A HIGH-POWER FREE ELECTRON LASER USING A SHORT RAYLEIGH LENGTH

W. B. Colson [a], A. Todd [b], and G. R. Neil [c]

[a] Physics Department, Naval Postgraduate School, Monterey, California 93943 USA

[b] Advanced Energy Systems, P.O. Box 7455, Princeton, NJ 08543 USA

[c] Free Electron Laser Department, Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606 USA

ABSTRACT

Free Electron Lasers (FELs) have always had the potential for high average power, since the laser medium cannot be damaged and is transparent to all wavelengths while the exhaust heat is removed at the speed of light. At MW power levels, the resonator mirrors of the oscillator are vulnerable to damage because of the small beam size in the undulator. We present a description of an FEL that uses a resonator with a short Rayleigh length in order to increase the mode area at the mirrors and reduce the intensity. The corresponding undulator must also be short. The whole FEL system is designed to be compact and efficient, producing about 1 MW of power at 1μm infrared wavelength using an electron beam of about 140 MeV with about 0.6A of recirculating average current.

PACS-2001 Code: 41.60Cr

Keywords: free electron laser, high power, Rayleigh length

Motivation

The free electron laser (FEL) has the potential to be developed into a compact, efficient, and powerful tool for military or industrial applications. An exciting military application is the destruction of missiles at ranges around 5 km. This requires about 1 MW of power at 1 μm wavelength for a couple of seconds duration in order to destroy about 1 liter of missile material, causing the missile to break up in flight.

The Thomas Jefferson National Accelerator Facility (TJNAF) FEL [1,2] has demonstrated 2 kW output power with a design that appears attractive for high power applications. This FEL uses a superconducting, high-gradient accelerator and recirculates the electron beam back through the accelerator to increase efficiency and to reduce the shielding at the beam dump. The 1 MW FEL has an estimated size of 12mx4mx4m, weighing about 40 Tons, with an efficiency of about 10% and costing about $60 M. The accelerator runs along one side of the box while the optical resonator lies along the opposite side. Bending magnets guide the intense electron beam around the recirculation path within the box.

Resonator Optics with a Short Rayleigh Length

The goal is to design the MW FEL to fit inside the 12mx4mx4m box which means the resonator can only be $S = 12$m long. Normally, the FEL interaction along the undulator would take place over several meters with an optical mode of a few millimeters diameter. The Rayleigh length, $Z_0 = \pi w_0^2/\lambda$, for such a beam would be about 5 m so that the laser spot would still be a few millimeters diameter at the resonator mirror. Assuming 25% output coupling and a stored power of 4 MW, the power density on the mirrors would be about 30 MW/cm^2 so that no mirrors could survive the intensity.

A short Rayleigh length resonator is necessary to increase the spot size on the mirrors leaving a small waist for the intense FEL interaction in the undulator [3]. A Rayleigh length of $Z_0 = 1.8$ cm increases the spot size on the resonator mirrors separated by $S = 12$m to over 5 cm diameter so that the intensity on the mirrors is about 210 kW/cm^2. It is estimated that cooled saphire mirrors with a transmissive coating can handle this intensity without damage. The optical mode waist in the middle of the resonator is then $w_0 = 0.08$mm.

Short FEL Undulator

The undulator used in a resonator with a short Rayleigh length must also be short in order to avoid having the intense laser beam scrape the edges of the undulator magnets. The undulator length is only $L = 60$ cm consisting of only $N = 20$ periods of wavelength $\lambda_0 = 3$ cm. The undulator gap is 1 cm so only a small amount of power scrapes the magnets; the optical mode radius at the end of the undulator is only 0.1 cm. In this case, the short Rayleigh length restricts the undulator length to only 1/20th of the resonator length. The undulator could actually be longer, but more periods would decrease the FEL's natural extraction efficiency of $1/4N$. On axis, the magnetic field yields an rms undulator parameter of $K = 2$.

