Various Fusion Concepts

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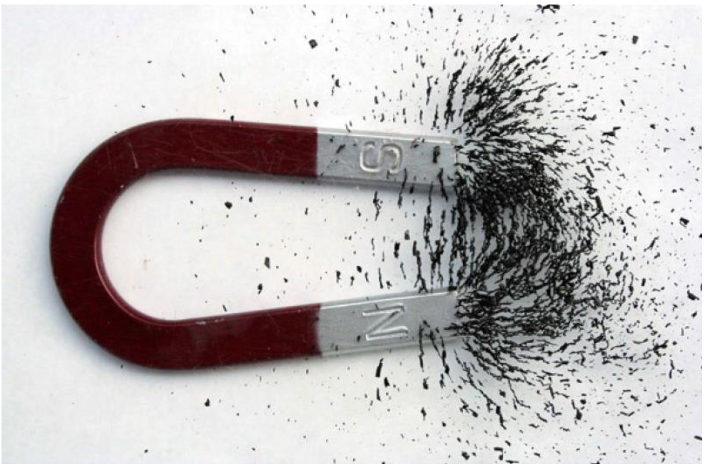
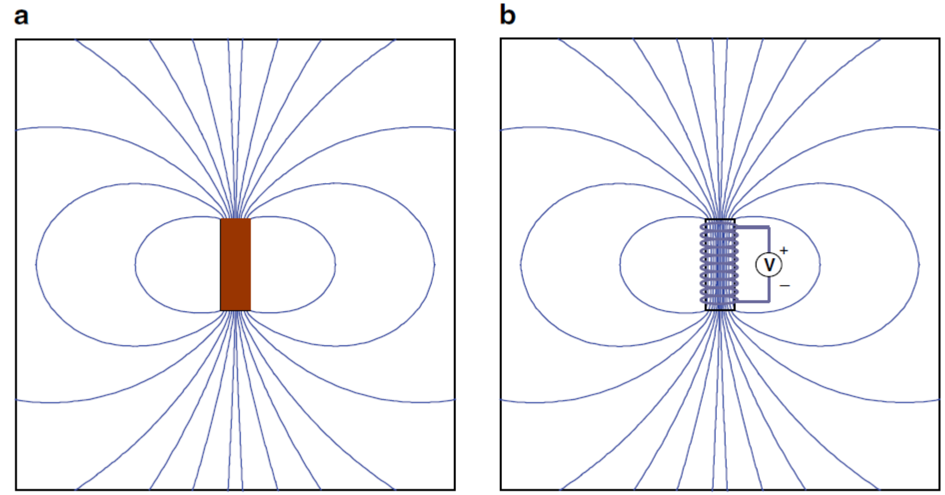
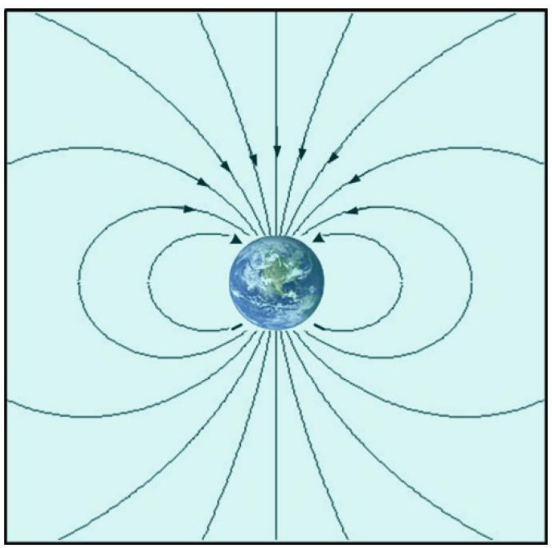
Introduction

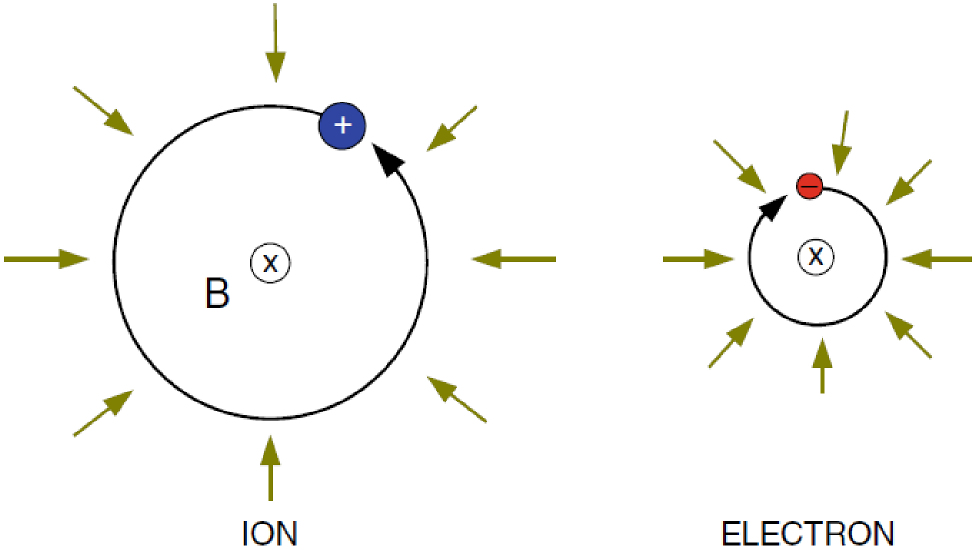
- Classification by confinement method
  - Magnetic confinement fusion (MCF)
    - ✓ Toroidal pinch
    - ✓ Tokamak, spherical tokamak (ST)
    - ✓ Stellarator
    - ✓ Field reverse configuration (FRC)
    - ✓ Magnetic mirror
  - Inertial confinement fusion (ICF)
    - ✓ Laser fusion (direct drive, indirect drive)
    - ✓ Inertial electrostatic confinement (IEC), Polywell
    - ✓ Fast z-pinch, MagLIF (magnetized linear inertial fusion)
- Alternative concepts
  - Cold fusion
  - Bubble fusion
  - Muon-catalyzed fusion

How can a magnetic field hold a plasma?









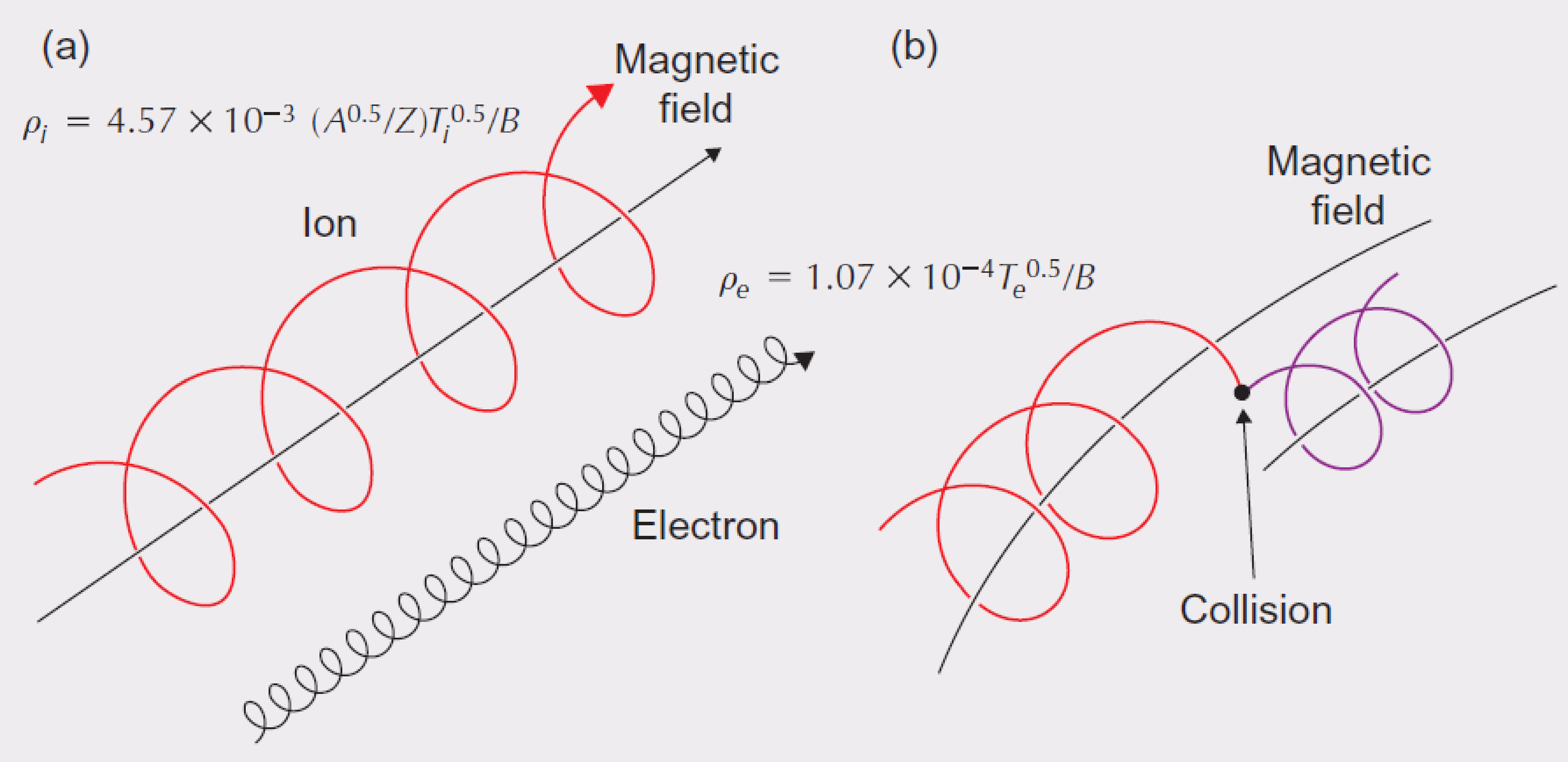
Magnetic field of earth ~ 0.5 gauss ~ 0.00005 T

Particle motions in magnetic field

(a) Schematic of an ion and an electron gyrating in a straight magnetic field.

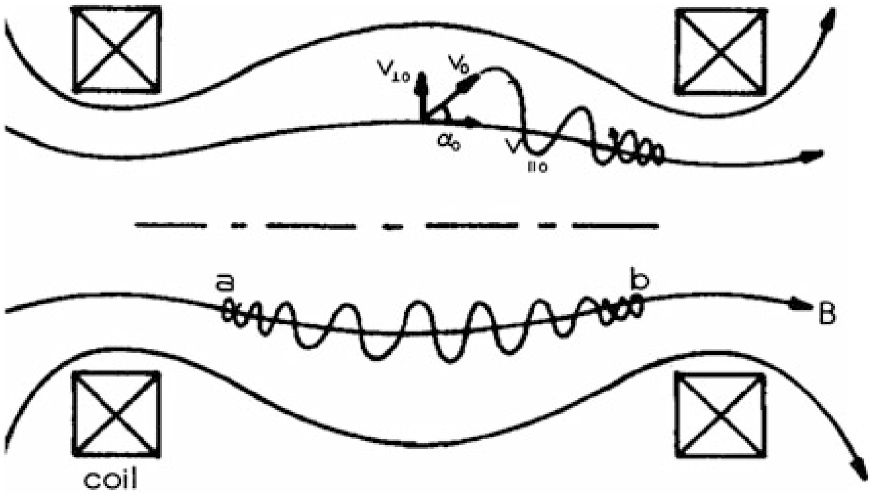
(b) An ion collision resulting in the ion's being displaced to a new orbit.

