# P-24: Plasma Physics

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## Introduction

The Plasma Physics Group (P-24) researches the basic properties of plasmas with a view to applications in important Los Alamos National Laboratory and national programs. Plasmas occur in nature when matter exceeds temperatures of roughly 10,000°C. At these temperatures, the constituent atoms and molecules of matter begin to lose their bound electrons to form a substance composed of positive or negative ions and free electrons. All principal phenomena in plasmas can be traced to the fact that ions and electrons interact with each other through long-range electromagnetic forces. The electromagnetic interactions of groups of charged particles are often coherent, leading to collective modes of plasma behavior. This collective interaction of charged particles, a many-body problem, is the essence of the field of plasma physics.

Roughly 99% of the matter in the universe is in a plasma state. Plasmas can exist over a large range of temperatures and densities. For example, interstellar space contains plasmas with densities of less than one ion or electron per cubic meter at temperatures exceeding 1,000°C. In contrast, plasmas created by intense laser compression of micropellets achieve densities up to $10^{26}$ ions or electrons per cubic centimeter at temperatures exceeding 10,000,000°C. The understanding and application of such diverse plasmas is a Los Alamos core competency.

P-24 is composed of a diverse technical staff with expertise in plasma physics, plasma chemistry, atomic physics, and laser and optical science. The group uses both on-site and off-site experimental facilities to address problems of national significance in inertial and magnetic fusion, high-energy-density physics, conventional defense, environmental management, and plasma-based advanced or green manufacturing. Our agenda includes basic research in the properties of energetic matter and applied research that supports the principal Laboratory mission of reducing the nuclear danger. The pursuit of this agenda entails the physics of plasmas over a wide and diverse range of conditions, as shown in Fig. 1.

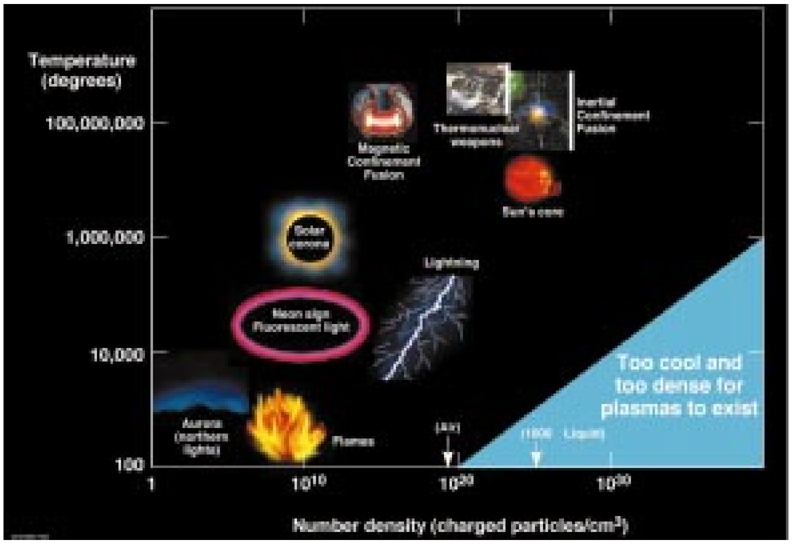


***Fig. 1** As this illustration of the plasma state shows, the physics of plasmas entails a wide and diverse range of conditions.* **(Illustration courtesy of Dr. Don Correll, Lawrence Livermore National Laboratory)**

## Atlas

Atlas, a 24-MJ, 30-MA advanced pulsed-power facility scheduled for completion in late 2000, will be capable of imploding 40-g cylindrical liners at velocities of up to 20 km/s on timescales of several microseconds. Such implosions will produce material pressures of several tens of megabars, magnetic fields up to 1,000 T, material strain rates of $10^6$ $s^{-1}$, and highly coupled plasmas of nearly solid densities at temperatures of several electron volts. P-24 is involved in several aspects of the physical design of Atlas, specifically in defining and designing the experimental agenda for the first several years of operation, developing advanced diagnostics to be fielded on these experiments, and fielding experiments on Pegasus and Ranchero to prepare for Atlas operation.

P-24 has responsibility for the design, testing and fabrication of the Atlas power-flow system that transports energy from energy storage capacitors to the load. The power-flow channel is the most difficult component to design because the radial forces on the conductors increase inversely as the square of radius. Thus, significant damage to hardware in the region near the load is expected. As presently envisioned, the power-flow channel will be insulated with solid-dielectric to minimize the relatively large inductance in this region. The conductors will be diskline feeding a conical line connected to the load. The conductors will be held in place during the shot by steel weights placed in contact with both transmission lines.

