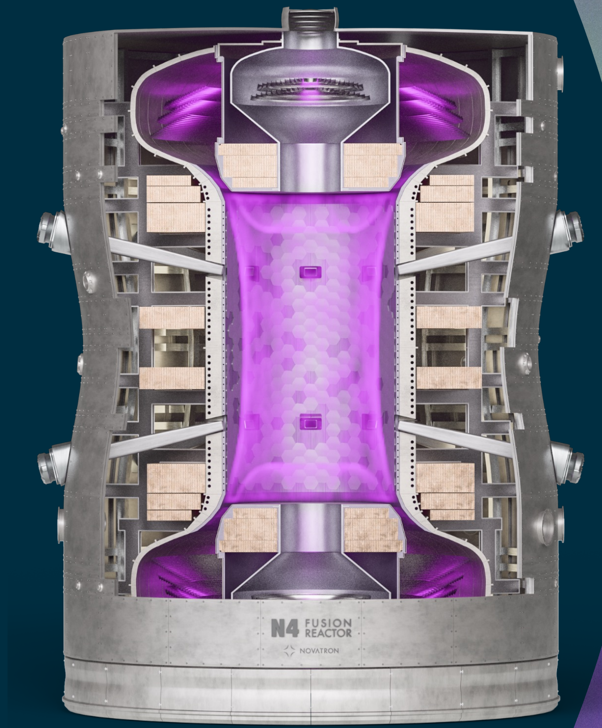
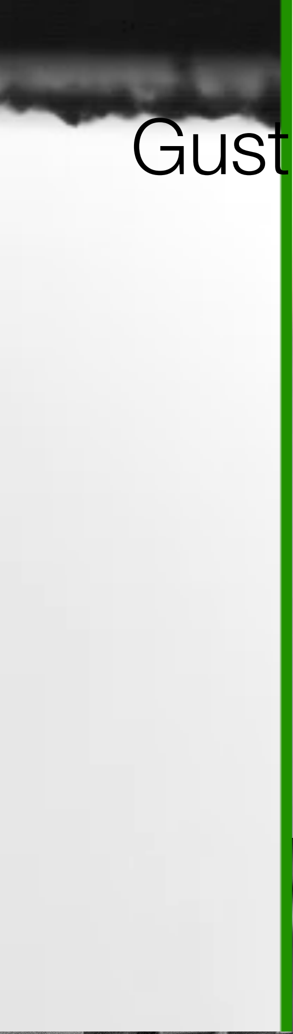
NOVATRON

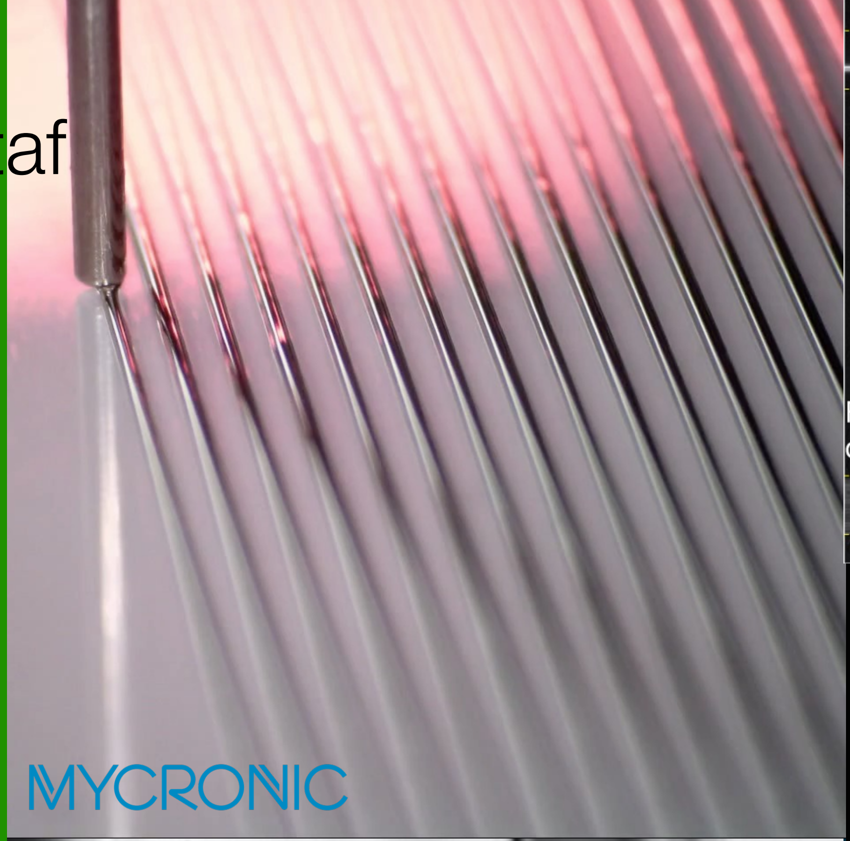
Continuous clean energy through fusion power



Gustaf Mårtensson
March 6, 2024

Gustaf

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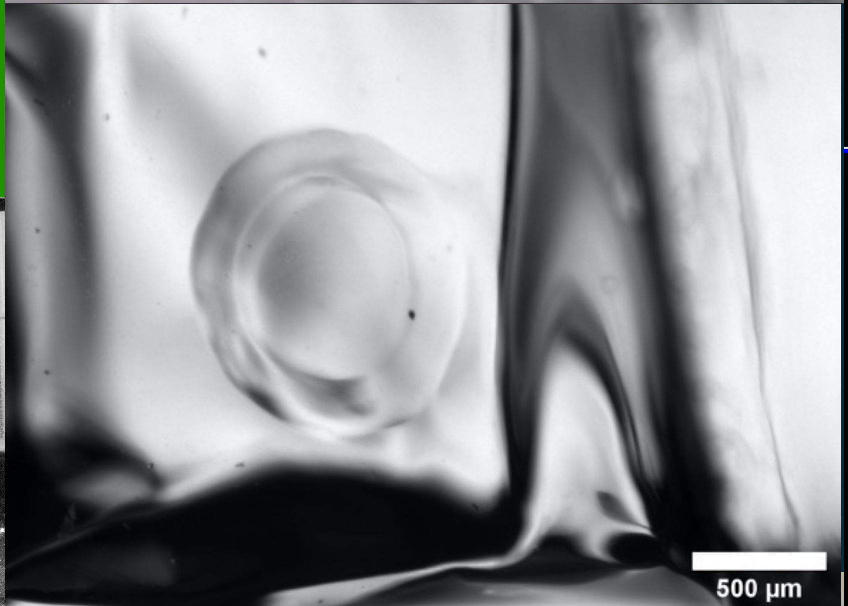
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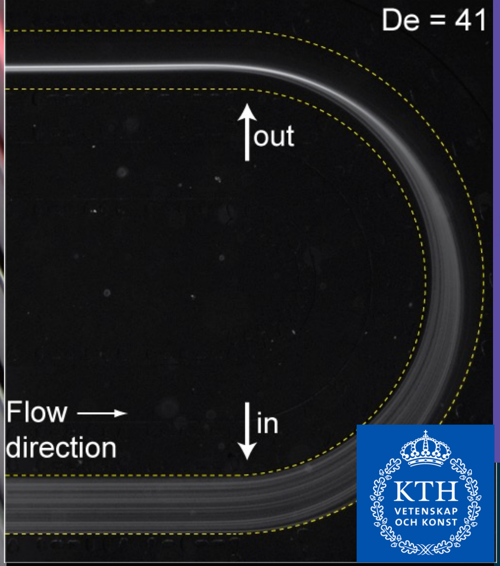
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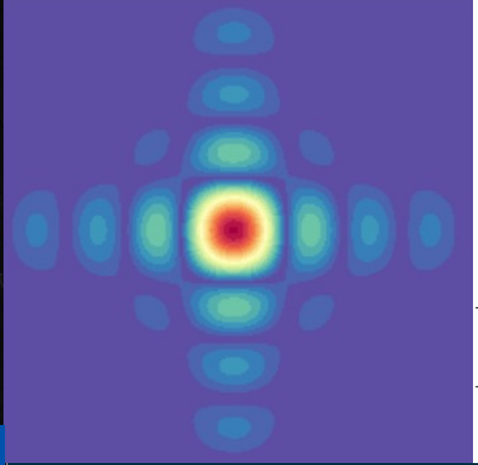

