INERTIAL CONFINEMENT FUSION

3/9/2021

"Prediction is difficult – especially of the future."
Niels Bohr

"Ad Astra per Aspera"
To the stars through difficulties

INTRODUCTION

Inertial Confinement Fusion or ICF aims at achieving fusion by compressing the fusion fuel to high densities albeit for a short period of time. Lasers or particle beams can be used to create conditions that make fusion feasible: in a time-span of two microseconds, they heat the isotopes of hydrogen (H), deuterium (D) and tritium (T) to 100 million degrees Celsius or 180 million degrees Fahrenheit and implode them with enough pressure and at sufficient speed to release fusion energy. The process is similar to what happens on an astrophysical scale in stars that have exhausted their nuclear fuel, hence inertially or gravitationally collapsing and generating a supernova explosion (Fig.1).

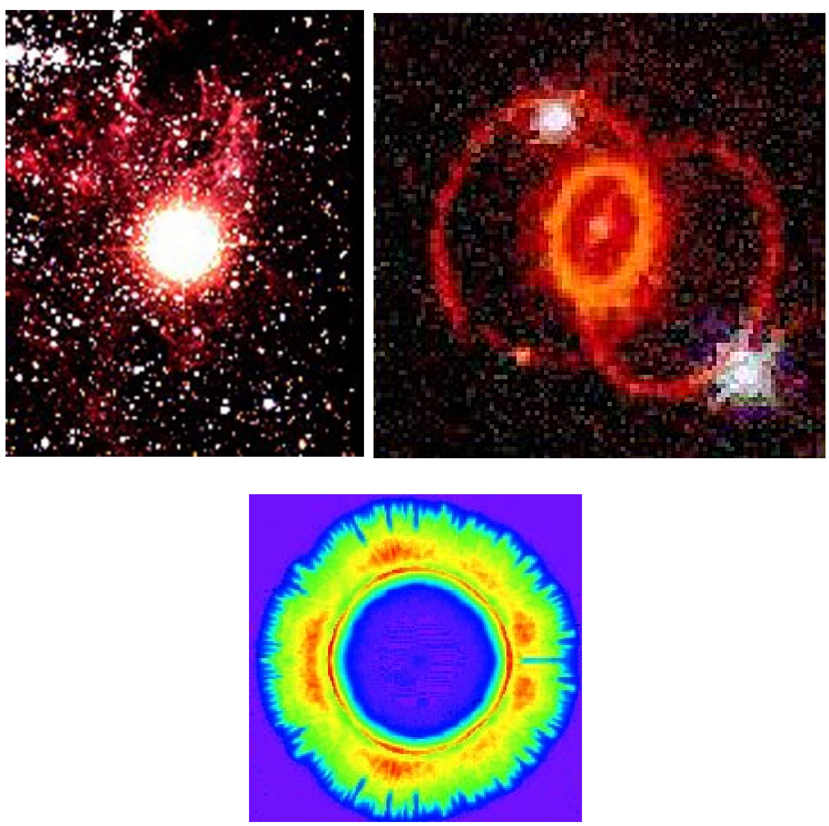

Figure 1. Type Ia supernova 1987a (top), and an inertial confinement pellet 500 psec from ignition (bottom).

Three approaches exist for inertial confinement: a multiple beams direct a multiple beams indirect and a single beam direct approach. In a direct drive approach lasers heavy or light ion beams irradiate the surface of a fusion pellet (Fig. 2). For uniform illumination of the target's surface to avoid the occurrence of Rayleigh Taylor hydrodynamic instabilities, this would require a large number of beams. In the indirect approach, the laser light is converted into soft x rays which are trapped inside a hohlraum chamber surrounding the fusion fuel irradiating it uniformly.

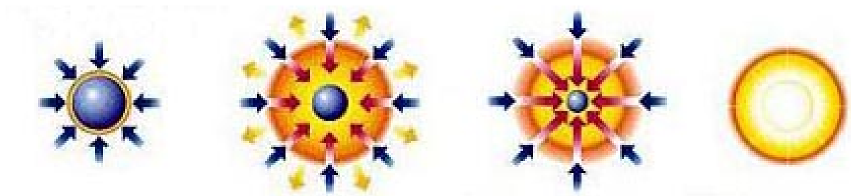

Figure 2. Direct laser drive compression of a fusion pellet.

The Rayleigh Taylor instabilities occur when a lower density fluid such as oil is underlies a higher density fluid such as water. In inertial confinement the higher density fluid is the pellet surface, and the lower density fluid is the plasma surrounding it and compressing the pellet through the inverse rocket action of the implosion process.

DIRECT DRIVE FUSION

In direct drive inertial confinement fusion, the compression and heating of the fuel is accomplished by depositing massive amounts of energy on the outside of a solid, spherical fuel capsule. As this energy is deposited in a thin ablator layer on the outside of the capsule, that layer heats up and the over pressure in this narrow region leads to both the ablation of material outward and the launching of a shock wave inward.

Possible material choices include a polystyrene ablator (32.5 μm) which is irradiated with a laser beam. The ablator generates a shock wave that passes through an iodine doped preheat polystyrene shield (102 μm). Part of the shock is reflected and a part is transmitted through a layer of aluminum pusher (62 μm) to compress the pellet interior.

The compression proceeds along several steps:

1. Atmosphere formation: The laser beams rapidly heat up the surface of the fusion pellet forming a surrounding plasma region.
2. Compression: The fuel is compressed by the inverse rocket blowoff of the hot surface material.
3. Ignition: In the final part of the laser pulse the fusion fuel reaches about 20 times the density of Pb (10.1 gm/cm^3) or 202 gm/cm^3, and ignition is initiated at 100×10^6 ^oC.
4. Burn: The thermonuclear burn spreads rapidly through the compressed fuel amplifying the input energy for a net energy return.

If the characteristics of the ablation and the shock waves are controlled precisely, then a small region in the interior of the fuel capsule can enter the region of temperature-density parameter space in which fusion reactions efficiently occur. The fusion energy from such an initial hot spot is then deposited in the rest of the capsule, generating further reactions.

INDIRECT DRIVE: THE HOHLRAUM

In indirect-drive inertial confinement fusion the energy source that drives the ablation and compression is soft x rays radiation which is produced by the conversion of a non-thermal, directed energy source such as lasers or ion beams into thermal radiation inside a high-opacity enclosure, referred to as a hohlraum (Fig. 3). A hohlraum denotes an imaginary, perfectly absorbing and radiating enclosure invoked to derive the thermal photon Planck, or blackbody spectrum.

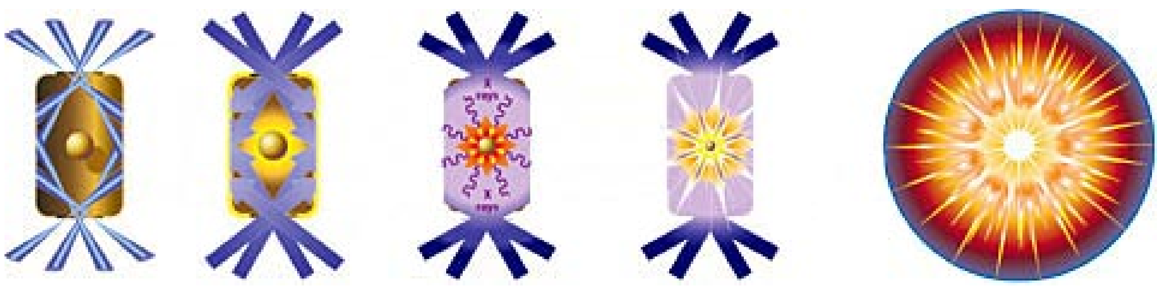

Figure 3. Indirect soft x-ray hohlraum drive compression of a fusion pellet.

The compression proceeds along several steps:

1. Laser illumination: The laser beams rapidly heat the inside surface of the hohlraum.
2. Indirect drive illumination: The walls of the hohlraum create an inverse rocket effect from the blowoff of the fusion pellet surface, compressing the inner fuel portion of the pellet.
3. Fuel pellet compression: During the final part of the implosion process the fuel core reaches a high density and temperature.
4. Fuel ignition and burn: The thermonuclear burn propagates through the compressed fusion fuel amplifying the input energy in a fusion fuel burn.

SINGLE BEAM IGNITOR CONCEPT

A single beam is used for the compression along the following steps:

1. Atmosphere formation: A laser or a particle beam rapidly heats up the surface of the fusion pellet surrounding it with a plasma envelope.
2. Compression: The fuel is compressed by the inverse rocket blowoff of the pellet surface imploding it inwards.
3. Beam fuel ignition: at the instant of maximum compression a short high intensity pulse ignites the compressed core. An intensity of 10^{19} [Watts/cm^2] is contemplated with a pulse duration of 1-10 pisoseconds.
4. Burn phase: The thermonuclear burn propagates through the compressed fusion fuel yielding several times the driver input energy.