The Atlas Physics Design Team, which includes P-24 staff, has developed a list of the varieties of experiments to be fielded in the first 200 shots (the first two years of Atlas operation). Included on this list are experiments to investigate Rayleigh-Taylor mix, Bell-Plesset deformation of the liner, friction at high relative velocities, on-hugoniot EOS measurements, calibration of the NTS nuclear impedance-matching EOS experiments, multiple-shock EOS, quasi-adiabatic compression of materials, release isentropes, high-strain-rate phenomena, dense-plasma EOS and transport, hydrodynamics and instabilities in strongly coupled plasmas, magnetized target fusion (MTF), and high magnetic field generation. Specific experimental campaigns are now being designed to determine the diagnostic and experimental configuration requirements. As part of a successful Laboratory Directed Research and Development (LDRD) proposal, we will be assisting in the development of a variety of advanced diagnostics to be fielded on Atlas, including linear and nonlinear optical techniques, x-ray diffraction, photoelectron spectroscopy, and flash neutron resonance spectroscopy. All of these techniques are well developed for steady-state measurements, and the development effort lies in adapting them to the dynamic Atlas environment. A number of shots in FY99 have been allocated in the Pegasus imploding liner facility and the Ranchero explosively driven pulsed-power program to develop Atlas diagnostic techniques, explore liner behavior under Atlas conditions, and test certain physical components of the Atlas system.

*Fig. 2 Laser driver of the Trident laser facility.*

## Trident Laser Facility

Trident is the multipurpose laboratory at Los Alamos for conducting experiments requiring high-energy laser-light pulses. As a user facility, it is operated primarily for inertial confinement fusion (ICF) research, high-energy-density physics, and basic research. Features include flexible driver characteristics and illumination geometries, a broad resident diagnostic capability, and flexible scheduling. A dedicated staff maintains and operates the facility and assists visiting experimenters. Target fabrication is available through the Laboratory's Target-Fabrication Facility.

The principal resource at Trident is the laser driver (Fig. 2). It employs a neodymium-doped, yttrium-lithium-fluoride (Nd:YLF) master oscillator and a chain of Nd:phosphate glass-rod and disk amplifiers in a conventional master-oscillator, power amplifier architecture. The oscillator output pulse is temporally shaped, amplified, split into two beams, amplified again, frequency-doubled, transported, and focused onto the target. A third beamline can be used as an optical probe or to provide an x-ray backlighting capability. Its pulse can be either 100 ps in length or the same length and shape as those of the main drive beams. Although the third beamline is normally operated at 527 nm, it can also be operated at 1,054 nm or 351 nm (fundamental and third harmonic output, respectively). The third beam can be timed to become active before or up to 5 ns after the main drive beams. The output of the master oscillator may also be frequency-broadened and "chirped" before amplification to allow compression to subpicosecond pulse lengths.

The main high-vacuum target chamber is a cylinder approximately 150 cm long and 75 cm in diameter. Single- or double-sided illumination of targets is possible through several 20-cm-diameter ports on each end of the chamber. More than 40 smaller ports are available for diagnostic instrumentation. Individual targets are inserted through an airlock. The target insertion and positioning mechanism provides *x-y-z* and rotation adjustment under computer control with 1-µm linear and 0.01° angular resolution. The three-axis target-viewing system has a 20-µm resolution. The chamber is fitted with a Nova standard six-inch manipulator (SIM) to accept all SIM-based instruments for checkout, characterization, or use. Trident is located in an area of the Laboratory that can accomodate both unclassified and classified research.

Optical diagnostics include illumination and backscattered-light calorimeters, backscattered-light spectrometers, and high-bandwidth (5-GHz) and streak-camera-based power monitors. Target x-ray emission is monitored by filtered, photoconductive diamond detectors and an x-ray streak camera with <10-ps resolution. Gated, filtered x-ray images covering 1 ns in 16 images are provided with 80-ps resolution by a Nova standard gated x-ray imager. Various filtered x-ray power and spectral diagnostics can be installed as needed. These cover the energy range of 0–35 keV. Static x-ray pinhole cameras are also available. Most optical and target diagnostics are available for either the main target chamber or the ultrahigh-irradiance chamber.

Trident is available to Laboratory and outside experimenters. The quality of proposed research and its relevance to Laboratory missions are major criteria in determining what experiments are fielded. Trident is operated by P-24 as a user facility that principally supports Inertial Fusion and other programs in the Nuclear Weapons Directorate. It is funded through and operated for the ICF Program Office. The resources of the Laboratory's Target-Fabrication Facility, operated by the Materials Science and Technology (MST) Division, are also available to assist experimenters in designing, fabricating, and characterizing targets for Trident experiments.

In May 1998, a second target bay and target chamber were added to the Trident Facility as part of the High Energy Density Experimental Laboratory addition to the Trident building. The target chamber was acquired from the University of Rochester Laboratory for Laser Energetics where it was the target chamber used on the original Omega 24-beam laser system. The chamber, focusing lenses, transport optics, frequency conversion crystals, and experimental diagnostics from the original Omega system were all acquired from the University of Rochester in April 1998. A ten-inch manipulator (TIM), which is the new ICF standard for positioning diagnostics, will be installed on this chamber soon, and the facility will be available for check out and testing of TIM-based diagnostics.

