From weapons to white dwarfs

Military research centres that use giant lasers to study conditions inside nuclear warheads are increasingly opening their doors to university scientists. **Edwin Cartlidge** asks what the labs and the researchers have to gain from the arrangement

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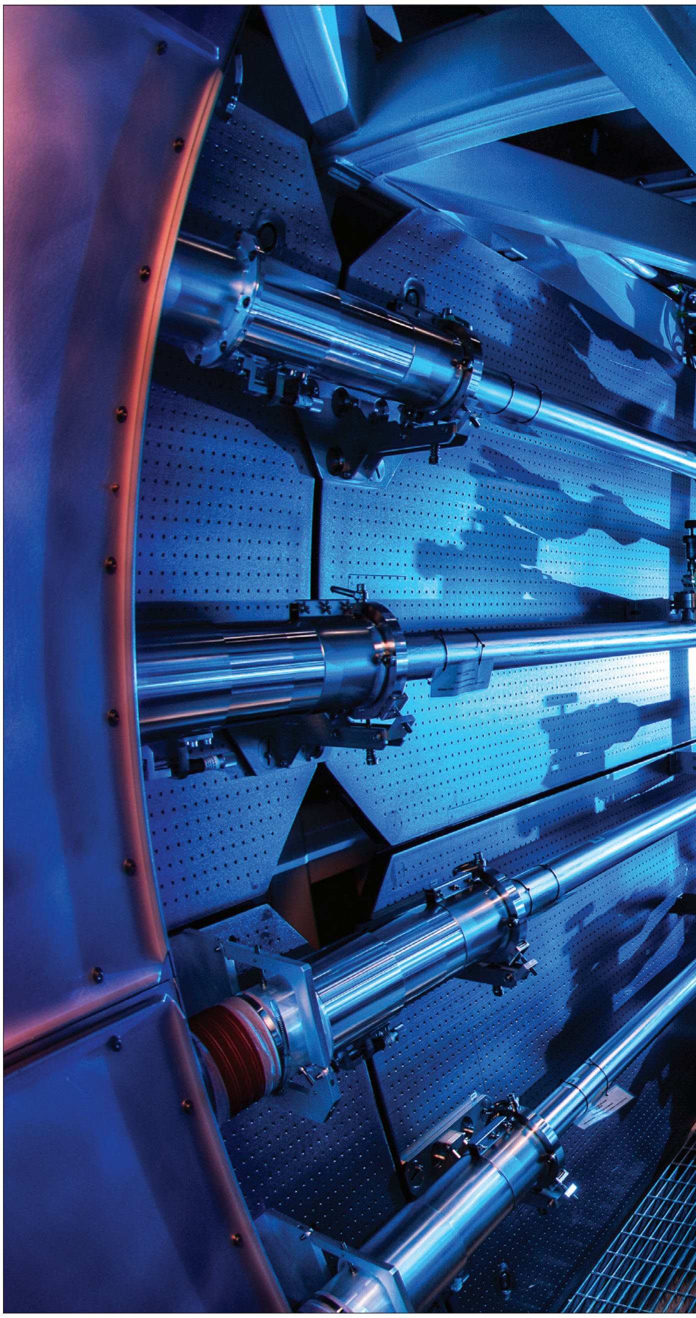
In the minds of many, the Atomic Weapons Establishment (AWE) near the picturesque village of Aldermaston, some 70 km west of London, is a secretive and impenetrable place. The vast site, owned by the Ministry of Defence, is where the UK develops and maintains the warheads that constitute its nuclear deterrent. As such, much of the work carried out there is classified and so inaccessible to the wider scientific world. However, there is a corner of the site where the rules are a little different – a place where academics can come and do research that they are free to report to their peers.

