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The role of the National Ignition Facility in energy production from inertial fusion

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The 1993 declassification of virtually all inertial confinement fusion (ICF) target information relevant to fusion energy development, and demonstrable successes in the physics and technology related to ICF, have laid the ground work for a development plan for an Inertial Fusion Energy (IFE) programme. The ICF programme, funded by the Defense Program in the USA, has clearly demonstrated there is sufficient confidence in ignition and gain to proceed with construction of the National Ignition Facility, which will test the detailed physics of targets suitable for IFE. In September 1998, the facility was about 40% complete and on schedule and within budget for completion in 2003. X-ray-drive ignition is planned for 2007, followed by direct-drive ignition experiments. The other major elements of an IFE development programme, namely, driver, target factory, and target chamber developments can be investigated separately in affordable programmes. Although much work remains, there are concepts for adequately high driver efficiency and target gain, target cost and target chamber survivability to make an exploratory programme in IFE attractive.

Keywords: inertial fusion energy; laser fusion; ignition (lasers); thermonuclear gain; National Ignition Facility; Nova

1. Introduction

There are several necessary conditions to develop a sustainable fusion energy programme:

(i) there must be a credible and affordable cost of electricity (COE), competitive with advanced fossil, fission or renewable energy sources with full life-cycle cost and environmental costs included;

(ii) public concerns about nuclear energy—accidental release of radioactivity, waste disposal and nuclear weapons proliferation—must be manageable;

(iii) there must be an affordable development path with clear milestones and objectives;

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(iv) the development programme must be robust against political changes by having sufficient scientific and technical spin-offs to continually remind the public and government of the value of the programme.

The December 1993 declassification by the US Department of Energy (DOE) of virtually all target information relevant to IFE, demonstrable successes in the physics and technology and funding of ICF, and scientific broadening of the US ICF Program on Nova and Omega have increased the credibility of IFE against these demanding requirements.

Moreover, IFE has several advantages that allow a credible plan for IFE development.

1. *Dual mission but with different timescales.* The National Ignition Facility (NIF) will give an understanding of hot-spot ignition plasmas at a scale close to that needed for fusion energy. Nearly all of the scientific issues of ignition and gain for IFE targets will be tested on the NIF. The NIF, however, is a major investment by the DOE Defense Program (NIF 1994) which has the urgent deliverable in the next decade of ignition to help maintain confidence in the safety and reliability of the US nuclear stockpile. Many of the declared nuclear states have similar programmes. A high-average fusion power IFE development facility can follow once the ignition target physics is unequivocally demonstrated on the NIF. There are many previous examples both in this and earlier centuries where the urgent timescale of national security has led to technologies critical to civilian use: roads, explosives, air travel, radar and microwave ovens, space satellites, computers etc. Dual use has clearly worked time and time again.

2. *Public confidence.* The openness following a major declassification of ICF by the US Government can allow a demonstration to the public of the manageable environmental, safety and nuclear proliferation issues of the NIF in the near term and of IFE over a longer term. Moreover, the ICF programme has demonstrated the scientific diversity of the high-energy density physics that can be performed with high-energy lasers, e.g. astrophysical studies, materials physics, equation of state at very high pressures, high-intensity laser physics, hydrodynamics, etc. (Lee *et al.* 1995). This will allow a continual demonstration to the scientific community outside of IFE of the important collateral benefits of the programme.

3. *Modular programme elements.* The technological, engineering and economic feasibility of drivers, target factory and reactor chambers are largely decoupled from one another and from the ignition and high-gain science. Most of these can be developed independently in affordable, parallel programme elements. Some driver–chamber interface and beam chamber propagation issues at 10 Hz pulse repetition rates may require integrated testing in non-nuclear experiments before any high average fusion power IFE facility that would follow the NIF.

Although independent from the mission of the DOE's Defense Program there is an extensive infrastructure in the Defense Program which can be used to minimize the cost of the IFE programme. This includes target fabrication, 10–100 Tflop computers, diagnostics and facilities for the planned (NIF) and existing (Nova, Omega, Nike, and Z) ICF facilities.

4. *Affordable development costs.* There is a low initial development cost for IFE. Laser drivers consist of many (e.g. 192 for the NIF) parallel and identical beam lines and only one has to be developed as an engineering prototype. Likewise, heavy ion drivers have most of the risk in the early stages of acceleration.

In this paper we first review the features of hot-spot ignition, IFE targets, and the important criteria for affordable COE. In contrast to magnetic fusion, ignition is not the most difficult to achieve parameter for IFE. The key target issue for laser-driven IFE is the attainment of a high enough gain to overcome the relatively low efficiency of known lasers (7–15%) at the required laser energy (*ca.* 1–3 MJ). In general, the product of driver efficiency and the target gain (see below) should be of the order of 10 or greater. For a 10% efficient driver, target gains of the order of 100 should be adequate. The use of ion beam drivers with higher projected efficiencies is described in an accompanying paper (Bangerter, this issue). An advanced laser concept, the fast ignitor, is described by Key *et al.* (1998) and Willi (this issue).

The physics of igniting IFE targets will be tested on the NIF with both X-ray and direct drive. Direct-drive targets' potential can achieve gain larger than indirect-drive capsules (approximately a factor of 3). To test direct-drive IFE targets on the NIF, will require few differences from the laser conditions used to achieve ignition; however, the laser driver will need to be much more efficient than the flashlamp-pumped NIF.

A decade-long programme on ICF facilities in the USA, France, UK, and Japan has demonstrated high confidence in the target physics for X-ray-driven ignition and moderate gain on the NIF. The key advance in laser-driven ICF in the late 1980s was the change to 0.35 μm laser wavelength irradiation from longer wavelengths. For ignition hohlraums, the laser intensity must be about 2×10^{15} W cm^{-2}. The frequency conversion to shorter wavelength ensured that stimulated scattering (Raman (SRS) and Brillouin (SBS)) at 2×10^{15} W cm^{-2} could be controlled because the intensity wavelength squared product ($I\lambda^2$) was kept low enough that the ripple velocity of electrons could be kept comparable with thermal velocities. Laser absorption can then be dominated by collisional absorption.

Despite the short wavelength, in some plasma conditions there can still be significant plasma instability coupling (SRS, SBS, and laser–plasma filamentation). Although not a problem for preheat, the filamentation in the plasma flowing out of the laser entrance hole of a hohlraum can cause a shift in the position of the laser beams in the hohlraum wall. Recent Nova experiments have shown that if beam smoothing using techniques discovered for direct drive is applied, the shift in beam position is made much smaller, as well as reducing backscattering. Average laser absorption of 90–95% in plasmas emulating NIF ignition plasmas are measured.

For ignition in the laboratory, radial convergences (initial capsule radius/final fuel radius) of around 30 fuel filled shells are required. By simple arrival time arguments, the degree of drive asymmetry imploding a shell has to be approximately less than 1/30. A 10-beam geometry, such as Nova, can only control the time-averaged symmetry. Nova has achieved a time-averaged radiation asymmetry of a few per cent. The NIF, with two rings on beams either side of a hohlraum, allows control of the time history of the drive asymmetry by 'phasing' the laser power in each ring. Larger numbers (N) of beams, such as on the Omega laser at the University of Rochester (*ca.* 40 into a cylindrical hohlraum), and NIF (192), also allows the RMS fluctuation in drive due to beam power imbalance and pointing errors to be made smaller, approximately as $1/N^{1/2}$.

An implosion is Rayleigh–Taylor (RT) unstable with the surface roughness growing. However, ablative flow of material through the unstable region can reduce the RT growth rate from the classical value $A(kg)^{1/2}$ (where A is the Attwood number, k is the wavenumber, and g is the acceleration) by factors of 2–3 under conditions close to ignition implosions. An ambitious set of experiments over several years measured the reduction of the linear growth rates because of ablative stabilization and the transition from linear growth to mode coupling and mode saturation in two and three dimensions, all in agreement with detailed calculations.

Finally, experiments have demonstrated integral implosions with convergences consistent with the limited precision afforded by Nova's 10 beams and Omega's 40 beams into a cylindrical hohlraum. With unusually small capsules on Nova, capsules with convergences greater than 20, achieved hot fuel densities of 20 g cm^{-3} and ablator densities of 150–200 g cm^{-3} (the comparable ignition densities are 70–100 g cm^{-3} in the hot spot and 900–1200 g cm^{-3} in the surrounding cold fuel).

