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AN OVERVIEW OF THE LAWRENCE LIVERMORE NATIONAL LABORATORY FREE ELECTRON LASER PROGRAM*

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Abstract

This paper reviews the current status of the Lawrence Livermore National Laboratory Free Electron Laser Program.

Introduction

The Lawrence Livermore National Laboratory Free Electron Laser Program (LLNL FEL) conducts balanced research in the component technologies necessary for the development of a high average power laser. As illustrated in Fig. 1, the LLNL approach employs three major components, a linear induction electron accelerator, a master oscillator, and a linearly polarized wiggler as a FEL amplifier. Before discussing the accelerator and wiggler technologies, we heuristically summarize the FEL operation.

In contrast to FEL designs which use rf linacs and FEL oscillators, the electron pulse from an induction linac several tens of nanoseconds long, enters the wiggler without being bunched in the accelerator into short packets, and the laser beam makes only a single pass through the FEL amplifier. The magnetic fields of the wiggler are alternately up and down, and, hence, the undulatory motion of the electrons is in the horizontal plane and does not spiral around the axis as in a helical wiggler. Because of Lorentz contraction and relativistic Doppler shift, the oscillatory period of the electrons, several centimeters long in the lab frame, is resonant with laser light, which has wavelengths of order γ^2 shorter.[1] Electron beams of high energy, typically a few to hundreds of MeV's, can thus be used to amplify laser beams in the range of wavelengths from several mm's to less than one μm. The pondermotive forces of the combined laser beam and wiggler magnetic fields erect potential wells, which tend to bunch the electrons. Because of this bunching, the oscillating electrons radiate coherently at the resonant wavelength. As the electrons radiate, the laser intensity grows, the potential wells deepen, and eventually some fraction of the electrons are trapped in the pontential wells. To sustain resonance conditions for these trapped electrons as they continue to radiate, the wiggler period may be shortened or the magnetic field may be decreased.[2] The LLNL FEL Program is examining both techniques, but favors the latter.

Electron Accelerator Development

Successful trapping of a large fraction of the electrons requires that there not be a large variation of beam energy over the duration of the pulse and that there not be a large spread in the component of velocity parallel to the beam axis.[1-3] The first requirement dictates that the accelerator cumulative voltage have small "sweep" as a function of time, less than several tenths of a percent. The second requirement implies principally that the cone of velocities be tightly clustered about the axis, that the beam occupy a small volume in phase space. The current must also be large simply to provide the necessary power, and so the quotient of the current and its volume in phase space, the electron beam "brightness," must be very large. Volume in phase space cannot decrease over the entire length of the accelerator, and, hence, the injector at the input to the accelerator must have very high brightness. Brightness can be lost in the accelerating process if any of a variety of instabilities occur.[4] Care must be exercised in the design and fabrication of the accelerating cells, depicted as transformer loops in Fig. 1, to avoid such "beam break up." Finally, if the FEL is to have high average power, the accelerator and the other two components must have a high repetition rate capability.

Lawrence Livermore National Laboratory has a long history of pioneering linear induction electron accelerators, but we mention here only the last few stages in the quest for brightness, current, energy, and repetition rate. The Experimental Test Accelerator (ETA), inaugurated in 1979, has a maximum current of 10 kA with a central current of 1200 A at a brightness of 1E4 A/(rad-cm)^2, and at a maximum energy of 5 MeV. It is capable of operation at 1 Hz.[5] Its successor, the Advanced Test Accelerator (ATA), employs field emission cathodes to achieve brightness of the order of 1E5 A/(rad-cm)^2 at currents of a few kA and at energies of 40 to 50 MeV. The use of Blumleins with gas blown spark-gap switches permit repetition rates of kHz over short durations.[6] The High Brightness Test Stand (HBTS) has replaced these switches with branched magnetics with saturable inductors to attain high repetition rates over extended periods. The use of thermionic dispenser cathodes in its injector has permitted achieving brightnesses of 1E6 A/(rad-cm).[2-7] The HBTS is a relatively low-energy accelerator (about 3.5 MeV) and typifies our technique of pursuing technological development off-line and in parallel with large, major experiments.

