Physics of Fusion

Lecture 15: Inertial Confinement Fusion

Lecturer: Dirk O. Gericke

Two Different Ways to Fusion

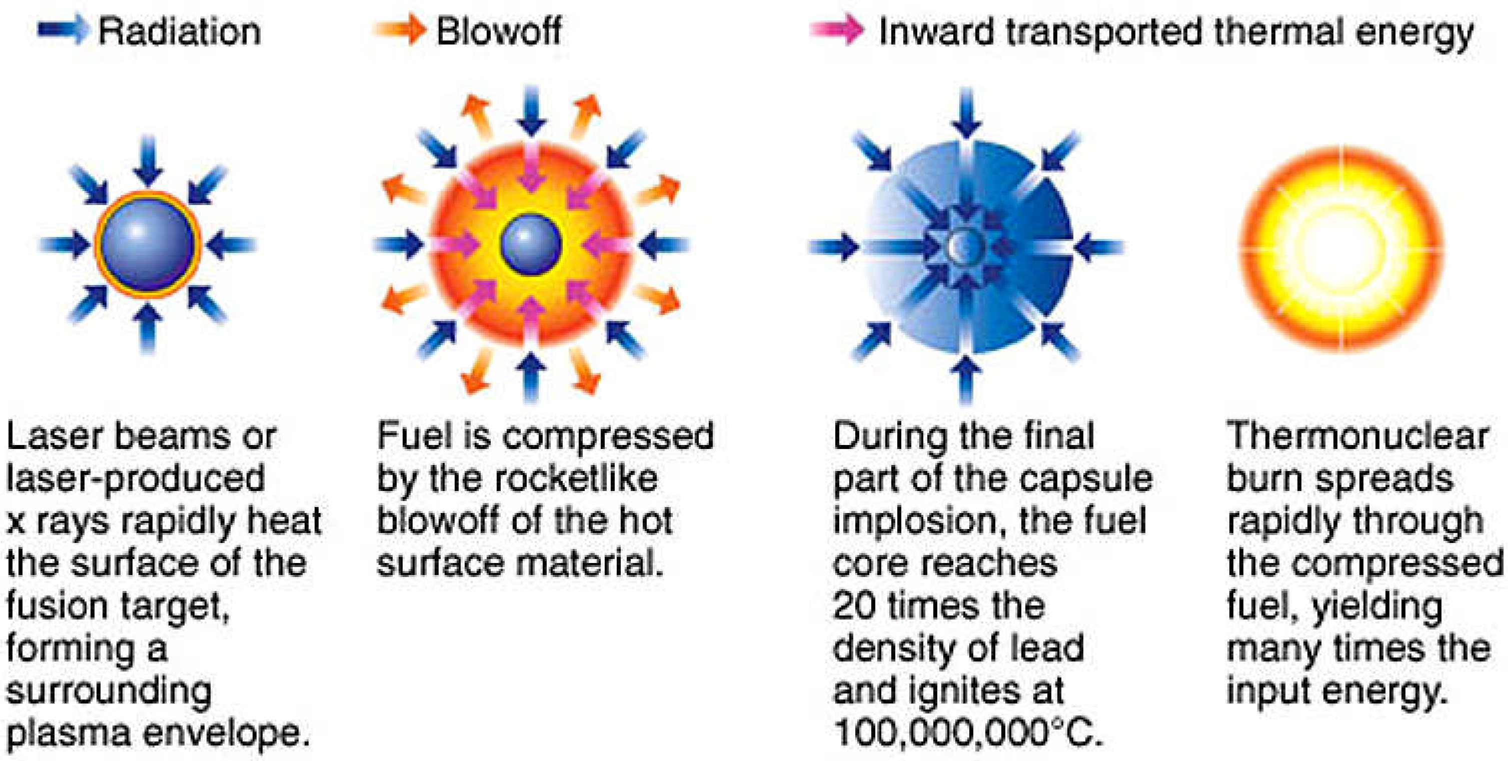
- Lawson Criterion: must be achieved $$n_{20} T_k \tau_E > 30 \ \ \text{Ignition}$$
- Temperature must be around T = 6 ... 15 eV
- Two ways to fulfil Lawson criterion:

(1) First solution (magnetically confined plasmas): increase confinement time

(2) Other solution (inertial confinement fusion - ICF): increase density of fusion plasma

✶ Many similarities, but a few decisive differences!

