Introduction to Nuclear Fusion
(409.308A, 3 Credits)

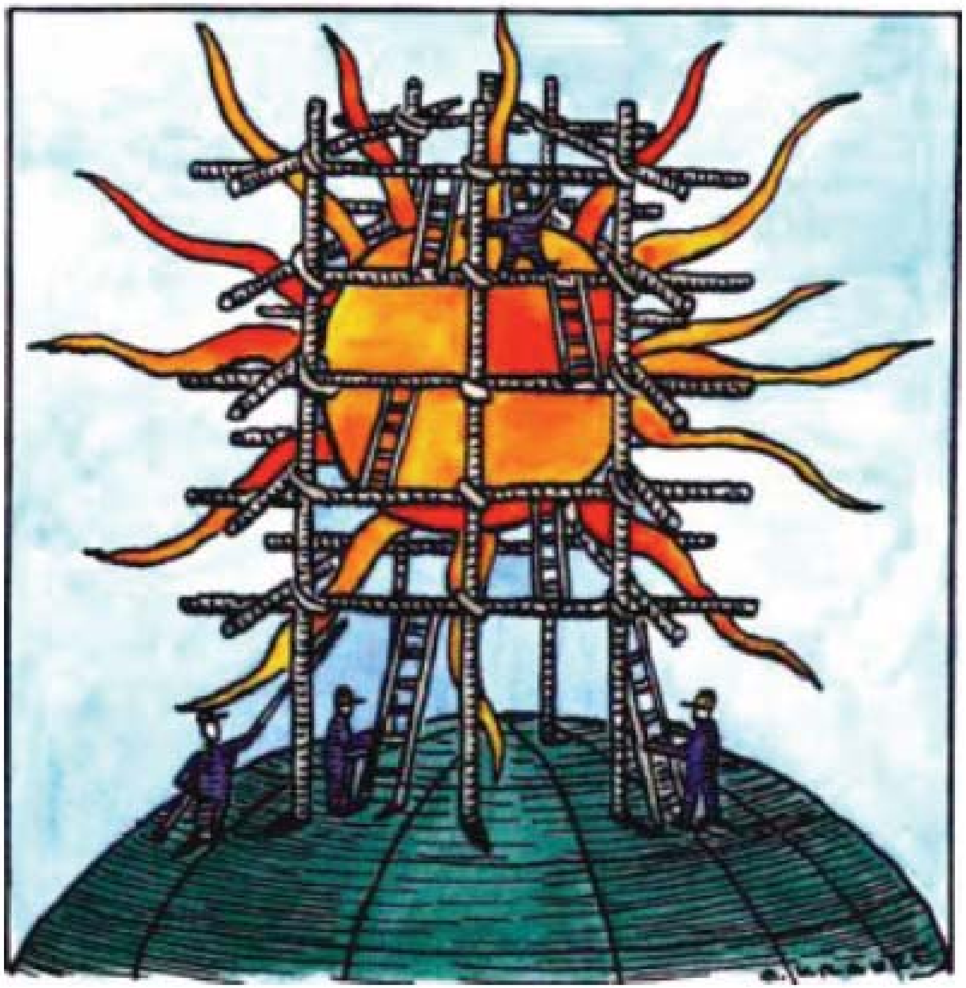
Prof. Dr. Yong-Su Na

(32-206, Tel. 880-7204)

