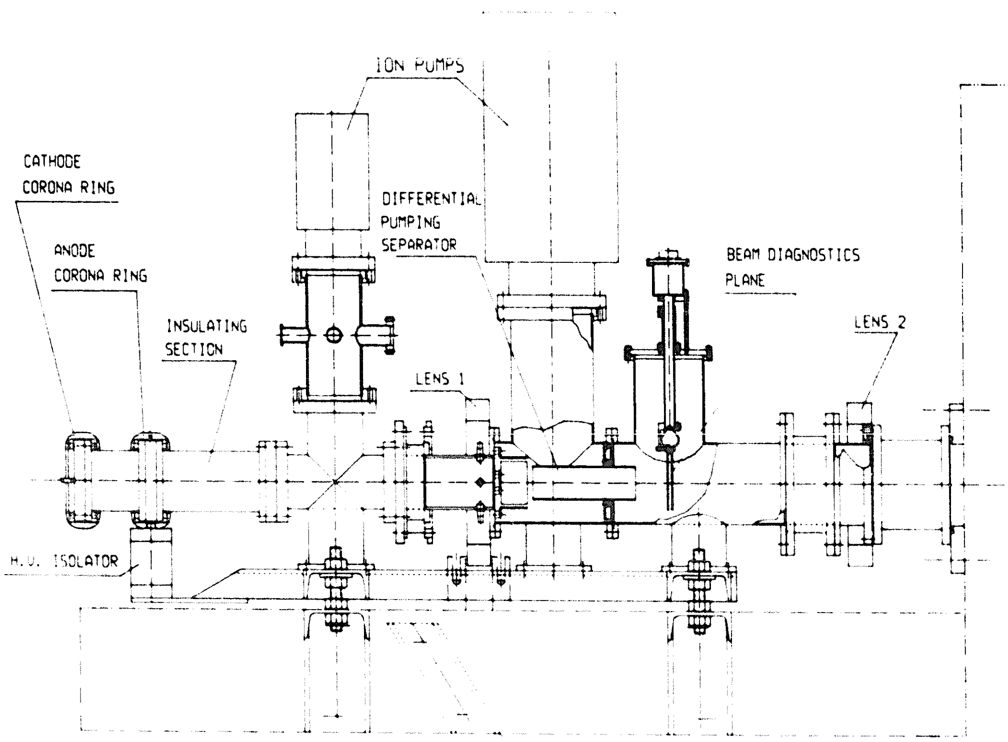

Fig. 2. The electron gun injector and its associated magnetic lenses.

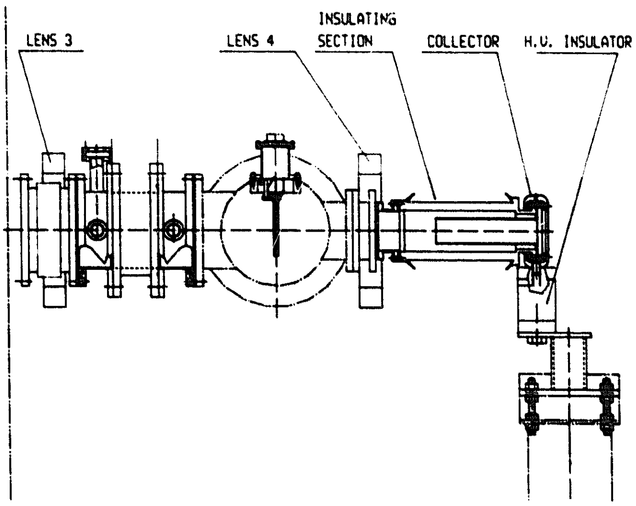

Fig. 3. The collector end with its magnetic lenses.

incorporated in the system. Each wire is electrically isolated, the outputs of all the wires are being 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, showing the shape and intensity of the beam.

5. Computer simulations

The electron beam dynamics was followed by a computer simulation code from the gun exit to the collector. For the regions inside the accelerator the code solves an envelope equation, which takes into account the external electric field, the self-field of the beam and the beam emittance [10]. The effect of magnetic lenses was calculated by using a matrix formulation. The beam envelope calculations and kinetic model calculations were compared and found to be in very good agreement. Fig. 5 shows one of those simulations for the terminal voltage of 3.84 MV and focusing coils of approximately 1600 ampere turns.

