Fusion by Mechanical Adiabatic Compression of a Dense Plasma

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ICENES2007
Istanbul, Turkey
June 8, 2007

Nuclear fusion rates $\approx n^2$

n = particle density

Magnetic confinement methods:

Thin plasmas: $n \approx 10^{15}$ cm^3

$\Rightarrow$ Require $T \approx 10^8$ K

<u>Propose</u>

Method to exploit n^2 factor

$\Rightarrow$ interesting fusion rates at lower T

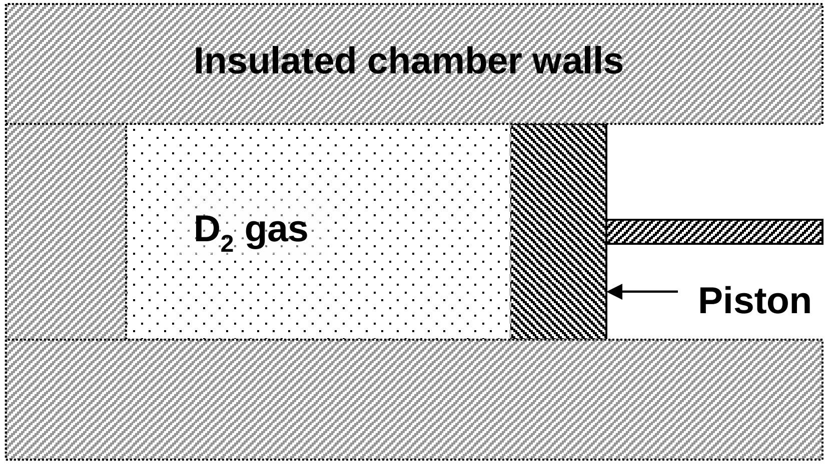
Dedication: Dr. Lloyd Motz (1910 - 2004)

Professor *Emeritus*, Columbia University

Motz suggested:
Consider fusion process analagous to that in stars

Recall:
Opening remarks of Dr. Eliezer (Session 4A)

Mechanical adiabatic compression



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

Caveat

Will make simplifying assumptions

May neglect important effects

Compensate: conservative estimates

- <u>Starting conditions</u>

  One mole D_2 at atmospheric pressure and room temperature: $T_0 = 300$ K; $V_0 = 2.46 \times 10^4$ cm^3

  $n_0 = 2N_A / V_0 = 4.90 \times 10^{19}$ cm^{-3}

  N_A = Avogadro's no.

  Factor of 2: Have 2 atoms/molecule

  <u>Apply compression</u>

  T increases

  D_2 molecules dissociate $\Rightarrow$ D_2 atoms

  D_2 atoms ionize $\Rightarrow$ deuteron-electron plasma

  $\Rightarrow$ Fusion of deuterons

Assumptions

Reversible adiabatic compression

Apply equilibrium thermodynamics

Ideal gas behavior: $PV = NRT$

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: $\beta = V_0 / V$

Work to compress gas

$$W = -\int_{V_0}^{V} P\,dV = -P_0 V_0^{\gamma} \int_{V_0}^{V} V^{-\gamma}\,dV$$

$$= \frac{P_0 V_0}{\gamma - 1}\left(\beta^{\gamma-1} - 1\right)$$

$$\approx \frac{P_0 V_0 \beta^{\gamma-1}}{\gamma - 1}$$

Degrees of freedom

- γ related to number of degrees of freedom f of the gas:
  - $\gamma = (f + 2) / f$
- Rewrite eqns: $T = T_0\, \beta^{2/f}$ $W = ½P_0V_0f\, \beta^{2/f}$
- For monoatomic gas: f = 3

If deprive particles of some freedom of motion
$\Rightarrow$ larger T increase for given energy input.
(1) External magnetic field(s)
(2) Electric discharge in direction of piston motion
Also $\Rightarrow$ Pinch Effect

- <u>Energy Release</u>

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

- <u>Simplification</u>

  Fusions occur only at end of compression

- Energy release in time δt: $\delta E = r\, Q\, V\, \delta t$

  Q = average energy release/reaction

  V = final volume

Fuel Burnup Fraction

Fraction of fuel consumed in volume *V* and time interval δt:

$$\frac{rV\,\delta t}{n_0 V_0} = \frac{r\,\delta t}{n_0\,\beta}$$

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

- Secondary reactions
- D +T $\rightarrow$ α + n + 17.6 MeV
- D + ^{3}He $\rightarrow$ α + p + 18.3 MeV

