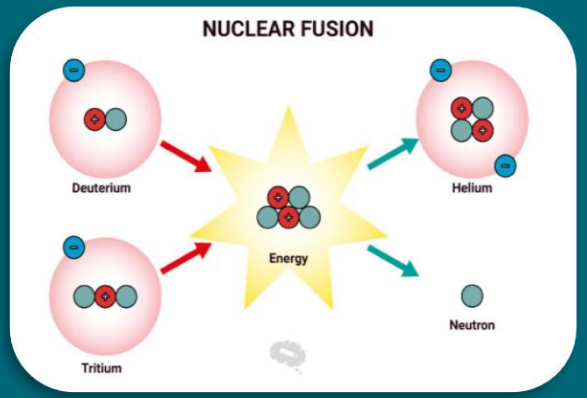
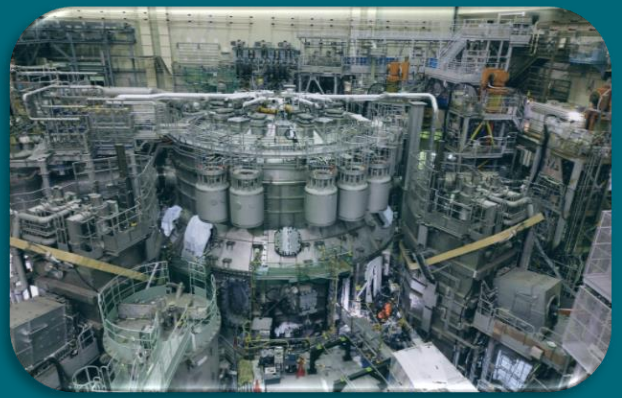
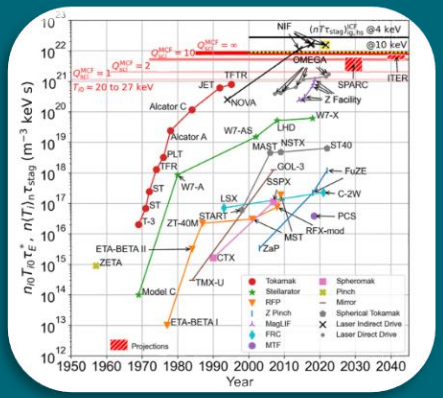








SAPIENZA
UNIVERSITÀ DI ROMA

Tecnologie e stato dell'arte del processo di fusione nucleare

Webinar Consiglio Nazionale degli Ingegneri – 9 Novembre 2026

Alessandro Tassone email: alessandro.tassone@uniroma1.it

- Welcome!
- Fusion energy: a quick introduction
- The case for fusion
- Fundamentals of magnetic fusion technology
- The state of the field in 2026
- Conclusions

Dr. Alessandro Tassone



Education
- M. Eng & PhD, Sapienza University of Rome
- EUROfusion Engineering Grantee

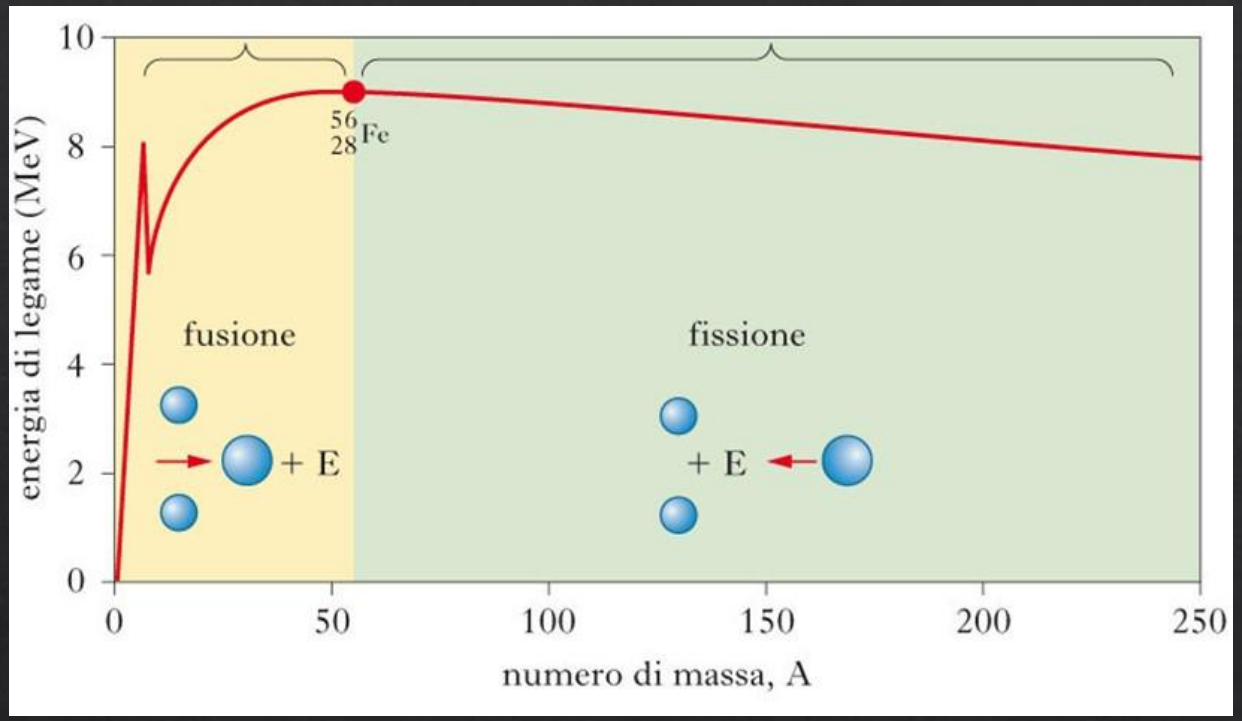
Professional experience
- Research Fellow 06/2018 – 07/2022
- Assistant Professor 08/2022 – 07/2025
- Associate Professor 08/2025 – …

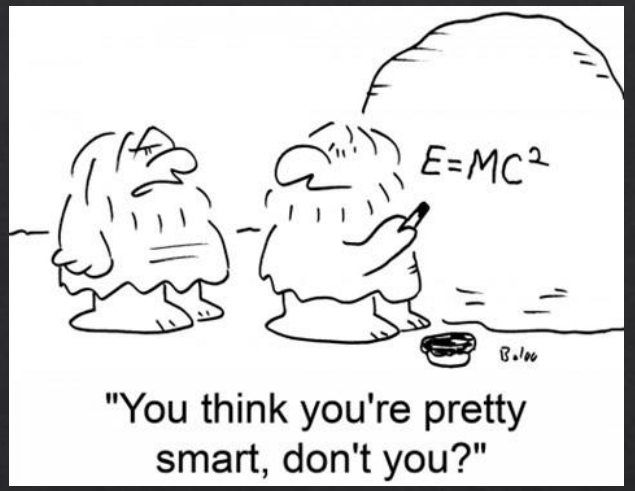
Scientific production
- 45+ papers published in peer-reviewed journals
- 1’000+ citations, H-index 15

Research interests:
Liquid metal magnetohydrodynamics (MHD) and thermal-hydraulics, computational fluid dynamics (CFD), system thermal-hydraulic codes (SYS-TH), nuclear fusion reactors, GEN-IV fission reactors, nuclear reactors and propulsion for space applications

More about me:
- Scopus database profile
- Personal page on Sapienza Course Catalogue and Research Database
- Full resume on course website

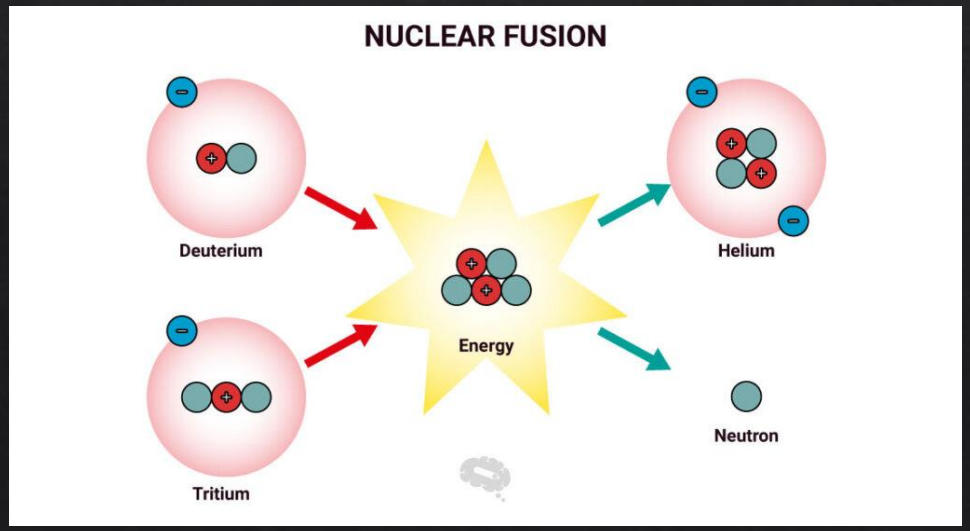
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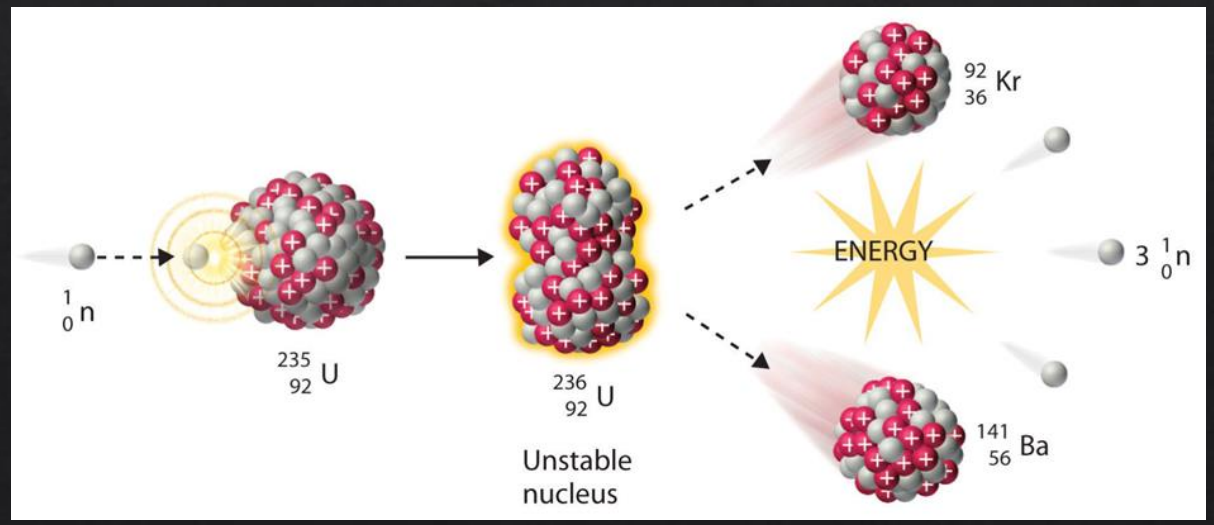




A: mass number (neutrons + protons)

Z: atomic number (only protons)





Electrostatic (Coulomb) repulsion prevents fusion until the nuclei are within the range of action of the **(attractive) strong nuclear force**

$$V_C = \frac{Z_1 Z_2 e^2}{r}$$

Sum of nuclear radii: $r_n = 1.44\times10^{-13}\left(A_1^{1/3} + A_2^{1/3}\right)$ cm

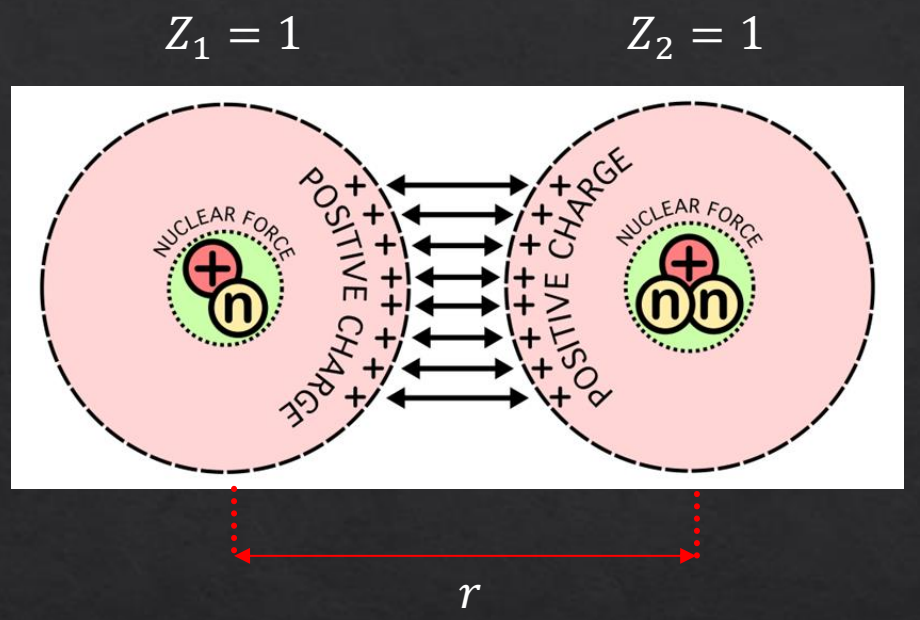
$$V_b = V_C(r_n) \approx \frac{Z_1 Z_2}{A_1^{1/3} + A_2^{1/3}} \text{ MeV}$$

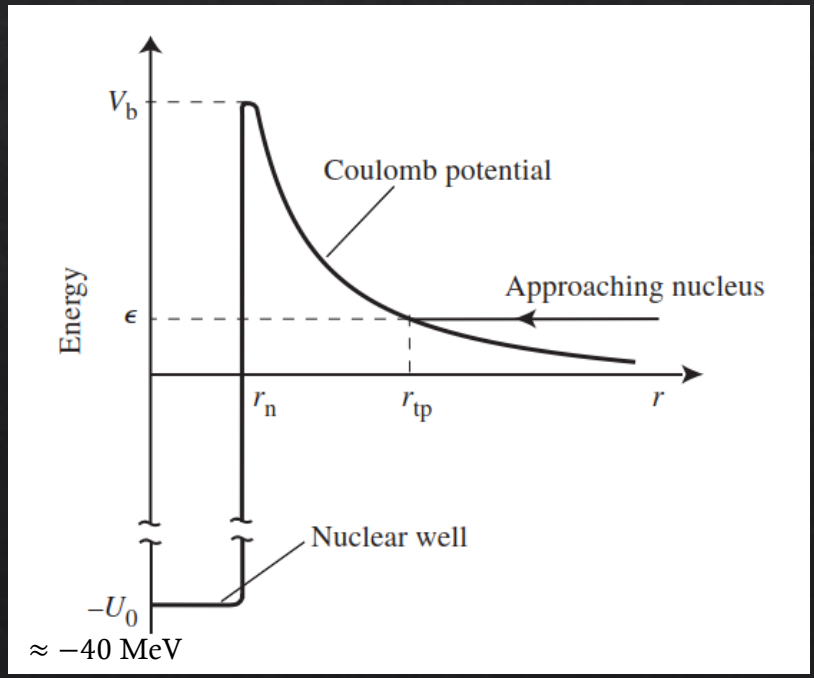
Coulomb barrier peak is typically < 1 MeV.

According to classical mechanics, nuclei can fuse if the **energy of their center of mass**, $\epsilon \geq V_b$, is sufficient to overcome the barrier

$$\epsilon = \frac{1}{2}\frac{m_1 m_2}{m_1 + m_2} v^2$$

Quantum tunneling effects make the Coulomb barrier "transparent", so that fusion can happen also at $\epsilon < V_b$. This phenomenon is strongly favored for low-Z nuclei





Fusion **cross-section** depends strongly on the nuclei involved and on the center-of-mass energy

$\sigma \propto \frac{1}{\epsilon} \times \mathcal{T}$ where $\mathcal{T} = \mathcal{T}(Z_1, Z_2, \epsilon)$ is the transparency factor

1. Deuterium-tritium (**D-T**) reaction

$H_1^2 + H_1^3 \rightarrow He_2^4\ (3.5\ \text{MeV}) + n_0^1\ (14.1\ \text{MeV})$

2. Deuterium-deuterium (**D-D**) reaction

a. $H_1^2 + H_1^2 \rightarrow H_1^3 (1.01\ \text{MeV}) + p_1^1 (3.03\ \text{MeV})$
b. $H_1^2 + H_1^2 \rightarrow He_2^3 (0.82\ \text{MeV}) + n_0^1\ (2.45\ \text{MeV})$

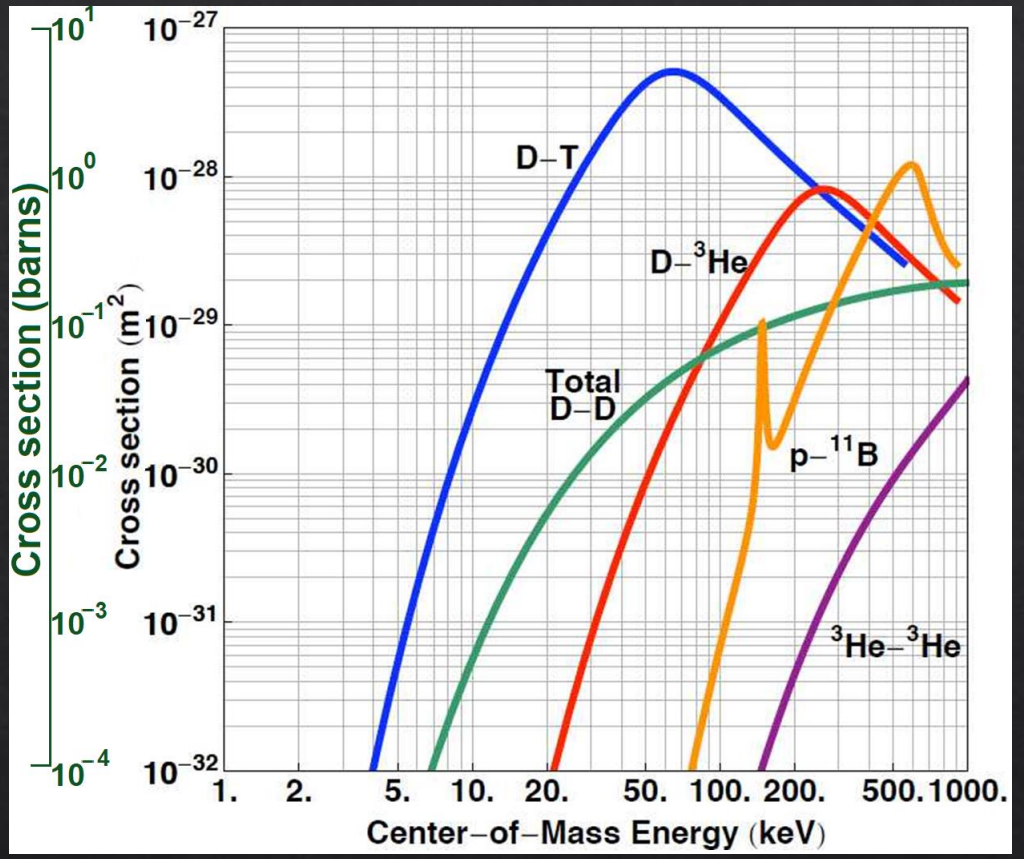
50%-50% probability

3. Deuterium-helium-3 (**D-He^3**) reaction

$H_1^2 + He_2^3 \rightarrow He_2^4\ (3.6\ \text{MeV}) + p_1^1\ (14.7\ \text{MeV})$

4. Proton-boron (**p-B^{11}**) reaction

$p_1^1 + B_5^{11} \rightarrow 3\ He_2^4\ (8.68\ \text{MeV})$



Cross-section as a function of the center-of-mass energy (ϵ) for some notable fusion reactions

$1\ \text{keV} = 10^3 \times 1.60218 \times 10^{-19} \frac{J}{eV}\ eV \approx 1.60218 \times 10^{-16}\ J$

Note that p_1^1 is a proton (nucleus of basic hydrogen or protium) and n_0^1 is a neutron

The **D-T reaction** is characterized by the highest cross-section at the lowest energy and is hence considered the **most feasible**

For a monatomic gas species in thermal equilibrium, the mean kinetic energy is related to the temperature

$$\bar{E} = \frac{3}{2} k_B T \quad \text{where} \quad k_B = 8.6173 \times 10^{-5}\ \text{eV/K}$$

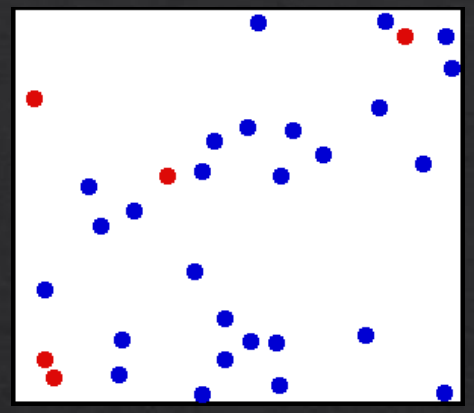
$$\bar{E} = 1 \sim 1000\ \text{keV} \rightarrow 11.6 \times 10^{6} \sim 11.6 \times 10^{9}\ \text{K}$$

At these temperatures, the fusion fuel will be completely ionized. In these **thermonuclear** conditions, matter is found in the so-called **plasma** state

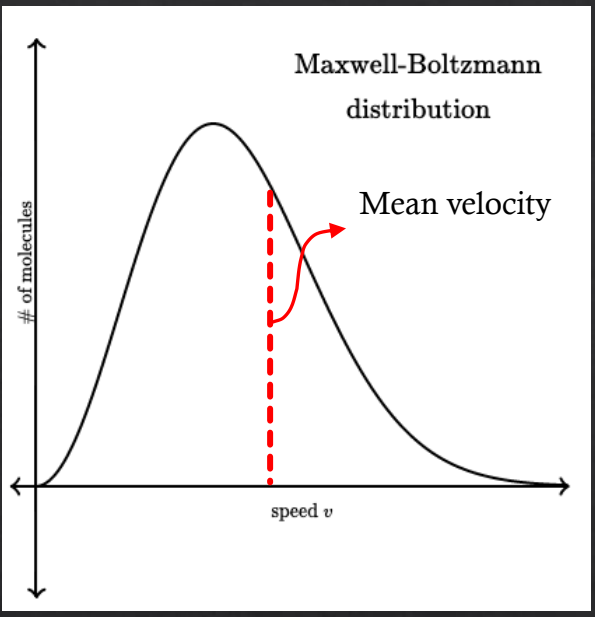
"A quasi-neutral gas composed of charged and neutral particles that exhibit collective behavior"

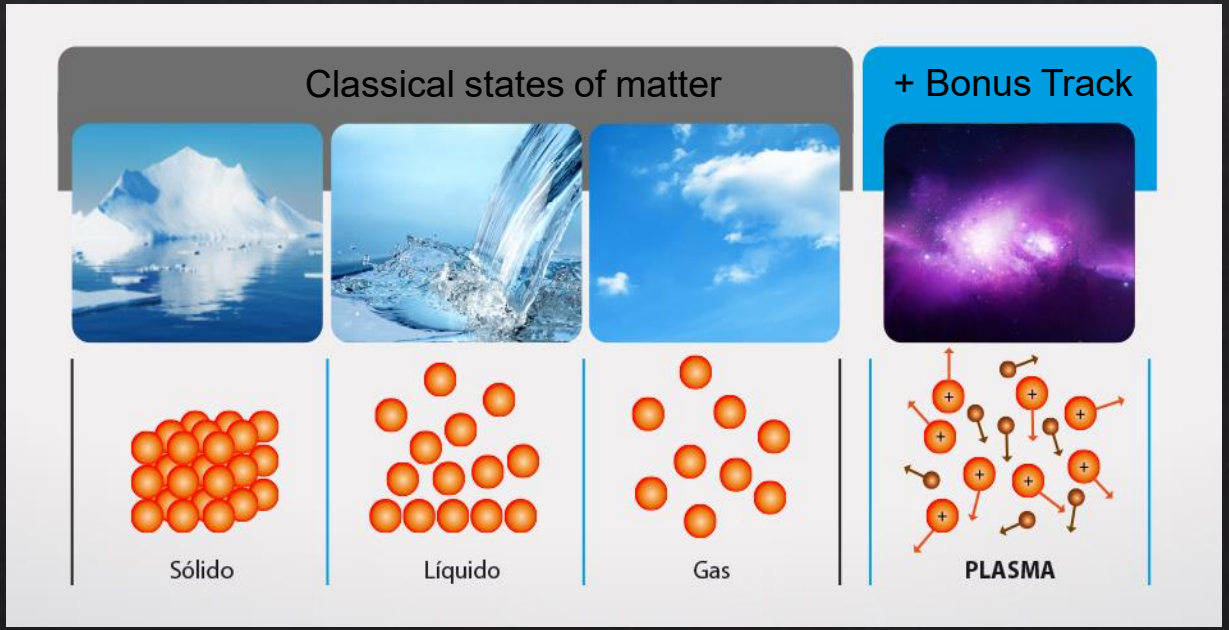
Collective behavior: long-range interactions due to electromagnetic forces, shaping movement and often dominating collisional processes

Quasi-neutral: overall balance of charge



Low-pressure, high-temperature gas





Effectiveness of the reaction is determined by its **reactivity**, defined as the probability per unit time and volume

$$\langle \sigma v \rangle = \int_0^\infty \sigma(v)\, v\, f(v)\, dv \quad \mathrm{cm}^3/\mathrm{s}$$

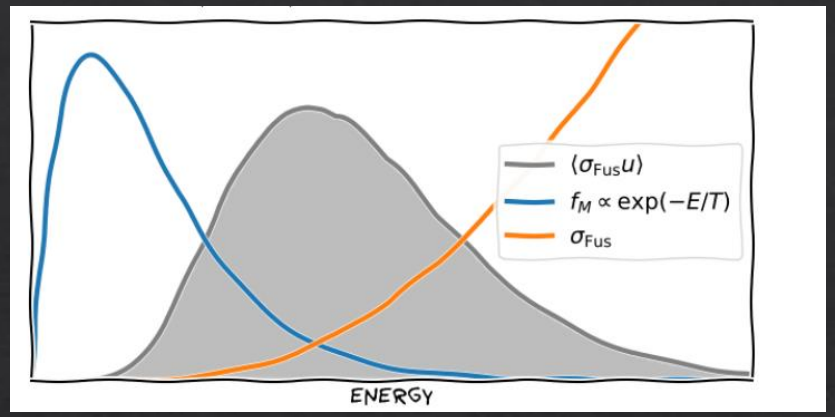
Where v is the particle velocity and $f(v)$ is the velocity distribution

For species in thermal equilibrium, $f(v)$ is the **Maxwell-Boltzmann distribution** (f_M). At a given temperature, particles may exist with a range of velocities (hence energies)