Inertial Confinement Fusion Concept



Plasma Conditions During ICF

- **Before compression and ignition**

  Density: solid DT ice at 0.225 g/cm^3 and gas
  Temperature: few Kelvin

- **During the burn phase**

  Density: 300 to 1000 times liquid density
  300 to 1000 g/cm^3 ≈ 10^{26} cm^{-3}
  Temperature: around 10.000.000 K or 10 keV
  Pressure: around 10^{12} bar

- **Confinement time needed**: around 200 ps

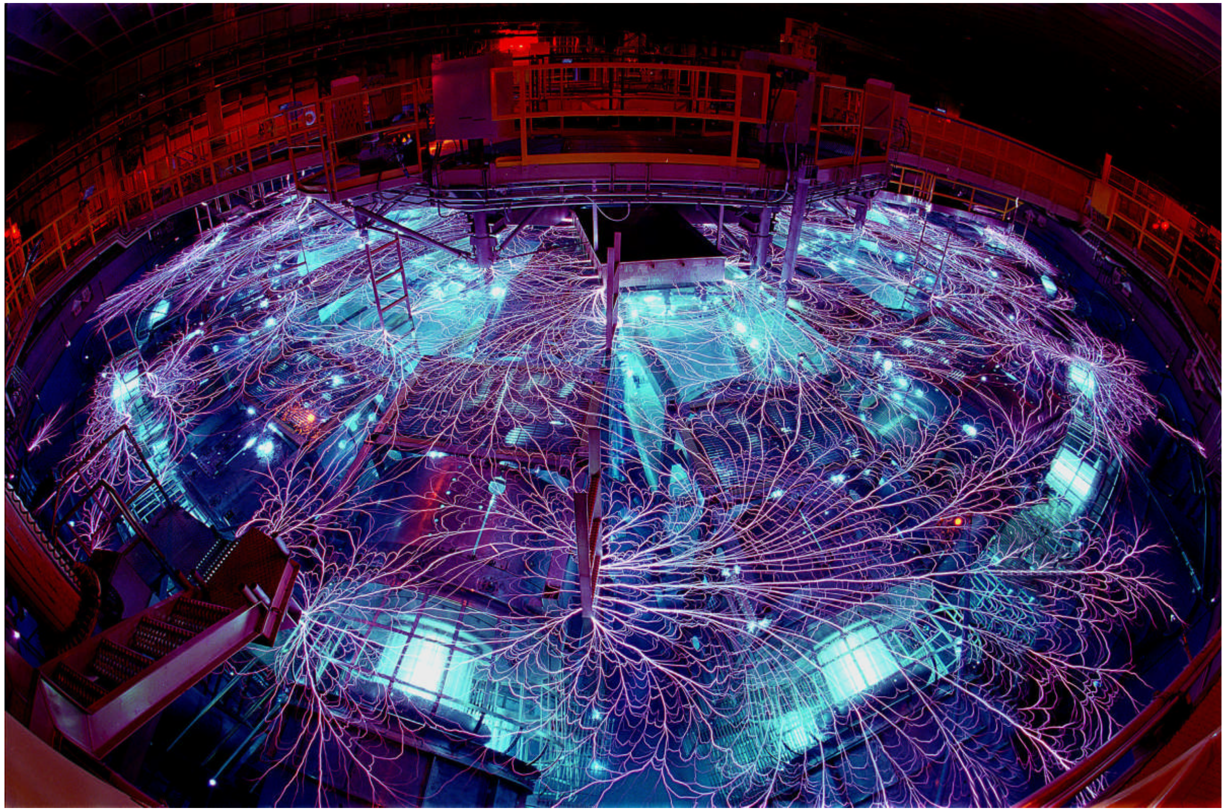
Calculating the ‘Confinement’ Time

- Consider homogeneous sphere of DT-fuel at $t=0$ with Radius $R(t)$ and constant temperature and density
- Sphere ‘explodes’ with sound speed $c_s = (2\, k_B T/ M)^{1/2}$ (fastest speed to transport information, fix parameter)
- Mass confinement time: $t_{conf} = R(t=0) / c_s$
- Time needed for fusion: $t_{fusion} = 1 / \langle \sigma v \rangle\, n_0$
- Ratio t_{conf} / t_{fusion} depend on product: $n_0\, t_{conf}$
- $n_0\, t_{conf} = (1 / Mc_s)\, \rho R$ with $\rho = M\, n_0$ mass density
- Parameter ρR must be as large as possible

