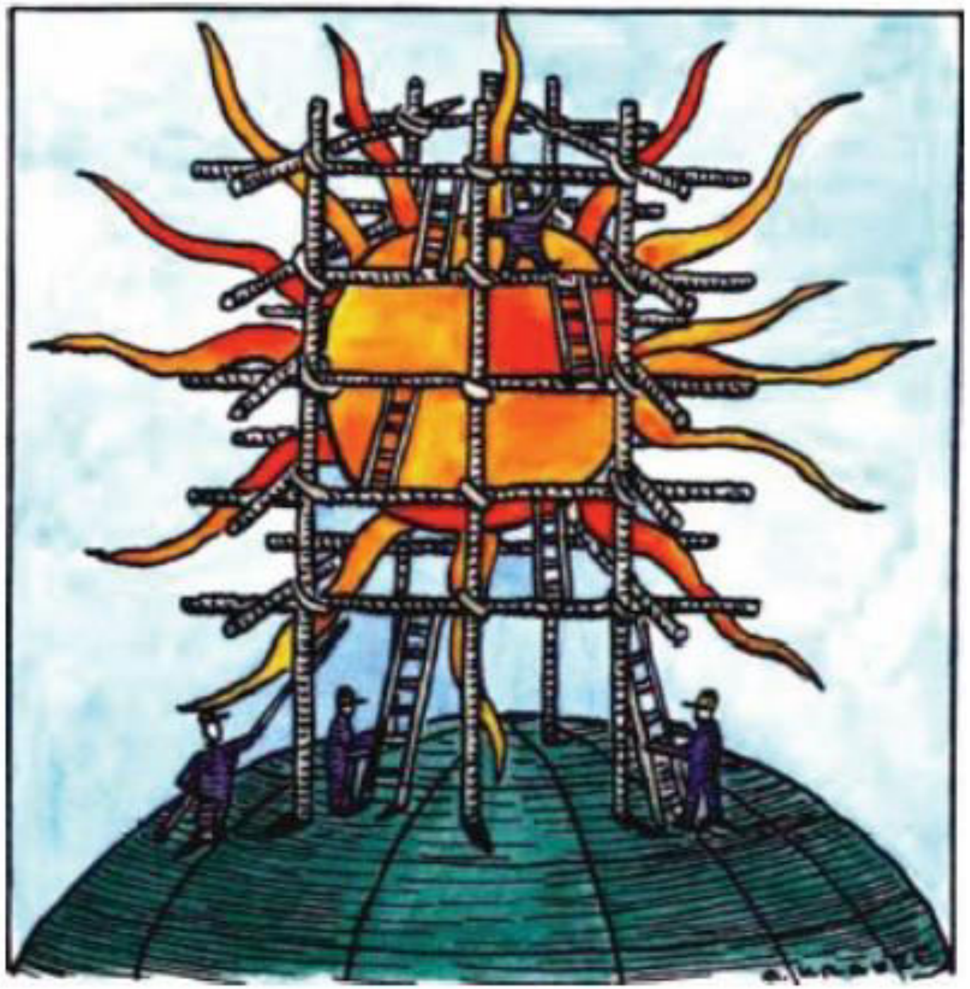
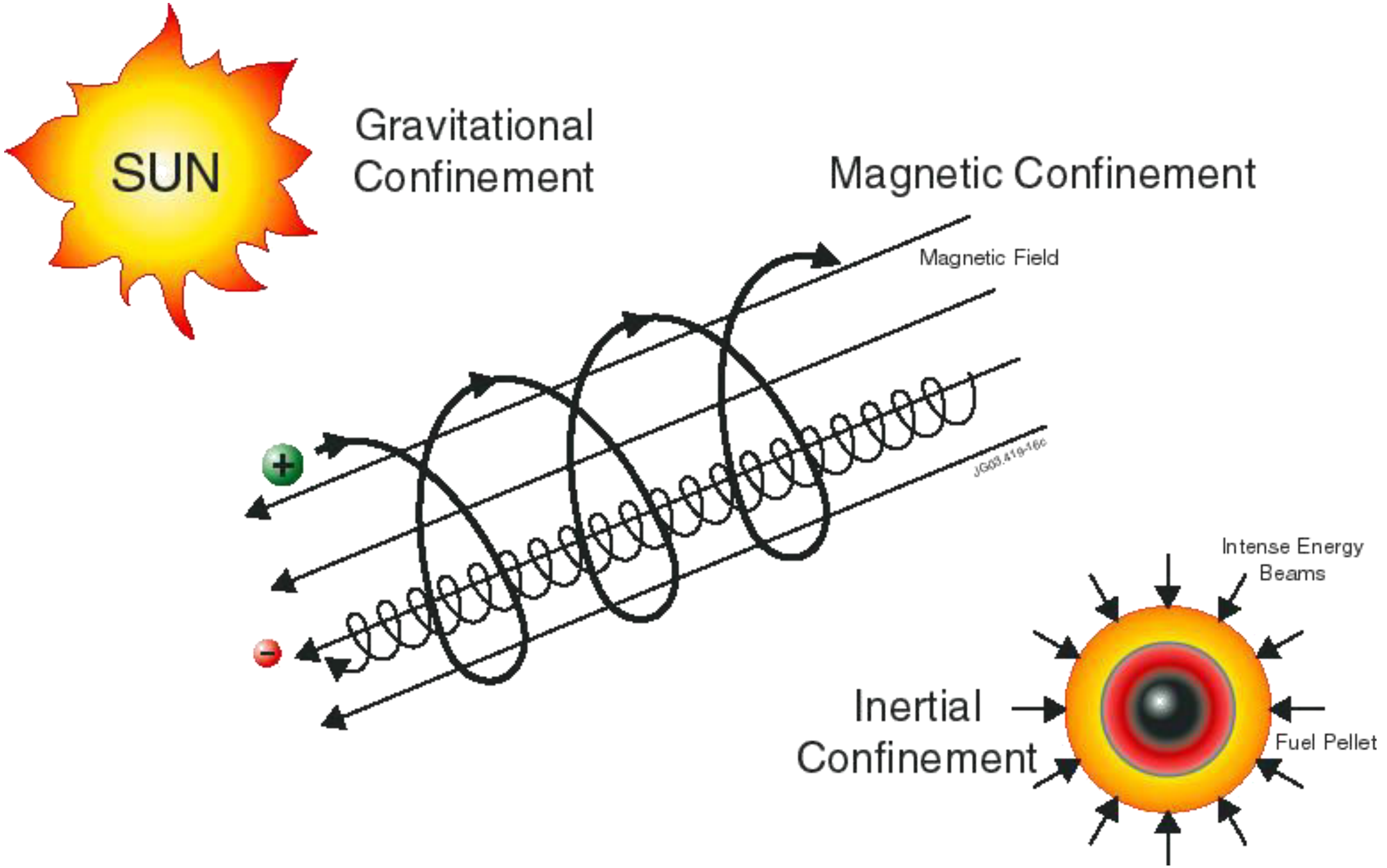
Introduction to Nuclear Fusion

Prof. Dr. Yong-Su Na

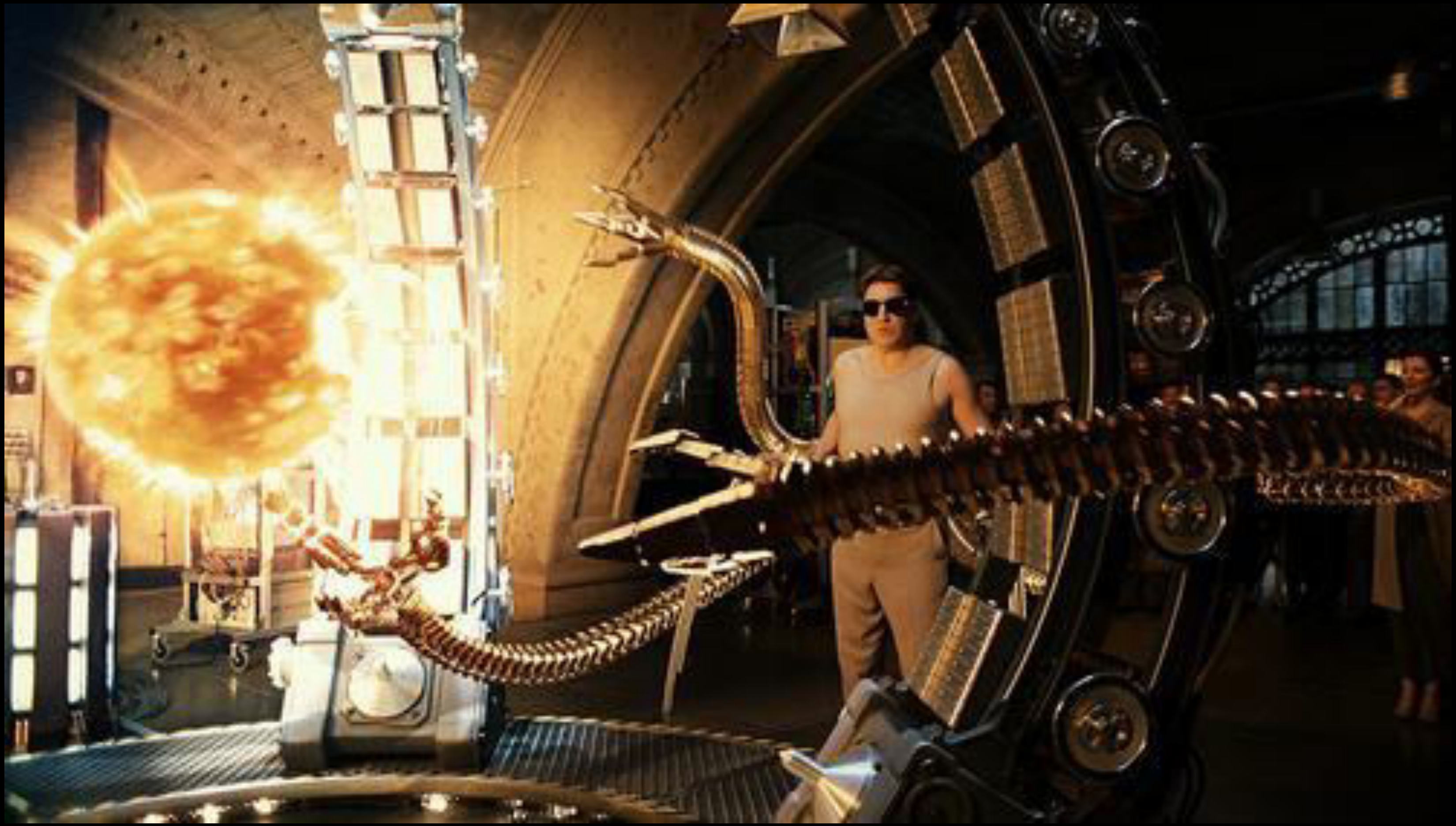
To build a sun on earth



To build a sun on earth



What is inertial confinement?

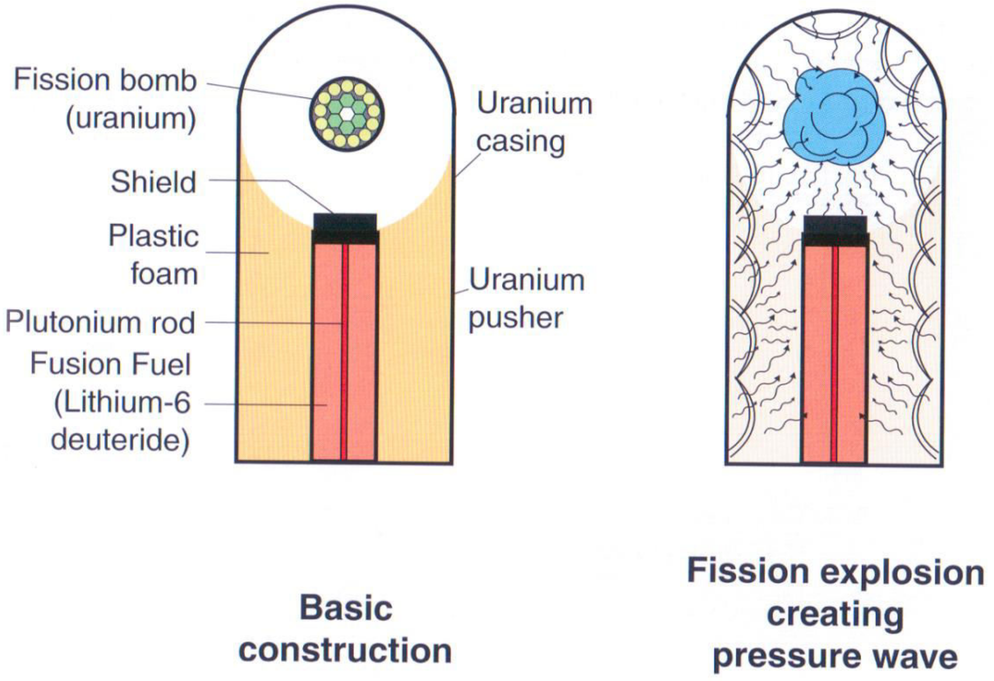


Spiderman 2 (2004), Columbia Pictures

Spiderman II

Spiderman 2 (2004), Columbia Pictures

Hydrogen Bomb



Ivy Mike (1 November 1952)

- **Teller–Ulam configuration (radiation implosion)**

- A fission explosion is first triggered, contained inside a heavy metal case.
- The radiation (X-rays) from the fission bomb reaches the nearby fusion fuel almost instantaneously and be used to compress, then 2nd fission explosion heats the already compressed fusion fuel to ignite before it is blown apart by the blast wave from the fission explosion.

