CFEL-I : A Compact Free Electron Laser

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Abstract

We discuss the design and predicted performance of the CREOL - UCF Compact Free Electron Laser (CFEL-I). This device will consist of a 1.7 MV Pelletron electrostatic accelerator that will be able to provide electron beam energies between 800 keV and 1.7 MeV. A 200 milliamp electron beam will be used to achieve output laser power up to 1 kW. Highly efficient electron beam transport and collection will enable this device to have a large duty cycle, and eventually it may operate on a CW basis. Construction of a microundulator is underway. The 8 millimeter microundulator period will allow device operation between 250 microns and one millimeter.

I. Introduction

The CREOL-UCF Compact Free Electron Laser (CFEL-I) has been designed to operate in the sub-millimeter region with an order of magnitude more compact technology, three orders of magnitude higher average power and efficiency and two to three orders of magnitude better time-averaged laser spectral purity than that of any existing FEL. These improvements stem mainly from the utilization of short-period magnetic undulators (microundulators) and from the unique advantage possessed by electrostatic accelerators to generate very high optical quality electron beams.

CFEL-I will build on the success of both the UCSB FEL and the UW-NEC electron cooler prototype development. The UCSB FEL has shown reliable operation in the FIR-sub-millimeter region using a 6 MeV Pelletron that was modified for ampere-level *pulsed* electron beam recovery[1]. The UW-NEC experiment demonstrated *continuous* generation of a 2 MeV, 100 mA electron beam[2]. Both experiments demonstrated that electrostatic accelerators are uniquely suited to produce the very high optical quality electron beams demanded not only by FELs using long microundulators, but most importantly, the stringent beam quality requirements imposed by the electron beam recovery system.

CFEL-I represents a major step in technology and size improvement of FELs. The successful demonstration of CFEL-I will pave the way for the development of low-cost, compact, small-laboratory-size FELs, capable of operating in other spectral regions, such as the FIR, IR, visible, and possibly the soft X-ray.

II. Electron Beam Optics

CFEL-I is shown in Figure 1. All ninety degree bends are designed to have zero dispersion by using a quadrupole singlet placed between the two 45 degree dipole magnets. The electron optics for CFEL-I were calculated using the TRANSPORT[3] and SCAT[4] computer codes. Tables I and II present parameters of the CFEL-I dipoles and quadrupoles.

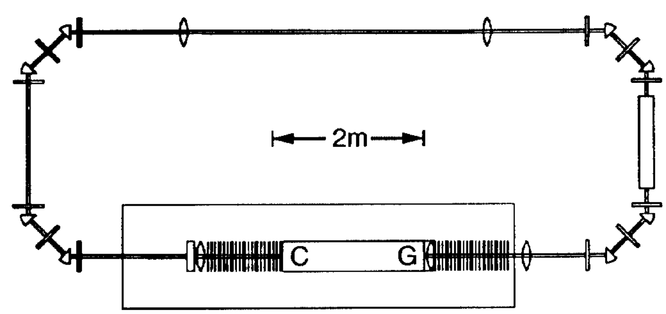

Figure 1. Diagram of the CREOL Compact FEL. Electron beam is formed in an electron gun (G) located in the terminal (inner rectangle) of a 1.7 MeV electrostatic accelerator, focused by a solenoid (lens shaped object), accelerated in the acceleration tube (hashed lines), focused by a solenoid, matched and bent into the undulator (long rectangular box) by quadrupoles (thin rectangles) and dipoles (pie shaped pieces), matched and bent into a long drift return, bent by a 180 degree bend, focused, sent into the deceleration tube and collected (C) in the terminal of the electrostatic accelerator. The outer rectangle is the high pressure SF_6 containment vessel.

