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Energy and Technology Review

November 1988

**Lawrence
Livermore
National
Laboratory**

About the Cover

The mechanics of crater formation (such as fragmentation, ejection, and subsidence) in jointed geologic media can be studied effectively through the use of discrete-element computer modeling. Our lead article describes how we have used such techniques with superior results in analyzing cratering effects of underground explosions.

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About the Journal

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Energy and Technology Review

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November 1988

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MASTER

Cratering Phenomenology Revealed Through Discrete-Element Modeling

Our use of discrete-element modeling in analyzing underground explosions has permitted us to capture the mechanics of fragmentation, ejection, and subsidence of jointed geologic media during cratering. The technique takes us well beyond the results of the continuum models traditionally used in estimating ground motion.

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Explosive cratering in hard rocks is of interest to workers in diverse fields, such as energy research, defense, and planetary science. The analysis of explosion-related ground motion has traditionally been performed with dynamic continuum codes, which are largely based on finite-difference or finite-element approximations (a glossary of relevant terms is on p. 4). Although such codes have been useful in predicting ground-shock effects, they are inadequate for representing the full process of cratering in geologic materials.

What a continuum code does and why the physics of cratering phenomenology remains beyond its reach can be shown quickly in an illustration. Figure 1 is a continuum simulation of an underground nuclear explosion in hard rock. The vectors represent the total displacement at points in the medium. The vector direction illustrates total displacement direction. Vector length, however, represents total displacement magnitude in the material and accurately represents displacements less than 1 m. All

displacements greater than 1 m are depicted as 1 m. This constraint is imposed on the graphical presentation of the data to make it more readily intelligible.

The figure shows a large (>60-m) mounding of the surface and sharp displacement discontinuities over a zone extending from the cavity to the surface. However, it is clear that extensive rock breakage would take place in the medium, in the mound, and along the surfaces of displacement discontinuities prior to material being ejected. In addition, block motion would take place in the ejecta, with attendant dilation due to that block motion. Even if continuum codes contain so-called "damage" models for tensile and shear failure, they cannot adequately treat these important processes because they describe only the onset of the fragmentation process.

Empirical models of ballistic-ejecta throwout and crater-lip slumping have occasionally been coupled to continuum models in an attempt to predict final crater dimensions. However, such models have ill-defined parameters (such as the bulking factor), and they include untested criteria for initiation and fragmentation. In addition, they do not account for the transfer of momentum between rock blocks colliding with one another.

To understand the complete phenomenology of cratering in geologic materials, we need more

realistic fragmentation models and models that can track discrete polyhedral (irregularly shaped) particles, correctly accounting for their dynamic interaction. Figure 2 (which may be contrasted with the continuum calculation shown in Figure 1) shows the results obtained for two cratering events with the code we call the discrete interacting block system (DIBS), developed at LLNL. Here, we see the discrete-element kinematics resulting from a large displacement discontinuity (Figure 2a) or mound breakup (Figure 2b).

In this article, we summarize the essential features of the DIBS code and present the results from three recent DIBS calculations of cratering and subsidence. In the final section, we discuss current limitations of our modeling efforts and suggest future work that remains to be done.

Discrete-Particle Modeling

Simulation of discrete-particle motion has its origins in the field of molecular dynamics. In this discipline, the bulk properties of systems of particles on a molecular scale are obtained by space- and time-averaging the velocities and forces acting on individual particles. Models on a molecular scale, however, do not handle the properties specific to rock masses, such as

Figure 1. A continuum calculation of an underground explosion. The arrows are vectors representing the material displacement at selected points. A large mound has developed, and displacement discontinuities (regions where the displacements are counter-directed on opposite sides of zones) can be seen in a zone from the cavity bottom to the side of the mound. Continuum models are ill-suited to describe the mound break-up and the progressive development of shear zones in blocky media.

(a)

(b)

Figure 2. DIBS calculations showing (a) shear surface development and (b) mound breakup following a simulated underground explosion. In contrast to the results in Figure 1, these calculations account in a natural fashion for certain behaviors specific to rock masses (blocks), such as inelastic block contacts, block rotations, and bulking during shear and tensile failure.

inelastic normal forces, irregular shapes, and tangential friction at contacts.

Over the past several years, a few numerical models have been developed that were specifically aimed at simulating the motion of macroscopic, inelastic, frictional particles.¹⁻⁷ The DIBS model is representative of this type of numerical model. DIBS is a two-dimensional, polygonal-particle model that was originally applied to the flow behavior of granular solids. In simple terms, the model tracks the motion of individual particles (or elements) in a system of many elements under applied loads and gravity, as each one interacts with other particles and with boundaries.

To calculate more efficiently the forces and motions of many distinct blocks of geologic material, DIBS incorporates several simplifications concerning the interactions among elements and the properties of the elements themselves. The major assumptions are as follows:

- Elements consist of arbitrary (nearly convex) polygonal shapes.
- Elements are quasi-rigid (that is, they retain their shape).
- Contacts are modeled as corner-on-side (that is, temporary, sliding-joint elements are attached at polygonal vertices, as needed).
- Contact-joint elements are visco-elastic in both normal and tangential directions. The maximum tangential force is limited by a shear resistance that is the sum of a cohesion (independent of normal stress) and a friction dependent on normal stress.
- Small, but finite, overlaps can occur as normal forces are developed.
- A finite, elastic shear strain develops in joint elements before frictional sliding is initiated.

The DIBS calculation itself starts with a given geometric configuration and a set of initial velocities and applied forces. Next, the forces acting on all particles due to the initial configuration, applied loads, and gravity are determined. Then, we carry out an explicit, finite-difference calculation for the equations of motion of all particles over a small time interval to determine new positions and velocities for the particles. The particles are moved, time and velocities are updated, and the procedure is repeated. This method has been verified through comparison with analytic predictions and with laboratory tests of the motion of individual blocks and assemblies of particles.

Simulations of Cratering, Ejecta, and Subsidence

To simulate blasts in systems consisting of close-packed, fractured rocks, we added a Voronoi polygon-generation algorithm to the DIBS model. Voronoi polygons (see glossary, p. 4) uniquely partition two-dimensional space into convex polygonal elements. Each polygon circumscribes the region closest to its generating center.

To construct initial configurations for our series of three blast simulations, we initially arranged a group of generating points (or centers) in a nearly regular pattern, with mean center-to-center spacing approximately equal to the block size we desired. The coordinates of the centers were then randomly displaced to create a quasi-random set of generating points that would produce blocks of the desired mean size. Voronoi polygons were then constructed around these points, with the vertices of the polygons becoming the initial element vertices

for the DIBS model. Large, fixed, rectangular blocks with the same properties as the active elements were placed below and on each side of the set of Voronoi polygons. The entire assembly of particles was allowed to settle into the space bounded by the large, rectangular blocks to establish a realistic *in situ* stress state prior to the simulation of the buried explosion.

We modeled the load from an explosive charge by applying a brief, radial force-time history to each block around a predetermined initial cavity. After the initial force-time history ended, we set all external forces (except gravity) to zero, and we allowed the momentum of the particles to propagate naturally through the system of elements. Each calculation then consisted of integrating the equations of motion and determining contact forces, as required. We did not simulate air drag forces. The angle of frictional contact between blocks was 27 deg, and our choice of spring and dashpot gave a coefficient of restitution from 0.05 to 0.25, depending on block size.

Simulation of the Sulky Event

In the Sulky Event, a 90-ton device was detonated at a depth of 27.4 m in dry basalt.⁸⁻⁹ Preshot geologic exploration revealed the fracture spacing and block size of the rock to be on the order of 1 to 2 m. Spall velocity was measured during the event to be 26 m/s. After the shot, the mound size was determined, but cavity size was not established. From LLNL hydrodynamic code calculations, we estimated the cavity size to be between 9 and 11 m; thus, we chose a 10-m diameter for our analysis.

Glossary of Terms Used in Modeling Craters

In seeking to understand the physics of cratering, scientists have recourse to both empirical testing and computer modeling. The following terms are used in such efforts.

Block. A discrete element of rock mass surrounded by natural rock fractures.