G. McCracken, P. Stott, "Fusion The Energy of the Universe", Elsevier (2005)   *http://www.quimlab.com.br/guiadoselementos/einstenio.htm*

Inertial Fusion Energy (IFE)

- **1963**

Nikolay G. Basov, Aleksandr M. Prokhorov at the Lebedev Institute in Moscow put forward the idea of achieving nuclear fusion by laser irradiation of a small target

WIKIPEDIA
The Free Encyclopedia

Nicolai Basov (1922-2001)

Aleksandr Prokhorov (1916-2002)

- Nobel Laureate in physics jointly with Charles Townes in 1964 for their development of the field of quantum electronics, which led to the discovery of the laser.
- Nicolai Basov was the leader of the Soviet program on inertial-confinement fusion for many years.

Inertial Fusion Energy (IFE)

NATURE VOL. 239 SEPTEMBER 15 1972 139

Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) Applications

JOHN NUCKOLLS, LOWELL WOOD,
ALBERT THIESSEN & GEORGE ZIMMERMAN
University of California Lawrence Livermore Laboratory

Hydrogen may be compressed to more than 10,000 times liquid density by an implosion system energized by a high energy laser. This scheme makes possible efficient thermonuclear burn of small pellets of heavy hydrogen isotopes, and makes feasible fusion power reactors using practical lasers.

The electrons in white dwarf cores are Fermi-degenerate, so the pressure is a minimum determined by the quantum mechanical uncertainty and exclusion principles[7]. The pressure of dense hydrogen with Fermi-degenerate electrons is[8]

$$P = \frac{2}{3} n_e \varepsilon_F \left[\frac{3}{5} + \frac{\pi^2}{4} \left(\frac{kT}{\varepsilon_F} \right)^2 - \frac{3\pi^4}{80} \left(\frac{kT}{\varepsilon_F} \right)^4 + \cdots \right]$$

where n_e is the electron density; $\varepsilon_F = \frac{h^2}{8m} \left(\frac{3}{\pi} n_e \right)^{2/3}$ is the Fermi energy; kT is the thermal energy; h is Planck's constant, and m

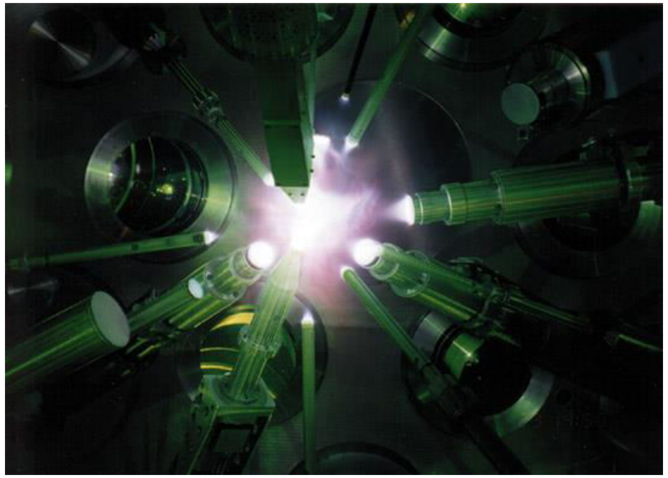
Inertial Fusion Energy (IFE)

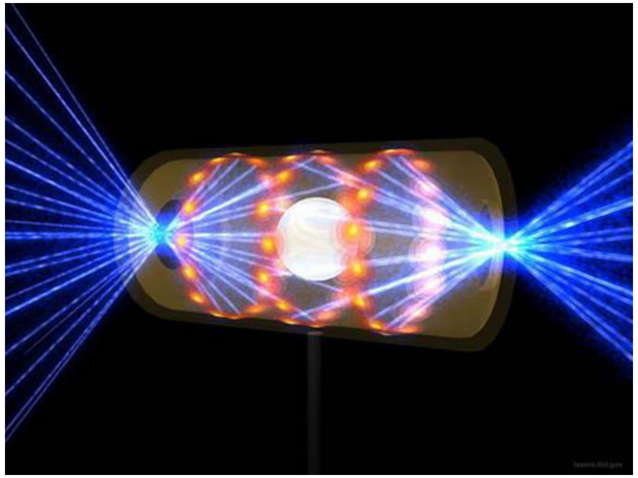
- Interest in inertial confinement fusion energy emerged later than that in magnetic confinement fusion.
- Its relevance to power production became apparent when it was recognised that concentrated beams from powerful pulsed lasers could be used to initiate a compressive process in a small solid or liquid target pellet, possibly resulting in a sufficient number of fusion reactions to yield a net energy gain.

	Inertial confinement	**Magnetic confinement**
Density (m^{-3})	10^{31}-10^{32} (exceeding that of solid and stars)	$< 10^{21}$ (Lower than that of atmosphere $\sim 10^{25}$)
Energy confinement time (s)	10^{-9}	1

Inertial Fusion Energy (IFE)

- A process where nuclear fusion reactions are initiated by heating and compressing a fuel target, typically in the form of a pellet that most often contains deuterium and tritium
- To compress and heat the fuel, energy is delivered to the outer layer of the target using laser beams, ion beams, or X-ray radiation.
- Aim: to produce a condition known as "ignition", where this heating process causes a chain reaction that burns a significant portion of the fuel

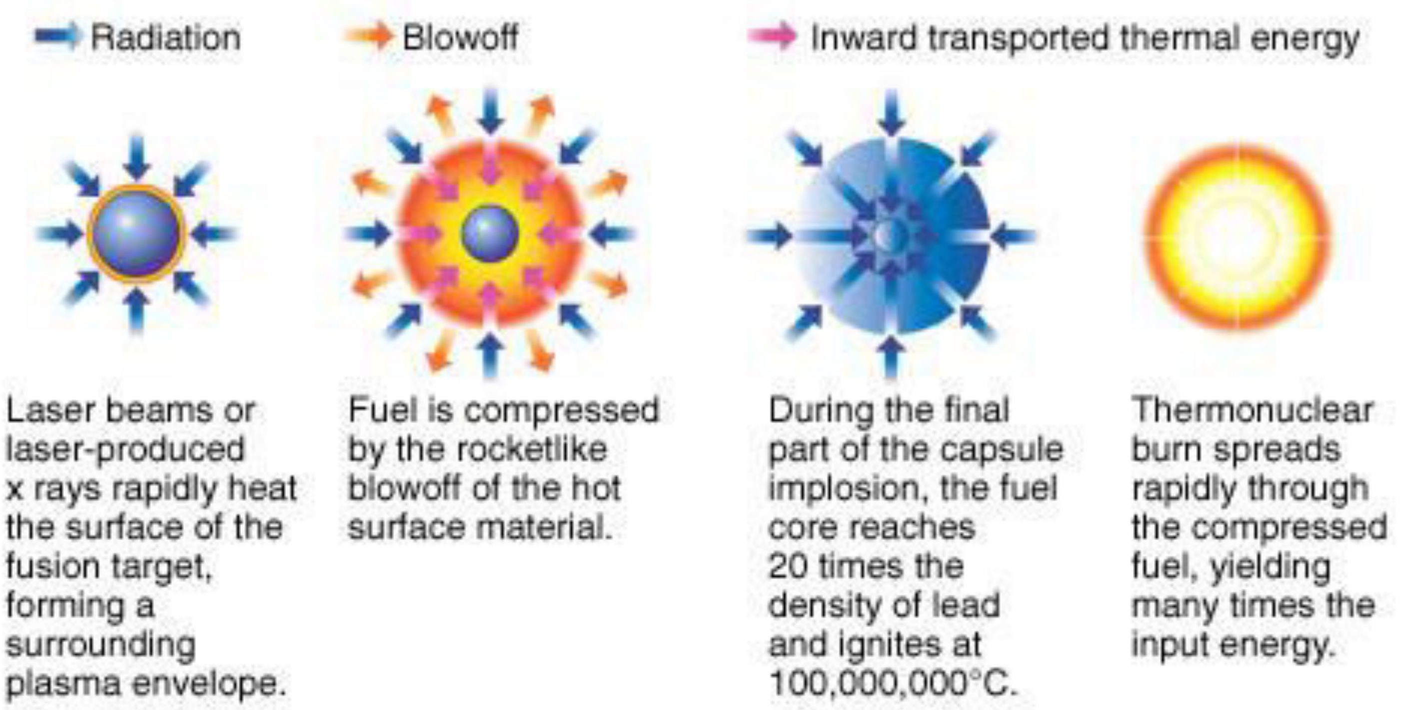




http://www.americansecurityproject.org/mans-next-greatest-achievement/
http://www.sciencecodex.com/new_software_to_support_interest_in_extreme_science

IFE – Direct Drive

- **Sequence of events – mini explosions**



- 10^{31}-10^{32} /m^3 exceeding even densities found in stars
- 20-100 times the density of lead (10^6 kg/m^3)
- ~10 keV
- Time interval of the order of 10^{-9} s

http://www.michaelcapewell.com/creative_content/fusion.htm

IFE – Direct Drive

- **Sequence of events**

1. Irradiation with high intensity beams: A small pellet, with a radius less than ~5 mm and containing a mixture of fuel atoms, is symmetrically struck by energetic pulses of EM radiation from laser beams or by high energy ion beams from an accelerator.

2. Corona formation: Absorption of this energy below the surface of the pellet leads to local ionisation and a plasma-corona formation.

3. Ablation and compression: Outward directed mass transfer by ablation and an inward directed pressure-shock wave
(A follow-up shock wave driven by the next laser or ion beam pulse propagates into an already compressed region)

4. Heating, fusion, and disassembly: With the temperature and fuel density sufficiently high, the fusion reactions will occur until the pellet dissembles in a time interval of about 10^{-8} s, corresponding to the propagation of a pressure wave across the pellet with sonic speed v_s.

IFE – Direct Drive

- **Requirements**

- Symmetric strike of the pellet by the incident laser or ion beam and efficient energy coupling between the beam and the target: deeper penetration using high frequency laser beams
- Very rapid attainment of high density of the inner core before internal pressure build-up by e-heating that opposes high compression → cold target, ion beam
- Achievement of substantial fusion reaction before pellet disintegration: $\tau_b < \tau_{dis}$
- More than 10 explosions/second
  Cf. car: 3200 explosions/second (4 cylinders at 800 rpm)

IFE – Direct Drive

- **Requirements**

- Lawson criterion: ρR (fuel areal density) > 30 kg/m^2 (R: final radius) $\rho R > \frac{2 m_i v_{dis}}{\langle \sigma v \rangle_{dt}} \left(\frac{f_b}{1 - f_b} \right)$

Corresponding to $n\tau > 2 \times 10^{21}$ s/m^3

$$\frac{dn_d}{dt} = -n_d n_t \langle \sigma v \rangle_{dt}$$

$$f_B = 1 - \frac{n_d(t=\tau)}{n_d(t=0)} = 1 - \frac{n_t(t=\tau)}{n_t(t=0)} = \frac{\tau / \tau_r}{1 + \tau / \tau_r}$$ Burn fraction

$$\tau_r = \langle \sigma v \rangle_{dt} n_d (t=0)$$

$$\tau \approx \frac{1}{4} \frac{R}{C_S}$$ Disassembly time (confinement time)

$$C_S = (2T / m_i)^{1/2}$$ Sound speed

$$f_B = \frac{\rho R}{\rho R + \beta(T)} \qquad \beta(T) = \frac{8 m_i C_S}{\langle \sigma v \rangle_{dt}}$$

$f_B \geq 30\%$ required for $\eta G = 10$
(η: driver efficiency, $G = E_F/E_d$: thermonuclear gain
E_F: fusion energy released from a single capsule,
E_d: driver energy delivered to the reaction chamber)

IFE – Direct Drive

- **Instabilities**

- Rayleigh-Taylor instability

- Parametric instability: Plasma waves can be generated and much of the incoming light is reflected back toward the laser.

