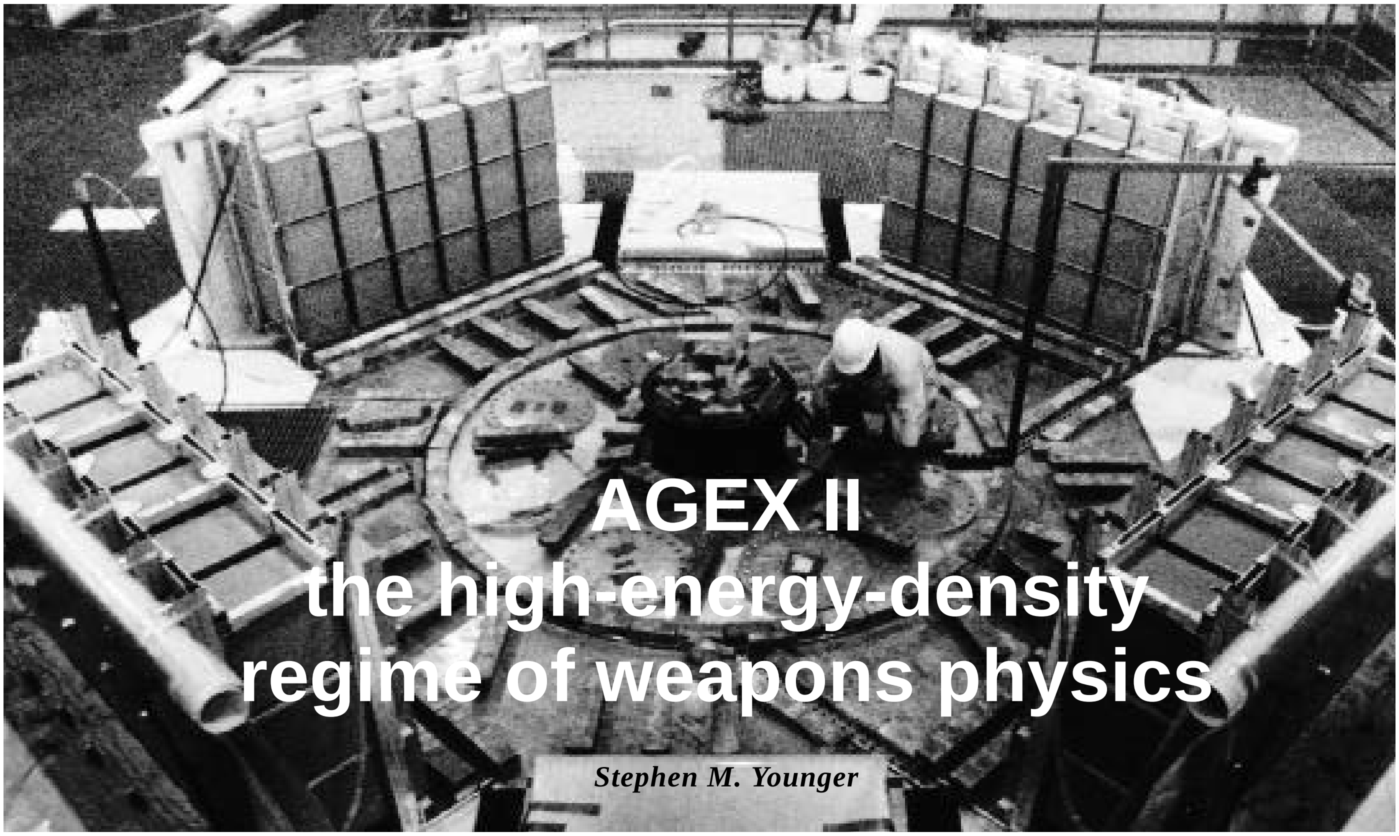


AGEX II
the high-energy-density regime of weapons physics

Stephen M. Younger

The Pegasus II capacitor bank for pulsed-power experiments

Nuclear explosives achieve higher temperatures and pressures than any other object in our solar system. Pressures in excess of ten million atmospheres, temperatures over 1000 electron volts (1 eV corresponds to 11,600 kelvins) and very high densities typify a nuclear explosion. Under these conditions even the heaviest atoms are almost completely ionized, and neutron radiation is so intense that higher-order nuclear processes (such as multple capture) become common. Our knowledge of such extreme energy-density conditions has been gained through a combination of theoretical calculations and experiments performed on actual nuclear explosions. With the reduction in the number of underground nuclear tests, however, our access to these unique conditions has been sharply reduced, and by the end of 1996 it will disappear entirely. There is an urgent need to develop laboratory techniques that will allow us to simulate the conditions found in a nuclear explosive both to provide more accurate information on the physics of matter at high energy density and to provide a vehicle for continued development of the special skills required to maintain an understanding of nuclear weapons.

The Physics of Nuclear Explosives

Nuclear weapons are very complex devices. During the high-explosive phase of the weapon, materials are subjected to pressures of several hundred kilobars and reach temperatures of several eV. These conditions are reproducible in the laboratory and a great deal of data are available to describe material response and hydrodynamic processes at these pressures. (See “AGEX I—The Explosives Regime of Weapons Physics.”) When the fissionable material in the weapon reaches a critical mass, however, a chain reaction occurs, which causes the rapid generation of energy. This chain reaction occurs on a time scale short compared to the ratio of the size of the device to the sound speed, so the material does not have a chance to expand during the energy-generation phase. Since the energy cannot go into kinetic energy, it goes into thermal energy, raising the temperature of the material to extraordinary values and thus raising the pressure to many millions of atmospheres.

