IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

HYBRID ACCELERATOR DESIGN FOR A FREE ELECTRON LASER

S. B. Segall, KMS Fusion, Inc., Ann Arbor, MI 48106

Abstract

An accelerator system for a free electron laser (FEL) is described that incorporates both an electrostatic accelerator and an RF linac. The purpose of the design is to minimize the emittance of the high current pulses injected into the RF linac. Emittance contributes to the effective energy spread of the beam in the FEL. A large effective energy spread will reduce gain and conversion efficiency. The pulses leaving the electrostatic accelerator are compressed in a dispersive magnetic buncher before injection into the linac. After the beam leaves the FEL, energy is recovered in an RF decelerator followed by a decelerating and collecting column in the electrostatic accelerator. A new electrostatic accelerator design is presented to both provide high charging current and collect an electron beam with a large fractional energy spread.

Introduction

Short-wavelength (visible-UV) free electron lasers require low-emittance, low-energy-spread electron beams to efficiently produce light via the FEL interaction mechanism. The RF linac is the preferred accelerator for high-power short-wave-length FELs because it can easily accelerate high-current bunches to the energies required for short-wavelength operation (~ 100 MeV).

The emittance of the beam produced in a conventional RF linac is, however, marginal for short-wavelength FEL operation. The primary contributor to emittance is the low-energy bunching process used to prepare electron bunches for injections into the linac.

Emittance growth may be reduced using an electrostatic accelerator to produce a beam with an energy of a few MeV, which would then be bunched and injected into the RF linac. At this energy the beam is already highly relativistic, and space charge effects are minimal.

Accelerator System Conceptual Design

We are investigating the design of an FEL that utilizes an electrostatic accelerator as the source of current pulses for an RF linac. This system is shown schematically in Figure 1. Electron pulses originate in the dome of a two-column horizontally-aligned electrostatic accelerator. These pulses, on the order of one nanosecond in length, pass through a dispersive bunching system consisting of an RF cavity, two 180^0 bending magnets, quadrupole focusing magnets and a second RF cavity. The dispersive bunching system is designed to compress the pulses by about a factor of 10 without increasing the transverse beam emittance. After the beam is bunched, it is accelerated in the RF linac to the energy required to produce the desired wavelength in the FEL. After passing through the wiggler the electron energy not converted to photon energy is recovered.

Energy is recovered in a two-step process. First the beam is decelerated in an RF decelerator. The energy loss of electrons in the RF decelerator is about the same as the energy gain in the RF accelerator. Following the RF decelerator, the remaining electron energy is recovered in a decelerating column in the electrostatic accelerator.

The two new elements in this design are the electrostatic accelerator and the dispersive buncher. The RF accelerator-FEL-RF decelerator section of this system would be similar to the FEL being investigated at Los Alamos National Laboratory.[1] The design of the electrostatic accelerator and dispersive buncher will be discussed in more detail in the following sections.

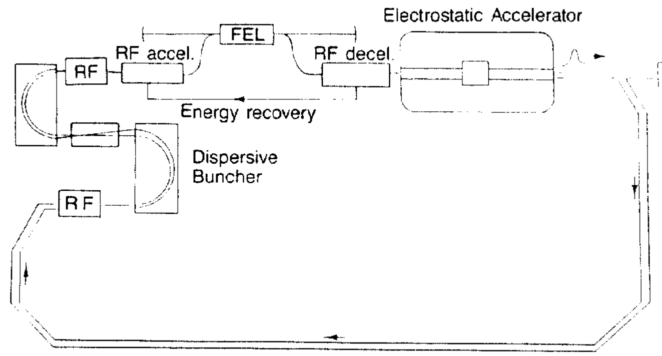

Figure 1. Schematic diagram of the FEL system.

The Electrostatic Accelerator

A free electron laser has been operated using a two-column electrostatic accelerator at the University of California Santa Barbara (UCSB).[2] The UCSB accelerator design would not be suitable for this application, primarily because it could not accept the large energy spread that would be produced in the return beam.

