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Author(s): Richard L. Sheffield, L-4; Claude A. Conner,
Clifford M. Fortgang, J. M. Kinross-Wright,
Richard D. Lovato, Dinh C. Nguyen, John G.
Plato, Robert M. Wheat, and Scott K. Volz, L-9;
Michael E. Weber, CST-1; Steve M. Gierman,
David J. Goldstein, and Kara L. Hayes, U. of
Cal.-San Diego

Submitted to: DOE Office of Scientific and Technical
Information (OSTI) 29

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A 1-kW Power Demonstration from the Advanced Free Electron Laser

Richard L. Sheffield*, Claude A. Conner, Clifford M. Fortgang,
J. M. Kinross-Wright, Richard D. Lovato, Dinh C. Nguyen,
John G. Plato, Michael E. Weber, Robert M. Wheat, and Scott K. Volz
Los Alamos National Laboratory

Steve M. Gierman, David J. Goldstein, and Kara L. Hayes
University of California, San Diego

Abstract

This is the final report of a one-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The main objective of this project was to engineer and procure an electron beamline compatible with the operation of a 1-kW free-electron laser (FEL). Another major task is the physics design of the electron beam line from the end of the wiggler to the electron beam dump. This task is especially difficult because the electron beam is expected to have 20 kW of average power and to simultaneously have a 25% energy spread. The project goals were accomplished. The high-power electron design was completed. All of the hardware necessary for high-power operation was designed and procured.

1. Background and Research Objectives

Free-electron lasers (FELs) have existed for over a decade. An FEL is a system that converts the energy from a relativistic electron beam into a laser beam. The FEL has three main components: the accelerator, the wiggler, and the laser optics after the wiggler. The accelerator generates the energetic electron beam. In our experiment the beam energy is 17 MeV. The wiggler converts electron energy into light by oscillating the electrons transversely to the direction of propagation. The light comes out of the wiggler as a laser beam coaxial with the electron beam. The laser optics directs and focuses the resulting laser beam.

FELs are not considered competitive with conventional laser systems mainly because of complexity and cost per unit of optical power. Presently, the highest average power FEL is limited to approximately 10 watts of power. The power limitation has to do with the high cost of a high-efficiency wiggler and damage to optical components at high powers. The system

*Principal investigator, e-mail: rsheffield@lanl.gov

cost is also driven by the large number of system components required for the FEL.

The four approaches to FELs presently used or suggested are: oscillator, amplifier, externally-seeded amplifier, or oscillator-amplifier. In an oscillator, relatively high reflectivity mirrors are used to recirculate the light in an optical resonator. In this type of FEL the recirculating light interacts with the electron beam causing more light to be generated. To attain high laser powers out of the FEL therefore requires even higher recirculating power inside the resonator. The recirculating powers are at least three times higher than the output power, but more typically ten to twenty times the output power. For a high-average power device, the mirror coatings damage and the mirror cooling requirements add cost and complexity. Also, an oscillator has very tight tolerances on mirror alignment and length positioning, causing problems in system stability and ease of use.

An amplifier does not have the problems with optics since optics are not required for recirculation. However, to attain high-powers requires a much longer wiggler than an oscillator, increasing cost and complexity. Also, an amplifier has no frequency control, and so the optical output can vary from pulse to pulse. Another drawback is that the optical mode can grow larger than the transport tube in the wiggler, causing a loss of optical power.

An externally-seeded amplifier has the same basic constraints as an amplifier except that the frequency is determined by an external laser. An external laser adds cost and complexity. Also, an external laser may not be available that can produce the required optical wavelength.

The oscillator-amplifier combines the advantages of an oscillator and amplifier. The oscillator is used to attain a moderate power level, a power level that is still below the damage level of the optics. Also, the frequency stability is determined to a large degree by the resonator feedback. By the addition of a frequency selective device, the frequency can be tuned or precisely controlled (keeping in mind the damage limits for these types of devices tend to be much lower than high-power optics). The amplifier then is used to attain a high efficiency. This system is obviously much more complex than either the oscillator or amplifier alone.

