Physics of Fusion

Lecture 15: Inertial Confinement Fusion

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Two Different Ways to Fusion

- Lawson Criterion: $n_{20} T_k \tau_E > 30$ Ignition
- Temperature must be around $T = 6 \ldots 15$ 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

- **Radiation**: Laser beams or laser-produced x rays rapidly heat the surface of the fusion target, forming a surrounding plasma envelope.
- **Blowoff**: Fuel is compressed by the rocketlike blowoff of the hot surface material.
- **Inward transported thermal energy**: During the final part of the capsule implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C.
- **Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.**
Plasma Conditions During ICF

- **Before compression and ignition**
  
  Density: solid DT ice at 0.225 g/cm³ and gas
  Temperature: few Kelvin

- **During the burn phase**
  
  Density: 300 to 1000 times liquid density
  300 to 1000 g/cm³ ≈ 10²⁶ 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 \( c_s = (2 \ k_B T / M)^{\frac{1}{2}} \) (fastest speed to transport information, fix parameter).

- Mass confinement time: \( t_{\text{conf}} = R(t=0) / c_s \)

- Time needed for fusion: \( t_{\text{fusion}} = 1 / <\sigma v> \ n_0 \)

- Ratio \( t_{\text{conf}} / t_{\text{fusion}} \) depend on product: \( n_0 \ t_{\text{conf}} \)

- \( n_0 \ t_{\text{conf}} = (1 / M c_s) \ \rho R \) with \( \rho = M \ n_0 \) mass density

- Parameter \( \rho R \) 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 $\Delta V$ and energy input $\Delta U$.
  - 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 beneficial.
- Total energy needed to compress a few mg DT: $\sim 1$ MJ.
Possible Drivers: Z - Pinches

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

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

Z-Maschine, Sandia labs, Albuquerque USA
Possible Drivers: Ion Beams

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

Disadvantages:
- Concept was never tested
- Beam intensity is still too low

Planed FAIR facility, Darmstadt, Germany

10 to 20 rings needed for fusion power plant!
Possible Drivers: Lasers (Best Shot)

Advantages:
- Well advanced technology
- Good control of energy release

Disadvantages:
- Bad energy conversion
- Very expensive to build

National Ignition Facility (NIF), Livermore, USA
Possible Drivers: Lasers (Best Shot)

Advantages:
- Well advanced technology
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National Ignition Facility (NIF), Livermore, USA
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:

Advantages:
- Well advanced technology
- Good control of energy release

Disadvantages:
- Bad energy conversion
- Very expensive to build

Engineering challenges at NIF
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 symmetric 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 symmetric as possible!
Reminder: Direct Drive Scheme

**Radiation**

Laser beams or laser-produced x rays rapidly heat the surface of the fusion target, forming a surrounding plasma envelope.

**Blowoff**

Fuel is compressed by the rocketlike blowoff of the hot surface material.

**Inward transported thermal energy**

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**Thermonuclear burn spread**

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.
Relaxing the Symmetry Conditions – Indirect Drive

- 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