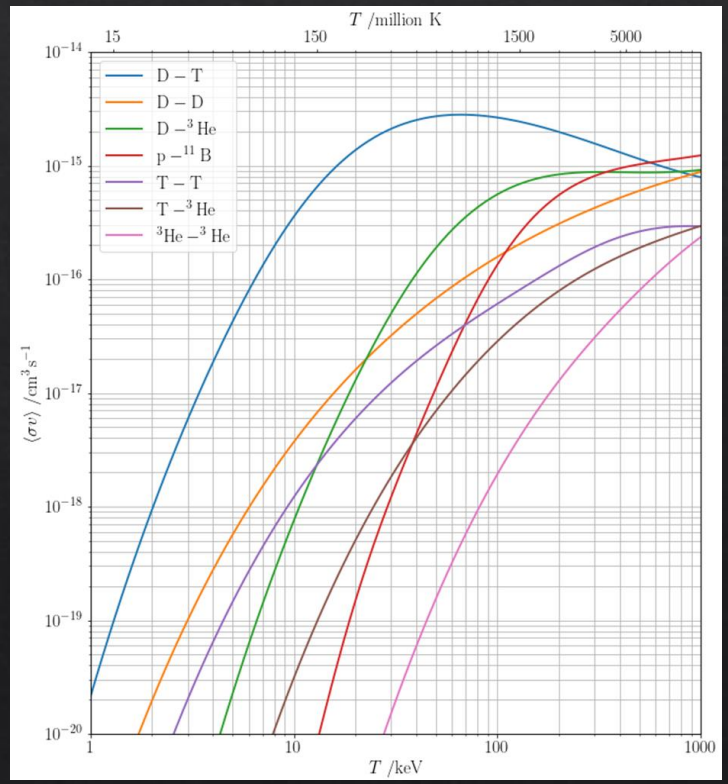
Fusion power (P_{fus}) generated in the plasma depends on the density (n) of the two reacting ion species (n_1, n_2) and the energy produced by the reaction (E_{fus})

$$P_{fus} = \int_V n_1 n_2 \langle \sigma v \rangle E_{fus} dV$$

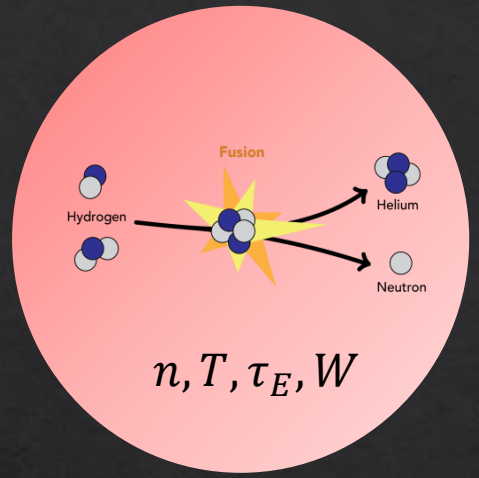
DT is the most effective reaction, having the highest reactivity at the lowest temperature



Credit: Alf Köhn-Seemann, Uni Stuttgart



Reactivity of notable fusion reactions for species in thermal equilibrium at a given temperature. Note that 1 eV ≈ 11’600 K



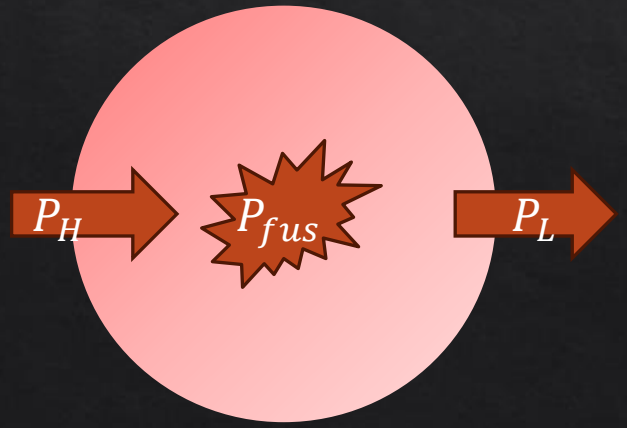
Important plasma parameters:

- Density, n, in $10^{20}\ m^{-3}$
- Temperature, T, in keV
- Volume, V, in m^3
- Thermal energy, W, in J
- Energy confinement time, $\tau = W/P_L$, in s

} Can be expressed for both ions and electrons

Steady-state plasma performance can be described by a combination of density, temperature and energy confinement time or **triple product**

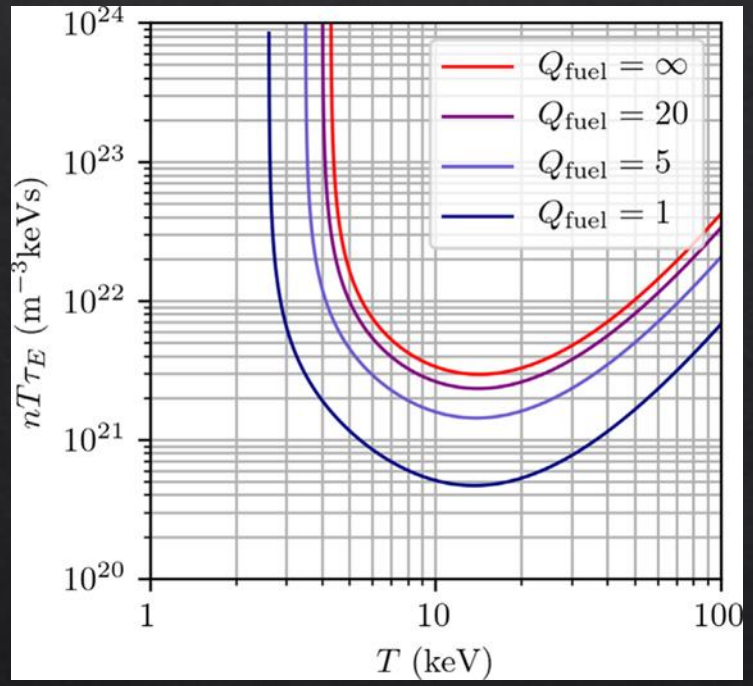
The Lawson criterion gives the minimum triple product needed to achieve performance targets.



Breakeven: a plasma in which **generated fusion power, P_{fus}**, compensates the **(external) heating power, P_H**

Ignition: also called burning plasma regime, $P_{fus} \gg P_H$

Plasma power loss, P_L, typically includes diffusive and radiative mechanisms, excluding any power carried by neutrons, if present



Triple product as a function of operating temperature for several scientific gain factor targets

We can define the **thermal power gain factor** (also called scientific gain factor) as

$$Q_{\text{sci/fuel}} = \frac{\text{Output thermal power}}{\text{Input thermal power}} = \frac{P_{fus}}{P_H} = \frac{5P_\alpha}{P_H}$$

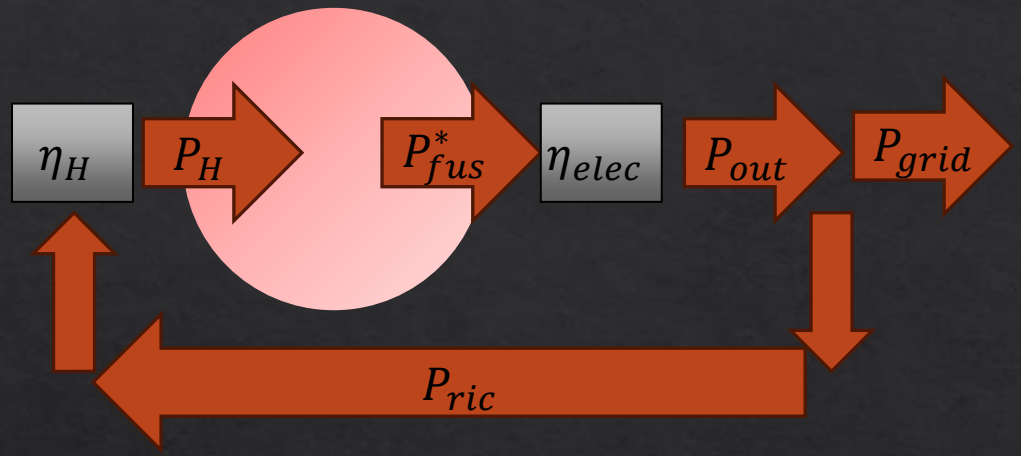
In an **ignited plasma**, by definition, $\boldsymbol{Q_{sci} = \infty}$ since losses are entirely compensated by internal heating

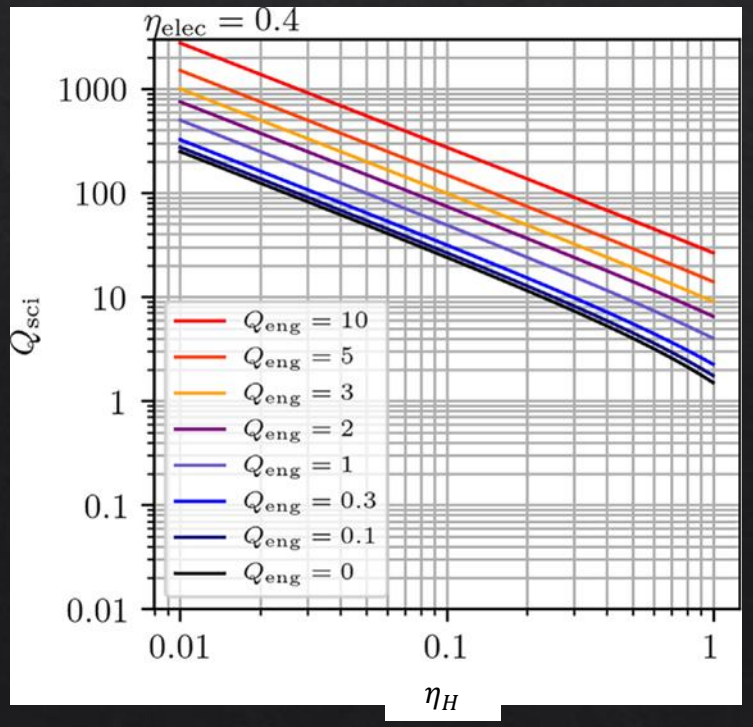
Scientific breakeven (or simply breakeven) is reached for a plasma characterized by $\boldsymbol{Q_{sci} = 1}$

Given a certain Q_{sci}, it is possible to plot the triple product necessary to achieve it at a given operating temperature

Scientific breakeven is considered a fundamental milestone toward demonstrating the feasibility of artificial fusion as an industrial energy source

Wurzel, S. E., & Hsu, S. C. (2022). Progress toward fusion energy breakeven and gain as measured against the Lawson criterion. Physics of Plasmas, 29(6).





Wurzel, S. E., & Hsu, S. C. (2022). Progress toward fusion energy breakeven and gain as measured against the Lawson criterion. Physics of Plasmas, 29(6).

Similarly, an **electric power gain factor** may be defined to characterize the fusion power plant performance

$$Q_{\text{eng}} = \frac{\text{Output electric power}}{\text{Input electric power}} = \frac{P_{out} - P_{ric}}{P_{ric}} = \frac{P_{grid}}{P_{ric}}$$

To provide net electric power to the grid, $Q_{eng} > 0$

It is connected to Q_{sci} and determined by the **power conversion cycle efficiency**, η_{elec}, and the **auxiliary heating system efficiency**, η_H

$P_{out} = \eta_{elec} P^*_{fus}$ gross electric power output

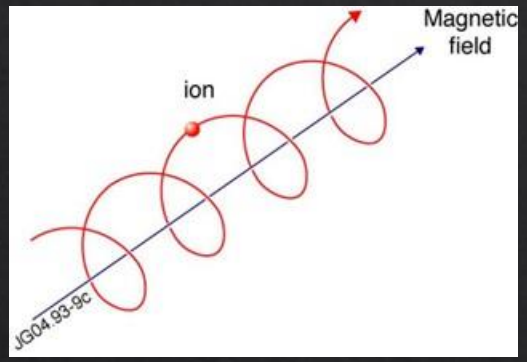
$P_H = \eta_H P_{ric}$ heating power delivered to plasma

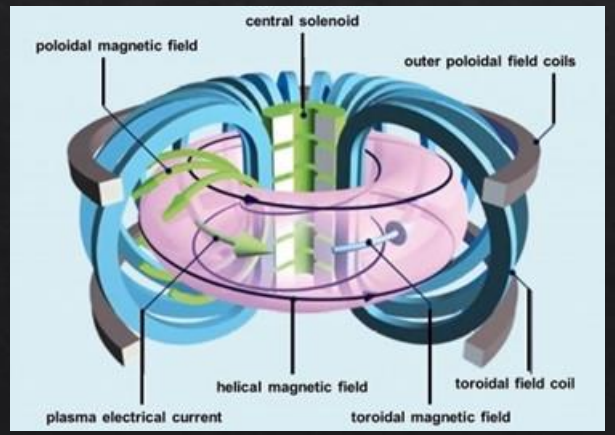
For a successful power plant, recirculating power must be minimized, hence we aim for $Q_{eng} > 1$.

A possible parameter space for a power-producing reactor corresponds to $Q_{sci} \geq 20$ for $\eta_{elec} = 0.4$ and $\eta_H = 0.5$

1. Magnetic

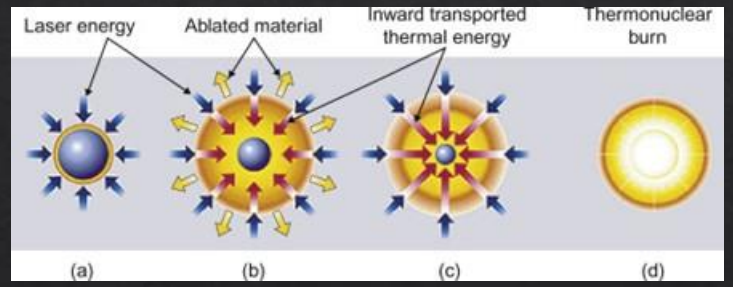
- Low plasma density ($\sim 10^{20}\ m^{-3}$)
- Long confinement time ($\sim 10^{0}$ s)

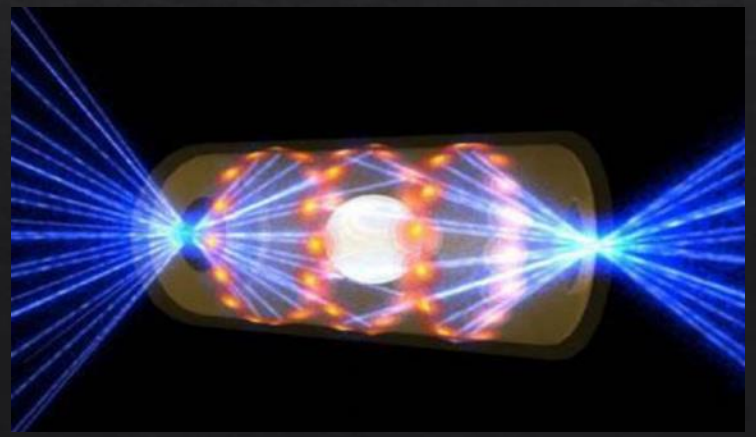




2. Inertial

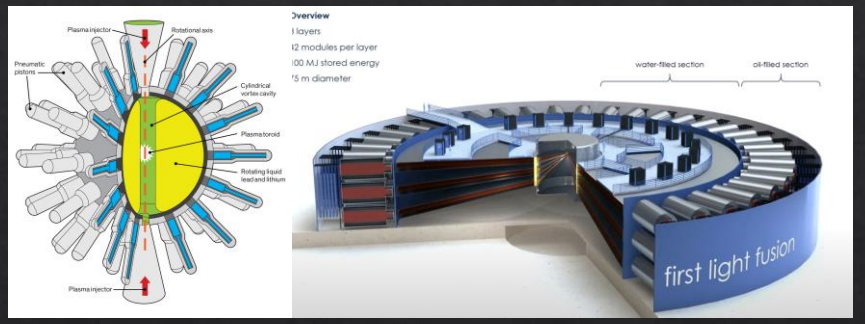
- High plasma density ($\sim 10^{31}\ m^{-3}$)
- Short confinement time ($\sim 10^{-11}$ s)

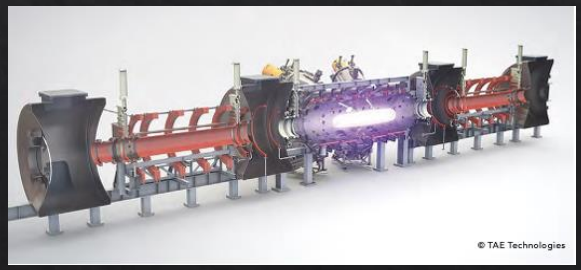


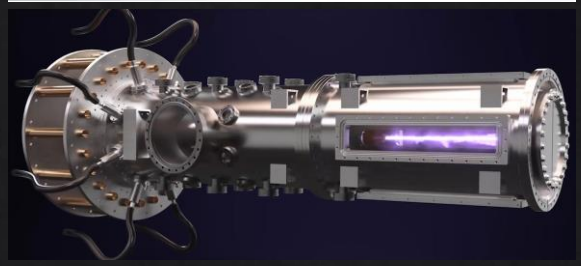


3. Alternative approaches

They exist in the spectrum between the two extremes of magnetic and inertial fusion







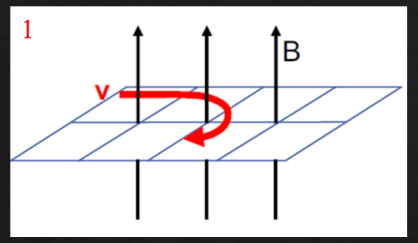
How to create your **magnetic confinement** in three* easy steps!

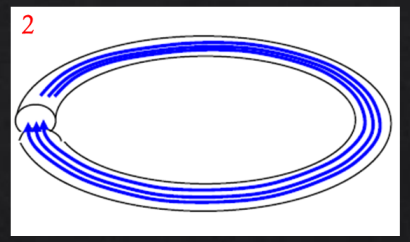
1. Induce a **strong magnetic field** in order to create a Lorentz force that constrains ions and electrons in a plasma and forces them to gyrate around magnetic field lines!

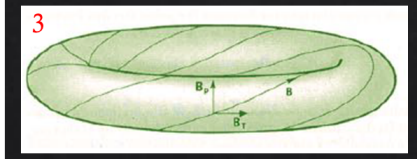
2. Bend magnetic field lines in a circular ring (**torus**) to avoid particle losses!

3. **Twist the magnetic field lines** to minimize field imbalances in the plasma!

What can possibly go wrong?

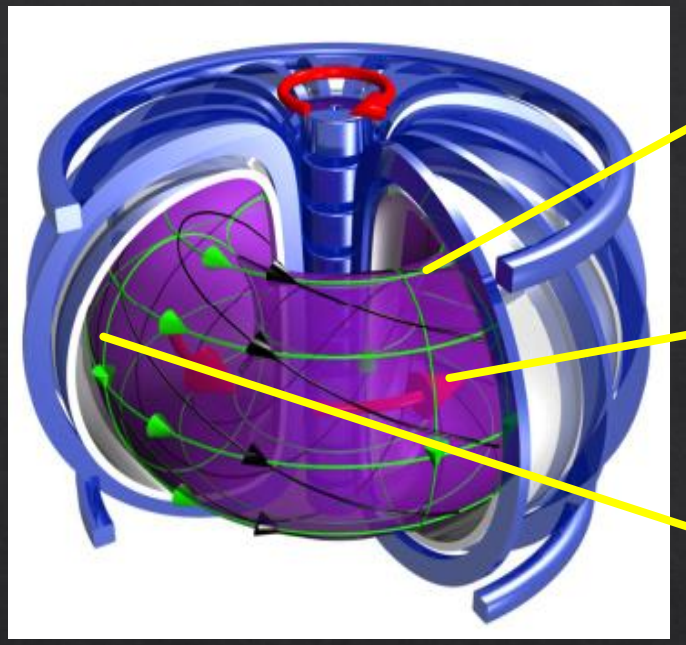




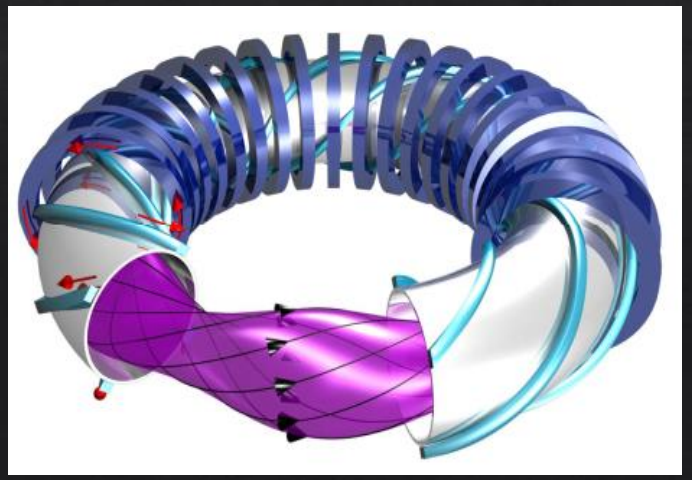


*Terms and conditions apply.

wikiHow to do anything

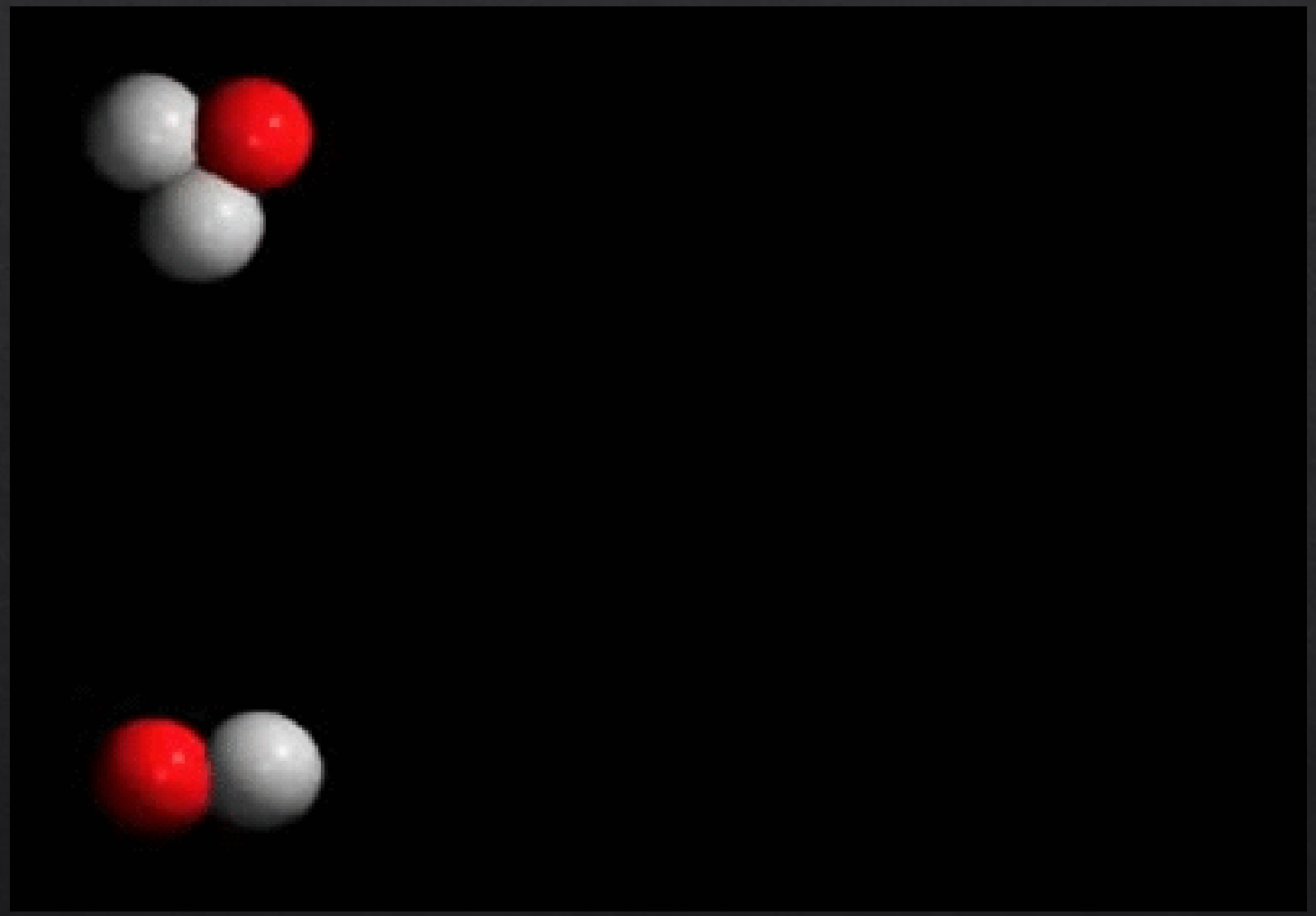


Tokamak



Stellarator

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Fusion is **energy-dense**

$$D_1^2 + T_1^3 \rightarrow He_2^4 + n_0^1 + 17.6\ MeV$$

A fusion reaction outstrips the energy density of all industrial energy sources:

- x4 fission reactions
- x10^6 chemical reactions



≈



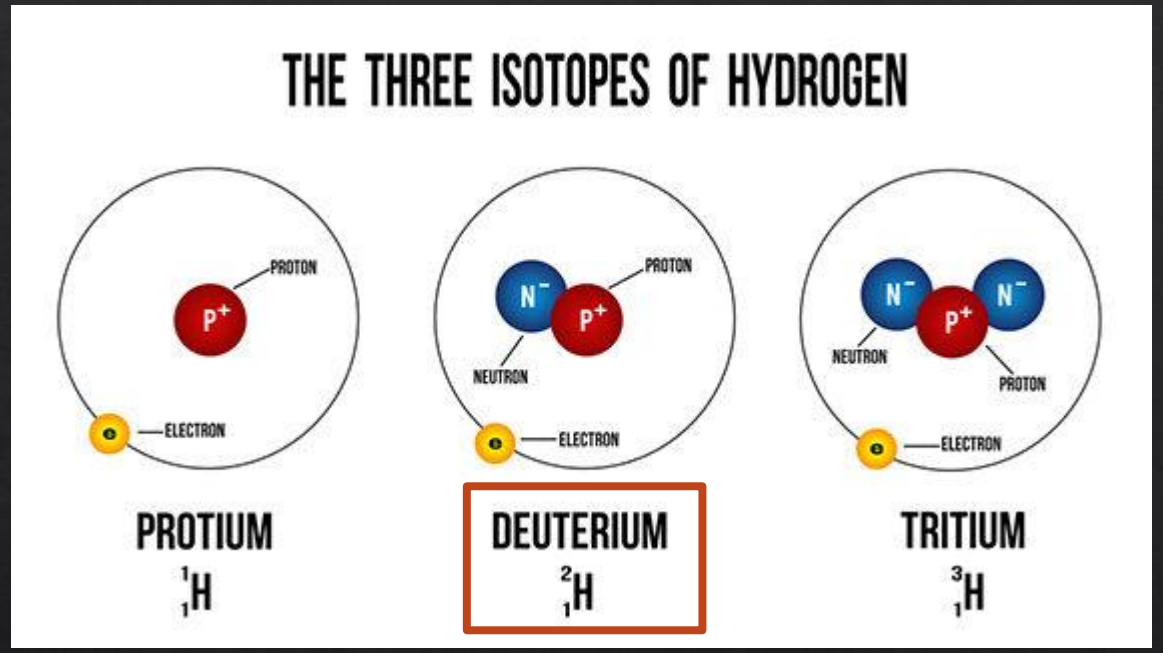
≈



A few kg of fusion fuel

A few tons of UO2

Many thousands of tons of coal



Fusion fuel is **uniformly distributed**, and its supply is virtually **inexhaustible**

DEUTERIUM
One in every 6400 hydrogen atoms

Ocean volume $\approx 10^{18}\ m^3$

Hydrogen (all isotopes) mass $\approx 10^{20}$ kg

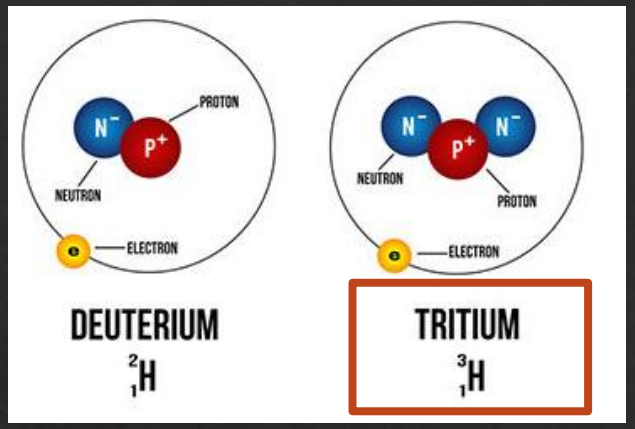
Deuterium mass $\approx 10^{16}$ kg

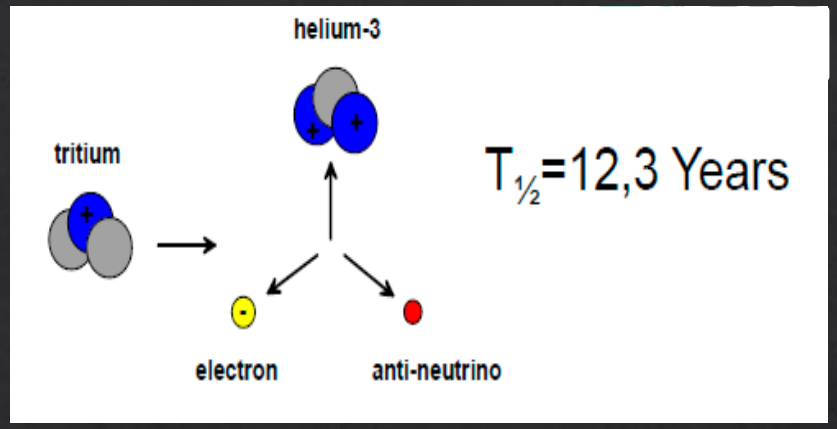
Energy from ocean deuterium $\approx 10^{14}\ TWh$

