



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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IAEA



COLEGIO DE INGENIEROS DEL PERÚ

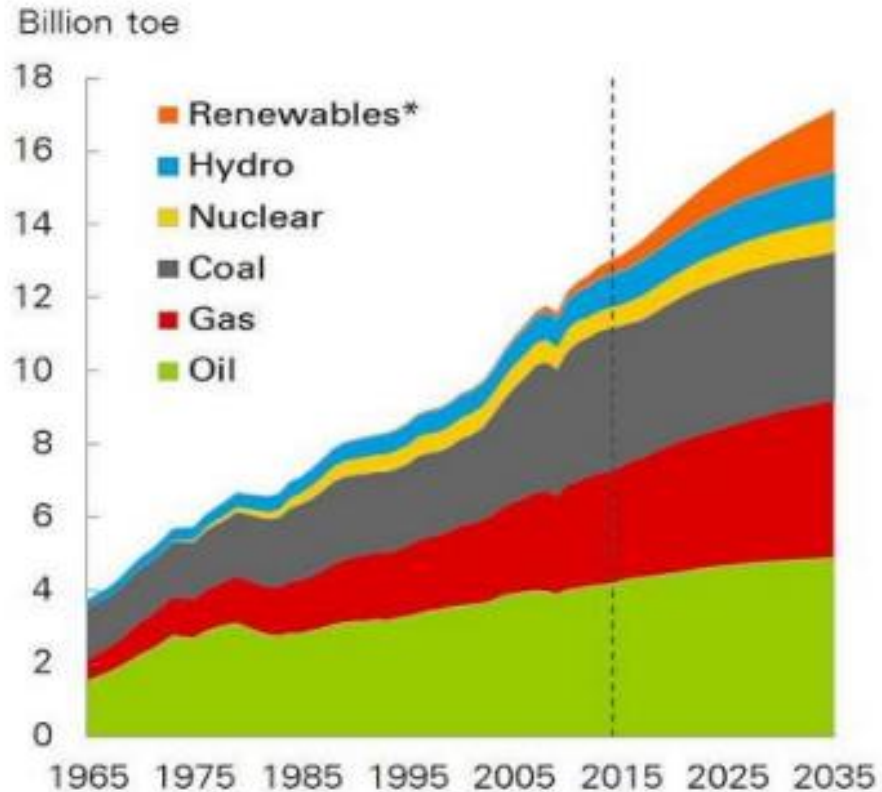
Outline

- 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



Energy consumption projection – next 15 years

Primary energy consumption by fuel



*Renewables includes wind, solar, geothermal, biomass, and biofuel

2017 Energy Outlook

COP26
THE GLASGOW
CLIMATE PACT

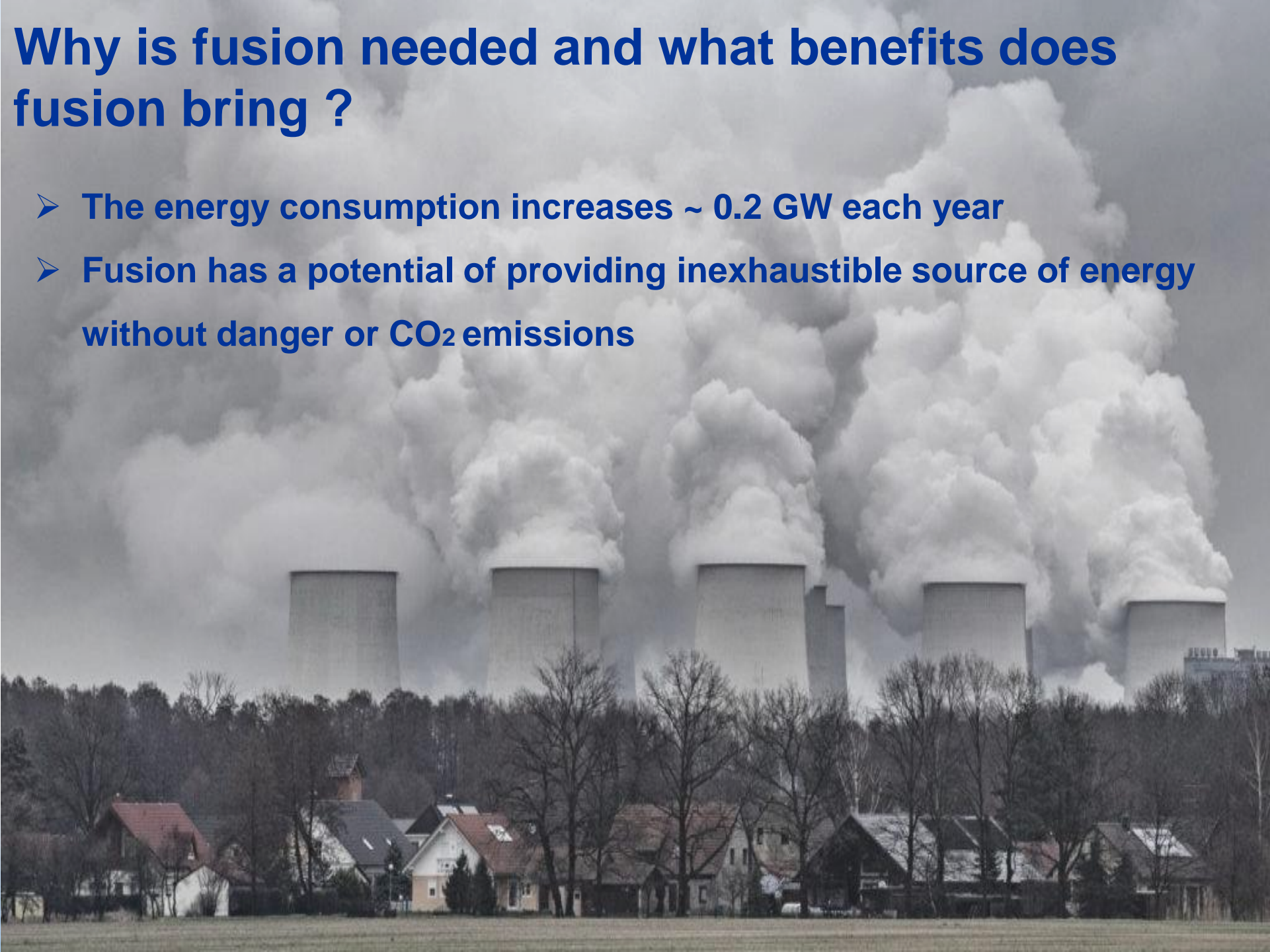
- **Mitigation** - reducing emissions
- **Adaptation** - helping those already impacted by climate change
- **Finance** - enabling countries to deliver on their climate goals
- **Collaboration** - working together to deliver even greater action

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

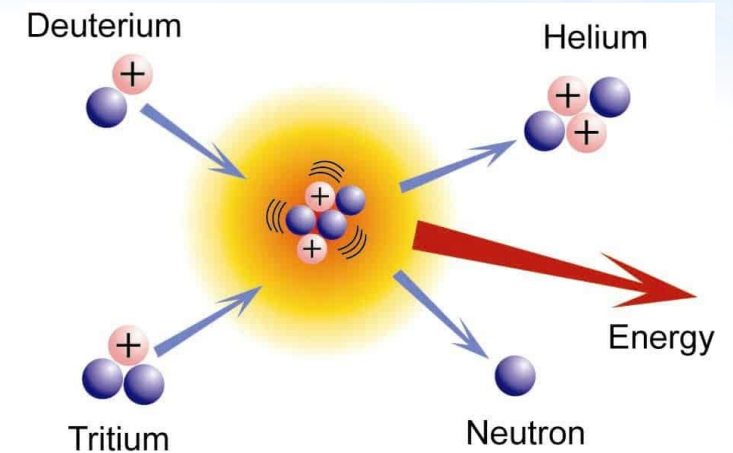
Why is fusion needed and what benefits does fusion bring ?

- The energy consumption increases ~ 0.2 GW each year
- Fusion has a potential of providing inexhaustible source of energy without danger or CO₂ 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

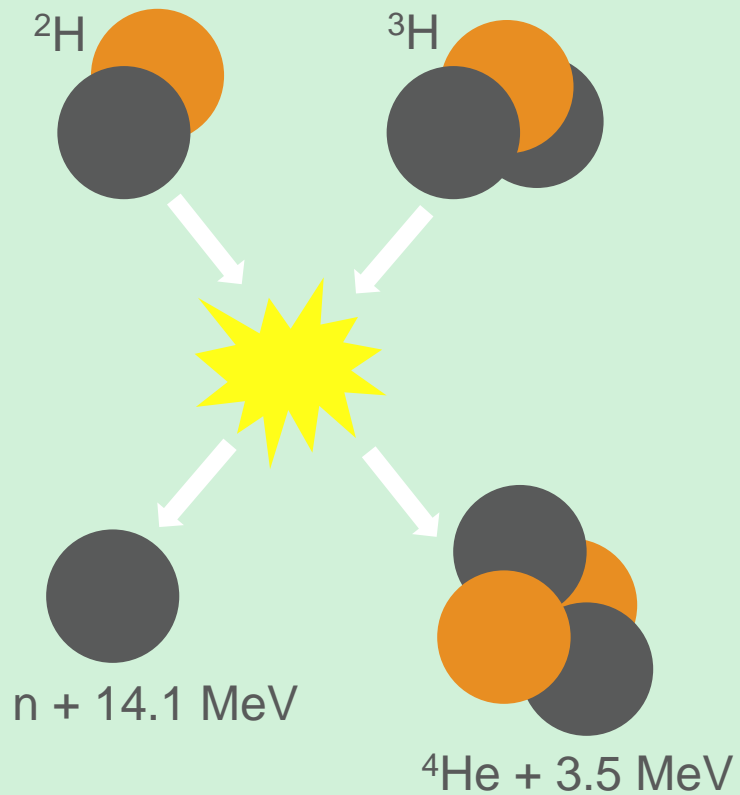
Energy released

- 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

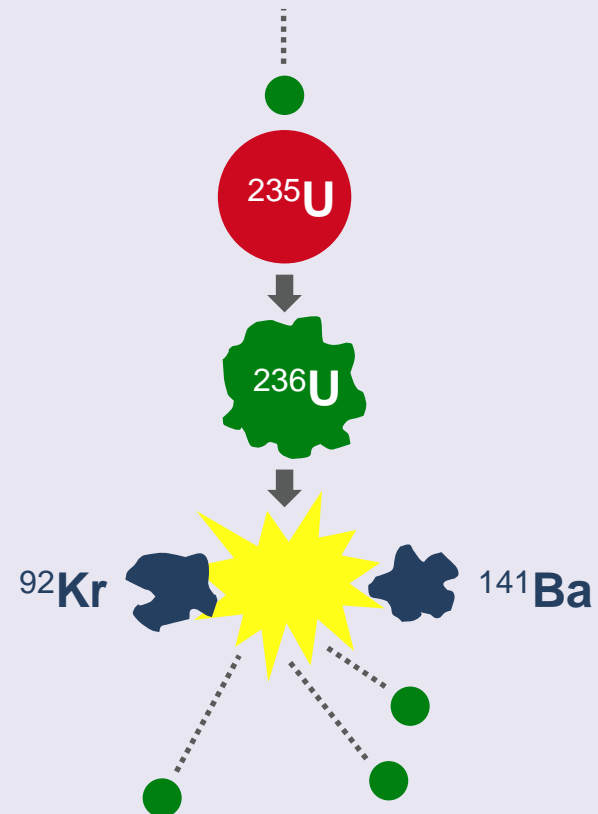
FUSION

Two small nuclei bind making a bigger one.