Limits for Compression and Radius

- Radius is limited by total mass and related energy that can be handled in target chamber
- Compression limited by energy available in driver since first law of thermodynamics, $dU = T\,dS - p\,dV$, relates compression ΔV and energy input ΔU
- ➢ Isentropic compression ($dS = 0$) is better than shocks
- Work, i.e. $p\,dV$, is defined by $p(n,T)$
  ► classical ideal gas: $p = n\,k_B T$
  ► degenerate quantum gas at high densities $p \sim n^{5/3}$
- Again cold, isentropic compression are benificial
- Total energy needed to compress a few mg DT: ~ 1 MJ

Possible Drivers: Z - Pinches



Z-Maschine, Sandia labs, Albuquerque USA

Advantages:

- Good energy coupling (many x-rays)
- Large Targets

Disadvantages:

- **Very slow** (one shot / day)
- Only one device worldwide

Possible Drivers: Ion Beams

planed FAIR facility,
Darmstadt, Germany

10 to 20 rings needed
for fusion power plant!

Advantages:

- Excellent conversion from electric power to beam energy
- Large targets

Disadvantages:

- **Concept was never tested**
- Beam intensity is still too low

Possible Drivers: Lasers (Best Shot)

National Ignition Facility (NIF), Livermore, USA

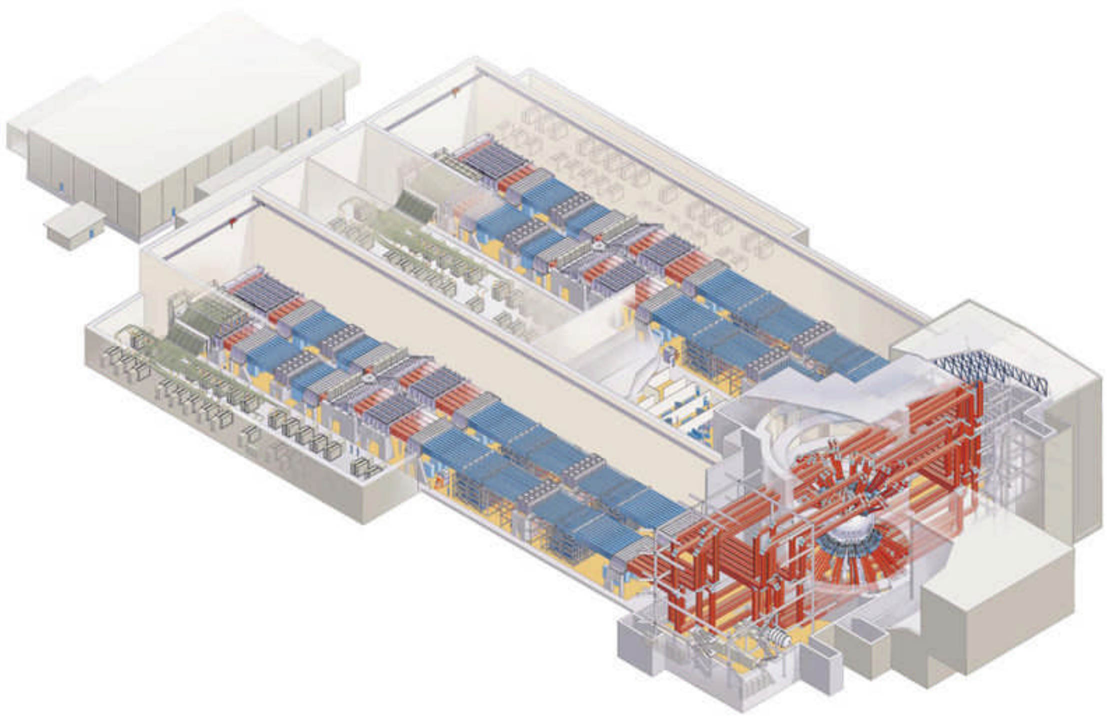
Advantages:

- Well advanced technology
- Good control of energy release

Disadvantages:

- **Bad energy conversion**
- Very expensive to build

Possible Drivers: Lasers (Best Shot)



National Ignition Facility (NIF), Livermore, USA

Advantages:

- Well advanced technology
- Good control of energy release

Disadvantages:

- **Bad energy conversion**
- Very expensive to build

Possible Drivers: Lasers (Best Shot)

