

Fusion Reactors: The Ultimate Nuclear Power Plant

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- A fusion reactor *would have* several of the attractive features of present-day nuclear power plants:

Abundant fuel supply

Efficient conversion of mass to energy

No air pollution or contribution to global warming

- But it would *not have* the critical negative concerns that have stopped the development of fission reactors:

No risk of uncontrolled energy release

Greatly reduced quantity of high level waste

Greatly reduced threat to non-proliferation of weapons material

A Fusion Reactor Would Have Abundant Fuel Supply

- The first fusion reactor would probably burn two isotopes of Hydrogen, Deuterium and Tritium, which differ from Hydrogen in the number of neutrons in the nucleus.



- The ratio of naturally occurring Deuterium to Hydrogen atoms is about 1:6000. Said another way, there are more than 10^{13} tons of Deuterium in the surface waters of the earth. This is truly an inexhaustible fuel supply!
- Tritium is radioactive (β -emitter) and decays with a half-life of about 12 years. Therefore it does not occur naturally and must be bred in the fusion reactor, for example through the nuclear reaction (Natural Lithium is $\sim 92.5\%$ ${}^7\text{Li}$)



The Lithium from land deposits or sea water is sufficient for *thousands of years'* energy supply

A Fusion Reactor Would Have Abundant Fuel Supply (Cont'd)

- While the first generation fusion reactor would burn D-T, a second generation reactor would likely burn only Deuterium. This requires some advance of present day plasma physics, but would greatly simplify the fuel cycle.

Like Fission, Fusion Efficiently Converts Mass to Energy

In Fission, the energy release is about 1 MeV per Nucleon

In D-T Fusion, the energy release is about 3.5 MeV per Nucleon

By comparison, fossil fuels are grossly inefficient, less than 1 eV per Nucleon!

This efficiency translates to correspondingly smaller requirements for the fuel supply system and waste disposal:

To generate 1000 MW in one day requires *9000 tons of coal* and generates *30,000 tons of CO₂* (plus other noxious gases, e.g., SO₂ and NO₂). To generate the same amount of energy from fusion requires about *2.5 pounds of D + T and makes 2 pounds of He!*

Fusion Reactors, Like Fission Reactors Do Not Contribute to Air Pollution or Global Warming

- There are no routine emissions from fission or fusion reactors
- Interestingly, coal plants release more radioactive gases (Radon) than fission plants!

In a Fusion Reactor There is No Threat of an Uncontrolled Energy Release

The amount of fuel in the reactor at any time is sufficient to burn for only ~ 10 s. Fuel is continuously supplied and can be shut off by a simple valve, much like the way fuel is supplied to a gas burner.

In addition, fusion reactions are easily extinguished by injection of heavier impurity gases or a “poison pellet”.

A “melt-down” cannot occur! Fusion reactors are passively safe.

A Fusion Reactor Would Produce Negligible Quantities of High-Level Waste

No Actinides are produced in the fusion fuel cycle

The neutron from D-T fusion will cause some activation as it interacts with material walls. But structural materials can be used which minimize the production of radioactive isotopes and their environmental consequences.

Advanced designs for fusion reactors permit recycling of materials or shallow burial about 100 years after shutdown.

So, If the Potential is so Great, Why Aren't We Building a Fusion Reactor ?

We are, but why did it take so long?

- Lack of Interest in Developing New Energy Resources, especially in the US.

This is in spite of the following argument, which is by no means new:

- Assume that the World's population grows to 10 billion over the next 50 years, and that the World per-capita usage of energy doubles during this time (still a factor of 3 short of the US per capita usage!) Then a minimum of 15,000 new plants operating at 1 GW will be needed by 2050. (Some estimates are far greater.) *How will this power be generated?*
- As with a new generation of fission plants, the push to develop fusion may come from the rapidly growing energy demand from countries with rapidly developing economies, e.g., China and India.
- Choosing a career in energy R&D looks like a good choice!

