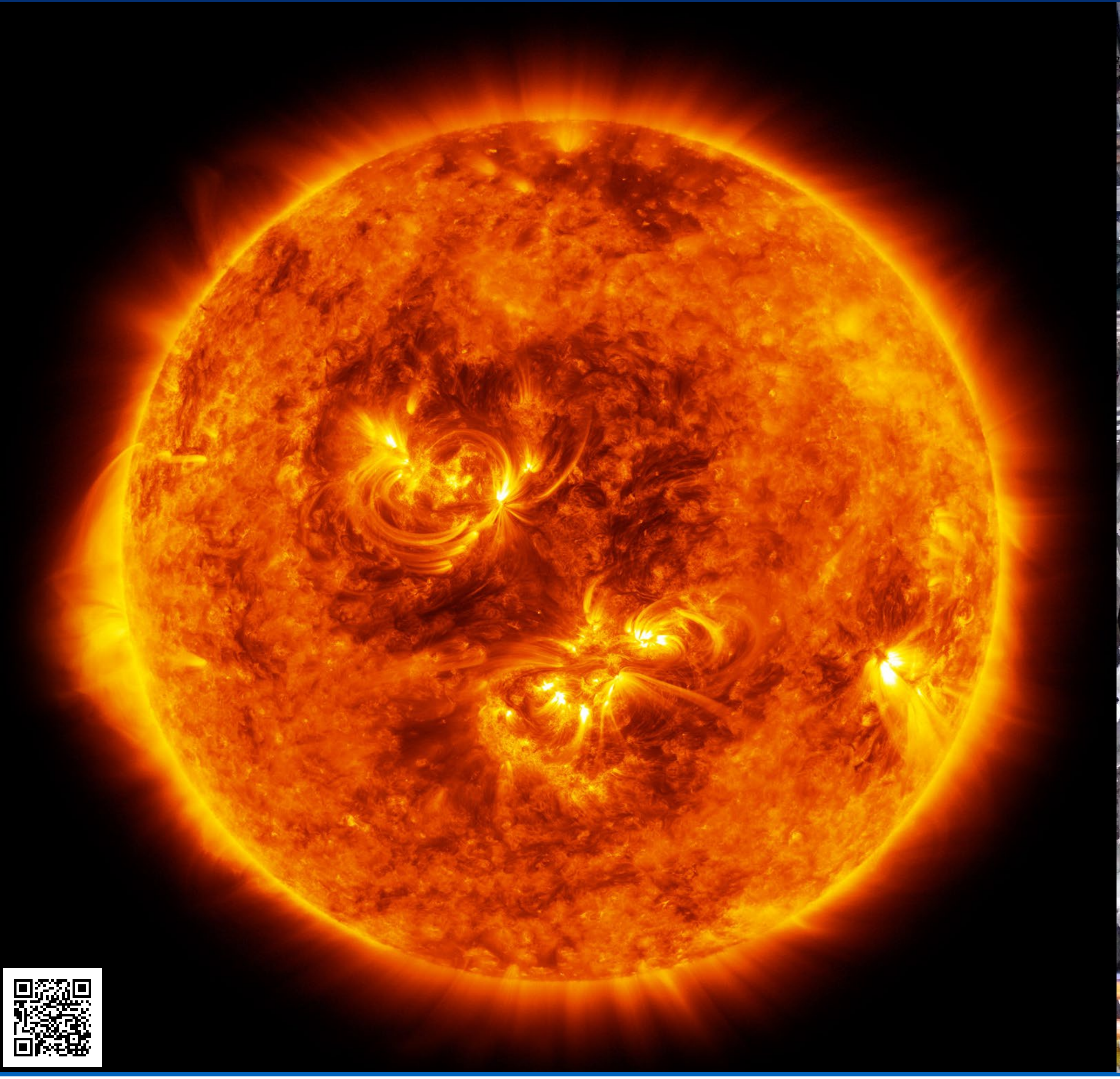
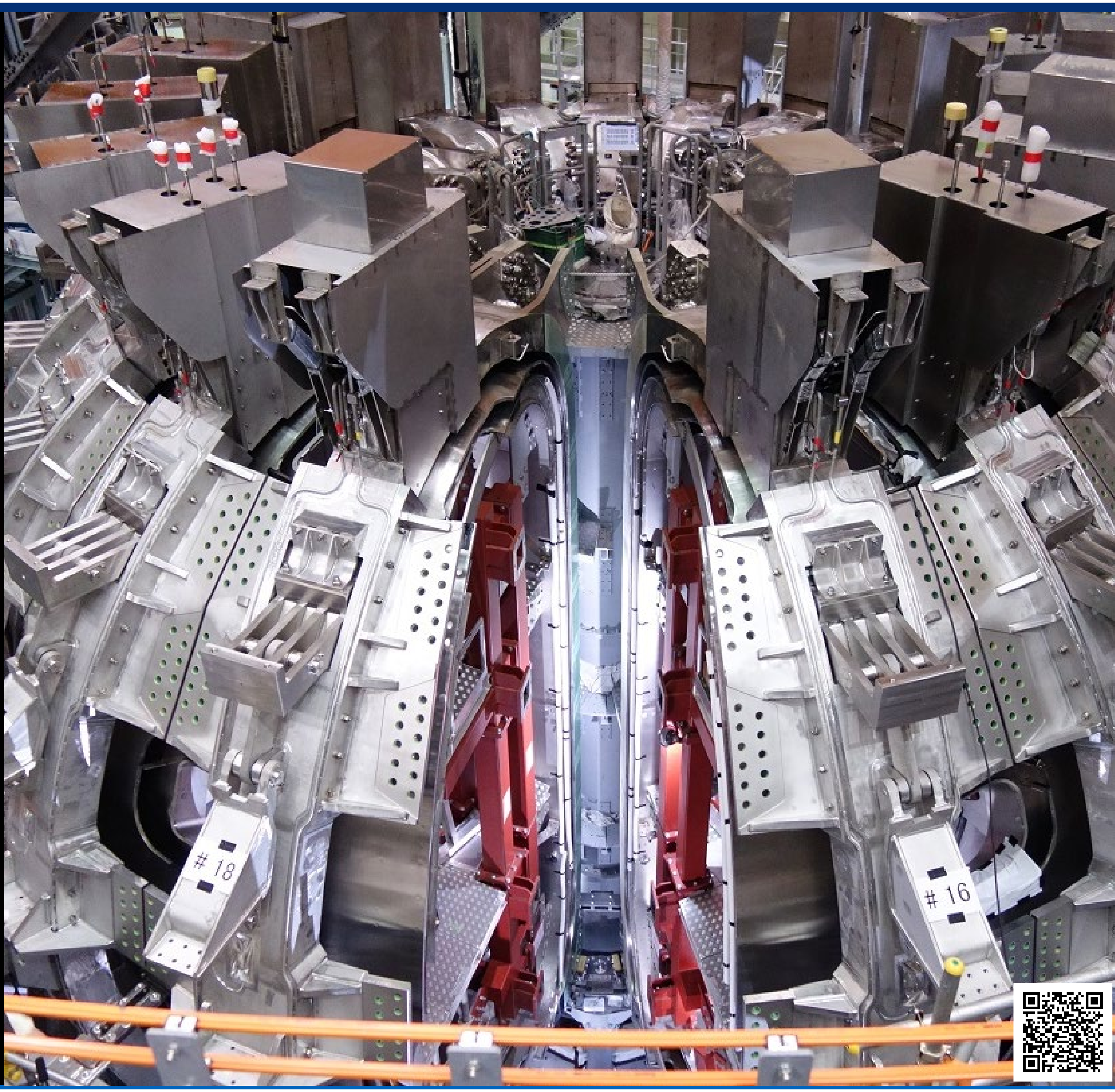
FUSION FOR ENERGY

Physics and engineering Tokamak Overview

Nuclear Fusion

Introduction





What is Nuclear Fusion

- **Nuclear fusion** is the process by which two atomic nuclei are combined to form a heavier atomic nucleus and subatomic particles

- The **mass difference** between the reactants and products corresponds to a release or absorption of energy and arises due to the **difference in atomic binding energy** between the different nuclei

- Fusion is the process that **powers the stars**, where large amounts of energy are released

Nuclear Fusion Energy

- When two light nuclei fuse together, the reaction is **exothermic**, and energy can be released in the form of:
  - **Kinetic energy** of the heavier nucleus
  - **Kinetic energy** of subnuclear particles (e.g. neutrons, protons, neutrinos, etc.)
  - electromagnetic **radiation** (e.g. photons)

- The unit of energy used in nuclear physics is the **electronvolt [eV]**
- 1 eV is the amount of energy gained by a single electron accelerated from rest through an electric potential difference of 1 Volt in vacuum

$$\mathbf{1\ eV = 1.602 \cdot 10^{-19}\ J}$$

The nuclear binding energy

- The **Nuclear binding energy** is
  - the minimum energy that is required to **disassemble** the nucleus of an atom into its constituent protons and neutrons, or
  - the energy that would be liberated by **combining** individual protons and neutrons into a single nucleus.
- It represents the energy of the nucleus **relative** to the energy of the constituent nucleons when they are infinitely far apart
- Is related to the **balance** of strong force (attraction) and electromagnetic force (repulsion) in the nucleus

The mass defect

- The mass of an atomic nucleus is less than the sum of the individual masses of the free constituent protons and neutrons

$$\boldsymbol{m_A < Z \cdot m_p + N \cdot m_n}$$

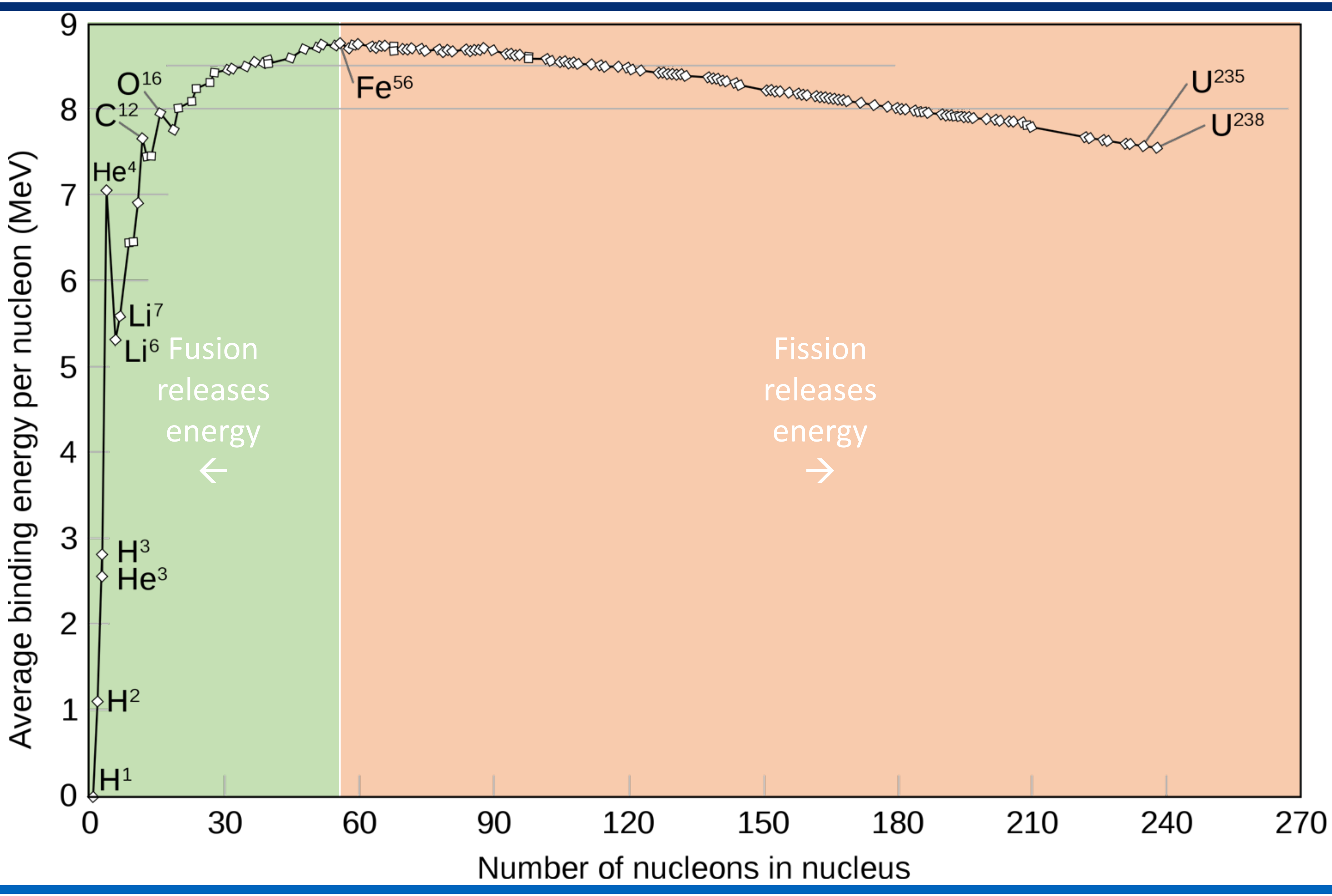
- The missing mass is known as the **mass defect**, and represents the energy that was released when the nucleus was formed

$$\boldsymbol{\Delta m = Z \cdot m_p + N \cdot m_n - m_A}$$

$$\boldsymbol{\Delta E = \Delta m \cdot c^2}$$

- Such energy can be released as electromagnetic radiation and/or kinetic energy of the products

Binding energy per nucleon vs. atomic mass



Binding energy per nucleon vs. atomic mass

- The **average binding energy per nucleon** is the ratio $\boldsymbol{\Delta E/A}$
- $\Delta E/A$ increases fast for the very light nuclei, then changes slope and slowly decrease for A > 56
- The absolute maximum of the curve is at A = 56 and close to the maximum are species with **high nuclear stability**, like **Nickel** or **Iron**
- **Fission and Fusion fuels** are at the two extremes of this curve
  - If a nucleus undergoes **fission**, and the sum of the binding energy of the products is higher than the binding energy of the reactant, the reaction is **exothermic**
  - If two nuclei undergo **fusion**, and the binding energy of the product is higher than the sum of the binding energies of the reactants, the reaction is **exothermic**

The special case of ^{4}He

- Helium-4 shows a pronounced local peak
- This means that fusing lighter nuclei to obtain ^{4}He is particularly convenient in terms of released energy

Let's make an example:

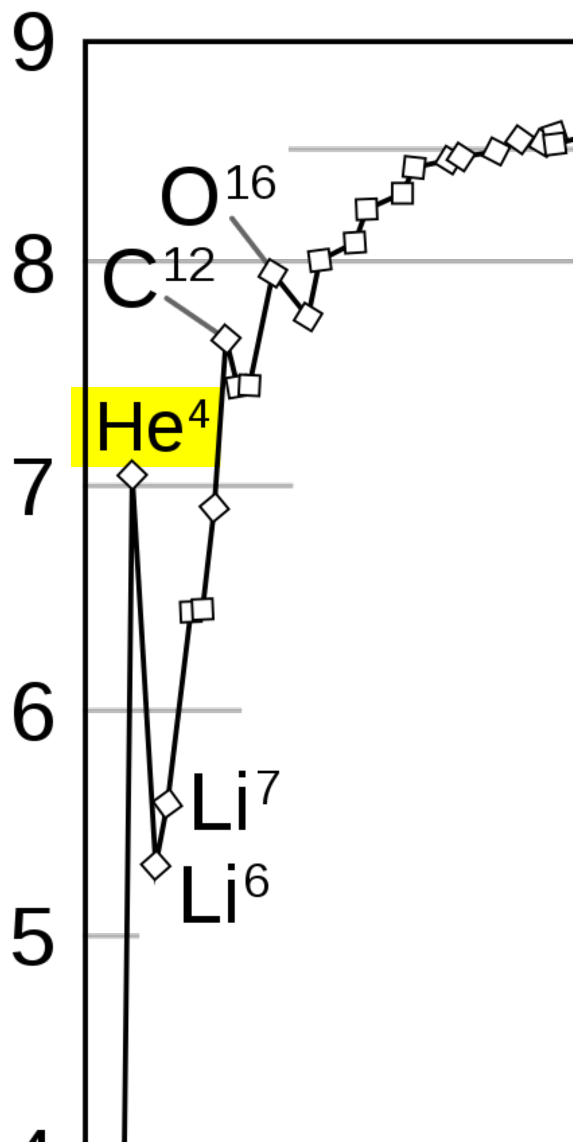
$^{2}H + ^{3}H \rightarrow ^{4}He + n$

^{4}He binding energy = 28.296 MeV

^{2}H binding energy = 2.225 MeV

^{3}H binding energy = 8.482 MeV

Fusion energy = 28.296 – 2.225 – 8.482 = **17.589 MeV**



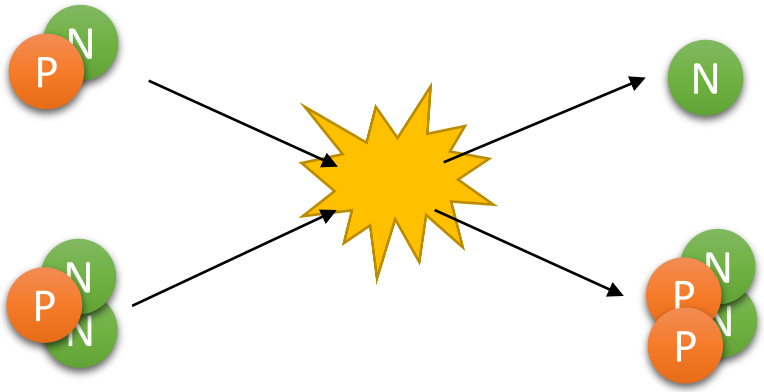
Important Nuclear fusion reactions of light nuclei

D-T	**$T(D,n)\,^4He$**	**$D + T \rightarrow \alpha\ (3.52) + n\ (14.1) + 17.59$ MeV**
D-D	$D(D,p)T$	$D + D \rightarrow T\ (1.01) + p\ (3.02) + 4.03$ MeV
	$D(D,n)\,^3He$	$D + D \rightarrow\ ^3He\ (0.82) + n\ (2.45) + 3.27$ MeV
T-T	$T(T,2n)\,^4He$	$T + T \rightarrow \alpha + 2n + 11.3$ MeV
$D\text{-}^3He$	$^3He\,(D,p)\,^4He$	$D +\ ^3He \rightarrow \alpha\ (3.66) + p\ (14.69) + 18.35$ MeV
$p\text{-}^6Li$	$^6Li\,(p,\alpha)\,^3He$	$p +\ ^6Li \rightarrow \alpha +\ ^3He + 4.02$ MeV
$p\text{-}^{11}B$	$^{11}B\,(p,2\alpha)\,^4He$	$p +\ ^{11}B \rightarrow 3\alpha + 8.68$ MeV

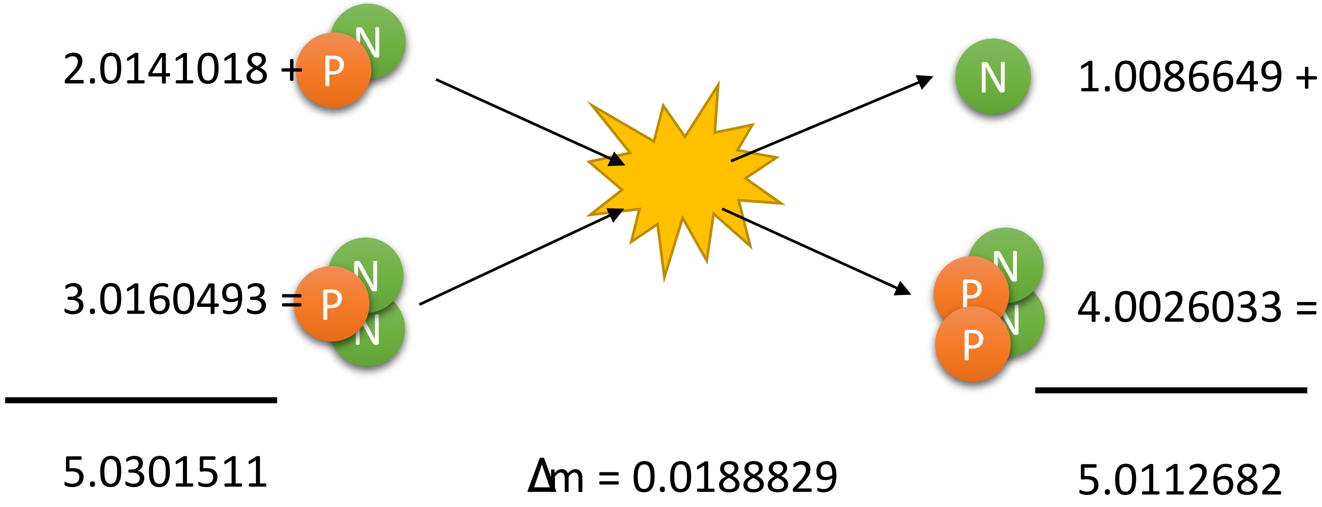
$D = H^2$
$T = H^3$
$\alpha = He^4$

The D-T fusion reaction

- For several reasons, the **D + T fusion reaction** is the most **easily achievable** reaction for **energy production**
  - Already feasible at relatively low energy (lower temperature ➔ easier to obtain)
  - Fusion events happen in relatively large numbers (good cross sections)
  - Relatively large energy release (kinetic energy of the fusion products)



The D-T fusion reaction



D + T → α (3.52) +n (14.1) + 17.59 MeV

Z		A	Binding energy (MeV)	Atomic mass (amu)
0	n	1	0	1.0086649
1	H	1	0	1.0078250
		2	2.225	2.0141018
		3	8.482	3.0160493
2	He	3	7.718	3.0160293
		4	28.296	4.0026033

amu = $1.66053907 \cdot 10^{-27}$ [kg]
c = 299792458 [m/s]

$$\Delta E = \Delta m \cdot c^2 = 0.0188829 \cdot 1.66053907 \cdot 10^{-27} \cdot 299792458^2 = 2.8181181 \cdot 10^{-12}\ \text{J} = 17.59\ \text{MeV}$$

Fusion energy production

Let's calculate the specific energy of the D-T reaction, and compare it with fossil fuels:

$$1 \text{ g of D-T} = 6.02214086\times10^{23} / 5.0301511 = 1.197\times10^{23} \text{ reactions}$$

$$1.197\times10^{23} \text{ reactions} \times 2.82\times10^{-12}\text{ J} = 3.374\times10^{11}\text{ J}$$

D – T fusion specific energy = 3.374×10^{8} MJ/kg

Fossil Fuel	Specific Energy [MJ/kg]
Coal	29.3 – 33.5
Crude Oil	41.9
Natural Gas	38 – 50
Fission Fuel	**Specific Energy [MJ/kg]**
Uranium 235	77×10^{6}

Fusion energy production

- **Deuterium** is a **stable** and the second-most **abundant** Hydrogen isotope.
- **Tritium** spontaneously **decays** with 12.4 y half-life, and is **scarce** on earth.
- **Tritium** can be **generated** inside the fusion devices from **Lithium**

$$n + {}^{6}Li \rightarrow {}^{3}H + {}^{4}He + 4.78\ MeV$$
$$n + {}^{7}Li \longrightarrow {}^{3}H + {}^{4}He + n - 2.5\ MeV$$

- **Lithium** is therefore part of the **fuel mix**.
- Deuterium and Lithium **resources** are estimated to last **thousands of years**
  - 1 Deuterium out of every 5000 hydrogen atoms in seawater
  - The Lithium content of seawater is estimated as 230 billion tonnes
  - Lithium constitutes about 0.002 percent of Earth's crust

How fusion occurs

- In order to fuse, two colliding nuclei must win the coulomb repelling forces.

$$F = \frac{Z_1 Z_2 e^2}{4\pi\varepsilon_0 r^2}$$

F = Coulomb repelling force [N]
r = Distance between the nuclei
Z_1 = Number of protons in nucleus 1
Z_2 = Number of protons in nucleus 2
e = Elementary charge $1.602 \cdot 10^{-19}$ [C]
ε_0 = Permittivity constant in vacuum $8.85 \cdot 10^{-12}$ [F/m]

- The Coulomb repelling force is proportional to the product of the atomic numbers of the interacting particles and grows rapidly when nuclei distance decreases (with the inverse of the square of the distance).

How fusion occurs

- One would imagine that coulomb repulsive force would increase to infinite as the distance goes down to zero.
- At shorter range, the **strong interaction** becomes predominant, and let the nuclei overcome the coulomb repulsion and fuse together.

The Four Fundamental Forces			
Type	**Range**	**Relative strength**	**Interaction time**
Strong	**1 fm**	**1**	10^{-23} s
Electromagnetism	**∞**	**10^{-2}**	$10^{-14} \div 10^{-20}$ s
Weak	10^{-3} fm	10^{-7}	$10^{-14} \div 10^{-20}$ s
Gravitation	∞	10^{-38}	years

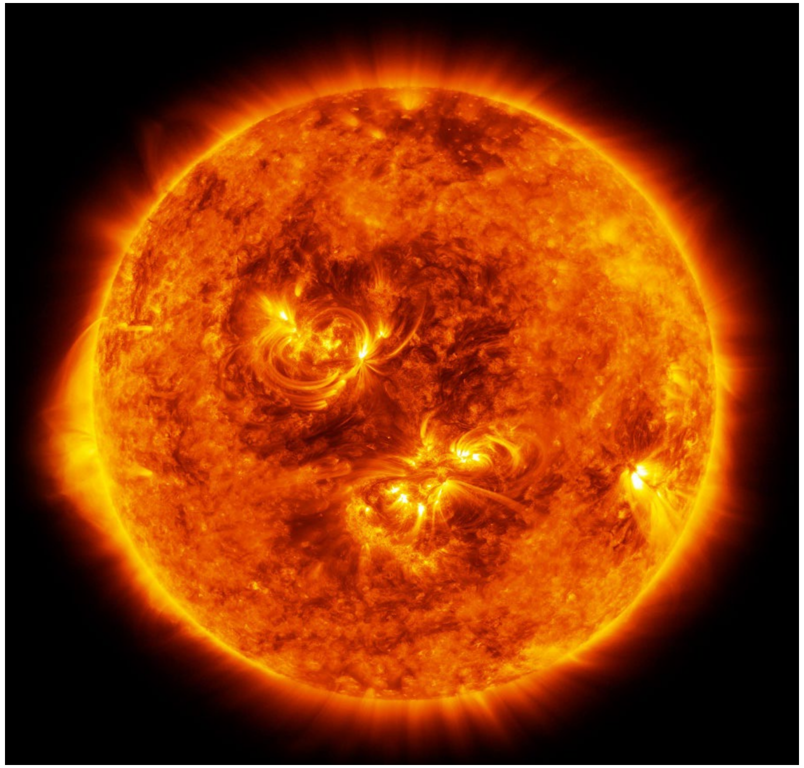
FUSION FOR ENERGY

Thermonuclear Fusion

- Charged particles, like nuclei, interact with each other via **Coulomb collisions** ➔ Binary elastic collisions between two charged particles interacting through their own electric field.
- To fuse two nuclei, they must get in close proximity, so that the strong nuclear force becomes dominant with respect to the electrostatic repulsion ➔ the **Coulomb barrier** must be overcome.
- In order to overcome the coulomb barrier, **high energies** of the fusing nuclei are required ➔ high particle **temperature**
- When fusion occurs by mean of high particles temperature, the process is called **Thermonuclear Fusion**.

