IAEA
International Atomic Energy Agency

Fusion Energy. An introduction

7 March 2022

International Webinar

GLOBAL CHALLENGES OF ENERGY PRODUCTION IN THE COMING DECADES

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COLEGIO DE INGENIEROS DEL PERÚ

Outline

- Energy consumption
- What is Fusion?
- Basics of Fusion
- Scientific and Engineering feasibility
- History of Fusion
- Different concepts
  - IFE
  - Tokamaks and stellarators
    - W7X
    - ITER
    - Key elements in a Tokamak
    - DEMO
- Fusion at IAEA
- Conclusions

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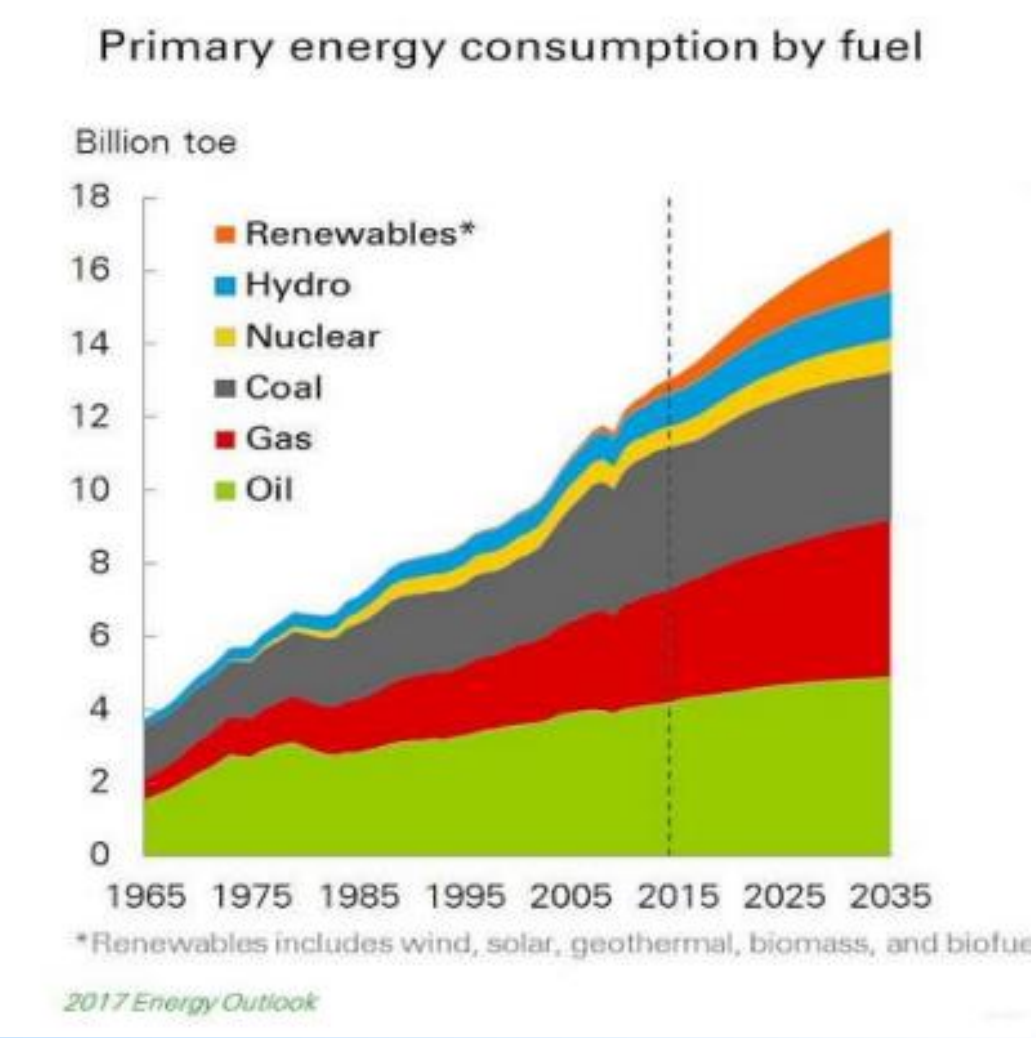
Energy consumption projection – next 15 years



COP26
THE GLASGOW
CLIMATE PACT

- **Mitigation** - reducing emissions
- **Adaptation** - helping those already impacted by climate change
- **Finance** - enabling countries to deliver on their climate goals
- **Collaboration** - working together to deliver even greater action

Global net zero

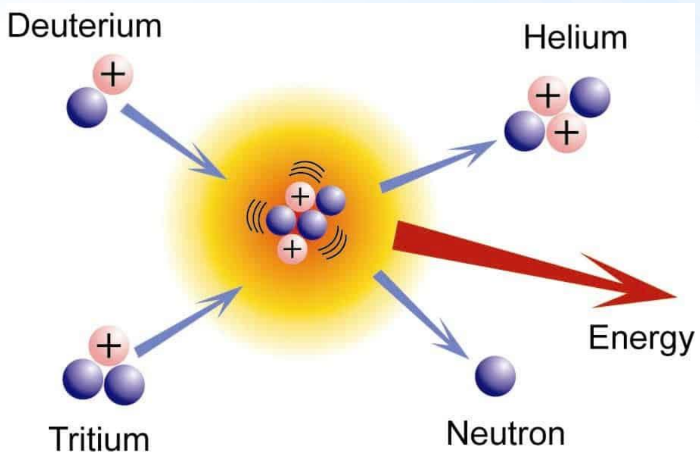
"COP26 is sending a clear message that time is up for fossil fuel subsidies and unabated coal" - European Commission President Ursula von der Leyen on the outcome of COP26

Why is fusion needed and what benefits does fusion bring ?

- The energy consumption increases ~ 0.2 GW each year
- Fusion has a potential of providing inexhaustible source of energy without danger or CO_2 emissions

WHAT IS FUSION?

- Fusion is the universe’s ubiquitous power source: it is what causes the sun and the stars to shine, since they are powered by the fusion reaction taking place in their core.
- Fusion takes light atoms and combines them to form heavier atoms (the resulting loss of mass is released in



Source: chemwiki.ucdavis.edu

D + T→ ^{4}He (3.5 MeV) + n (14.1 MeV)

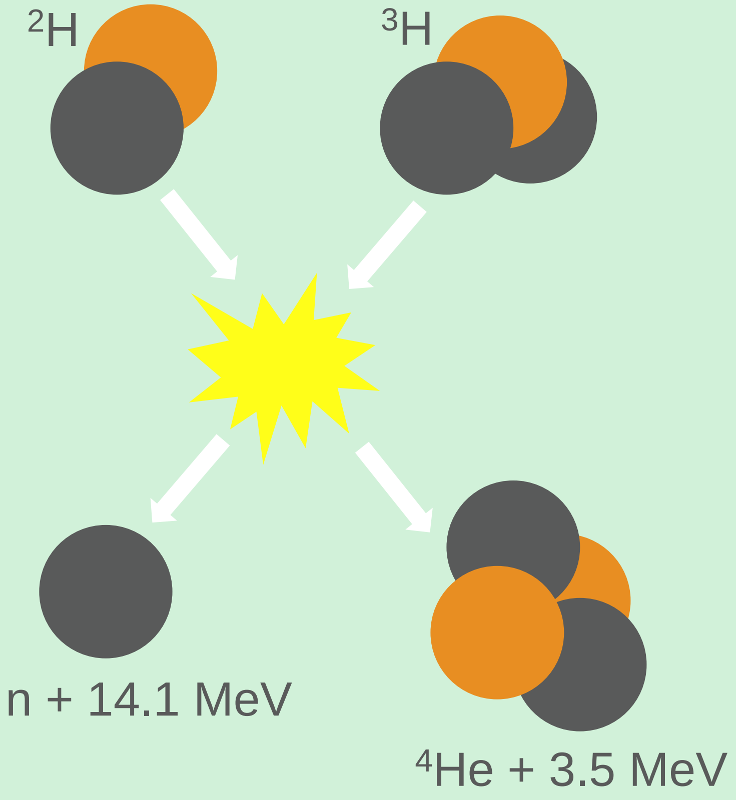
Energy released

- 4 times greater than fission reactions (at equal mass)
- 4 million times higher than burning of coal, oil or gas (at equal mass)

Fusion/Fission

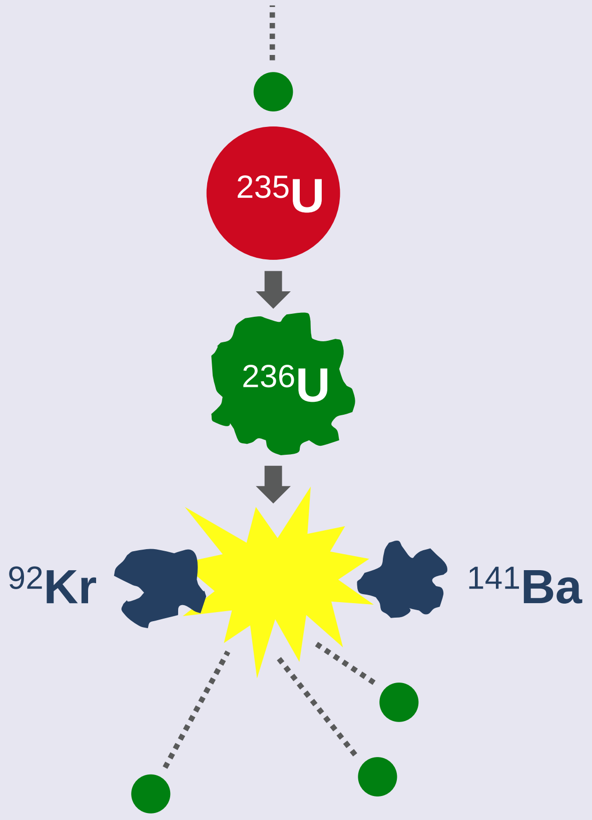
FUSION

Two small nuclei bind making a bigger one.