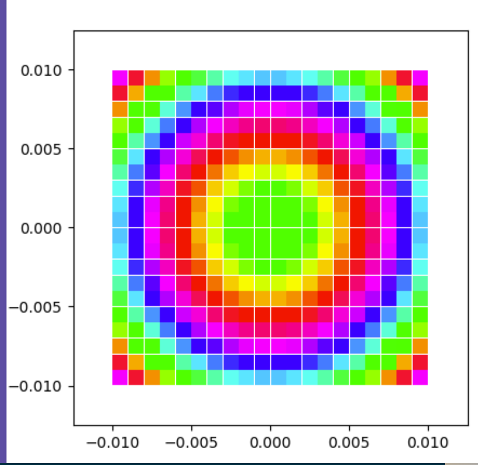
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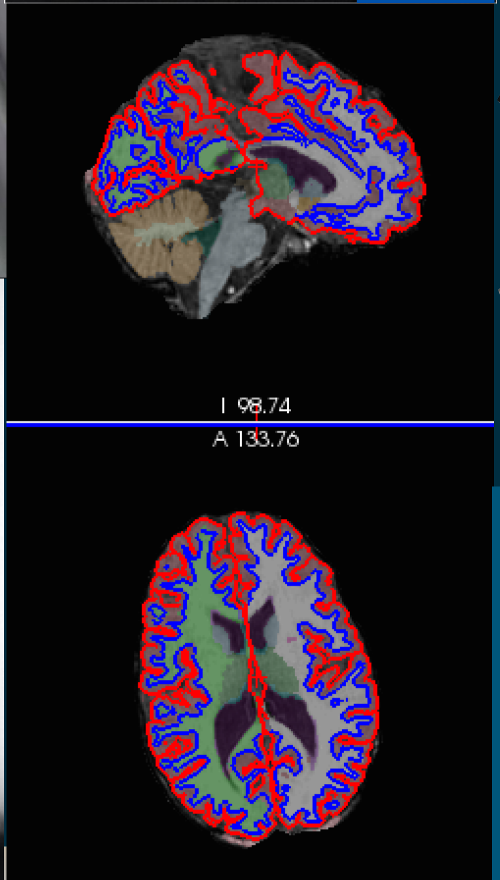
I 98.74
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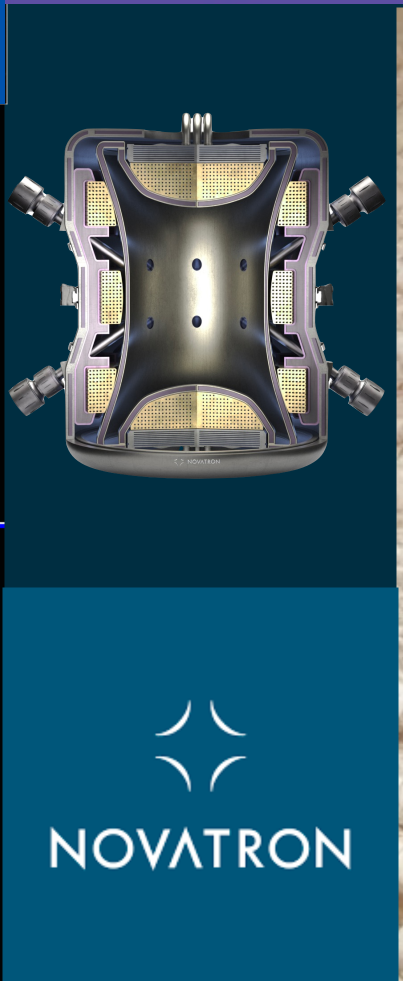
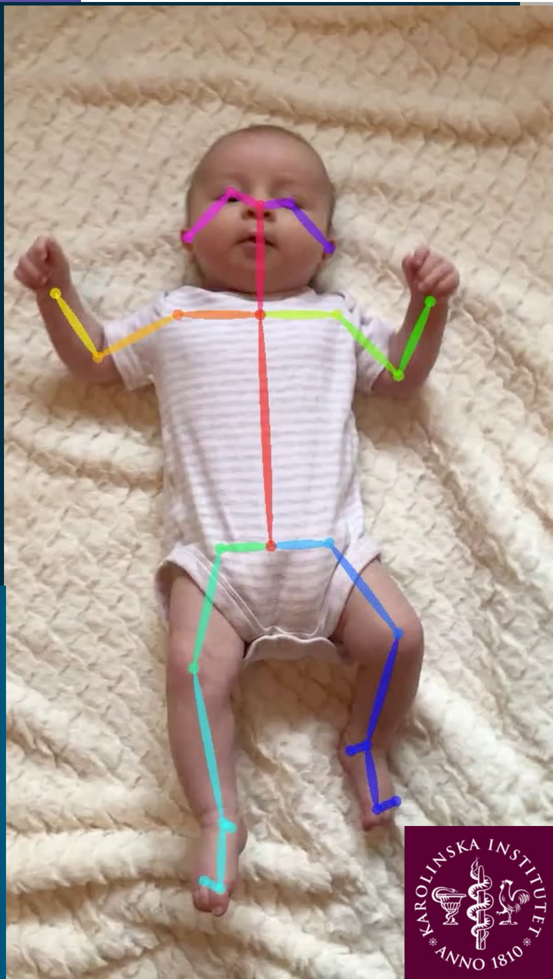

