The confirmation in January 2001 by the United Nations' Inter-Governmental Panel on Climate Change that the rise in global temperatures in the past 50 years has resulted from human activity must stand as a clear warning to us all. It reminds us that the burning of fossil fuels and the consequent rise in greenhouse gas emissions is becoming a major problem for the environment. Clearly, the quest for alternative sources of electricity that are both clean and safe is becoming increasingly urgent for society—and remains a major challenge today. Renewable alternatives such as solar, wind, and tidal power schemes appear attractive in terms of safety, but are not without environmental and ecological costs—and are unlikely to fully satisfy the world’s energy requirements in the coming decades.

Controlled thermonuclear fusion promises a source of electricity that is environmentally benign and ecologically friendly. It requires isotopes of hydrogen, such as deuterium, whose natural abundance is so plentiful that it will allow an almost limitless supply of fuel from the oceans. Developing nuclear fusion into a useful source of electricity has taken a lot longer to achieve than originally envisaged, however. The principal obstacle is that nuclear fusion requires temperatures of tens of millions of degrees centigrade so that the hydrogen isotopes have sufficient kinetic energy to overcome the repulsive coulomb force between the ions so that the strong nuclear force can fuse them into new elements. Clearly, no vessel can withstand direct physical contact with matter at such temperatures—the heated fuel must be confined in some manner to prevent this.

Two possibilities have been pursued to overcome this hurdle. The magnetic confinement fusion approach is based on the concept of confining fusion fuel by strong magnetic fields for many seconds at a density and temperature necessary to satisfy the criteria for energy gain. The process is analogous to that of a conventional furnace—fuel is constantly injected to replenish the spent fuel and the energy is released on a continuous basis. Alternatively, the laser-fusion scenario involves compressing the fuel to ultra-high density, and fusion occurs so rapidly that the dense fuel does not have time to disassemble. The laser fusion approach is similar to that of the internal combustion engine—the fuel is periodically compressed and a “spark” is delivered that allows the fuel to explode, and the release of
energy then drives the pistons.

The physics community's confidence that the obstacles to controlled thermonuclear fusion can be overcome has led to the design of machines that will test physics issues for both routes to controlled fusion. The final decision on where and whether to construct the International Thermonuclear Experimental Reactor is close at hand. The physics base of the alternative route—laser fusion—has developed to the extent that the construction of multi-megajoule lasers such as the National Ignition Facility (NIF; Livermore, CA) in the United States and the Laser Megajoule (Bordeaux, France) is already underway.

**LASER fusion**

The invention of the laser promised the capability of depositing huge energy densities onto matter. By the early 1970s, laser pulses could be focused onto a target with intensities above $10^{15}$ W/cm², which is equivalent to electric fields in the laser focus of $1 \times 10^9$ V/cm. Clearly, any atom placed within a field of this magnitude will be ionized within one or two oscillations of the laser electric field. This means that the bulk of the laser pulse interacts not with solid-density material but with a plasma. Researchers quickly realized that because of the enormous energy density, laser plasmas could be heated to millions of degrees centigrade at near solid density. These densities and temperatures generate pressures of millions of atmospheres for the duration of a nanosecond laser pulse.

These pressures generated by laser plasmas can be used to compress a shell containing deuterium-tritium fuel to ultra-high densities by spherical convergence. The plasma generated on the outer surface of the spherical shell expands rapidly into the surrounding vacuum, imparting momentum to the remaining shell such that it implodes with high velocity. The implosion stops only when the internal plasma pressure (i.e., the density and temperature product of the compressed fuel) prevents further compression.

When the laser pulse generates the plasma on the surface of the shell, it drives a shockwave through the shell before the material starts to accelerate. But here is a contradiction—a strong shock will always heat material behind the shock front, whereas to compress matter to high densities, a low temperature is required. To start the fusion process, a number of carefully timed shocks of increasing amplitude are allowed to collapse simultaneously at the center of the fuel to generate a hot spark while minimizing the shock heating of the fuel. Provided a sufficient number of alpha-particles (generated during the fusion of deuterium-tritium in the spark) are stopped in the surrounding cold fuel, localized heating will occur and a fusion burn wave can propagate through the rest of the cold dense fuel, leading to controlled energy gain. Balancing the contradictory requirements of low-entropy compression and spark formation is, however, expensive energetically and demands the use of the multi-megajoule-class lasers now under construction.

**FAST ignition**

In 1994, Max Tabak and colleagues from the Lawrence Livermore National Laboratory (LLNL; Livermore, CA) proposed separating the two processes of compression and heating. In this scenario, a petawatt laser is used to provide the hot spark. Copious numbers of energetic electrons are accelerated to mega-electron-volt energies during the petawatt laser/matter interaction. These electrons slow down in the compressed material, thereby heating the material on a timescale so short that the compressed matter does not have time to disassemble.