The Fusion Process

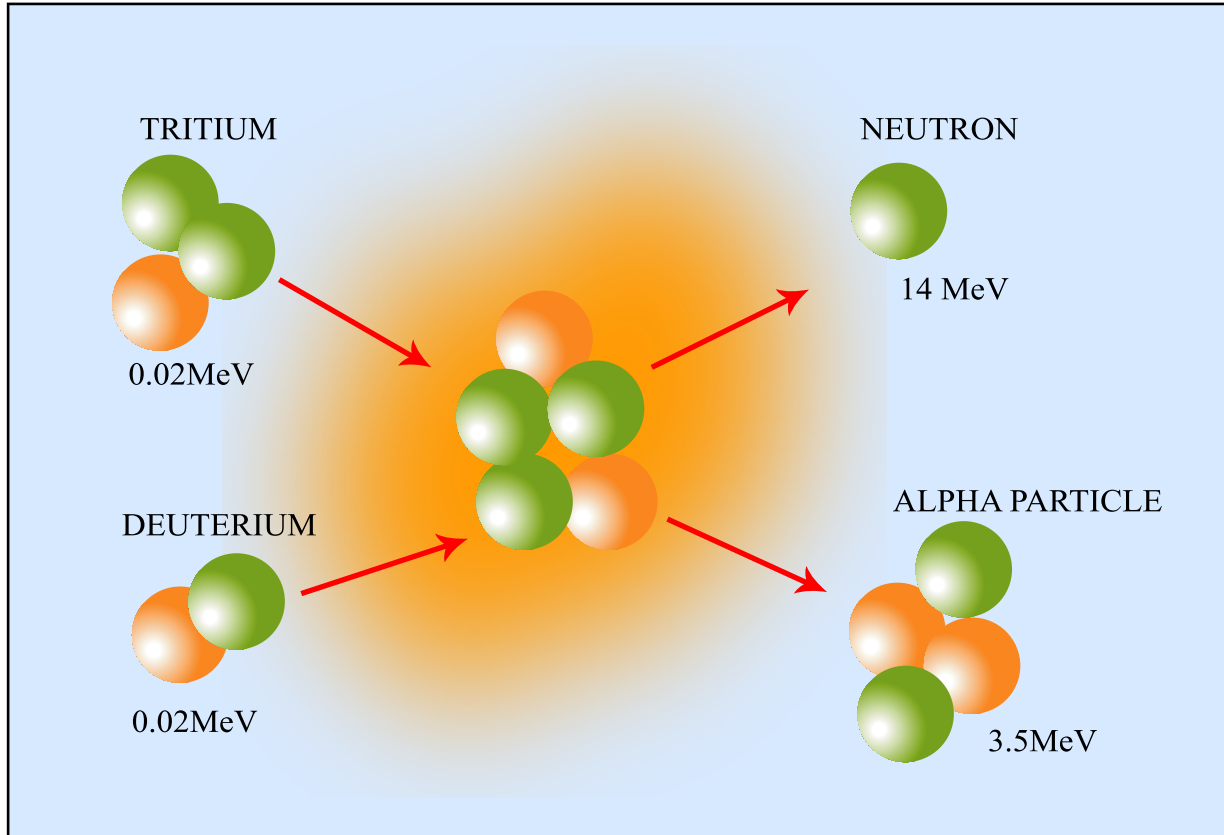