Laboratory studies of the properties of high-energy-density matter face two major challenges: First, one must reproduce the very high densities and temperatures typical of a nuclear explosion. Second, one must be able to probe the conditions in the sample, usually via an x-ray burst (to probe atomic properties) or a pressure pulse (to probe material equations of state). The energy required to heat a sample is roughly given by $(3/2)nkT$, where n is the density of particles (nuclei plus ionized electrons), k is Boltzmann's constant, and T is the temperature. A simple calculation shows that normal-density uranium at 1 keV has an energy density of about 500 megajoules per cubic centimeter. Even for a sample 1 millimeter across the net energy required is 500 kilojoules, a substantial amount for laboratory experiments. Also, in contrast to fissioning metals, which generate heat internally, laboratory samples must be heated by an outside energy source. The heating takes several nanoseconds, long enough for the sample to begin to disassemble. The resulting density and temperature gradients complicate the interpretation of the experiment. Reducing the density allows one somewhat greater flexibility, since hydrodynamic tampers can be used to keep the material from expanding during the experiment. Unfortunately, low-density samples lack some of the unique aspects of dense plasma. The relevant figure of merit for dense matter is the coupling parameter, Γ, the ratio of the average electrostatic energy between neighboring ions to the average thermal kinetic energy. For low Γ thermal processes dominate and the plasma behaves as an ensemble of individual particles. For high Γ the electrostatic force dominates, the plasma becomes "stiff," and it can even condense into a solid phase. The goal of high-energy-density physics is to produce a sample dense enough to resemble a strongly coupled plasma yet hot enough for the level of ionization to be representative of the material in a nuclear explosive. This requires both raw energy, to heat a sample of significant size, and power, to rapidly heat the sample before it expands to low density.