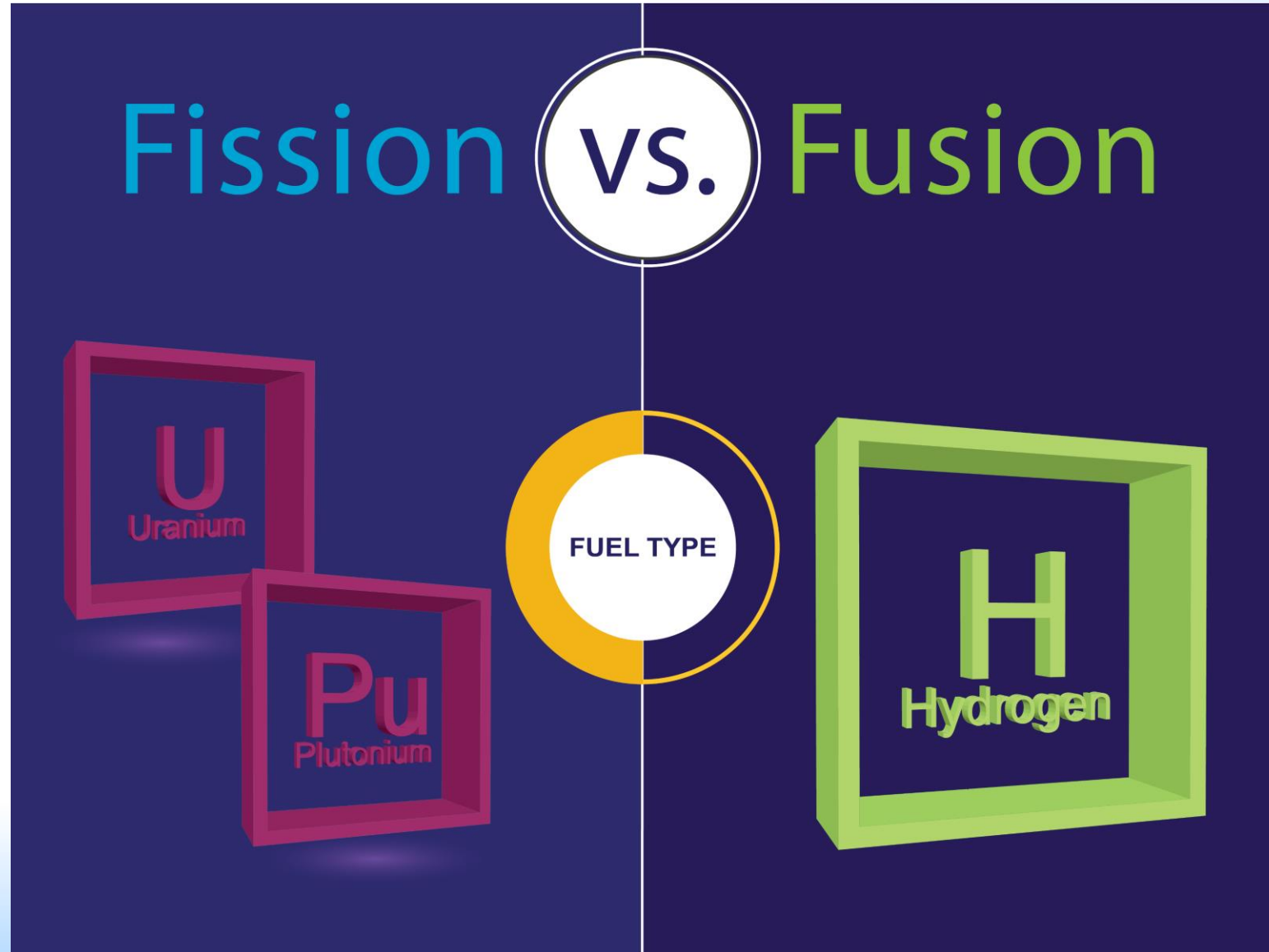
FISSION

One large nucleus breaks up into smaller ones.