NOVATRON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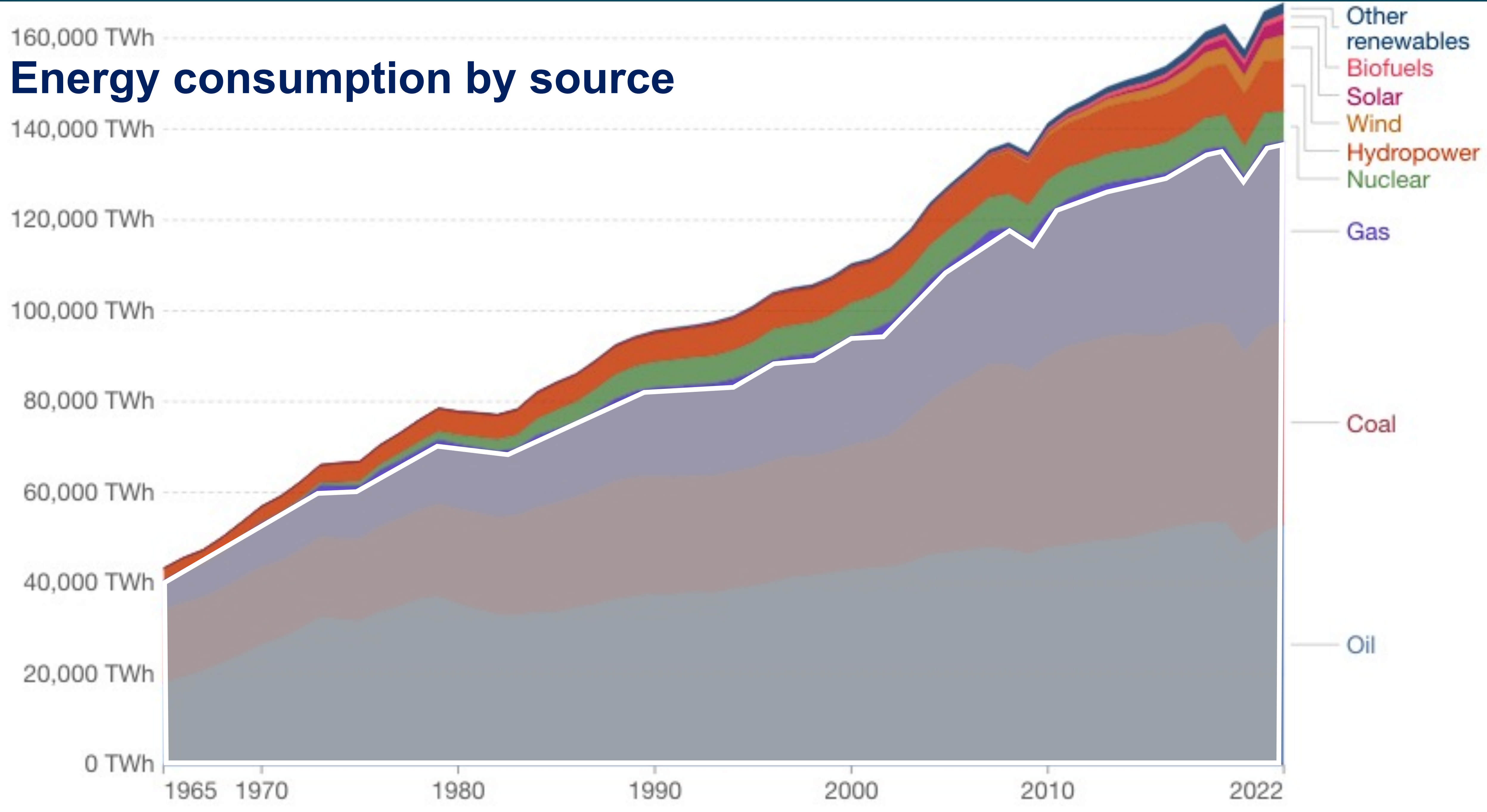
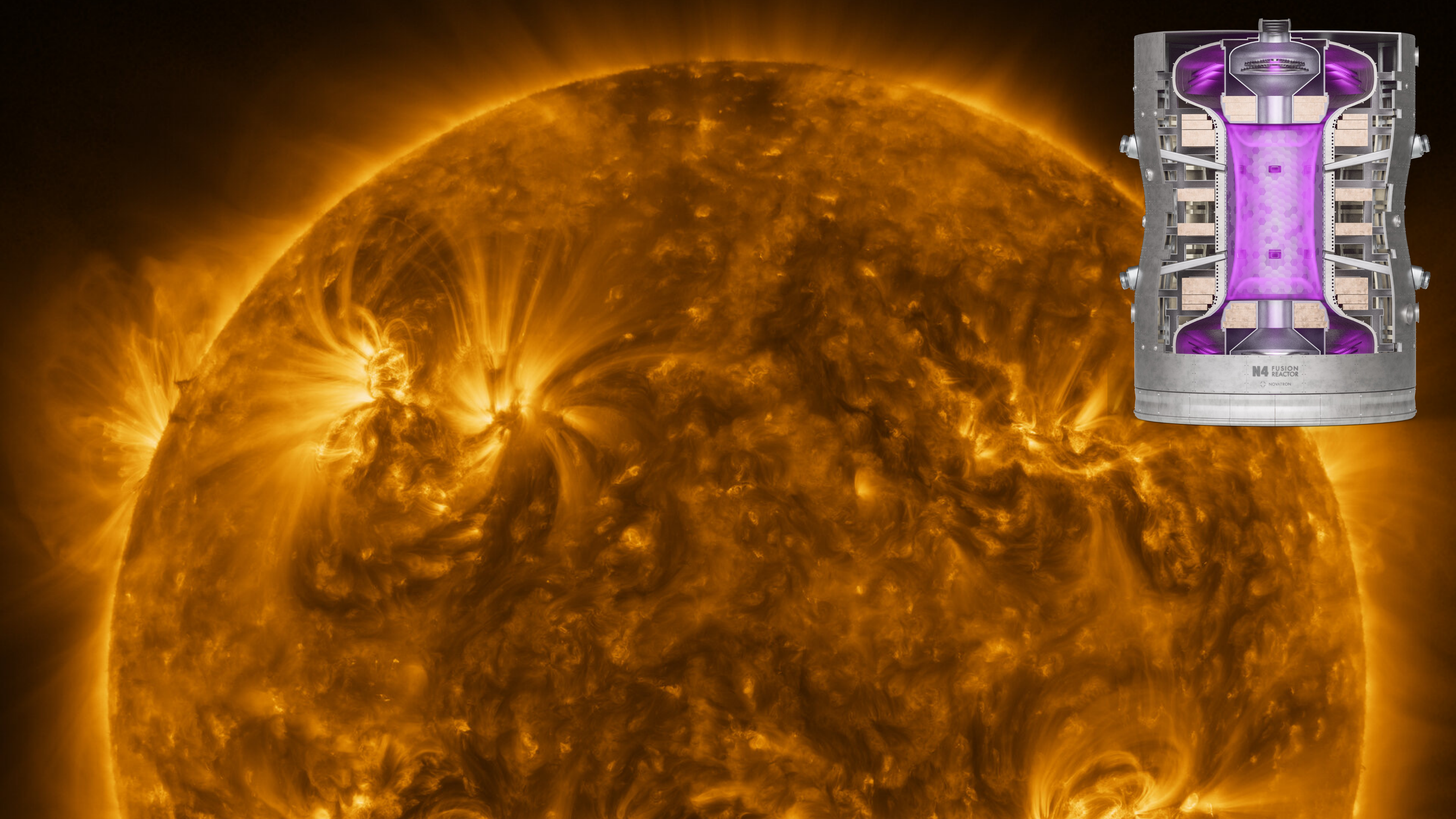
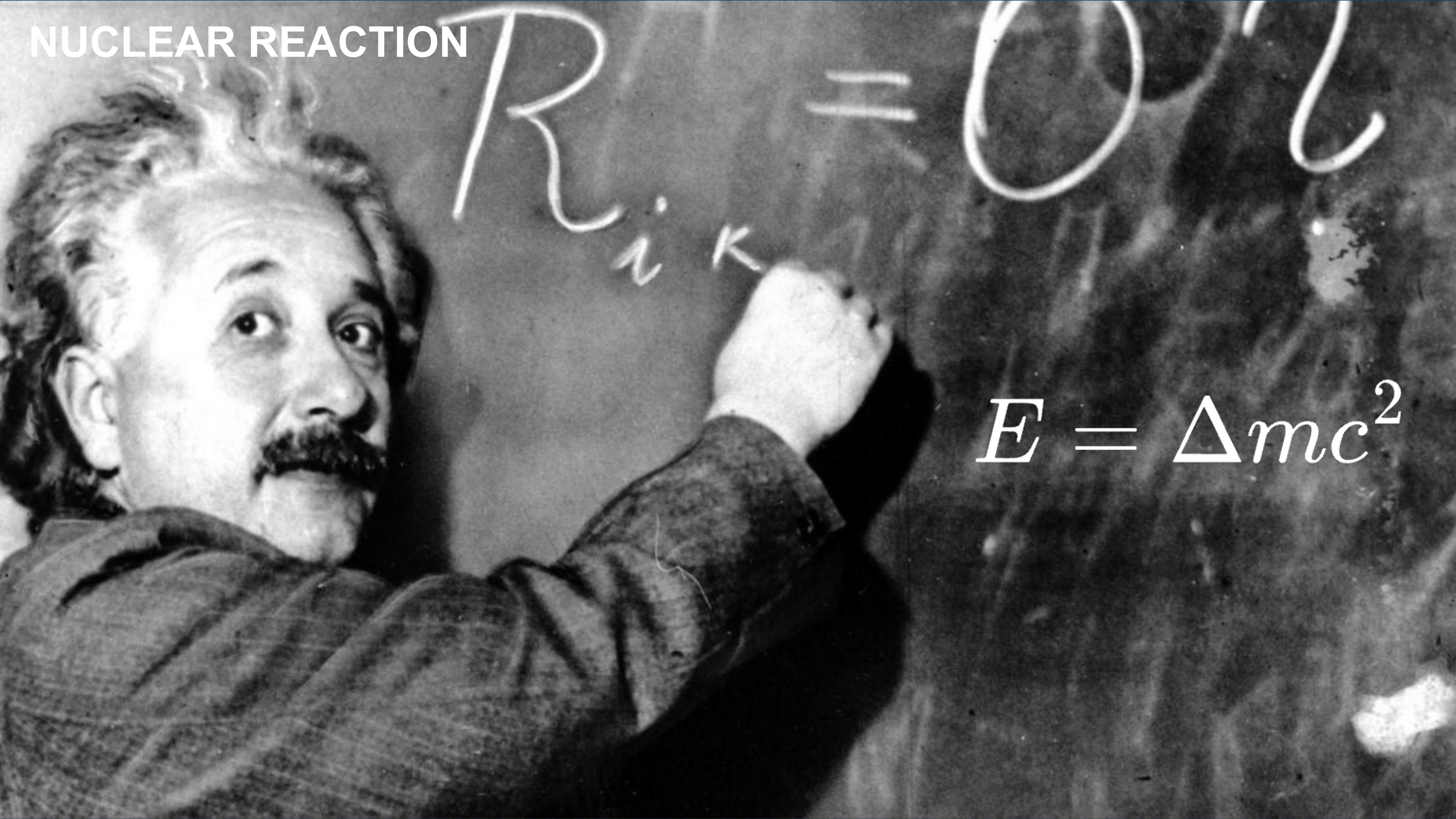
Energy consumption by source