Examples of High-Energy-Density Physics

	The Sun	Jupiter	High explosives	Lasers	Pulsed power	Nuclear explosions
Temperature (eV)	10^3	1	~1	>100	100	$>10^3$
Pressure (atm)	10^9	10^6	10^5	10^8	10^7	$>10^7$
Density (g/cm^3)	10	1	1	100	10	>10

Diagnosing a high-energy-density plasma is also challenging. No material probe can withstand the conditions of a hot dense plasma, so remote measurements are essential. X rays, either those emitted by the plasma itself or those absorbed when an intense probe signal is passed through the plasma, can reveal much about the atomic properties of the material. Strong shock waves can be launched into the sample to determine its equation of state via the measurement of shock and particle velocities. Such experiments are made more complex by the presence of the hydrodynamic tamper or other artifacts of the plasma-containment mechanism.

No single above-ground experimental facility can simultaneously reproduce all of the relevant conditions found in a nuclear explosion. At Los Alamos we have assembled a broad array of high-energy-density facilities, including pulsed-power machines, lasers, and the LAMPF accelerator, that allow us to access a broad range of high-energy-density conditions for the study of physics relevant to nuclear explosives.

Athena: Pulsed Power for High-Energy-Density Physics

In Greek mythology Athena was the goddess of wisdom who carried the thunderbolts of Zeus. At Los Alamos Athena is the program that uses pulsed-power technology to explore high-energy-density physics in support of the nuclear weapons program. The advantage of pulsed power for high-energy-density physics is that many megajoules of energy can be stored in very compact devices and then rapidly delivered to an experiment. The Athena program uses two methods to generate intense electrical pulses: a large capacitor bank called Pegasus II and a high-explosive pulsed-power generator called Procyon.

Capacitor-bank pulsed power. The Pegasus II capacitor bank consists of 144 capacitors wired in parallel and arranged around a central target chamber. Over the course of several minutes, a high-voltage power supply charges the capacitors. Pegasus

II can reach a maximum voltage of about 100 kilovolts and store up to 4.3 megajoules of electrical energy. At full voltage, the power supply is disconnected, and the stored electrical energy is rapidly discharged into a target located in a central chamber. Depending on the switching, the discharge time can be from 0.3 to 6 microseconds. At peak current, around 10 megamps, the power flow in Pegasus II exceeds that produced by the electrical generating capacity of the United States.

The target in Pegasus II experiments is typically a hollow metal cylinder, several centimeters in diameter and a few centimeters tall, oriented with its axis connnecting the two current-carrying electrodes of the capacitor bank. A current I flowing in the cylinder produces a magnetic field

$$B = \mu I/2\pi r$$

(where $\mu = 4\pi \times 10^7$). The interaction of this magnetic field with the drive current results in an inward pressure,

$$P = B^2/2\mu,$$

that causes the rapid implosion of the cylinder. When the Pegasus II capacitor bank at full charge is discharged through a gold-foil cylinder with outer radius of 2 centimeters and wall thickness of 0.1 millimeter, the cylinder implodes in about 6 microseconds. The peak pressure is 1.1 megabar and the peak implosion velocity is about 1.3 centimeters per microsecond.

Pegasus II can be used for three main classes of experiments. Simply discharging the bank through a cylindrical target provides a test bed for studying implosion hydrodynamics and material properties. To study the growth of hydrodynamic instabilites, asymmetric or otherwise deliberately perturbed cylinders are imploded and the results compared to numerical simulations that use various theoretical models for instability growth. The time sequence in Figure 1 shows a side view of a very thin-walled cylinder as it implodes during a Pegasus experiment. The onset of small-scale instabilities, their evolution to larger-scale perturbations, and finally the complete breakup of the imploding shell are clearly visible. We have done a number of experimental studies to assess how instability growth depends on wall thickness, material, and other implosion parameters.

In the second class of experiments, a sample is placed inside the imploding cylinder to study its material properties under extreme pressures and temperatures. An imploding cylinder can compress a sample to a pressure of several megabars. At this extreme pressure the atomic structure of the sample becomes distorted. The forced overlap of atomic orbitals causes changes in the transport rates of heat, charge, and photons. Serious research on those transport phenomena in hot dense matter is just beginning to be pursued. Since the implosions are nearly adiabatic and create high-pressure conditions that last on the order of a microsecond, Pegasus II is an ideal test bed in which to study the structure and dynamics of matter under extreme conditions.

