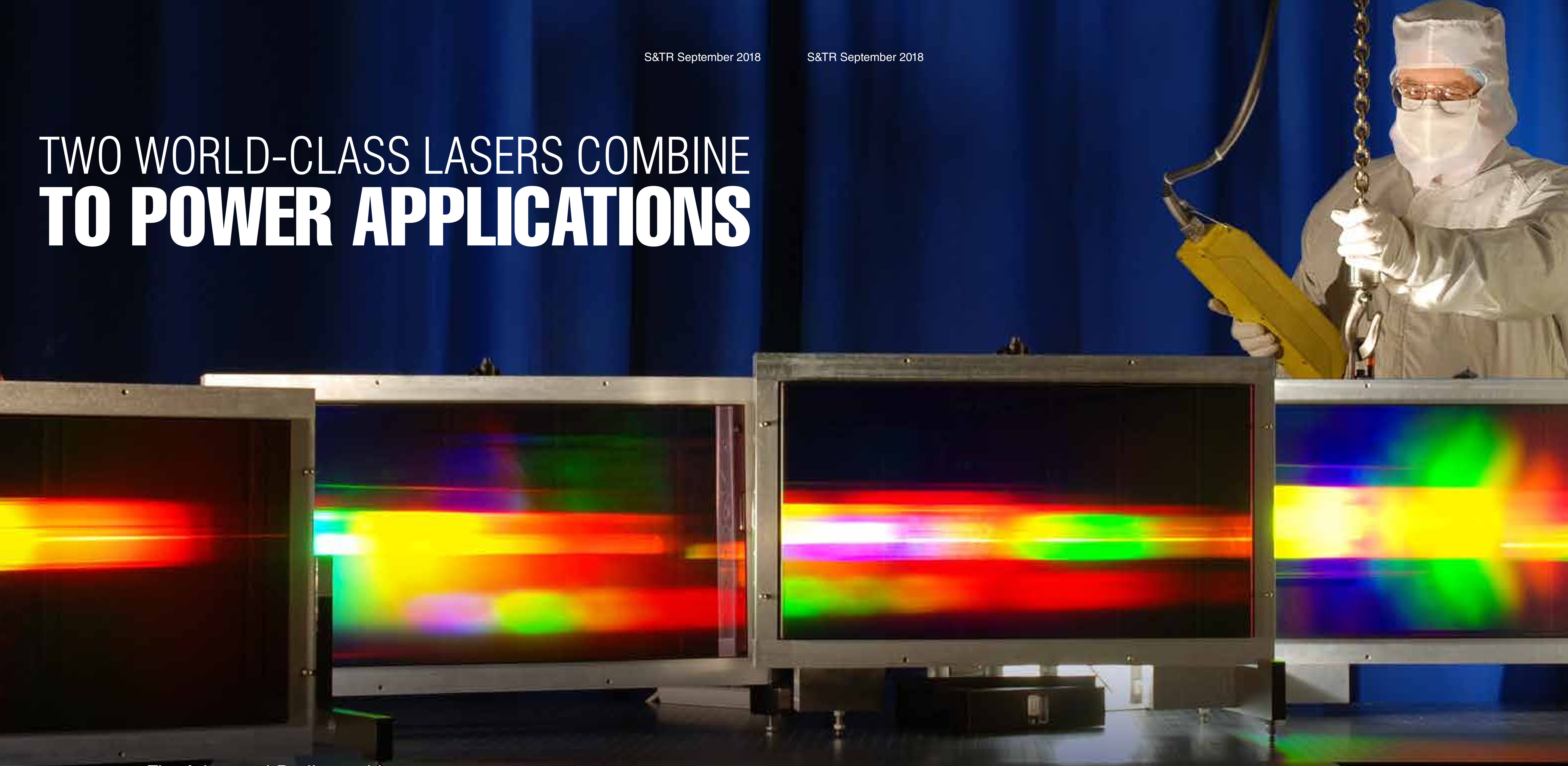
TWO WORLD-CLASS LASERS COMBINE
TO POWER APPLICATIONS



The Advanced Radiographic Capability laser shines high-intensity light on extreme conditions inside the National Ignition Facility.

PREVIOUSLY, Livermore's Petawatt laser was built into a beamline of the Nova laser. Today, the Advanced Radiographic Capability (ARC) laser follows the same "laser within a laser" strategy. The most energetic short-pulse laser in the world, ARC resides within the National Ignition Facility (NIF)—the most energetic of all the world's lasers. Both operate simultaneously during experiments, and synchronizing the enormous amounts of energy released by the billionths-of-a-second NIF with the trillionths-of-a-second ARC is nothing short of an operational wonder.

