

Lecture #25 The Holy Grail of Plasma Physics:
Controlled Thermonuclear Fusion

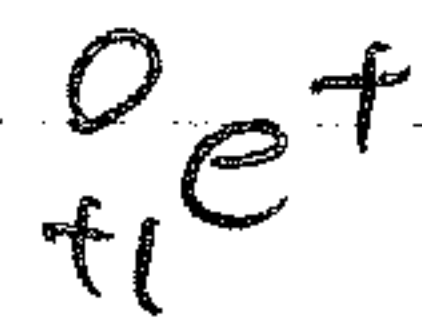
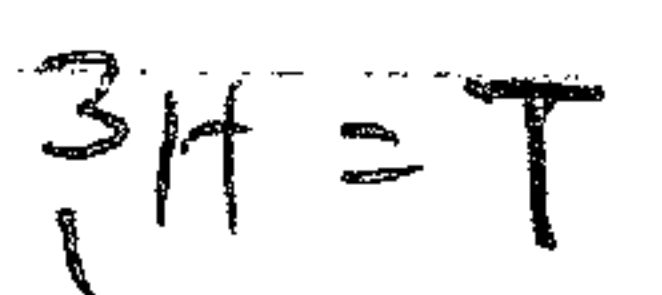
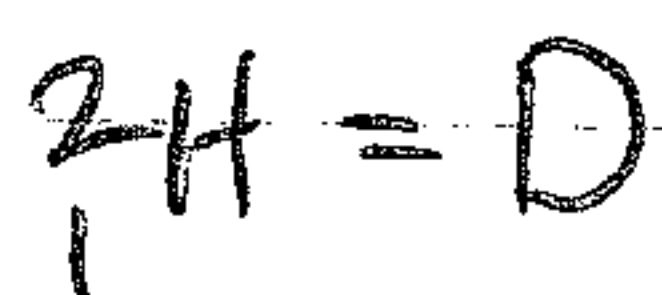
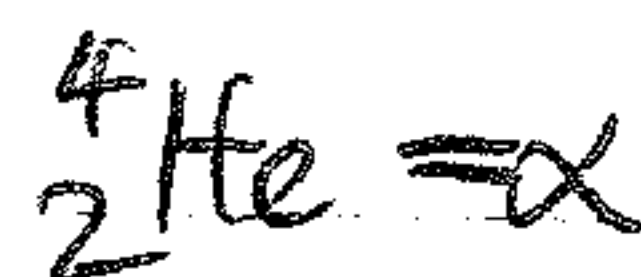
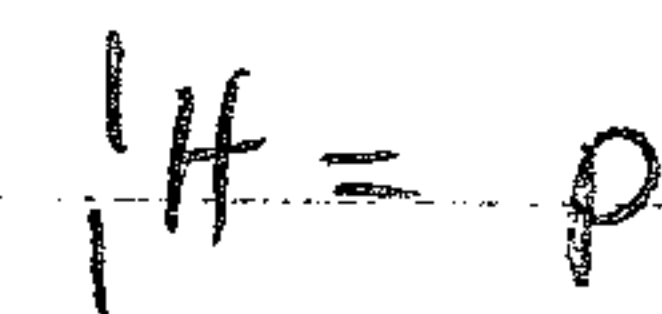
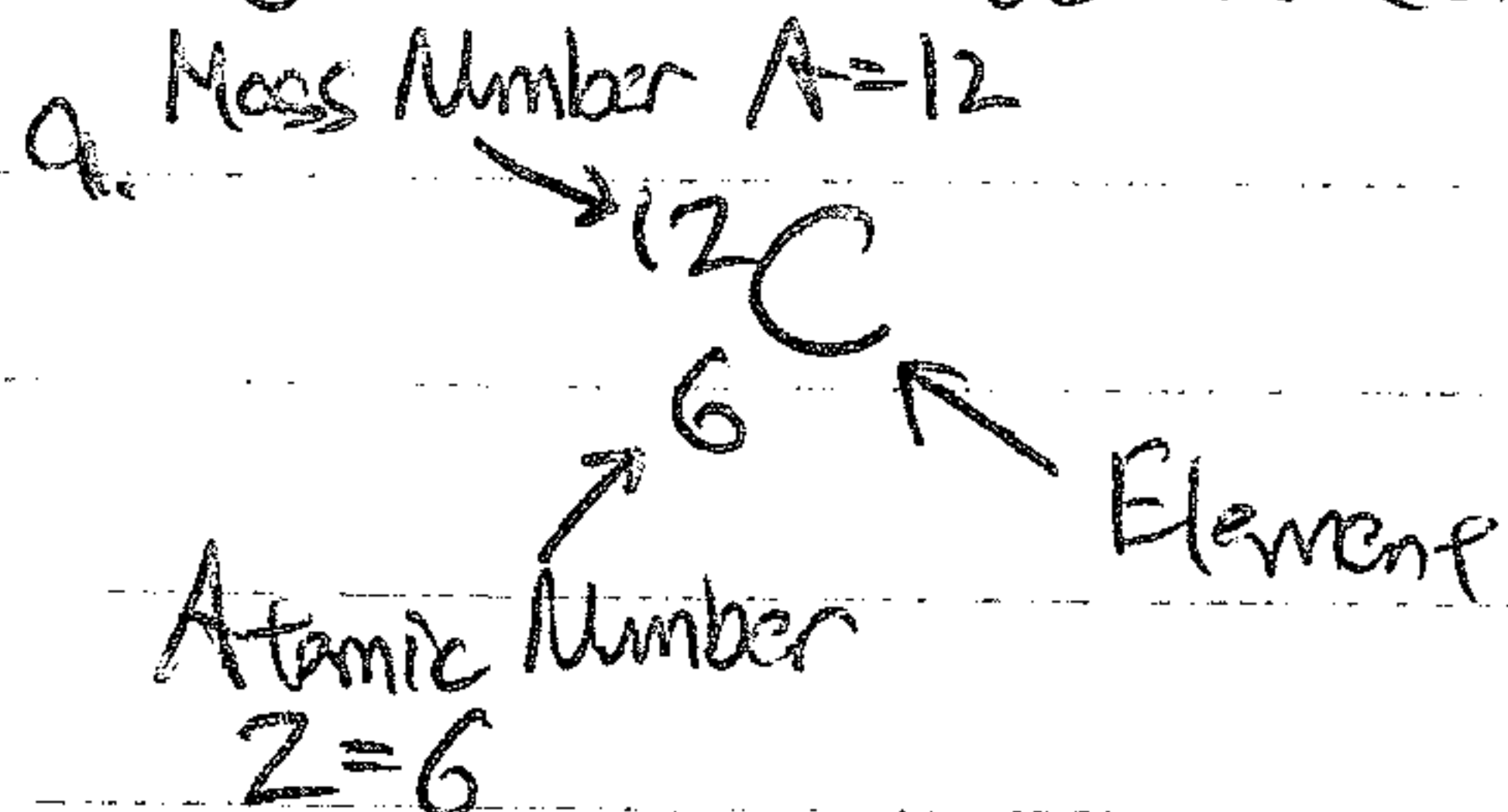
Hawes ①

