Why is it so attractive?
- It could guarantee practically unlimited source of energy
- Ecologic hazards significantly decreased compared to nuclear fission
- No weapon materials proliferation issues

Why mankind needs a novel energy source
- Resources of fossil fuels and fission materials are limited
- Ecological issues of burning fossil fuels and fission
- Limitation of renewable energy resources

Global energy balance
- Sun delivers to earth $2 \times 10^{24}$ J/year, global consumption $5.7 \times 10^{20}$ J = 13699 Mtoe (toe = ton of oilequivalent)
- Low concentration is the drawback of solar energy
Global graphs

The earth’s energy budget

Global energy consumption 2013
- Fossil Fuels = 87%
- Oil: 33%
- Gas: 24%
- Coal: 7%
- Nuclear: 6%
- Hydro: 4%
- Wind: 3%
- Solar: 1%
- Geothermal & biomass: 1%
- Biofuels: 0%

Energy Matters
EuanMearns.com
BP 2014 data

CO₂ from 2000 back 60 kyears

Cost generating electricity
*no cost of CO₂ emissions included
Differences in binding energy per nucleon are exploited for energy production

- The most stable nucleus is $^{56}\text{Fe}$ (Z=26, A = 56)
- Energy gained either by fission of heavy nuclei
- or by fusion of light nuclei
- $\alpha$ particle ($^4\text{He}$) – high B/A

- Coulomb repulsion prevents nuclei from fusing – height $\sim$1 MeV
- Fortunately, quantum tunneling enables fusion at lower energy
- Fusion cross-section is $\sim10^6\times$ less than for elastic collisions $\Rightarrow$ beam-target interaction cannot produce energy gain
Fusion reactions

- Reaction $D + T \rightarrow n + ^4\text{He} + 17.6 \text{ MeV}$
  highest cross-section at low energies
  high energy $340 \text{ GJ/g of fuel}$
  $1 \text{ g DT} \cong 4.5 \text{ g } ^{235}\text{U} \cong 10 \text{ t coal}$
- Tritium is missing in nature, but it can be produced from abundant Li
  $n + ^6\text{Li} \rightarrow ^4\text{He} (2.1 \text{ MeV}) + T (2.7 \text{ MeV})$
  $n + ^7\text{Li} \rightarrow ^4\text{He} + n + T - 2.47 \text{ MeV}$
- Ideal ignition temperature (fusion energy = radiation losses) $T_{id} = 4.3 \text{ keV}$

DT drawback energetic $n$ (how is energy distributed between $n$ and $^4\text{He}$ ?)

DD reaction – only slow neutrons, higher threshold, lower yield
2 channels $D + D \rightarrow p + T + 4 \text{ MeV} ; D + D \rightarrow n + ^3\text{He} + 3.27 \text{ MeV}$

Neutronless fusion – charged products (no radioactivity), $T_{id} \sim 100 \text{ keV}$
$p + ^{11}\text{B} \rightarrow 3 \times ^4\text{He} + 8.7 \text{ MeV} ; p + ^6\text{Li} \rightarrow ^4\text{He} + ^3\text{He} + 4 \text{ MeV}$
Fusion energy balance

\[ Q = \frac{E_F}{E_B + E_p} \]

\( E_B \) – bremsstrahlung losses = \( \alpha_B n^2 T^{1/2} \tau \)

\( E_p \) – plasma energy = \( 2(3/2 \ n \ k_B \ T) \)

\( \eta (E_{FS} + E_B + E_p) \geq E_p + E_B \Rightarrow Q \geq 1/\eta - 1 = 1/(1/3)-1 = 2 \)

Choice \( \eta = 1/3 \) – Lawson

Fusion energy gain

\[ E_{TS} = \frac{1}{4} n^2 \langle \sigma v \rangle \varepsilon_S \tau \]

\[ Q = \frac{n \tau \left( \frac{1}{4} \langle \sigma v \rangle_T \varepsilon_S \right)}{3k_B T + \alpha_B T^{1/2} n \tau} = f(n \tau, T) \quad T \approx 10 \text{ keV (1.16} \times 10^8 \text{ K)} \]

\( n \ \tau \geq 10^{14} \text{ cm}^{-3}\text{s} \) \quad Lawson criterion \(^{(1)}\)

2 basic options – \( n \sim 10^{14} \text{ cm}^{-3}, \tau \sim 1 \text{ s} \) – magnetic confinement

– \( n \sim 10^{23} \text{ cm}^{-3}, \tau \sim 10^{-9} \text{ s} \) - inertial confinement

