Nuclear Fusion as a future energy source?

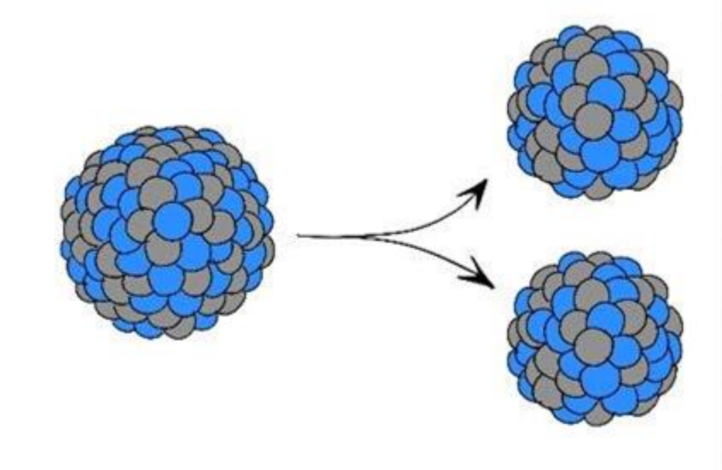
Woo Pok
Man Hei Nok

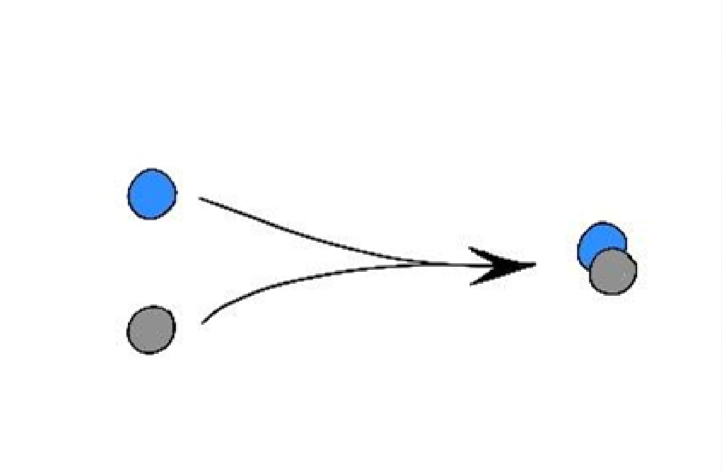
01

Introduction

Nuclear energy

- Nuclear fission
  - Heavy nucleus split into two
  - More radioactive
  - Easier to achieve and sustain
- Nuclear fusion
  - Two light nuclei combine into one
  - More energy density
  - More adequate fuel





Nuclear fusion

- Mostly adopted nuclear fusion equation

$$D + T \rightarrow {}^4_2He + n + 17.6\ MeV$$

- Requires high temperature to overcome strong repulsion (~10^8K)
    - Heat the fuel to become plasma
- Can achieve artificial nuclear fusion, though inefficiently
- Deuterium can be found in heavy water
- Tritium is produced by the process:

$${}^6_3Li + n \rightarrow {}^4_2He + T + 4.8\ MeV$$

02

Theory

Steps of achieving fusion power

Heating

Heat up the fuel to a thermonuclear temperature (in order of 10^8 K)