This project is based on a high-gain amplifier FEL operating with a very small amount of optical feedback, much smaller than previously considered acceptable. In this configuration, the optical gains on a single pass through the amplifier exceed the loss by a large enough margin so that after a few passes through the amplifier high powers are reached. The main feedback mirror has a large hole to allow unperturbed passage of the high-power laser beam. For example, in present designs less than 2% feedback is required, with greater than 98% of the main optical beam passing through the hole. The optical mode is large at small power levels and much smaller at power levels near saturation. During optical power build-up, the light is mainly reflected from the mirror, and then at saturation most of the power is passed through the mirror. The small amount of feedback light is directed back to the upstream mirror, and then

refocused to the front wiggler section. This light is then amplified through the wiggler. In present designs, only five passes are required for the laser to reach full saturation. This shorter wiggler design also reduces the constraint imposed by the size of the optical mode in the wiggler. A single long wiggler would cause the loss of the majority of optical power to occur on the optical transport tube inside the wiggler.

Although this system has the high gains associated with an amplifier, light wavelength stability can also be obtained, similar to an oscillator. If the feedback light is passed through an optical element in the feedback leg, then either wavelength stability or narrow bandwidth can be obtained. Since the feedback leg has low optical powers, the associated optics are not illuminated with damaging optical power levels.

Another advantage of this type of system is the small number of components required. This reduces overall system cost, improves system reliability, and reduces maintenance. Figure 1 is a schematic of two possible configurations of this concept. Our system, shown in Figure 2, is based on a combination of both designs shown in Figure 1. Our system uses an output mirror with a large hole, but passes the light around the wiggler.

2. Importance to LANL's Science and Technology Base and National R&D Needs

FEL research is directly related to several of the Laboratory's core competencies and capabilities. In particular, FELs require advanced control systems, high-level computational capability, and detailed knowledge of accelerator technology.

Besides the spin-off benefits in controls and rf systems for the APT (Accelerator Production of Tritium) program, this effort is directly applicable to the Navy FEL program on shipboard defense. A shipboard defense places a high priority on size and maintenance. Our effort is aimed at reducing cost, size, complexity, and maintenance of high-average power free-electron lasers. Also, development of low-cost, low-maintenance FELs enables other military and commercial applications of FEL technology.

3. Scientific Approach and Accomplishments

The main objective of this project was to engineer and procure an electron beamline compatible with the operation of a 1-kW FEL. Another major task is the physics design of the electron beam line from the end of the wiggler to the electron beam dump [1]. This task is especially difficult because the electron beam is expected to have 20 kW of average power and to simultaneously have a 25% energy spread. The project goals were accomplished. The high-

power electron design was completed. All of the hardware necessary for high-power operation was designed and procured.

Publications

1. Nguyen, D., "Synchronously Injected Amplifiers, A Novel Approach to High-Average-Power FELs," Proceedings of the FEL '96 conference (to be published).
2. Goldstein, J., "Theoretical Study of the Design and Performance of a High-Gain, High Extraction-Efficiency FEL," Proceedings of the FEL '96 conference (to be published).
3. Sheffield, R., "Electron Beamline Design for Los Alamos national Laboratory 1 kW FEL," Proceedings of the FEL '96 conference (to be published).

References:

- [1] Sheffield, R., "1 kW electron beamline design", RLS96-2, (1996).

Figure 1. Representative configurations. In the upper schematic, the two mirrors have holes either on or off-axis. In the upstream mirror the hole allows passage of the electron beam. In the downstream mirror, the hole allows passage of the high power optical beam from the FEL. In the lower schematic, the two mirrors are located off-axis, allowing passage of the electron beam and high-power laser beam. The lower box could include gratings or an interferometer for frequency selection or bandwidth control. The lower box could also include an amplitude feedback element for amplitude correction or an amplitude modulation element for time-varying amplitude implementation.

Figure 2. Engineering layout of the new high-power FEL beamline at the Advanced Free-electron Laser Facility. The 1.3 GHz radiofrequency linear accelerator is on the left. The long narrow rectangular box in the middle of a 6 foot by 10 foot vertically-mounted optical table is a 2 meter long wiggler. The optical feedback passes through the tube located above the wiggler box. The laser output beam exits through a hole in the wall located on the right of the figure.