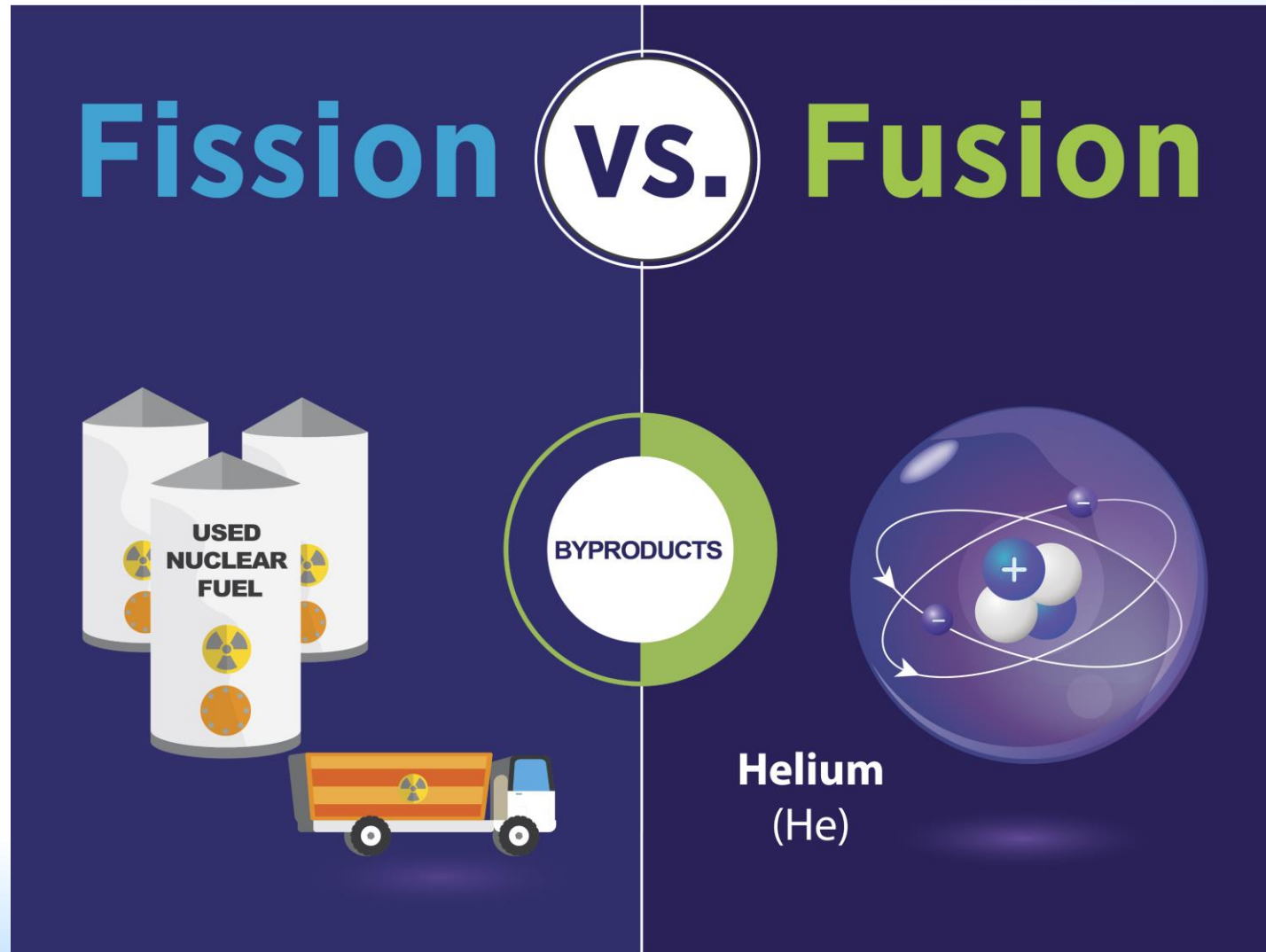
Basics of fusion

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



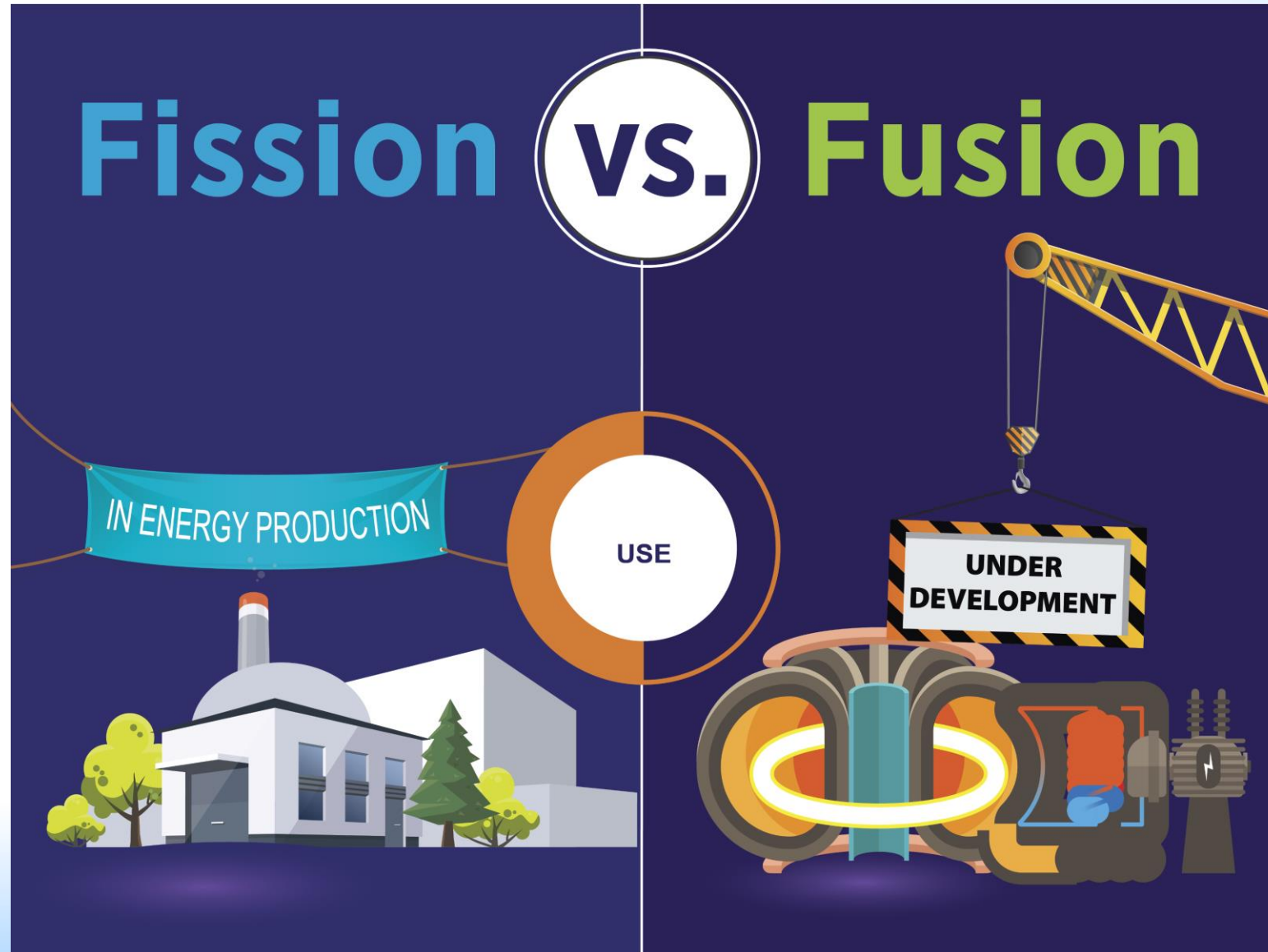
Basics of fusion

➤ 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

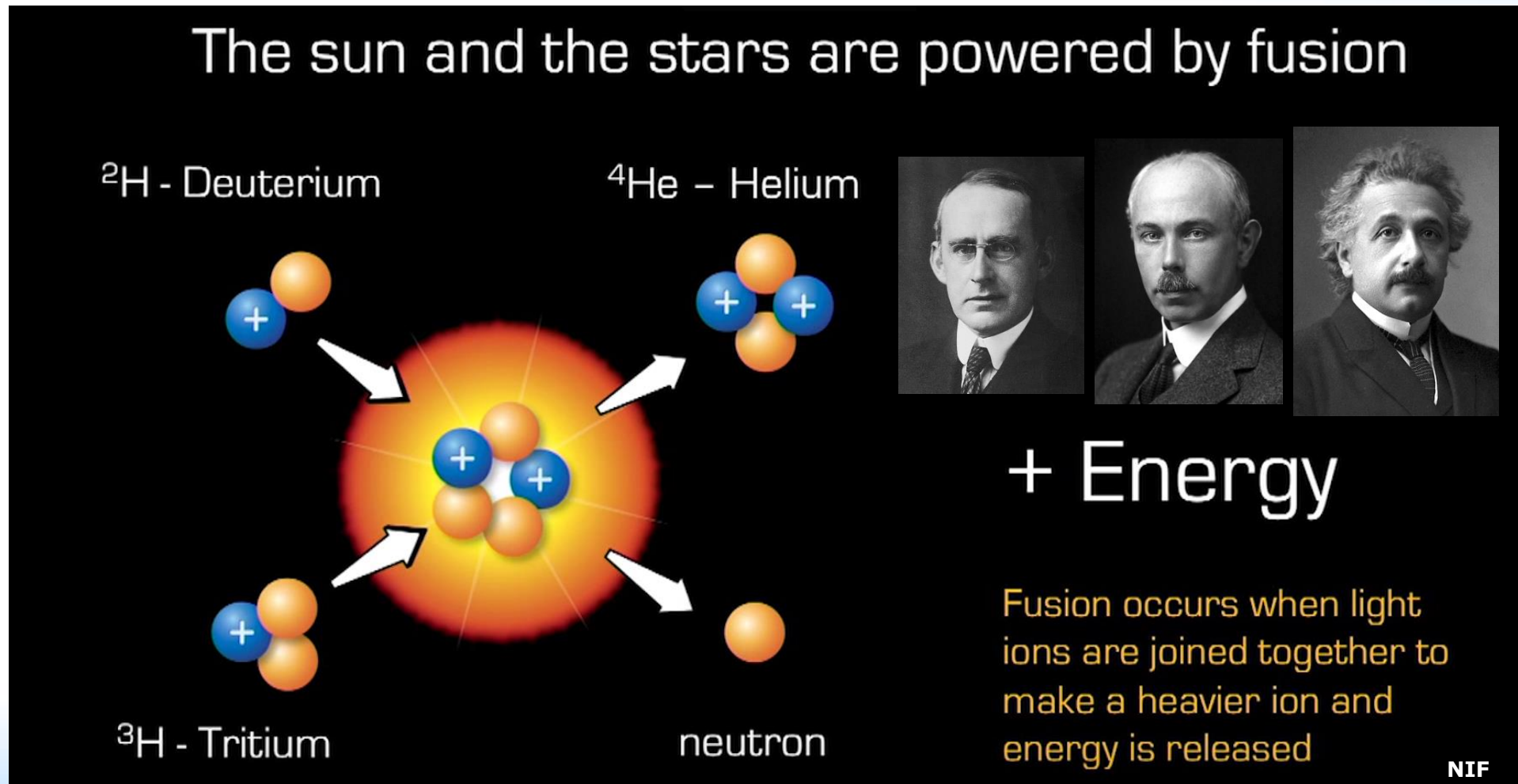
Unlimited fuel

Reliable

Fusion – WHEN?

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

The sun and the stars are powered by fusion



The diagram illustrates the fusion process. On the left, two isotopes of hydrogen are shown: Deuterium (^2H) and Tritium (^3H). Deuterium is represented by one blue sphere (proton) and one orange sphere (neutron). Tritium is represented by one blue sphere (proton) and two orange spheres (neutrons). Arrows point from these two isotopes towards a central glowing orange sphere representing the fusion reaction. From this central sphere, two arrows point outwards to the products: Helium (^4He) and a neutron. Helium is shown as two blue spheres (protons) and two orange spheres (neutrons). The neutron is a single orange sphere. To the right of the diagram are three black and white portraits of scientists: Arthur Eddington, Frederick Aston, and Albert Einstein. Below the portraits, the text '+ Energy' is written in large white font. At the bottom right, a text box explains: 'Fusion occurs when light ions are joined together to make a heavier ion and energy is released'. The NIF logo is in the bottom right corner.

^2H - Deuterium

^4He - Helium

^3H - Tritium

neutron

+ Energy

Fusion occurs when light ions are joined together to make a heavier ion and energy is released

