

An Electrostatic Accelerator FEL Amplifier as a Possible Microwave Power Source for Linear Colliders

L.R. Elias and D. J. Larson

Center for Research in Electro-Optics and Lasers (CREOL) and Physics Department

University of Central Florida

Orlando, FL 32816

and

I. Boscolo

University of Milan, Italy

Abstract

Electrostatic-accelerator FELs are well suited to meet economically and efficiently the RF source requirements imposed by the next generation of linear colliders. A discussion is presented of a scheme whereby a single electrostatic accelerator can deliver ten or more 50 ns, 100 MW FEL pulses to ten meters of a high-gradient (100 MV/m) accelerating structure. With fewer than 1000 electrostatic accelerators, it may be possible to drive a 10 km, 1 TeV linear collider.

compact 2-3 MeV single ended electrostatic accelerator operating with a pulsed 100-150 ampere electron beam can provide satisfactorily the desired RF power. For example, with a conservative 20-50 % power extraction efficiency, the FEL can generate about 100 MW of RF power. This power is less than what has already been demonstrated by the ELF experiment (1GW RF power at 35 GHz with 34% extraction efficiency) at Livermore using a tapered undulator [7]. In our scheme the complexity and cost of the RF source is considerably reduced because a relatively small number of electrostatic accelerators are needed to produce the desired power with better than 30 % wall-power efficiency. The expected large overall efficiency of the system stems from the high electron to RF conversion

I. Introduction

For the same RF power, smaller (higher frequency)

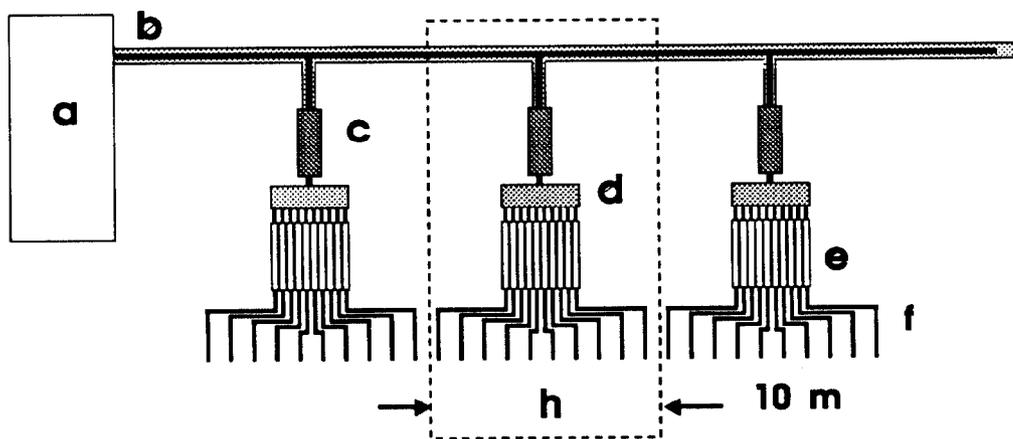


Figure 1. Electrostatic-Accelerator RF-FEL Source. (a) HV DC power source, (b) HV DC transmission line, (c) electrostatic accelerator, (d) electron pulse splitter, (e) high-power FEL amplifier, (f) RF power feed to HG accelerating cavity, (h) basic FEL unit.

cavities produce larger accelerating gradients. Recent studies [1] indicate that 100 MW, 10-30 GHz, 50 ns RF pulses are needed to drive each meter of a 10 km, 1 TeV collider. Presently, superconducting linacs, relativistic klystrons, and induction linac FELs are being considered as attractive RF sources for large colliders [2,3,4]. In our approach [5,6] electrostatic accelerators are used as the sources of electrons. Our first estimates indicate that a

efficiency and the direct efficient use of a centralized HV DC power source, similar to the ones used to produce HV DC power transported in commercial transmission lines.

An overview of the major components of the system is presented in section II. Conceptual details of a single RF FEL unit are discussed in section III. In section IV we review possible DC power generation and transmission concepts.