Bulking factor. The ratio of the volume of a rock mass after failure and deformation to its initial volume.

Chimney collapse. The large-scale subsidence of fractured rock above a cavity created by an underground explosion.

Coefficient of restitution. A parameter characterizing the momentum exchange of rock blocks undergoing nonelastic collisions.

Continuum code. A computer model in which the medium is divided (discretized) into small cells (elements or zones) that are at first perfectly bonded to each other without incipient weaknesses.

Dashpot. A viscous damper in which stress is proportional to strain rate.

Dilation. Separation of rock surfaces during rupture in tension or shear. Dilation increases the volume of a rock mass.

Discrete-element kinematics. The permissible modes of motion in assemblies of discrete blocks.

Displacement discontinuity. A region in which a displacement field is reversed. In a displacement discontinuity, pronounced shear motion is developed.

Ejecta. The material ejected or thrown out during a cratering event.

Force-time history. The change of a force function over elapsed time.

Finite-difference approximation. A numerical method for solving differential equations in small, discrete steps

in space and time. The terms of the governing differential equations are approximated by their finite-difference formulas.

Finite-element approximation. A method for analysis of stress and flow fields, in which the medium is approximated by a lattice of elements, and the solution usually is obtained through a variational principle.

Jointed rocks. A rock mass penetrated by natural geologic discontinuities such as joints and faults.

Spall velocity. The velocity of the ground surface when a shock from an underground explosion reaches and lifts that surface.

Spring. A one-dimensional mechanical device with an elastic, linear, or nonlinear relation between displacement and applied force.

Subsidence. Caving of the ground when undermined by a man-made or natural cavity.

Voronoi polygon. (See figure.) Given an arbitrarily chosen point or "center" and a collection of neighboring centers, a segment (or line) is first drawn from that center to each neighbor. The perpendicular bisectors that are then drawn through each segment at its midpoint form a Voronoi polygon about the initial center.

We designed a grid of blocks to approximate the average block size in the Sulky mound, and we placed the cavity 27.4 m below the surface. We adjusted the initial force-time history applied radially to the centers of gravity of the blocks immediately surrounding the cavity until the free-surface block velocity matched the measured spall velocity. Our final choice was equivalent to a peak pressure of 31.4 MPa, declining to zero in steps over 65 ms.

Figure 3 shows the sequence of the cratering process revealed by DIBS. The salient feature of this analysis is the large (up to 45 deg) redirecting of velocity vectors from a radial direction to one that is more vertical. Such redirection is caused by forces acting when blocks begin to rotate within oblique failure zones extending upward at nearly 45-deg angles on each side of the cavity. The redirected velocities can be seen at 0.5 s in Figure 3b. This near-vertical motion is precisely the one revealed by motion pictures of the Sulky Event.

Our Sulky simulation also captured the approximate height of the rubble mound. However, a two-dimensional model does not account for bulking in the third dimension or for the radial, spherical movement of blocks. Such movement can lessen their interactions if they experience significant outward radial displacement.

Simulation of a Shallower Explosion

We performed a second calculation using a similar set of blocks to simulate a shallower explosion. The cavity radius and forces around the cavity were identical to those that produced the matching free-surface velocity in the Sulky calculations. This time, however, we moved the center of the

Figure 3. DIBS sequence for simulation of the 90-ton Sulky Event from 0.001 to 6.5 s after detonation. The device was detonated at a depth of 27.4 m. One of the most significant outcomes is revealed as the large rotation (up to 45 deg) of velocity vectors from radial to a more vertical direction. The redirection, most clearly visible at 0.5 s, is due to the development of shear failures forming the initial crater. This near-vertical motion was precisely the one revealed by motion pictures of the Sulky Event.

Figure 4. DIBS sequence of block motions for a depth of burial of 15 m. (Note the change in scale at the middle of this time series, where two adjacent images show the same configuration at the same point in time (0.5 s) at the two different scales. The change in scales is necessary to show the larger configuration of ejecta at later times.) This calculation produced a peak surface velocity of 89.5 m/s compared to 26 m/s obtained for the Sulky Event. The maximum height of ejecta was over 400 m, resulting in a much broader blanket of ejected rock compared to that in Figure 3.

cavity upward from 27.4 to 15 m below the surface.

Figure 4 shows the sequence of block motions up to about 10 s after the shallower explosion. We stopped the calculation at that time because the complete fall-back of rocks would take another 10 s and would not significantly alter the shape of the crater. The same forces acting over the same times as those for the Sulky calculation produced a peak surface velocity of 89.5 m/s, significantly greater than the value of 26 m/s obtained for Sulky. The maximum height of ejecta was over 400 m compared to a height of about 35 m in the first calculation. As is clear from Figure 4, the shallower explosion resulted in a much broader blanket of ejected rock compared to that for the 27.4-m-deep explosion.

Simulation of a Deeper Explosion

Figure 5 shows the results of a DIBS simulation for an explosion at a depth of 54 m under the same impulse as that for the previous two analyses. The peak surface velocity was 8.5 m/s, giving a maximum block rise of about 3.7 m. Owing to restrictions of computer memory and the use of a larger calculational grid, the mean block size in the region above the cavity was approximately 50% larger in this calculation than in the earlier cases.

This overburied explosive charge did not give rise to a recognizable crater. In addition, no collapse chimney propagated to the free surface. It is possible that the use of smaller particles might have allowed chimney collapse to occur; however, when we did shrink the size of the particles close to and above the cavity, collapse was initiated and a stable arch formed quickly in the

compact Voronoi polygon set representing the fractured rock above the cavity region.

Conclusions

The realism of our cratering calculations can be measured by their success in duplicating surface spall velocities. We established the

impulse delivered by the simulated explosion in the first calculation by matching the known free-surface velocity in the Sulky Event, which was 26 m/s. Although a unique solution is by no means guaranteed, both the shallower and deeper calculations produced spall velocities that were within a few percent of those expected from similar

explosions at these depths. For the shallow explosion at 15 m, the predicted velocity was 91 m/s based on two-dimensional scaling of momentum, while the DIBS calculation was 89.5 m/s, a difference of less than 2%. For the deeper explosion at 54 m, we used the formula developed empirically from measurements of U.S. nuclear shots

Figure 5. DIBS simulation for an explosion at a depth of 54 m under the same impulse as that used in the previous two analyses. This explosive charge did not give rise to a recognizable crater, and no collapse chimney propagated to the free surface.

in hard rock. The predicted velocity was 9.1 m/s, while the DIBS calculation was 8.5 m/s, a difference of 7%. (The shallow event could not be estimated according to the U.S. data base because it fell outside the range of scaled depths.)

We believe our computer simulations demonstrate that a realistic approach to modeling ejecta and subsidence phenomena in jointed rocks must include discrete blocks. Figures 3 through 5 clearly show the changes in kinematic behavior with depth of burial.

It is clear that discrete-element modeling is also very well suited to evaluating the stability of tunnels in jointed rocks under dynamic loadings, as well as analyzing the progression of chimney collapse above cavities formed during nuclear tests in those geologies. Such is not the case for continuum models.

Future Directions

More extensive analyses with models such as DIBS could shed additional light on the relative roles

of gravity and energy in cratering phenomena. However, a two-dimensional configuration does not allow us to model out-of-plane rotations and bulking. For the purposes of quantitative prediction, three-dimensional models are certainly warranted, and a few stand-alone versions exist today. What is required is a comprehensive modeling tool that begins with initial behavior, progresses through the fragmentation phase, and then completes the simulation of block motions. The creation of such a tool is well within the capabilities of current technology and should be actively pursued.

Key Words: Computer code; discrete interacting block system (DIBS); cratering phenomenology; Sulky Event.

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High-Intensity Short-Pulse Lasers

We are developing short-pulse laser systems capable of producing extreme values of laser intensity and electric field strength. These sources will make possible research in an entirely new physical regime.