SBS (Stimulated Brillouin Scattering): ion acoustic wave

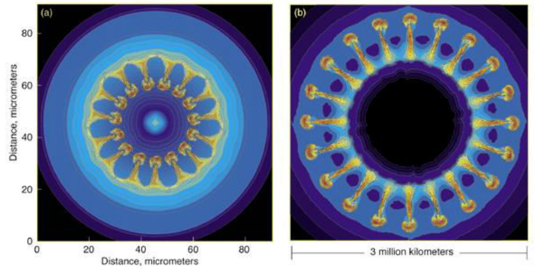
SRS (Stimulated Raman Scattering): electron plasma wave

accelerating a beam of electrons (preheating)

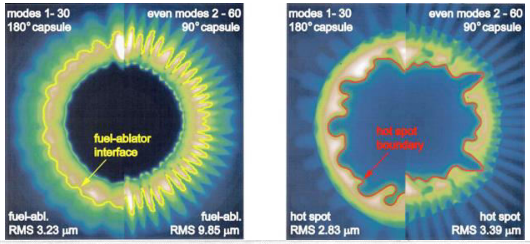
thin electron beams producing magnetic field

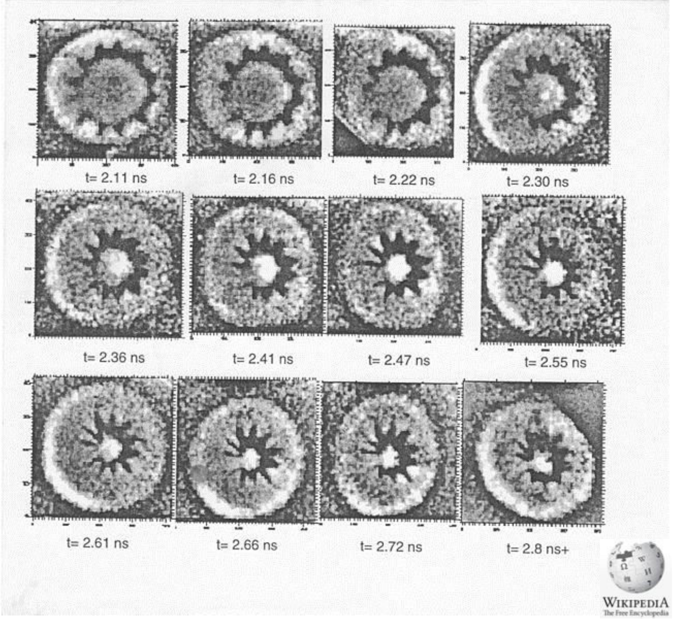
→ pinch effect

⇒ The higher the frequency of the laser light, the higher are the densities where SBS and SRS occur: Higher frequencies will penetrate more deeply into the plasma corona and minimise these instabilities.



Striking similarities exist between hydrodynamic instabilities in (a) inertial confinement fusion capsule implosions and (b) core-collapse supernova explosions. [Image (a) is from Sakagami and Nishihara, *Physics of Fluids B* **2**, 2715 (1990); image (b) is from Hachisu et al., *Astrophysical Journal* **368**, L27 (1991).]





D.S. Clark et al, Phys. Plasmas ***17*** *052703 (2010)*

IFE – Beams

- **Lasers**

- The requirements of pellet compression and beam-target coupling impose some very stringent demands on beam energy and the details of pellet composition.
- Status of current laser technology and requirements

Parameter	Nd (Neodymium)	KrF (Krypton-fluoride)	Required
Wavelength (μm)	1.06	0.25	~0.3
Pulse rate (Hz)	0.001	5 (using no glass)	~5
Beam energy (MJ)	0.03	0.1	~1
Representative peak power (TW)	30	100	~1000
etc		Expensive electron beam used	

A.A. Harms et al, "Principles of Fusion Energy", World Scientific Publishing (2000)

IFE – Beams

- **Energetic ion beams**

- Energetic ion beams introduce another set of problems:
    - beam focusing down to a small target for high current
    - accelerators need for large high-vacuum ion transport facilities
- Status of current accelerator technology and requirements

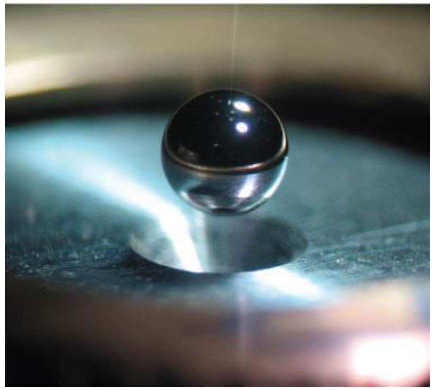
Parameter	Electron	Light ions	Heavy ions	Required
Beam particle	e^-	p, α, C^{4+}	Xe, …, U	-
Particle energy (MeV)	~10	~50	~30000	> 10
Beam energy (MJ)	1	1	5	~5
Peak power (TW)	20	20	200	~1000

A.A. Harms et al, "Principles of Fusion Energy", World Scientific Publishing (2000)

IFE – Targets

- **Targets**
  - Typical fuel pellets (microcapsules or micro balloons) are about the size of a pinhead and contain around 10 milligrams of fuel:
    In practice, only a small proportion of this fuel will undergo fusion, but if all this fuel was consumed it would release the energy equivalent to burning a barrel of oil.
- **Major objectives**
  - To optimise energy transfer, minimise hot electron production, and reduce requirements for symmetric beam energy deposition
- **Types**
  - Glass microballoons
  - Multiple shell pellets
  - High-gain ion beam pellets

Image of an inertial confinement fusion fuel microcapsule. Taken from LLNL Sep. 2002 ST&R publication.

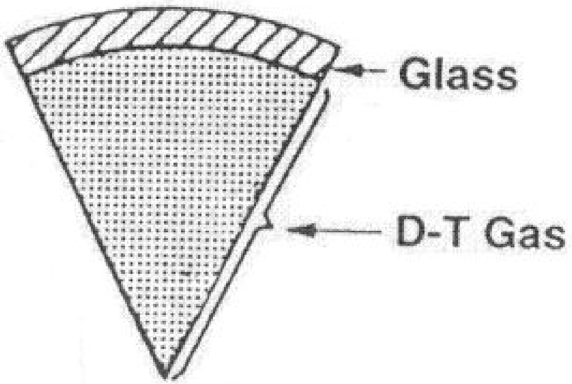


The polished beryllium capsule (2 mm in diameter)

IFE – Targets

- **Glass micro balloons**

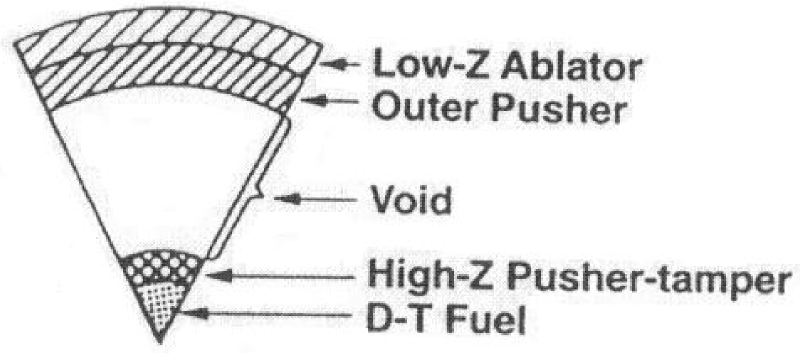
- Consisting of thin walled glass shells containing a D_2-T_2 gas under high pressure
- The incident beam energy is deposited in the glass shell causing it to explode with part of its mass pushing inward and the remaining mass outward.
- Being widely used in experiment, however more efficient designs needed for power plants



A.A. Harms et al, "Principles of Fusion Energy", World Scientific Publishing (2000)

IFE – Targets

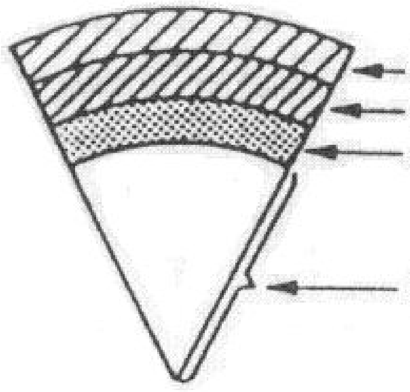
- **Multiple shell pellets**
  - Consisting of an inner D-T solid fuel core surrounded by a high-Z inner pusher-tamper, a thicker layer of low density gas surrounded by a pusher layer and an outer low-Z ablator material
  - The outer layer is to ablate quickly and completely when struck by the incident beam
  - The inner high-Z pusher-tamper is to shield the inner core region against preheating by hot electrons and X-rays



A.A. Harms et al, "Principles of Fusion Energy", World Scientific Publishing (2000)

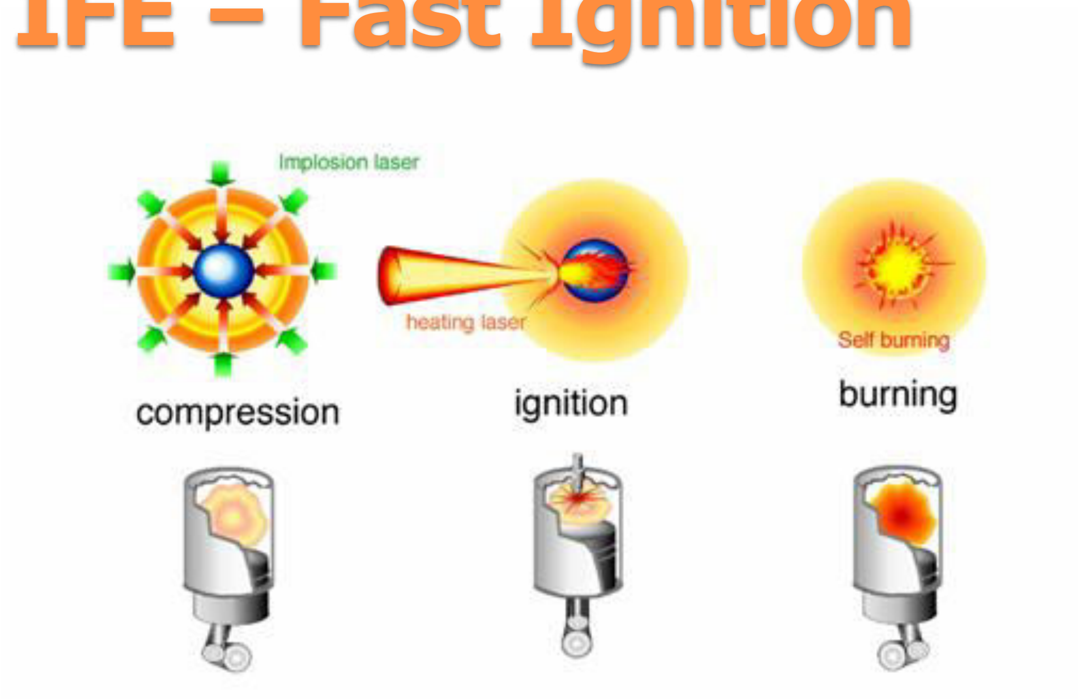
IFE – Targets

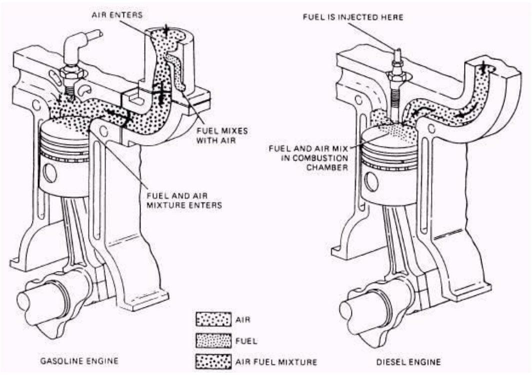
- **High-gain ion beam pellets**
  - Consisting of a vacuum sphere surrounded by a D_2-T_2-DT fuel shell surrounded by tamper-pusher materials
  - Thickness of the tamper-pusher materials carefully matched to the type and energy of the incident beams