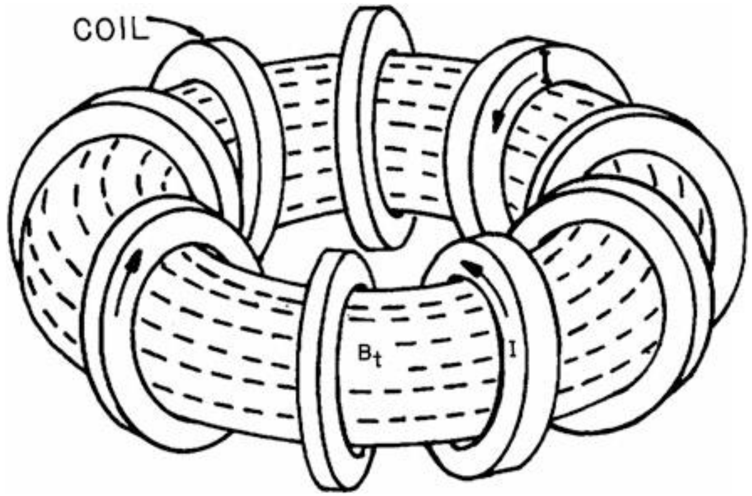
$$F = q\boldsymbol{v} \times \boldsymbol{B}$$



Magnetic confinement: open vs. closed

- Magnetic fields may be either ‘open’ or ‘closed’.

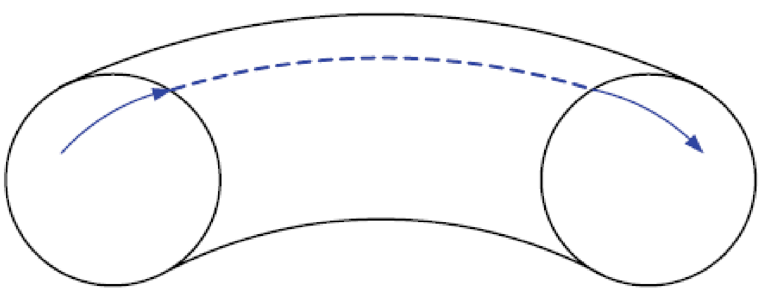




- The simplest shape that will work is a torus. The torus is entirely filled with magnetic field, so that plasma placed inside will not, in principle, escape.

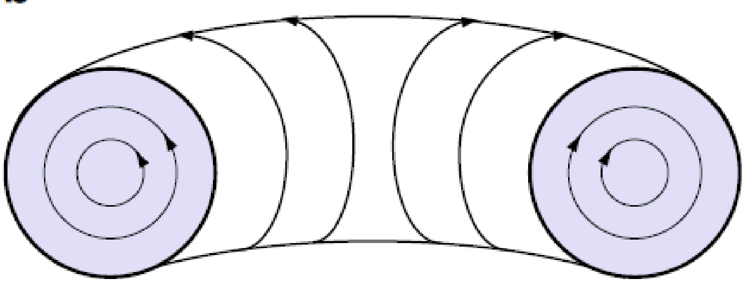
a

Toroidal field line



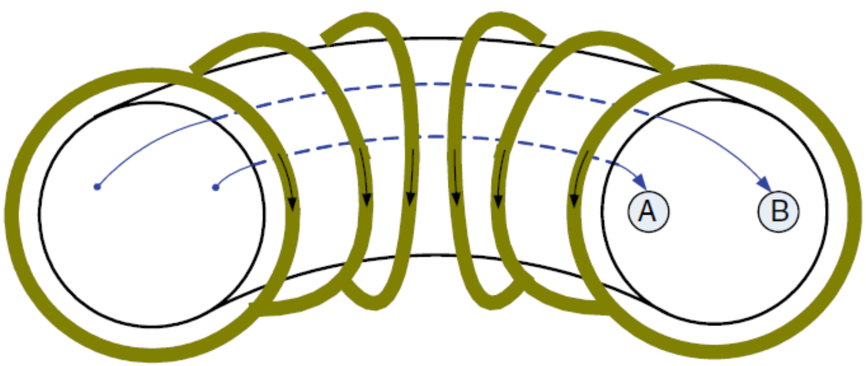
b

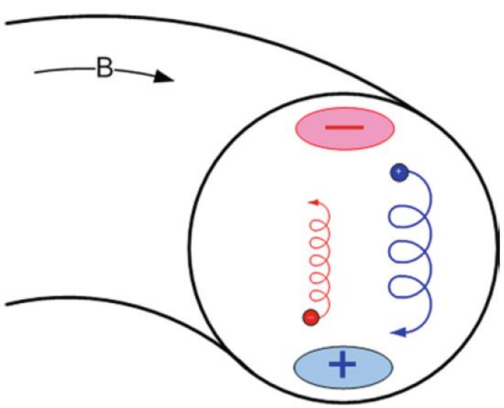
Poloidal field line

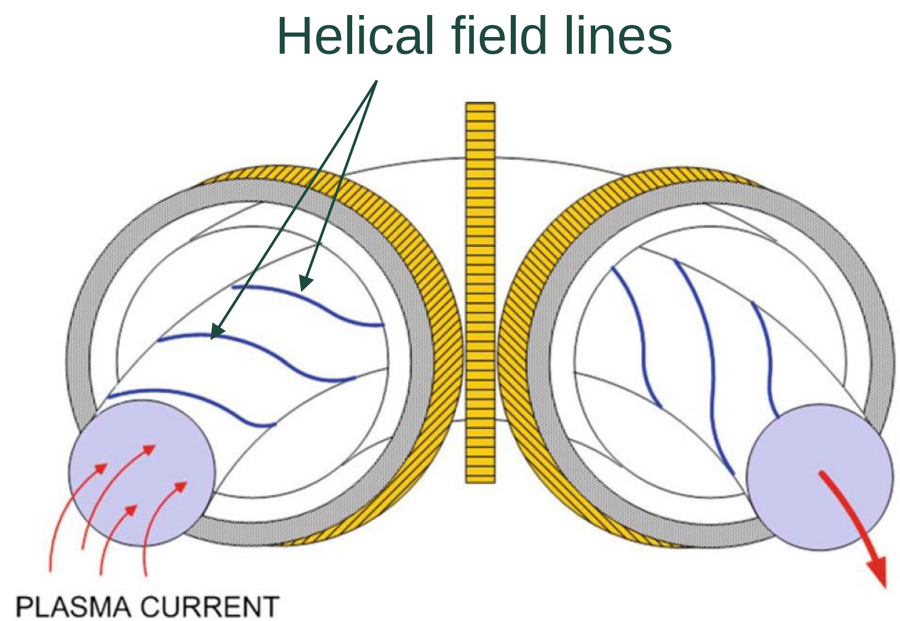


Why the field lines have to be twisted

- When we bend a cylinder into a torus so that the field lines do not strike a wall, the first of several toroidal effects comes into play.
- The magnetic field is always larger on the inside of a torus than on the outside. This is a toroidal effect that does not happen in a cylinder. The consequence of this effect is that charged particles no longer gyrate in perfect circles.



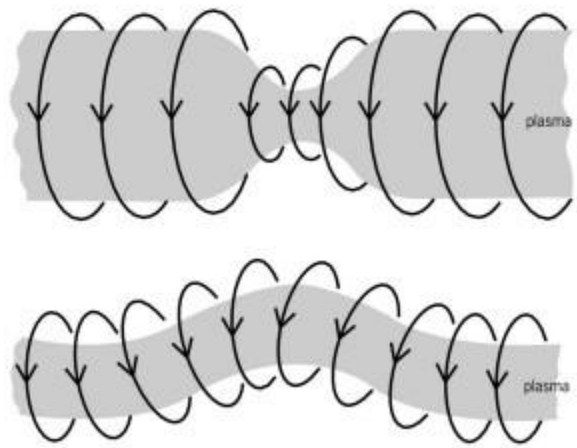


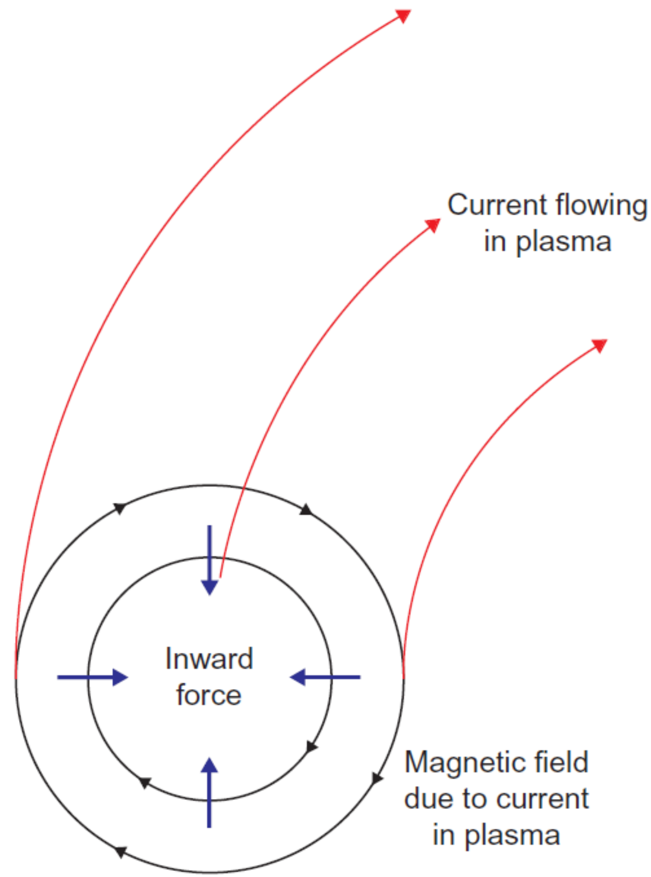


Curvature drift + grad-B drift ⇨ ExB drift

Pinch effect

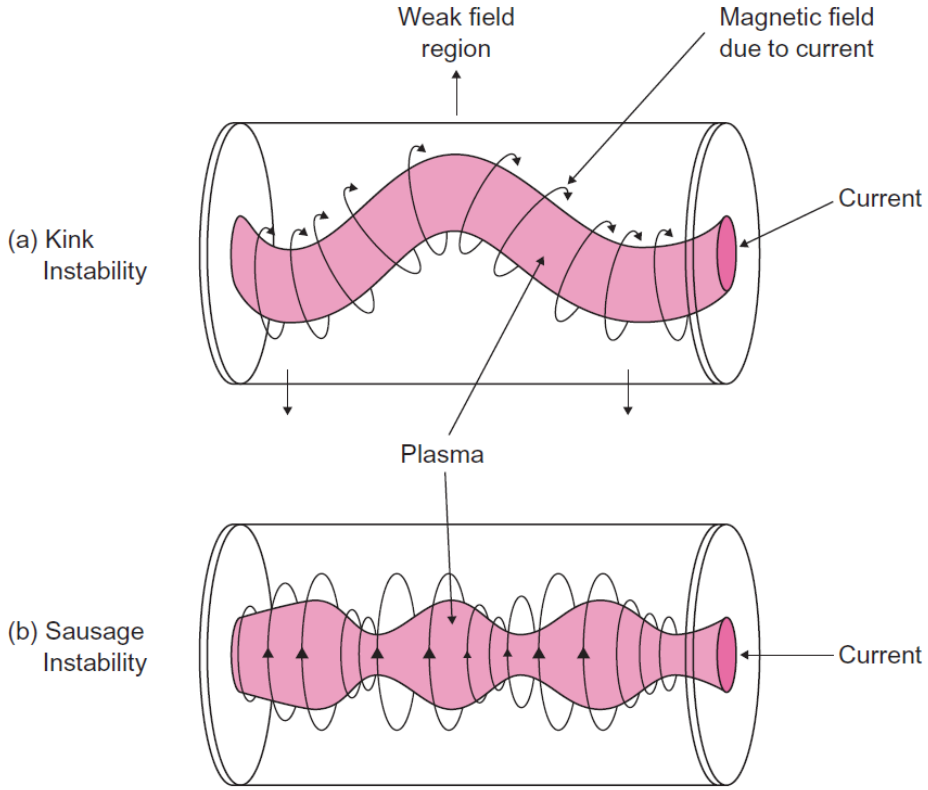
- A pinch is the compression of an electrically conducting filament by magnetic forces. The conductor is usually a plasma, but could also be a solid or liquid metal. Pinches were the first type of device used for controlled nuclear fusion.