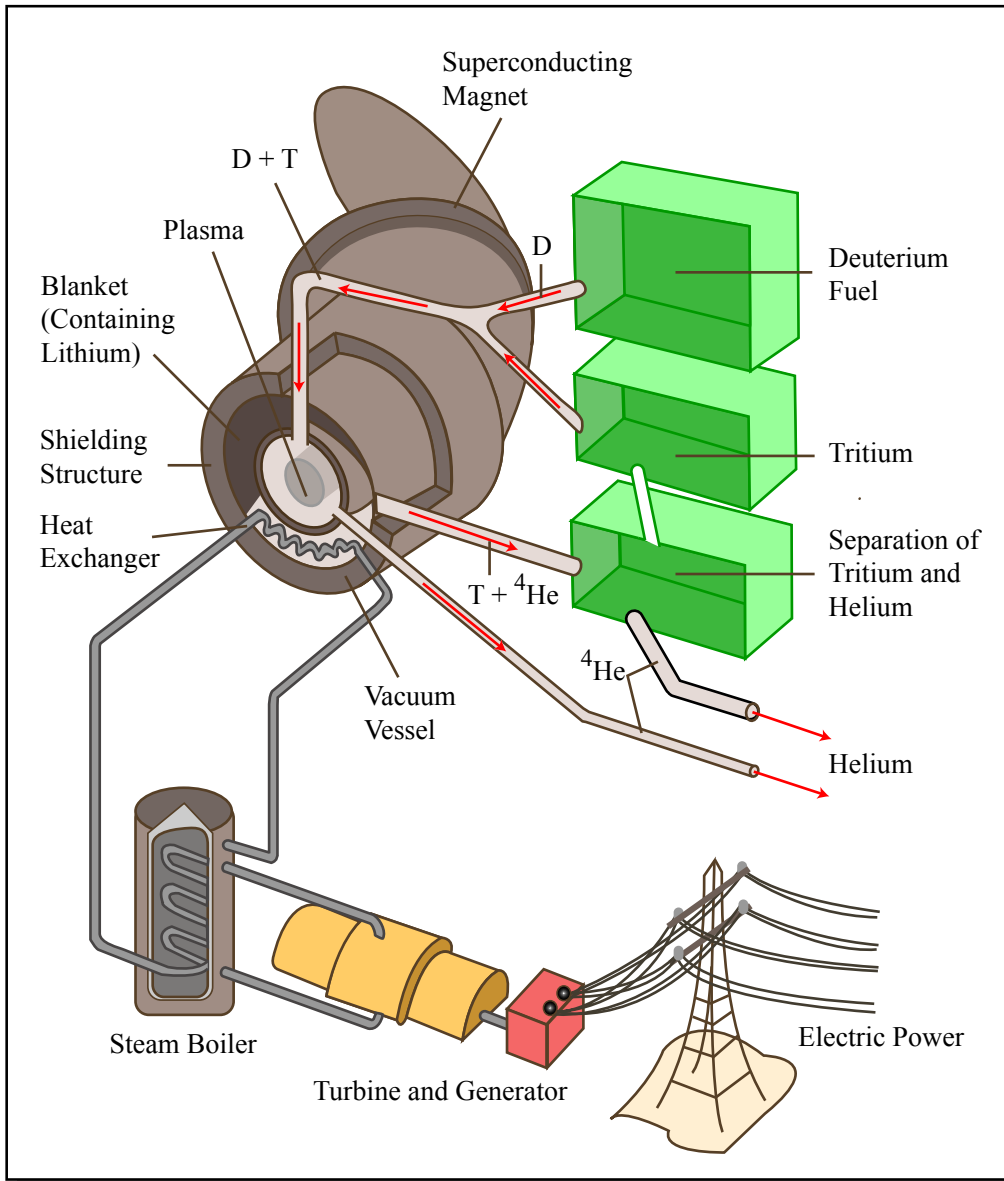