The ratio of hohlraum radius to capsule radius governs the geometric variation of short wavelength radiation flux variations. With this ratio emulating the NIF and with similar RT growth factors as the NIF, Nova can only achieve convergences of *ca.* 10 before there is significant degradation in yield. Omega, with a high number of beams, can achieve convergences up to *ca.* 20 with the NIF-like hohlraum/capsule ratio and RT growth factors. It is therefore credible that convergences of greater than 30 can be achieved with the NIF's 192 beams.

As a result of this programme of work, the US ICF programme is going ahead with the 1.8 MJ, $1.2 billion NIF at the Lawrence Livermore National Laboratory. In the summer of 1998, the project is *ca.* 40% complete, and on cost and on schedule for completion in 2003. Full energy is planned for 2004, with X-ray-drive ignition planned around 2007, assuming no unknown physics issues arise.

France and the USA have had a joint laser technology development programme for several years. France is currently building an 8-beam laser with each beam similar to a beam of the NIF. This laser, the Laser Integration Ligne (LIL), in Bordeaux, is planned to start operation about the same time as the NIF. France then plans to build a 240-beam laser, Laser MegaJoule, with completion about 2008, within a few hundred metres of LIL.

Many of the scientific aspects of the implosion physics will be tested with X-ray-drive ignition. Beginning about 2008, the demonstration of direct-drive ignition will complete the scientific aspects of laser fusion by both direct and indirect drive on the NIF. In addition the flexibility of laser-driven facilities allows the NIF to be reconfigured for direct drive. DOE's modification of the specifications of the NIF to allow for direct drive is a clear demonstration by the USA of its commitment to multiple missions for the NIF.

Recent advances in laser technologies (Bodner *et al.* 1998) of KrF lasers and of diode-pumped solid-state lasers (DPSSLs) have made it credible that a multi-year driver development programme could demonstrate affordability, efficiency, and lifetime of these laser drivers, consistent with expectations in COE models.

International collaboration in IFE has been made possible by the major declassification of ICF in the USA. Moreover, the decade-long target physics and laser development programme for ICF in the USA has resulted in so many scientific and technological spin-offs, such as laboratory-based astrophysics, laboratory X-ray lasers, EUV lithography and laser material processing, that it is easy to extrapo-

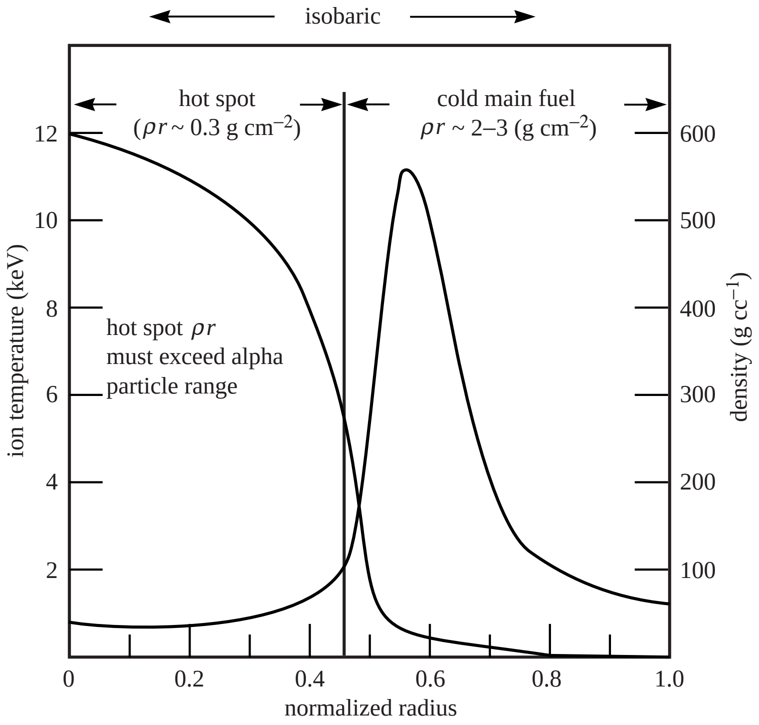

Figure 1. The isobaric hot-spot ignition model for ignition.

late that similar benefits will continue for IFE during a similarly long development programme.

2. Hot-spot ignition and high gain

The hot-spot model of ignition (Meyer-ter-Vehn 1982) shown in figure 1 gives the highest predicted gain when modelled with the fullest description of the physics including laser–plasma interactions and hydrodynamic instability. In its final configuration, the fuel is nearly isobaric at pressures up to *ca.* 200 Gbar, but consists of two effectively distinct regions: a central hot spot, containing *ca.* 2–5% of the fuel, and a dense, cooler main fuel region comprising the remaining mass. Fusion begins in this central region, and ignition occurs when energy production and α-particle deposition from the central hot spot are sufficient to initiate a self-sustaining burn wave that propagates into the surrounding main fuel producing a high gain. To compensate for driver and implosion inefficiencies, IFE targets must have a high burn efficiency, and most of the fuel must be heated by the burn wave propagating outward from the hot spot. This is easier for higher laser energy as the gain increases as the amount of fuel increases. The efficient assembly of the fuel into this configuration places stringent requirements on the details of the driver coupling, including the time history of the irradiance and the hydrodynamics of the implosion.

Target gain, defined as the ratio of thermonuclear energy produced to driver energy on target, is the closest equivalent to Q in MFE. Energy production in ICF requires target gains high enough that the product of gain times driver efficiency allows a competitive COE. Depending on driver efficiency, target gains of 30–100 or more are required to satisfy this condition.

The energy needed to achieve ignition is lowest when the main fuel is Fermi degenerate so that the density is highest for a given pressure. The isentrope parameter α is defined as

$$\alpha = P_{\text{fuel}}/P_{\text{F}}, \qquad \text{with the specific energy } \varepsilon_{\text{fuel}} = \alpha\varepsilon_{\text{F}},$$

where P_{fuel} ($\varepsilon_{\text{fuel}}$) is the pressure (specific energy) in the fuel and P_{F} is pressure (specific energy) of the plasma with Fermi degenerate electrons.

In the limit of high gain at constant pressure, the gain $G \approx \alpha^{-3/5}$, i.e. the gain is maximized by keeping the fuel as close to Fermi degenerate as possible. Detailed calculations give a gain curve for various values of α shown in figure 2. Unfortunately, the RT instability prevents values of α close to unity and a major research effort in instabilities for direct drive has shown that values of $\alpha \approx 2$–3 in a simple homogeneous shell are the lowest that can optimistically be expected while retaining a low enough growth of the RT instability.

Recently, more complex target designs have started to be evaluated (Bodner *et al.* 1998). The basic idea is to heat the ablator more than the fuel so that the target has the advantage of ablative stabilization of the RT instability from hotter material yet keeps the fuel nearly Fermi degenerate. Further work is needed in this area.

There is a difference between IFE and magnetic fusion energy (MFE) in the relevant parameters for affordable fusion energy because of the repetitively pulsed nature of IFE. Ignition has different meanings for these two approaches to fusion.

In MFE, which requires steady-state or near steady-state operation for most energy production approaches, ignition is defined in terms of power balance. In this approach, ignition occurs when energy deposition from thermonuclear burn products during one energy confinement time equals the energy required to heat the plasma to thermonuclear burn temperatures. When this occurs in steady state, the plasma can sustain itself indefinitely with no external heating.

As a measure of the fusion power performance for an MFE device, the fusion power gain is defined by $Q = P_{\text{f}}/P_{\text{i}}$, where P_{f} is the fusion power and P_{i} is the input power. Ignition occurs when $P_{\text{i}} = 0.0$ or when $Q = \infty$. An actual MFE reactor would run somewhat below the ignition limit, to maintain a stable operating regime, so that $Q \approx 20$ is desirable (Cordey *et al.* 1992). Recent experiments on TFTR (Strachen *et al.* 1994; Keilhacker *et al.* 1999; Watkins *et al.* 1999) with D–T plasmas have achieved $Q \approx 1/4$ with $Q \approx 0.6$–0.9 in JET (Strachen *et al.* 1994; Keilhacker *et al.* 1999; Watkins *et al.* 1999). Target gain in ICF, defined as the ratio of thermonuclear energy produced to driver energy on target, is the closest equivalent to Q.