- Simplification
- Consider only D+D: Average Q = 3.65 MeV

Calculate $\delta E/W$ and burnup fraction for

Q = 3.65 MeV δt = 0.001 s

f = 3, 2, 1 β = 100, 200

Ideal gas data

f	β	T (K)	$\delta E/W$	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

Interesting cases: f =1, β = 100, 200
(Better for longer δt)

Non ideal gas behavior

Van der Waals equation of state:

$$\left(P + a\frac{N^2}{V^2}\right)(V - Nb) = NRT$$

N = number of moles

Pressure correction: intermolecular forces

Volume correction: finite size of molecules

Limits compression factor: $\beta < V_0 / Nb$

Take H values for *a*, *b*

$b \approx 0.027$ L-mol^{-1}

Temperature increase for van der Waals gas

Adiabatic conditions:

$$
\begin{aligned}
T &= T_0 \left(\frac{V_0 - Nb}{V - Nb} \right)^{\gamma - 1} \\
&= T_0 \beta^{2/f} \left(\frac{V_0 - Nb}{V_0 - \beta Nb} \right)^{2/f} \\
&= T_{ideal} \left(\frac{V_0 - Nb}{V_0 - \beta Nb} \right)^{2/f}
\end{aligned}
$$

Work to compress van der Waals gas

$$W = -NRT(V_0 - Nb)^{\gamma-1}\int_{V_0}^{V}(V - Nb)^{-\gamma}dV + aN^2\int_{V_0}^{V}V^{-2}dV$$

$$= \frac{NRT}{\gamma-1}\left[\left(\frac{V_0 - Nb}{V - Nb}\right)^{\gamma-1} - 1\right] - aN^2\left(\frac{1}{V} - \frac{1}{V_0}\right).$$

Work to compress van der Waals gas

Substitute $\beta = V_0 / V$ and $\gamma - 1 = 2/f$

$$W = \frac{NRT_0 f \beta^{2/f}}{2}\left[\left(\frac{V_0 - Nb}{V_0 - \beta Nb}\right)^{2/f} - \beta^{-2/f}\right] - \frac{aN^2}{V_0}(\beta - 1)$$

$$= W_{ideal}\left[\left(\frac{V_0 - Nb}{V_0 - \beta Nb}\right)^{2/f} - \beta^{-2/f}\right] - \frac{aN^2}{V_0}(\beta - 1)$$

Van der Waals gas data

f	β	T(K)	$\delta E/W$	Burn
3	100	8×10^{3}	$\sim10^{-80}$	$\sim10^{-92}$
3	200	2×10^{4}	$\sim10^{-60}$	$\sim10^{-78}$
2	100	4×10^{4}	$\sim10^{-63}$	$\sim10^{-74}$
2	200	1×10^{5}	$\sim10^{-47}$	$\sim10^{-62}$
1	100	5×10^{6}	~0.1	$\sim10^{-8}$
1	200	5×10^{7}	~4000	$\sim10^{-3}$

