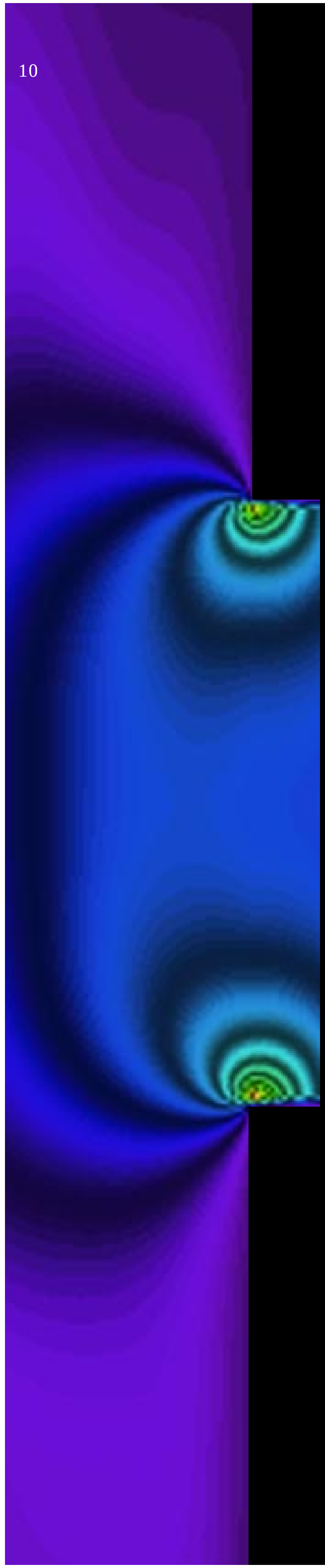


Computational Electromagnetics: Codes and Capabilities

Livermore’s computational electronics and electromagnetics engineers have a very direct mission: Give researchers the best electromagnetic modeling tools to solve real analysis and production problems.

LAWRENCE Livermore has long been recognized as a leader in the world of scientific computer simulations—creating multidimensional models of the dynamic and complex forces unleashed by nuclear explosives, visualizing the processes at work in the birth and death of stars, and studying the effects of greenhouse gases on global climate and of pollutants in our environment. It is not surprising, then, that the Laboratory is also a leading developer of computer codes that simulate propagation and interaction of electromagnetic (EM) fields.

Livermore’s EM field experts study and model wave phenomena covering almost the entire electromagnetic spectrum (Figure 1). Applications are as varied as the wavelengths of interest: particle accelerator components, material science and pulsed power subsystems, photonic and optoelectronic devices, aerospace and radar systems, and microwave and microelectronics devices.

Building from its seminal work on time-domain algorithms[1] in the 1960s, the Laboratory has fashioned top-notch resources in electromagnetics and electronics modeling and characterization. Using Laboratory-developed two-dimensional and three-dimensional EM field and propagation modeling codes and EM measurement facilities, Livermore personnel can evaluate, design, fabricate, and test a wide range of accelerator systems and both impulse and continuous-wave RF (radio-frequency) microwave systems.

Center of Developing Technology

The Laboratory’s unique connectivity has kindled progress in many key areas of accelerator design and photonic, opto-electronic, and RF systems. The focal point for these activities is the computational electronics and electromagnetics thrust area, which provides technical support for existing and developing programs. “We are a resource that crosses technical boundaries, yet we are integral to Livermore’s major program areas,” says thrust area leader Cliff Shang.

Administratively a part of Electronic Engineering’s Defense Sciences Engineering Division, the thrust area operates like a technology development center. “With the EM Laboratory and EE personnel, the thrust area champions development of the best electromagnetic modeling capability available,” says Richard Twogood, Deputy Associate Director for Electronics Engineering.

The thrust area has created a variety of production computer codes. (See the box on p. 13 for a summary of Livermore codes.) For example, Figure 2 shows how the NEC code is used in the development of an antenna for micropower impulse radar (MIR). Other codes are also in development.

With the codes, the EM Laboratory personnel fabricate the resulting systems and components and then analyze the prototypes against the codes.