That place is home to Orion, a £170m laser that fires 12 high-powered beams at tiny targets positioned at the centre of a 4 m-diameter metal chamber. The immense pressures and temperatures generated in the targets allow AWE's in-house scientists to recreate the kind of conditions that exist inside nuclear explosions, albeit on a very small scale and over very short time periods. But because similar conditions also occur at the centre of stars and large planets, Orion is a valuable tool for astrophysicists and other scientists pushing our understanding of terrestrial material properties.

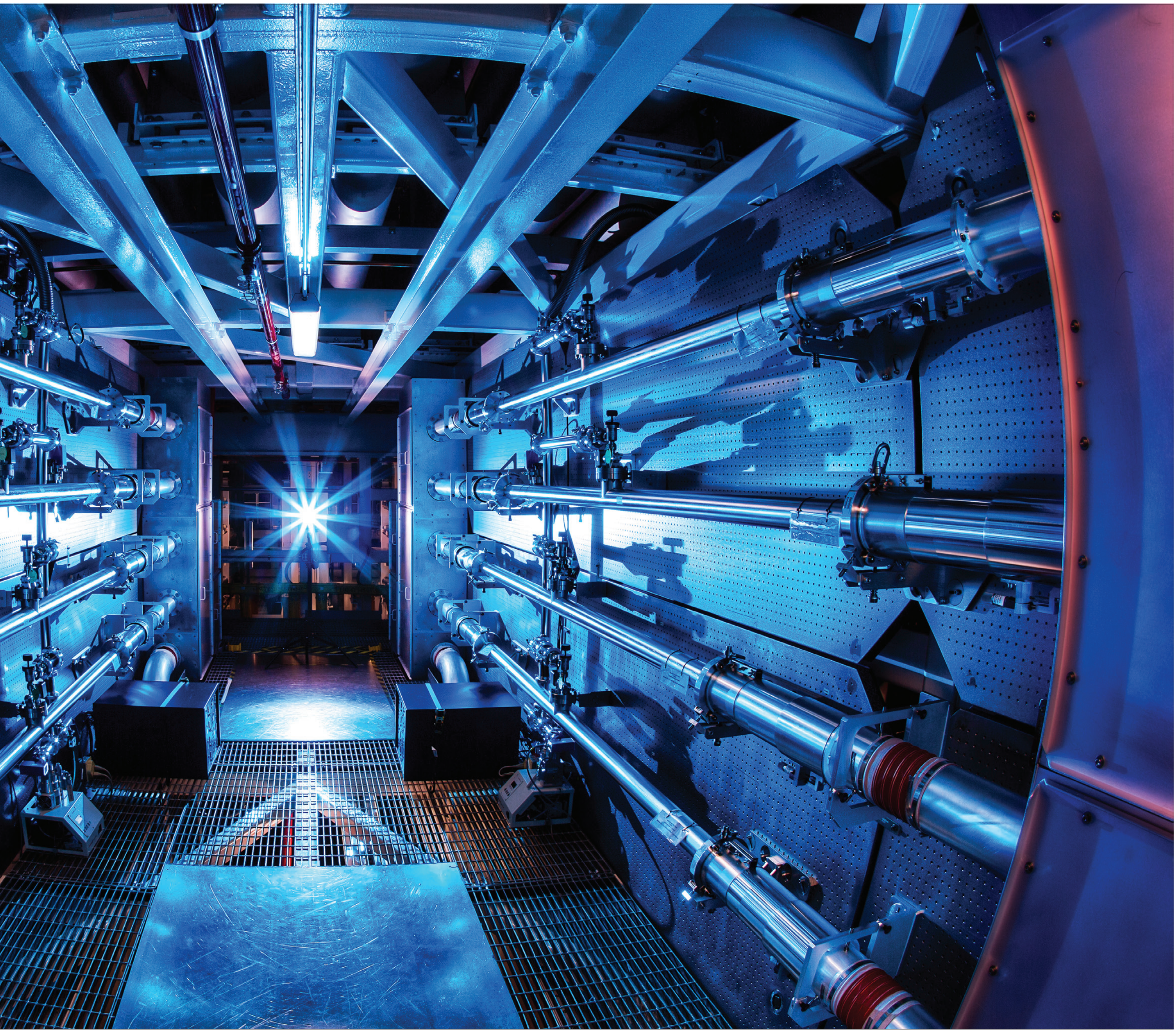
Although most of Orion's "beam time" is given over to weapons work, for a few weeks each year the facility is dedicated to research campaigns defined by British university scientists and their international collaborators. This programme of "academic access" has been ongoing since 2013, shortly after Orion was commissioned, and this spring finally bore fruit – in the form of published papers by the first two groups to make the trip to Aldermaston.

