Fusion

By Deuce of FurryMUCK =^.^=

Additional art by Richard Bartrop (http://rjbartrop.deviantart.com)

What Is Fusion?

- Fusing light elements (usually hydrogen) into heavier elements (usually helium) produces energy.

- Needs to be hot enough for nuclei to get close to each other (10-100 keV, 100M+ K).
- Needs to be dense enough and held long enough for reactions to happen.

Conditions For Fusion

- Fusion Cross-Section
  - Chance of fusion per collision.

- Lawson Criterion: nt
  - Density * time > threshold
  - Not a sharp boundary!

- Triple Product: nTt
  - More useful (pressure * time)

Astrophysical Fusion

- Very low temperature!
- Very high density, very long confinement.

- Common reactions:
  – Proton proton chain (smaller stars)
  – CNO cycle (larger stars)
  – Triple alpha (helium to carbon)
    - Helium flash

Astrophysical Fusion

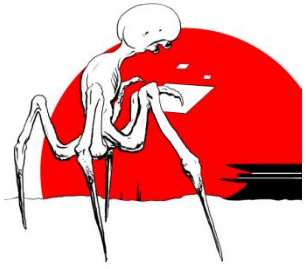
- Other reactions:
  - Deuterium burning and lithium burning
  - Heavier elements in pre-supernova stars
  - R-process, S-process in heavy stars and supernovae

- Stellar processes not useful on earth.
  - Weak Force reactions are slow (low cross section)
  - Triple alpha requires high density

Astrophysical Fusion

- Stellar processes let us check models of fusion.
- Stars are very efficient.
  - Solar power is a very useful form of fusion power.



Fusion on Earth

- Reactions of interest.
  - Only Strong Force reactions (fast)
  - No gamma rays (carry away energy)

- D+T (nTt = 2.8e+21) (keV * s / m^3)
  - Easiest by far; requires breeding tritium.
- D+D (nTt = 1.1e+23) (**40x D+T**)
  - No breeding, lots of fuel, but difficult.
- D+3He (nTt = 4.4e+22) (**16x D+T**)
  - Fewer neutrons, requires breeding 3He from tritium.
- p+11B (nTt = 1.4e+24) (**500x D+T**)
  - Very few neutrons, very difficult, Bremsstrahlung losses.

Inertial Confinement Fusion

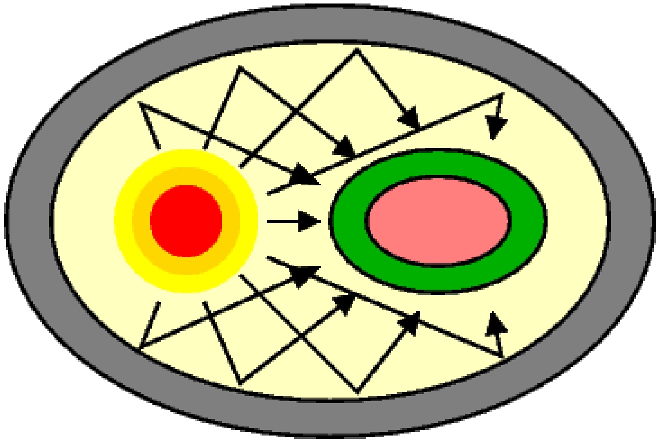
- Super-dense, ultra-high-pressure.
- Very short confinement time.

- Confinement time limited by time to fly apart.
  - Gives size*density constraint.
  - D+T: $\rho * r > 1 g/cm^2$

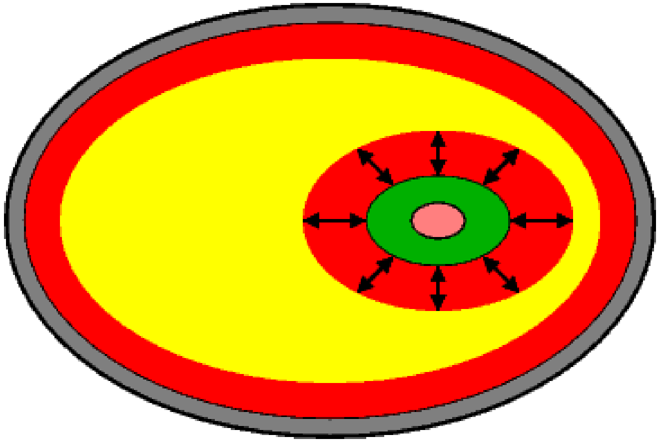
- Example: D+T breakeven diameter vs density.
  - Solid (0.2 g/cc): 10 cm, 60 ns, 130 GJ (30 T TNT)
  - 100x: 1 mm, 0.6 ns, 13 MJ (3 kg TNT)
  - 10000x: 10 microns, 6 ps, 1.3 kJ

Inertial: Fusion Bombs

- Tellar-Ulam design
  - Fission bomb heats LiD fuel.
  - Casing reflects x-rays to focus heat.
  - Uranium tamper holds fuel in place.