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FEL Amplifier Development - Key Issues

In order to be useful for a variety of high average power applications, the FEL amplifier must meet demanding requirements in several areas. Its gain and extraction efficiency must be high to minimize size of the master oscillator and accelerator, respectively. For applications demanding propagation over great distances, the output optical mode should be TEM_{00} to very high purity. Even with very high gain per unit length of wiggler, most contemplated applications will still require wigglers many Rayleigh ranges long; that is, if diffraction were not otherwise balanced, the laser beam would diffract out of the electron beam before being adequately amplified. In the exponential gain regime the beam size is dominated by gain guiding, an effect well known in ordinary lasers; in the saturated gain regime, an additional mechanism, refractive guiding, is calculated to balance diffraction.[8] Because of the bunching of the electrons into "buckets," the real part of the index of refraction is modified to be slightly greater than one (the same mechanism producing net gain in the imaginary part). The laser beam is thus confined refractively as in an optical fiber. One item on the agenda of the LLNL FEL Program is to confirm this predicted effect experimentally. Another item of interest is the relative amplitude of sideband radiation, which results because of the coupling of light modulations with electron synchrotron motion within the "bucket." The use of linear, rather than helical, wigglers is expected to produce a small amount of radiation in the higher, principally odd, harmonics. The relative content of these spectral adulterants can be rather important in the subsequent laser beam processing for certain applications.

In all the components technologies, extensive numerical modeling is conducted for designing, for predicting performance and comparing with experiment, and for specifying detail engineering tolerances. We mention here the capabilities of the family of computer codes used at LLNL for designing FEL wigglers. The progenitor code, FRED, tracks a slice of electrons the entire length of the wiggler and follows their complete motion in the x-y transverse coordinates.[9] FRED accounts for betatron motion in the focusing fields and for longitudinal electrostatic effects. The approximation for radiative process uses the equation for the oscillatory motion averaged over a full wavelength. The laser radiation is calculated in two-dimensional cylindrical geometry. The same field solver is used for waveguide microwave calculations as for free space optical wavelength calculations so that the early microwave experiments may benchmark code predictions even for much shorter wavelength FEL's. FRED is a time-independent code in the sense that the slippage of the slice of electrons with respect to electromagnetic radiation is not considered explicitly. The derivative code FRED3D extends the paraxial equations to three-dimensional to permit the calculation of the full spatial modes of the laser radiation.[10] GINGER considers relative slippage of the electrons in a time-dependent treatment with cyclical boundary conditions in order to estimate the amount of sideband radiation.[11] NUTMEG estimates the odd order, high harmonic content, in practice up to the third harmonic.[12]

FEL Amplifier Development - ELF Experiments

From 1983 until the present, LLNL has been conducting a sequence of experiments in the microwave regime on the Electron Laser Facility (ELF) with the beam from ETA. These have comprised small and large signal gain and extraction measurements on tapered and untapered wigglers,[13] measurements of spatial modal content, measurements of the relative power in the third harmonic,[14] determination of the phase shift as a function of wiggler length,[15] and, most recently, an examination of relative intensity of the sideband radiation. These experiments have all focused on the laser wavelength of 8.6 mm (about 35 GHz) with a wiggler wavelength of 9.8 cm and a maximum wiggler length of 3 m. The electron beam energy was roughly 3.5 MeV; its brightness was 2×10^4 A/(rad-cm)^2 for the core beam of about 800 A. The microwave amplifications of the TE_{01} mode was conducted inside an oversized waveguide (3 x 10 cm).

Figure 2 summarizes the results of the gain and extraction efficiency measurements.[13] The amplified power is depicted as a function of active wiggler length with the +'s representing the data taken with a properly tapered wiggler field profile and the o's, with an untapered wiggler. The solid lines show the FRED results. Clearly, both experiment and theory confirm the advantage of tapering the wiggler. Without tapering, the electrons remove energy from the laser field after saturation. The greatest extraction efficiency obtained with a tapered wiggler was about 35% at a microwave power of about 1 GW. The greatest system gain was about 45 dB and the greatest gain in the exponential region, about 40 dB/m.

The next most significant modes were the degenerate TE_{21} and TM_{21} modes, whose resonant frequency was only about 2% above the fundamental TE_{01}. In an untapered wiggler, these two modes competed strongly with the fundamental after saturation with the power oscillating back and forth between modes with roughly the synchrotron period as energy was exchanged between the overlapping buckets of the modes. Tapering the wiggler reduced the fractional content of the higher order spatial modes.[13]

Radiation into the higher harmonics is simply coherent spontaneous emission and so does not increase as the fundamental amplification is increased by tapering the wiggler.[13] With an untapered wiggler the power into the third harmonic was about 1% of the peak saturated power, on the order of 1 to 2 MW. Figure 3 shows that tapering the wiggler has substantially increased the power in the fundamental, but left that in the third harmonic unchanged. Note too the good agreement between the measurements and the NUTMEG calculations. Recent measurements also corroborate the theoretical estimates of laser phase shifts with amplification.[14]

In addition to benchmarking the FEL codes, these microwave experiments have inspired several new applications. Tapping off the 35 GHz microwaves into a small disk-loaded structure might permit the use of significantly higher electric fields in future accelerators, the so-called "two-beam-accelerator".[15] The FEL microwaves might also be used to heat magnetic fusion machines.[16]