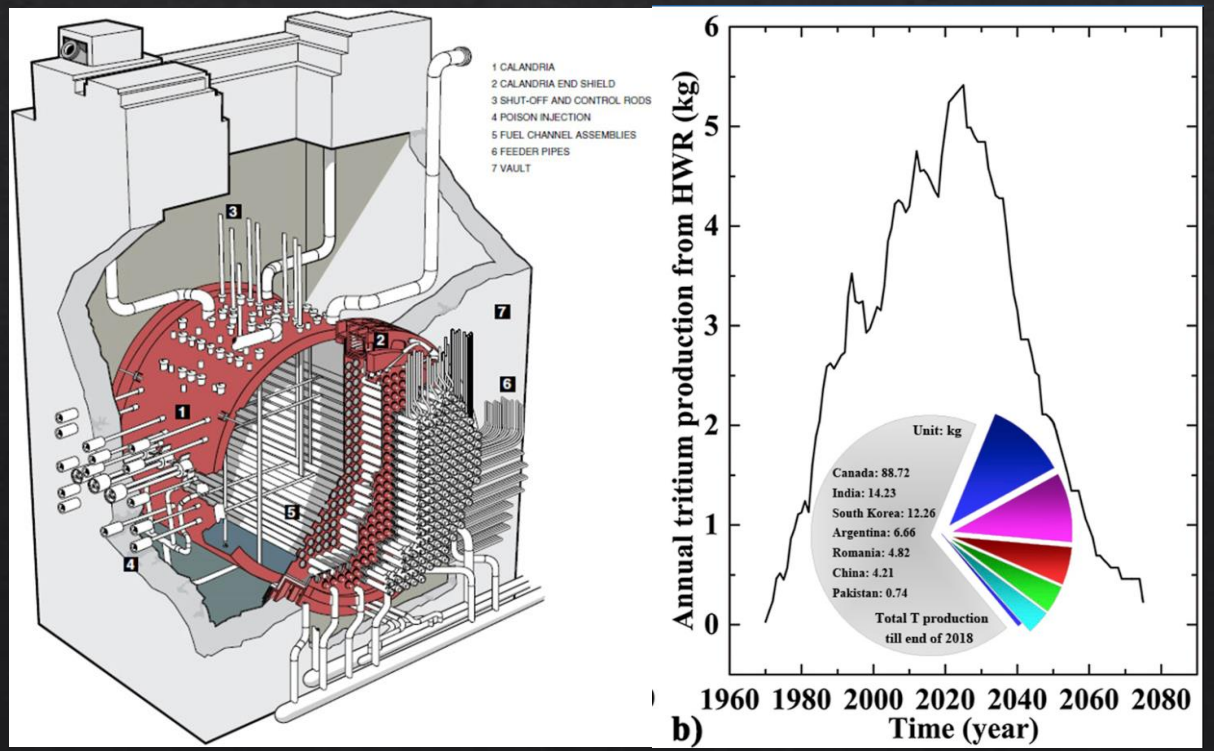
World energy consumption (2025):
$1.80 \times 10^{5}\ TWh$

Deuterium fuel supply: ~ 600 million years

Deuterium extraction from seawater is a technology already established at the industrial level (isotopic exchange - Girdler sulfide process followed by distillation for enrichment)







a) Schematic of the CANDU 6 reactor core design, b) Tritium production from HWR

TRITIUM

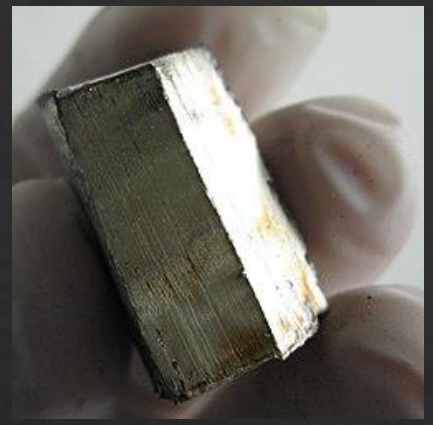
Occurring naturally only in traces due to relatively fast radioactive decay

Main sources are anthropogenic

Neutron capture reactions in heavy water (D_2O) moderated/cooled fission reactors (HWR) like CANDU. HWRs have been built in Canada, Romania, India, and South Korea. Tritium production is **≈ 0.22 kg per fpy per GWe**

Current world supply is estimated at 20–40 kg

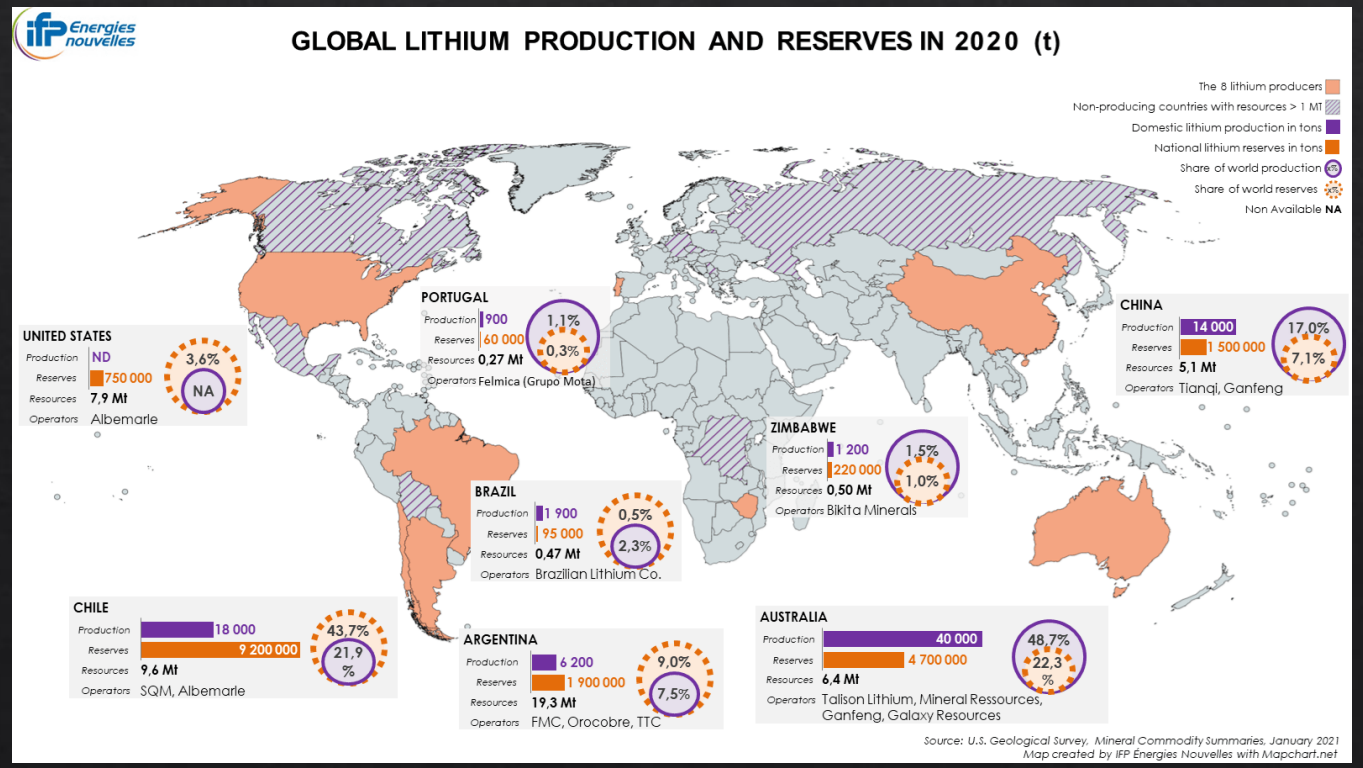
Reactor consumption for $P_{fus} = 1\ GW$ is estimated at 55 kg/fpy



Neutron capture reactions with lithium

$$n + {}^{6}Li \rightarrow T + {}^{4}He + 4.8\ MeV \quad (exoergic)$$

$$n + {}^{7}Li \rightarrow T + {}^{4}He + n - 2.8\ MeV \quad (endoergic)$$



LITHIUM

A technical solution involves **in-situ production** by leveraging the neutrons produced by the fusion reaction itself

Tritium breeding using lithium

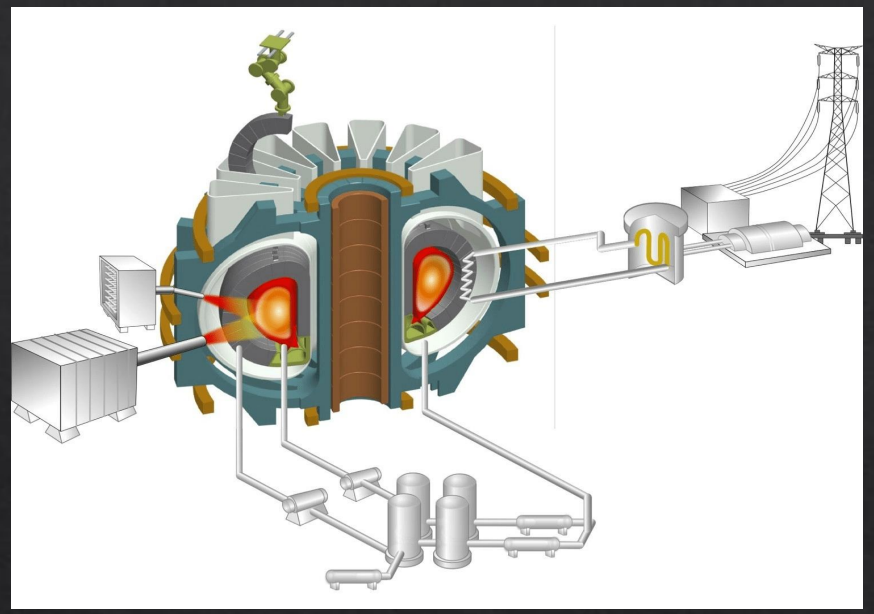
Land-based lithium reserves: 3×10^{10} kg (over 50% of world resources in South America)

Can be extracted from seawater, if necessary, to increase supply (2×10^{14} kg)

High energy density allows fusion power production to outbid other industries to secure lithium supply

1 g of Li = 8×10^{4} kWh $\approx 10^{4}$ €/g

Nuclear **fusion** power plant (FPP)



- Low carbon, programmable, scalable
- Intrinsically safe nuclear reaction
- No production of high-level waste BUT a very large quantity of intermediate-level waste
- Not yet available for the energy transition

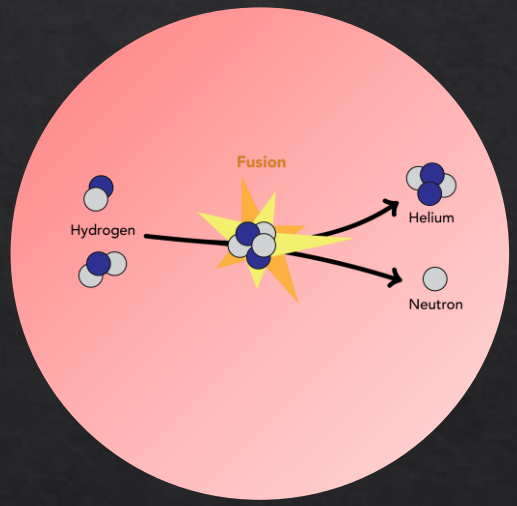
Nuclear **fission** power plant (NPP)

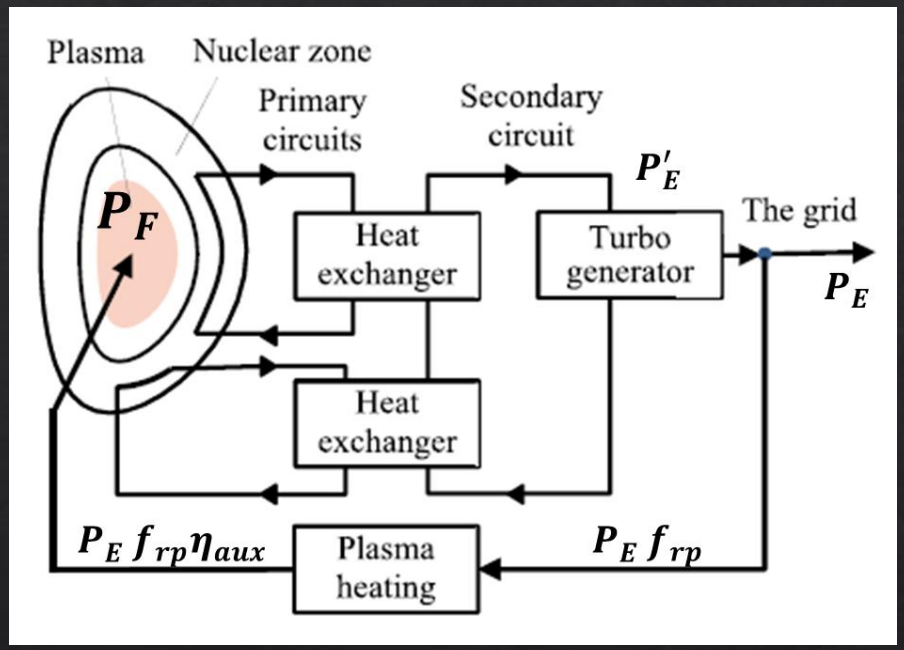


- Low carbon, programmable, scalable
- Possible runaway chain reaction
- Limited but significant production of high-level waste and a large quantity of intermediate-level waste
- Available for the energy transition

- Welcome!
- Fusion energy: a quick introduction
- The case for fusion
- Fundamentals of magnetic fusion technology
- The state of the field in 2026
- Conclusions

What does it take to move from a **burning plasma**…

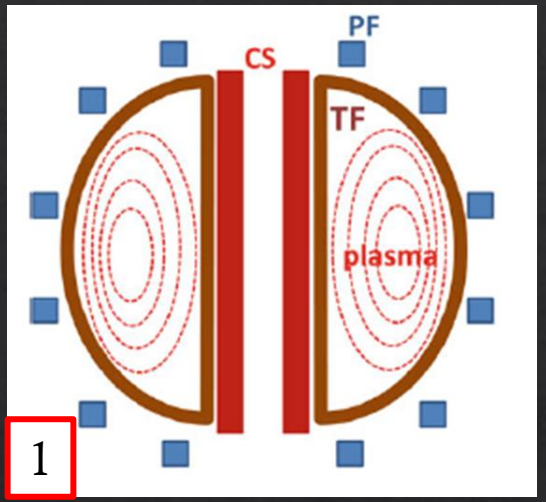




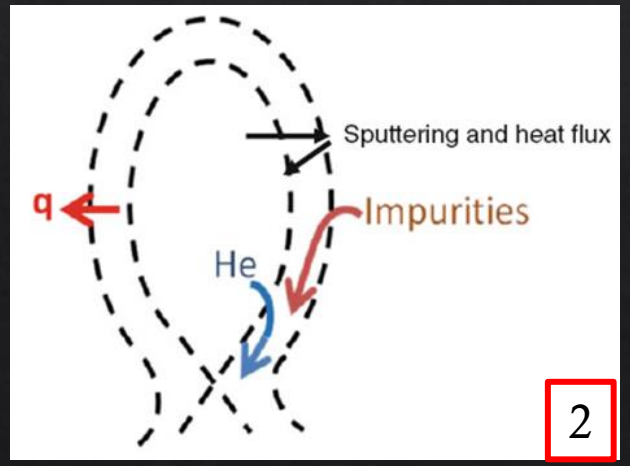
… to a **pilot plant** able to generate electrical power?

A fusion reactor is characterized by five key technical **challenges**

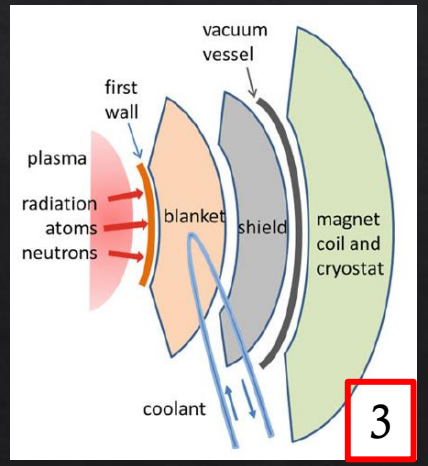
1. Plasma Confinement and Control
2. Power and Particle Exhaust Management
3. Fuel Breeding and Power Extraction
4. Materials
5. System Integration



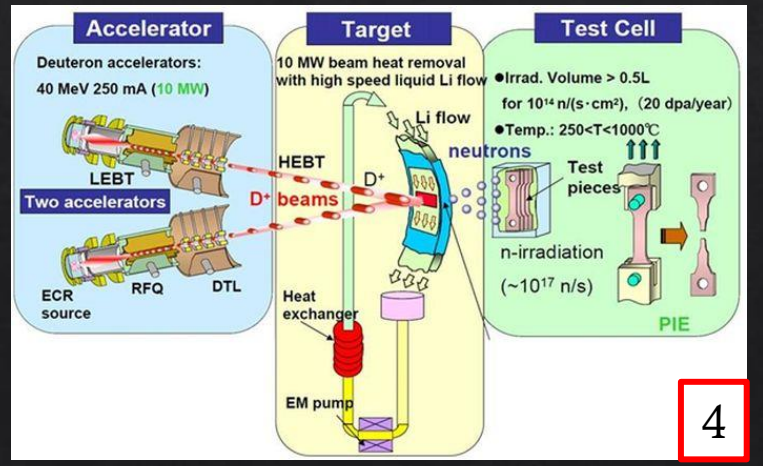
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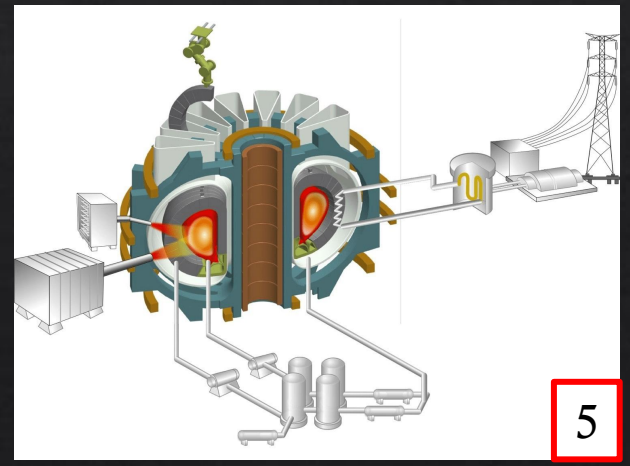
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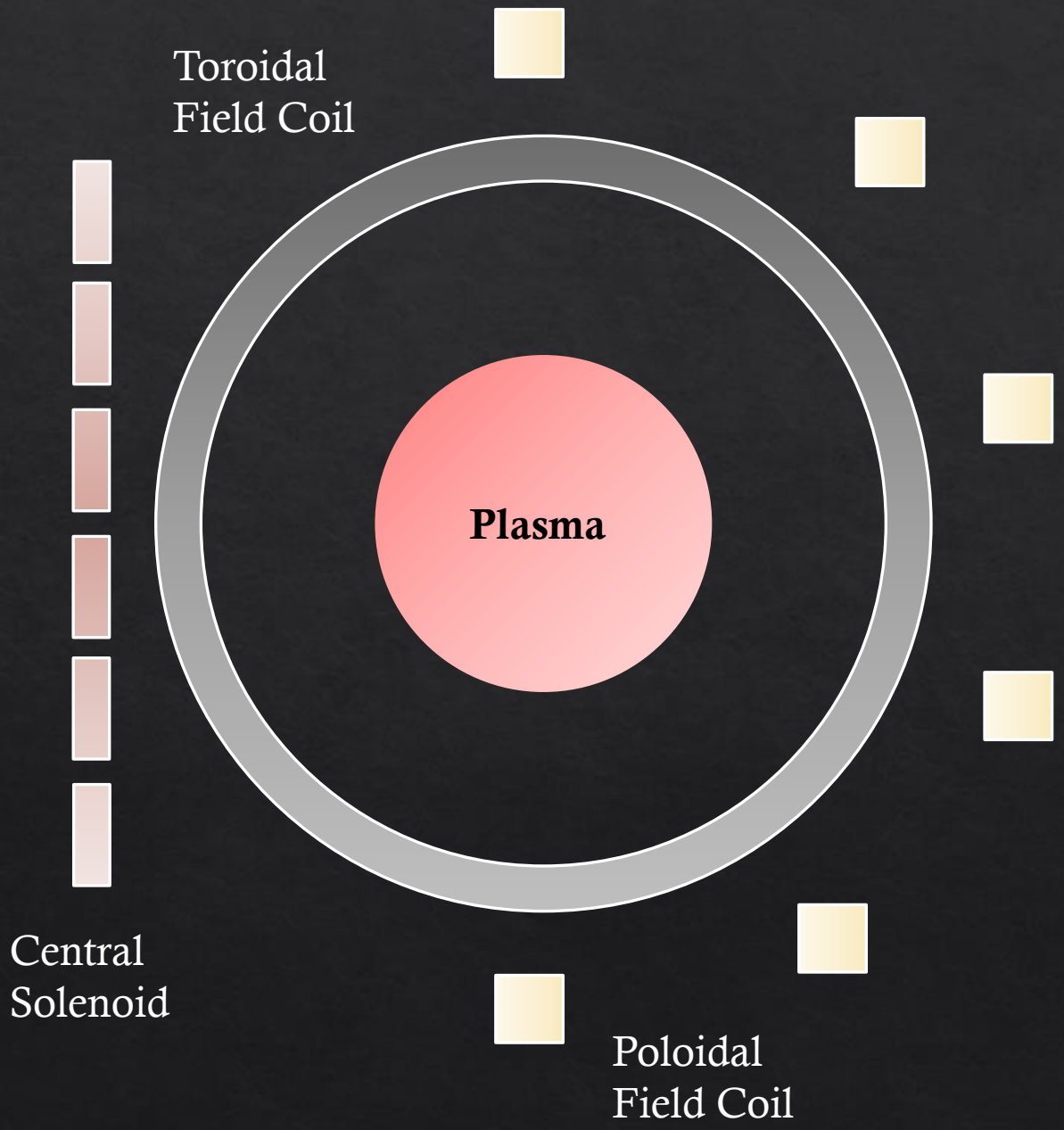
3



4


5

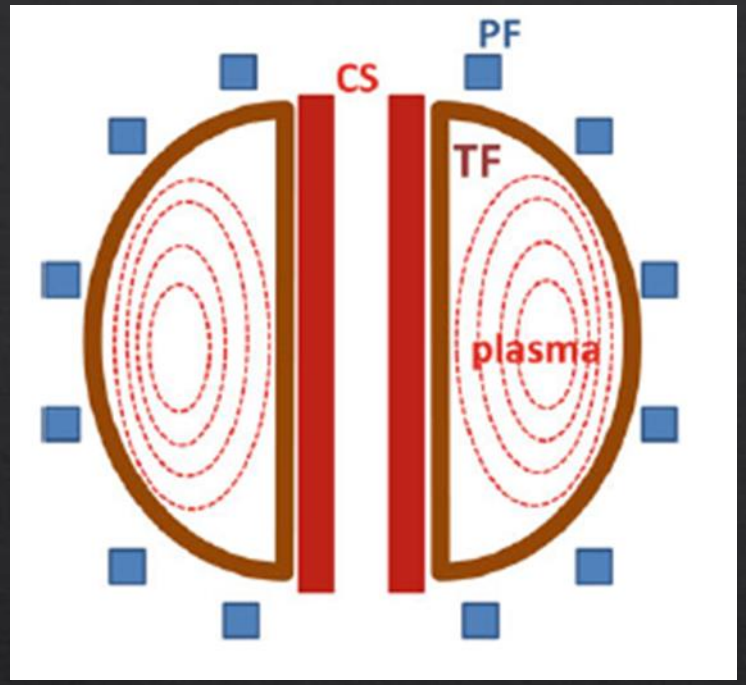
Magnetic **plasma confinement** is provided by coils made of low-temperature superconductors (~ 4 K)

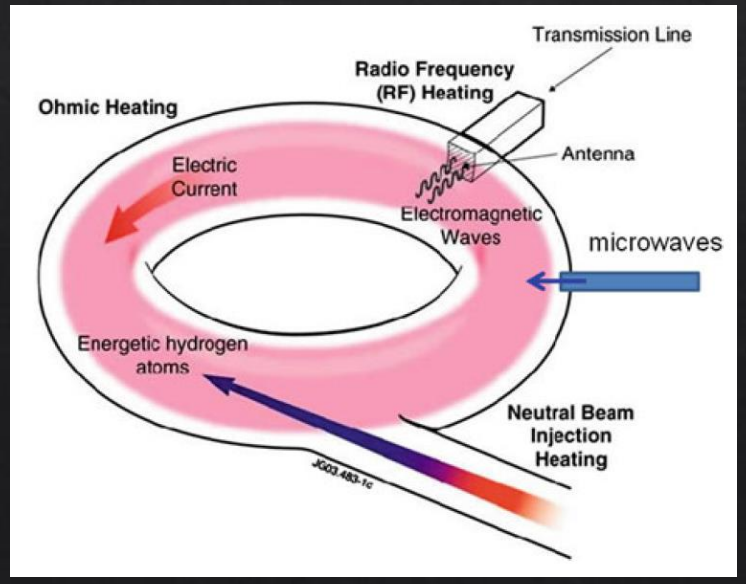












Magnet system composed of three main coil sets

- Toroidal field coils (TF)
- Poloidal field coils (PF)
- Central solenoid (CS)

…plus auxiliary coil systems not shown for clarity

Produce appropriate **magnetic field topology and pressure**

- Intense magnetic fields (> 5 T)
- Strong toroidal current (>15 MA)

Huge power dissipation for conventional electromagnets!