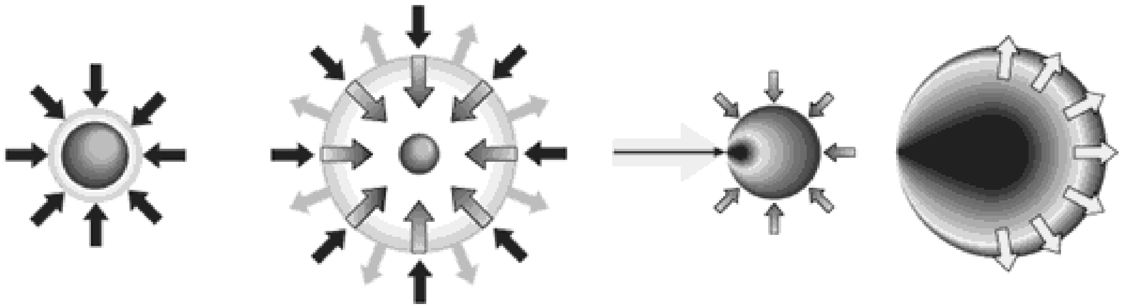

Figure 4. Single Beam ignitor concept for fusion pellets.

THE IMPLOSION PROCESS

The term implosion denotes a violent inward collapse or compression using an inverse rocket process. It fits many different physical schemes for rapidly compressing materials to high densities. An implosion may be adiabatic or shock induced, or both; the geometry of the compression may be one, two, or three dimensional. An implosion process can be symmetric about one, two, or three spatial axes.

LINEAR COMPRESSION

An example of one dimensional compression or linear compression is the compression of the fuel and air mixture in the cylinder of an internal combustion engine. If r_0 is the original length of the gas column in the cylinder, and r is the length after compression, V the volume, with A is the cross sectional area of the cylinder, remaining constant, then by invoking conservation of mass of the gas in the cylinder we can obtain an expression for the density after compression as:

$$\begin{aligned} V_0\rho_0 &= V\rho = \text{mass=constant} \\ Ar_0\rho_0 &= Ar\rho = \text{constant} \\ r_0\rho_0 &= r\rho = \text{constant} \\ \frac{\rho}{\rho_0} &= \frac{r_0}{r} \\ \rho &= \rho_0\frac{r_0}{r} \end{aligned} \tag{1}$$

This suggests that the compressed density is inversely proportional to the change in scale or the relative change in length.

CYLINDRICAL COMPRESSION

Two dimensional or cylindrical compression can be thought of as squeezing a tube so that its radius decreases uniformly remaining as a cylinder albeit with a decreasing radius. If r_0 denotes the original radius, V the volume, L is the length of the cylinder remaining constant, and r_1 the radius after compression then we can say:

$$V_0\rho_0 = V\rho = \text{mass=constant}$$
$$L\pi r_0^2\rho_0 = L\pi r^2\rho = \text{constant}$$
$$r_0^2\rho_0 = r^2\rho = \text{constant} \qquad (2)$$
$$\frac{\rho}{\rho_0} = \left(\frac{r_0}{r}\right)^2$$
$$\rho = \rho_0\left(\frac{r_0}{r}\right)^2$$

which means that the compressed density is now inversely proportional to the square of the change in scale.

SPHERICAL COMPRESSION

Three dimensional compression or spherical compression can be thought of as squeezing a sphere so that its radius decreases uniformly. In this case we can say:

$$V_0\rho_0 = V\rho = \text{mass=constant}$$
$$\frac{4}{3}\pi r_0^3\rho_0 = \frac{4}{3}\pi r^3\rho = \text{constant}$$
$$r_0^3\rho_0 = r^3\rho = \text{constant} \qquad (3)$$
$$\frac{\rho}{\rho_0} = \left(\frac{r_0}{r}\right)^3$$
$$\rho = \rho_0\left(\frac{r_0}{r}\right)^3$$

i.e. it is inversely proportional to the cube of the change in scale.

In general:

$$\rho = \rho_0\left(\frac{r_0}{r}\right)^n, \text{ n = compression dimension.} \qquad (4)$$

As an example, in spherical or three dimensional with n = 3 compression, a reduction in the radius by a factor of ½:

$$r = \frac{r_0}{2}$$

increases the density by a factor of 8:

$$\rho = \rho_0 2^3 = 8\rho_0$$

If the radius could be reduced by a factor of 1/10:

$$r = \frac{r_0}{10}$$

this increases the density by a phenomenal factor of 1,000:

$$\rho = \rho_0 10^3 = 1,000\,\rho_0$$

For the same change in scale, a higher dimensional implosion produces a much greater degree of compression. The relatively inefficient linear case in fact is rarely thought of as being an implosion process.

The spherical implosion gives the most rapid compression and, being symmetrical in all directions, it is also easier to analyze theoretically.

FUSION TARGETS DESIGNS

Ingenious designs for inertial confinement fusion have been developed. One device designated as gasbag is composed of two submicron thick planar polyimide films which are bonded to opposite sides of a washer that has been fitted with DT or DD gas fill tubes (Fig. 5). The device is then pressurized, deforming the polyimide films such that the target becomes nearly spherical. The overall dimensions of the gas volume are 2.75 mm inside diameter of the washer, and 2.4 mm across from the centers of the polyimide windows. With polyimide films measuring 3,500 angstroms in thickness, this gasbag target will hold one atmosphere of fill gas pressure.

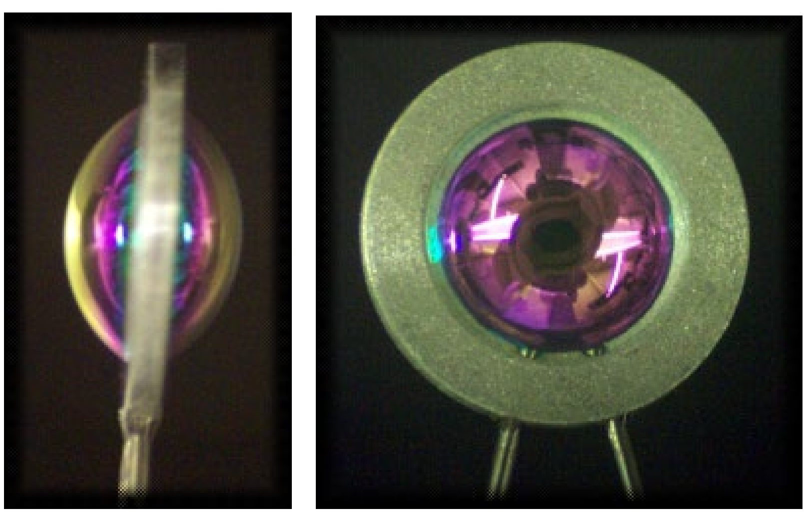

Figure 5. Laser pellet gas bag design with its gas filling tubes.

The interaction between high power laser radiation and gold is very efficient in the production of soft x rays. In a gold cavity called a hohlraum, up to 50 percent of the laser energy can be converted to x ray radiation. A simple cylindrical gold hohlraum is shown in Fig. 6.

Figure 6. Laser beam gold hohlraum.

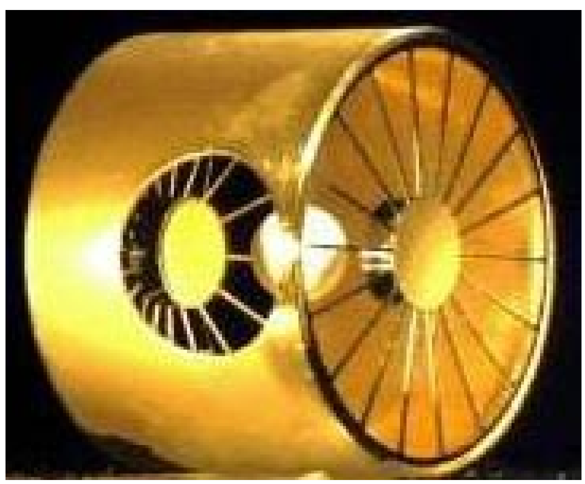

Figure 7. Beryllium wagon wheel design with gold hohlraum and polysterene foam sphere.

Another design employs polyimide windows bonded to the ends of a cylindrical gold hohlraum target body in the form of a wagon wheel with Be spokes. A laser entrance window ranges from 3,500 - 12,000 angstroms thick polyimide and are 1.2 - 3.8 mm in diameter. The windows generally hold one atmosphere of pressure, and there is very little deflection of the window under pressure, typically less than 0.2 mm.