I. Nuclear Fusion: The Energy Source of the Stars

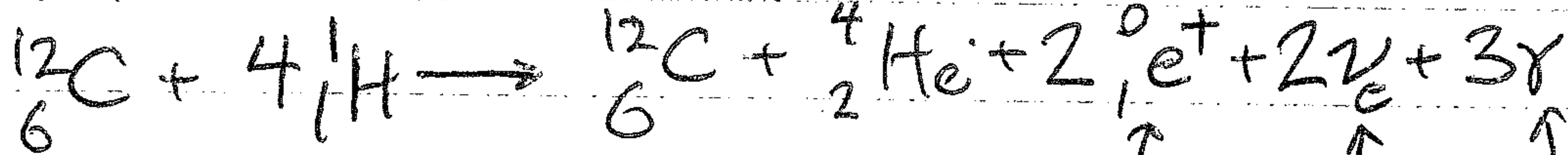
A. The CNO Cycle

1. In 1938/1939, Carl von Weizsäcker & Hans Bethe independently proposed this chain of nuclear reactions as the source for stellar luminosity

2. $^{12}_6\text{C}$ acts as a catalyst to fuse four protons into an alpha particle



b. Thus, the net reaction is



(6 reactions)

↑
positron

↑
electron
neutrino

↑
gamma
ray

3. This is the dominant power source for stars with $M > 1.5 M_\odot$

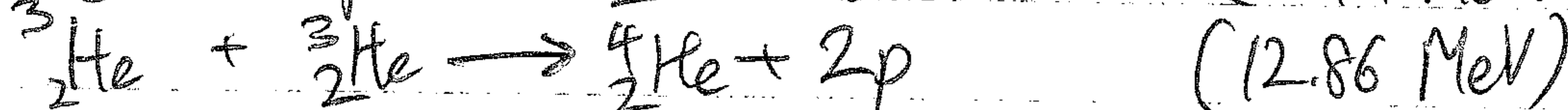
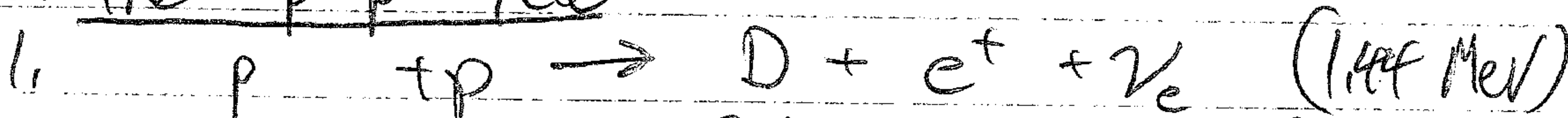
a. CNO reactions occurs for $T > 1.3 \times 10^7 \text{K}$

b. Our sun has a central temperature $T \approx 1.57 \times 10^6 \text{K}$

\Rightarrow only 1.7% of α 's are produced by CNO in sun.

c. At $T > 1.7 \times 10^7 \text{K}$ CNO begins to dominate.

B. The p-p cycle



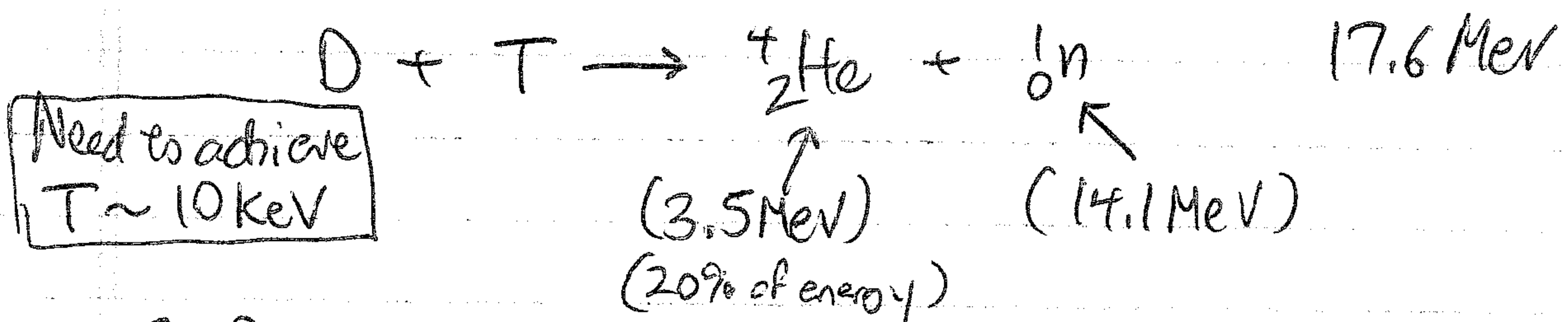
Lecture #25 (Continued)

Z.B. (Continued)

2. The lower central temperatures in the sun lead to dominance of the p-p cycle
3. p-p cycle requires $T > 4 \times 10^6 \text{ K}$.