(less frequent middle option – \( n \sim 10^{18} \text{ cm}^{-3}, \tau \sim 10^{-4} \text{ s} \) – pinch – dense magnetized plasma) – historically the first one studied

\(^{(1)}\)Lawson criterion derived from energy production arguments (original derivation)
Fusion power balance

- Fusion products – neutron escapes from fuel but $\alpha$-particles are basically stopped in the fuel and heat it, let $\eta_\alpha$ is the part of $\alpha$ energy heating the fuel, then the heating power is

$$S_\alpha = \frac{1}{4} \eta_\alpha E_\alpha n^2 \langle \sigma v \rangle = \frac{1}{16} \eta_\alpha E_\alpha \frac{P^2}{(k_B T)^2} \langle \sigma v \rangle$$

- Power loss by radiation (bremstrahlung emission) and due to finite energy confinement time $\tau_E$ are

$$S_B = C_B Z_{\text{eff}} n^2 T^{1/2} \approx C_B n^2 T^{1/2} = C_B \frac{P^2}{k_B T^{3/2}}$$

$$S_C = \frac{3}{2} \frac{P}{\tau_E}$$

- At threshold $S_\alpha = S_B + S_C$. For $\eta_\alpha = 1$ plotted threshold versus $T$

- Minimum $P \tau_E \approx 8.3 \text{ bar.s}$ at $T = 15 \text{ keV}$ corresponds to $n \tau_E = 1.7 \times 10^{14} \text{ cm}^{-3} \text{s}$ (1)

- At 5 keV threshold $P \tau_E \approx 36 \text{ bar.s}$

(1) Lawson criterion derived from power balance arguments
Confinement and burn

• Hot fuel has to be confined for sufficient time $\tau$ to allow significant burn fraction $\Psi$
Let $n_f$ is cumulative number of fusion reactions in unit volume, $n_D$, $n_T$ is deuterium and tritium density, then

$$\frac{d n_f}{d t} = n_D n_T \langle \sigma v \rangle$$

for $t=0$ $n_D=n_T=n_0/2$ and $n_f = 0$

$$n_f(t) = \Psi(t) \times n_0/2 \quad \text{and} \quad \frac{n_0}{2} \frac{d \Psi}{d t} = \frac{n_0^2}{4} \langle \sigma v \rangle \left(1 - \Psi \right)^2$$

for constant reaction rate ($T_i \approx 20$ keV = $2.32 \times 10^8$ K)

$$\Psi(\tau) = \left(1 + \frac{2}{n_0 \langle \sigma v \rangle \tau} \right)^{-1}$$

to reach $\Psi = 1/3 \Rightarrow n_0 \tau \geq \langle \sigma v \rangle^{-1} \approx 10^{15}$ cm$^{-3}$s

• Confinement
  – Gravitational (stars) – p-p cycle (Sun); CNO cycle ($\uparrow$T); CC reactions (WD)
  – Magnetic (tokamaks, stellarators, $n_0 \approx 10^{14}$ cm$^{-3}$, $n_0 \tau_E \geq 10^{14}$ cm$^{-3}$s, $\tau > \tau_E$)
  – Inertial (direct drive; indirect drive)
Magnetic confinement

Many schemes of magnetic confinement do exist

- **Closed systems**
  - *Stellarators*
  - *Tokamaks*
  - Multipoles
  - Devices with relativistic electron beam (ASTRON)

- **Magnetic mirrors**
  - Magnetic cusp
  - Baseball-seam coil

- **Pinches**
  - z-pinch
  - θ-pinches

Problems – stability – typical **kink**

(a) Kink instability
Closed systems

Simple torus is unstable

- Curvature and $\text{grad}B$ drifts cause electrons and ions drifting to opposite sides
- Space charges $\Rightarrow$ $E$ field
- $E\times B$ drift moves plasma out

Instability mitigation

- Sheared magnetic field
- Magnetic field with minimum inside
- Dynamic stabilization

Sheared magnetic field in torus
Stellarator

Toroidal equilibrium stationary system – external heating
Magnetic field formed only by external coils, field lines stay at nearly constant minor radius. Field lines form magnetic surfaces, do not leave magnetic surfaces. In 2015, physical experiments started on new supraconductive stellarator Wendelstein-7X in Germany (plasma 30 m³ x JET 100 m³)
Tokamak (from Russian – toroidal chamber with magnetic coils) – basically a transformer where toroidal plasma acts as the secondary circuit, plasma current creates poloidal field. Besides toroidal field created by external coils, third vertical (poloidal) magnetic field is also needed (external coils).
Works in pulsed regime, primary Ohmic heating cannot reach fusion temperature, secondary heating – neutral particle beams or RF antennas
5 big tokamaks in 1980’s– JET (UK), now ITER under construction (2025?)
Mutipoles, magnetic mirrors

Mutipoles – with parallel conductors in toroidal shape form minimum-B configuration that is MHD stable.