The inside walls of a cylindrical hohlraum 1 mm in diameter, irradiated with a number of laser beams emit radiation with a temperature of more than a million degrees.

The growth rate of the Rayleigh-Taylor instability can be measured in a wavelength range not previously accessible. Depending on the x ray flux the ionization front propagation will either be supersonic which doesn't generate a hydrodynamic disturbance, or subsonic in which case a strong shock is launched.

The detail of a larger hohlraum for multiple beam irradiations is shown in Fig. 8.

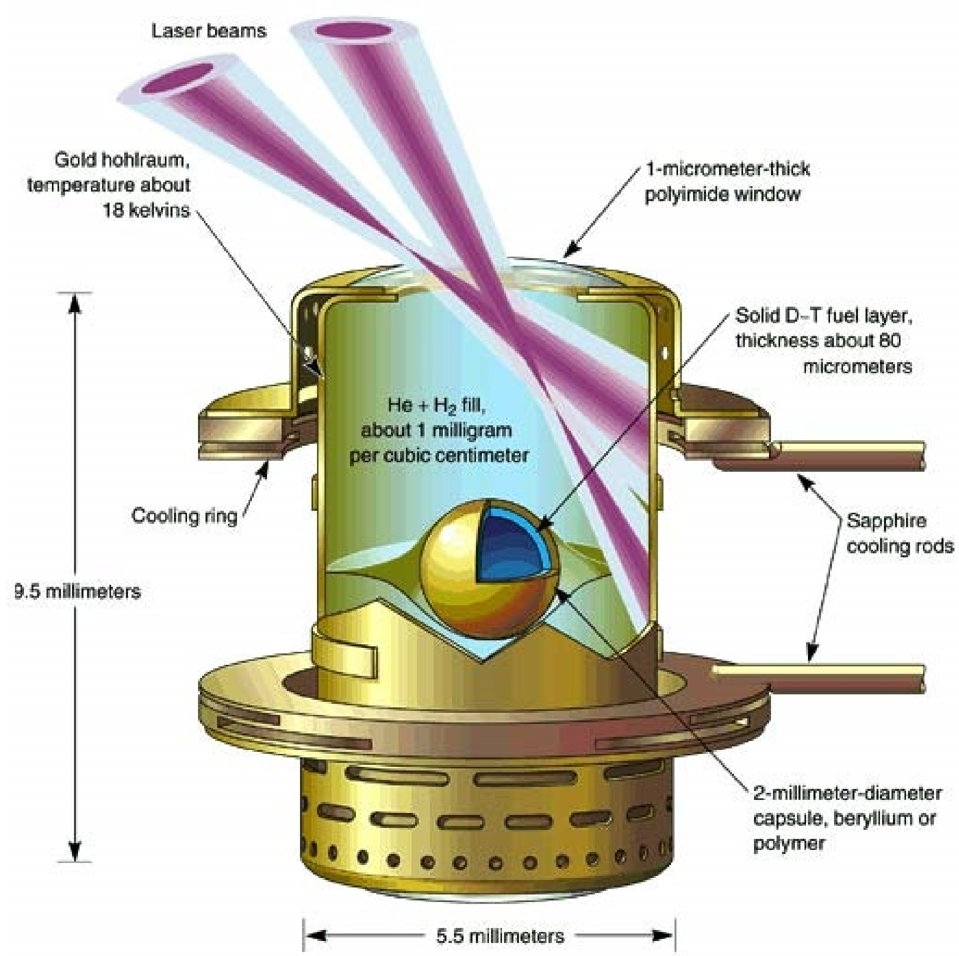

Figure 8. Indirect drive using hohlraum for multiple beams inertial confinement fusion.

Figure 9 shows the configuration of a cylindrical hohlraum irradiated by five laser beam on each side. Figure 10 shows an x rays picture of the hot spots generated by such an irradiation scheme. The irradiation studies involve several physics areas. The fusion pellet or capsule physics involve the symmetry of irradiation, pulse shaping hydrodynamic stability and mix, fuel ignition and propagation and the capsule drive. The entrance hole studies involve its closure and x ray losses from it. The laser beam plasma channel issues involve Brillouin scatter, Raman scatter and filamentation. The high Z element casing issues under study are absorption of laser energy, x ray conversion and wall losses.

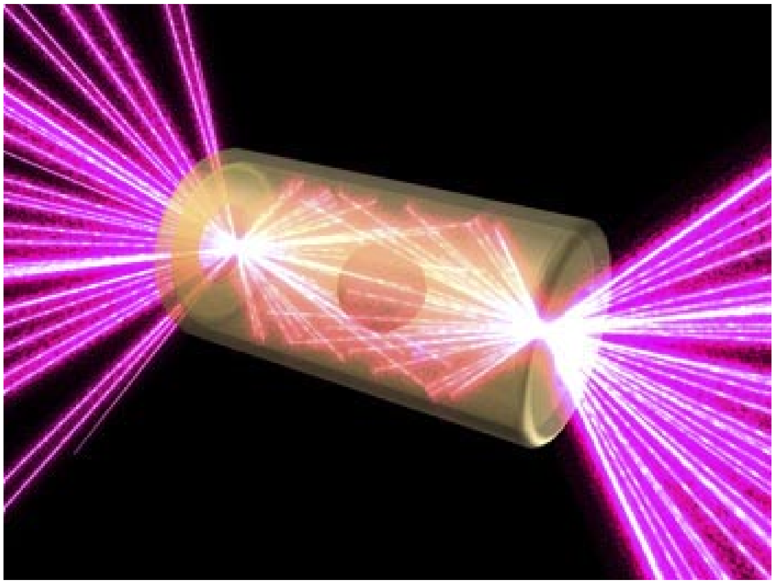

Figure 9. Laser beams deposit their energy on the inside surface of a metal cylinder or hohlraum generating x rays that implode the inner spherical fusion target.

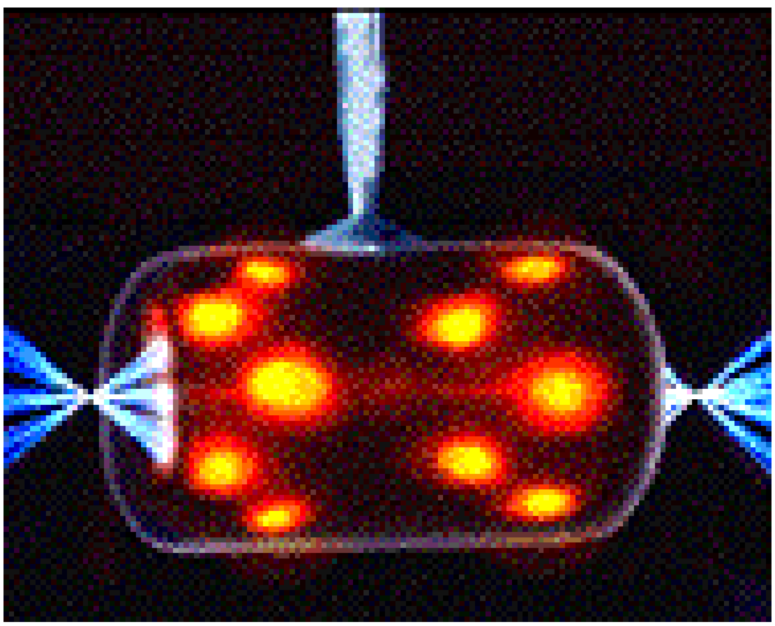

Figure 10. X ray photograph of NOVA laser hot spots inside hohlraum target.

DYNAMIC HOHLRAUM

Foams with densities in the range of 14 mg/cm^3 have been used in Dynamic Hohlraum experiments where the shaped foam is designed to modify a cylindrical pinch into a curved radiation field imploding a spherical target in its center. Some experiments had a 3,000 angstroms metal foil embedded 2 mm into the foam. Such experiments have reproducibly produced thermo nuclear neutrons.