Target chamber, NIF with 192 laser beams

Advantages:

- Well advanced technology
- Good control of energy release

Disadvantages:

- **Bad energy conversion**
- Very expensive to build

Possible Drivers: Lasers (Best Shot)

~1000 large Optics:

192 beam lines:

Engineering challeges at NIF

Advantages:

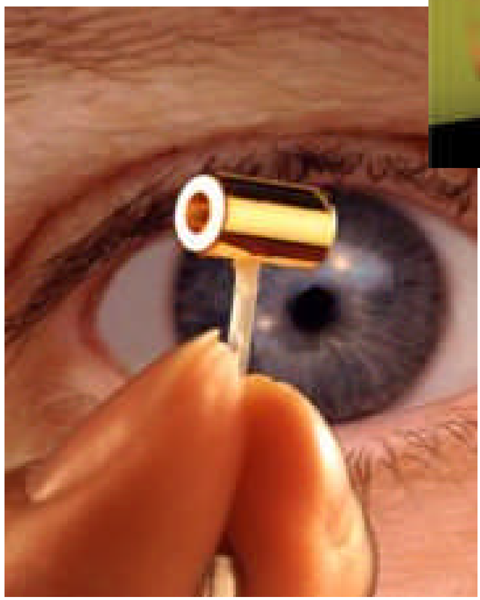
- Well advanced technology
- Good control of energy release

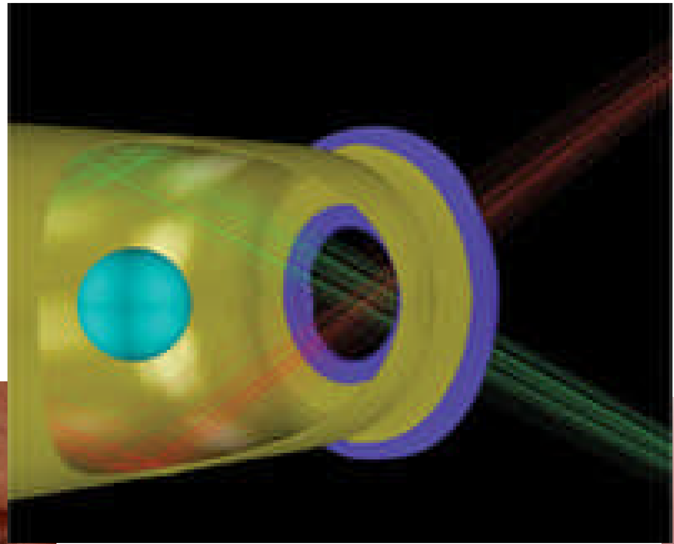
Disadvantages:

- **Bad energy conversion**
- Very expensive to build

Compare Driver to Target Sizes!