Specialized Models for Analysis and Design

Creating new codes and refining production codes are the thrust area’s primary activities, but the work does not occur in a vacuum. “We are not out just to design and develop EM codes,” Shang says. “We develop modeling technology that can be directly applied to design problems, and we are adding new EM capabilities to anticipate future requirements of Laboratory programs. To accomplish these tasks effectively, our specialists work closely with program personnel.”

Shang points out that “pairing experts from different disciplines—characteristic of the way the Laboratory does business—is essential for code development. This is the case in accelerator physics as well as in photonics and opto-electronics. The communities overlap. When you take the relevant knowledge and best codes from each to solve problems, you can end up with a new and very interesting set of codes.”

Such codes are important because photonic devices are central to the growth of high-speed communications and computation. Signals in photonic networks can travel long distances at the speed of light, with very little power loss. These optoelectronic networks are made up of fibers, waveguides, sources, receivers, converters, and a host of other devices—all of which must be carefully designed if they are to work well together. Simulating a device before fabrication saves money and effort.

Many of the specialized codes created at Livermore have been made available to other government laboratories, universities, and industry. “The original NEC code is one of our most well-known codes,” says Shang, “from the Department of Defense radar community to ham radio operators who design their own antennas.”

In addition to their work in photonics and opto-electronics, EM thrust area personnel support a wide variety of Livermore R&D programs. Major emphases are stockpile stewardship and non-nuclear defense. For example, they are using their expertise and codes to support development of an advanced accelerator, which will help assure the safety and reliability of the nation’s stockpiled nuclear weapons. They also support the Department of Defense (DoD) in assessing EM susceptibilities in conventional military systems.

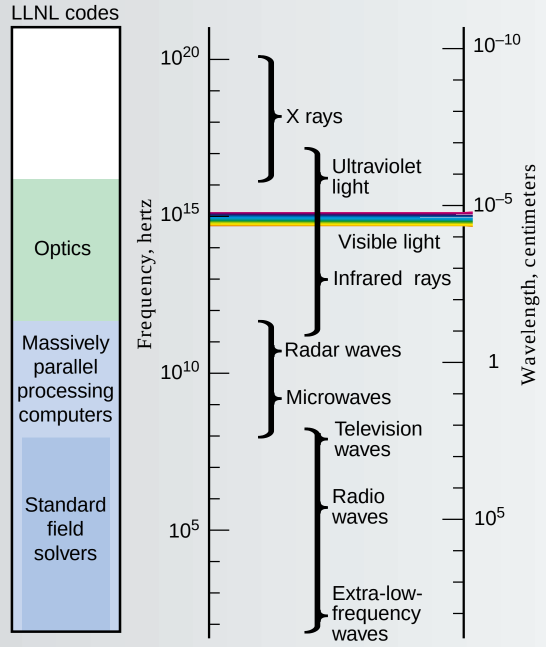


Figure 1. Laboratory expertise in computational electromagnetics is applied to problems across a wide area of the electromagnetic spectrum.

Focusing on Stockpile Stewardship

The Laboratory's capability to simulate, design, fabricate, and characterize accelerator technologies is being brought to bear in support of the nation's nuclear stockpile. As Livermore researchers design an advanced multibeamline accelerator for a proposed DOE program, a critical question is whether beam quality can be maintained when a single long-pulse (200-nanosecond to 2-microsecond) electron beam is split and channeled a number of times down subsidiary beam lines.

"It is a most difficult and complex problem, a true Grand Challenge," says Shang of the EM work on the design for what the DOE calls the Advanced Hydrotest Facility (AHF). Lawrence Livermore, Sandia, and Los Alamos national laboratories are coordinating separate technological approaches for the AHF. A DOE decision on which technology to adopt is expected in the year 2000, with the multimillion-dollar AHF operational in 2007. (See also the Contained Firing Facility article, beginning on p. 4.)

A 21st century diagnostic tool, AHF will provide multiple-angle, high-resolution x-ray images of materials in motion, such as an imploding device, to assure nuclear weapon reliability and safety. With the AHF, scientists will be able to assess the effect of high explosives on the weapon case. Livermore's role is to explore a linear induction accelerator that would generate a high-current (5-kiloamp), high-energy (20-megaelectron-volt) electron beam to produce x rays for radiography applications.