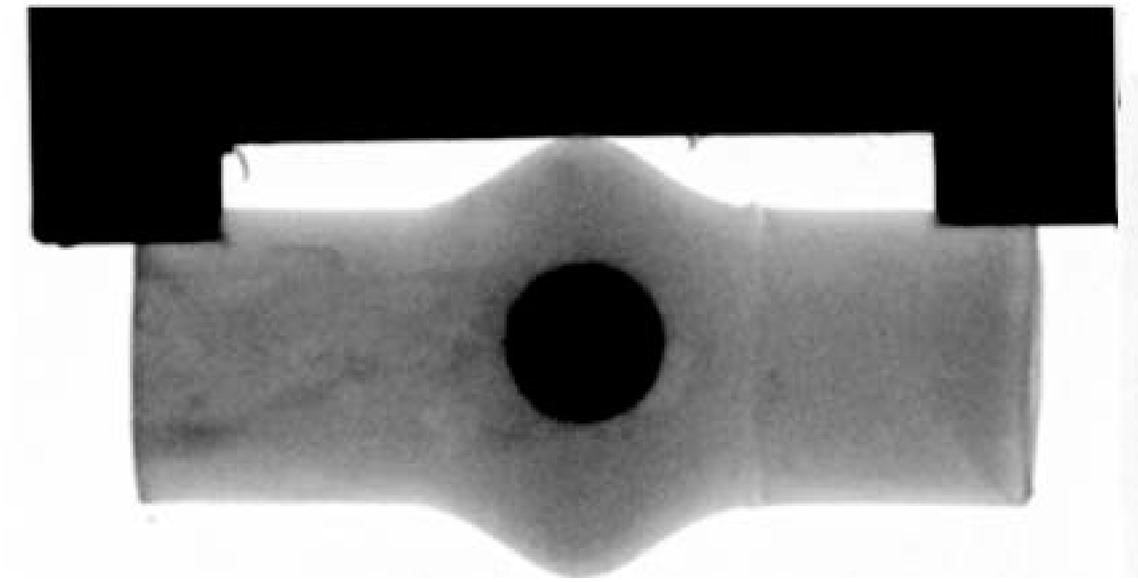

Figure 11. X ray of dynamic hohlraum radiation shaping.

DOUBLE SHELL TARGETS

Double-shell targets may be required for the next generation of inertial confinement fusion targets since the energy available for driving the implosion is limited with current drivers. The use of double shell targets to provide a velocity multiplication driven implosion is an alternative to increased driver energy.

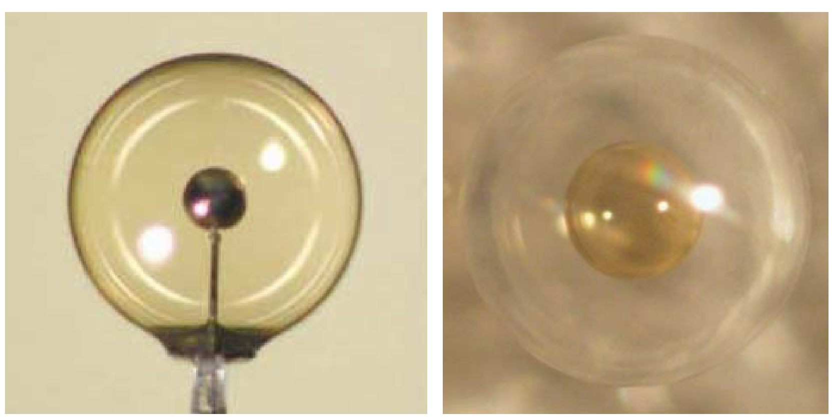

Figure 12. Stalk mounted and foam levitated double shell hammer and anvil targets. The right pellet consists of an inner fuel capsule supported in an aerogel and surrounded by a plastic outer shell ablator.

The two layers are separated by cast or machined foams which could be a silica aerogel, organic foam or doped foam with densities ranging from 3 to 850 mg/cm^3. The materials used are polysterene, divinyl benzene (DVB), recorcinol formaldehyde (RF) aerogel, carbonized resorcinol-formaldehyde and poly 4-methyl-1-pentene (TPX). Multiple glow discharge polymer layers have been produced by doping them with Si, Ge, Cl, Cu or D. Foams are generally used in fusion targets to prevent diagnostic holes closure or to support the diagnostics or capsules.

Table 1. Different foams used in fusion targets.

Foam	Density [mg/cm^3]	Cell size	Chemical Composition
HIPE Polysterene	15-700	1-10 µm	CH
Resorcinol Formaldehyde (RF)Aerogel	20-850	nm	62 w/0 C, 38 w/0 O&H Carbonized 93 w/0 C
Silica Aerogel	10-700	nm	SiO
Divinyl Benzene (DVB)	15-200	1 µm -4 µm	CH
Poly 4-methyl-1-pentene, TPX	3-250	1-15	CH_2

For deuterium and tritium gases a permeation barrier made of poly vinyl alcohol (PVA), which has one of the lower permeation rated against hydrogen among polymers. SiO_2 coatings can be used as a permeation barrier for deuterium.

In stalk mounted double shells, the inner shell could be glass or a polymer, and the outer shell is machined to allow the mounting of the inner shell. A gas permeation barrier is placed on the outer shell to allow the filling of the void between the two shells.

The x rays generated by lasers in a double shell target hit the outer ablator whose surface evaporates and through an inverse rocket action implodes and collides with the smaller inner shell containing a DT fuel. The plastic ablator is made of polysterene doped with bromine. The aerogel is made of silica dioxide aerogel, one of the lowest density materials in existence. When the ablator shell implodes hydrodynamic stability near the fuel is crucial to attain ignition conditions of billions of atmospheres in pressure and tens of millions of degrees in temperature.

MATERIALS CHOICES

Indirect drive targets have used a 50 percent mixture of Au and Gd for hohlraum wall materials, for high reflectivity to soft x-rays. Materials for power plant targets will have additional requirements including the feasibility and cost of fabrication, of recycling, and issues associated with radioactivity activation, chemical safety, and corrosion.

Table 2 compares some choices on the basis of the driver energy absorbed in the wall. Some choices perform as well as Au and Gd, but other factors also need consideration. Both mercury and lead will attack steel, and are chemically toxic. Mercury volatility results in 10,000 times lower inventory than with lead, and therefore lower corrosion.

Table 2. Effect of hohlraum wall material choices on energy at the wall surface with a gold-gadolinium as a reference.

Hohlraum wall material composition	$\frac{E_{material\ at\ wall}}{E_{AuGd}}$
Au:Gd (50:50)	1.0
Au	1.25
Pb	1.28
Hg	1.26
Hg:Xe (50:50)	1.18
Hg:Ta:Cs (45:20:35)	1.03
Pb:Hf (70:30)	1.04
Pb:Hf:Xe (45:20:35)	1.00
Pb:Hf:Xe:Kr (45:20:20:15)	1.00

The different choices lead to different engineering problems. Mercury has a higher saturation concentration in air, and lead precipitates and freezes out on surfaces making recovery and maintenance difficult. Hafnium can be separated by contact with beryllium in an on-line slipstream, as planned to reduce the molten salt and remove corrosion products. The beryllium electrodes would be processed off line to remove the hafnium. At 6 Hz repetition rate, about 0.25 g of these materials on the inside of each hohlraum, gives 50 tons/y to recycle. Xenon, with krypton, would be frozen on the surface along with mercury and hafnium. The optimum materials choices because the costs of safety, corrosion protection, fabrication and reprocessing could counterbalance higher accelerator costs needed to compensate for lower target gain resulting from the extra wall losses.

DRIVERS FOR INERTIAL CONFINEMENT FUSION

The fusion targets can be illuminated with the energy of different drivers. The primary efforts in inertial confinement exist in the USA, France and Japan. Some major drivers efforts at the USA sites includes:

1. Heavy ions driver at Lawrence Berkeley National Laboratory, LBNL (Fig. 13).
2, Diode pumped solid state neodymium lasers at Lawrence Livermore National Lab oratory, LLNL (Fig. 14).
3. Krypton Fluoride KrF lasers at the USA Naval Research Laboratory, NRL (Fig. 15).
4. The Z pinch x rays at Sandia National Laboratory, SNL (Figs. 16, 17).
5. Laser capsules irradiation at the University of Rochester.
6. Capsules fabrication at General Atomics, GA.

Light ions and electron beams are also under consideration.

Figure 13. Heavy ion four beams accelerator at Lawrence Berkeley National Laboratory.

Figure 14. National Ignition Facility, NIF, Lawrence Livermore National Laboratory, LLNL.

