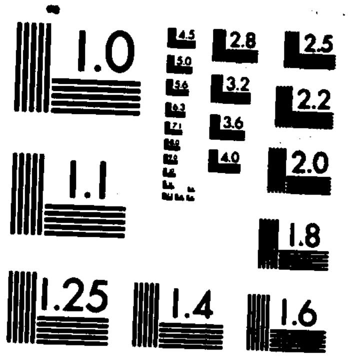
AD-A164 471 ELECTROSTATIC ACCELERATOR FREE ELECTRON LASERS(U) 1/1
CALIFORNIA UNIV SANTA BARBARA QUANTUM INST L R ELIAS
1983 QIFEL-004/80 N00014-80-C-0308

UNCLASSIFIED F/G 20/5 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Unclassified/Unlimited

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(12)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER No. 4	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Electrostatic Accelerator Free Electron Lasers		5. TYPE OF REPORT & PERIOD COVERED Technical Report 10/01/82 - 09/30/83
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Luis R. Elias		8. CONTRACT OR GRANT NUMBER(s) N00014-80-C-0308
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of California Quantum Institute Santa Barbara, CA 93106		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61153N; RR011-07-06; NR603-001
11. CONTROLLING OFFICE NAME AND ADDRESS ONR 1030 E. Green St. Pasadena, CA 91106		12. REPORT DATE 1983
		13. NUMBER OF PAGES 17
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified/Unlimited
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Published in The Free Electron Laser, ed. S. Martelluci, A. Chester, p. 617, Plenum Press 1983.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Electrostatic, Accelerator, Lasers.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The present paper addresses the problem of increasing the power and efficiency of free electron lasers from a point of view which is fundamentally different from any known schemes. The schemes discussed here are based on the utilization electron lasers for comercial of laboratory applications. Three schemes will be discussed here: a) short pulse operation with no energy recovery, b) CW single-stage operation with energy recovery and c) CW two-stage operation with energy recovery. Also, a review is made of the electron beam quality required by the FEL.

DD FORM 1 JAN 73 1473

Unclassified/Unlimited

SECURITY CLASSIFICATION OF THIS PAGE

ELECTROSTATIC ACCELERATOR FREE ELECTRON LASERS*

Luis R. Elias
Quantum Institute
University of California
Santa Barbara
93106

QIFEL004/80

---

*Research supported in part by the U.S. Office of Naval Research Contract No. N000-14-80-C-0308 1/81.

INTRODUCTION.

The amplification of short wavelength coherent electromagnetic radiation by relativistic electrons moving through a spatially periodic transverse magnetic field was first demonstrated at Stanford University [1]. These experiments were carried out using the bunched electron beam emerging from a radio frequency linear accelerator. Although the electron beam quality was ideally suited to study the most important operating characteristics of the free electron laser, the small amount of available average electron beam current coupled with only a small laser extraction efficiency contributed to limit both the amount of average laser power produced (P=0.5 watts) and the overall operating efficiency of the device (e<0.1%).

Since the Stanford experiments a considerable amount of work has been done to study various schemes directed toward the development of efficient high power free electron lasers. In some of the schemes high single pass laser extraction efficiency is pursued using for example variable parameter wigglers [2], constant period wigglers consisting of only a few magnet periods [3] and constant period gain-expanded wigglers [4]. In other schemes the electron beam is recirculated several times through the laser interaction region [4,5] to increase total overall efficiency while retaining the characteristically small single pass efficiency of a constant period wiggler.

The present paper addresses the problem of increasing the power and efficiency of free electron lasers from a point of view which is fundamentally different from the schemes mentioned above. The schemes discussed here are based on the utilization electron lasers for commercial or laboratory applications.

Three schemes will be discussed here: a) short pulse operation with no energy recovery, b) CW single-stage operation with energy recovery and c) CW two-stage operation with energy recovery. Also, a review is made of the electron beam quality required by the FEL.

ELECTROSTATIC ACCELERATOR FEL WITH NO ENERGY RECOVERY.