Over the next few years, we will upgrade the Trident laser using refurbished Nova laser components. This upgraded laser system is based on a multipass architecture with Nova 31.5-cm disk amplifiers. This new laser system would eventually have eight beamlines operating at 700 J each in 1 ns at 351 nm. Construction of the first phase (two beams) has begun. This new facility will use the Omega 24-beam target chamber, allowing great flexibility in illumination geometries. As envisioned, the Trident upgrade will remain a very flexible, high-shot-rate facility that provides a staging capability to higher energy facilities such as Omega, the future National Ignition Facility (NIF), and Sandia National Laboratory's Z pulsed-power machine. The proposed Trident Upgrade will also greatly enhance present Trident capabilities in performing experiments in laser-matter interactions and other fundamental science topics, and it will serve as an attractor for high-quality scientific research relevant to ICF and stockpile stewardship.

## Inertial Confinement Fusion

The ICF program at Los Alamos is a principal component of the national ICF program. The national program is focused on the goal of achieving thermonuclear ignition in the laboratory, one of the grand scientific challenges of the 20th century. This goal is part of the broader mission to provide scientific knowledge, experimental facilities, and technological expertise to support the DOE Stockpile Stewardship Management Plan for nuclear weapons. In pursuit of the ICF mission, P-24 designs, diagnoses, executes, and analyzes the results from experiments at high-energy laser facilities worldwide. P-24 partners with other Los Alamos groups that focus on theory, modeling, and target fabrication to execute the program, with the ultimate goal of understanding laser-matter interaction physics.

***Fig. 3 Aerial view of the National Ignition Facility, a state-of-the-art, $1.2B laser facility presently under construction at Lawrence Livermore National Laboratory. This facility will be a key component in the national ICF program, which aims at achieving thermonuclear ignition in a laboratory setting.***

NIF, a state-of-the-art, $1.2B laser facility presently under construction at Livermore (Fig. 3), will be the world's most powerful laser by far and the principal focus of the national ICF program. Los Alamos and Sandia have been participating with Livermore in the design and construction of special equipment for this immense laser facility, which will be ~300 ft × 500 ft upon completion and operate at an energy of 1.8 MJ. Design and construction of the facility is currently 35% complete. In the early 1990's Los Alamos scientists collaborated with other members of the National ICF Program to establish the functional requirements and primary criteria that are the basis for this facility. Los Alamos scientists and engineers have been participating since FY93 in the conceptual, preliminary, and detailed designs of a variety of NIF subsystems. Currently, Los Alamos engineers are finishing the detailed design and beginning the engineering (fabrication, installation, and procurement) of four major subsystems: the target chamber service system, the roving mirror diagnostic assembly, the deformable mirror support structure, and the periscope (which includes the mirror support, plasma electrode Pockels cell, and polarizer support structures). P-24 is also a principal participant in the NIF Joint Central Diagnostic Team, and P-24 personnel have worked on the conceptual design for the 351-nm power and energy diagnostics and the preliminary design of a time-resolved x-ray imaging system. In addition, P-24 personnel have been involved with the management of this collaborative project.

NIF is a flexible laser, capable of greatly advancing both the ignition and weapons-physics missions. NIF is designed to drive a capsule filled with deuterium-tritium fuel to thermonuclear ignition by one of two distinct methods: direct or indirect drive. Direct drive involves the implosion of a capsule that is directly illuminated by the laser beams. Indirect drive involves laser illumination of the interior walls of a cavity (called a hohlraum) that contains the capsule. The hohlraum converts the laser energy into x-rays, which illuminate and implode the capsule very symmetrically, analogous to the process of baking an object evenly in an oven. Since both methods have different potential failure modes, both are being pursued to increase the likelihood of achieving ignition on NIF.

Considerable challenges face us in preparation for achieving fusion ignition on NIF, which will first be attempted using indirect drive. These challenges include developing novel diagnostic methods and instruments, and improving our understanding in several scientific areas, including laser-plasma instabilities, hydrodynamic instabilities, hohlraum dynamics, and dynamic properties of materials. P-24 has contributed significantly in all of these areas with target-physics experiments using present lasers: Nova at Livermore, Omega Upgrade at the University of Rochester, and Trident at Los Alamos.

P-24 personnel have devoted considerable effort to studying laser-plasma parametric instability (LPI) processes. We have focused on Raman and Brillouin scattering, and on the novel phenomena of beam deflection by plasma flow. LPIs pose a significant threat to ignition hohlraums because they could potentially scatter most of the laser light, decreasing both the drive efficiency and the capsule illumination symmetry. During the past two years, P-24 has pursued a dual-track strategy of complementary experimental campaigns at Nova and Trident. P-24 researchers have applied the extensive Nova diagnostic suite on ignition-relevant hohlraums designed at Los Alamos, the most NIF-like plasmas ever made.