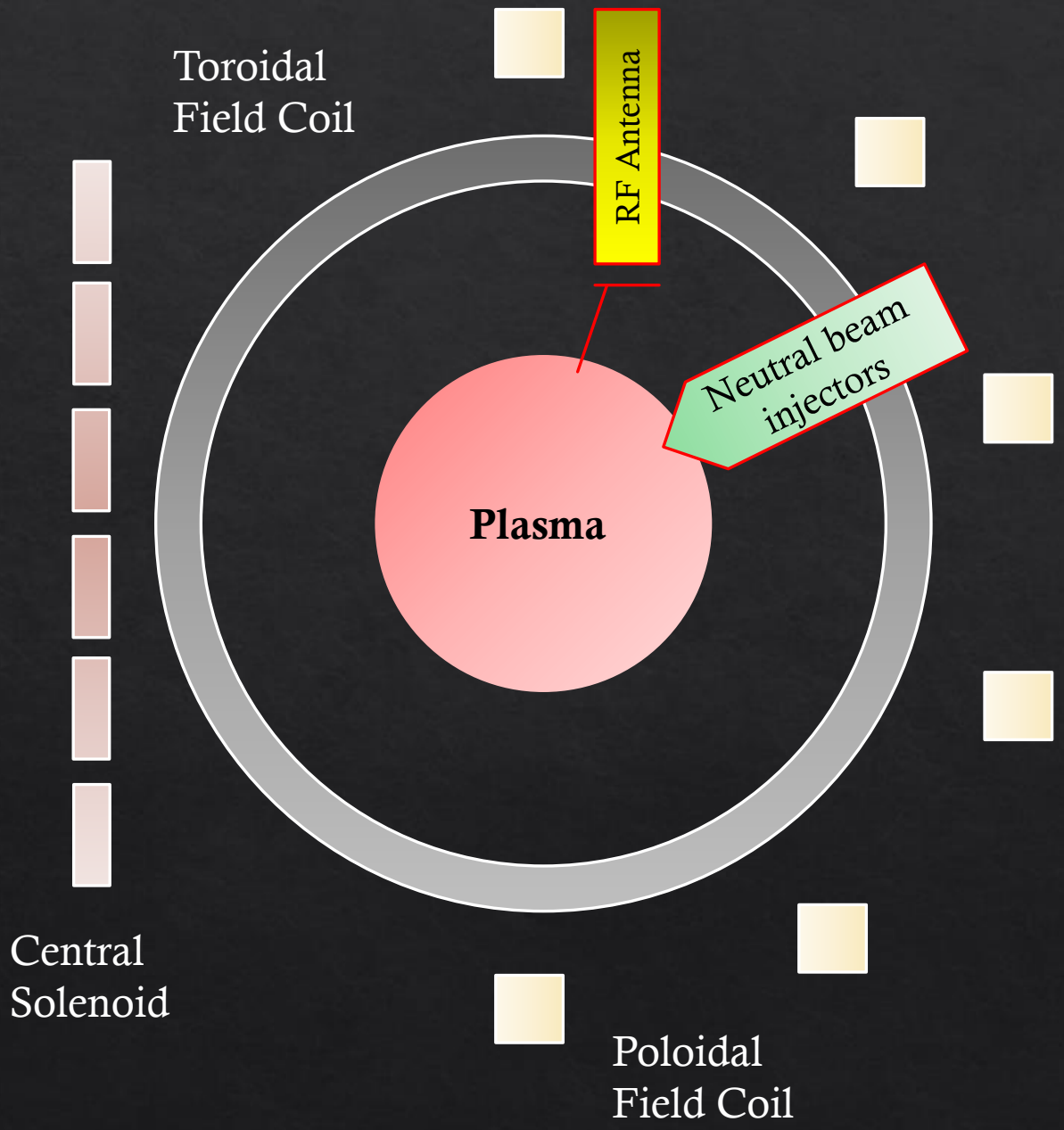
Superconducting coils

- Low temperature in a large volume (4.2 K)
- Minimize radiation on coils

Generate and control the plasma to keep it in suitable conditions

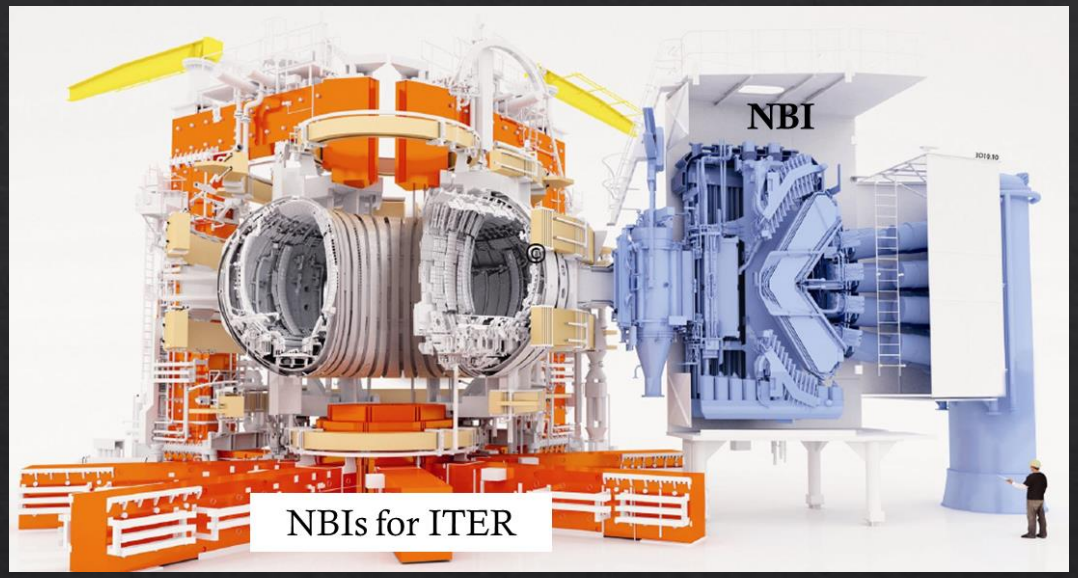
- Fuel ionization and plasma formation
- Position and magnetic pressure control
- Instability prevention and machine protection

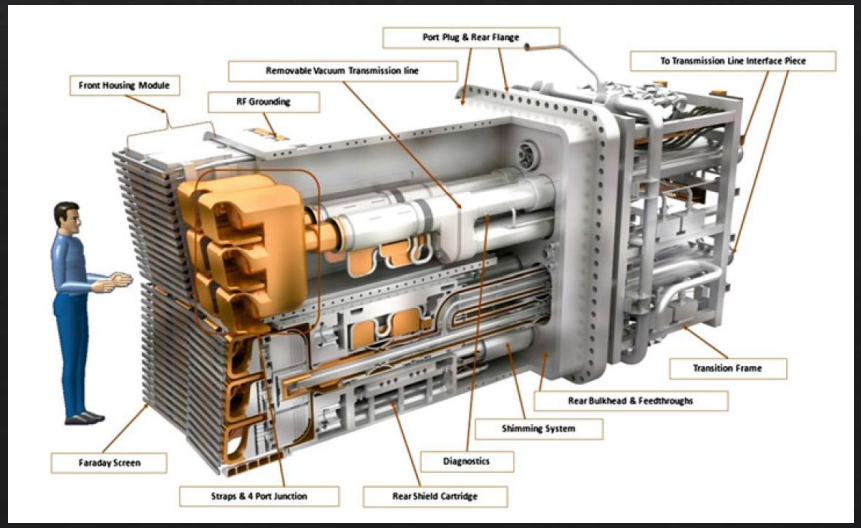
Intense electromagnetic loads on the structures

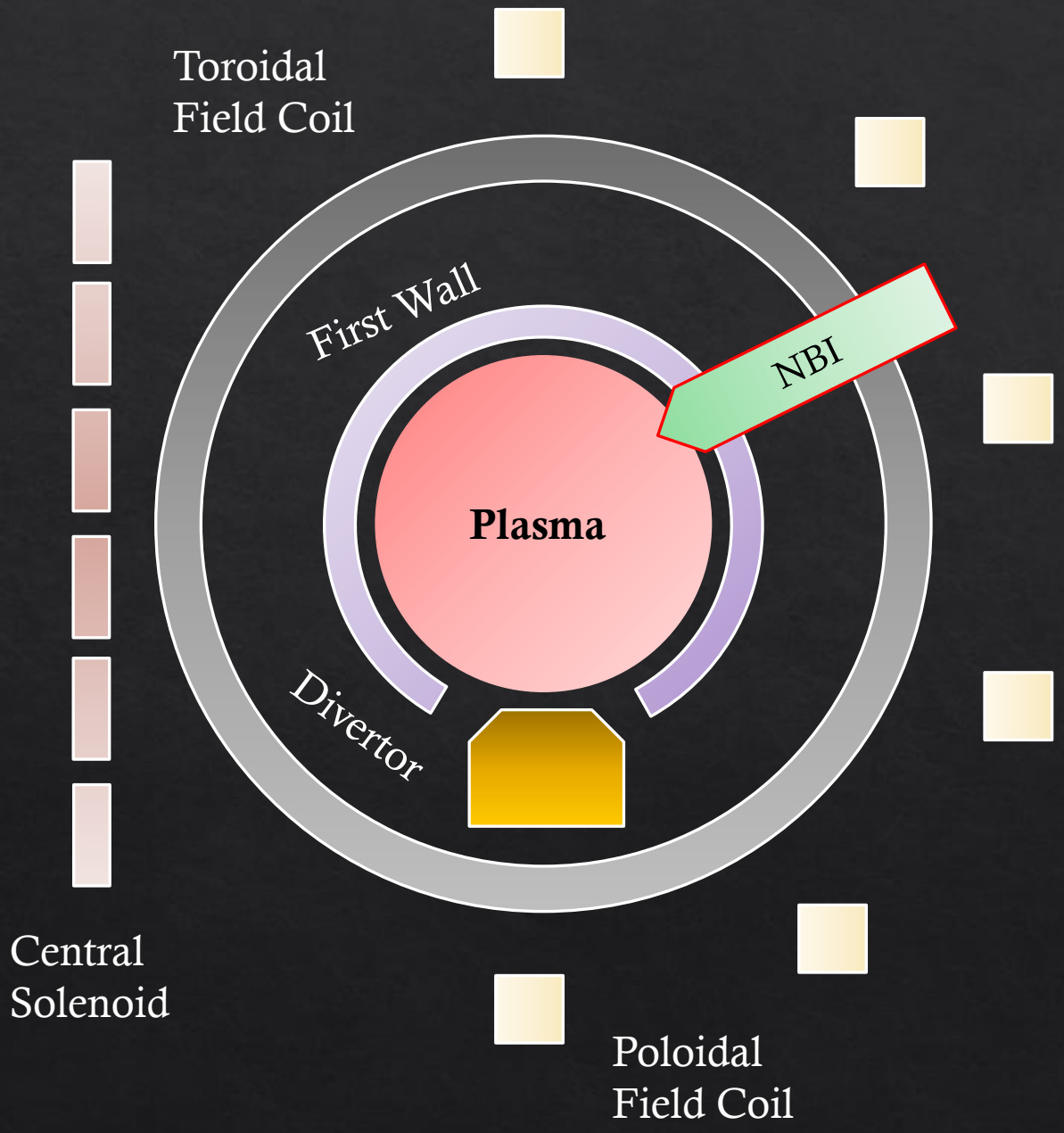


Plasma heating, current drive and diagnostics

- Heating and measuring plasma quantities

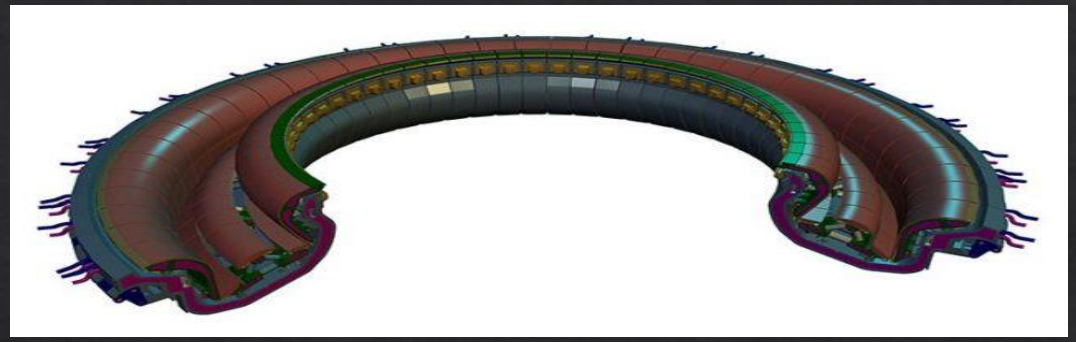


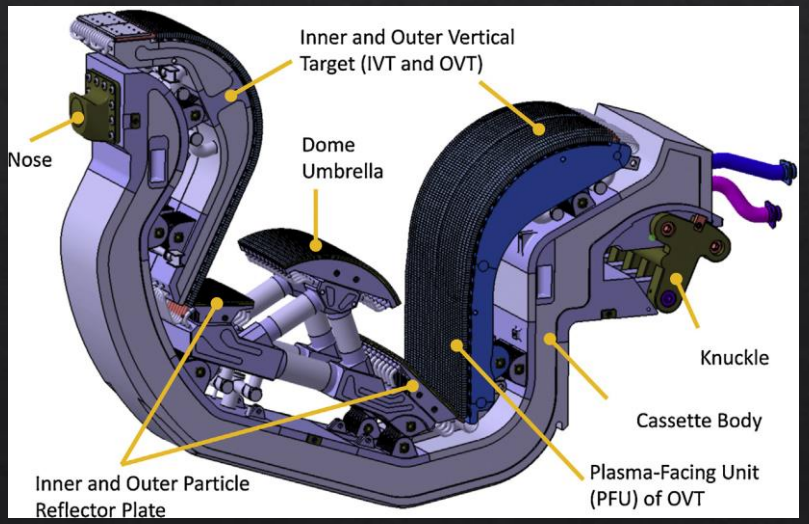




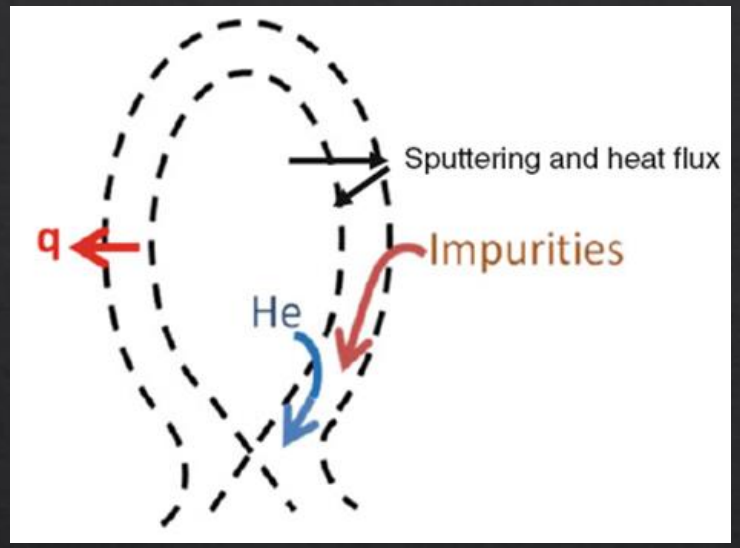
Plasma-facing components

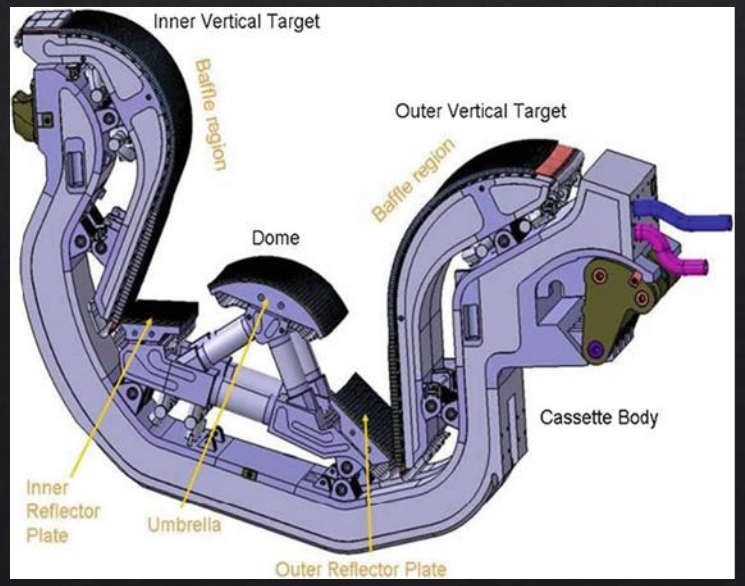
- First wall: plasma-machine physical boundary
- Divertor: power and particle exhaust management
- Limiter: machine protection during transients









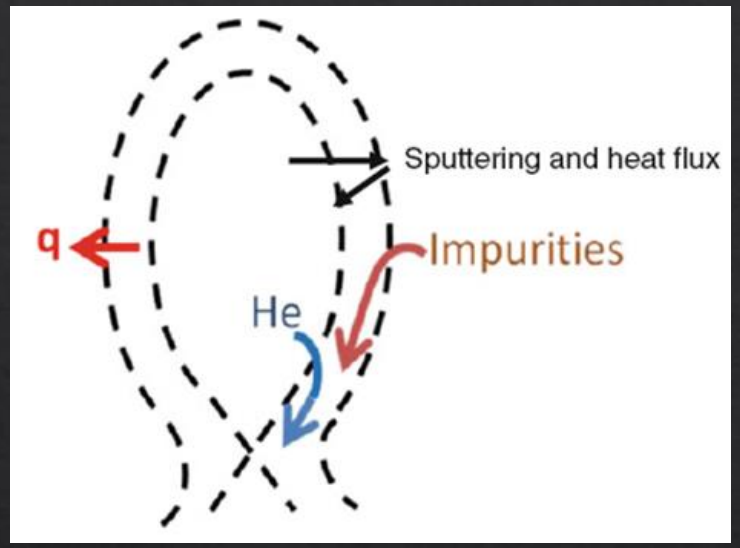


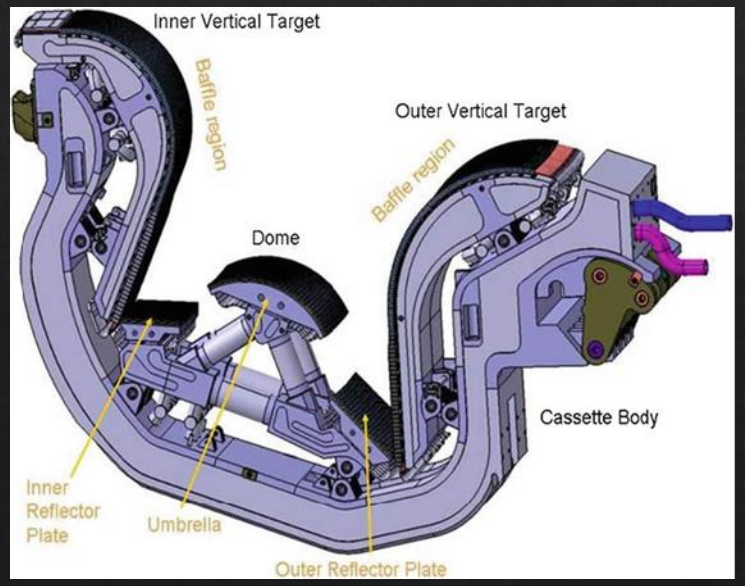
ITER divertor

Impurities cool the plasma and increase the probability of onset of critical plasma instabilities (disruptions)

- Self-produced helium ash
- Sputtering from wall (high or low Z)
- Hydrogen recycling (wall absorption)

Provide a route for impurity removal and management of particle exhaust → **Divertor**





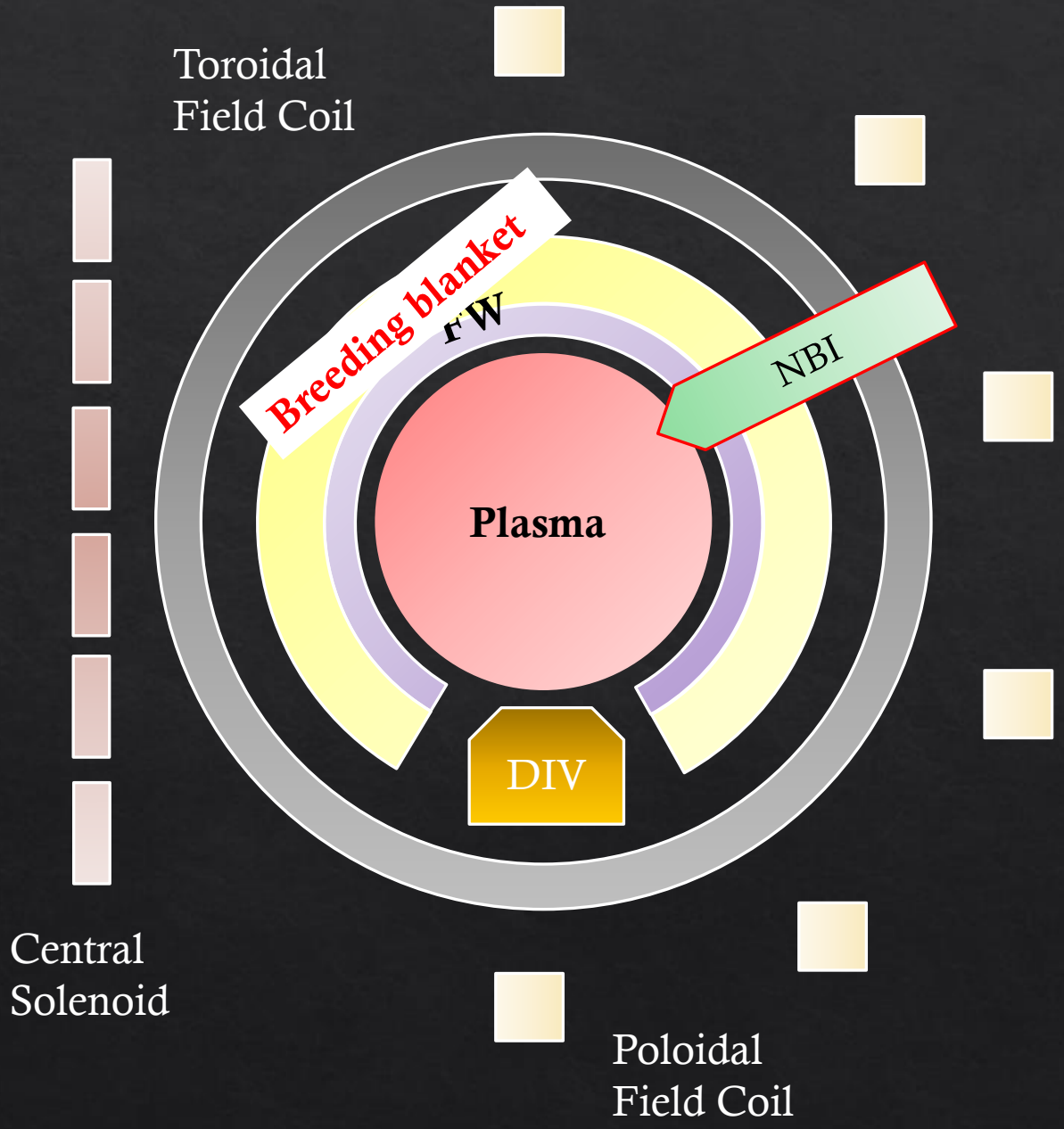
ITER divertor

Manage heat flux to plasma-facing components in normal (MW/m^2) and off-normal scenarios (GW/m^2)

- Open magnetic flux surface in the Scrape-Off Layer (SOL) to convey impurities and part of the heat flux to a specific place → **Divertor**
- Armor tiles (**FW**) and sacrificial elements (**limiters**) to protect structural materials

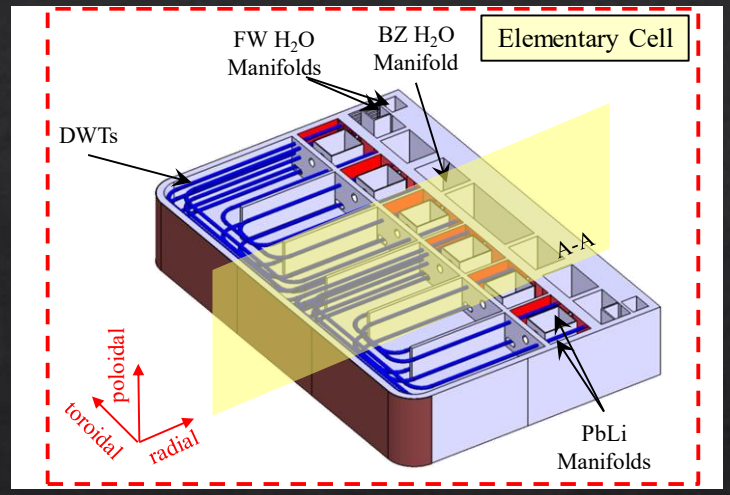
Water cooling at low pressure (4 MPa) in the nucleate boiling regime; R&D toward helium cooling and liquid-metal components

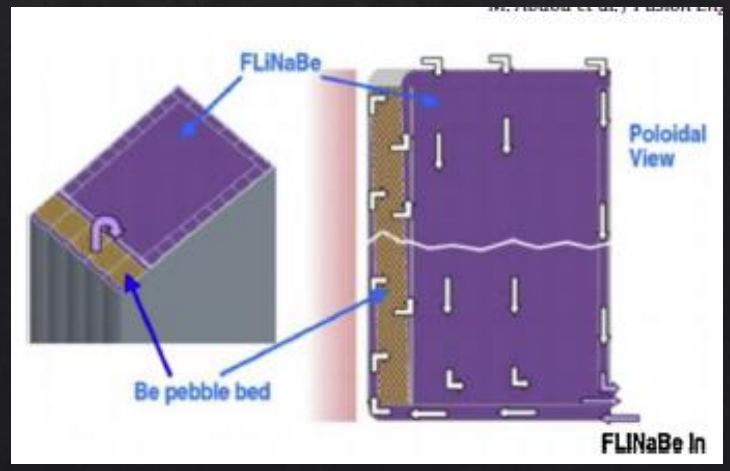


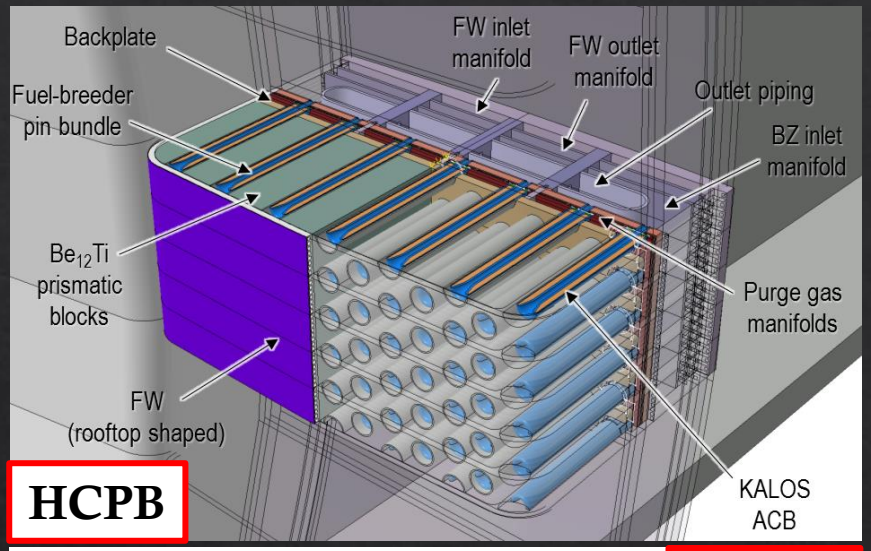


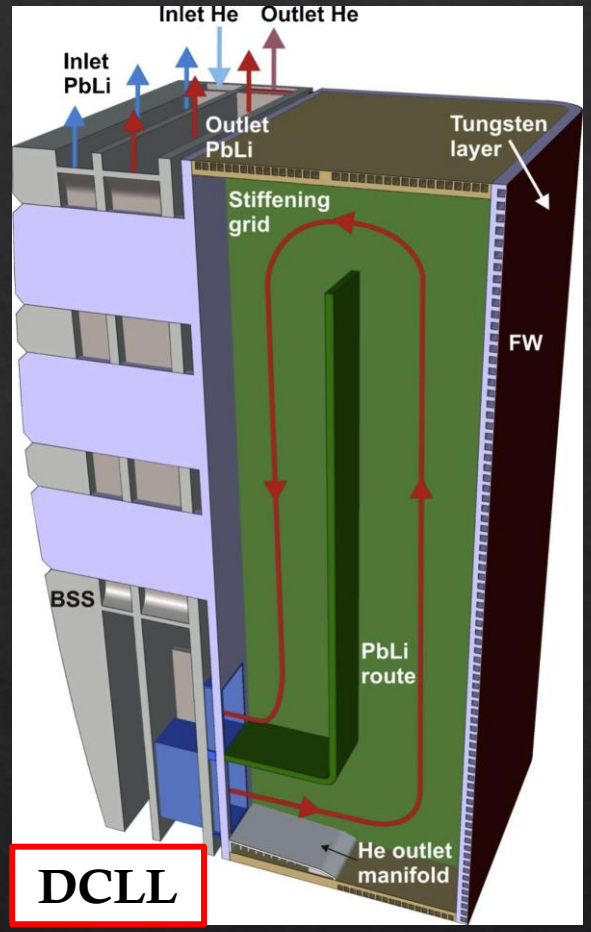
Breeding blanket

- Radiation shield
- Thermal power extraction
- Fuel breeding









Breeding blanket concepts investigated in the European fusion programme, counter-clockwise from top-left: Helium-Cooled Pebble Bed, Water-Cooled Lead Lithium, Dual Coolant Lead Lithium

Blanket architecture is defined primarily to maximize fuel breeding

$$TBR = \frac{\dot{N}_B}{\dot{N}_P} = \frac{\dot{N}_B}{P_{fus}/E_{fus}}$$

Breeder material contains lithium to exploit neutron capture reactions

$$n + {}^{6}Li \rightarrow T + {}^{4}He + 4.8\ MeV \quad (exoergic)$$

Either in **solid** or **liquid** state:

- Lithium ceramic compounds (LiO_2, Li_4SiO_4, etc.)
- Eutectic alloy with lead (PbLi)
- Molten fluoride salts (FLiBe)

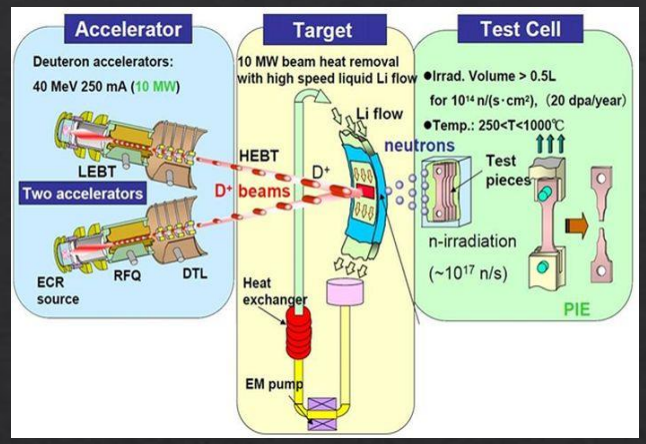
A liquid breeder can also act as coolant and tritium carrier (otherwise water or helium cooling)

Large R&D program to develop materials suitable for the extreme conditions of fusion

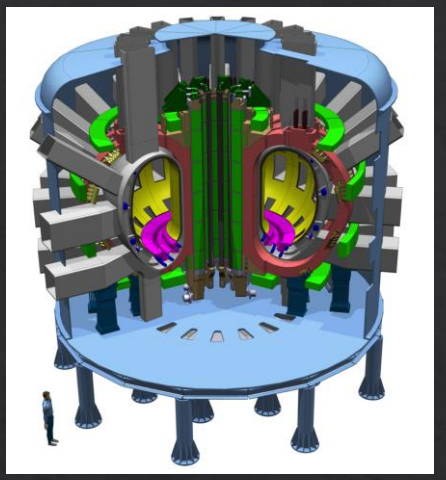
- Large temperature gradients
- **Extreme heat fluxes**
- High magnetic fields
- **Intense neutron fluence at high energy**
- Induced activation
- Embrittlement (hydrogen, liquid metal)
- Mechanical and thermal pulsed strain cycles (if not steady state)

Reduced-activation steels are considered for structural materials (EUROFER, F82H)

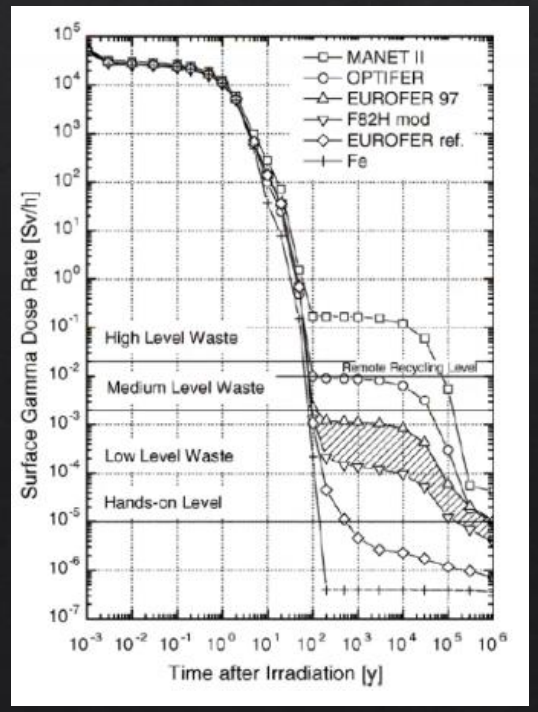
Tungsten blocks and tiles for divertor and first wall armor



DEMO-Oriented Neutron Source (Spain)

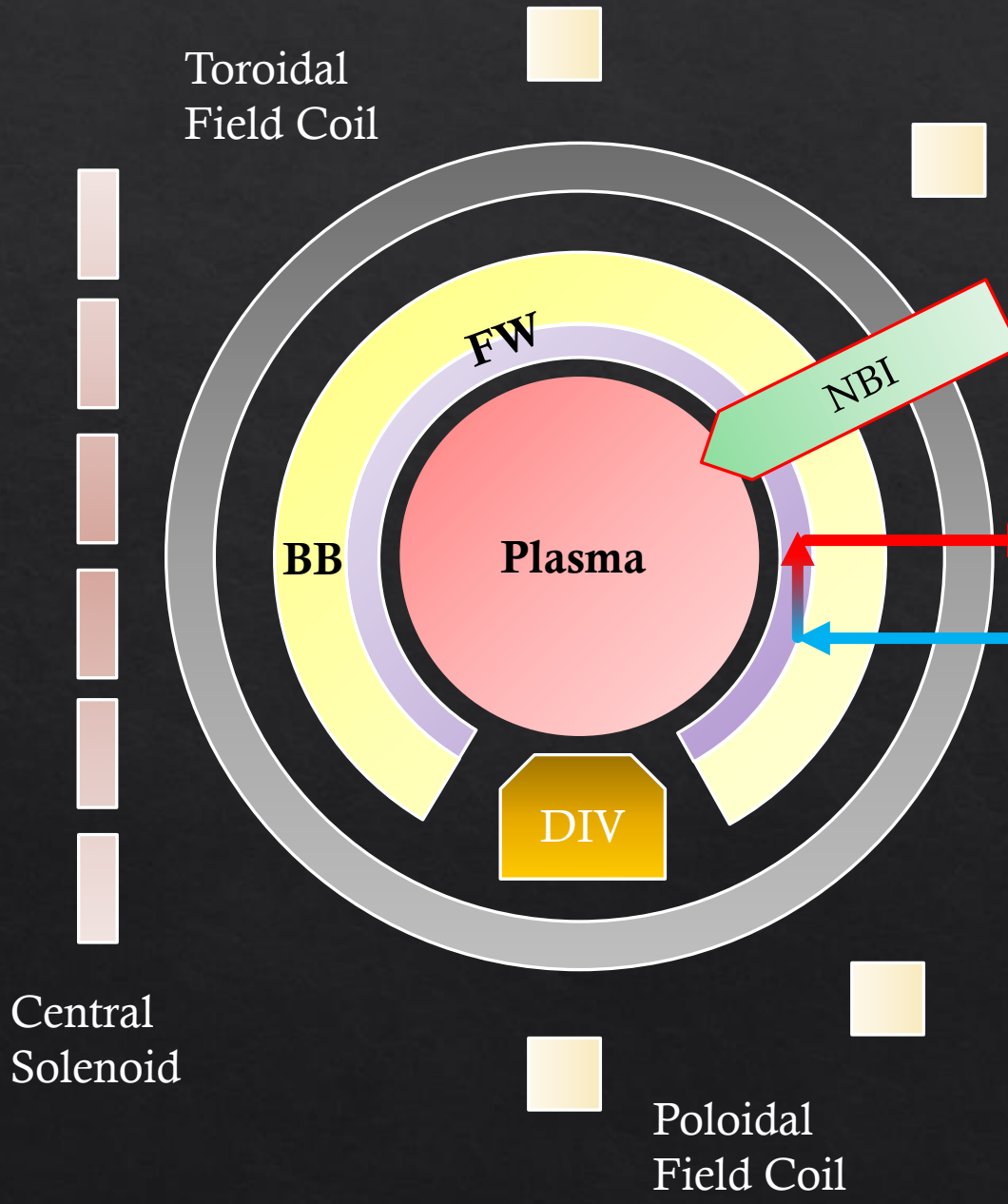


Divertor Tokamak Test (Italy)



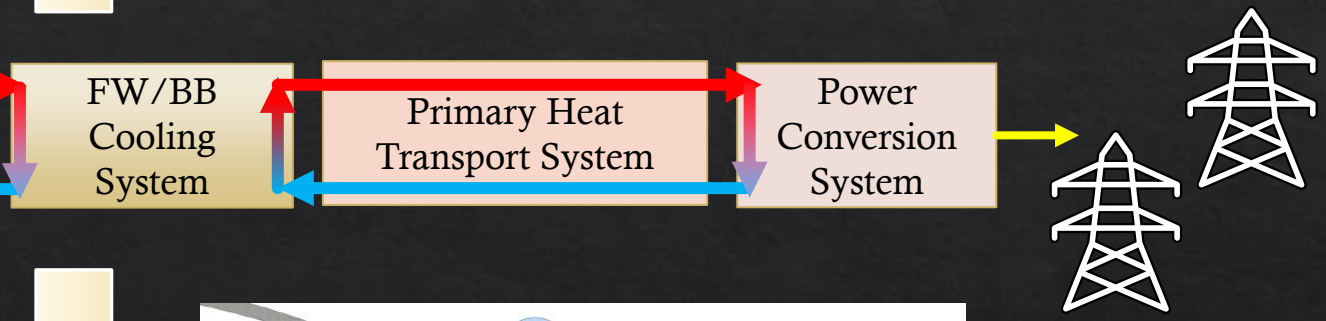
Key goals

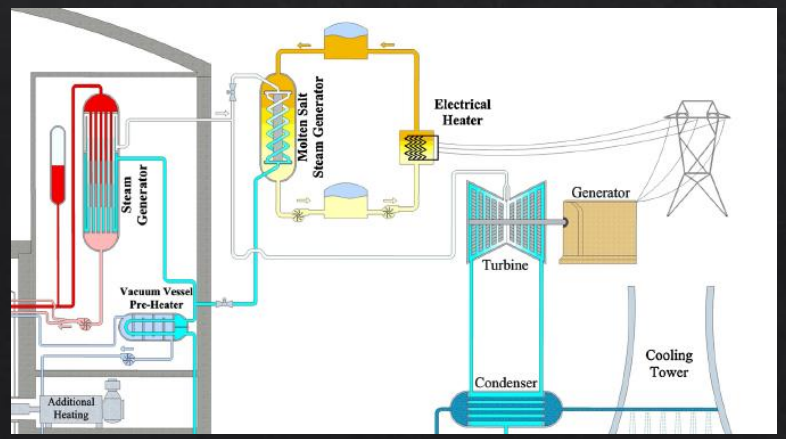
- Be able to **survive irradiation** for a reasonable amount of time (> 1 fpy)
- **Limit activation** to low-level waste within 100 years of irradiation

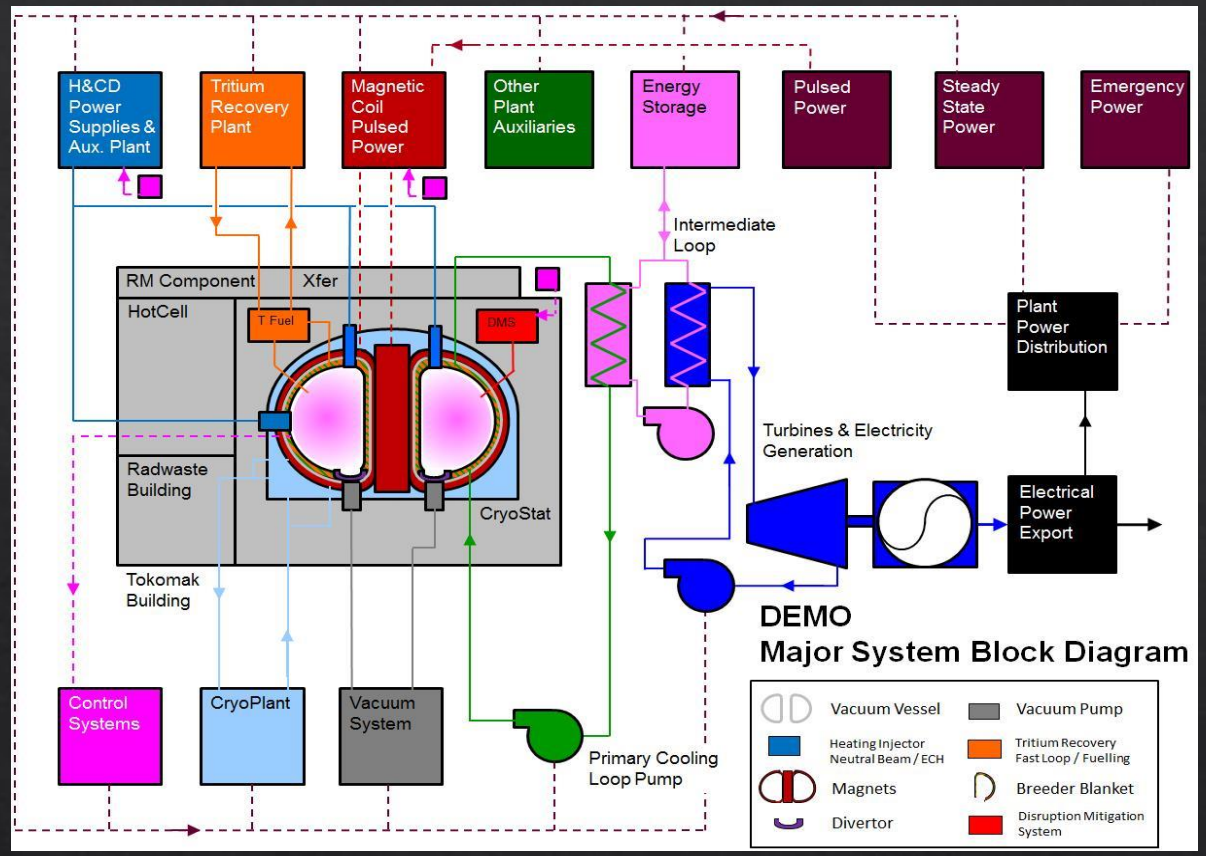


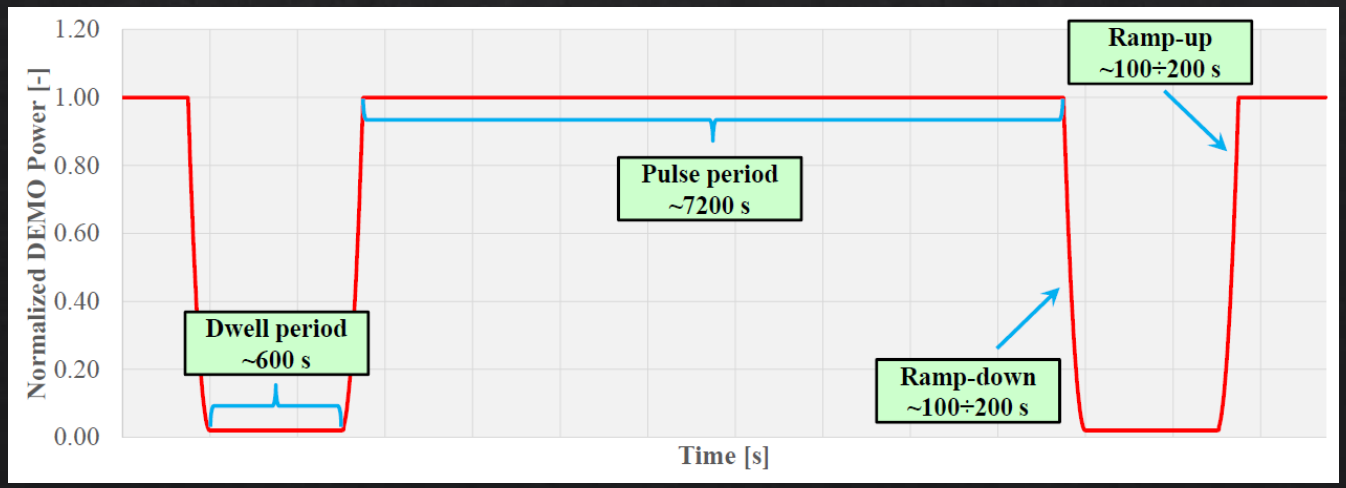
Heat transport and power conversion system

- First wall and breeding blanket cooling system
- Heat transport to power conversion system
- Conversion to electrical energy to be delivered to the grid









Power extraction is focused on the FW/BB, where 80% of the total thermal power is deposited; the remaining 20% is recovered at the divertor and vacuum vessel at lower temperatures

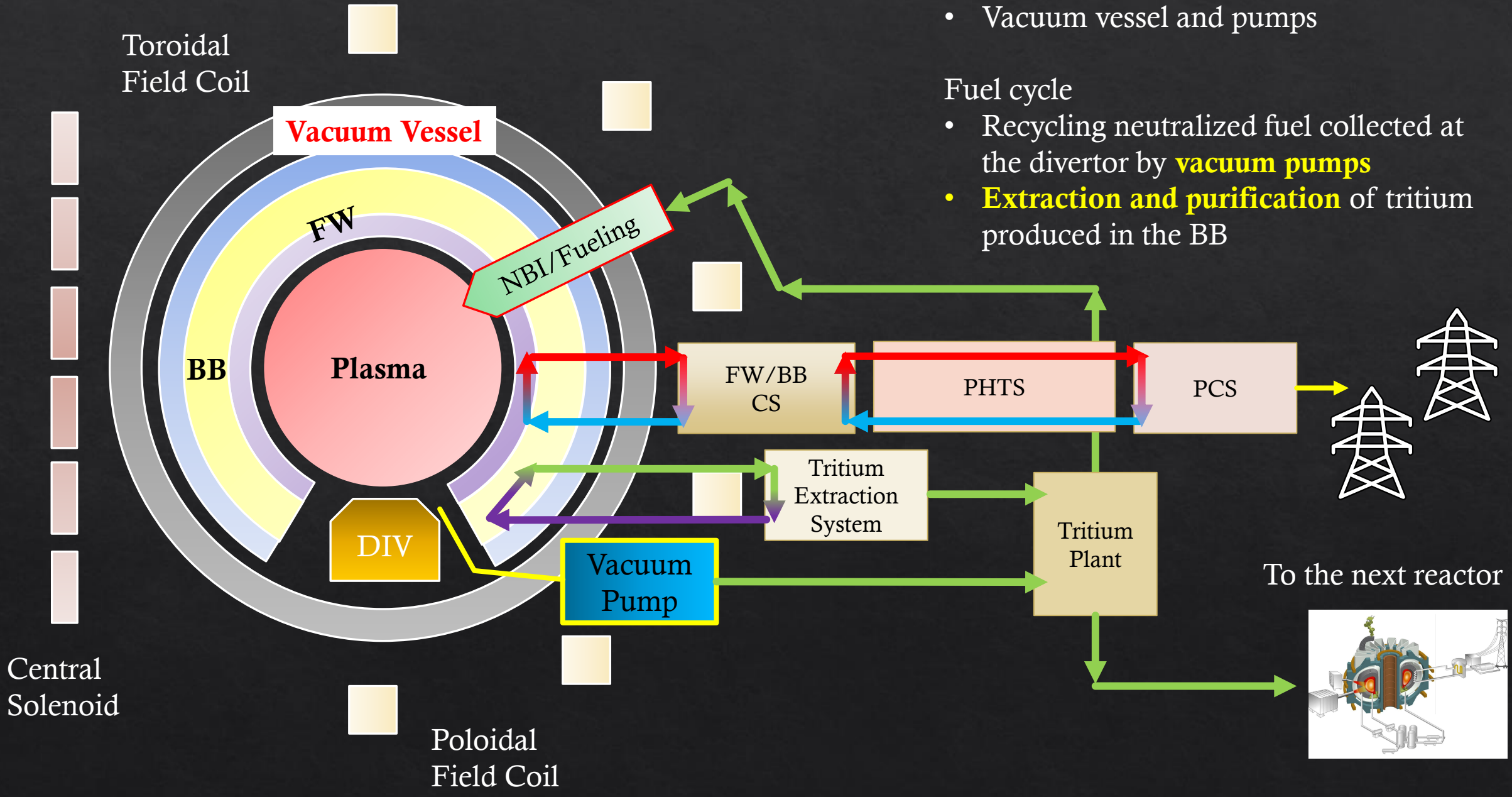
The main technological challenge is designing components able to withstand the pulsed duty cycle of the reactor

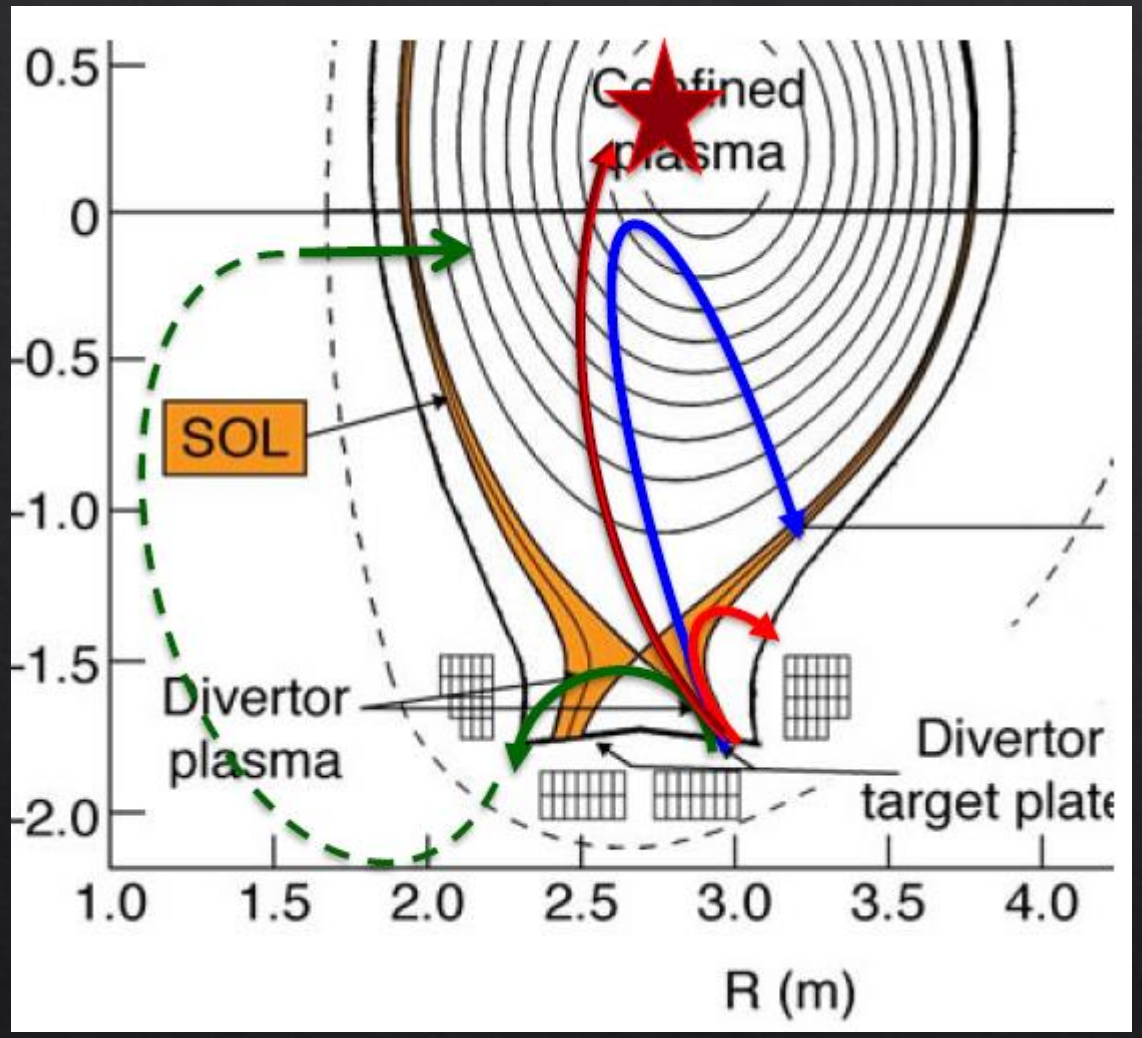
Thermal energy storage (molten salt-based intermediate system) adopted to supply power to the power conversion system during the dwell

Alternative solutions require an auxiliary power source or the motorization of the alternator shaft

Vacuum system
- Vacuum vessel and pumps

Fuel cycle
- Recycling neutralized fuel collected at the divertor by **vacuum pumps**
- **Extraction and purification** of tritium produced in the BB





The reactor must produce the tritium needed for its own operation (≈ 110 kg of tritium per full-power year of a 2 GWth reactor) and to start up other reactors

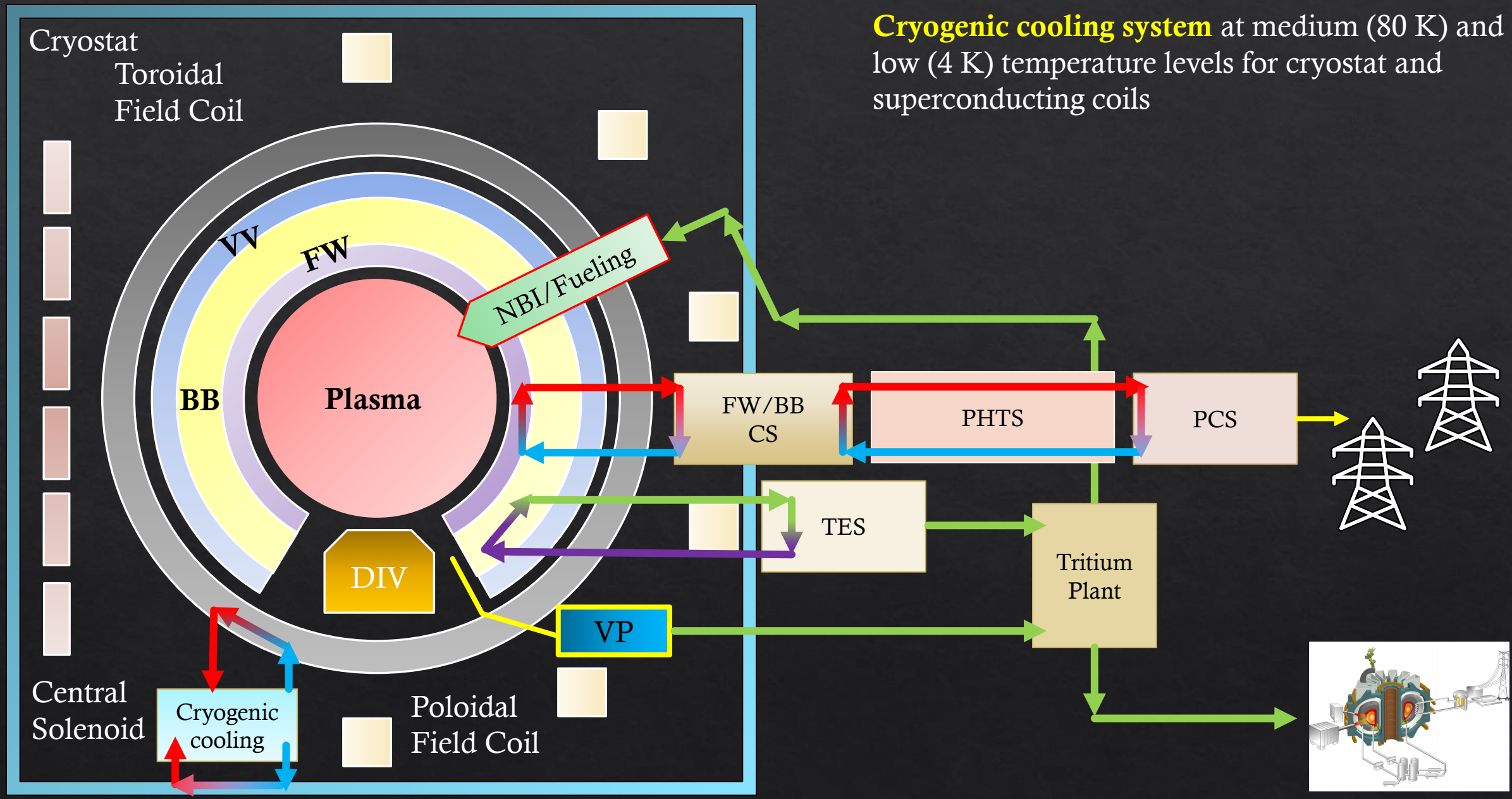
To account for contingencies, the **tritium breeding ratio** must be:

$TBR > 1.05$ and ideally $TBR > 1.15$

Fuel burnup in the plasma is quite limited (< 1%) and tritium tends to be deposited and recycled through PFM (implantation, hydrogen recycling) via **plasma-wall interactions**