C. Laboratory Fusion: D-T reaction

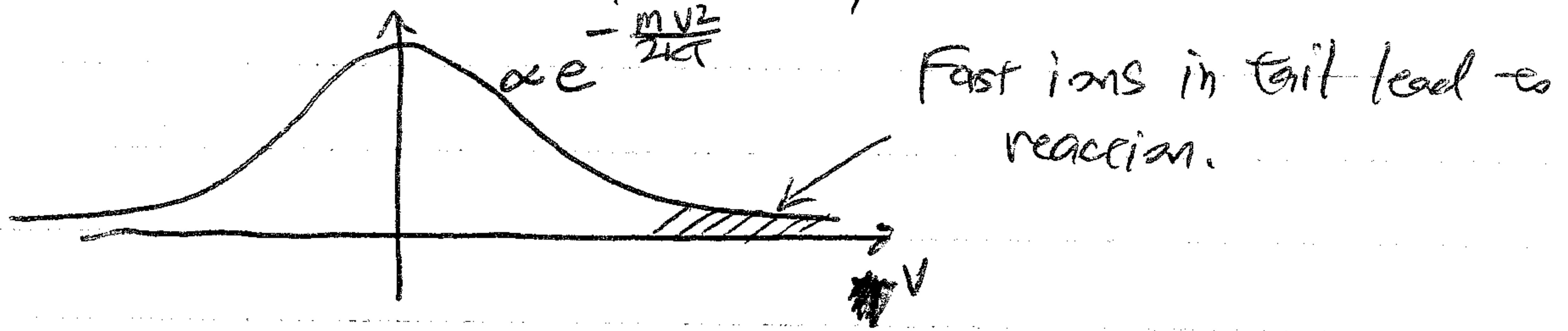
1. Base characteristics for fusion in the lab:



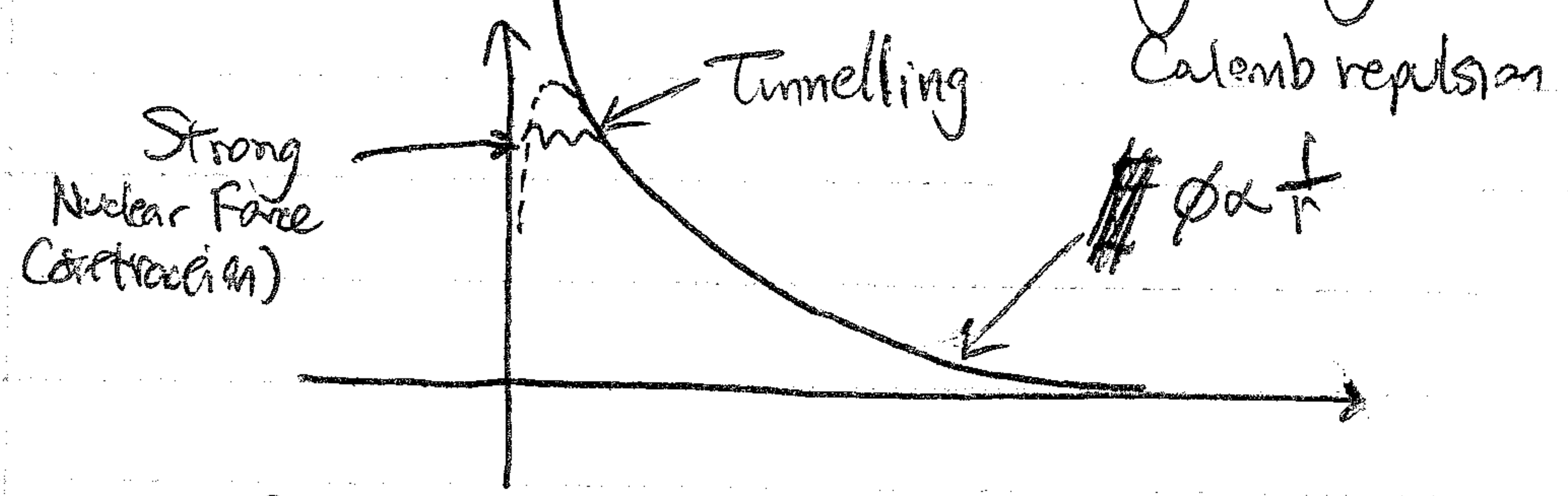
2. Reactions relevant to Laboratory Fusion \Rightarrow p.44-45 NRL Plasma Formulary.

3. DT reaction ~~cross-section~~ cross-section peaks at $\sim 50 \text{ keV}$, but you do not need a plasma with $T \sim 50 \text{ keV} \sim 6 \times 10^8 \text{ K}$.

a. For a Maxwellian equilibrium,



b. Quantum Mechanical Tunnelling through Coulomb Barrier.