The Laboratory's experience in designing, building, and refining linear induction accelerators spans four decades. The current workhorse, the Flash X-Ray (FXR) radiography machine, has a single-pulse design (Figure 3). It is currently going through a second upgrade, this time to become a double-pulse system. Thrust area support includes modeling the injector performance and upgrading beam dynamics codes used to model high-current electron-beam transport.

Like the proposed AHF, the FXR allows scientists to assess issues related to safety, reliability, and performance of

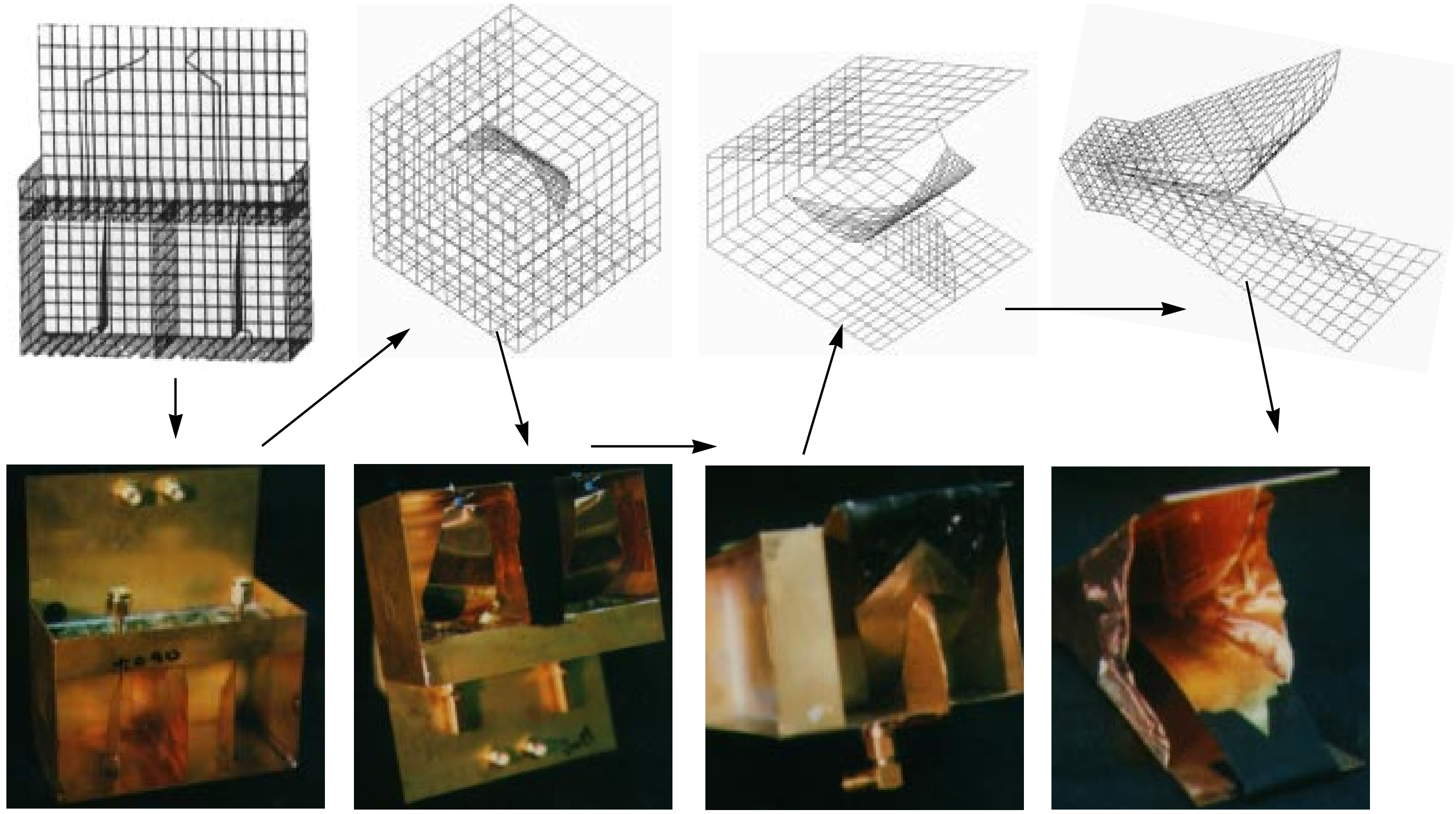


Figure 2. The Laboratory's specialists in EM used the NEC code in an iterative process to create a pulsed antenna to meet bandwidth and gain specifications. The project was a bridge deck inspection system using the Laboratory's micropower impulse radar (MIR) system (see the *S&TR* article on MIR, January/February 1996, p. 16–29.)