In the third class of experiments, very fast implosions are used to generate intense x-ray bursts. These bursts are needed for a wide range of experiments on radiation transport and the interaction of x rays with matter. When the cylindrical foil implodes to its axis, the kinetic energy of collapse is converted to thermal energy, and the matter in the foil becomes a hot plasma. The matter then rapidly cools by emitting an intense burst of x rays. Kinetic energy is proportional to the square of the velocity, so implosions at higher velocities produce more x rays. Since the magnetic pressure during the implosion is independent of the mass of the foil, the implosion velocity can be increased by reducing the thickness of the foil. Cylindrical

Figure 1. Implosion of a Thin Foil Cylinder at Pegasus II
A side view of the implosion of a 2500-angstrom-thick, 5-centimeter-radius, aluminum cylinder on the Pegasus capacitor bank is shown at various times, with an arbitrary zero time. Note the onset of short-wavelength perturbations at early times, followed by the growth of longer-wavelength perturbations, and eventually the complete breakup of the aluminum foil.

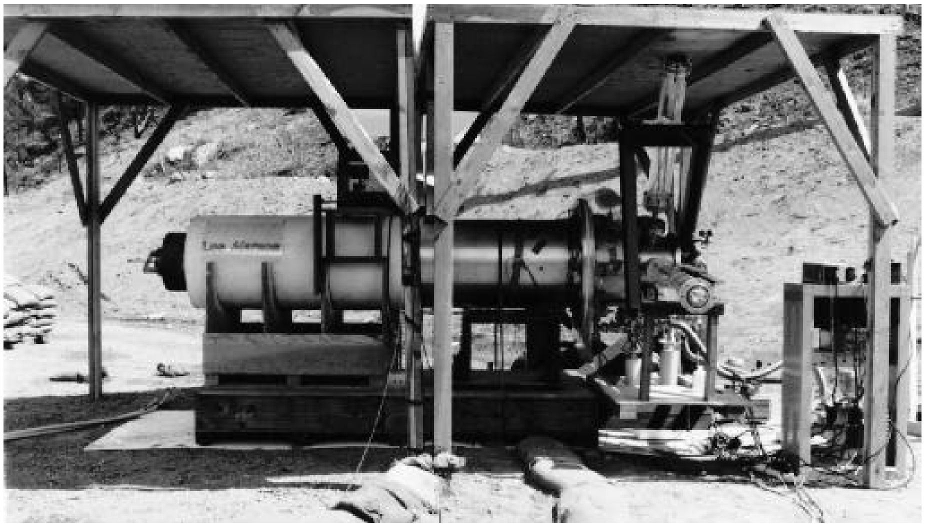


Figure 2. The Procyon High-Explosives Pulsed-Power System
The white cylinder at left is a Mark IX high-explosive generator. To the right is an explosive opening switch, and at the extreme right are the plasma flow switch and the implosion target. The clear tubes extending from the target contain diagnostic equipment.

