Phenomenal progress has been made in high power laser systems in the last few years. The National Ignition Facility (NIF) under construction in California is a 192-beam laser system that will be able to produce 1.8 megajoules of ultraviolet laser energy. Dr Ed Moses, the Director of the NIF, writes about the centre due to open in the summer of 2009. Later in the article, Professor Mike Dunne, Director of the UK’s Central Laser Facility, tells of European plans for creating fusion energy.

Large laser systems could one day provide carbon-free energy from hydrogen fusion. Work now under way is paving a path from current laser technology to a fully-functioning laser-fusion power plant. The NIF, now nearing full operation at Lawrence Livermore National Laboratory in California, will be the world’s most energetic laser with an energy output of 1.8 megajoules. The NIF expects to begin the first ignition experiments using inertial confinement fusion in 2010. This will be the culmination of a 50-year quest for fusion ignition and thermonuclear burn in a laboratory setting. The European Union is now considering a proposal to build a next-generation research facility called HiPER (High Power Laser Energy Research Facility).

Although significant improvements in laser-repetition rate and efficiency in high energy lasers are needed to achieve an operating laser fusion power plant, there is great confidence in the future success of this mission.
Fusion Energy

One of the most important promises of hydrogen fusion is its long-term potential to produce clean, safe and abundant energy. Nuclear fusion drives the sun, and it drives most of the energy in the universe. The fusion of deuterium and tritium is the simplest fusion process — as deuterium is readily available from seawater. Lithium, a relatively abundant resource, can be transformed to tritium and thus supplies of fuel for fusion energy could be virtually limitless. An added bonus is that a fusion reactor would produce no greenhouse gases or other air pollutants and would generate significantly shorter-lived and less hazardous waste than current operational fusion reactors.

While it is unlikely that any single technology will be able to meet the planet’s growing energy needs, fusion — creating a miniature sun on the Earth — could well be among the most promising approaches to providing large amounts of energy without causing irreparable damage to the global environment. It is a daunting technical challenge with a very high potential payoff.

There are two major approaches to fusion energy: magnetic confinement fusion and inertial confinement fusion. The International Tokamak Experimental Reactor (ITER), a US$12 billion magnetic fusion facility now under construction in France with the participation of Europe, Asia and the United States. Magnetic fusion faces many difficult technical challenges, but it is currently the focus of much international attention and support. This article focuses on the other major approach — laser-driven inertial confinement fusion.

The immense size and energy of NIF are necessary because inertial confinement fusion involves extraordinarily high temperatures — some 300 to 400 million kelvins during fusion “burn” — pressures of 30,000 billion atmospheres, and densities of more than 1,000 g/cm³, 100 times denser than lead.

The immense size and energy of NIF are necessary because inertial confinement fusion involves extraordinarily high temperatures — some 300 to 400 million kelvins during fusion “burn” — pressures of 30,000 billion atmospheres, and densities of more than 1,000 g/cm³, 100 times denser than lead.

Energy for the Future

Several sources point to a doubling in the developing world’s energy demands from 2000 to 2050. If those plants are primarily powered by carbon-generating fossil fuels, the consequences will have a major impact on global warming. Most large power plants generate about one gigawatt. To meet the world’s growing need for energy, fusion ignition — providing large amounts of energy must be generated in a fusion ignition and burn, and energy-gain in the laboratory. Its success occurred just a few weeks after Theodore Maiman demonstrated the laser for the first time at Hughes Aircraft in Malibu, California, in 1960. Almost immediately, visionary scientists at Lawrence Livermore National Laboratory recognised the possibility of using lasers to implode and ignite deuterium-tritium fuel and produce fusion energy.

Early laser fusion work was classified and was little known outside the national strategic laboratories in France, the UK, the former Soviet Union and the United States. In a seminal paper in 1972 by John Nuckolls and his colleagues from Livermore, this work was published for the first time at Hughes Aircraft in Malibu, California, in 1960. Almost immediately, visionary scientists at Lawrence Livermore National Laboratory recognised the possibility of using lasers to produce fusion energy. NIF nearing completion

By the middle of 2009, construction of the NIF will be completed — today more than one-half of its beamlines are already operational. The target chamber is about 12 metres high with square openings for the laser beamlines and round openings for diagnostic equipment. In the interior is an arm that precisely positions and holds the target (see photo on preceding page).