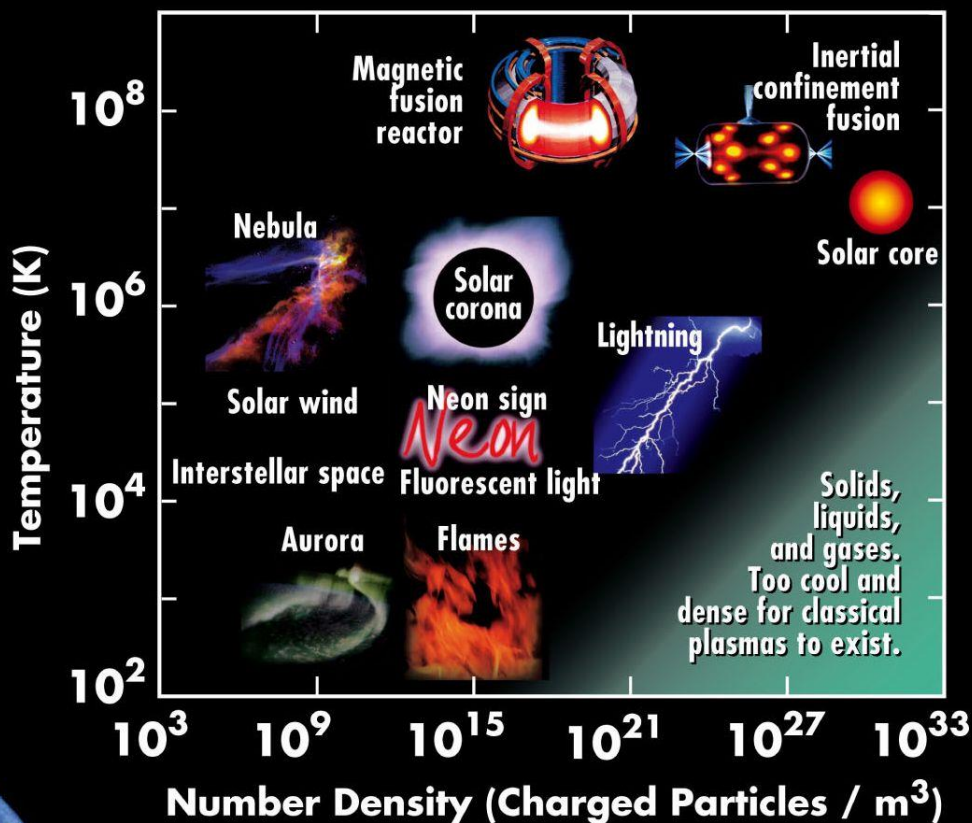
NIF

Learning from the Sun – PLASMA

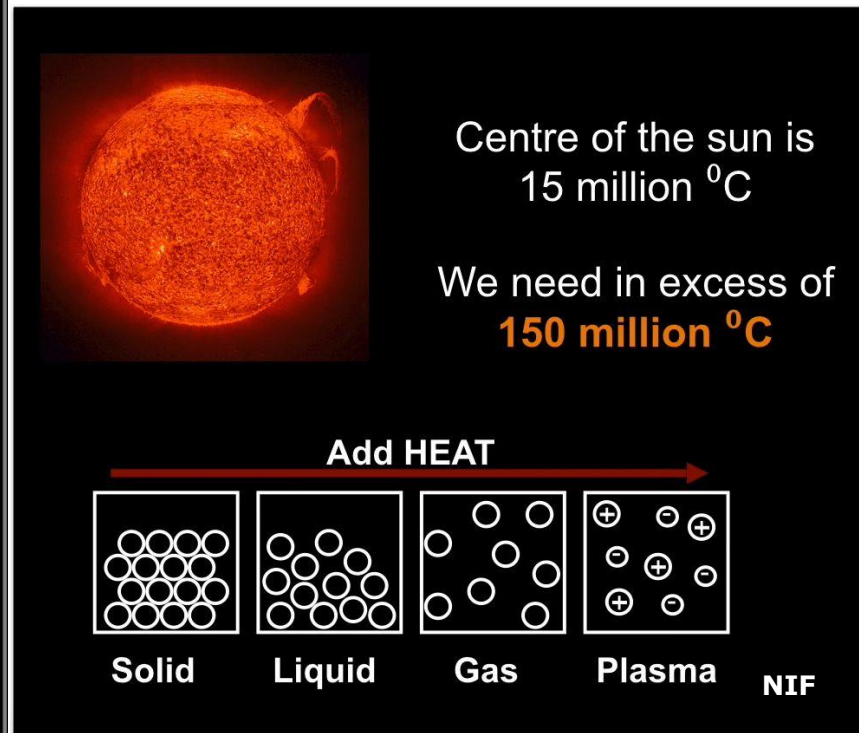
PLASMAS – THE 4th STATE OF MATTER

CHARACTERISTICS OF TYPICAL PLASMAS

Plasmas consist of freely moving charged particles, i.e., electrons and ions. Formed at high temperatures when electrons are stripped from neutral atoms, plasmas are common in nature. For instance, stars are predominantly plasma. Plasmas are a “Fourth State of Matter” because of their unique physical properties, distinct from solids, liquids and gases. Plasma densities and temperatures vary widely.



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




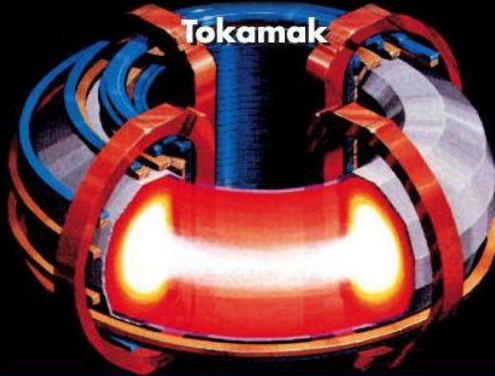

Tapping the Energy – CONFINEMENT

CPEP

CREATING THE CONDITIONS FOR FUSION

PLASMA CONFINEMENT AND HEATING

Confinement:
Fusion requires high temperature plasmas confined long enough at high density to release appreciable energy.

Gravity	Magnetic Fields	Inertia
 <p>Star Formation Plasma</p>	 <p>Tokamak</p>	 <p>Laser Beam-Driven Fusion</p>

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).

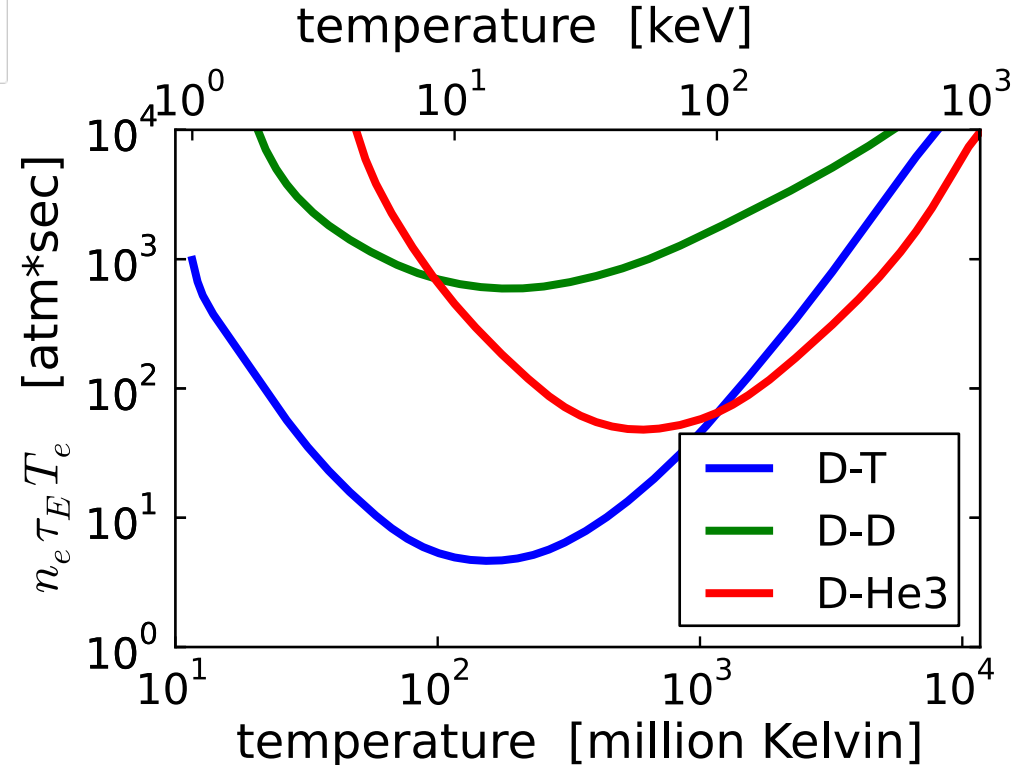
Scientific and Engineering feasibility

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

Scientific and Engineering feasibility

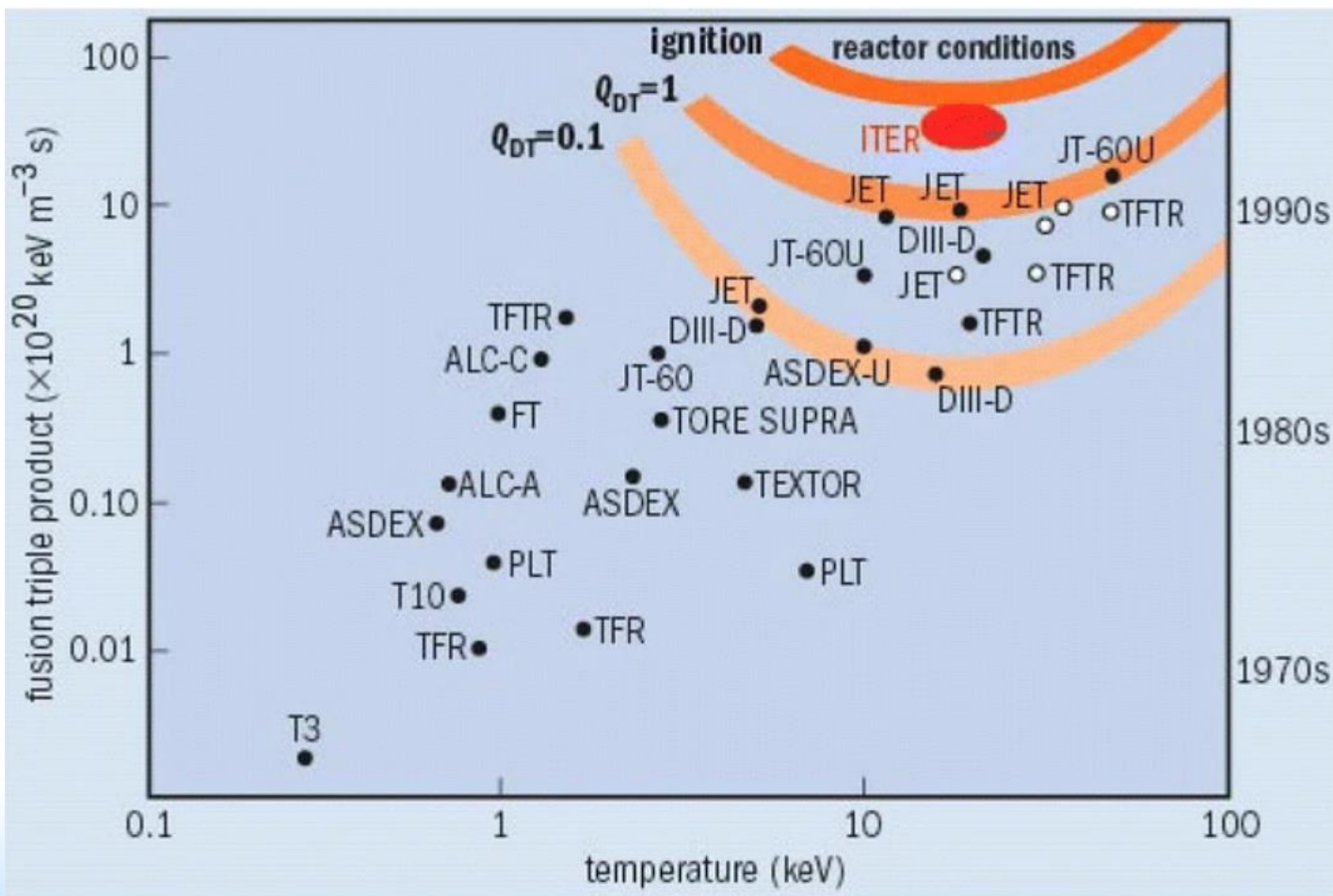


- **Burning plasma** (self-heating plasma): A burning plasma is one in which most of the plasma heating comes from fusion reactions involving thermal plasma ions. In a burning fusion plasma so many fusion processes occur that the energy of the **helium nuclei produced is almost or completely sufficient 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.