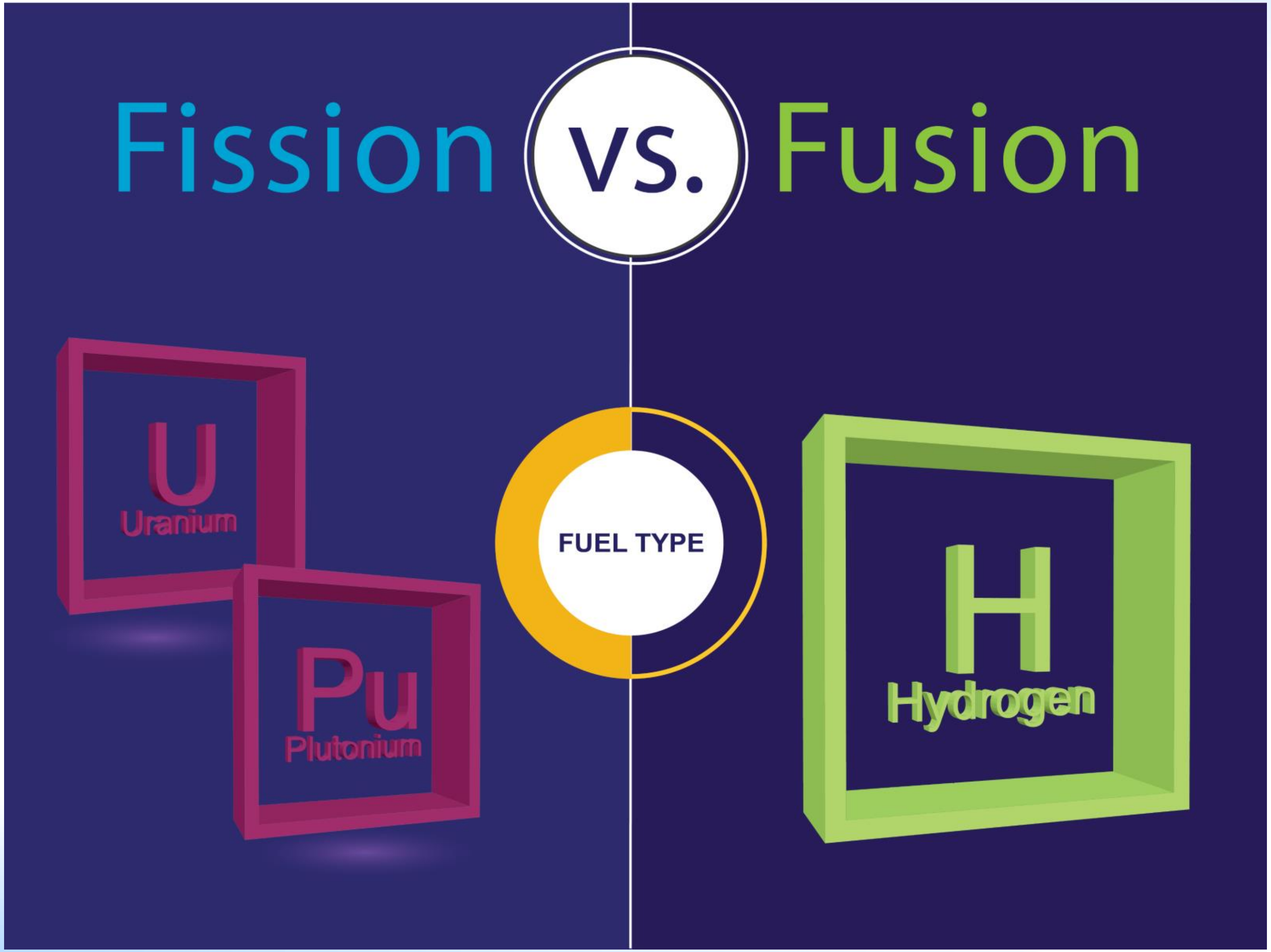
FISSION

One large nucleus breaks up into smaller ones.



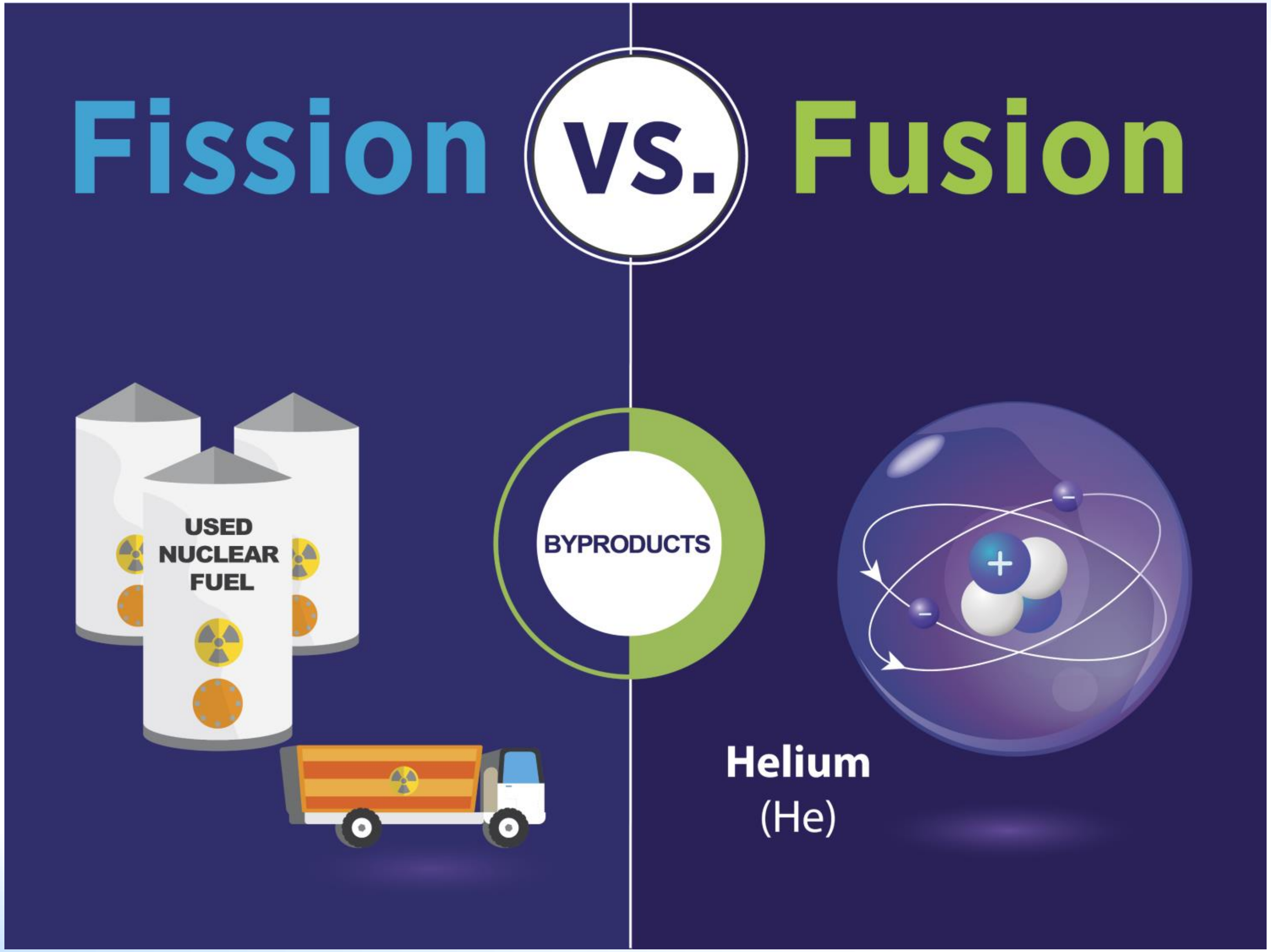
Basics of fusion

- What is the difference between **fission** and **fusion**?



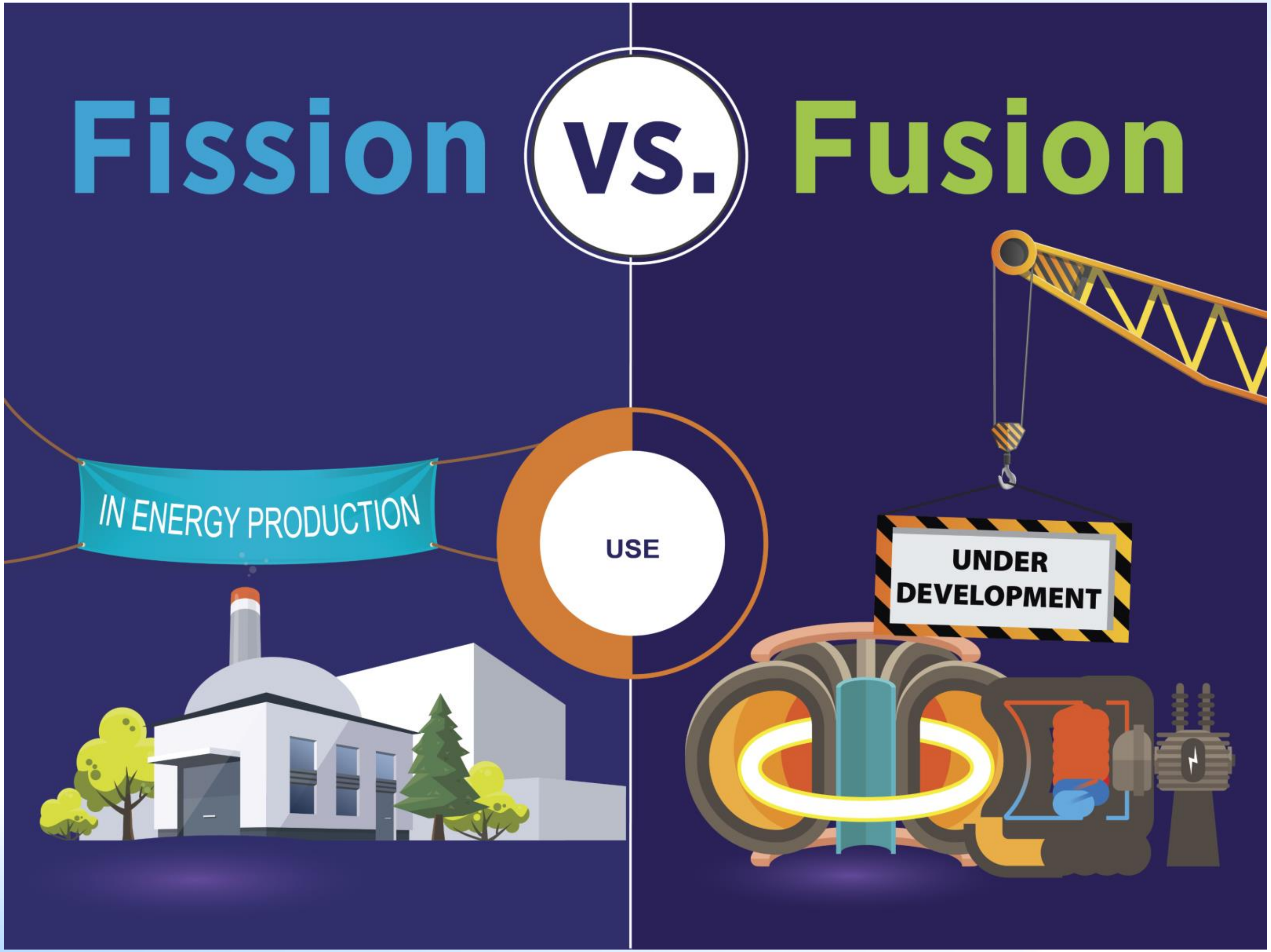
Basics of fusion

- What is the difference between **fission** and **fusion**?



Basics of Fusion

- What is the difference between **fission** and **fusion**?