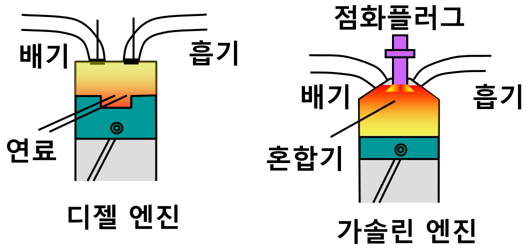


A.A. Harms et al, "Principles of Fusion Energy", World Scientific Publishing (2000)

IFE – Fast Ignition



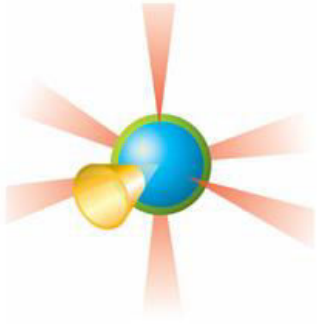




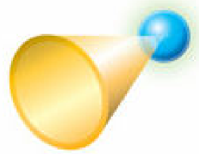
- A new scheme separating the compression and heating phases much like a petrol combustion engine: In the petrol engine the fuel is compressed by the piston and then ignited via the spark plug. In the case of fast ignition, the driving lasers are the pistons, compressing the fuel to high density around the tip of a gold cone.
- The spark plug in this case is a multi kJ, short pulse laser which is injected into the tip of the gold cone.

http://www.osaka-u.ac.jp/en/research/annual-report/volume-3/selection/02a.html

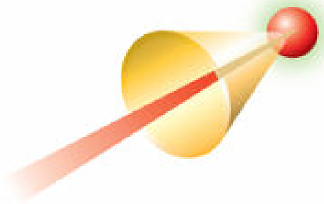
IFE – Fast Ignition



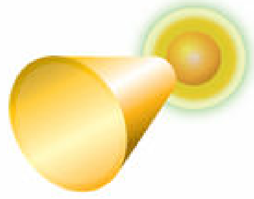
- Many powerful laser beams irradiate a capsule of DT fuel. The lasers are arranged symmetrically around the capsule and heat a thin layer of the capsule causing it to expand rapidly. This forces the rest of the material in the opposite direction.



- The material converges around the tip of a gold cone. The density of the DT is now hundreds of times the density of solid material.



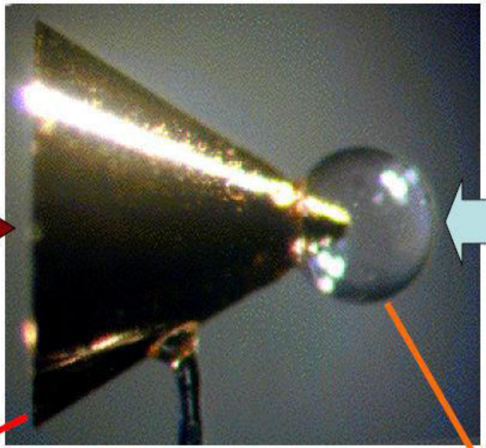
- An ultra intense laser is fired into the gold cone. When the laser interacts with the tip of the gold cone a large number of energetic electrons are produced.



- The energetic electrons travel into the dense DT fuel and deposit their energy. This raises the fuel to 100 million degrees centigrade which is hot enough to initiate the fusion reactions.

IFE – Fast Ignition

PW for heating
1 beam / 300 J
1.053 μm / 0.5ps

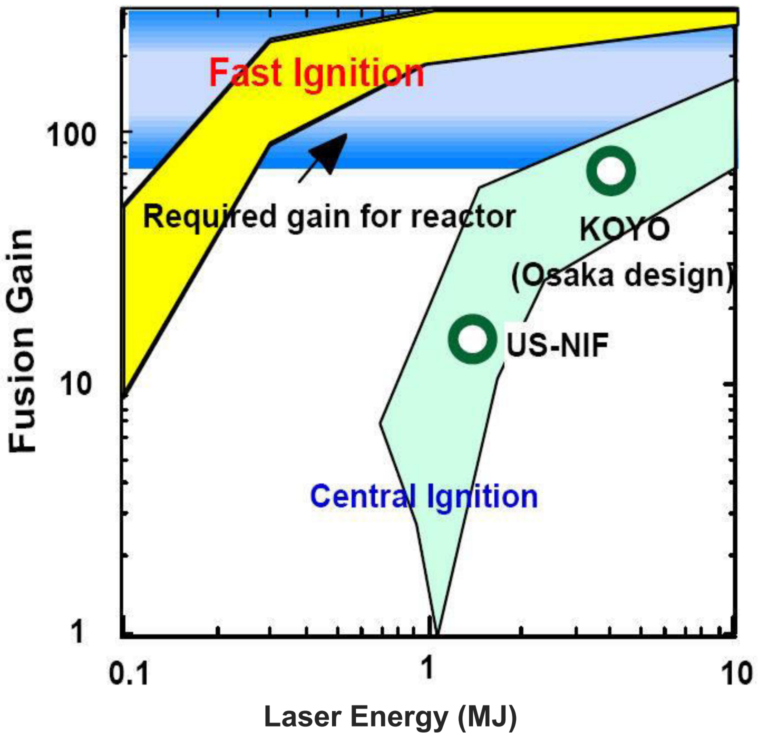


GXII for implosion
9 beams / 2.5 kJ/0.53 μm

1.2ns Flat Top w/ RPP

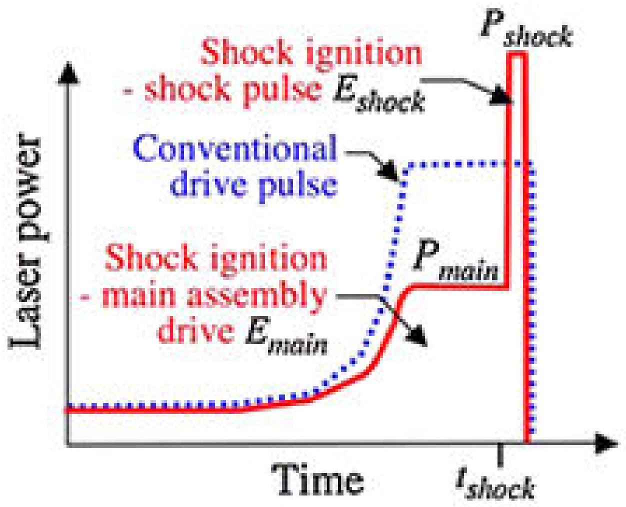
Au cone
30 ° open angle (the picture: 60deg)
Thickness of the cone top: 5μm
Distance of the cone top: 50μm from the center

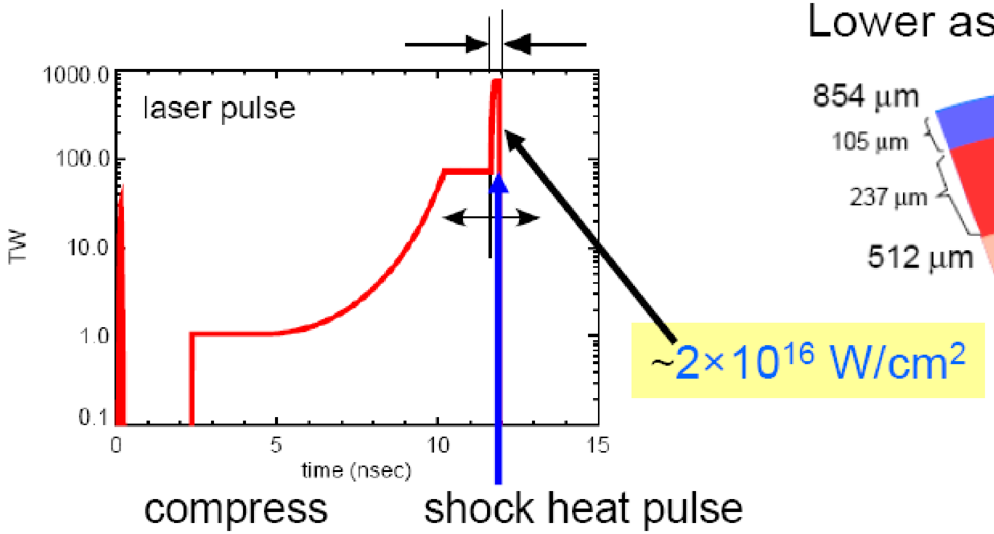
CD shell
500μmϕ/6-7μmt

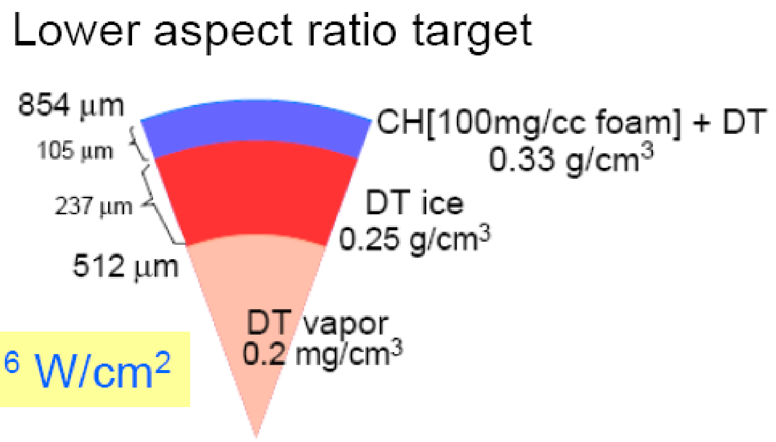


http://fsc.lle.rochester.edu/techinfo.php
http://www.ile.osaka-u.ac.jp/gakujutsu/HomePage/kenkyu/kenkyu_ni_tsuite/kenkyunitsuite.htm

IFE – Shock Ignition

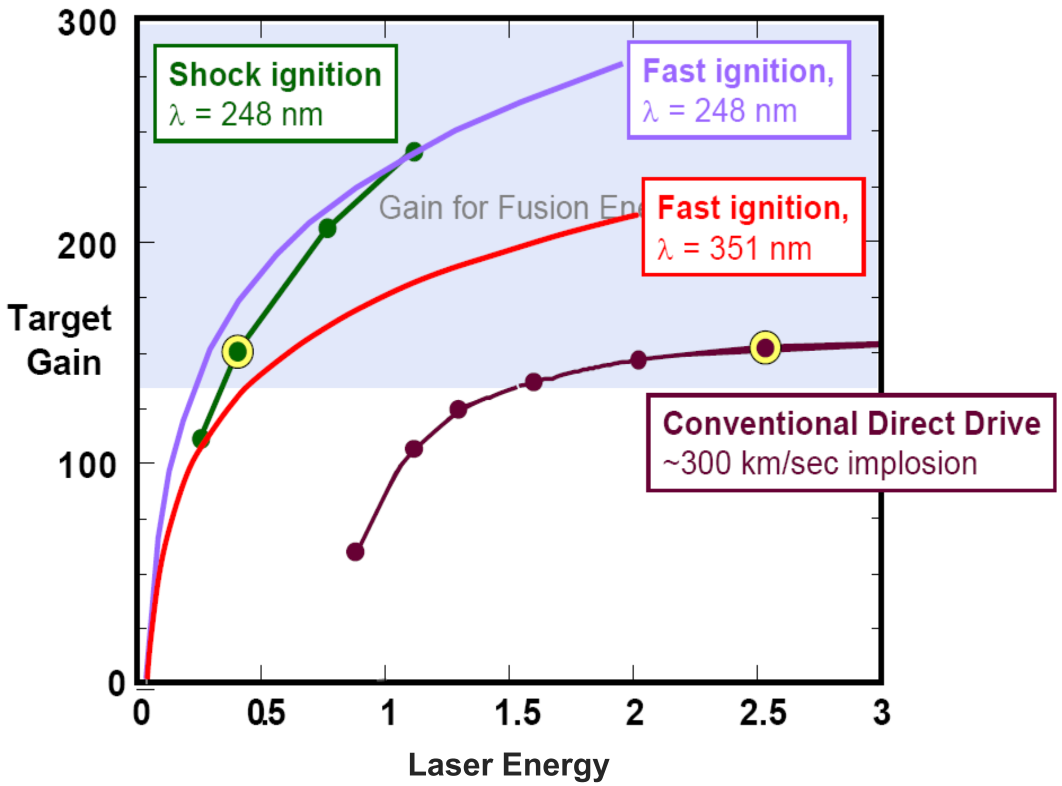






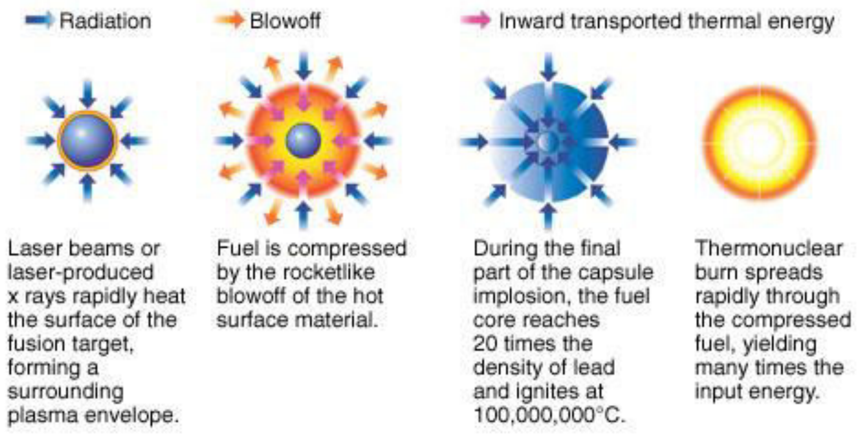
2-D studies also give promising performance
Collaborations with NRL (Schmitt) & LLNL (Perkins)