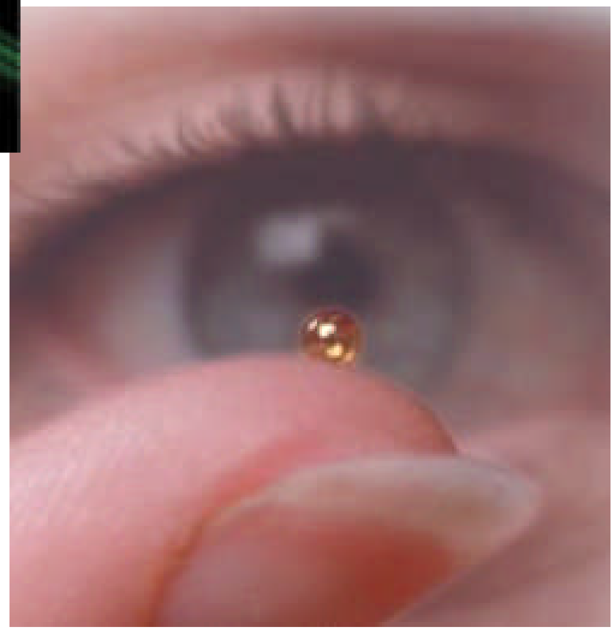
real NIF target





Schematic

DT capsule



Problems blocking Fusion Energy

Technical and Engineering Problems

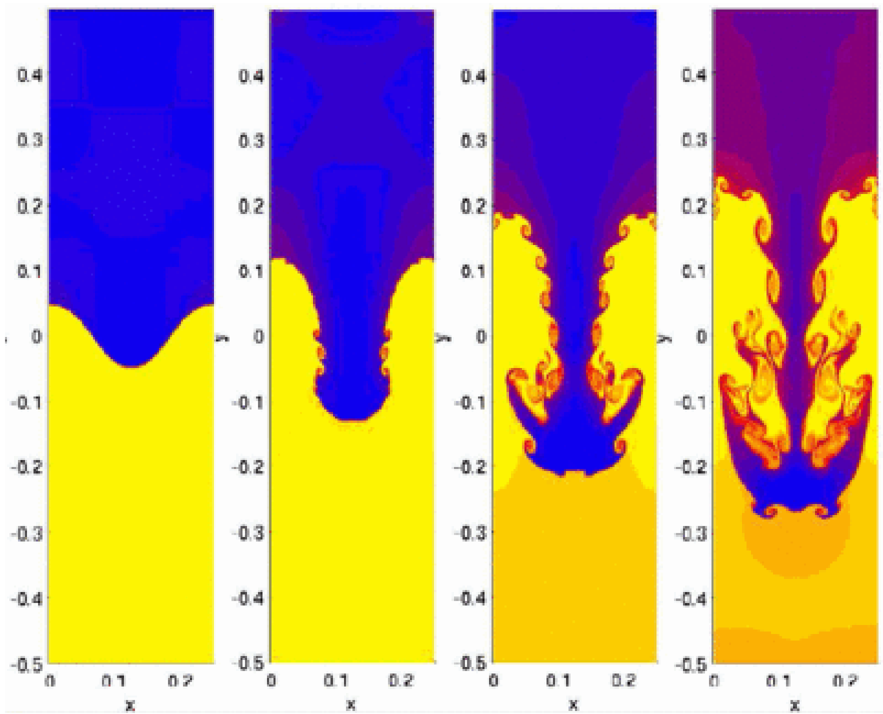
- High energy drivers are expensive and untested
- Energy conversion is too low (gain of >100 needed now)
- Repetition rate of drivers are too low (3-10 Hz needed)

Physics Problems

- Instabilities and Mixing
  - ► Rayleigh-Taylor unstable compression
  - ► Break of symmetry destroys confinement
- How to improve energy coupling into target
- What is the best material for the first wall?