Data source: Energy Institute - Statistical Review of World Energy (2023)

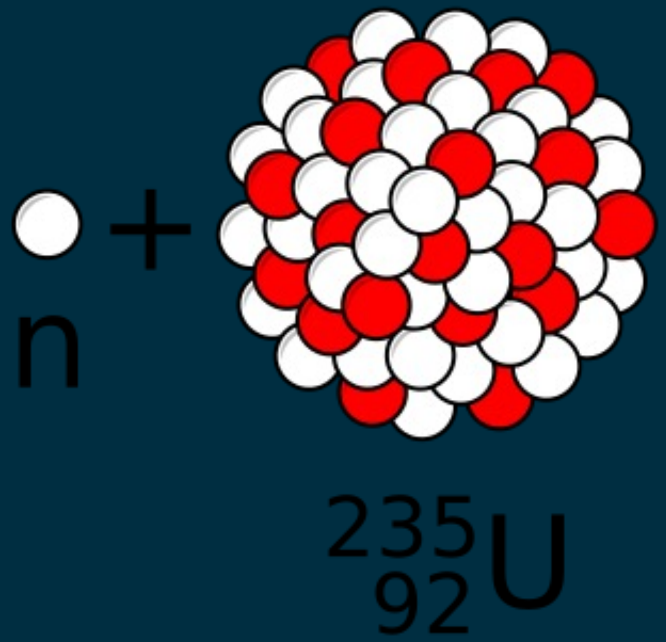

N4 FUSION REACTOR
NOVATRON

NUCLEAR REACTION



$$E = \Delta mc^2$$

Fission



Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

ON bombarding uranium with neutrons, Fermi and collaborators[1] found that at least four radioactive substances were produced, to two of which atomic numbers larger than 92 were ascribed. Further investigations[2] demonstrated the existence of at least nine radioactive periods, six of which were assigned to elements beyond uranium, and nuclear isomerism had to be assumed in order to account for their chemical behaviour together with their genetic relations.

It might be mentioned that the body with half-life 24 min.[2] which was chemically identified with uranium is probably really ^{239}U, and goes over into an eka-rhenium which appears inactive but may decay slowly, probably with emission of alpha particles. (From inspection of the natural radioactive elements, ^{239}U cannot be expected to give more than one or two beta decays; the long chain of observed decays has always puzzled us.) The formation of this body is a typical resonance process[9]; the compound state must have a life-time a million times longer than the time it would take the nucleus to divide itself. Perhaps this state corresponds to some highly symmetrical type of motion of nuclear matter which does not favour 'fission' of the nucleus.