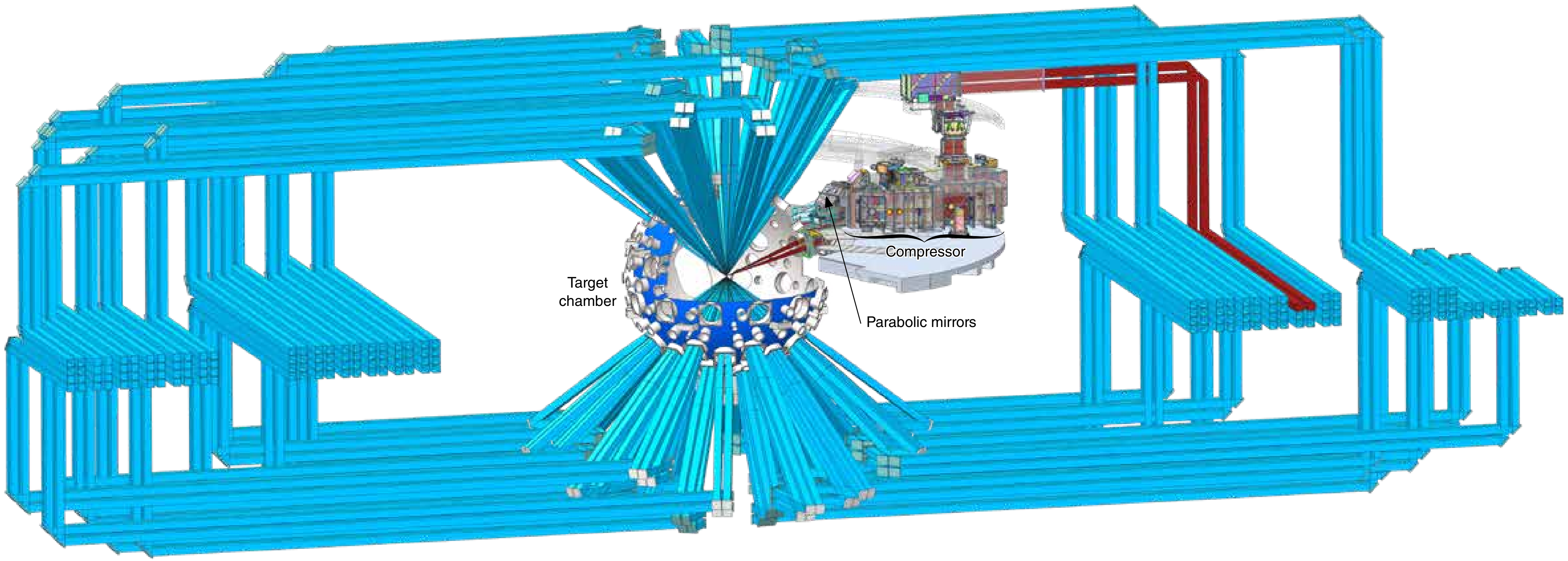
A major challenge for researchers using NIF to study high-energy-density (HED) plasmas and inertial confinement fusion (ICF) for the Stockpile Stewardship Program has been examining the inside of the target to ensure that implosion is occurring in a highly spherical manner. (See *S&TR*, July 2015, pp. 3–14.) The greater the asymmetries and shape swings as the target compresses, the more performance is compromised. Different Laboratory missions require different target materials, and instabilities can adversely impact experiments in a multitude of ways,

A technician prepares four diffraction gratings for installation inside the Advanced Radiographic Capability's (ARC's) compressor vessel. The gratings squeeze each ARC beamlet into a high-energy, ultrashort laser pulse.

including reduced fusion yield in the case of ICF. As they strive to improve symmetry and robustness, researchers require a diagnostic tool that can reveal the shape of the target as it compresses, and increasingly ARC is being used to unlock these never-before-measured extremes. “ARC opens up an avenue that we didn’t previously have at NIF,” says David Martinez, a Livermore physicist researching HED science and who heads the team developing ARC for HED backlighting. “As we use NIF’s main laser to drive our targets to higher densities, pressures, and compressions, we now have in ARC a diagnostic that can see through these objects, look at perturbations, and probe further in time.”