High-Power Electron Beam

The undulator converts the energy of the relativistic electron beam into laser light. The compact MW FEL uses a 140 MeV electron beam with an average current of 0.6 A made up of picosecond micropulses 0.3 mm in length. The high-power electron beam provides 84 MW flowing through the FEL interaction region with a relativistic Lorentz factor of $\gamma = 275$. The peak current in an electron micropulse is 800 A containing charge $q = 0.8$ nC. The electron beam micropulses arrive at the beginning of the undulator at the accelerator RF frequency 750 MHz in a beam radius of 0.08 mm, giving an electron density of $8 \times 10^{14}/\mathrm{cm}^3$ in each pulse. The electron beam radius is comparable to the optical mode waist of $w_0 = 0.08$ mm, so that some electrons at the edge of the beam do not interact with light in the middle of the undulator. At the ends of the undulator, the optical mode is considerable larger than the electron beam reducing FEL gain. This is a price for using the short Rayleigh length.

The accelerator length needed to reach 140 MeV is about 8 m with a 17 MeV/m gradient. It is desirable to keep the full accelerator section on one side of the 12mx4mx4m box leaving the other side for the undulator and optical mode. Half of the box's volume is used for the liquid helium refrigerator that provides sufficient cooling for continuous operation if required. The short 0.6m long undulator in the middle of the 12m long resonator leaves room for devices that can be used to prepare the electron micropulse for lasing in the undulator and/or recirculation of the beam after the undulator.

High-Power Laser Beam

The resonant optical wavelength for the 140 MeV electron beam in this undulator is $\lambda = 1\ \mu$m. The short electron pulses amplify picosecond long optical pulses each pass through the undulator. The electron pulse length is 15 times longer than the slippage distance $N\lambda$ so that short-pulse effects are minimal. Using the natural efficiency of the undulator, $\eta \approx 1/4N = 1.25$ %, the estimated laser power is $P = 1$ MW. There is also an induced energy spread of $\Delta\gamma/\gamma \approx 2/N \approx 10$ % (full-width) which can make recirculation of the electron beam difficult. It appears that it is possible to recirculate a spread as large as 15 %, so that 10 % can be considered feasible. Safe recirculation of 84 MW in a beam a mm in diameter still remains a risky aspect of this design.

The short Rayleigh length is important for distributing the high power over larger resonator mirrors, but also modifies the FEL interaction. The normalized Rayleigh length, $z_0 = Z_0/L$=0.03, is much smaller than the conventional value of $z_0 = 1/\sqrt{12} \approx 0.3$ which minimizes the optical mode volume along the undulator. With the short Rayleigh length, the optical field varies significantly along the undulator peaking in the middle where the resonator mode is sharply focused. There is also an optical phase shift accompanying the diffracting wavefront which modifies the interaction with the bunching electron beam. A numerical simulation can follow all of these effects self-consistently, and indicates FEL gains of several hundred percent with efficiency of more than 1 % as needed for 1 MW output. The intense laser focus in the middle of the undulator causes a larger induced energy spread than anticipated in the range of 13 % which is still acceptable for recirculation.

Conclusions

The development of a MW level FEL with a short Rayleigh appears feasible. Parameters lead to challenging issues, like beam transport, but overall the system values can be altered and still reach the goal of 1 MW output power in slightly alternate ways.

Acknowledgements

Work supported by the U. S. Department of Energy under contract DE-AC05-84-ER40150, the Office of Naval Research, the Commonwealth of Virginia, the Laser Processing Consortium, and Advanced Energy Systems.

REFERENCES

1. G. R. Neil, et. al., "First Operation of an FEL in Same-cell Energy Recovery Mode", Proceedings of the 21st International FEL Conference, Hamburg, Germany (August, 1999).
2. D. Douglas, et. al., "Driver Accelerator Design for the 10kW Upgrade of the Jefferson Lab IR FEL", Linear Accelerator Conference, August 2000.
3. D. W. Small, R. K. Wong, W. B. Colson and R. L. Armstead, "Free Electron Lasers with Short Rayleigh Length", Nuclear Instruments and Methods in Physics Research **A393**, 262-264 (1997).