The FEL produces an energy spread comparable to or greater than the fraction of the electron beam energy converted to photon energy. This energy spread can be a large fraction of the total potential difference on the electrostatic accelerator. For example, assume a 100-MeV beam is produced by a 5-MV electrostatic accelerator followed by an RF linac that increases the electron energy by 95 MeV. If a 2 percent energy spread were produced in the FEL at 100 MeV, and the RF decelerator recovered 95 MeV per electron, the energy spread of the beam entering the return column of the electrostatic accelerator would be 40%. The maximum energy spread that could be accepted by a conventional electrostatic accelerator is equal to the potential difference between the potential on the cathode of the electron gun and the dome of the accelerator. This is typically on the order of one percent of the dome potential.

A second deficiency of conventional electrostatic accelerators is that the charging current is very low. Total charging current for the UCSB system is less than 0.5 mamp. To maintain high average beam current with low charging current, charge recovery must be very high. For example, with 0.5 mamp of charging current and 99% charge recovery, the average beam current that could be maintained continuously would be 50 mamp. Average beam currents on the order of an ampere are desirable for a high-power short-wavelength FEL. The highest recovery efficiency that has been achieved to date at UCSB with the FEL operating is 97%.

One way to operate the system of Figure 1 to permit the electrostatic accelerator to accept a large-fractional-energy-spread beam would be to decelerate the electron beam less in the RF decelerator than it is accelerated in the RF accelerator. A significant amount of waste heat would have to be removed from the dome under these conditions. This solution would also not address the problem of increasing the charging current of the electrostatic accelerator.

0018-9499/85/1000-3380$01.00© 1985 IEEE

An alternative solution, that would address both the problems of large energy spread and low charging current, is to design the electrostatic accelerator so that electrons could be recovered along the length of the decelerating column and returned to the dome of the accelerator. This could be done if the voltage on the dome of the accelerator were produced by an array of power supplies connected in series, rather than by a charging belt or chain. Electrons collected on plates in the column would be returned to dome potential through the power supplies. The power supplies could be powered by an array of permanent-magnet generators driven by an electric motor through an insulated drive shaft as shown in Figure 2.

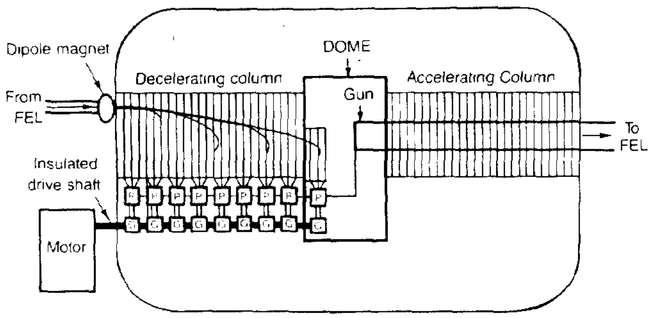

Figure 2. Schematic diagram of proposed electrostatic accelerator design.

The accelerator design shown in Figure 2 would not only permit collection of electrons with energies lower than the dome potential, but would also provide a large charging current. Maximum charging current is obtained when no return current is being collected. The charging current is then equal to the total power supplied by the generators divided by the terminal voltage. For example, if 1 megawatt of power were supplied by the generators and the voltage on the terminal were 5 MV, then the charging current would be 200 mamp. If some or most of the input power to the accelerator were needed to raise electrons from intermediate voltages to dome potential, the current from ground would be correspondingly less. Even with partial loading of the power supplies by the return beam, the charging current from ground would still be very much greater than for belt- or chain-charged systems.

With higher charging current in the electrostatic accelerator, higher average current could be maintained for a given collection efficiency. For example, with 100 mamp of charging current and 97% collection efficiency an average beam current of 3.3 amps could be maintained.

Whatever the charging current, losses in the transport line should be minimized. Because the electrostatic accelerator can produce an electron beam with a beam emittance of only a few times the thermal limit,[3] the beam can be easily transported with minimal losses up to the FEL. In the FEL the energy spread produced would be small relative to the total beam energy, and control of the beam would still be relatively straightforward.

Once the beam starts losing energy, however, the relative energy spread increases and control of the beam becomes increasingly difficult. For this reason, the beam line in Figure 1 is designed so that no bending of the beam is required during the deceleration process. If needed, the beam entering the electrostatic accelerator could be slightly deflected to enhance collection efficiency (Figure 2).