NIF is a remarkable engineering and technology success story. Karlsruhe scientists and laser physicists, working with engineers, have designed a facility that contains 6,400 large (micron-scale) optics, 30,000 small optics and 60,000 control points. The optics and other components are assembled in such a way that every part of the NIF is available to a beamline that must operate with a maximum efficiency and reliability. The laser system produces some 500,000 energy pulses for NIF each year, with each pulse lasting less than a second.

Although NIF is referred to as a “laser,” it is not a run-of-the-mill laser. Before NIF’s laser light reaches its “target,” it is converted from infrared (1,067 nanometres) to ultraviolet (351 nanometres), a more effective wavelength for achieving fusion. This process is about 50% efficient, so nearly four megajoules of infrared energy must be generated in order for NIF to meet its design requirement of 1.8 megajoules in the ultraviolet. This is at least 60 times more energy than any other laser in existence. The immense size and energy of NIF are necessary because inertial confinement fusion involves extraordinarily high temperatures — some 300 to 400 million kelvins during fusion “burn” — pressures of 30,000 billion atmospheres, and densities of more than 1,000 g/cm³, 100 times denser than lead. At those densities, materials do not act “normally” — their strength and many other properties are completely different and difficult to predict by theory.

Newton and Einstein meet

For its initial experiments, NIF will employ the indirect-drive approach to inertial confinement fusion. The deuterium and tritium in the NIF target will be cryogenically cooled to the triple point of hydrogen — about 20 kelvins, nearly absolute zero. The hohlraum, the gold capsule containing the target (see Figure 1), can be likened to an oven. The energy from the NIF’s lasers heats the hohlraum to millions of degrees in a few nanoseconds, generating a uniform bath of soft X-rays that ablate (blow off at very high velocities) the outside wall of the beryllium target. The explosion of the fuel capsule’s outer surface forces a rocket-like implosion, consistent with Newton’s third law, which symmetrically compresses the hydrogen gas in the target. The resulting fusion reaction could release many times more energy than the amount of laser energy required to initiate the reaction, all in accordance with Einstein’s formula E=mc².
PREPARING THE GROUND
To meet these challenges, all of the structures holding NIF’s mirrors and lenses were designed with extreme stability in mind. At the beginning of the project – before any hardware had been designed – precise vibration measurements of the ground at the site were made. The engineering team characterised every local vibration source including pumps, motors and transformers, and estimated their effect on each of the most sensitive laser components – generally the laser mirrors. The budget for vibration (<1 Hz) and drift (<1 Hz/s) was met using this detailed model, and tests on the prototype beamline demonstrated performance at, or better than, the 50 micrometer requirement. Critical beampath component endures (generally for mirrors and lenses), many weighing tens of tonnes, were located to a precision of 100 microns using a rigorous engineering process for design validation and an installed verification. This information was then provided to the design team, which engineered structures that were both sufficiently soft and had sufficient damping that the response of the structures to both ground vibration and the anticipated vibration from building equipment would meet overall stability requirements. The design solutions included thick concrete foundations, lightweight steel platforms and extensive vibration isolation mechanisms at all sources of vibration. Exhaustive structural analyses were conducted to convince the engineers of the feasibility of the design, and a comprehensive construction plan was executed to ensure that all design details were meticulously implemented. As a result of this integrated and comprehensive end-to-end programme, NIF has been able to achieve all of its stability requirements on a routine basis.

SIGNIFICANT CHALLENGES REMAIN
Like magnetic fusion, the use of inertial confinement fusion to produce energy presents significant challenges. At the outset, NIF’s lasers will be able to fire only about once every 10,000 seconds to prevent distortion of the laser glass. The electrical efficiency of the NIF beamlines is less than 1%, so only a small portion of the energy used to power the lasers actually gets to the target chamber. A viable fusion energy plant would have to fire 5 to 10 shots a second – 100,000 times faster than NIF – with an electrical efficiency of about 10%.

New technologies, however, are already being developed to meet these challenges. Laser glass could be replaced by ceramics or crystals. Flashlamps will be supplanted by solid-state diode light sources. These and other improvements could increase the repetition rate to 100,000 times per second and increase the electrical efficiency by a factor of 40. And fast ignition technology holds the possibility of reduced laser-driven energy and substantially increased fusion energy gain – as much as 300 times the energy input.

AN INTERNATIONAL EFFORT
While NIF shows great promise of demonstrating fusion ignition, the challenges of fusion energy are beyond the capabilities of any one project, or any one nation. All countries with access to this technology have a responsibility and an opportunity to explore this source of energy for the future.