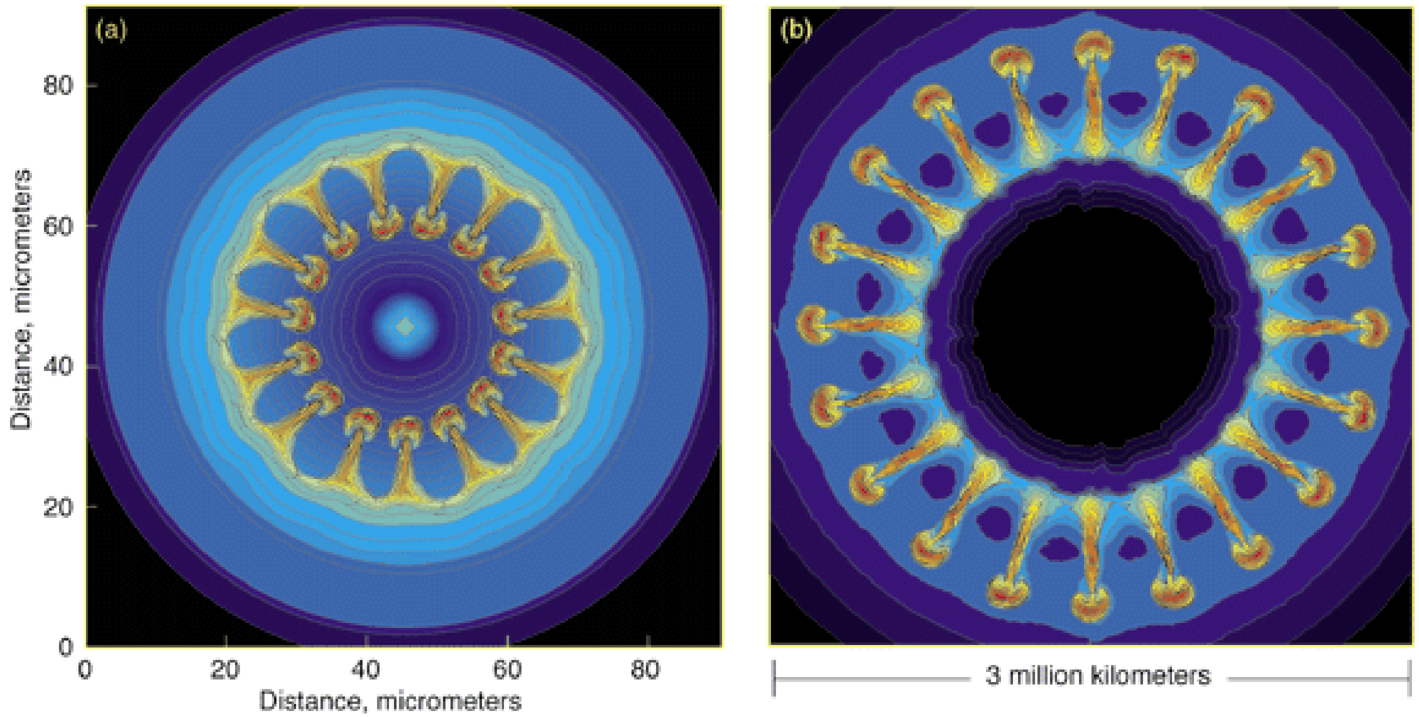
Rayleigh-Taylor Instability

- Major instability:
  heavy material pushes
  on low density one
- Will always occur since
  driver is never
  100% symmetric
- The Rayleigh-Taylor
  instability always grows



➢ **Energy must be delivered as sysmmetric as possible!**

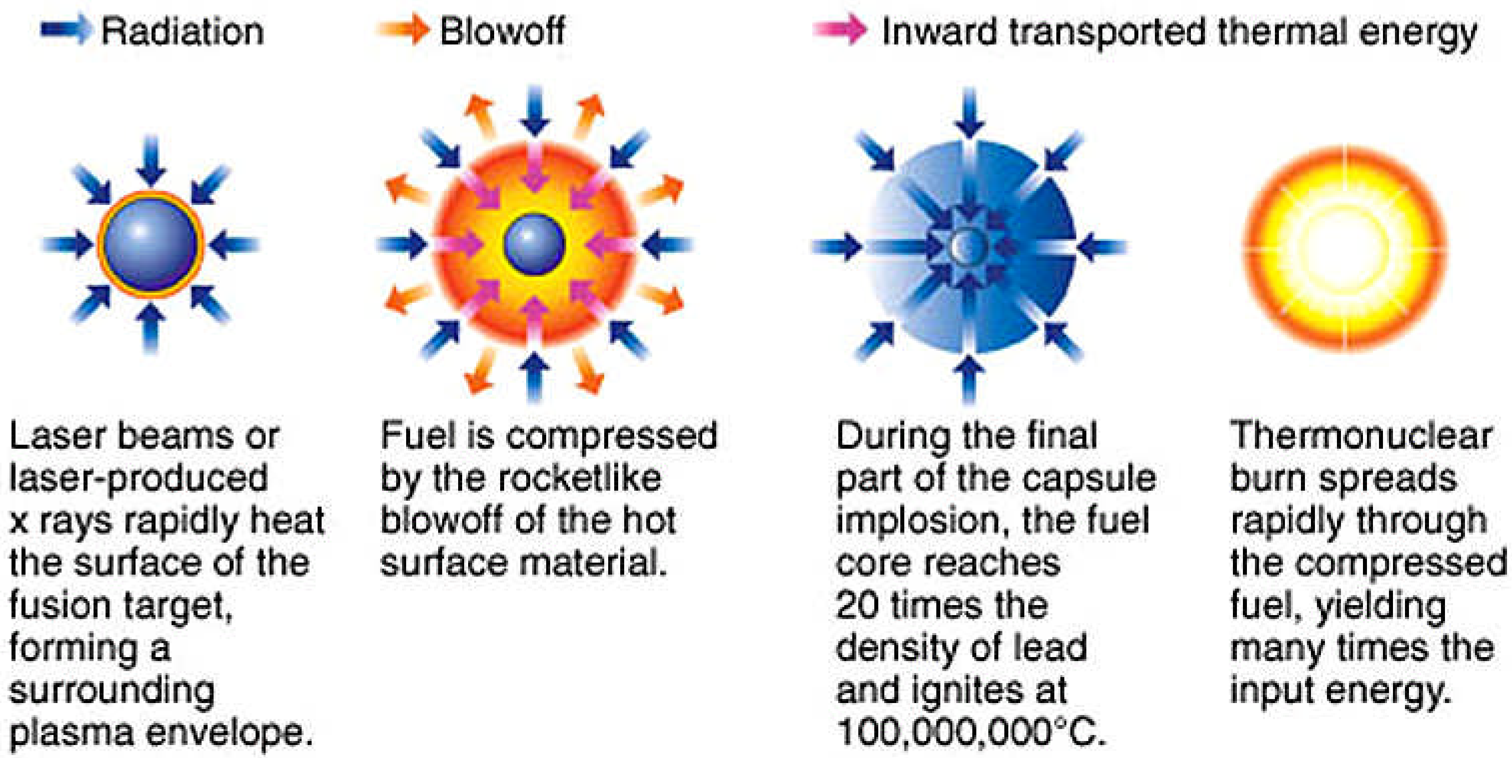
Rayleigh-Taylor Instability – spherical implosions / explosions