In ICF, which is inherently pulsed, ignition occurs when energy production and local α-particle deposition from the central hot spot are sufficient to bootstrap the fuel temperature from the temperatures obtained by the PdV work of compression to temperatures at which significant thermonuclear burn up can be obtained before decompression. In figure 2, for example, ignition occurs at *ca.* 150 kJ at a gain *ca.* 1. To achieve high gain or high yield at reasonable driver size, which is the ultimate goal of the ICF programme, most of the fuel must be heated by a self-sustaining burn wave propagating outward from a central hot spot.

A hot spot forms in ICF targets during compression of material at the centre of the fuel, which is on a high isentrope. The hot-spot temperature will increase as long as the energy gained due to the PdV work done by the imploding main fuel material and charged-particle energy deposition exceed energy lost due to radiation and electron thermal conduction (Lindl 1995). Beyond a threshold implosion velocity for a given capsule size, PdV work can compress the hot spot to the ρr and temperature at which α-particle deposition and electron conduction can cause bootstrapping of the fuel temperature and initiation of a burn wave which propagates outward into the main fuel layer. Burn propagation in D–T will occur when the central temperature reaches about 10 keV with $\rho r \approx 0.2$–$0.3\ \mathrm{g\,cm^{-2}}$ in the hot spot.

For NIF-scale capsules the threshold ignition velocity is expected to be 3.5–$4.0 \times 10^7\ \mathrm{cm\,s^{-1}}$. At implosion velocities below the ignition threshold, which result in a burn-averaged temperature below about 3 keV, negligible α-particle deposition occurs, and the observed increase in fusion yield with implosion velocity follows that expected for the purely hydrodynamic compression increase in fusion reaction rate. Ignition results in a rapid increase in yield as implosion velocity is increased gradually beyond the ignition threshold velocity. Experimentally, the implosion velocity can be increased, while keeping the fuel on the same isentrope, by varying the peak drive temperature, i.e. flux at the end of the pulse or by varying the length of the pulse.

3. Importance of high gain for IFE

In an IFE power plant, some of the electric power generated must be used to run the laser or heavy-ion driver. The fraction of the total electric power that is used by the driver is referred to as the driver recirculating power fraction and is given by

$$\mathrm{RPF} = 1/\eta G M \varepsilon,$$

where η is the driver efficiency, equal to the ratio of beam energy on target to electric energy input, M is the energy multiplication factor due to neutron reactions with materials in the chamber, and ε is the thermal-to-electric conversion efficiency for the power plant.

For chamber designs considered in IFE, the energy multiplication factor is typically *ca.* 1.1–1.2, and the thermal-to-electric conversion efficiency ranges from about 40 to 50%. The driver efficiency depends on the type of driver and ranges from about 7 to 9% for KrF, *ca.* 10% for DPSSLs, to over 30% for some heavy-ion driver designs. The target gain also depends on the characteristics of the driver beams and the type of target (direct or indirect drive).

Figure 2 illustrates how the RPF decreases with increasing driver energy for direct drive for two values of the isentrope multiplier α. In this example, based on the Sombrero power plant design (Meier 1994), the driver efficiency is 7%, the energy multiplication factor is 1.1, and the power conversion efficiency is 47%. Reducing the recirculating power fraction increases the amount of power available for sale. If this can be done without increasing the cost of the plant (e.g. by increasing the target gain or driver efficiency at a fixed driver energy and cost), the COE will decrease. If higher gain is achieved by increasing the driver energy, there is a trade-off between higher capital cost and increased net power production, and we find a minimum in the COE versus driver energy curve. For example, using the upper gain curve with the Sombrero power plant gives a minimum COE at a driver energy of 2.7 MJ corresponding to a target gain of 107 and a RPF of 26%.

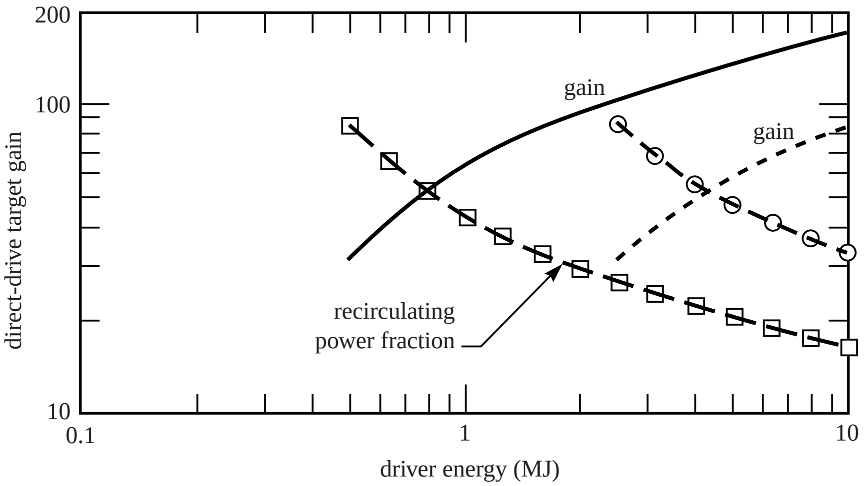

Figure 2. Direct-drive target gain versus driver energy for isentrope parameter $\alpha = 2$ (solid line) and $\alpha = 4$ (dashed line) and corresponding recirculating power fractions (%) for $\alpha = 2$ (boxes) and $\alpha = 4$ (circles). Ignition occurs at gain of a few.

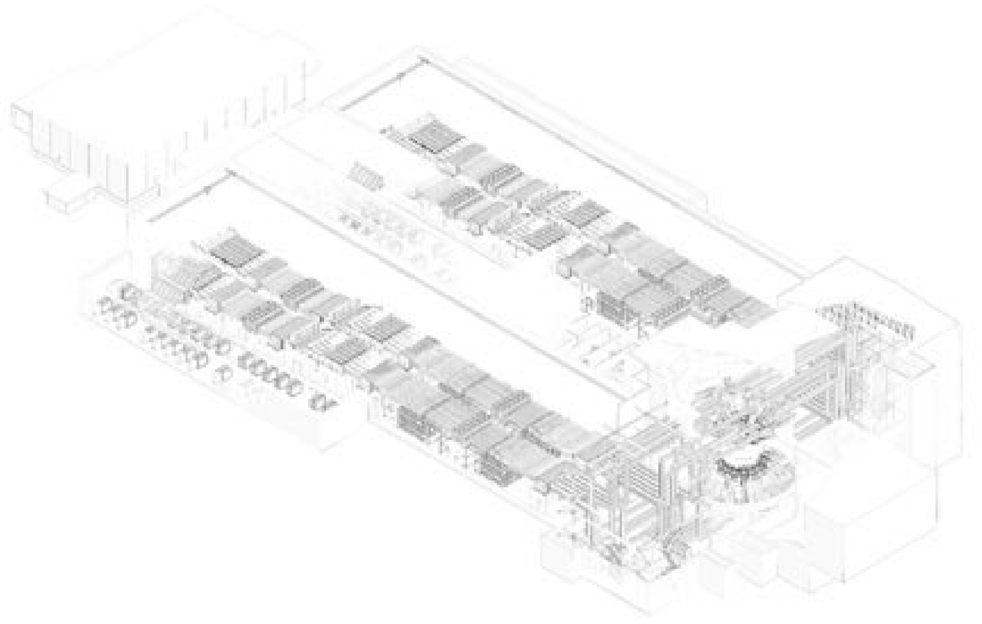

Figure 3. An isometric view of the National Ignition Facility.