Confinement

Confine the hot plasma stably

Conversion

Convert the energies to electricity

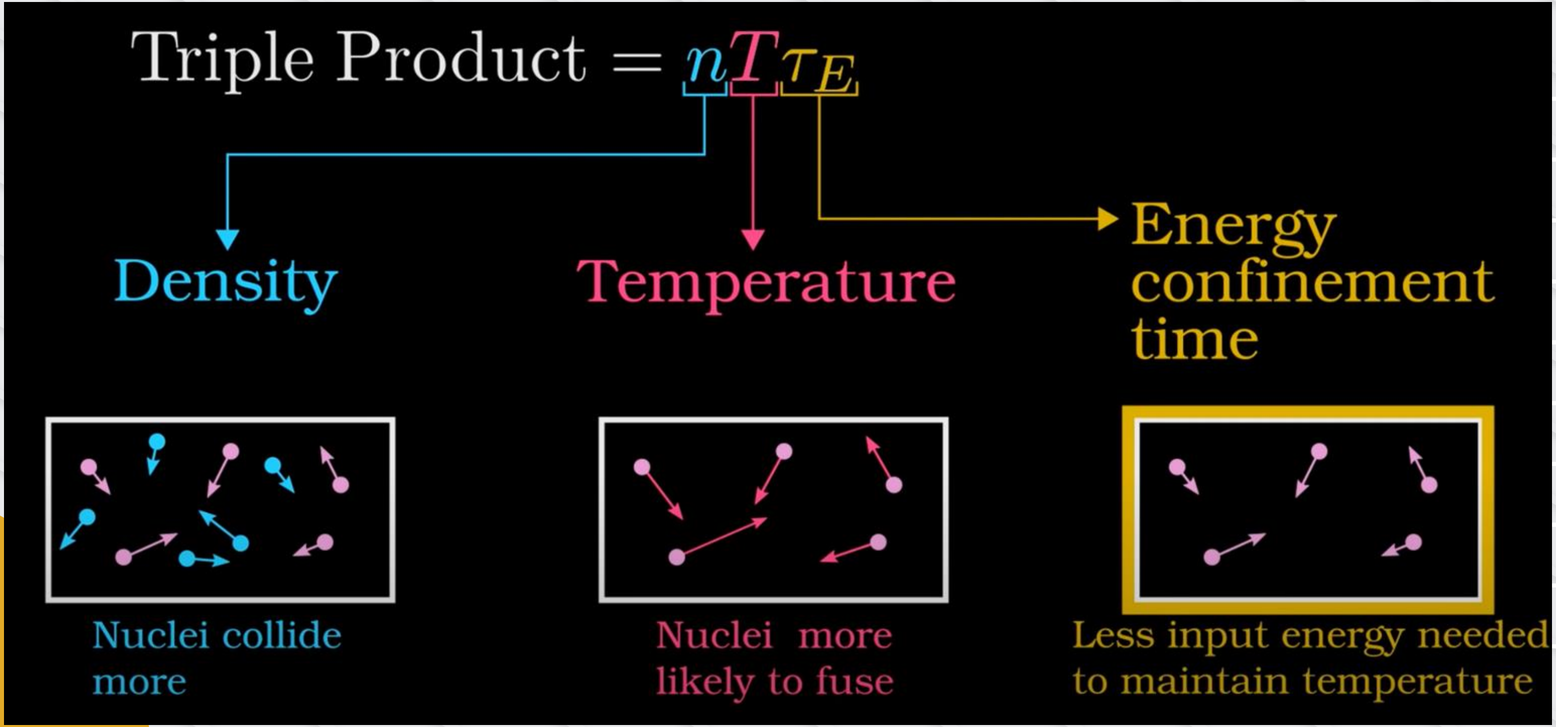
Confinement – the hard one

- Confinement of the hot plasma

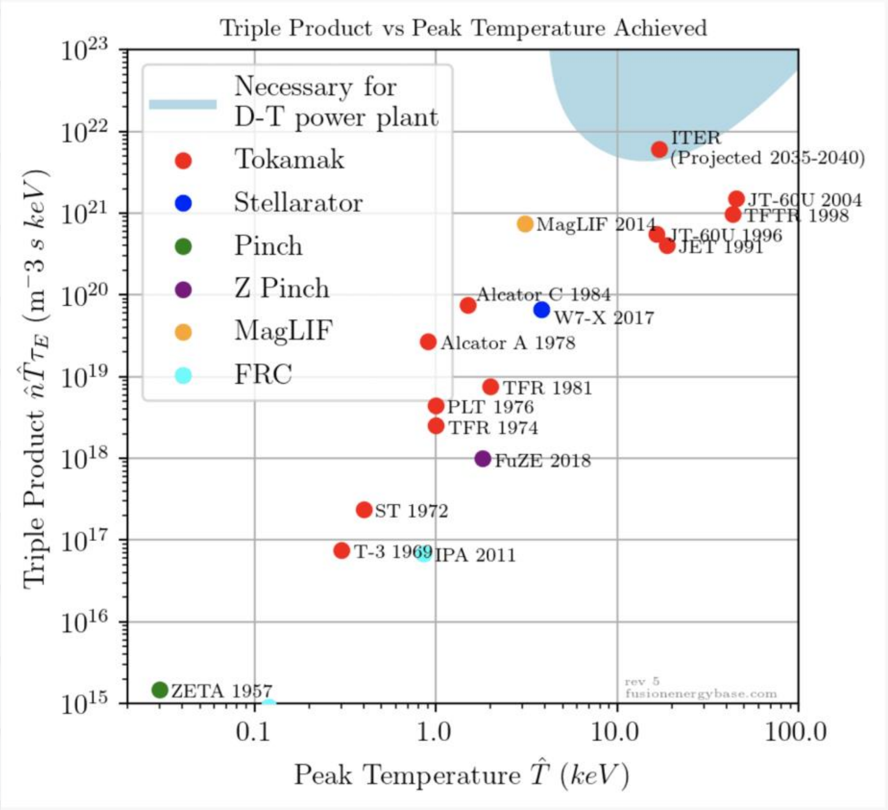
- Hot plasma exerts outside pressure -> disassemble itself
  - Nuclei spread too out to each other
  - Heat conducted to walls and lost

- Hot plasma is unstable
  - Turbulence
  - Bremsstrahlung

The Triple Product



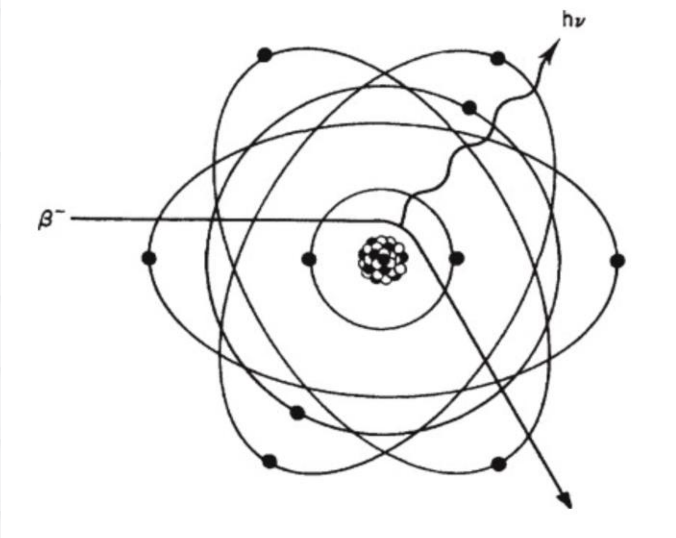
The Triple Product



Bremsstrahlung

- *“Braking radiation”* in German
- Charged particles emit photon when deflected i.e decelerated
    - $hv = E_i - E_f$
- emitted photons usually leave the plasma,

  so as the energies.



1 - NUCLEAR RADIATION, ITS INTERACTION WITH MATTER AND RADIOISOTOPE DECAY, MICHAEL F.L'ANNUNZIATA

Bremsstrahlung

- Bremsstrahlung power density in plasma

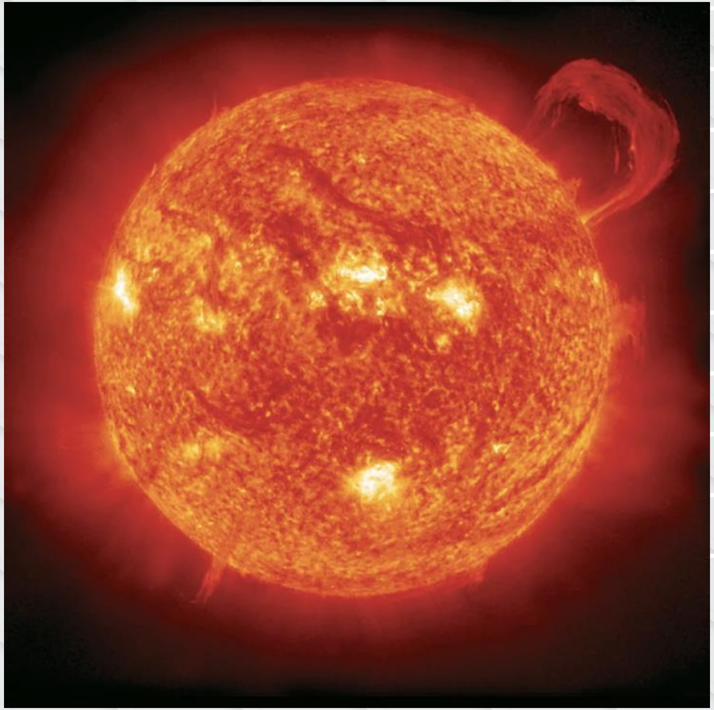
$$P_{\mathrm{Br}}\left[\mathrm{W/m^3}\right] = \frac{Z_i^2 n_i n_e}{\left[7.69 \times 10^{18}\mathrm{m^{-3}}\right]^2} T_e\left[\mathrm{eV}\right]^{\frac{1}{2}} .$$

-
  - $P \propto Z^2$ Charge of the constituent ions
  - $P \propto n_i n_e$ Number density of electrons and ions
  - $P \propto T_e$ Temperature

