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

Howes 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. $^{12}_{6}C$ acts as a catalyst to fuse four protons into an alpha particle

a. Mass Number $A=12$ $\searrow$

$$^{12}_{6}C$$

$\nearrow$ Atomic Number $Z=6$ $\nwarrow$ Element

$^{1}_{1}H = p$ $\quad$ $^{4}_{2}He = \alpha$

$^{2}_{1}H = D$ $\quad$ $^{1}_{0}n$

$^{3}_{1}H = T$ $\quad$ $^{0}_{-1}e$ $\quad$ $^{0}_{+1}e^{+}$

b. Thus, the net reaction is

$$^{12}_{6}C + 4\,^{1}_{1}H \longrightarrow \,^{12}_{6}C + \,^{4}_{2}He + 2\underset{\substack{\uparrow\\ \text{positron}}}{^{0}_{1}e^{+}} + 2\underset{\substack{\uparrow\\ \text{electron neutrino}}}{\nu_e} + 3\underset{\substack{\uparrow\\ \text{gamma ray}}}{\gamma}$$

(6 reactions)

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

a. CNO reactions occurs for $T > 1.3\times10^{7}$ K

b. Our sun has a central temperature $T \simeq 1.57\times10^{6}$ K

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

c. At $T > 1.7\times10^{7}$ K CNO begins to dominate.

B. The p-p cycle

1.
$$\begin{aligned} p + p &\longrightarrow D + e^{+} + \nu_e && (1.44 \text{ MeV})\\ D + p &\longrightarrow \,^{3}_{2}He + \gamma && (5.49 \text{ MeV})\\ ^{3}_{2}He + \,^{3}_{2}He &\longrightarrow \,^{4}_{2}He + 2p && (12.86 \text{ MeV}) \end{aligned}$$

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I. B. Continued)

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

C. Laboratory Fusion: D-T reaction

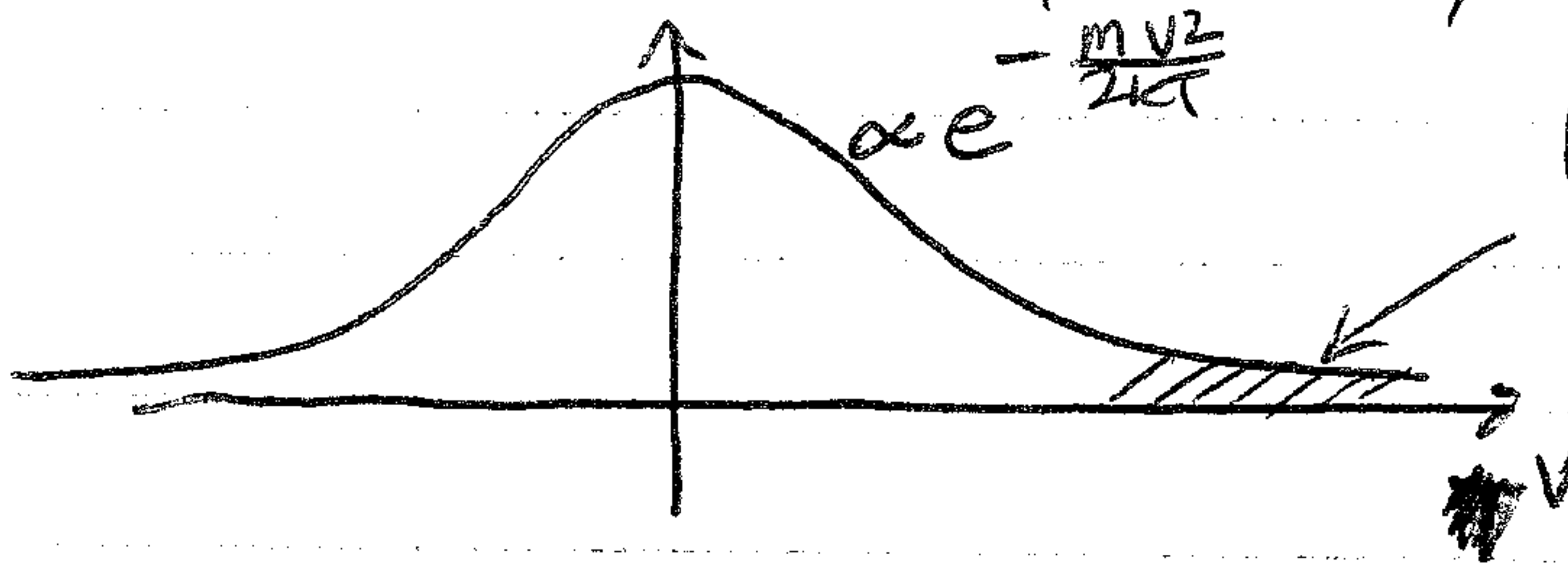
1. Basic characteristics for fusion in the lab:

$$D + T \longrightarrow \underset{(3.5\,\text{MeV})}{{}^4_2He} + \underset{(14.1\,\text{MeV})}{{}^1_0 n} \qquad 17.6\ \text{MeV}$$

(20% of energy)

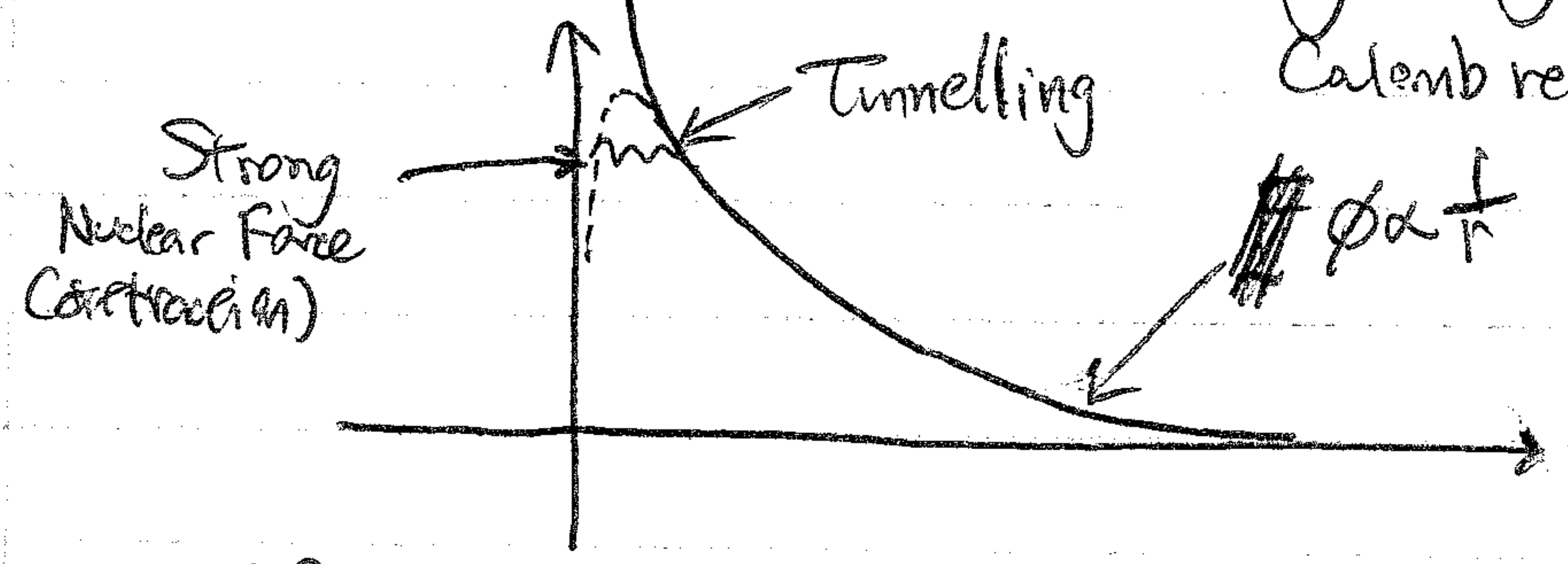
Need to achieve $T \sim 10$ keV

2. Reactions relevant to Laboratory Fusion ⇒ p.44-45 NRL Plasma Formulary.
3. D-T reaction cross-section peaks at ~50 keV, but you don't need a plasma with $T \sim 50\ \text{keV} \sim 6 \times 10^8$ K.
   a. For a Maxwellian equilibrium,



Fast ions in tail lead to reaction.

   b. Quantum Mechanical Tunnelling through Coulomb Barrier.