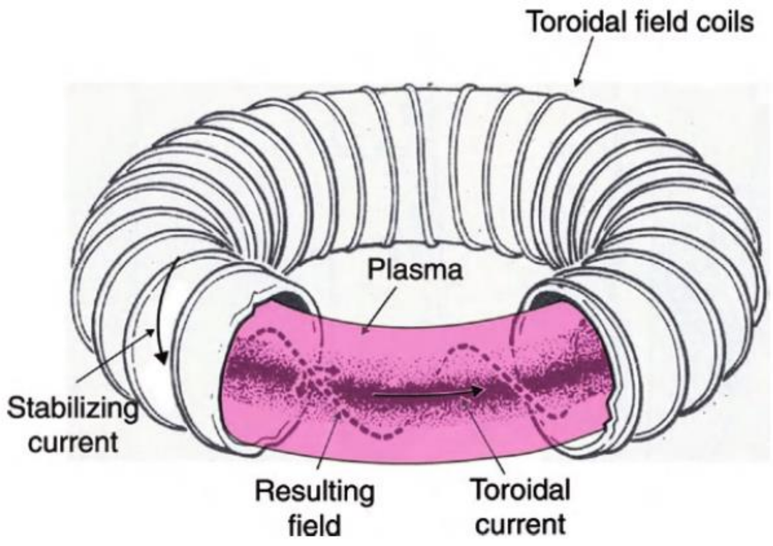




Toroidal pinch

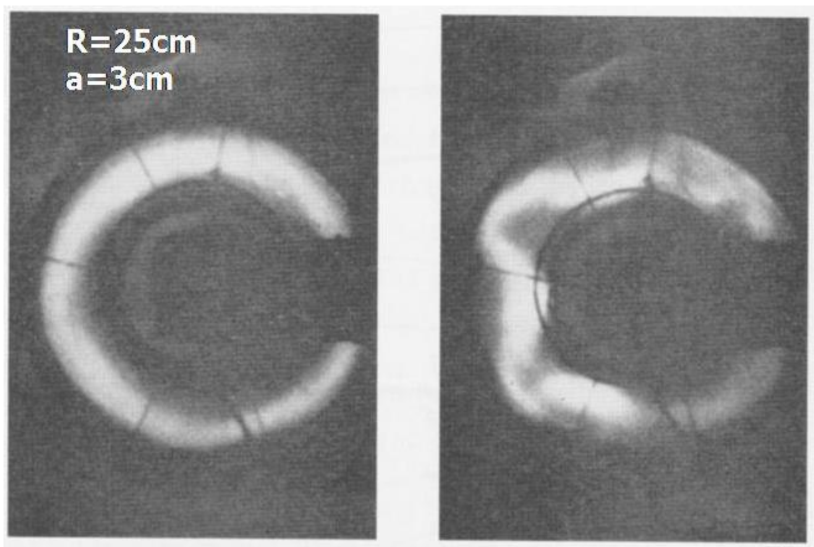
- Two magnetic fields are applied to suppress instabilities: a poloidal field generated by the current flowing around in the plasma and a toroidal field produced by the external coils. The poloidal field is much stronger than the toroidal field. The combined field twists helically around the torus.

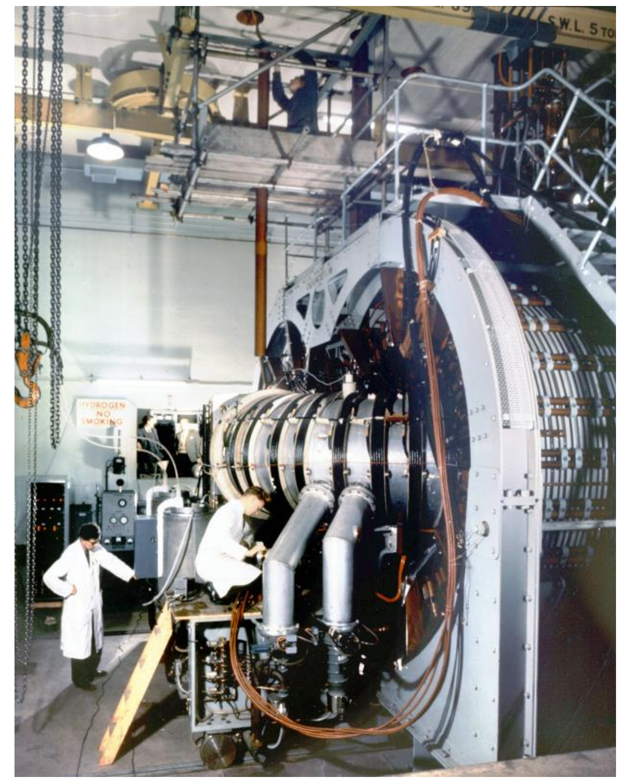




Zeta (UK, 1957)

- ZETA (Zero Energy Thermonuclear Assembly) was a major experiment in the early history of fusion power research. Based on the pinch plasma confinement technique, and built at the Atomic Energy Research Establishment in England, ZETA was larger and more powerful than any fusion machine in the world at that time.





Harwell's director, John Cockcroft, was less cautious, and at a press conference he was drawn into saying that he was "90% certain" that the neutrons were thermonuclear.
The matter was soon resolved by a series of elegant measurements that showed the neutrons were not thermonuclear.

Stellarator

- At Princeton University in New Jersey, astrophysicist Lyman Spitzer invented a plasma-confinement device that he called the stellarator.
- Unlike the pinch, where the magnetic field was generated mainly by currents flowing in the plasma itself, the magnetic field in the stellarator was produced entirely by external coils. → continuous operation
- It is still considered to have the potential to be the confinement system for a fusion power plant, and active research on stellarators is being pursued in some fusion laboratories (LHD, W7-X).

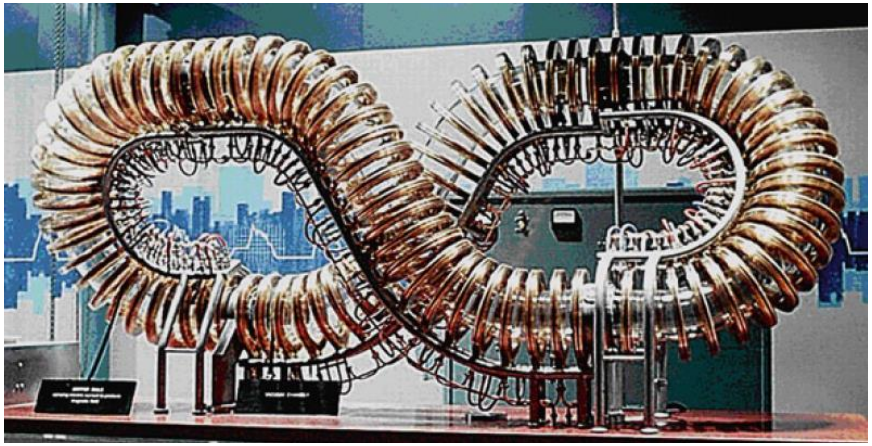
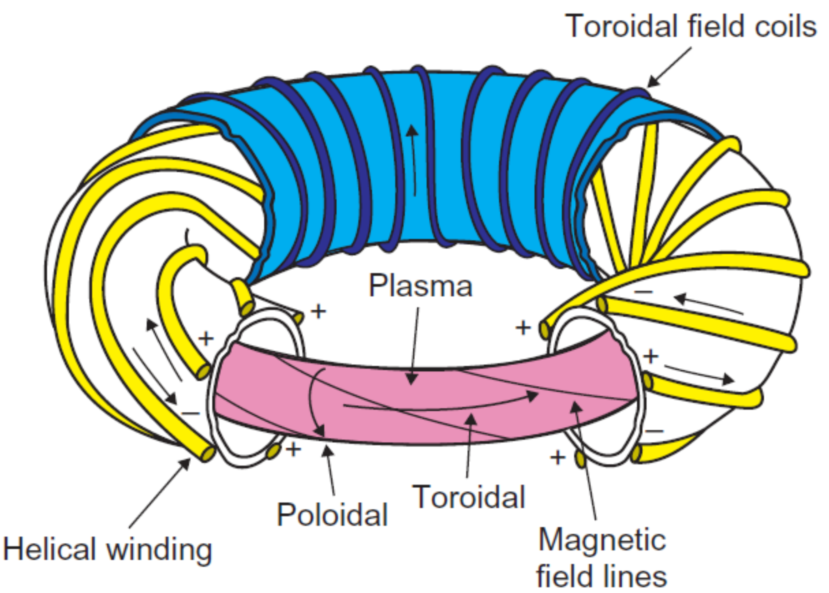


