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A Novel Approach to Fusion Power Generation

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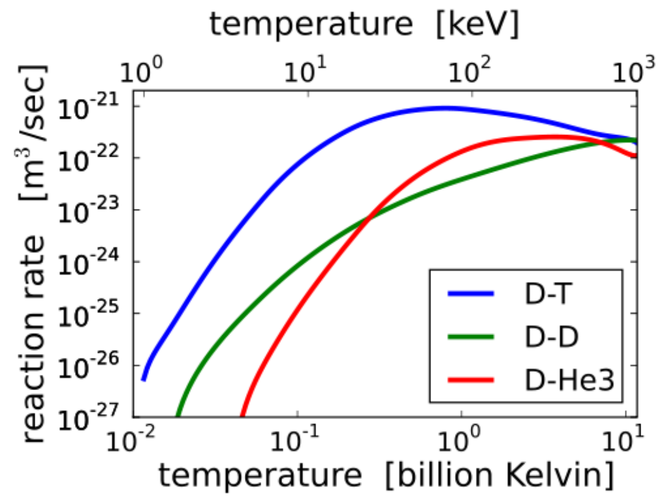
What is Nuclear Fusion?

Energy is released when light nuclei fuse to form heavier nuclei. This is the energy which powers stars such as the Sun. The amount of energy released is related to the difference in the masses of the initial and final nuclei according to $E = mc^2$.

Nuclear forces are of short range. Hence reactions occur only when nuclei are in close proximity and to achieve this they must have energy sufficient to overcome their repulsive electrostatic forces. This requires such high temperatures as 15,000,000 K as in the Sun.

Challenges and objectives

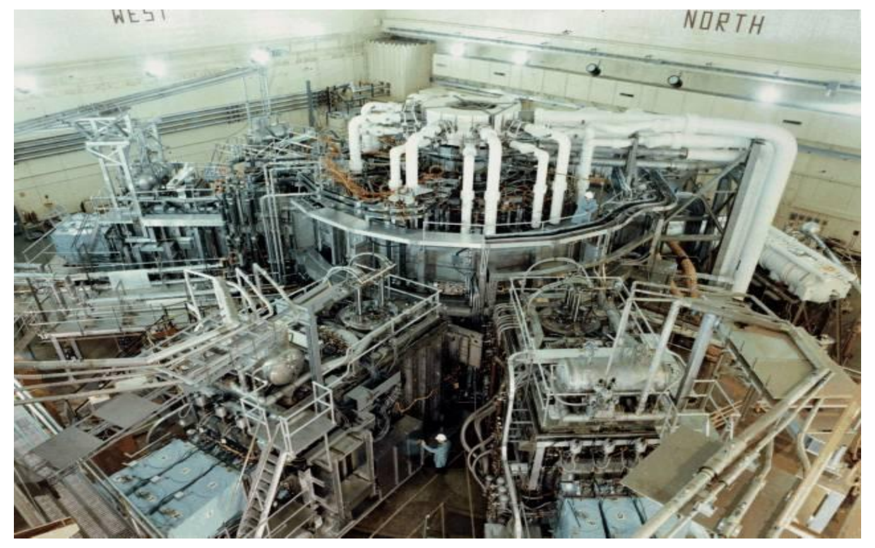
- Achieve temperatures such as that in the Sun's interior;
- Confine reacting species long enough for fusion reactions to occur;
- Achieve energy break-even: output energy compensates input energy.



Two Major Approaches to Fusion

Magnetic confinement. A low density plasma of H^+ ions is confined by magnetic fields.

Inertial confinement. A pellet of solid H is bombarded by high-intensity lasers.



Primary reactions:
D + D → T + p + 4.03 MeV;   D + D → ^{3}He + n + 3.27 MeV
$\langle\sigma v\rangle \approx 10^{-14}\, T^{-2/3} \exp(-19T^{-1/3})$ cm^3 / s for T < 50 keV

Secondary reactions
D + T → α + n + 17.6 MeV;   D + ^{3}He → α + p + 18.3 MeV

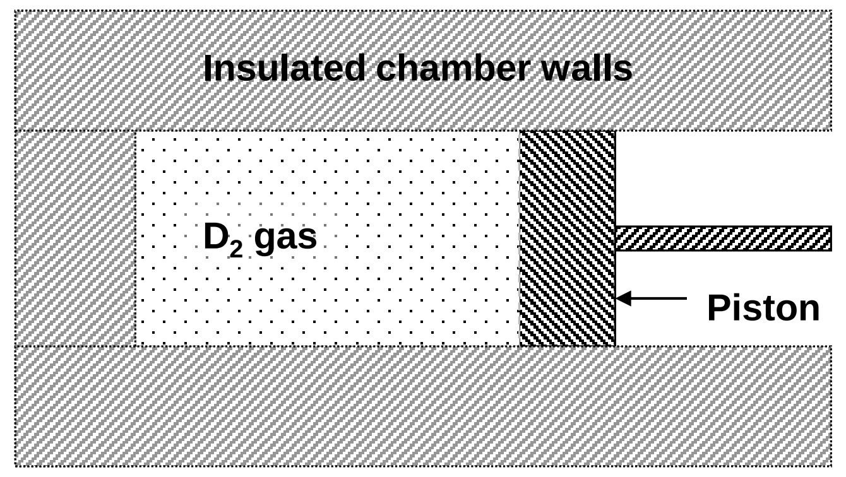
Fusion reaction rates proportional to n^2.

n = particle density.
Magnetic confinement methods: $n \approx 10^{15}$ cm^3 ⇒ requires $T \approx 10^8$ K

Proposed Method

Exploit n^2 factor and reduced degrees of freedom
Perform under adiabatic conditions
⇒ appreciable fusion rates at lower T

Mechanical adiabatic compression



Dense gas of D_2 undergoes adiabatic compression
Rapid process - - explosively driven
Well-insulated chamber – retain energy internally

Starting conditions.