Fusion in nature

- Even if at microscopic level the fusion of two light nuclei releases a high energy, few fusion reactions in a large mass and in long times will not produce a large total quantity of energy in useful times (i.e. power).
- In order to produce a large quantity of energy a large number of fusion reactions must occur. For this to occur nuclei must:
  - be in a large number in the same space (**high density**)
  - be confined for enough time and (**long confinement time**)
  - have enough kinetic energy (**high temperature**).
- Nuclear fusion in nature occurs only in the **stars**



Fusion power production – the D-T case

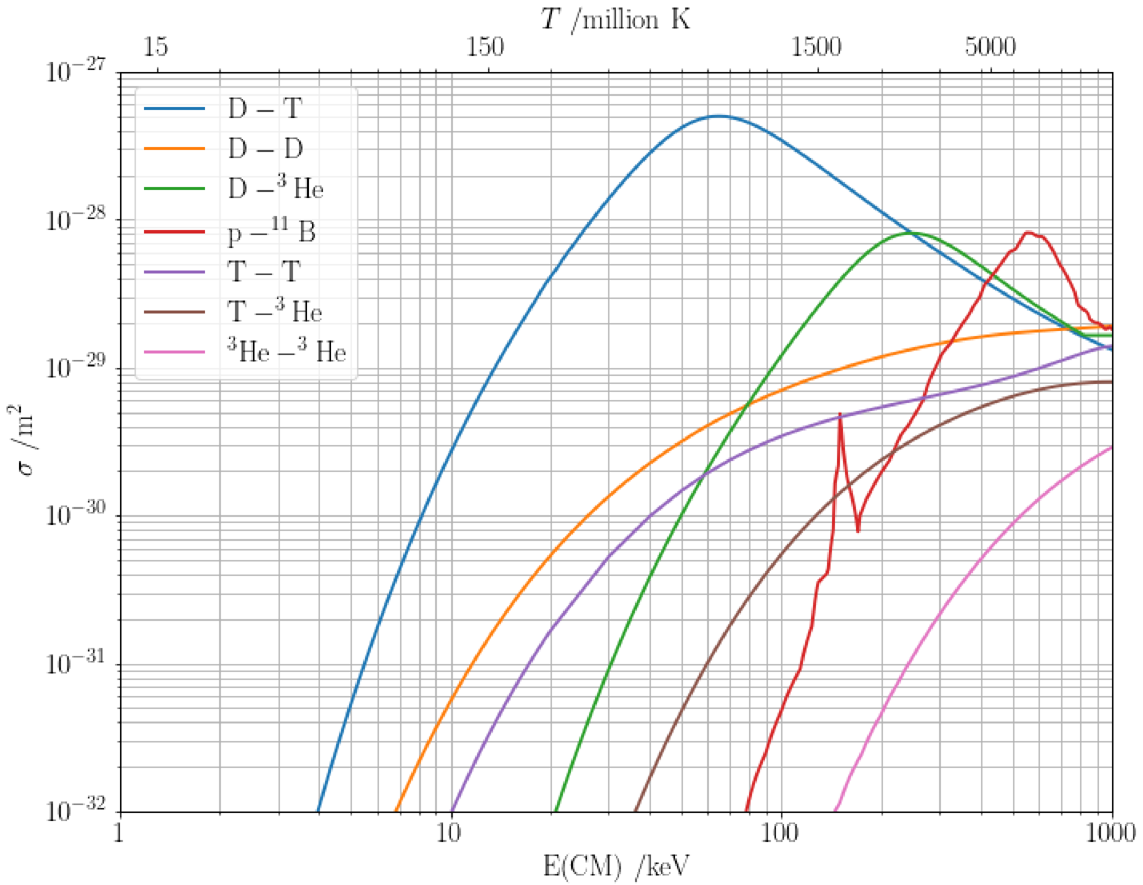
- In a thermonuclear device using a mixture of Deuterium and Tritium the thermonuclear power produced per m³ is:

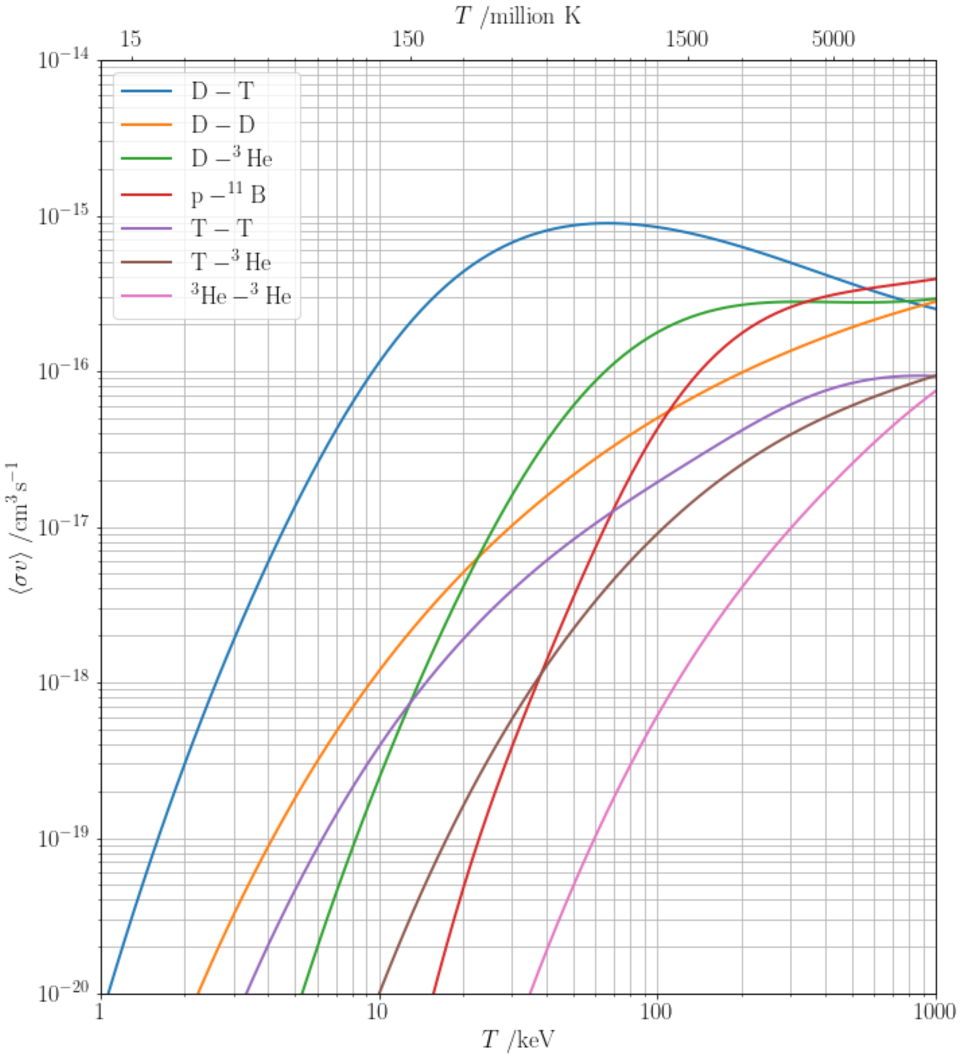
$$\boldsymbol{p_{DT} = n_D n_T < \sigma v > E = n_D n_T < \sigma v > (E_\alpha + E_n)}$$

  - n_D, n_T = deuterium and tritium particle density
  - $< \sigma v >$ = D-T reactivity
  - E = Energy released per reaction (17,59 MeV for D-T)
  - E_α, E_n = Energy released in the α (3.52 MeV) and in the neutron (14.07 MeV) per reaction.
- Considering a pure mixture then $n = n_D + n_T$. The output power is maximized when $n_D = n_T$.
- In this case the thermonuclear power produced per unit volume in a D-T Plasma with a 50-50% D-T mixture is:

$$\boldsymbol{p_{DT} = \tfrac{1}{4} n^2 < \sigma v > E}$$

Cross sections, reactivity





Fusion power losses and external heating

- In fusion devices there is also a continuous **loss of energy** from the plasma.
- The **power loss** by the plasma in a fusion device can be written as:

$$\boldsymbol{P_L = \frac{E}{\tau_E}}$$

- Where τ_E is called the **energy confinement time**.
- In present devices operating with D-D reaction at relatively low T (i.e. low reaction rates), there are few fusion reactions and therefore a very small internal heating of the plasma.
- In order to achieve a relatively long operation time, we have to balance the losses with **external heating**, namely $P_H = P_L$ and therefore:

$$\boldsymbol{\tau_E = \frac{E}{P_H}}$$

Alpha particle heating and ignition

- In conditions similar to power reactors instead a large amount of D-T fusion reactions occurs:

$$D + T \rightarrow \alpha + n + 17.59\ \text{MeV}$$

- For each reaction about 1/5 of the 17.59 MeV are taken by the α particle as kinetic energy (~3.5 MeV). The rest is taken by the neutron (~14.1 MeV).
- The neutron is electrically neutral so that it leaves the plasma without interactions. Its energy does not remain in the plasma.
- The α particle instead remains confined with the other particles and can transfer its (higher) energy to the other particles by collisions, so heating the plasma.

Alpha particle heating and ignition

- When the D-T plasma temperature increases in thermonuclear conditions and enough confinement is provided, the α particles heating increases consequently and at a certain condition it is enough to entirely compensate the power losses.
- At this point the external heating can be switched off and the plasma temperature can be sustained only by internal heating.
- This condition is called **Ignition**.
- Using for DT reaction E_α = 3.5 MeV the ignition condition is expressed as:

$$nT\tau_E > 3\times10^{21}\ \text{m}^{-3}\ \text{keV s}$$

- $nT\tau_E$ is called the **Fusion Product** (or **Triple Product**). It gives a quantitative value of the performances of a device, i.e. how far is the device from reactor conditions (ignition).
- For example in a magnetic confinement device the ignition conditions can be reached at:

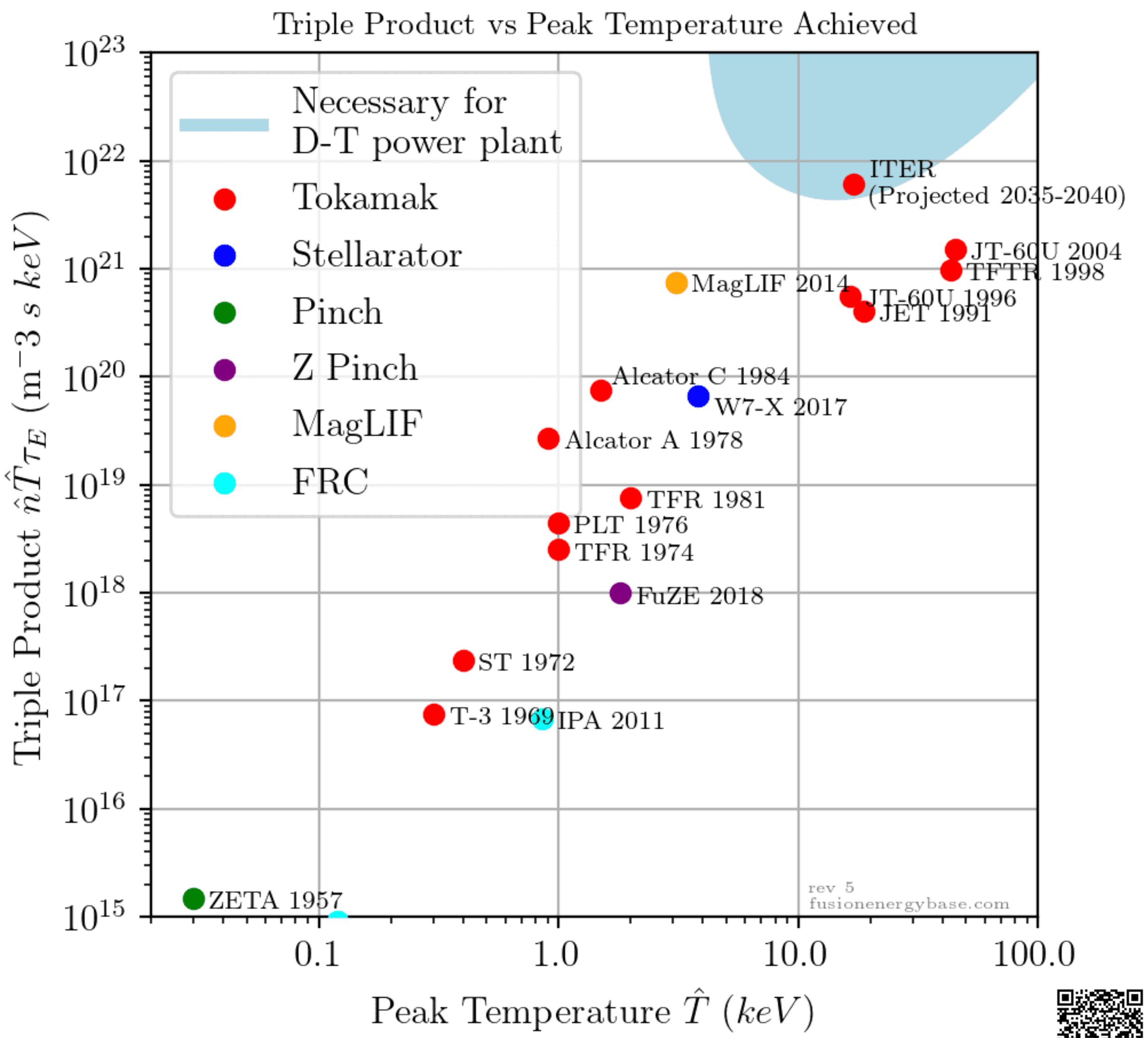
$$\boldsymbol{n} = 10^{20}\ \text{m}^{-3} \quad \boldsymbol{T} = 10\ \text{keV} \quad \boldsymbol{\tau_E} = 3\ \text{s}$$

Fusion Product and Q parameter

- A measure of the success of a device is the **parameter Q**, which is the ratio between the thermonuclear power produced and the heating power supplied
- Since in D-T reactions the energy E is 5 times the energy of the alpha E_α:

$$\boldsymbol{Q = \frac{5P_\alpha}{P_H}}$$

- Thus $Q = 1$ when P_α = 20% of P_H. (**$Q_{IGNITION}$ → ∞**)
- However ignition is not strictly required for a fusion reactor. $\boldsymbol{Q = 10}$ is considered a minimum for economical reasons.



Nuclear Fusion: Confinement

Confinement

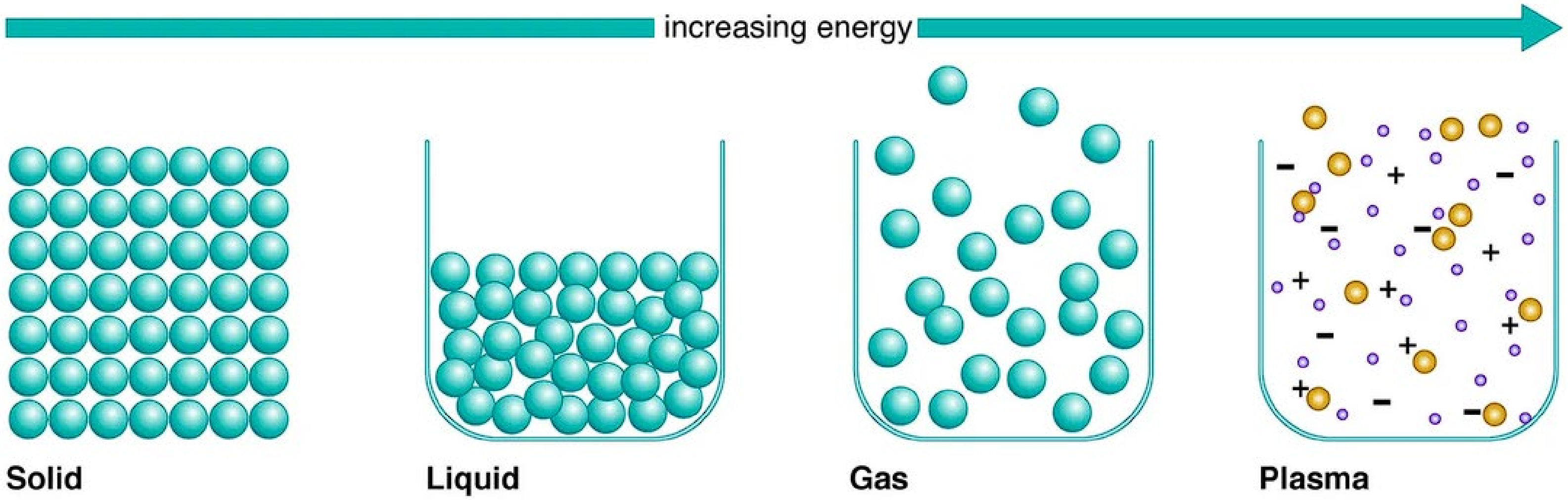
- Mankind has been able to create significant quantities of nuclear fusion by two main confinement methods:

Magnetic Confinement – Inertial Confinement

- In **magnetic confinement** the fusion fuel is in plasma state (high temperature ionized gas) and is kept confined in a closed space by using **magnetic fields**.
- In **inertial confinement** the fusion reactions occur in an extremely short time (explosive method) so that the **inertia** of the mass can keep the matter confined for a sufficient time to fuse it.

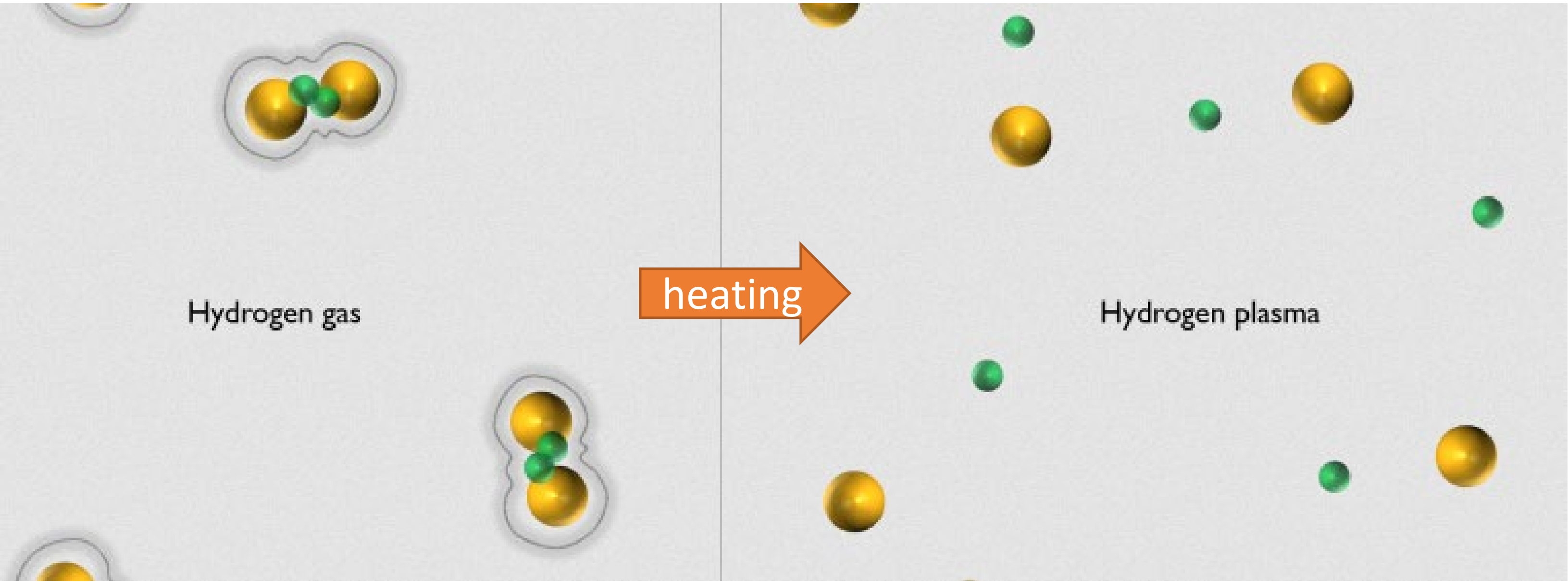
Plasma – the fourth state of matter

- Plasma is the fourth fundamental state of matter. It is made of **charged particles** (i.e. ions and/or electrons) and is the **most abundant** form of ordinary matter in the universe. Plasma is what stars are made of.
- Plasma can be artificially generated by **heating** a neutral gas or subjecting it to a strong **electromagnetic field**.
- The presence of charged particles makes plasma **electrically conductive**, and the dynamics of individual particles is affected by internal and external electromagnetic fields.



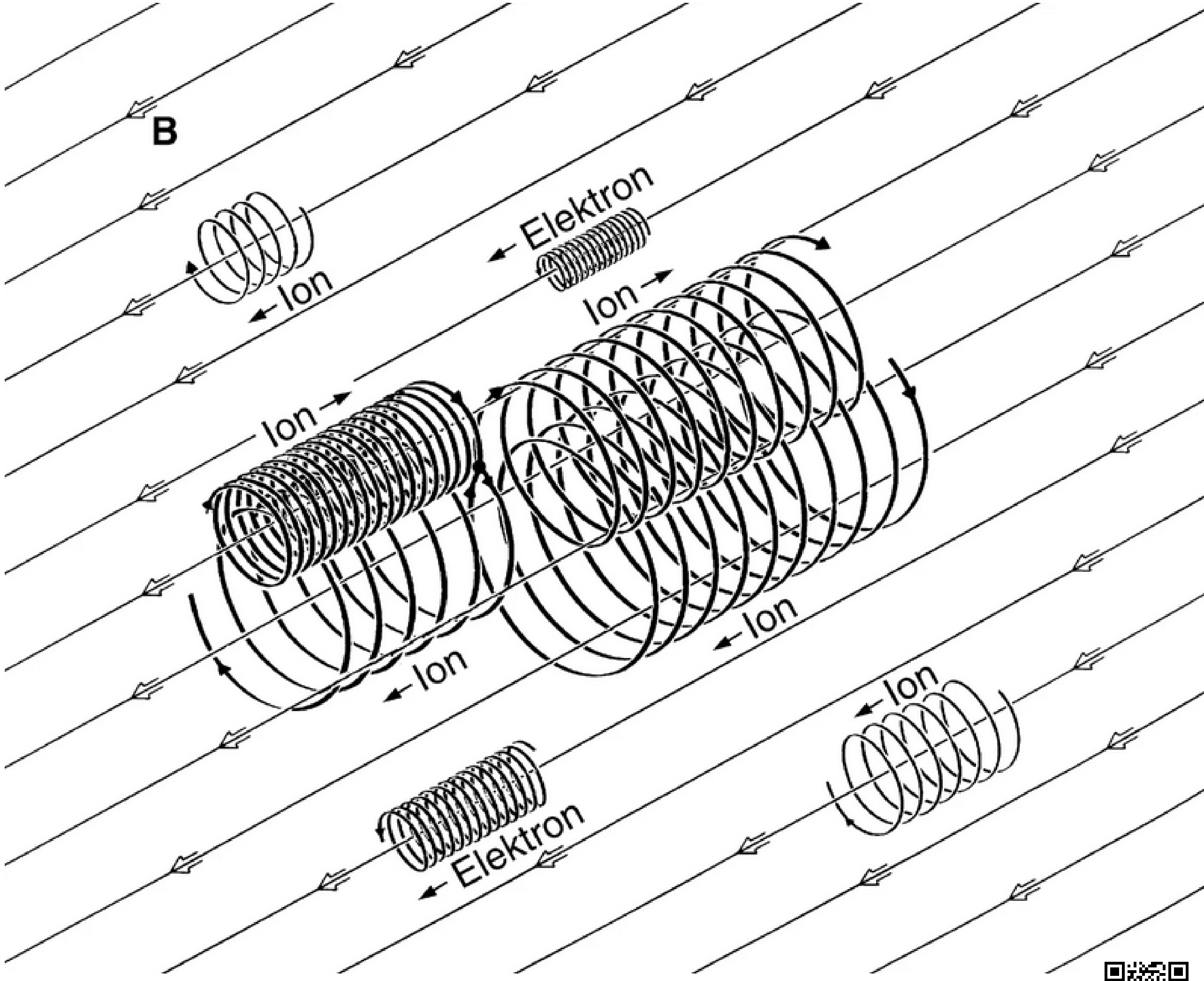
Magnetic Confinement – basics

- We can create the conditions suitable for nuclear fusion by **heating** and **confining** our fuel long enough in a limited portion of space
- In a confined space, with a high average energy, the particles in the high tail of the energy spectrum will eventually fuse together
- But we need to increase the temperature of the fuel up to > 100 MK. The fuel will be in the **plasma** state, and due to its temperature it cannot be physically contained



Magnetic Confinement – basics

- **Magnetic confinement** devices use magnetic fields to confine the fusion fuel in the form of a hot plasma, avoiding the direct contact of the hot part of the plasma with the surrounding walls
- Ions and electrons are forced into **circular and helical orbits** around the magnetic field lines.
- The particles are thus ‘tied’ to the field lines, but they can **move freely in the longitudinal direction** along the field lines.
- In a suitably shaped magnetic field cage it is therefore possible to **confine a plasma** and keep it away from material walls.



Magnetic Confinement – Lorentz force

- A charged particle q_i with mass m_i that enters with a velocity v_i in a magnetic field B is subjected to the Lorentz force.

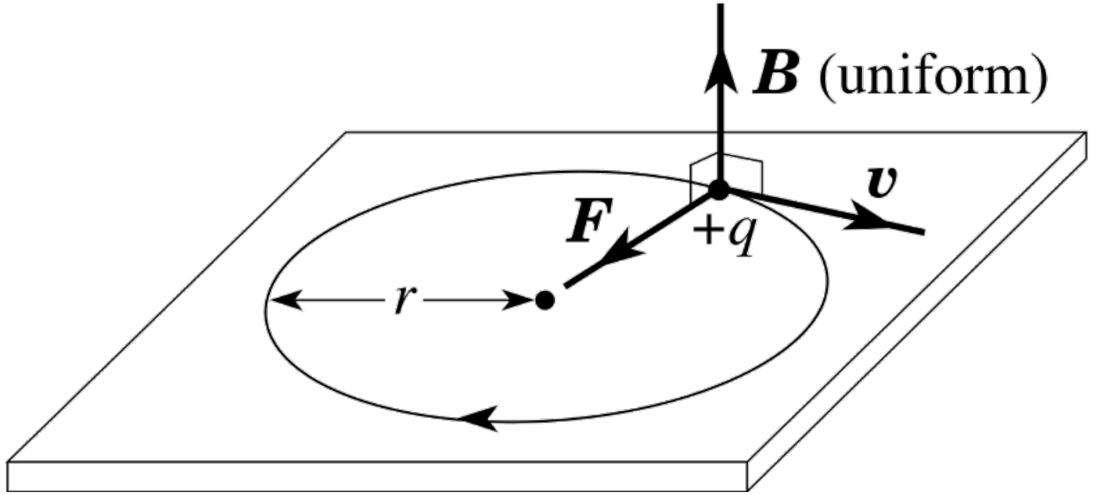
$$\overrightarrow{\boldsymbol{F_L}} = m_i a_i = m_i \frac{d\vec{v}}{dt} = \boldsymbol{q_i \vec{v} \times \vec{B}}$$

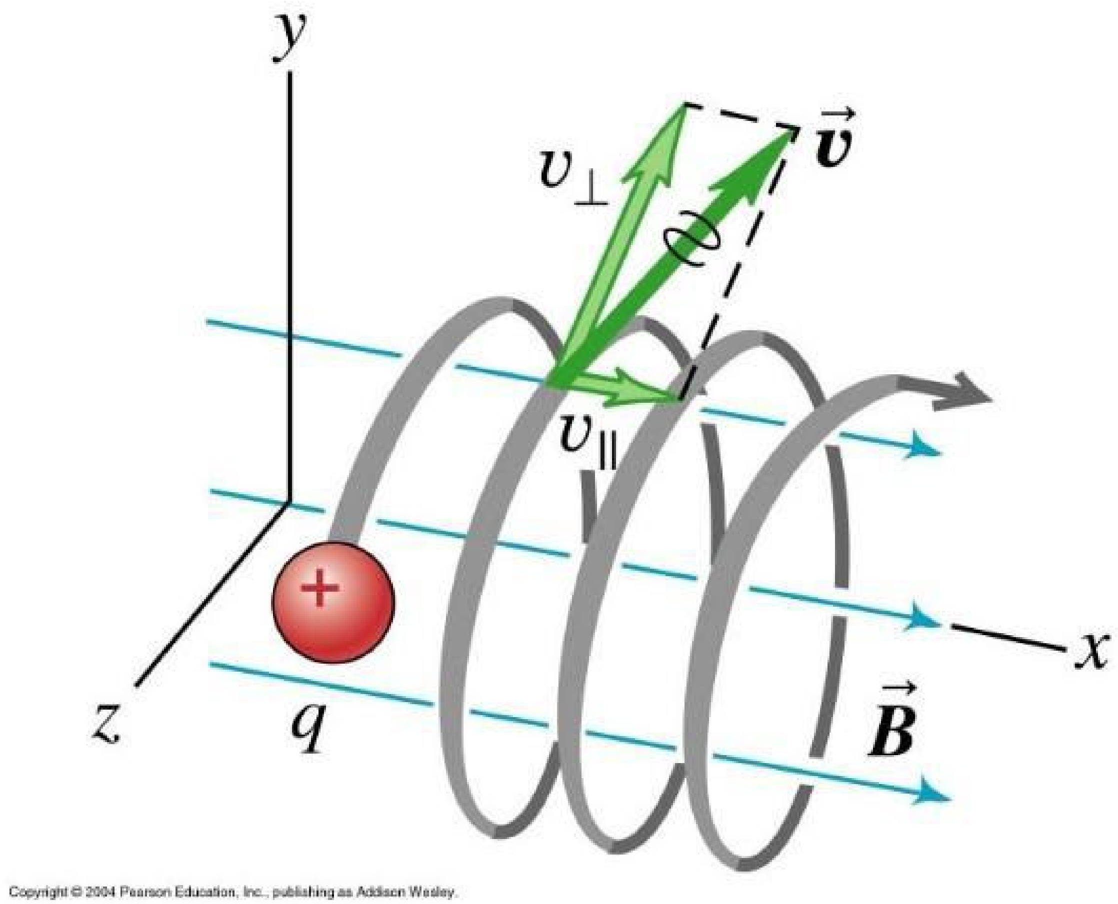
- If the magnetic field is constant in time and homogeneous and we consider the two components of the particle velocity $v_\perp$ perpendicular to the field line and $v_\parallel$ parallel to the field line, we have:

$$\boldsymbol{F_L = q_i v_\perp B}$$

Magnetic Confinement – Lorentz force

- The force will act perpendicularly to the field line and to $v_\perp$ forcing the particle to rotate around the field line. If we superimpose the velocity $v_\parallel$, which is not influenced by the Lorentz force, the particle trajectory is a helix around the field line.