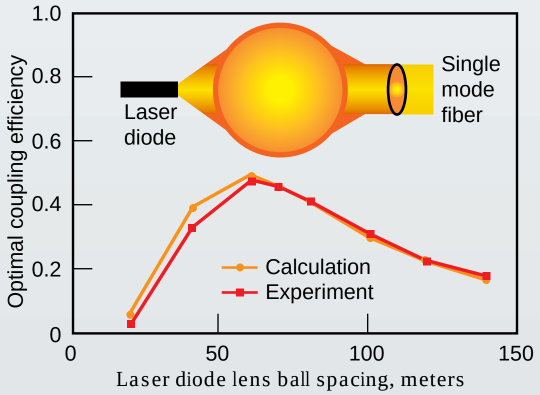
Livermore Codes

Rick Ratowsky calls it a Virtual Optical Bench, a user-friendly graphics interface for designers of photonic circuits, the optical world's equivalent of electronic circuits. "It is a photonics design tool with broad applicability," says Ratowsky, an electrical engineer.

Some photonics components have very small features, at a single wavelength scale; some features are very large, say thousands of wavelengths. Such devices have been very difficult to design because there is no easy way to put these differently scaled parts together.

A modeling code known as MELD (Multi-Scale Electrodynamics) will allow different length scales to be used concurrently—saving optoelectronics researchers much time and effort. (See figure to right.) The MELD code draws on techniques of both the electromagnetics and optics communities and integrates them in a way never used before.

"I can't say that all the techniques themselves are unique to Livermore," observes Ratowsky, "but their implementation and integration are." MELD joins a long list of EM codes developed at Livermore. Following is a brief summary of key modeling codes. All are used to solve equations arising from the fundamental classical electromagnetic field equations enunciated by James Clerk Maxwell in 1873.



Because devices such as laser diodes and fiber optic cables have different spot sizes, intercomponent coupling of optical power is a major limitation of integrated opto-electronic systems. The solution to the problem may be a ball lens optical mode converter (above) developed jointly by Lawrence Livermore and Hewlett–Packard to match optical fields. Laboratory photonic codes were used to design the optimal match.

Code	Recent application	Function
AMOS	Analysis of FXR accelerator structure (also ATA, ETA-II, and DARHT)	Solves 2.5-D axisymmetric and planar extrusion problems
NEC	Simulation of LLNL's MIR antenna	Models wire and patch antennas in the frequency domain (3-D)
TSAR	Simulation of RAH-66 Comanche helicopter	Models field behavior
MELD[a]	Laser diode optimization	Integrates hybrid full-wave electromagnetic and optical algorithms
TIGER	Aceleration kicker and RF structures	Performs 3-D time-domain calculations on unstructured grids in a massively parallel processing environment
BEEMER	Optical directional couplers, lenses, and curved fibers	Designs and simulates 2-D integrated optical systems using the beam-propagation method
EIGER	Broadband, ridged-waveguide, horn antenna	Calculates 3-D steady-state EM fields in the presence of interesting materials

[a] MELD includes SPHERE2 and TSARLITE.