4. Ignition and moderate gain on the NIF

The ICF programme in the USA has clearly demonstrated there is sufficient confidence in ignition and gain with an affordable laser facility to go ahead with the NIF, which will test the detailed physics of fusion energy targets. The NIF, shown in figure 3, is a 192-beam, multi-megajoule glass laser which will be sited at LLNL. The

10 m diameter aluminium target chamber is shown on the lower right with 24 clusters of four beams entering from the top of the target chamber and 24 similar clusters from beneath the target chamber, as used in the X-ray-drive configuration. There are two separate laser bays. The laser beamlines use a 4-pass cavity amplifier followed by single-pass booster amplifiers. At the top left on figure 3 is the Optics Assembly Building for clean assembly of the modules of the laser. The facility is funded by the Department of Energy and the project to construct the facility has followed the DOE processes for large capital acquisitions. Mission need (CD1) was agreed in January 1993, allowing a comprehensive Conceptual Design Report (NIF 1994). Project start (CD2) was in October 1994, with Congressional funding for preliminary design in January 1996. Start of construction (CD3) was March 1997 and completion of detailed design (Title II) is occurring in the summer of 1998. These activities have occurred on a schedule that was proposed in 1993 and has been adhered to, giving credence to future predictions of schedule for ICF systems.

One of the main missions of the NIF is achieving thermonuclear ignition and moderate gain, first with X-ray-driven implosions of deuterium–tritium (D–T) filled capsules, and then with direct-driven implosions. There has been extensive two- and three-dimensional numerical modelling design of the 'hot-spot' (Haan *et al.* 1995; Krauser *et al.* 1996) ignition targets considered for the NIF. In these designs with the most comprehensive descriptions of laser–plasma interactions and hydrodynamic instabilities seeded by target surface roughness and low-mode drive asymmetry, etc., a 1.3 MJ laser absorption produces more than 10 MJ of yield.

The scientific basis of the critical hohlraum and capsule physics needed for ignition has been reviewed extensively by the DOE-mandated Inertial Confinement Fusion Advisory Committee (ICFAC) and by the National Academy of Science (NAS 1990). The reviews have been technically intensive and generally supportive. The NAS review led to a Nova Technical Contract (NTC) in 1990 to prove the viability of ICF ignition. On the basis of these reviews and the NTC results, the Secretary of Energy agreed to construction start (CD3) in March 1997.

It is not possible in this kind of top level paper to do justice to the reasons for confidence in ignition on the NIF, and the details are in the several hundred papers on ICF published in refereed journals since declassification. ICF relies on complex computer codes to design ignition targets. Nova and Omega experiments have quantitatively verified that the details of these codes are correct with the important parameters at the scales of ignition targets. Table 1 shows the most important parameters of the NIF ignition targets, compared to Nova and Omega experiments. The maximum thermonuclear gains of targets presently shot on Nova and Omega are of order 1%, but this number cannot be meaningfully compared to the NIF gains. Because of their limited energy (30–50 kJ) current ICF facilities cannot simultaneously test the critical parameters of the NIF ignition design. However, the Nova and Omega experiments have separately tested the critical parameters and quantitative predictability of the critical physics.

The key scientific issues of laser hohlraum coupling and X-ray-drive symmetry were specified by the NAS in 1990 (LLNL 1995) in seven performance goals (called hohlraum laser plasma (HLP) 1–7). The key scientific issues relevant to implosions, the hydrodynamic instability issues, and the high convergences required were also specified (LLNL 1995) in another five performance goals (called hydrodynamically equivalent physics (HEP) 1–5). Concurrence that these goals known as the Nova

Table 1. *Comparison of NIF and current target parameters*

physical parameter	NIF	Nova (Omega)	NTC campaign
drive temperature (eV)	250–300	230 (pulse-shaped and gas-filled) > 300 (1 ns)	HLP1 HLP2
drive symmetry			
number of beams	192	10 (60)	HLP4
RMS capsule drive asymmetry	1%	4% (2%)	
implosion averaged (P_2)	$\sim$1%	$\sim$1%	
time swings (P_2)	$< \pm 10\%$	$\pm 15\%$ ($\pm 7\%$)	
laser–plasma conditions	$L \sim 3$–4 mm	$L \sim 1$–2 mm, f/8	HLP5
(in hohlraums) 1–2×10^{15} W cm^{-2}	f/8		
$n/n_{\mathrm{cr}} \sim 0.07$–0.25	goal:	$\sim$4%	
	scattering		
$T_{\mathrm{e}} \sim 3$–4 keV	<10%		
capsule convergence ratio			
capsule hydrotest	25–35	24	HEP1
NIF-like case/capsule	25–35	10 (17–20)	HEP4
hydro-instability e-foldings			
acceleration, deceleration	6–7	4–5 planar	HEP2
acceleration, deceleration		4–5 spherical	HEP1,4
pusher density (g cm^{-3})	700–1200	140–170	HEP1
hot-spot density (g cm^{-3})	45–75	20–30	HEP1
areal density (g cm^{-2})	0.3	0.02	

Technical Contract (NTC) had been essentially achieved was given by the ICFAC in November 1995, and the work summarized in the LLNL ICF Quarterly Report (LLNL 1995). A similar technical contract is the focus of the work on Omega for direct drive that is expected to be completed by 2002. The success of the technical contract is the basis for high confidence in achieving ignition and gain by both direct- and indirect-drive on the NIF.

The target designs for ignition and moderate gain with X-ray drive require about 1 MJ of energy absorbed in a hohlraum target. The X-ray-drive ignition pulses typically have radiative temperature foots at $T_{\mathrm{rad}} \approx 100$ eV, lasting for *ca.* 7 ns before ramping up to a 3–4 ns peak with $T_{\mathrm{rad}} \approx 300$ eV. For HLP2, Nova experiments showed values of $T_{\mathrm{rad}} > 270$ eV for 1 ns square pulses.

Higher drive temperatures would allow lower laser energies but are more difficult to achieve because the higher intensities required in the laser beam may cause laser–plasma instabilities to grow sufficiently to reduce the laser hohlraum coupling or to impact the symmetry by scattering the laser beams to unexpected parts of the hohlraum. To simulate the conditions for laser–plasma interactions on the NIF, hohlraums on Nova have been filled to 1 atm of methane. Nova experiments to produce plasma conditions similar to the NIF in terms of laser beam intensity, and linear gain coefficients for SRS and SBS, show that NIF-like beam smoothing reduces backscatter losses from 15% to a few per cent. Because of the increased absorption, the radiation temperatures increase from 200 ± 5 eV to 213 ± 5 eV satisfying HLP1. For shorter pulse lengths in shaped pulses, peak temperatures up to 230 eV are measured with a standard deviation of ± 4 eV in gas-filled hohlraums, in agreement with LASNEX calculations. The scaling of the radiative temperatures in the gas-filled hohlraums is also in agreement with a simple Marshak scaling with an X-ray conversion coefficient *ca.* 0.9.

Other Nova experiments with laser intensity *ca.* 1–2 × 10^{15} W cm^{-2} at electron densities *ca.* 10^{21} cm^{-3} and scale lengths 1–2 mm (at 0.35 μm wavelength) showed less than 10% coupling of laser energy into SBS and SRS, satisfying HLP5.

In ignition hohlraums, much lower drive temperatures with higher aspect ratio capsules are similarly precluded because of hydrodynamic instabilities. Nova experiments on planar targets with hydrodynamic instability growth factors up to 70 showed a quantitative understanding of the ablative stabilization of the RT instability under X-ray drive, satisfying HEP2.

X-ray-drive symmetry is most simply represented by the Legendre harmonics P_0, P_2, P_4, etc., where only the low orders matter because of the large hohlraum smoothing effect for high-order modes. For a 30–40-fold convergence (C_r initial capsule radius/final fuel radius) ignition implosion, the time-integrated symmetry must be less than 2% in P_2 with time varying swings less than 10% for 3 ns in the foot and less than 5–10% during the peak. On Nova, the variation with time of drive symmetry cannot be reduced to less than *ca.* ±15% (at the NIF case/capsule ratios) because there are only single 'rings' of beams. Additionally, there is significant azimuthal dependence because there are only five beams per 'ring'. On Nova, the reproducibility of the time-integrated P_2 symmetry with hohlraum tuning was demonstrated to *ca.* 1% to satisfy HLP4. An implosion with a high C_r of 24 was possible on Nova, albeit with higher hohlraum case/capsule ratio to increase the level of drive symmetry, and was demonstrated for HEP1. On the NIF, the high level of time-dependent symmetry control requires two rings of beams with slightly different pulse shapes, as well as a gas-filled hohlraum to reduce the motion of the X-ray emitting region. On Nova (with NIF-like case/capsule ratio), good implosions are achieved at $C_\mathrm{r} \approx 10$. On Omega, with 60 beams, good implosions have so far been achieved at $C_\mathrm{r} \approx 17$.