Efficient **vacuum pumping** is essential to keep the reactor operational through **impurity extraction** and to recover tritium for the fuel cycle

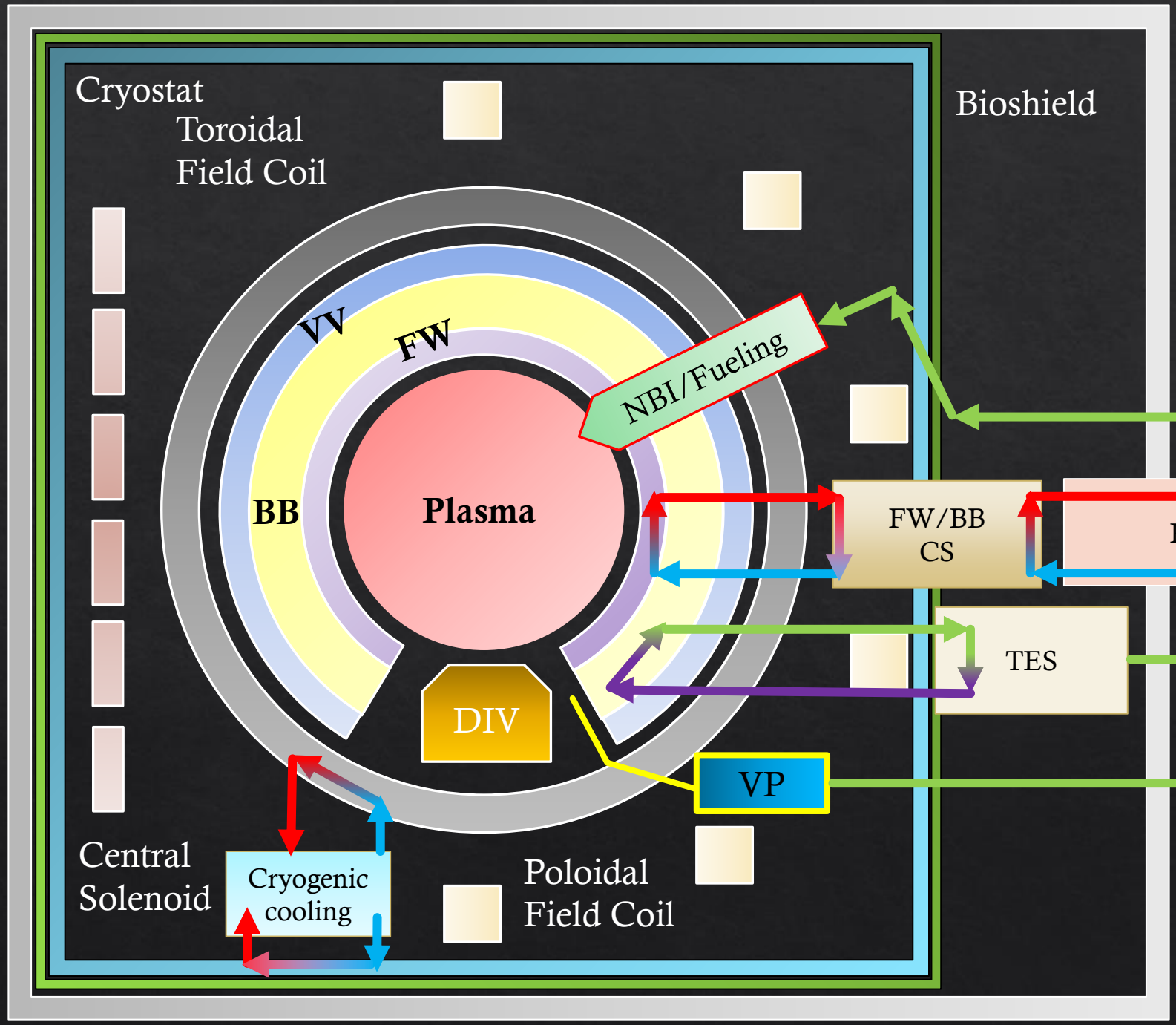
Cryogenic cooling system at medium (80 K) and low (4 K) temperature levels for cryostat and superconducting coils

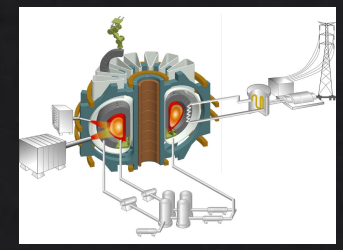


Containment structures to minimize radiological risks to personnel, public and environment

Radiological hazards:

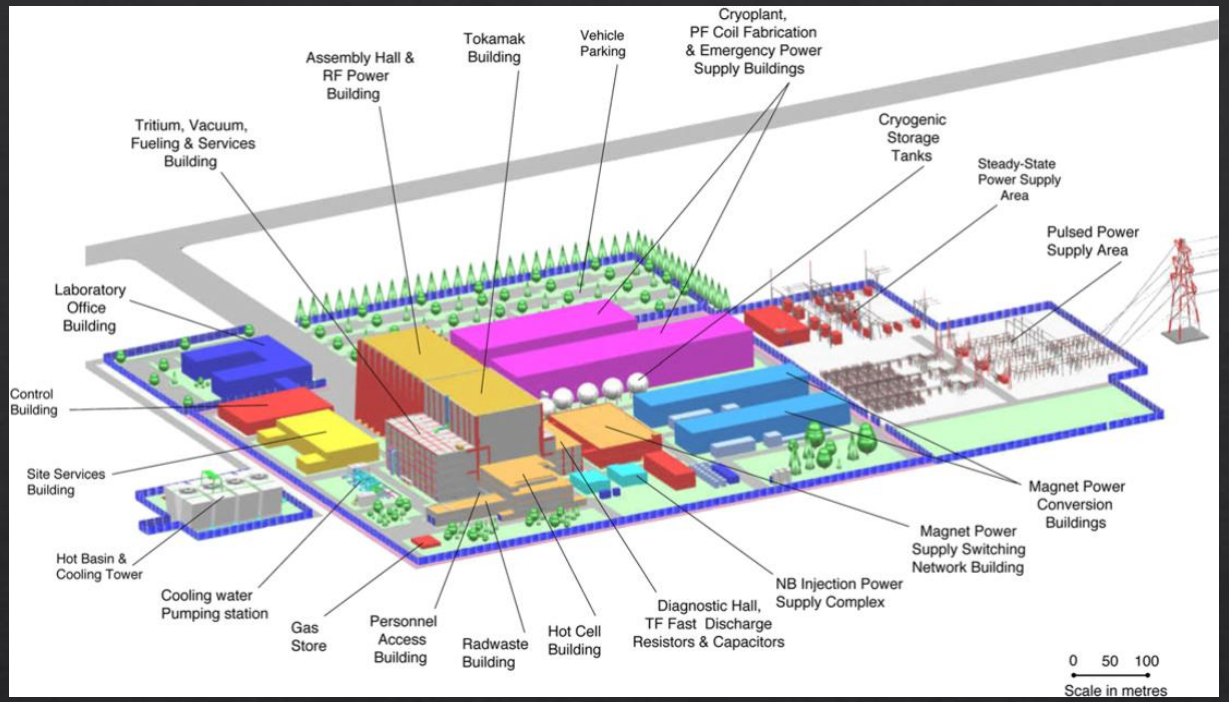
- Tritium
- Activated reactor materials (steel, plasma-facing materials)



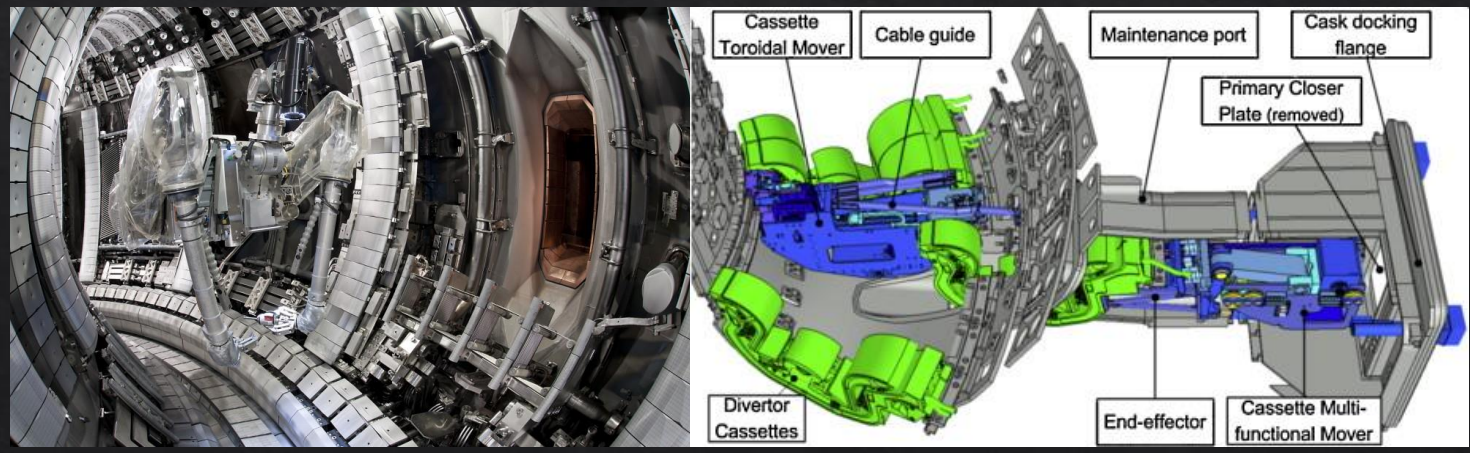


Huge effort to solve the **integration** problem

- All the separate tokamak systems must work at the same time at high performance
- Incredibly tight tolerances in **assembly** and **positioning**
- Highly radioactive large-volume environment requires the widespread use of **remote handling tools**
- Ensure **nuclear and radiological safety** of personnel, public and environment
- Ensure **economic competitiveness**
  Public acceptance
  Reasonable capital cost
  Availability = time fp/time ≈ 0.75
  Competitive cost of electricity

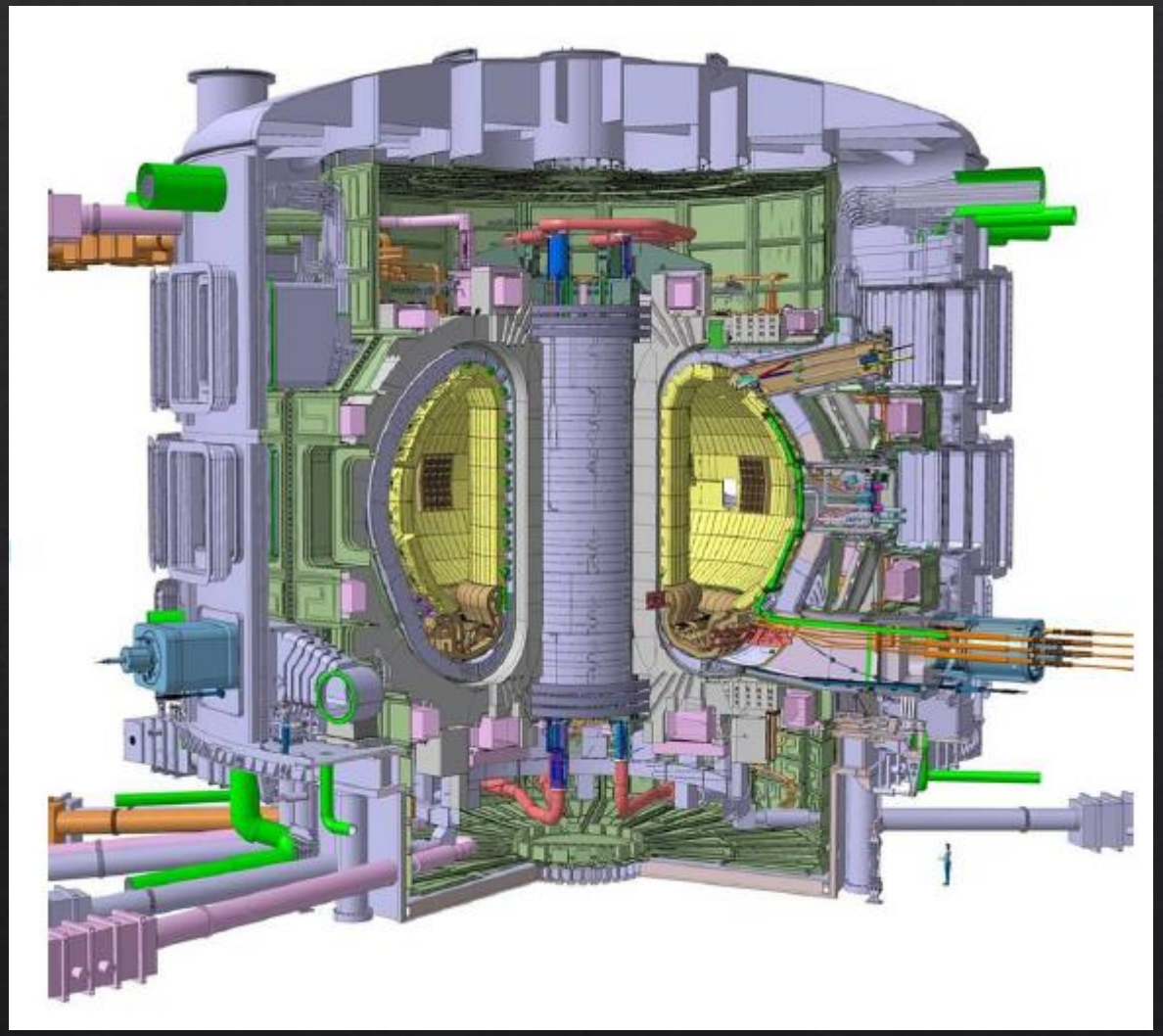


A sketch of the generic ITER site



Remote handling in JET and ITER (detail of divertor system)

ESQUÉ, Salvador, et al. Progress in the design, R&D and procurement preparation of the ITER divertor remote handling system. *Fusion Engineering and Design*, 2014, 89.9-10: 2373-2377.



ITER on-site tritium inventory is expected to be ≈4 kg

Reactors routinely operating with DT fusion (as FPP are expected to be) pose radiological hazards and are subject to licensing **as nuclear installations**

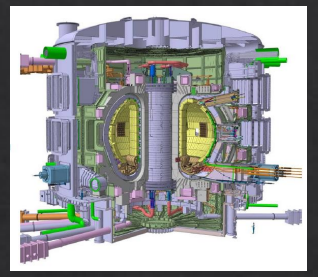
- ITER was the first fusion reactor to be licensed by a nuclear authority (ASN) following the established procedure for NPPs
- The UK has announced that forthcoming fusion facilities will be regulated under a framework closer to that for accelerators; US is discussing a similar approach

The **main radioactive source** during operation is the **plasma** itself:

- Neutron source ($\sim 3.5\times10^{21}\ s^{-1}$ for 1 GWth)
- Weak (1-100 keV) gamma photons from Bremsstrahlung, synchrotron and line radiation ($\sim 10^{22}\ s^{-1}$ for 1 GWth)

For release estimates and for decommissioning, the main radiological concerns are **tritium and activated reactor materials** (steel and plasma-facing materials)

- Welcome!
- Fusion energy: a quick introduction
- The case for fusion
- Fundamentals of magnetic fusion technology
- The state of the field in 2026
- Conclusions



ITER

Experimental fusion reactors

Goals (**scientific feasibility**)

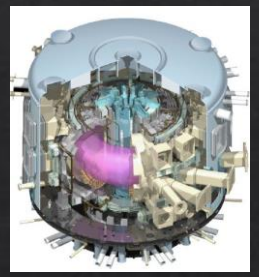
- Advance scientific understanding of plasma physics (burning plasma)
- Provide a testbed for innovative technologies and engineering solutions
- Demonstrate a net thermal power output from the plasma

*Efforts to this end since at least the 1970s

≈ 2020s – 2030s*

≈ 2030s – 2050s

> 2050s



DEMO-FPP

Fusion pilot plant (or technological demonstrator)

Goals (**technological feasibility**)

- Demonstrate integrated operation of FPP systems
- Demonstrate radiological safety and cost viability
- Acquire data on component lifetime
- Demonstrate electric production and fuel self-sufficiency



1952

MTR



1958

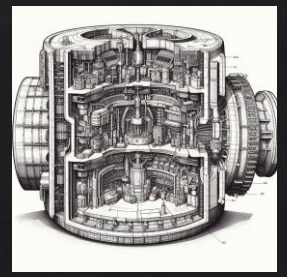
Shippingport Power Station



1968

Connecticut Yankee NPP

Reference timeline for light water fission reactors



MOAK FPP

Many-of-a-kind Commercial Power plant

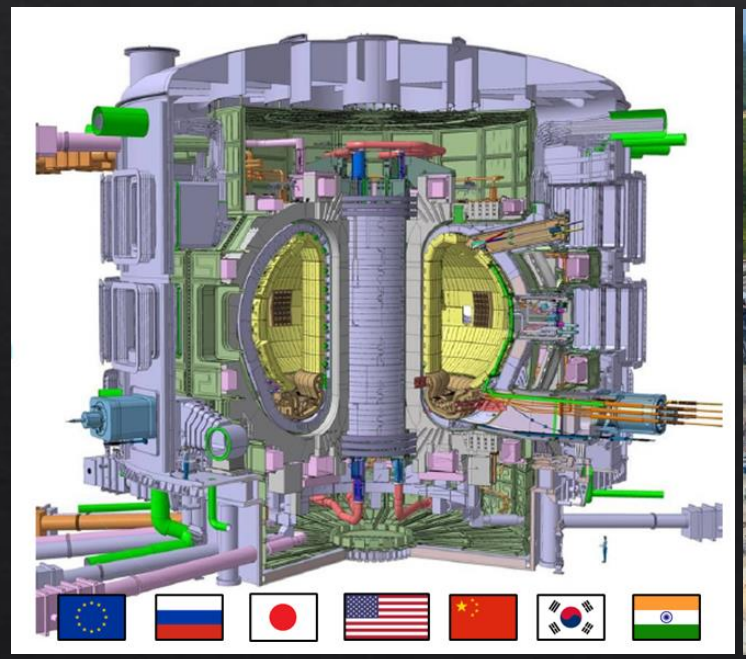
Goals (**economic feasibility**)

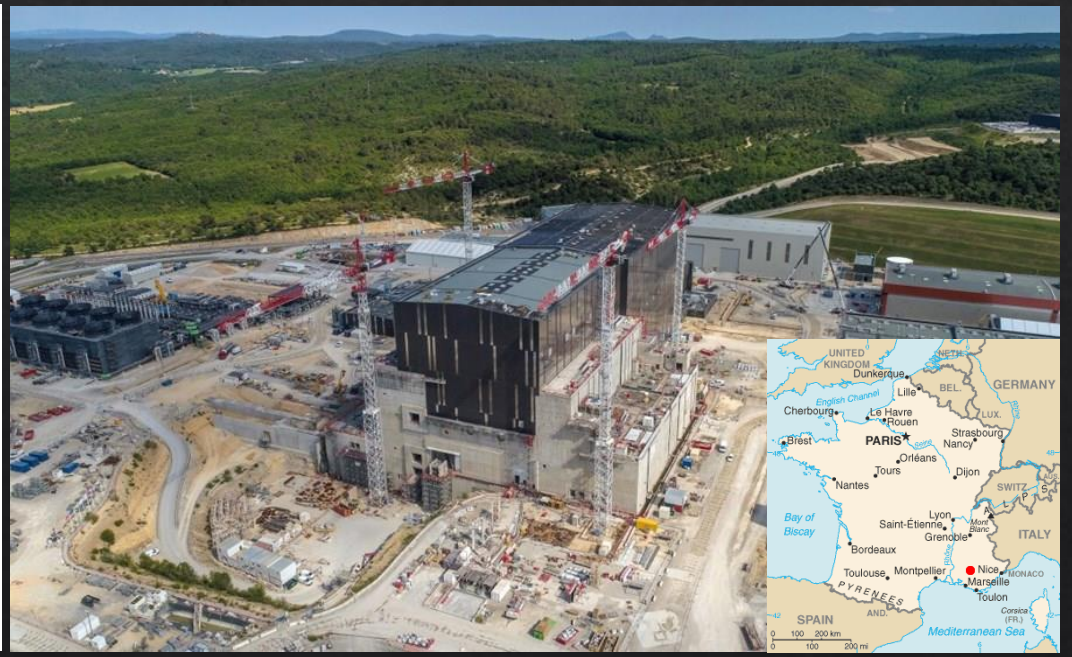
- Operation scale-up
- Minimization of capital cost
- Demonstrate improved performance and capacity factor



About 103 **experimental reactors** in the world, of which 56 are tokamaks (a magnetic confinement scheme)

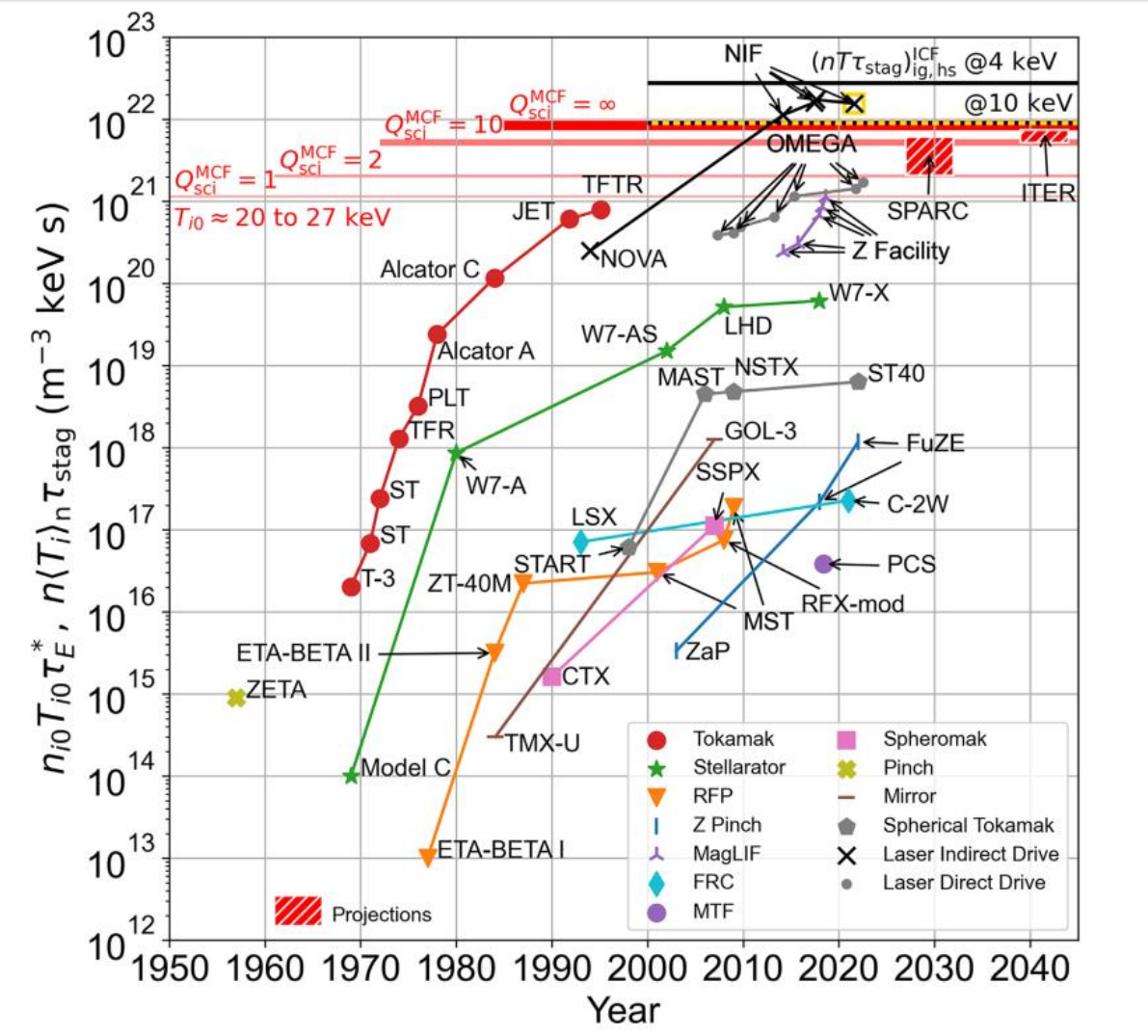
Joint European Torus (JET), operated at Culham, UK from 1983 to 2023, set the record for largest amount of thermal energy, 69 MJ, and thermal power, 16 MW, produced





ITER (the way)
Demonstrate $Q_{sci} = 10$

- Conceived in 1984
- Design completed in 2010
- $\approx 22 \div 35$ billions €
- Start operation ~2035



Steady progress of tokamak reactors toward Q_{sci} target until the 90s (JET, TFTR)

The need for ever-larger machines, combined with reduced funding, stalled progress pending the next-generation experiment (ITER)

Alternative configurations (stellarator, spherical tokamak, etc) have been explored but with fewer resources

Recent developments have spurred new interest:

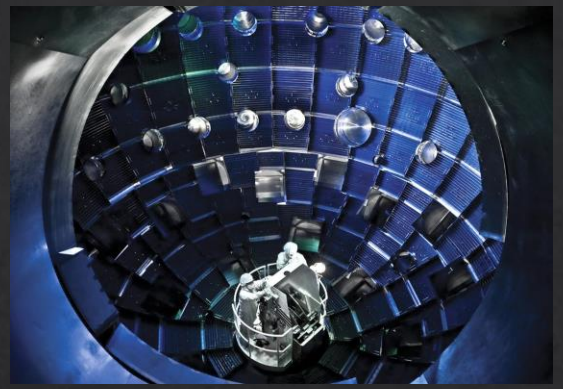
- Development of new coil materials (high-temperature superconductors) to achieve higher magnetic fields and more compact machines
- Progress in **inertial confinement experiments** driven by stockpile stewardship programs

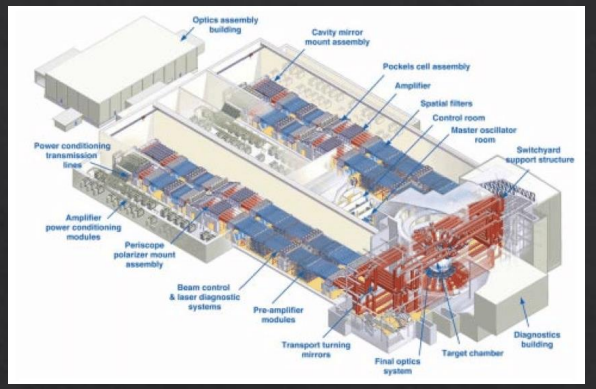
Wurzel, Samuel E., and Scott C. Hsu. "Continuing progress toward fusion energy breakeven and gain as measured against the Lawson criteria." Physics of Plasmas 32.11 (2025).