- Power plant proposal: Liquid metal waterfall.



Inertial: Laser Fusion

- Zap a hollow pellet with lasers or ion beams.
  - Outer layers explode.
  - Pressure compresses inner layers to ultra-density.

- Variant: Hohlraum
  - Lasers heat hohlraum.
  - Hohlraum gives off x-rays.
  - Pellet absorbs x-rays better than laser light.

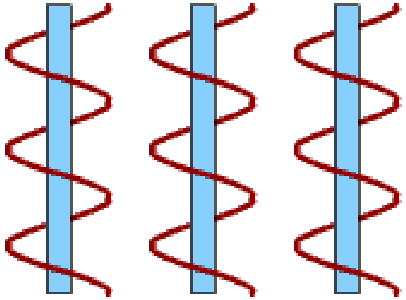
Inertial: Laser Fusion

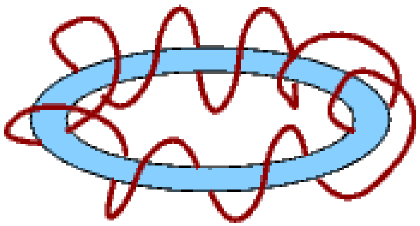
- National Ignition Facility (USA)
- Laser Megajoule (France)

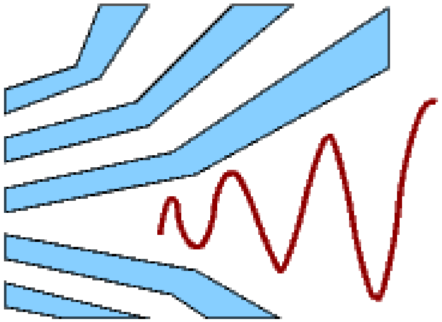
- Not useful for fusion power!
  - Wall-plug efficiency is far too low.
- Used for studying fusion and materials.
  - "Equations of state" for materials under conditions inside a nuclear weapon.

Magnetic Confinement Fusion

- How it works:
  - Ions orbit magnetic field lines.
  - Move along lines but not across.
  - Field lines that form loops hold particles.
  - Pinches (“magnetic mirrors”) reflect particles.







Magnetic Confinement Fusion

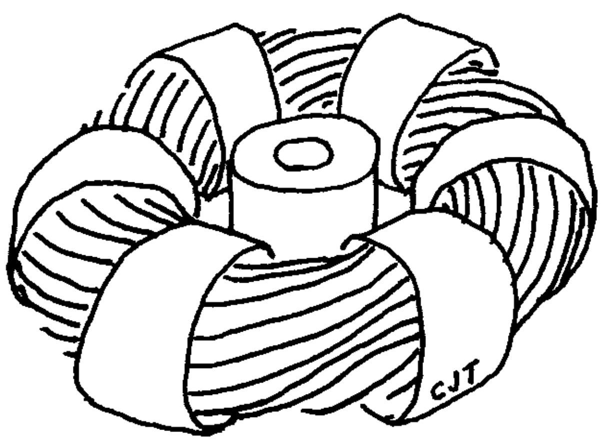
- Low density, long confinement time.

- Limits:
  - Confinement isn’t perfect (drift from scattering).
  - Pressure is limited (less than magnet pressure).
  - Turbulence limits density even more.
    - Plasma has to stay stable for a long time.