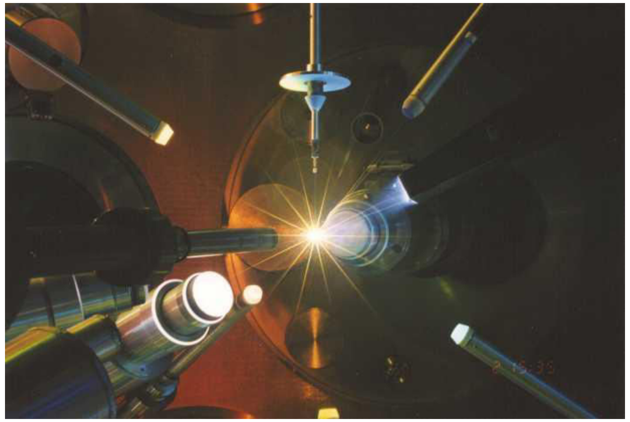
IFE – Shock Ignition



- Nano-timescale laser pulse applied
- No need of cones and lasers for ignition
  → economic competitiveness compared with fast ignition

IFE – Limits of Direct Drive





- This puts a very high requirement on symmetry of the spherical capsule and of the distribution of energy contained within the driving lasers/radiation.
- If these are not symmetrical then different parts of the capsule will reach maximum density at different times and the capsule will break apart without the fusion process taking place.

http://www.michaelcapewell.com/creative_content/fusion.htm

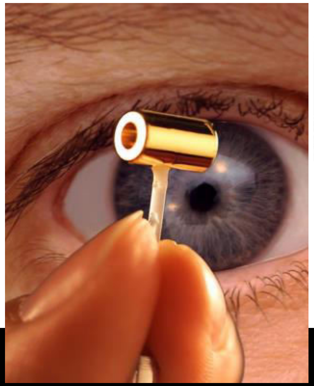
IFE – Indirect Drive

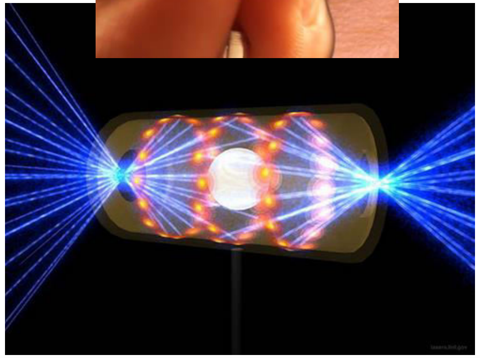
- **Indirect drive**

- To achieve increased symmetric energy deposition over the surface of the pellet
- Composed of a fuel pellet and a small cylindrical cavity (Hohlraum)

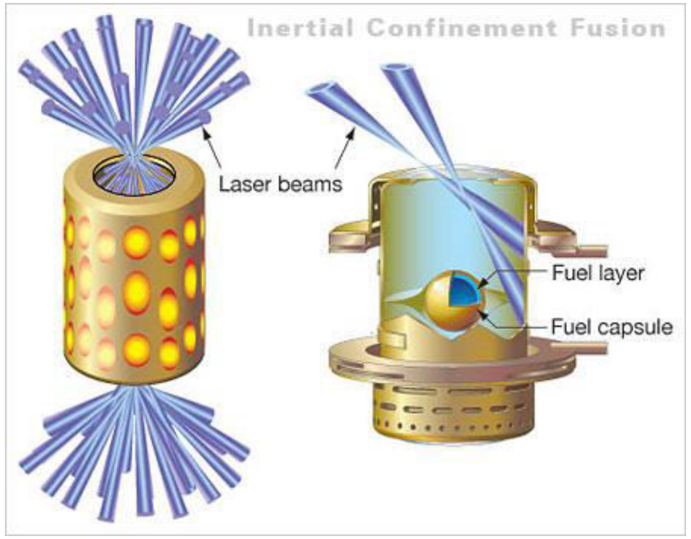
  Hohlraum: a few cm long, made of a high-*Z* material such as gold or other metal, having "windows" transparent to the driver on each end
- The beams enter both ends of the hohlraum obliquely and ablate the inner surface of the cavity.
- The high-*Z* material of the hohlraum emits soft X-rays and by focusing the driver beams to the appropriate points inside the cavity, a highly symmetric irradiation of the fuel pellet results

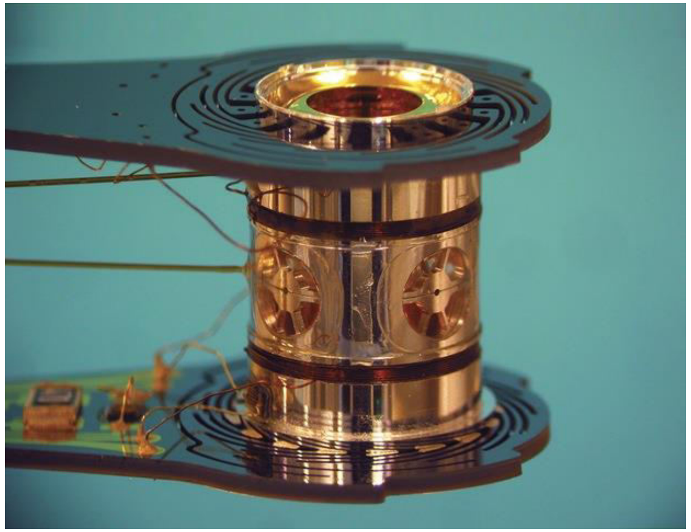
  → optimal pointing of the laser beams important

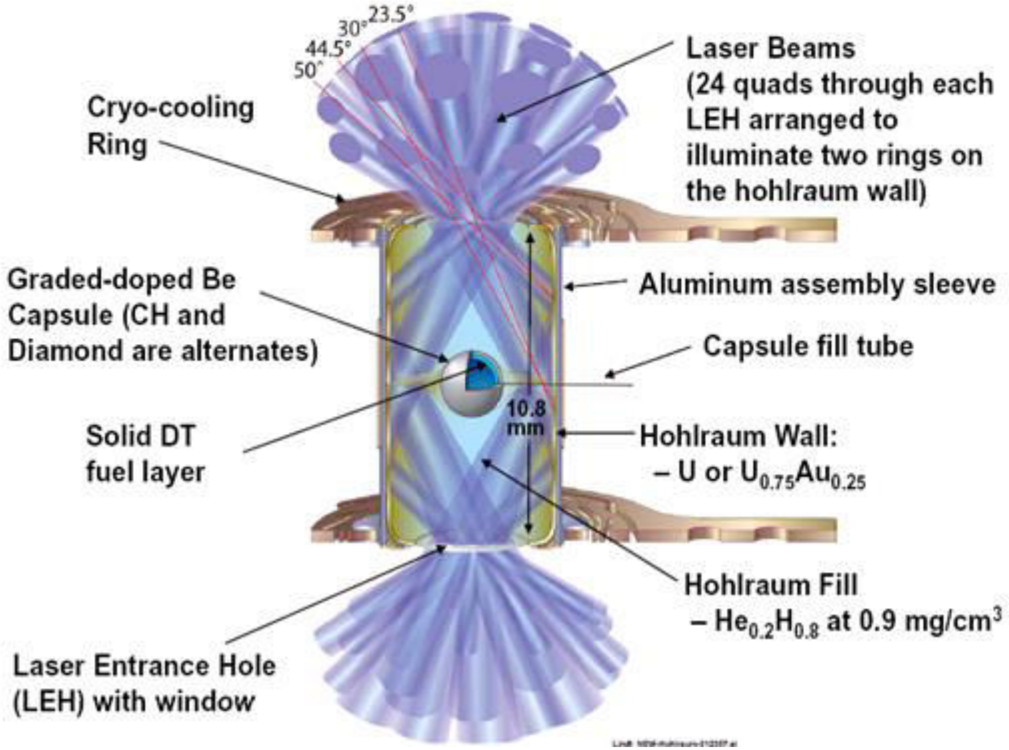




IFE – Indirect Drive







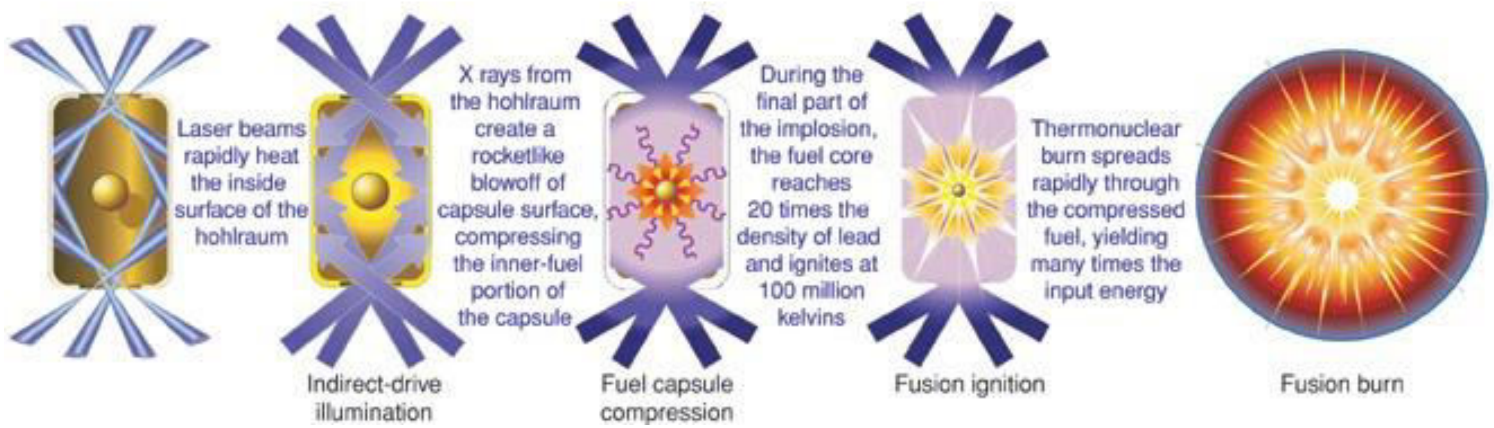
Schematic of NIF ignition target and capsule (credit: M. J. Edwards et al., *Physics of Plasmas*)