How the sun works

- Sun is massive and huge
  - Gravitational confinement
  - large volume of plasma in a star traps bremsstrahlung

- Hard to be done on earth



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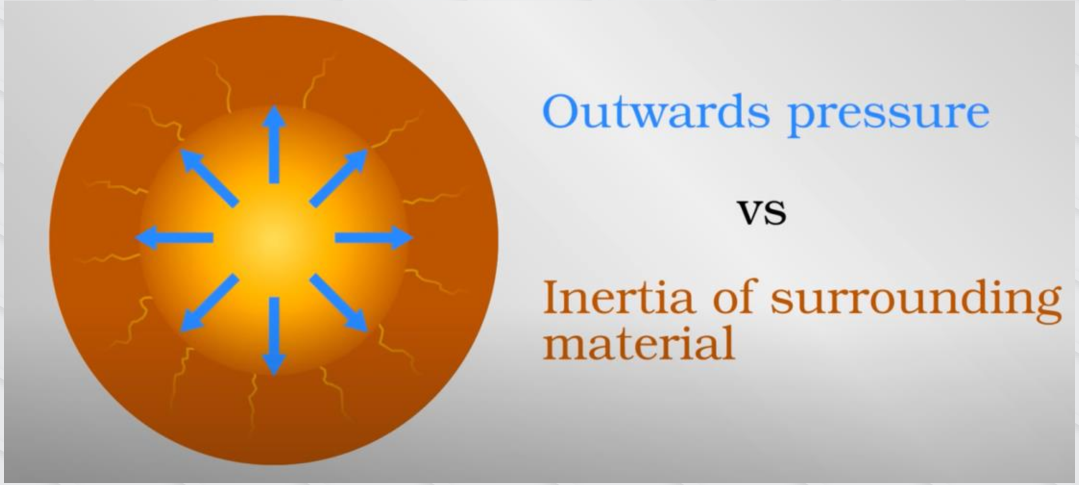
Confinement technics

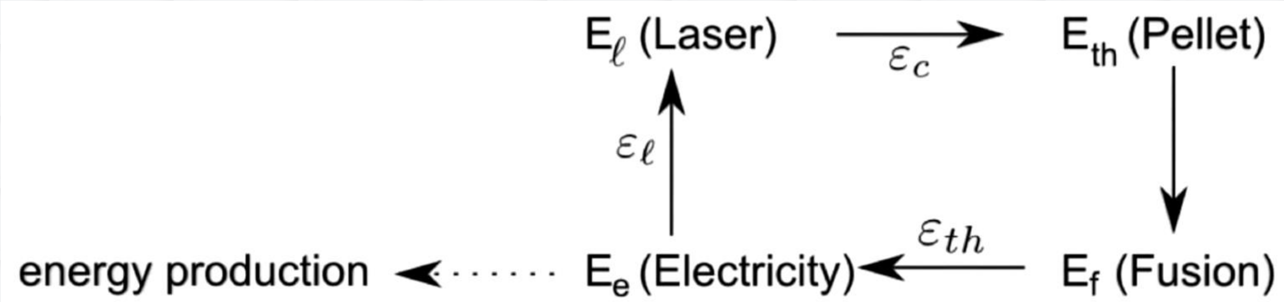
Inertial confinement

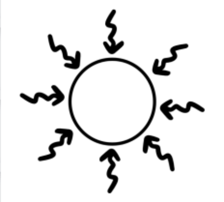
Basic Principle

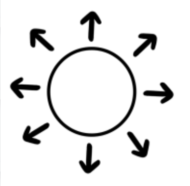
- The inertia of the fuel keeps it from escaping
  - Compressed in dense shell
  - Heated quickly and burns before it has time to escape



Energy Balance







$$E_\ell \simeq \frac{1}{(\varepsilon_\ell \varepsilon_{th})^3 \varepsilon_c^4} \left(\frac{n_0}{n}\right)^2 \text{ in MJ}$$

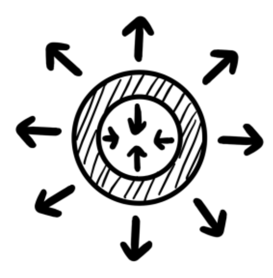
Energy need in driver

$$E_\ell \simeq \frac{1}{(\varepsilon_\ell \varepsilon_{th})^3 \varepsilon_c^4} \left(\frac{n_0}{n}\right)^2 \text{ in MJ}$$

- Take $\varepsilon_c = 0.2$, $\varepsilon_l = 0.08$, $\varepsilon_{th} = 0.4$, $n = n_0$ -> $E_l \sim 10^7$ MJ
  - Where current achieved laser pulse energies < 10 MJ
- Take $\varepsilon_c = 0.2$, $\varepsilon_l = 0.08$, $\varepsilon_{th} = 0.4$, $E_l = 2$ MJ -> $n = 3000\ n_0$
  - Pressure ~ $3000\ n_0 T \sim 2 \times 10^{17}$ N m^{-2}
  - Where current achieved laser pressure ~ 10^{12} N m^{-2}

Rocket effect

- How to boost the pressure?
- Idea: Generate implosion by ablating matter at the pallet surface
  - Rocket effect: Conservation of momentum



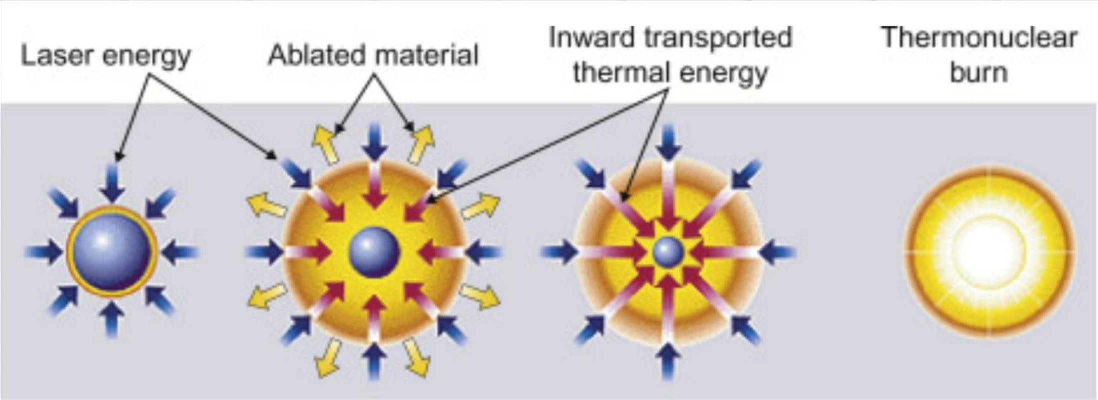
$$F = \frac{P}{S} = \frac{d}{dt}\left(\frac{1}{2}mv^2\right)\frac{1}{S} \approx \frac{1}{2}\frac{v^2}{S}\frac{dm}{dt}$$