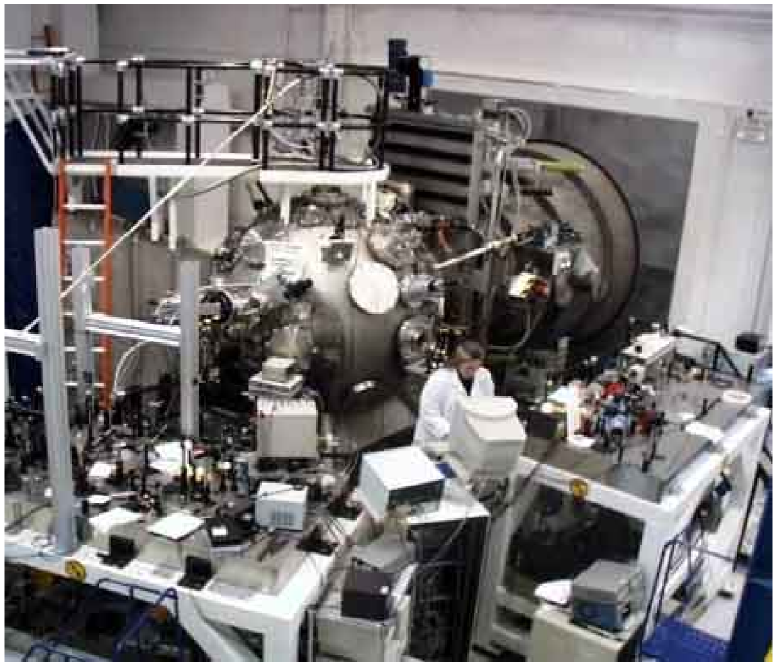

Figure 15. Nike Krypton Fluoride KrF laser chamber at the Naval National Laboratory, NRL.

Figure 16. The 20-MA Z-pinch facility at Sandia National Laboratory (SNL).

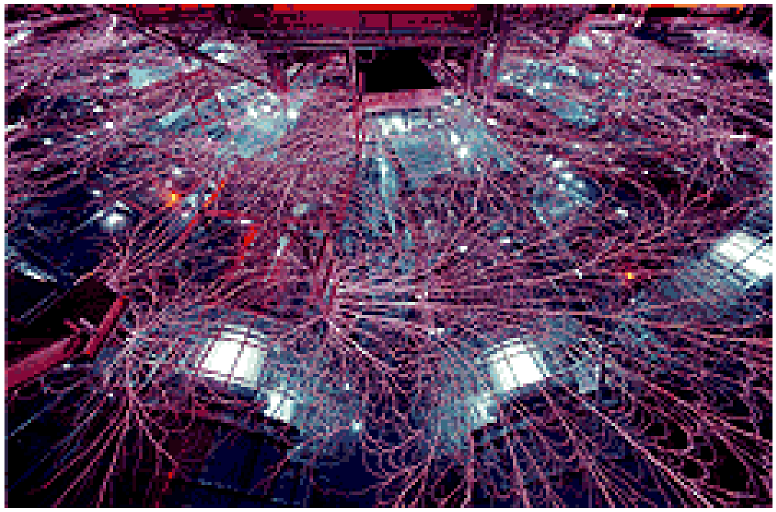

Figure 17. The Z-pinch facility at Sandia National Laboratory (SNL), showing electrical discharges in water along beam lines.

LIGHT ION BEAM DRIVER

Light ion beams are one of the best options for an Inertial Confinement Fusion (ICF) driver from the standpoint of efficiency, standoff, repetition rate operation and cost. This approach uses high-energy density pulsed power to accelerate ions efficiently at fields of 0.5 to 1.0 GV/m, producing a medium energy (30 MeV), high-current (1 MA) beam of light ions that have an appropriate range to couple to an ICF target. Ion beams provide the ability for medium distance transport at around 4 meters of the ions to the target, and standoff of the driver from high-yield implosions. Repetition rate operation of high current ion sources has also been demonstrated for industrial applications and could be developed for ICF. Although these factors make light ions the best long-term pulsed power approach to ICF, light-ion research at Sandia National Laboratory (SNL) was placed on hold in 1996 in order to develop a z-pinch-driven approach to ICF x ray implosion capsule research that has an excellent opportunity to achieve the USA Department of Energy goal of high-yield fusion on a single-shot basis.

TRIDENT SYSTEM AT LANL

Trident is Los Alamos National Laboratory (LANL) multipurpose system for conducting experiments requiring high-energy laser-light pulses. It supports laser-driven high energy density (HED) physics experiments and associated diagnostic development in ICF, weapons physics, and basic science. Trident has a three-beam frequency-doubled Nd:glass laser driver and two vacuum target chambers. It has operated reliably for a decade, principally at its design pulse-length range of 0.1–2.5 ns, producing up to 250 Joules in each of its two main beam lines and up to 60 J in the third, smaller beam line. I

NATIONAL IGNITION FACILITY, NIF AT LLNL

The National Ignition Facility (NIF) arena-sized building houses 192 laser beams designed to deliver 1.8 million joules of ultraviolet laser energy and 500 terawatts of power to millimeter-sized targets located at the center of its 10-meter-diameter target chamber (Fig. 14).

The Injection Laser System creates a precisely shaped nanojoule-level laser pulse, which is amplified by a factor of more than 1,000,000 before entering the laser beam path. There, two stages of laser amplifiers again increase the laser energy, using the world's largest optical switch to enable multi-pass amplification.

Beam Transport components direct the beams through the laser beam path while adaptive optics eliminate wave front aberrations and opto-mechanical components smoothing and filter the beams, retaining their specific spatial and temporal characteristics. Final Optics Assemblies convert the wavelength of the laser from near infrared to ultraviolet and precisely focus the beams to the target chamber center, for the purpose of creating extreme temperatures and pressures in high energy density experiments or for creating conditions necessary to achieve fusion ignition.

TARGETS PREPARATION

For high energy density and fusion ignition experiments, the target is a metal cylinder, typically made of gold or lead, about 6 mm in diameter and 10-mm long. The cylinder contains a plastic fusion capsule about 3 mm in diameter. The capsule is chilled to a few degrees above absolute zero and is lined with a layer of solid DT fusion fuel. The hollow interior also contains a small amount of DT gas.

Laser beams deposit their energy on the inside surface of the metal cylinder or hohlraum where the energy is converted to thermal x-rays. The x-rays fill up the hohlraum and uniformly heat and ablate the plastic surface of the ignition capsule, causing an inverse rocket-like pressure on the capsule and forcing it to implode.

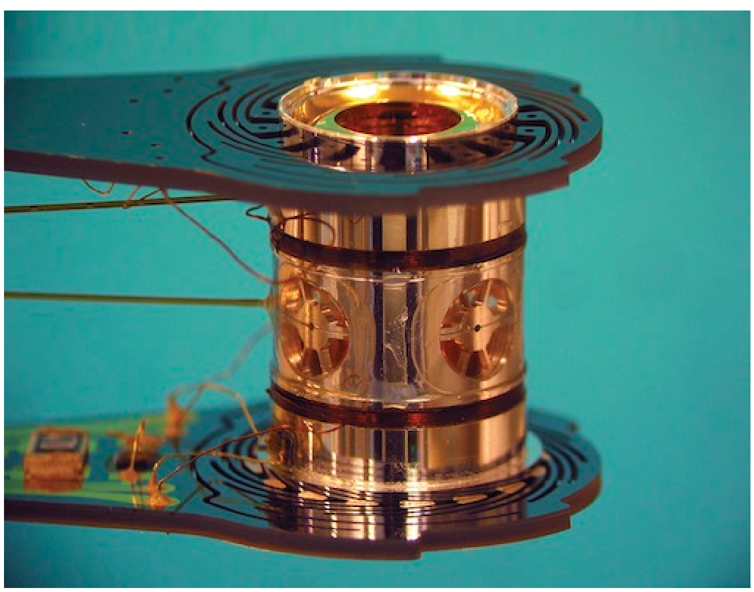

Figure 18. Hohlraum target at National Ignition Facility (NIF).

TARGET CHAMBER

The target chamber (Fig. 18) is a 1,000,000 pound, 10-meter-diameter aluminum sphere that is the mechanical interface between the final optics assemblies and the target positioned at the chamber center.

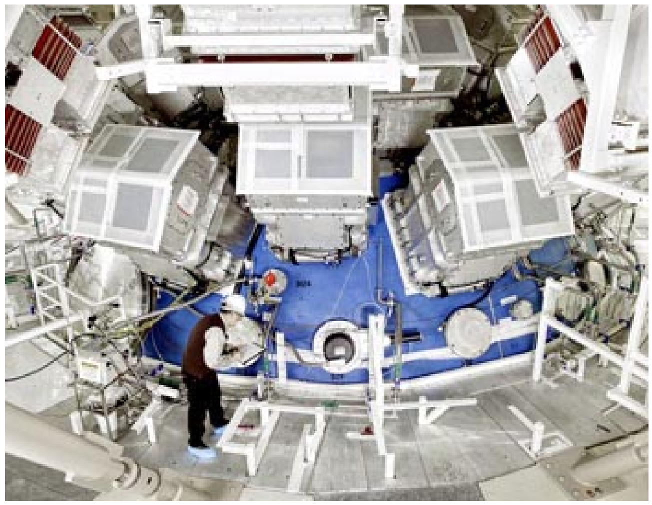

Figure 19. Top of NOVA target chamber.