Note favorable cases: f = 1, β = 100, 200

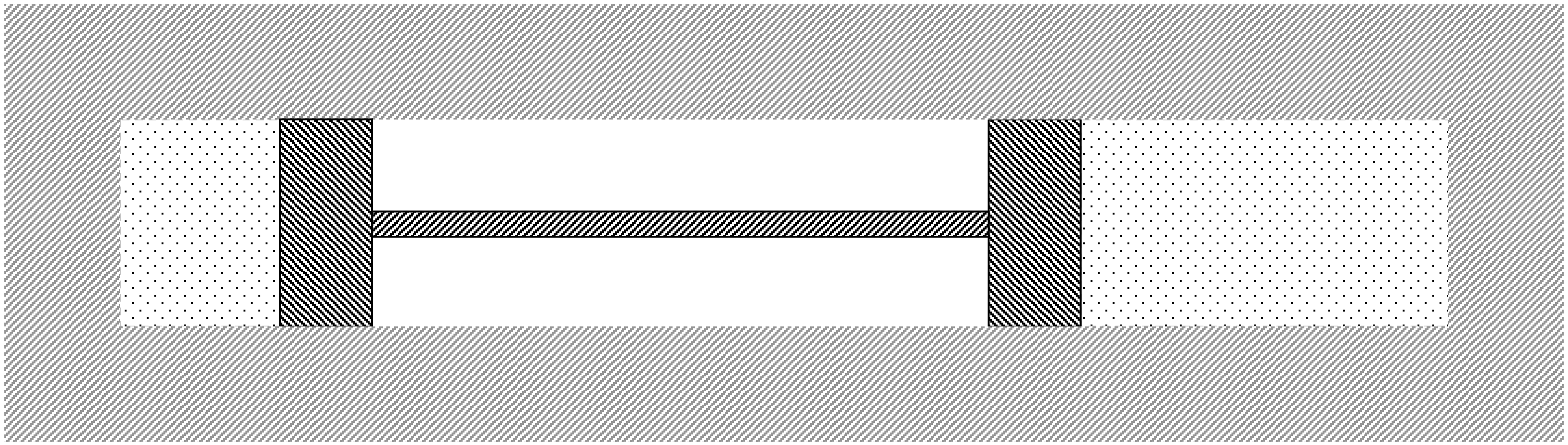
Higher yields than for ideal gas!

Applications

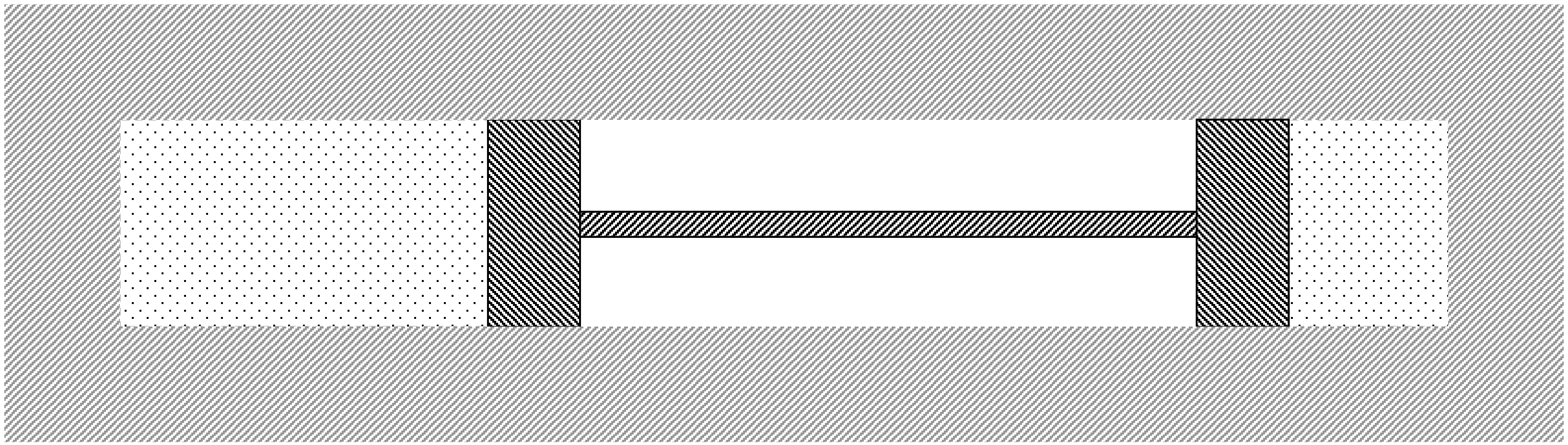
Single compression
  Neutron source to initiate fission ?