$$\Rightarrow \frac{dm}{dt} = \frac{2SF}{v^2}$$

$$P_{rocket} = \frac{\frac{d}{dt}(mv)}{surface} \approx \frac{v\frac{dm}{dt}}{S} = \frac{v}{s}\frac{2SF}{v^2} = \frac{2F}{v}$$

$$\frac{P_{rocket}}{P_{laser}} = \frac{2F}{v}\frac{c}{F} = 2\frac{c}{v} \gg 1$$

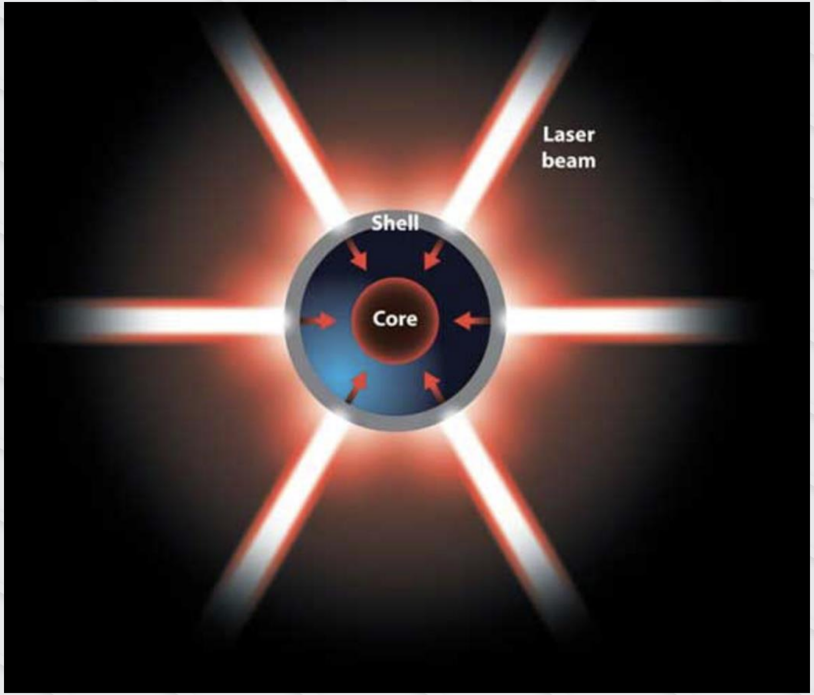
The ICF Sequence



- The laser beam heats the surface and forms a plasma
- Outer material ablates and cause rocket effect
- Implosion compress the core to very high density
- The compressed fuel burns

Driving the pellet - Direct drive

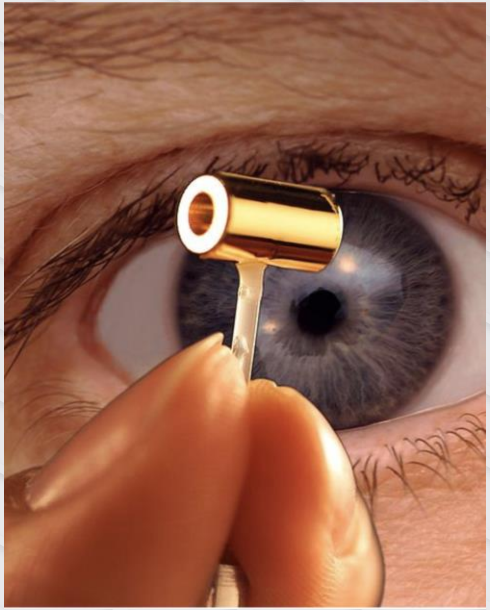
- Pellet directly targeted by hundreds of laser beams
- The beams must be arranged symmetrically

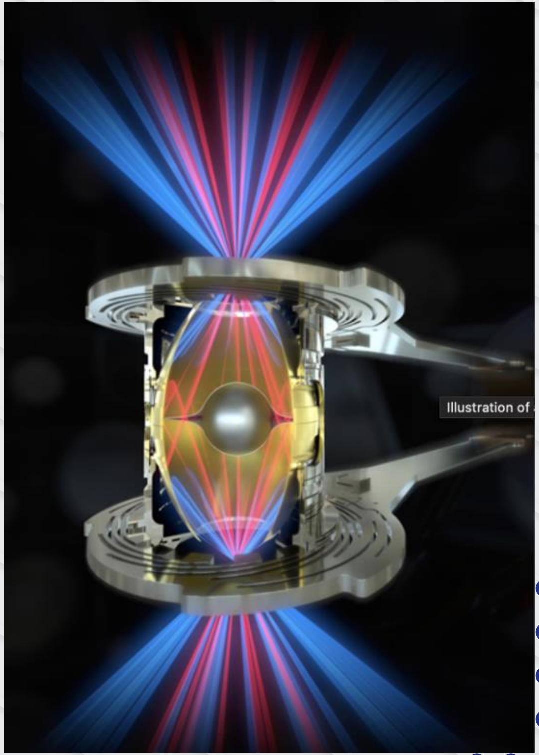


Reports Recommend Stepped-Up U.S. Investment in Fusion Energy - NIF

Driving the pellet - Indirect drive

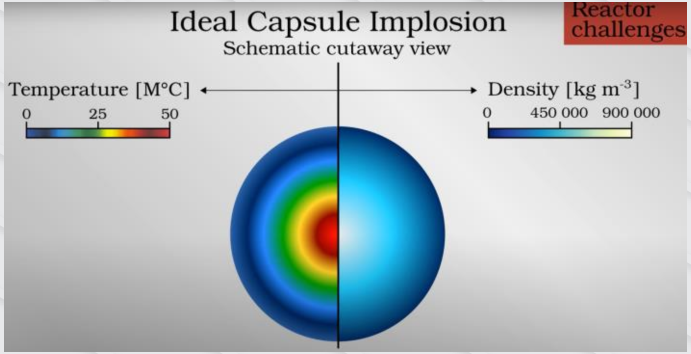
- *Hohlraum*, a very small, little chamber around the pellet
- Receives the laser beams through two holes
- Acts like a black body radiator of x-rays
- The X-ray bath is more symmetric than the lasers