MERITS OF FUSION

Carbon free
Zero gas emission

Virtually clean

Low level, manageable waste
No long-lived radioactive waste production

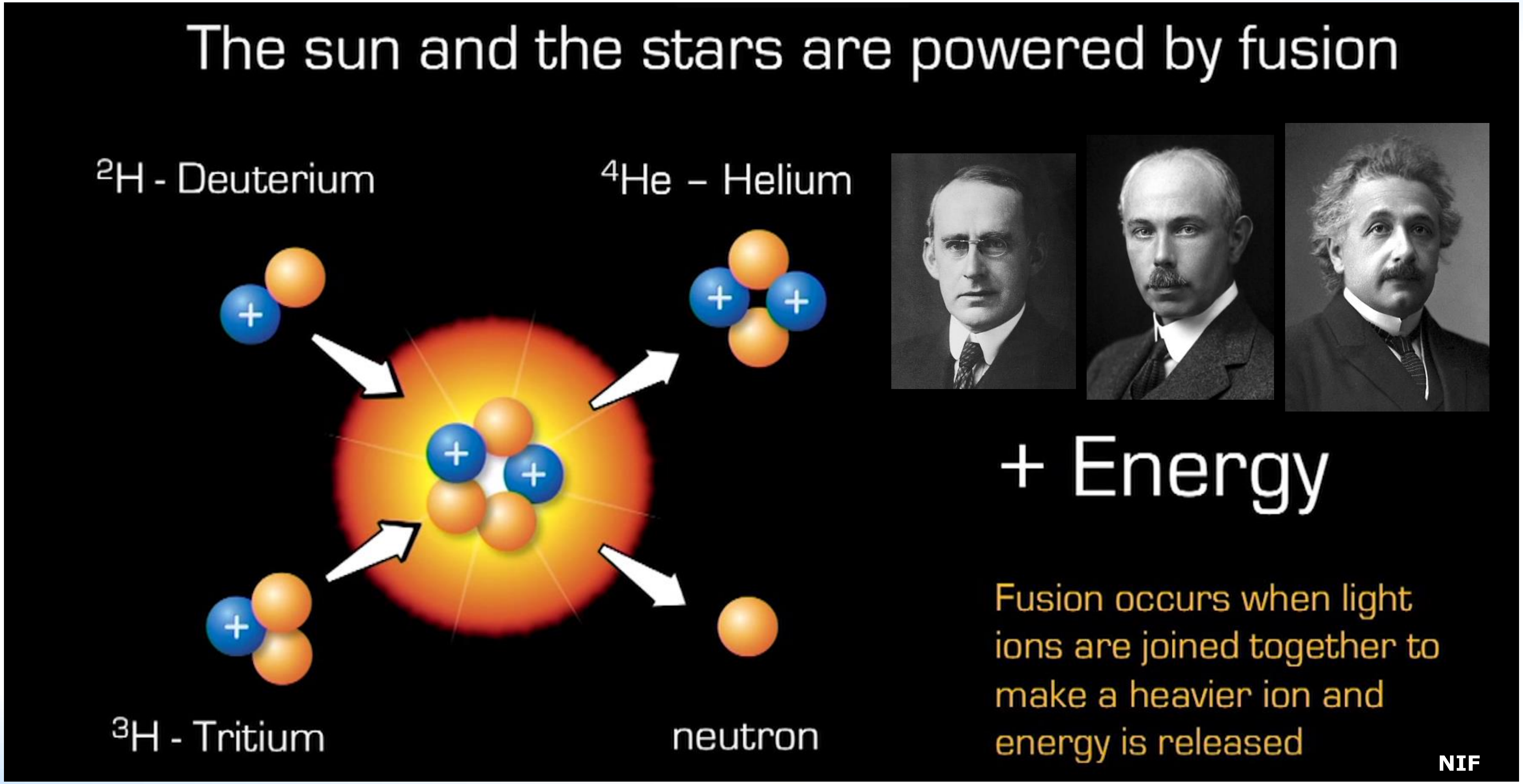
Inherently safe
No chain reaction

Unlimited fuel

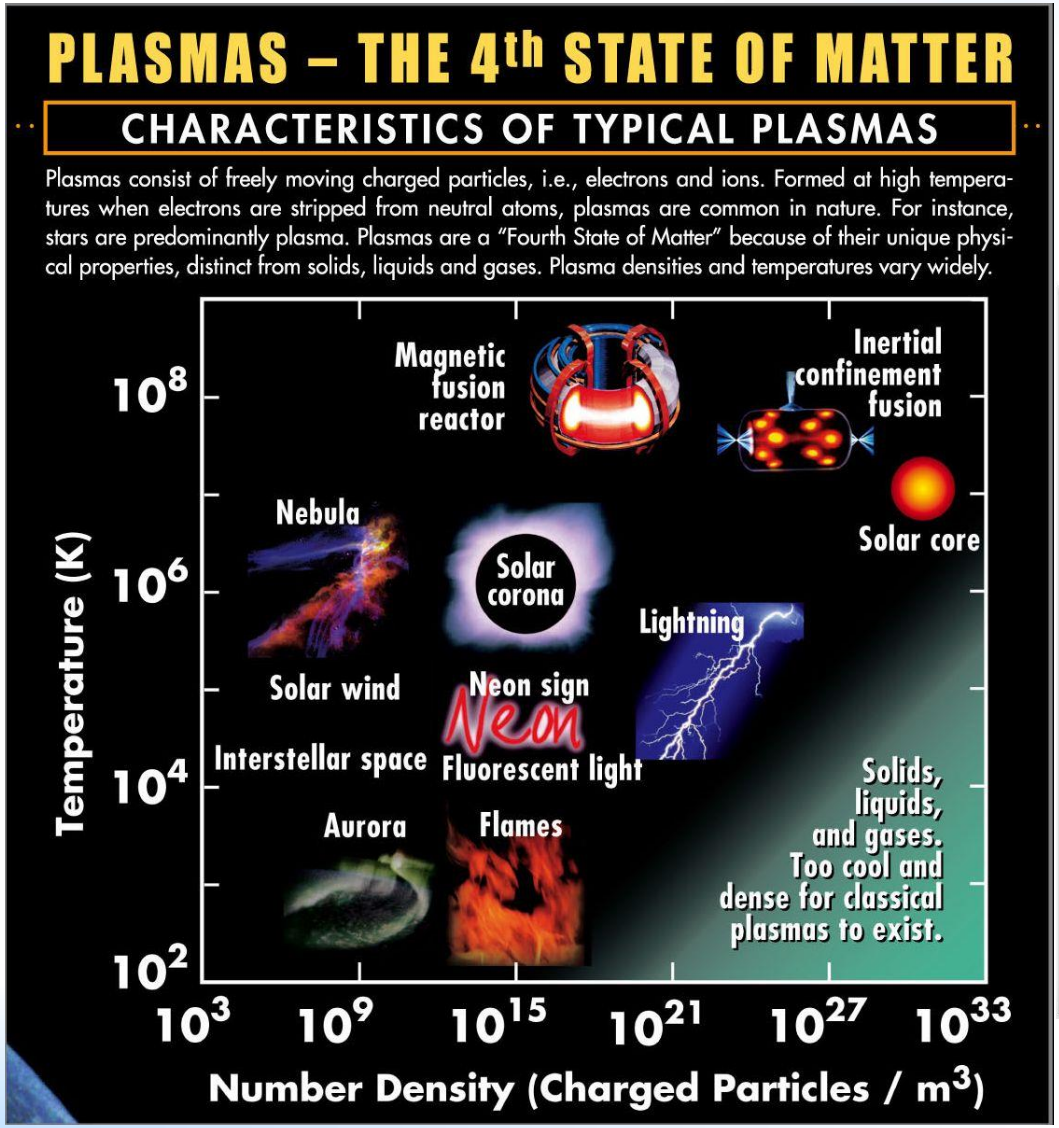
Reliable

Fusion – WHEN?

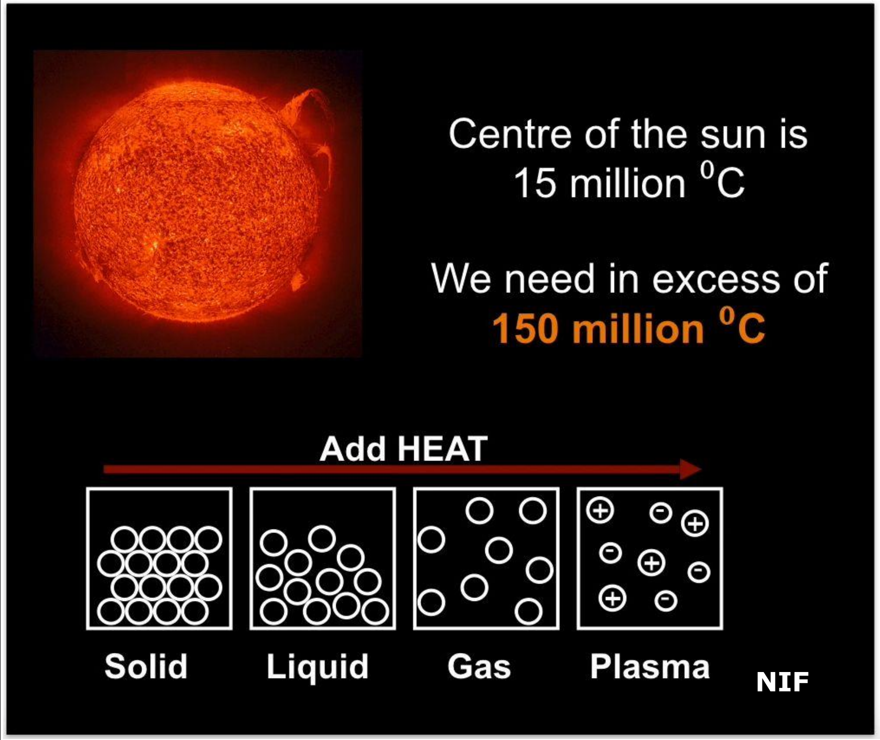
- **1920**, **Eddington** based on **Aston's experiments** and **Einstein's theory** suggests* that:



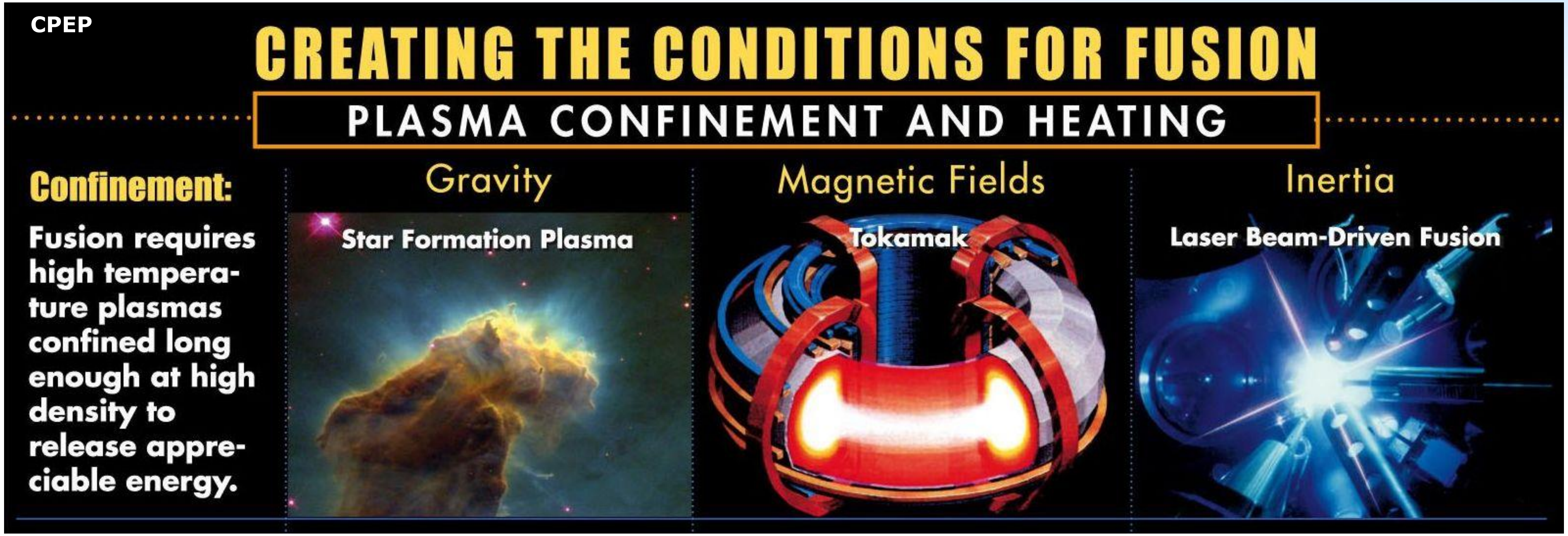
Learning from the Sun – PLASMA



More than 99% of the Universe exists as plasma, including interstellar matter, stars and the Sun.