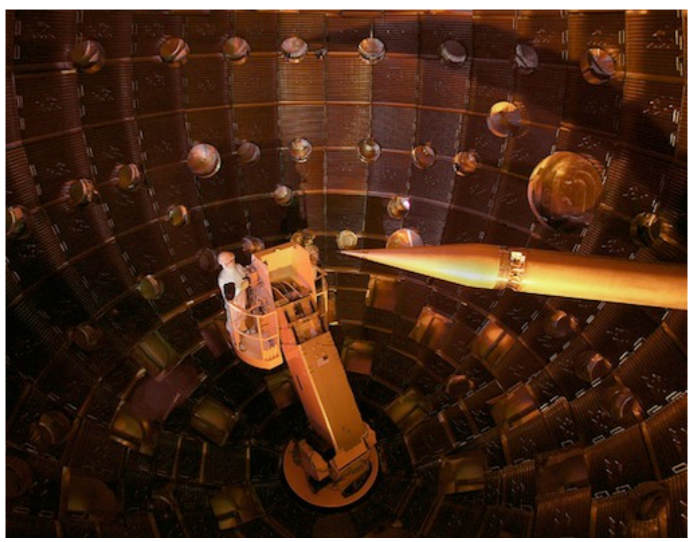

Figure 20. Interior of target chamber at NIF.

Laser beams in groups of four as 2 by 2 arrays pass through the final optics assemblies frequency-conversion crystals, then through wedge-shaped lenses that focus the ultraviolet beams on a fusion target.

Figure 21. Target chamber for the NOVA laser.

Figure 22. Laser beam lines of NOVA laser.

The target chamber provides a vacuum environment for the target and numerous mounting and alignment points for the final optics assemblies and diagnostics that record experimental results. Diagnostic instruments, such as x-ray spectrometers, microscopes, and cameras, can be mounted around the equator and at the poles of the target chamber using 120 available diagnostic ports. The chamber also has 72 final optic assemblies ports, 48 of which are configured for 192-beam indirect-drive experiments.

FINAL OPTICS ASSEMBLIES

The neodymium glass laser generates light at a wavelength of about 1.053 micrometers in the infrared region. However, inertial fusion targets perform more efficiently when they are driven with ultraviolet radiation. Target-chamber mounted Final Optics Assemblies convert the infrared of 1.053-micron wavelength light to the ultraviolet region at approximately 0.351 micron, using a system of two nonlinear crystal plates made of potassium dihydrogen phosphate (KDP) crystal (Fig. 21).

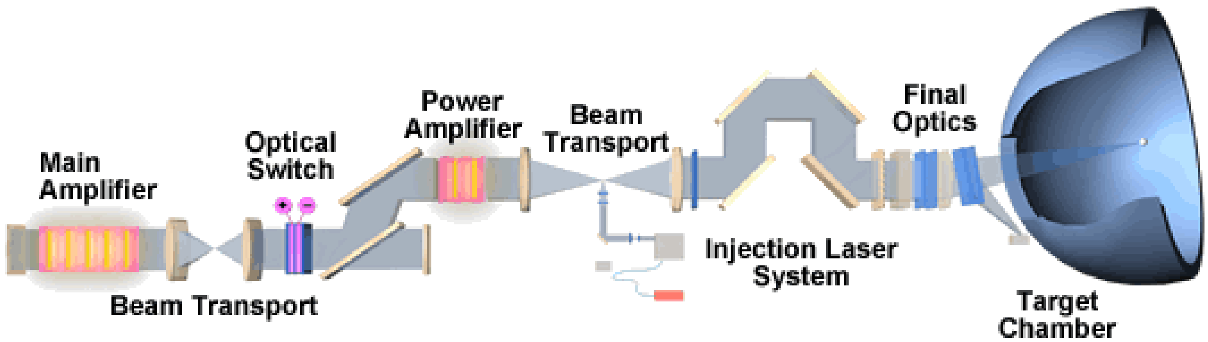

Figure 23. National Ignition Facility laser beam line.

The first plate converts two-thirds of the incident 1.05-micron radiation to the second harmonic at 0.53 microns. Then, the second crystal mixes that radiation with the remaining 1.05-micron light to produce radiation at 0.35 microns. This process has a peak efficiency greater than 80 percent, and the efficiency can exceed 60 percent for the complex pulse shapes used to drive ignition targets.

The final optics assemblies are the last element of the main laser system and the first of the target area systems. At NIF, 192 beamlines feed into the 48 final optics assemblies mounted to the surface of the target chamber. The conversion crystals are mounted and precisely aligned to the beamline. The lens focuses the light to the target location, and a beam-smoothing phase plate is located with the debris shield for ease of changeout. The final optics assemblies provide a vacuum barrier for the target chamber, and provide a protective shield from target debris.

HURDLES TO BE SURMOUNTED

To achieve fusion ignition, NIF scientists need to implode the fuel at a speed of 360 kms / sec and compress it with a pressure equal to 350 billion Earth atmospheres. In April 2012, they reached the speed of 330 kms / sec and 202 billion atmospheres, still away from the ignition goal by energy loss processes.

Laser beams entering the hohlraum are generating fewer x-rays than initially expected. The implosions that are intended to be symmetrical to reduce energy loss, are shaped more like apples or pears. Misdirected energy melts the frozen fuel before fusion is initiated.

Experimentation is ongoing with longer hohlraums to reposition the laser beams and increase symmetry. Fuel pellets that are thicker, oblong in shape like foot-balls and coated with boron carbide are tried with the hope of boosting pressure to 250 billion atmospheres.

The inefficiency of the indirect drive method is being addressed. During a typical test, less than 2 percent of laser energy reaches the fuel mostly heating the hohlraum. This could be overcome by expanding to 3 MJs of energy with upgraded laser lenses.

The National Academy of Sciences is calling for continued experiments with the direct drive approach, in which laser light is deposited directly at the surface of the fuel creating an inverse rocket process.

To attain commercial fusion power production, laser diodes made of silicon or germanium crystals that conduct electricity and that can fire at a repetition rate of 10 times per second, will be needed. The neutron energy from the DT reaction would be extracted in a lithium blanket surrounding the reactor in which tritium will also be bred from lithium.

IGNITION GOAL

The projected NIF progression toward energy breakeven, plasma burn then ignition is shown in Fig. 24 in terms of the Lawson parameter or breakeven criterion at which the energy output from the plasma exceeds the energy input used to generate it and the associated losses:

$$n_i \tau_E T_i \geq 10^{20} [\frac{ions.\sec.keV}{m^3}] \tag{5}$$

where: n_i is the ions density in [ions/m^3],

τ_E is the energy confinement time [sec],

T_i is the plasma ion energy in keV.

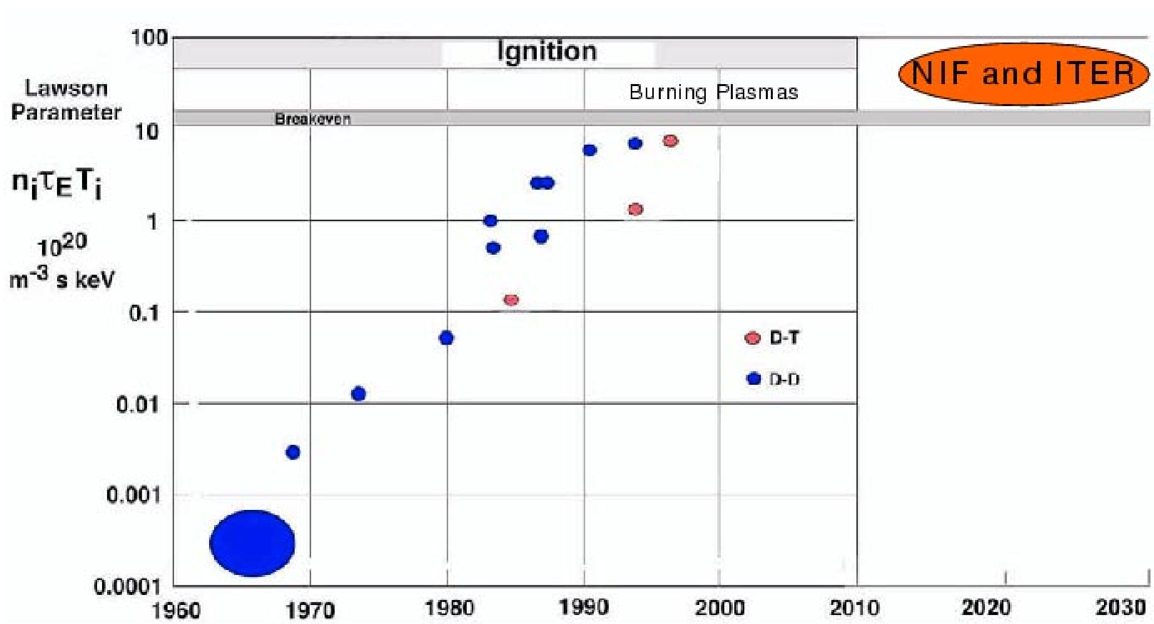

Figure 24. Progress toward breakeven conditions, burning plasmas then ignition in inertial confinement (NIF) and magnetic confinement (ITER) fusion in terms of the Lawson criterion.