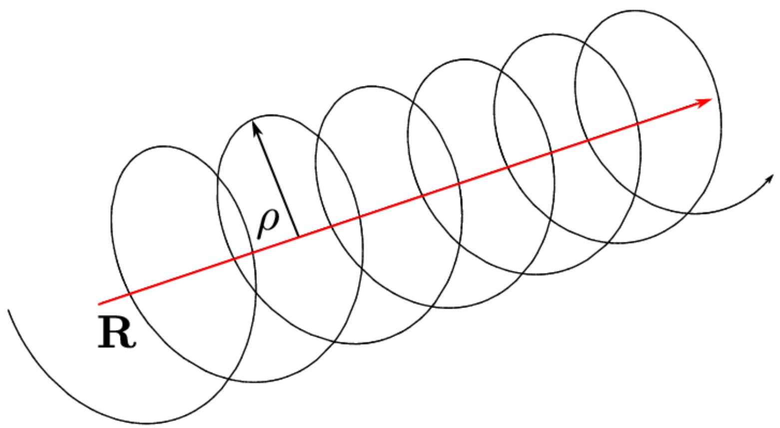
Magnetic Confinement – Larmor radius

- The **radius of gyration $\boldsymbol{\rho}$** is given by the equilibrium between the Lorentz force and the centrifugal force:

$$\vec{F}_L = \vec{F}_C = \frac{v_\perp^2}{\rho} m_i; \quad q_i v_\perp B = \frac{v_\perp^2}{\rho} m_i; \qquad \boldsymbol{\rho = \frac{v_\perp m_i}{q_i B}};$$

- ρ is called the **Larmor radius**. The centre of the circular orbit line is called **guiding centre**. This (due to $v_\parallel$) forms a line around which the particle gyrate. In the case of the presence only of an uniform B, the guiding centre follows the field line.
- The angular frequency of the particle is:

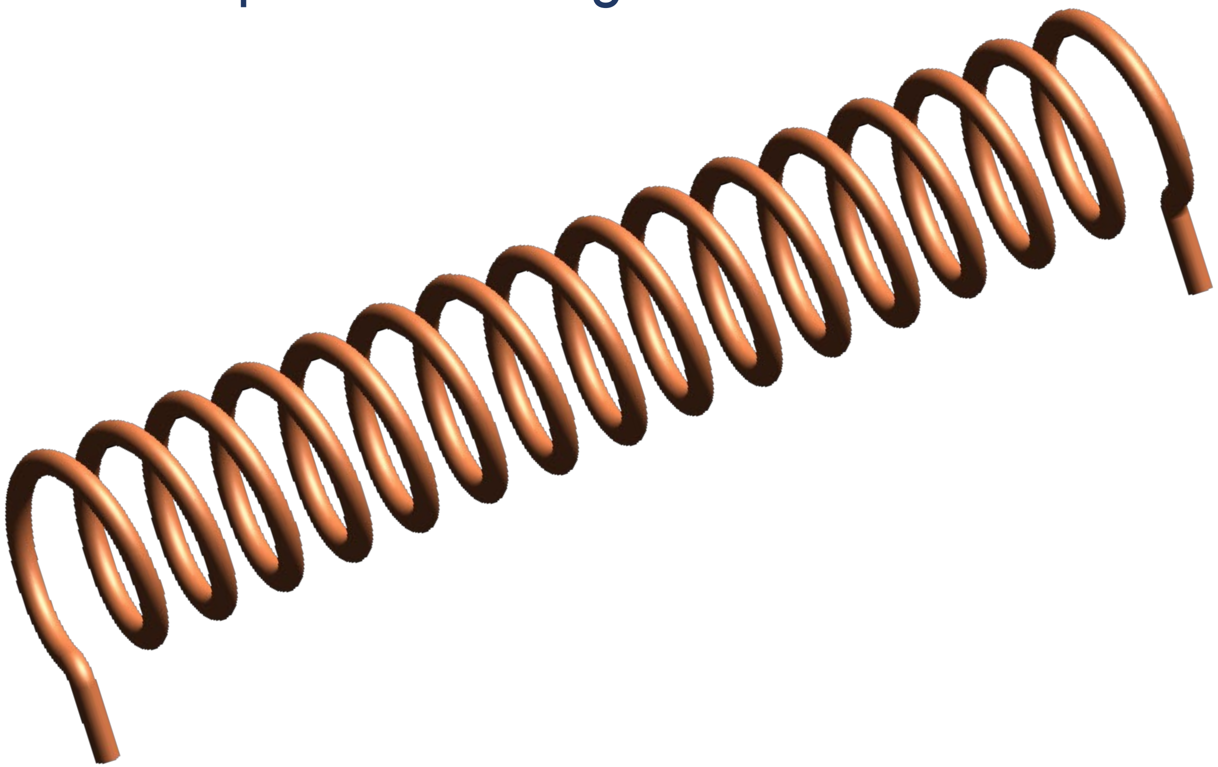
$$\boldsymbol{\omega_{cy} = \frac{v_\perp}{\rho} = \frac{q_i B}{m_i}};$$

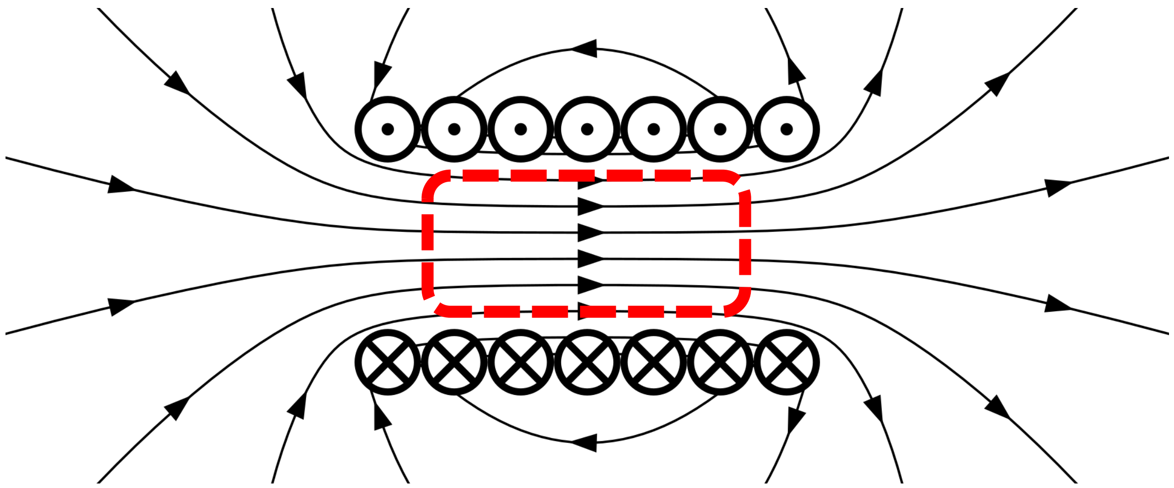


- ω_{cy} is commonly called **gyrofrequency** or **cyclotron frequency** and is expressed in rad/s

Magnetic Confinement – solenoids

- A **solenoid** is a type of electromagnet formed by a helical coil of wire whose length is substantially greater than its diameter, which generates a controlled magnetic field.
- The coil can produce a uniform magnetic field in a volume of space when an electric current is passed through it.



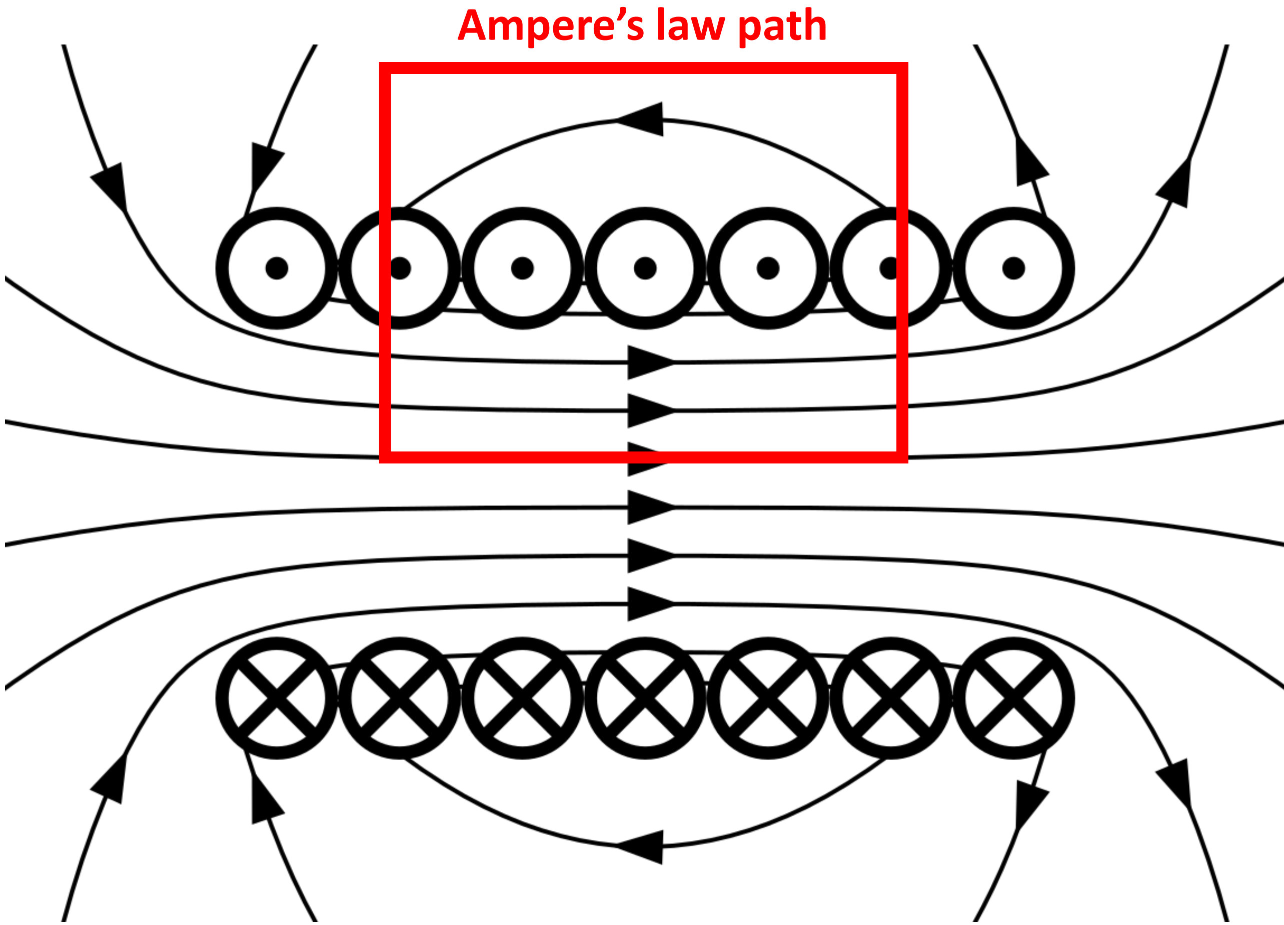


The magnetic field generated by a solenoid
Inside the solenoid the field is 'almost' uniform

Magnetic Confinement – solenoids

- A solenoid magnetic field can guide the particles, but being open-ended it cannot contain them.
- The value of the uniform magnetic field B inside a solenoid can be calculated using the Ampere's law:

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 i_{enc}$$



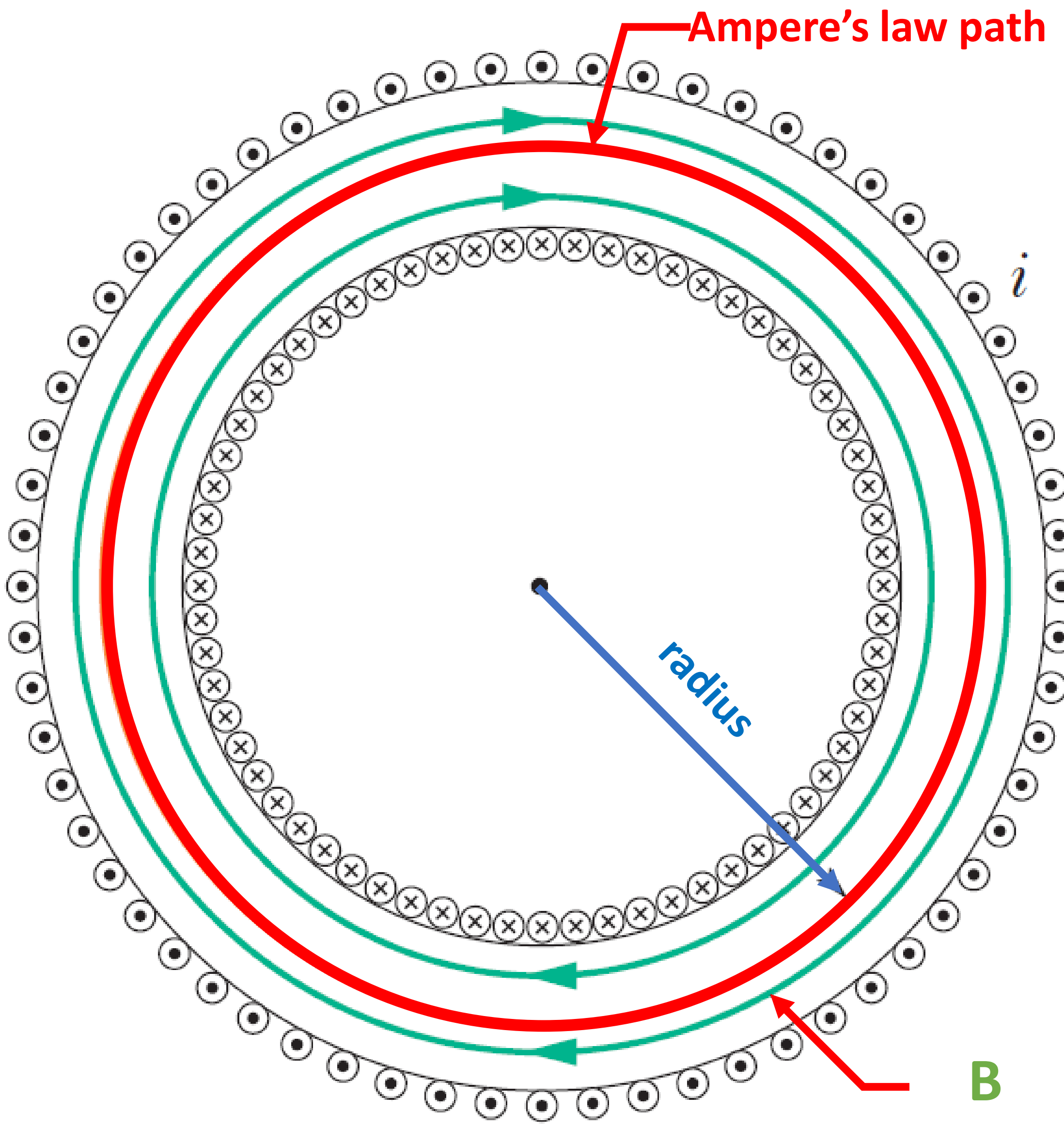
Magnetic Confinement – toroids

- An idea could be to bend the solenoid in order to form a **toroid**, so that the field lines close inside the toroid itself. The field lines are then only toroidal.
- The value of the magnetic field B inside a toroid can be calculated using the Ampere's law:

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 i_{enc}$$

- In this case it is not uniform, but it is an inverse function of the radius r:

$$\boldsymbol{B(r) = \frac{\mu_0 i N}{2\pi r}}$$

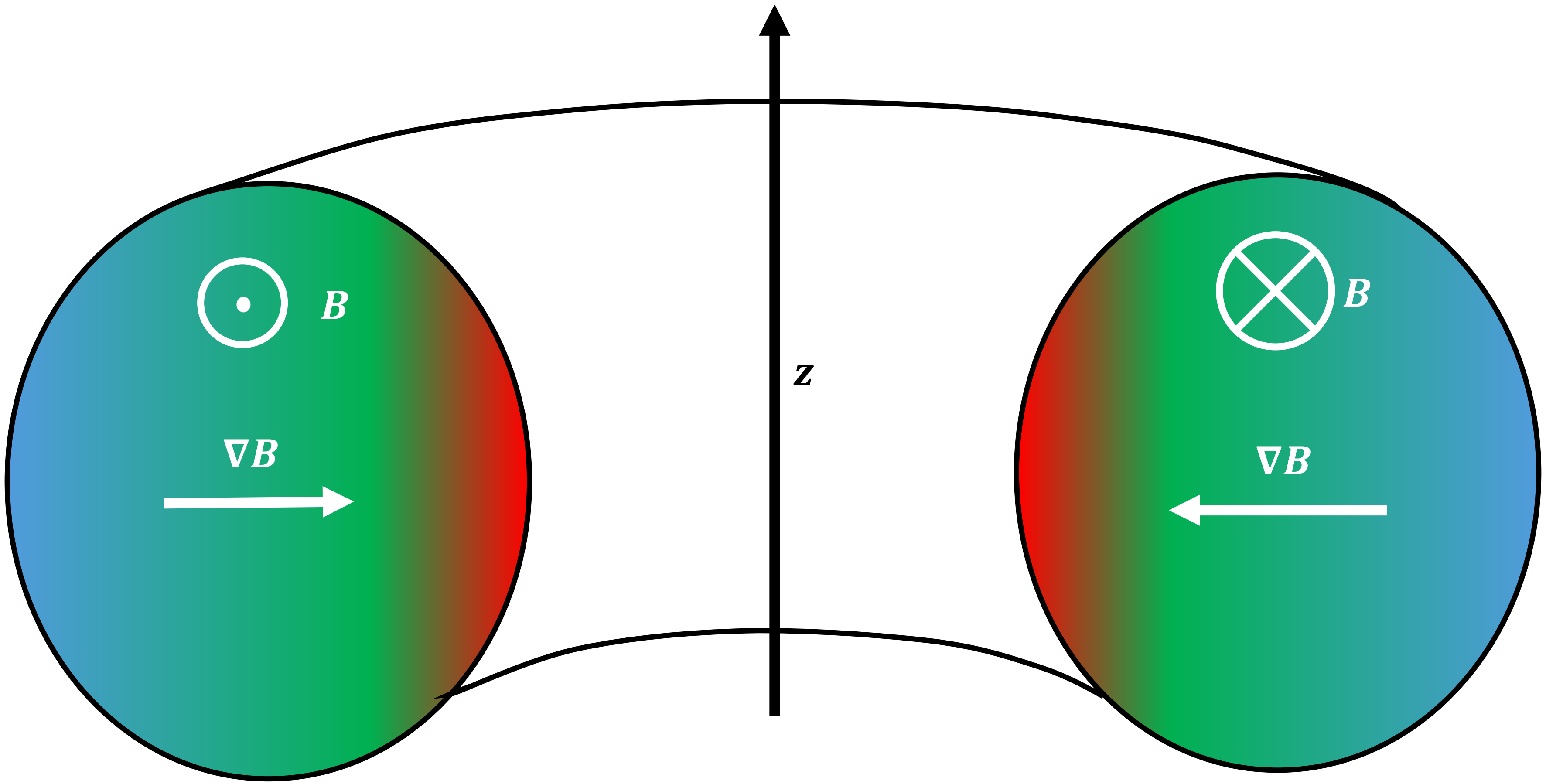


Magnetic Confinement – velocity drifts

- The magnetic field is **not constant** inside the toroid and it is **curved**. It is inversely proportional to the radius and therefore is **higher at the inboard**
- The experience show that **non uniformities**, e.g. **curvatures** and presence of generic **forces** can cause **velocity drifts**
- The velocity drifts push the particles outside the confined space
- Therefore a **simple toroid**, not having an uniform field and having a field curvature **cannot confine** stably particles
- The particle guiding centres will **migrate** because of the velocity drifts until the particles hit the walls
- This drastically affects the confinement time

Magnetic Confinement – toroid, again

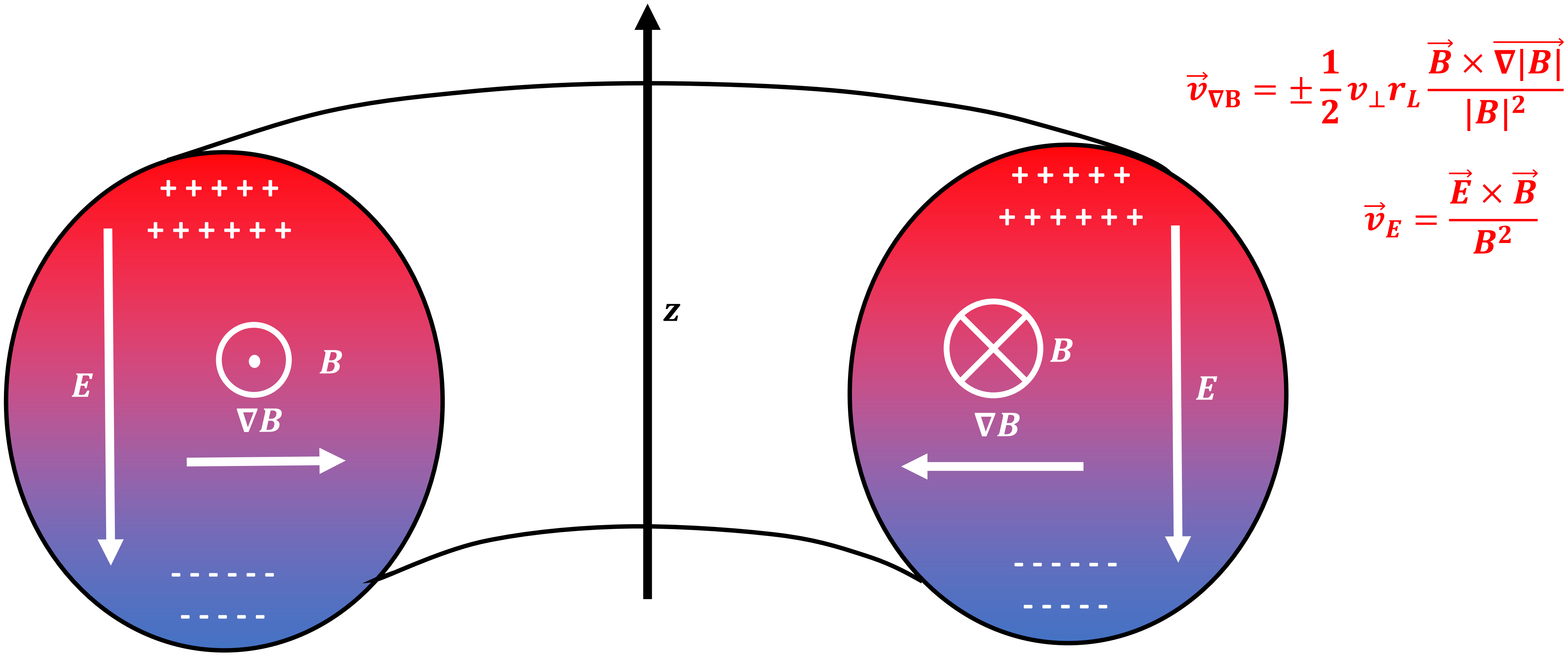
- We know that the ∇B points towards the axis, and the amplitude of B is proportional to $1/r$.



$$B(r) = \frac{\mu_0 i N}{2\pi r}$$

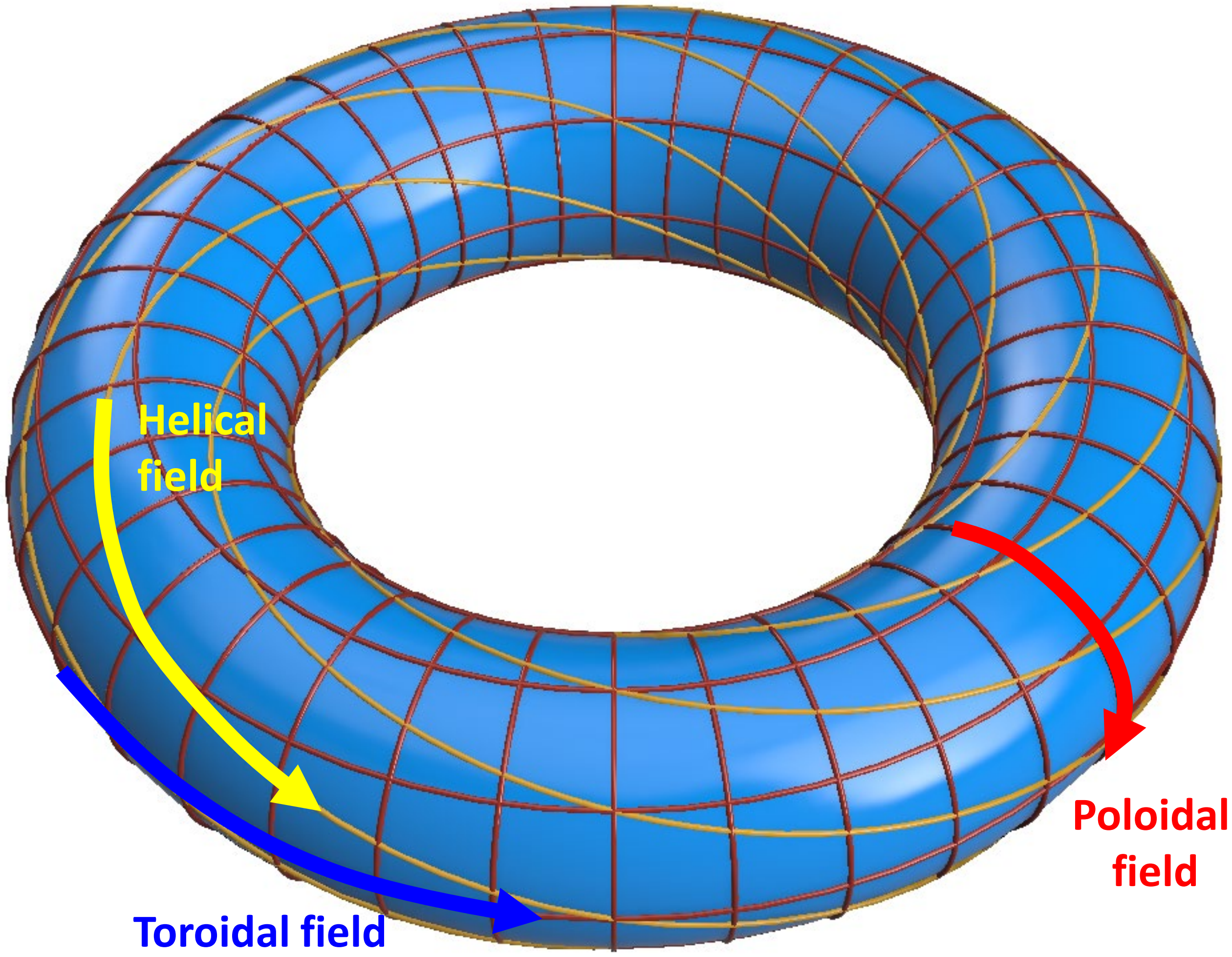
Magnetic Confinement – toroid, again

- The effect of the ∇B drift pushes electrons and ions on the opposite sides of the torus. The resulting charge separation creates an electric field E.
- The combined effect of $E \times B$ and curvature drift pushes the particles radially out



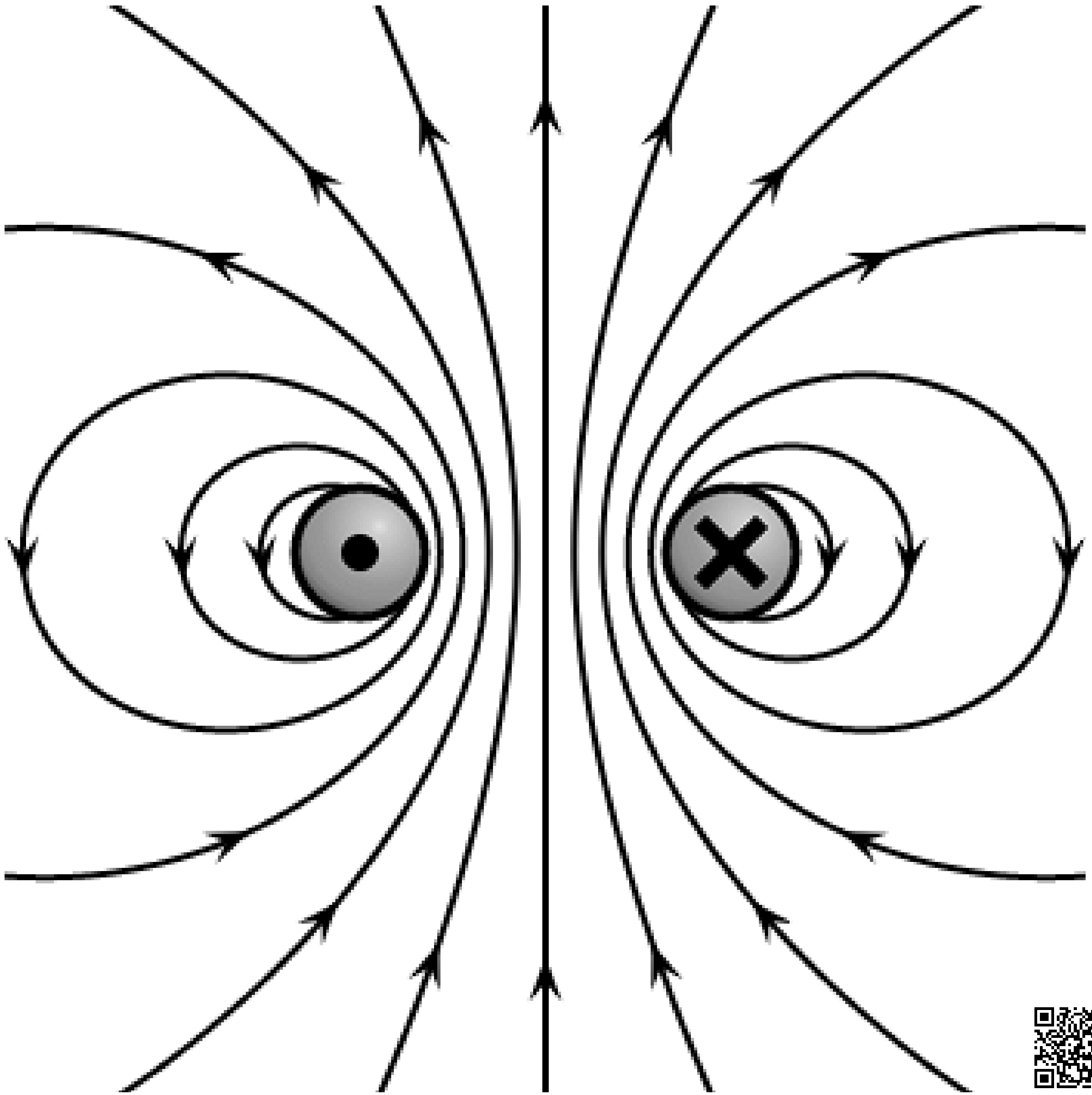
The Tokamak Principle

- To overcome the confinement issue, we need to add to the toroidal field, a **poloidal field**.
- The poloidal field will transform the circular field lines in **helical field lines**.
- In this way the particles will move along the helical field lines around the torus, and no charge accumulation will occur.
- This will solve the issue of the $E \times B$ drift, allowing confinement of the particles



The Tokamak Principle

- We already know hot to create a toroidal magnetic field (spoiler: **toroid**). How to create a poloidal field?
- Ideally we would need to create a **current** loop in the center of the plasma, so that a poloidal magnetic field would be created, as in the illustration here on the right.
- But it‘s not easy to lay a physical current loop in the center of a 100 MK hot plasma, isn‘t it?
- **What if the current was flowing in the plasma itself?**