These LPI experiments on Nova are now complete, and data analysis is proceeding to complete our extensive LPI database, which will guide theoretical modeling and future experiments. The database includes calorimetry and time-resolved spectrometry of the scattered light, time-gated images of the scattered light within the target plasma, and other measurements that confirm the target plasma conditions in the hohlraum design. The scattered light measurements were done as important plasma parameters (*e.g.*, plasma density, ion species, and laser parameters like intensity, $f$ number, and beam smoothing) were changed one at a time. So far, this approach has allowed us to identify qualitatively important trends in LPI processes of NIF-like plasmas, constrain emerging theoretical LPI models, and assess the threat of LPIs to ignition prior to NIF construction.

Our LPI experimental thrust has shifted to the application of new state-of-the-art capabilities and diagnostics on Trident long-scale NIF-relevant plasmas to allow more detailed measurements and comparisons of theory with experiment. These new capabilities include a nearly diffraction-limited interaction beam capable of the intensity range relevant to parametric instabilities in ignition-hohlraum plasmas. Imaging Thomson scattering now yields direct measurements of the spatial profile of important plasma parameters, such as electron density and temperature, ion temperature, plasma-flow velocity, and the location of the electrostatic waves responsible for laser scattering. We now can thoroughly benchmark the radiation-hydrodynamic codes used to design the plasma conditions in the first place. The coupling of these recent diagnostics with reflected and transmitted beam diagnostics, such as those previously implemented at Nova, already has allowed unprecedented studies of the time evolution of parametric instabilities and beam deflection. In the longer term, the plan is to exploit the fact that the single-hot-spot Trident system is sufficiently small for direct modeling by an emerging suite of codes incorporating new theoretical models. From these comparisons, we hope to develop simplified “reduced-description” models that are suitable for NIF-scale plasmas.

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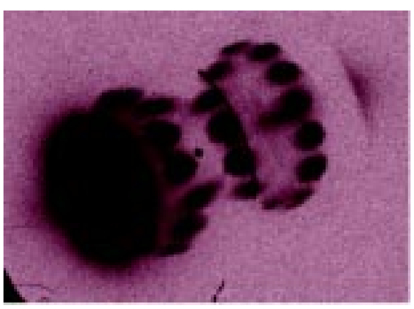

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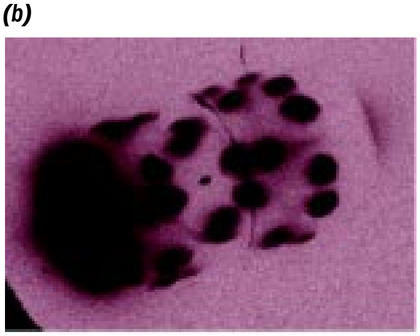


***Fig. 4** Cylindrical hohlraums with single-ring (a) and two-ring (b) configurations of beam spots. Experiments with such hohlraums are the first step in developing “beam phasing,” in which many beams are arranged into multiple beam cones to control implosion symmetry.*

P-24 personnel have had important successes in advancing our understanding and capabilities in hohlraum dynamics. We have extended our understanding of and capabilities with cylindrical hohlraums, which will be used in the first indirect-drive ignition attempts on NIF. On Nova, we demonstrated control of beam deflection and its effects on capsule-illumination symmetry by spatial smoothing of the laser-beam. On Omega Upgrade, we collaborated with Livermore researchers in an important experimental series that exploited the larger number of Omega beams. As many as 40 beams were arranged into multiple beam cones (Fig. 4). These experiments constituted a first step in the development of “beam phasing,” in which beams were arranged into multiple beam cones, forming multiple rings of beam spots on the inner surface of a cylindrical hohlraum. Beam phasing will be necessary on NIF to tune both the time-integrated and time-dependent capsule-flux asymmetry by adjustment of the beam pointing and the power history in the different rings. These initial experiments have demonstrated our ability to model hohlraums incorporating multiple beams cones. We have also demonstrated unprecedented time-integrated illumination symmetry using an advanced hohlraum design developed at Los Alamos for deployment at Omega Upgrade, featuring a spherical radiation case and laserentrance holes in a tetrahedral arrangement (see Fig. 5). Since the unique mission of Omega Upgrade is direct drive, the beams enter the target chamber in a spherical geometry, a non-optimal arrangement for cylindrical hohlraums. But tetrahedral hohlraums in Omega Upgrade can use all 60 beams and drive higher energy implosions than cylindrical implosions, an added advantage to the improved symmetry.

There was significant activity and progress in the area of hydrodynamic instability. In the NIF, capsules with cryogenic fuel will have to be compressed to large convergence ratios (about 30) in order to ignite. Convergence is ultimately limited by hydrodynamic instability. To date, laser-driven capsule implosions have only achieved moderate convergence ratios (below 10), due at least in part to the known limitations of past laser systems, including Nova. During the past two years, P-24 fielded the initial attempts at implosions of double-shell capsules, first at Nova and subsequently at Omega Upgrade, in tetrahedral hohlraums.