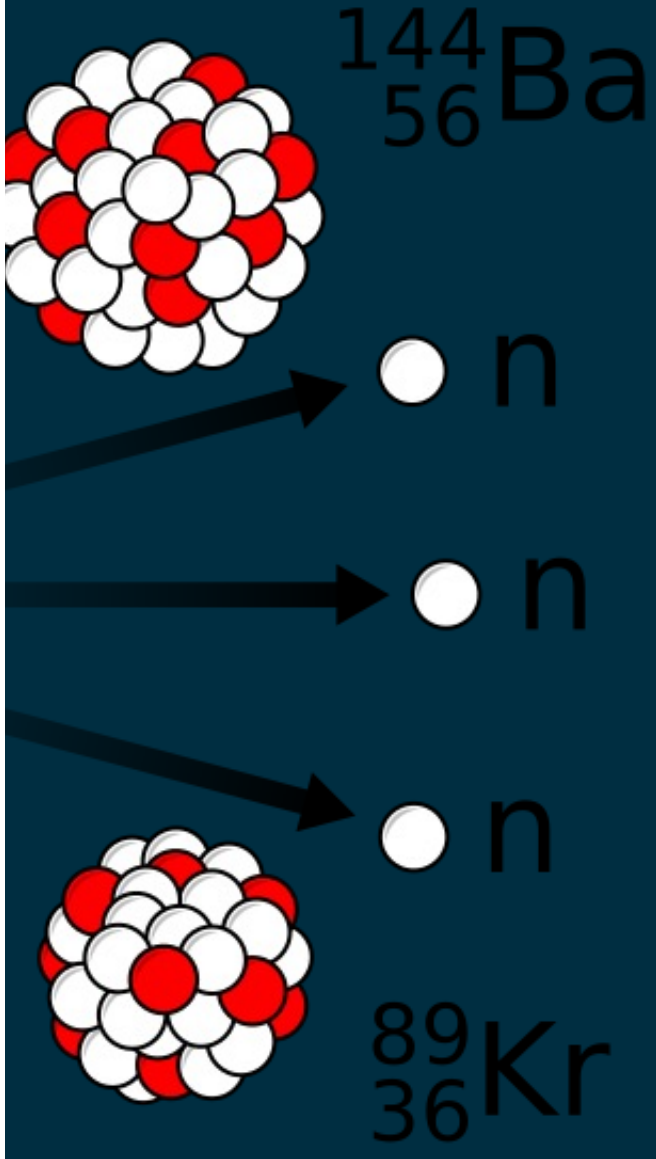
LISE MEITNER.

Physical Institute,
Academy of Sciences,
Stockholm.

O. R. FRISCH.

Institute of Theoretical Physics,
University,
Copenhagen.

Jan. 16.

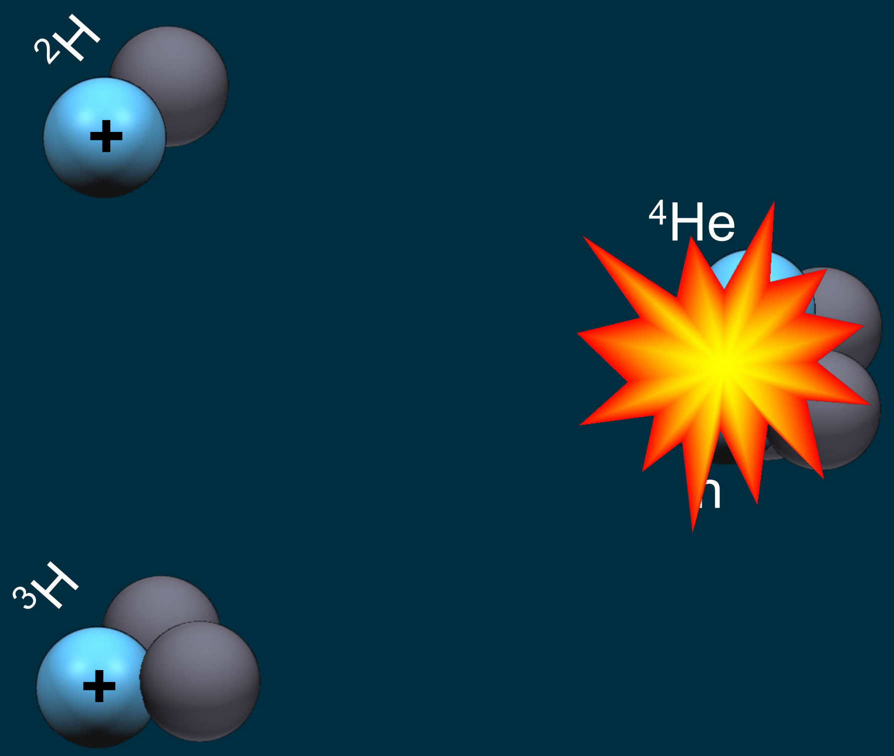


Fusion : Deuterium-Tritium Reaction

To overcome the electrostatic repulsion force the particles require high kinetic energies– which is possible in a high temperature plasma!

$$\underset{\text{(deuterium)}}{{}^{2}H} + \underset{\text{(tritium)}}{{}^{3}H} \rightarrow \underset{\text{(helium)}}{{}^{4}He} + n + \text{Energy}$$

$$E = \Delta mc^2 \approx 2 \cdot 10^{-12} J$$



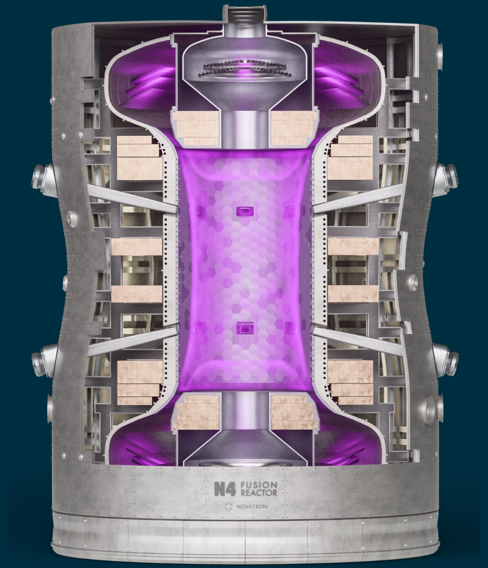
3.5 MeV

14.1 MeV

1MeV≈1.6 10^{-13}J

ADVANTAGES OF A NUCLEAR FUSION PLANTS

- No green-house gas emissions
- Virtually unlimited fuel
- Low risk for nuclear accidents - no chain reactions
- No long-lived radioactive waste is produced



DEUTERIUM AND TRITIUM FUEL

- **Deuterium** can be extracted from sea water.
  - each m^3 of water contains 35 g of deuterium
  - there is enough deuterium for millions of years

- **Tritium** has a 12 year decay time
  → no resources of tritium in nature

- Tritium can be produced from lithium using the neutrons from the fusion reaction

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

- There is enough lithium for millions of years if used as fusion fuel
- A 1 GW fusion reactor requires for one year of operation:
  - 100 kg of deuterium
  - 3 tons of lithium