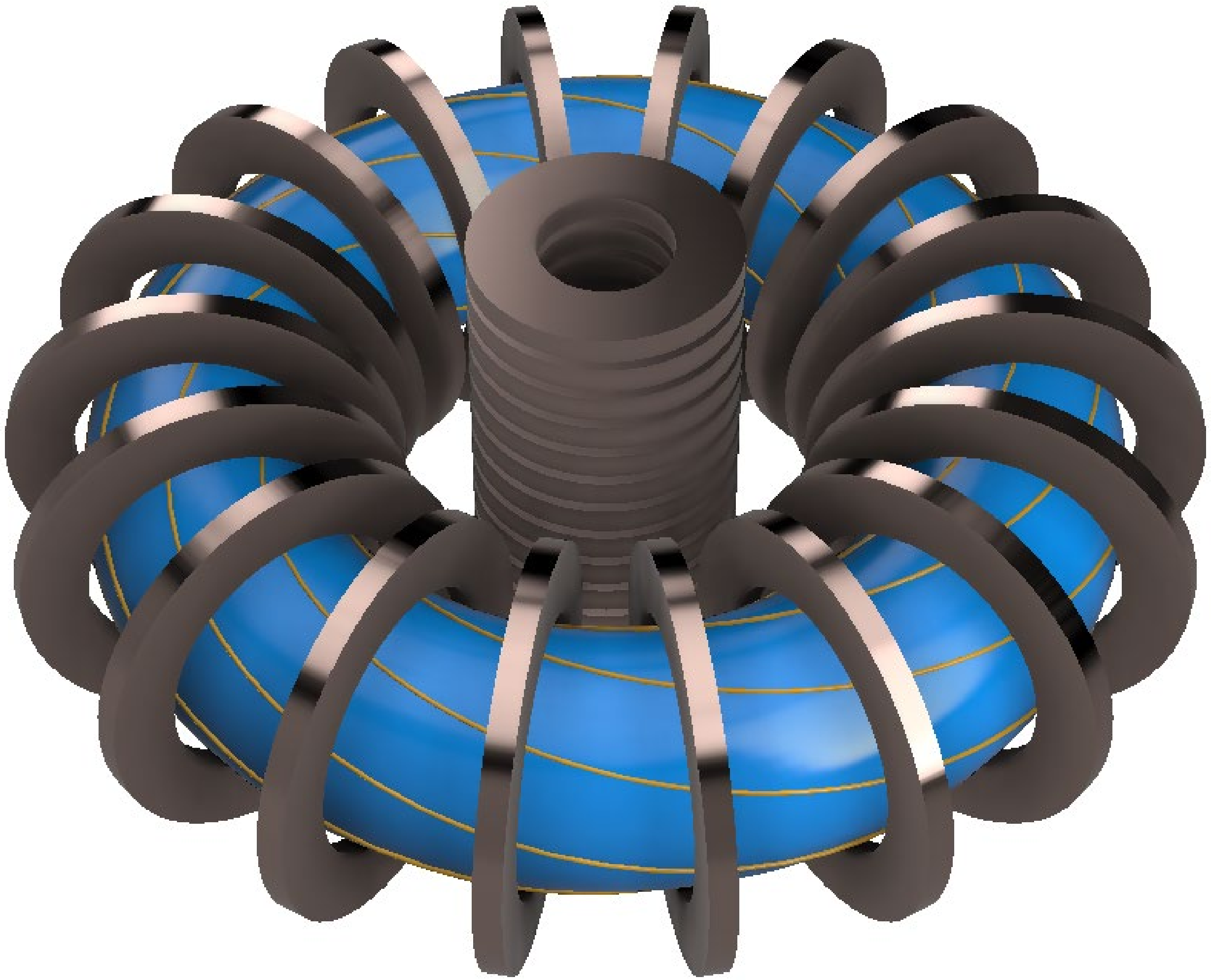


The Tokamak Principle

- To induce a current to flow in the plasma we need to go through the following steps:
  - Creation of the toroidal field (main confinement)
  - Injection of fusion fuel (e.g. D-T gas)
  - Current variation in the **central solenoid** creating a variable magnetic field
  - An **electrical field** is **induced** around the solenoid, following Maxwell-Faraday‘s law

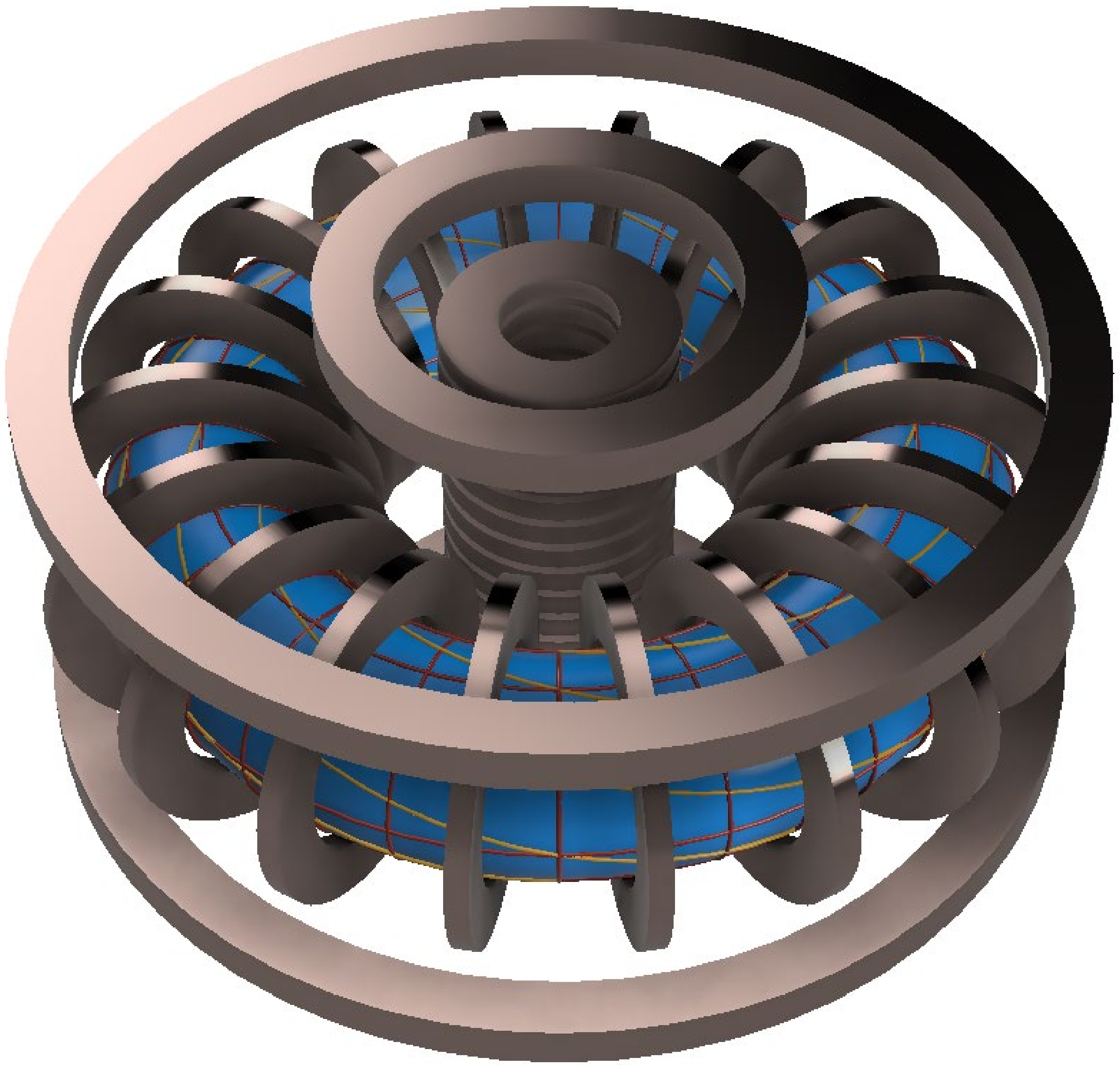
$$\oint_{\partial\Sigma} \boldsymbol{E} \cdot d\boldsymbol{l} = -\int_{\Sigma} \frac{\partial \boldsymbol{B}}{\partial t} \cdot d\boldsymbol{A}$$

  - When the induced field is strong enough, the gas will ionize, becoming plasma → **breakdown**
  - The charged particles will be **accelerated** by the induced electric field, creating **current**



The Tokamak Principle

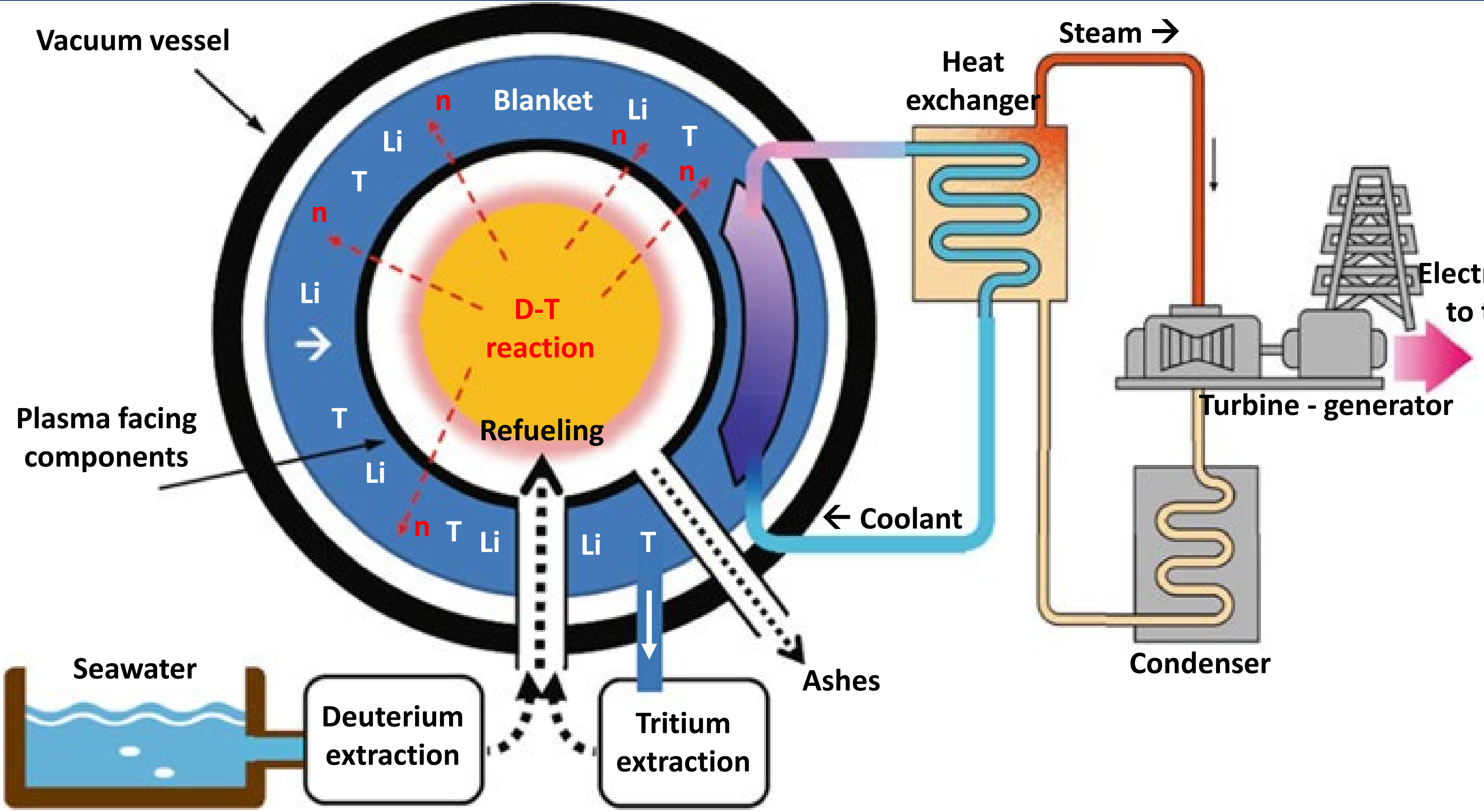
- Additional **poloidal** (vertical) **field coils** are used in Tokamak to improve **equilibrium** and to provide **shaping** of the plasma.
- The Tokamak is a **pulsed** machine. The current in the plasma circulates until the increasing current in the central solenoid reaches the maximum (**saturation**).
- After that both plasma current and central solenoid current are **ramped down** and a **new cycle** can be started.
- Tokamaks Main Advantages
  - Intrinsic Heating (plasma current)
  - Most Advanced Concept (several generations)
- Tokamaks Main Disadvantages
  - Pulsed operation (induced current saturation)
  - Disruptions possible (plasma collapse)



Tokamak layout

FUSION FOR ENERGY

Thermonuclear Fusion Reactor



Thermonuclear Fusion Reactor

- A Thermonuclear Fusion Reactor consists of:
  - The **Plasma** where the D-T reaction occurs and produces the energy, releasing α particles and fast neutrons.
  - A **First Wall** that withstands and exhausts the radiative and convective heat flux and the neutron heat load from the fusion reactions.
  - An **exhaust system** for the He ashes and other particles (e.g. impurities from the walls).
  - A **Shielding and Breeding Blanket** to protect the outer components from heat, neutron and γ radiation and to use the fast neutron to generate T (Lithium reactions).
  - A **Vacuum Vessel** (VV) which is the first safety barrier, and is a pressure retaining part. Ultrahigh vacuum (UHV) conditions (typically 10^{-9} mbar) are generated inside the VV, which is also used as a further neutron and γ shielding.
  - A **UHV system** consisting of several special vacuum pumps (rough, turbo-molecular and cryopumps).
  - The **Tritium and Lithium supply system**, including a **Tritium Plant** for the **recover** and **reprocessing** of the Tritium.

Thermonuclear Fusion Reactor

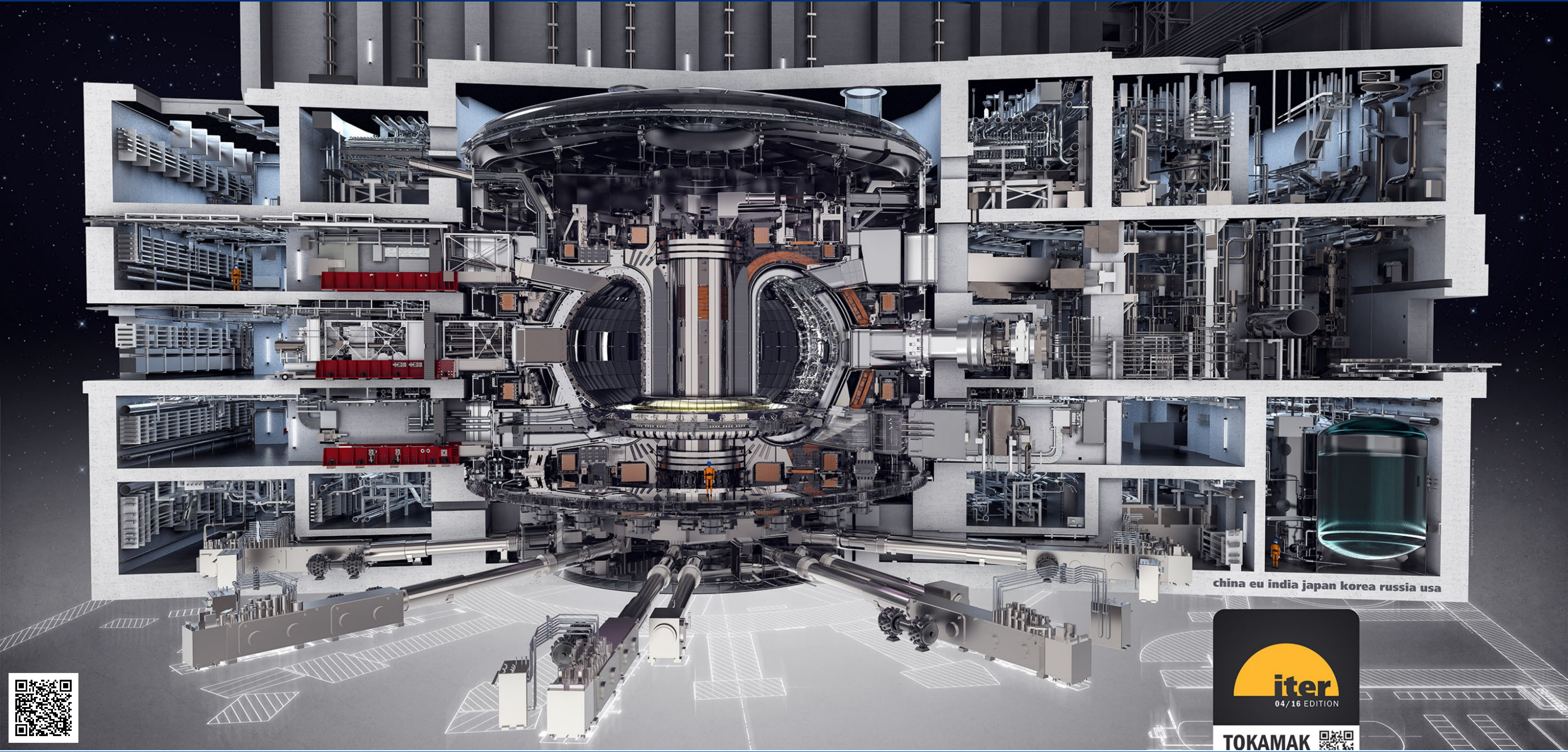
- A Thermonuclear Fusion Reactor consists of (cont'd):
  - A **Superconducting Magnet system** for containing the plasma (in a magnetic confinement device).
  - A **Heating System**: an external system to transfer energy to the D-T particles (e.g. Neutral Injector System, Radiofrequency Heating System)
  - A **Remote Handling** system, to maintain or replace components inside the reactor.
  - A **Cryostat**, an insulated container to maintain the cryogenic temperature.
  - A **Primary Cooling System**, to pump and circulate the main coolant
  - A **Steam Generator**, to extract heat from the primary and generate steam to drive the secondary loop
  - A **Secondary Cooling System**, including turbine and generator to produce electrical power
  - Finally **Cooling Towers**, to remove excess heat and to ensure the cooling of the entire system.

The Tokamak plasma operation

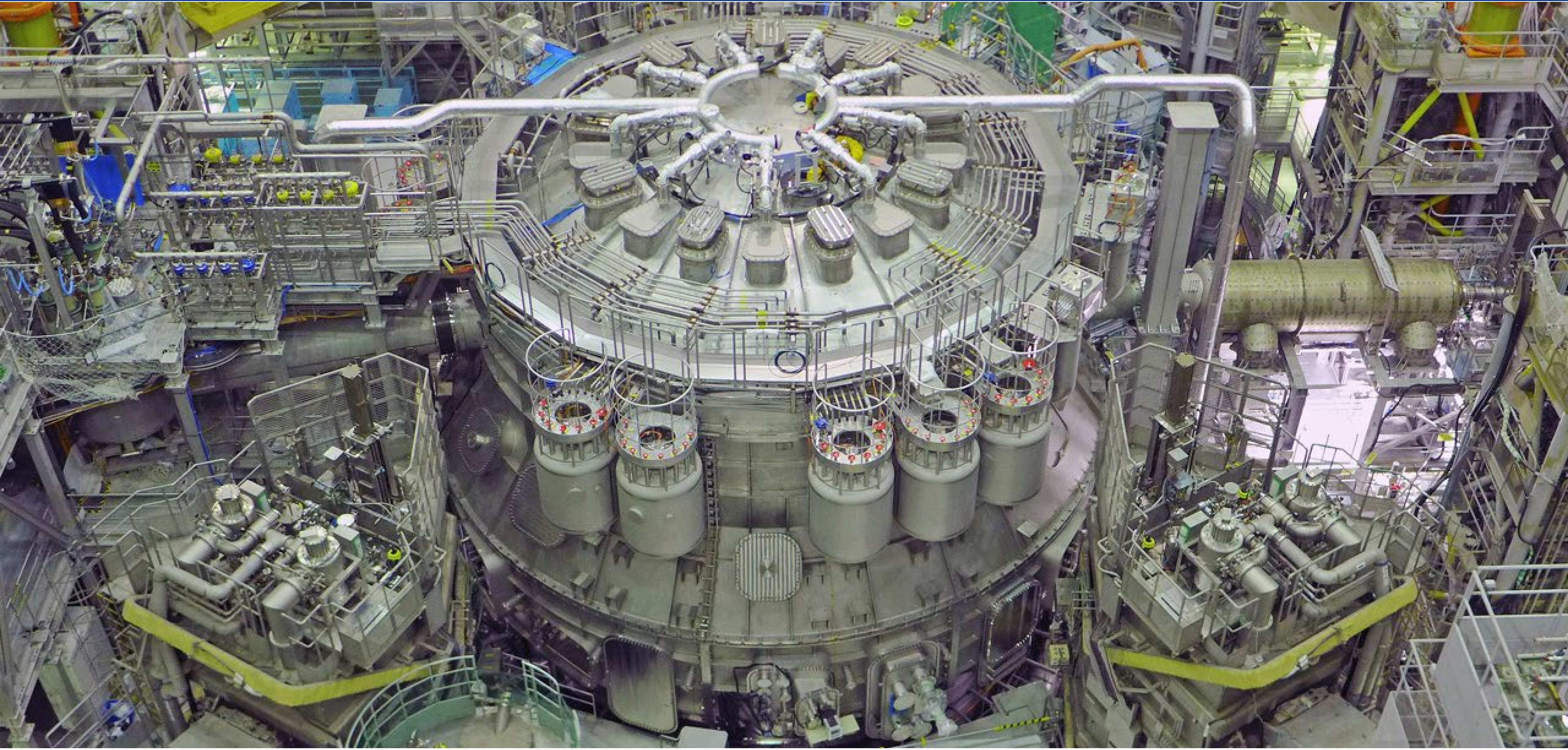
- In a Tokamak operation each discharge cycle can be distinguished in three main phases:
  - The **Ramp-up**
  - The **Flat-top** (burn)
  - The **Ramp-down**
- The ramp-up and ramp-down phases are normally operated with **inductive current drive**, in which the plasma current is fully induced by the variation of the current in the central solenoid.
- During flat-top operation a part of the current can instead be **non-inductive**, driven by Neutral Beam Injectors, Radiofrequency, Microwaves or a self generated plasma currents called Bootstrap current, driven by the density gradients.
- An area of the Tokamak research is devoted to develop non-inductive current drive, with the final goal to achieve a **steady state operation**.