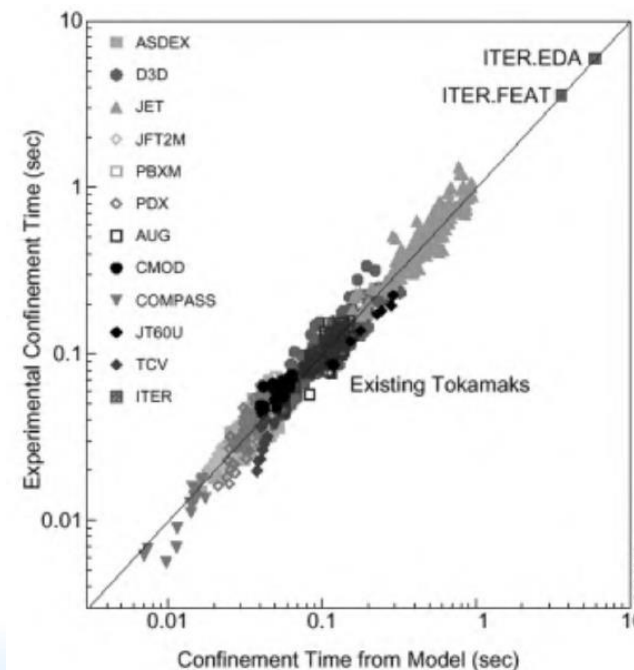
The Sun is a burning plasma that has reached “ignition,” meaning the Sun’s plasma temperature is maintained solely by energy released from fusion.

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

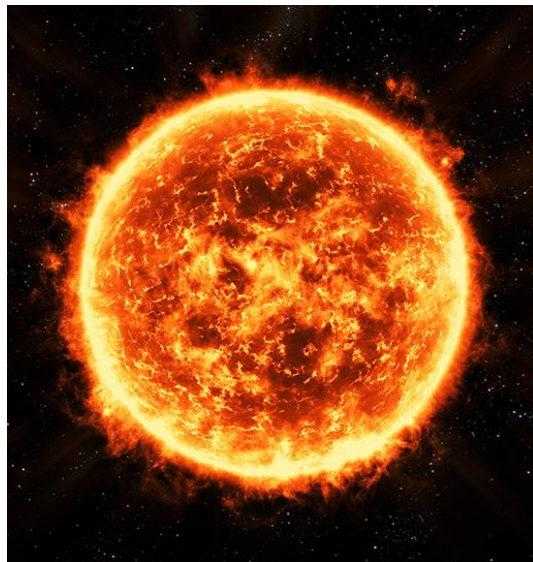


- ~ 4.603 billion years ago - First nuclear fusion reactions began in Our Sun
- 1926 British astrophysicist Arthur Eddington suggested that stars draw their energy from the fusion of hydrogen into helium
- 1934 Rutherford showed experimentally the fusion of deuterium into helium
- Thin man followed by 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.

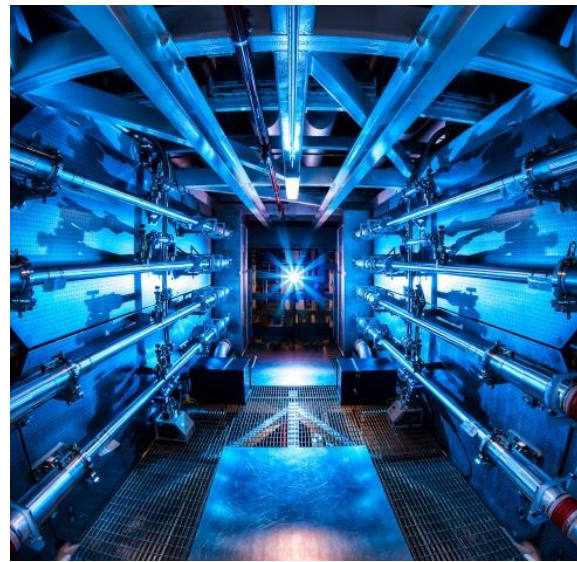
Scientific and Engineering feasibility

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

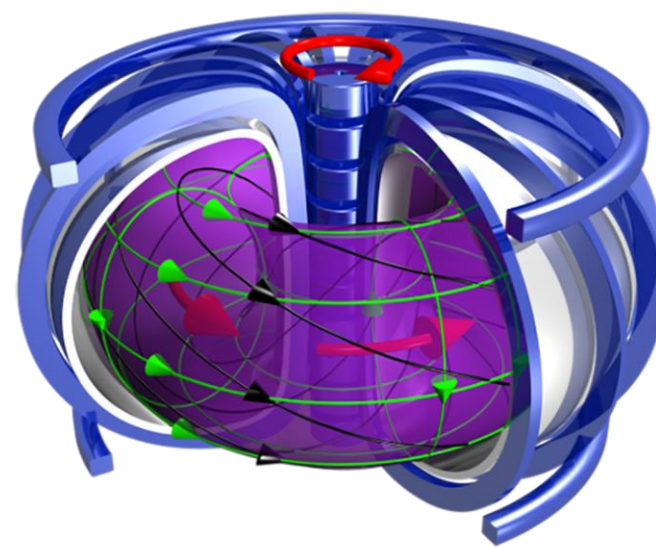
➤ Gravity



➤ Inertial Fusion



➤ Magnetic confinement

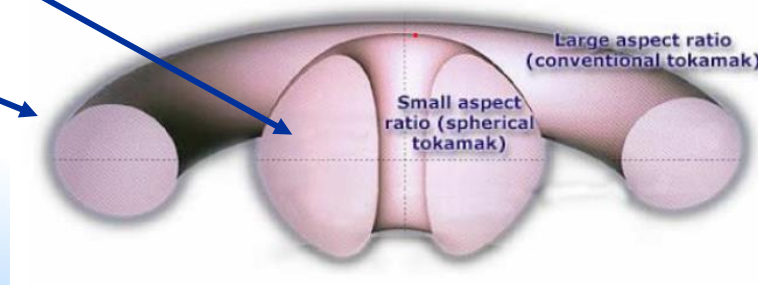
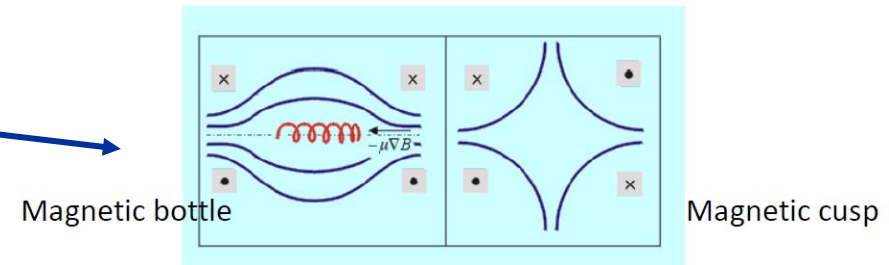
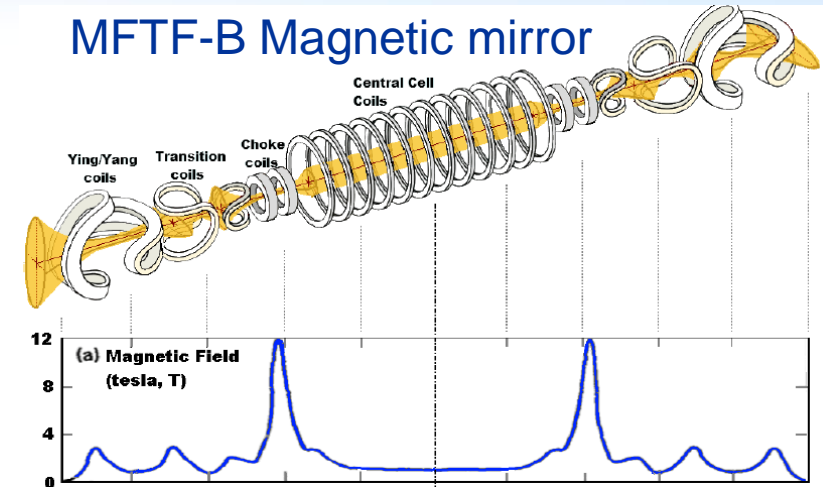


Different concepts

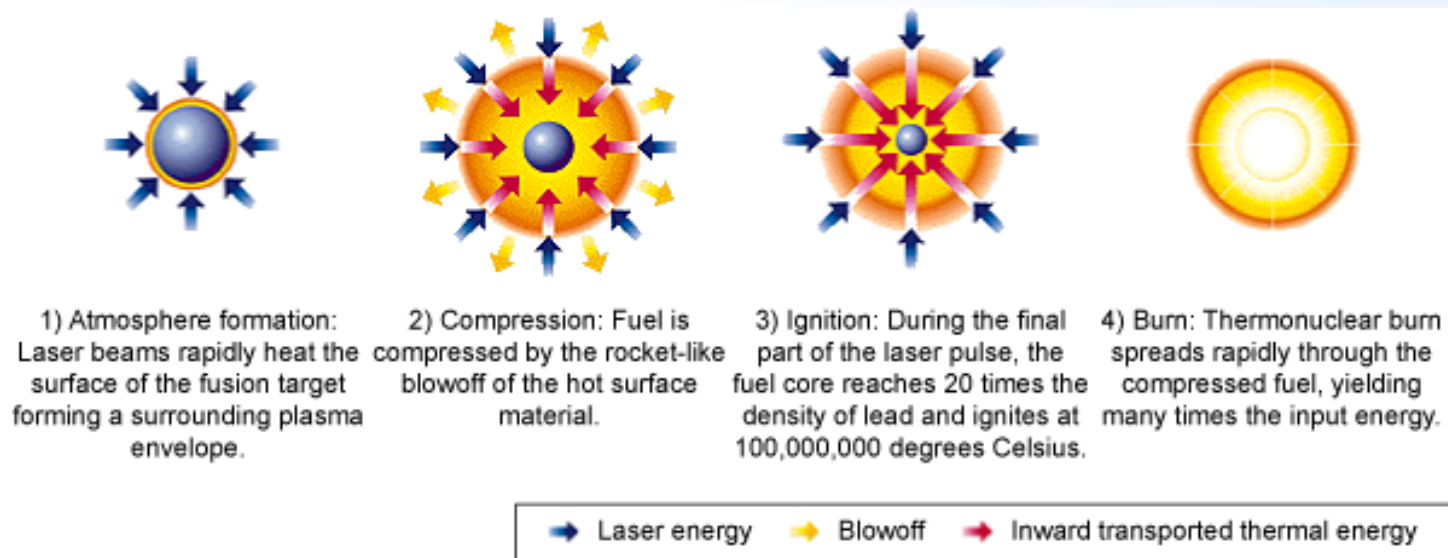
- Inertial fusion systems:
 - H-bombs
 - Particle accelerators
 - Lasers
 - Electrostatic potential wells (fusors)