Currently indirect drive only been examined using laser drivers

http://www.physicscentral.com/explore/action/fusion-at-nif.cfm

IFE – Indirect Drive

- **Sequence of events**



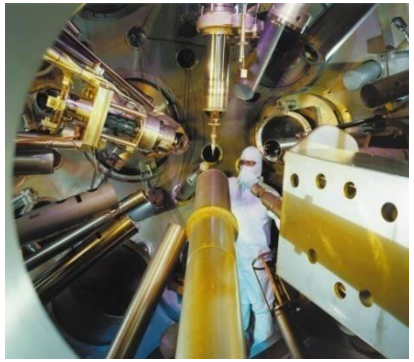
IFE – Indirect Drive

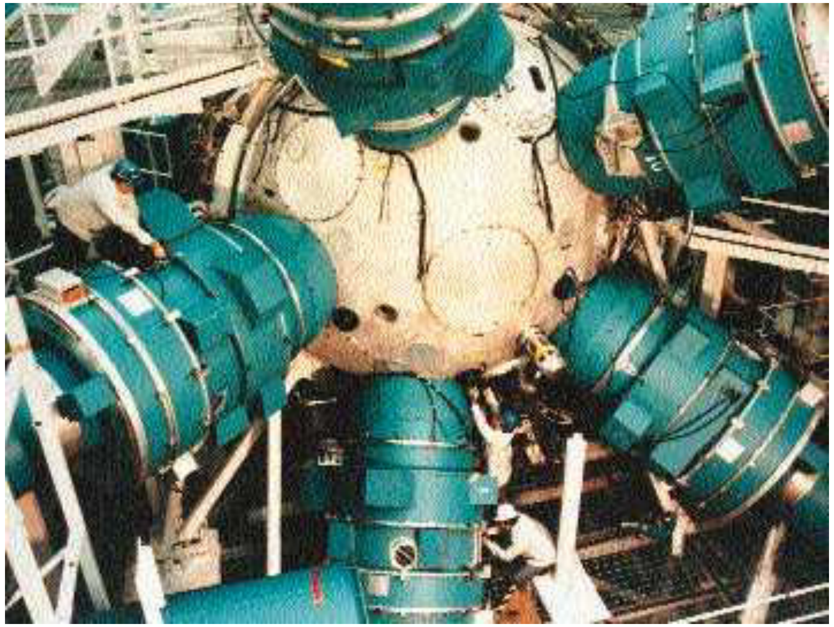
- **Pros and Cons compared with the direct drive**

- Symmetric energy deposition on the pellet surface is efficient compared with the direct drive where all the driver beams must symmetrically impinge directly on the pellet.
- Better ablation and subsequent compression with X-rays
- Reduced instabilities during pellet compression (X-rays → high frequency → not subject to parametric instability)

- Reduced energy coupling from the beam to the pellet
- Increased complexities of hohlraum manufacture and suspension at the centre of the chamber

IFE – Nova



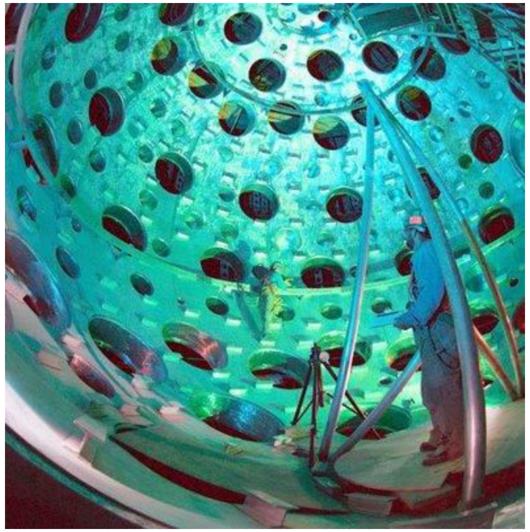


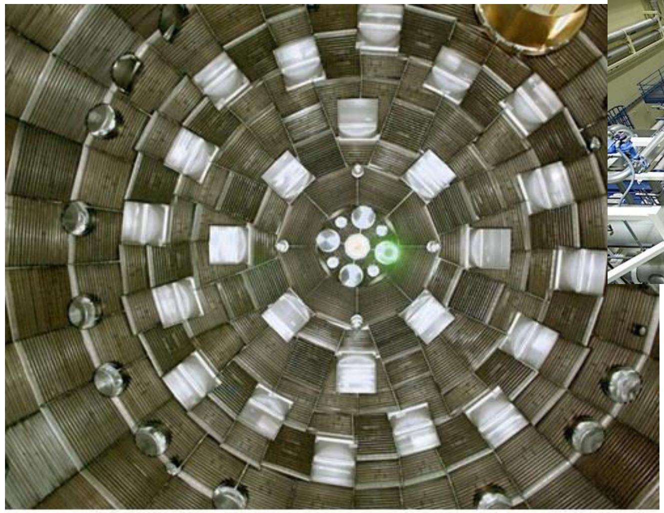
http://www.aps.org/publications/apsnews/200012/dpp.cfm

- Lawrence Livermore – Shiva and **Nova (1984)**

- Neodymium-YAG laser
- Producing over a kilowatt of continuous power at 1065 nm
- Achieving extremely high power in a pulsed mode (10^8 MW)

IFE – National Ignition Facility (NIF)





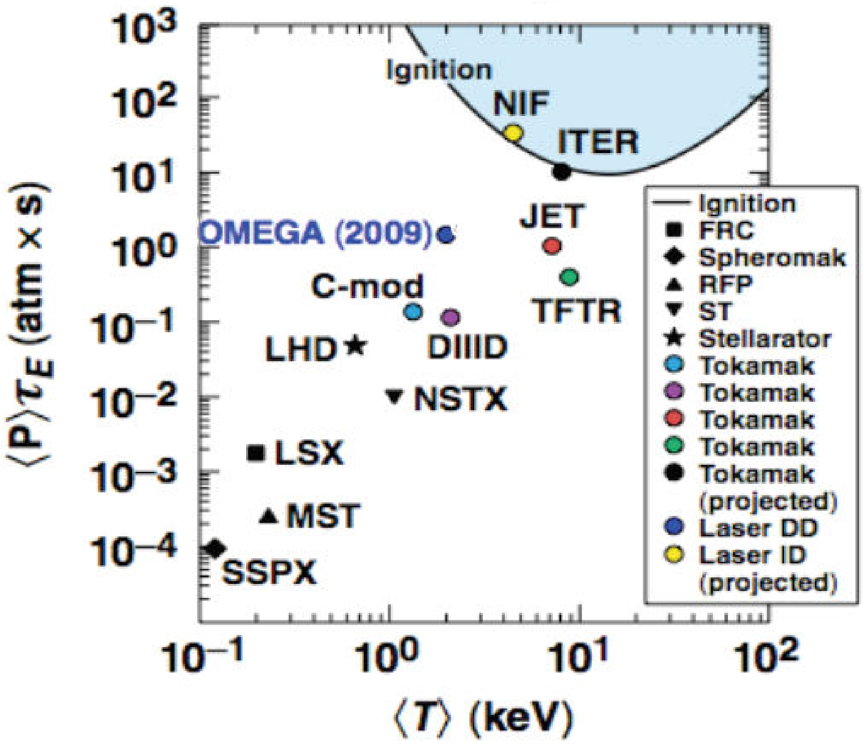
Installation of the first wall inside the Target Chamber was complete in March 2005

- Very large facility, the size of a sports stadium
- Very small target, the size of a BB-gun pellet
- Very powerful laser system (192 laser beams, 1.8 MJ of energy), equal to 1000 times the electric generating power of the USA
- Very short laser pulse, a few billionths of a second
- Nd-glass lasers at third harmonic frequency (3ω, almost half the light intensity) used to avoid parametric instabilities

https://theempowermentfactor.wordpress.com/2013/05/11/world-view-101-national-ignition-facility-crystals/

IFE – National Ignition Facility (NIF)

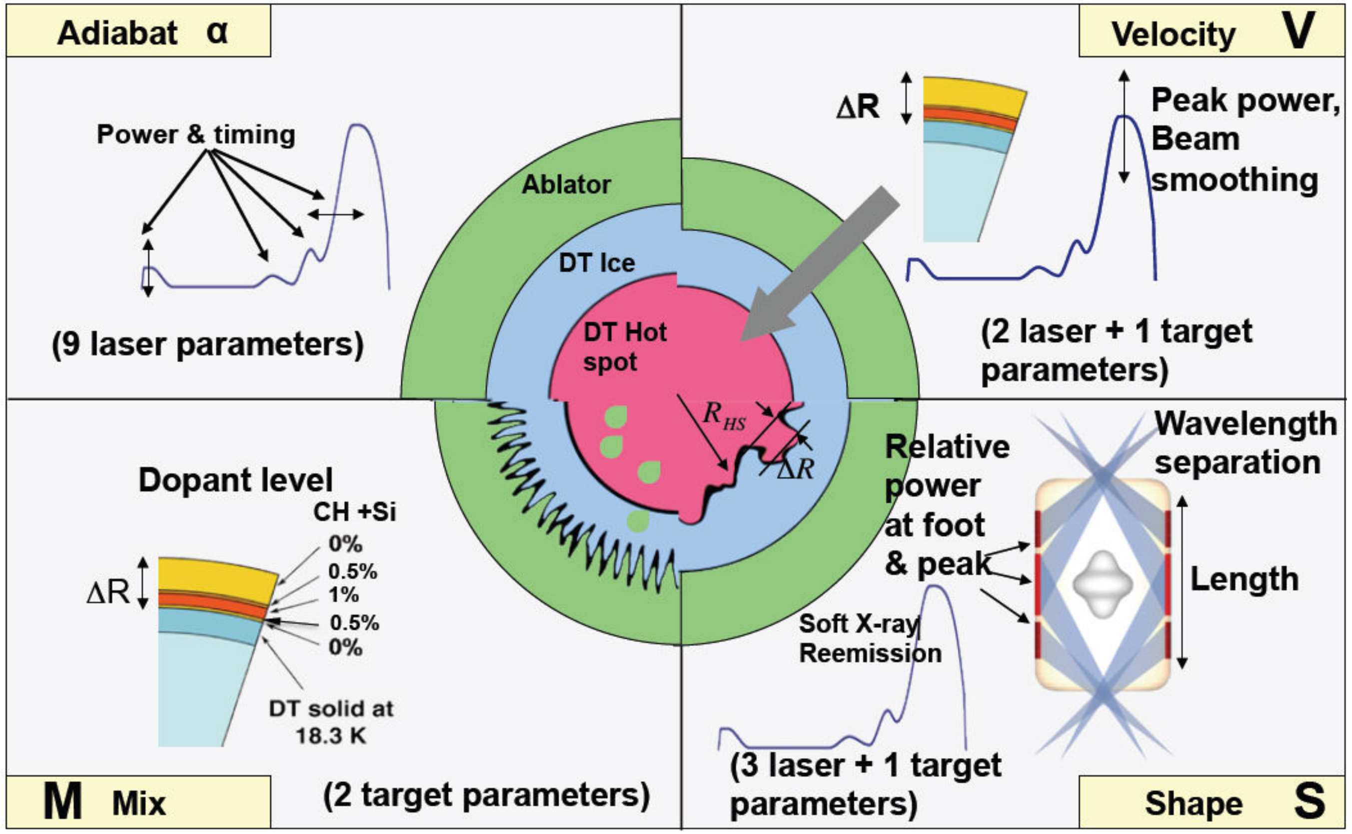
R. Betti et al., PHYS. PLASMAS 17, 058102 (2010)
with data from J. P. Freidberg MIT.