Tapping the Energy – CONFINEMENT



Three conditions must be fulfilled to achieve fusion in a laboratory:

- ***Very high temperature*** *(to provoke high-energy collisions);*
- ***Sufficient plasma particle density*** *(to increase the likelihood that collisions do occur);*
- ***Sufficient confinement time*** *(to hold the plasma, which has a propensity to expand, within a defined volume).*

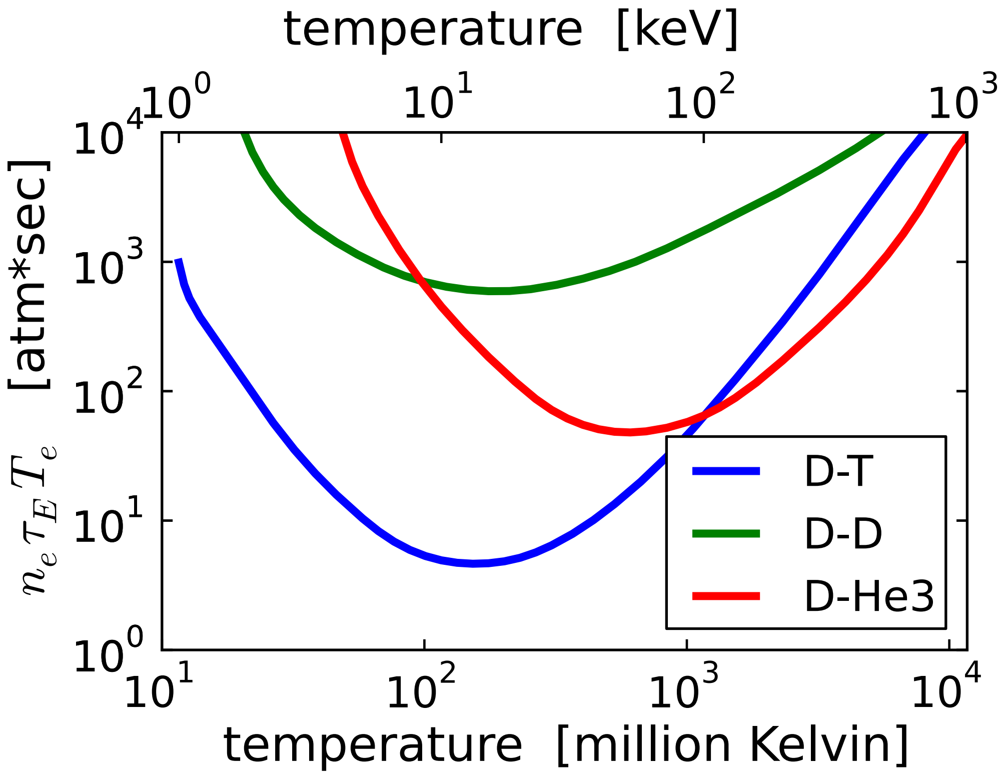
Scientific and Engineering feasibility

What conditions are needed for fusion?

- **The Lawson Criterium** (1957) can be written also as "**triple product**":

$$nT\tau_E > 3 \times 10^{21} m^{-3} keVs$$

- The until now not-so-obvious choice of D-T reaction is explained:
- D-T reaction has 2x higher reaction cross-section than D-D, thus the lowest ***T*** and $\boldsymbol{\tau}$ are needed, however:
  - Fast neutrons are produced
  - Only 20% energy goes to charged particles
  - We need T and Li



Basics of Fusion

- Possible **fusion** reactions, which lead to gain of energy

Reaction name	Reaction equation	
DT	**$D + T \rightarrow {}^4He\ (3{,}5\ MeV) + n\ (14{,}1\ MeV)$**	→ **ITER**
DD	$D + D \rightarrow {}^3He\ (1{,}8\ MeV) + n\ (2{,}5\ MeV)$	
	$\rightarrow T\ (1{,}0\ MeV) + p\ (3\ MeV)$	
TT	$T + T \rightarrow n + n + {}^4He$ …………… 11,3 MeV	
D-^{3}He	$D + {}^3He \rightarrow {}^4He\ (3{,}7\ MeV) + p\ (14{,}6\ MeV)$	
p-^{6}Li	$p + {}^6Li \rightarrow {}^4He + {}^3He$ …………… 4,0 MeV	
p-^{11}B	$p + {}^{11}B \rightarrow 3\ {}^4He$ …………… 8,7 MeV	
DD Catalyzed:	$6\ D \rightarrow 2\ p + 2\ n + 2\ {}^4He + 43{,}2\ MeV$	

Scientific and Engineering feasibility

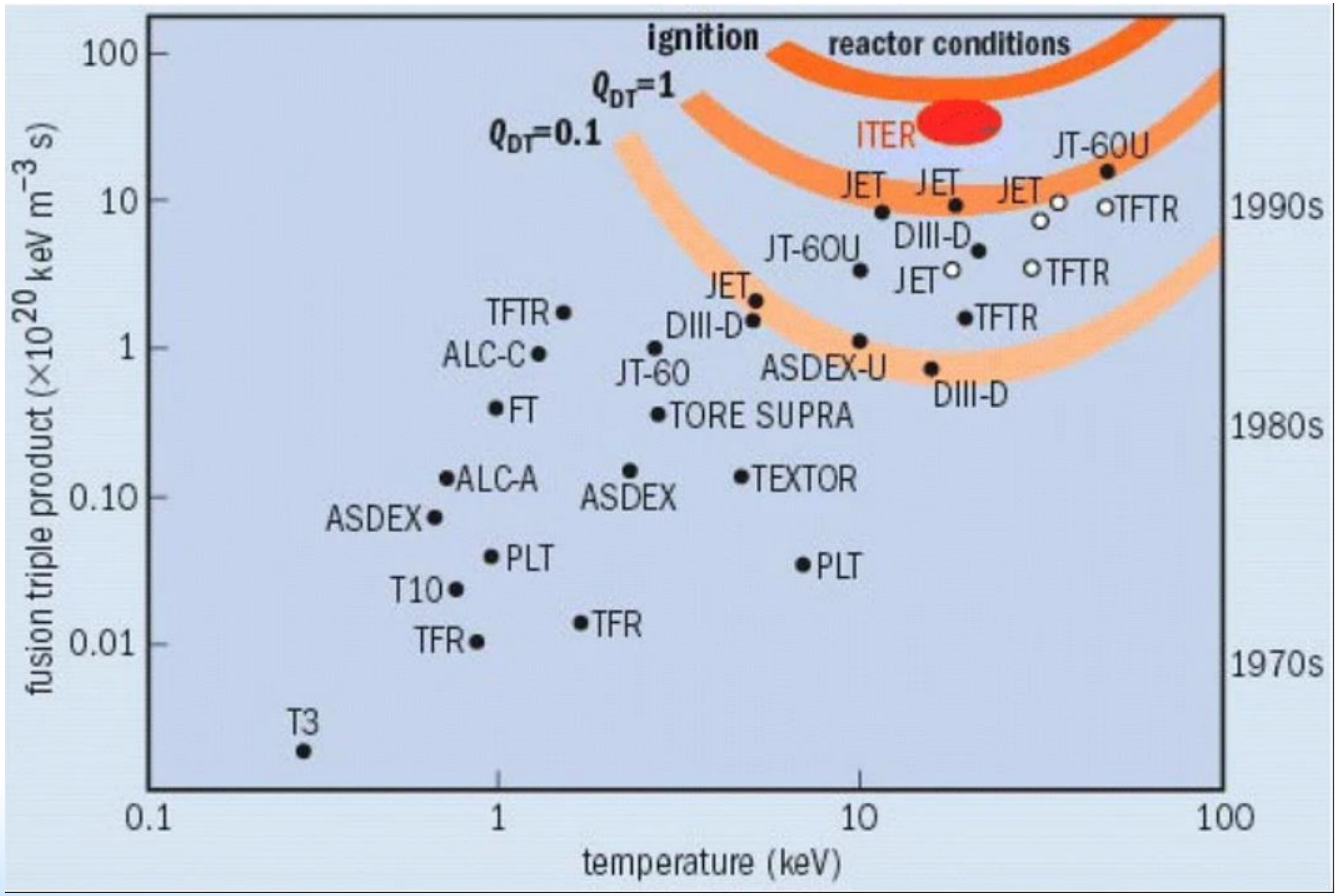
- **Burning plasma** (self-heating plasma): A burning plasma is one in which most of the plasma heating comes from fusion reactions involving thermal plasma ions. In a burning fusion plasma so many fusion processes occur that the energy of the **helium nuclei produced is almost or completely sufficient to maintain the temperature of the plasma.** The external heating can be strongly reduced or switched off altogether. All in all, the fusion reactions yield an energy output greater than the energy input

- **Ignition:** Fusion ignition is the point at which a **nuclear fusion reaction becomes self-sustaining**. This occurs when the energy being given off by the fusion reactions heats the fuel mass more rapidly than various loss mechanisms cool it. At this point, the external energy needed to heat the fuel to fusion temperatures is no longer needed. As the rate of fusion varies with temperature, the point of ignition for any given machine is typically expressed as a temperature.

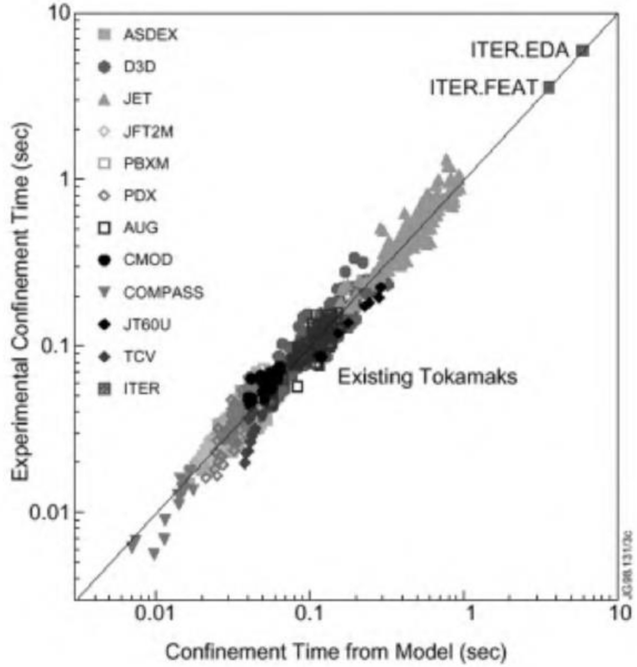
The Sun is a burning plasma that has reached “ignition,” meaning the Sun’s plasma temperature is maintained solely by energy released from fusion.

Scientific and Engineering feasibility

- How close to ignition (Lawson criterion) are we now ?



John D. Lawson (4 April 1923-15 January 2008)



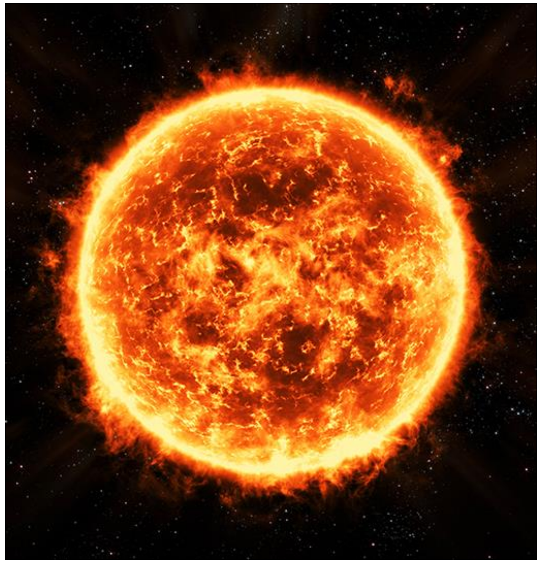
History of Fusion

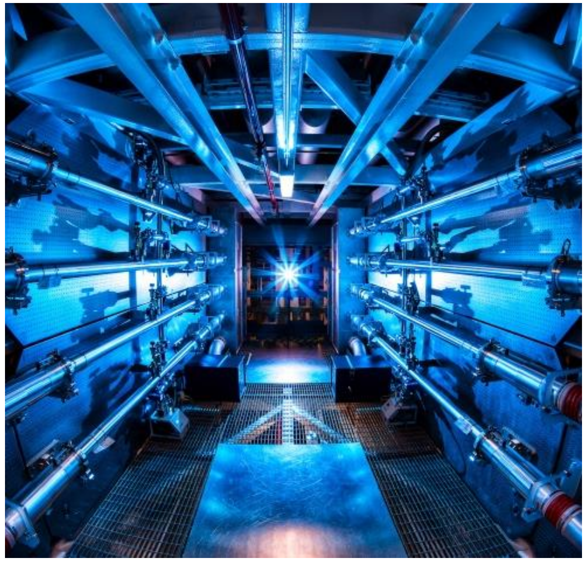
- ~ 4.603 billion years ago - First nuclear fusion reactions began in Our Sun
- 1926 British astrophysicist Arthur Eddington suggested that stars draw their energy from the fusion of hydrogen into helium
- 1934 Rutherford showed experimentally the fusion of deuterium into helium
- Thin man followed by Nagasaki 1945 the 1st Fusion bomb on earth
- 1950 soviet scientists Andrei Sakharov and Igor Tamm proposed the design for a type of magnetic confinement fusion device, the **tokamak**.
- 1951 Lyman Spitzer's concept for the **stellarator**
- **1958 The First tokamak T-1 was built**
- 1973 European countries came together and began design work on the tokamak JET Joint European Torus
- 1997 D-T powered JET set the current world record fusion output at 16 MW from an input of 24 MW of heating.