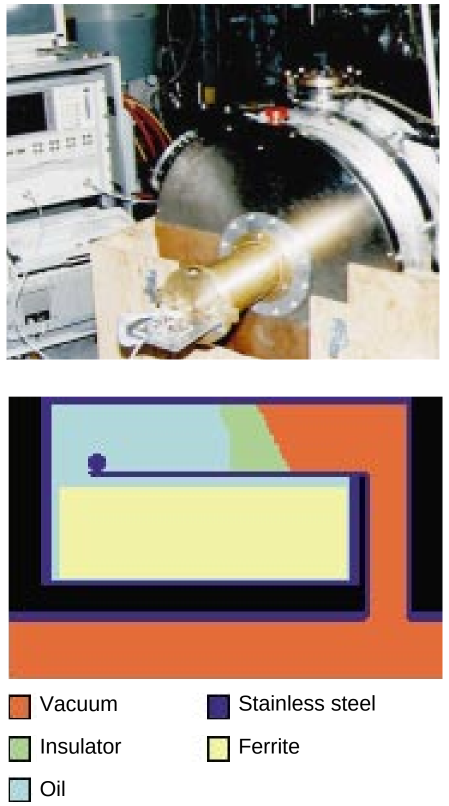


Figure 3. One accelerator cell of the Livermore Flash X Ray (FXR) (top) and its computational model (bottom), which will be used to design improvements to the machine.

a nuclear weapon's "primary," its fission trigger. In FXR hydrodynamic experiments, high explosives are detonated to produce pressures so high that solid materials, even when not melted, flow like fluids. X rays are created when charged particles generated by the FXR slam into a target made of a dense metal such as tantalum and provide images that are later analyzed. The FXR, however, offers only a single line-of-sight x-ray record. Stockpile weapons analysis requires simultaneous x-ray images from multiple angles, which the AHF will provide.

Ringing the high-explosive chamber with several linear accelerators to produce x rays for multiple imaging is very expensive. A Lawrence Livermore option proposes using a single linear induction accelerator that exploits a new and novel beamline component called the "kicker." The kicker (Figure 4) would displace a single electron beam pulse, effectively creating multiple pulses. Each pulse would travel down separate curved beamlines to encounter additional kickers for further splitting. Splitting would occur as many times as necessary to produce a specified number of beamlines for AHF diagnostics. An advanced kicker is also being developed by Livermore that could steer the beam horizontally as well as vertically, thus providing four or more different output beamlines from a single device. The challenge is to maintain beam quality in each subsidiary line. Proof-of-concept experiments for the AHF will be performed this year when Livermore's Experimental Test Accelerator-II (ETA-II) is refurbished and fitted with a kicker unit.

Understanding Wakefields

A charged particle beam traveling through an accelerator transport system, or beamline, has an associated electromagnetic (EM) field.

If the beamline is free of perturbations, the beam's EM field is not disturbed. However, a perturbation can modify the local electrodynamic properties of the structure.

Perturbations can consist of changes in cross section, apertures in the transport system wall, curved beamlines, or the introduction of different materials into the beam transport line.

As the charged particle beam streams past these perturbations in the structure, the beam's EM field is scattered from the structure. This EM field is called a wakefield (Figure 3) because the scattering occurs in the wake of the very-high-velocity particle.

This wakefield can interact with other particles traveling down the beamline behind the exciting particle, sometimes in an undesirable way, leading to the beam's degradation or, worse, breakup.

As part of the Laboratory's AHF design team, the EM experts are doing electromagnetic modeling of the beamline components. Of particular interest are electromagnetic wakefields that could have an adverse impact on beam quality (see box and illustrations this page and p. 15).

"Our approach is to design an accelerator beamline component and simulate the design with our model. This iterative process refines the design before machinists begin fabricating accelerator components," explains electrical engineer Brian Poole. "We use those scattered wakefields to calculate the forces on charged particles that are injected into the beamline at subsequent times and to see how the beam quality is maintained."

Understanding AHF electromagnetic dynamics requires the utmost in computer resources. Solutions to some wakefield problems take a month or more of continuous supercomputer time, so some models are run on a smaller scale because of computer resources. For really large models that simulate the accelerator system being designed, the DOE's ASCI (Accelerated Strategic Computing Initiative) platform will be used. ASCI will allow more than a thousandfold increase in computational speed and data storage. Shang noted that thrust area personnel are developing three-dimensional, massively parallel, time-domain EM production codes that will exploit the new high-performance computing capabilities when they become available.