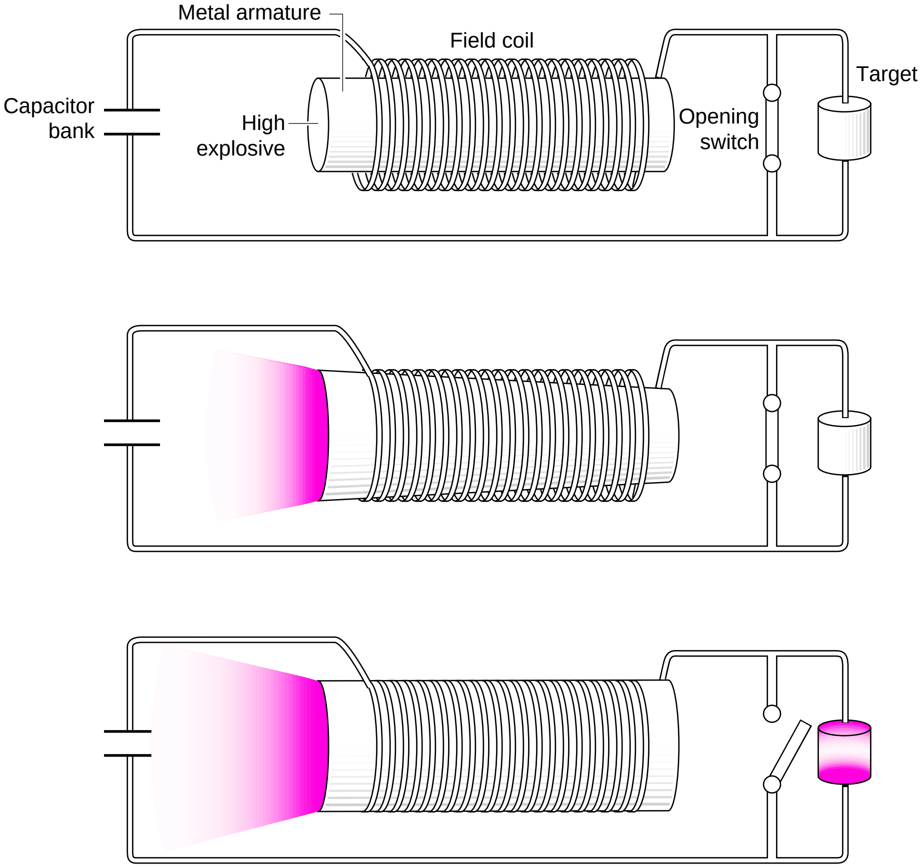
foils as thin as 2500 angstroms (less than the wavelength of visible light) have been imploded on Pegasus II to velocities in excess of 10 centimeters per microsecond. However, the onset of hydrodynamic instabilities limits the usefulness of very thin foils. The very rapid acceleration endured by these foils enhances the growth of Rayleigh-Taylor instabilities. The foils can become so unstable that they break up before reaching the axis, in which case various pieces of the foil arrive at different times. This prolongation of the arrival of the imploding shell results in a lower effective energy density in the plasma and hence a softer x-ray spectrum. Also, if the implosion velocity is so high that the implosion is over before the capacitor bank has the opportunity to deposit all of its energy in the target, then the resulting x-ray burst will be less intense. Two techniques are available to overcome these limitations. First, by using special switching techniques to reduce the rise time of the bank from several microseconds to several hundred nanoseconds, we can make energy deposition in the cylindrical foil more efficient. Second, by increasing the radius of the foils, we can extend the implosion time. We hope that an optimal combination of the two techniques will maximize the coupling of the energy in the capacitor bank to the kinetic energy of the foil while minimizing the growth of deleterious hydrodynamic instabilities.

High-explosive pulsed power. Pegasus II produces pressures of megabars and energy densities of hundreds of kilojoules per cubic centimeter in a volume of about a cubic centimeter. The production of significantly higher pressures in a similar-sized volume would require storing tens to over a hundred megajoules of electrical energy in a very large capacitor bank. This can be an expensive proposition. Fortunately there is a relatively low-cost alternative, namely, the amplification of electric power pulses with high explosives. At Los Alamos we have developed a series of high-explosive pulsed-power generators that have produced currents as high as 150 million amperes in compact, relatively low-cost units. The present device, called Procyon (Figure 2), can deliver more than 1 megajoule of energy into an implosion.