Figure by MIT OCW.

- D and T are both positively charged and repel each other through the Coulomb force
- If D and T ions manage to touch then the nuclear force takes over and turns $D + T \Rightarrow \text{He}(3.5\text{MeV}) + n(14.1\text{MeV})$
- Repulsion is overcome by increasing the speed or energy of D and T...in a hot fusion plasma, the D and T nuclei are hot enough to fuse...

Fusion Power Generation



- In steady-state, the energy from the fusion reactions are radiated to the first wall and blanket.
- Tritium is not available naturally but can be readily bred with lithium.
- The 14.1 MeV neutron is absorbed into a blanket containing lithium in order to breed tritium.
- The hot blanket and first wall is cooled; the thermal energy is extracted from the coolant for power generation.

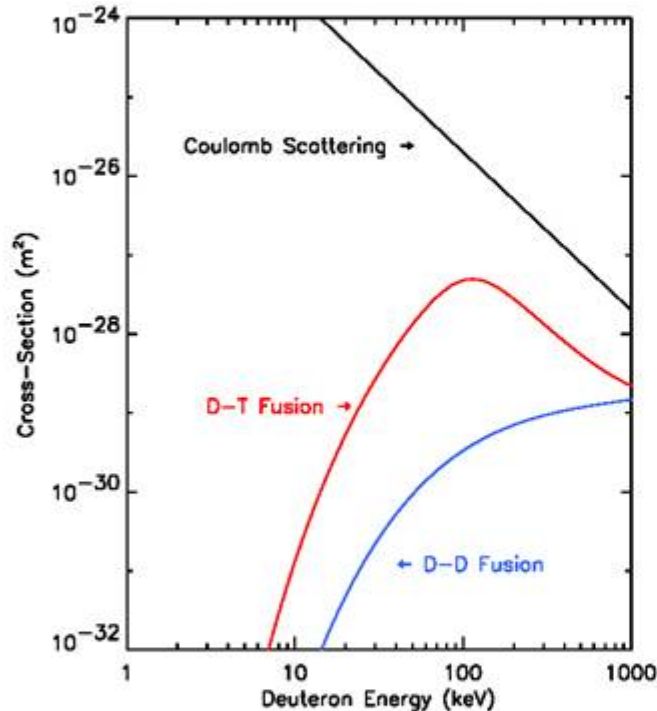
Figure by MIT OCW.

Fusion Energy Requirements

- Need enough particles to fuse: n
- Need to keep the plasma together long enough for fusion reactions to occur: τ
- Need enough energy for the particles to fuse : T

So the product $n \tau T$ must be large enough to sustain fusion events at a sufficient level to produce net power

Fusion requires high $n \tau_E T_i$



Optimum $T_i \sim 20 \text{ keV} \sim 230 \text{ million K}$

Gases fully ionized: **PLASMA**

n = density (m^{-3})

τ_E = "confinement time" (s) [plasma energy/power in]

T_i = ion temperature (keV)

For ignition, we need:

$$P_{\text{fusion}} = n_D n_T \cdot \text{Rate/Ion} \cdot E / \text{reaction}$$

$$\propto n^2 F(T)$$

$$P_{\text{loss}} = \text{Confinement Loss} + \text{Rad'n Loss}$$

$$= \frac{3nT}{\tau_E} + n^2 R(T)$$

$$n\tau_E T \geq 8 \times 10^{20} \text{ s/m}^3 \text{ keV} \quad (\text{Break-even})$$

But how do we confine a 230 Million K plasma?

Charge particles are susceptible to E&M fields...Magnetic Confinement..