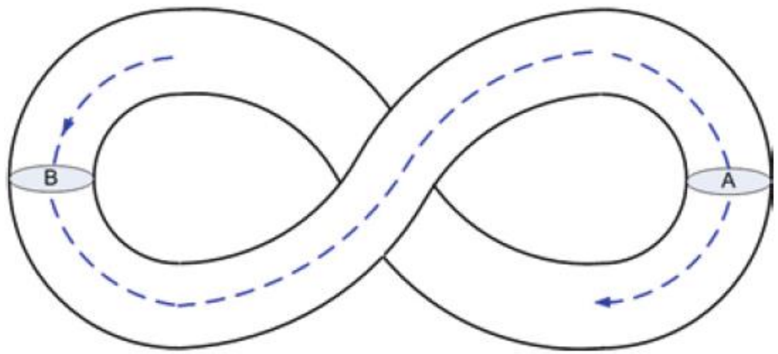
Figure 8 configuration

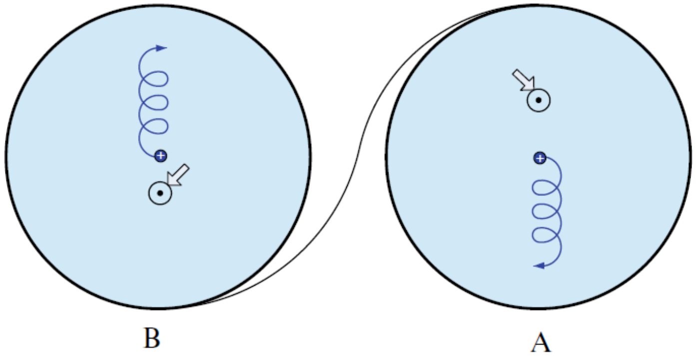


Addition of helical winding

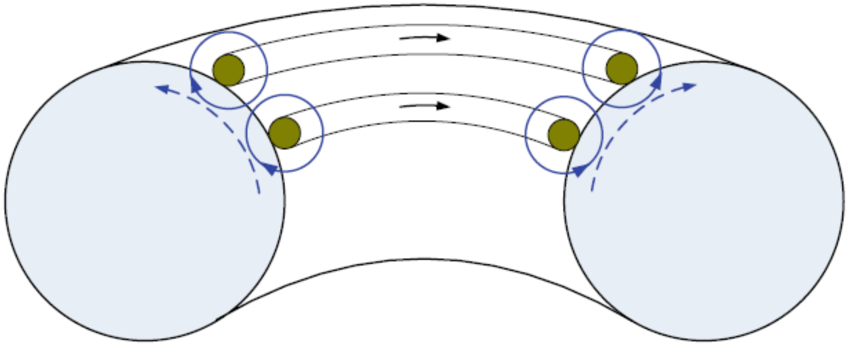
Stellarator: canceling particle drifts

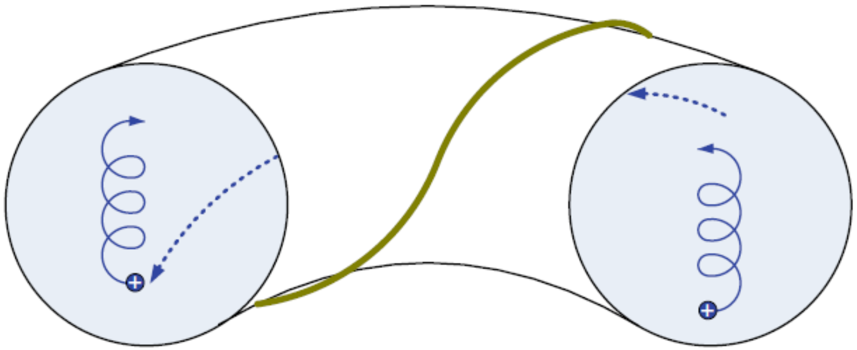
- Figure-8 torus





- Helical winding



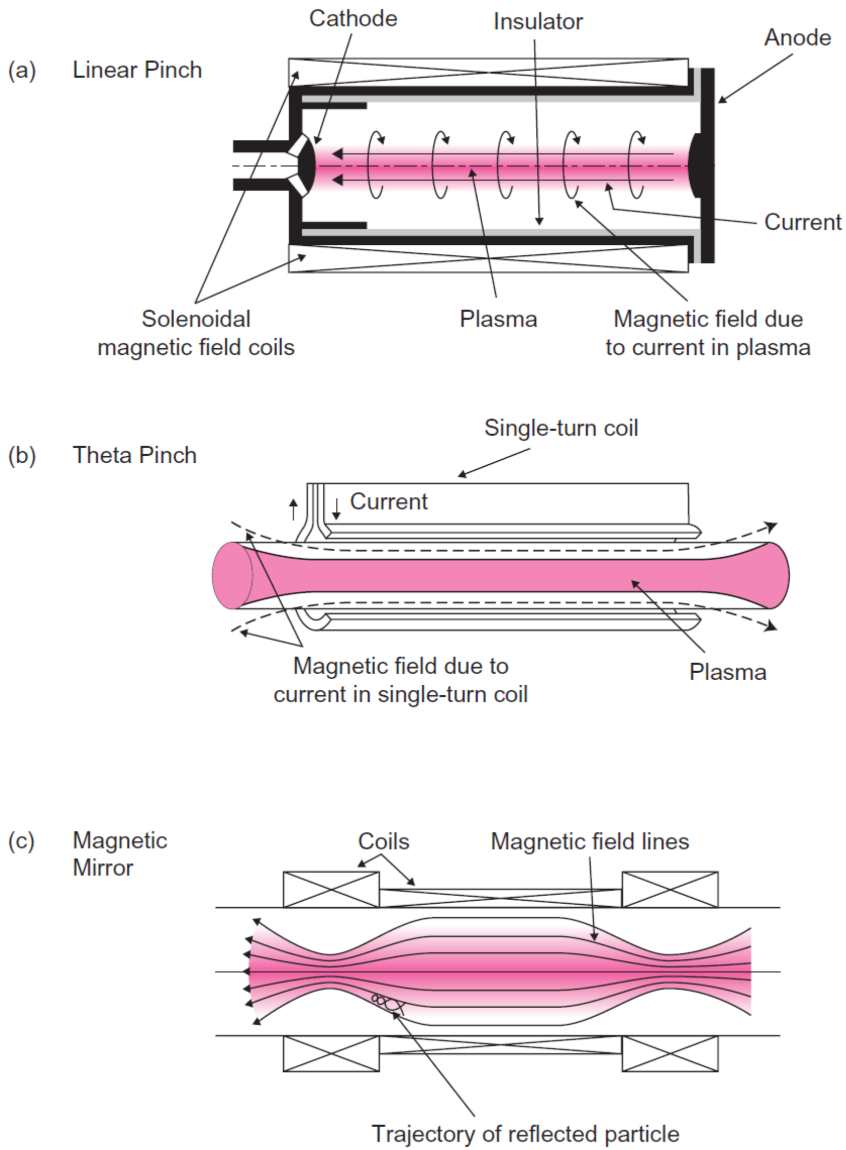


Linear magnetic configurations

a. In the linear Z-pinch, a plasma current flowing along the axis between two end electrodes produces an azimuthal magnetic field that compresses (or pinches) the plasma away from the walls.

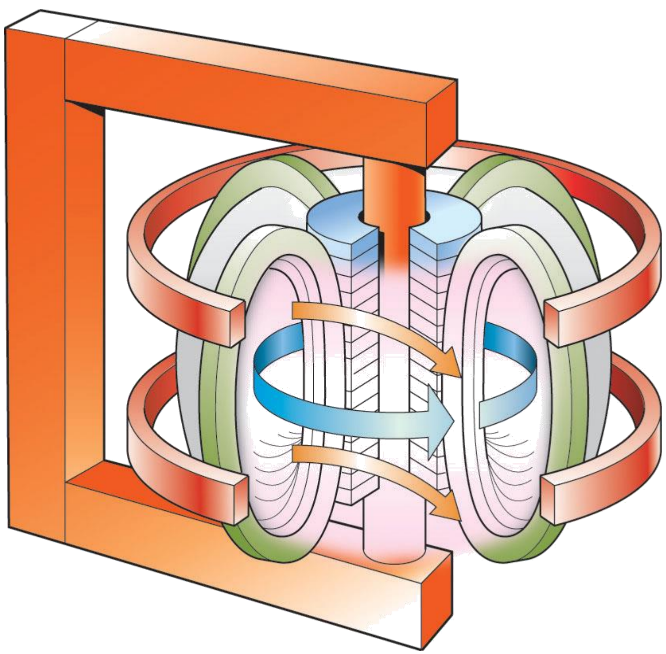
b. The theta pinch is generated by a fast-rising azimuthal current in a single turn external conductor that is wrapped around the plasma tube.

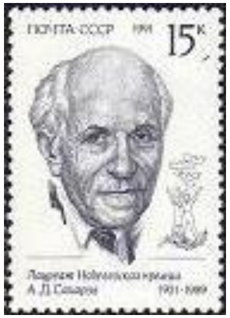
c. A solenoid coil produces a steady-state axial magnetic field that increases in strength at the ends. These regions of higher field, the magnetic mirrors, serve to trap the bulk of the plasma in the central lower field region of the solenoid, although ions and electrons with a large parallel component of velocity can escape through the mirrors.



Tokamak

- The name tokamak comes from the Russian words toroidalnaya kamera magnitnaya katushka meaning “toroidal chamber magnetic coils.”
- It was developed by a team led by Academician Lev Artsimovich on an idea of Andrei Sakharov and Igor Tamm in 1952.
- This device was unveiled at the 1958 Geneva Conference. The tokamak turned out to be the one that worked the best and is the leading type of magnetic plasma container today.





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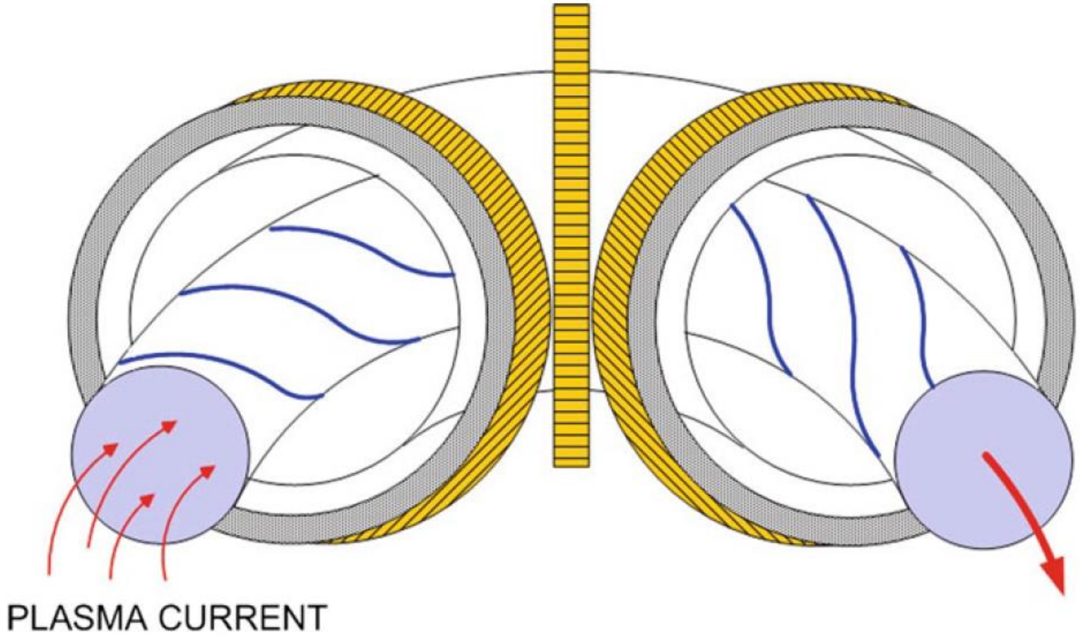
Tokamak

- A strong field in the toroidal direction is created by external coils (TF coils, toroidal field coils).
- A toroidal current is driven through the plasma inside this surface, and this creates a poloidal field, which adds to the toroidal field to form a twisted helical field.
- Depending on how much current there is inside each magnetic surface, the amount of twist differs from one surface to the next, and so the field is also sheared to prevent instabilities.