The Dispersive Buncher

Current pulses on the order of 0.1 nsec are needed for injection into the RF linac. It is desirable to keep the current density in these pulses low at low energy, and to bunch the beam to high peak currents only after it has reached relativistic energies. A dispersive buncher could compress the beam by about a factor of 10 at energies of a few MeV.

Pulses on the order of 1 nsec could be produced using a pulser with fast electronic switching. Alternatively, these pulses could be produced by an electron gun with a photocathode triggered by a train of short, low-power laser pulses. A port is shown following the electrostatic accelerator in Figure 1 that could be used to inject a train of laser pulses for triggering.

The dispersive bunching system that follows the electrostatic accelerator is shown in Figure 1. The effect of the various components of the buncher on the longitudinal phase space of the beam are shown in Figure 3.

To compress the pulse we would first pass it through a low frequency RF cavity, in which an energy variation is produced across the pulse (Figure 3b). When this pulse is passed through a 180^0 bending magnet, the more energetic electrons follow a path

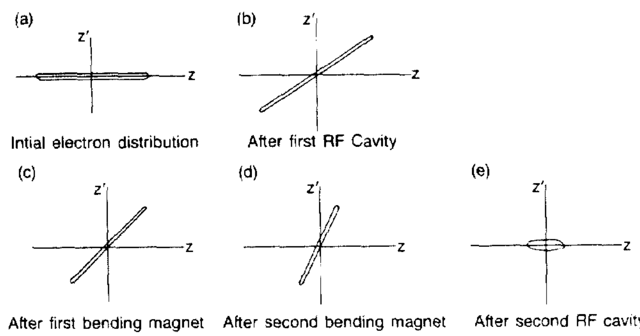

Figure 3. Effect of components of the pulse compression system on the longitudinal phase space of the electron beam.

with a longer radius of curvature and therefore fall back in position relative to the less energetic electrons. This compresses the pulse longitudinally, but skews it transversely. To correct this transverse skew and further compress the pulse, the image of the pulse is inverted by a series of quadrupole magnets, and the pulse is again passed through a 180^0 bending magnet. When the pulse emerges from the second 180^0 bending magnet, the transverse skew has been eliminated and the pulse length is significantly reduced. However, the large variation in electron energy as a function of position, imposed in order to obtain the pulse compression, still remains (see Fig. 3d). To reduce the energy variation across the pulse, the shortened pulse is passed through a second RF cavity that cancels the variation of energy with position produced by the first cavity (Figure 3e). If the electron optics are carefully designed, there should be negligible coupling between the longitudinal and transverse components of the electron momentum, and the pulse compression will take place without appreciable growth in the transverse emittance.

Magnet Parameters for the Dispersive Buncher

The radius of curvature, r, of an electron in a dipole field of magnitude B is given by

$$r = \frac{mv}{eB} = \frac{(E^2 - m_0{}^2c^4)^{1/2}}{ecB} = \frac{(E_k{}^2 + 2\, m_0c^2E_k)^{1/2}}{ecB} \qquad (1)$$

where m is the total mass of the electron, m_0 is the electron rest mass, v is the electron velocity, E is the total electron energy and E_k is the electron kinetic energy. For two electrons with kinetic energies $E_0 + \Delta E$ and $E_0 - \Delta E$ the difference in path length produced in a single 180^0 bending magnet is given by

$$\Delta \ell = \frac{E_0 + m_0c^2}{(E_0^2 + 2\,m_0c^2\,E_0)^{1/2}}\,\frac{2\pi\,\Delta E}{ecB}\,. \qquad (2)$$

Equation (2) was obtained by differentiating (1) with respect to E_k and using the relation $d\ell = \pi dr$ for the bending magnet. Using the expression for r from (1) in (2) we obtain

$$\Delta \ell = \frac{E_0 + m_0c^2}{E_0 + 2\,m_0c^2}\;2\pi r_0\left(\frac{\Delta E}{E_0}\right), \qquad (3)$$

where the radii of the electron trajectories are $r_0 + \Delta r$ to $r_0 - \Delta r$. Defining

$$\delta \equiv \frac{E_0 + m_0c^2}{E_0 + 2\,m_0c^2} \cong 1 \qquad (4)$$

we have

$$\Delta \ell = 2\pi\delta\, r_0\,\frac{\Delta E}{E_0} \qquad (5)$$

or

$$\frac{\Delta r}{r_0} = \delta\frac{\Delta E}{E_0}\,. \qquad (6)$$

Once E_0 has been given by the operating energy of the accelerator and ΔE is fixed by the RF cavity, $\Delta r/r_0$ is fixed. The only way to increase Δr is by increasing the radius of curvature. From Equation (1) this can only be done by decreasing the magnetic field.