Ordinary magnetic mirror is also unstable, but magnetic cusp is stable.

Stable configuration is achieved by adding Ioffe rods. The topologically same configuration is achieved in the baseball-seam coil.
Pinch – z-pinch and θ-pinch

Z-pinch – magnetic field created by high-current discharge can compress it – pinch effect classical z-pinch unstable equilibrium

\[
\frac{d}{dr}\left(p + \frac{B^2}{2\mu_0}\right) = \frac{1}{\mu_0}(\nabla B) \cdot \bar{B} = -\frac{B^2}{\mu_0 r}
\]

\[B = \frac{I}{2\pi r \varepsilon_0 c^2} \Rightarrow I^2 = 2 \times 10^7 N k_B T, \text{ electron number per length } N = \pi R^2 n\]

the Bennett relation

Z-machine in Sandia National Laboratory, USA

θ-pinch – current in θ direction in the outer shell induces opposite θ current in plasma column surprisingly stable, may be also used in toroidal geometry

θ-pinch
Inertial fusion – compression necessity

- Inertial confinement – hardly any confinement, due to inertia disassembling of hot fuel takes final time
- Spherical hot fuel assembly assumed (radius $R$), then $\tau \approx R/3c_s$ (ion sound velocity $\sim T^{1/2}$) and $n_0 \approx \rho/2.5m_p \Rightarrow \Psi = \frac{\rho R}{\rho R + H_B}, H_B \approx 6.3 \text{ g/cm}^2, \Psi = 1/3 \Rightarrow \rho R = 3 \text{ g/cm}^2$
- Fuel pressure $P [\text{bar}] \approx 8 \times 10^8 \rho T_i [\text{keV}]$
- In ICF (inertial confinement fusion) conditions: $\rho R \approx 3 \text{ g/cm}^2$, $T \approx 10 \text{ keV} \Rightarrow PR \sim 3 \times 10^{10} \text{ bar} \times \text{cm} \Rightarrow E \sim PV \sim 3 \times 10^9 R^2 [\text{J}]$
- If $E \sim 300 \text{ kJ}$ can be delivered to the fuel, then $R \sim 100 \mu\text{m}$, $P \sim 3 \text{ Tbar}$, $\rho \sim 300 \text{ g/cm}^3$ (solid DT density $\rho_{\text{DT}} = 0.25 \text{ g/cm}^3$)
- *How to achieve such tremendous pressures and densities? Carefully tuned spherical implosions!!*
Indirect and direct drive

Indirect Drive

Lasers, heavy ion beams or Z-pinches produce in a miniature cavity called hohlraum X-rays that ablate capsule

Direct Drive

Lasers directly irradiate and ablate the capsule
Ablation and compression

Low-Z ablator for efficient absorption

- Acceleration comes from particle momentum
- Irradiance is balanced by the outflow of heated material
- For ID $I_{x-ray} \approx \sigma_{SB} T_r^4 \sim nTc_s \Rightarrow P_{abl} \sim \sigma_{SB} T_r^4/c_s \sim T_r^{3.5}$
- Typically $T_r \approx 300$ eV $\Rightarrow I_{x-ray} \approx 8 \times 10^{14}$ W/cm² $\Rightarrow P_{abl} \approx 100$ Mbar
- Similar laser intensities used, short $\lambda$ to avoid fast electron preheat
- Stagnation (max. compression) $P_{sg}V_{sg} \approx P_{abl}V_0$ and $P_{sg} \sim 10^4 P_{abl}$
  $\Rightarrow V_{sg} \sim 10^{-4} V_0 \Rightarrow R_0/R_{sg} \sim 20$ (like compressing football to a pea)
Energy flow and gain

- Driver energy $E_D$ is coupled with efficiency $\eta_c$ to capsule.
- Capsule energy $\eta_c E_D$ is converted with hydro (rocket) efficiency $\eta_H$ into energy of imploding fuel.
- Typically

<table>
<thead>
<tr>
<th></th>
<th>Direct Drive (DD)</th>
<th>Indirect Drive (ID)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c$</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>$\eta_H$</td>
<td>0.1</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- So overall efficiency $\eta_T$ is $\sim 0.08$ for DD and $\sim 0.04$ for ID.
- Theoretical fusion energy gain seems high:

$$G \approx \frac{17.6 \text{ MeV}}{4 \times \frac{3}{2} k_B T} \cdot \frac{17.6 \text{ MeV}}{6 \times 5 \text{ keV}} \Psi = 580 \Psi \sim 190$$

- But overall target gain is $G_T \sim \eta_T G \sim 16$ (DD) and $\sim 8$ (ID).
  Considering the efficiency of heat conversion into electricity and electricity into driver energy, this is far too low.
- So volume heated DT cannot work for energy production.
Spark ignition

- Solution – heat a small part of the fuel to high $T$ and fusion $\alpha$ particles heat the surrounding cold dense fuel and fusion burn wave propagates.