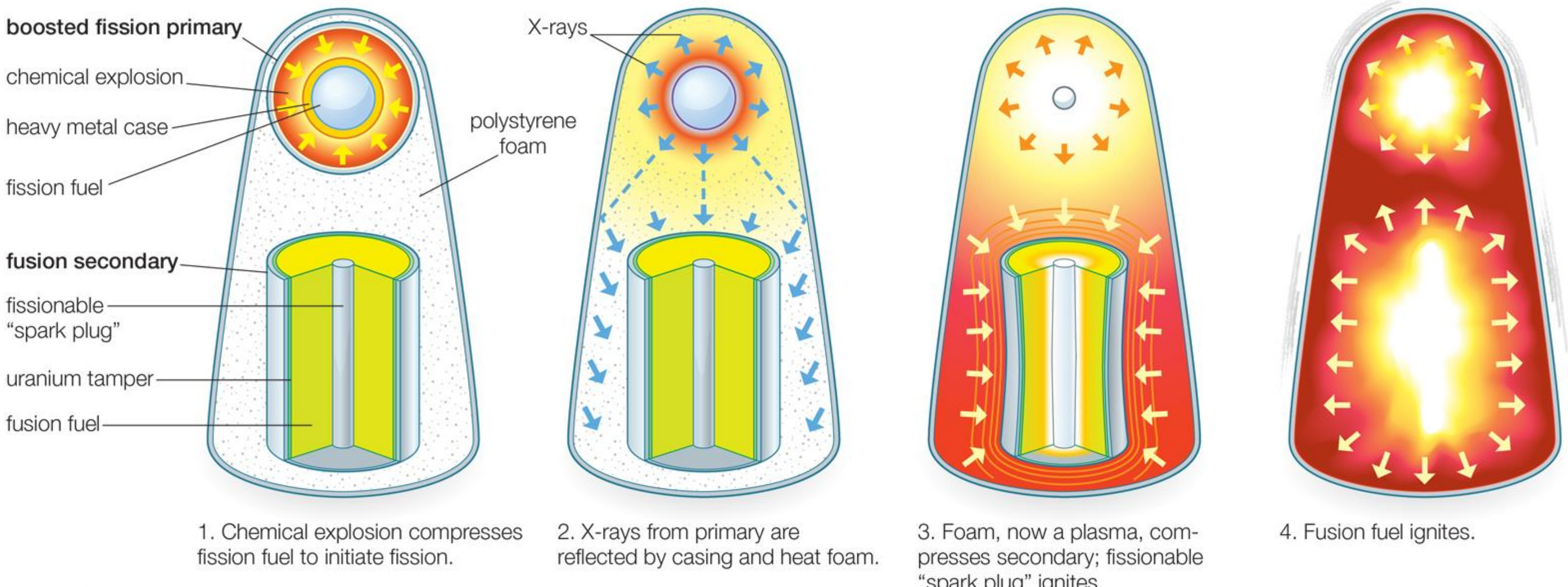


The hydrogen bomb

- Even as early as 1941, before he had built the very first nuclear (fission) reactor in Chicago, the physicist Enrico Fermi speculated to Edward Teller that a fission bomb might be able to ignite the fusion reaction in deuterium in order to produce an even more powerful weapon—this became known as the hydrogen bomb, or H-bomb.

- Teller-Ulam configuration (1951)

Teller-Ulam two-stage thermonuclear bomb design



Inertial confinement fusion (mini-explosion)

- The inertial-confinement route to controlled-fusion energy is based on the same general principle as that used in the hydrogen bomb—fuel is compressed and heated so quickly that it reaches the conditions for fusion and burns before it has time to escape. The inertia of the fuel keeps it from escaping—hence the name inertial-confinement fusion (ICF).

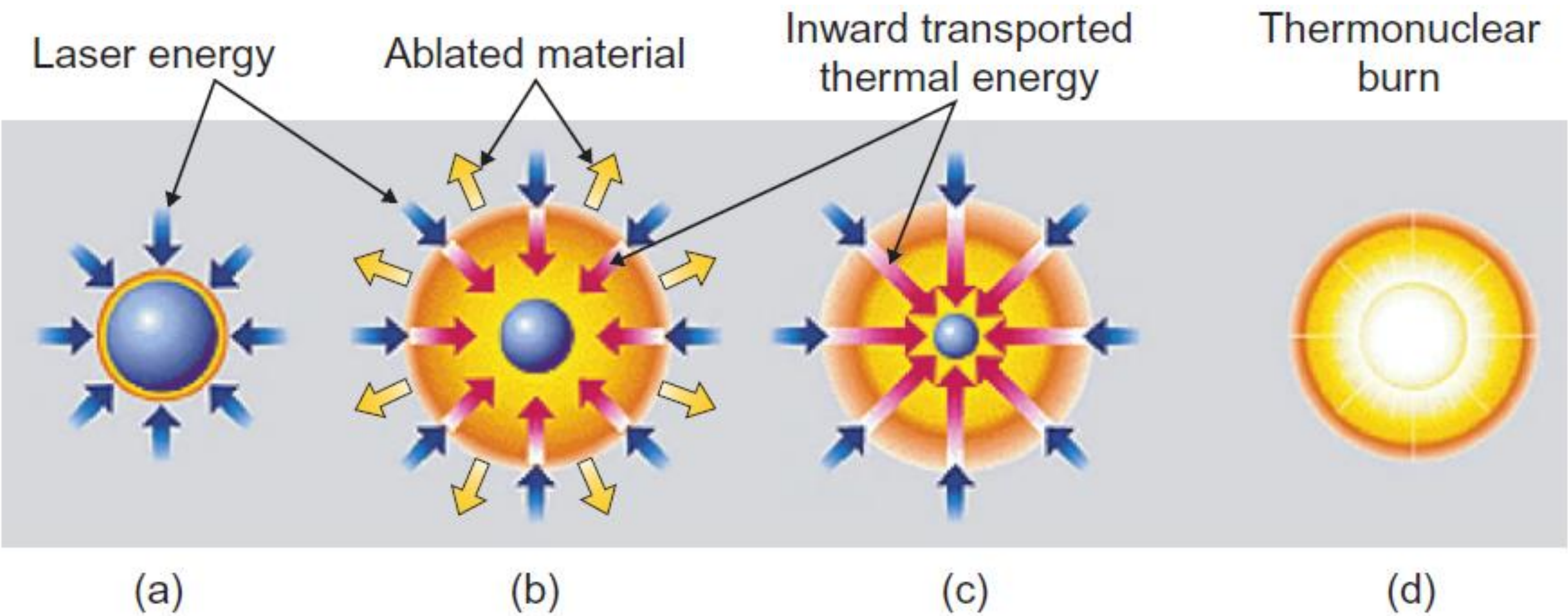


FIGURE 7.1 The four stages of a fusion reaction in an inertial-confinement capsule: (a) Laser heating of the outer layer. (b) Ablation of the outer layer compresses the capsule. (c) The core reaches the density and temperature for ignition. (d) The fusion reaction spreads rapidly through the compressed fuel.

Conditions for inertial confinement

- The conditions required for ICF are determined by the requirement that the fusion energy produced in one pulse has to be larger than the energy required to heat the fuel to the ignition temperature. For breakeven,

$$\frac{1}{4}n^2 < \sigma v > \times (17.6\times 10^3)\times k \times \varepsilon \times \tau > 3nkT$$

Overall efficiency of converting fusion energy in the form of heat into effective capsule heating (ε)

Pulse duration (capsule burn time) (τ)

$$n\tau > (6.82\times 10^{-4})\frac{T\ (\mathrm{keV})}{<\sigma v>\ (\mathrm{m^3 s^{-1}})}\varepsilon^{-1}\quad [\mathrm{m^{-3}s}]$$

$\tau = r/4v_i \qquad v_i = (2\times 10^5)T^{0.5}\ \mathrm{m^3 s}$

$\approx 2.1\times 10^{23}\ \mathrm{keV^{1.5}m^{-3}s}\ @T\approx 20\ \mathrm{keV}$

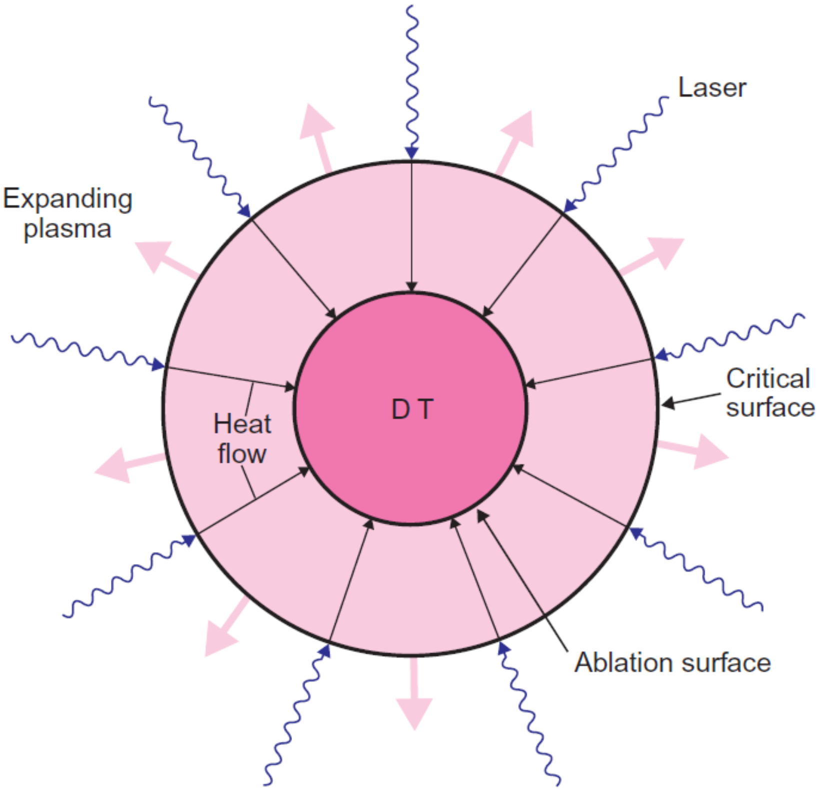
$$nr > 545\frac{T^{1.5}\ (\mathrm{keV})}{<\sigma v>\ (\mathrm{m^3 s^{-1}})}\varepsilon^{-1}\quad [\mathrm{m^{-2}}]$$

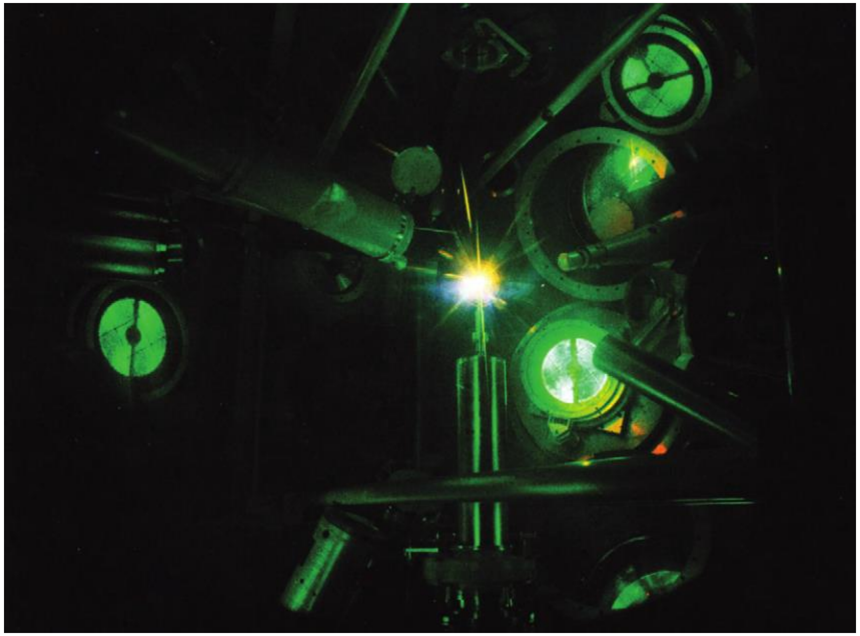
\+ $\rho = (4.18\times 10^{-27})\times n\ \ \mathrm{kg\,m^{-3}}$

⇨ $$\rho r > 0.48\,\varepsilon^{-1}\quad [\mathrm{kg\,m^{-2}}]\quad (\text{or } 0.04\,\varepsilon^{-1}[\mathrm{g\,cm^{-2}}])$$

Using lasers

- The development of the laser suggested a method of compressing and heating fuel capsules on a sufficiently fast time scale. A laser is a very intense light source that can be focused down to a small spot size and turned on for just the right length of time to compress and heat the capsule.