Gianluca Gregori of the University of Oxford, UK, and colleagues wrote in *Nature Communications* about creating a laboratory analogue of the shock wave thought to occur when a magnetized white dwarf sucks in plasma from a neighbouring star (**7** ncomms11899). Meanwhile, Justin Wark, also at Oxford, and Andrew Higginbotham, now at the University of York, UK, led a team that studied how silicon changes phase when subject to very high pressures. Their work was published in *Scientific Reports* (**6** 24211).



These papers make Orion the second large-scale laser at a defence laboratory to yield peer-reviewed research through academic access. The first to do so was the National Ignition Facility (NIF), a controversial multi-billion-dollar project carried out at the Lawrence Livermore National Laboratory in California, US, which has seen nearly 40 papers published via its "Discovery Science" programme since it was turned on in 2009. Next up will be the Laser Mégajoule (LMJ), located near Bordeaux in France, which is due to start hosting academic experiments in 2017.

Colin Danson, who is in charge of academic access at AWE, says the latest work shows that Orion, like NIF, produces "research of the highest quality". He adds that "the collaboration of university researchers with AWE is mutually beneficial" and that together they can fully exploit its huge laser.



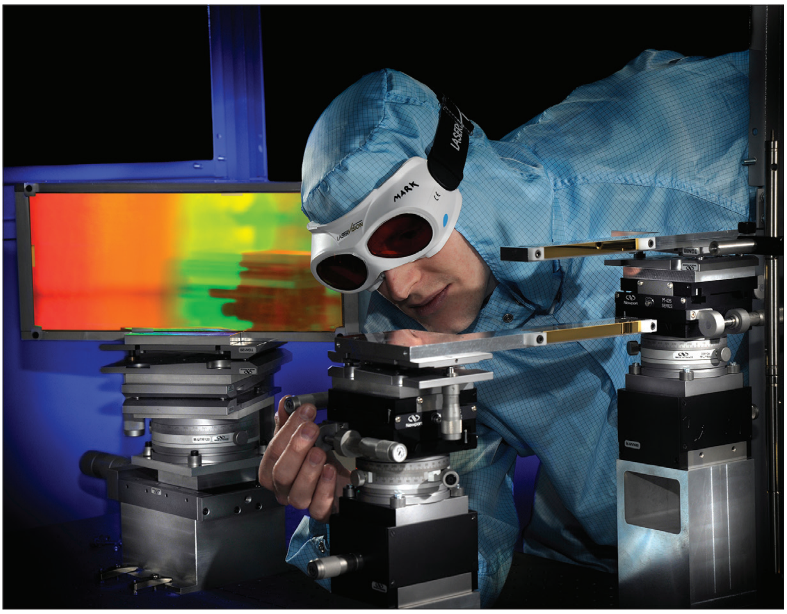
Damien Jemison

Packing a scientific punch

Weapons labs started designing these huge lasers after the Comprehensive Nuclear-Test-Ban Treaty brought an end to nuclear testing in the mid-1990s. The labs' scientists ensure the continued safety and reliability of weapons by simulating the behaviour of warheads using algorithms run on very powerful supercomputers. But they are unable to calculate opacity, strength and other material properties of the plasma created inside an exploding warhead using algorithms alone, which is why they also need to verify these algorithms experimentally. It is here that the lasers come in. (In fact, both AWE and Lawrence Livermore used lasers as far back as the 1970s, but did so (initially) in conjunction with underground weapons tests.)