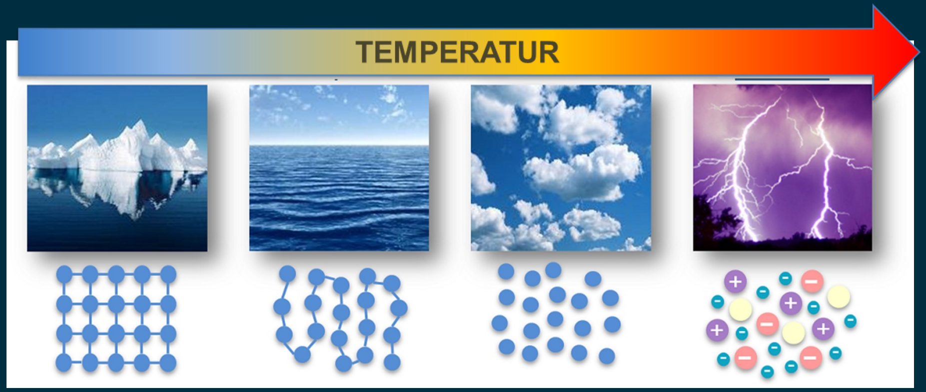
WHAT IS REQUIRED FOR A FUSION POWER PLANT?

- The fuel of the fusion plant is abundant on earth in form of water and lithium – used to produce hydrogen isotopes ^{2}H and ^{3}H

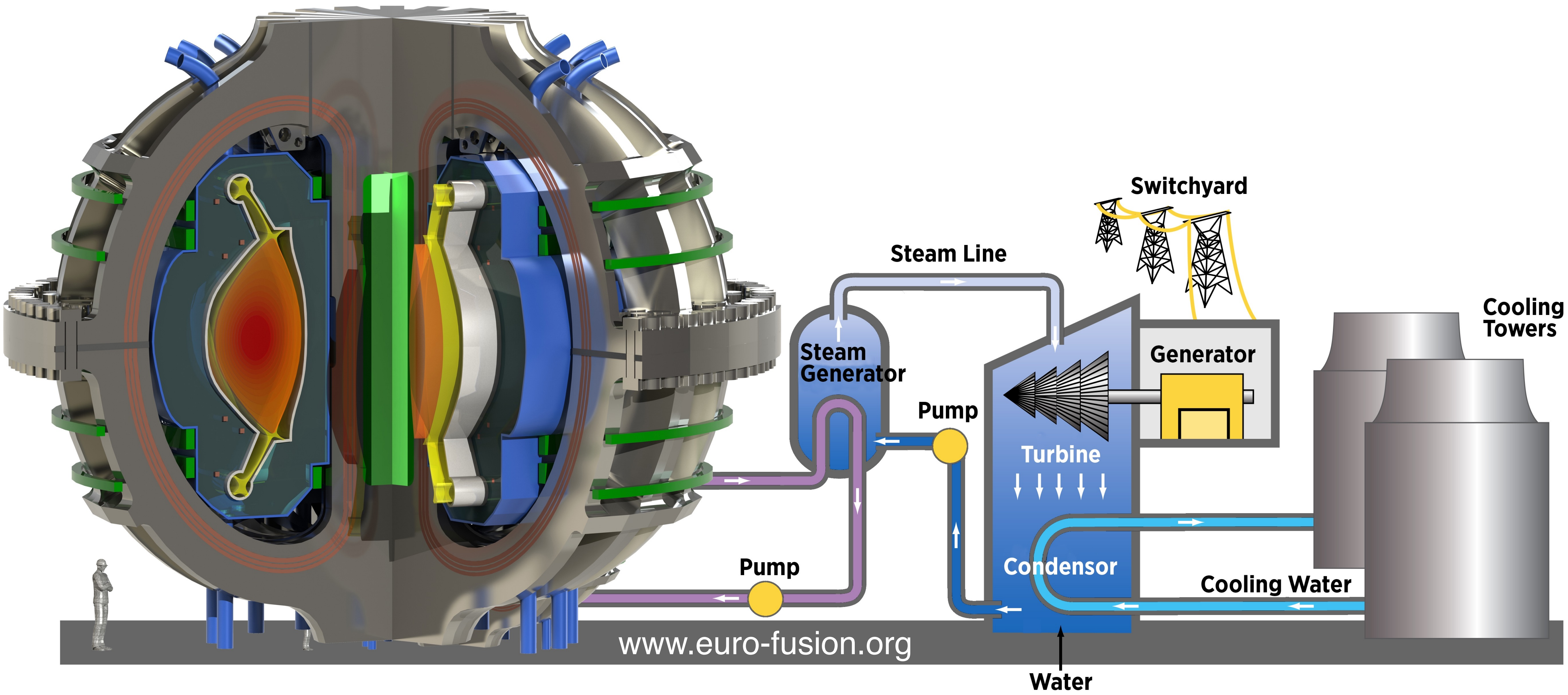
Water is required for extraction of ^{2}H (deuterium)

Lithium is required for production of ^{3}H (tritium) in the fusion plant

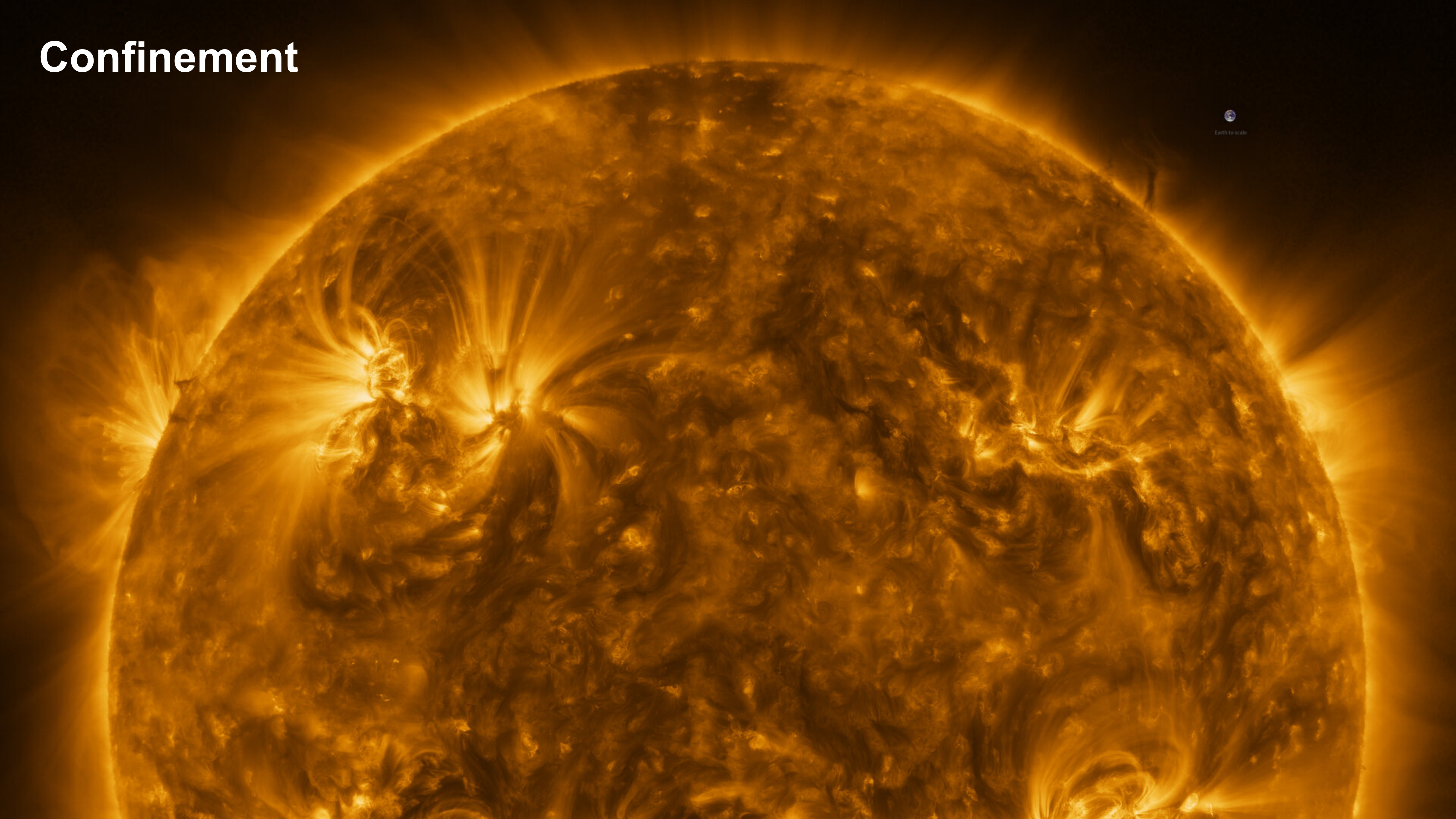
- The hydrogen has to be heated to a temperature of around 200 million degrees in the plant – the main approach is **magnetic confinement fusion**