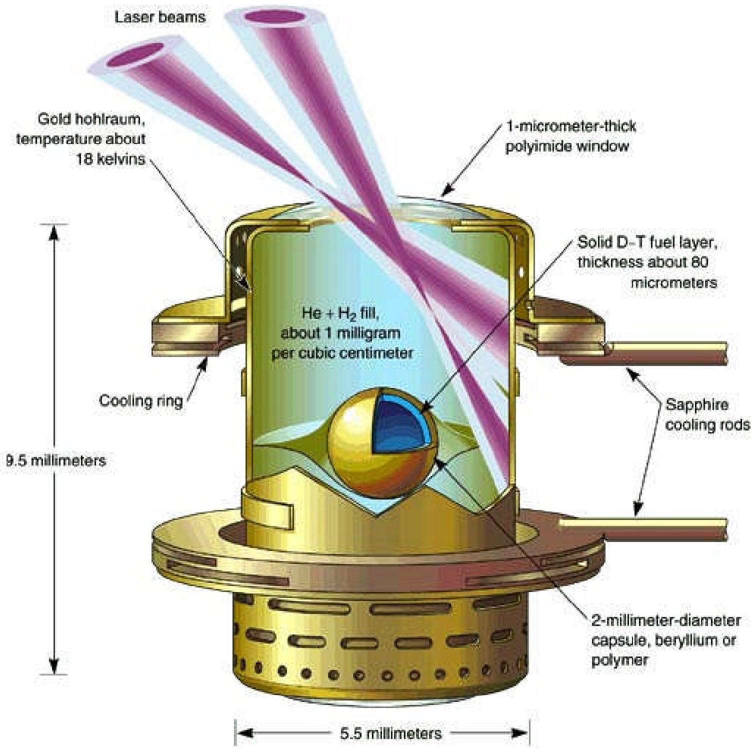
Striking similarities exist between hydrodynamic instabilities in (a) inertial confinement fusion capsule implosions and (b) core-collapse supernova explosions. [Image (a) is from Sakagami and Nishihara, *Physics of Fluids B* **2**, 2715 (1990); image (b) is from Hachisu et al., *Astrophysical Journal*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

➢**Energy must be delivered as sysmmetric as possible!**

Reminder: Direct Drive Scheme



Relaxing the Symmetry Conditions – Indirect Drive

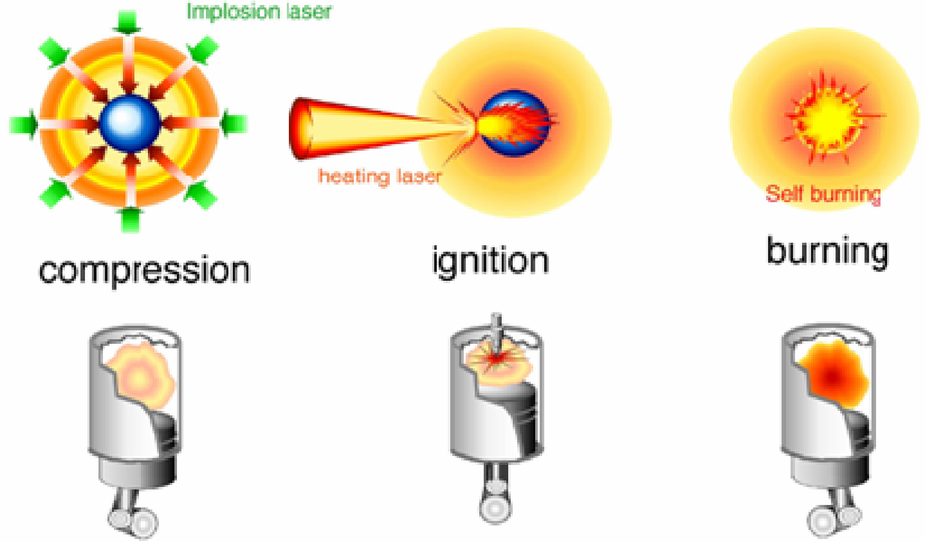


NIF design (laser)