Multiple compressions in dual chambers
  Reciprocating device

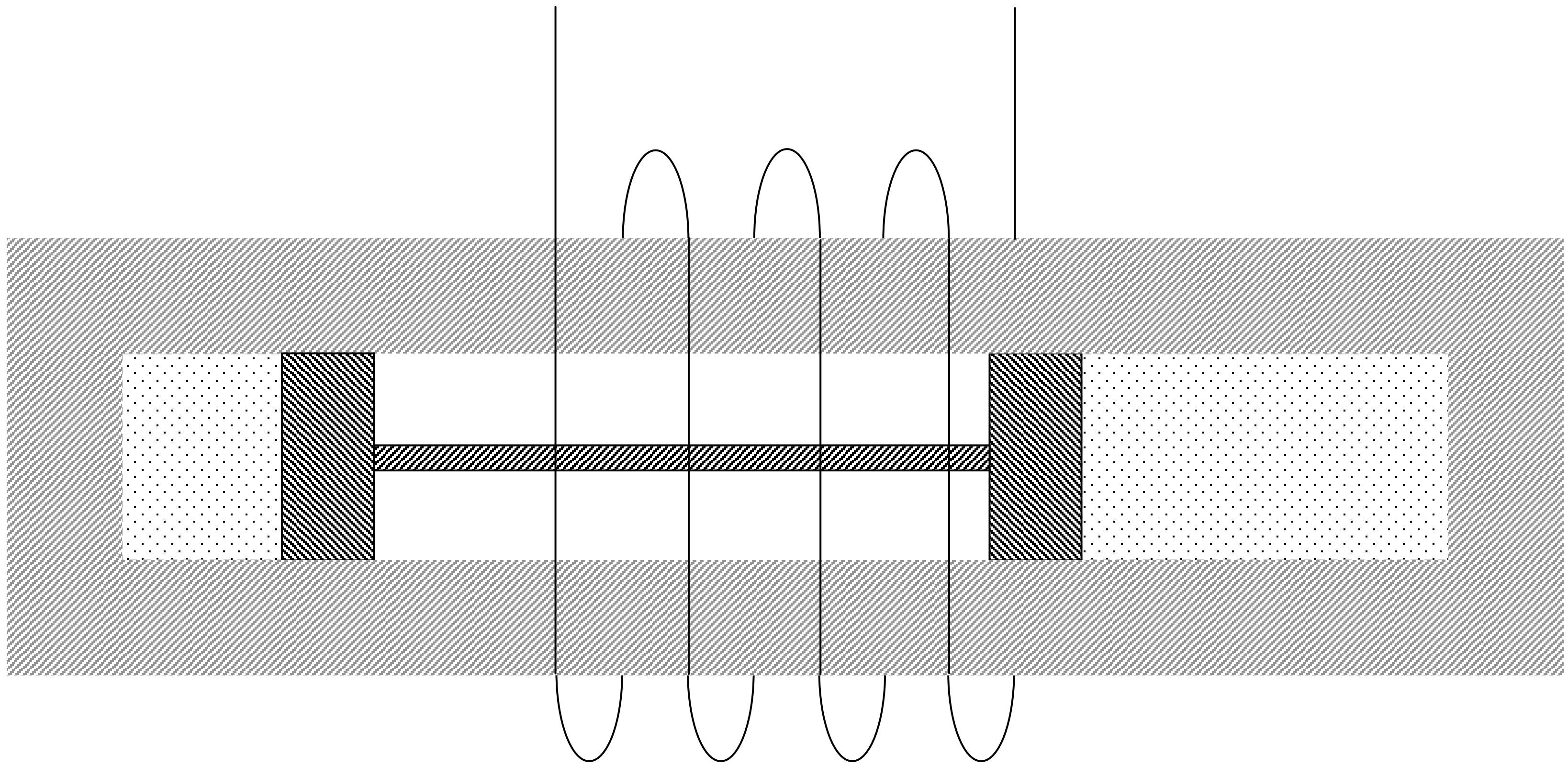
Dual Pistons-1



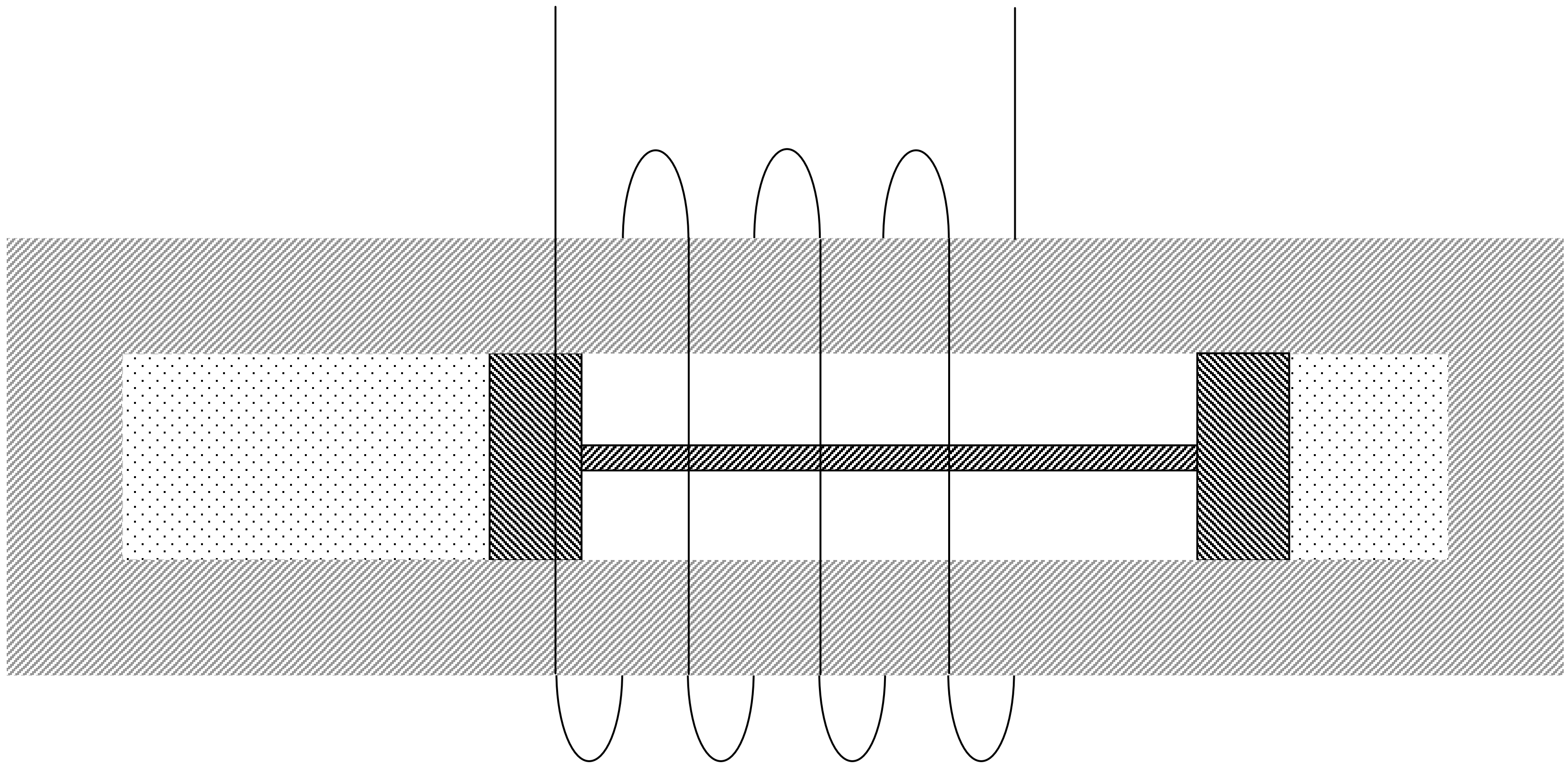
Dual Pistons-2



Dual Pistons with Coil to Extract Work-1



Dual Pistons with Coil to Extract Work-2



Summary and Conclusions

- Exploited n^2 factor and reduced degrees of freedom
- Adiabatic conditions $\Rightarrow$ energy retained internally
- Found some favorable cases
- To be more realistic:
  - Not all the input energy serves to compress gas
  - Take into account work needed to establish fields
  - Consider particle losses via leakage

Try to compensate by ignoring:

- Further D-D burns
- D-T reactions (more energetic than D-D)
- Volume compression from Pinch Effect
- Possible enhancement factors
  - Coat walls with deuterides to increase n
  - Screening effects of electrons

Although analysis was performed under the simplest assumptions, some favorable results suggest deeper study is warranted.

Should consider:

Continuous process via reaction kinetic formulation Solve coupled differential equations at closely-spaced instants during compression interval

Other equations of state

Implementation

Requires ingenuity to overcome technical challenges

HOPE SOMEONE CAN TRY IT!!

Thank you