NIF is a vast enterprise, its lasers occupying an area equivalent to three football pitches and generating 192 separate beams. These beams are directed by mirrors inside a 10-storey structure to the centre of a 10 m-diameter aluminium target chamber shielded by concrete. The target usually consists of a centimetre-long hollow gold cylinder containing a plastic-coated, peppercorn-sized sphere of deuterium and tritium nuclei. Laser beams striking the inside of the cylinder create X-rays that crush the sphere and in the process set off a shock wave that heats the nuclei to about 50 million degrees Celsius, so causing them to merge – a process known as inertial confinement fusion.

As its name implies, NIF's main goal is to generate what is known as ignition, which means that the alpha particles given off when nuclei fuse heat up the fusion plasma enough to create a self-sustaining reaction that gives off more energy than is supplied by the laser. Demonstrating this phenomenon would not only be useful for reproducing conditions inside a nuclear warhead, but might also allow scientists to



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Fine-tuning Laser scientist adjusting the laser pulse stretcher in Orion's front-end system.

achieve the long-sought goal of harnessing fusion energy on Earth.

However, by replacing the deuterium–tritium-containing capsule with different types of targets and changing the way those targets are compressed, NIF can be used to carry out a wide range of other scientific research. For example, Maria Gatu Johnson of the Massachusetts Institute of Technology (MIT) and colleagues have been fusing certain nuclei, including tritium and helium-3, to mimic the creation of elements inside stars. In this case, the fusing nuclei are housed inside thin glass-walled spherical capsules, which are exposed directly to the incoming laser beams.

Also at NIF, Wark and Lawrence Livermore scientist Jon Eggert head an international team that is compressing carbon to several tens of millions of atmospheres. The aim here is to find out whether the element enters a new, very hard, crystalline phase at those pressures, as has been predicted theoretically – a phase that, like industrial diamond, might remain intact when the pressure is subsequently removed. "One of our goals is to create materials that can only currently exist on another planet," he says.

Orion is smaller than NIF and is not designed to fuse nuclei. It uses 10 long-pulse (nanosecond-length) beams and two powerful short-pulse (sub-picosecond-length) petawatt beams to create very high densities and temperatures, but does so on samples that are far smaller than those used at the American facility – having diameters of a few tens of microns, rather than several millimetres. Data from these experiments are used to better understand, among other things, how X-rays and electrons are transported around very hot plasmas. "We are not using these experiments to simulate a weapon but to get an understanding of some of the conditions produced," says Danson.

While the energy delivered in each of Orion's pulses is much less than that of the rival lasers – 5 kJ, as opposed to 1.8 MJ at NIF and a design value of 1.5 MJ at the LMJ – it is still considerably higher than most civilian facilities. And energy, or more precisely energy density, is the name of the game when it comes to generating very high temperatures and pressures. (Academic lasers instead tend to focus on intensity.)

For example, in the work by Gregori and colleagues, higher energies mean hotter plasmas being sucked up by the simulated white dwarf. That equates to stronger shocks, which, if strong enough, cause the plasma to emit significant radiation at long X-ray wavelengths. "This gets us closer to astrophysical phenomena," says Gregori. "In terrestrial shocks, such as those created by aeroplanes, most of the energy instead remains in the flow of the fluid within the shock wave."

Happy customers

In many ways, the way research is organized at these military complexes resembles what goes on at any other large, centralized facility. Laboratory management oversees the research process and issues periodic calls for proposals. An independent committee of experts then reviews those proposals and decides which should be awarded beam time. And a third group representing users interacts with both the management and the expert committee.

What differs is the size of the operation involved, says Wark, who set up and then chaired the NIF user group for three years. At a typical synchrotron facility, he notes, "many users can turn up and do an experiment with just a little help from a beam-line scientist". At the lasers, in contrast, visiting scientists are guided through a painstaking and bureaucratic planning process to ensure that the proposed experiments withstand the demanding laboratory conditions and perform as intended.