4. Difficulties

- a. Confinement
- b. Fast neutrons
- c. Tritium supply.

I.C. (Continued)

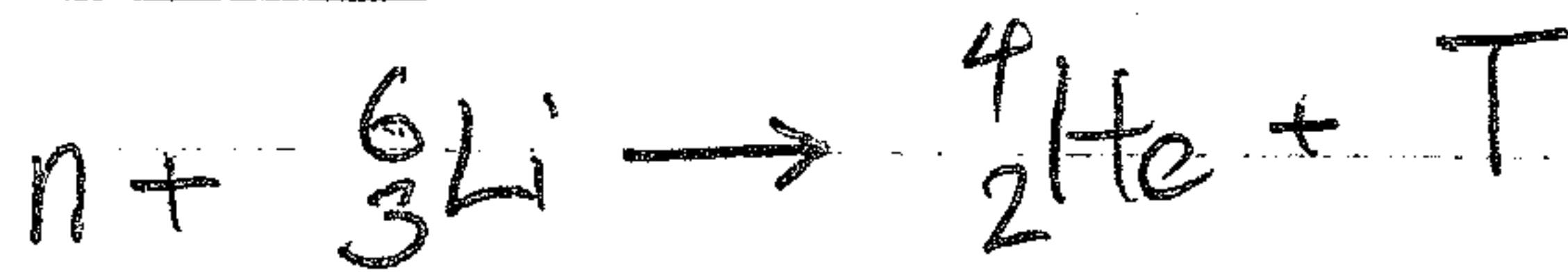
5. Neutrons: 14.1 MeV neutrons are not contained
 ⇒ Can cause severe damage and weakening of reactor material.

6. Tritium:

a. Cost for tritium is estimated at \$84,000 to \$130,000/gram.

b. Need a way to produce tritium

⇒ Breeder Reactions: Lithium Blanket



c. Can use neutrons from D-T reaction to produce more T.

d. World's supply of Lithium is limited, but sufficient to supply world's energy demands for thousands of years.

D. The Lawson Criterion:

1. Balance power lost by plasma with power released by fusion reaction.

2. Fusion power in α 's:

a. $n_D = n_T = n$

b. $P_\alpha = \frac{1}{4} \langle \sigma v \rangle n^2 E_\alpha$ $E_\alpha = 3.5 \text{ MeV}$

cross-section \times velocity
 averaged over a Maxwellian distribution

c. Efficiency for retaining α power in plasma: η

3. Power Loss: a. Loss of confinement $P_c = \frac{3nKT}{\tau}$

τ = confinement time

b. Radiative losses (for example, Bremsstrahlung from $P_B = \alpha n^2 T^{3/2}$ α = const. electron collisions)

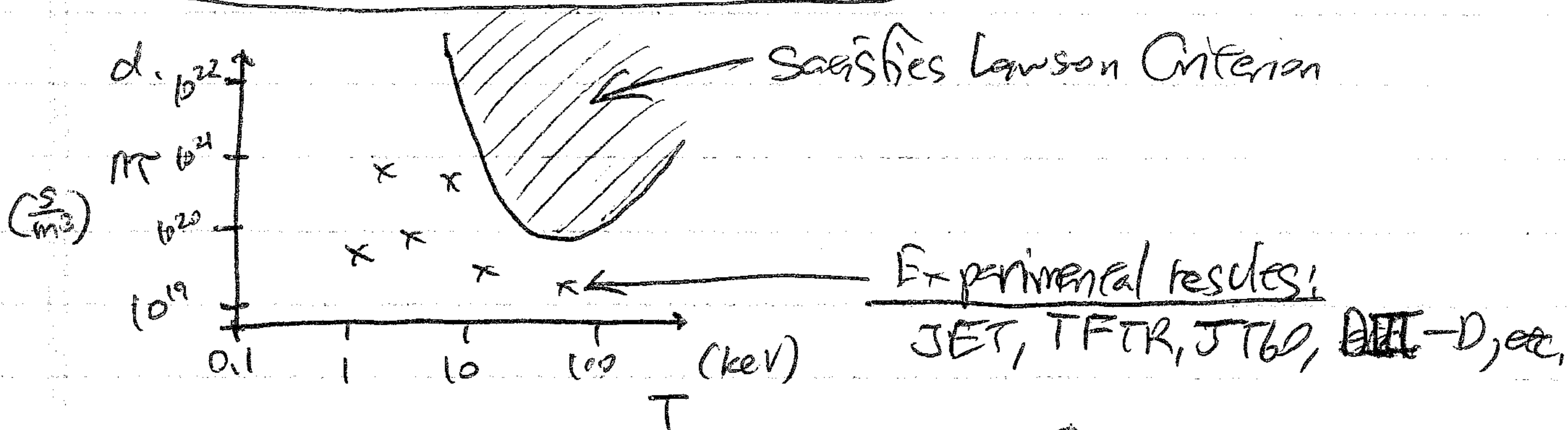
I.D. (Continued)