- Opened systems:
 - Magnetic mirrors
 - Pinches (theta, Z) or magnetized targets
 - Multipoles

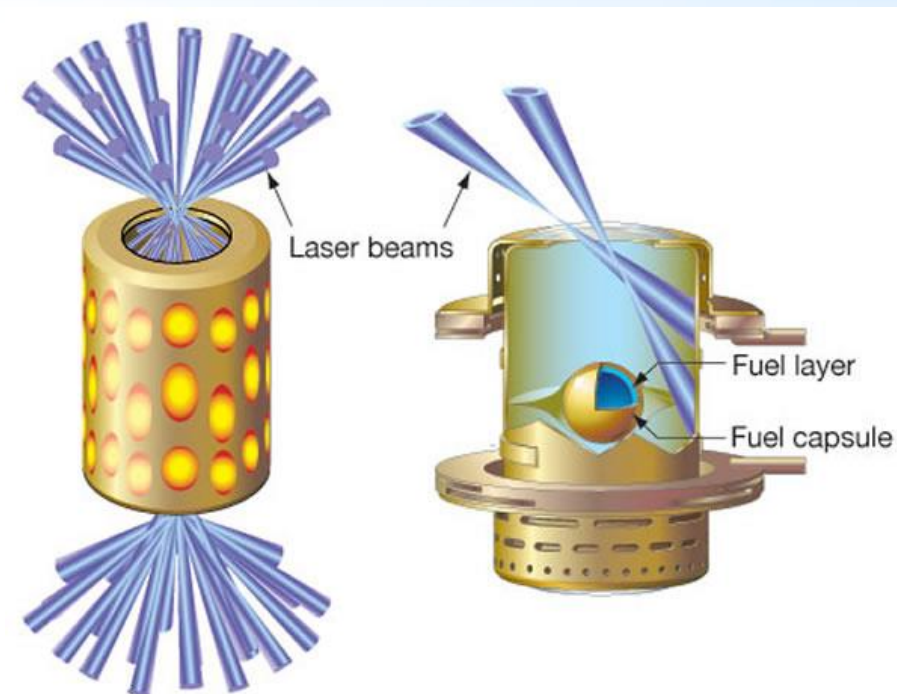
- Closed Systems:
 - Torus of mirrors or cusps
 - Field reverse configurations
 - Spheromaks
 - **Stellarators**
 - **Tokamaks**



Inertial Confinement Fusion (ICF)



- 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.



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.

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**)

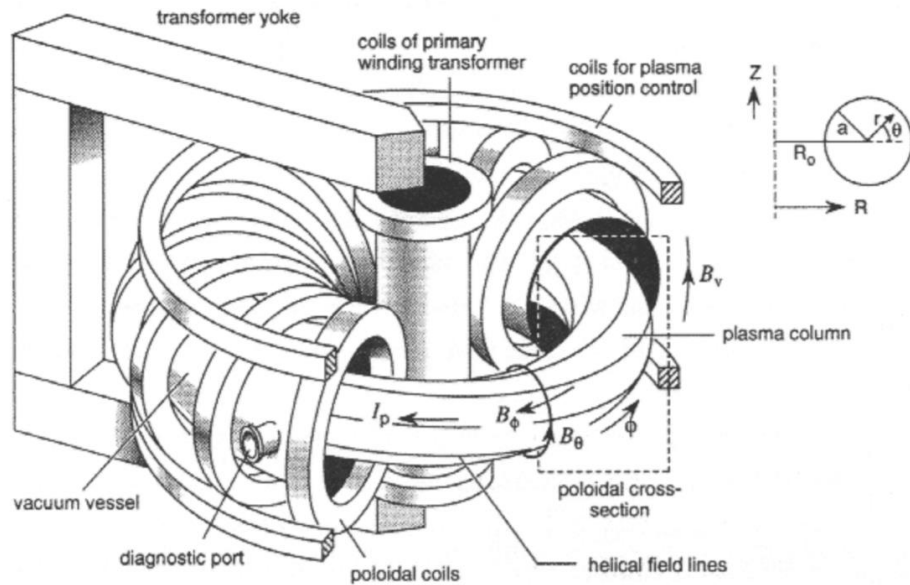
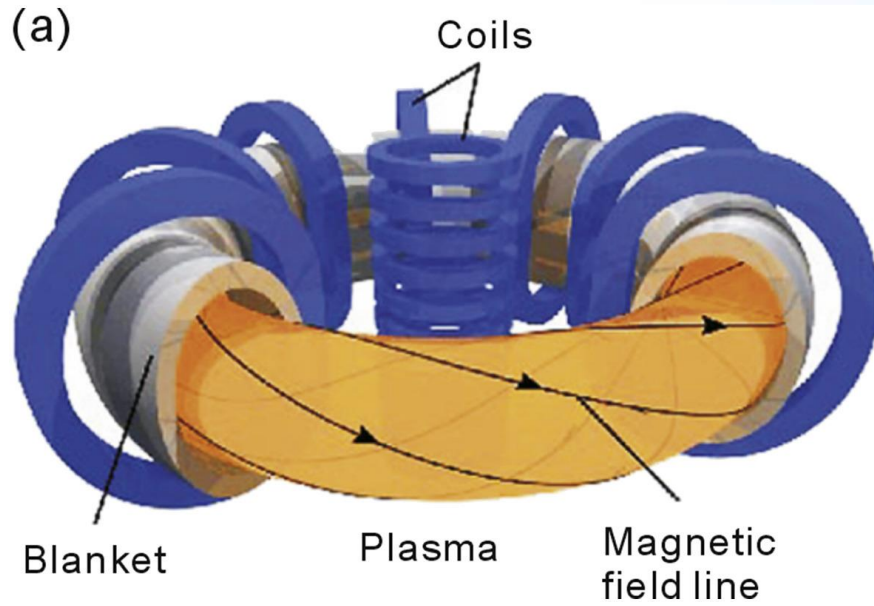
In tokamaks the twisting is produced by a toroidal plasma current and in stellarators by external non-axisymmetric coils.

This brings clear difference for the two systems:

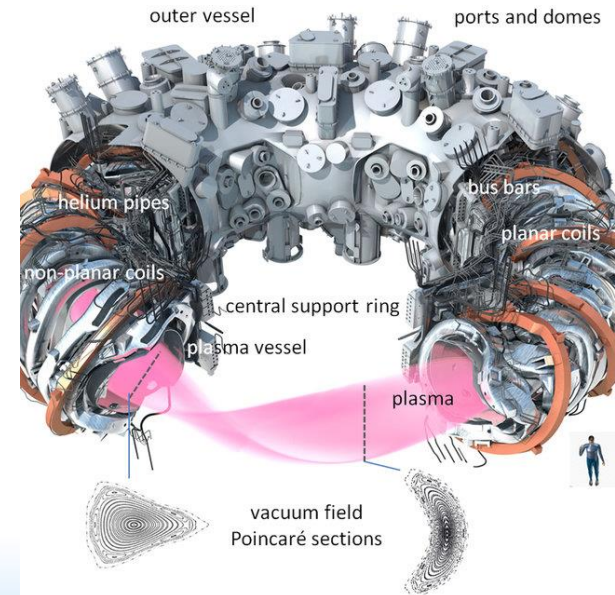
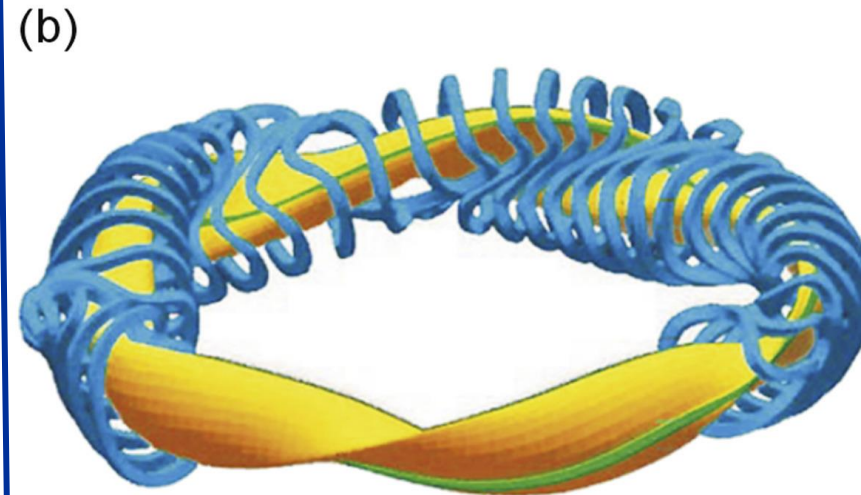
- For example, **tokamaks** are axisymmetric and can confine all collisionless particles and have relatively good plasma confinement. But the toroidal current is normally generated by a transformer, which makes the device vulnerable to current-driven instabilities and difficult to operate in a steady 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