6. 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 $\frac{3}{4}$ of the decelerating tube. About 75% of the beam reaches the collector; we believe that with more careful choice of the beam optics parameters we shall increase the recovery rate substantially.

7. 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 fit for studying 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

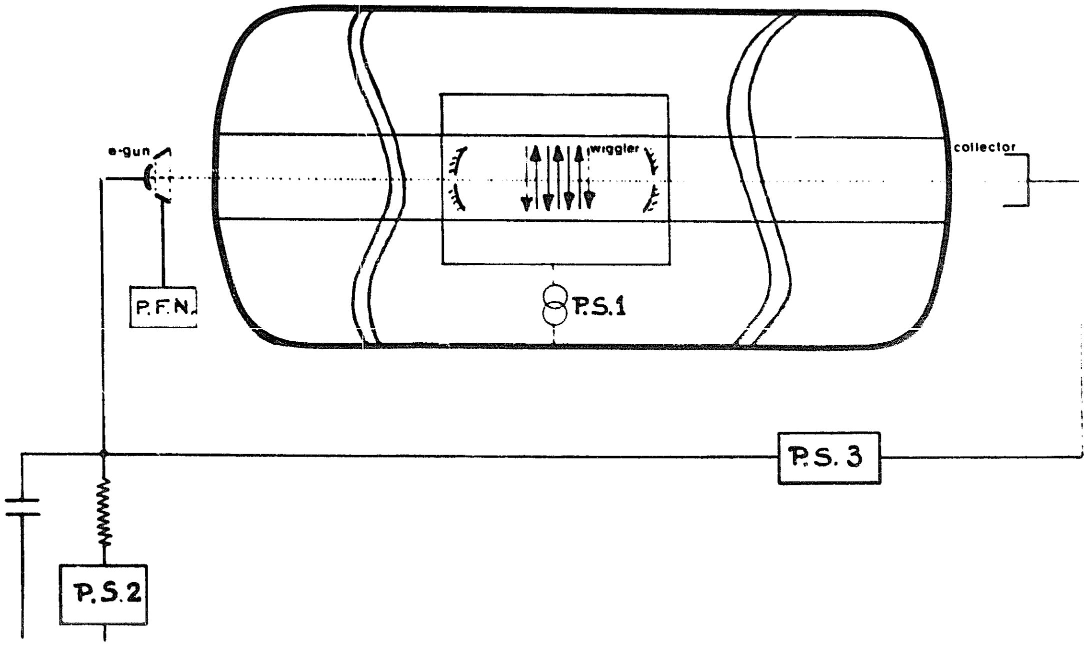

Fig. 4. A simplified schematic of the tandem accelerator including the FEL.

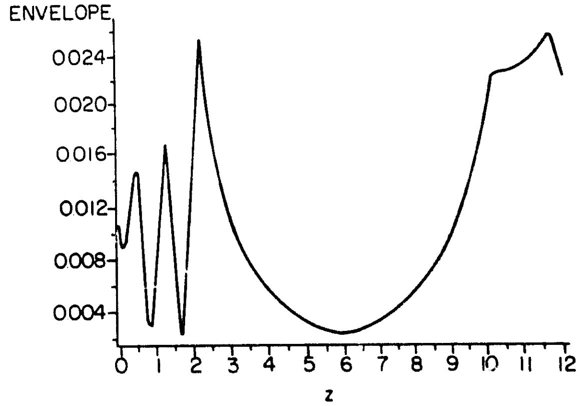

Fig. 5. The electron beam path simulation using computer code.