4. Difficulties
   a. Confinement
   b. Fast neutrons
   c. Tritium supply.

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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 Reactors: Lithium Blanket

$$n + {}^{6}_{3}Li \longrightarrow {}^{4}_{2}He + T$$

   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. $P_\alpha = \frac{1}{4}\underbrace{\langle \sigma v \rangle}_{\substack{\text{cross-section} \times \text{velocity} \\ \text{averaged over a Maxwellian distribution}}} n^2 E_\alpha$ $\qquad E_\alpha = 3.5$ MeV
   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 $P_B = \alpha n^2 T^{\frac{1}{2}}$ α = const. electron-ion collisions)

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I. D. (Continued)

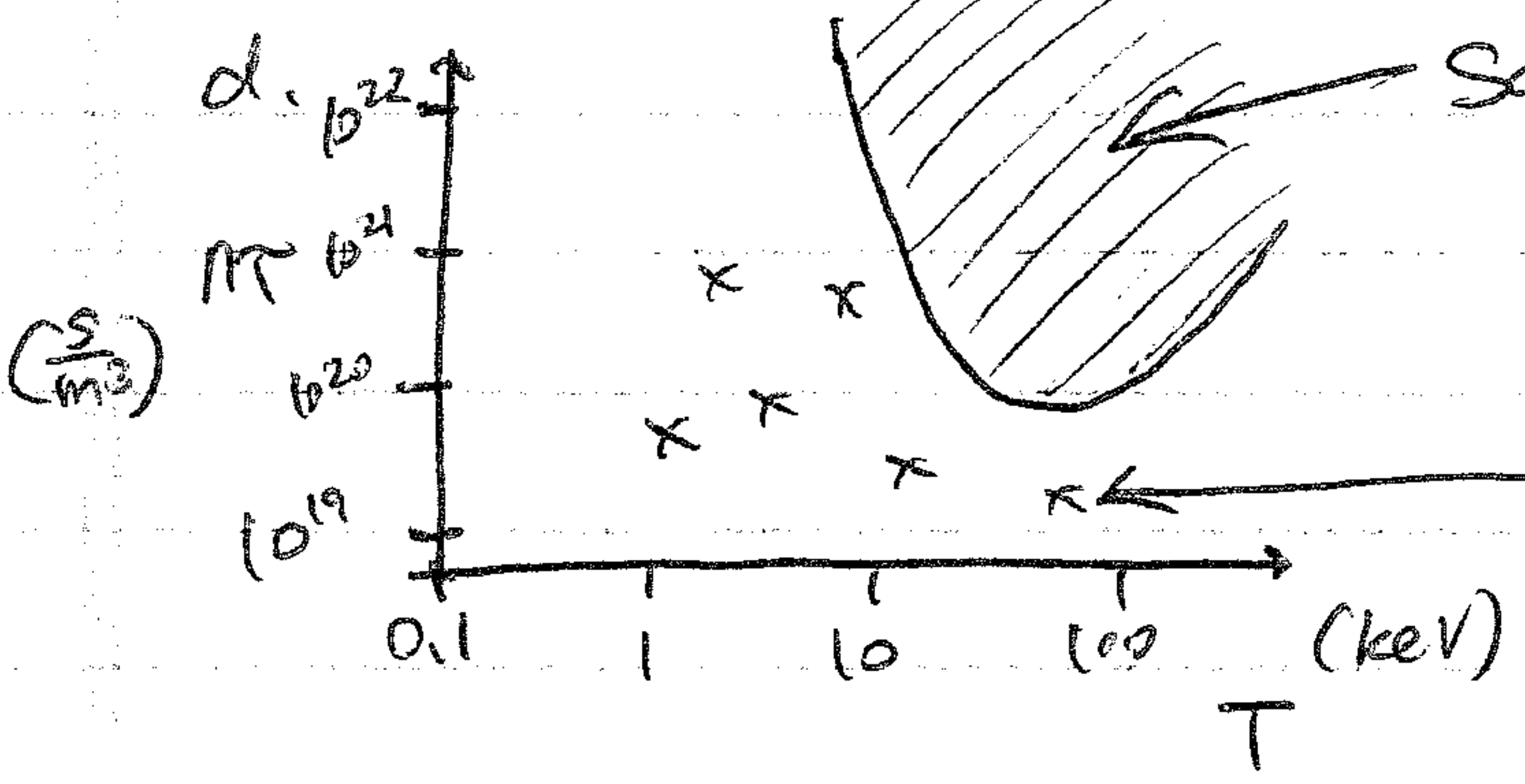
4. Power Balance: $P_\alpha + P_B + P_C > 0$ to sustain fusion