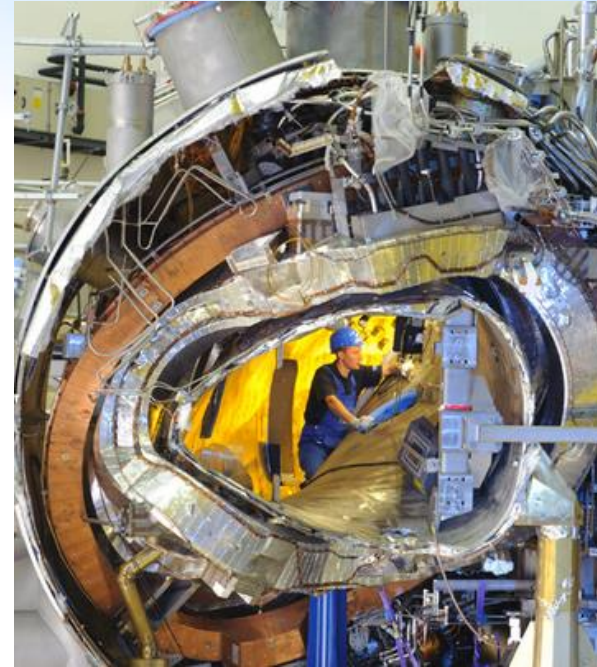


Stellarators



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



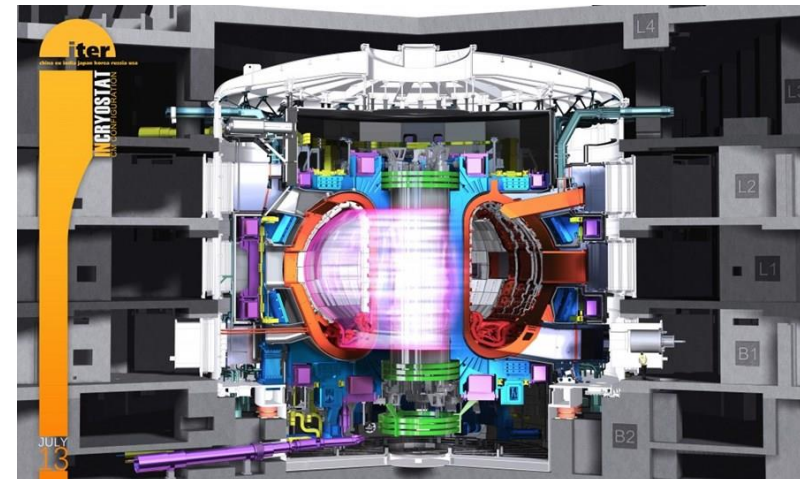
Wendelstein 7-X produced first hydrogen plasma. 3 February 2016

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;

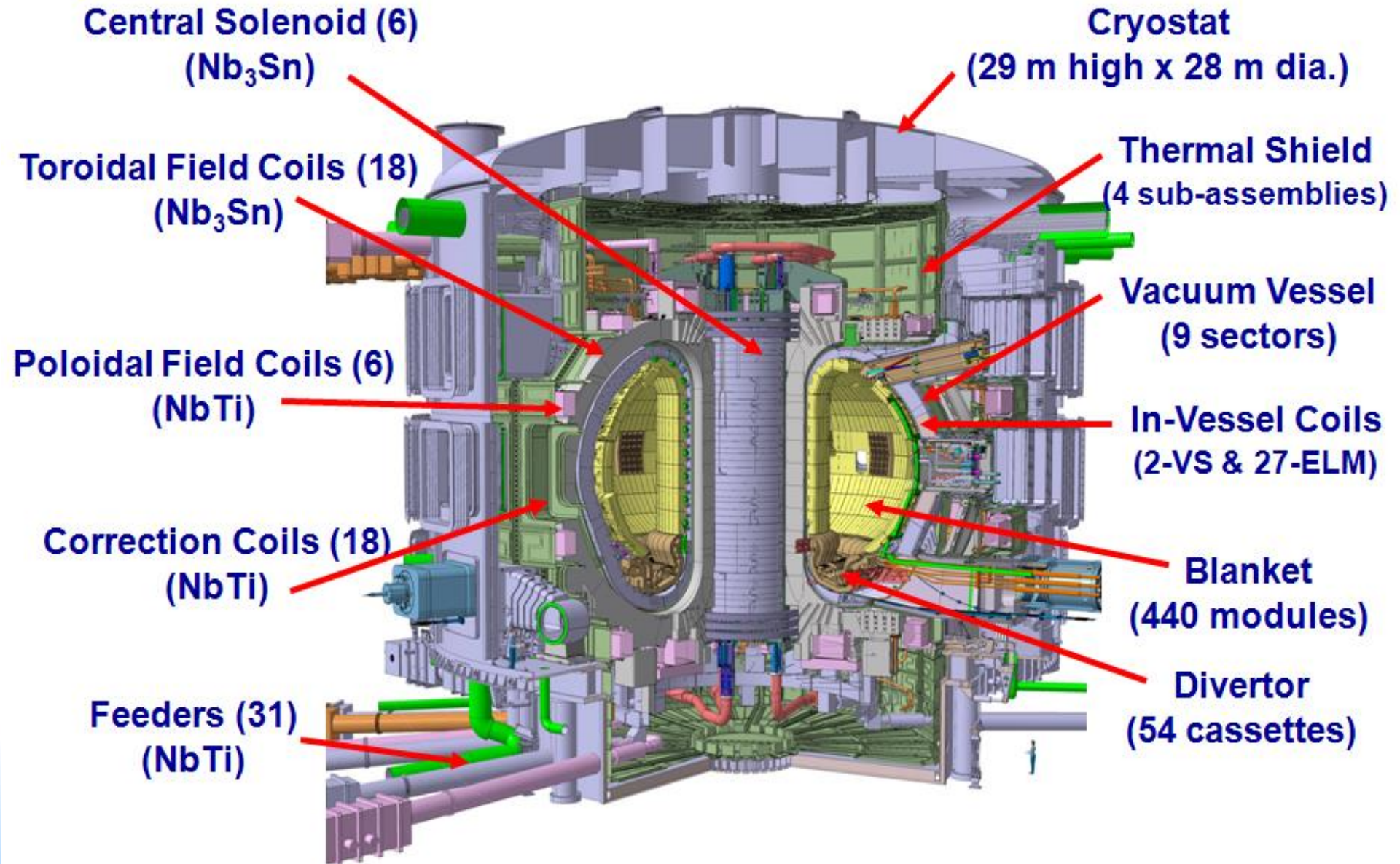


Aerial view, 2021



Tokamak view (simulation)

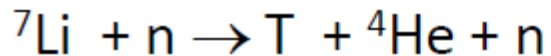
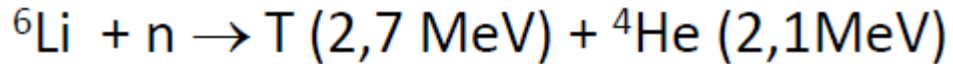
Plasma Physics in a tokamak



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:



- 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.

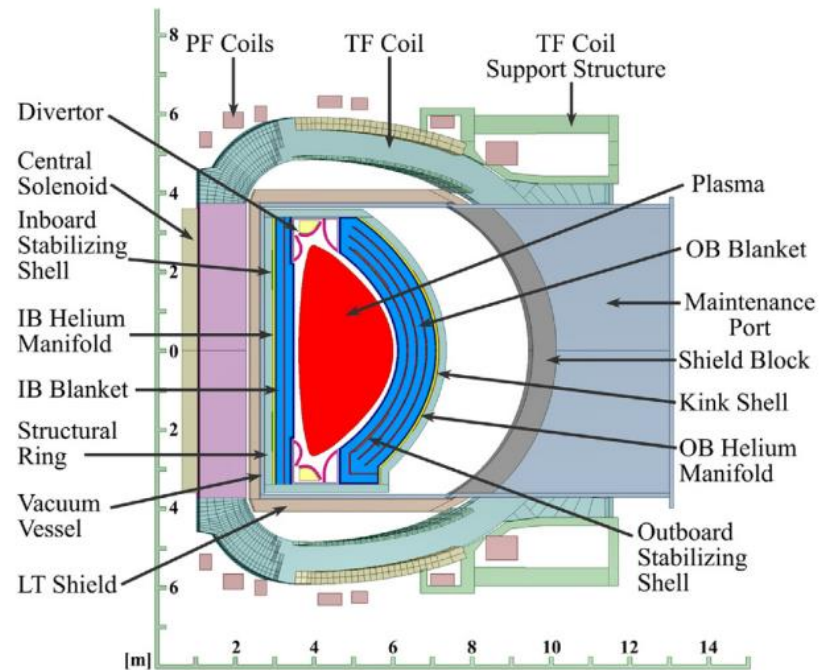
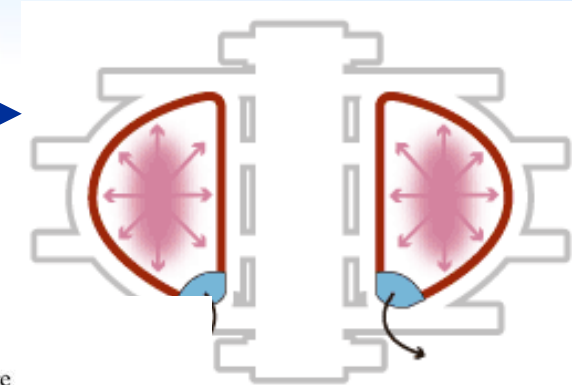
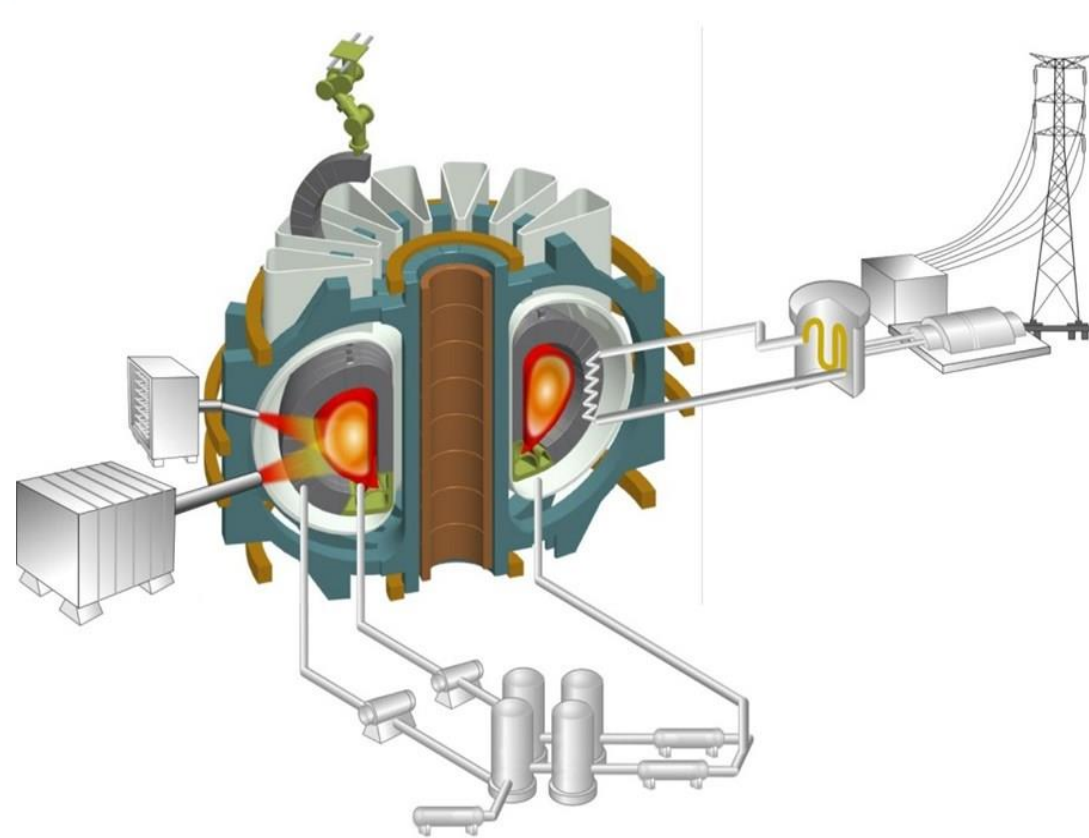