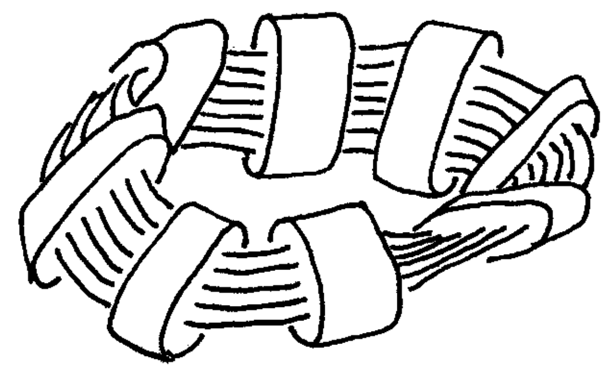
Torus Design (Tokamak, Stellarator)

- All field lines are closed loops.
  - No easy leakage paths.

- Field lines twisted to reduce drift.
  - Tokamak uses induced field (pulsed).
  - Stellarator uses twisted magnets (steady state).



TOKAMAK



STELLARATOR

Torus Design (Tokamak, Stellarator)

- Approaching wall-plug breakeven.

- Problems for power generation:
  - 10x neutron flux of fission.
    - Materials degrade faster than fission core.
    - Materials activated (become radioactive waste).
  - Much more complex and expensive than fission.
  - Power density much lower than fission.

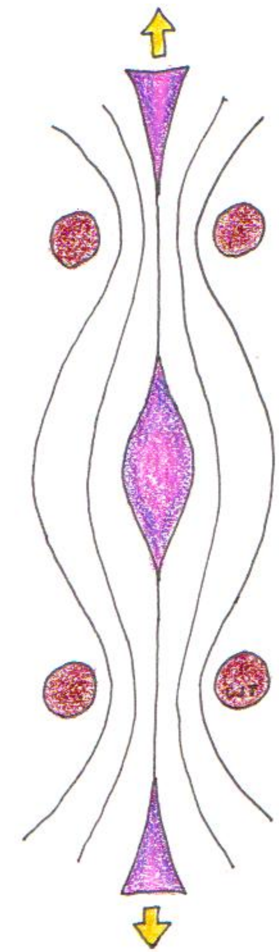
Historical and Research Designs

- Current Pinch (Sandia "Z Machine")
  - Current discharge through plasma implodes the plasma to high density.
  - Problem: Severe instability.
    - Current path twists and kinks and pinches off.
    - Very short confinement time.
  - Variant: Use for inertial confinement.
    - Imploding wires heat a hohlraum

Historical and Research Designs

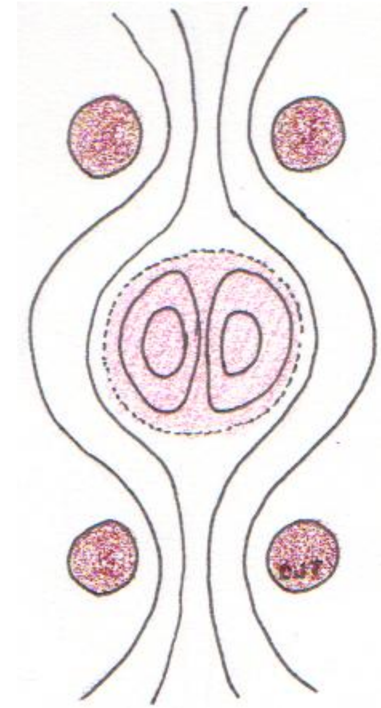
- Mirror fields ("magnetic bottle")
  - Pinch at either end of a field to reflect ions.
  - Fails: very leaky.

- Variant: Fusion version of VASIMR rocket.

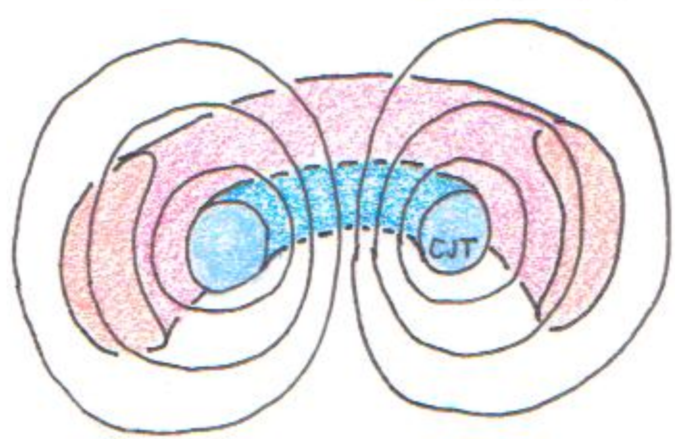


Historical and Research Designs

- Field Reversed Configuration
  - Apply field; plasma “freezes it in”.
  - Reverse field, compressing plasma.
  - Stability problems.