Figure 3 illustrates the operation of a high-explosive pulsed-power generator. A small capacitor bank sends a current pulse through a coil wound loosely about a copper cylinder that is filled with high explosives. This current creates a magnetic field in the gap between the coil and the copper cylinder. As the magnetic field reaches its peak value, the high explosive in the copper cylinder is detonated. The cylinder expands, and as it closes the gap between itself and the coil, it squeezes the magnetic field into a smaller and smaller volume and thereby increases the magnetic-field energy. At maximum field compression the switch shown in the figure is opened, allowing the field energy to be extracted in the form of a greatly amplified current pulse that flows through the target.

Even though high-explosive pulsed-power generators can produce tens or even hundreds of megajoules of electrical energy in a single pulse at affordable prices, the pulse is several microseconds long, so the power eventually delivered to a target is at most a few tens of terawatts (1 terawatt = 10^{12} watts). At present it is difficult to compress this energy into a much shorter, higher-power pulse, which would be useful for the production of intense x-ray bursts or ultrahigh pressures,

Figure 2. Operation of a High-Explosive Pulsed-Power System



As the capacitor bank discharges through the field coil, the current in the coil generates a magnetic field between the coil and the metal armature. The opening switch is in the closed position, preventing current from flowing to the target.

The high explosive is detonated at one end and expands the armature. The magnetic field is squeezed between the expanding armature and the field coil and greatly increases in magnitude. In this way high-explosive energy is converted into magnetic-field energy. The field energy, in turn, amplifies the current.

At peak compression of the magnetic field the switch is opened and a greatly amplified current pulse flows through the target.

although a variety of options are being evaluated. To reach significantly higher powers, one must employ other technologies more suited to short-pulse generation. Chief among those are high-power lasers.

Lasers: Higher Energy Densities for Shorter Times

Lasers can produce very short, high-power pulses and direct them into small volumes to create very high energy densities. But the current high-power lasers are very expensive energy sources and maintain high energy densities in a target for only a nanosecond or so and over volumes only of the order of a cubic millimeter. In spite of these limitations, high-power lasers have proven to be very versatile in the study of high-energy-density physics.

Trident is a neodymium-doped glass laser at Los Alamos that delivers two simultaneous pulses, each 100 picoseconds long and carrying 100 joules of energy. The laser consists of a very low-energy oscillator that forms the laser pulse, a series of rod amplifiers that increase the energy in the pulse to about 1 joule, and a set of disk amplifiers that provide the final amplification. The pulses are directed into a target chamber outfitted with a wide array of diagnostics, including x-ray and optical spectrometers, framing cameras, and streak cameras.

A Trident 100-picosecond laser pulse focused into a volume a few hundred microns in diameter yields an energy density of over 1 megajoule per cubic centimeter. Although the energy density is higher than that produced in experiments using Pegasus II, our 4-megajoule capacitor bank, the temporal and spatial scales of the experiments are much smaller and very sophisticated diagnostics are required to acquire data. The inertial-fusion program has made impressive progress in diagnostics development, so that it is now possible to obtain x-ray images of experiments with spatial resolution of less than 5 microns and temporal resolution of less than 100 picoseconds.

Trident was designed to be an easy-to-use tool for high-energy-density physics. It can deliver laser pulses with a wide variety of lengths and shapes for different experiments. Trident also has a small third laser beam, which is used to create a short x-ray pulse next to the target. X radiographs of evolving experiments can be obtained from the x-ray pulses and are particularly useful for the study of high-pressure hydrodynamics. Trident pulses, when applied to appropriate targets, can produce shock-wave pressures of several megabars and x-ray pulses of moderate temperatures.

Still higher temperatures over somewhat larger volumes can be obtained on the Nova laser at Lawrence Livermore National Laboratory. Nova, the largest glass laser in the world, produces pulses of up to 40 kilojoules in one nanosecond. We have fielded a number of experiments on Nova related to radiation hydrodynamics and x-ray-driven implosions.