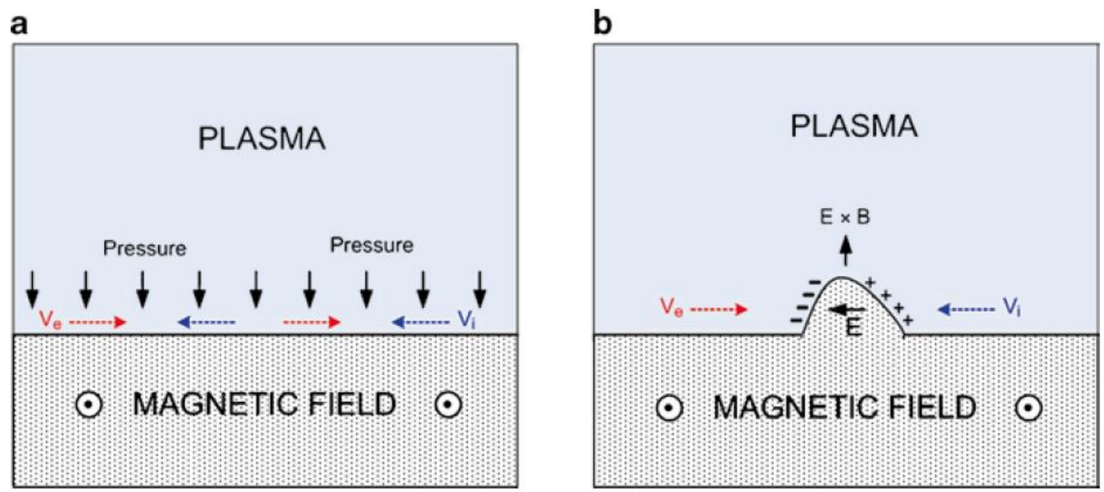




NOVA facility (LLNL)

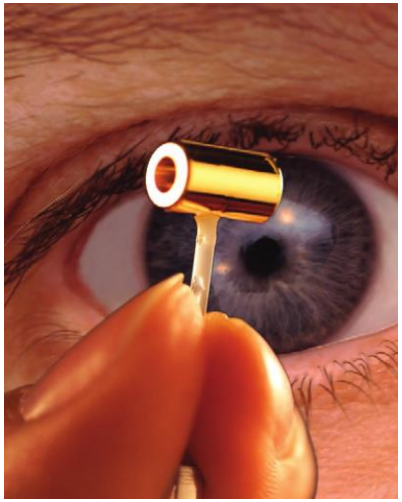
Rayleigh-Taylor instability

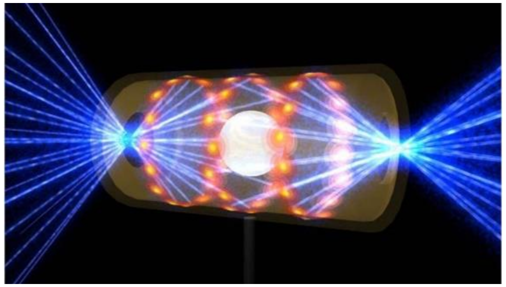
- It occurs at the boundary between two fluids of different density and can be observed if a layer of water is carefully floated on top of a less dense fluid, such as oil. As soon as there is any small disturbance of the boundary between the water and the oil, the boundary becomes unstable and the two fluids exchange position so that the less dense oil floats on top of the denser water.
- A similar effect causes the compressed capsule to distort unless its surface is heated very uniformly. A uniformity of better than 1% is called for, requiring many separate laser beams, each of which has to be of very high optical quality, uniformly spaced all around the surface of the capsule.

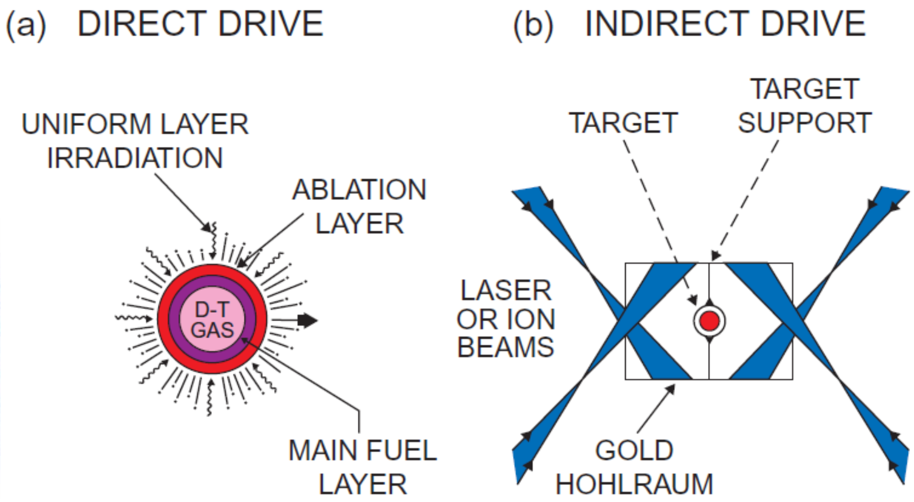


Indirect drive

- An ingenious way of obtaining a high degree of uniformity was developed at Livermore around 1975.
- The laser beams are focused through holes onto the interior surfaces of a hohlraum (German, cavity) rather than directly onto the capsule. The intense laser energy evaporates the inner surface of the cavity, producing a dense metal plasma. The laser energy is converted into X-rays, which bounce around inside the hohlraum, being absorbed and reemitted many times, rather like light in a room where the walls are completely covered by mirrors. The bouncing X-rays strike the capsule many times and from all directions, smoothing out any irregularities in the original laser beams.

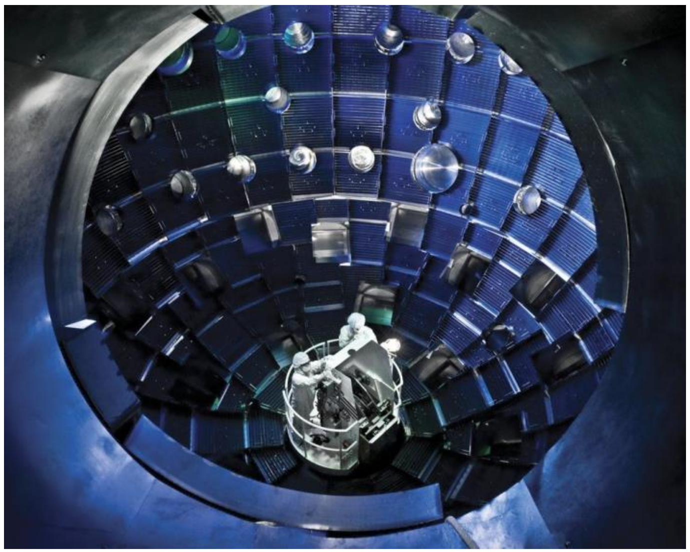


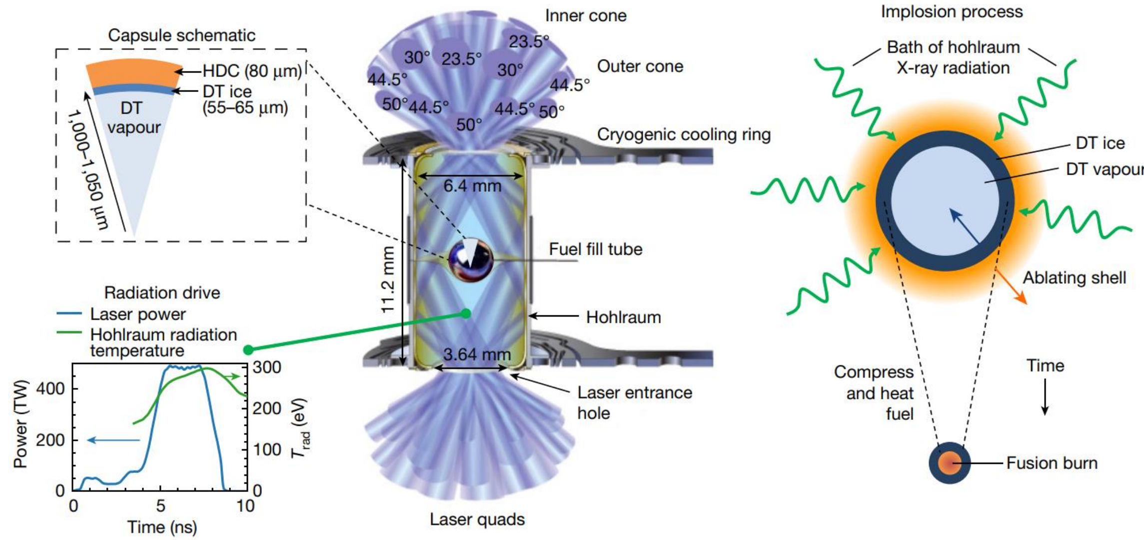




NIF (LLNL)

- NIF is the world's most precise and reproducible laser system. It precisely guides, amplifies, reflects, and focuses 192 powerful laser beams into a target about the size of a pencil eraser in a few billionths of a second, delivering more than 2 MJ of ultraviolet energy and 500 TW of peak power.