- This works fine in 1D spherical numerical simulations, but life is not 1D.

- **Mixing must be avoided** of cold fuel into hot spot material.

- Implosion symmetry is important issue, small non-uniformities are magnified when shell is imploded to very small radius.

- Hydroinstabilities during implosion are major concern.
Rayleigh-Taylor instabilities (RTI)

- RTI is major concern
- RTI may appear where $\nabla \rho \cdot \nabla P < 0$
- Classically interface between upper heavier fluid and lighter one below
  - When approaching ablation surface from outside - density $\uparrow$ pressure $\downarrow$
  - Deceleration phase - unstable region
  - At stagnation – perturbations lead to mix of cold fuel with hot spot that can quench the burn
- 3D calculations are used to assess capsule performance in the presence of perturbations
National Ignition Facility

- 1 building, 5 hectares (2 soccer fields)
- Height 10-stores house
- 10 years construction
- 30 years operation
- > 4 G$ - financed for maintaining nuclear weapons stockpile
- Indirect drive - primary as similar to H bomb
- 192 beams of Nd-laser in 48 quads converted to $3\omega$ – 1.8 MJ in 20 ns shaped pulses
- 1 shot/8 hours, $\eta < 1\%$
- Full energy 2009
- Operates perfectly

Similar lab. LMJ near Bordeaux starts operation now
NIF missions

- Global Security
- Energy Security
- Stockpile Science
- Scientific Leadership
- Forensics and Effects
- Laser Inertial Fusion Energy
- Non-Ignition Stockpile Science Experiments
- Ignition
- High Yield >100 MJ
- Reduced Uncertainties
- Applications of Ignition
- New Ideas
- Planetary Systems
- NIF Missions
NIF interaction chamber and targets

Target chamber $\varnothing$ 10 m view from equator (diagnostics and target)
Laser beams from upper and lower side
Cryogenic target at 17.3 K Hohlraum, lasers in 4 cones
Capsule with plastic layered ablator doped by Si
Experiments

- Hohlraum and capsule must be perfectly matched with laser pulse, capsule precise shape.
- The original scheme developed over 10 years was based on 4 shocks with low energy picket ⇒ low foot radiation $T_r$ ⇒ small 1st shock ⇒ to keep fuel at low adiabat ($P/P_{\text{Fermi}} \sim 1.45$).
- Outer cones laser $\lambda$ is tuned to modify cross-beam energy transfer (CBET) and reach macroscopically symmetric capsule irradiation (time dependence still uncertain, modelling capability insufficient).

In the point design – peak $T_r = 300$ eV, $v_{\text{impl}} \approx 370$ km/s, $P = 375$ Gbar, gain $\sim 10$ (5×10^{18} neutrons).

- Instabilities and fuel mix underestimated in simulations ⇒ max. fusion yield $\sim 10^{15}$ neutrons.
- Unstable growth of baroclinic vorticity ($\nabla \rho \times \nabla P / \rho^2$) seeded by the tent.
- Partial cure – high foot + 3-shocks - stability ↑, gain ↑, predictability ↑ (price paid– adiabat ↑⇒ lower compression).
High foot experiments

- High foot – foot $T_r \sim 90$ eV ($1.5 \times T_r$ for low foot) to increase ablation velocity and density scale length $\Rightarrow$ ablative RT instability is suppressed
- Higher adiabat ($P/P_{\text{Fermi}} \approx 2.5$) reduces convergence ratio, final compression, theoretical core pressures and $\rho R$. Lower amplification of asymmetries. No ignition possible for present $\eta_C$, $\eta_H$.
- 1.9 MJ of $3\omega$ radiation accelerated DT to 380 km/s, fuel kinetic energy 12 kJ, neutron yield $\sim 10^{16}$, released fusion energy 26 kJ $> 2x$ fuel energy (**but $\sim 1.5\%$ of laser energy**)
- More than doubling fusion yield due to $\alpha$-particle self-heating
- Confinement $\rho R \approx 1.1$ g/cm$^2$, $T_i \approx 5$ keV, $P > 200$ Gbar, $P \tau \approx 20$ bar.s (for ICF ignition at 5 keV 36 bar.s required)
- Demonstrated mitigation of RTI consistent with theory predictions
- 2017 – released fusion energy increased to 52 kJ (7.5 ns laser pulse of energy 1.5 MJ) - depleted uranium hohlraum, HDC ablator, hot spot $\rho R = 0.3$ g/cm$^2$, $p = 360$ Gbar, $T_i = 4.5$ keV
Alternative drivers for Indirect Drive