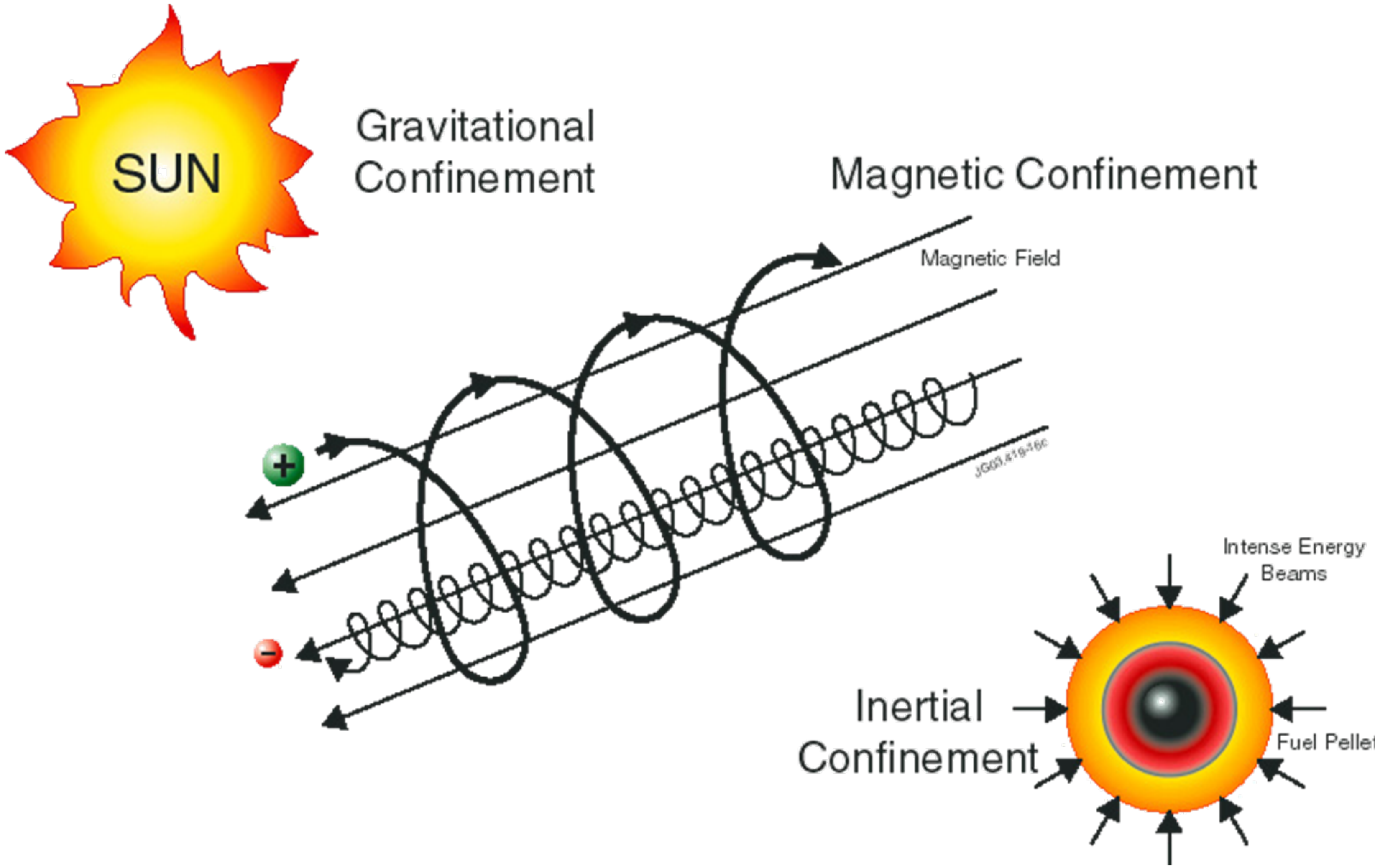
Contents

Contents

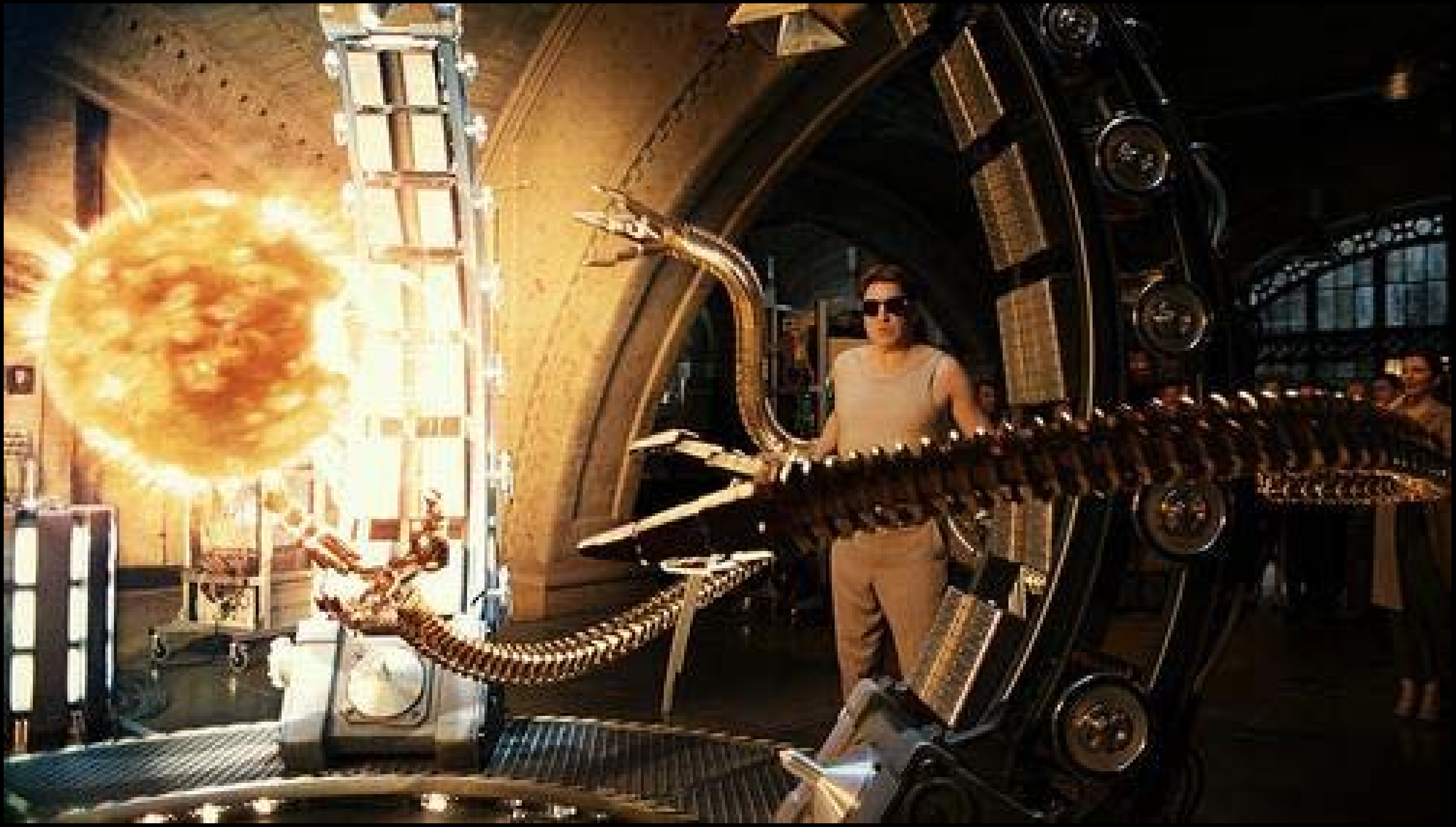
To build a sun on earth



To build a sun on earth

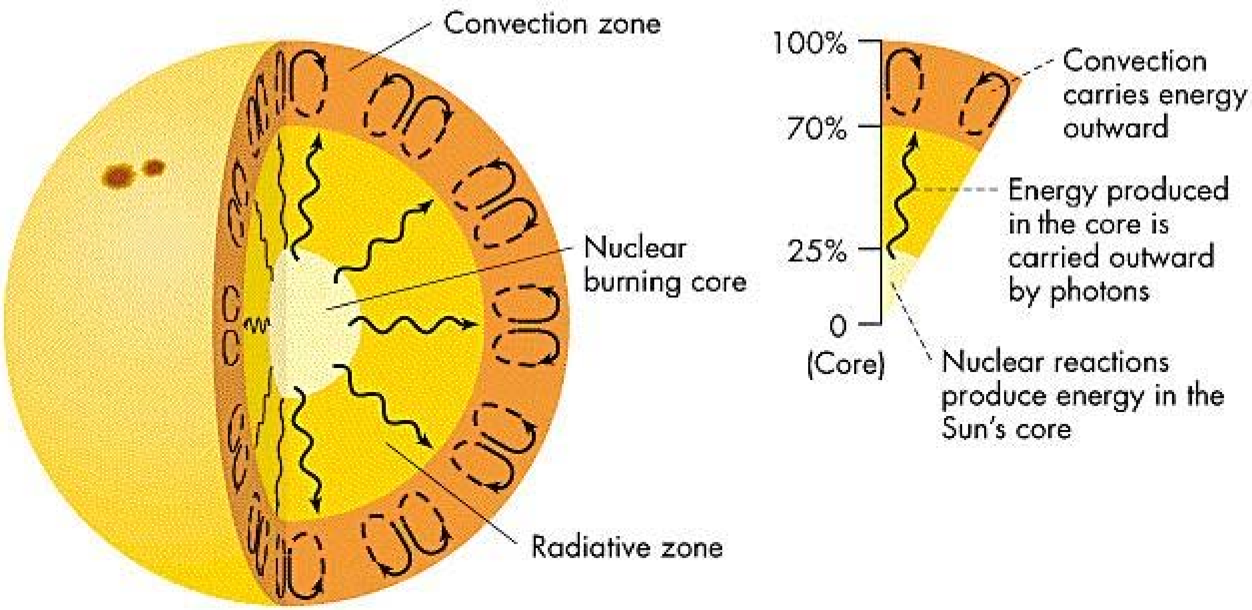


Spiderman II



Spiderman II

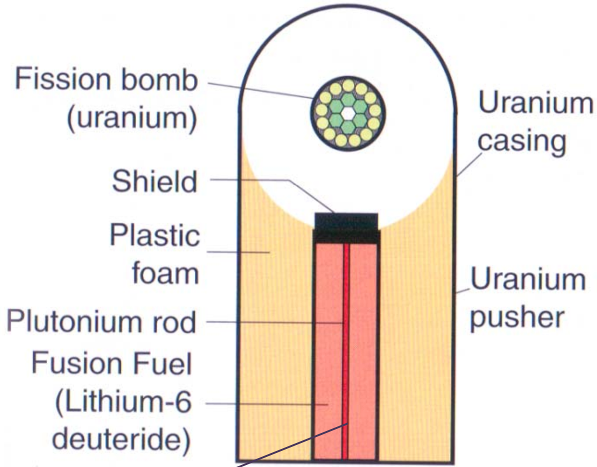
The Sun



Why the sun does not consume the whole hydrogen simultaneously?

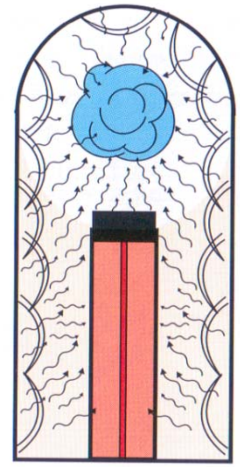
How old is the sun?

Hydrogen Bomb



2nd fission bomb to heat the already compressed fusion fuel

Basic construction



Fission explosion creating pressure wave

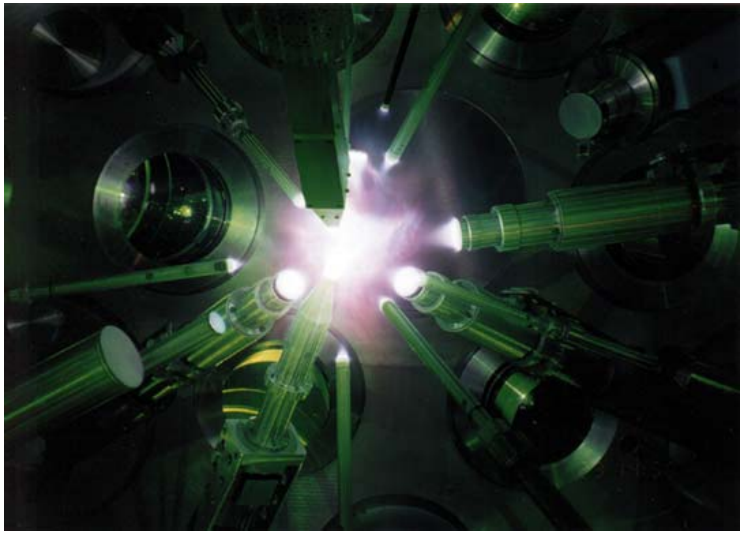
Ivy Mike (1 November 1952)