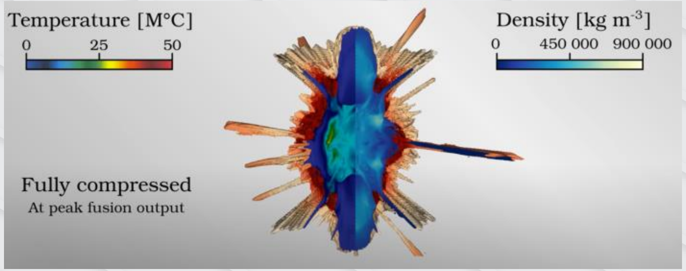




Challenges

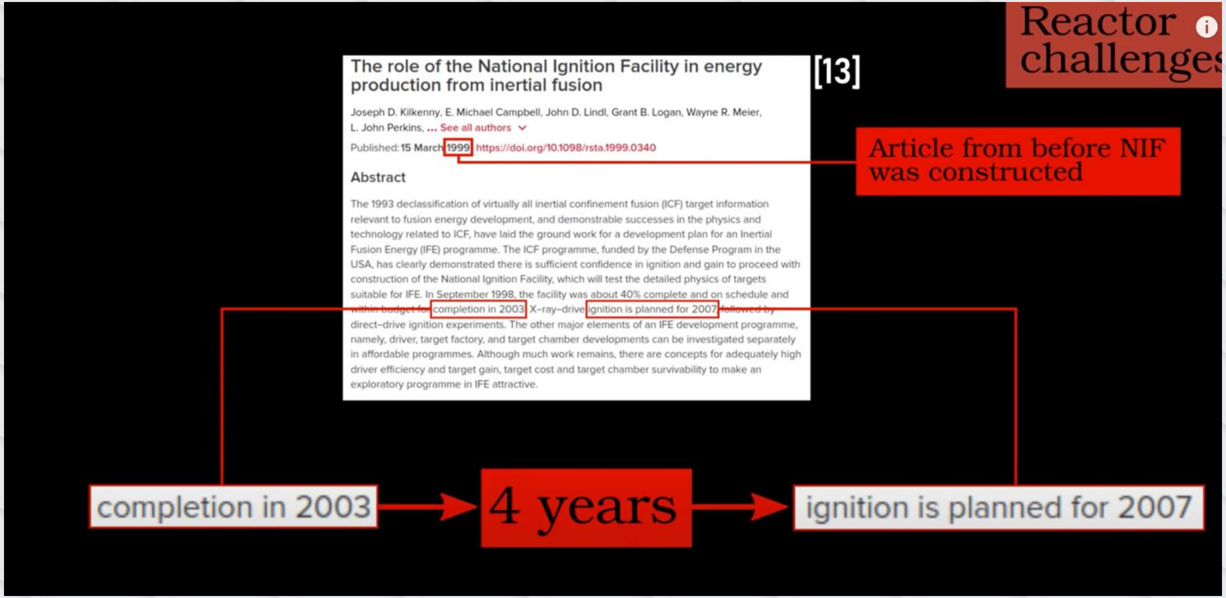
- Plasma Instability
- Rayleigh-Taylor Instability
  - Cannot form a central hotspot
- Bremsstrahlung
- No efficient ignition





Challenges

- Pellets and hohlraum are expensive and run out quickly
- Not economical



04

Confinement technics

Magnetic confinement

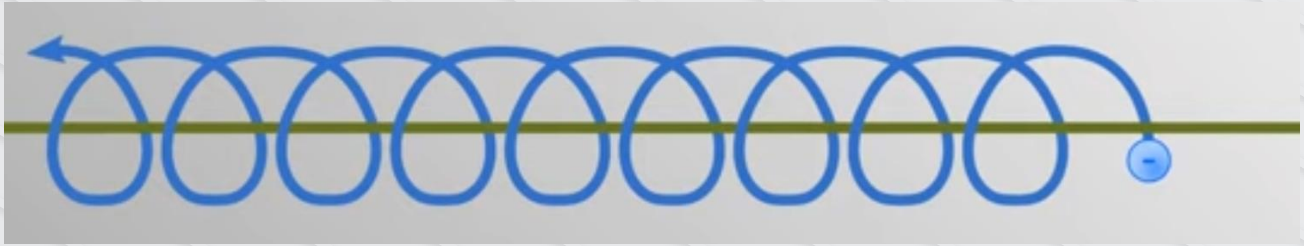
Basic principles

- Magnetic force is a non-contact force
- For charged particles, under B-field, force experienced :

$$m\frac{d\vec{v}}{dt} = q\vec{v} \times \vec{B}$$

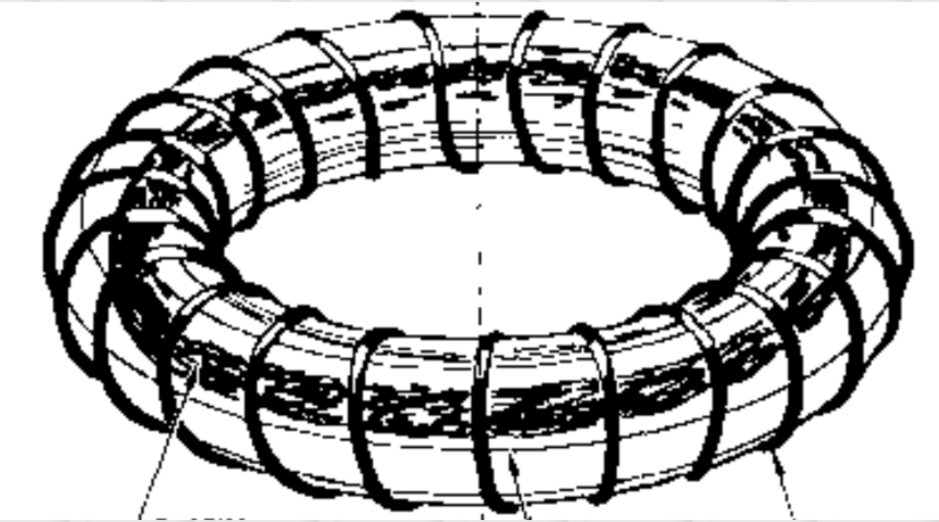
- No work done by B-field
- Helix movement along the B-field line

$$\vec{v} = (v_{\perp}\cos\omega t\,, -v_{\perp}\sin\omega t\,, v_{//})$$



Basic principles

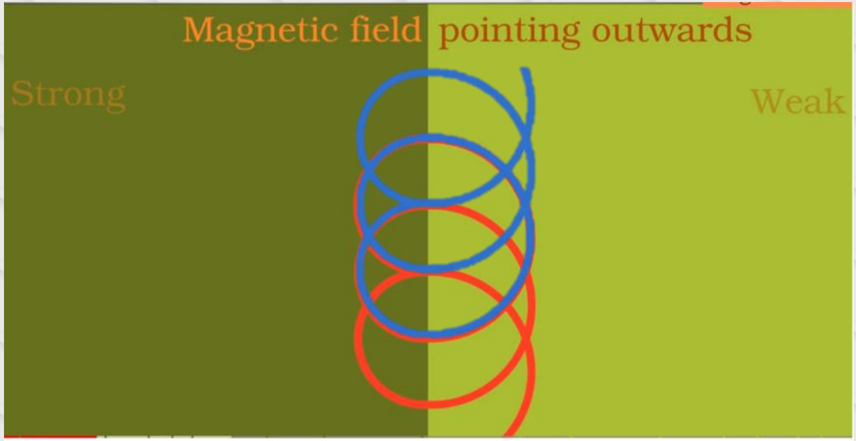
- Torus shape of container is used
- Coils provides (almost) uniform B-field along the z-direction
- Plasma flowing in the torus