X rays image a target’s interior in a manner similar to a doctor taking an image of a patient’s body. To block the x rays from parts of the body not being examined, the doctor has the patient wear a lead-filled apron. However, if lead can stop x rays during a doctor’s visit, how can NIF image the interior of something far denser? For many applications, NIF accomplishes this feat by diverting a small subset of its main laser beams from the experimental target to a separate metal foil target for generating probing x rays of much higher energy. Yet even these NIF-driven x rays are not of high enough energy or flux to probe the target during the final stages of implosion or to see details in lightweight materials such as hydrogen isotopes, an important fuel for ICF. ARC seeks to overcome these limitations.

Since being commissioned in December 2015, ARC has been used in at least 64 shots, including platform-development firings. Beyond backlighting applications, ARC enables exciting new and diverse research into exotic matter and particle generation. Potential studies range from better understanding the nature of the most energetic events in the universe to improving methods for treating cancer.



A diagram shows ARC beamlet path (red) moving from the National Ignition Facility’s (NIF’s) main beamlines to the compressor, parabolic mirrors, and into the target chamber (in cutaway). Some beamlines have been omitted to show ARC’s beam path.

Powerful Backlighters

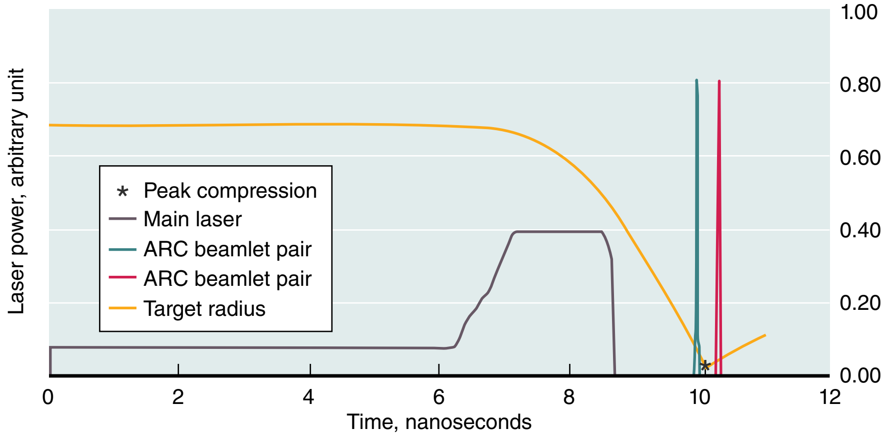
In an ICF experiment, up to 192 main laser beams of NIF are fired into the interior of a hohlraum, a 1-centimeter-long, hollow gold cylinder. Inside the hohlraum is a spherical target capsule 2 millimeters (mm) in diameter and filled with a fuel comprising deuterium and tritium, both isotopes of hydrogen. From interactions between the laser beams and the gold, a flux of x rays is formed from all around the curved hohlraum wall, bathing the target capsule in an “oven” of x rays. The high flux of x rays, in turn, transforms the capsule’s outer shell into a rapidly expanding, high-temperature plasma, blasting like a rocket engine. The massive force accelerates the shell inward at a speed reaching over half a million miles per hour, compressing the target capsule to a sphere only 0.05 mm in diameter, or 40 times smaller than its original size. Squeezed at such enormous pressure, the fuel inside the capsule becomes more than 22 times denser than lead, and the resulting central hot spot reaches a temperature exceeding 100 million degrees Celsius. Under these conditions, the hydrogen isotopes undergo nuclear fusion. This is how the energy of a star is born inside NIF.

With early backlighter technology, x rays were generated by up to eight of NIF’s main laser beams focused onto a small metal foil, delivering as much as 60 kilojoules (kJ) of energy at an intensity of 2×10^{16} watts per square centimeter (W/cm^2). The x rays formed through laser–material interaction in a manner similar to when NIF’s beams strike the hohlraum’s gold wall. The specific energy depends on laser beam characteristics and the material comprising the foil. Metals such as iron, zinc, and molybdenum all emit different line spectra of x rays when irradiated, yielding photon energies ranging between 6 and 18 kiloelectronvolts (keV). However, this x-ray approach allowed researchers to peer inside the target capsule only during the early stages of compression, before the implosion became too dense. (In general, the higher the energy of an x ray, the better the penetration. The more x rays generated, the better the signal-to-noise ratio and clearer the x-ray radiographs of the target.) Furthermore, these backlighters relied primarily on the target capsule’s atoms absorbing x rays by a process called photoelectric absorption, where the amount of absorption depends on the element and its density—the higher the atomic number (Z) and the more atoms there are, the more x rays are absorbed. With flesh and bone, for example, x rays pass readily through flesh, which is made of lighter elements than bone, which blocks many more x rays.