(a)

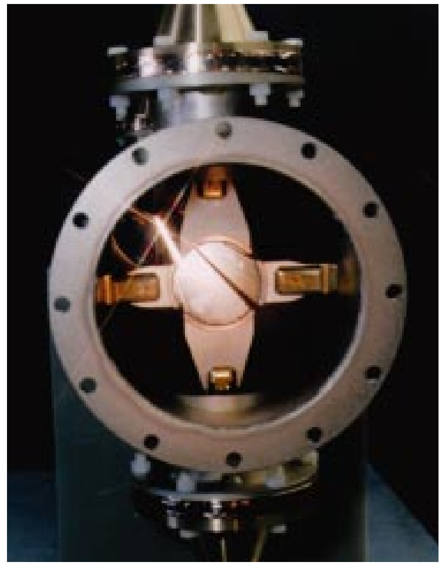
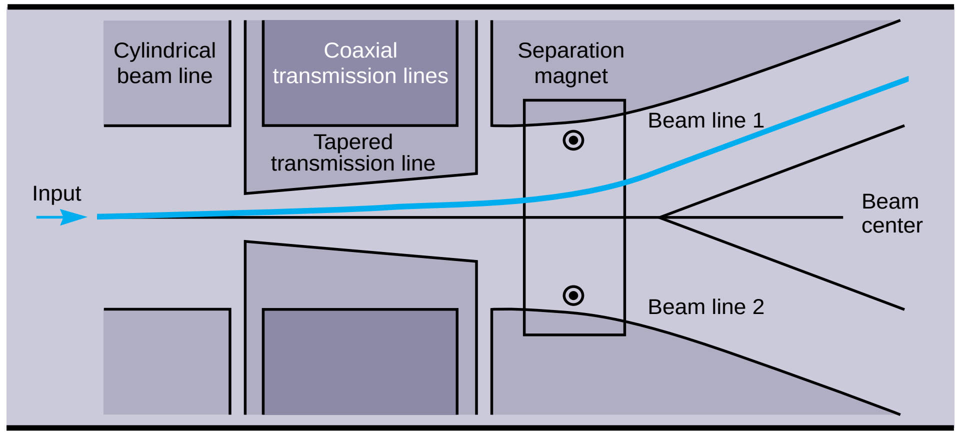
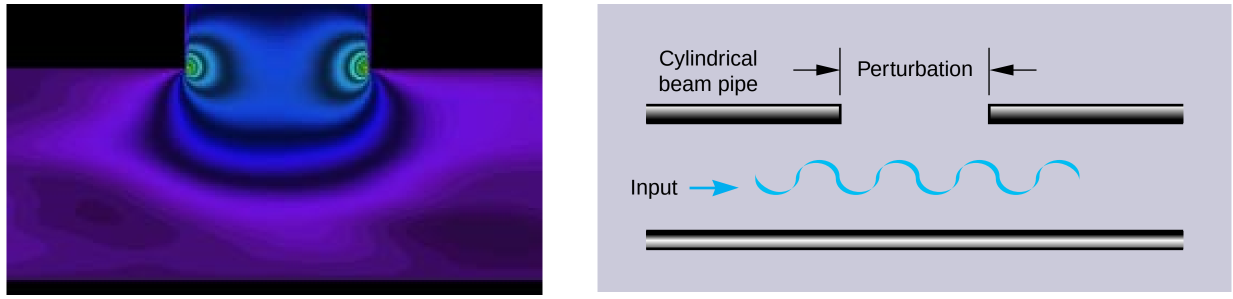


Figure 4. (a) The "kicker" structure developed for the proposed Advanced Hydrotest Facility consists of two pairs of nonlinearly tapered transmission lines enclosed in a cylindrical beamline. Each downstream beam may be split again into separate beams using additional kickers. (b) This schematic of the kicker shows the external coaxial transmission lines connecting the top and bottom strip lines. (c and d) Image and schematic of a wakefield calculation. The spectral characteristics of the longitudinal and transverse forces are determined on a test charge subjected to the wakefield.