a. $\frac{\eta}{4}\langle\sigma v\rangle n^2 E_\alpha - \alpha n^2 T^{\frac{1}{2}} - \frac{3nkT}{\tau} > 0$

b. $\frac{\eta}{4}\langle\sigma v\rangle E_\alpha - \alpha T^{\frac{1}{2}} > \frac{3nkT}{n^2\tau}$

c. $\boxed{n\tau > \frac{3kT}{\frac{\eta}{4}\langle\sigma v\rangle E_\alpha - \alpha T^{\frac{1}{2}}}}$ Lawson Criterion

d.

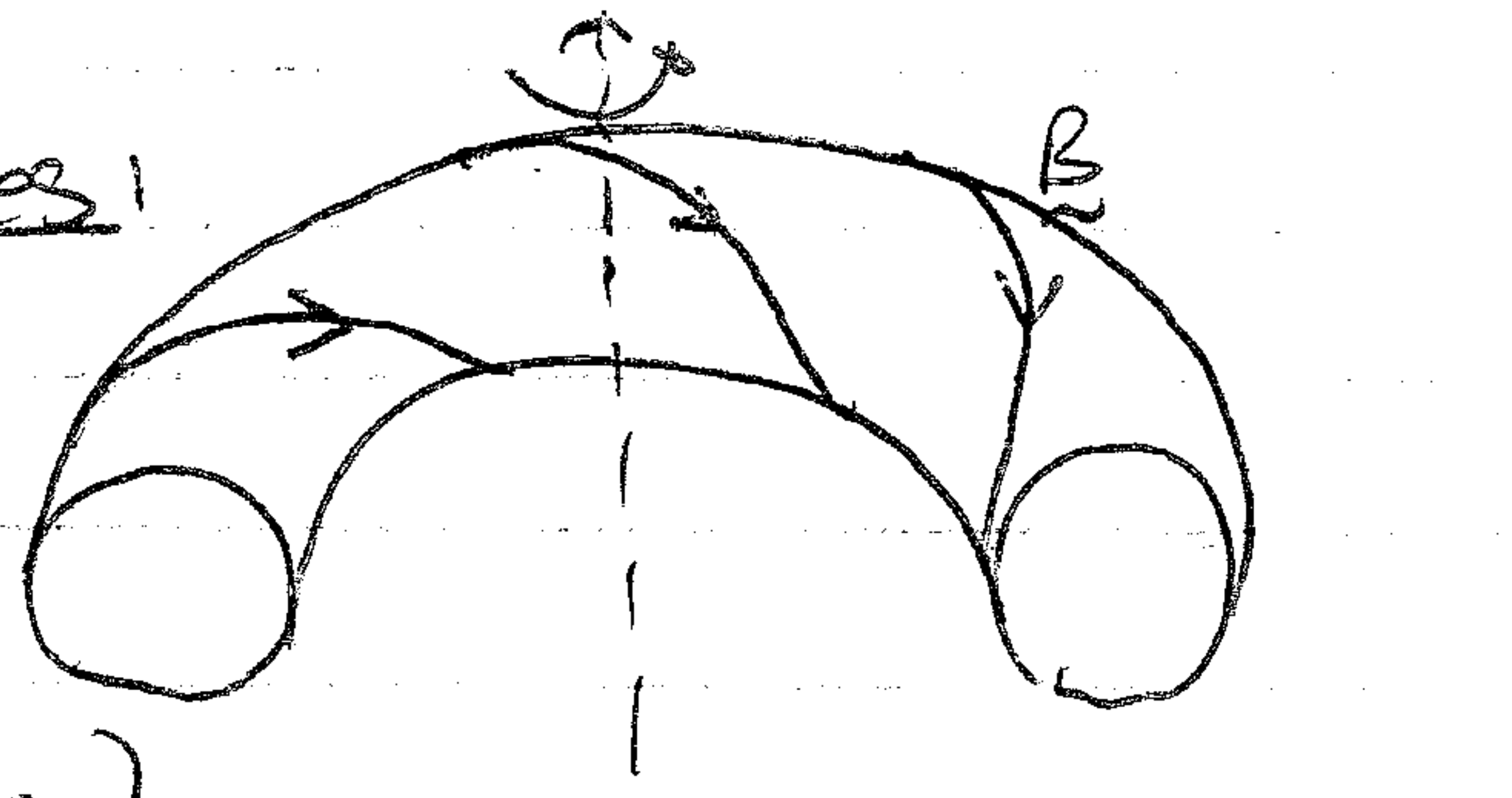


Satisfies Lawson Criterion

Experimental results:
JET, TFTR, JT60, DIII-D, etc.

II. Plasma Confinement Schemes:

A. Magnetic Confinement:



1. Tokamak: Most successful.

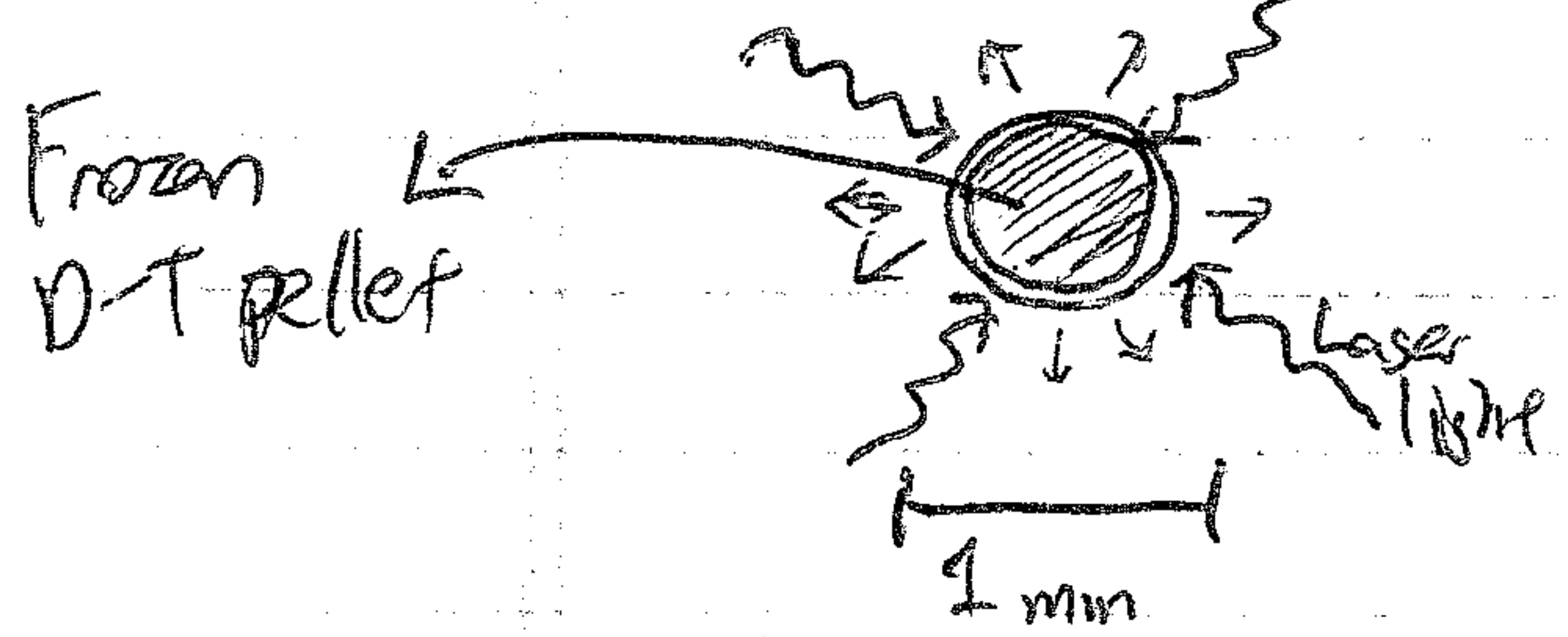
(Russian: Toroidal Magnetic Chamber)