Forces of Fields on Plasma

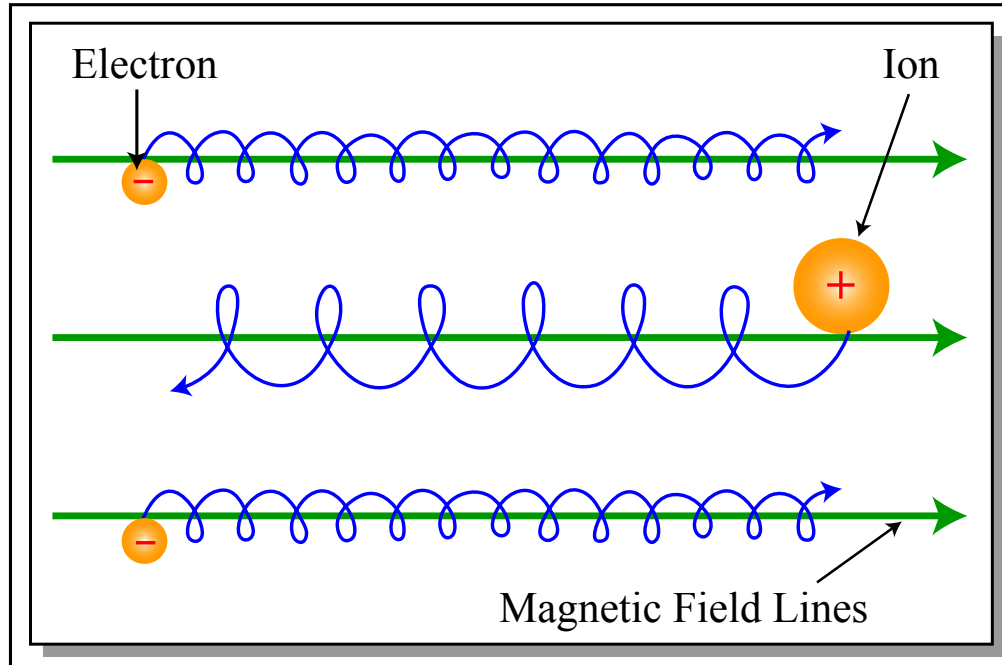


Figure by MIT OCW.

- The plasma now feels a force from the magnetic field
- Ions and electrons follow the field lines
- Plasma is confined
- More organization
- A linear device, however, has end losses!