Double shell capsules are an attractive alternative for NIF because they do not require cryogenics for ignition, although they are potentially more hydrodynamically unstable than single-shell capsules. The improved illumination symmetry in tetrahedral hohlraums now allows reasonable attempts at high-convergence implosions with double-shell capsules prior to deployment of the Omega Upgrade cryogenics system.

The first experimental series with Omega Upgrade capsules did not reach the predicted performance. Potential culprits have been identified and further investigation is proceeding. P-24 hydrodynamics research has also focused on cylindrical implosion targets, which are much easier to diagnose than capsules and yet retain important convergent effects (see the research highlight on this topic in Chapter 2). P-24 researchers have completed a study of the nonlinear growth of multi-mode perturbations in x-ray-driven cylindrical targets due to the ablative Raleigh-Taylor (RT) instability on Nova, and the results were in good agreement with theoretical modeling. Moreover, there was spectacular success in deploying direct-drive cylindrical implosions of Los Alamos design, capable of significantly higher RT growth than the indirect-drive design. Our initial single-mode RT experiment showed significantly lower growth factors than predicted, and additional investigation is proceeding.

In collaboration with other groups in the Laboratory's Physics, Applied Theoretical and Computational Physics (X), and Dynamic Experimentation (DX) Divisions, as well as Oxford University, the University of California at San Diego, Sandia, and Livermore, P-24 is using the Trident laser system to pursue studies of the dynamic properties of materials that are of interest to the ICF Program and

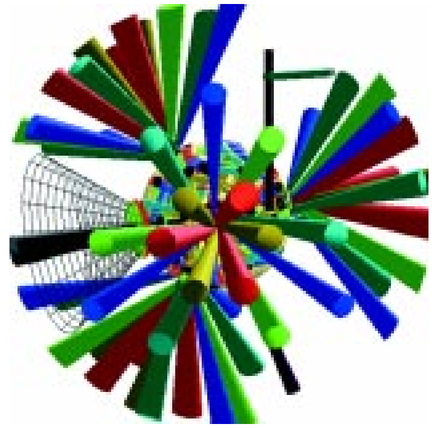


***Fig. 5** 3-D schematic of a spherical radiation case with tetrahedral symmetry. This design allows for use of all 60 Omega Upgrade laser beams to drive a higher-energy implosion with improved symmetry.*

to weapons science. The Trident laser is used to drive high-pressure (from tens of kilobars to several megabars), temporally shaped shocks into condensed materials under study. Separate beams of the laser system can be used to create accurately synchronized, powerful x-ray and optical pulses that are used for probing the shocked material. Using this configuration, the group has developed new diagnostic methods such as transient x-ray diffraction (TXD). TXD has in turn been used to measure the dynamic properties of phase changes in materials.

The methods developed on Trident are being applied to materials of central interest to ICF, such as beryllium. One of the ultimate goals of this research program is detailed characterization of beryllium alloys such as beryllium-copper. These materials will be used as the ablator in advanced, Los Alamos-designed ignition capsules with superior hydrodynamic stability. Exact determination of the melt transition in these materials is crucial for predicting their hydrodynamic behavior during implosion. The temporally resolved measurements of solid-solid phase transitions that have already been demonstrated are an important precursor to measurement of melt dynamics.

P-24 personnel deployed several diagnostics and support systems for the ICF program. The biggest effort was associated with Omega Upgrade. An optical Cassegrain microscope, which fits in the standard ten-inch reentrant diagnostic manipulator, was fielded successfully and is already in use for Los Alamos campaigns. This instrument has added the capability to diagnose the propagation of shocks (and thus hohlraum radiation temperature) by detecting the shock breakout from a calibrated material sample. P-24 has also deployed the Omega “bang-time” diagnostic, part of the customary diagnostic suite for capsule implosions. The Kirkpatrick-Baez x-ray microscope previously deployed by P-24 at Omega was the beneficiary of a major upgrade. A target metrology station for Omega, engineered and deployed by P-24, has proven to be another success.

Closer to home, a local x-ray calibration facility has been set up to test various x-ray diagnostics under development in P-24 and to maintain existing ones. This facility should eliminate the wasteful use of laser system shots for such purposes. Looking towards our future on NIF, P-24 completed the conceptual design for the time-resolved x-ray imaging system, a Phase-1 NIF diagnostic. Moreover, we have demonstrated successfully the rapid-pad-polishing technique for NIF optical fabrication, which is now moving to the production stage.

### High Energy Density Experiments in Support of Stockpile Stewardship

P-24 performs laser and pulsed-power-based experiments that are intended to enhance understanding of the basic physical processes that underlie nuclear weapons operation. In collaboration with weapons designers and other theoreticians, these experiments are designed to address issues in areas such as radiation hydrodynamics, fluid instabilities, shock wave physics, and materials science. The experiments use the Trident laser and the Pegasus pulsed-power machine at Los Alamos, and also larger facilities including the Nova laser, the Omega laser, the Helen laser at the Atomic Weapons Establishment (AWE) Laboratory in the United Kingdom, and Sandia's Z pulsed-power machine. We have formed strong world-wide collaborations in the disciplines central to high energy density physics.