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For laser pulses of a given energy, the shorter the pulse the higher the peak power. A decade ago, 1 ns was considered a short pulse. Shortly after that, "ultrafast" dye lasers pushed the limit to a few picoseconds. Recent developments now enable us to work with pulses a thousand times shorter, as short as 6 fs.¹ By applying these techniques to glass laser systems, we can achieve, in principle, focused intensities approaching 10^{21} W/cm²—more than a million times the intensity available from our Nova laser.

In this article we briefly survey the several areas of research that have needs for high-intensity, short-pulse lasers. We outline the possible approaches to these types of laser and describe our development of a table-top glass laser system capable of producing pulses with peak power in excess of 10 TW. This is the first step in our program to produce the first petawatt laser (10^{15} W), capable of achieving focused intensities of 10^{21} W/cm².

Potential Areas of Application

The availability of a 1000-TW laser system capable of producing focused intensities exceeding 10^{21} W/cm² will make possible the study of matter at field strengths that have until recently been thought unattainable in the laboratory, opening an entirely new physical

regime to study. Such a laser has possible applications in many areas of research, including nuclear physics, plasma physics, laser-atom interactions, x-ray lasers, spectroscopy, and inertial confinement fusion.

Three aspects of the pulse at the laser focus present opportunities for experiments in a wide range of physics. The first involves the extraordinary electric field, which at an intensity of 10^{21} W/cm² is nearly 100 TV/m. This is about 200 times stronger than the field binding electrons to atomic nuclei. No atom can survive it unscathed. As the intensity rises throughout the laser pulse, any species present at the focus will undergo multiphoton ionization.

The second is the high energy density, which at an intensity of 10^{21} W/cm² is more than 30 GJ/cm³. This energy density is equivalent to that of a 10-keV blackbody and is more than a hundred times that produced in current laser fusion plasmas.

The third is the quiver energy of a charged particle, the energy it acquires by oscillating in response to an applied electromagnetic field. This "ponderomotive" potential is usually neglected in laser-atom interactions because it is seldom more than a few millielectron volts. At the intensities that would be available with the proposed laser, the quiver energy of a free electron would be more than 20 MeV, and the motion would be extremely relativistic.

Recombination X-Ray Lasers

Since we first demonstrated stimulated amplification in the soft x-ray region at 20 nm, much of the

effort in the field has been directed toward pushing the operating wavelength below the carbon K-absorption edge at 4.376 nm. To do this, however, we would need at least a hundred times as much pump laser intensity; reaching the saturation fluence with such an x-ray laser would take even more pump power. Achieving this by increasing the beam energy in present systems is currently unreasonable; our Nova laser is already at the practical upper limit. The other approach is to increase the peak power by reducing the pulse width.

As the pulse width decreases and the peak power increases, different and increasingly efficient lasing schemes, such as those relying on inner-shell photo-ionization, become possible. In this approach, the high-intensity primary beam strikes an intermediate material to produce a very short, high-intensity burst of x rays that photo-ionize the lasing medium (usually a gas). Researchers at Stanford University recently achieved saturation in krypton at 90 nm on a table-top system using chirped-pulse amplification.²

X-ray laser schemes based on three-body recombination (Figure 1) are expected to benefit most from the development of high-intensity, short-pulse lasers. In these schemes, a dense plasma of fully stripped ions is allowed to cool adiabatically by expansion into a vacuum, populating the high-lying states of the hydrogen-like ions (nuclei holding one electron) by three-body recombination. This process, coupled with the fast radiative decay of the lower levels, leads to population inversions among

levels with principal quantum numbers between 2 and 4.

High-intensity picosecond or subpicosecond pulses capable of producing highly charged ions by multiphoton ionization create a unique plasma ideally suited for recombination because the laser pulses are too short to heat the plasma significantly. Hence, a very dense, cold plasma is created far from thermal equilibrium, with ion states determined almost solely by the peak laser intensity rather than by the plasma conditions. Since the three-body recombination rate increases with plasma density and also increases rapidly with decreasing

electron temperature, such a dense, cold plasma would be nearly ideal for a recombination laser scheme.

To demonstrate the potential of a high-intensity, short-pulse source such as our high-brightness laser (HBL) for recombination x-ray laser experiments, we have calculated the gain on the $3 \rightarrow 2$, $4 \rightarrow 3$, and $4 \rightarrow 2$ transitions in hydrogen-like carbon or aluminum following photo-ionization by a typical 1- to 2-ps pulse from the HBL. A $1.05\text{-}\mu\text{m}$ infrared laser light intensity of 10^{18} W/cm^2 , well within the HBL's capabilities over lengths exceeding 1 cm, should be enough to produce fully stripped carbon or aluminum.

Our simulation starts with a cylindrical plasma consisting of fully stripped carbon (or aluminum) ions and lets it expand freely into a vacuum. We assign the plasma an "effective" temperature equal to that required to produce fully stripped ions in ionization equilibrium, and set the ion temperature equal to the electron temperature at all times. (These temperature assumptions represent a worst-case limit, since the ions may actually be much cooler than the electrons if the laser pulse is too short to produce significant heating.)

Figure 2 shows two curves for the calculated $3 \rightarrow 2$ (18.2-nm) gain in carbon. The long, low pulse represents the result of irradiating a $5\text{-}\mu\text{m}$ -diam carbon fiber with a 100-ps pulse, giving an initial electron temperature of 90 eV, an electron density of $1.2 \times 10^{20}/\text{cm}^3$, and an initial plasma radius of $20\text{ }\mu\text{m}$. The peak $3 \rightarrow 2$ gain in this case is about 8 cm^{-1} , in close agreement with previous calculations.³

The high spike in Figure 2 represents the calculated $3 \rightarrow 2$ gain as a function of time following irradiation of a similar carbon fiber with a 1-ps pulse. The initial temperature in this case is the same (90 eV), but the density is much higher ($10^{21}/\text{cm}^3$) and the radius smaller ($5\text{ }\mu\text{m}$) because the plasma has had little time to expand during the laser pulse. The gain in this case is much higher (about 40 cm^{-1}), primarily because of the higher density at the end of the laser pulse.

The calculations, while still preliminary, illustrate the enormous potential of short-pulse, high-intensity lasers for producing short-wavelength (x-ray) lasers. As we learn more about x-ray lasers, it is apparent that we will be able to attain efficient, small-scale, x-ray lasers only by using intense, short-pulse, visible lasers as the pump source.

Figure 1. Scheme for producing an ultrashort-wavelength x-ray laser in a rapidly expanding carbon plasma by three-body recombination. Three-body recombination rapidly populates the $n = 4$ and $n = 3$ levels of the five-times ionized (hydrogen-like) carbon ions. Stimulated decay from the $n = 3$ to the $n = 2$ level produces 18.2-nm x rays.

Electron-Positron Pair Production

A focused intensity of 10^{21} W/cm² should be more than enough to produce relativistic plasma waves that would efficiently accelerate electrons to perhaps 10 MeV.⁴ Most of the energy of these electrons would be converted into energetic bremsstrahlung radiation, but about a millionth would appear in the form of electron-positron pairs. For an incident pulse energy of 1 kJ, this corresponds to more than 10^{10} pairs per pulse, a number that would be easily detectable with standard coincidence counting systems.⁵

The positrons produced would quickly combine with electrons outside the laser focus, forming positronium, which would decay over its characteristic lifetime of 125 ps. The resulting pulse of 511-keV x rays radiating from the vicinity of the laser focus would have a power of about 10 MW. Such a bright source of 511-keV radiation may have many applications in nuclear physics and solid-state studies.

Laser-Plasma Linear Accelerator

High-energy particle accelerators operating on conventional principles have become enormous and very expensive. A "beat-wave" accelerator excited with a short-pulse laser could theoretically achieve acceleration gradients of almost 30 GeV/m (about a thousandfold higher than in present linear accelerators).⁶ Calculations indicate that our HBL would be able to power an acceleration stage 30 cm long, yielding 10-GeV electrons; a hundred such stages in series would yield 1-TeV electrons. Smaller-scale experiments with similar laser-plasma techniques are currently under way at several laboratories.