Hohlraum
for the
Z-maschine

- Laser beams heat walls
- Walls emit thermally (x-rays)
- X-rays compress and heat the fusion capsule
- **X-rays highly symmetric!**

Relaxing the Symmetry Conditions – Fast Ignition



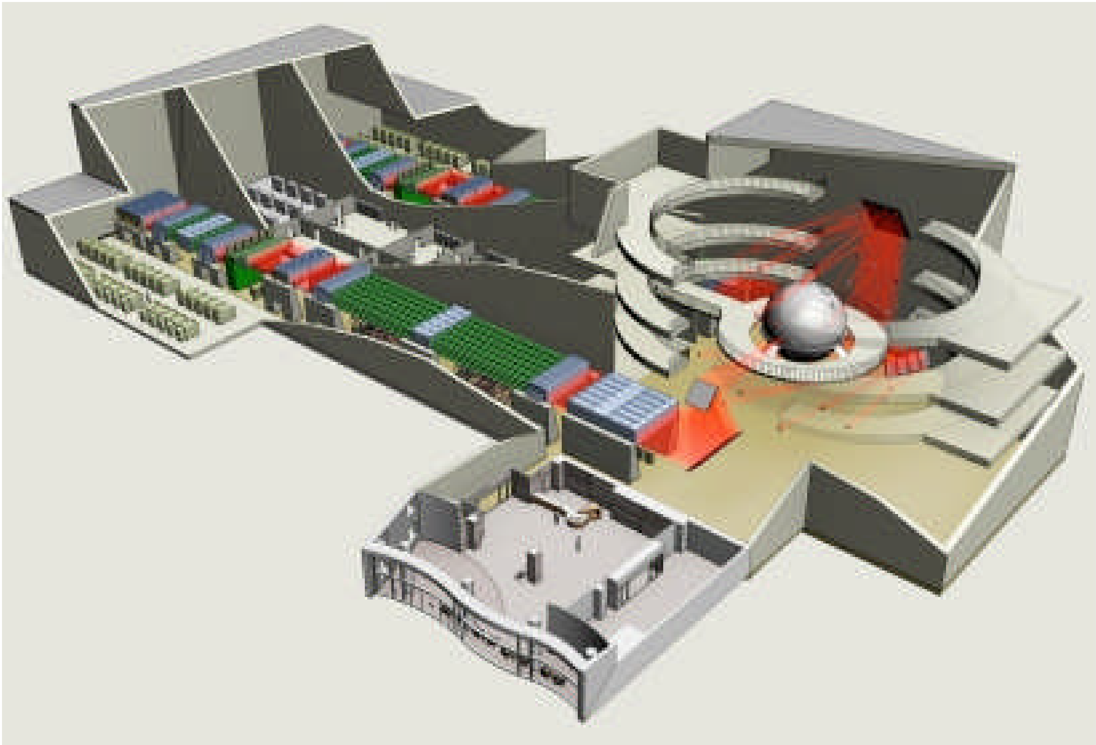
Fast ignition scheme
with many facets

- Idea: separate compression and ignition with two pulses
  - Less compression, cooler targets, lower densities
- **Problem: How can energy be transferred to hot spot?**

Interesting Experiments to Come

- National Ignition Facility (NIF, Livermore, USA)
  - ► More than 90% completed, first tests done
  - ► First full scale experiments this year; ignition in 2010?
- Laser Mega-Joule (LMJ, France)
  - ► Commissioning (full scale) in 2011
- FIREX I and FIREX II (ILE, Osaka, Japan)
  - ► Fast ignition experiments showed prove-of-principle
  - ► Fully integrated experiments in 2010 / 2011
- HiPER project (Europe, R.A.L. ???)
  - ► European fast ignition proposal based on NIF
  - ► Design work funded last year; full funding pending

Future: HiPER ???



Artist view of the fast ignition experiment HiPER