Current work in the group includes

- nonlinear fluid instability studies driven by a variety of pressure sources;
- imploding liner studies of the basic nature of material friction;
- propagation of structured shocks in a variety of media (Fig. 6);
- development of transient x-ray diffraction for the study of solid phase changes, plastic flow, and other materials phenomena;
- study of the implosion of cylindrical and spherical shells with various defects;
- study of high-energy, laser-based x-ray radiography for diagnosis of fluid instability experiments; and
- study (in collaboration with Sandia) of the fundamental properties of beryllium that are of interest to inertial fusion and other applications.

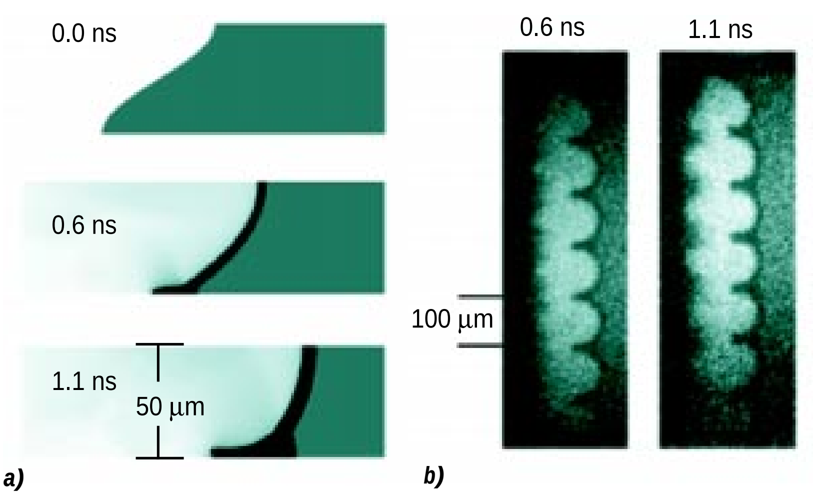



***Fig. 6** A simulation of a half-wavelength segment (a) and experimental data for five to six full wavelengths (b) of a temporally shaped shock propagating in brominated polystyrene. This exeriment was designed and fielded at the Nova laser by Los Alamos personnel.*

In the pursuit of our research, we are developing advanced diagnostic measurement systems. This work includes research on very high-resolution x-ray imaging that will be applied to hydrodynamic, shock-wave, and materials experiments. We also pursue research in fundamentally improving the quantitative analysis of temporally gated x-ray imaging.

## Magnetic Confinement Fusion

Magnetic fusion energy research, and its associated science, is an important constituent of P-24's plasma physics portfolio. We are capitalizing on the recent strategic shift in national fusion research priorities, to increase the emphasis on innovative fusion confinement approaches. To that end, P-24 is working with the Los Alamos Magnetic Fusion Energy (MFE) Program office to develop new low-cost concepts for fusion energy. Central to this effort is magnetized target fusion (MTF), a truly different fusion concept intermediate in density between traditional magnetic fusion and inertial fusion. We specifically propose to form and preheat a compact toroid target plasma using well-established techniques, and then compress this target plasma with imploding liner technology developed by DOE defense programs (Fig. 7).

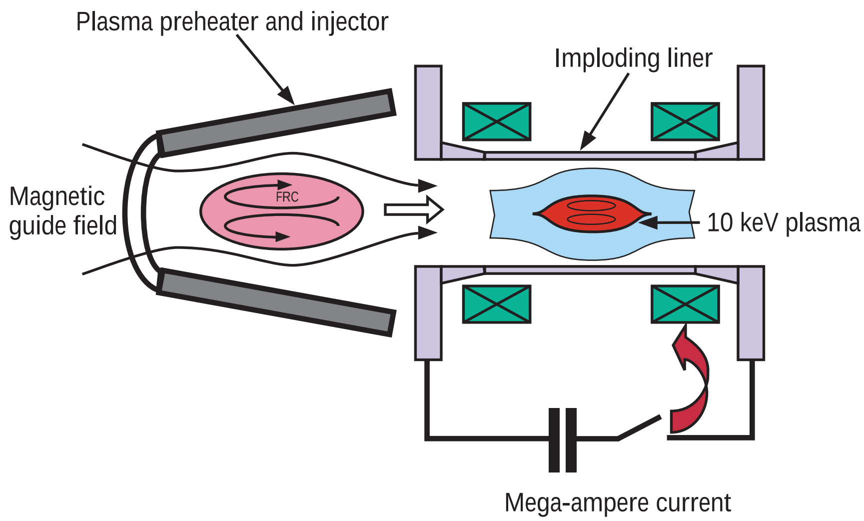



***Fig. 7 A schematic of the Los Alamos MTF experiment. A dense, field-reversed configuration (FRC) target plasma is formed and translated into a 10-cm-diameter, 30-cm-long aluminum liner (flux conserver). The liner is subsequently imploded to a final diameter of 1 cm at velocities up to 1 cm/μs. The compressed plasma will reach 5 to 10 keV under adiabatic compression if losses can be kept low.***