II. RF Source System Overview

Figure 1 illustrates the major components of the proposed RF-FEL source. It includes a 2-4 MV DC power supply, a HV DC power transmission line and three of perhaps a total of 1000 basic RF-FEL units. Each basic FEL unit contains one electrostatic accelerator, each driving 10 high-power RF FEL amplifiers. The amplified power output is fed to each meter of a high-gradient accelerating unit. Not included in the figure is the low-power master RF oscillator feeding each FEL amplifier. The basic direction of power flow is as follows. DC power is transmitted directly to the high-voltage terminal of each of the electrostatic accelerators. By means of a pulsed electron gun and a DC accelerating field, the electrostatic accelerators generates electrons and converts their electrostatic potential energy into electron kinetic energy. A fraction of the electron's kinetic energy (40% for example) is then converted into RF energy by means of an FEL Master-Oscillator-Power-Amplifier (FEL-MOPA). The RF power is then fed into each of the high-gradient accelerating structures, where another beam of electron or positrons is accelerated to the desired 1 TeV energy.

III. Basic RF-FEL unit

Figure 2 contains the major components of a single RF-FEL unit. Unlike the ten amplifiers shown in Figure 1, for simplicity of discussion only 4 are considered in this figure. The electron gun located inside the HV terminal generates a constant 100 A, 200 ns long electron pulse. Because of the HV-terminal's finite capacitance, its voltage will drop linearly with time. If needed, the continuous linear drop in voltage can be converted into four discontinuous voltage steps, each 50 ns long, so that the energy of the electrons remains constant during each step.

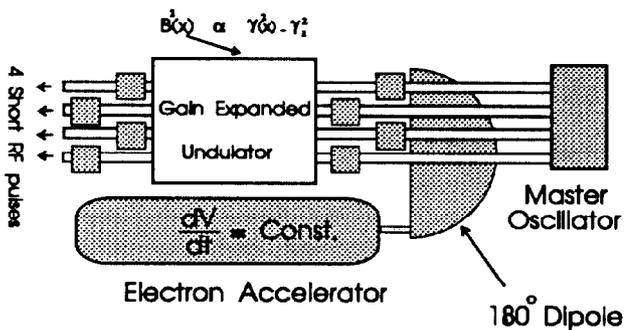


Figure 2. A basic RF-FEL unit.

As the electrons move through the 180° bending magnet, the energy dispersive properties of the magnet will separate it spatially (x -direction) into four 50 ns pulses as shown in figure 3. The spatially dispersed short (50 ns) electron pulses are then magnetically injected into four separate parallel waveguides-FEL amplifiers. As the electron pulse

moves through the variable parameter undulator it amplifies the low-power pulse (50 kW) generated by the master oscillator. Each pulse is amplified to a level of 100 MW. Since the energy of the short electron pulses is resolved in

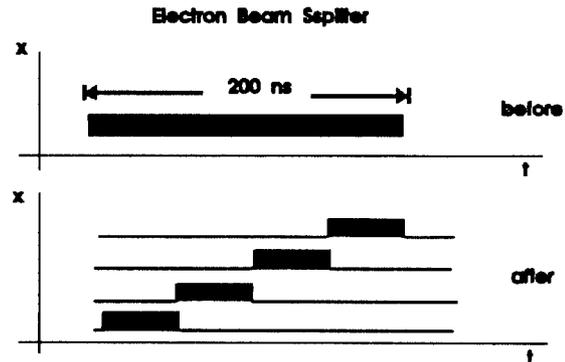


Figure 3. Electron beam splitter.