HIPER EUROPEAN LASER PROJECT
Within Europe, senior scientists have been planning for two years to determine how the field of laser fusion science should progress over the coming years, anticipating success of the NIF. These considerations have materialized themselves as a next-generation laser facility project called the High Power Laser Energy Research Facility. This project was accepted onto the strategic European roadmap for future research infrastructures in late 2006. The UK agreed to lead the proposal in early 2007, and a consortium of seven nations (Czech Republic, France, Greece, Italy, Portugal, Spain, and the UK) put forward an integrated project plan midyear through the same year. Funding for the pre-construction ‘preparatory phase’ is now on track for the project to start in April 2008 centred at the Rutherford Appleton Laboratory and in Bordeaux.

To offer an internationally competitive capability, the HIPER project will adopt a different approach to laser fusion, in which the compression and heating phases of the fusion ignition are separated.

To offer an internationally competitive capability, the HIPER project will adopt a different approach to laser fusion, in which the compression and heating phases of the fusion ignition are separated.

A WINDOW ON THE COSMOS
Answers to many questions about the cosmos may become possible through high energy density experiments at the NIF. What is happening in stars? What causes nucleosynthesis in supernovae? What are neutron stars really like? What are the conditions that exist in the cores of giant planets, or in the accretion rings around black holes? What is the cause of Earth’s magnetic field?

contained in approximately 6,000 modular units, which can be replaced quickly when necessary to ensure continuous operation of the facility.

The NIF laser pulses travel about one kilometre from initial pulse formation in the master oscillator room to the target in 1.3 microseconds, arriving at the target chamber centre within less than 10 picoseconds of each other with an accuracy of 50 microns – a picosecond is one millionth of one millionth of a second). This is a feat of other with an accuracy of 50 millionth of one millionth of a second). This is a feat of

An aerial view of the NIF at Lawrence Livermore National Laboratory in California. The facility, at around 70,000 m² on the roof, is about the size of two soccer pitches © Lawrence Livermore National Laboratory

EMERGING TECHNOLOGIES
evidence to assess the credibility of this approach by early next decade – coincident with the likely achievement of ignition on the NIF.

The technology still requires detailed consideration. For example, the short pulse beams require phase-locked mirror arrays with approximately 10m overall diameter to ensure the multiple beams combine as one single coherent beam.

Fortunately, such technology has been developed for the optical telescope community (an example is the Gran Telescopio Canarias), although there needs to be further thought on the specific requirements for a pulsed, high intensity laser facility. Perhaps the most daunting technical challenge is in the micro-fabrication of the fusion targets, which requires nanometre-scale roughness and three-dimensional embedded cones for the baseline target design. For a fusion reactor to work, such targets would need to be made in bulk quantity (five per second) at a cost of a fraction of a euro apiece. This will take a step-change in the manufacturing process.

The HiPER facility is being designed to operate at as high a repetition rate as possible, to drive both the scientific and energy missions to new levels. The repetition rate will be limited not by the laser itself, but by the system control and remote operation techniques for the fusion target and associated infrastructure. Lessons from the nuclear fission and other remote handling industries need to be adopted to ensure the most effective scientific use can be made of the facility.

The purpose of the upcoming preparatory phase is to ensure sufficient progress is made on the scientific and technological fronts to coincide with the expected achievement of fusion ignition on the NIF. This will allow an informed decision to be made on the future development and exploitation of the NIF itself, and also new options within Europe such as HiPER.

In June 2001, the 120,000 kg, 10 metre-diameter target chamber was hoisted by one of the largest cranes in the world and gently installed into its berth in the NIF target bay, a breathtaking event that took only about 30 minutes.

© Lawrence Livermore National Laboratory

GENERATING LASER ENERGY

THE TYPE 45 DESTROYER. IT LOOKED GOOD ON PAPER. IT LOOKS EVEN BETTER AT SEA.

The HiPER facility is being designed to operate at as high a repetition rate as possible, to drive both the scientific and energy missions to new levels. The repetition rate will be limited not by the laser itself, but by the system control and remote operation techniques for the fusion target and associated infrastructure. Lessons from the nuclear fission and other remote handling industries need to be adopted to ensure the most effective scientific use can be made of the facility.

This summer the first Daring class Type 45 destroyer successfully completed her stage one sea trials on schedule. It’s been designed to identify and prioritise potential dangers, engage multiple targets simultaneously and protect against them. Supplying the most advanced warship in the Royal Navy’s fleet is just one of the ways that BAE Systems is delivering real advantage in the real world.