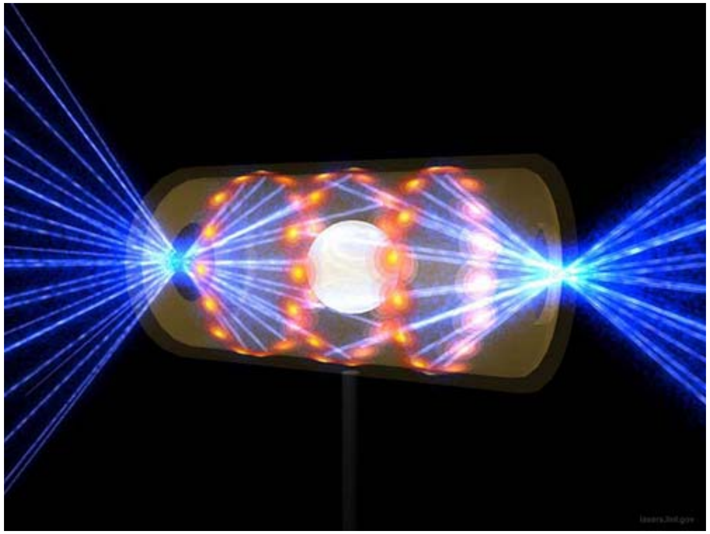
- **Teller –Ulam configuration (radiation implosion)**

- 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 and ignite it before it is blown apart by the blast wave from the fission explosion.

Inertial Confinement Fusion (ICF)

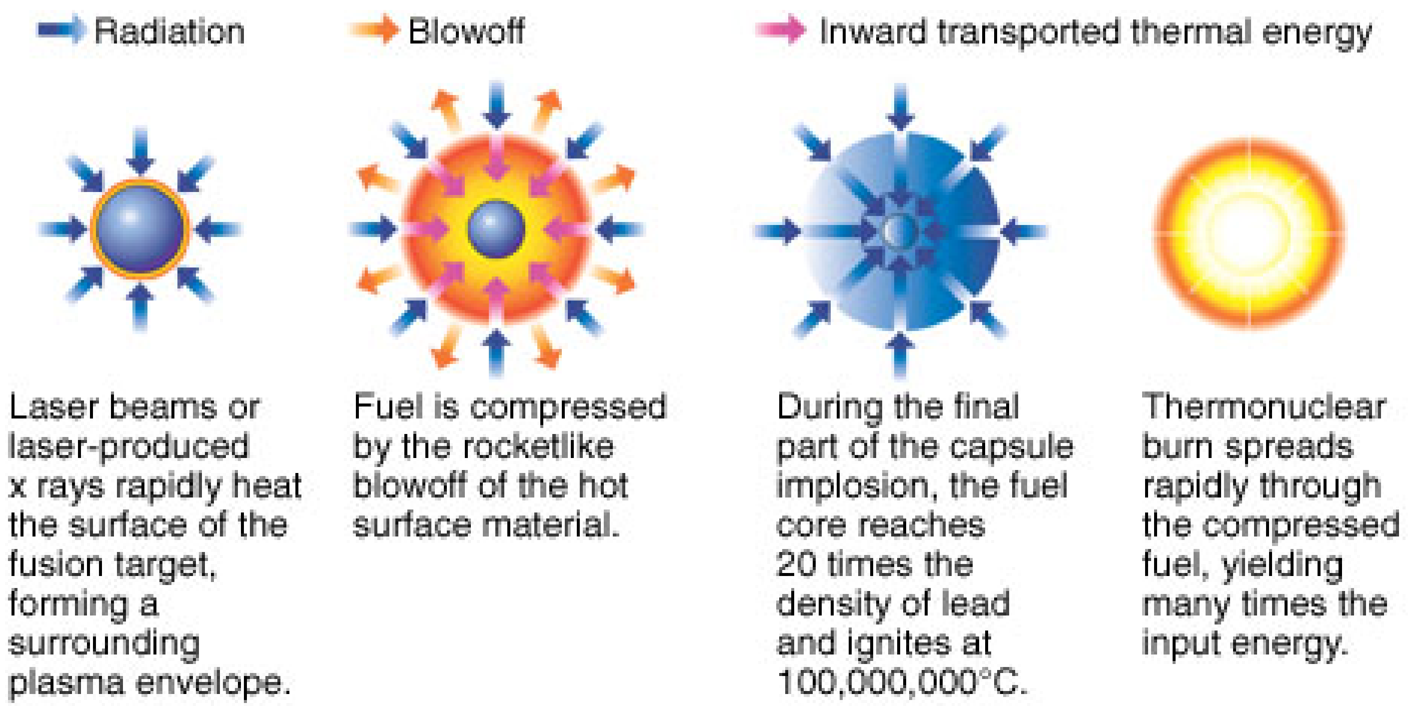
- A process where nuclear fusion reactions are initiated by heating and compressing a fuel target, typically in the form of a pellet that most often contains deuterium and tritium
- To compress and heat the fuel, energy is delivered to the outer layer of the target using laser beams, ion beams, or X-ray 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





ICF – Direct Drive

- Sequence of events – mini explosions



ICF – Direct Drive

- **Sequence of events**

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

ICF – 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

ICF – Direct Drive

- **Requirements**

- Very rapid attainment of high density of the inner core before internal pressure build-up by e-heating that opposes high compression:

The cloud of plasma formed by laser beams shields the fuel pellet from being struck by further laser light so the laser light doesn't reach the surface anymore, where it can impart maximum momentum. The plasma begins to act like a mirror, reflecting the light. When laser light is reflected it creates waves in the plasma, which in turn shoot energetic electrons to the core of the fuel pellet. The very high energy electrons generated by the initial laser penetrate into the centre before the arrival of the pressure wave thereby causing an undesirable preheating of the central core region resulting in an expanding outward force effect to retard compression.

The trick is to keep the target cold, gently pushing on it until it reaches hundreds of times solid density.

Accelerators transfer the beam energy more directly to ions in the target → more efficient

ICF – 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

- Achievement of substantial fusion reaction before pellet disintegration

ICF – 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	KrF	Required
Wavelength (μm)	1.06	0.25	~ 0.3
Pulse rate (Hz)	0.001	5	~ 5
Beam energy (MJ)	0.03	0.1	~ 1
Representative peak power (TW)	30	100	~ 1000

ICF – Beams

- **Energetic ion beams**

- Energetic ion beams introduce another set of problems:
  beam focusing 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

ICF – Targets

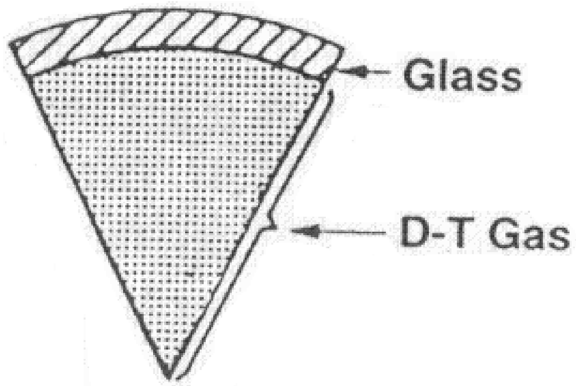
- **Targets**
  - Typical fuel pellets (microcapsules or micro balloons) are about the size of a pinhead and contain around 10 milligrams of fuel: in practice, only a small proportion of this fuel will undergo fusion, but if all this fuel was consumed it would release the energy equivalent to burning 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)

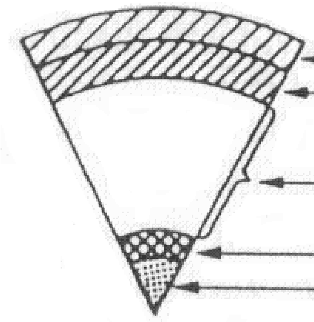
ICF – Targets

- **Glass microballoons**
  - 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