PALADIN Experiments

While the ELF microwave experiments have greatly increased our confidence in the modeling codes, a number of issues merit direct experimental elucidation at the earliest possible time before advancing to short wavelength optical FEL's. The results of the phase shift measurements on ELF indirectly support the underlying mechanism of refractive guiding, but unequivocal experimental confirmation is needed. Likewise, we need to examine directly the modal purity at optical wavelengths without waveguide boundaries. In addition to these and other "physics" tests, there are many "engineering" questions: testing the use of curved pole piece focusing to maintain a small electron beam radius along a long wiggler, for example. With the existing beam (several kA at 40 to 50 MeV and at 1 to 2 A/[cm-rad]^2) at ATA and commercially available CO_2 master oscillators, it is possible to conduct the "PALADIN" experiments at 10.6 μm which illuminate many of these issues.[17] The construction of the first phase of these experiments is now completed, and initial activation tuning has begun.

Later phases of the PALADIN experiments require a rather long wiggler, 25 m, a fact which has posed challenging design problems for the wiggler. A cut-away view of a few pole pieces of the hybrid (electromagnetic and permanent magnetics) wiggler, originally conceived by K. Halbach,[18] is shown in Fig. 4. The pole pieces themselves are soft iron which are energized by the electromagnetic coils. Their B-H curves are biased away from zero by the permanent magnets positioned on either side of each pole piece; this hybrid design permits tuning the wiggler field over a much larger range and reduces its sensitivity to the iron magnetic properties. In order to prevent random walk of electrons because of random field errors, this wiggler has been constructed with gap errors less than 0.2%. Horizontal steering by the coils wrapped around the yoke field return path can partially compensate for remaining wiggler field errors. To preserve tight focusing on the electron beam the pole pieces have been shaped to produce a sextuple field.[19] Very considerable development has been invested in bringing this design to fruition.

Conclusion

We have presented here just a brief glimpse of the LLNL FEL program. In this program there are sequences of major experiments in each of the central component technologies, electron accelerator, wiggler, and master oscillator. Each area is guided by extensive modeling. In addition, key sub-component technologies, such as branched magnetic switches and wiggler magnetics, have parallel off-line development efforts. With the interactive feed-back from the experiments, the models are benchmarked and used as predictive guides in comprehensive system analysis motivating overall program direction.

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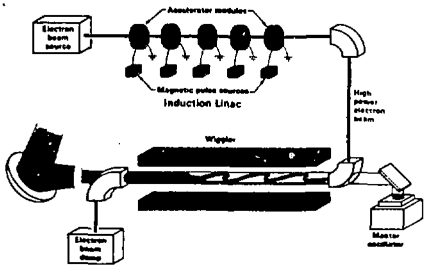

Figure 1. Schematic layout of a high power FEL with the key components emphasized.

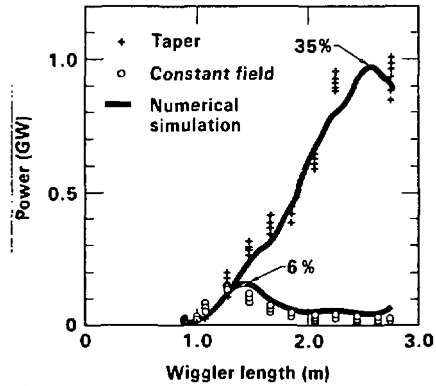

Figure 2. Microwave power as a function of wiggler length in the ELF experiment. Both theoretical calculations and experimental results are shown for tapered and untapered wiggler field configuration.

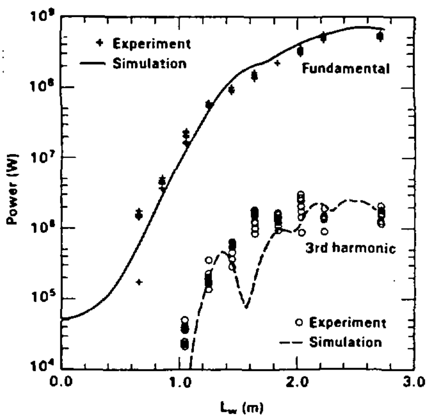

Figure 3. Microwave power in the fundamental and third harmonic versus wiggler length in ELF experiment. This experiment used a tapered wiggler.

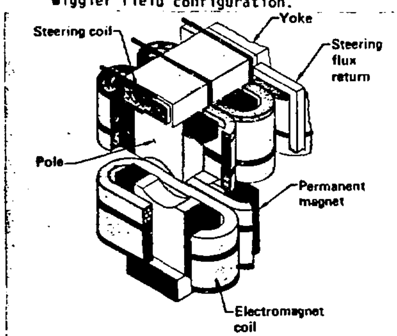

Figure 4. Cut-away view of PALADIN hybrid wiggler.