The technology of high-voltage electrostatic accelerators is now well established. Since the 1950's these machines have been operated quite reliably to produce very high quality continuous beams of electrons or ions in the medium voltage range from 1 MV to 25MV. The maximum DC beam current (I_B) that can be extracted during conventional operation from these devices is entirely determined by the maximum amount of charging current (I_C) required to maintain the HV terminal charged at constant electric potential. Extracting more beam current than the charging current ($I_B > I_C$) results in a situation whereby the electric potential of the high-voltage terminal and hence the electron's kinetic energy will decrease steadily with time. During normal operation (no energy recovery) these devices are capable of generating on a steady state basis from a few tens of milliamps of beam current at low votage to a few hundred microamperes at high voltage. A schematic diagram of a single stage free electron laser using an electrostatic accelerator without electron beam recovery is shown in Figure 1.

Assuming that I_C is the charging current reaching the high voltage terminal and I_B is the electron beam current extracted from the accelerator, then the rate of change of voltage with time can be readily calculated as follows

$$\frac{dV}{dt} = - \frac{[I_B - I_C]}{C} \tag{1}$$

where C is the electrical capacitance to ground of the high-voltage terminal. Typically C=200 picofarad. For constant wavelength operations, the free electron laser operating in the single particle regime requires an electron beam whose energy spread is smaller than the energy width of H's gain curve. This requirement imposes a maximum acceptable drop in the HV electrostatic potential of

$$\left[\frac{\Delta V}{V}\right]_{MAX} = \frac{1}{2N} \tag{2}$$

where N is the number of FEL wiggler periods. Equation (1) and (2) can be combined to yield a value for the maximum electron pulse length that can be used with a free electron laser operating in this mode:

$$[\Delta t]_{MAX} = \frac{CV}{2N(I_B - I_C)} \tag{3}$$

Before another electron pulse can be initiated, the accelerator HV terminal value must be recharged to its initial potential. The charging rate is given by

$$\frac{dV}{dt} = \frac{I_C}{C} \tag{4}$$

The total recharging time can thus be calculated combining equations (2) and (4) to obtain $[\Delta t]_{CH} = CV/2NI_C$.

accelerators this is done in a straight forward way as shown in Figure 2.

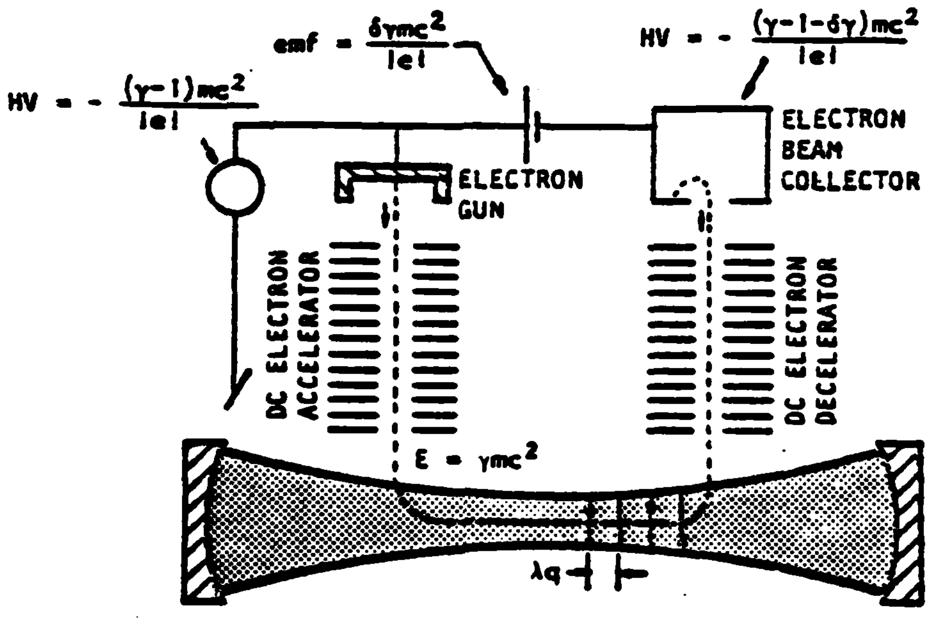


Figure 2. An electrostatic accelerator FEL operating with electron beam energy recovery.