The drifting problem

- B-field is not perfectly constant inside the torus
- This cause drifting on charges
- Opposite charges drift to opposite side
- Finally will hit the wall

$$\overrightarrow{V_{\nabla E}} = \frac{mv^2}{2qB}\frac{\vec{B} \times \nabla B}{B^2}$$



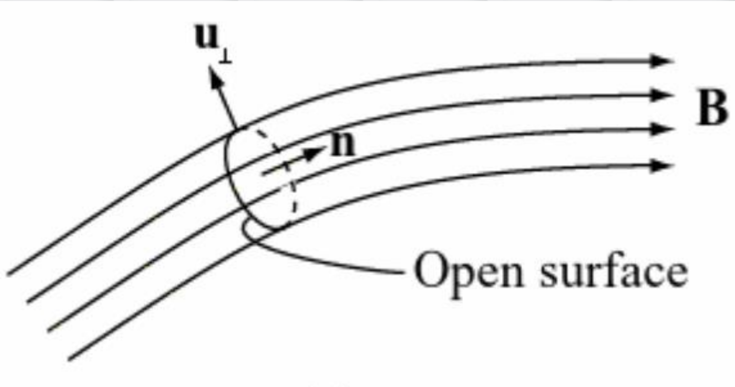
Magnetohydrodynamics problem

- Ions in plasma also create magnetic dipole
- Theoretically, the B-field line is “frozen” into plasma

$$\varphi(t) = \int \vec{B} \cdot \hat{n}\, dS$$

$$\frac{d\varphi}{dt} = \int \frac{\partial \vec{B}}{\partial t} \cdot \hat{n}\, dS + \oint \vec{B} \times \hat{u}_{\perp} \cdot d\vec{L}$$

Boundary moving velocity



Magnetohydrodynamics problem

- By Faraday's Law,

$$\frac{d\varphi}{dt} = -\int \nabla \times \vec{E} \cdot \hat{n}\, dS - \oint \hat{u}_{\perp} \times \vec{B} \cdot d\vec{L}$$

Plasma moving velocity

$$\vec{E} = -\overrightarrow{v_{\perp}} \times \vec{B}$$

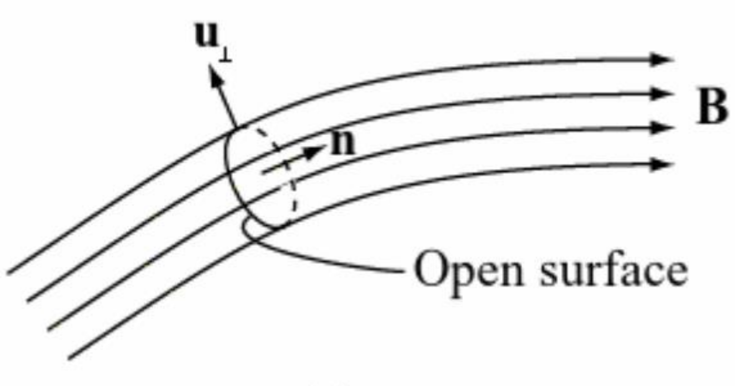
- By Stoke's theorem and setting

$$\frac{d\varphi}{dt} = \oint [(\overrightarrow{v_{\perp}} - \overrightarrow{u_{\perp}}) \times \vec{B}] \cdot d\vec{L} = 0$$

- By conservation law of flux,

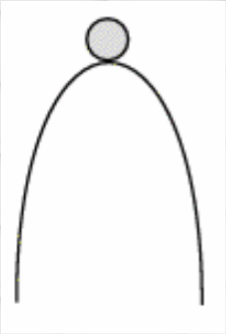
$$\overrightarrow{v_{\perp}} = \overrightarrow{u_{\perp}}$$