Tokamak engineering Overview

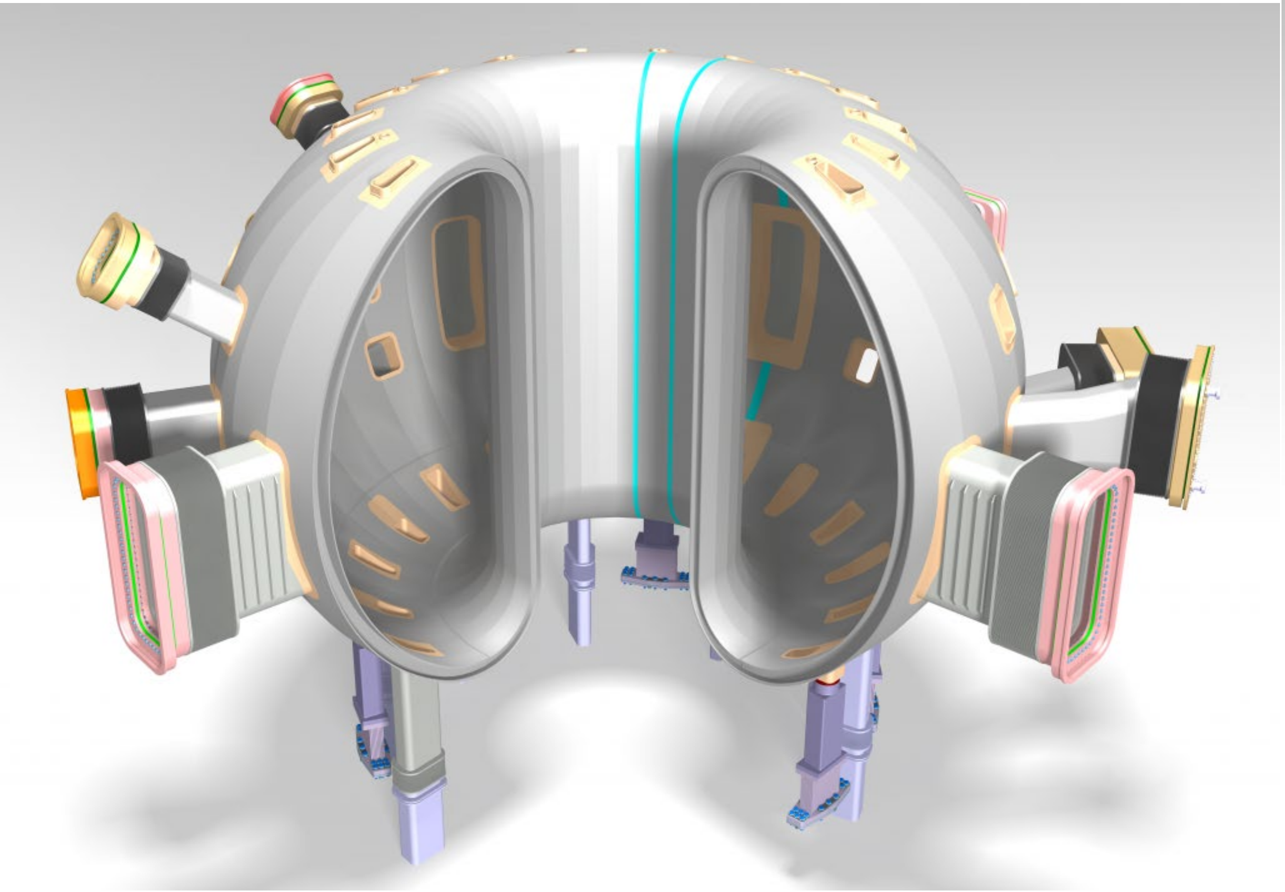
ITER


china eu india japan korea russia usa
iter
04/16 EDITION
TOKAMAK

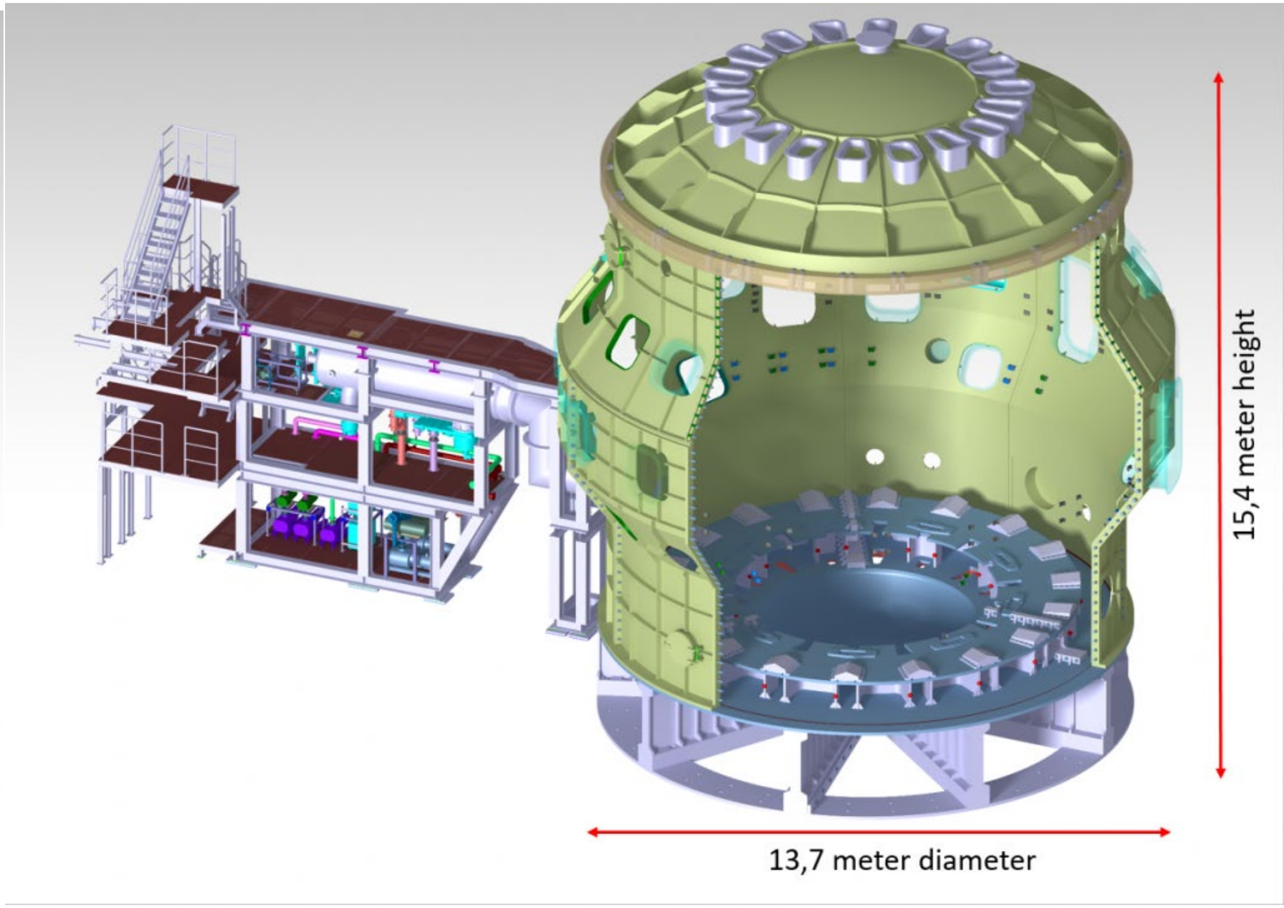
JT-60



Vacuum vessel / cryostat



The JT-60SA Vacuum Vessel

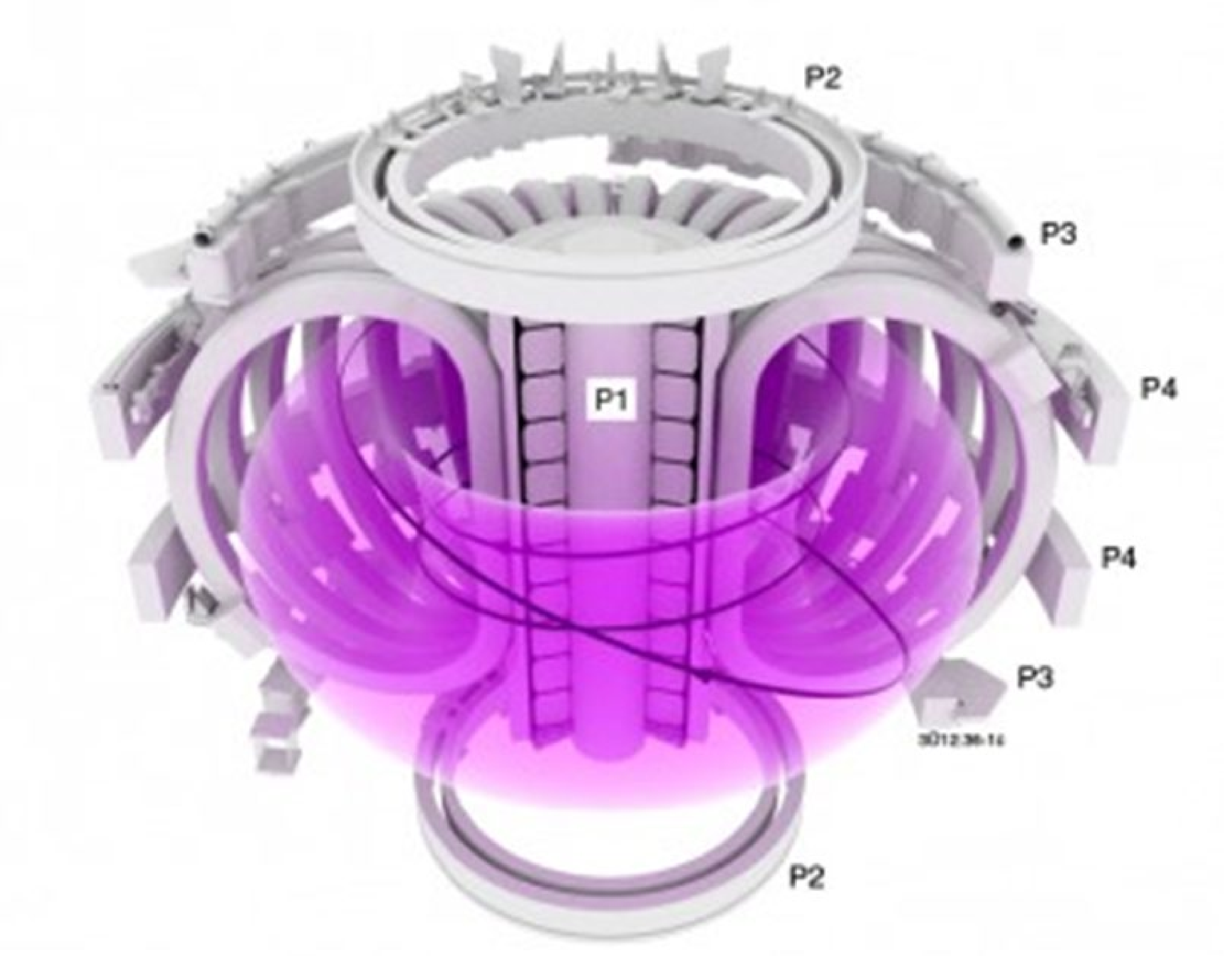


The JT-60SA Cryostat

Superconducting Magnets

Superconducting Magnets Technology

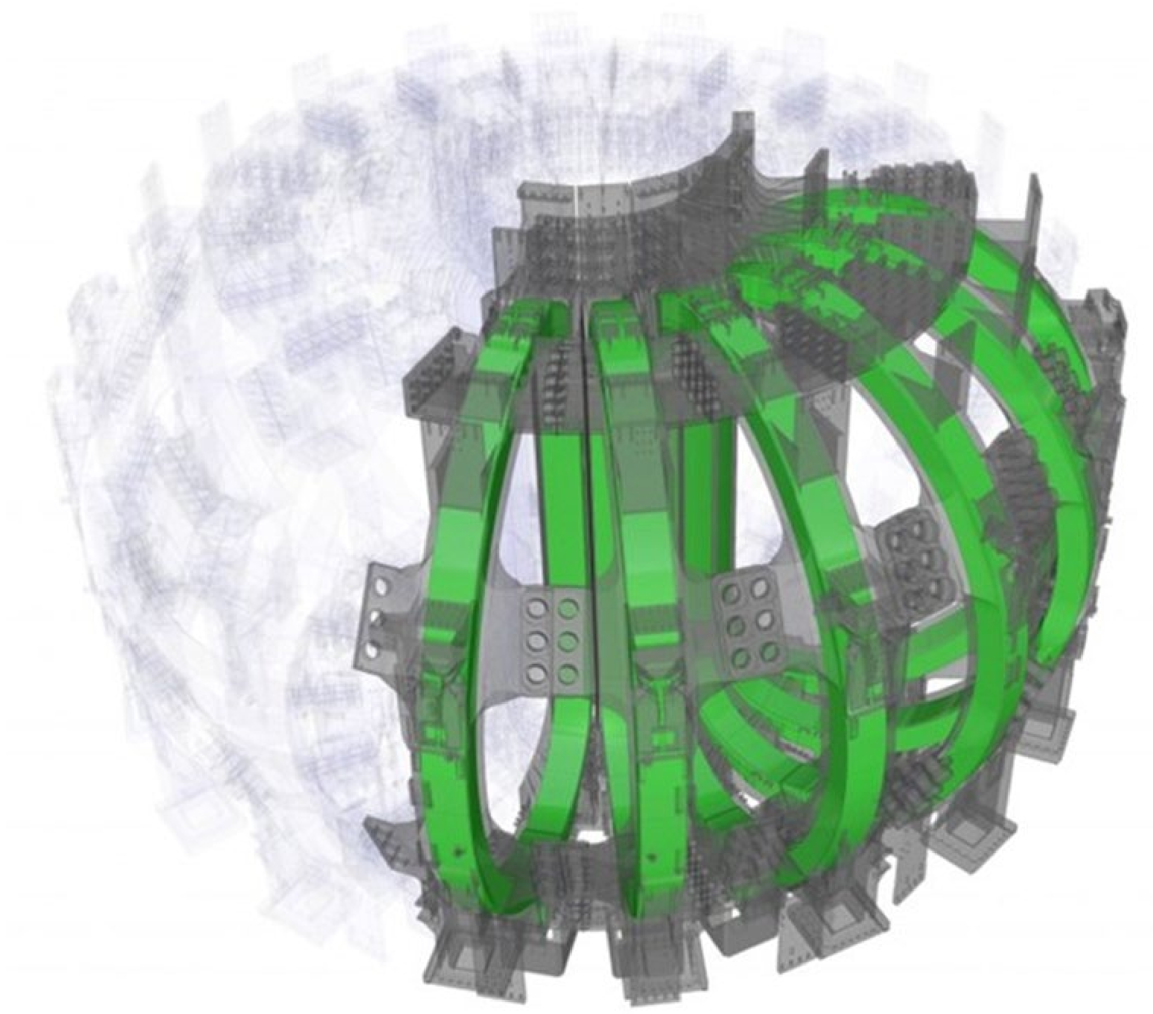
- The **magnet system** is the **backbone** of each experimental fusion device
- The magnet system of a Tokamak is divided in to **three main subsystems**:
  - The **Toroidal** Field Magnet
  - The **Poloidal** Field Coils
  - The Central **Solenoid**
- Stellarators have a different structure, e.g. W7-X, a modular stellarator:
  - **Non planar** coils
  - **Planar** coils



The electromagnetic coil arrangement at JET.

Superconducting Magnets Technology

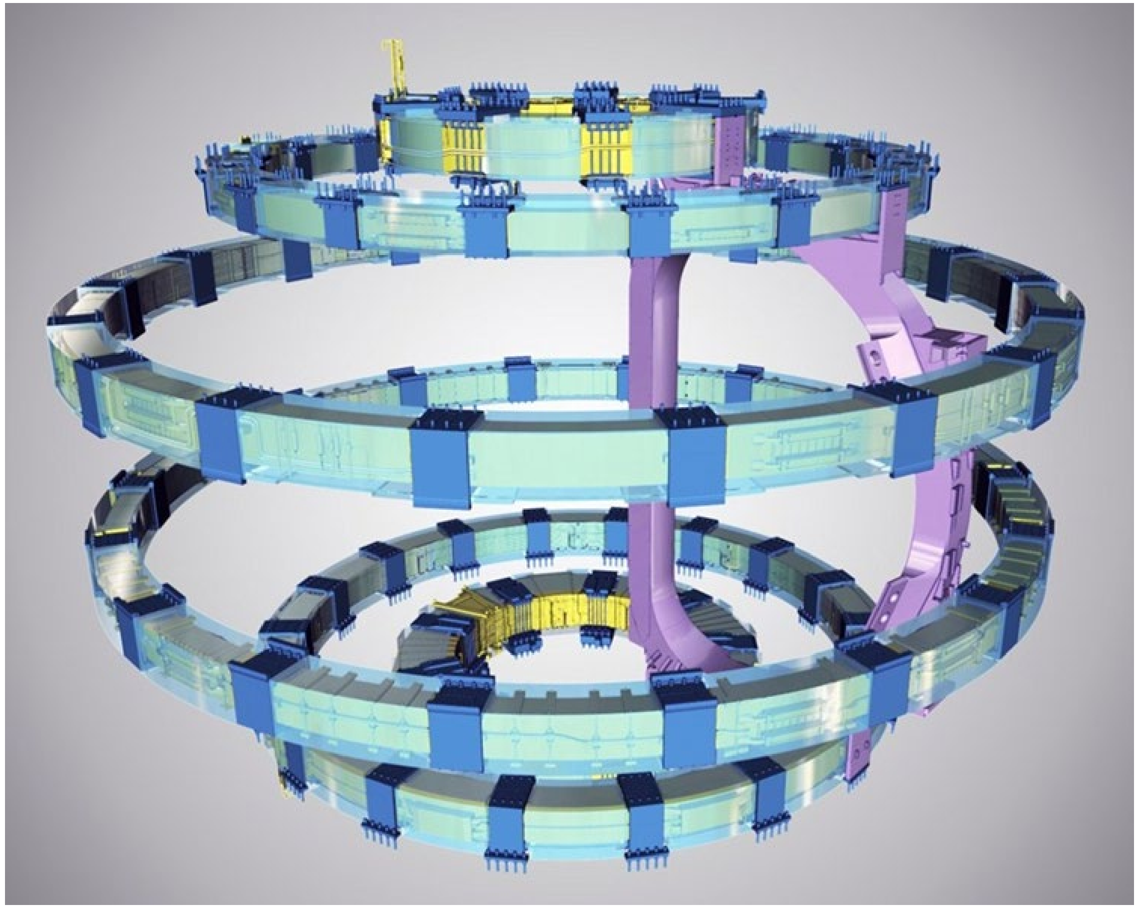
- The **Toroidal Field Magnet**
  - Provides the basic **confinement** field
  - It is **constantly energized** during operation
  - It has to withstand **strong** centripetal and out of plane **forces**
- The **Poloidal Field Coils**
  - Vertical **stability**
  - Plasma **shaping** and **control**
- The **Central Solenoid**
  - Primary **transformer** coil
  - **Induces** current in the Plasma
  - **Heats** the Plasma via Ohmic heating



The ITER TF Magnet

Superconducting Magnets Technology

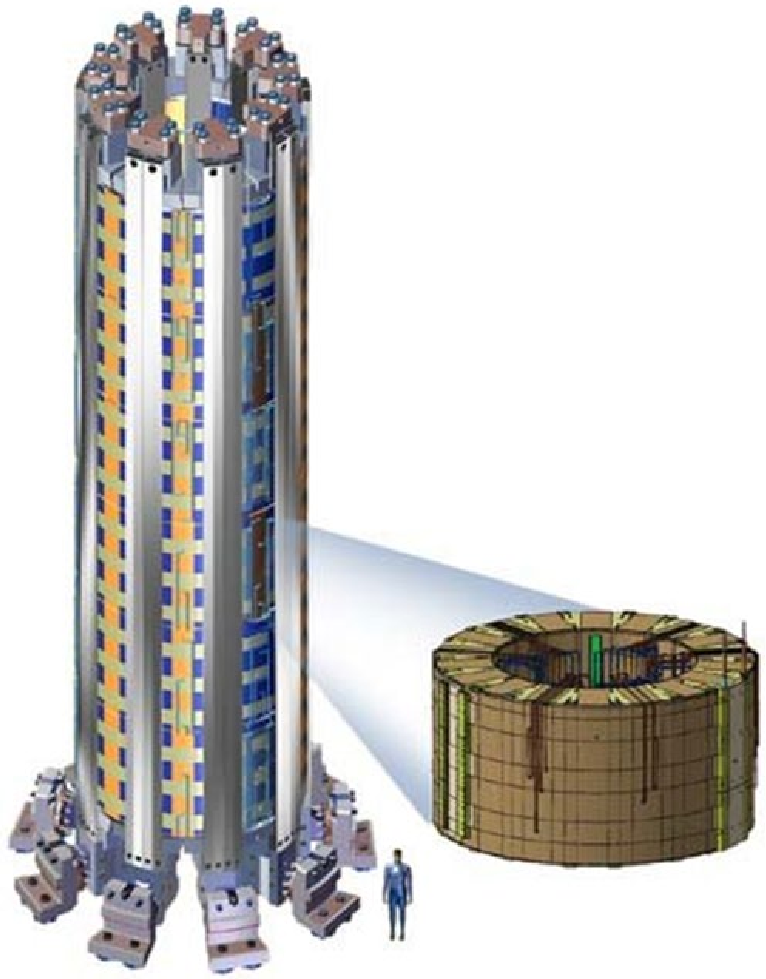
- The **Toroidal Field Magnet**
  - Provides the basic **confinement** field
  - It is **constantly energized** during operation
  - It has to withstand **strong** centripetal and out of plane **forces**
- The **Poloidal Field Coils**
  - Vertical **stability**
  - Plasma **shaping** and **control**
- The **Central Solenoid**
  - Primary **transformer** coil
  - **Induces** current in the Plasma
  - **Heats** the Plasma via Ohmic heating



The ITER PF Coils

Superconducting Magnets Technology

- The **Toroidal Field Magnet**
  - Provides the basic **confinement** field
  - It is **constantly energized** during operation
  - It has to withstand **strong** centripetal and out of plane **forces**
- The **Poloidal Field Coils**
  - Vertical **stability**
  - Plasma **shaping** and **control**
- The **Central Solenoid**
  - Primary **transformer** coil
  - **Induces** current in the Plasma
  - **Heats** the Plasma via Ohmic heating



The ITER Central Solenoid

Superconducting Magnets Technology

- Large Superconducting Magnets for fusion experiments are at the **cutting edge of technology**
- They have to operate reliably under **extremely demanding conditions**:
  - **Cryogenic** temperature (4 K = - 269 degrees C)
  - High **magnetic field** (up to 14 T)
  - High **mechanical loads** (hundreds of MN)
  - High **vacuum** (10^{-6} mbar)
  - High **voltage** (several tens of kV)

Superconductivity for Fusion Magnets

- Why superconductivity for fusion magnets?
  - Efficient nuclear fusion (**ignition**) requires high particle density $\boldsymbol{n}$, high temperature $\boldsymbol{T}$ and long energy confinement time $\boldsymbol{\tau_e}$

$$nT\tau_e \geq \frac{12k}{E_\alpha}\frac{T^2}{<\sigma v>}$$

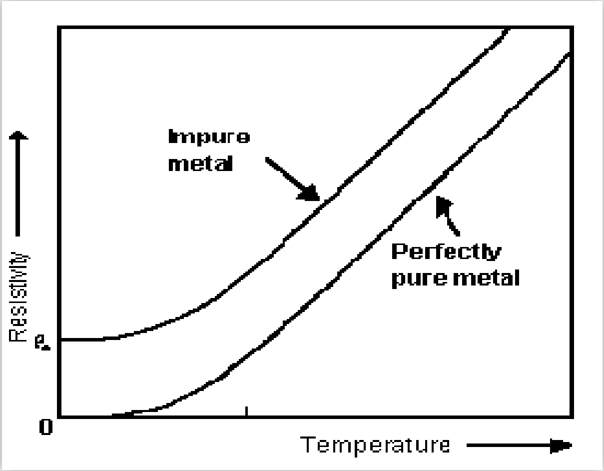
  - The product $\boldsymbol{nT}$ is proportional to the square of the magnetic field $\boldsymbol{B}$
  - The magnetic field $\boldsymbol{B}$ is proportional to the electric current in the confinement coils $\boldsymbol{I}$

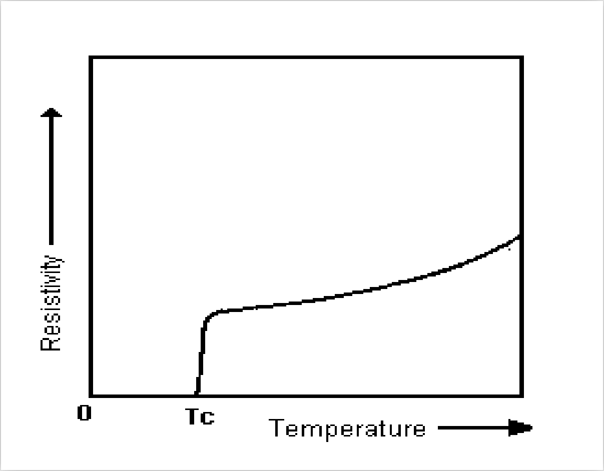
$$B = \frac{\mu_0 NI}{2\pi \mathrm{r}}$$

- A magnet system for fusion devices must have:
  - **High current** capability, both **steady state** and **pulsed**
  - **High magnetic fields**, both **toroidal** (confinement) and **poloidal** (control, current drive)
  - **High current density**, J [A/mm2], to **save construction space**
  - Very **low consumption** of energy – **no joule losses**
  - Ability to **withstand** high **neutron fluxes**, strong **EM forces**, etc.

Basic superconductivity concepts

- Superconductivity is a quantum mechanical effect.
  - An electrical current in a superconductor can flow for an indefinitely long time without any external power source.
- **Normal** vs. **Super** conductors:
  - In **normal conductors**, such as copper, the **resistance decreases as temperature decreases**. This decrease depends on the impurity in the conductor but also at the absolute zero temperature the material present a small resistance.
  - The **superconductor**, in spite of small imperfections, **switches** to the state of superconductor below its T_c.





Superconductivity for Fusion Magnets

At present state:

- **NbTi** and **Nb_3Sn** are the most used superconducting materials for cables.
    - **NbTi** is normally used for **fields below 7 T** (e.g. ITER PF coils)
    - **Nb_3Sn** is used for higher **fields up to 14 T** (e.g. ITER TF coils and Central Solenoid)

- The large fusion devices recently built or under construction use superconducting magnets. The largest in the world are being built for **ITER**.
- A large part of the effort has been devoted to the development of suitable superconducting cables.
- **Cable-in-conduit** type of conductors have been developed due to the large volume, energy and required stability for high performance magnets.
- Advanced multi-strand Nb_3Sn have been used to increase the operating magnetic fields.

Section of the Cable-in-conduit-conductor (CICC) for the ITER magnets

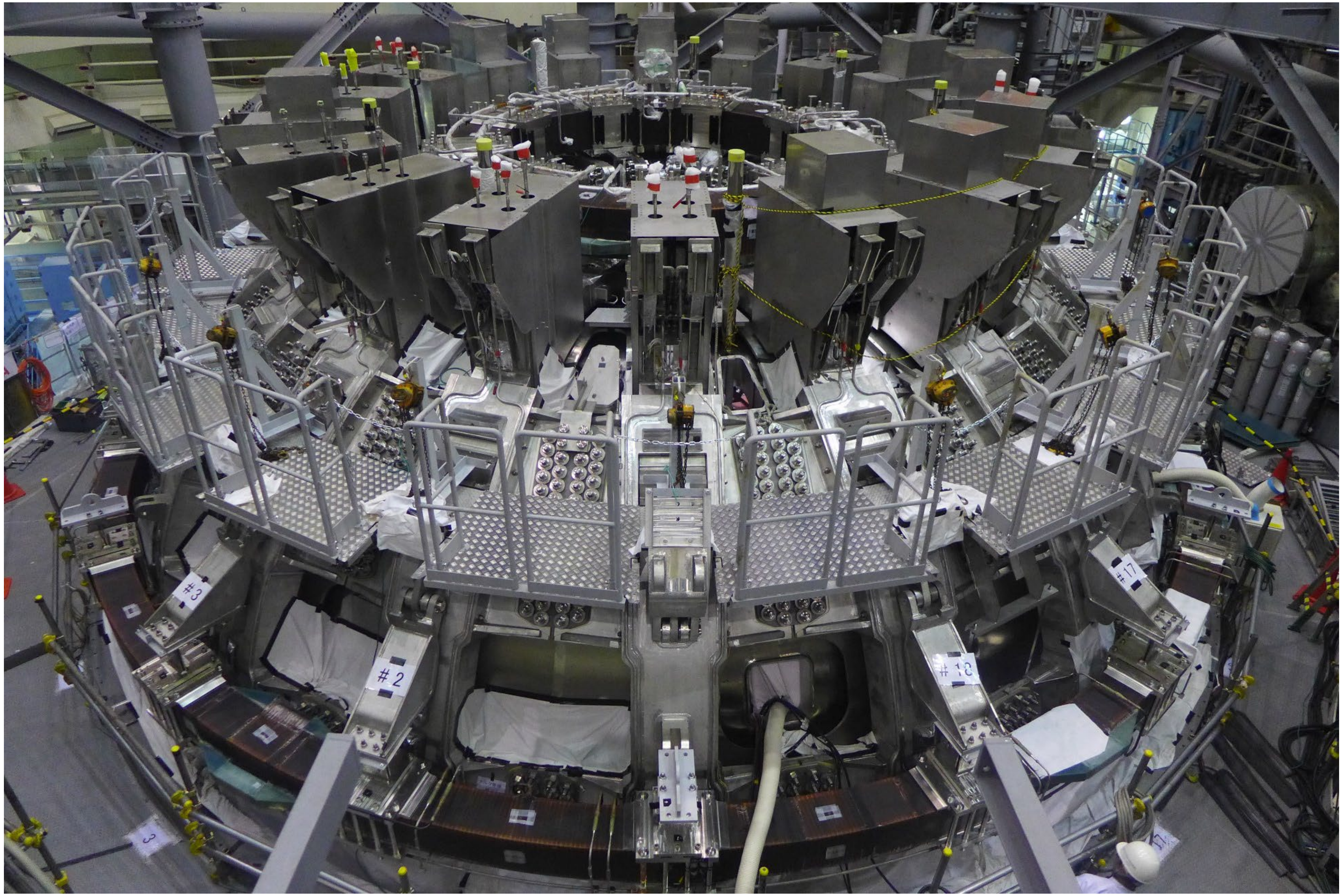
Superconducting Magnets Fabrication

Courtesy GE

Superconducting Magnets Fabrication

Courtesy QST

Superconducting Magnets Fabrication

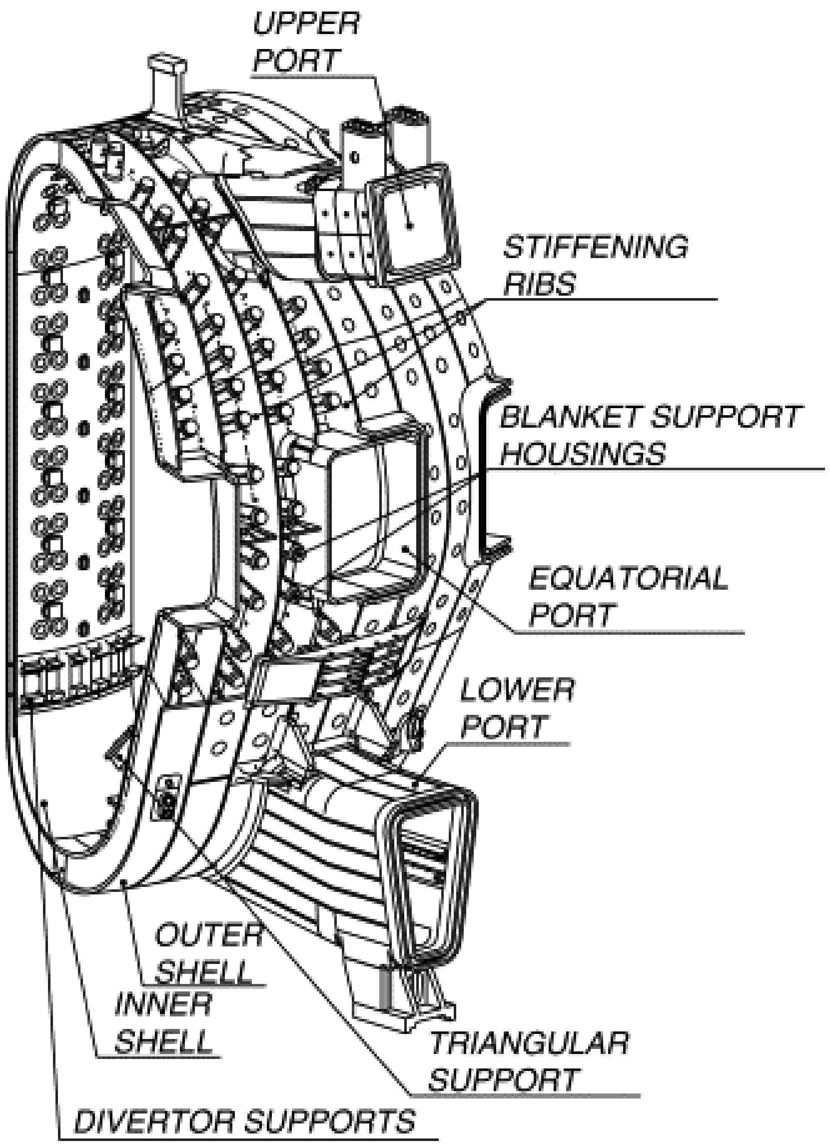


Courtesy QST

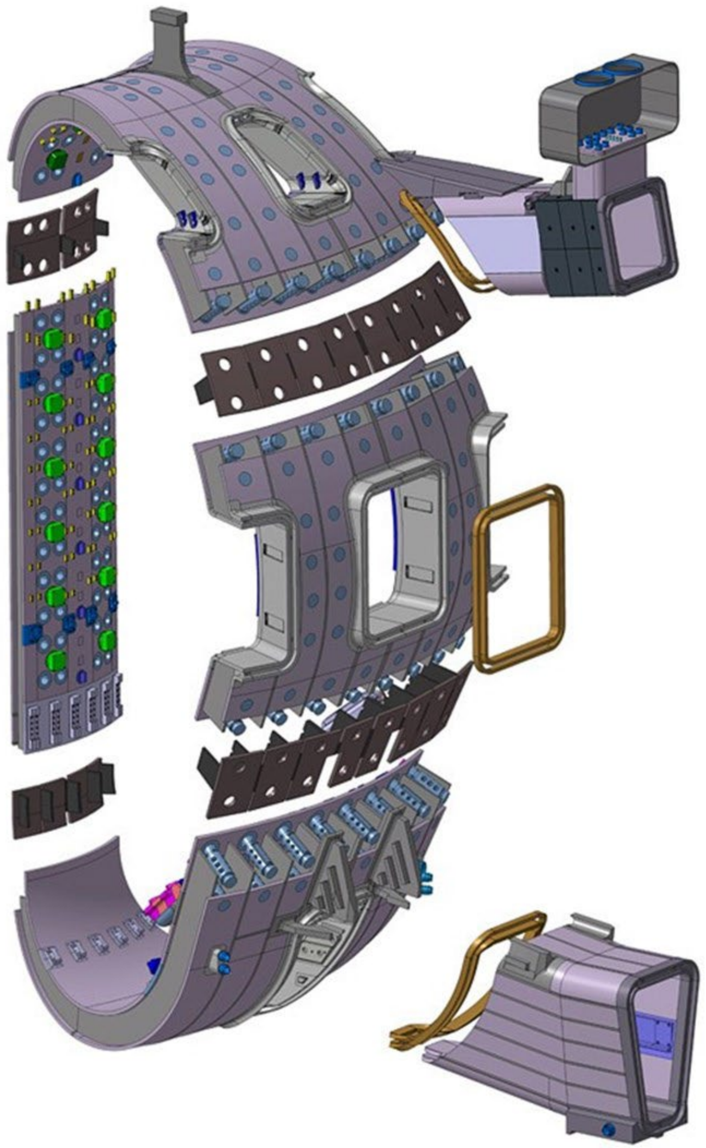
ITER Vacuum Vessel

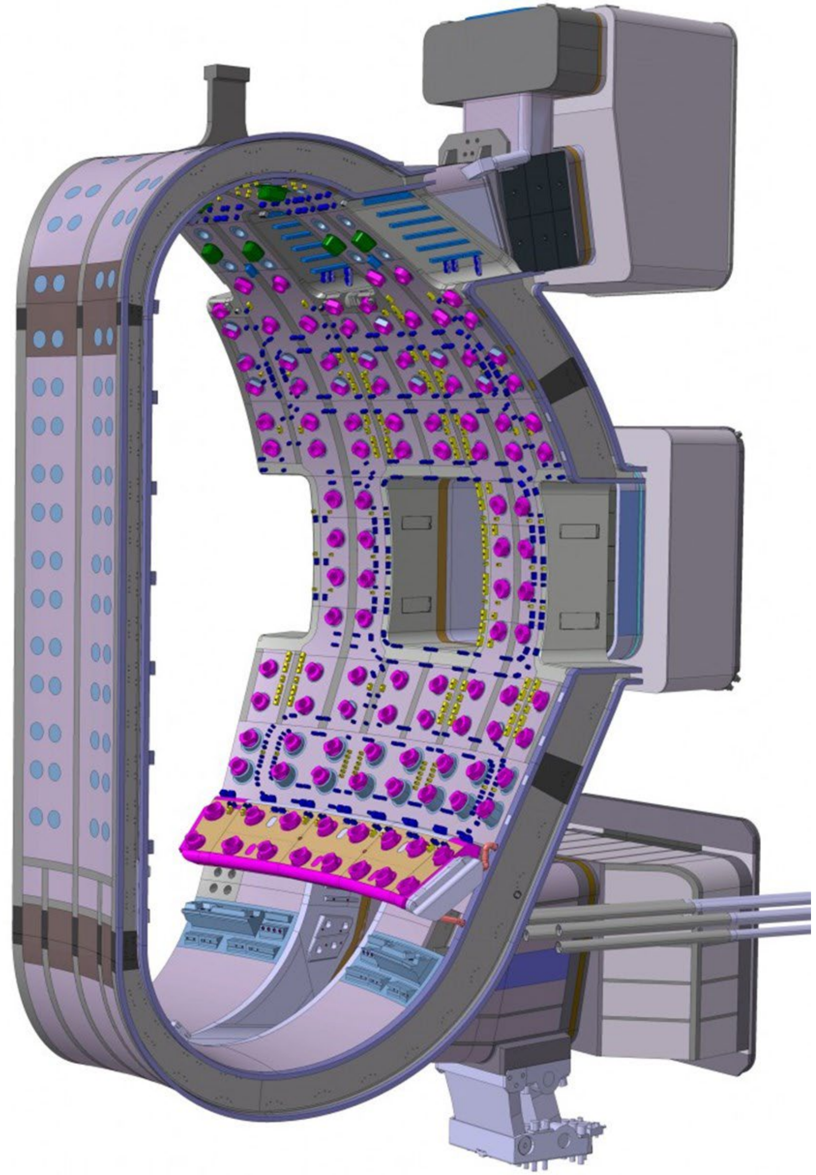
Complex manufacturing: The ITER Vacuum Vessel