ICF – Targets

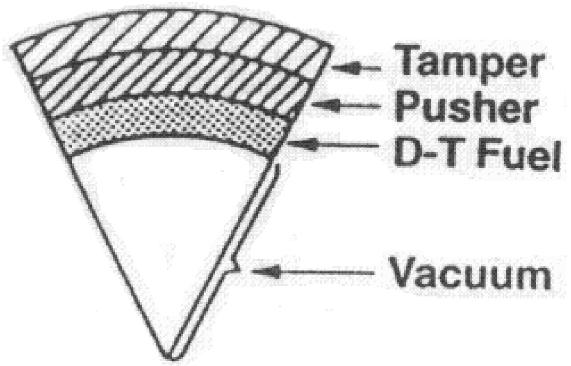
- **Multiple shell pellets**
  - Consisting of an inner D-T solid fuel core surrounded by a high-Z inner pusher-tamper, a thicker layer of low density gas surrounded by a pusher layer and an outer low-Z ablator material
  - The outer layer is to ablate quickly and completely when struck by the incident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



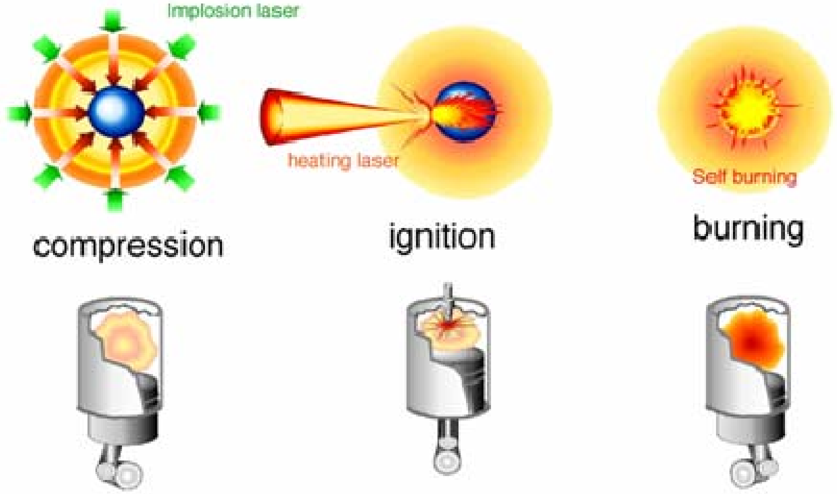
ICF – Targets

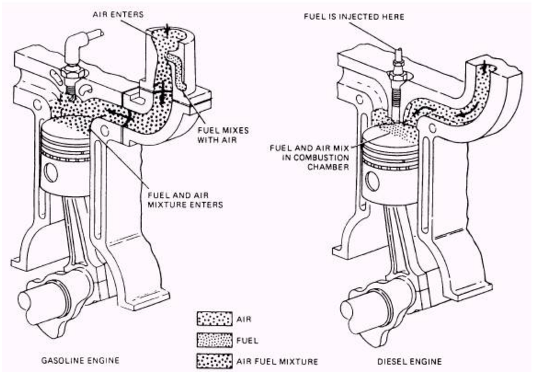
- **High-gain ion beam pellets**

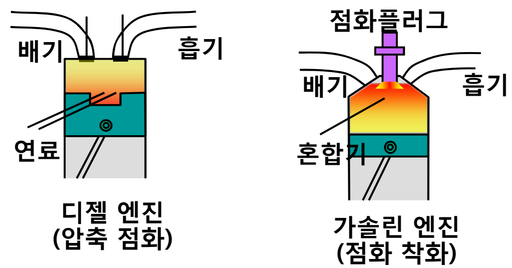
- Consisting of a vacuum sphere surrounded by a D_2-T_2-DT fuel shell surrounded by tamper-pusher materials
- Thickness of the tamper-pusher materials carefully matched to the type and energy of the incident beams



ICF – Fast Ignition



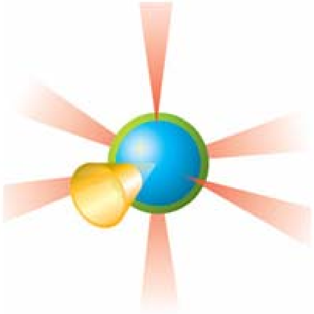




- A new scheme separates the compression and heating phases much like a petrol combustion engine. In the petrol engine the fuel is compressed by the piston and then ignited via the spark plug. In the case of fast ignition, the driving lasers are the pistons, compressing the fuel to high density around the tip of a gold cone.

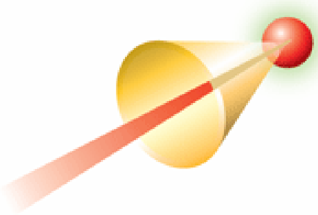
- The spark plug in this case is a multi kj, short pulse laser which is injected into the tip of the gold cone. When the laser interacts with the gold, plasma is formed and energetic electrons produced travel into the dense fuel to deposit their energy and raise the fuel to fusion temperatures.

ICF – Fast Ignition

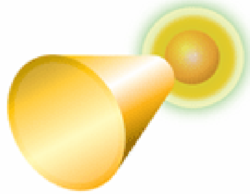


- Many powerful laser beams irradiate a capsule of DT fuel.
  The lasers are arranged symmetrically around the capsule and heat a thin layer of the capsule causing it to expand rapidly. This forces the rest of the material in the opposite direction.

- 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.



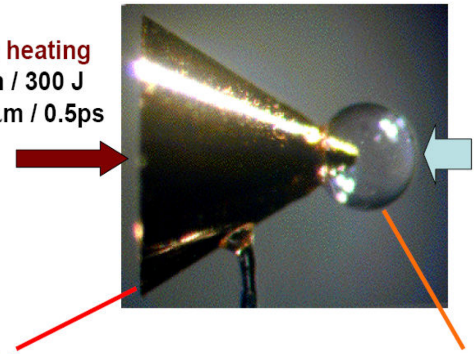
- An ultra intense laser is fired into the gold cone.
  When the laser interacts with the tip of the gold cone a large number of energetic electrons are produced.



- 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.

ICF – Fast Ignition

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

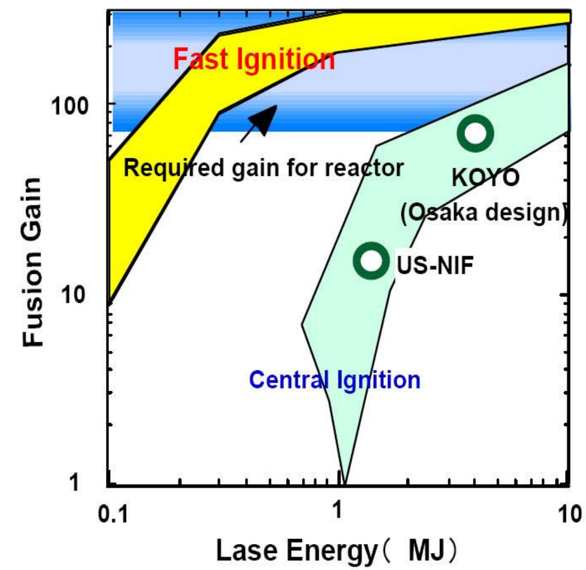


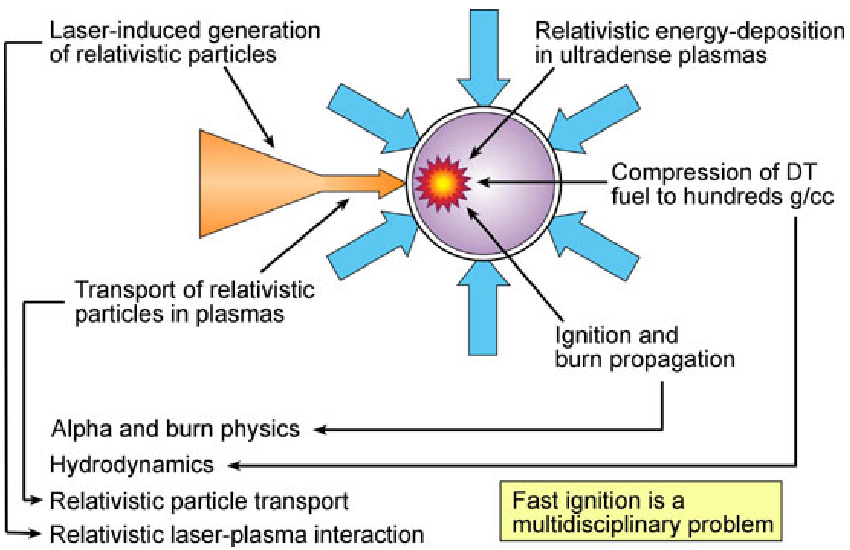
GXII for implosion
9 beams / 2.5 kJ/0.53 μm