- 1997-2009: NIF project
- 2006-2012: NIC (National Ignition Campaign)
  ~85% of energy coupling and ignition goal (ρR) achieved

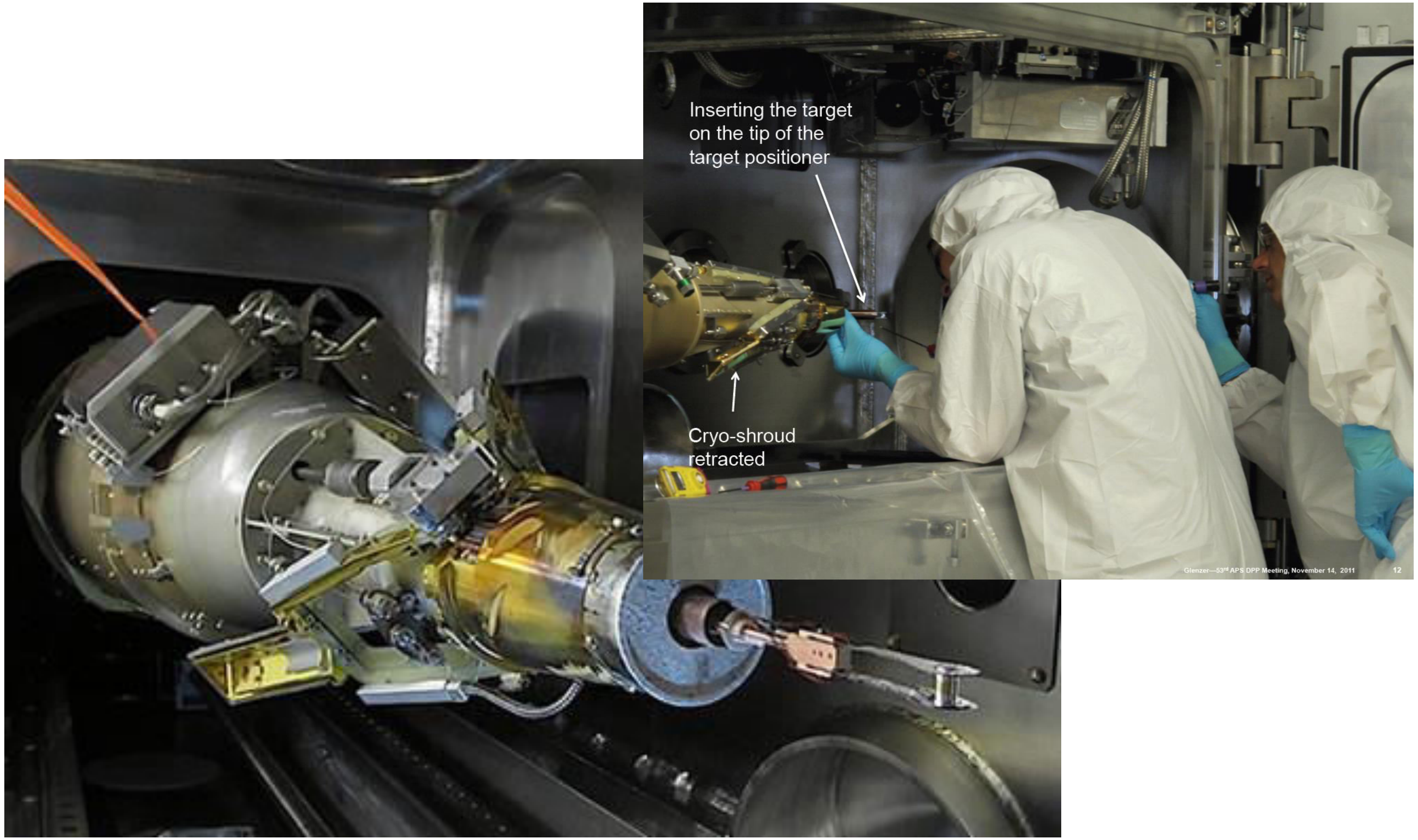
NIC
National Ignition Campaign

IFE – National Ignition Facility (NIF)



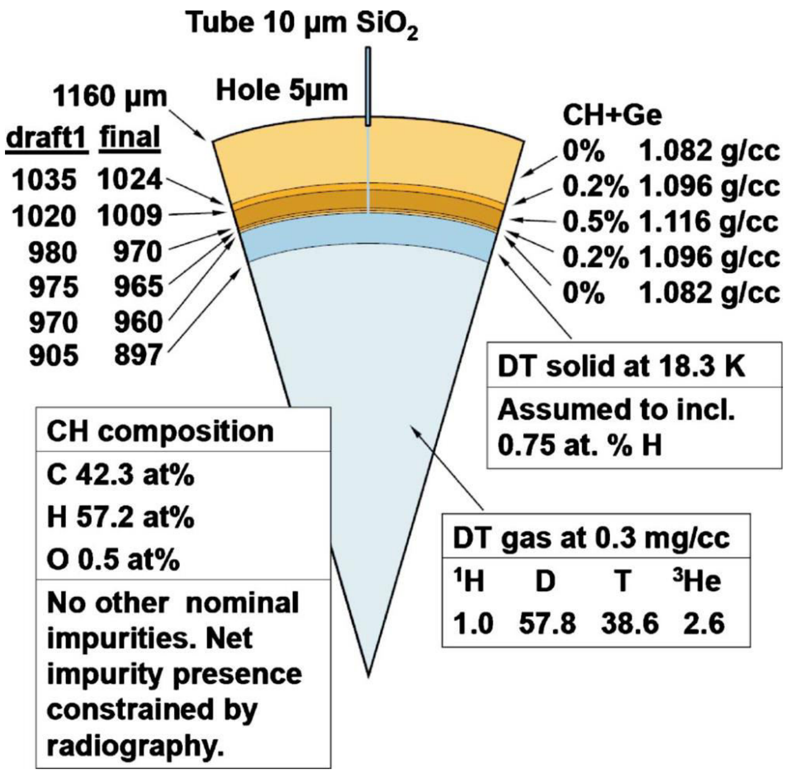
- To optimize the target for ignition, adiabat, velocity, mix, and shape adjusted

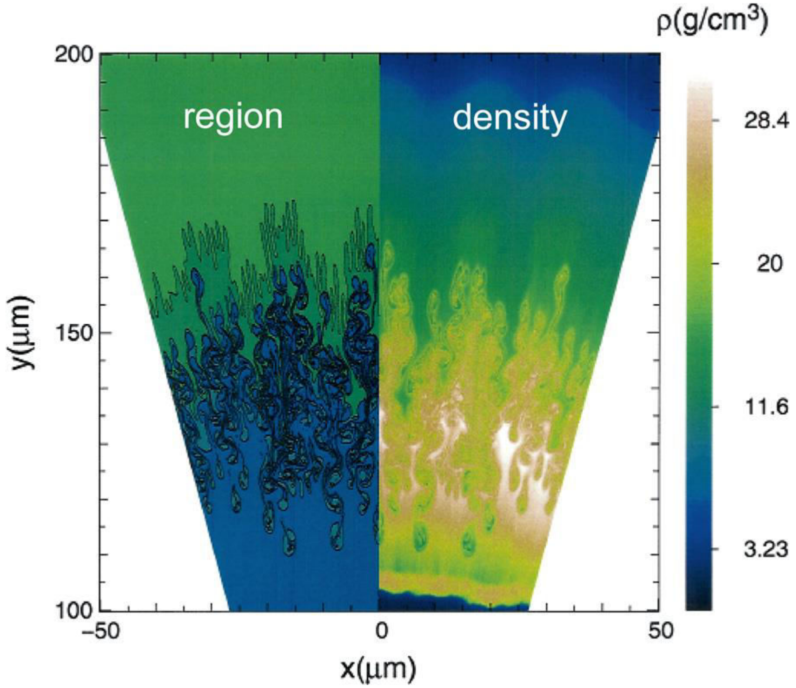
IFE – National Ignition Facility (NIF)



https://lasers.llnl.gov/news/experimental-highlights/2014/october

IFE – National Ignition Facility (NIF)

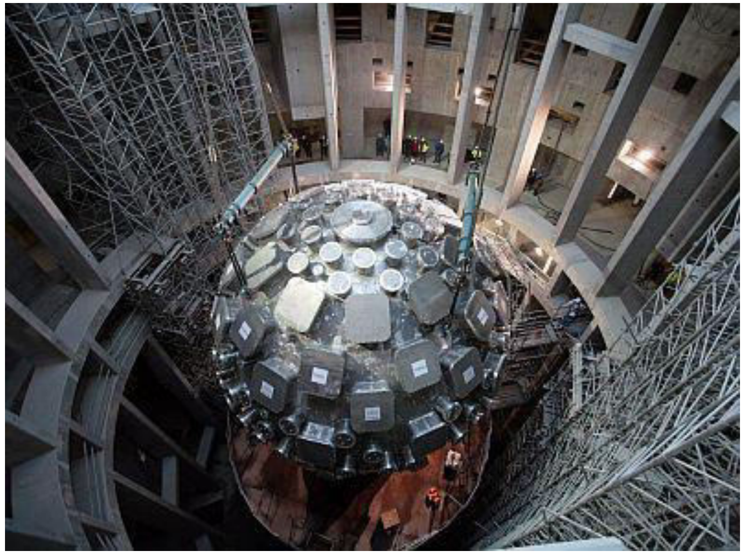


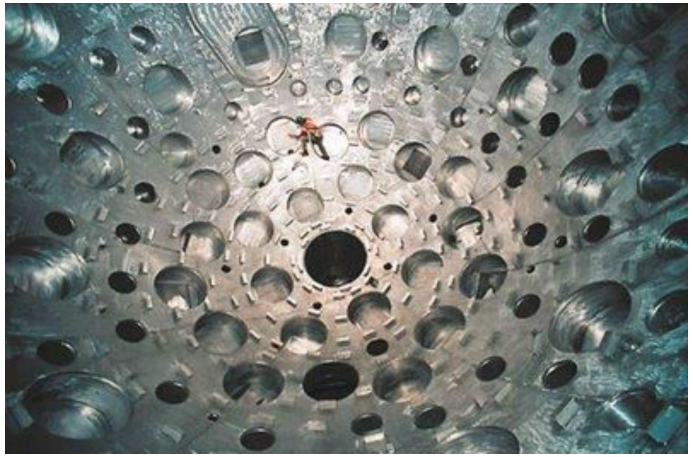


Kelvin-Helmholtz vortices

*D.S. Clark et al, Phys. Plasmas **18** 082701 (2011)*

IFE – Laser MegaJoule (LMJ)

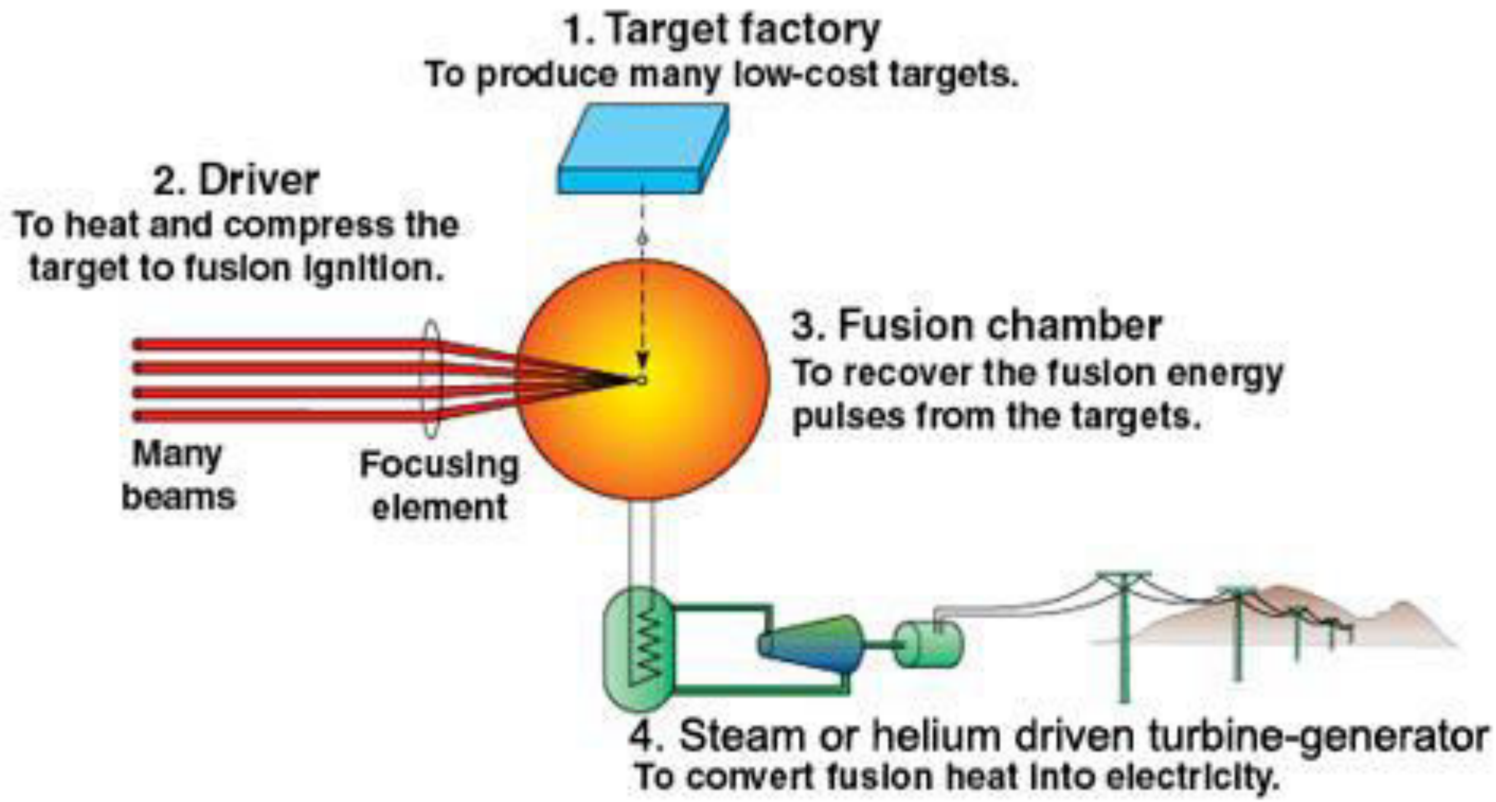




- CEA, France
- Built near Bordeaux
- Operation entered on October 2014
- 1.8 MJ of laser energy from a series of 176 laser beamlines
- Focusing on indirect drive

http://www.nonaumissilem51.org/index.html?echosNov2006
https://theempowermentfactor.wordpress.com/2013/05/11/world-view-101-national-ignition-facility-crystals/