Laser Enhancement of Nuclear Beta Decay

Even at the enormous intensity of 10^{21} W/cm², the electric field of

the laser is only about a millionth of the field strength within the nucleus. However, intense laser fields can influence nuclear phenomena indirectly. One such indirect mechanism involves polarizing the inner-shell electrons by the strong field; another involves modifying the final states of decay products, which would make observable changes in the decay rates. For example, it has been calculated that a laser intensity of 1.3×10^{18} W/cm² would increase the beta-decay rate of tritium by twenty thousandfold.⁷

Optically Induced Nuclear Fusion

When a laser pulse ejects electrons from the focus region, the intense electric field (and space charge) also strongly accelerate the ions left behind. At laser intensities exceeding 10^{19} W/cm², the pondermotive potential can maintain electrostatic potentials greater than 1 MeV. This electrostatic field can then accelerate ions to several tens of kilovolts before the laser field disappears.

As a specific example, a 10^{20} W/cm² picosecond laser pulse focused into a deuterium-tritium gas mixture would accelerate deuterium ions to about 20 keV. On striking neutral tritium atoms outside the focus, these energetic deuterium ions would produce nearly 10^8 fusion reactions within 100 ps. This

enormously bright source of 14.1-MeV neutrons would be valuable for calibrating neutron diagnostics for our laser program.

Short-Pulse Technology

The fundamental Fourier Transform relationship that exists between laser pulsewidth and bandwidth requires the lasing medium to have a broad bandwidth in order to produce a short pulse. For a Gaussian pulse, this relation is $\Delta\nu\Delta t > 0.441$, where $\Delta\nu$ is the bandwidth and Δt is the laser pulsewidth. (For the shortest pulse on record, 6 fs at $\lambda = 550$ nm, the corresponding bandwidth is more than 70 nm, nearly one-third of the entire visible spectrum, resulting in a multicolored laser beam.) Until very recently, only organic dyes, rare-gas halide excimers, and special laser glasses had bandwidths of more than even a few nanometers.

Organic dye lasers have inherently large bandwidths because of the very large number of vibrational and rotational modes associated with each electronic level in the dye molecules; commercial lasers capable of producing subpicosecond pulses of a few kilowatts are available. However, when such pulses are amplified for applications requiring much higher power, the short storage time of the high-gain dye amplifiers

Figure 2. Calculated gain ($3 \rightarrow 2$ transition) for a laser formed by three-body recombination upon irradiating a 7- μ m carbon fiber with the beam from our high-brightness laser. With a 100-ps pulse, the initial conditions are a plasma temperature of 90 eV, a plasma radius of 20 μ m, and an electron density of 10^{20} /cm³. The calculated gain is low and spread over a relatively long interval (black curve). With a 1-ps pulse, the plasma temperature is still 90 eV, but the plasma radius is only 5 μ m and the electron density is 10^{21} /cm³. The result is a much higher gain and shorter pulse (blue curve).

results in amplified spontaneous emission (ASE), which robs the amplifiers of energy and introduces a low-level background pulse lasting several thousand times longer than the subpicosecond pulse. Even with elaborate techniques for isolating the amplifier stages from one another, this ASE can amount to a few percent of the total pulse energy, enough to interfere with many high-intensity experiments.

We have developed a dye laser system that avoids ASE by pumping the amplifiers with a laser pulse shorter than the storage time of the dye (Figure 3). This 80-ps pump pulse permits the short "seed" pulse from the laser oscillator to extract nearly all the stored energy in the amplifier before ASE can develop.

The result is a 1-ps pulse with a maximum energy of 5 mJ (or a 350-fs, 2.8-mJ pulse) with less than 0.01% of ASE background, obtained without any elaborate isolation between amplifier stages.

However, this performance is close to the limit that can be obtained from dye laser systems because of the very small saturation fluence (about 1 mJ/cm^2) common to all organic dyes. This means that even dye amplifiers several centimeters in diameter can produce pulse energies of only a few millijoules while maintaining a short pulse.

Excimer lasers are also limited by low saturation fluences and short storage times. Although a few large-diameter excimer systems have recently been developed that amplify

subpicosecond pulses up to an energy of nearly 300 mJ, the cost and complexity of the elaborate measures required to combat ASE have seriously limited their usefulness.

Solid-State Lasers and Chirped-Pulse Amplification

Solid-state amplifier materials such as neodymium glass, alexandrite, and titanium-doped sapphire all have high saturation fluences, making it possible to extract several joules of energy from modest-scale laser systems. They also have the large-gain bandwidths needed to amplify subpicosecond pulses. Their limitation comes from the tendency of bright beams to self-focus destructively (a result

Figure 3 Schematic arrangement of our short-pulse dye laser designed to avoid amplified spontaneous emission (ASE). The mode-locked Nd:YAG laser pumps the dye amplifiers with a 70-ps pulse, shorter than the dye's storage time. Hence the subpicosecond pulse can extract nearly all the amplifier's stored energy before ASE has time to occur. Delay lines are adjusted to maintain precise synchronization between the 70-ps pump pulse and the subpicosecond dye pulse as it passes through the various stages of amplification.

of nonlinearity in the index of refraction), which makes it necessary to limit the intensity present in amplifiers of reasonable length to less than 10 GW/cm^2 .

We are working on a technique known as chirped-pulse amplification (CPA) that holds the promise of removing this obstacle. Briefly, the idea is to use nonlinear refraction to generate a broad-bandwidth pulse that can be stretched out in time so that it can be amplified without harming the amplifier, and then compress it back into a short pulse of extremely high power.

The first step is to produce the short pulse. In an ideal material with a perfectly linear refractive index (constant regardless of light intensity), even a very powerful laser pulse would pass through unchanged. In real materials the frequency spectrum of the pulse is broadened by an amount that depends on the incident intensity, which (with a powerful enough pulse) can result in a controllable frequency sweep or "chirp." This produces a pulse that is moderately short ($\sim 50 \text{ ps}$) but broad in bandwidth. By controlling the chirp, this pulse can be compressed to a subpicosecond pulse.

In a chirped pulse, the different frequencies occur at different times. A device that delays certain frequencies relative to others can, in principle, stretch a short pulse over a longer time or, alternatively, compress a long pulse into a short one.

A diffraction grating, which sends light rays of different frequencies in different directions, can serve as the basis for such a device (Figure 4). A pair of gratings can be arranged in such a way as to send the higher-frequency (blue) light over a longer path than the lower-frequency (redder) light, stretching out the pulse. Conversely, delaying the redder light more than the bluer compresses the pulse.

Figure 4. Optical components used in chirped-pulse amplification. (a) The optical fiber whose nonlinear index of refraction broadens the pulse both in time and in wavelength. The leading part of the pulse contains the longer wavelengths. (b) A pair of gratings arranged to send shorter wavelengths (blue) over a longer path, delaying them still further and stretching the chirped pulse. (c) A pair of gratings arranged to shorten the path of the short wavelengths, compressing the long, amplified pulse back into a short pulse.

(a)

(b)

Figure 5. Schematic of our 3-TW picosecond laser system. (a) The oscillator section. The acoustic-optic (AO) modulator following the oscillator uses feedback from the final output to regulate the intensity of light incident on the chirp-producing optical fiber. (b) The amplifier section. The 1-ns pulse from the stretcher is spatially filtered before it enters the 16-mm amplifier. After two passes through this amplifier, it is spatially filtered again before going once through the 25-mm amplifier and thence to the pulse compressor, where it is compressed to less than 1 ps. The Pockels cells (PC) protect the amplifier rods from their self-destructive tendency to amplify back reflections.

We are developing a laser system employing this technique (Figure 5). The system starts with a cw mode-locked laser built around a rod of yttrium lithium fluoride glass doped with neodymium (abbreviated Nd:YLF) producing 3-kW, 50-ps pulses. We focus about 30% of the pulse into a long, single-mode, polarization-preserving, fused-silica optical fiber whose nonlinear refractive index imposes a frequency chirp about 5 nm wide onto the pulse, while group-velocity dispersion stretches the pulse from 50 to 150 ps. We then stretch the pulse to nearly 1 ns using a pair of antiparallel gratings, reducing its peak power by a factor of 20 before injection into the amplifier.