Experiments with gas-filled Nova hohlraums and unsmoothed laser beams demonstrated an unexpected shift in the experimental tuning of best symmetry compared to calculations and empty hohlraums. This was hypothesized as being due to laser beam filamentation in *ca.* 10% critical density plasma. Laser beam smoothing was subsequently shown to eliminate this problem and produce experimental results matching simulations.

A precise pulse shape is required for the laser because the cryogenic deuterium–tritium fuel must be kept on a low adiabat and the (four) weak shocks generated by the drive must all break out on the inside of the cryogenic ice simultaneously.

A wide range of target designs for the NIF are calculated to ignite in 2D and 3D fully integrated calculations with realistic initial target surface finishes for ablators of Be, plastic, and polyamide. (Although less advanced, there is also a variety of direct-drive designs that ignite, the most interesting of which give gains of the order of 60 for the same stability criteria used as a figure of merit in evaluating the indirect-drive ignition capsules. The direct-drive designs also require precise pulse shaping and advanced beam smoothing techniques that have been tested on Omega and can be implemented on the NIF for direct-drive ignition demonstration.) For all single-shell target designs (both for direct- and indirect-drive capsules) discovered so far, the deuterium–tritium (D–T) fuel must start at cryogenic temperatures and densities, with an RMS surface finish on the interior ice surface of about 1 μm. This level of internal cryogenic surface finishes of D–T ice layers in millimetre-scale shells was demonstrated by the natural β-decay process of the tritium which enhances sublimation from thicker regions of ice, a process known as β-layering.

The design requirements for direct drive on the NIF have some overlap with X-ray drive, but have some significantly different features, notably the higher degree of smoothing of the laser beams required to avoid imprinting unacceptable hydrodynamic perturbations on the target. The programme of work for direct-drive ignition preparedness is being executed on the Omega laser at the University of Rochester and Nike at the Naval Research Laboratory (Bodner *et al.* 1998).

The laser specifications for the NIF have been set by the requirements to achieve X-ray-driven ignition for a set of hot-spot ignition designs with a margin in the laser power and energy. The principal laser specifications are as follows.

laser wavelength	0.35 μm
laser energy and power	1.8 MJ and 500 TW in a temporally shaped pulse absorbed in the hohlraum
number of beams	192 in 48 clusters of four beams (quads)
number of beam cones	4:2 inner cones at 24–28° to the axis and 2 outer cones at 48–60° to the axis

This beam geometry is the configuration for X-ray drive with cylindrical hohlraums, as shown at the top of figure 4. To increase the versatility of the facility, provision has also been made to allow the target chamber to field direct-drive targets (Eimerl 1995), as well as tetrahedral hohlraums (Phillion & Pollaine 1994) for X-ray drive. As shown in figure 4, this can be achieved by moving 2×4 quads of beams from the inner cones and 2×8 quads of beams from the outer cones closer (*ca.* 72° to the axis) to the equator of the target chamber. The non-uniformity of direct drive in spherical harmonic modes, modes $L = 1$–20, will be approximately 1% for this geometry. Provision has also been made to upgrade the smoothing of the laser beams from one-dimensional smoothing by spectral dispersion (SSD) to two-dimensional SSD. This modification will probably result in a speckle smoothness for high L-modes (21–500) of 2–3% averaged over the pulse. This work is presently being vigorously investigated on the Omega laser at the University of Rochester. At this stage of development these and other concepts are still being developed to increase the level of speckle smoothness for direct drive. The main cost of the NIF is in the glass power amplifiers and so modifications to the final optics or the oscillators to incorporate improvements, such as 2D-SSD or novel phase plates can be incorporated at relatively low cost.

The other principal objective of the NIF is for the Nuclear Weapons Stockpile Stewardship Program (US DOE 1995). The facility also has other objectives and it is designed to have a high degree of flexibility, e.g. (1) energies in excess of 2 MJ at 0.35 μm will be possible for pulses longer than the 3.5 ns shaped ignition pulse, allowing radiation temperatures in excess of 100 eV and ablation pressures of many megabars for 10 ns in macroscopic-sized hohlraums (64 mm long × 40 mm diameter); (2) target irradiation at a wavelength of 0.53 μm will be possible; (3) target irradiation up to 25 cm from the chamber centre will be possible.

One of the NIF's additional missions is scientific outreach. In a preliminary form this is being tested on Nova with the Scientific Use of Nova (SUN) programme. In

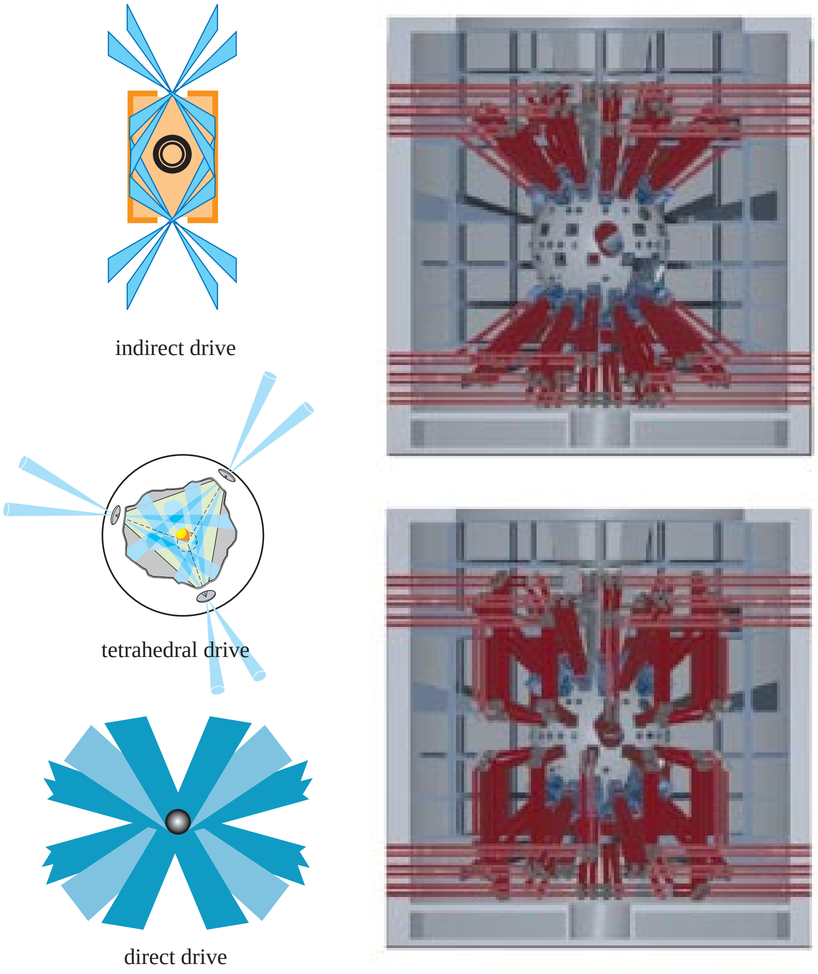

Figure 4. The flexible drive symmetry of the NIF allows cylindrical X-ray drive (upper), direct-drive (lower), and tetrahedral X-ray drive (middle).

addition, DOE funds the National Laser User Facility at the University of Rochester and the DOE University Grants Program. At LLNL, 10% of Nova's shots have been devoted to SUN since 1996. It is clear that the high-energy density physics that can be studied with high-energy/intensity lasers has applications in many other scientific disciplines (Lee *et al.* 1995). So far the astrophysics community (Kane *et al.* 1997; Remington *et al.* 1997; Drake *et al.* 1999) and the material properties communities (DaSilva *et al.* 1997; Cauble *et al.* 1997) have begun to use existing ICF facilities. For Nova, for example from 67 proposals from universities over the three years of SUN's operation, 22 have been approved resulting in over 20 publications and 20 invited talks at scientific conferences in areas such as laboratory astrophysics, equation of state, material strength, etc.