1.2ns Flat Top w/ RPP

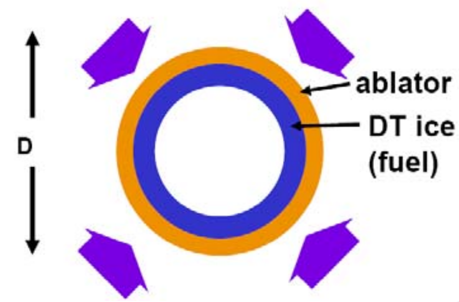
Au cone
30 ° open angle (the picture: 60deg)
Thickness of the cone top: 5μm
Distance of the cone top: 50μm from the center

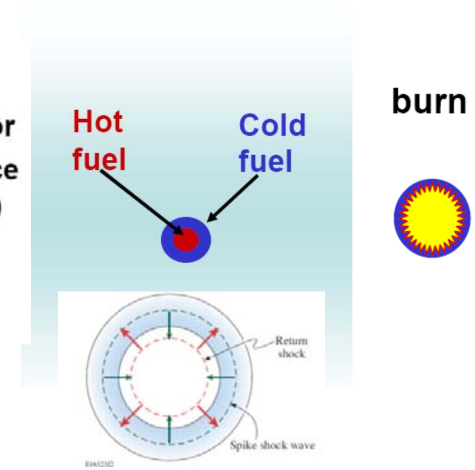
CD shell
500μmϕ/6-7μmt

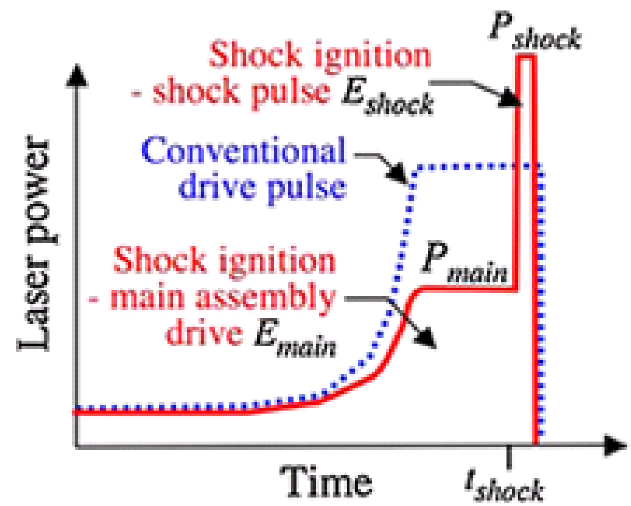


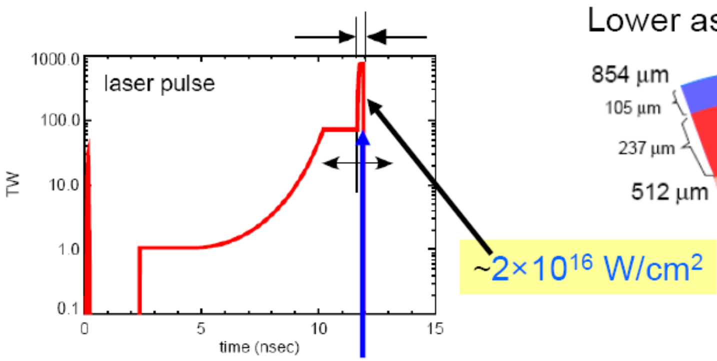


ICF – Shock Ignition



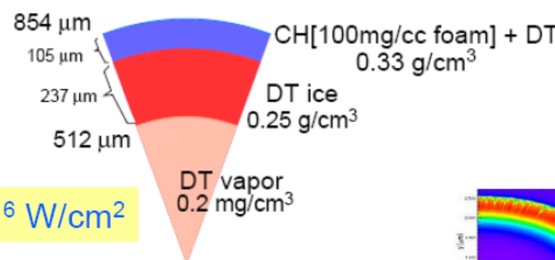


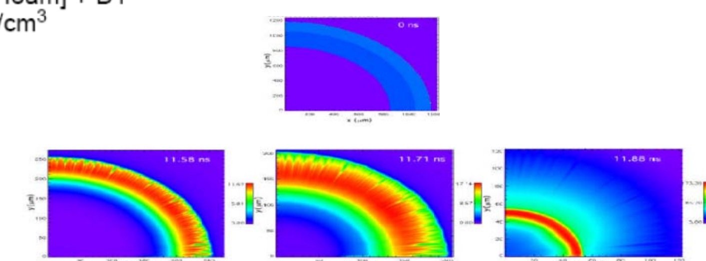




compress shock heat pulse

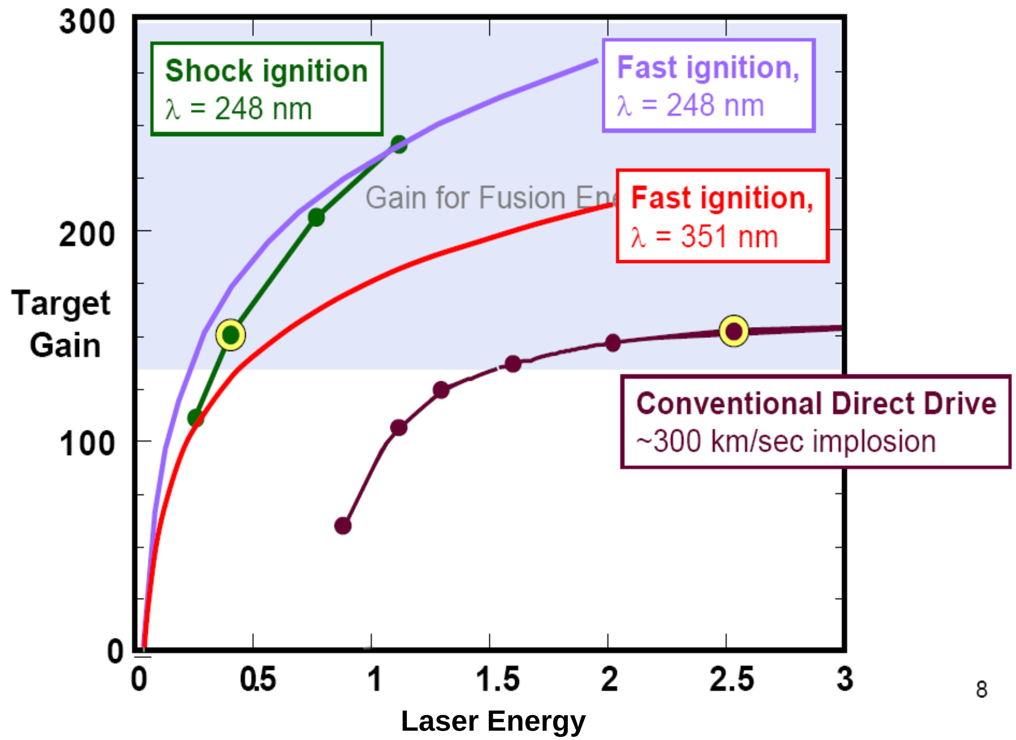
Lower aspect ratio target





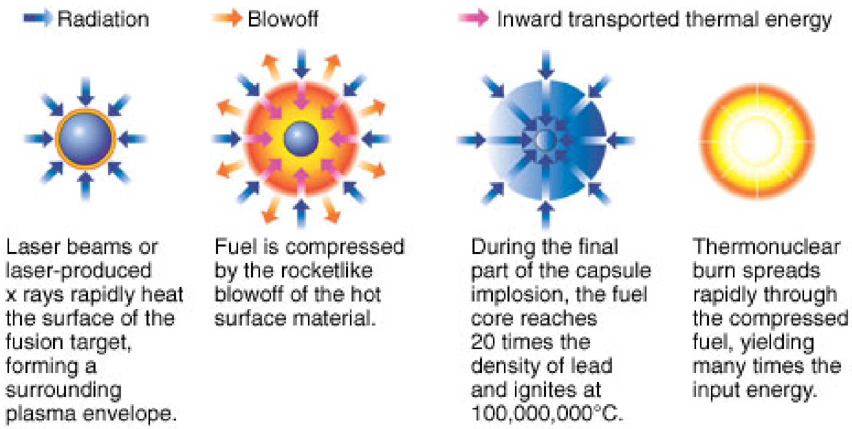
2-D studies also give promising performance
Collaborations with NRL (Schmitt) & LLNL (Perkins)