EU FUSION POWER PLANT PROTOTYPE



Confinement

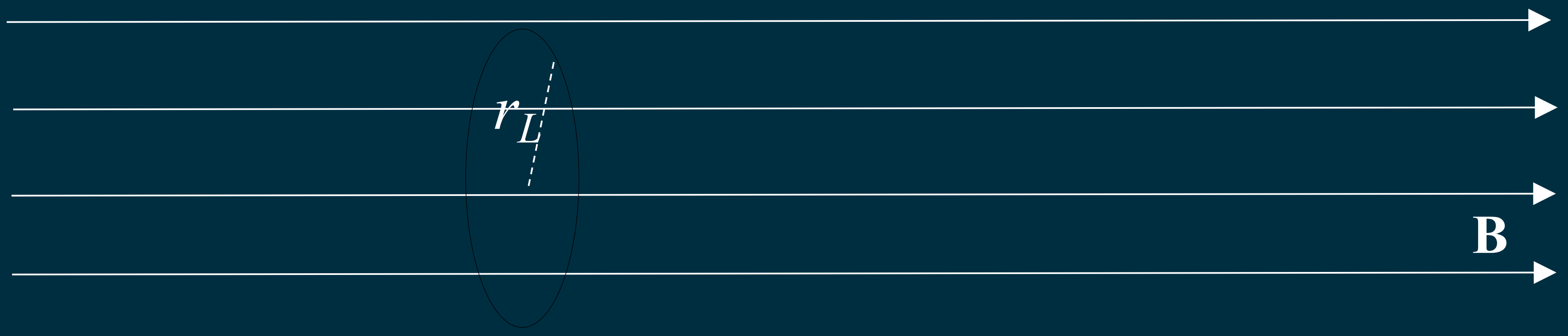


Confinement

$$F = q\vec{v} \times \vec{B}$$ (Lorentz force)

$$qv_{\perp}B = m\frac{v_{\perp}^2}{r} \quad \Rightarrow \quad r_L = \frac{mv_{\perp}}{qB}$$

(Larmor radius)