Researchers at the Lawrence Livermore National Laboratory (LLNL) announced on February 12, 2014 that they have achieved conditions at the National Ignition Facility nuclear fusion system producing more energy than it initially absorbed. Reporting in the journal Nature, researchers said they were the first to tease more energy out of a fusion reaction than had been absorbed by the fuel used to spark it.

They focused 192 laser beams onto a spot narrower than the width of a human hair to generate enough energy to compress a tiny fuel-containing capsule to 1 / 35th of its original size. Lasting less than a billionth of a second, the reaction put out the equivalent of the energy stored in two AA batteries or about 17,000 joules in their latest experiment in November 2013. The output was higher than the estimated 9,000-12,000 joules of energy taken up by the fuel. The yield was 10 times greater than previously achieved.

However, it was not a sustained reaction or ignition. It still does not answer the efficiency challenge of releasing more fusion energy than is consumed overall, according to the Lawson criterion. The lasers put out about 1.9 million joules of energy or the equivalent energy in a small car battery of which only 9,000-12,000 joules were absorbed by the fuel. Only something one percent of the energy put in from the laser ends up in the fuel. The method needs to be refined and the yield boosted 100 times before getting to the point of ignition.

Ignition requires self-propagation, in which the first fused particles cause the heat and pressure to build even further, thus creating more particles, and so on, to boost the energy yield.

The lasers were focused at a gold cylinder two millimetres or 0.08 inches in diameter that was coated on the inside with a frozen layer of the deuterium-tritium fuel. The light entered through holes on one end and re-focused in x-rays that blasted off the cylinder's outer shell and caused the remainder to implode on a scale likened to shrinking a basketball to the size of a pea. The process generated pressure 150 billion times stronger than that exerted by Earth's atmosphere and a density 2.5 to three times greater than the core of the Sun, the scientists said.

The research, published in the Journal Nature, involved a Petawatt power laser used to try to ignite fusion plasma fuel in a confined space. Each pulse of the laser, which delivered a peak power of 10^{15} Watts, lasted less than 30 femtoseconds, or 30×10^{-15} second.

The laser, at the National Ignition Facility (NIF), uses 192 beams 300 yards long that focus on a fuel cell about the diameter of a No. 2 pencil. Target handling systems precisely position the target and freeze it to cryogenic temperatures (18 kelvins, or -427 degrees Fahrenheit) so that a fusion reaction is more easily achieved.

While powerful, the laser has not yet been able to ignite the plasma fuel. When and if it does, the fuel would begin to burn in a self-sustaining reaction to such a degree that it will produce a megajoule of energy. In the case of laser fusion, the burn time is typically a few tens of picoseconds. The latest achievement marks the accomplishment of a key goal on the way to plasma fuel ignition: the project generated energy through a fusion reaction that exceeded the amount of energy deposited into deuterium-tritium fusion fuel and hot spot during the implosion process, resulting in a fuel gain greater than unity. Reaching ignition is planned over the 2014-2030 time period.

HYBRID FUSION FISSION APPROACH

INTRODUCTION

The DT fusion reaction produces about 17.6 MeV of energy, whereas a fission reaction produces about eleven times this amount at 200 MeV of energy per fission event. However, the neutrons from the DT fusion reaction have an energy of 14.06 MeV which about seven times the average energy of a fission neutron at 1.99 MeV.

Fusion is from that perspective neutron rich but energy poor, fission can be considered as energy rich but neutron poor. Combinations of fusion and fission can use these characteristics to produce hybrids that can be more effective than using either one of them alone. In that context three possibilities offer themselves:

1. Amplify the energy from the fusion reaction by using its highly energetic 14.06 MeV neutrons to fission the fissionable but not fissile uranium isotope U^{238} which has a 6.1 MeV threshold for the fission reaction. In this case neutrons with energy lower than the threshold do not generate fission processes in U^{238}. Depleted uranium can be used for this purpose. Alternatively the cheaper and more abundant fissionable Th^{232} isotope can be used. Other minor actinide fissionable actinide isotopes such as U^{236} or Pu^{240} can be used if available as byproducts from the fission fuel cycle.
2. For a broader range of energy amplification with neutrons over the whole energy range one could use the fissile isotopes U^{233}, U^{235}, Pu^{239}, Pu^{241} and possibly Np^{237}. In this case the amounts used do not need to reach a critical mass.
3. Instead of using neutrons, channel the energy release from the fusion reaction in the form of blast shock wave and x rays to compress a small mass of a fissile isotope to its critical mass in the compressed state. In this case micro amounts of the fissile fuel could be used to generate micro fission explosions. These could be particularly useful if the ionized products of the micro fission explosion can be directed by a magnetic field through a nozzle for rocket propulsion. Such a rocket would possess a considerably larger specific impulse than a chemical rocket. For a Mars trip, the mission travel time could be reduced from a year to just weeks in duration.

Channeling the energy from the fusion target to the micro fission pellet using suitable geometrical configurations and physical phenomena becomes a necessity.

LOGARITHMIC SPIRAL RADIATION SHAPING

The radiation from the fusion pellet can be shaped to uniformly compress a fission small fissile mass that is otherwise subcritical to a compressed critical or supercritical configuration if two materials possessing different propagation velocities to the radiation emitted from the fusion pellet are used. For instance one material could be plastic foam, and the other a vacuum or gas filled gas space. Recall that sound waves, for instance, travel faster in a solid such as rail road tracks than in air signaling the arrival of a train earlier than the sound waves traveling in air.

The material with the higher propagation velocity v_A would have to envelop the material with the lower propagation velocity v_B. For uniform irradiation of the fission micro pellet, the rays impinging directly onto it along the radius r_0 with the smaller propagation velocity v_B must arrive there at the same time as the rays that travel initially along the path [ab] in the material with the larger propagation velocity v_A then with the smaller velocity v_B along the radius r to the fission micro pellet.

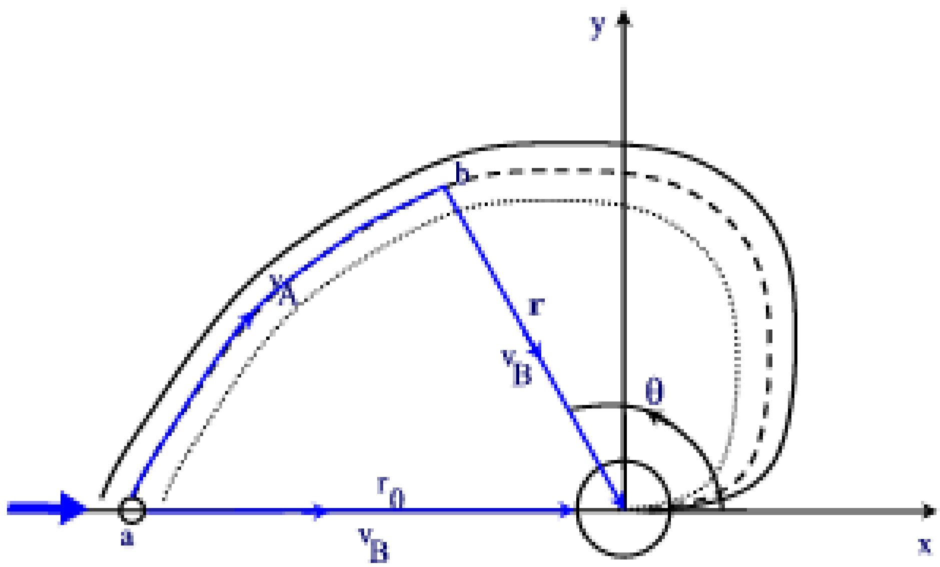

Figure 25. Radiation shaping from a fusion target used to compress a fission target at the origin using a logarithmic spiral.