Table I. CFEL-I Dipole Magnets	
Bend Angle	45°
Magnetic Field	719 Gauss
Gap	1 Inch
Physical length	2 Inches
Effective Mag. Length	3 Inches
Entrance Edge Angle	22.5°
Exit Edge Angle	22.5°
Integrated $\Delta B/B_0$ @ .25"	.0004
Height, Width	6.25, 8.25 Inches
Power Consumption	22.5 Watts

Table II. CFEL-I Quadrupole Magnets	
Magnetic Field Gradient	250 Gauss/Inch
Gap	1.25 Inch
Physical length	1 Inch
Effective Mag. Length	1.66 Inches
Height, Width	5.7, 5.7 Inches
Power Consumption	22.5 Watts

The electron gun for CFEL-I is shown in Figure 2. The electron gun has been designed to produce an electron beam with an emittance equal to the thermal limit. The gun uses a standard Pierce geometry. The anode voltage of 20 KV was chosen so that the beam has a sufficiently high energy upon its return to the terminal to assure a large collection efficiency. An intermediate electrode will be used to control the current output of the gun. The multistage collector designed for CFEL-I is shown in Figure 3. A small (two millimeter diameter) beam size at the entrance to the collector should result in excellent collector operation. A magnetic trap located at the input to the collector will reduce backstreaming. Table III presents design parameters of the electron gun and collector.

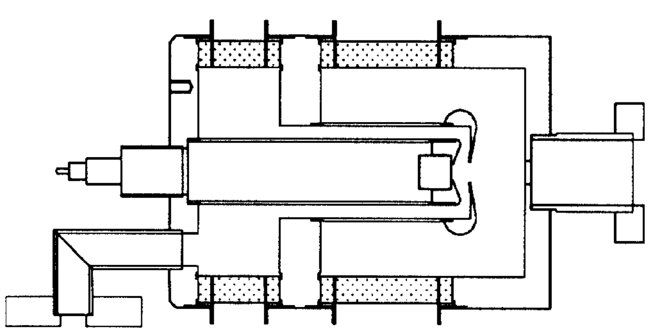

Figure 2. CFEL-I Electron Gun. The gun uses a standard Pierce geometry to acheive a beam emittance close to the thermal limit. The 3.2 mm diameter cathode produces the 200 mA beam with a cathode loading of 0.7 A/cm^2.

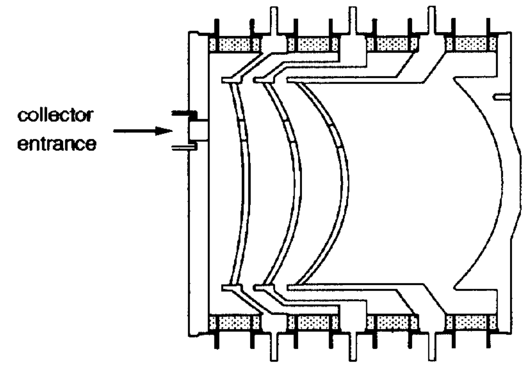

Figure 3. CFEL-I Electron Beam Collector. The collector uses three collection plates and one repulser plate to efficiently collect the electron beam.

Table III. CFEL-I Electron Gun and Collector	
Gun Parameters	
Perveance	.071 μPervs
Anode Voltage	20 KV
Output Current	0-200 mA
Normalized Emittance	2 π mm-mr
Grid Voltage (Gun On)	4 KV
Grid Voltage (Gun Off)	-2 KV
Collector Parameters	
# of collecting plates	3
Collection Voltage 1	14 KV
Collection Voltage 2	6.8 KV
Collection Voltage 3	2 KV
Suppressor Voltage	-4 KV
Input aperture	1 cm diameter

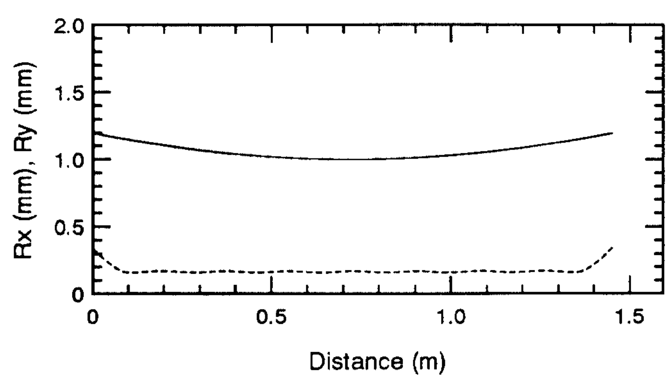

Figure 4. Electron optics in the undulator. Careful matching of the input beam optics results in very smooth beam transmission through the undulator. The natural focusing of the undulator in the vertical direction has been matched by the defocusing caused by space charge and emittance, resulting in beam transmission without a large betatron motion of the beam envelope.