How far can one go in increasing energy density by shortening the pulse length of the laser and reducing the size of the focused optical spot? Another laser at Los Alamos, Bright Source II, is providing the answer. Bright Source II pushes the limits of energy density by directing a relatively small amount of energy (only a quarter of a joule at present, although a 10-joule machine is on the horizon) into an incredibly short pulse that can be focused down to only a few microns. Bright Source II pulses last less than 300 femtoseconds, so that even though it is moving with the speed of light, a pulse is only about 900 microns long. The focused pulses have intensities of more than 5×10^{18} watts per square centimeter, well above pulse intensities produced by Trident or even Nova. The impact of a laser pulse on the surface of a target sample creates pressures of more than 1 gigabar, but only for about one picosecond, after which the sample expands under thermal pressure. (It is interesting to note that the radiation pressure—the pressure due to the momentum of the light itself—is 1 gigabar, which is comparable to the induced thermal pressure in the target.) During such a short pulse the atoms in the target do not have a chance to equilibrate and may not approximate fully the equilibrium conditions found in a nuclear explosion. Nevertheless, Bright Source II can heat thin solid foils to keV temperatures, creating a high-density and very hot plasma. Hence this laser can be used to probe the structure and dynamics of matter at conditions that approach those found in a nuclear explosion. The hot plasma cools both by expansion and by the emission of x rays. Figure 4 shows a typical x-ray spectrum from an aluminum sample illuminated by a Bright Source II pulse. Up to 1 percent of the incident laser energy is converted to line radiation around 2 keV. The line radiation is useful for studying the interaction of x rays with matter.

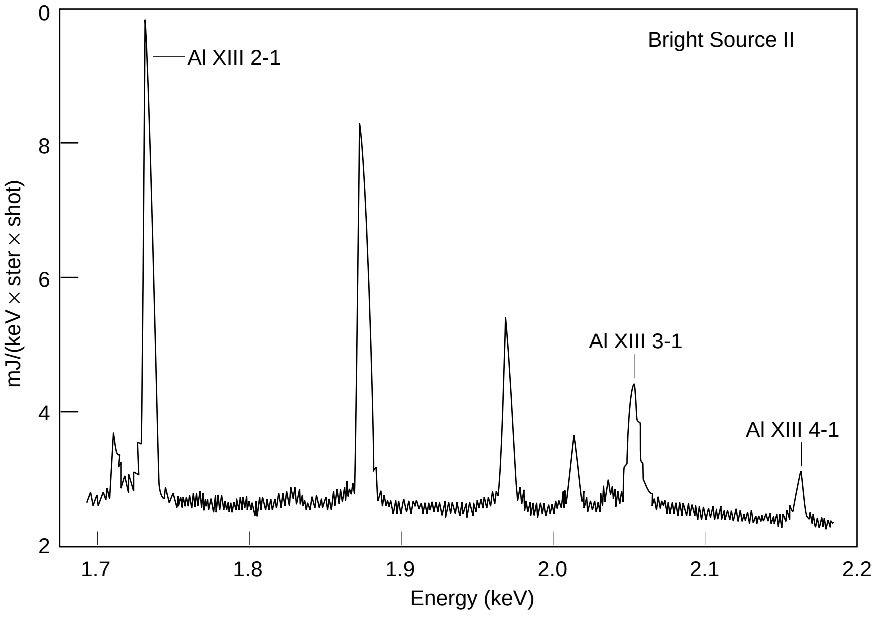


Figure 4. X-Ray Spectrum Induced by a Pulse from Bright Source II
The x-ray spectrum results from the impact of a 0.25-joule, 300-picosecond pulse from the Bright Source II laser on an aluminum foil. The intense lines serve both as a diagnostic of the conditions in the dense radiating plasma and as valuable probes for use in other experiments.

The extremely short pulses available from the Bright Source II laser also provide an effective means to study very rapid processes, such as transient chemical reactions. In typical chemical detonations several transient molecular species such as OH radicals persist only for a short time but are important in determining the overall energy balance in the detonation products. An experiment is currently underway at Bright Source II to measure the OH radical in a forced detonation—the first such measurement of its kind for an explosive process.