4. Power Balance: $P_\alpha + P_B + P_C > 0$ to sustain fusion

a. $\frac{3}{4} \langle \sigma v \rangle n^2 E_\alpha - \alpha n^2 T^{3/2} - \frac{3n k T}{T} > 0$

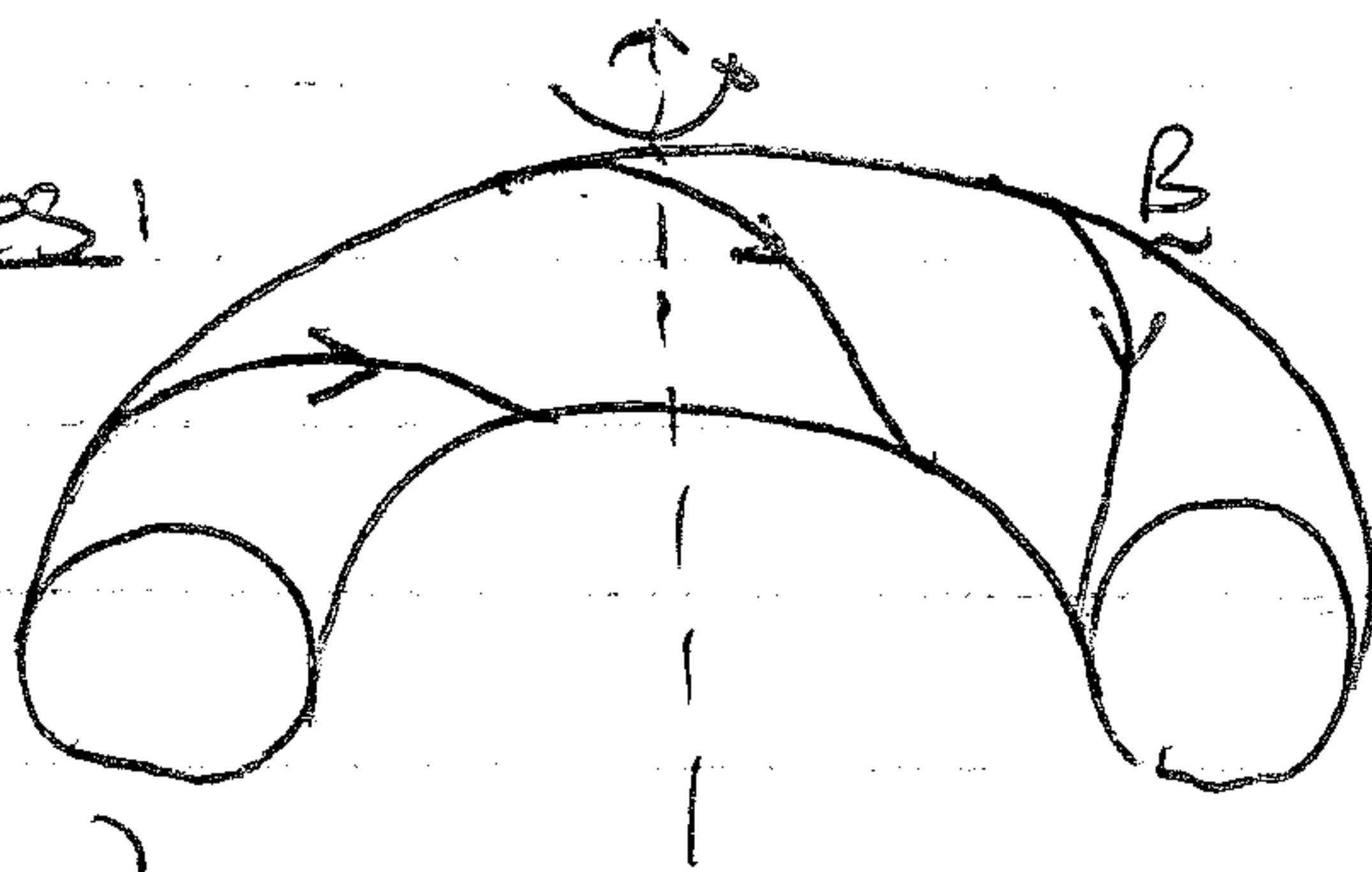
b. $\frac{3}{4} \langle \sigma v \rangle E_\alpha - \alpha T^{3/2} > \frac{3n k T}{n \tau}$