Tokamak Coils

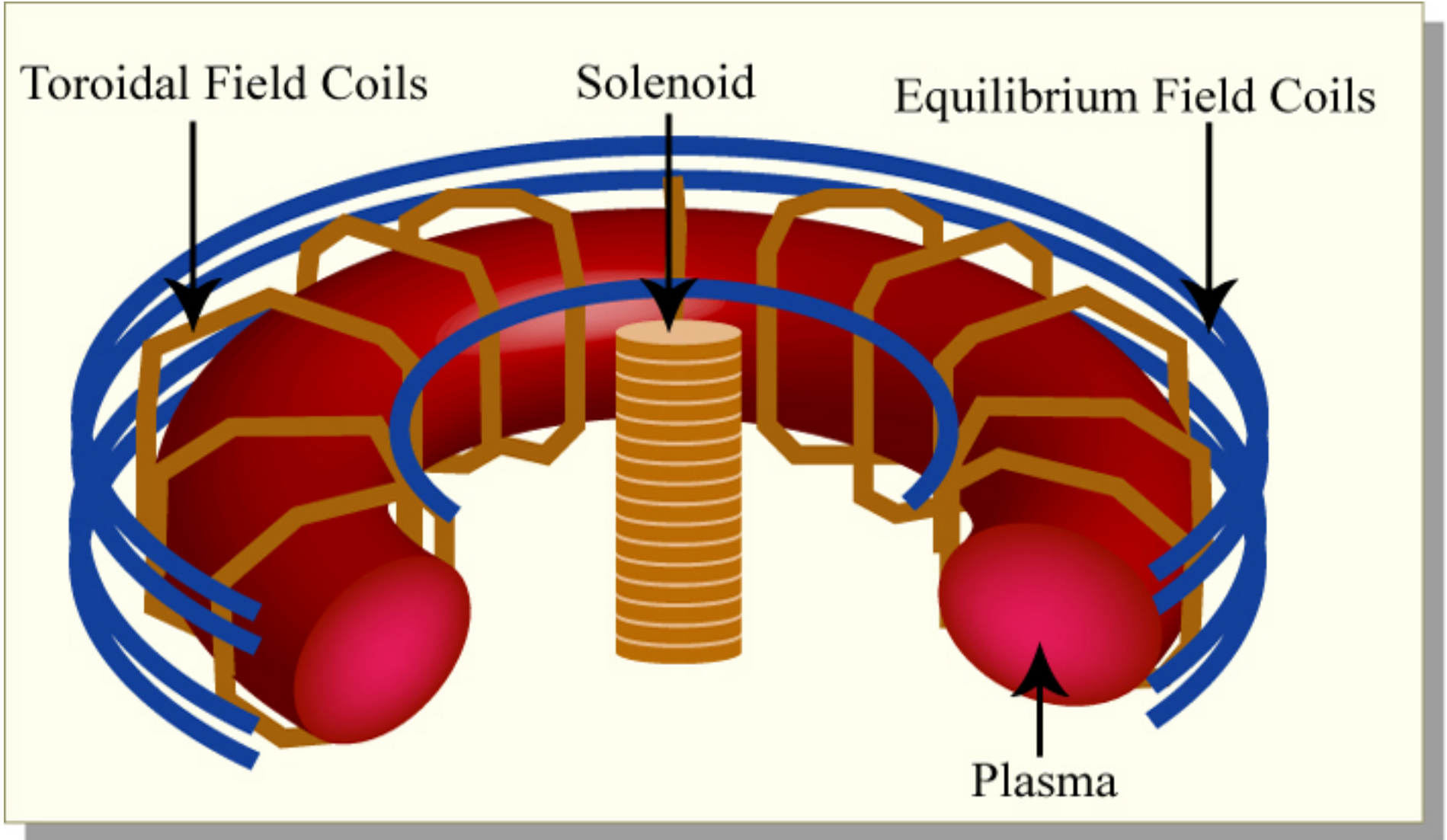
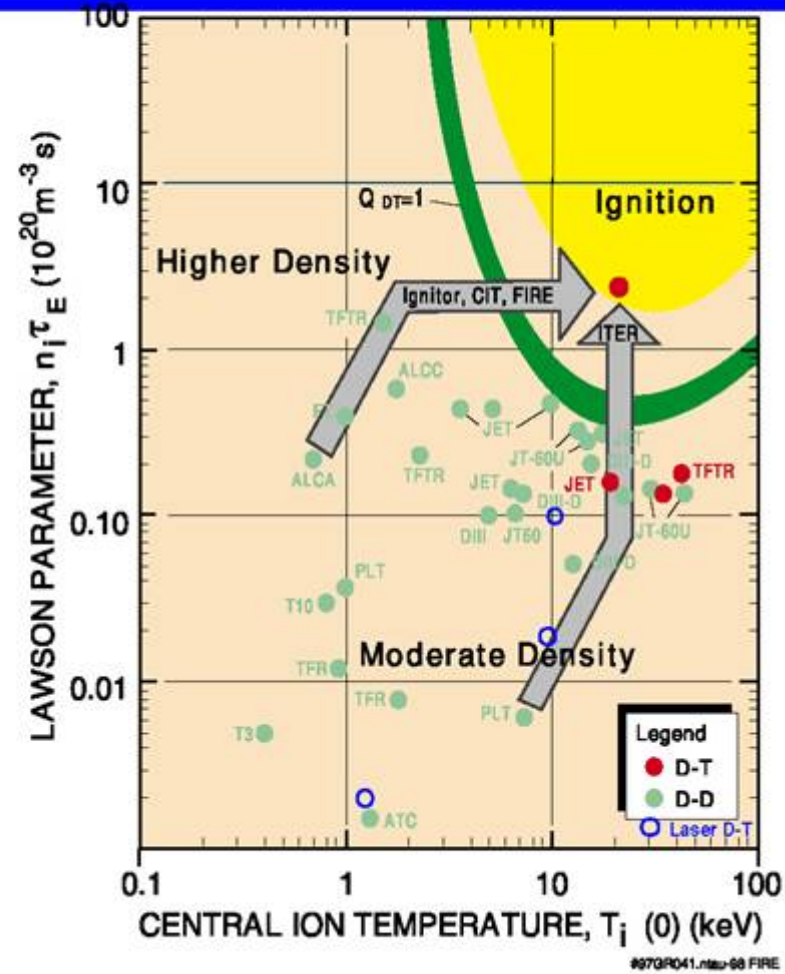


Figure by MIT OCW.

The largest fusion experiments have approached energy breakeven



Courtesy of Princeton Plasma Physics Laboratory.