- The Vacuum vessel is made of 9 nearly identical sectors
- Each sector consists of **inner** and **outer shells**, **ribs**, **shield** structures, **splice plates**, shielding structures for field joints, and **mechanical structures** on the inner and outer shells to support **in-vessel components** and to support the vessel **weight.**
- The ITER vacuum vessel has
  - **18 ports** at the **upper level** of the machine,
  - **14 regular** and **3 NB ports** at the **equatorial level**
  - **9 port** and **18 local penetrations** at the **lower level**

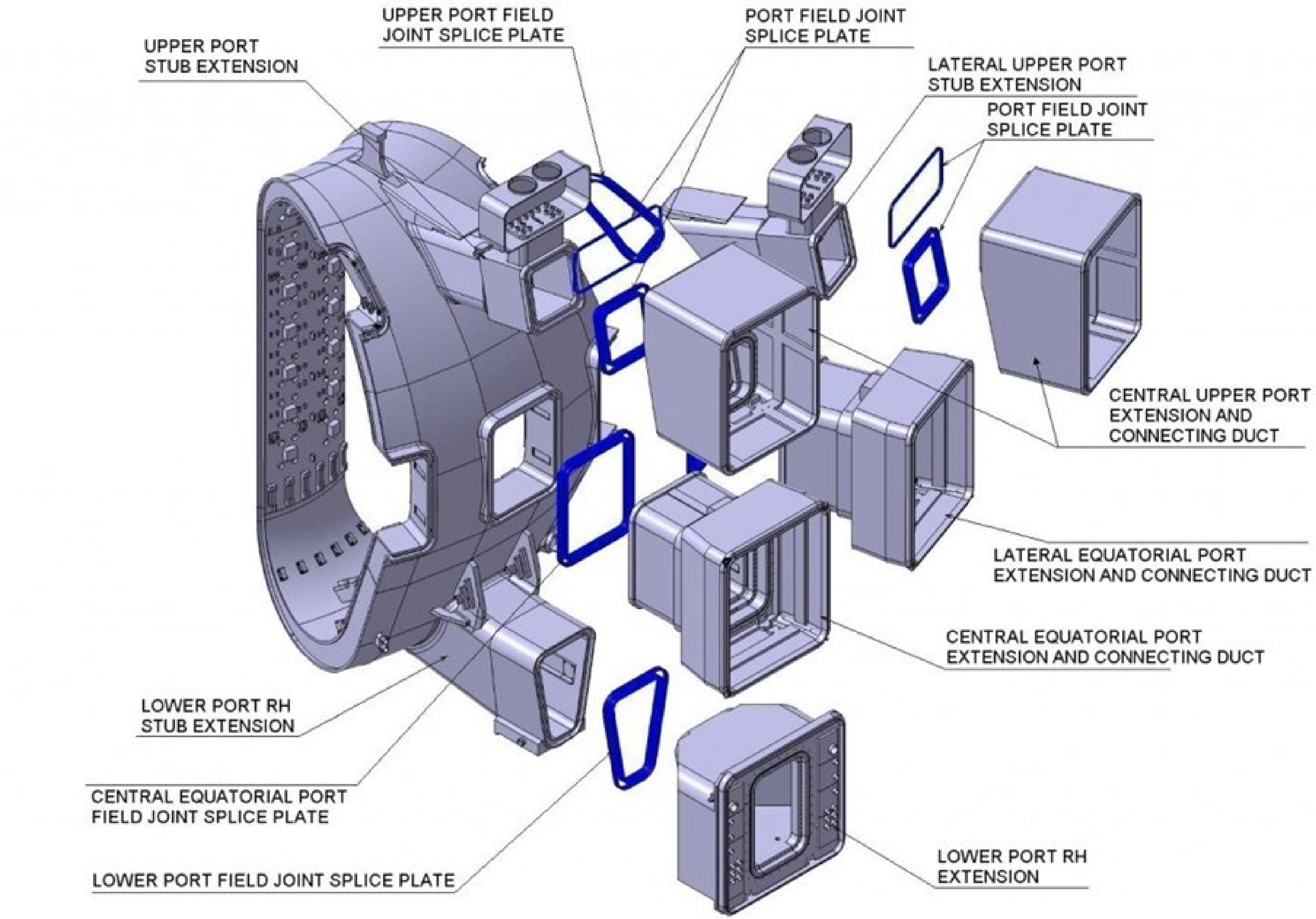


Complex manufacturing: The ITER Vacuum Vessel

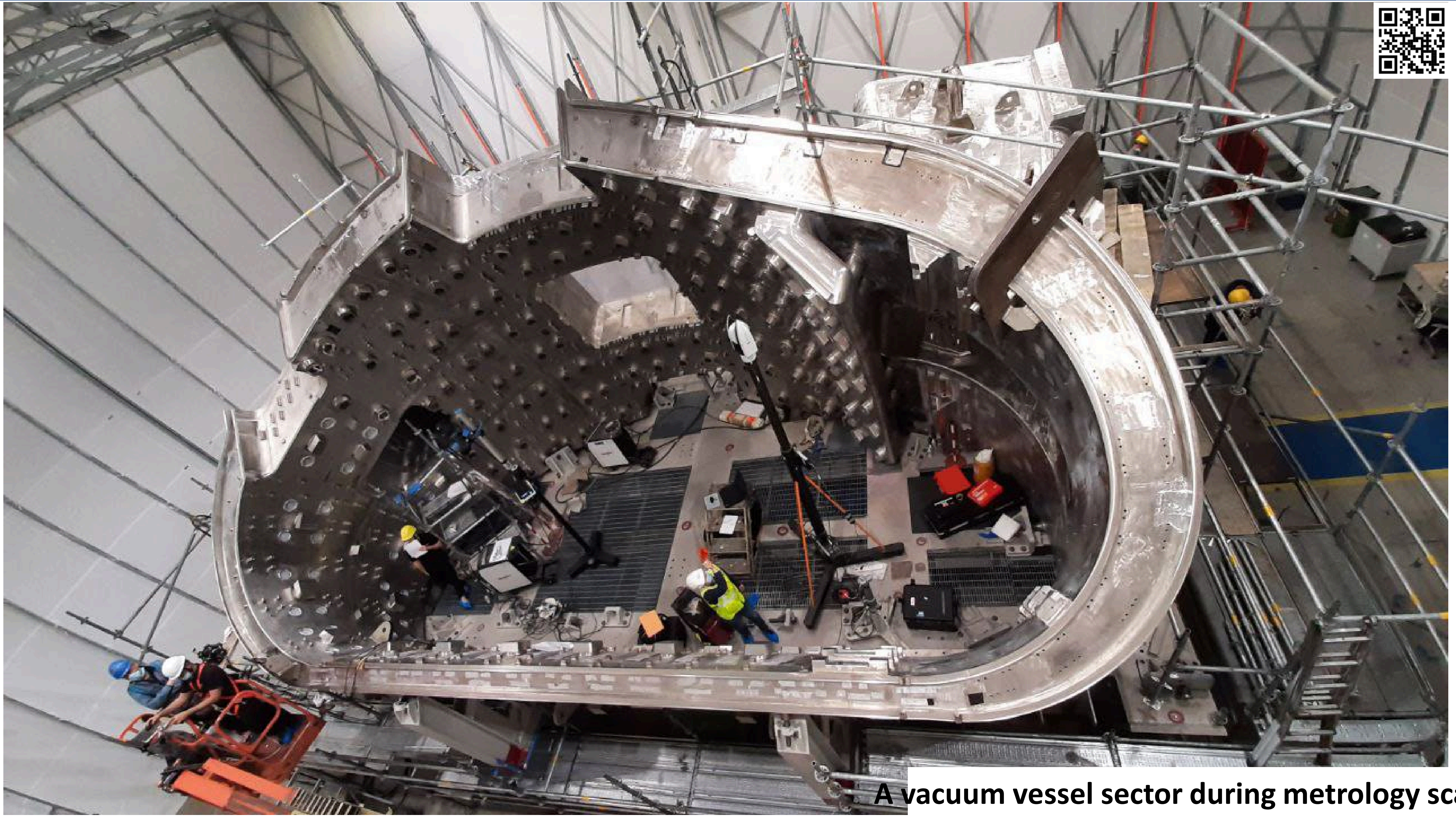




Complex manufacturing: The ITER Vacuum Vessel



Complex manufacturing: The ITER Vacuum Vessel



A vacuum vessel sector during metrology scan

Complex manufacturing: The ITER Vacuum Vessel

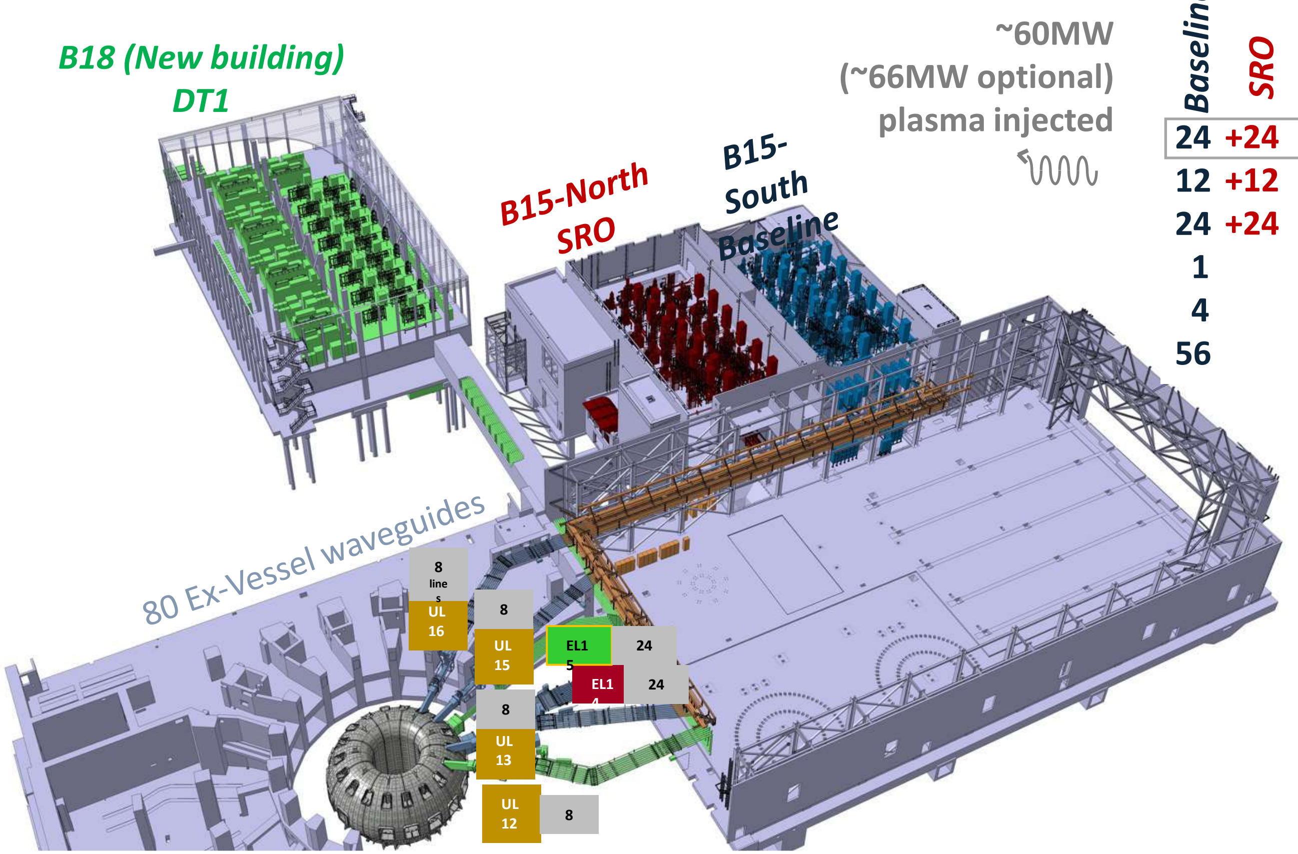
A vacuum vessel sector during metrology scan

Complex manufacturing: The ITER Vacuum Vessel

A vacuum vessel sector being prepared for installation in the toka

Heating systems

Heating systems – EC system



Baseline	SRO	DT1
24	+24	+ **24** RF Sources (+8 optional)
12	+12	+ **12** High Voltage PS (+4 optional)
24	+24	+ **24** Transmission lines (+8 optional)
1		+ **1** Equatorial Launcher (EL15)
4		+ 0 Upper Launcher
56		+ **24** Ex-Vessel Waveguides
		+ Control cubicles
		+ Ancillaries, supports

TOTAL POWER = 72MW installed (80MW optional)

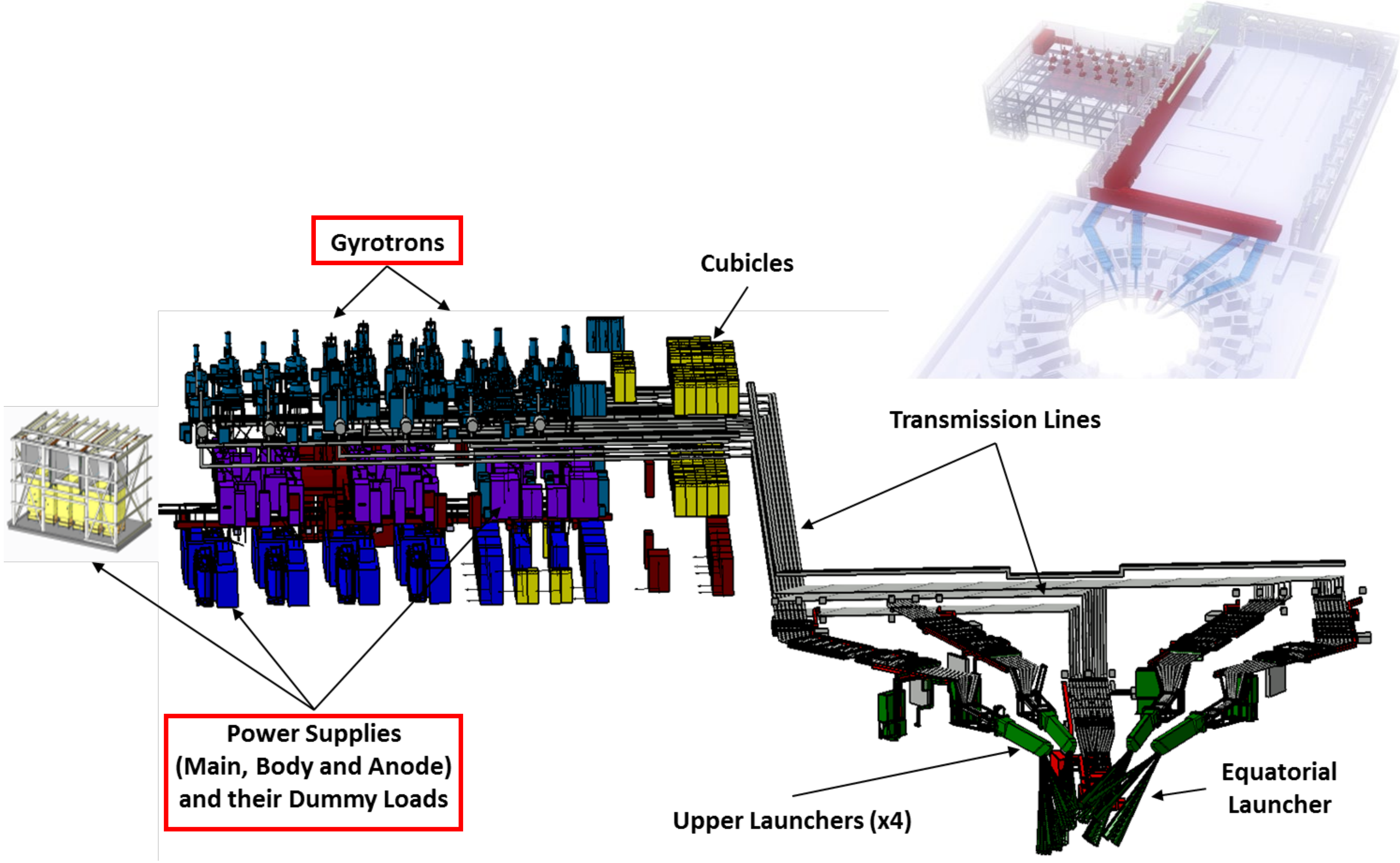
Other implications:

- Construction of new building #18 with new bridge
- New transmission line routing
- SSEN/ PPEN additional significant loads
- Associated services (e.g., vacuum, CCWS-1A adaptation)

New EC hardware (SRO + DT1):

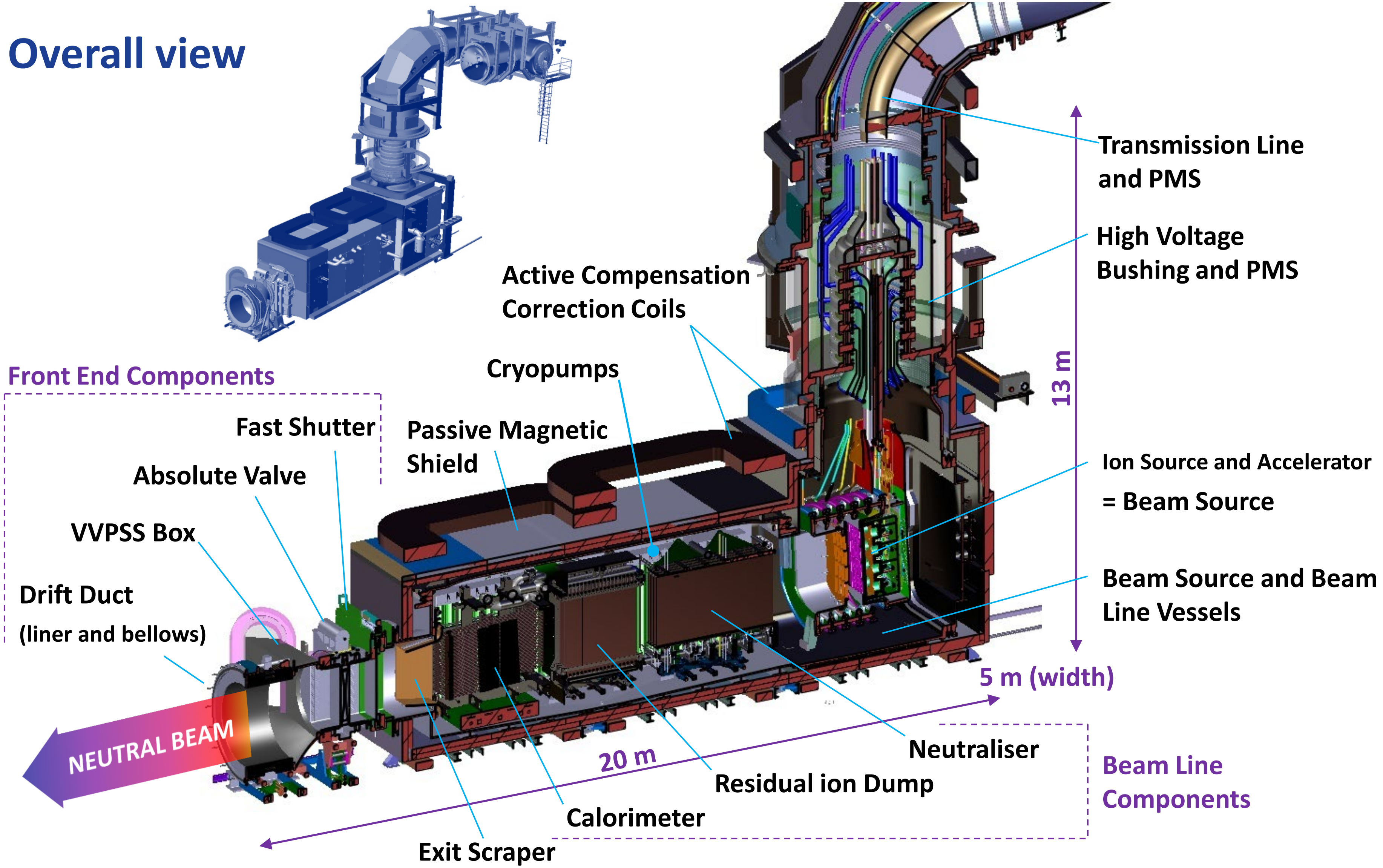
+ **48** RF Sources (+8 optional)
+ **24** High Voltage PS (+4 optional)
+ **48** Transmission lines (+8 optional)
+ **1** Equatorial Launcher (EL15) *(+UL12 optional)* and **24** Ex-Vessel Waveguides
+ Control cubicles
+ Ancillaries, supports

Heating systems - EC system



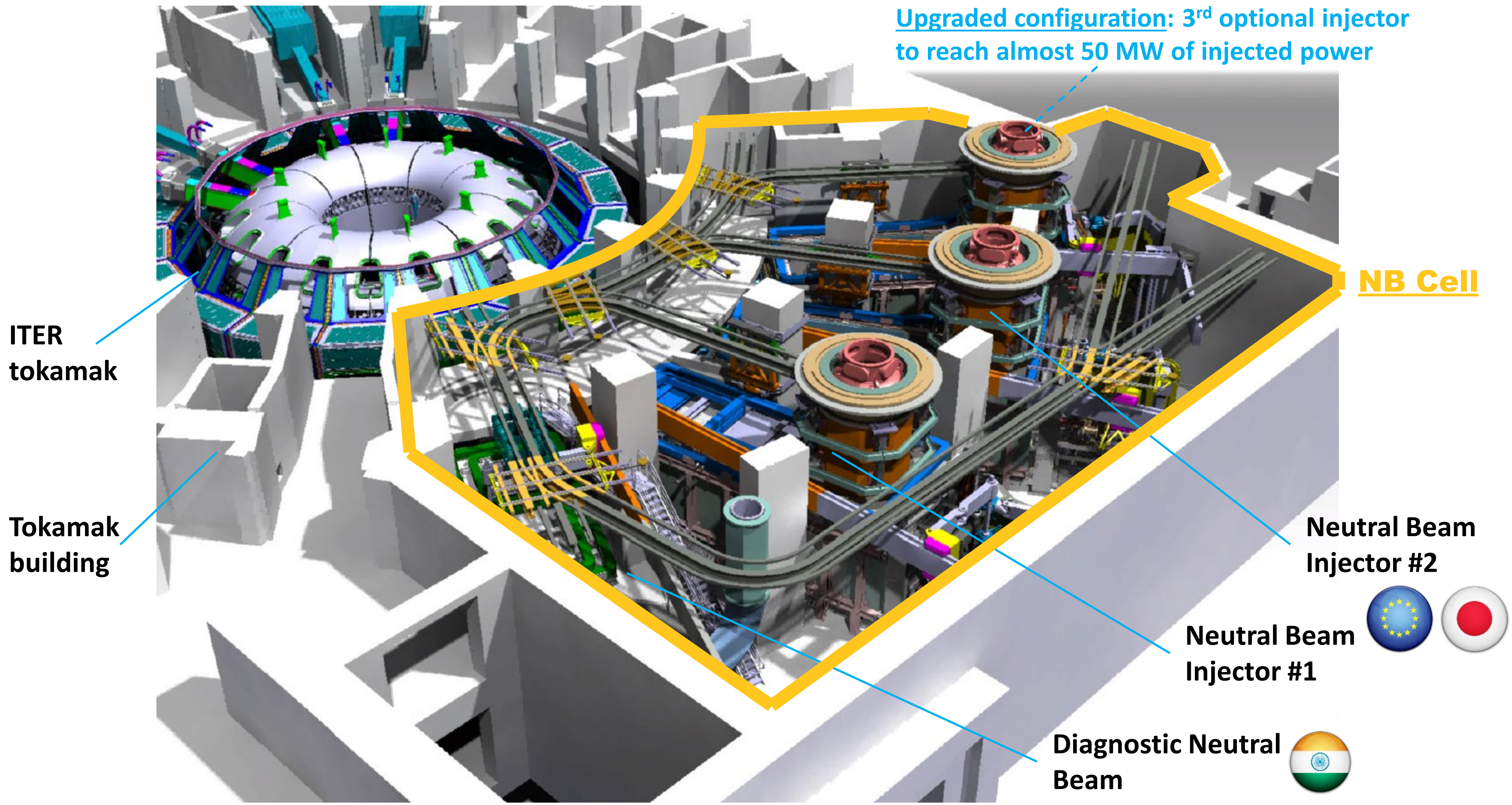
Heating systems – Neutral Beam Injector

Overall view



Heating systems – Neutral Beam Injector

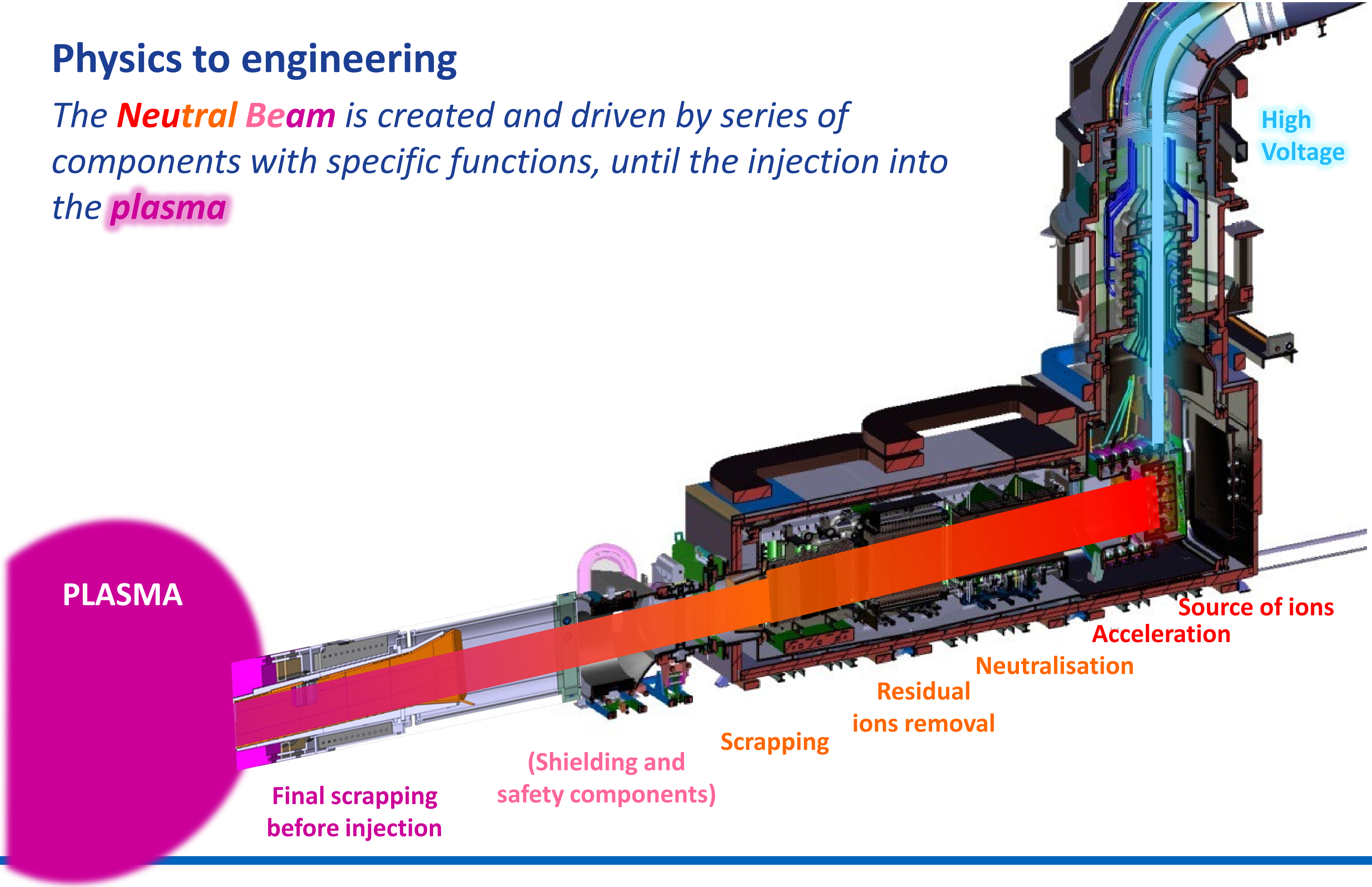
Configuration of the Neutral Beam Injectors



Heating systems – Neutral Beam Injector

Physics to engineering

*The **Neutral Beam** is created and driven by series of components with specific functions, until the injection into the **plasma***



Handling of large components

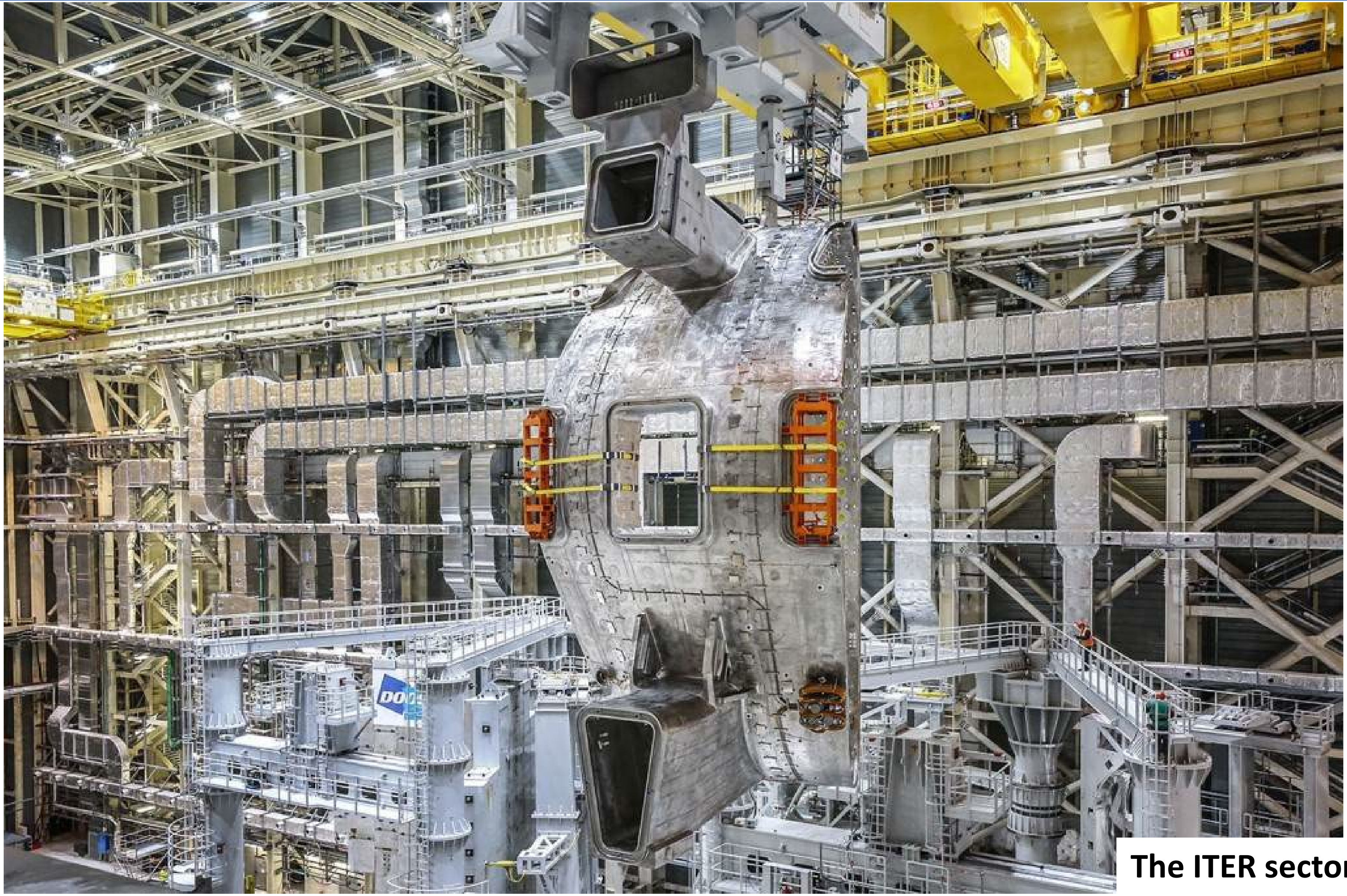
Handling of large components

- Once the components have been inspected, they are ready to be hauled to the assembly hall for their installation in the experiment.
- For large experiments, like ITER, precise and safe handling of components requires maximum effort and customized solutions.
- To be noted that, especially for fusion experiments components, the ratio of weight to volume is particularly high. That is, there are several components which need to be moved in a single lift, and which have very large weight (1000 t and more).
- In more conventional engineering, even if the plants themselves are much larger than e.g. the ITER site, the single components to be assembled are generally lighter.
- For ITER very specific lifting, uplifting and assembly tools have been developed.