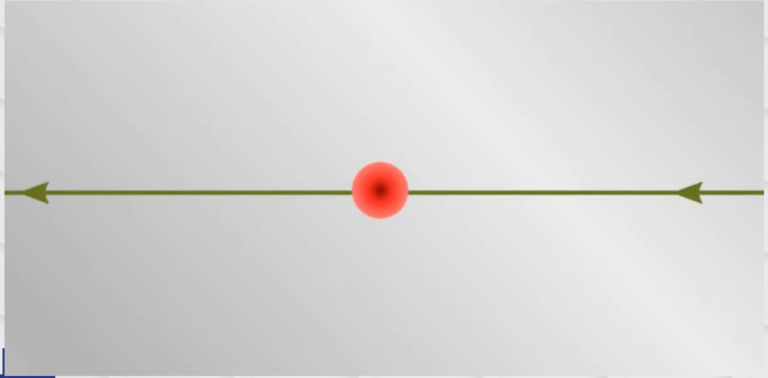
- B-field line moves along the plasma

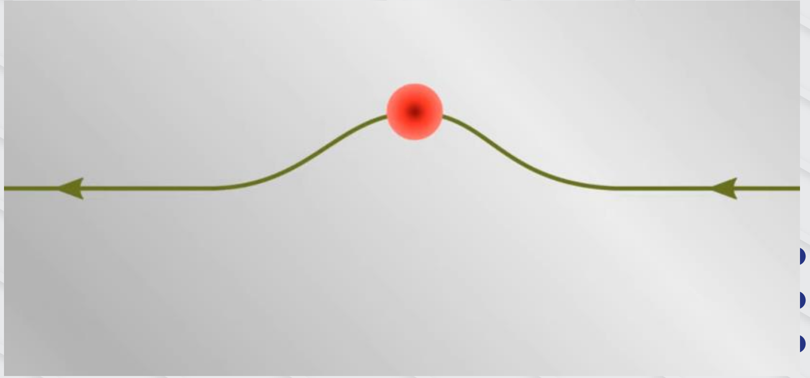


Magnetohydrodynamics problem

- At unstable equilibrium
- Small turbulence would be magnified



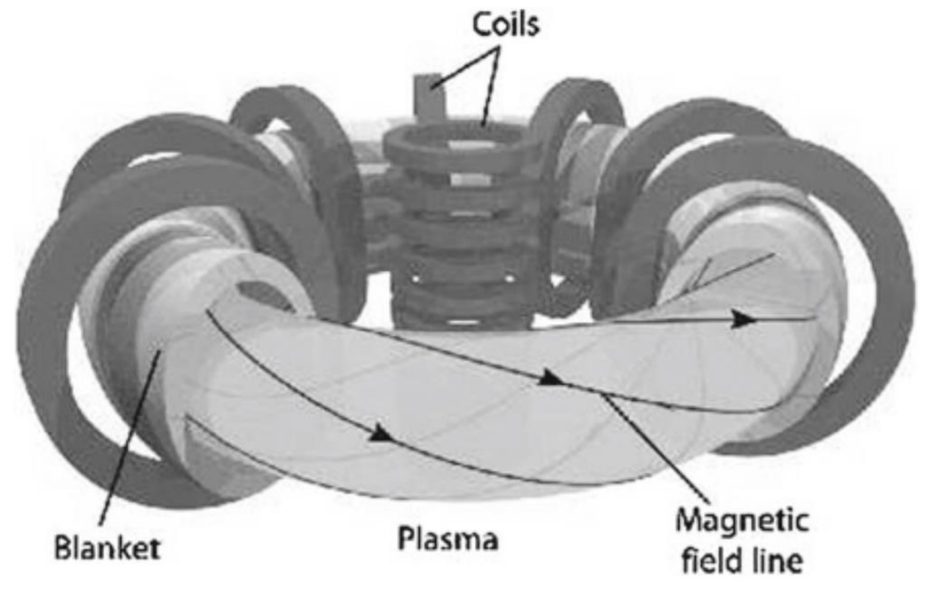




Design 1: Tokamak

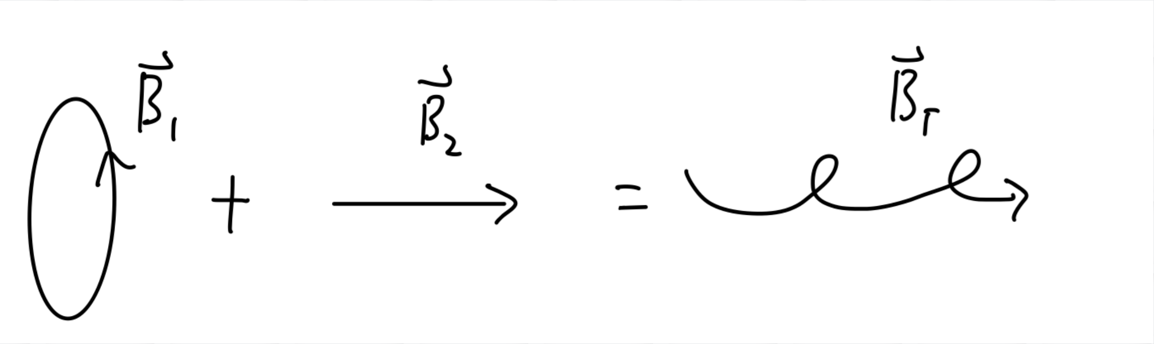
- Invented by Soviet Union in late 1950s
- Stands for TOroidal Chamber MAgnetic Coil
- Invented to solve the drifting problem

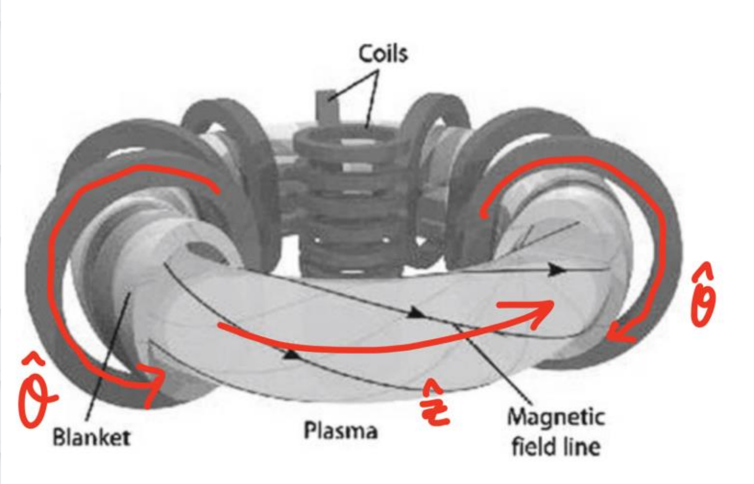
A Tokmak device



Design 1: Tokamak

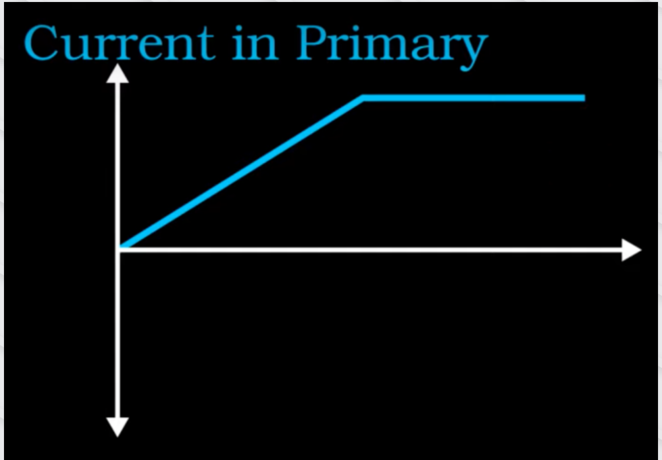
- Insert a circulating coil at the centre of the torus
- Induce the plasma to circulate aglon z-direction (Transformer)
- creates B-field along θ-direction
- Combine the original B-field in z-direction to form a helical B-field
- Solve the drifting problem