Explaining the drawbacks of these early backlighters, Martinez says, “Hydrogen is the lightest element and is mostly transparent to x rays even at higher densities. The shell compressing the fuel is higher density, sometimes a metal. So, what we typically observed using those backlighters was only the shell around the compressed fuel. In addition, an x-ray burst of up to 15 keV is produced by the hot, dense core at peak compression. For the measurements not to be overpowered by x rays from this flash, the backlighter needs to produce stronger x rays, but most of the early backlighters produced x rays below 15 kiloelectronvolts.”

Synergy between Lasers

Incorporating the ARC laser into NIF’s main laser enables x rays of higher energy and flux to greatly exceed previous diagnostic capabilities. ARC uses two beamlines from a single NIF quad (a group of four beamlines). In addition, ARC does not use the entire beamline but instead only the main and power amplifiers, with a specialized front end injecting the



The timings of the NIF main laser and two ARC beamlets are shown in relation to peak compression of a subscale target.

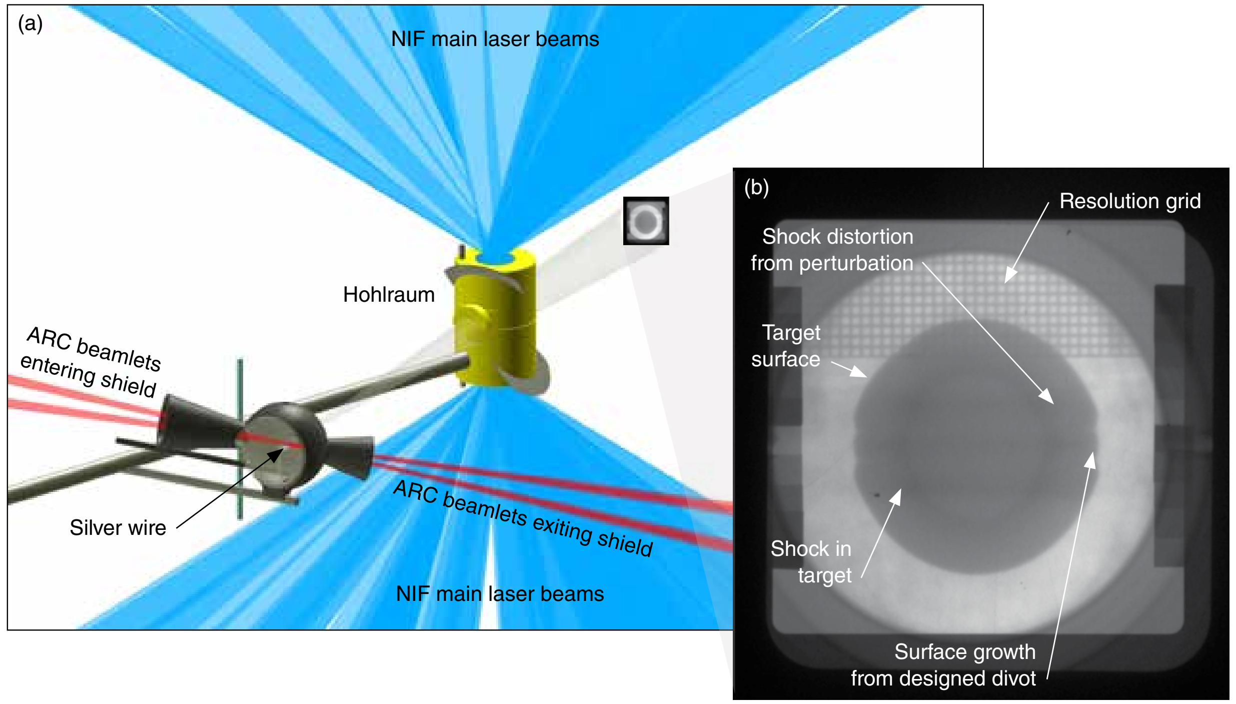
initial laser. In a process called chirped-pulse amplification, ARC’s beamlets are stretched in time to spread out the laser energy and injected into the two beamlines in pairs travelling side by side through the amplifiers, after which the four beamlets are diverted from NIF’s main laser beam path into a compressor for temporal recompression to provide a shorter pulse. The four resulting short-pulse beamlets are then each independently focused with parabolic mirrors and directed to the target through a dedicated port into the target chamber. (See *S&TR*, December 2011, pp. 12–15.)