Nuclear Physics at LAMPF

Moving up again in the energy scale, we encounter nuclear energy densities—where the relevant energy parameters are not kiloelectronvolts as in plasmas but megaelectronvolts.

The formation of a critical mass during the detonation of a nuclear explosive and the attendant chain reaction result in an intense neutron burst. Neutrons interact with nuclei through a complex set of scattering and capture processes, some leading to the production of additional neutrons and/or the initiation of fission and others to the production of stable isotopes. To model the dynamics of fission in weapons, we must have accurate descriptions of all of the dominant neutronics processes. The knowledge of weaker processes (such as those involving transient nuclear states) can provide valuable diagnostics on the progress of the nuclear burn and contribute to radiochemical analyses of nuclear explosions. The Laboratory has conducted an extensive series of experiments on nuclear physics important for weapons at LAMPF and other nuclear facilities.

LAMPF is the most powerful accelerator in the world. Although some machines accelerate charged particles to higher energies, none is capable of delivering as many particles per unit time to the target as LAMPF. This capability is important when one wants to study weak processes, including the study of higher-order nuclear cross sections. In addition to the accelerator itself, the LAMPF facility includes several target areas. The areas of particular concern for the weapons program are the Weapons Neutron Research (WNR) facility and the Manuel Lujan, Jr. Neutron Scattering Center (LANSCE).

LAMPF has been extensively used by the weapons program. Fundamental aspects of fission have been studied by examining the relative timing of fission and neutron emission in fissioning nuclei. Angular distributions of neutrons, gamma rays, and fission decay products have been measured to determine the energy and momentum balance in fission. Detectors used in nuclear tests have been calibrated on LAMPF to provide absolute measurements of the neutron flux from the nuclear device. We are currently evaluating new techniques for using proton and neutron sources to image dynamic phenomena in opaque samples.

The Future

The next several years promise to be among the most interesting and productive ever for high-energy-density physics. We have assembled an array of facilities to investigate a wide range of physics issues of importance to the nuclear weapons program. The structure and transport properties of hot dense matter will be systematically studied in a regime where single-atom theories break down and many-body effects are important. The interaction of strong shock waves and x-ray pulses with matter will continue to be studied with the aim of providing quantitative data for use in our computer models of nuclear explosions. Experimental data on hydrodynamics and hydrodynamic instabilities will allow us to validate increasingly sophisticated algorithms in new computer codes, particularly those that will need to be developed to exploit the promise of massively parallel computers.

Each of our capabilities can be extended to higher energies for even more interesting applications. The next advance in Laboratory capacitor banks is Atlas, a 25-megajoule machine that will permit us to study high energy densities over tens of cubic centimeters. The Procyon high-explosive pulsed-power generator will be followed by a more advanced system that will deliver in excess of 200 million amperes. Bright Source III is being designed to produce focused intensities over 10^{20} watts per square centimeter to permit the study of multiphoton x-ray interactions. This intensity is high enough to rip apart the vacuum in the electrostatic field near a nucleus to create electron-positron pairs, literally creating matter from energy. ■

Stephen M. Younger is the Program Director for Inertial Confinement Fusion and High Energy Density Physics at the Laboratory. He received a Ph.D. in theoretical physics from the University of Maryland in 1978. From 1974 to 1982 he performed theoretical studies of atomic processes at the National Bureau of Standards in Washington, D.C., concentrating on electron scattering from atoms and ions. From 1982 to 1989 he was a staff member and group leader at Lawrence Livermore National Laboratory, where he specialized in advanced thermonuclear weapons design, x-ray lasers, electromagnetic weapons, and other defense programs. In 1989 he came to Los Alamos and in 1991 he was named to his present position. In addition to working on defense issues, Younger has continued to contribute to fundamental atomic and plasma physics. He is a Fellow of the American Physical Society and has served on numerous government panels and committees.