After interacting with the FEL the spent electron beam's kinetic energy is reduced from a few megavolts to a few kilovolts by the electrostatic decelerating column shown in the figure. Subsequently, the relatively low kinetic energy beam enters the electron charge collector where the electrons are separated according to energy and captured by the collector surfaces with minimum production of heat or ionizing radiation. The technique of recovering electron beam energy by means of "depressed collectors" is used frequently with many modern microwave tubes as discussed by Rechtel [8].

The battery shown between the cathode and collector replaces increased from $[\Delta t]$max with no energy recovery to 10 times $[\Delta t]$ max when 10% of the beam current is not recovered. Also, in this example the average power and overall efficiency has also been increased by a factor of 10. The ideal situation is, of course, to recover all of the electron beam current.

Table II summarizes the possible performance of single-stage electrostatic accelerator free electron lasers having various levels of electron beam energy and current recovery. The efficiency figure is defines as follows: $e = \frac{\text{AVERAGE POWER}}{\text{PEAK POWER}} \times 100\%$.

Table II. Performance of electrostatic accelerator free electron lasers with various degrees of energy recovery. (V=5MV, C=200 picofarads, I_B=2A, I_C=500μA, N=250)

α	P(peak)	$\overline{P}$	$[\Delta t]_{MAX}$	Efficiency
1	20kW	5W	10^{-6}sec	.025%
0.1	20kW	50W	10^{-5}sec	.025%
0	20kW	20kW	∞	100%

The results shown in Table II indicate that with electron beam energy recovery (α <1) it is possible to operate FEL's at high power and high overall efficiency using electrostatic accelerators even if the charging current I_C is small. Also, since during the electron beam collection process the electrons have only small kinetic energies, the amount of ionizing radiation produced is small. A more detailed discussion of the electron collection process can be found elsewhere in this book under the title "The UCSB FEL Experimental Program".

Note that in the calculation of overall efficiency, power supply losses have not been included. If these losses are taken into account, then in some cases the overall laser efficiencies

As shown in the figure a continuous beam of monochromatic electrons of energy $E = \gamma mc^2$ emerges from the electrostatic accelerator column shown on the left side of the figure. The beam interacts with the FEL wiggler to excite a long wavelength laser TEMoo mode which resonates between the two spherical mirrors. The wavelength of this mode is given approximately by the relation

$$\lambda p = \frac{\lambda o}{2\gamma^2}$$

where λo is the period of the magnetic wiggler, γmc^2 is the energy of the incoming electrons. The resonator mirrors are constructed of highly reflective materials at the operating wavelength λp to allow the intensity of the optical mode to grow to values in the range $10^8 - 10^9$ Mwatts/cm^2. At this high level of optical power density the same electron beam can interact again with the intense optical mode to produce coherent radiation at a much shorter wavelength

$$\lambda = \frac{\lambda p}{4\gamma^2} = \frac{\lambda o}{8\gamma^4}$$

The short wavelength optical mode (second-stage FEL) is shown in white as a TEMoo gaussian mode propagating along the axis of the resonator.

A second two-stage FEL scheme is illustrated in Figure 4. Here, separate electron beams are used to excite independently the first and second FEL stages. The major advantages of this scheme are: a) the wavelength of the second stage can be tuned without perturbing the operation of the first stage, b) the small signal gain of the second stage laser can be optimized by choosing correctly the ratio of pump wavelength λp to second-stage wavelength λ and c) the FEL interaction length of the second

ELECTRON BEAM REQUIREMENTS.

A. Beam Quality Requirements. In a free electron laser the axial velocity β_z of the electron beam determines whether or not the electrons radiate coherently. The maximum spread of axial velocities that can be acepted by a constant period FEL wiggler can be calculated from the energy width of the FEL gain curve at fixed wavelength. The maximum velocity spread that can be accepted by a FEL is given by

$$[\delta\beta_z]_{MAX} = \frac{1}{2N\gamma^2} \tag{9}$$

where N is the number of magnetic periods in the wiggler and γmc^2 is the relativistic energy of the electron beam. If β is the total speed of an electron in the beam and $\beta_\perp$ is its total transverse speed then in a FEL:

$$\beta^2 = \beta_z^2 + \beta_\perp^2 = \beta_z^2 + \frac{K^2}{1\,\gamma^2} + \beta_{\perp o}^2 \tag{10}$$