The main NIF laser beams are converted from an infrared wavelength of 1,053 nanometers (nm) to an ultraviolet wavelength of 351 nm for better coupling to the hohlraum target. However, ARC bypasses this step both to mitigate the energy loss that occurs during wavelength conversion and to take advantage of target physics in which the conversion of laser energy to high-energy x rays is improved at longer laser wavelengths. ARC also differs in pulse duration. Whereas NIF runs on the order of nanoseconds (ns), or billionths of a second, ARC clocks in about 1,000 times faster, at 1.3 to 38 picoseconds (ps), or trillionths of a second.

“The ARC beamlets propagate down the beamlines more than 60 nanoseconds before NIF’s main laser fires because the longer path through the compressor delays the beamlets arriving at target chamber center,” explains Dan Kalantar, senior target area scientist and co-leader of the integrated product team that helps ARC users develop their target platforms. “For example, setting the timing to view an implosion at 16 nanoseconds after arrival of the main laser beams at target chamber center requires ARC beamlets to precede the main laser by close to 50 nanoseconds. Keep in mind that for some shots, ARC beamlets are typically staggered in pairs with a separation of only 200 picoseconds.” Because of the extremely high energy of both NIF’s main laser and ARC, shielding the target and backlighter from each other and from the side effects of the lasers, plasmas, and other forms of radiation is critical to minimize unintended interactions.

High-Energy Backlighter

Each of ARC’s four beamlets can deliver more than 1 kJ of energy at an intensity exceeding 10^{17} W/cm^2, yielding x rays with photon energies of 10 to 200 keV. “For high-energy backlighting, we use the point projection radiography technique in conjunction with ARC to produce bremsstrahlung radiation,” explains Martinez. “This process generates an x-ray band of about 10 to 100 kiloelectronvolts.” In a typical HED setup to study high-*Z* materials, an ARC beamlet focuses to a spot of approximately 0.06 mm by 0.12 mm on a 0.01-mm-diameter metal wire positioned side-on to the oncoming laser light, creating a bright source of hard x rays. The diameter of the wire determines the size of the x-ray source—the narrower the wire, the higher the resolution—so that small details in the target can be captured.



(a) An illustration shows the setup for the high-energy ARC backlighter experiment. (b) The work yielded a radiograph of a driven, spherical target.

Although the process is still in development, results from recent experiments are highly positive. Martinez says, “We took radiographic images of a driven HED target—a copper foam ball—to see where the shock and ablation surfaces were as a factor of time, something that was very difficult to do with the previous backlighters. In addition, researchers were able to track the shock surface all the way to convergence, which is important because it reveals how well our drive is coupling to the target. We obtained the data we wanted, and they looked good.” Now, the team is optimizing the high-energy backlighter and expanding its use to larger systems and to conditions later in time. Because ARC’s beamlets can be focused independently and fired at slightly different times from one another, ARC could enable not just one radiograph but up to four. “We’d like to take multiple radiographs during the same experiment,” says Martinez. “With more beamlets, you can separate them out in space and time, almost like a movie.”

Compton Radiography Backlighting

With ICF targets, radiographs more suited to imaging low-*Z* materials can be obtained using Compton scattering rather than traditional photoabsorption. Riccardo Tommasini, a plasma physicist working on ICF and leading Compton radiography development, explains, “Compton scattering originates from collisions between an x ray and a bound or free electron. In contrast to photoelectric absorption, which scales as the third power of *Z*, Compton scattering is sensitive only to the electron density of the material.” This difference makes Compton scattering ideal for probing the dense but low-*Z* deuterium–tritium fuel in ICF implosions near peak compression. Tommasini adds, “The radiograph reveals a deficit in x rays traveling through the material, largely because x-ray photons are scattered away from the line of sight by Compton scattering. Being relatively independent of photon energy, broadband detection and the continuum emission of hard x rays of approximately 100 kiloelectronvolts can be used to filter out the x-ray flash produced by the implosion.”

For backlighting using Compton radiography, two pairs of ARC beamlets fire into a shielding cone to generate x rays by striking gold wires contained within plasma mirrors.