Next, using a regenerative amplifier, we amplify the stretched (and attenuated) pulse about a millionfold and then another factor of a thousand (to about 4 J) using a series of small neodymium-glass amplifiers similar to those used as preamplifiers in our Nova laser. Finally, we compress the pulse to about 1 ps with another pair of gratings. This design should produce nearly diffraction-limited pulse power in excess of 3 TW, which we should be able to focus to an intensity of more than 10^{18} W/cm². By adding a 5-cm amplifier before the final grating pair, we should be able to produce pulses nearly equal in power

to those from Nova's most powerful beamline (>10 TW), but in a much smaller system. With additional component development, we should be able to obtain 1000-TW pulses capable of being focused to intensities exceeding 10^{21} W/cm².

Alexandrite and titanium:sapphire hold even greater promise for the amplification of ultrashort laser pulses. Their very broad spectral profiles and large saturation fluences should enable them to amplify 100-fs pulses. Already, our coworkers at the Laboratory for Laser Energetics, University of Rochester, have succeeded in using chirped-pulse amplification with an alexandrite regenerative amplifier to produce tunable 250-fs radiation with a pulse energy of more than 2 mJ. Adding a second alexandrite amplifier should boost the pulse energy to several hundred millijoules.

Summary

Recent advances in short-pulse laser technology should allow us to develop table-top laser systems that yield focus intensities exceeding those of our Nova laser system, the world's largest. Applying these techniques on large lasers using new solid-state materials should make it possible to produce pulses of more than 10^{15} -W peak power and focused intensities near 10^{21} W/cm². The ability to generate such a laser field

opens up an entirely new physical regime for research and development. Fields of study expected to benefit include nuclear physics, plasma physics, laser-atom interactions, x-ray lasers, spectroscopy, and inertial confinement fusion.

Key Words: alexandrite; beta-decay enhancement; chirped-pulse amplification; electron-positron pair production; linear accelerator—laser plasma; laser—dye, high-intensity; Nova; recombination x-ray, short-pulse, solid-state; optically induced nuclear fusion.

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Localized Transmission of Wave Energy

New solutions of Maxwell's equations and the wave equation support the possibility of propagating localized pulses of electromagnetic energy over long distances without loss. Such localized transmissions could have applications in communications, remote sensing, power transmission, and directed-energy weapons.

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Following the pioneering work of J. N. Brittingham,¹ various groups²⁻⁶ have been actively pursuing the possibility that solutions to the wave equation can be found that allow the transmission of localized, slowly decaying pulses of energy, variously described as electromagnetic missiles or bullets, Bessel beams, transient beam fields, and splash pulses. These efforts have in common the space-time nature of the solutions being investigated and their potential launching mechanisms, pulse-driven antennas.

Brittingham's original work involved a search, over a period of about 15 years, for packet-like solutions of Maxwell's equations (the equations that describe how electromagnetic waves propagate). The solutions sought were to be continuous and nonsingular (well-behaved, realizable), three-dimensional in pulse structure (localized), and nondispersive for all time (faithfully maintaining their shape). They were also to move at the velocity of light in straight lines and carry finite electromagnetic energy. The solutions discovered, termed focus wave modes (FWMs), had all the aforementioned properties except the last; like plane-wave solutions to the same equations, they were found

to have finite energy density but infinite energy, despite all attempts to remove this deficiency.

A few years ago we discovered⁷ that the original FWMs could be related to exact solutions of the three-dimensional scalar wave equation in a homogeneous, isotropic medium (one that has the same properties at any distance in all directions). This equation has solutions that describe, for example, the familiar spherical acoustic waves emanating from a sound source in air. We have now uncovered other allowable but unexpected solutions that apply to a broad range of wave phenomena. We present results of our continuing theoretical and experimental investigations of physically realizable versions of "photon torpedoes" in this and the following article (p. 24).

The Focus Wave Modes

The FWMs are related to solutions that represent Gaussian beams propagating with only local deformation, i.e., a Gaussian-shaped packet that propagates with changes only within the packet. Such a pulse, moving along the z axis, with transverse distance denoted by ρ ,

$$\Phi_k(r, t) = e^{ik(z+ct)} \left\{ \frac{e^{-k\rho^2/l_0 + i(z-ct)}}{4\pi i[l_0 + i(z-ct)]} \right\} \quad (1)$$

is an exact solution of the scalar wave equation referred to above. Figure 1 is a scaled plot of this fundamental

pulse, which is a Gaussian beam that translates through space-time with only local variations.

These fundamental Gaussian pulses^{7,8} have a number of interesting characteristics. They appear as either a transverse plane wave or a particle, depending on whether k is small or large (see Figure 2). Moreover, for all k they share with plane waves the property of having finite energy density but infinite total energy.

We recognized that a superposition of the FWM pulses can produce finite-energy solutions to the wave equation and to Maxwell's equations.^{7,8} As with plane waves, the infinite-energy property is not to be considered an insurmountable drawback *per se*. The variable k in the solution provides an added degree of freedom, and these fundamental Gaussian pulse fields can be used as basis functions, a superposition of which could represent new transient solutions of the wave equation. In other words, these infinite-energy solutions can be added together, with the proper weighting, to yield physically realizable, finite-energy solutions.

For example, either the real or imaginary part of the function

$$f(r, t) = \int_0^\infty \Phi_k(r, t) F(k) dk$$

is also an exact, source-free solution of the wave equation. The $F(k)$ function is the weighting function

(the spectrum), and the resulting pulses have finite energy if $F(k)$ satisfies certain integrability conditions.⁸ This representation utilizes basis functions that are localized in space and, by their very nature, are a natural basis for synthesizing pulse solutions that can be tailored to give directed wave energy transfer in space. A bidirectional representation is also possible, which leads to analogous solutions in geometries that have boundaries (propagation of waves in waveguides).⁹

Solutions to Maxwell's equations follow naturally from these scalar wave equation solutions. Such electromagnetic pulses, characterized

by their high directionality and slow energy decay, have been called electromagnetic directed-energy pulse trains (EDEPTs). They are a step closer to a classical description of a photon, a finite-energy solution of Maxwell's equations that exhibits a wave/particle duality. The corresponding acoustic pulses, which are solutions of the scalar wave equation, are called ADEPTs.

Localized Transmission

We have considered several different solutions to the wave equation and Maxwell's equations. A particularly interesting spectrum we investigated was a modified

power spectrum (MPS), which yields the associated MPS pulse:⁸

$$f(r, t) = \operatorname{Re} \left[\frac{1}{z_0 + i(z - ct)} \frac{1}{\left(\frac{s}{\beta} + a \right)^\alpha} e^{-hs/\beta} \right], \quad (4)$$

where α and β are parameters that we adjust to achieve specific characteristics, and s is defined by

$$s = \rho^2 / [z_0 + i(z - ct)] - i(z + ct).$$

The physical characteristics of the MPS pulse are very appealing. This pulse can be optimized so that it is localized and its original amplitude

Figure 1. Surface plots and the corresponding contours of a Gaussian electromagnetic pulse with $z_0 = 1$ cm and $k = 0.333/\text{cm}$. (a) The initial pulse when t is zero and the pulse center is at $z = 0$. (b) The pulse at $t = \pi$ ms with pulse center at $z = 942$ km. The spatial variation is presented in coordinates about this point. The pulse is moving in the positive z direction at the speed of light.

is recovered out to extremely large distances from its initial location. In particular, for a distance $z \ll \beta/2b$ and $z < \beta a/2$, the amplitude of the pulse at the pulse center is constant. It then becomes oscillatory with an oscillation length of $\pi\beta/b$ in an intermediate zone, $\beta/2b < z < \beta a/2$, recovering its original amplitude when $z = n(\pi\beta/b)$, n being any positive integer. Finally, when the observation point is very far away from the origin, $z > \beta a/2$, the MPS pulse decays like $1/z^\alpha$. Therefore, the initial amplitude of the MPS pulse is recovered until the distance $z \sim \beta a/2$; and since β is a free parameter, this distance can be made arbitrarily large.