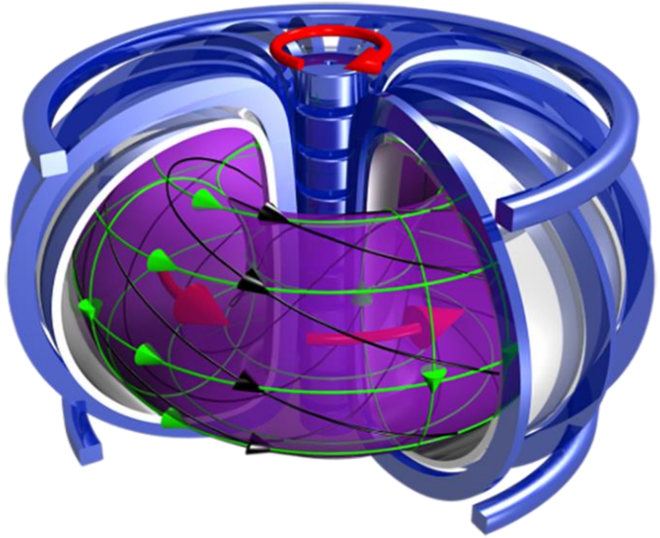
Scientific and Engineering feasibility

- **HOW TO CONFINE $T = 10^8$ [K] PLASMA? It will melt any known material !**

- Gravity
- Inertial Fusion
- Magnetic confinement

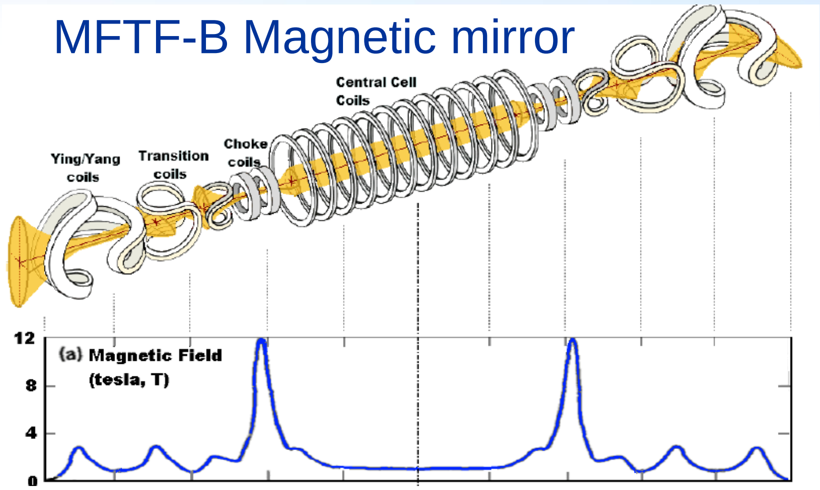


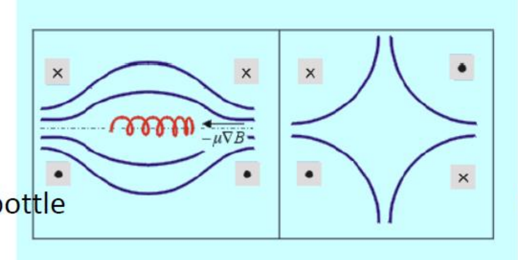




Different concepts

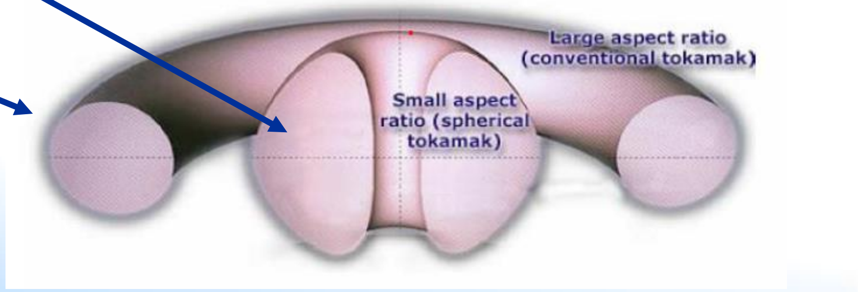
- Inertial fusion systems:
  - H-bombs
  - Particle accelerators
  - Lasers
  - Electrostatic potential wells (fusors)
- Opened systems:
  - Magnetic mirrors
  - Pinches (theta, Z) or magnetized targets
  - Multipoles
- Closed Systems:
  - Torus of mirrors or cusps
  - Field reverse configurations
  - Spheromaks
  - **Stellarators**
  - **Tokamaks**



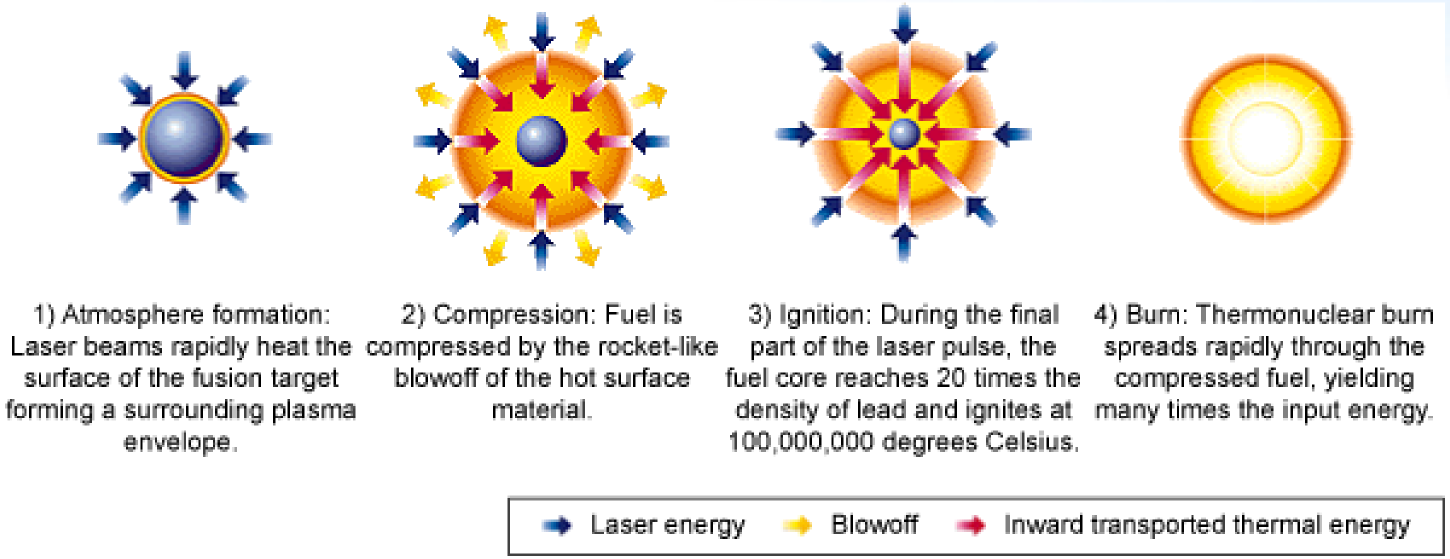


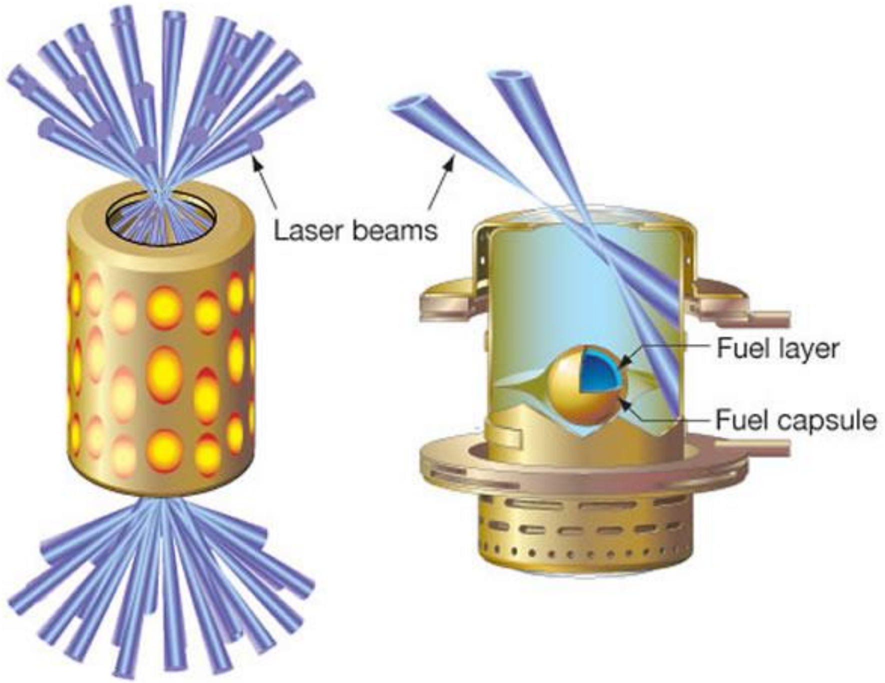
Magnetic bottle

Magnetic cusp



Inertial Confinement Fusion (ICF)





All of the energy of NIF's 192 beams is directed inside a gold cylinder called a hohlraum, which is about the size of a dime. A tiny capsule inside the hohlraum contains atoms of deuterium and tritium that fuel the ignition process.

- Fuel is compressed and heated so quickly that it reaches the conditions for fusion and burns before it has time to escape
- Fuel: few milligrams of a mixture of deuterium and tritium—in solid form this is a small spherical pellet, or capsule, with a radius of a few millimetres.