Although the NIF is a 192-beam laser, it is constructed of modules of eight-beam laser bundles and line replaceable units, allowing the system to be activated bundle by

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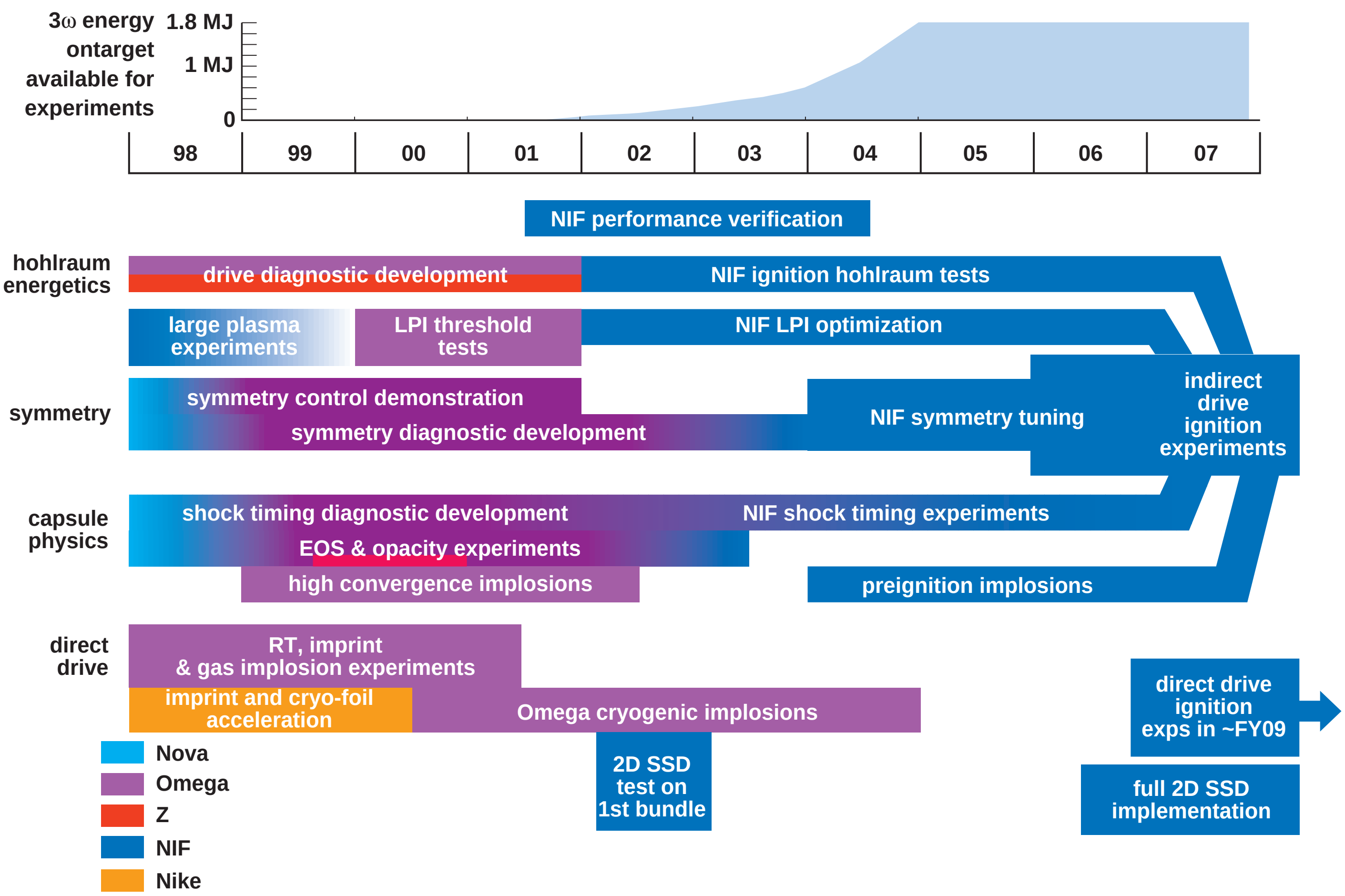

Figure 5. The schedule for ignition preparedness on the NIF using the various facilities of the US ICF Program.

bundle. For example, the amplifiers are 4×2 modules, 4 beams high by 2 beams wide. The first bundle of 8 beams will be operational by approximately 2002. The early use of the first bundle will give operational experience and will allow experiments with energy up to 80 kJ at a wavelength of 0.35 μm for ignition studies starting in the summer of 2001. Subsequently, other beam bundles will be activated allowing increasing levels of laser beam energy for experiments. Project completion (CD4) will be at the end of 2003, with half of the beams activated. Full energy will be available on target at the end of 2004.

For ignition, a work breakdown structure (WBS) to prepare for ignition has been agreed between the participants (LLNL, LANL, LLE, NRL, and SNL) in the US ICF programme. The WBS is aligned with hohlraum energetics, drive symmetry capsule physics and direct drive. DOE guidelines are that *ca.* 42% of the NIF's shots will be used for ignition. Scoping of the issues which require experimental resolution and the facilities (Nova, Omega, Z, and the NIF), and resources available have produced an approximate schedule for ignition on the NIF, shown in figure 5. Shown at the top of the figure is the NIF energy available to use for experiments versus year as increasing numbers of 4 × 2 bundles of the NIF beams become available. Before the NIF becomes available experiments on Nova, Omega, and Z will be used to refine the NIF target diagnostics, laser specifications and target specifications for ignition targets. When Nova closes in the summer of 1999, the support programme preparing for X-ray-driven ignition will shift to the Omega laser at the University of Rochester, Z at SNL, and Nike at Naval Research Laboratory before ignition preparedness experiments start on the NIF in 2001.

For hohlraum energetics, the accuracy of the measurement of X-ray drive will be improved by experiments on Omega. The issues are the closure of diagnostic holes in the hohlraum wall or the use of laser entrance holes for diagnosis. The hohlraum temperature is currently measured to an accuracy of ±5 eV, but with undesirable lower accuracy at the end of the laser pulse. In parallel, the Z machine at SNL will be used to develop and 'ruggedize' calibrated soft X-ray spectrometers for the NIF.

The main question for hohlraum energetics, apart from diagnosis, is the level of laser energy backscattered and sidescattered by the turbulent low-density plasma in the hohlraum. The plasma turbulence can be stimulated (stimulated Brillouin and Raman scattering SBS and SRS) at a sufficiently high laser beam intensity. However, laser beam smoothing reduces the levels of backscattered energy by reducing the fraction of laser power at high intensity. The Nova experiments showed that SSD reduces the levels of SBS and SRS in gas-filled hohlraums. As shown in figure 5, Nova will be used to test the exact beam smoothing by characteristics needed for the NIF. After the closure of Nova in the summer of 1999, figure 5 shows that the Omega laser will be used to measure the thresholds for laser–plasma interactions at a function of laser intensity and smoothing scheme.

Figure 5 shows that for symmetry, Omega is being used to demonstrate control of the higher order spherical harmonic Legendre modes (P_4, P_6, P_8) to show that a high convergence implosion with a convergence ratio of *ca.* 20 with NIF-like case/capsule ratio can be achieved on Omega. The control of symmetry will need to be improved for the NIF and diagnostic development activities in this area will also be conducted on Omega.

Figure 5 outlines the plan for developing our understanding of capsule physics. Nova will be used to develop techniques to more accurately measure the shock timing for the NIF. Active shock breakout techniques coupled with more accurate measurement of the equation of state of cryogenic deuterium ice will be required, particularly for the foot of the laser pulse. The Z facility at SNL will also be used for some of these experiments.

Once the NIF starts to become available in 2002, the laser control and measurement techniques must be refined to meet the requirements of drive symmetry and shock timing. Further experiments before the NIF will improve our detailed and quantitative knowledge of key material properties, such as X-ray opacity and material equation of state needed. Nevertheless, fine-tuning of the NIF hohlraum symmetry and pulse shape will be required on the NIF system for ignition.

Although there is a lot of uncertainty in predictions of schedules nearly ten years in the future, a plan is essential and in this plan ignition experiments are anticipated *ca.* 2007. As shown in figure 5, once X-ray-driven ignition is achieved, the laser beam geometry can be reconfigured (figure 4) to a direct-drive configuration.