- Levitating toroid
  - Lower density
  - Glitch events

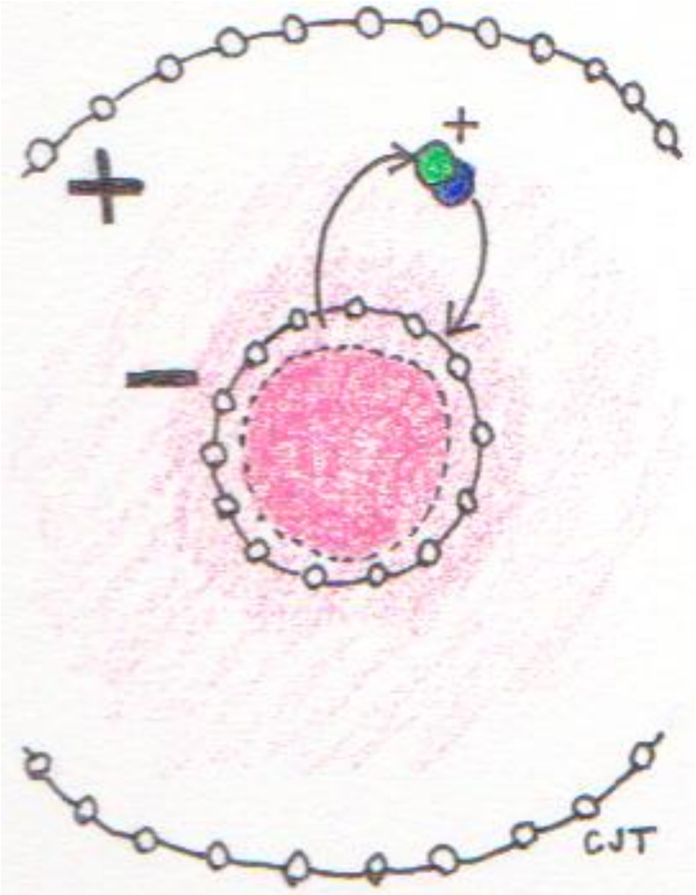


Fringe and Hobbyist Designs

- Produce detectable fusion (not hard).
  - Still a fun hobby!
- Usually variants of known concepts/designs.
- Usually inflated claims.
  - Proposed for “aneutronic” p+11B, but can’t even break even with D+T.
  - Claiming that full-size devices will perform many orders of magnitude better than prototype ones.

Fringe: Farnsworth-Hirsch

- Farnsworth-Hirsch Fusor
- Principles:
  - Ions trapped by electrostatic confinement.
  - Inner electrode grid (negative) is inside plasma.