(b)



(c) (d)



In addition to their work on radiographic systems such as FXR and AHF, thrust area personnel are involved in several other stockpile stewardship initiatives. They include:

- Designing the linear induction accelerator second-axis option of the Dual Axis Radiographic Hydrodynamic Test (DARHT) facility proposed for Los Alamos. DARHT would produce radiographic images with significantly higher spatial resolution and illumination intensity than are possible with present facilities.
- Developing integrated computer programs that will be used to design photonic circuits in the high-speed diagnostics of the National Ignition Facility (NIF). Analyzing high-power performance of optical components is another assignment performed for NIF, the 192-arm laser system that will simulate conditions of pressure, temperature, and density close to those that occur during the detonation of a nuclear weapon. (For more information on NIF, see *Energy & Technology Review*, November/December 1994.)
- Designing high-power microwave components and systems for the proposed Accelerator-Produced Tritium facility, an option being considered by the DOE as the primary source of tritium in the 21st century to replace the aging tritium in stockpiled nuclear weapons.
- Modeling and measuring the correct beam interaction physics in the

accelerating structure for the Short-Pulse Spallation Source (a Los Alamos program).

- Analyzing and designing high-gradient insulation for development of compact accelerators.
- Analyzing heat dissipation in high-power optical components for NIF.
- Simulating beam controls for heavy-ion fusion.

Supporting Conventional Defense

Applying EM field theory to accelerator development is a multidisciplinary task that goes beyond traditional methods. However, these classical methods occupy a prime spot in the EM toolkit when researchers deal with problems that surface in today's commercially oriented, circuit-based microchip world. For example, aboard a commercial airliner, passengers are cautioned about when to use a cellular phone or laptop computer. The concern is that EM fields produced by the devices could interfere with the plane's electronic instruments and controls.

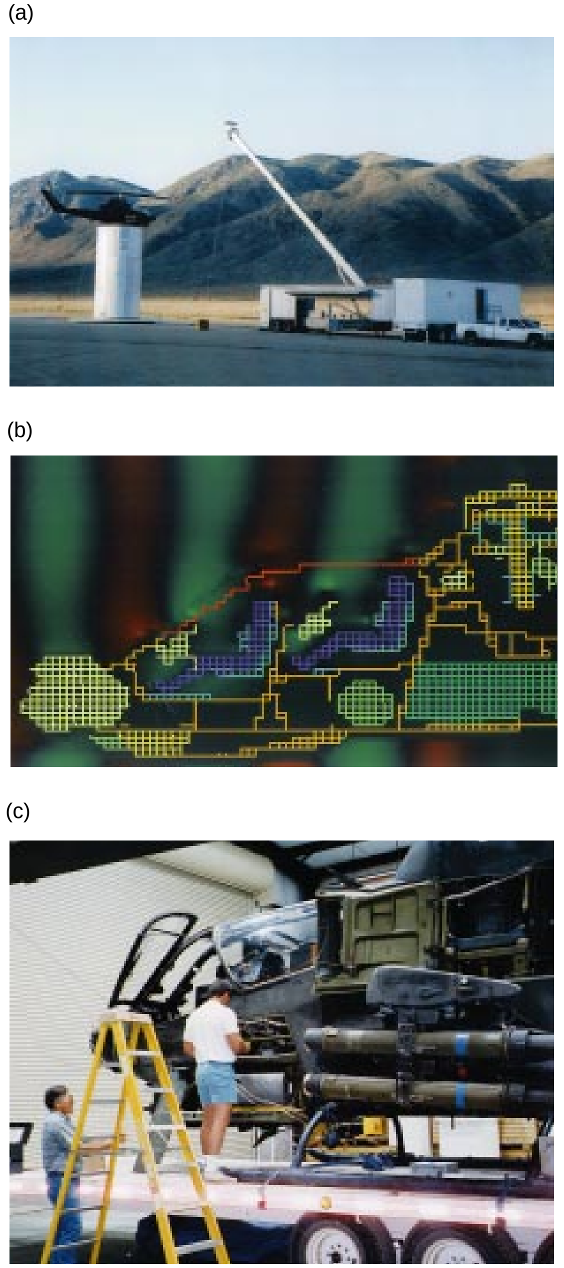


Figure 5. Low-power experiments at the Naval Air Warfare Center, China Lake, involve (a) positioning an AH-1S Cobra helicopter on a support tower. Livermore's portable time–frequency source and diagnostics trailer was used for monitoring the AH-1S testing points via fiber-optic connections. (b) Continuous-wave coupling measurements over a broad range represent a threat spectrum and include high-frequency-induced current measurements for monitoring the connecting signal lines and cavity coupling measurements. (c) Technicians place sensitive, nonobtrusive, RF sensors in the helicopter.