5. Laser development for IFE

The two most promising laser driver schemes for IFE are KrF and DPSSLs. The ideal laser for IFE needs to satisfy demanding and conflicting criteria in wavelength, efficiency, repetition rate, beam smoothness, and longevity. It is not clear at this stage which if either of these two systems is most suited for IFE; however, the modularity of lasers, where the IFE driver would consist of many parallel beam lines makes it possible to evaluate these and other concepts with affordable programmes.

In DPSSLs, the flashlamps in lasers such as the NIF are replaced by efficient (50%), low-voltage semiconductor laser diode arrays, which produce direct, nearly monochromatic pump light (Orth *et al.* 1996). The Nd-doped glass lasing medium is replaced with a rare-earth-doped crystal with a longer-lived upper state and an absorption band chosen to efficiently use the diode output. Ytterbium-doped strontium fluoroapitite (Yb:S-FAP) is currently proposed because of its 1 ms storage time, reasonable gain cross-section, and minimum thermal deposition. In single-shot devices like the NIF, cooling of the amplifying medium limits the repetition rate to hours. To allow a repetitively pumped IFE system, it is proposed (Emmett *et al.* 1983) that the Nd:glass is replaced by a higher thermal conductivity crystal and face cooled by turbulent helium gas flow.

To demonstrate for the first time the integrated laser technologies for DPSSL-driven IFE, LLNL is now building the Mercury laser with the goal of 100 J at 1 µm with 10% efficiency and 10 Hz repetition rate. Subsequent developments in DPSSL technology will be required to demonstrate higher efficiency and average power frequency conversion to the ultraviolet with the required levels of beam smoothness and component lifetime needed for an IFE plant.

The module for a KrF laser for IFE would be similar in size to the amplifier for the Nike laser at NRL (Obenschain *et al.* 1996) The existing pulse power technology would be upgraded in efficiency and reliability particularly in the switching. Reactor studies (Sviatoslavsky *et al.* 1992) estimated the total efficiency of KrF laser at up to 9.5% using waste heat and with a 75% efficient pulse power system. DPSSLs could have somewhat higher efficiencies and some proponents argue that efficiencies could approach 20%.

The DPSSL systems should easily handle a 100 Hz repetition rate and the Mercury project at LLNL will evaluate the beam quality as the repetition rate is increased. The key issues for repetition-rated KrF lasers are foil cooling at repetition rate and maintaining adequate beam quality with gas flow.

The current cost of laser diodes is much too high to be envisioned for IFE, and must be reduced by 100 times to less than $0.1 per peak watt. However, the costs should dramatically reduce as production quantities increase and a 2D diode array fabrication method is developed. With very low diode costs, the efficiency of DPSSL systems can increase.

For an IFE laser, a lifetime of *ca.* 10^9 shots is required. KrF lasers need further development in the electron beam window and the anti-reflection coating on the laser cell. Lifetimes of 10^5 shots have been achieved on some e-beam windows and concepts for enhancing the lifetime of the coatings exist. The lifetime of laser diodes is already approaching IFE plant specifications, although it must be proven specifically for the IFE pumping conditions.

KrF lasers, because of their 3 THz bandwidth have demonstrated an beam profile smooth enough (less than 1% speckle smoothness) in one beam. The proposed lasing medium for DPSSLs, Yb^{3+}-doped $Sr_5(PO_4)_3F$ (Yb:S-FAP), has a much narrower bandwidth (*ca.* 0.3 THz). Alternative Yb-doped materials with larger bandwidths or targets which can withstand a greater degree of speckle non-uniformity will also need to be considered.

6. Overall IFE development strategy

Recent progress in target physics and target design for high-energy gain in inertial fusion research has greatly improved prospects for developing an attractive fusion power plant using either laser or heavy ion drivers. Studies show the promise of an acceptable cost of electricity and an environmentally attractive plant. The appropriate strategy for IFE development is a phased approach, with a set of near-term evaluation points, that is illustrated in figure 6 below. Working backwards in time (downward in figure 6) from the desired end point, the plan would provide an early assessment of the overall scientific, engineering, and economic feasibilities of inertial fusion energy (IFE), while avoiding any premature down selection. Because of the modular nature of inertial fusion, and because it is possible to leverage the large investments by US DOE Defense Programs, the cost of this strategy is moderate (*ca.* 20% of the current US fusion energy research budget). Within the next decade, the NIF, together with advanced numerical models, will give us confidence that the gains needed in future IFE plants can be achieved.

Next-step facilities in Phase 2 in figure 6, called Integrated Research Experiment(s) (IRE), must focus laser or ion beams with sufficient beam quality and intensity onto non-igniting targets, at focal distances and high pulse rates required for IFE, such that one or two IREs, together with the NIF, are the only major facilities needed to justify a high average fusion power IFE facility following in Phase III. By similar arguments working backwards from the IRE Phase II, the Phase I IFE research programme over the next four years would be required to provide the scientific and technical basis for all qualified direct- and indirect-drive approaches. We propose a sufficiently broad IFE programme in Phase I so that the candidacy of heavy-ion accelerators with indirect-drive, and both solid state and KrF lasers with direct drive,

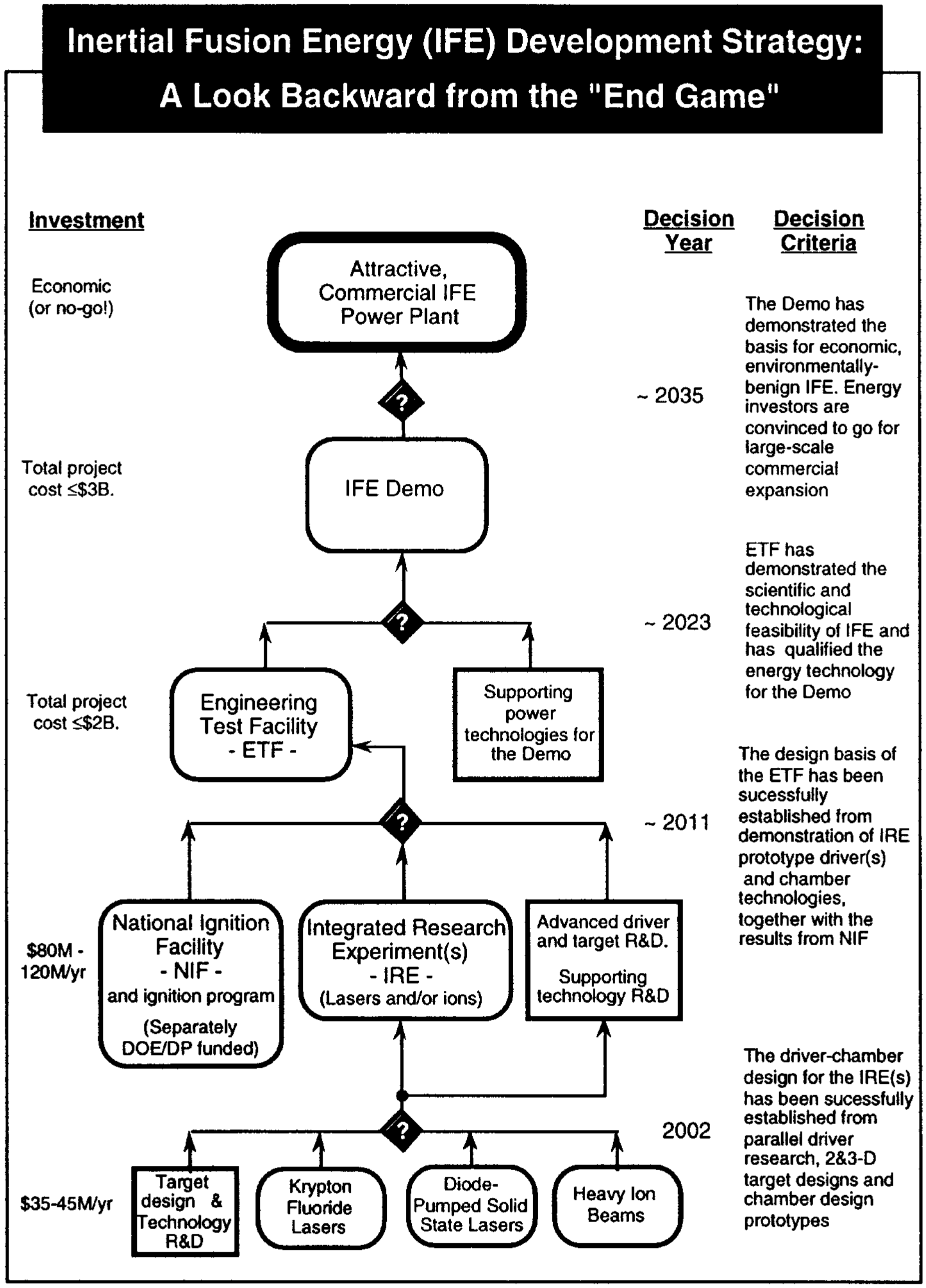

Figure 6. Overall IFE development strategy based on a phased-decision approach, working backwards in time (vertical direction) from requirements for an attractive power plant.