Toroidal plasma confinement systems: Tokamaks and Stellarators

The plasmas are confined by a magnetic field. In order to have an equilibrium between the plasma pressure and the magnetic forces it is necessary to have a rotational transform of the toroidal magnetic field. Such a rotational transform may prevent the curvature drift of the guiding center of plasma particles towards the wall. As proposed by Spitzer and Mercier there are three different ways to twist the magnetic field:

(i) creating a poloidal field by a toroidal electric current (TOKAMAK)
(ii) rotating the poloidal cross-section of stretched flux surfaces around the torus (STELLARATORS)
(iii) making the magnetic axis non-planar (STELLARATORS)

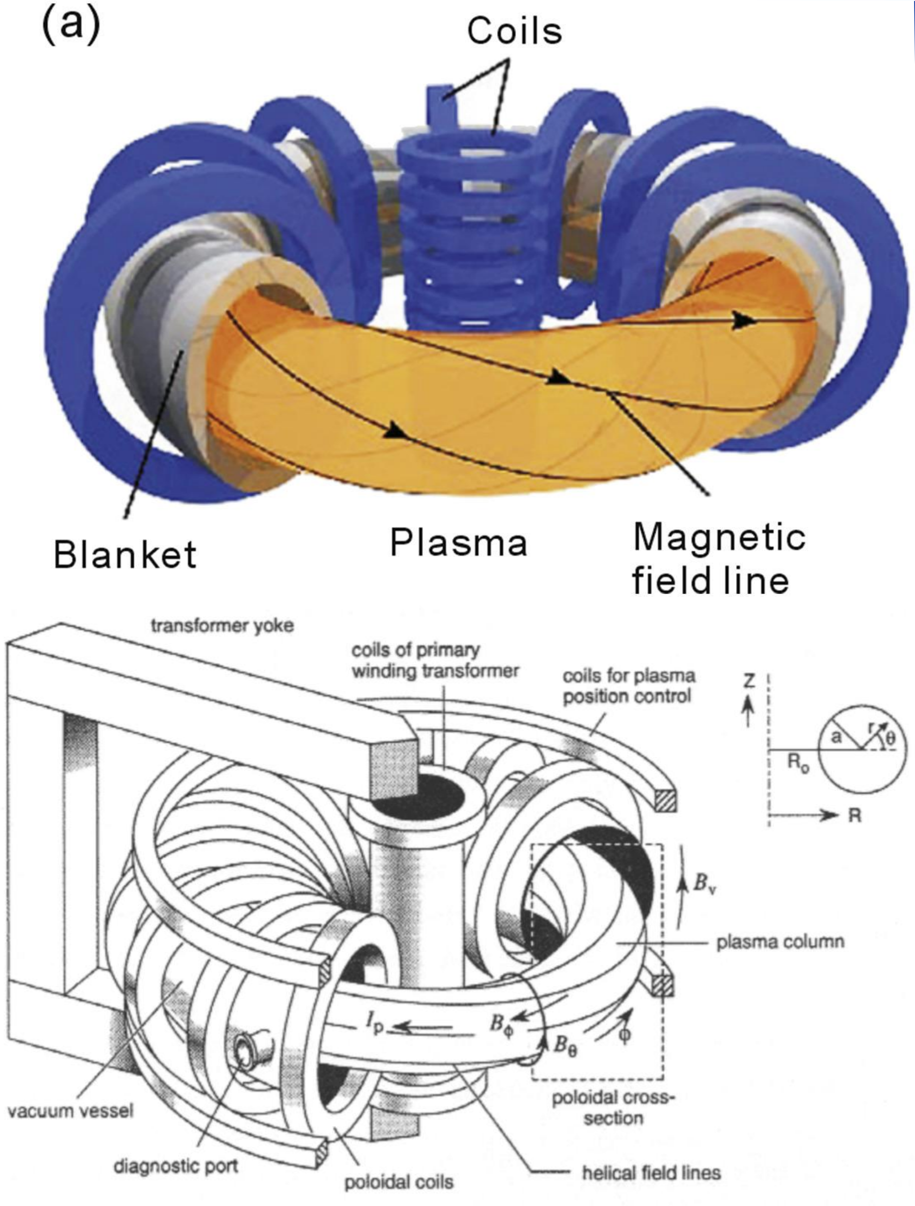
In tokamaks the twisting is produced by a toroidal plasma current and in stellarators by external non-axisymmetric coils.

This brings clear difference for the two systems:

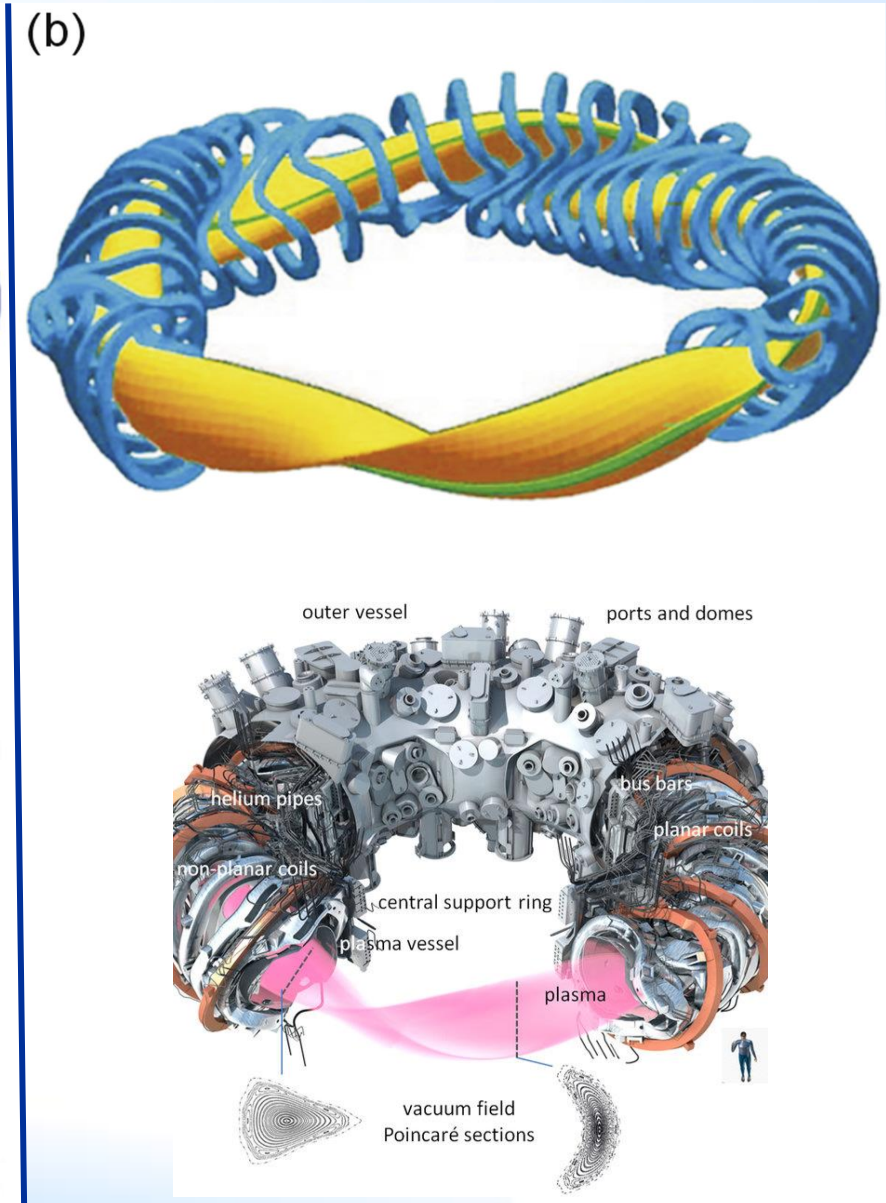
- For example, tokamaks are axisymmetric and can confine all collisionless particles and have relatively good plasma confinement. But the toroidal current is normally generated by a transformer, which makes the device vulnerable to current-driven instabilities and difficult to operate in a steady state.
- The stellarators, on the other hand, are inherently current free, and thus, able to operate the plasma in a steady state. But more unconfined particle orbits in stellarators can lead to high neoclassical transport of energetic and thermal particles.

Tokamaks and Stellarators

Tokamak

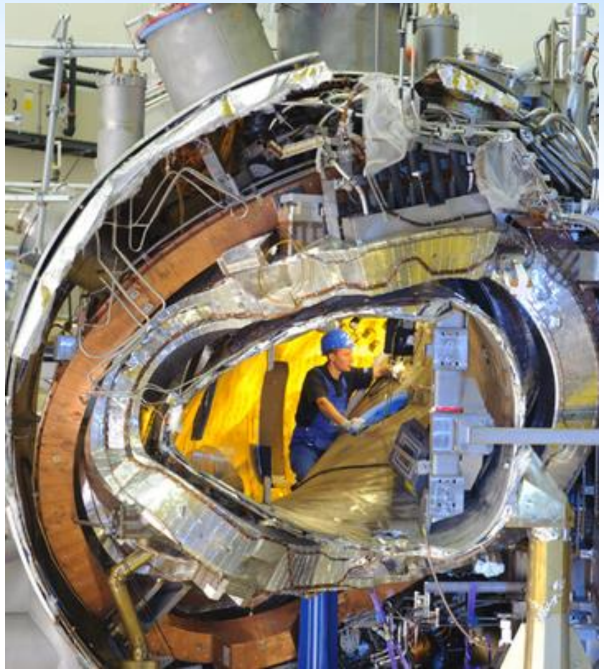


Stellarators



Stellarators: Wendelstein 7-X

- Largest Superconducting stellarator
- Completed in October 2015
- The first three experimental phases of Wendelstein 7-X were highly successful: Among other things, the team was already able to set the stellarator world record for the triple product of temperature, density and confinement time
- designed to achieve enclosure of up to 30 minutes of continuous plasma discharge in 2021