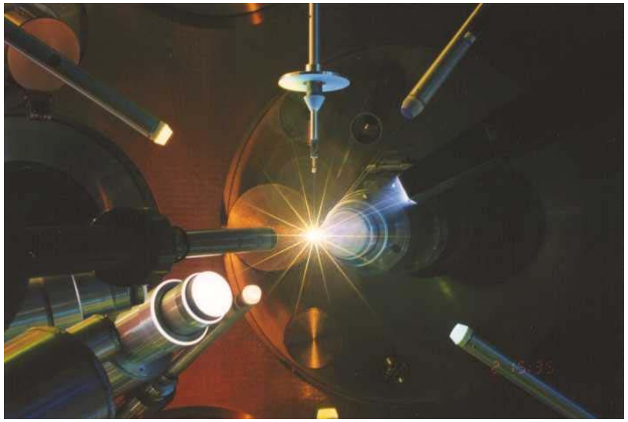
ICF – Shock Ignition



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

ICF – Limits of Direct Drive



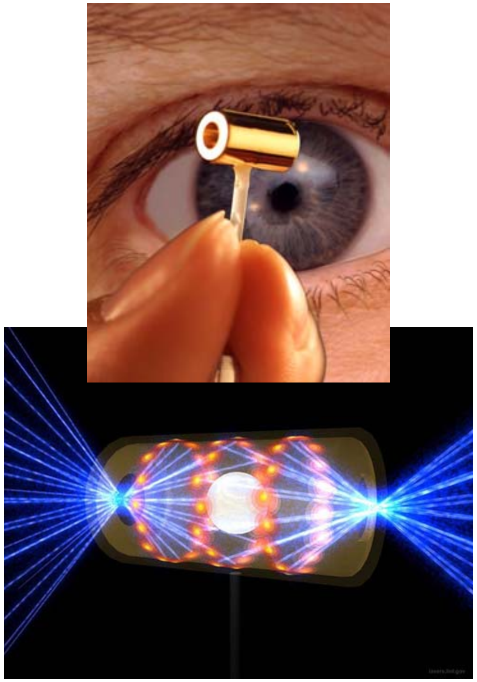


- This puts a very high requirement on symmetry of the spherical capsule and of the distribution of energy contained within the driving lasers/radiation.
- If these are not symmetrical then different parts of the capsule will reach maximum density at different times and the capsule will break apart without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

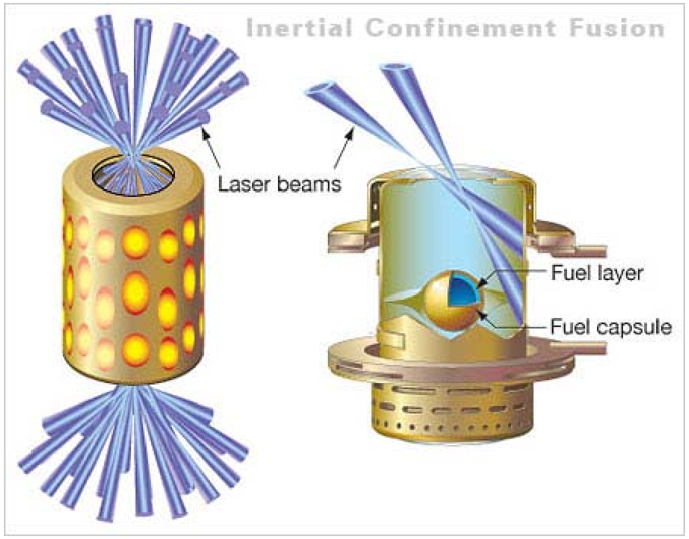
ICF – Indirect Drive

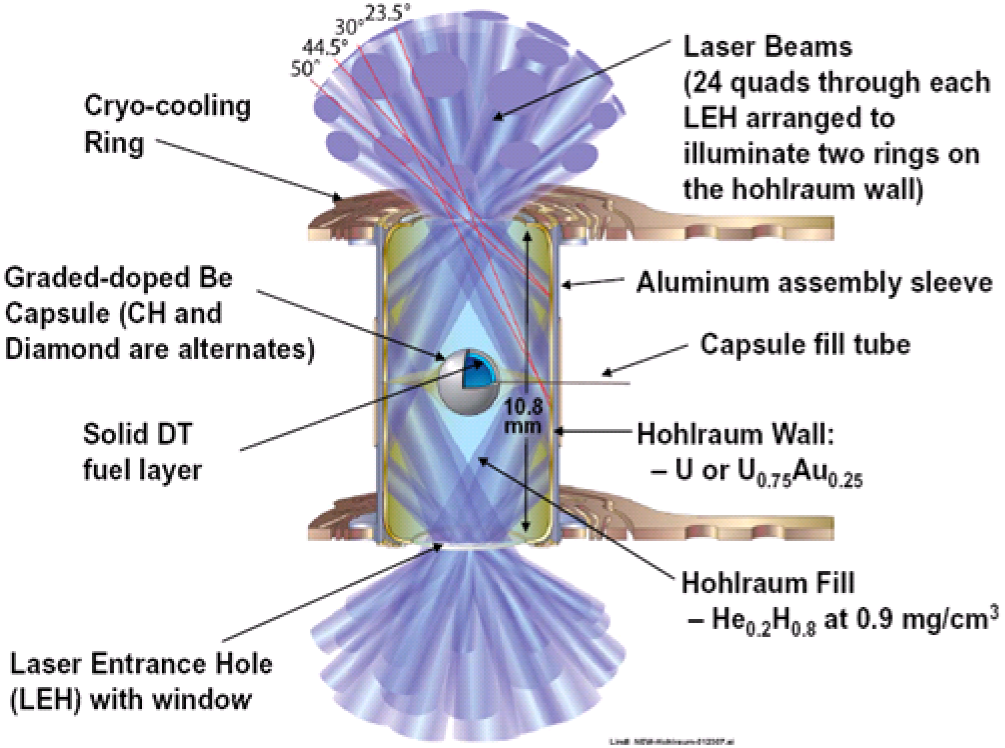
- **Indirect drive**

- 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 is important.