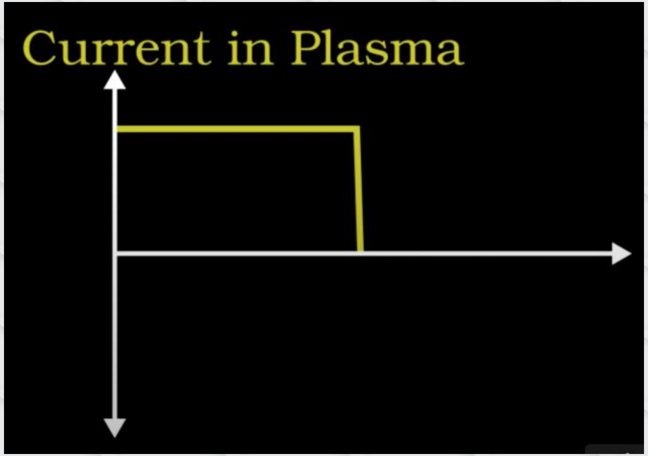




Problems of Tokamak

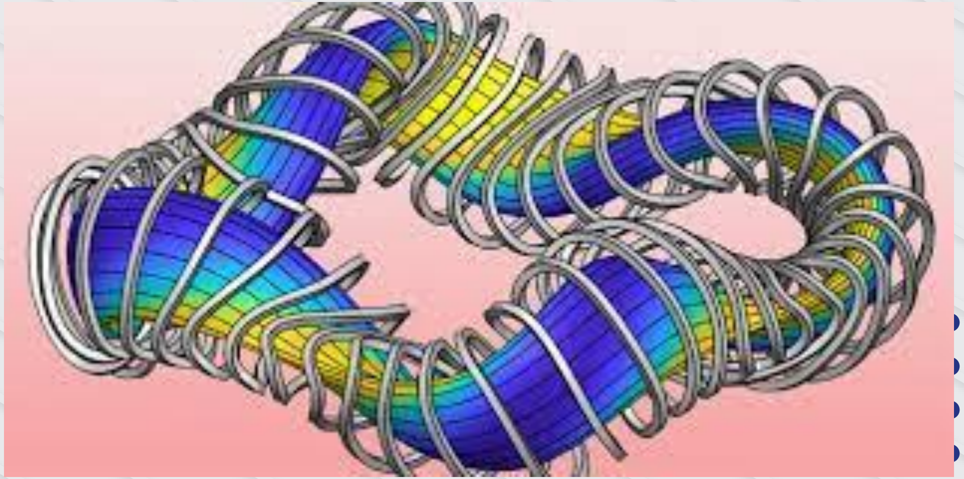
- Current of central coil must be changing
- but the plasma current must be constant
- From Faraday's law, $I_{\text{plasma}} \propto \frac{d}{dt} I_{\text{coil}}$
- Current of central coil must increase linearly, until reaching technical limit





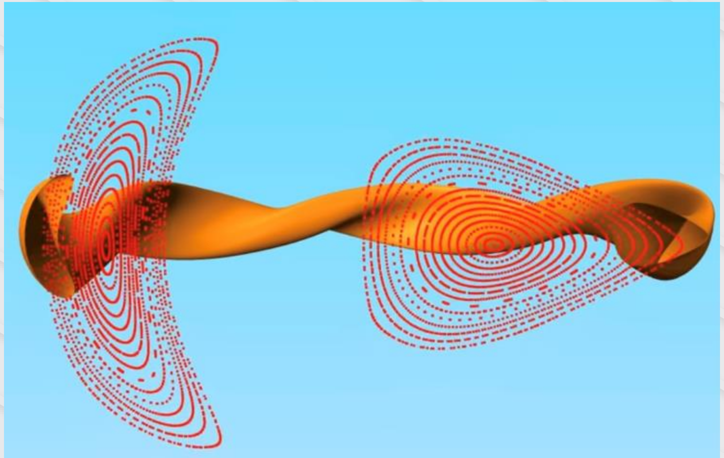
Design 2: Stellarator

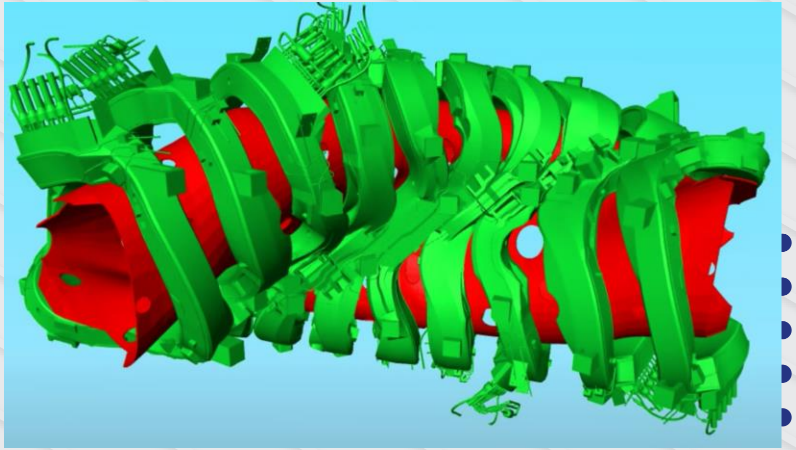
- Started by US in 1950s, kept modifying
- Twisted coil and twisted torus
- Complex details calculated by modern computer



Design 2: Stellarator

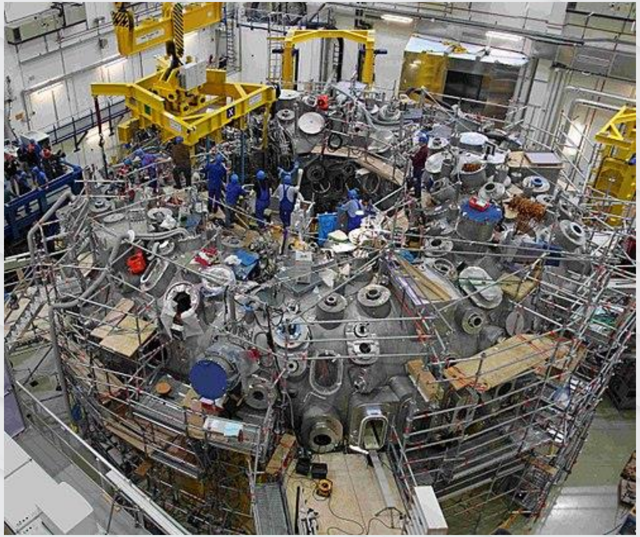
- Complex & well-calculated B-field patterns stabilize the plasma
- Circulating coils currents are in superconducting state
- Do not need energy input after starting up
- Can operate continuously





Problems of Stellarator

- High construction cost
- Requires high precision of engineering (up to few mm)



05

Future

Main practical problems

- Output energy << Input energy (ratio of ~0.02)
  - Better designs
  - Better materials for conducting wires (graphene, YBCO)
- High construction cost and difficulties
  - Precision
  - Large in size

“Sustainable energy”

- Large amount of water will be consumed to extract fuel (Deuterium & Lithium)
- Environmental threats from large-scale of fuel acquisition
- Lithium also as essential to batteries

06

Conclusion

Conclusion

- Confinement issue is the main obstacle of nuclear fusion
- Difficult to produce sustainable, efficient nuclear fusion reaction
- Recent materials is not capable enough to carry practical nuclear fusion

Reference

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- Chapter 7 - Inertial-Confinement Fusion Author links open overlay panelGarryMcCrackenPeterStott
- Nuclear Fusion Power Author links open overlay panelM.R.GordinieraJ.W.DavisaF.R.ScottbK.R.Schultzc a McDonnell Douglas Astronautics, Boeing Company, Huntington Beach, California, USA
- National Ignition Facility & Photon Science https://lasers.llnl.gov/