space (x -direction), the magnetic undulator field must have a field gradient in the x -direction. The magnetic field profile $B(x)$ can be calculated from the frequency of an FEL operating in a waveguide:

$$v = \frac{c\gamma_z^2\beta_z}{\lambda_w} \left[1 \pm \beta_z \sqrt{1 - \left(\frac{\lambda_w}{\lambda_c\beta_z\gamma_z} \right)^2} \right],$$

$$\text{with } \gamma_z = \frac{\gamma}{\sqrt{1 + \kappa^2}}, \quad \beta_z = \sqrt{1 - \frac{1}{\gamma_z^2}},$$

$$\text{and } \kappa = \frac{eB\lambda_w}{\sqrt{22}\pi mc},$$

where B is the magnetic field of the undulator, λ_w is the magnet period, λ_c is the waveguide cutoff wavelength, and κ is the undulator parameter. γ is the normalized total electron energy. To maintain the same frequency the x -profile of κ must be related to x -profile of γ through the following formula:

$$\kappa(x) := \frac{1}{\gamma_z} \sqrt{\gamma(x)^2 - \gamma_z^2}$$

Because of its long period, the magnetic undulator can be constructed from relatively inexpensive electromagnets. Typical design parameters of an FEL-MOPA amplifier are listed in Table 1.

Energy	2.5	MeV
Current	100	A
Input Power	50	KW
Output Power	100	MW
Pulse length	50	ns
Rep. Rate	1	kHz

The most critical issue that needs to be resolved in our approach, is the demonstration of high current acceleration in electrostatic accelerating tubes. The UCSB FEL group has demonstrated acceleration of more than 3 amperes with better than 99 % transmission. This is 3 to four order of magnitudes more current than had been possible before. However a factor of 30 improvement in current accelerating capabilities must be demonstrated. A possible accelerator

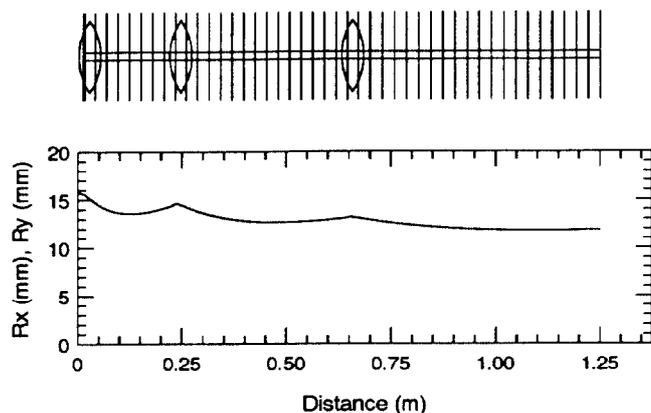


Figure 4. 100 Ampere accelerator beam optics

electron beam optics design is illustrated in Figure 4. The calculations used the SCAT [8] computer code. The input beam is generated by a 100 A, 250 kV gun operating with a 10 A/cm² cathode loading. Once the beam leaves the electron gun it is immediately focused by a permanent magnet solenoid. The solenoidal focusing is required to offset beam growth caused by the large space charge force. Another solenoid is needed 333KV down stream from the anode, and a third solenoid is needed 1 MV downstream from the anode. With these beam focusing elements the beam can be kept to less than an inch and a quarter in diameter. This maximum beam size is compatible with present accelerator tube geometry.

IV. DC Power Generation and Transmission

In a typical electrostatic accelerator, HV is generated by means of rubber belts, pelletron chains, voltage multipliers, etc. We propose to separate physically the generation of HV DC power from the accelerating function of the electrostatic accelerator. As shown in Figure 1(a), the HV DC power generation is centralized in one unit. It is then transmitted to individual electrostatic accelerators by means of SF₆ gas-insulated coaxial transmission lines. For example, a 0.75 m outside diameter coaxial line could easily hold 2 MV. Each electrostatic accelerator is consequently a quite simple entity, comprised of an electron gun, all metal and ceramic accelerator tube, a few permanent magnet solenoids and a high pressure SF₆ containment tank. The dimensions of the accelerator tank would not be larger than 1 m diameter by 4 m in length.

Another important advantage of centralizing the HV DC power source is that existing HV DC power generation technology, such as the one employed by commercial power companies, can be directly used. However, instead of using tall HV power transmission lines in air, we propose to use the HV coaxial transmission lines discussed above.

Given the reduced mechanical and electrical complexity of our scheme it is expected that construction and development cost should be low. Rough estimates indicate that the system construction cost could be maintained below 10K\$/m.

V. Reference

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