The transverse behavior of this MPS pulse at the pulse center is essentially $f(\rho, z = ct) \sim \exp(-b\rho^2/\beta z_0) f(0, z = ct)$. Thus, by adjusting the ratio $b/\beta z_0$, one can adjust the degree of transverse localization. The MPS pulse is also localized longitudinally, decaying along z as $1/[z_0^2 + (z - ct)^2]$ away from the pulse center.

Now, what do we mean by localized transmission (high directionality) and slow energy decay? Let the parameters α , β , and z_0 of the MPS pulse be selected to achieve a pulse within the microwave spectrum and possibly within the realm of our physical appreciation and experience. In

particular, set the MPS parameters to be $a = 1$ m, $\alpha = 1$, $b = 10^{14}$ m, $\beta = 6 \times 10^{15}$, and $z_0 = 1$ cm. The peak of the spectrum of this pulse is in the microwave region at 8.4 GHz. (Note, however, that these parameters can be varied to design pulses with similar characteristics in different frequency regimes.)

Figure 3 shows surface plots and the corresponding contour plots of the electromagnetic energy density of the electromagnetic MPS pulse relative to the pulse center locations $z = 0$ km and 9.42×10^9 km. These results definitively show the localization of the field near the direction of propagation over very

(a) Spread Gaussian pulse

(b) Localized Gaussian pulse

Figure 2. A representation of the fundamental Gaussian pulse as a function of ρ and z . Shown in the figures is the real part of $4\pi\Phi_0$ squared. (a) For small values of k , the pulse looks like a transverse plane wave. (b) For large k , the pulse is very localized and looks like a particle.

large distances. The recovery of the initial energy density in this case actually occurs out to $z = \beta a/2 = 3.00 \times 10^{12}$ km (about one-third light year).

Of particular interest is a comparison of our specific choice of pulse representation and the classically popular Gaussian beam. The electromagnetic MPS pulse characteristics are dramatically better. Referring to Figure 4, let the waist of zero-order Gaussian beam field at $z = 0$ be w and let λ be its wavelength. Along the direction of propagation its amplitude varies as $1/[1 + (\lambda z/\pi w^2)^2]^{1/2}$ so that the distance to the near/far-field boundary or Rayleigh length, where it begins to decay as $1/z$, is

nominally reached when $z \sim \pi w^2/\lambda$. The square of the amplitude at that point is half its initial value and its radius has spread to $\sqrt{2} w$ and increases as $\theta z \sim (\lambda/\pi w)z$ in the far-field.

Now, with the above MPS pulse parameters, the waist w of an equivalent Gaussian beam = $(\nu/\beta z_0)^{-1/2} = 1.3$ m. The highest frequency of the spectrum for this MPS pulse is $f_{max} = 50$ GHz; the corresponding wavelength is $\lambda_{min} = c/f_{max} = 6$ mm. For the equivalent diffraction-limited Gaussian beam field these defining parameters give the distance to the far-field as 0.872 km and the spread of the field at 10^{10} km as 1.5×10^7 km. The field amplitude at 10^{10} km

is essentially 10^{-10} its initial value. The localization of the electromagnetic MPS pulse near the z -axis and the recovery of its initial amplitude well beyond the classical far-field distance confirms that the MPS pulse has propagation characteristics that are much better than the corresponding diffraction-limited Hermite-Gaussian laser field.

From Theory to Practice

Having found a class of theoretical pulses that satisfy the wave equation and describe localized transmission of energy, the next task was to determine if such pulses could be produced by a real antenna, e.g., a finite planar array of radiating

Figure 3. The field energy density of the electromagnetic MPS pulse with $a = 1$ m, $\alpha = 1$, $b = 10^{14}/\text{m}$, $\beta = 6 \times 10^{15}$, and $z_0 = 1$ cm, normalized to its maximum value at $t = 0$. (a) At $t = 0$. (b) At $t = 10$ million seconds and $z = 9.42$ billion kilometers (farther than from here to Pluto).

elements. The hope was that if we could produce fields that were extremely close facsimiles of the exact solutions, the resulting pulses would behave like their theoretical counterparts.

In a conventional antenna system, such as a phased array driven with a monochromatic signal, only spatial phasing is possible. The resulting diffraction-limited signal pulse begins to spread and decay when it reaches the Rayleigh length L_R . For

an axisymmetric geometry, an array of radius a , and a driving wavelength of λ , L_R is about a^2/λ .

There have been several previous attempts to achieve localized transmission beyond this Rayleigh distance with conventional systems. The best known of these are the super-gain or super-directive antennas, where the goal was to produce a field whose amplitude decays as one over the distance from the antenna, but whose angular

spread can be as narrow as desired. There are theoretical solutions to this problem, but they turn out to be impractical; the smallest deviation from the exact solution completely ruins the desired characteristics.

We have been studying the physical realizability of launching the scalar MPS pulse with numerical simulations and with an acoustic experiment (see the article on p. 24). The assumed antenna system is a finite planar array of point sources,

Figure 4. The contrast between the traditional Gaussian beam solution of the wave equation (a) and our new localized transmission solutions (b), which have a large bandwidth and maintain their spatial and temporal frequency distribution over long distances.

each of which radiates spherical pulses that can be combined using a Huygens representation into the array field. (The Rayleigh distance for a point source is zero, so we are always in the far field of each radiating element and can readily obtain the overall field response of the array by superposition.)

The antennas we have studied include circular, rectangular, and hexagonal arrays of equally spaced elements. The driving function for each element is a broad-bandwidth waveshape determined from the exact wave-equation solution and its derivatives. This is in marked contrast to conventional arrays, whose elements are driven with monochromatic signals (Figure 5).

As shown in Figure 6, the resulting field (the sum of these individually radiated time histories) is a localized pulse that maintains its shape and compactness at distances well beyond the conventional Rayleigh distance. Furthermore, the ADEPT/EDEPT-driven arrays appear to be very robust (not strongly sensitive either to parameters defining the array or to perturbations in the initial aperture distributions).

A difficult issue, and probably the one most used as a figure of merit, is the distance over which localization will occur for the ADEPT/EDEPT array-launched pulse as compared with traditional fields. There is no exact value for the Rayleigh distance in the case of an ADEPT/EDEPT array because of the broadband pulsed nature of these solutions, which have little in common with the monochromatic radiation on which the Rayleigh-distance concept is based. Whether the Rayleigh distance is dramatically surpassed or is simply reached by our new array may be moot—it depends greatly on the intended application.

Consider, for instance, an acoustic MPS pulse traveling at the

Figure 5. The ADEPT/EDEPT array consists of many sources in a plane, each driven with a particular time function having a large frequency bandwidth. Representative driving pulses, each different, are shown for three individual radiating elements.

Figure 6. The pulses radiated by each element in an ADEPT/EDEPT array combine to form the resulting localized packet of wave energy.

speed of sound in water (1.5 km/s) with $a = 1$ m, $\alpha = 600$ m, $\beta = 300$, and $z_0 = 0.45$ mm. The value at pulse center remains constant for about 25 cm, where it begins to oscillate. It recovers its initial amplitude every 1.571 m out to about 150 m, where the $1/z$ behavior begins to dominate. The pulse amplitude falls off to $1/e$ (a little more than one-third) of its value at the pulse center, the criterion that defines the pulse waist, over a cross-range distance of 1.5 cm.

Figure 7 shows the associated driving function at the center of a 6-cm-square, 21-element planar ADEPT array, and its frequency spectrum. This spectrum is also the envelope of the spectra for all the other driving functions. Its peak energy is at 0.6 MHz, and 98% of its energy is below 2 MHz.

Figure 7. The driving function (a) at the center of the ADEPT array and its Fourier spectrum (b) show the broad-band nature of the excitations.

The Rayleigh length (distance at which the pulse begins to decay as inverse distance) for a conventional CW, zero-order, symmetric Gaussian pulse with the same waist would be about 28 cm for a frequency of 0.6 MHz, or about 94 cm for 2 MHz. With the highest frequency, at a distance of 150 m, the waist of the corresponding Gaussian beam would have spread to about 239 cm, and its amplitude would be less than 1% of what it was at the start. As with the previous EDEPT example, the localization of the exact MPS pulse near the z axis (waist about 1.5 cm at a distance of 150 m) and the recovery of its initial amplitude well beyond the classical far-field distance confirm the localization of the theoretical pulse much farther than the corresponding Gaussian beam.