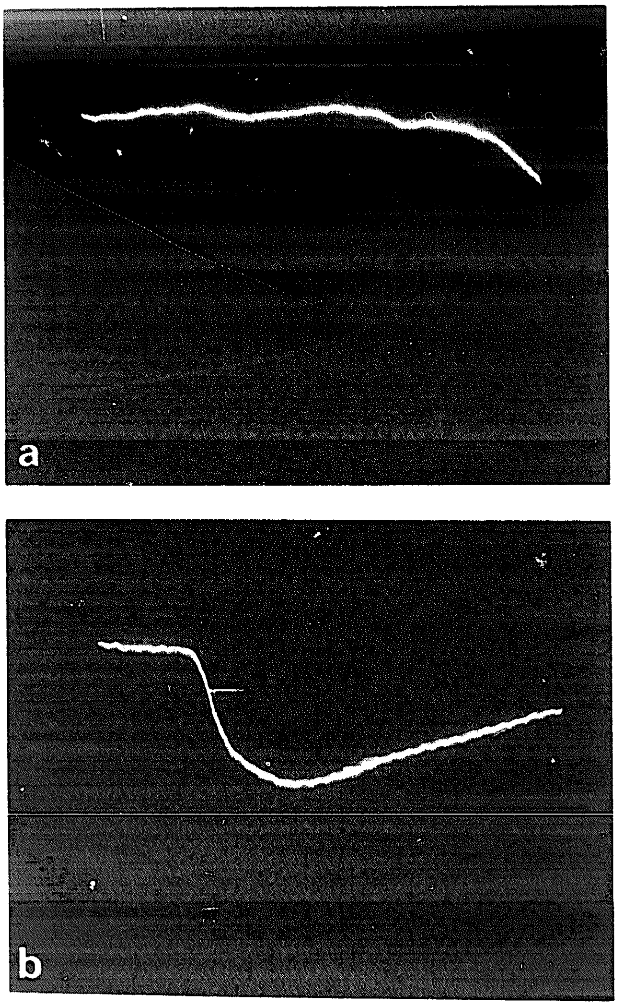

Fig. 6. The terminal voltage behaviour as a result of a short (2 μs) beam pulse. (a) V_0 = 3.8 MV; vertical scale – 34 kV per box; horizontal scale – 1 ms per box; (b) V_0 = 3.8 MV; vertical scale = 136 kV/box; horizontal scale = 10 ms/box.

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 starts decreasing promptly as soon as the beam current is switched on. The difference between the 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 reduces the effective time available for mode competition at a given wavelength.

When operating the tandem electron accelerator, we have noticed, that the charging effect of the beam hitting the last third of the decelerating tube effects the terminal voltage only milliseconds after its occurrence. In other words the terminal voltage remains stable for milliseconds, as long as one does not hit the terminal directly. Fig. 6. shows the terminal voltage after a beam pulse; one can see that only after about 10 ms some voltage droop of the terminal could be noticed. Thus in our configuration, i.e. the electron gun at ground potential and the wiggler inside the high voltage terminal we may be able to produce very long electron beam pulses with stable terminal voltage.

8. The principle of the long pulse effect

In the case of a tandem accelerator, where the electron gun and the collector are not in the terminal, the fact that not all of the beam is recovered has no immediate effect on the terminal voltage except for the current intercepted directly at the terminal. However, the small geometrical emittance of the beam at the terminal allows it to pass through the terminal and the wiggler with little or no interception and we can operate the machine in an essentially droop-free mode in the long pulse mode, even with a current recovery of 75%.

This phenomenon of an FEL operating for milliseconds, undisturbed by beam loss may seem strange. Where does the energy for the FEL operation come from? Why does the disturbance arrive at the terminal only after that long time? Can one explain the shape and magnitude of the delayed terminal voltage response? We are beginning to have a quantitative understanding of the process. Suppose that the beam loss occurs somewhere at the decelerating tube. (The scenario of a beam loss at the accelerating tube is similar.) When the beam hits the deceleration tube at any point it discharges the tube electrodes at the interception point. If the process goes on long enough then the voltage of this point becomes negative enough to repel the beam and it will impact an electrode nearer the terminal and start discharging it too. This process can take a long time since there is a large amount of stored energy in the many tube electrodes.

While the beam is discharging the tube electrodes, the terminal voltage is hardly affected. The electrical circuit of the tube acts as an attenuator consisting of many capacitive voltage divider sections. These sections are composed of series and parallel capacitances, the series being the interelectrode capacitances and the parallel – the capacitances between the tube and the tank.