- **Nuclear explosion** – in Halite/Centurion program in 1980’s
  X-rays from underground nuclear test shined into a hohlraum and
  ignited inertial fusion in a capsule

- **Heavy ion beam** - driver
  with efficiency >50% and
  10 Hz feasible, nobody will
  finance large installation
  before ignition with lasers

- **Z-pincher (wire array)** –
  Z-machine Sandia 2 MJ X-ray energy, 15% plug-to-X-rays efficiency
Direct drive

- Main experiments at Omega laser in LLE Univ. Rochester, USA
- 60 laser beams symmetrically irradiate cryogenic capsule
- Total laser energy 30 kJ, laser smoothing techniques adopted
- Intensity slightly < $10^{15}$ W/cm² to control laser-plasma instabilities
- Implosion performance scales hydrodynamically to ~2x $\alpha$ heating at NIF energy (higher $\eta_C$, but lower implosion quality)
- NIF – polar direct drive (symmetric impossible) – preliminary experiments started, enhanced losses due to CBET
Advanced fusion schemes

• Advanced schemes use external means to increase temperature of compressed (either by DD or ID) fuel
  – **Fast ignition (FI)** – energetic particle beam (electrons or ions)
  – **Shock ignition (SI)** – spherically convergent shocks
  – **Magnetized ICF** or magneto-inertial fusion (**MIF**) – magnetic fields

• The basic idea of FI and SI is to use long (ns) laser pulse for compression to reach sufficient $\rho R$ with low temperature and then to use short (ps) pulse to heat and ignite the fuel

• Though idea of decoupling compression and heating was proposed earlier, interest started with emergence of high-power ultrashort-pulse lasers (chirped pulse amplification)
Inertial fusion energy

1. Target factory
   To produce many low-cost targets

2. Driver
   To heat and compress the target to fusion ignition
   Many beams
   Focusing element

3. Fusion chamber
   To recover the fusion energy pulses from the targets

4. Steam plant
   To convert fusion heat into electricity

A power-plant driver would fire about five targets per second to produce as much electricity as today’s 1000-megawatt power plant.
IFE power balance

\[ P_{IN} = f \ P_{out} = f \ \eta_T \ G \ \eta_D \ P_{IN} \Rightarrow f \ \eta_T \ G \ \eta_D = 1 \]

The cycling power should not be too high, let \( f = 0.25 \)

With \( \eta_T = 0.4 \Rightarrow \eta_D \ G \geq 10 \)

Representative numbers for \((1-f)\) \(P_{out} = 1000\) MW block and 10% driver efficiency \( (\eta_D) – f = 0.23, P_{IN} = 300\) MW, driver 6 MJ, 5 Hz (30 MW), \( G = 100\), output 3 GW (600 MJ), \( \eta_T = 0.43\), \( P_{out} = 1.3\) GW
Reactor target chamber

- 600 MJ is the energy released in explosion of 1/7 ton TNT
  - However, damage to chamber is caused by momentum $p$ and $p = m v = (2 E m)^{1/2}$ and for $m_{DT} = 5.4$ mg is the momentum equivalent expsion of $m_{TNT} = 29 \text{ g}$
  - Protecting the first wall against radiation introduces more mass

**Reactor chamber requirements**

- Regenerate chamber conditions for target injection, driver beam propagation, and ignition at sufficiently high rates
- Protect chamber structures for several to many years or allow easy replacement of inexpensive modular components
- Extract fusion energy in high-temperature coolant, regenerate tritium
- Reduce radioactive waste generation, inventory, and possible release fractions low enough to meet no-public-evacuation standards

- Chamber cost accounts for 7 – 15 % of power station cost
IFE power plant concepts

- Many concepts propose and analyzed, here just 1 example
- **HYLIFE–II** – heavy ion driver, uses oscillating liquid jets of FLIBE (a F, Li and Be molten salt) to protect fusion chamber from neutrons and also to produce Tritium