Figure 8 compares the array-generated ADEPT pulse and the corresponding array-launched Gaussian pulse (each element is driven with the broad-band center function in Figure 7 and weighted with a Gaussian whose waist is 1.5 cm). The figure depicts contours of field intensity at distances of 25 and 100 cm. The vertical scales represent -3 cm to $+3$ cm; the horizontal axes represent 2.56 s in time or equivalently 3.84 mm. Each figure has been normalized to one; the colored contours indicate where the intensity has fallen by 15%, 30%, 45%, and 90% below the maximum.

Figure 8 shows that the Gaussian-beam waist spreads at a rate corresponding to 0.6 MHz, the frequency of the driving function's spectral peak. Using this frequency

Figure 8. The fields generated at $z = 25$ cm and at $z = 100$ cm by a Gaussian (a) and an ADEPT driven array (b), showing how the Gaussian pulse spreads and ADEPT pulse remains localized.

to define the Rayleigh distance, the ADEPT pulse at about $3L_R$ is much more localized than the reference Gaussian, an effect that lasts, even with this simple set of driving functions, out to about $5L_R$. Even at the maximum frequency, the ADEPT array surpasses the Rayleigh distance. These results indicate that a modest-size array can generate pulses that travel substantial distances without spreading.

Having shown that even a simple unoptimized array can reproduce the MPS pulse at significant distances, the next task is to see how far beyond the classical Rayleigh length one can reach. One possible approach is to look for ways to squeeze a large array into a smaller one, and one way to do that is to drive the array with a more complicated set of pulse shapes whose functions are derived from the ADEPT solution within the array distance and beyond it. The solutions beyond the maximum distance are "folded" into the interior of the array in a particular way, trading a simple source distribution for a much more complicated one.

The result of this maneuver on the array-launched ADEPT field is dramatic, however. We have detected localization for the above case out to about 10 m, which is more than $30L_R$. We are actively investigating exactly how far out localization can be maintained.

Summary

The unique aspect of the ADEPT/EDEPT solutions is their intrinsic space-time nature. An MPS pulse can be designed to recover its initial amplitude after propagating very large distances while spreading very

little. The pulse moves virtually unchanged in the "near" zone, "sloshes" about the pulse center in the "intermediate" zone, recovering its initial amplitude at intervals out to very large distances, and finally falls off as inverse distance in the "far" zone. These pulses can be produced with a finite array of radiating elements individually driven with appropriately shaped pulses. A Huygens reconstruction based on the causal, time-retarded Green's function and a finite planar array of point sources reproduced the MPS pulses at large distances. The array-generated MPS pulse appears to be very robust and insensitive to perturbations in the initial source distributions. The article that follows (p. 24) discusses acoustic experiments to verify the ADEPT concepts.

The many potential applications for acoustic and electromagnetic pulses with localized transmission characteristics include remote sensing, communications, power transmission, and directed-energy weapons. All of these applications raise a number of questions as to the stability of the ADEPT/EDEPT solutions in dispersive, lossy, inhomogeneous environments. We are actively studying these issues and are planning a number of experiments to compare with the theoretical predictions. If we succeed, the resulting beams would revolutionize communications technology as well as remote sensing and directed energy systems.

Key Words: acoustic directed-energy pulse train (ADEPT); electromagnetic directed-energy pulse train (EDEPT); focus wave mode (FWM); modified power spectrum (MPS); photon torpedo.

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Evidence of Localized Wave Transmission

We have made experimental measurements that confirm the existence of acoustic directed-energy pulse trains (ADEPTs) for ultrasonic waves in water. These pulses exhibit localized transmission of wave energy.

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We have developed a theory based on recently discovered solutions to Maxwell's and the scalar wave equations (see the preceding article for an elementary description of the theory and its implications). We have performed proof-of-principle experiments that confirm the existence of localized wave packets. Our first experiments have been in the acoustic regime using our Ultrasonic Test Bed.

What makes our newly discovered solutions unique is their intrinsic space-time nature. In our acoustic work, we refer to the solutions as acoustic directed-energy pulse trains (ADEPTs). An attractive feature of the ADEPTs is that they can be generated with a finite array of radiating elements by specifying both their spatial and their temporal distributions. The driving functions for the array elements are determined by the exact solution and its derivatives. We have demonstrated theoretically several characteristics of the ADEPTs using computer simulations. In particular, a Huygens reconstruction based on a computer model of a finite planar array of point sources reproduces the modified

power spectrum (MPS) pulses at large distances away from the array. The array-generated MPS pulse appears to be very robust and insensitive to perturbations in the specified source distributions. These results are also insensitive to the type of array (circular, rectangular, or hexagonal) considered.

The following is a description of a straightforward experimental approach to determine the feasibility of launching an acoustic MPS pulse. After comparison of the experimental results and the simplest numerical simulations, our analysis indicated that substantial improvements can be made. These will be checked in future experiments.

Computational and Experimental Verification

The verification experiments that we undertook were based on ultrasonic pulses propagating in water. The ADEPT parameters were identical to those chosen for the illustrative example (Figures 7 and 8, p. 22) of the preceding article. This pulse had the desired propagation characteristics and was within the realm of our experimental capabilities. The localization of the MPS pulse near the z -axis and the recovery of its initial amplitude well beyond the classical far-field distance would confirm the improved transmission of ADEPTs over conventional diffraction-limited beams.

We have chosen our pulse parameters to facilitate the design of an acoustic experiment. Its pulse (waist = 1.5 cm) and its spectrum (peak at 0.6 MHz and practically all of its energy below 2.0 MHz), coupled with the choice of array geometry and array element size, permit the desired effects to occur in a distance less than 2 m, the effective length of our water tank. In particular, with the Rayleigh distance L_R at the peak frequency being 28 cm, there are about $7 L_R$ available in the tank.

The Experiment

We chose to generate our pulses with an array that is computationally and experimentally simple and within the scope of our experimental resources. The latter limitation imposed some significant constraints and dictated our experimental arrangements.

To produce the field generated by an array, we would have to drive each element of the array with the appropriate waveform for that particular element. Thus we would need a generator and transducer for each element.

In this, the first stage of a planned experimental program, we minimized the complexity introduced by independent generators and transducers by constructing a synthetic array. In such a construct, each element of the array would be

driven individually by its own source, each source having an appropriate waveform: the field generated in this configuration would be recorded. This procedure requires only one generator and one transducer (element) at any one time to provide the contribution of a given element to the array performance. After all elements were so driven and their radiated fields recorded, the array field would be synthesized by superposition of the fields previously recorded. Thus, we were able to generate the field radiated by an array by computational reconstruction,

using experimentally measured contributions from individual radiators.

Also, we chose to use an acoustic field detector that has a minimal impact on the measured field quantity, i.e., the presence of the detector does not impact the variable being measured. We used a laser beam/photodiode combination that measures sound-wave-induced changes in the refractive index of water. The laser beam propagates through the water tank at right angles to the direction of sound propagation and through a window to strike a

photodiode (Figure 1). A lens placed between the water tank and the photodiode puts a reduced virtual image of the photodiode within the tank near the sound field. The sound field creates local variations in the optical refractive index of the water in the tank. At low ultrasonic frequencies, the total effect on the optical beam is a phase modulation that occurs at a unique plane as the light beam transverses the sound wave.^{2,3}

The magnitude of the phase modulation is the effective optical path length through the local

Figure 1. The experiment system used to verify localized transmission of ADEPT waves. The sending system consists of a programmable waveform generator, a power amplifier, and a piezoelectric ultrasonic transducer, with a computer to down-load the different waveforms to the generator. The receiving system consists of a laser beam to probe the ultrasound pulse field and a lens-photodiode combination that places a virtual image of the photodiode inside the immersion tank very near the critical plane. The position controller moves the transducer forward and backward, up and down, and sideways to place the virtual image in different parts of the pulse field. The system computer issues commands to the pulser and the position controller and files data from the photodiode.

variations of refractive index.⁴ In other words, it is the line integral of the refractive index through the regions of optical retardation and speed-up induced by the sound. The intensity of the light propagating across the sound field is proportional to the curvature in the wavefronts, which is, in turn, the second derivative of the phase modulation. The photodetector thus measures the second time derivative of the acoustic field interacting with the laser beam.