Handling of large components

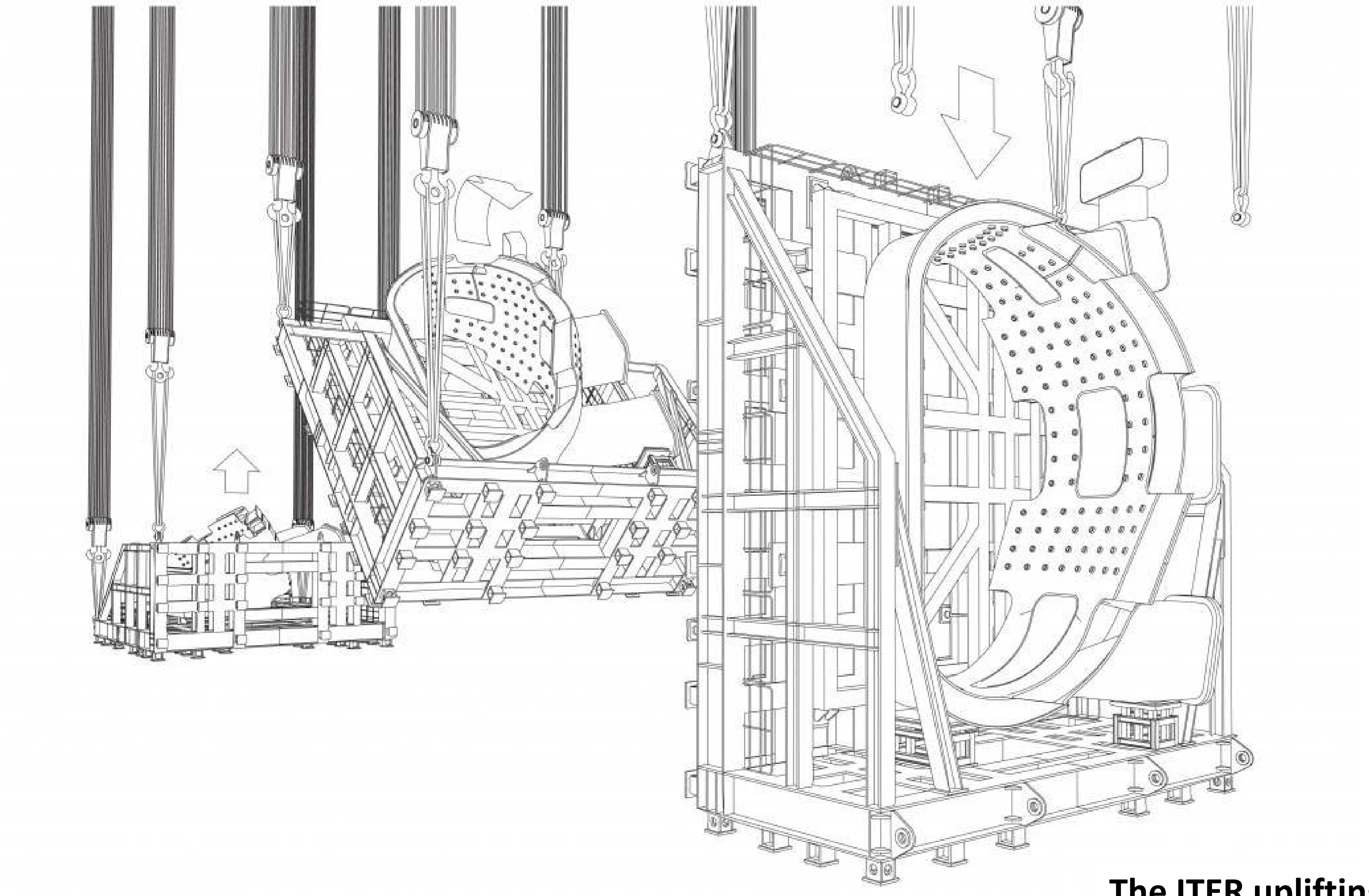
The ITER sector lifting tool

Handling of large components



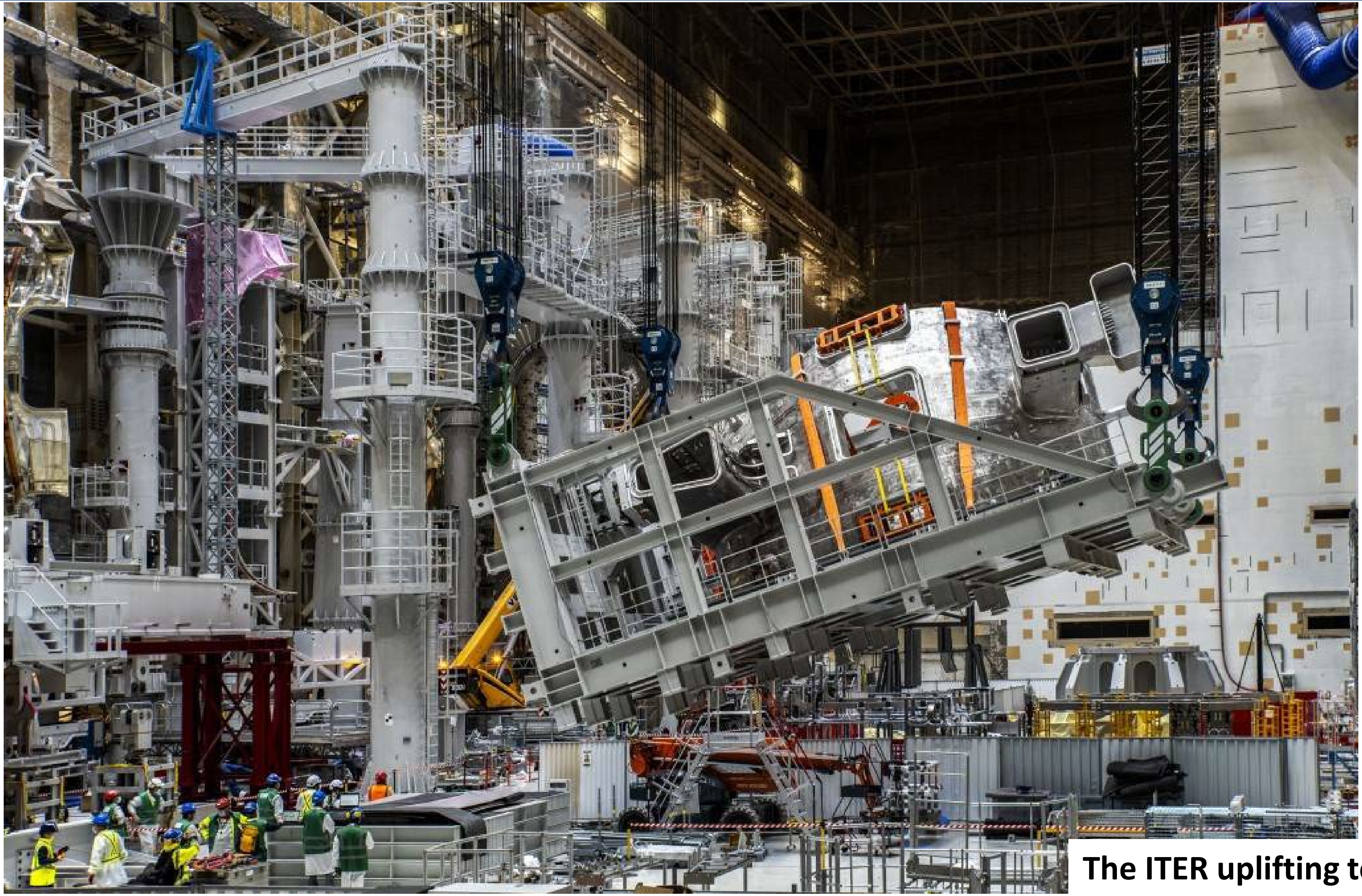
The ITER sector lifting tool

Handling of large components



The ITER uplifting tool

Handling of large components



The ITER uplifting tool

Handling of large components

The ITER uplifting tool

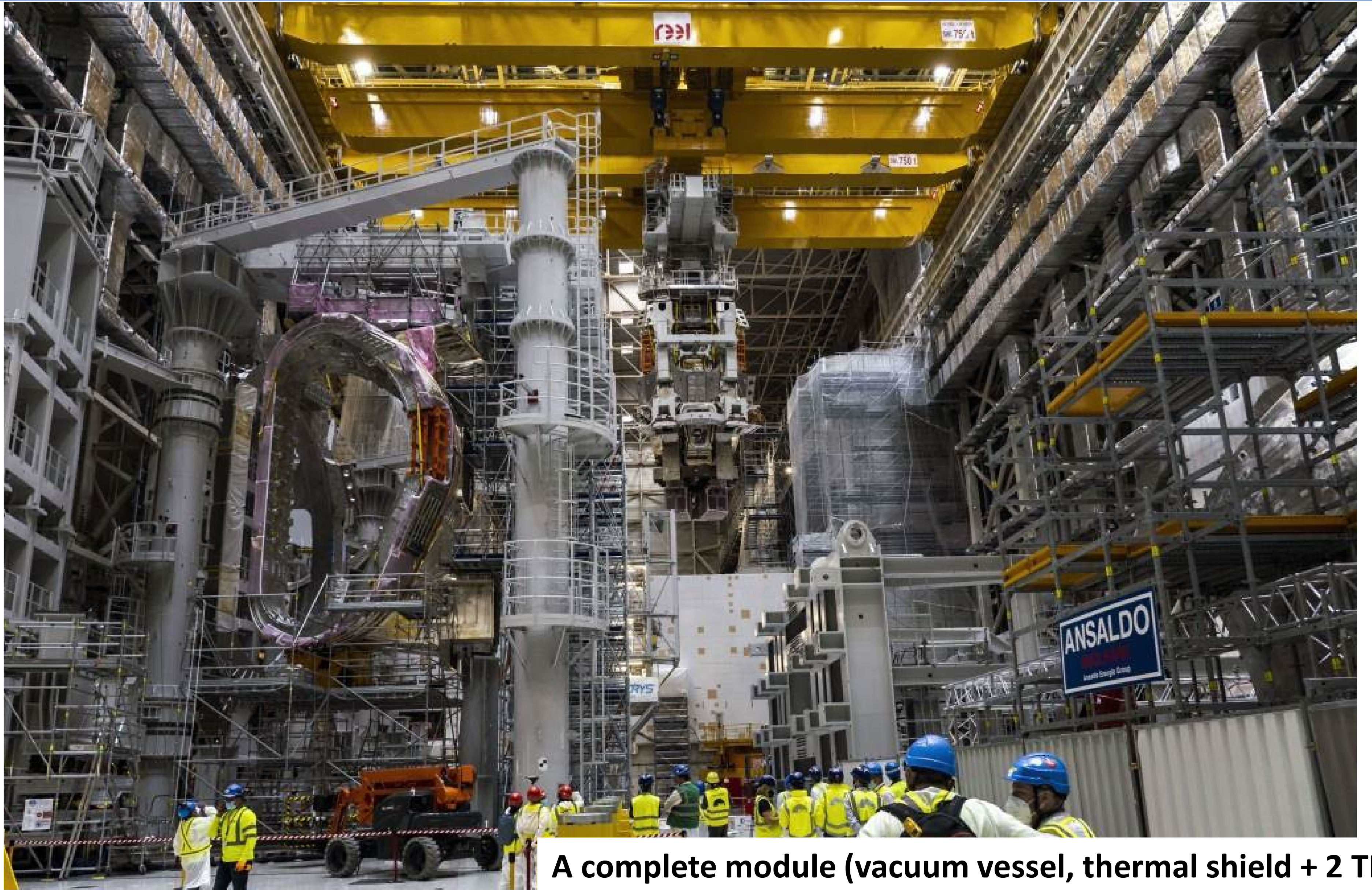
Handling of large components

The ITER sub-assembly tools

Handling of large components

The ITER in-pit assembly tools

Handling of large components



A complete module (vacuum vessel, thermal shield + 2 TF coils) being mov

Handling of large components

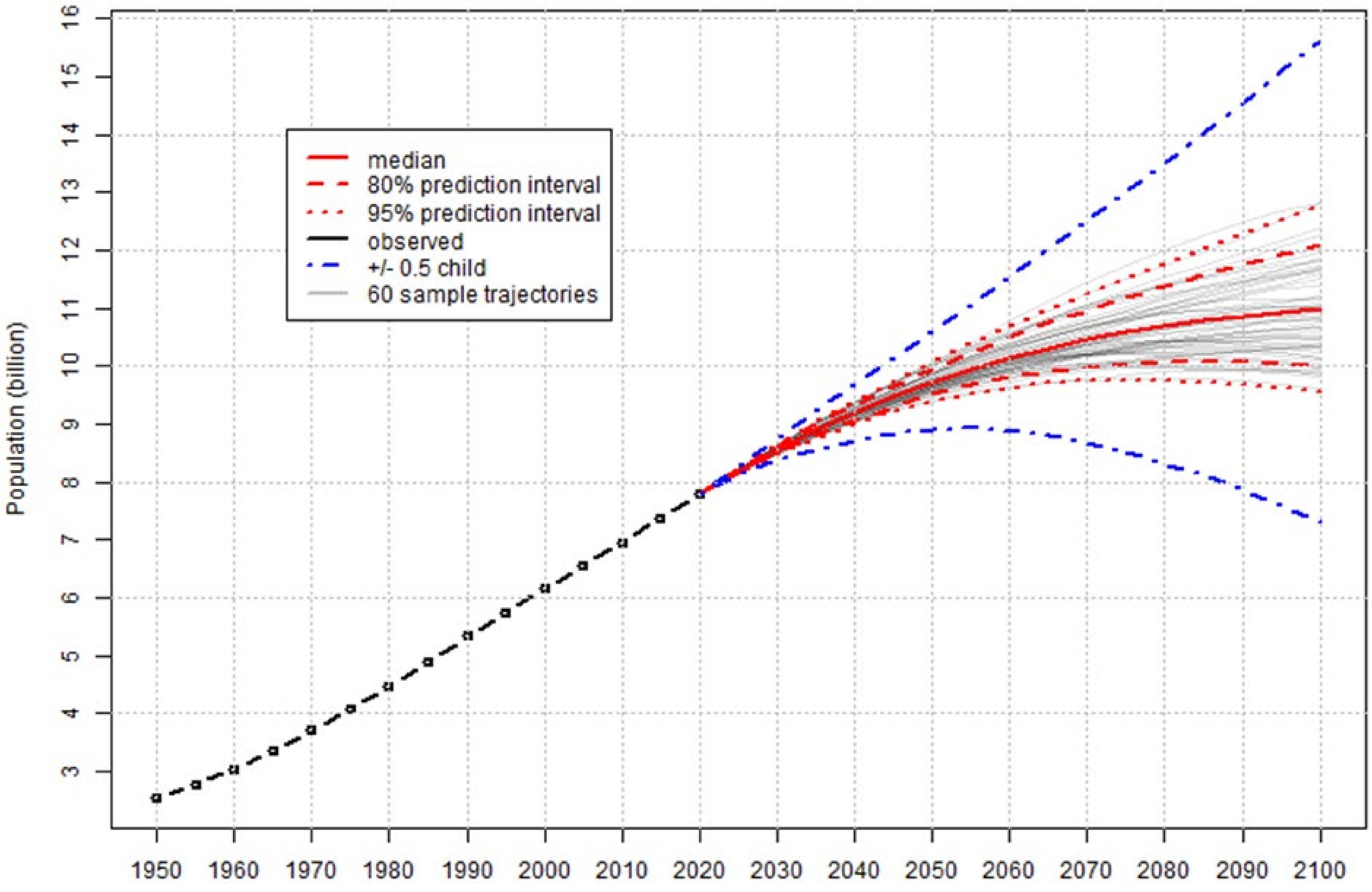
Total weight = 1380 t

A complete module (vacuum vessel, thermal shield + 2 TF coils) being mov

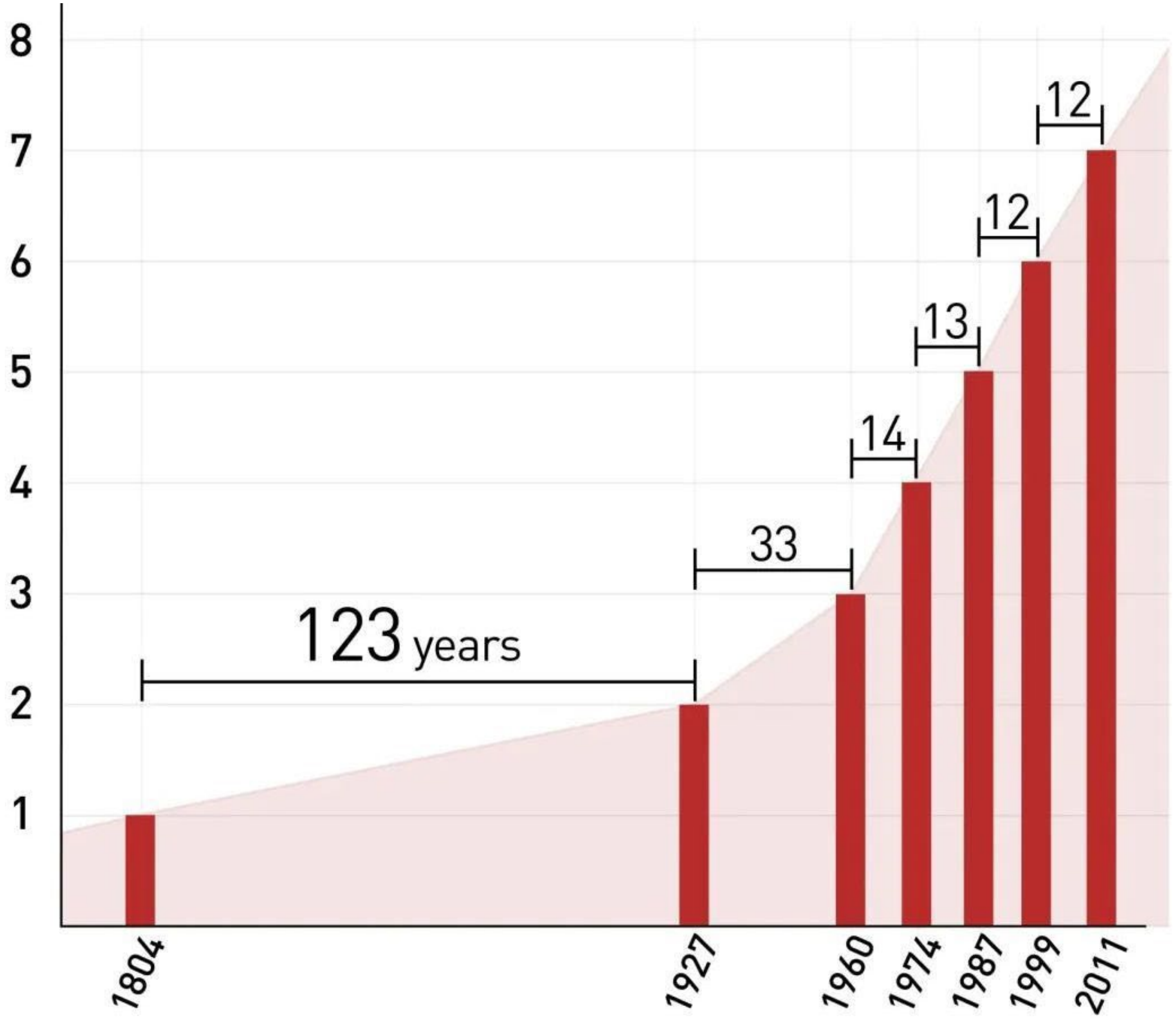
Backup Slides

Why Nuclear Fusion

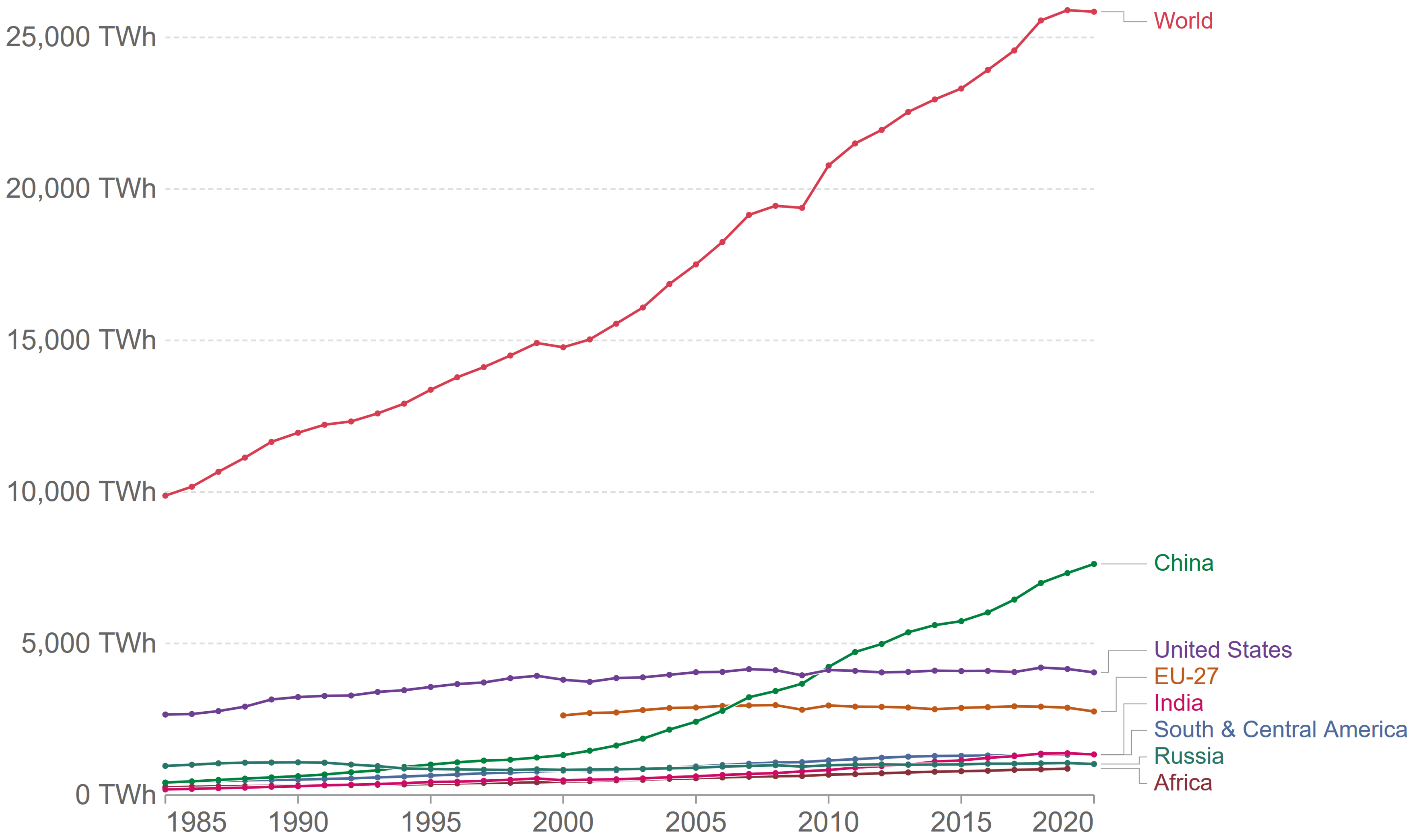
World Total Population Trend



World Population Billions Milestones

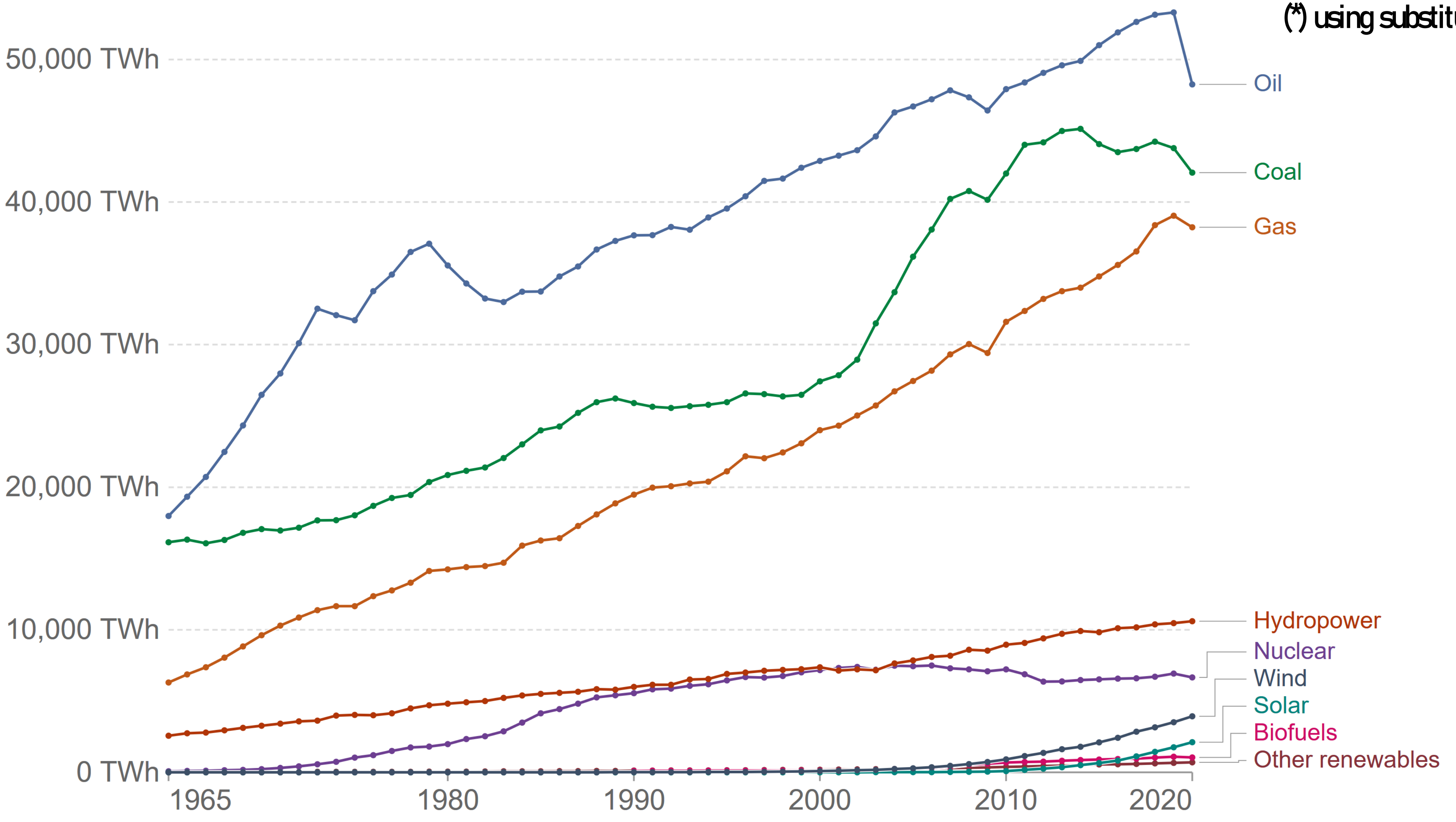


World Total Primary Energy Production



Primary energy consumption* by source

(*) using substitution method



Why Nuclear Fusion

- World population **increases** now **steadily** at the rate of 1 billion every 12 years.
- World energy production roughly follows population increase, but most of it comes from **non-renewable sources** (coal, gas).
- The strive for higher living standards is driving the energy demand.
- It is expected that the energy consumption will roughly **triple** by year 2050.
- Renewable energies might not be enough to cover this increase and substitute fossil fuels.
- Nuclear fission could play a larger role in substituting fossil fuels and in reducing CO_2 emissions.
- Energy saving, birth control, better welfare could only theoretically mitigate the demand.
- **Nuclear fusion** has the potential to provide a **reliable** and **safe energy source** for the **long term needs** of mankind

Main Definitions from Nuclear Physics

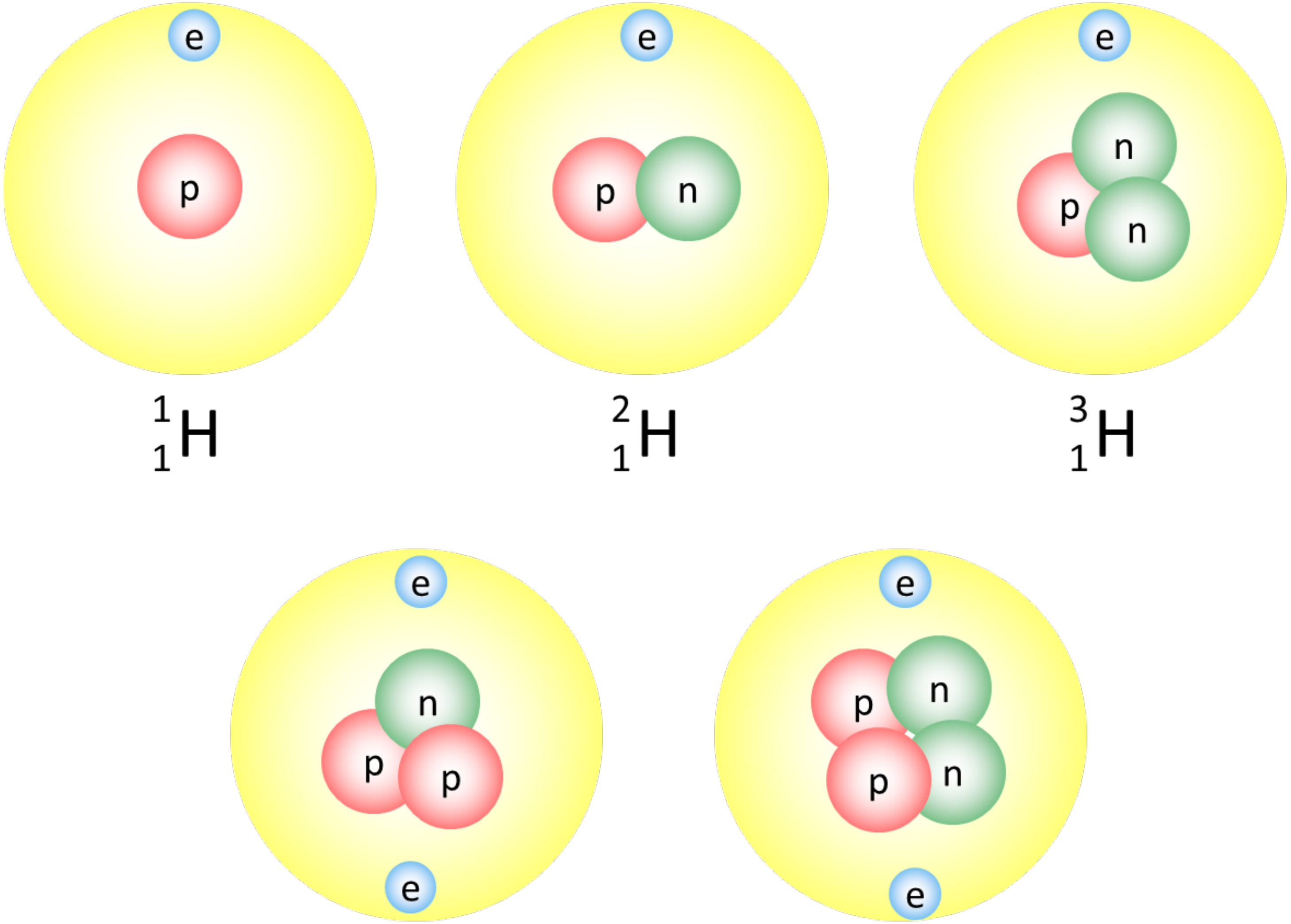
Main Definitions from Nuclear Physics

- An **atom** is the smallest unit of ordinary matter that forms a chemical element.