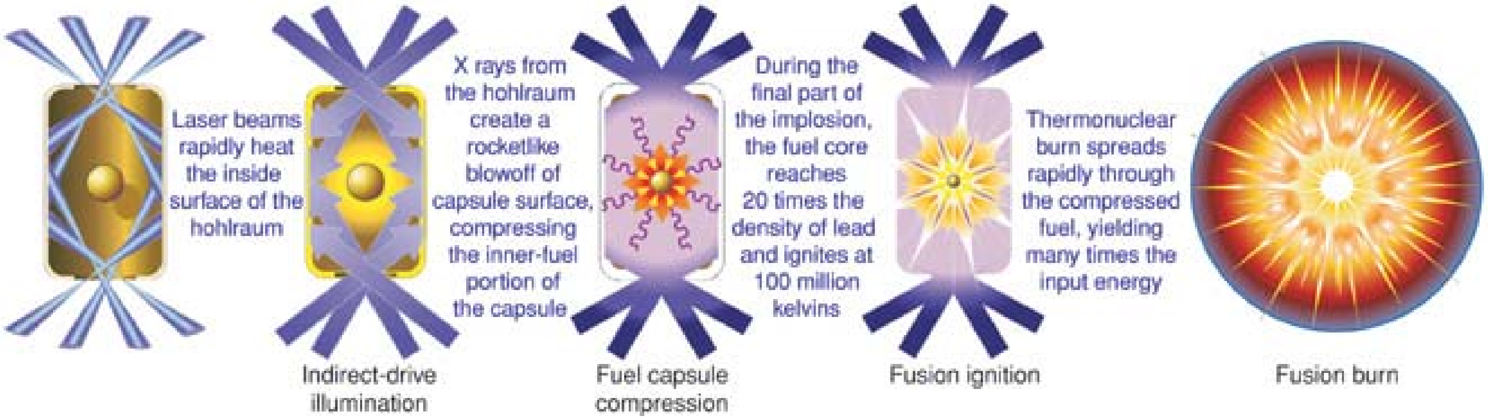
ICF – Indirect Drive





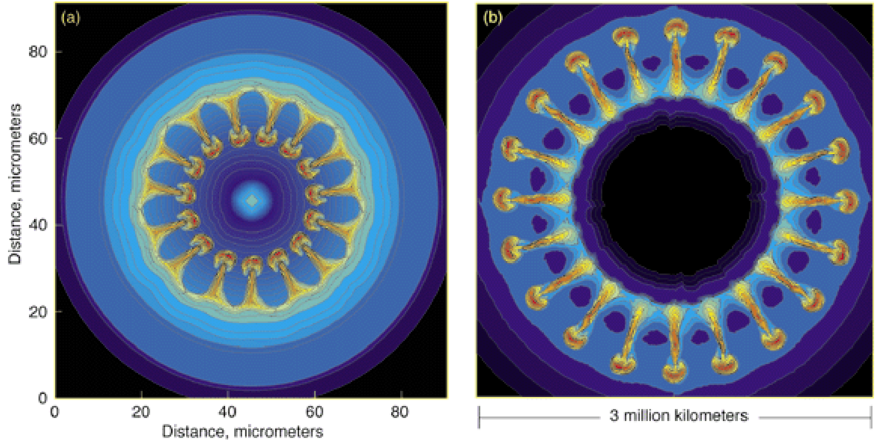
ICF – Indirect Drive

- **Sequence of events**



ICF – Indirect Drive

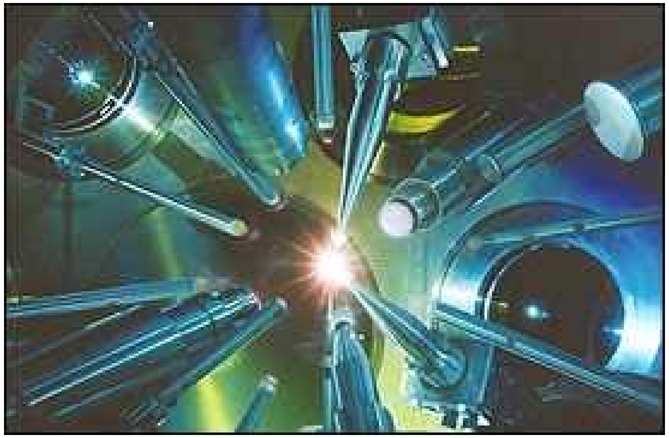
- **Pros and Cons compared with the direct drive**
  - Symmetric energy deposition on the pellet surface is efficient compared with the direct drive where all the driver beams must symmetrically impinge directly on the pellet.
  - Better ablation and subsequent compression with X-rays
  - Reduced instabilities during pellet compression
  - Reduced energy coupling from the beam to the pellet
  - Increased complexities of hohlraum manufacture

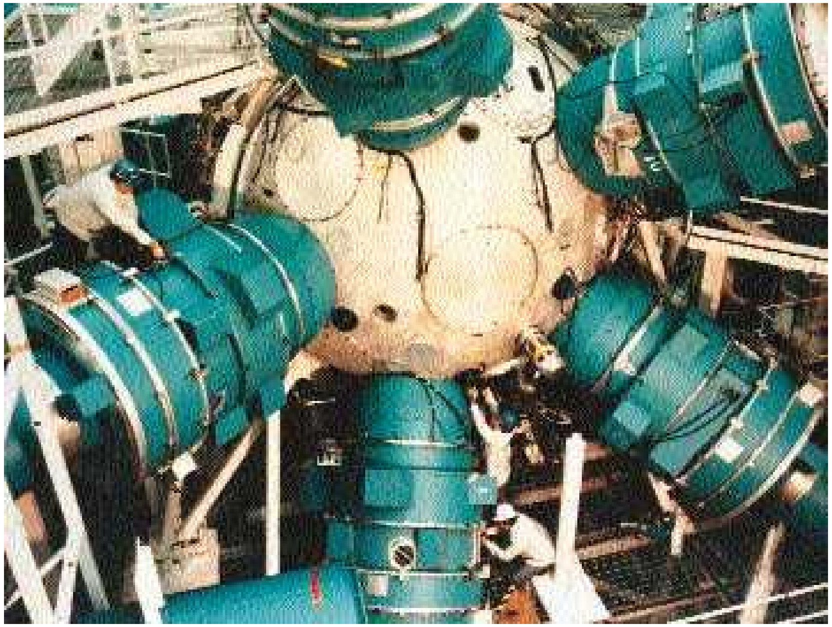


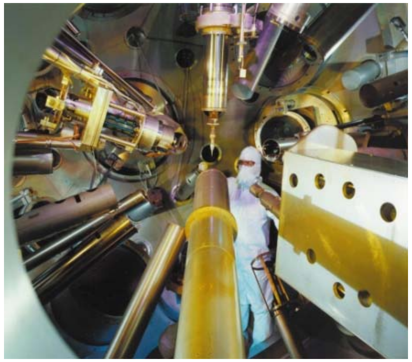
Striking similarities exist between hydrodynamic instabilities in (a) inertial confinement fusion capsule implosions and (b) core-collapse supernova explosions. [Image (a) is from Sakagami and Nishihara, *Physics of Fluids B* **2**, 2715 (1990); image (b) is from Hachisu et al., *Astrophysical Journal*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

Richtmyer-Meshkov instability (RMI): the instability occuring at an impulsively accelerated interface between two different gases.

ICF – Nova



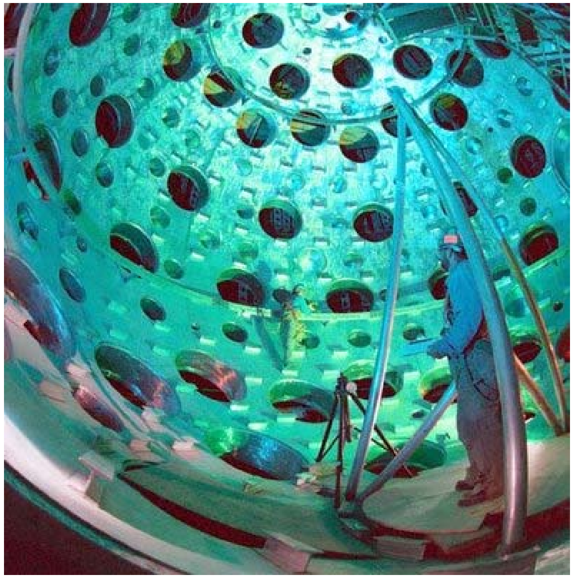




- Lawrence Livermore – Siva and **Nova (1984)**

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

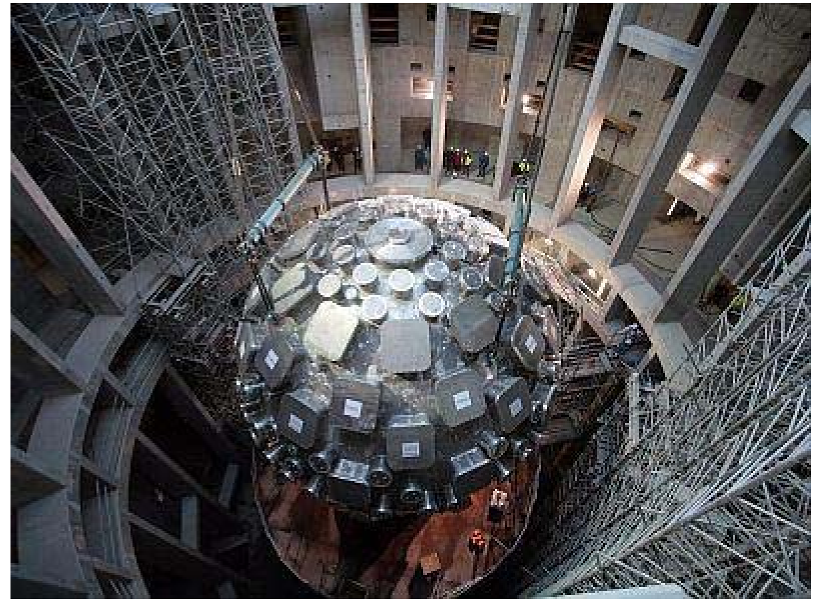
ICF – National Ignition Facility (NIF)