A Compton radiography backlighter involves two ARC beamlets hitting an approximately 1-mm-long, 0.025-mm-diameter gold wire. The wire tip faces the target, acting as a point source. Because the x ray pulse closely follows the ARC pulse in duration, the time resolution is 30 ps or less, depending on laser pulse duration. A filter in front of the detector blocks x rays of less than 40 keV, so that x rays generated by the capsule’s hot spot cannot affect the radiographs. An experiment typically uses two Compton radiography backlighters to generate two independently timed radiographs 100 to 200 ps apart.

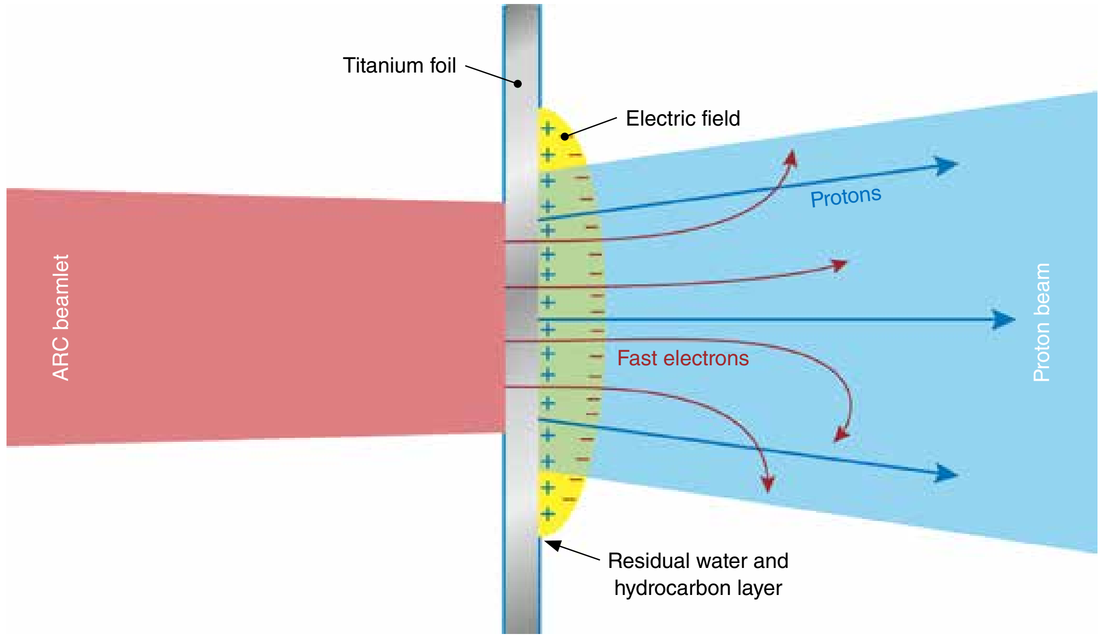
Any experiment using ARC faces alignment challenges similar to those of other types of high-energy backlighting. Having the ARC beamlets hit exactly the right spot ensures that the maximum amount of laser energy transfers to heating the gold wire that generates the x rays. An improvement to backlighter design positions the gold wire at the bottom of a V-shaped plastic wedge. Acting as a plasma mirror, the wedge not only concentrates the laser light but also mitigates fluctuations in beamlet pointing by redirecting misaligned laser light onto the wire. “Using this plasma mirror around the wire, we have generated backlighters with x-ray yields approximately three times greater than with a bare wire,” says Tommasini. He adds, “Recently, we have tested a parabolic-shaped plastic plasma mirror, which has produced even brighter x-ray emissions from the wire by achieving a higher concentration of laser light.” These backlighters have achieved record-high conversion efficiencies of laser energy into x-ray energy, with the potential of generating radiographs with higher reproducibility and signal-to-noise ratio. This achievement represents a remarkable step for several applications requiring efficient x-ray sources and will be used to generate Compton radiographs of ICF targets at cryogenic temperatures.