One mole D_2 at atmospheric pressure and room temperature.

Apply compression. T increases.
D_2 molecules → D_2 atoms → D_2 atoms ionize
→ deuteron-electron plasma → Fusion of deuterons.

Assumptions. Make simplifying assumptions.
Reversible adiabatic compression
Apply equilibrium thermodynamics
Ideal gas behavior: PV = NRT (Initially, then non-ideal gas)

Adiabatic compression of ideal gas
PV^γ = constant; $TV^{\gamma-1}$ = constant; γ = specific heat ratio.
$P = P_0\,\beta^\gamma$, $T = T_0\,\beta^{\gamma-1}$, Compression factor: $\beta = V_0 / V$.

Degrees of freedom

γ related to number of degrees of freedom f of the gas: $\gamma = (f + 2) / f$

Rewrite eq'ns in terms of f: $T = T_0\,\beta^{2/f}$ $W = \tfrac{1}{2} P_0 V_0 f\, \beta^{2/f}$.

For monoatomic gas: f = 3
Deprive particles of freedom of motion ⇒ larger T increase for given energy input. Accomplish with
(1) External magnetic field(s)
(2) Electric discharge in direction of piston motion. Also ⇒ Pinch Effect

Work to compress ideal gas

$$W = -\int_{V_0}^{V} P\,dV = -P_0 V_0^{\gamma} \int_{V_0}^{V} V^{-\gamma}\,dV = \frac{P_0 V_0}{\gamma - 1}\left(\beta^{\gamma-1} - 1\right) \approx \frac{P_0 V_0 \beta^{\gamma-1}}{\gamma - 1}.$$

Energy release

Reaction rate: $r = \tfrac{1}{2} n^2 \langle\sigma v\rangle$
σ = reaction cross section; v = relative velocity of interacting nuclei

Simplification Fusion occurs only at end of compression.
Energy release in time Δt: ΔE = r Q V Δt
Q = average energy release/reaction; V = final volume

Data for Ideal Gas

Consider only D+D: Av'g Q = 3.65 MeV

Calculate ΔE / *W* and burnup fraction $r\,\Delta t\,(n_0\beta)^{-1}$ for : *Q* = 3.65 MeV, Δt = 0.001 s,
f = 3, 2, 1,   β = 100, 200.

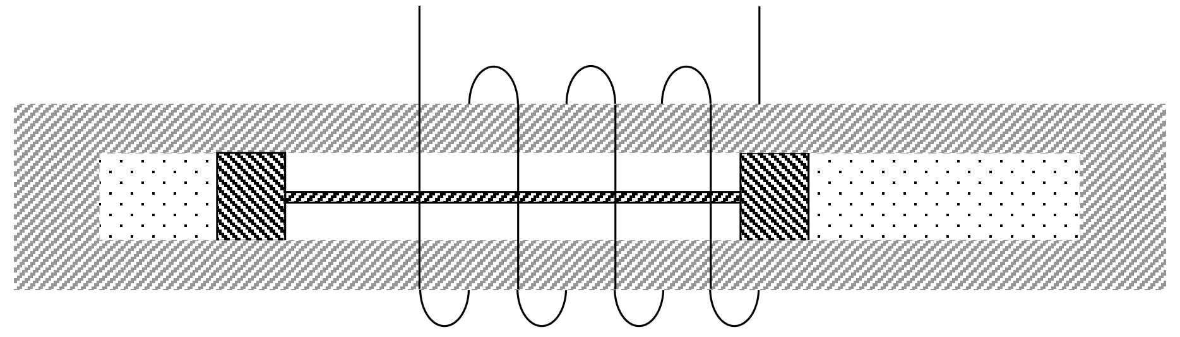
f	β	T (K)	δ*E* / *W*	Burn
3	100	6×10^3	$\sim 10^{-85}$	$\sim 10^{-92}$
3	200	1×10^4	$\sim 10^{-71}$	$\sim 10^{-78}$
2	100	3×10^4	$\sim 10^{-68}$	$\sim 10^{-74}$
2	200	6×10^4	$\sim 10^{-56}$	$\sim 10^{-62}$
1	100	3×10^6	~ 0.001	$\sim 10^{-8}$
1	200	1×10^7	14	~ 0.001

Note: f =1, β = 100, 200. Improve with longer Δt.

Applications

Single shot: Neutron source to initiate fission.
Multiple compressions in dual chambers.

Dual pistons with coil to extract work



Summary and conclusions

Exploited n^2 factor and reduced degrees of freedom.
Adiabatic conditions ⇒ energy retained internally.
Found some favorable cases.
To be more realistic:
  Not all input energy serves to compress gas.
  Consider particle losses via leakage.
Compensated by ignoring:
  D-T reactions; Pinch Effect.
  Enhancements: Deuterated walls; Screening effects of electrons.