From Equation (2) we see that the change in path length as a function of magnet field is virtually independent of electron energy. The primary effect of changing the electron energy is to change the size of the magnet required to achieve a given pulse compression, but not its field. Radius of curvature is shown as a function of magnetic field in Figure 4. For ΔE = 300 kV the total change in path length through the two-magnet system is shown in Figure 5. To within a few percent the graph in Figure 5 is independent of electron energy.

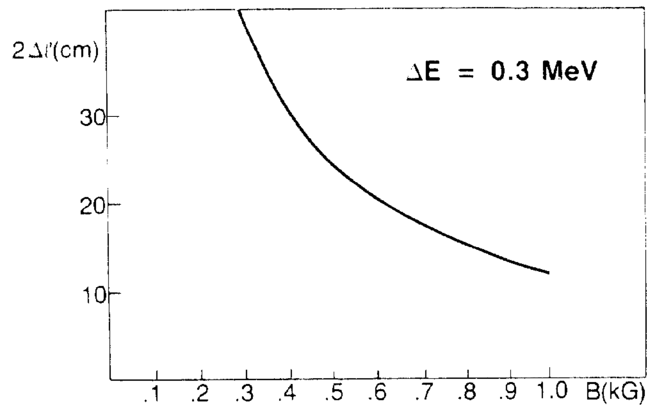

Figure 5. Changes in the length of an electron pulse in a pulse compressor as a function of magnetic field strength for an imposed variation of energy with position of 600 kV across the beam.

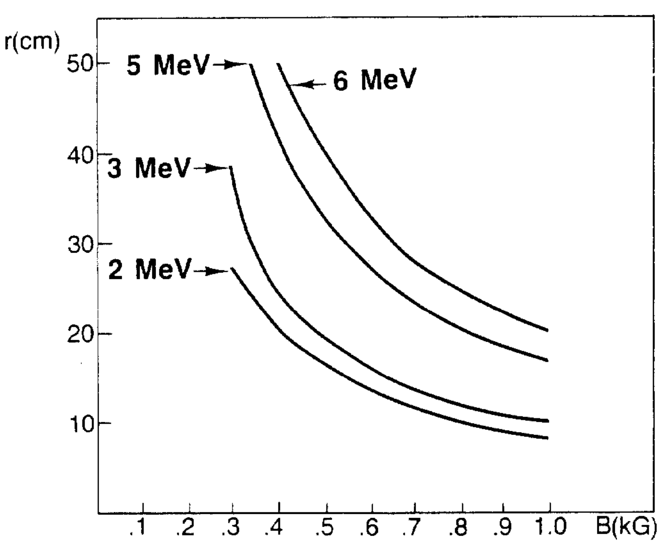

Figure 4. Radius of curvature of an electron beam in a dipole magnetic field as a function of field strength. Curves are shown for a number of different electron energies.

Conclusion

A conceptual design has been presented for an accelerator system that would optimize the performance of a short-wavelength FEL. The electrostatic accelerator would produce a train of very low emittance pulses, the dispersive buncher would compress the pulses for injection into the RF linac without introducing significant emittance growth, and the electron beam would be collected with very high efficiency by a collector column in the electrostatic accelerator after leaving the RF decelerator. A new design for a high-charging-current electrostatic accelerator would be needed in which the terminal voltage is produced by an array of high voltage power supplies.

Acknowledgement

The work was supported by the U.S. Office of Naval Research.

References

1. J.M. Watson, "The Los Alamos free-electron laser," Proceedings 1985 Particle Accelerator Conference.

2. L.R. Elias and G.J. Ramian, "Status report of the UCSB FEL experimental program," Proc. SPIE 453, 137, (1984)

3. D.B. Cline, D.J. Larson, W. Kells, F.E. Mills, J. Adney, J. Ferry, and M. Sundquist, IEEE Trans. on Nucl. Science NS-30, 2370 (1983).