This idea stirred immediate and intense interest around the world for two reasons. First, the approach removes the requirement to drive a series of shocks through the compressed fuel to form the spark at the center, allowing more fuel to be compressed for the same laser drive energy. Since the fusion-energy gain depends only on the amount of fuel present, once the spark has been formed, the energy gain rises by a factor of 300 rather than the factor of 15 obtained with indirect holraum drive, as expected from the NIF.

Second, if more fuel can be compressed during the implosion, then the in-flight aspect ratio (the ratio of the thickness of the remaining shell and fuel during the acceleration phase of the implosion to the initial shell radius) can be much smaller than for the conventional scheme. This, in turn, substantially reduces the implosion symmetry needed to assemble the fuel to high density, because the growth rate of...
petawatt level. It is only with the very recent advent of picosecond, petawatt-class lasers that fast ignition became feasible. The fast ignition scenario, as originally discussed theoretically, requires three separate sets of laser pulses. Nanosecond pulses from a first laser would compress the deuterium-tritium fuel in the normal way. Shortly before peak compression, $10^{17}$ to $10^{19}$ W/cm$^2$ picosecond pulses from a second laser would form a channel in the plasma atmosphere. During this “hole-boring” phase, the critical surface would be pushed toward the dense core of plasma. When the implosion stopped, a 10-ps ignitor pulse from a third petawatt laser would pass into the channel formed by the second laser pulse. The huge energy density of the focused light would accelerate copious numbers of electrons at the critical surface to energies similar to the ponderomotive potential energy of the pulse—1 MeV or more. The electrons would then propagate into the dense plasma where they would be stopped. This process would lead to strong local heating and the ignition of a fusion burn wave.

The target featured a hollow gold cone inserted into a hollow deuterated plastic shell. The cone kept a channel completely clear of plasma exhaust as the shell imploded and the short-pulse laser interacted with the wall of the cone at its tip. The cone so that the mega-electron-volt electrons did not have far to propagate.

We demonstrated significant enhancement of fusion products by three orders of magnitude (from $10^4$ to $10^7$ neutrons without and with the heating pulse on). The results confirmed that the high heating efficiency observed previously was maintained as the short-pulse laser power was increased to the petawatt level.

MOVING forward

Work at RAL this year has concentrated on two very important and necessary objectives related to these new observations: confirmation of the result at an independent laboratory using similar laser conditions, and, perhaps more important, understanding energy transport in dense plasmas. The latter is vital to making the quantitative predictions needed to scale the results to full-scale ignition and energy gain. The UK-Japan team has been joined by U.S. experts from LLNL, the University of Rochester (Rochester, NY), General Atomics Corp. (San Diego, CA), and the University of California at Davis.

The idea of the campaign was to use the full 1.0 kJ nanosecond-duration IR output power of RAL’s Vulcan laser to drive the compression in six-beam cubic symmetry (see figure on page 13). At stagnation, the compressed plasma is heated using the Vulcan 100 TW beam. The stagnation time was measured at 3 ns after the peak of the drive pulse, and the compressed areal density achieved experimentally was 40 mg/cm$^2$ for a 6-µm wall thickness, 500-µm-diameter shell irradiated with 900 J of center-frequency illumination (1053 nm) $\omega_0$ in a 1-ns pulse.

These measurements are in good agreement with hydrodynamic simulations that include radiation transport. The areal-density measurements were made by the proton radiography technique pioneered by the group at QUB, and by 2-D x-ray imaging using a titanium $K_\alpha$ x-ray source and a spherically curved crystal pioneered by the American team. Preliminary analysis of the experiments indicated a substantial reduction of mega-electron-volt electrons escaping to the electron spectrometer when the compressed plasma was formed at the tip of the cone. Analysis of electron transport in cold, dense copper plasmas by x-ray $K_\alpha$ spectroscopy indicated substantial lateral energy transport. Analysis of the data is ongoing and will be presented at the American Physical Society’s Division of Plasma Physics meeting (27–31 October; Albuquerque, NM).

Future work will need to concentrate on energy transport in warm, compressed matter so that quantitative predictions of fusion energy gain can be made. The OMEGA Enhanced Performance upgrade (University of Rochester; see oemagazine, August 2003, page 9) will deliver 2.6 kJ of short-pulse energy when construction is completed in 2007. The FIREX project in Japan is designed to deliver a 10 kJ PW pulse at around the same time. In France, an additional 4 kJ PW beam will be added to the 60 kJ LiL laser (the prototype for the Laser Megajoule), also in 2007. All three systems may get close to equivalent conditions to energy breakeven by using deuteron-deuterium fusion reactions. The race is on— and we await the outcome with great anticipation. 

Peter Norreys leads the physics group at the Central Laser Facility, CCLRC Rutherford Appleton Laboratory, Chilton, UK. Phone: +44 1235 445300; fax: +44 1235 445888; e-mail: P.A.Norrays@rl.ac.uk.

References