where $\frac{K}{\gamma} = \frac{|e|B\lambda o}{2\pi mc\gamma}$ is the transverse speed acquired by the electron from the magnetic wiggler. B is the rms value of the magnetic field on axis and λ_o is the periodicity of the magnetic wiggler structure. $\beta_{\perp o}$ is the transverse drift velocity of the electrons with respect to the axis of the wiggler. $\beta_{\perp o}$ is finite if the electron is injected into the magnetic structure at the wrong angle. Changes in β_z can thus originate from variations in B written in KMS units as follows

$$G = \frac{5.24\ \lambda^{3/2} \lambda_o^{5/2}\ B^2\ I\ N^3}{(1+K^2)^{3/2} r^2} \tag{16}$$

where:

λ = signal wavelength
λ_o = magnet period
B = RMS magnetic field on axis
I = electron beam current
N = number of magnet periods
r = optical beam radius
K = o ... B/zitmc

The above gain equation has been normalized to give the correct gain value for the Stanford FEL. It is assumed here that the electron beam radius R is smaller or equal to the optical beam radius. At saturation (i.e. when the small signal gain is reduced by a factor of 2) the amount of power that can be extracted from the electron beam as laser radiation is

$$\bar{P} = \frac{IV}{2N} \tag{17}$$

The electron beam requirements and the typical expected performance of a single-stage free electron laser has been incorporated into Table 3. Similarly Table 4 summarizes the operating characteristics of a two-stage FEL based on the scheme illustrated in Figure 4.

CONCLUSIONS.

The operations of single-stage and two-stage free electron lasers using the electron beams produced by electrostatic accelerators has been discussed. The techniques of electron beam energy recovery revie in this chapter can be used to produce intense beams of coherent electromagnetic radiation in the far infrared region with high written in KMS units as follows

$$G = \frac{5.24\,\lambda^{3/2}\,\lambda_o^{5/2}\,B^2\,I\,N^3}{(1+K^2)^{3/2}\,r^2} \tag{16}$$

where:

λ = signal wavelength
λ_o= magnet period
B = RMS magnetic field on axis
I = electron beam current
N = number of magnet periods
r = optical beam radius
K = o ... B/zitmc

The above gain equation has been normalized to give the correct gain value for the Stanford FEL. It is assumed here that the electron beam radius R is smaller or equal to the optical beam radius. At saturation (i.e. when the small signal gain is reduced by a factor of 2) the amount of power that can be extracted from the electron beam as laser radiation is

$$\bar{P} = \frac{IV}{2N} \tag{17}$$

The electron beam requirements and the typical expected performance of a single-stage free electron laser has been incorporated into Table 3. Similarly Table 4 summarizes the operating characteristics of a two-stage FEL based on the scheme illustrated in Figure 4.

CONCLUSIONS.

The operations of single-stage and two-stage free electron lasers using the electron beams produced by electrostatic accelerators has been discussed. The techniques of electron beam energy recovery revie in this chapter can be used to produce intense beams of coherent electromagnetic radiation in the far infrared region with high

Table 3. Performance of a single-stage FEL and required electron beam characteristics.

Wavelength (μm)	360
Magnet period (cm)	3
# magnet periods	100
Magnetic field (Γ)	0.06
Small signal gain (Amp^{-1})	0.60
Average laser power (kW/Amp)	15
Overall efficiency (%)	-50
Elect. beam energy (MeV)	3
Maximum transverse emittance (mm-mrad)	π122
Maximum Δδ/γ	5×10^{-3}

Table 4. Performance of a two-stage FEL and required electron beam characteristics.

Wavelength (μm)	0.4	16
Pump wavelength (μm)	600	4000
Pumpwave intensity ($\mathrm{MW/cm}^2$)	250	60
Interaction length (m)	2.4	1.2
Small signal gain (Amp^{-1})	5×10^{-3}	8×10^{-3}
Power output (kW/Amp)	0.5	2
Overall efficiency (%)	0.3	1.5
Elect. beam energy (MeV)	9.38	3.55
Maximum transverse emittance (mm-mrad)	π0.8	π10
Maximum Δγ/γ	6×10^{-5}	0.8×10^{-3}

END
FILMED

3-86

DTIC