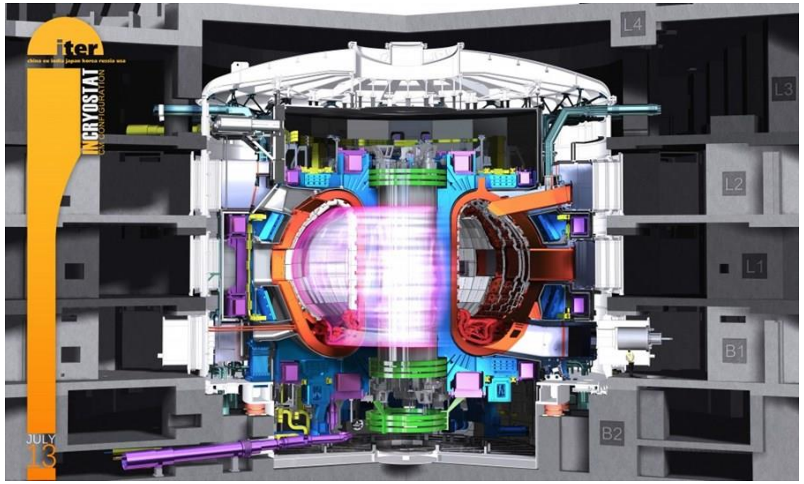


Wendelstein 7-X produced first hydrogen plasma. 3 February 2016

Tokamaks: ITER

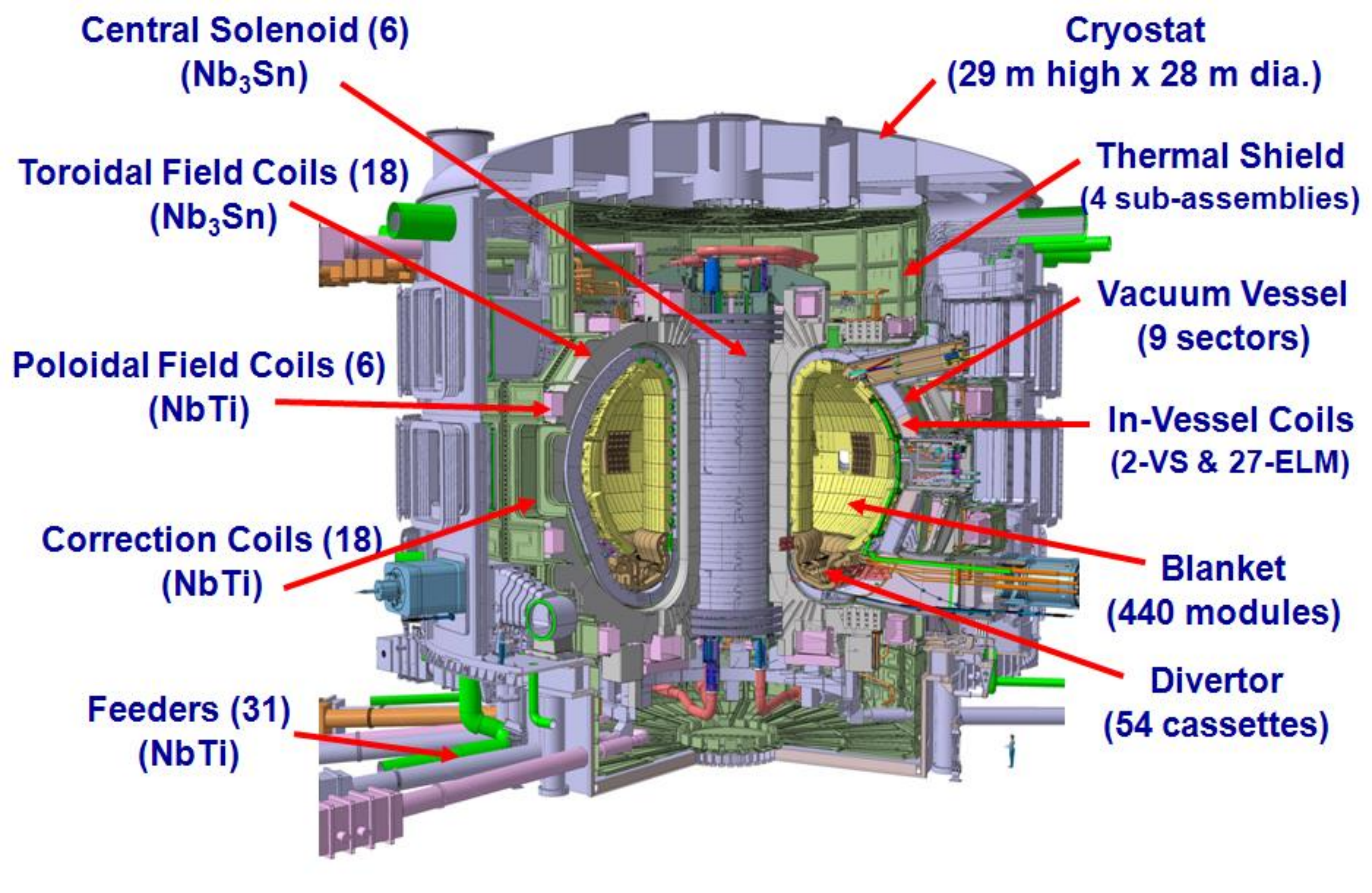
- ITER is an international project funded by 35 partner countries, including the European Union, the UK, Switzerland, China, India, Japan, Korea, Russia and the US
- The world's largest magnetic confinement plasma physics experiment
- First Plasma Dec 2025; Full nuclear fusion by 2035
- Goal is to achieve to produce 10 times as much thermal output power as thermal power absorbed by the plasma for short time periods;

Aerial view, 2021



Tokamak view (simulation)

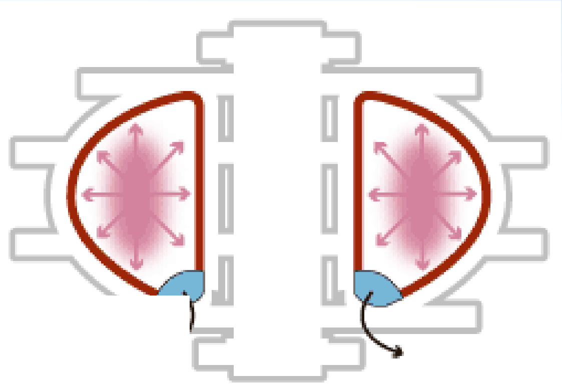
Plasma Physics in a tokamak



Key elements in a Tokamak

How to obtain Fuel for Fusion?

- Deuterium is found in found between Hydrogen at a rate 0.0153%
- Tritium can be obtained by breeding in a Fusion Blanket:



$$^{6}Li + n \rightarrow T\ (2{,}7\ MeV) + {}^{4}He\ (2{,}1 MeV)$$

$$^{7}Li + n \rightarrow T + {}^{4}He + n$$

- Neutrons escaping the plasma are slowed in the blankets – covering the inner walls of the vacuum vessel – converting their kinetic energy into heat energy collected by water coolant.

- 300 g of tritium will be required per day (100 kg per year) to produce 800 MW of electrical power.

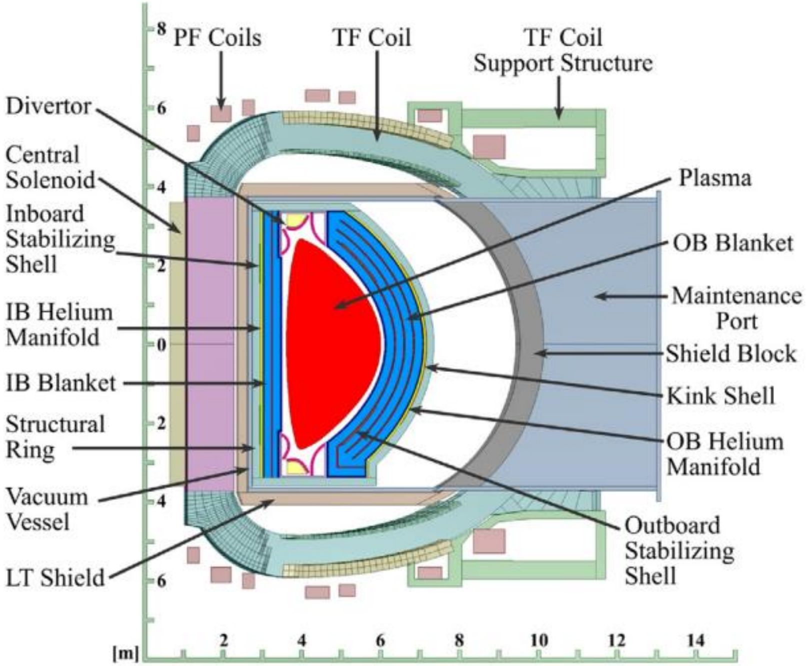
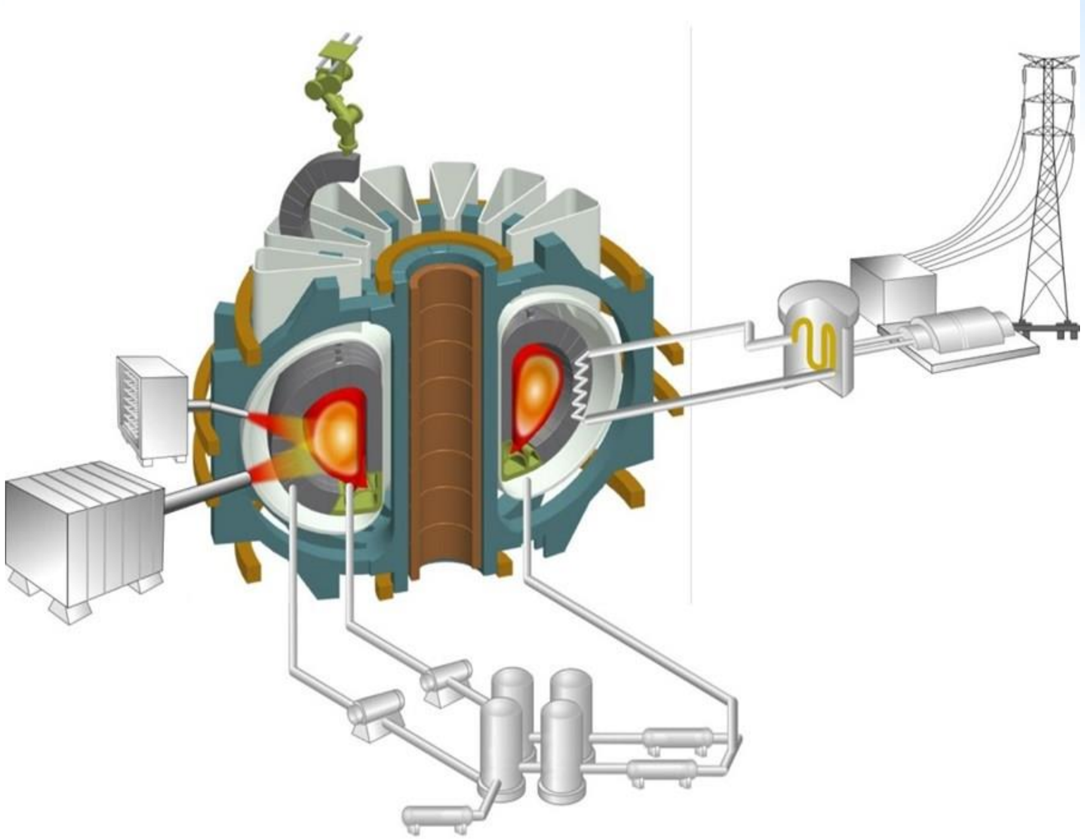


Fig. 1. Layout of the FNSF power core.

https://doi.org/10.1016/j.fusengdes.2017.04.099

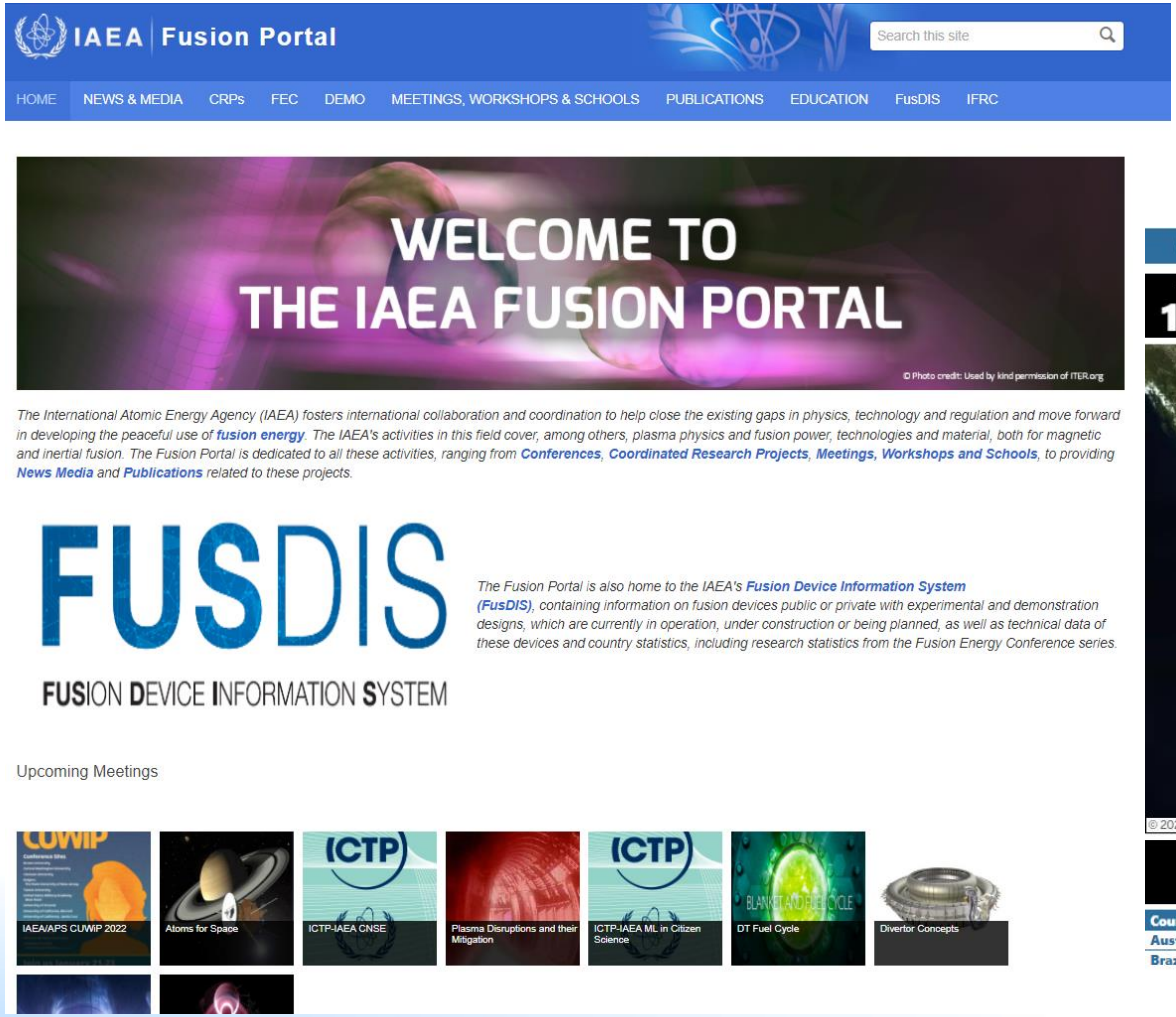
Next step after ITER: DEMO [DEMOnstration Power Plant]