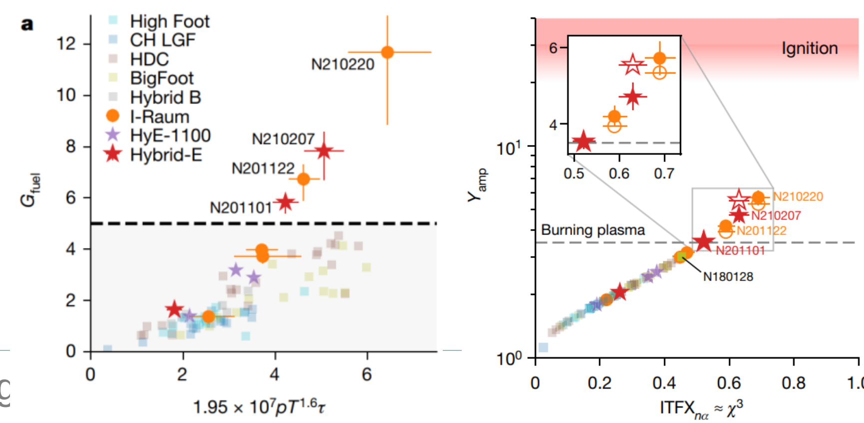




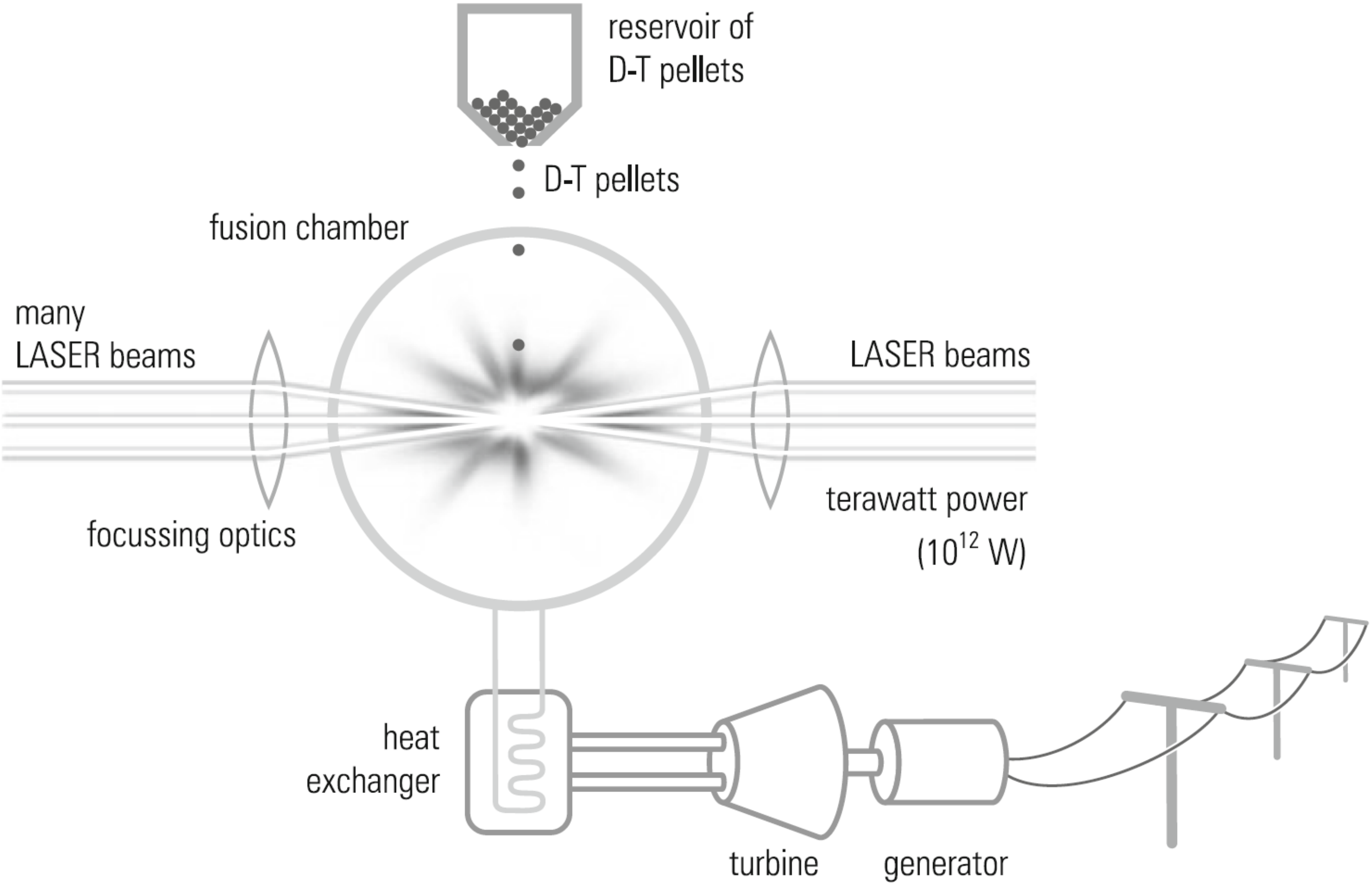
Article

Burning plasma achieved in inertial fusion

542 | Nature | Vol 601 | 27 January 2022



Concept of a power plant based on inertial fusion



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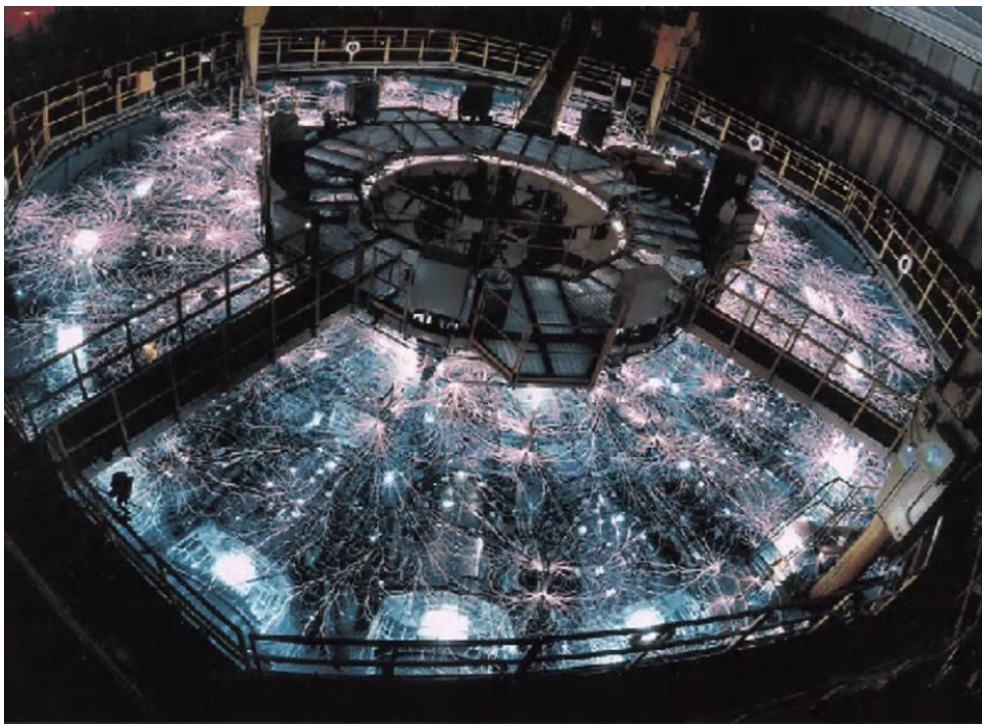
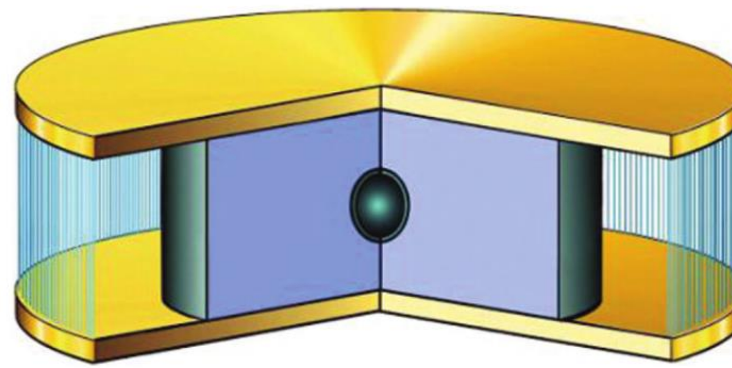
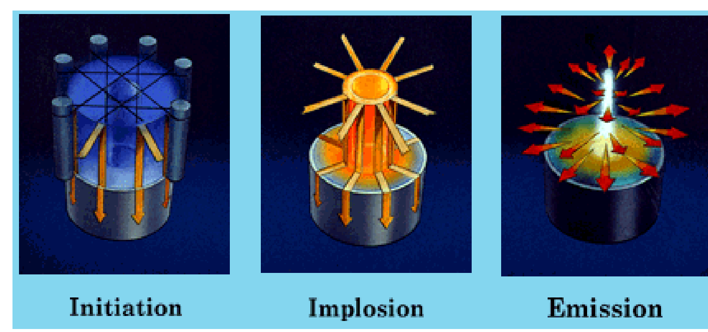
Dynamic z-pinch

- The tungsten wire array surrounds a high-gain ICF capsule in a block of low-density plastic foam. The imploding wire array forms a metal plasma shell that acts as the hohlraum wall, trapping the X-ray radiation that is formed when the plasma interacts with the foam and ablates the outer shell of the capsule.

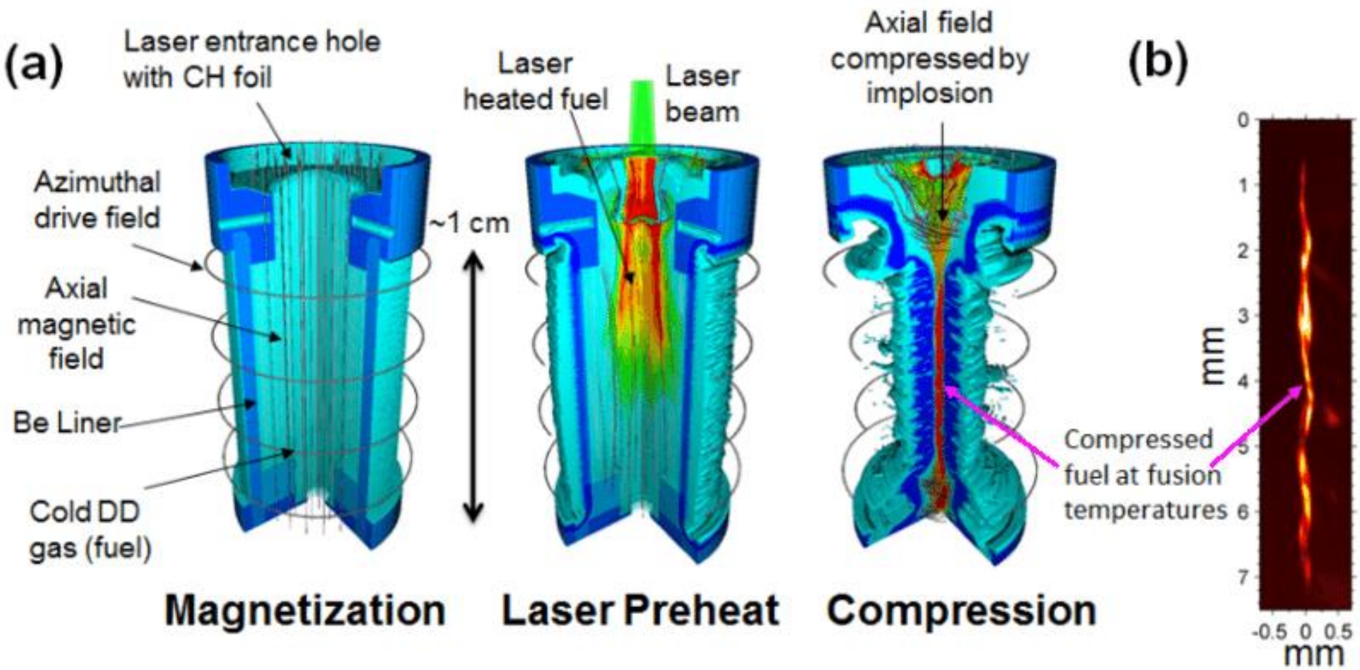


Z facility (SNL)