Proton Generation

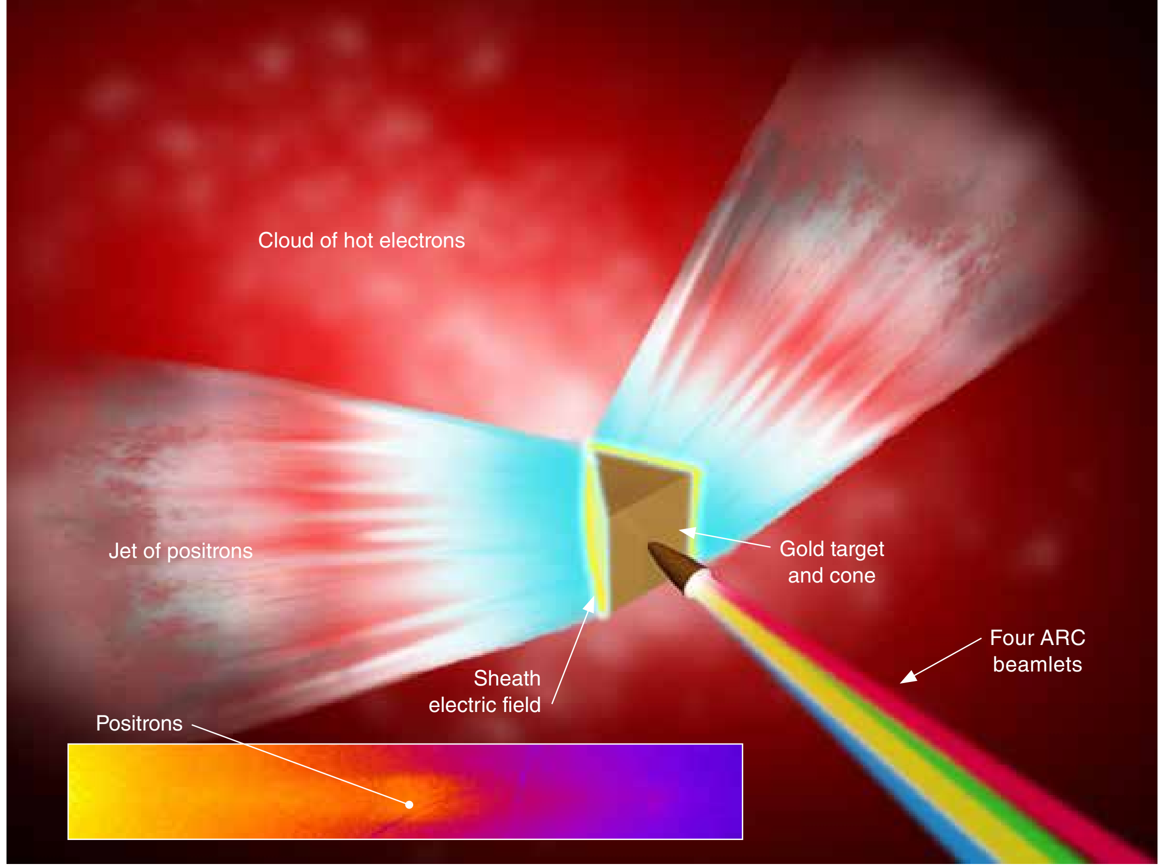
In addition to generating x rays for backlighting, ARC has proven highly promising for producing high-energy, high-flux particle beams. In a project funded by the Laboratory Directed Research and Development (LDRD) Program, plasma physicist and principal investigator Tammy Ma researches proton acceleration. She says, “Because of ARC’s high energy and multipicosecond pulse lengths, we’ve found new mechanisms for accelerating protons to high energies that are efficient and generate enormous numbers of energetic protons.” In two experiments conducted earlier this year, all four ARC beamlets fired simultaneously into different quadrants of a 0.033-mm-thick titanium foil. With pulse lengths of 10 ps and 1.3 ps—the latter the shortest pulse ever delivered by ARC—total laser energies of 2.4 kJ and 1 kJ, respectively, were achieved. The experiments also reached the highest peak power ever achieved by NIF—more than 700 terawatts (trillion watts).

Upon striking the foil, laser beams quickly ionize the material and accelerate many of the electrons into “fast” electrons that travel rapidly through the foil, exiting out of the rear surface and creating a strong electric field in the foil. Protons from the residual water and hydrocarbon layer on the back of the target then want to follow, and they accelerate in a jet perpendicular to the surface. In these initial ARC experiments, the proton energies peaked at over 18 megaelectronvolts (MeV), and the conversion efficiency—the amount of laser energy converted to proton energy—reached nearly 5 percent, producing a tremendous proton yield of approximately 80 joules (J). “We’d like to use protons to radiograph hohlraums,” says Ma. “Protons are a charged particle sensitive to electric and magnetic fields, whereas x rays are not. X rays can probe density but not fields.” Protons thus generated have a continuum of energies and so travel at different speeds, enabling temporal radiographs showing how fields change over very short timeframes.