- **Tokamak or stellarator?**
- Plans for DEMO reactor are intended to build upon the ITER experimental nuclear fusion reactor
- **To generate between 300 Megawatt to 500 Megawatt net electricity to the grid**
- **To operate with a closed fuel-cycle, meaning spent tritium fuel will be reprocessed,**

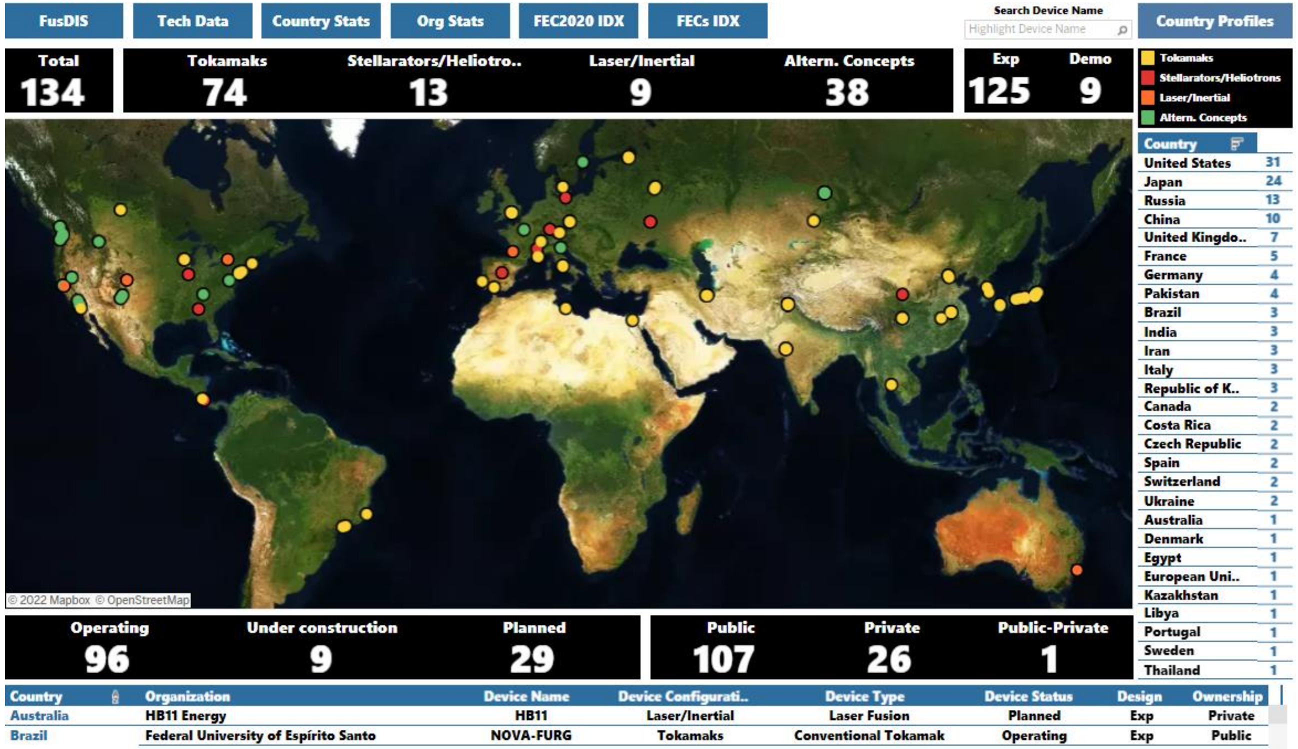


Fusion at IAEA: Fusion Portal

FusDIS – Fusion Device Information System
+9000 views since release in Sept. 2020
NOW UPGRADED



UPGRADE



https://nucleus.iaea.org/sites/fusionportal/Pages/FusDIS.aspx

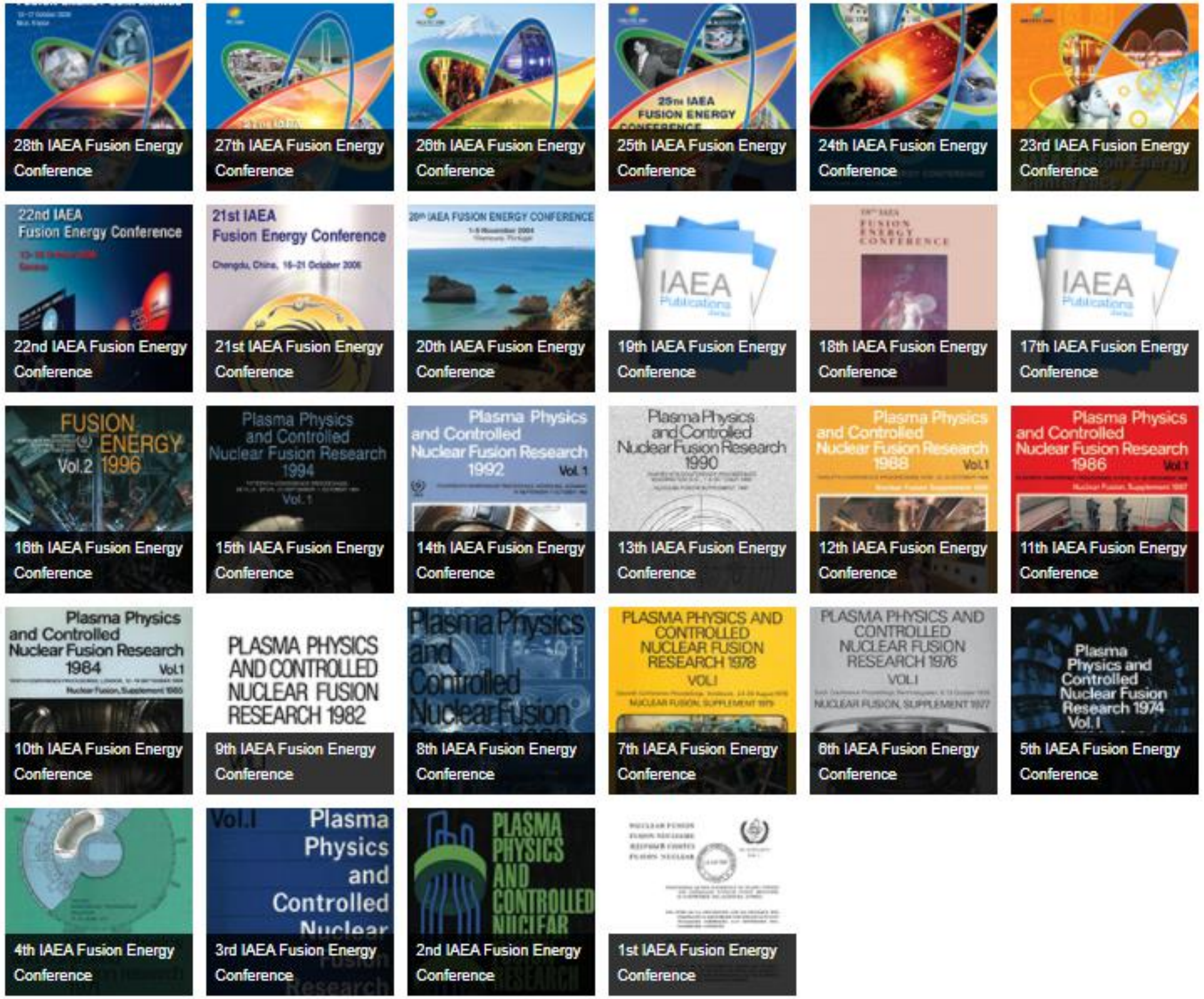
Fusion at IAEA. Leading events in Fusion

Fusion Energy Conference (FEC)

- **Premier event in the Field**
- **Established in 1961**

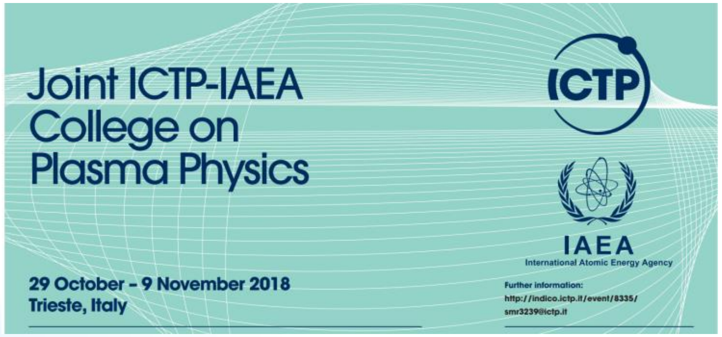
TOPICS

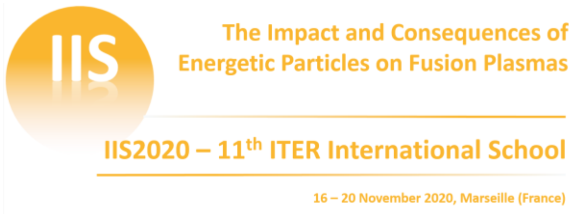
- Magnetic Fusion Experiments
- Magnetic Fusion Theory and Modelling
- Fusion Energy Technology
- Inertial Fusion Energy
- Innovative and Alternative Fusion Concepts



Fusion at IAEA: Events in Cooperation. Education & Training

- First Costa Rica **Training Workshop** in Fusion for the Latin-American Region, 25-29 Nov. 2019, Cartago, Costa Rica
- 6th ASEAN **School** on Plasma and Nuclear Fusion (ASPNF2020) and SOKENDAI Winter School, Nakhon Si Tammarat, **Thailand,** January 27 -31, 2020
- St. Petersburg Polytechnic-SOKENDAI **Summer School** on Plasma Physics and Controlled Fusion, Russia, July 13-24, 2020;
- The 11th **ITER International School**, hosted by Aix-Marseille University in Aix-en-Provence, France, 20 to 24 July 2020
- Joint ICTP/IAEA College on Plasma Physics, Trieste (since 1970)





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Conclusions

- **Energy consumption is growing – Net zero emission needs to be reached**
- **Fusion principles are known since the beginning of 20th century**
- **Scientific and Technical challenges are still present**
- **Progress is being done to close the gaps**
- **IAEA provides a unique platform to enable international collaboration and approached to support the development of fusion**

*"**When** will the first fusion power plant be built?"*

*“When there is great **need** for it.”*
L. Artsimovich

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Time for questions