Our interests have been directed toward measuring the fields radiated by an array at a point in space, not along a line, but our detector system measures line integrals of the field. In order to circumvent this problem, we called upon the reciprocity principle, by which we could interchange the role of transmitter and receiver without affecting the measured response. That is, we used the principle of reciprocity to interpret the field radiated by a point source and measured by a line detector as the field radiated by a line source and measured by a point detector.

In summary, our array is one-dimensional and synthetic and uses reciprocity to reverse the roles of emitter and receiver. The practical result is that we can determine the wave that each element of a pulsed array of line sources must radiate to produce an ADEPT pulse by substituting line detectors and irradiating them with waves emanating from point sources that mimic the properties of the ADEPT wave. Since we are synthesizing the array, we can use just one detector and move it to different positions. For each position of the detector, we record a time history of the received

pulse. Then we add up all the different time histories to yield the radiation the array would emit if we were pulsing its elements, each with the wave shape received at its location in the array.

The sound source we used consists of a single, commercial ultrasonic transducer designed for nondestructive testing. The transducer is a piezoelectric disk 6.2 mm in diameter, with acoustically matched damping material on its backside, that produces a piston-like motion in the water. For distances greater than 6 cm, the resulting sound beam is in the far field of the transducer. Within the approximations of our design, it is a signal proportional to the third derivative (one from the transducer and two from the optics) of the driving function (the electrical signal applied to the source element) that is eventually acquired by the data-acquisition system.

In the coordinate system indicated in Figure 1, let the linear array of the experimental element positions be along the y -axis, the laser measurement be taken along the x -axis, and the direction of propagation be along the z -axis. The synthetic linear array consisted of 21 element positions symmetrically arranged about $y = 0$ with 3-mm separation. Thus, 11 driving functions were employed, and the total array width was 6 cm. Time records of length 10.24 μ s were taken. The 176 unique experimental waveforms, launched with a normalized-to-one maximum amplitude, were weighted and superposed to construct the field of our synthetic linear array.

It should be emphasized that, save for multiplying the waveforms by a weighting coefficient dependent on

the assumed position in the array for each generated signal, we applied no other processing, either before or after the experiment.

As a control, we constructed a Gaussian beam from the same array with different weights but the same waveform from all array elements. Each element of that array was driven with the center ADEPT driving function and was weighted with a Gaussian amplitude $\exp(-\rho^2/w_0^2)$, where $w_0 = 1.5$ cm, the same initial transverse waist as the ADEPT. For both the experimental Gaussian control and the corresponding numerical simulations, a Gaussian beam field was fit to the data. The effective frequency was 0.6 MHz, the peak of the spectra of the driving wavefunctions. The effective Rayleigh length for the experiment was thus about 28 cm.

The Results

Experiments and computer simulations were conducted to verify the existence, behavior, and practical realizability of the ADEPT solutions with the parameters described above. Figure 2 illustrates typical results that lend support to the concept of the ADEPT. In Figure 2a, the energy density of the field measured in the experiment is shown for distances of 25 and 50 cm with the Rayleigh distance (near-far field boundary) at approximately 28 cm.

The horizontal axes represent 2.56 μ s in time or equivalently 0.384 cm; the vertical scales represent -3 cm to $+3$ cm. Time increases left to right. The peak values have been normalized to a maximum of 1. The yellow band is approximately 30% down from the

peak amplitude; the green band ~45%; the light blue band ~60%; and the light purple band >90%.

The synthetic linear array experiment is simulated (theoretical ADEPT) by driving each element at (x,y) in a rectangular array with the wavefunction at $(0,y)$. This ensures that the array appears "linear," as does the reciprocal laser diagnostic system. The simulated array is 6 cm $\times$ 6 cm and contains 441 elements in a 21×21 equally spaced

pattern. Three derivatives of the reconstructed ADEPT are taken to simulate the effects of the diagnostic system. The experimental and theoretical results are shown in Figures 2a and 2b, respectively. For the purpose of comparison, a control experiment involving a Gaussian beam was also performed; these results are presented in Figure 2c.

The experimental and theoretical ADEPT results are in excellent agreement. Both show the

remarkable retention of the pulse behavior well beyond two Rayleigh distances. Also, the contrast in compactness between the ADEPT and Gaussian pulses is evident.

We found both experimentally and numerically that the linear array produced fields that began to break up after 50 cm, $\sim 2L_R$. The rectangular-array-generated ADEPT avoids this effect because the off-axis elements compensate against any splitting.⁵

Figure 2. The energy density in propagating pulses at distances of 25 and 50 cm from the 6-cm-square array used in our experiments and simulations. Columns (a) and (b) display experimental and theoretical ADEPT results, respectively, which are in excellent agreement and show the retention of the pulse shape beyond the Rayleigh distance (about 30 cm). The control Gaussian pulse (c) spreads out much more than the ADEPT pulse at these distances.

The Future

Our goals for the future include more definitive experiments to study ADEPT's further and to investigate various features of these fields and arrays. As a first step, we plan to design an array of acoustic elements with individual acoustic generators so that we will not have to resort to synthesis. We will then sample the field in a point-wise fashion so that we can map the radiated field from the array of sources.

As part of our experimental investigation, we will look into folded arrays to space-constrain the physical layout as well as into other pulse waveforms.

Our goals include an experimental program in the electromagnetic regime. The measurement program is now in the early planning stages and awaits the availability of experimental facilities.

Key Words: ADEPT; reciprocity; synthetic antenna.

Notes and References

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5. See Figure 8 of the previous article, p. 22.

Abstracts

Cratering Phenomenology Revealed Through Discrete-Element Modeling

The discrete-element code DIBS (discrete interacting block system), developed at the Lawrence Livermore National Laboratory, provides much more realistic modeling of the fragmentation and particle interactions involved in cratering in jointed rocks than do the continuum models that traditionally have been used for such tasks. We have used the DIBS code to simulate the underground explosion in the Sulky Event, successfully capturing both the near-vertical motion recorded in motion pictures of the event and the approximate height of the rubble mound. It is clear that discrete-element modeling is also very well suited to evaluating the stability of tunnels in jointed rocks under dynamic loading and to analyzing the progression of chimney collapse above cavities formed during nuclear tests in those geologies.

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High-Intensity Short-Pulse Lasers

Recent advances in short-pulse laser technology should allow us to develop table-top laser systems that yield focus intensities a thousand times brighter than those of our Nova laser system (the world's largest). Applying these techniques on large-scale systems should make it possible to produce pulses of more than 10^{15} W peak power and focused intensities near 10^{21} W/cm². The ability to generate such a laser field opens up an entirely new physical regime for research. Fields of study expected to benefit include nuclear physics, plasma physics, laser-atom interactions, x-ray lasers, spectroscopy, and inertial confinement fusion.

Contact: Michael D. Perry (415) 423-4915.

Localized Transmission of Wave Energy

We are investigating new solutions of the wave equation that are a natural basis for synthesizing pulses that can be tailored to give localized transmission of energy. We are concurrently studying how these pulses can be generated by finite-sized arrays of radiating elements. There are many potential applications for pulses with localized transmission characteristics, including remote sensing, communications, power transmission, and directed-energy weapons.

Contact: Richard W. Ziolkowski (415) 422-3889.

Evidence of Localized Wave Transmission

LLNL experiments to test the feasibility of launching an acoustic, directed-energy pulse train (ADEPT) in water have demonstrated localized transmission of wave energy far beyond the classical Rayleigh length that defines the boundary between near-field and far-field transmission for Gaussian (diffraction-limited) pulses. The results of our experiments are in excellent agreement with computer simulations.

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