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

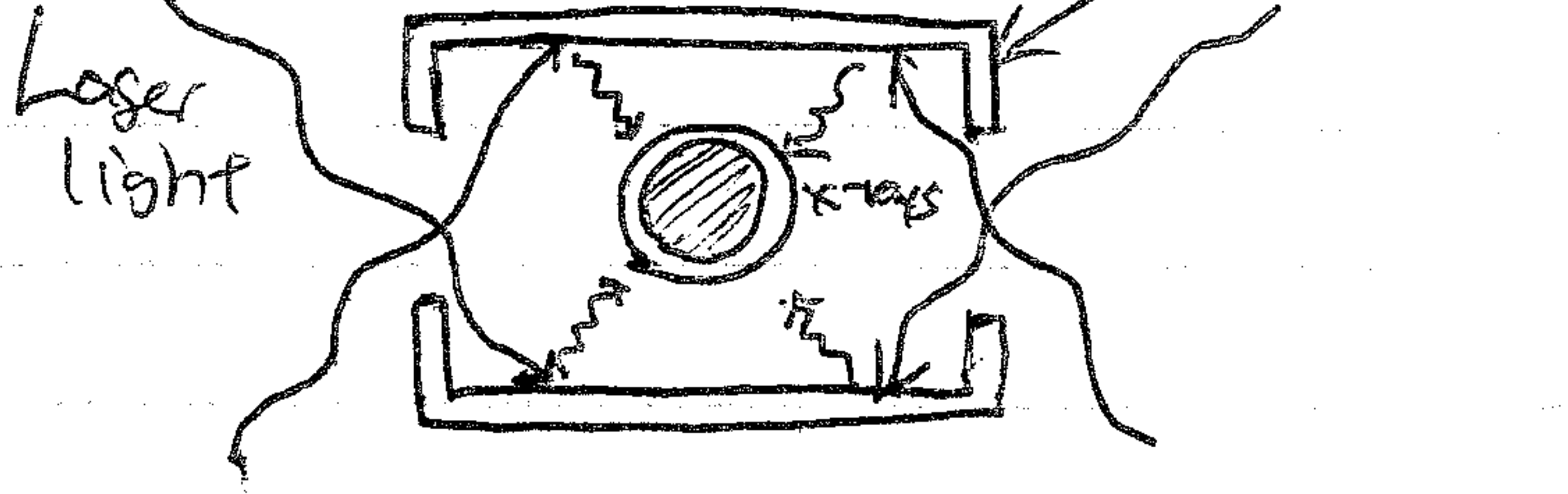
3. Requires plasma confinement times of at least a few seconds.

B. Inertial Confinement (Laser Fusion)

1. Direct Drive:



2. Indirect Drive:



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