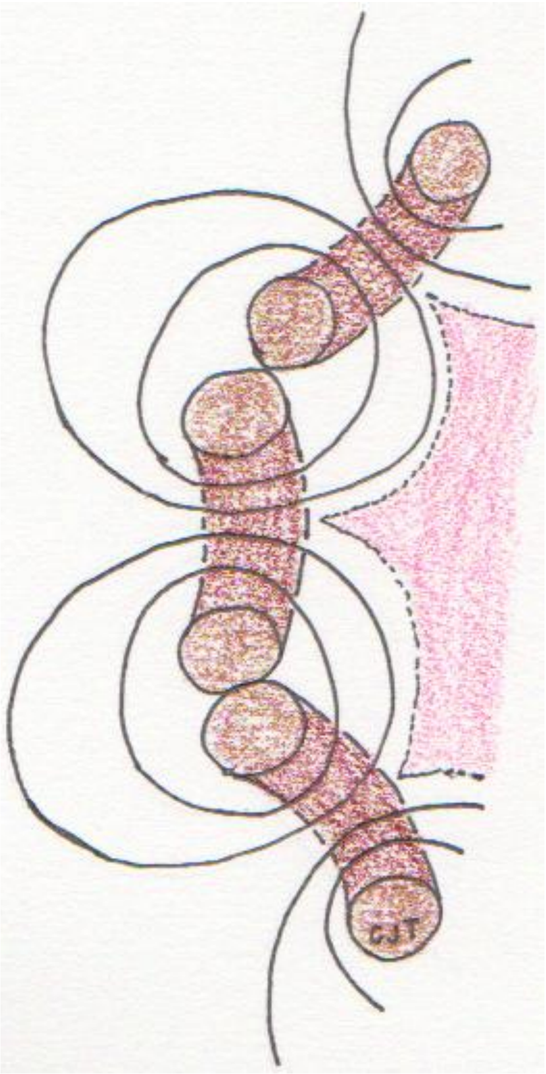
Fringe: Farnsworth-Hirsch

- Difficulties:
  - Plasma eats inner electrode
    - Contaminates plasma.
    - Cools plasma.
  - Academic analysis: cannot break even with thermal plasma, ever.

- Still a popular hobbyist project.
- Used commercially as a neutron source.

Fringe: Bussard Polywell

- Bussard "Polywell"
- Principles:
  - Magnetic mirrors trap electron plasma.
  - Electron plasma electrostatically confines ion plasma.

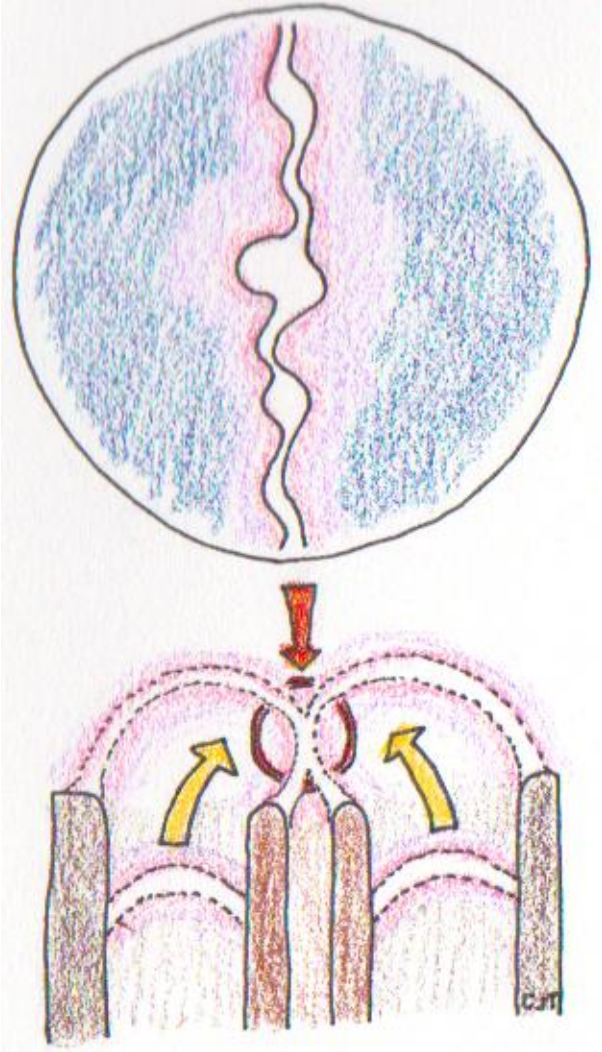


Fringe: Bussard Polywell

- Difficulties:
  - Fundamental principle is unsound.
    - Ions and electrons are tightly coupled.
    - Scattering in electron plasma allows drift to follow ions.
    - Scattering is always more common that fusion, so can’t avoid it.
  - Dubious scaling claims.
    - Claims big device works 10 million times better.

Fringe: Lerner Focus

- Lerner "Focus Fusion"
  - Type of "dense plasma focus" device (Mather and Filippov)
- Principles:
  - Arc between electrodes causes a current pinch.
  - Effects during destabilization form tiny ultra-dense regions for fusion.



Fringe: Lerner Focus

- Difficulties:
  - Current pinches already well-studied.
    - Wouldn’t “Z Machine” have found this already?
    - Proposing better (density * confinement time) product than much larger current pinch machines achieved.
  - Quantization principle is unsound.
    - Known effect, but only works for 2D plasmas, not 3D.
  - Many claims without sufficient measurements to back them up.
    - Measurements interpreted using models based on a large set of assumptions.

Looking Forwards

- Fusion is a very nifty topic!
- Important for understanding lives of stars.
- Studied for use on earth.
  - "Fusion power has been 10 years away for 50 years."
  - Niche applications in industry.
  - Fun hobbyist projects.
- Possible uses in future (power, space travel)