c. $n \tau > \frac{3 k T}{\frac{3}{4} \langle \sigma v \rangle E_\alpha - \alpha T^{3/2}}$ Lawson Criterion



II. Plasma Confinement Schemes:

A. Magnetic Confinement:



1. Tokamak: Most successful.

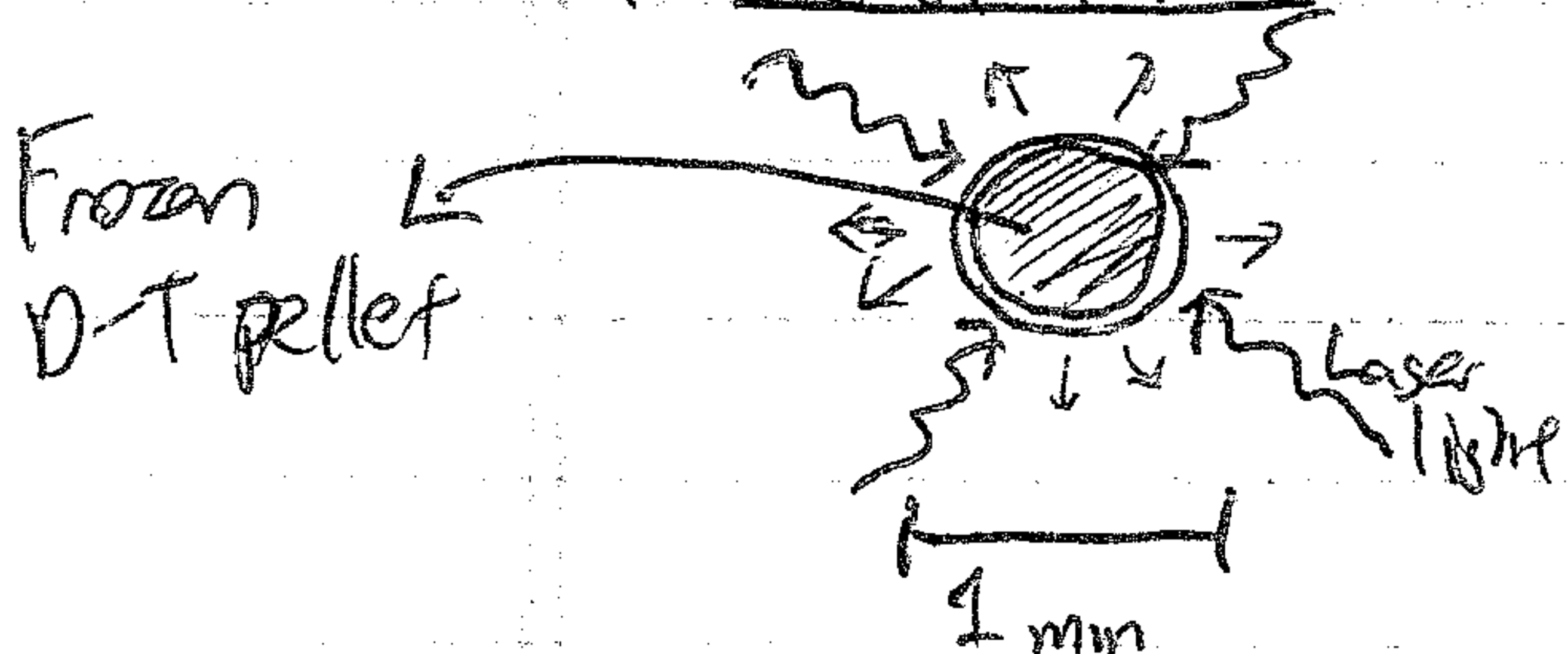
(Russian: Toroidal Magnetic Chamber)