In addition to radiography, proton beams can be used for heating in different NIF applications and other diverse uses. Ma says, “Proton therapy for tumor and cancer treatments would benefit. Protons can deposit their energy very accurately. Unlike chemotherapy or energetic x rays, which irradiate a lot of healthy tissue, protons could target a specific depth.” Other types of particles accelerated by this mechanism will be investigated on ARC soon. For instance, a deuteron beam or other heavy-ion beam can be generated by changing the foil material. Directing this initial particle beam at a secondary target of lithium or beryllium could then produce a neutron beam. Beams of neutrons and other particles can offer researchers more ways to analyze matter under extreme conditions.



Proton beam generation has applications not only in scientific experiments but also medical therapies such as tumor treatment. In the process, an ARC laser beamlet interacts with a thin metal foil to generate fast electrons. These electrons pass through the foil and create an electric field that accelerates protons from the residual layer to form a proton beam.



(top) Four beamlets, guided by the gold cone, strike a triangular solid target. The cone focuses and increases the laser intensity needed to generate relativistic electrons that interact with the gold atoms to produce gamma rays by bremsstrahlung. (bottom) The raw image from a particle spectrometer shows an orange band corresponding to positrons, with a peak number at around 10 megaelectronvolts (MeV) and maximum energy of about 25 MeV. (Illustration by Mark Meamber.)

Matter–Antimatter Plasma

For some ARC applications, using multiple beamlets to strike different parts of a target is sufficient. However, producing matter–antimatter plasma consisting of electron and proton pairs requires more laser intensity than even four separate beamlets can supply. Plasma physicist Hui Chen leads an LDRD project that is using ARC to study, in a laboratory, the most energetic processes in the universe. She says, “Matter–antimatter pairs are abundant in space—as in gamma-ray bursts near black holes and in neutron star collisions—and are an almost fundamental component of matter in the universe.” (See *S&TR*, April 2016, pp. 12–14.)

As part of NIF’s Discovery Science Program, researchers used ARC laser light to generate hot electrons inside a triangular-prism-shaped gold target. The electrons collide with the gold atoms to produce gamma rays, with each massless photon transforming into a positron and electron as governed by Einstein’s famous equation, $E = mc^2$. Some hot electrons depart from the target at relativistic speed and create very strong electric fields near the exit surfaces, which then attract and accelerate jets of positrons out of the target to mix with a surrounding plasma cloud of hot electrons. The relativistic speed of the positrons and electrons assures very little chance of the two interacting to instantaneously annihilate each other. Instead, the particles coexist as matter–antimatter pairs for a brief moment in time.

The experiments used a specially designed parabolic-shaped gold cone to effectively focus the four ARC beamlets—each 10 ps and 550 J. The resulting electron spectrum indicated a total laser intensity exceeding 4×10^{18} W/cm^2 onto the target based on scaling from prior experiments. Two high-energy, high-flux positron jets formed, peaking in number at an energy of 10 MeV and reaching a maximum energy of 25 MeV. Refinement of the process is underway to further increase laser intensity and improve positron yield.

Regarding future directions of pair plasma research, Chen says, “With a denser pair beam, we could send the beam into a plasma created by the main NIF laser to simulate astrophysical pair jets flowing though galactic plasma. In addition, once we have a sufficient number of positrons—about 10 times more than now—we may be able to conduct positron radiography of compressed capsules.” The gold parabolic plasma lens that proved vital to this experiment could also be applied to other uses requiring higher laser intensities or beamlet collimation.

As ARC’s applications advance, not only will each project build on its new knowledge, but the capabilities across all of ARC and NIF will be bolstered through cross-pollinating innovations. This progress will benefit the entire facility, its world-class laser inside a laser, and the broad range of Laboratory missions supported by this diverse research.

—Dan Linehan

Key Words: Advanced Radiographic Capability (ARC), backlighting, Compton scattering, electron–positron pair, fusion, high-energy laser, high-energy-density (HED) science, high-*Z* material, inertial confinement fusion (ICF), Laboratory Directed Research and Development (LDRD) Program, matter–antimatter pair, National Ignition Facility (NIF), petawatt, plasma, proton generation, relativistic electron, short-pulse laser, Stockpile Stewardship Program, x ray.

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