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 1,000 times the electric generating power of the USA
- Very short laser pulse, a few billionths of a second

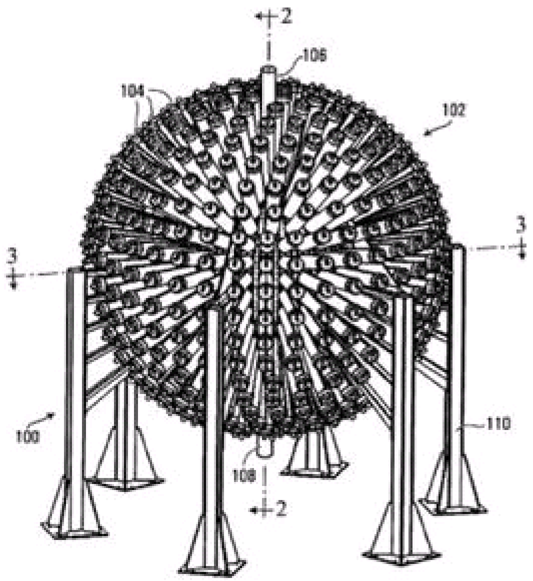
ICF – Laser MegaJoule (LMJ)

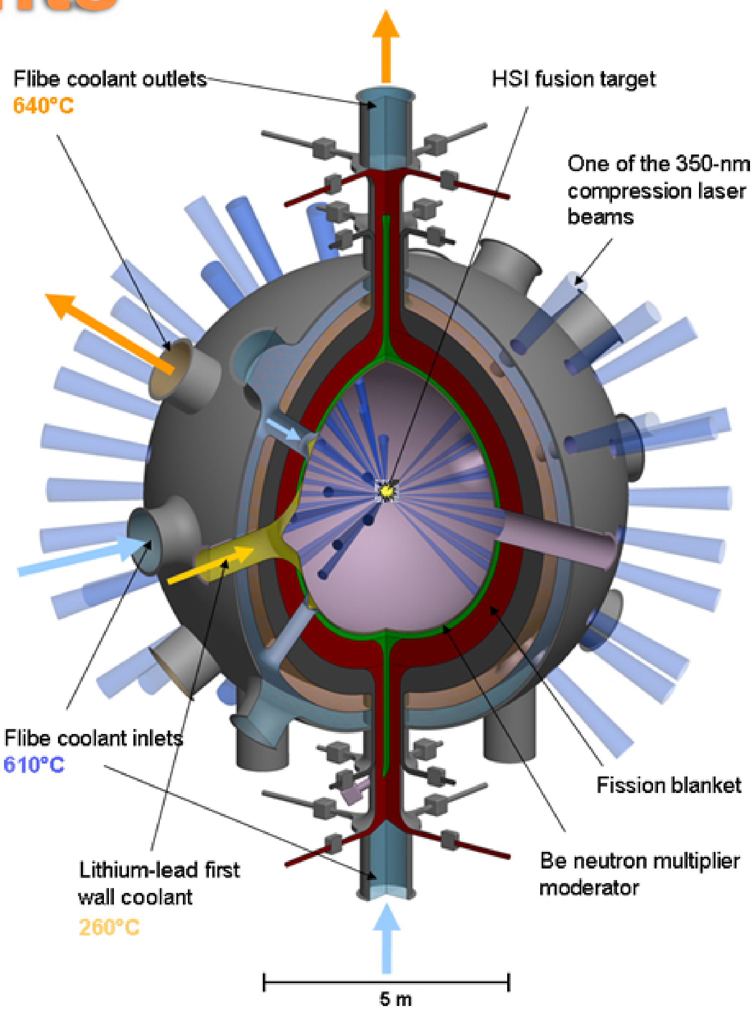


- CEA, France
- Being build near Bordeaux (expected to be completed in 2012)
- 1.8 MJ of laser energy
- Focusing on indirect drive

ICF – Power Plants

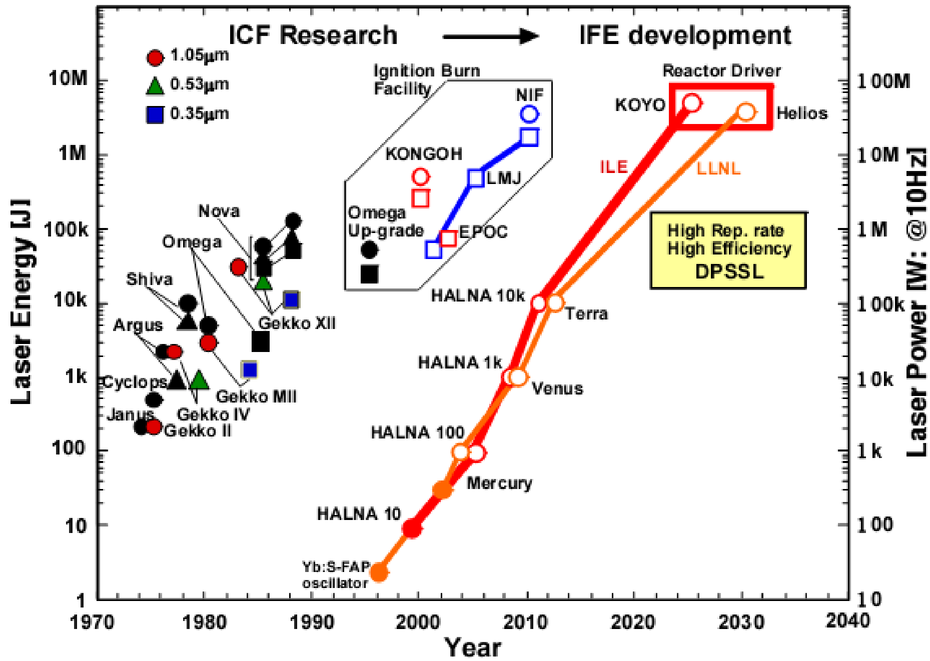
ICF – Power Plants

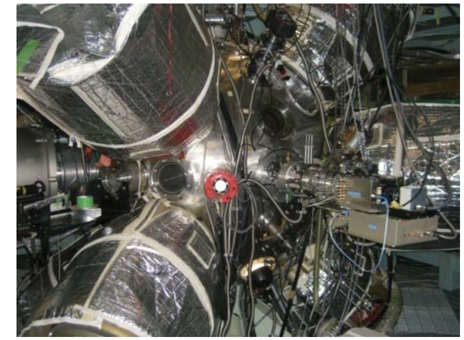




A LIFE fusion-fission chamber for a 37.5-megajoule (MJ) hot-spot ignition (HSI) target driven by a 1.4-MJ, 350-nanometer (ultraviolet) laser.

ICF – Power Plants



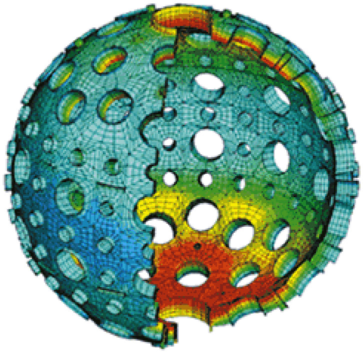


The GEKKO Laser
(Osaka Univ. 1983)

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.

ICF – Issues on Power Plants



- **Protection for the reaction chamber wall**
  - Against radiation and energy deposition by pellet debris released in a microexplosion
  - 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 needed in preparation 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

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

References

- *http://www.tgdaily.com/sustainability-features/42639-laser-fusion-plant-delivers-the-power-of-the-stars*
- *http://www.pocketburgers.com/2009_03_31_archive.html*
- *https://www.llnl.gov/str/JulAug07/Atherton.html*
- *http://www.mth.msu.edu/~wei/RMI.html*
- *http://www.tpub.com/eqopbas/3.htm*
- *http://www.mhhe.com/physsci/astronomy/fix/student/chapter17/17f01.html*