2. Other: Z-pinches, Reverse Field Pinches, ~~etc~~ Stellarator, etc.

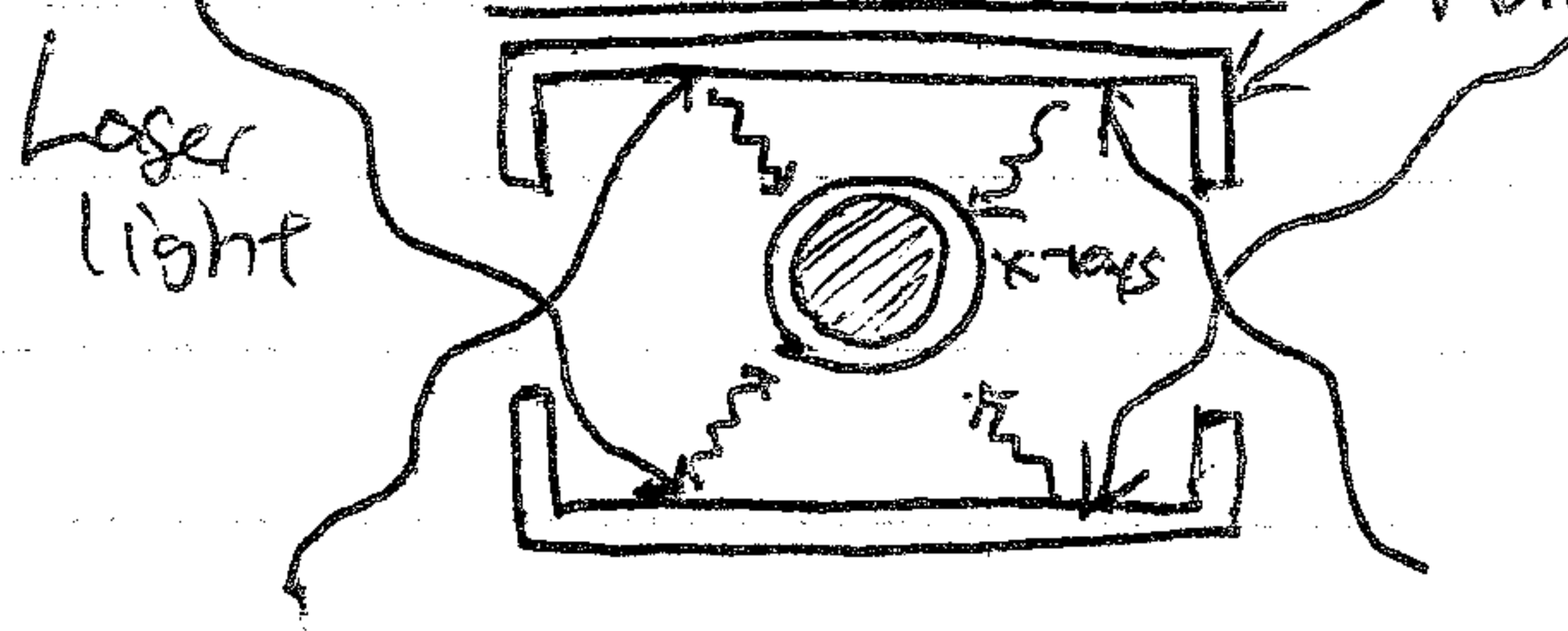
3. Requires plasma confinement times of at least a few seconds.

B. Inertial Confinement (Laser Fusion)

1. Direct Drive:



2. Indirect Drive: Hohlraum



3. Back reaction compresses plasma to 10^3 times liquid density for very short times.