To determine the appropriate needed path we assume a two dimensional spherical geometry configuration. The geometry turns into a three dimensional spherical geometry upon rotation around the x axis as an axis of symmetry.

We consider the general case ray that travels along the path [ab] with velocity v_A, then with the velocity v_B along the path r.

Fermat's principle from the field of geometrical optics states that the sum of the times spent by the ray in the two media is a minimum:

$$T = \tau_A + \tau_B = \text{Minimun} \qquad (6)$$

In terms of the path along the ray, the propagation time must satisfy:

$$T = \int_a^b \frac{ds}{\mathrm{v_A}} + \int_r \frac{ds}{\mathrm{v_B}} = \text{Minimum} \qquad (7)$$

For constant propagation speeds, the propagation time can be expressed as:

$$T = \frac{\int_{a}^{b} \mathrm{ds}}{\mathrm{v}_A} + \frac{r}{\mathrm{v}_B} = \text{Minimum} \qquad (8)$$

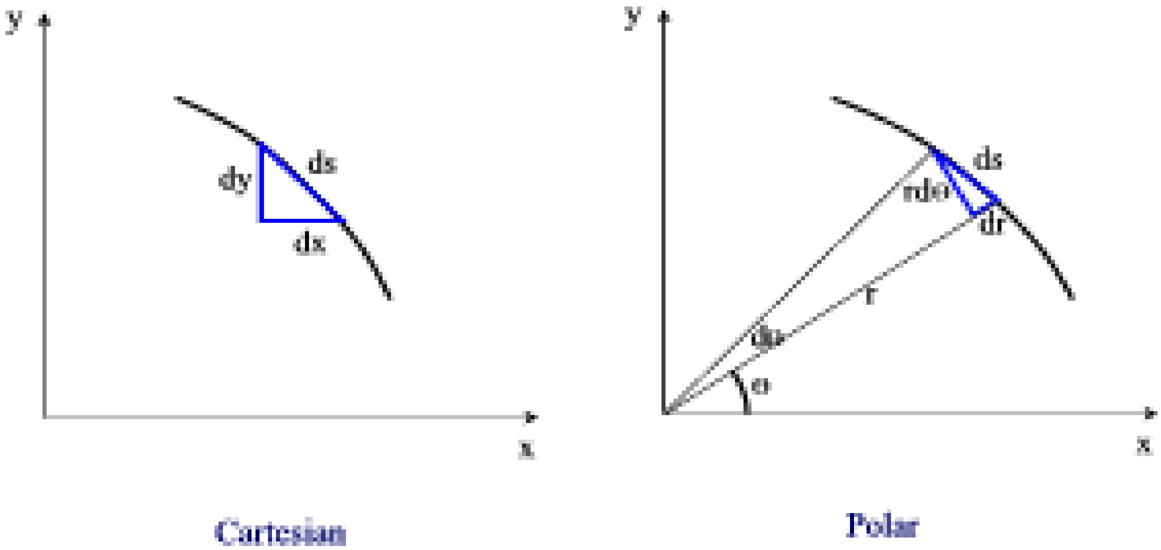

Figure 26. The Cartesian and Plane Polar coordinates systems.

In Cartesian coordinates, using the Pythagorean Theorem, the element of length ds is expressed as:

$$\begin{aligned} (ds)^2 &= (dx)^2 + (dy)^2 \\ ds &= \sqrt{1 + \left(\frac{dx}{dy}\right)^2}\,.dy \end{aligned} \qquad (9)$$

In plane polar coordinates, the element of length ds can be expressed as:

$$\begin{aligned} (ds)^2 &= (dr)^2 + (rd\theta)^2 \\ (ds)^2 &= [(\frac{dr}{d\theta})^2 + r^2](d\theta)^2 \\ ds &= \sqrt{r^2 + (\frac{dr}{d\theta})^2}\,.d\theta \end{aligned} \qquad (10)$$

Expressing the Fermat principle in plane polar coordinates by substituting the expression of ds with the path integral starting from the polar angle $\theta = \pi$ is:

$$T(r,\theta) = \frac{\int_{\pi}^{\theta} \left[r^2 + (\frac{dr}{d\theta})^2 \right]^{1/2} .d\theta}{\mathrm{v_A}} + \frac{r}{\mathrm{v_B}} = \text{Minimum} \qquad (11)$$

To satisfy the minimum condition, we estimate the partial first derivative of T with respect to θ and equate it to zero:

$$\frac{\partial T(r,\theta)}{\partial \theta} = \frac{1}{\mathrm{v_A}} \left[r^2 + (\frac{dr}{d\theta})^2 \right]^{1/2} + \frac{1}{\mathrm{v_B}} \frac{dr}{d\theta} = 0 \qquad (12)$$

By rearranging the equation we get:

$$\left[r^2 + (\frac{dr}{d\theta})^2 \right]^{1/2} = -\frac{\mathrm{v_A}}{\mathrm{v_B}} \frac{dr}{d\theta}$$

Squaring both sides:

$$r^2 + (\frac{dr}{d\theta})^2 = -(\frac{\mathrm{v_A}}{\mathrm{v_B}})^2 (\frac{dr}{d\theta})^2$$

Separating the derivative term:

$$(\frac{dr}{d\theta})^2 = \frac{r^2}{(\frac{\mathrm{v_A}}{\mathrm{v_B}})^2 - 1}$$

Taking the square root of both sides:

$$\frac{dr}{d\theta} = \frac{r}{\sqrt{(\frac{\mathrm{v_A}}{\mathrm{v_B}})^2 - 1}}$$

Denoting the velocities ratio as:

$$\begin{aligned} &\beta^2 = \left(\frac{\mathrm{v_A}}{\mathrm{v_B}} \right)^2 = n^2 \\ &\mathrm{v_A} > \mathrm{v_B} \\ &\beta > 1 \end{aligned} \qquad (13)$$

The velocity ratio β can be recognized as being the same as the refraction coefficient n in optics. Consequently we can write the first order differential equation defining the sought curve as:

$$\frac{dr}{d\theta} = \frac{r}{\sqrt{\beta^2 - 1}} \tag{14}$$

Separating the variables we get:

$$\frac{dr}{r} = \frac{d\theta}{\sqrt{\beta^2 - 1}}$$

Integration after setting the limits on r and θ we get:

$$\int_{r_0}^{r} \frac{dr}{r} = \frac{1}{\sqrt{\beta^2 - 1}} \int_{\pi}^{\theta} d\theta \tag{15}$$

Integration yields the geometrical curve that would channel the radiation from the fusion source to the fission target as:

$$\ln \frac{r}{r_0} = \frac{1}{\sqrt{\beta^2 - 1}} (\theta - \pi) \tag{16}$$

Taking the exponential of both sides yields:

$$r = r_0 e^{\frac{\theta - \pi}{\sqrt{\beta^2 - 1}}} \tag{17}$$

This is the equation of the Logarithmic Spiral in plane polar coordinates.

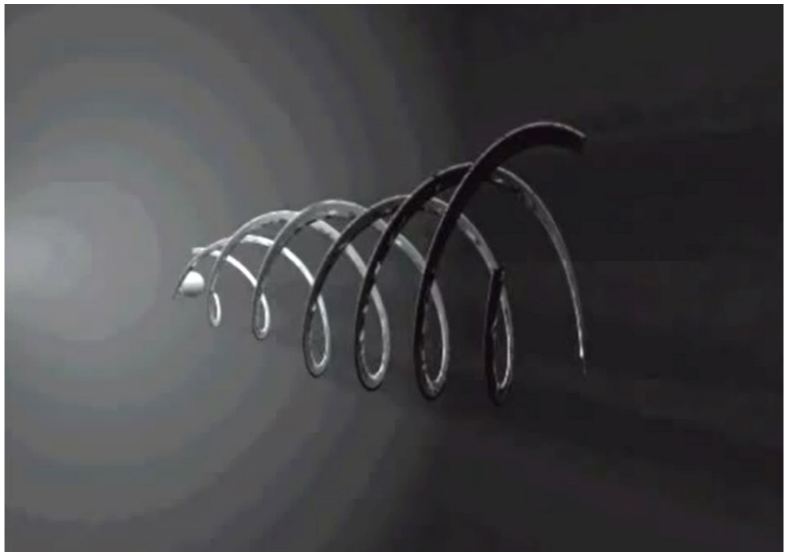

Figure 27. Three dimensional logarithmic spiral.

EXERCISES

1. Calculate the attainable density of metallic uranium if it is included in a hybrid fusion-fission pellet if it imploded in cylindrical and spherical geometry to:
    1. One half its initial radius
    2. One tenth its initial radius.

2. Derive the equation for the three dimensional logarithmic spiral using spherical coordinates.

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