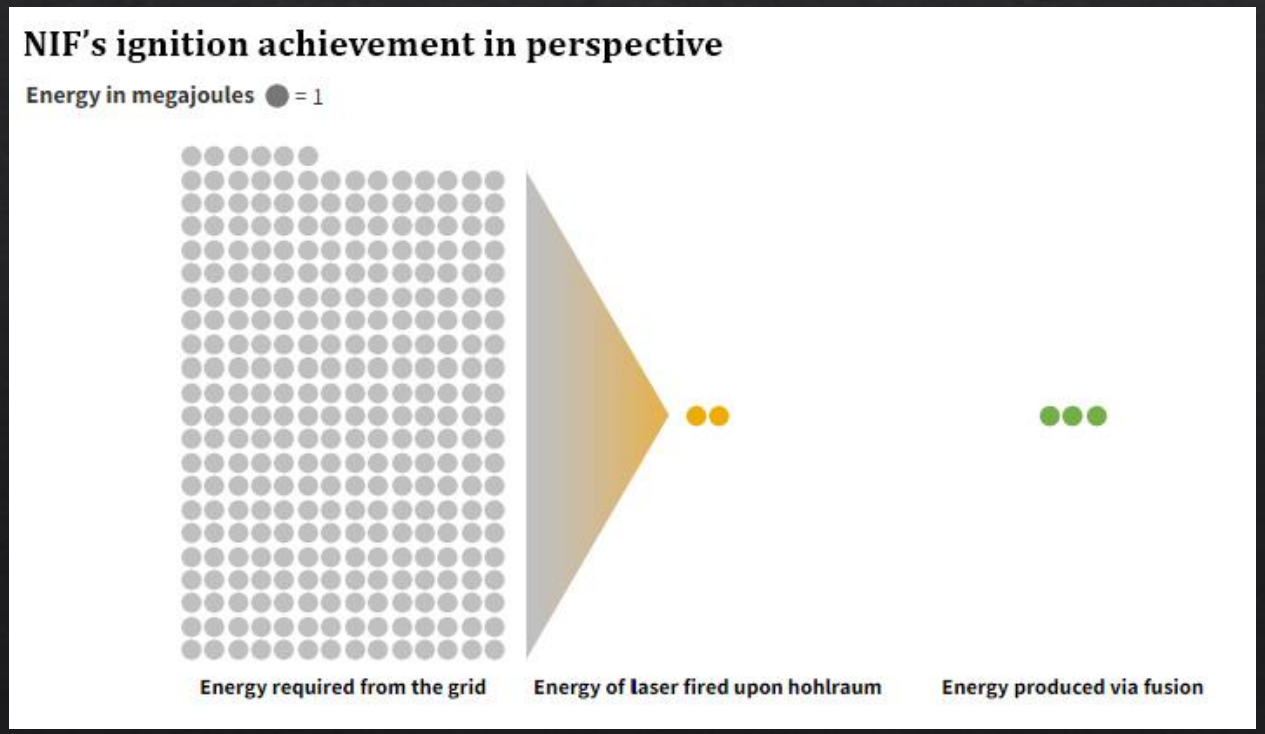
National Ignition Facility (NIF) surpasses long-awaited fusion milestone

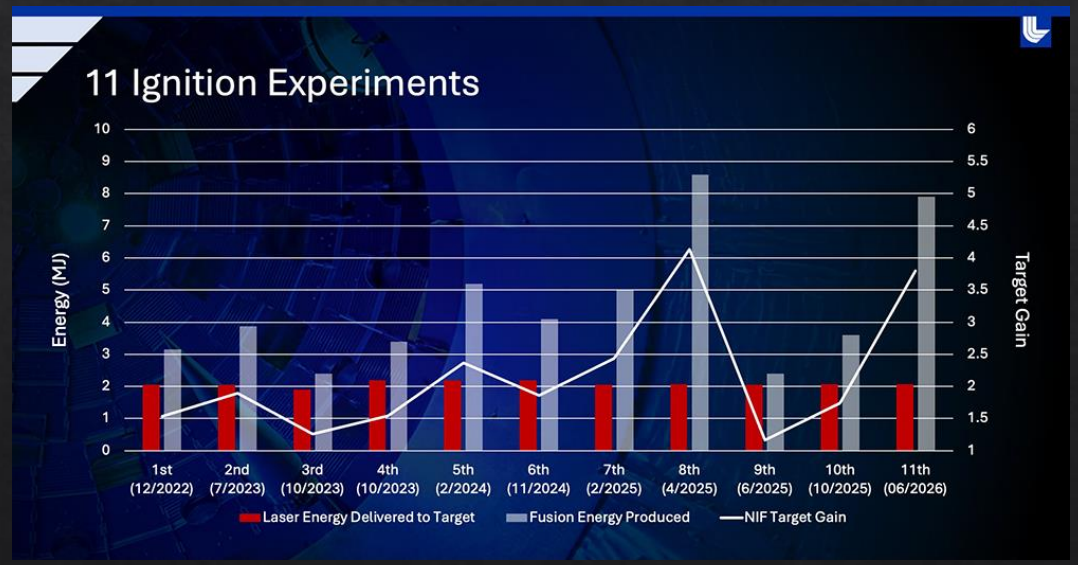
The shot at Lawrence Livermore National Laboratory on 5 December 2022 was the first-ever controlled fusion reaction to produce an energy gain. (source)

NIF has achieved $Q_{sci} > 1$ at least **eleven** times (06/2026)

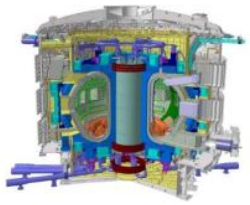
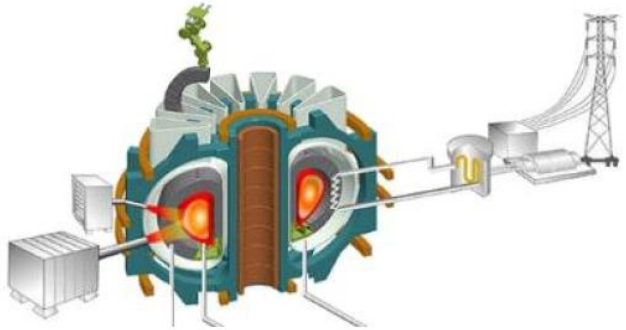








Credit: https://lasers.llnl.gov/science/achieving-fusion-ignition

JET	ITER	DEMO
		
D = 5.92 m V = 80 m^3 Q ≈ 0.6 P ≈ 16 MW_{th}	D = 12.4 m V = 800 m^3 Q ≈ 10 P ≈ 500 MW_{th}	D ≈ 13–19 m V ≈ 1000–3500 m^3 Q ≈ 25 P ≈ 2000–4000 MW_{th}
$P_E = 0$ MW_e	$P_E = 0$ MW_e	**$P_E = 500$ MW_e**

Planning is underway in several countries for a technological demonstrator for magnetic fusion reactors (**DEMO**)

- **EU-DEMO** EUROfusion
- JA-DEMO
- K-DEMO
- China Fusion Engineering Test Reactor (CFETR)
- Fusion Nuclear Science Facility (FNSF)

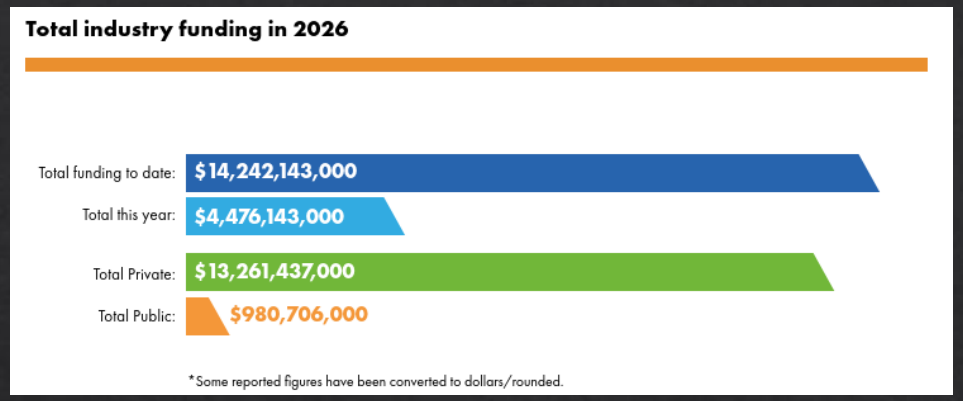
Objectives:

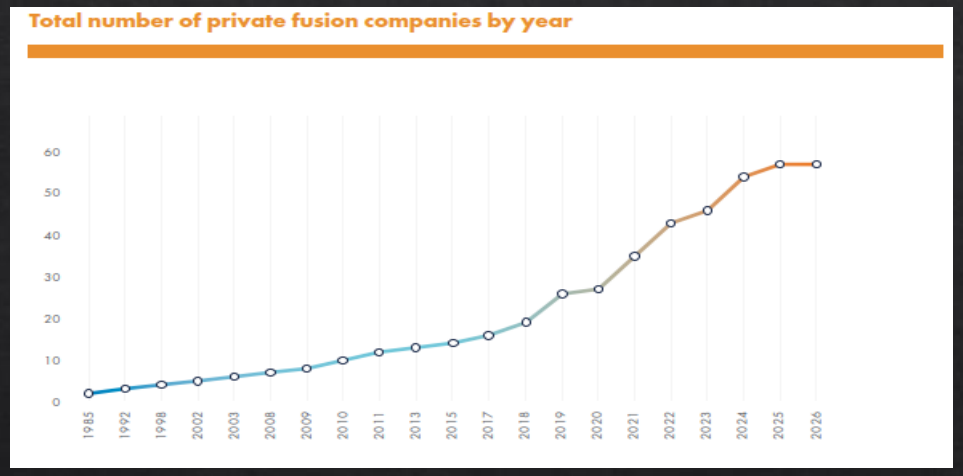
- Generate **electric power** to supply to the grid
- Bridge the technological gap between ITER and FPP
- Demonstrate **fuel self-sufficiency**

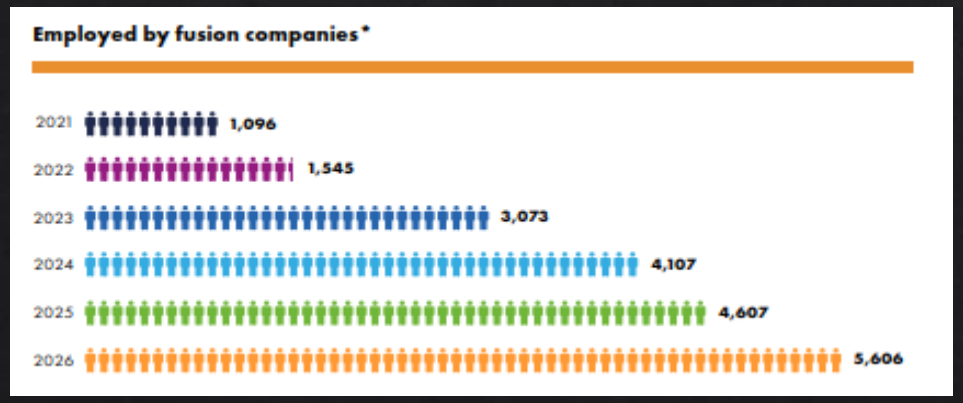
Timeline:
EU: conceptual design by 2027 – forecasted start of operation before **2060**

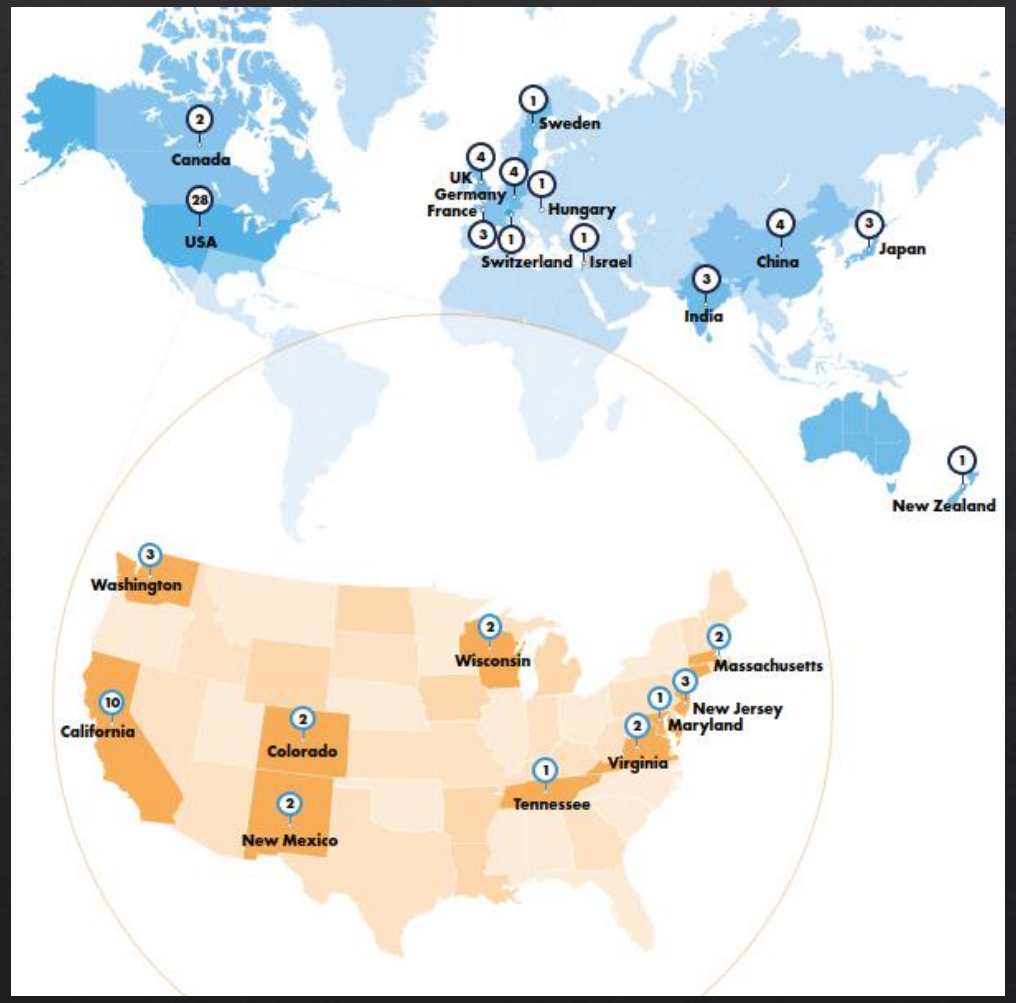
Some data for **private fusion enterprises*** as of July 2026

*Fusion Industry Association Survey 2026



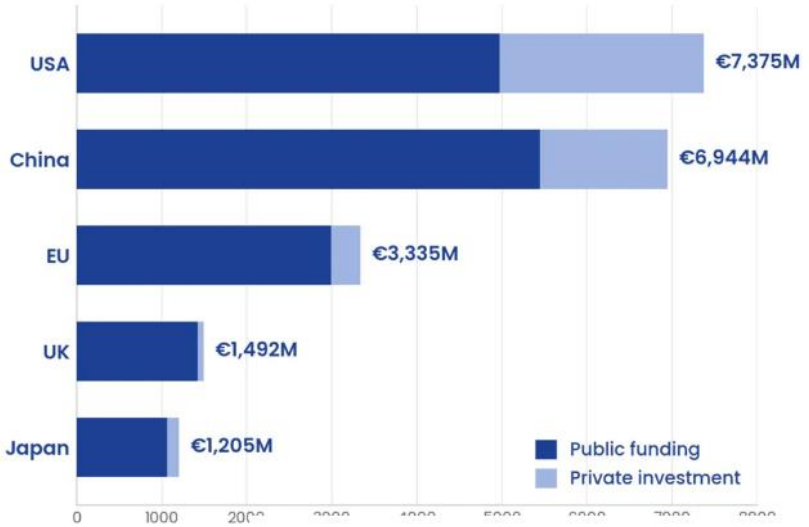


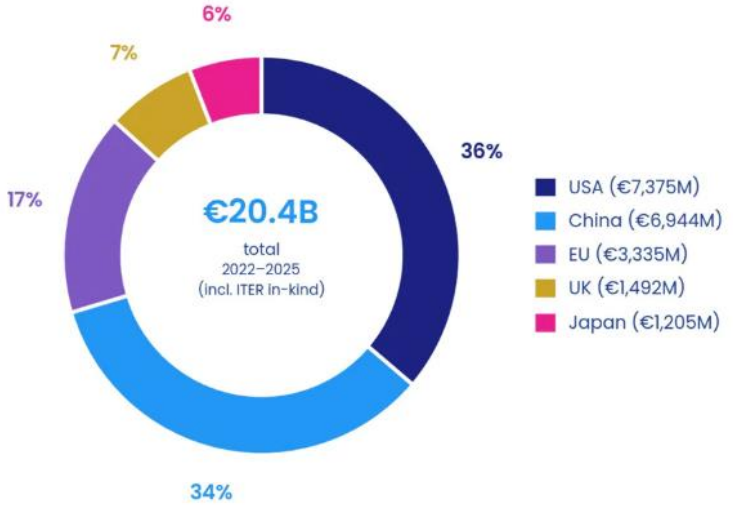




EUROfusion ≈ 3′800 across Europe [2023 EUROfusion Human Resources Survey]

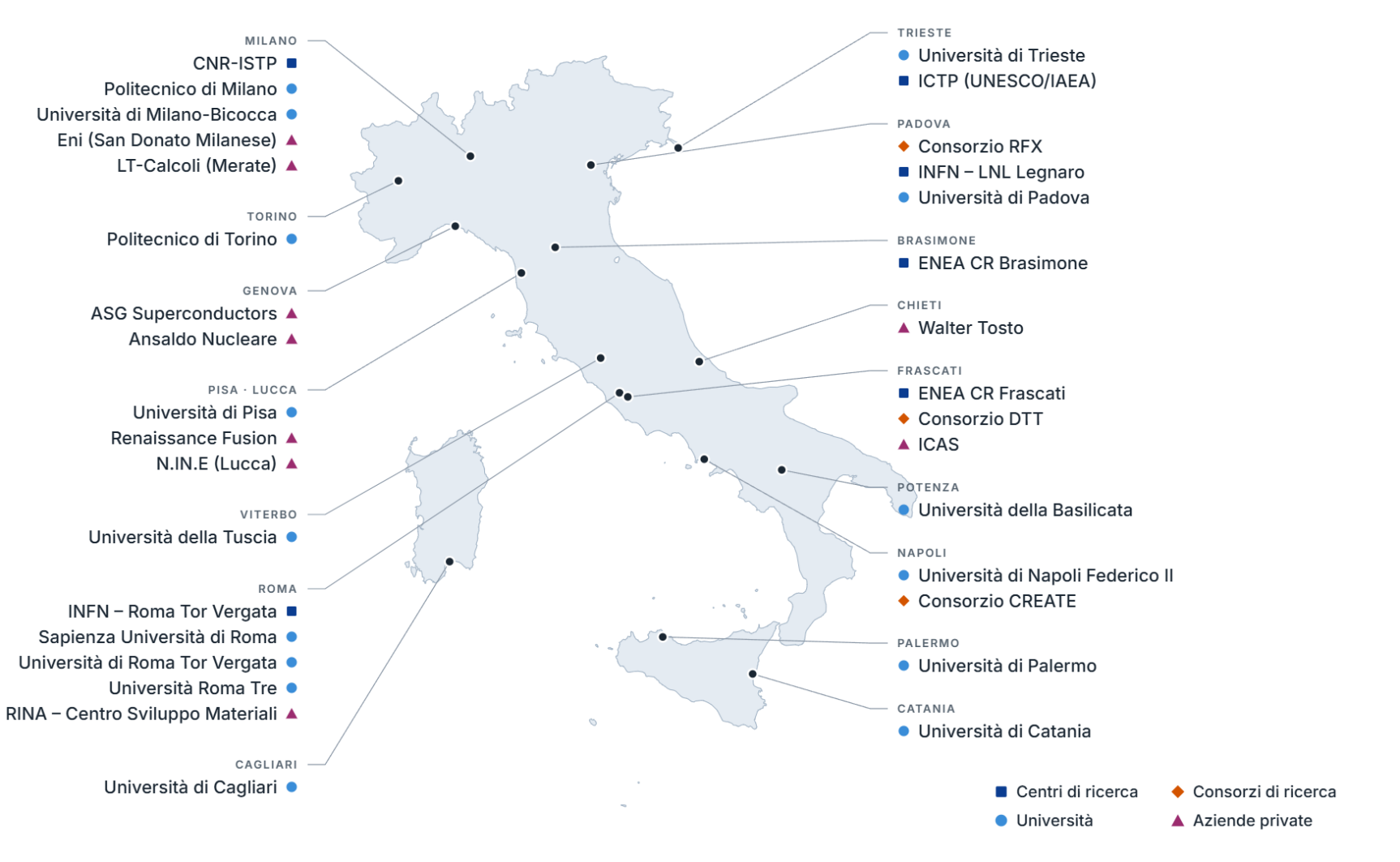
Comparable number of core public research personnel in the United States and China

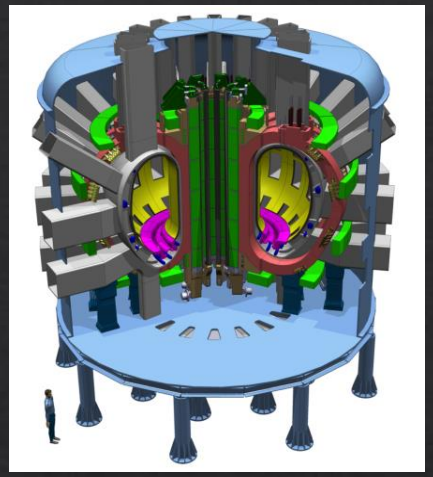




Identified fusion funding by actor, 2022–2025. Left: public funding, including ITER in-kind contributions, and private capital raised. Right: each actor's share of the five-actor total.
©F4E

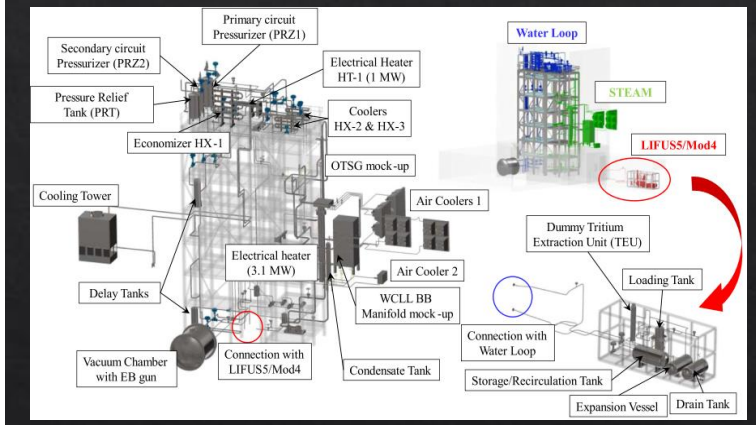






Divertor Tokamak Test (DTT)

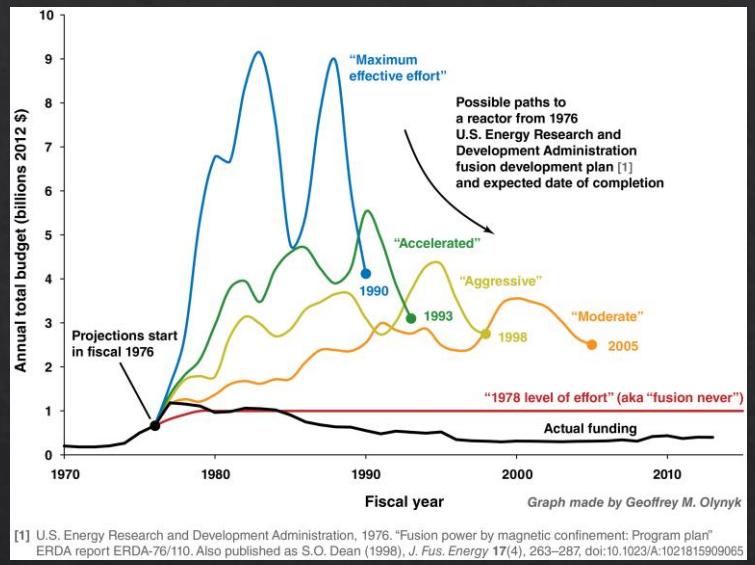
ENEA CR Frascati



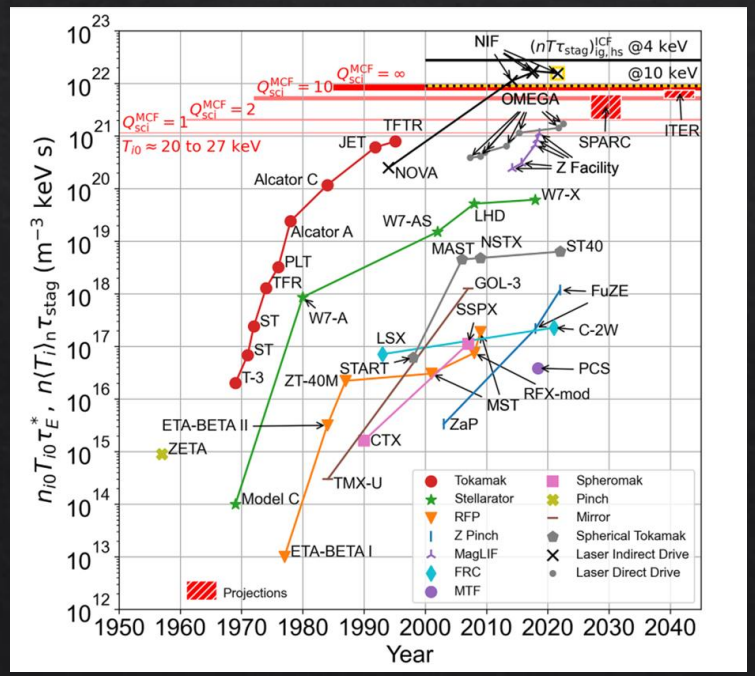
W-HYDRA

ENEA CR Frascati

- Welcome!
- Fusion energy: a quick introduction
- The case for fusion
- Fundamentals of magnetic fusion technology
- The state of the field in 2026
- Conclusions



[1] U.S. Energy Research and Development Administration, 1976. "Fusion power by magnetic confinement: Program plan" ERDA report ERDA-76/110. Also published as S.O. Dean (1998), *J. Fus. Energy* **17**(4), 263–287, doi:10.1023/A:1021815909065



Fusion is a **sustainable, programmable, and low-carbon energy source. The tokamak is the most** promising approach, but not the only one

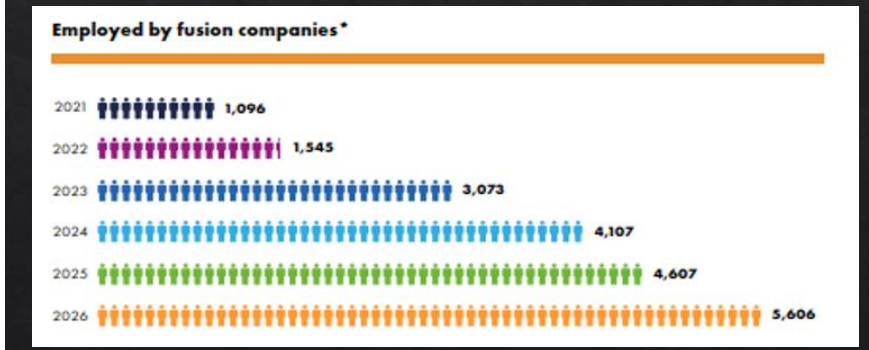
Great progress has been made in the past 80 years, despite volatile funding, toward the demonstration of **scientific and technological feasibility**

Significant challenges still remain to demonstrate the **technical and economic feasibility** of fusion power; the emergence of a **private sector** may mark an **inflection point** in development speed

ITER and the combined efforts of both the public and private sector are going to shape the future of the field in the decades to come …en route to a **Fusion Power Plant**

	2023					2014	
Degree type	No. of staff	% women	% foreign	% permanent	% student	No. of staff	% women
Physics	1802	17.4	29.3	62	21.7	1578	18.1%
Engineering	1304	13.7	11	74.5	8.1	1108	11.3%
Technician	457	12.5	6.5	90.4	2.8	905	7.2%
Computer Science	137	13.1	15.3	67.9	12.4		
Chemistry	101	49.5	8.9	83.2	7.9		
Mathematics	52	25	44.2	48.1	32.7		

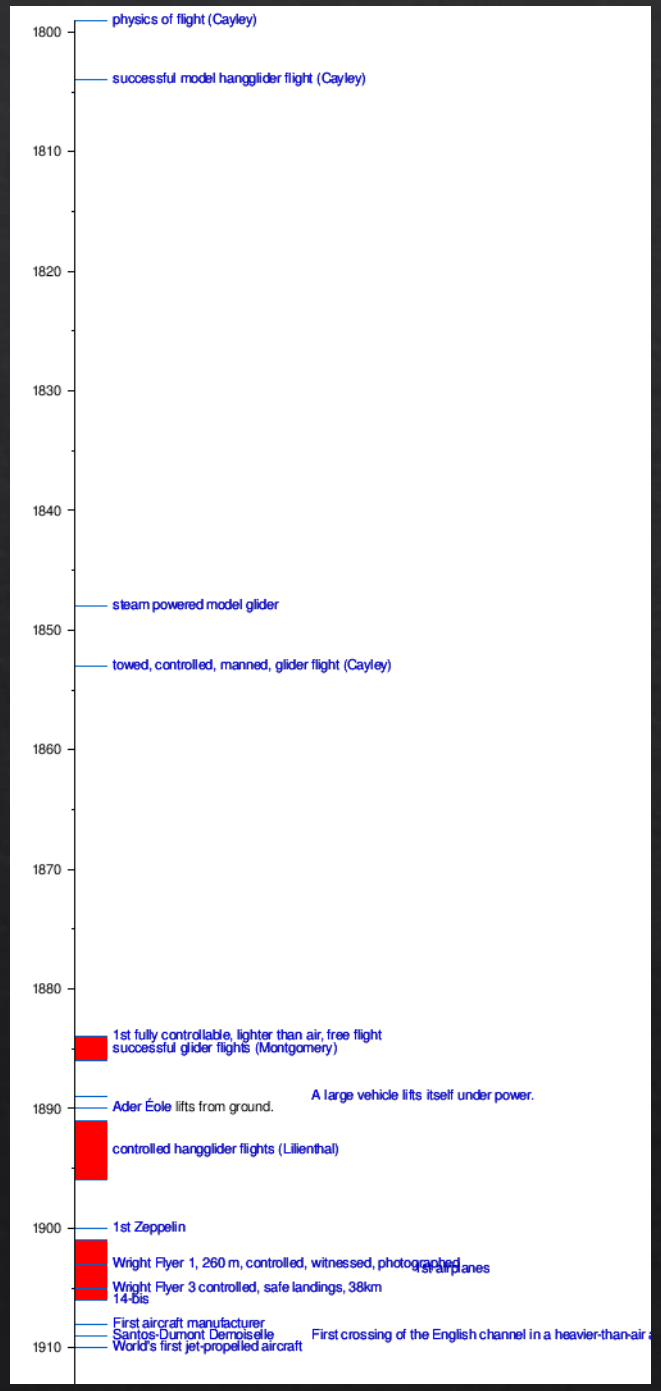
EUROfusion



2023 EUROfusion Human Resources Survey

Fusion Industry Association, 2026 Report

Wurzel, Samuel E., and Scott C. Hsu. "Continuing progress toward fusion energy breakeven and gain as measured against the Lawson criteria." Physics of Plasmas 32.11 (2025).