Three technical considerations explain why research in the MTF density regime is important. First, fusion reactivity, which scales as density squared, can be increased by many orders of magnitude over conventional MFE. Second, all characteristic plasma scale-lengths decrease with density. Hence, system size is naturally reduced at a high density. Third, magnetic insulation greatly reduces the required power and precision to compressionally-heat a plasma to fusion-relevant conditions compared with ICF, and brings the pulsed-power requirements for adiabatic plasma heating within reach of existing facilities. The future path for engineering development of MTF as an economic power source is less well-defined than for the more mature approaches of MFE and ICF. However, a number of possibilities are being discussed, and our research program will include scoping studies to identify the most promising approaches. If successful, MTF will achieve high performance fusion conditions with soon-to-be-realized pulsed-power facilities such as Atlas.

Historically, Los Alamos has had significant involvement in developing alternate approaches to fusion. This precedent has guided our development of collaborative programs with Columbia University, the University of Washington, Livermore, and the Princeton Plasma Physics Laboratory. In all four collaborations, we employ our engineering, physics, and diagnostics expertise to aid the development of exciting fusion concepts.

Our collaboration with Columbia University produced high-power amplifiers to suppress magnetohydrodynamic activity in the high-beta (HBT-EP) tokamak experiment. In collaboration with the University of Washington, we are developing a high-power modulator to drive plasma current in a field-reversed configuration (FRC) experiment by means of rotating magnetic fields. FRCs belong to the compact toroid class of fusion approaches and promise efficient magnetoplasma confinement with simple, compact reactor configurations. Our University of Washington collaboration current-drive experiments are central to the notion of steady-state FRC operation.

Two new experimental collaborations are also underway. We are joining with Livermore to take the next step in sustained spheromak confinement research. The Sustained Spheromak Physics Experiment, under construction at Livermore, was designed to achieve high plasma performance under quasi-steady-state conditions. Los Alamos expertise, developed over years of research on the Compact Torus Experiment spheromak, will be an important contributor to the success of this effort. We are also joining the national research team on the National Spherical Torus Experiment under construction at the Princeton Plasma Physics Laboratory. This experiment will investigate the confinement properties of very low-aspect-ratio tokamaks with a view to achieving efficient (high-beta) confinement in a compact toroidal system.

## Applied Plasma Technologies

P-24 develops and uses advanced plasma science and technology to solve problems in defense, the environment, and industrial manufacturing. The group has achieved international status and recognition in this pursuit, including two recent R&D 100 awards. The first R&D 100 award, presented in 1996, was in recognition of the development of the PLASMAX system, which takes advantage of plasma sheath properties combined with mechanical vibration to rapidly and effectively clean semiconductor wafers without water or other liquid solvents. The second R&D 100 award, presented in 1997, recognized the efforts of a multidisciplinary group (both Laboratory and industrial personnel) in the initial commercialization of plasma source ion implantation (PSII) (see the discussion below and the research highlight on this topic in Chapter 2). Major technology-development and program elements within the group include the following:

### *Atmospheric-Pressure Plasma Jet*

A nonthermal, uniform-glow discharge at atmospheric pressure in a cylindrical cavity with high gas-flow rates produces reactive radicals and metastables persisting for fractions of a second at atmospheric pressure. These reactive species remove surface contaminants and films, providing a new means of cleaning objects and substrates (Fig. 8). Current programs include chemical and biological decontamination for the neutralization of chemical agents on surfaces and graffiti removal.

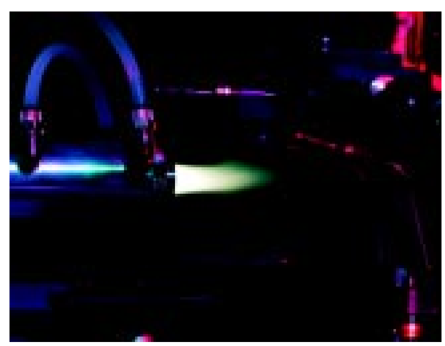


***Fig. 8 The atmospheric pressure plasma jet in operation, with a reactive gas stream exiting from the source.***

### Intense, Pulsed Ion Beams and Accelerated Plasmas

Several promising applications of intense ion beams and pulsed accelerated plasmas have emerged in the past few years. These include processing of materials, including surface modification through rapid melt and resolidification, ablative deposition for producing high-quality coatings, and nanophase powder synthesis; production of intense neutral beams for the next generation of tokamaks; and intense, pulsed neutron sources for the detection of nonmetallic mines, neutron radiography, neutron resonance spectroscopy, and spent nuclear fuel assay. We are nearing completion of two devices that address these applications: an intense, repetition-rated ion accelerator known as the continuous, high-average-power microsecond pulser (CHAMP), and an accelerated plasma source known as the magnetoplasma processing tool (MPT).