We have observed a delay of typically 10 to 90 ms between the time a beam pulse hits the deceleration tube until the voltage of the terminal responds. The response was then quite large, as much as one megavolt. This large voltage drop is much more than one expects from the charge in the beam pulse acting on the terminal capacitance. It is probably the result of some sparking of the tube electrodes triggered by the beam. However, the voltage of the terminal was very stable up to the time when the large disturbance arrived, allowing for a stable FEL operation.

It remains yet to be seen what is the undisturbed operating time at the terminal when one works under standard operating conditions, including millisecond long pulses and a beam recovery fraction of about 90% or better. We expect that the tandem configuration will allow for times as long as a milisecond and longer.

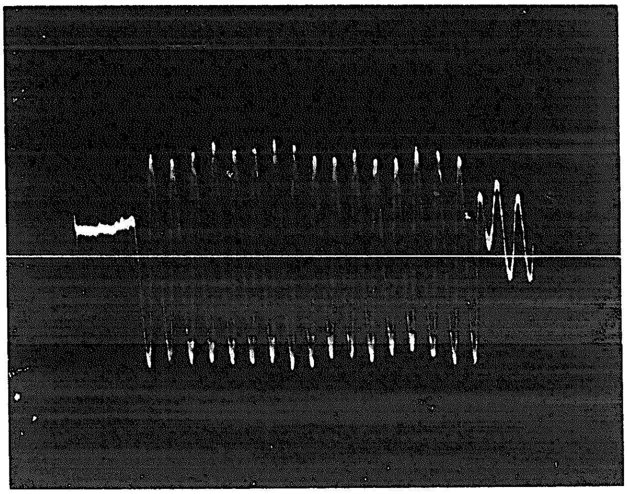

Fig. 7. Typical picture of the wiggler magnetic field measured using the pulsed-wire method.

9. Wiggler testing and installation

We use a wiggler made of permanent magnets in a Halbach [11] arrangement, its $\lambda_w = 4.4$ cm; the individual magnets were selected using 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. 7 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 to which will be transmitted through fiber optics.

10. Conclusions and future plans

The progress in the system construction looks very promising, especially the new feature of a long pulse operating mode is quite exciting. We hope to be ready for installation of the wiggler by the end of this Summer. In the meantime we want to check the shape and the size of the the beam in the terminal region by having a viewer and a system of windows and mirrors. During the next year we should be able to have the machine operational or at least be able to detect the spontaneous emission.

References

[1] E. Jerby, A. Gover, S. Rushin, H. Kleinman, I. Ben-Zvi, J.S. Sokolowski, S. Eckhouse, Y. Goren and J. Shiloh, Nucl. Instr. and Meth. A259 (1987) 263.

[2] I. Ben-Zvi, A. Gover, E. Jerby, J.S. Sokolowski and J. Wachtel, Nucl. Instr. and Meth. A268 (1988) 561.

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

[4] I. Kimel and L.R. Elias, Phys. Rev. A38 (1988) 2889.

[5] I. Kimel and L.R. Elias, Phys. Rev. A35 (1987) 3818.

[6] Ya.L. Bogomolov, V.L. Bratman, N.S. Ginsburg, M.I. Petelin and A.D. Yunakovsky, Opt. Commun. 36 (1981) 209.

[7] T.M Antonsen, Jr and B. Levush, Phys. Rev. Lett. 62 (1989) 1488.

[8] Proc. 10th Int. Conf. on FEL, Jerusalem, Israel, 1988, Nucl. Instr. and Meth. A285 (1,2) (1989); a. Round table discussion on coherence of FEL (K.J. Kim, chairman); b. Theoretical session on single mode and mode competition (R. Warren, chairman).

[9] W.B. Herrmannsfeldt, Nucl. Instr. and Meth. 181 (1984) 1208.
[10] J. Lawson, The Physics of Charged Particle Beams (Clarendon Press, London, 1977).
[11] K. Halbach, Nucl. Instr. and Meth. 187 (1981) 109.
[12] R.W. Warren, Nucl. Instr. and Meth. A272 (1988) 257.
[13] O. Shahal and R. Rohatgi, Proc. 10th Int. Conf. on FEL, Jerusalem, Israel, 1988, Nucl. Instr. and Meth. A285 (1989) 299.