FLYING MACHINES WHICH DO NOT FLY.

The ridiculous fiasco which attended the attempt at aerial navigation in the Langley flying machine was not unexpected, unless possibly by the distinguished Secretary of the Smithsonian Institution, who devised it, and his assistants. Prof. MANLY, who undertook the voyage, prudently clothed himself in a cork jacket—doubtless because cork is a good non-conductor and would tend to keep the wearer warm in the rarefied strata of the upper atmosphere in which he perhaps expected to cruise. However, as the machine was to be launched over the Potomac, it appears, as matters even-

[It] might be assumed that the flying machine which will really fly might be evolved by the combined and continuous efforts of mathematicians and mechanicians in from one million to ten million years... No doubt the problem has attractions for those it interests, but to the ordinary man it would seem as if effort might be employed more profitably.
- New York Times, 9th October 1903



"I confess that, in 1901, I said to my brother Orville that men would not fly for 50 years. Two years later, we were making flights. This demonstration of my inability as a prophet gave me such a shock that I have ever since refrained from all prediction."
-Wilbur Wright



Seconds into the Wright brothers' successful airplane flight, near Kitty Hawk, North Carolina, on December 17, 1903

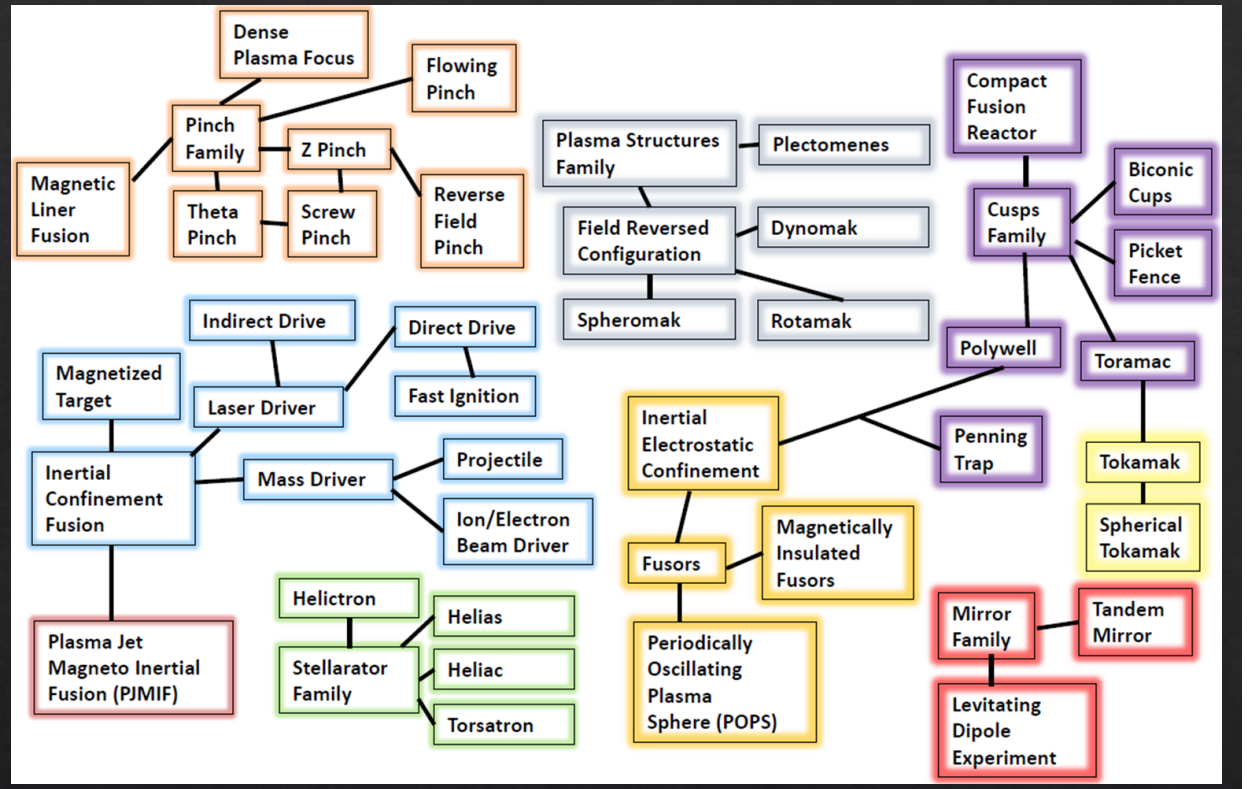
Questions?

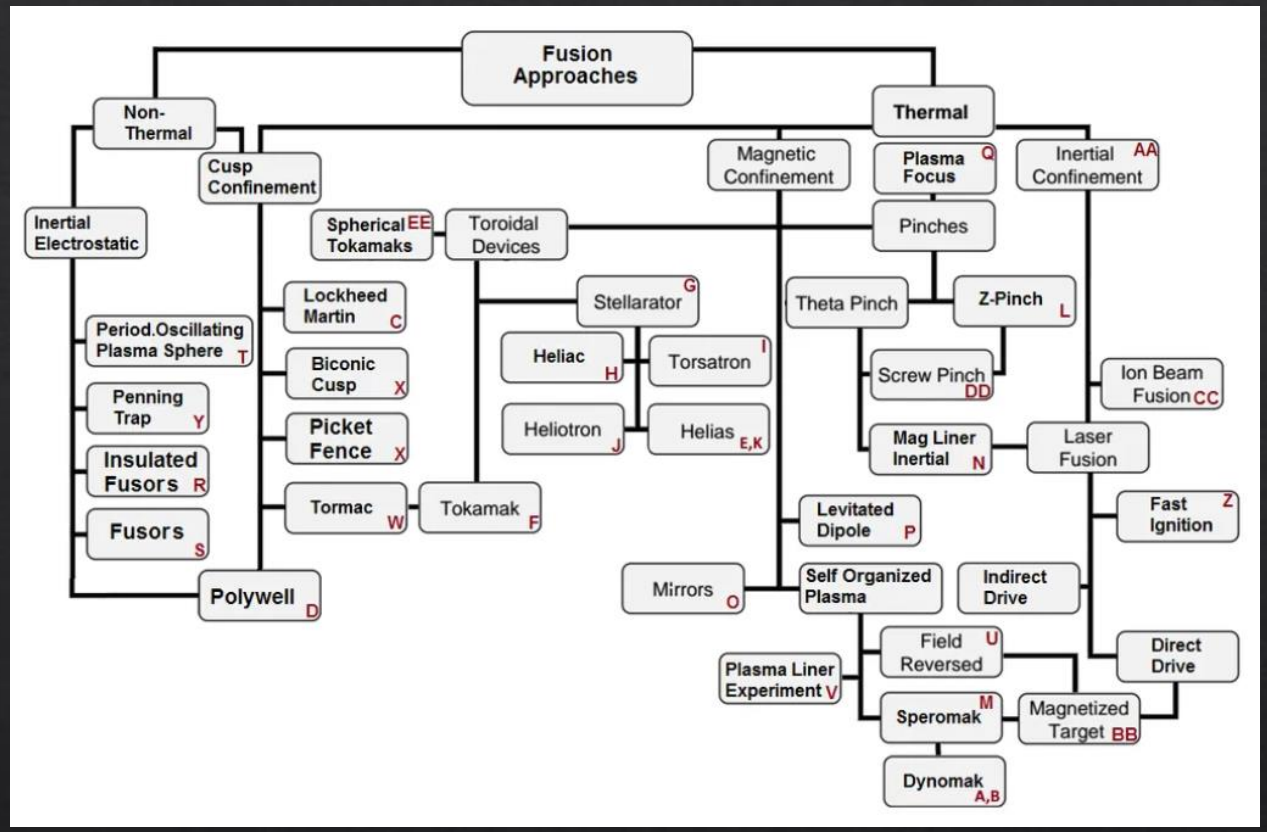


email: alessandro.tassone@uniroma1.it

Resources for further reading

- ITER organization website: https://www.iter.org/
- EUROfusion website: https://euro-fusion.org/
- European Research Roadmap for the Realization of Fusion Energy: https://euro-fusion.org/wp-content/uploads/2022/10/2018_Research_roadmap_long_version_01.pdf
- IAEA Fusion Portal: https://nucleus.iaea.org/sites/fusion-portal/SitePages/Home.aspx
- Fusion Industry Association website: https://www.fusionindustryassociation.org/
- National Ignition Facility @Lawrence Livermore National Lab: https://lasers.llnl.gov/





Various authors have also put forth ways to organize all the fusion approaches that have been tested over the past 80 years. The flow chart above groups the approaches into color coded families, these are: the Pinch Family (orange), the Mirror Family (red), Cusp Systems (violet), Tokamaks & Stellarators (green), Plasma Structures (gray), Inertial Electrostatic Confinement (dark yellow), Inertial Confinement Fusion (ICF, blue), Plasma Jet Magneto Inertial Fusion (PJMIF, dark pink).

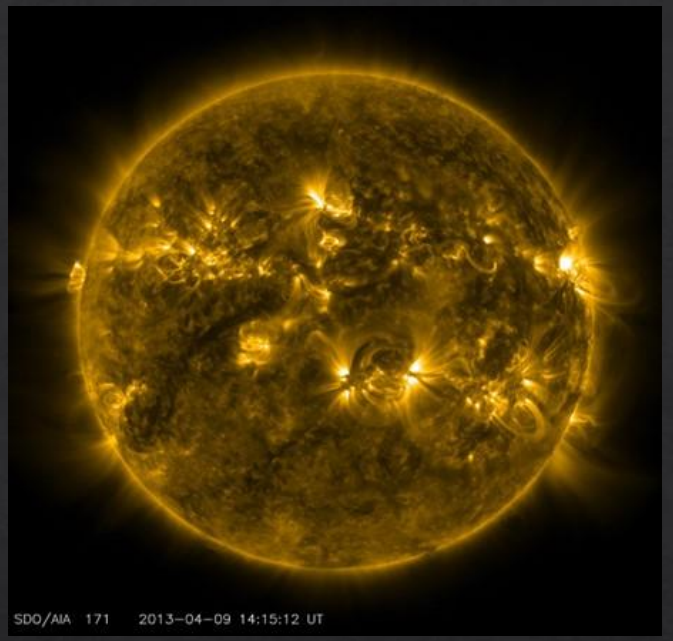
An alternative chart is available from here.

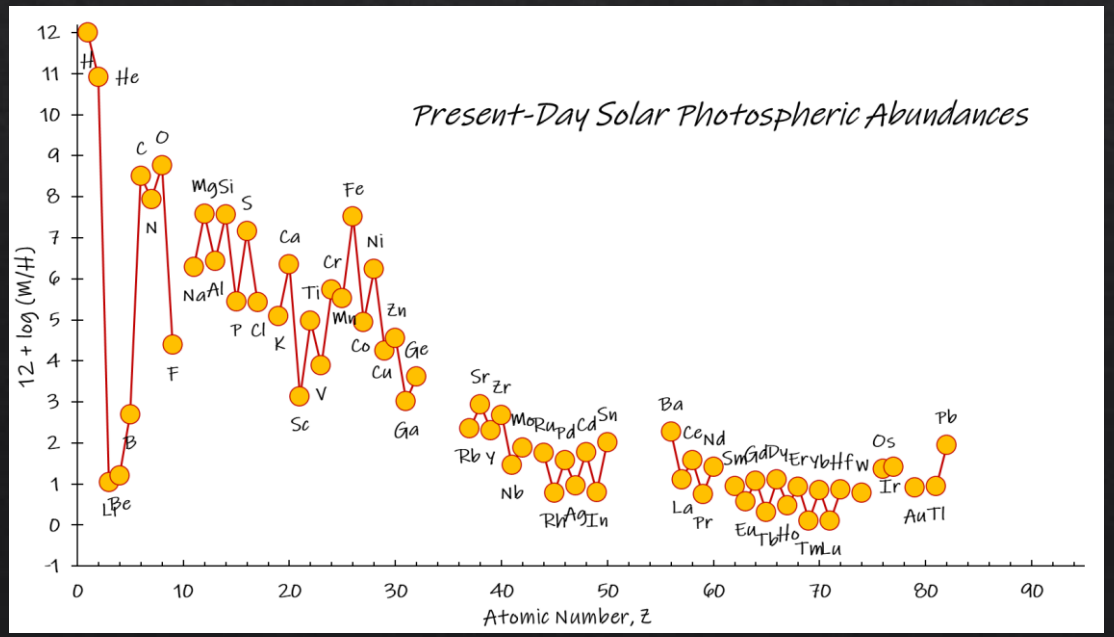
The Sun is composed mostly of hydrogen (74.9%) and **helium** (23.8%), spectral analysis (≈ 1920)

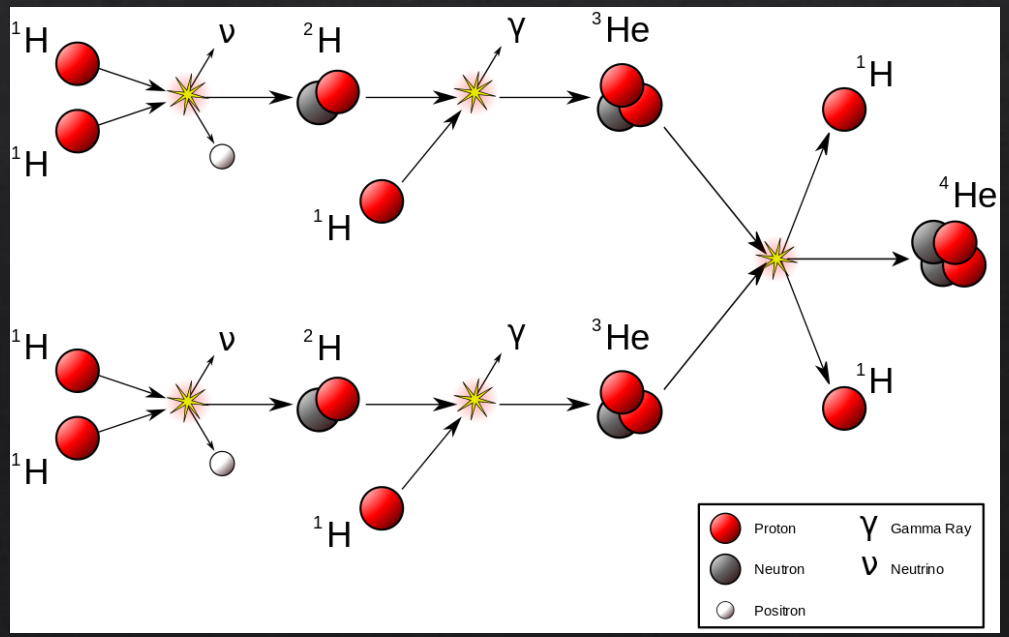
Proposal of **nuclear reactions** as the main power-generating mechanism by A. Eddington (1922)

Proton-proton chain identified by H. Bethe and C. Critchfield in 1938 as the primary energy mechanism

675 Mton of hydrogen fuse into 670 Mton of helium per second

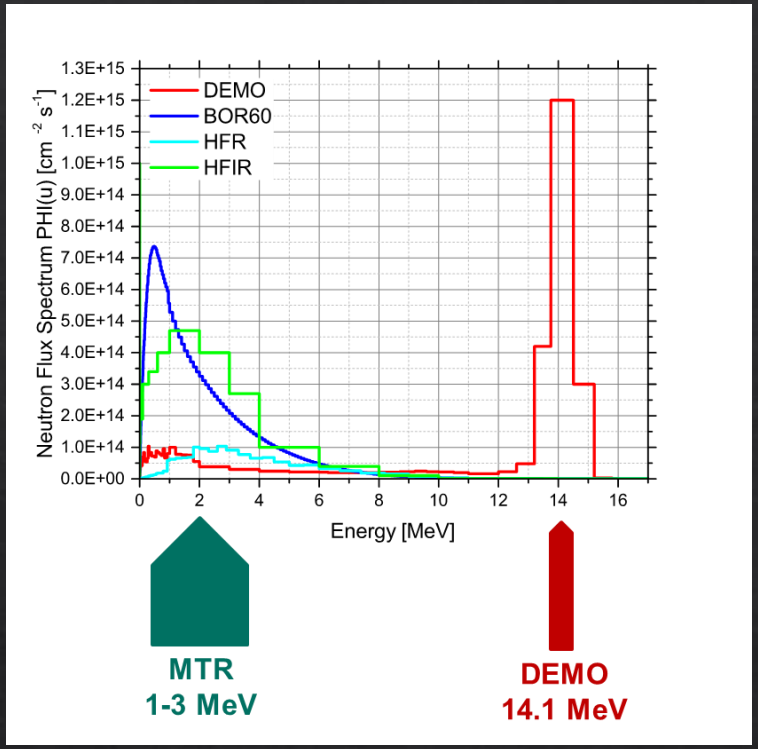


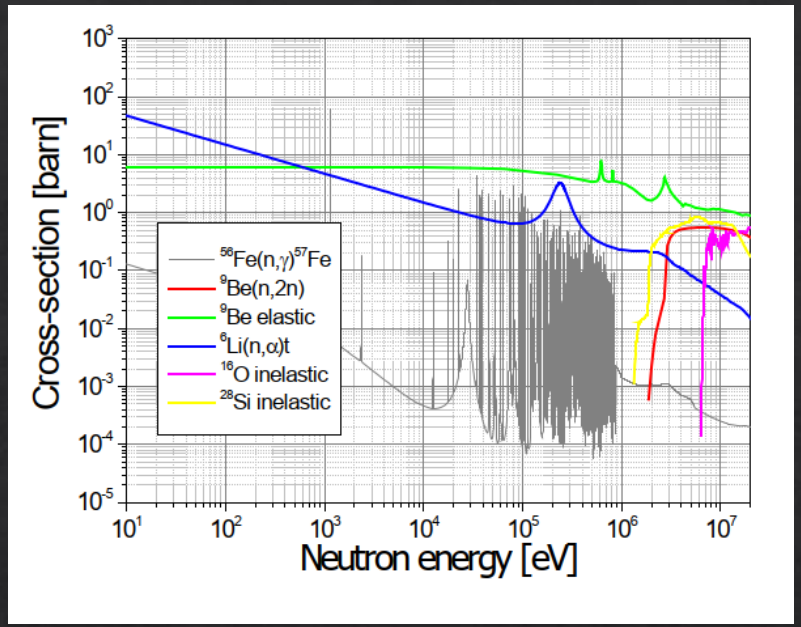


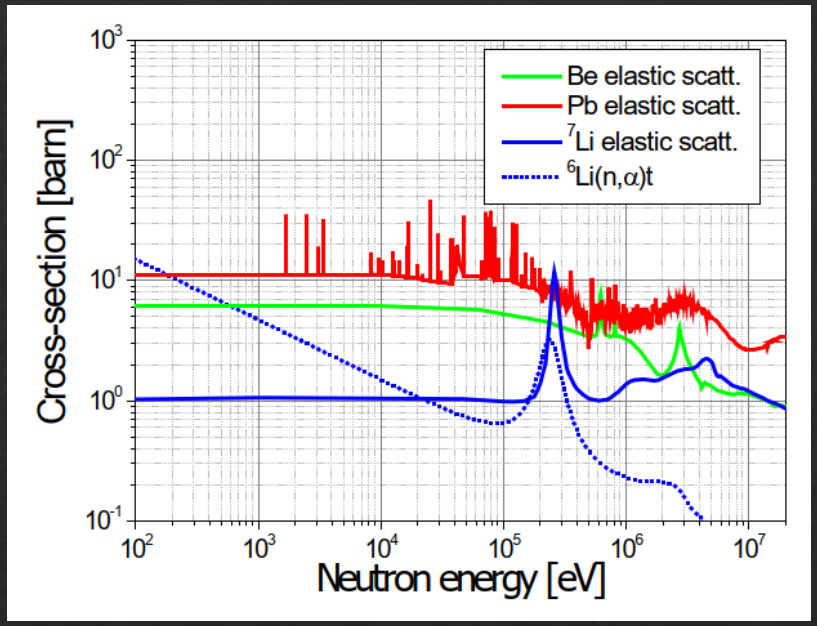


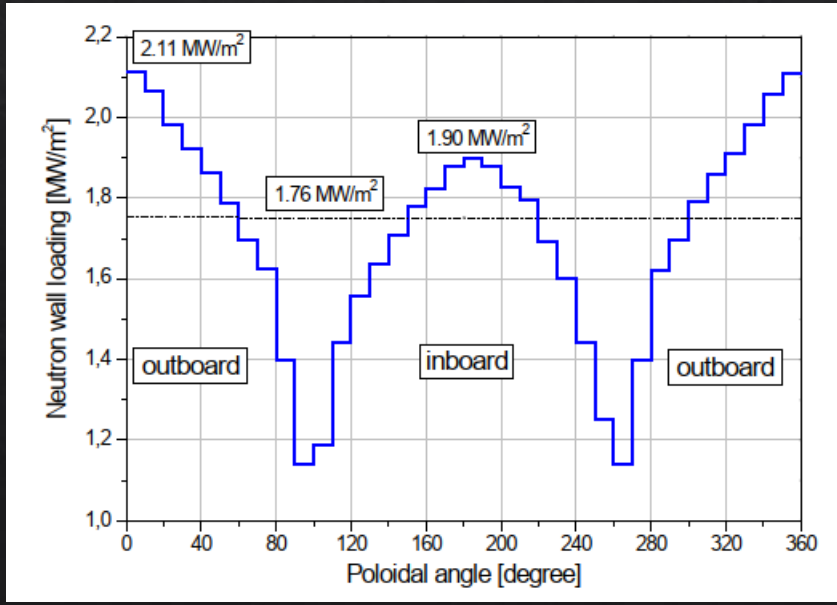
+26.7 MeV/reaction

Credit: Bergmann et al., https://arxiv.org/abs/2503.05402









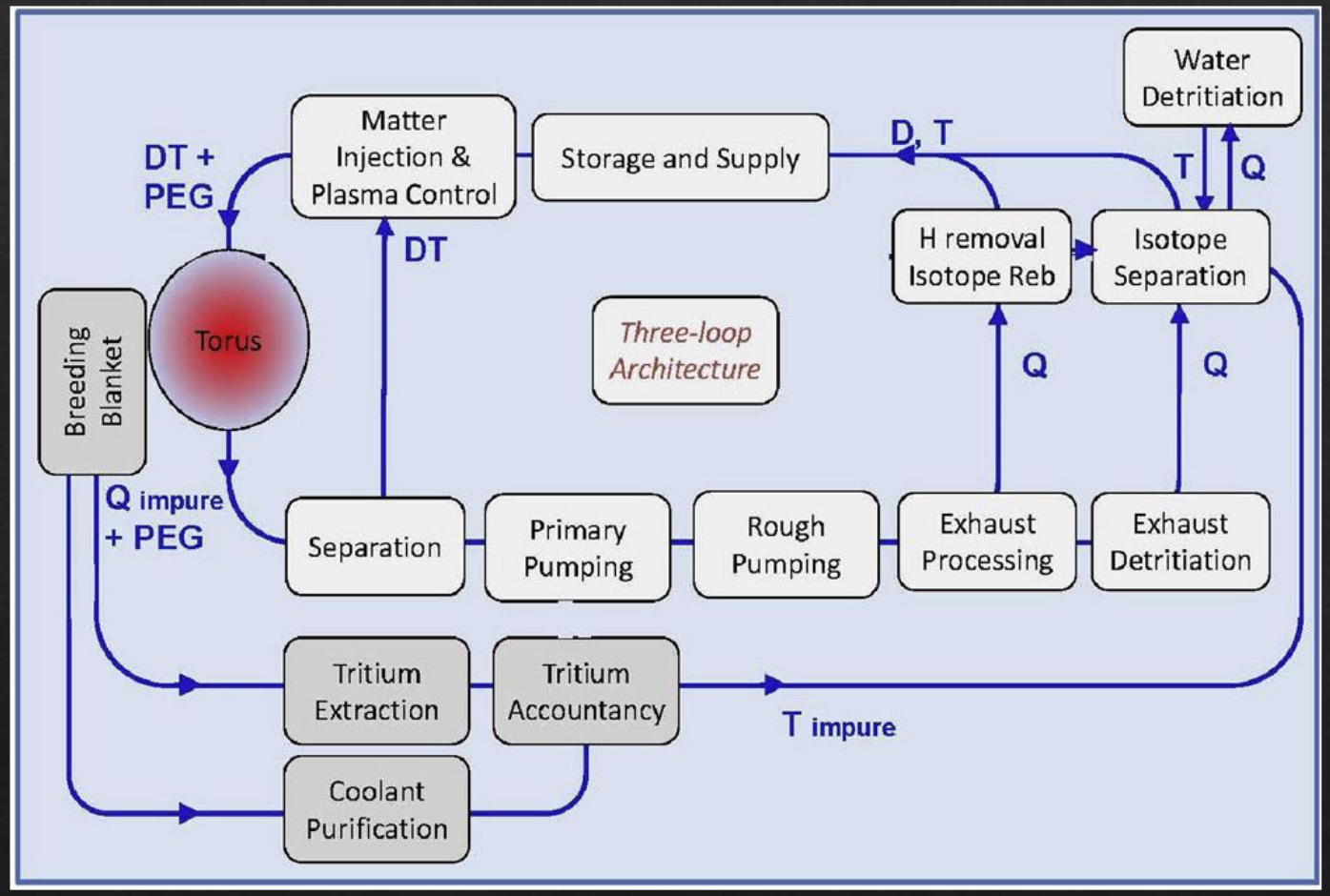
Neutron spectrum in a fusion reactor is significantly different from that in a fission reactor

Materials test reactor (MTR):

- Neutron energy peak at $\approx 2\ MeV$ (uranium fission)
- Relatively low fluence

Fusion reactor:

- Higher overall fluence
- Neutron energy at $\approx 14.1\ MeV$ (for DT plasma)



In-situ **fuel cycle architecture** relying on three nested loops

1. Separation of deuterium/tritium from torus exhaust for very rapid processing (< 1 h)

2. Recovery of tritium from reaction chamber auxiliaries, leakages, and secondary processing of torus exhaust for quick processing (< 6 h)

3. Tritium extraction and purification from breeding components, typically much slower (1-2 days), but essential to build-up supply

Minimize processing time to reduce inventory (lower radiological risk) and to improve economy of tritium production