CHAMP will produce a 12-kA, 250-keV, 1-μs ion beam from any gas puffed into its magnetized anode. This beam is ballistically focused to a 25- to 100-$cm^2$ spot, resulting in energy fluxes of tens of $J/cm^2$—enough to ablate the surface material. Lower energy fluxes can be obtained by working out of the focal plane. Due to the low gas-loading of this anode and the design of the accelerator, this technology is capable of being operated at 30 Hz, although as constructed CHAMP will operate at about 1 Hz. Calculations suggest that by hitting a tritiated metal target with a deuteron beam, a microsecond pulse of $2 \times 10^{12}$ DT neutrons could be produced in a device sufficiently portable to be fielded at experimental sites throughout the Laboratory.

The MPT produces a 10- to 30-kV accelerated plasma of any gas, and is capable of delivering up to 4 $J/cm^2$ over 1,000 $cm^2$ in a 200 μs pulse at an electrical-to-directed energy efficiency of up to 50%. Like CHAMP, this device can be transported easily. Applications include rapid, wide-area treatment of materials, such as etching and crosslinking of polymer surfaces.

### Plasma-Source Ion Implantation and Cathodic Arcs

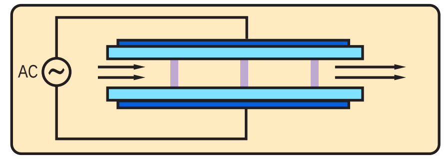
PSII is a non-line-of-sight method for implanting ions from a plasma into a target (usually, but not necessarily a conducting material) to achieve beneficial surface modifications. Typically, ions in plasma produced from a gaseous precursor are used, but cathodic arc technology allows metal ions to be implanted as well. PSII may be seamlessly combined with plasma-based surface-coating technologies to form highly adherent, relatively thick (many microns) coatings of materials such as diamond-like carbon (DLC) and ceramic metal oxides. Past and present programs include development of plasma-implanted and plasma-deposited erbia coatings in support of the weapons surety program; molten-plutonium-resistant coatings for near-net-shape casting molds;

highly adherent refractory coatings for wear- and corrosion-resistant gun barrels for the Army; and plasma-based surface treatment and adherent coatings for industrial tooling. The industrial support for research and development (R&D) in this area is part of a National Institute of Science and Technology (NIST) Advanced Technology Program with more than a dozen industrial partners.

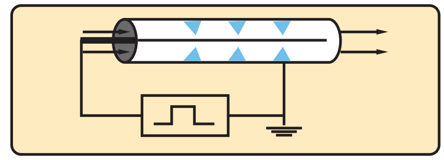
### *Silent-Electrical and Pulsed-Corona Discharges*

Nonthermal plasmas (NTPs), sometimes called nonequilibrium or "cold" plasmas, are characterized by conditions in which the various plasma species are not in thermal equilibrium—that is, electrons, ions, and neutral species have different temperatures, with the less massive electrons having the highest temperature (*e.g.*, 1–10 eV). Such plasmas are good sources of highly reactive oxidative and reductive species and plasma electrons. Via these reactive species, one can direct electrical energy into favorable gas chemistry through energetic electrons. NTPs can be easily created by an electrical discharge in a gas. Two example NTP reactors, a silent-discharge plasma reactor and a pulsed-corona reactor, are shown in Fig. 9. Both use the mechanism of transient electrical discharge streams to produce energetic electrons and associated active species in the process gas.

We are applying atmospheric-pressure NTP processing to hazardous-chemical destruction, pollution control, and chemical synthesis. The hazardous-chemical-processing and pollution-control applications range from the treatment of hydrocarbon and halocarbon compounds (many solvents) that are entrained in soil and water or are emitted as stack gases, to the treatment of oxides of nitrogen (nitric oxide, in particular) in flue and engine-exhaust gases. Our work has spanned the regimes of bench-scale studies to actual field demonstrations of this technology. Our more recent interests are directed toward the synthesis of higher-order hydrocarbon fuels from methane. Research in the area of NTPs represents a fusion of the fields of electrical-discharge physics, plasma chemistry, and pulsed power.




Silent discharge plasma reactor (dielectric-barrier discharge)



Pulsed corona reactor

***Fig. 9** Schematic drawings of silent-discharge plasma and pulsed-corona reactors. These reactors use an electrical discharge in a gas to create nonthermal plasmas that can be used for such purposes as destroying hazardous chemicals, controlling pollutants, and synthesizing chemicals.*

## Further Information

For further information on all of P-24's projects, refer to the project descriptions in Chapter 3. Some of our major achievements are also covered as research highlights in Chapter 2. These include our work at the Trident facility, our current PSII developments, cylindrical and spherical implosion research at Nova and Omega, and development of an infrared imaging bolometer for use in fusion plasma research.