This process involves designing the experiments, building the necessary targets, working out how the laser beams should be configured and ensuring that when the laser switches on, the debris from each "shot" doesn't damage the machine in the process. Getting an experiment up and running requires multiple reviews over a period of up to two years, and involves dozens of staff at the host labs. "A group is not simply going to turn up and do a shot," says Wark.

At NIF, every visiting group is given time on the laser in several 24-hour blocks that are typically spread out over a year or more, while at AWE – as will happen at the LMJ – each group usually carries out its experimental campaign continuously over two weeks. Although a single shot only lasts a few nanoseconds, researchers might typically manage two or three shots a day, given the time needed to allow the laser to cool, and to change the laser pulse shape and "diagnostics" – the instruments inserted into a target chamber that measure temperature, density, particle fluxes, energy spectra, magnetic fields and the other parameters of a plasma.

Wark has no doubt that all this effort is worthwhile. He points out that NIF not only provides unprecedented levels of energy but also allows users to specify exactly how they would like laser pulses to be "sculpted in time". In particular, he says, the facil-

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On target Long-pulse beamlines in the Orion laser hall.

ity can generate "ramped pulses" that act on a target more like a snow plough than an abrupt impact, which causes targets to heat up less quickly than their melting point rises, so keeping them solid – as is the case at the centre of very large planets. "The laser is a feat of exquisite engineering," he says.

Gregori adds that an additional advantage of the defence facilities is the availability of a comprehensive set of diagnostics. The huge number of groups that use civilian facilities means that scientists there often have to build their own instruments, whereas the relatively small number that get the chance to work at NIF or Orion can take advantage of the existing diagnostics. Although these afford less flexibility, he says that they generally produce "higher-quality data".

Richard Petrasso of MIT, who has carried out his own experiments at NIF as well as participating in the programmatic work on fusion, and has built a number of the laser's diagnostics, is also enthusiastic. He maintains that NIF allows researchers to "do very interesting science that they couldn't do otherwise". He also says that academics aren't usually involved with the classified experiments that take place, but that if they are it is because they have chosen to do so. "There have been no barriers that my students or myself have encountered working there," he adds.

In fact, visiting scientists are not entirely free to choose the kind of experiment they want to perform, given restrictions in some sensitive areas of research. For example, the LMJ user guide specifies that certain combinations of atomic number and pressure are not permitted in what are known as equation-of-state experiments. When it comes to uranium and heavier elements, all pressures are out of bounds.

For Wark, however, working at Orion or NIF feels little different to carrying out research at a civilian facility. He says that even the security checks are not that much more onerous than they are at, say, the Rutherford Appleton Laboratory some 30 km up the road from Aldermaston, given, as he points out, "the level of security at all scientific facilities in today's world". He adds: "People would like to hear the story that it is all hush-hush. But it is not like that at all."

More access, please

Eliciting this kind of positive reaction from visiting academics is exactly what Danson and his counterparts at the other weapons labs are looking to do. As Danson explains, the main reason for setting up access to Orion is to attract fresh talent, and the PhD students and postdoctoral researchers in university groups are a prime target. "Plasma physics is a critical skill for people at AWE," he says. "So we are trying to increase the visibility of the AWE brand and our capabilities to potential future recruits in plasma physics departments, giving us a chance to look at them and also to show what we can offer them here."

Likewise, Lawrence Livermore, in common with the other American weapons labs – Los Alamos and Sandia – is always on the lookout for new blood. Lawrence Livermore's director of academic access, Bruce Remington, says that students in visiting university groups provide "a rather steady state" of postdoctoral researchers for the lab. He says that there are "always places for really good people", adding that "they move us forward as a national lab and as a country".