Fig. 1. Layout of the FNSF power core.

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



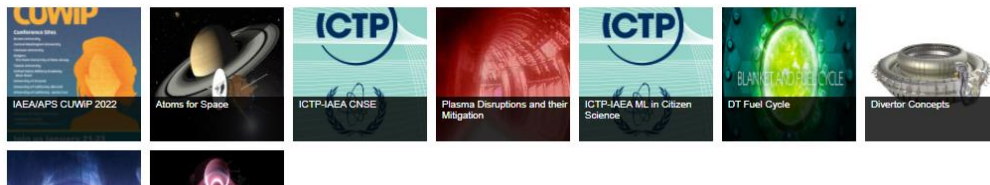
The International Atomic Energy Agency (IAEA) fosters international collaboration and coordination to help close the existing gaps in physics, technology and regulation and move forward in developing the peaceful use of fusion energy. The IAEA's activities in this field cover, among others, plasma physics and fusion power, technologies and material, both for magnetic and inertial fusion. The Fusion Portal is dedicated to all these activities, ranging from **Conferences, Coordinated Research Projects, Meetings, Workshops and Schools**, to providing **News Media and Publications** related to these projects.

FUSDIS

FUSION DEVICE INFORMATION SYSTEM

The Fusion Portal is also home to the IAEA's **Fusion Device Information System (FusDIS)**, containing information on fusion devices public or private with experimental and demonstration designs, which are currently in operation, under construction or being planned, as well as technical data of these devices and country statistics, including research statistics from the Fusion Energy Conference series.

Upcoming Meetings



FusDIS	Tech Data	Country Stats	Org Stats	FEC2020 IDX	FECs IDX	Search Device Name Highlight Device Name		Country Profiles
Total 134	Tokamaks 74	Stellarators/Heliotro.. 13	Laser/Inertial 9	Altern. Concepts 38	Exp 125	Demo 9		<ul style="list-style-type: none"> Tokamaks Stellarators/Heliotrons Laser/Inertial Altern. Concepts
Operating 96			Under construction 9		Planned 29		Public 107	
							Private 26	
							Public-Private 1	
Country	Organization	Device Name	Device Configurati..	Device Type	Device Status	Design	Ownership	
Australia	HB11 Energy	HB11	Laser/Inertial	Laser Fusion	Planned	Exp	Private	
Brazil	Federal University of Espirito Santo	NOVA-FURG	Tokamaks	Conventional Tokamak	Operating	Exp	Public	

Country	F
United States	31
Japan	24
Russia	13
China	10
United Kingdo..	7
France	5
Germany	4
Pakistan	4
Brazil	3
India	3
Iran	3
Italy	3
Republic of K..	3
Canada	2
Costa Rica	2
Czech Republic	2
Spain	2
Switzerland	2
Ukraine	2
Australia	1
Denmark	1
Egypt	1
European Uni..	1
Kazakhstan	1
Libya	1
Portugal	1
Sweden	1
Thailand	1

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

Fusion at IAEA. Leading events in Fusion

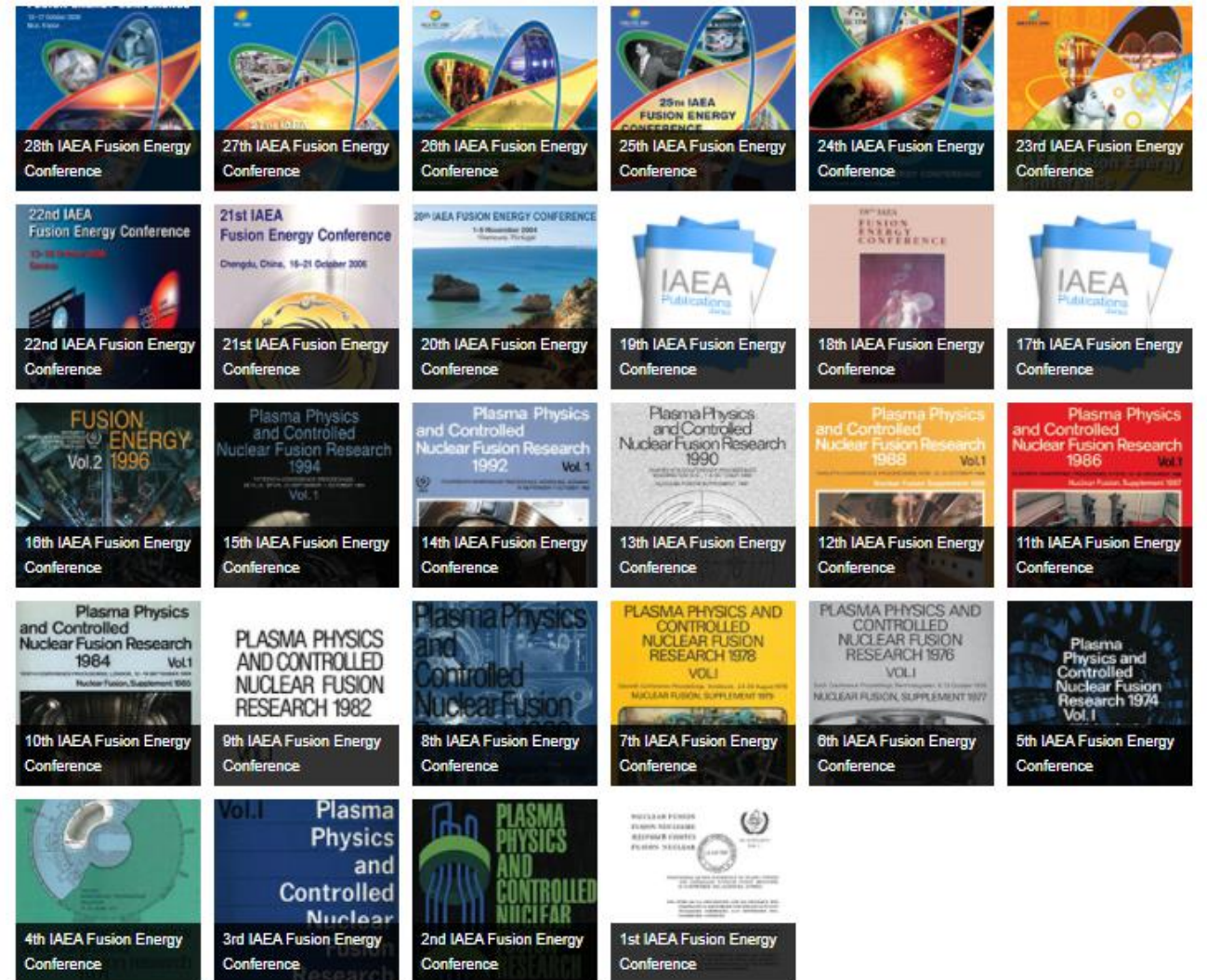


Fusion Energy Conference (FEC)

- Premier event in the Field
- Established in 1961

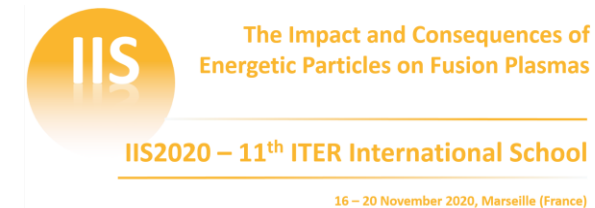
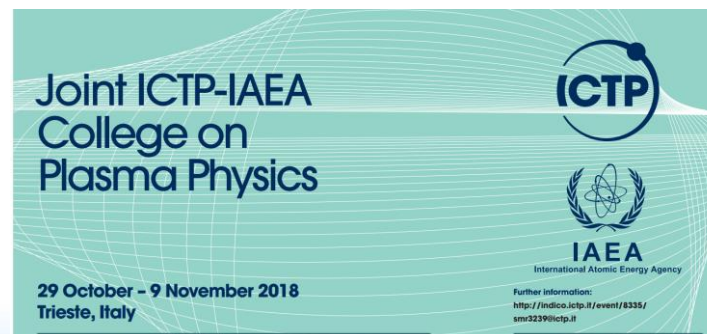
TOPICS

- 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 Thammarat, **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)





IAEA

International Atomic Energy Agency
Atoms for Peace and Development

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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International Atomic Energy Agency

Time for questions