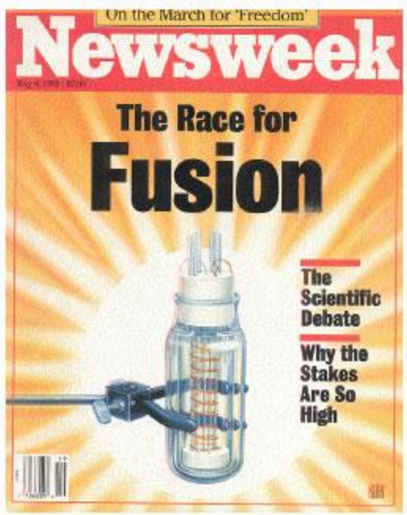
MagLIF (magnetized linear inertial fusion)

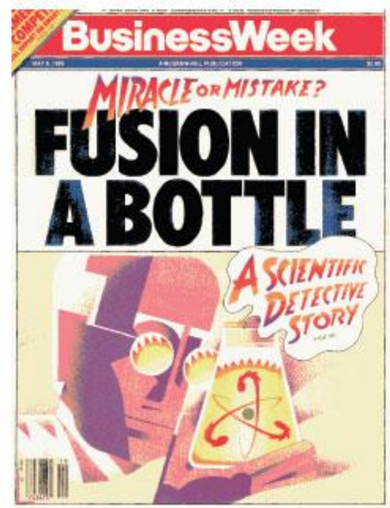


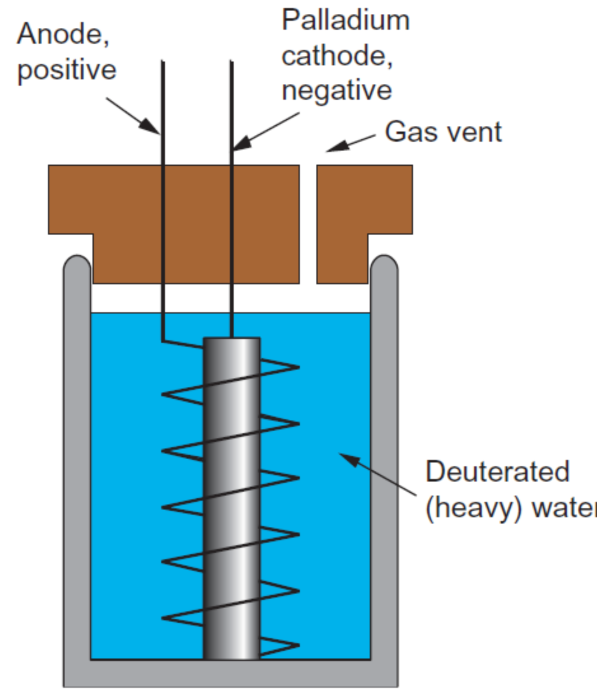
1. A large electrical current causes the shell to implode and compress the deuterium fuel contained within the shell. An axial magnetic field (vertical grey lines) helps keep the fuel hot during compression.
2. A laser quickly heats and ionizes the fuel into a plasma state just as the implosion begins.
3. The liner then implodes, which compresses and further heats the fuel to fusion relevant temperatures (above 10 million degrees) and densities (above 1 g/cm^3).

Cold fusion

- The world was taken by surprise in March 1989 when Stanley Pons and Martin Fleischmann held a press conference at the University of Utah in Salt Lake City to announce that they had achieved fusion at room temperature “in a test tube.”
- In their experiment, deuterated water is contained in a glass vessel into which two metal electrodes are inserted. A current is passed through the water, and the deuterium is ionized and accumulates at the palladium cathode. It was claimed that energy was released from the cathode due to the occurrence of fusion reactions in it.







Bubble fusion (sonofusion)

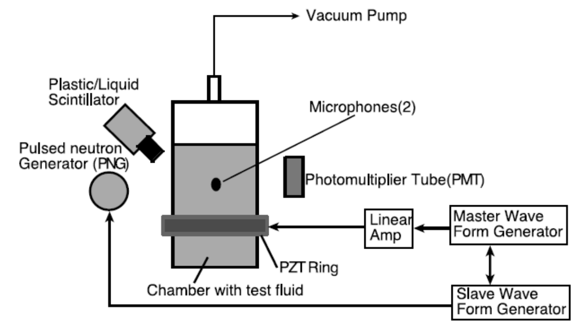
- In 2002, Rusi Taleyarkhan and colleagues at the Oak Ridge National Laboratory in the US claimed to have produced nuclear fusion in sonoluminescence experiments.
- They created very small bubbles (10 to 100 nm in diameter) in deuterated acetone (C_3D_6O) using 14 MeV neutrons and then applied sound waves that forced the bubbles first to expand to millimeter size and then to collapse. During the collapse, the vapor in the bubble heats up and produces a flash of light. It had also been speculated that nuclear fusion might be induced.

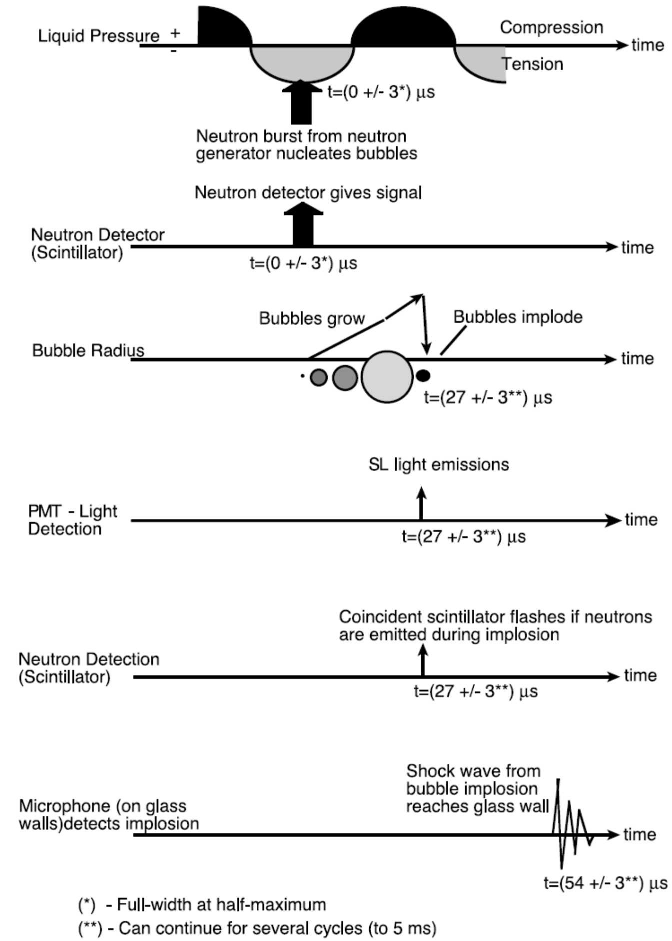
Evidence for Nuclear Emissions During Acoustic Cavitation

R. P. Taleyarkhan,[1*] C. D. West,[1†] J. S. Cho,[2] R. T. Lahey Jr.,[3] R. I. Nigmatulin,[4] R. C. Block[3†]

Science 08 Mar 2002:
Vol. 295, Issue 5561, pp. 1868-1873
DOI: 10.1126/science.1067589

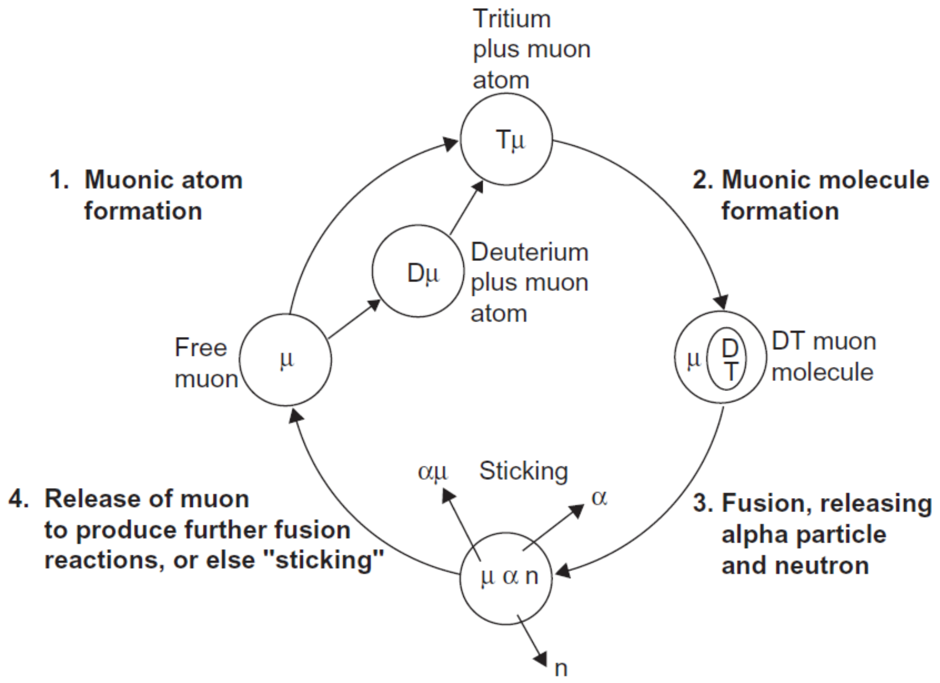
Fig. 1. Schematic of the experimental setup. The distance from the scintillator head to the PNG is ~15 cm; from the scintillator head to the chamber surface, ~0 to 2 cm; from the chamber center to the PNG, ~20 cm; and from the PMT to the chamber surface, ~5 cm. The system (the chamber, PNG, and PMT) is ~1.5 m above the floor.

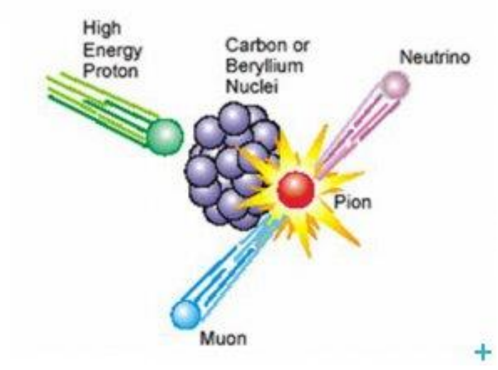




Muon-catalyzed fusion

- In 1947, Charles Frank at Bristol University, UK realized that it would be possible to substitute a muon for the electron in a hydrogen or deuterium atom.
- According to the rules of quantum mechanics, the muon would have an orbit around the nucleus with a radius inversely proportional to its mass. The muonic atom would be only 1/207 the size of a normal hydrogen atom. This means that such a muonic deuterium atom could approach very close to another deuterium or tritium atom and have the possibility of fusing and releasing energy.





- 207 times heavier than electron
- Electric charge of -e
- The mean lifetime is 2.2 μs