The success of the access programmes, argues Danson, is reflected in their over-subscription. At Orion, 27 proposals have been received for the seven experiments scheduled to date, while at NIF the

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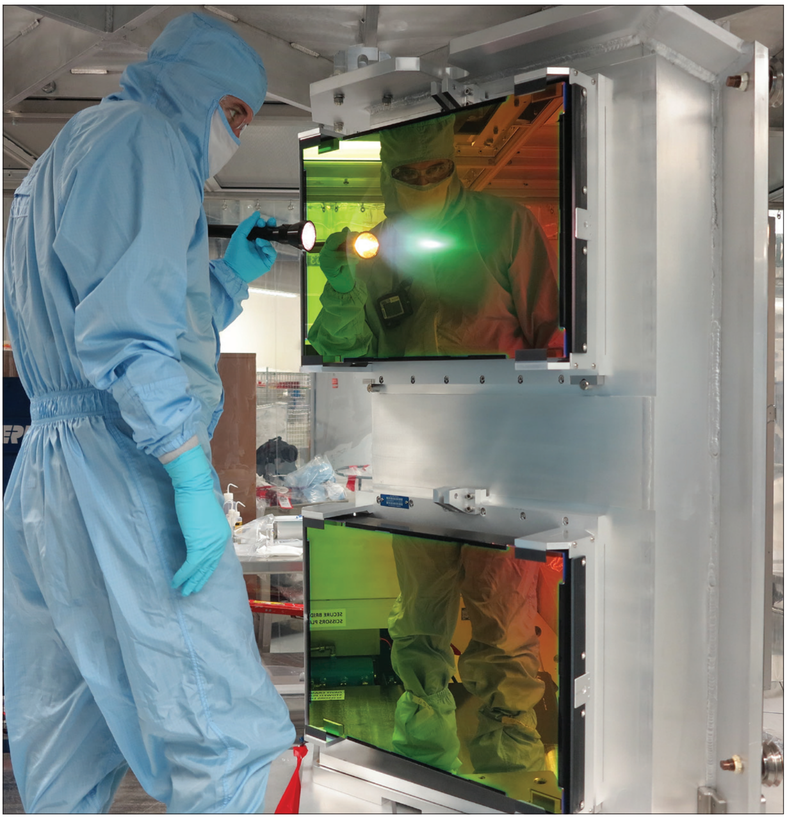

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Final check Inspecting the cleanliness of mirrors for the Advanced Radiographic Capability – a petawatt-class laser currently under development at the National Ignition Facility.

figures are 108 proposals for 25 experiments, and at the LMJ 16 proposals for the four experiment slots in 2017 and 2018.

However, there is one gripe that many academics have: that not enough of the laser shots go their way, as opposed to the work on fusion or defence. This was a particular problem for NIF after switching on in 2009. The first experiments in the Discovery Science programme were due to be finished within a year or two of the start-up, whereas they actually took five years to complete. In fact, during the first three years of operation, only nine of the 278 shots fired for experimental purposes were used for academic research.

According to Remington, the main problem was that the diagnostics weren't ready. When NIF switched on it was seven years behind schedule (and, with a price tag of $3.5bn, several times over budget), which meant, he says, that "people in the nation were impatient to get going". But because Lawrence Livermore had to give priority to its two "paying customers" – different branches of the Department of Energy responsible for the fusion and defence programmes – the non-paying academics had to be "fitted in as best they could", he says. "Enthusiasm got ahead of prudence a bit," he admits. "We got a lot of academic teams coming in and we were struggling to diagnose what was going on in their experiments."

In fact, in the rush to get going the fusion programme itself suffered. Lawrence Livermore launched a two-year campaign with the explicit goal of achieving ignition by September 2012. In the event, that date passed and NIF was still far from ignition – the fusion reactions generating only about one-thousandth of the energy supplied by the laser beams. According to Remington, "the laser itself performed as expected". The problem, he says, was that the computer simulations designed to predict NIF's performance – which scientists had been working on ever since the lab's previous big laser, NOVA, turned off in 1999 – were way off the mark. "After 10 years and thousands of simulations there was a lot of impatience to see what happens," he says. "We launched headlong into that."