The electron optics of the beam in the undulator were calculated by SCAT and are shown in Figure 4. The beam size in the vertical direction must have a half width less than 0.6 mm so that the nonlinear magnetic fields of the undulator are not appreciable. The beam has been designed to match ideally into the undulator so that the space charge and emittance defocusing are exactly cancelled by the magnetic focusing of the undulator in the vertical direction, resulting in a beam with half width equal to 0.2 mm vertically.

III. UNDULATOR AND RESONATOR DESIGN

Table IV lists the operating parameters of CFEL-I. An important advance in undulator parameters is the use of a very short period (8 mm) undulator. A hybrid configuration was considered for the undulator, but it was decided that a Halbach arrangement will be easier to assemble. (The Halbach arrangement will be made by gluing magnets together.) The individual magnets are plates of Neodymium-Iron-Boron. A representation of the undulator is shown in Figure 5.

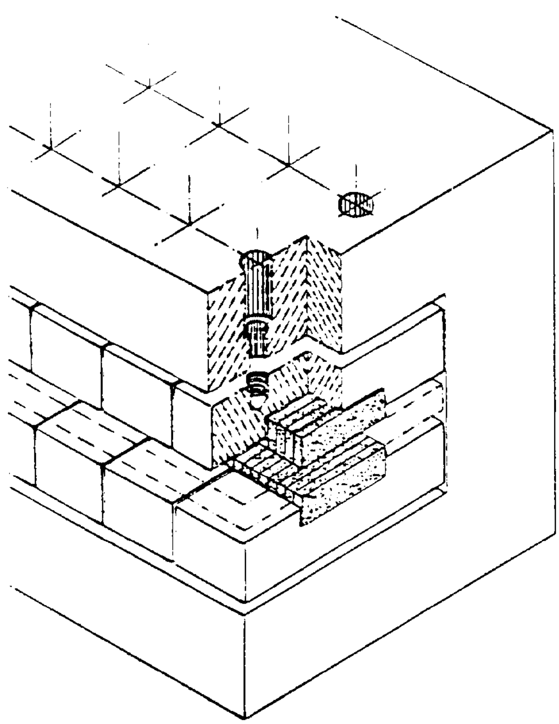

Figure 5. Halbach microundulator with supporting structure.

The resonator is rectangular with the width much larger than the height. In this way the optical modes are hybrid: the modes are guided vertically but free horizontally. The electromagnetic fields are extremely small at the top and bottom walls due to boundary conditions, and they are practically zero at the side walls because the Gaussian spot size is much smaller than the width of the undulator. The small values of the fields near the conductors will lead to very small propagation losses for the modes, while simultaneously allowing for a small enough guide height to obtain large undulating magnetic fields. This type of resonator was first used with the UCSB FEL[5].

Table IV. CFEL-I Design Parameters

Accelerator Voltage (MV)	1.7	0.9
Gamma	4.33	2.76
Beam Current (A)	0.2	0.2
Undulator Period (mm)	8	8
Number of Periods	156	156
Undulator Length (m)	1.248	1.248
Peak Magnetic Field (G)	1800	1800
Undulator Parameter	0.13	0.13
Wavelength (μm)	233	640
Frequency (THz)	1.29	0.469
Gain per Pass (%)	15.33	35.48
Loss per Pass (%)	2.11	6.18
Net Gain per Pass (%)	13.22	29.30
Max. Power Output (kW)	1.09	0.58

IV. ACKNOWLEDGEMENTS

The design of CFEL-I has involved outside experts from national labs and industry. Richard Hechtel designed the electron gun and collector and Ron Van Iderstine prepared mechanical designs for gun and collector construction. Stan Snowdon designed dipole and quadrupole magnets for use in CFEL-I. The Pelletron electrostatic accelerator for CFEL-I has been purchased from the National Electrostatics Corporation.

V. REFERENCES

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