can be adequately assessed for a major Phase II decision point in four years. This IFE programme would also be able to effectively leverage the Defense Programs' large investments in laser facilities, target design capabilities, and experimental infrastructure including target fabrication diagnostics.

In addition to the IFE driver development activities described above, a significant fraction of the total IFE programme in Phase I, and continuing through the later phases, will be devoted to broad supporting IFE research in the following areas:

(i) target design and optimization, including design and experiments with advanced targets such as fast ignition;

(ii) experiments on methods to mass-produced, low-cost targets and inject them into chambers;

(iii) IFE fusion chamber R&D including protection for walls and final optics, using modest-scale simulation experiments and materials tests;

(iv) IFE power plant studies that explore the compatibility and optimization of the above, including definition of appropriate high average fusion power IFE development facilities for Phase III.

Whereas both IFE and magnetic fusion energy (MFE) are at approximately the same stage of scientific understanding, the scientific and technological criteria by which these two distinct approaches will succeed or fail as power reactors are very different. To date, the majority of the world's fusion research funds in MFE have been expended on the tokamak approach. Because of the tokamak's capacity for holding heat and its effectiveness in achieving the required magnetic field configuration, it has proved a useful research tool for achieving fusion conditions in the laboratory. Presently, the proposed next step in the world MFE programme is the International Thermonuclear Experimental Reactor (ITER).

Magnetic confinement concepts evolve from concept development, through proof-of-principle and proof-of-performance stages to the engineering test reactor (ETR) stage, a high average-fusion-power facility that would permit the testing of nuclear-grade components. The ETR would then be followed by an attractive demonstration reactor (the Demo), prototypical of the ensuing commercial power plants. Previous MFE machines such as the Princeton Large Torus (PLT) have completed the proof-of-principle role for the tokamak and present large facilities like JET and JT60U are involved in the proof-of-performance phase. NIF and the IRE fulfil the analogous proof-of-performance phase for IFE. However, for MFE, it is the ETR stage, namely, ITER, which is proving problematic. In this context, IFE offers the following developmental advantages.

> The modularity and separability of the components of the IFE development facilities allow for a phased, cost-effective development programme with recognizable milestones. For example, many diverse target concepts—the 'confinement' system for IFE—can be explored and interchanged on the same driver facility.
>
> Similarly, because of the simplicity of the IFE target chamber, we can conceive of testing many different reactor chamber and blanket concepts on the same single test facility. Moreover, such a facility may be able to accommodate more than one driver type.
>
> The crucial ETR step is affordable. In particular, we believe that this step can be achieved at a cost of *ca.* \$2 billion total project cost with an average fusion power of a few hundred MW.

> IFE reactor chambers offer the potential for the use of thick liquid walls which provide for lifetime structural components and low-activation waste inventories at end of plant life which can be disposed of by on-site, shallow land burial.
>
> Completion of the NIF will provide the world's first laboratory demonstration of fusion ignition and the potential opportunity to test advanced concepts for IFE-relevant targets. This provides enormous leverage to the US fusion energy programme in that complementary funding in energy research can concentrate on needs specific to the fusion power plant.

Thus IFE offers an affordable route to a fusion power plant that is a paradigm shift from that of a tokamak and indeed all other fusion concepts of the magnetic confinement class. Because it sidesteps many of the scientific and technology problems associated with fusion concepts of the magnetic confinement class, it seems that IFE is deserving of the label as a 'true' alternative fusion concept.

7. Summary

The decade-long development programme for ICF on the USA's ICF facilities—Nova, Omega, and Nike—convinced a broad scientific audience that the essential physics of ignition and gain on MJ-scale lasers is quantitatively understood. The propitious timing of the completion of this work, the Comprehensive Test Ban Treaty and the readiness of flashlamp-pumped laser technology for a multi-megajoule laser convinced the US Government to go ahead with the National Ignition Facility for both Defense and Energy missions (as well as scientific and economic spin-offs). Within the next decade, the NIF, together with advanced numerical models, will give us confidence that the gains needed in future IFE plants can be achieved. This civilian application of the NIF will have been funded mainly by the more urgent national security mission. This will be another example of the strength of multiple missions for large undertakings.

In parallel with the effort on the NIF there should be a development programme to study the target chamber issues—the Integrated Reactor Experiment (IRE), and parallel driver development programme—to demonstrate the required specifications for an IFE driver. Development has begun on a repetitively pulsed, DPSSL programme and a programme to develop a repetitive KrF laser is being planned.

In a later phase, an ETR would be followed. This supporting IFE research should be carried out through a broader participation in the IFE programme by universities, other US fusion laboratories, and US industries, working in partnership with the major US IFE laboratories, and also through international cooperation where there is mutual and cost-effective benefits to advance IFE in both the US and in the countries of its international partners.

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Discussion

A. Gibson (*Bluebonnets, West End Cholsey, Oxfordshire, UK*). If I understood Dr Kilkenny correctly, ignition in the NIF will not correspond to a net energy gain. What qualitative difference do you expect to observe to demonstrate that ignition has occurred? Will he, for instance, be able to demonstrate beam propagation?

J. D. Kilkenny. The simplest way to demonstrate ignition would be to vary the D–T fraction, keeping the other implosion characteristics constant. As the tritium concentration is increased, both the yield and the ion temperature would suddenly increase with the bootstrapping effect of α-deposition. Without propagating burn, the increases in yield and T_{ion} would be less. Other more complex diagnostics will certainly be developed.

G. H. Wolf (*Institute for Plasma Physics, Jülich, Germany*). I understood that ignition with the NIF is expected for both direct and indirect drive, with direct drive required for a gain of $Q \gtrsim 1$. My question addresses the Japanese GEKKO results, which show that in the pellet core the required densities can be approached but that there is a deficiency in the necessary spark temperature. What will be different with the NIF in order not to face such results?

J. D. Kilkenny. To achieve a cold fuel surrounding a hot spot requires symmetry, to prevent a very distorted shell of fuel, and pulse shaping to keep the fuel on a low isentrope. These considerations set some of the design specifications of the NIF, namely the power balance and the pulse-shaping capability. The implosions on GEKKO XII were designed to be exploding pushers without significant pulse shaping, and with restricted symmetry.

D. C. Robinson (*UKAEA Fusion, Culham Science Centre, Abingdon, UK*). Am I right that the best result achieved with the 60-beam Omega facility is a Q (or gain) value about 10^{-2} (1%)?

J. D. Kilkenny. The highest yield on Omega, albeit with so-called exploding geometry is about 10^{14} neutrons for 30 kJ incident on the target. This is a gain (not Q) of $10^{14} \times 17 \times 1.6 \times 10^{-13}/3 \times 10^4 = 10^{-2}$.

R. Aymar (*ITER, La Jolla, USA*). Dr Kilkenny has rightly insisted on the similar role and level of performance gain G and Q for IF and MF, respectively. On the contrary, 'ignition' has vastly different meanings for IF and MF. Can he comment on their differences, and on the opportunity to use the same word for two different scientific concepts?

J. D. Kilkenny. I explained the differences in the text. The use of the term can cause a lot of confusion if the difference level of difficulty is not clearly understood.