- Every atom is composed of a **nucleus** and one or more **electrons** bound to the nucleus.

- The nucleus is made of one or more **protons** and **neutrons** (nucleons).
  - $\boldsymbol{Z}$ is the **Atomic number** or the number of protons in the nucleus and it defines to which chemical element the atom belongs.
  - $\boldsymbol{A}$ is the **Mass number** or the sum of the number of protons and the number of neutrons in an atom.
  - $\boldsymbol{N = A - Z}$ is the **number of neutrons** in the nucleus and it defines to which **isotope** of a chemical element the atom belongs.

Main Definitions from Nuclear Physics



$^{1}_{1}H$ $^{2}_{1}H$ $^{3}_{1}H$

$^{3}_{2}He$ $^{4}_{2}He$

$^{1}_{1}H$ = Protium

$^{2}_{1}H$ = Deuterium

$^{3}_{1}H$ = Tritium

$^{3}_{2}He$ = Helium-3

$^{4}_{2}He$ = Helium-4

Main Definitions from Nuclear Physics

The Four Fundamental Forces			
Type	**Range**	**Relative strength**	**Interaction time**
Strong	1 fm	1	10^{-23} s
Electromagnetism	∞	10^{-2}	$10^{-14} \div 10^{-20}$ s
Weak	10^{-3} fm	10^{-7}	$10^{-14} \div 10^{-20}$ s
Gravitation	∞	10^{-38}	years

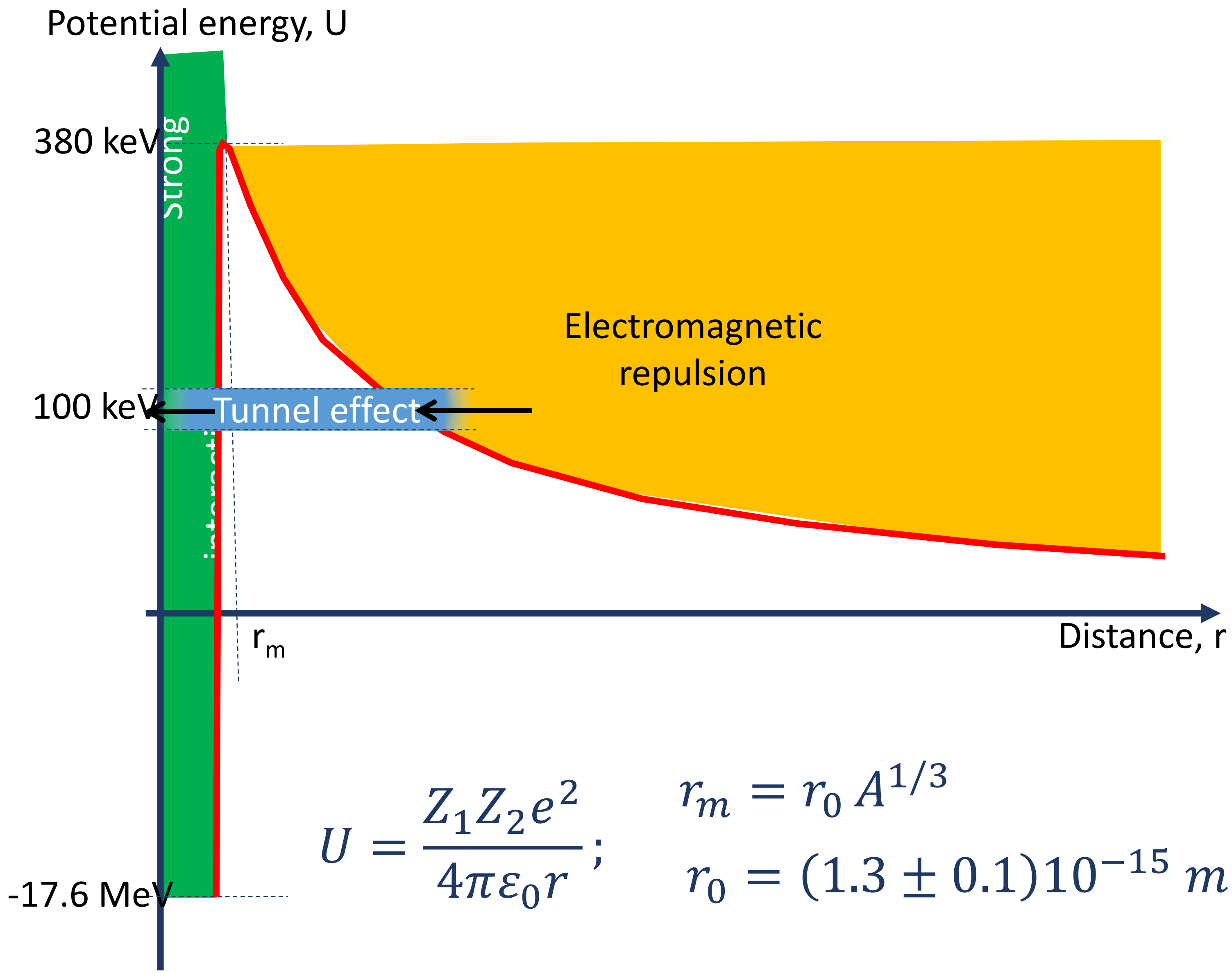
1 fm = 10^{-15}

Main Definitions from Nuclear Physics

Z →	**0**	**1**	**2**												
n ↓	**n**	**H**	**He**	**3**	**4**	**5**									
0		^{1}H		**Li**	**Be**	**B**	**6**								
1	^{1}n	^{2}H	^{3}He	^{4}Li	^{5}Be	^{6}B	**C**	**7**							
2		^{3}H	^{4}He	^{5}Li	^{6}Be	^{7}B	^{8}C	**N**	**8**						
3		^{4}H	^{5}He	^{6}Li	^{7}Be	^{8}B	^{9}C	^{10}N	**O**	**9**					
4		^{5}H	^{6}He	^{7}Li	^{8}Be	^{9}B	^{10}C	^{11}N	^{12}O	**F**	**10**			**13**	
5		^{6}H	^{7}He	^{8}Li	^{9}Be	^{10}B	^{11}C	^{12}N	^{13}O	^{14}F	**Ne**	**11**	**12**	**Al**	
6		^{7}H	^{8}He	^{9}Li	^{10}Be	^{11}B	^{12}C	^{13}N	^{14}O	^{15}F	^{16}Ne	**Na**	**Mg**	^{19}Al	**14**
		7	^{9}He	^{10}Li	^{11}Be	^{12}B	^{13}C	^{14}N	^{15}O	^{16}F	^{17}Ne	^{18}Na	^{19}Mg	^{20}Al	**Si**
		8	^{10}He	^{11}Li	^{12}Be	^{13}B	^{14}C	^{15}N	^{16}O	^{17}F	^{18}Ne	^{19}Na	^{20}Mg	^{21}Al	^{22}Si
			9	^{12}Li	^{13}Be	^{14}B	^{15}C	^{16}N	^{17}O	^{18}F	^{19}Ne	^{20}Na	^{21}Mg	^{22}Al	^{23}Si
				10	^{14}Be	^{15}B	^{16}C	^{17}N	^{18}O	^{19}F	^{20}Ne	^{21}Na	^{22}Mg	^{23}Al	^{24}Si

Tokamak operation and plasma instabilities

How fusion occurs



$$U = \frac{Z_1 Z_2 e^2}{4\pi\varepsilon_0 r};$$

$$r_m = r_0\, A^{1/3}$$

$$r_0 = (1.3 \pm 0.1)10^{-15}\ m$$

To overcome the coulomb potential barrier, the fusing D, T nuclei must have sufficient energy to get close enough for the strong interaction to prevail

It can be calculated that this energy is ~ 380 keV, much higher than that at which fusion occurs into fusion experiments (~ 100 keV)

This counterintuitive fact can only be explained by means of quantum mechanics / electrodynamics, which is a very complex topic!

To do that we have to abandon the deterministic approach of particles and embrace their definition of „probability amplitudes“

Magnetic Confinement – Larmor radius

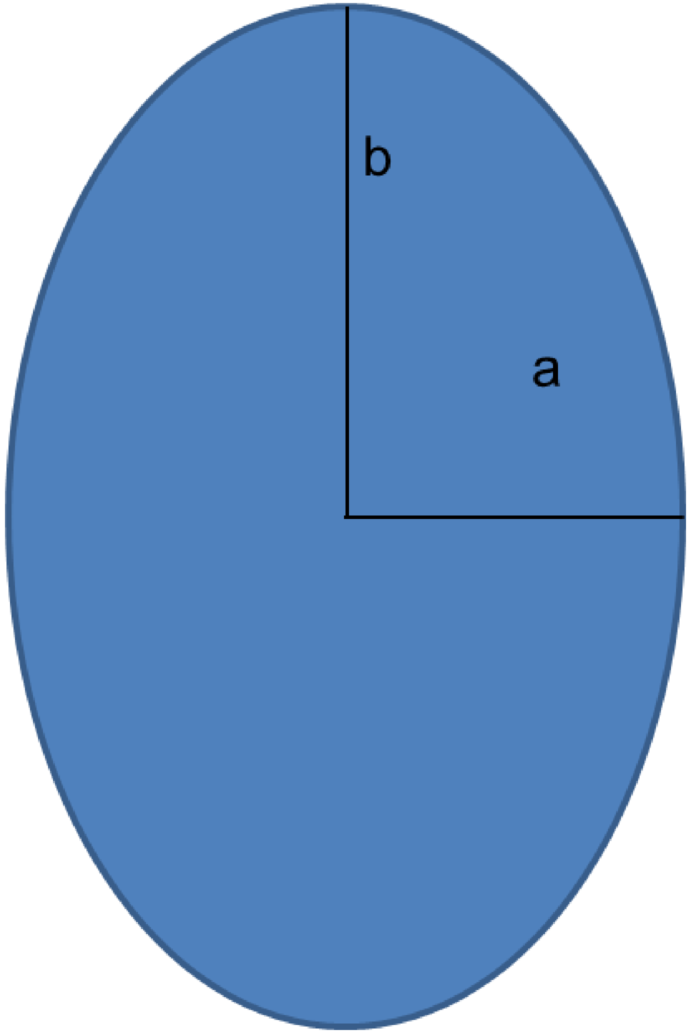
Larmor Radius for electrons and protons					
Magnetic field	Larmor radius	Temperature [keV]			
[T]	[mm]	0.01	0.1	1.0	10
3	ρ_e	0.003	0.011	0.035	0.11
	ρ_p	0.15	0.48	1.5	4.8
5	ρ_e	0.002	0.007	0.021	0.067
	ρ_p	0.09	0.29	0.91	2.9

Cyclotron frequency for electrons and protons			
Frequency	Magnetic field [T]		
	1	3	5
ω_{ce} [rad/s]	1.76×10^{11}	5.28×10^{11}	8.79×10^{11}
ω_{cp} [rad/s]	9.58×10^{7}	2.87×10^{8}	4.79×10^{8}
f_{ce} [GHz]	28	84	140
f_{cp} [GHz]	15	46	76

The Tokamak plasma operation

- For the **inductive drive** the main **limitation** is given by the capabilities of the **central solenoid**. The total magnetic flux is limited by the maximum current that can be reached in the central solenoid.
- In the ramp-up phase the plasma can be started in the inboard or outboard side of the plasma chamber. After breakdown the plasma current starts at low values and the growing plasma lays on the wall.
- Even if in this configuration (called **limiter configuration**) the plasma current is kept as low as possible, the direct contact of the plasma requires special means. The current is increased steadily and the plasma is shaped from almost circular to its final elongated form.
- Due to the **electrical resistance** of the plasma the current increases its temperature (Joule effect) during start-up.
- The ramp-up phase last typically in ITER about 50 s, but the trend is to reduce this time to a minimum, **reducing** the **heat load** in the limiting surfaces and reducing the **magnetic flux consumption**.

Plasma elongation



Definition of plasma elongation $\kappa = b/a$

In the late 70s it was found advantageous to have **vertically elongated plasmas**. For achieving that, a **“D” shape Toroidal Field Coil** magnet would have been optimal.

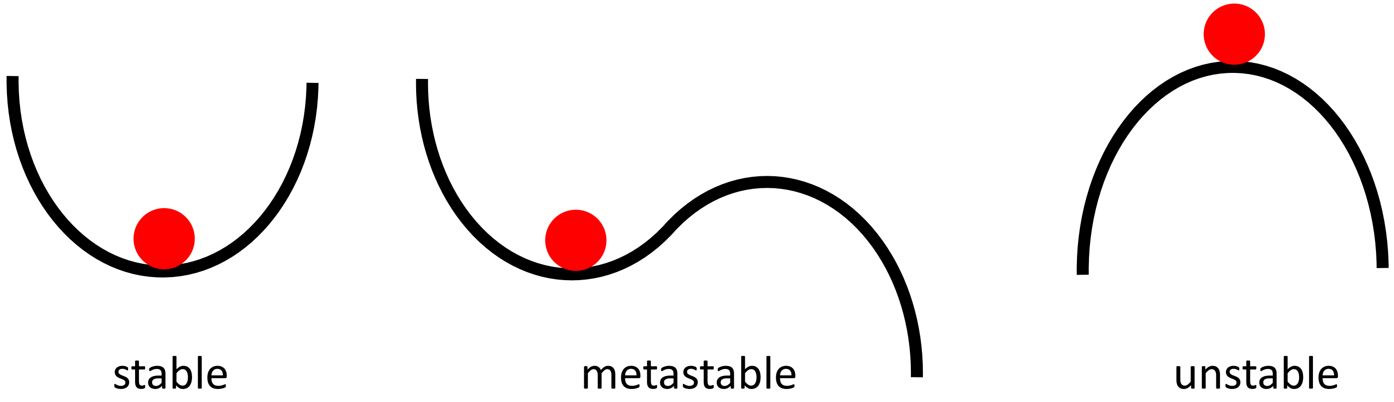
Since than, all the newly built Tokamaks (with only few exceptions, like Tore Supra) have been built with D shaped coils.

The confinement can be improved by getting higher currents without increasing the major radius.

Increasing the plasma radius at the outboard equatorial region is limited by the previous ripple considerations.

Plasma instabilities

- To obtain fusion, the plasma must be confined for sufficiently long time at high density and temperature. In a magnetically confined device, the ‘container’ is just the magnetic field.
- The plasma remains confined if its **internal pressure is balanced by the magnetic forces**. But even small fluctuations can trigger transients which can be **stable** or **unstable**.



Plasma instabilities

- Plasma **macro instabilities** involve **large movements** of the plasma, and can be studied as MHD phenomena
- Plasma **micro instabilities** are instead **local perturbations** which develop inside the plasma
- We can approach the (complex !) topic of instabilities with some simple intuitive steps:
  - Imagine to displace a plasma from equilibrium
  - If the restoring force gets **stronger** the configuration is **stable**, if it gets **weaker** the configuration is **unstable**
  - If the instability **amplifies** dramatically, the plasma can be **lost suddenly**, and a plasma **disruption** can occur

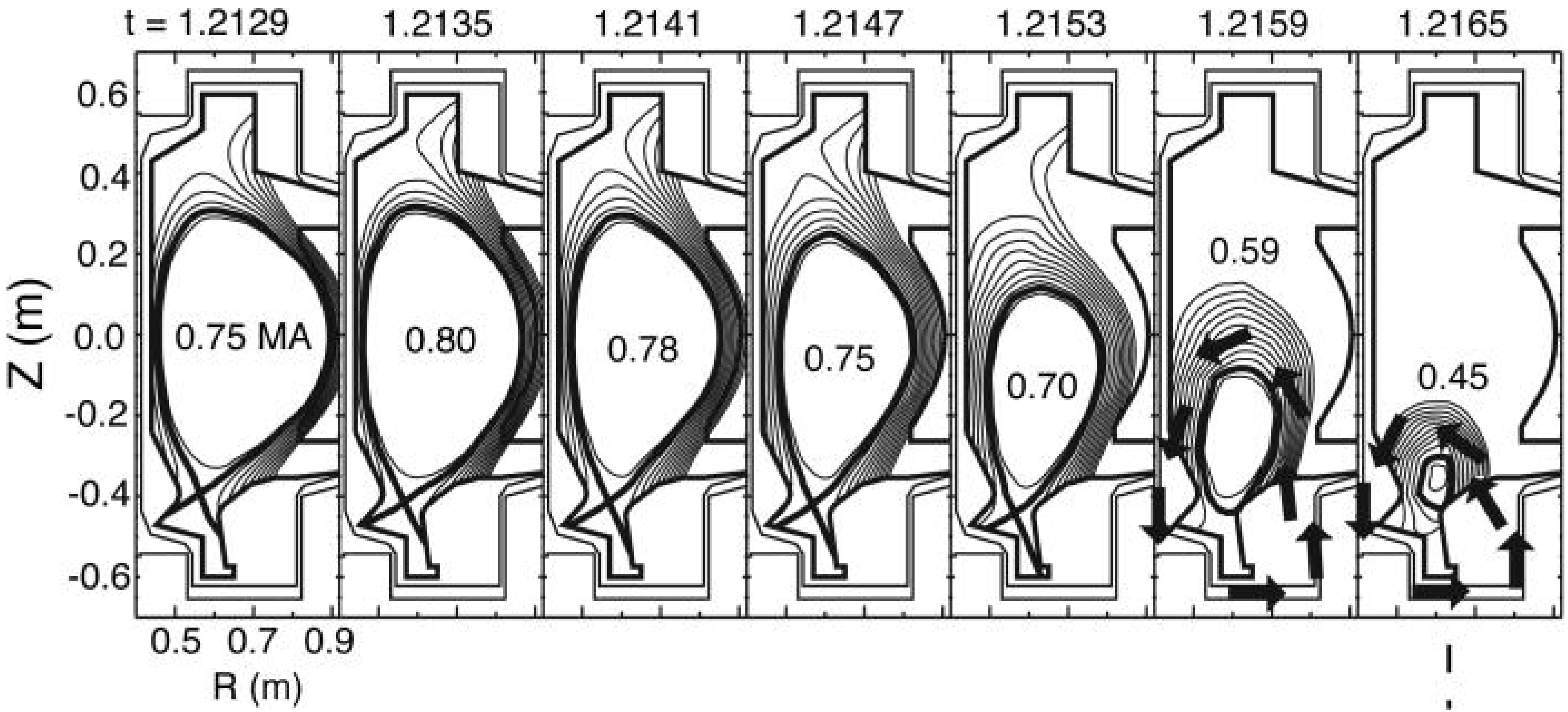
Plasma disruptions

- In tokamaks some instabilities can results in the plasma confinement being suddenly destroyed leading to a **disruption event**. In major disruptions this is followed by the complete **loss** of the plasma **current**.
- In tokamaks the plasma disruption can be highly **destructive** releasing **high energies** and causing **large forces** on the surrounding structures.
- Disruptions occur in present tokamaks mainly when the current or density **limits** are approached or if there is an accidental event such as a **foreign object** (e.g. a falling tile or a wall piece).
- The disruptions limit the plasma range of operations and cause intense and fast **heat loads** on the plasma facing components and large **electromagnetic loads** on the surrounding structures and on the plasma vessel, which is a large (normally) electrically continuous structure around the plasma.

Plasma disruptions

- Most of the large electromagnetic loads are due to the **fast quench** of the plasma current and associated **fast decay** of magnetic field. As a fundamental rule of magnetism this **induces currents** in the surrounding structures which tend to **counteract** the primary variation of the field.
- The interaction of these induced **eddy currents** with the toroidal magnetic field can give rise to huge **magnetic forces**.
- Most of the large heat loads are **heat shocks** caused by the plasma suddenly **hitting** the plasma facing components. Depending on the conditions, the material of the PFC can melt, in case of metals, and few layers can be vaporized.

Plasma disruptions

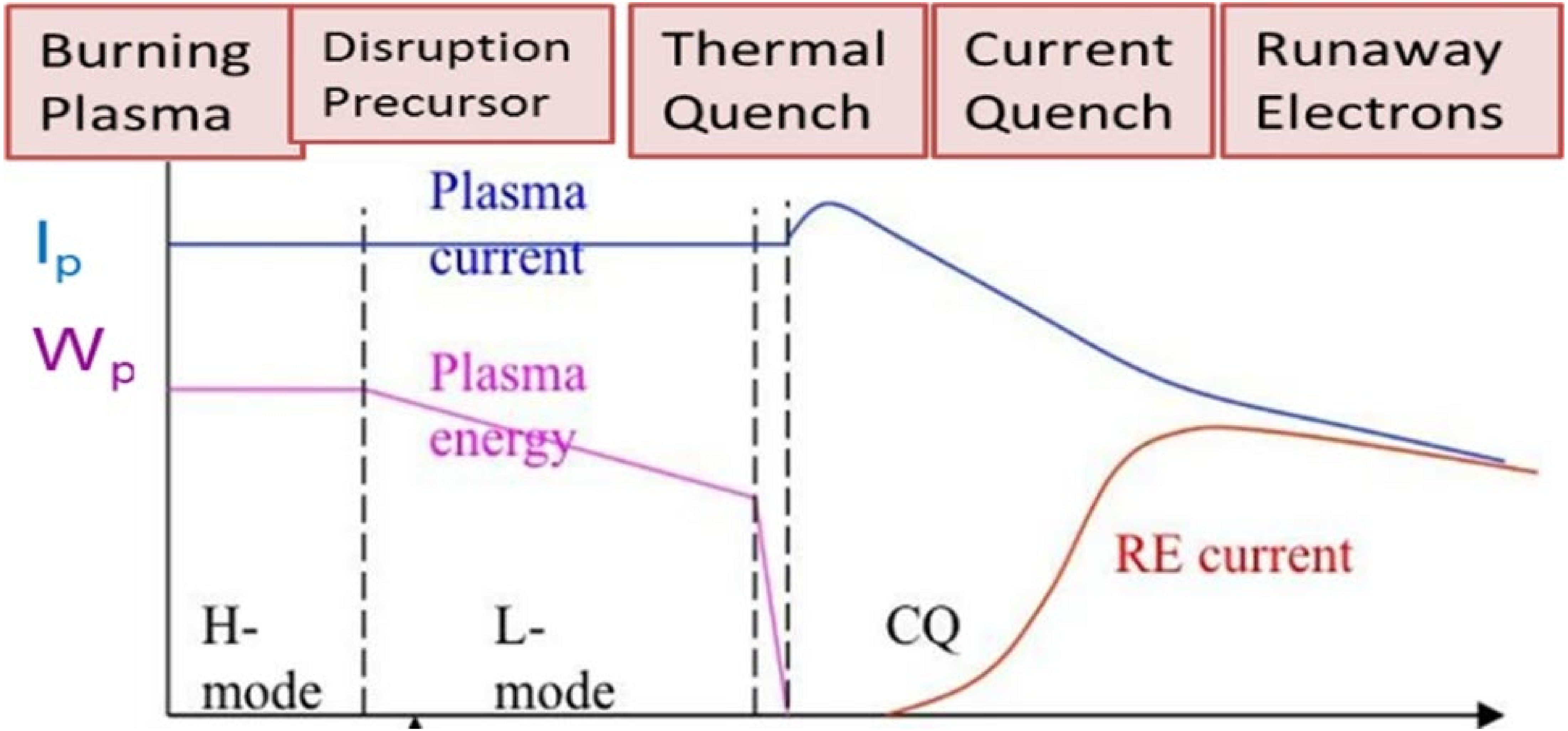


A typical disruption evolution

Plasma disruptions

- There are normally 4 phases in a disruption event:
  - **Pre-precursor phase** in which there is a change in conditions towards a more unstable situation (e.g. an increase in the current or density).
  - **Precursor phase** in which the condition change reaches a critical point where there is an on set of MHD instability (time range e.g. 10 ms).
  - **Thermal quench phase** in which the plasma central temperature collapses (~1 ms).
  - **Current quench phase** in which the plasma current decays to zero. The decay can have different time ranges (e.g. 100 MA/s).

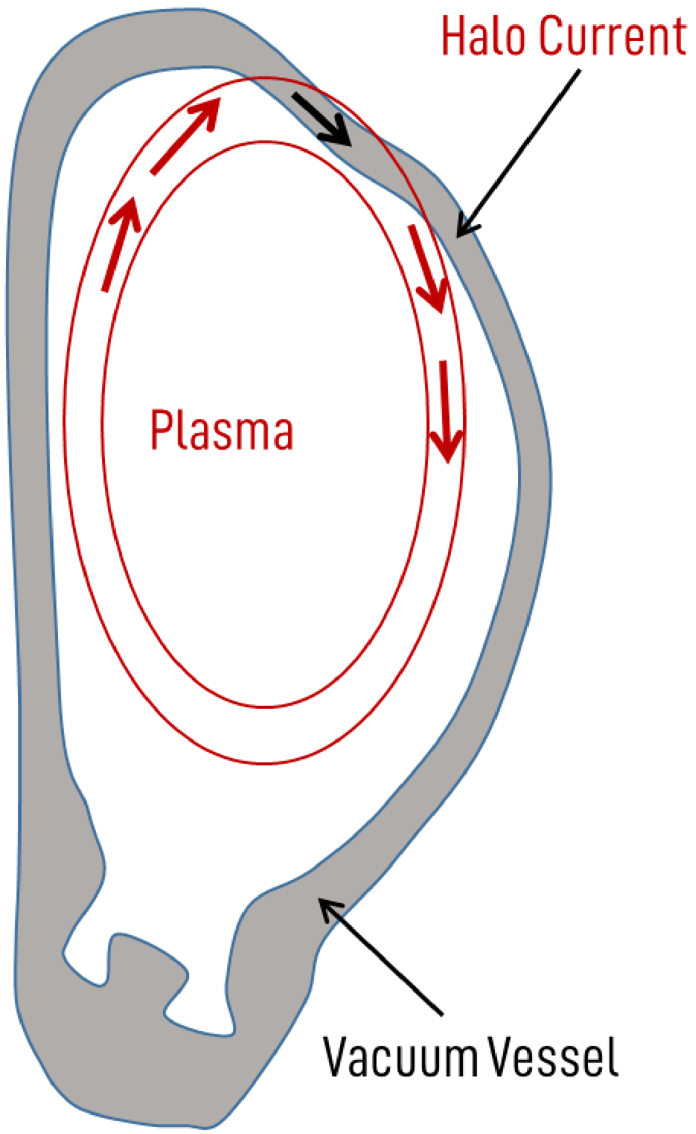
Plasma disruptions



A typical sequence of disruption phases

Plasma disruptions

- A particularly severe event is the large **Vertical Displacement Event (VDE)**. The large VDEs are considered as rare accidental events (to be avoided).
- The VDE is due to the **instability** of **elongated** plasmas to **gross vertical displacements**. A VDE can occur due to a **failure** of the **control system** or due to a **gross perturbation** resulting from a disruption.
- For large vertical displacements, the plasma may have a relatively **long** and **substantial contact** with the plasma facing components.
- The outer part of the flux surfaces will intersect the surfaces over a **halo region**.
- The **halo current** of the plasma flows parallel to the field lines. On entering the plasma facing components and the vacuum vessel the current circuit is closed on the conductive components.



FUSION FOR ENERGY

Stellarator (no central solenoid, complex 3D coils)

Fusion Devices: stellarator