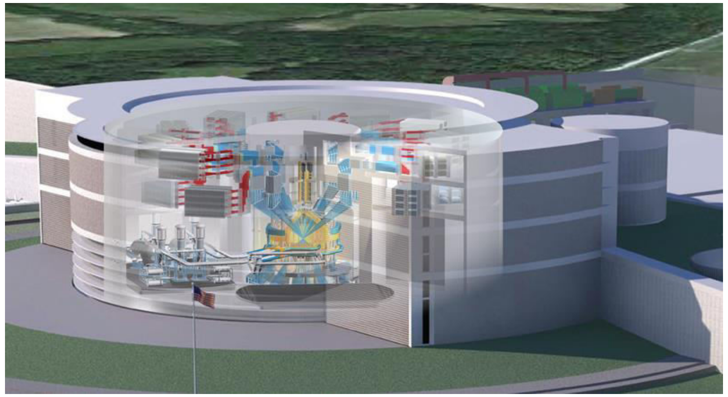
IFE – Power Plants

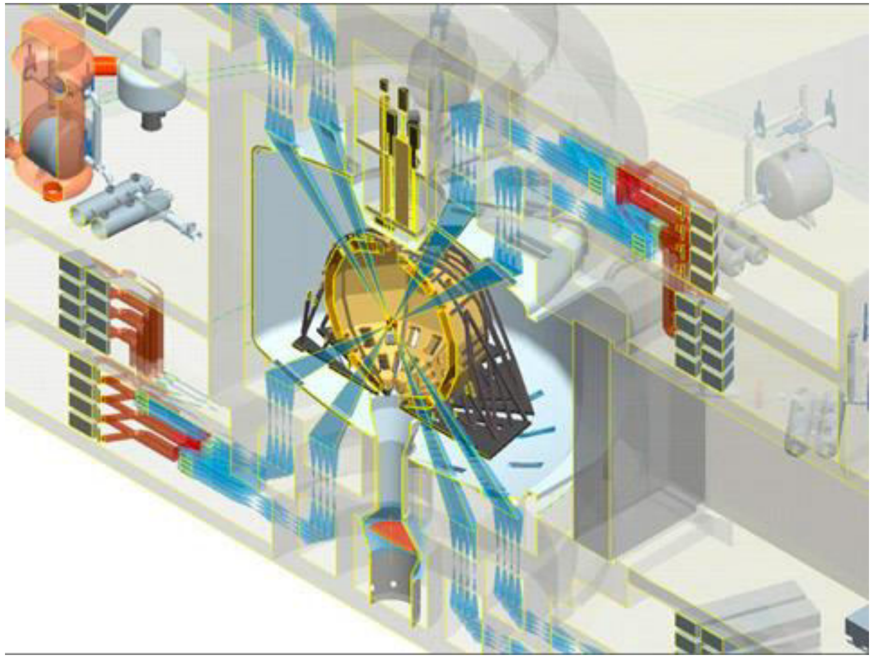


http://www.altenergymag.com/emagazine/2013/12/controlled-nuclear-fusionbrthe-energy-source-that-is-always-a-few-years-away/2197

IFE – Power Plants

IFE – Power Plants (LIFE)



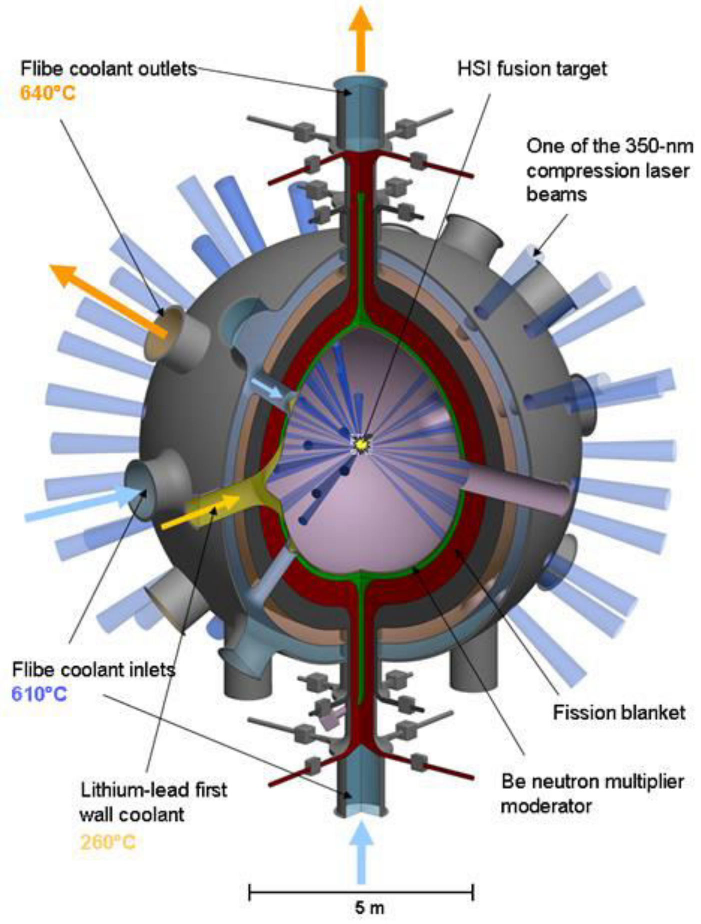


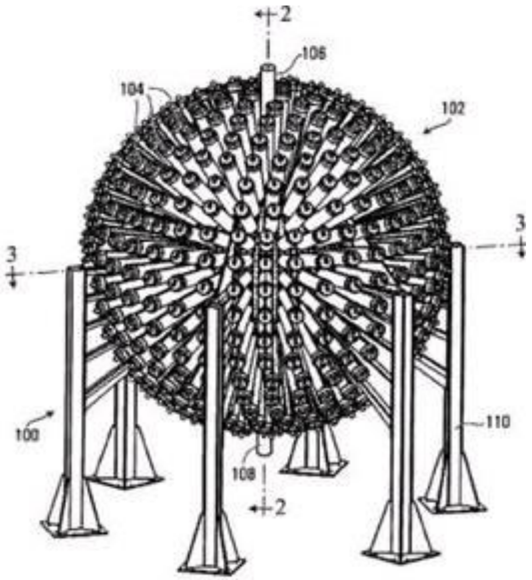
- Up to 1.5 GWe
- 2 MJ, 351 nm (ultraviolet) laser (384 beamlines)

https://life.llnl.gov/

http://www.360doc.com/content/12/0718/18/9807246_225087482.shtml

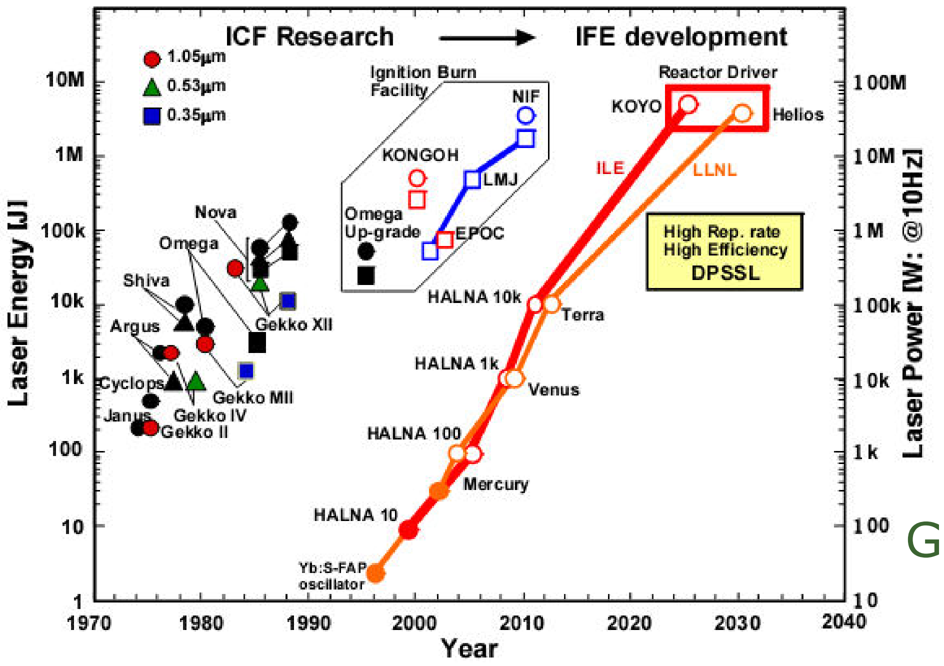
IFE – Power Plants (LIFE)

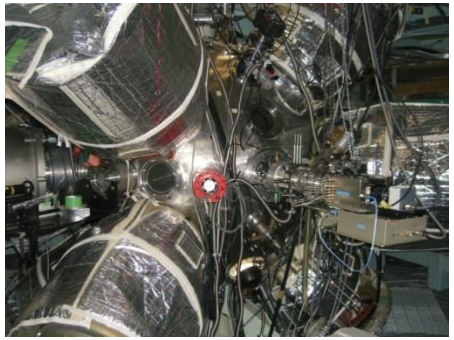




A LIFE fusion-fission chamber

IFE – Power Plants





The GEKKO Laser
(Osaka Univ. 1983)

Graph courtesy
S. Nakai

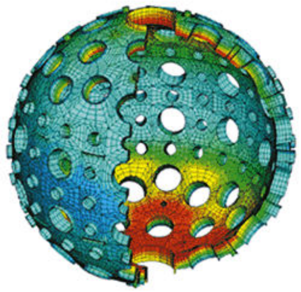
- Increasing power of ICF lasers over time,
  starting with the first "high-power" devices in the 1970s.
- Lasers with enough energy to create "ignition" are boxed near the middle of the graph, although KONGOH and EPOC were canceled, leaving only NIF and LMJ along the blue line.
- To the right are a series of lasers built not for high-power, but high repetition rates, which would be needed for a commercial power reactor. To date only the first two dots along the orange line have been built (FAP demonstrator and Mercury).
- The upper right of these lines represent hypothetical devices that have both the high-power and high-repetition rates needed for commercial power production.

IFE – Advantages

1 입력 레이저 에너지를 올리면 점화 온도가 비례하여 올라간다.
2. 핵융합 발전기의 규모에 대한 Scaling up-down이 가능하다.
3. 반응로와 레이저가 구분되어 Maintenance가 용이하다.
4. D-T 연료의 핵융합 점화 효율이 매우 높다. (거의 99% 이상 반응)
5. 반응로의 고 진공도가 필요없다.

공홍진 (KAIST), 물리학과 첨단기술 July/August 2009

IFE – Issues on Power Plants



- **Protection for the reaction chamber wall**
  - Against mechanical stress and radiation, mostly in the form of X-rays and energy deposition by pellet debris released in a microexplosion
  - Against fast α-particles forming He bubbles causing the wall to exfoliate
  - Dry wall and various wet wall concepts such as a falling liquid metal veil, liquid metal jets, liquid metal droplet sprays or a thin surface layer of liquid metal
  - Rapid purging of the chamber (~100 ms) needed for the next pulse

- **Pellet manufacture**
  - Spherical coating technology at the micro-scale of composition and geometry

- **Pellet handling and positioning in the chamber**
  - Entry by gravity combined with pneumatic injection demanding extreme trajectory precision

- **Protecting mirrors, focusing magnets for ion beams, other beam transport elements and protection of mirrors**

IFE – Issues on Power Plants

- Extremes of power transport, energy conversion, material flow, radiation damage, and highly co-ordinated electro-mechanical functions will evidently characterise the eventual operation of an ICF power system.
- Considerable research, design, and testing will still need to be undertaken to arrive at the continuingly elusive goal of such a working power station.