Remington says the situation is now under control. The lab no longer has a specific timetable for ignition, but is instead in the middle of a more deliberative process of working out exactly what went wrong and whether ignition is even possible at NIF (some experts doubt that it is). "Now we have to roll up our sleeves, get back to basic research and understand what the issues are that still need to be solved," he says.

Fresh perspective

Having "ironed out the bugs", as Remington puts it, the Discovery Science programme now appears to be on a more solid footing. The difficult first round of experiments has been completed, a second round is currently under way, and a third round is due to start next April. A fourth round should then follow in the spring of 2018, with a call for proposals having been issued this May. "Any arguments [with visiting scientists] are now intellectual ones, rather than 'when can we have our shots?'," he says, adding confidently: "Those days are over fortunately."

Even now, however, only around 8% of NIF's operating time is given over to Discovery Science – of the rest, roughly 40% goes to the fusion programme, about the same amount to weapons research, and another 5–10% on other national security work, while the balance is used as a reserve. On Orion the fraction that goes to basic research is a little higher – 15% – but Gregori argues that this is still not much, considering that it amounts to only three or four weeks a year (allowing for periods when the laser isn't operational).

On the LMJ the figure will be higher – a whopping 25% – because the Aquitaine region, which has funded the facility's short-pulse component (known as PETAL) insisted on significant academic access. But it will be some time before the machine is up to full speed. The French Alternative Energies and Atomic Energy Commission (CEA), which runs the LMJ, carried out its first weapons experiments in 2014, and next year the first university experiments are due to get under way with 16 out of a total of 176 beams. The second round of pure research, using 56 beams, should then take place between 2019 and 2020.

Remington says he hopes to boost the time spent on Discovery Science to about 15% – the percentage allocated to academic access at the OMEGA fusion laser at the University of Rochester, US. He adds that, as is the case for OMEGA, he would like also to provide a small amount of money for visiting academics. About $10–15m a year, he estimates,

> Setting up partnerships with academia and industry lessens insularity and reduces the potential for "group think" at weapons labs

should be enough to pay for target costs, diagnostic development, appropriate salaries and travel. "With academics a little money goes a long way," he notes.

Being able to attract more university scientists, he says, is not only important in terms of finding future employees, but also because of the fresh perspective that outsiders bring. Such a perspective, he believes, would have been invaluable in drawing up NIF's fusion programme. Over the course of 10 years, he says, "we were not sufficiently focused on the challenges posed by 3D hydrodynamic and plasma instabilities", referring to phenomena that their 2D models failed to capture but which subsequent experiments showed could limit fusion inside NIF targets. "No-one said they could be a show stopper."

The importance of external collaboration was echoed in a report reviewing progress towards ignition that was published by the National Nuclear Security Administration, which operates Lawrence Livermore, in May. Setting up partnerships with academia and industry, said the report, "lessens insularity and reduces the potential for group think" at weapons labs. Such partners, it went on, "serve as a pool of collaborators and as a scientific system of checks and balances".

Danson too agrees on the need for outside thinking. Although Orion has had a smoother ride than NIF because it was not set explicit goals, he notes that academics bring new techniques as well as specialist knowledge. "There is a huge intellectual pool in the academic community and not to tap into it would be criminal," he says.

For their part, academics appear happy to oblige. Gregori says that he doesn't know anyone working in high-energy-density physics who is reluctant to use the huge lasers because they are run by the military. In fact, before embarking on the white dwarf experiments, he asked his PhD students whether any of them had such misgivings and he says that none of them did. "We never felt like we were doing experiments for an ulterior purpose," he adds. "I think that the labs simply want to show that you do science as science, that their goal all the time is to get papers out in very high impact journals." That motivation will be very familiar to any physicist working in a university today. ■