Indeed, susceptibility to signal and component damage and interference from EM signals are getting increased attention today from the DoD's Live Fire Test and Evaluation Office. The office routinely conducts tests to assess how DoD's conventional weapons systems—roughly 80 of them—stand up to ballistic and explosive assault. Because the Live Fire organization does not perform EM susceptibility tests on a regular basis, they contacted Livermore for assistance. The project is led by Livermore electrical engineer Scott D. Nelson of the Defense Sciences Engineering Division.

"Weapons systems are much more hardened to EM interference than systems on a conventional airliner," Nelson says, "but an EM weapon with enough power could cause problems in helicopters, airplanes, tanks, trucks, or missiles."

This spring, a Livermore team will return to the Naval Air Warfare Center at the China Lake Naval Weapons Center, California, for electromagnetic-effects experiments involving the Vietnam-era AH-1S Cobra helicopter. Understanding how external EM sources couple with the Cobra's communications, guidance, and weapons systems is helping designers of the newest Army helicopter, the RAH-66 Comanche, to pinpoint its potential EM susceptibilities.

The Laboratory's existing EM computer simulation models have been validated with numerous test objects, ranging from missiles and ships to planes and tanks. Because helicopters are fairly complex and have different parameters than other objects that have been tested, the team is now validating a simulation model for the Cobra, using data from tests they began at China Lake last summer. DoD's Live Fire Test and Evaluation Office made two flightworthy Cobras available for the initial EM experiments. For the studies, a Cobra was positioned atop a 10-meter tower made of unbeaded polyurethane foam. The foam, "invisible" to the microwaves, offered the illusion to instruments that the copter was hovering. The tower's base was a turntable that rotates 360 degrees to subject different parts of the helicopter to the microwave "fire." (See Figure 5.)

The Laboratory set up its portable microwave and RF test trailer at China Lake. The first tests measured the effects of low-power microwaves (200 watts) aimed at the helicopter from a boom-mounted external antenna. A fiber-optic system, running from inside the helicopter to the command trailer, carried information on the amount of power striking the target. Sensors placed on the copter registered the EM effect on the Cobra.

This summer, high-power tests (4 kilovolts per meter at a distance of 1,300 meters) will be performed by using a pulser supplied by Phillips Laboratory, an Air Force contractor, and the Naval Air Warfare Center's own 10-meter dish reflector to illuminate the target. Using the complete suite of Cobra EM modeling and comparing it with the field test data, Livermore will model Comanche EM susceptibilities.

The Laboratory EM team also will participate in a separate series of DoD high-power EM exercises at China Lake. Designed as a "shake-out" study of EM testing methodology, the exercises eventually could be used for full assessments of DoD weapons delivery systems.

Of the Livermore team's role in the shake-out tests, Nelson said, "We will serve the DoD as an unbiased participant, verifying that the contractor's equipment works as expected, that the RF source delivers the expected fluence on target, that characterization and measurements of the test object use known and trusted test methodologies, and that EM assessments represent realistic or anticipated threats. It is a role we know well."

—Dale Sprouse

Key Words: electromagnetic field, electromagnetic susceptibility, kicker, modeling, opto-electronics, photonics, wakefield.

Reference

1. K. S. Yee, "Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equations in Isotopic Media," *IEEE Transactions on Antennas and Propagation* **AP-14**, 302–307 (May 1966).

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About the Engineers

Electrical engineers who collaborate in the Laboratory's computational electronics and electromagnetic thrust area include: (first row) DAVID STEICH, STEVE SAMPAYAN, JEFF KALLMAN, CLIFF SHANG, and BRIAN POOLE; (second row) RICK RATOWSKY, TOM ROSENBURY, and SCOTT D. NELSON. For more information about their work, visit their Internet home page on EM codes at http://www.llnl.gov/eng/ee/documents/ceeta.html and EM facilities at http://www-dsed.llnl.gov/documents/facilities.html. The group is pictured in front of the Experimental Test Accelerator-II (ETA-II). The ETA is a testbed for beam experiments n advanced hydrodynamics testing to characterize the accelerator and design key components such as the kicker described on p. 15. The accelerator ultimately will be a part of the Laboratory's Advanced Hydrotest Facility.