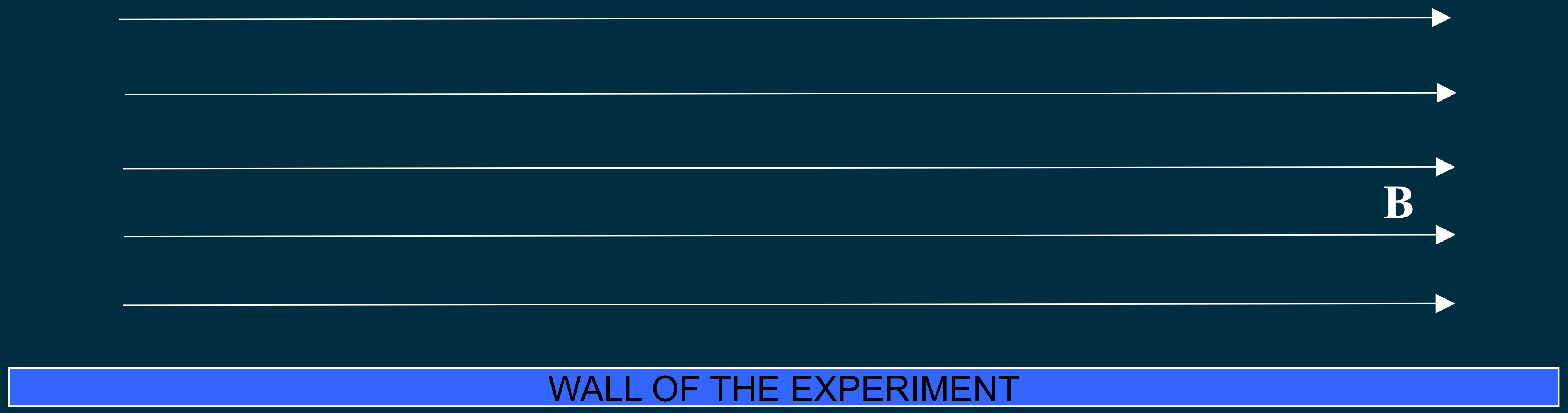
WALL OF THE EXPERIMENT

Plasma Confinement

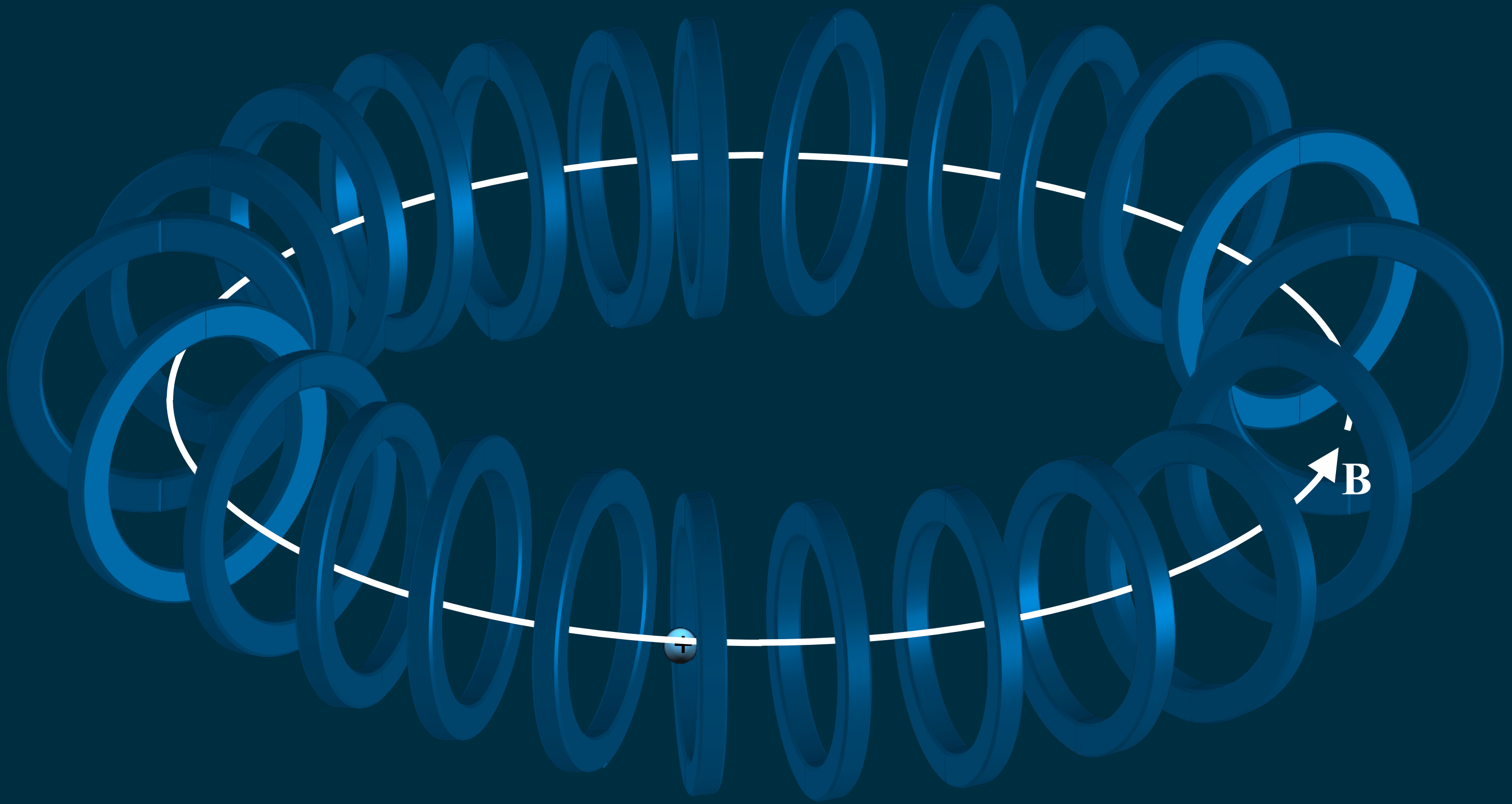
$$F = q\vec{v} \times \vec{B}$$ (Lorentz force)

$$r_L = \frac{mv_\perp}{qB}$$

(Larmor radius)

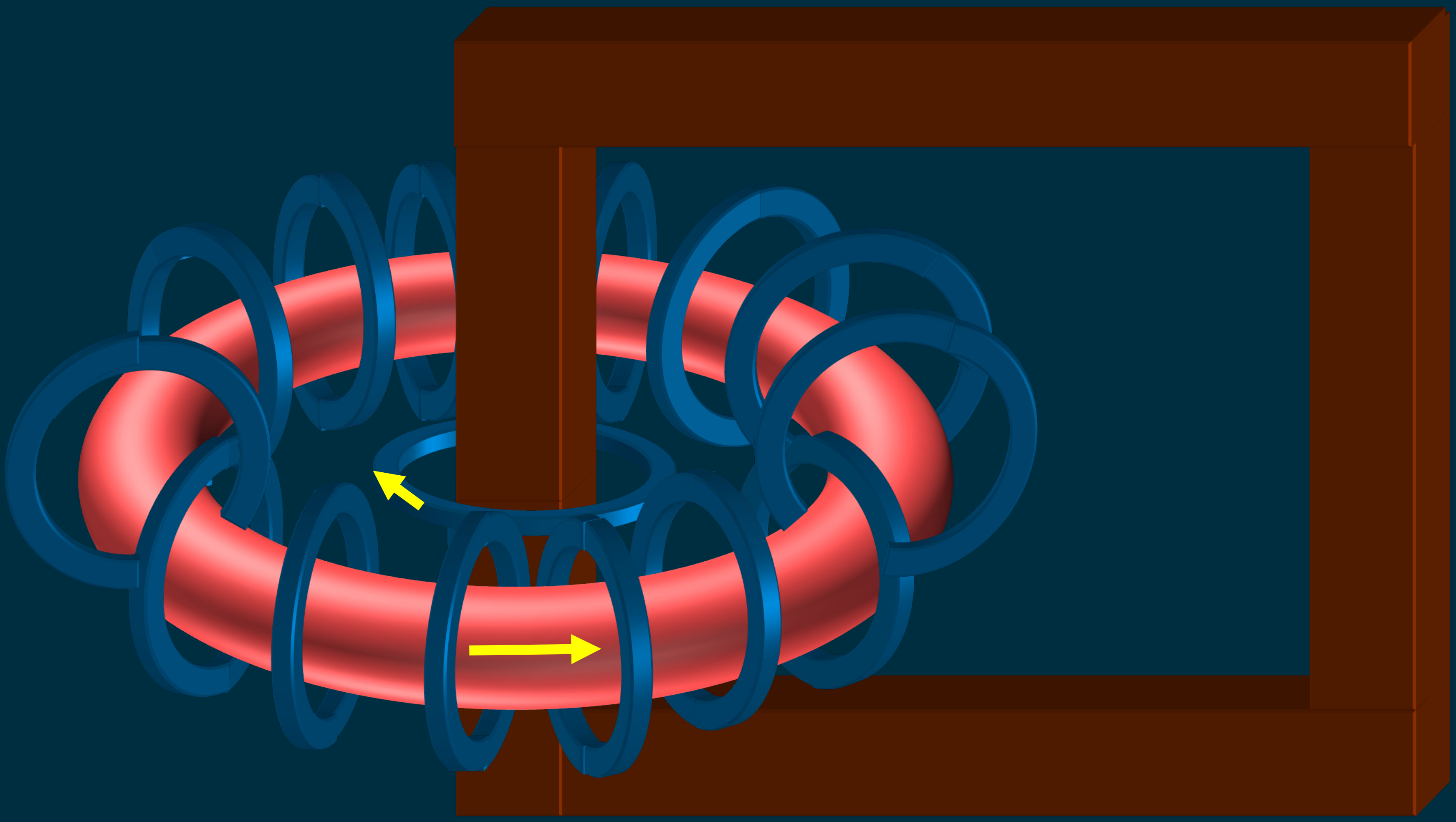


Plasma Confinement



Heat

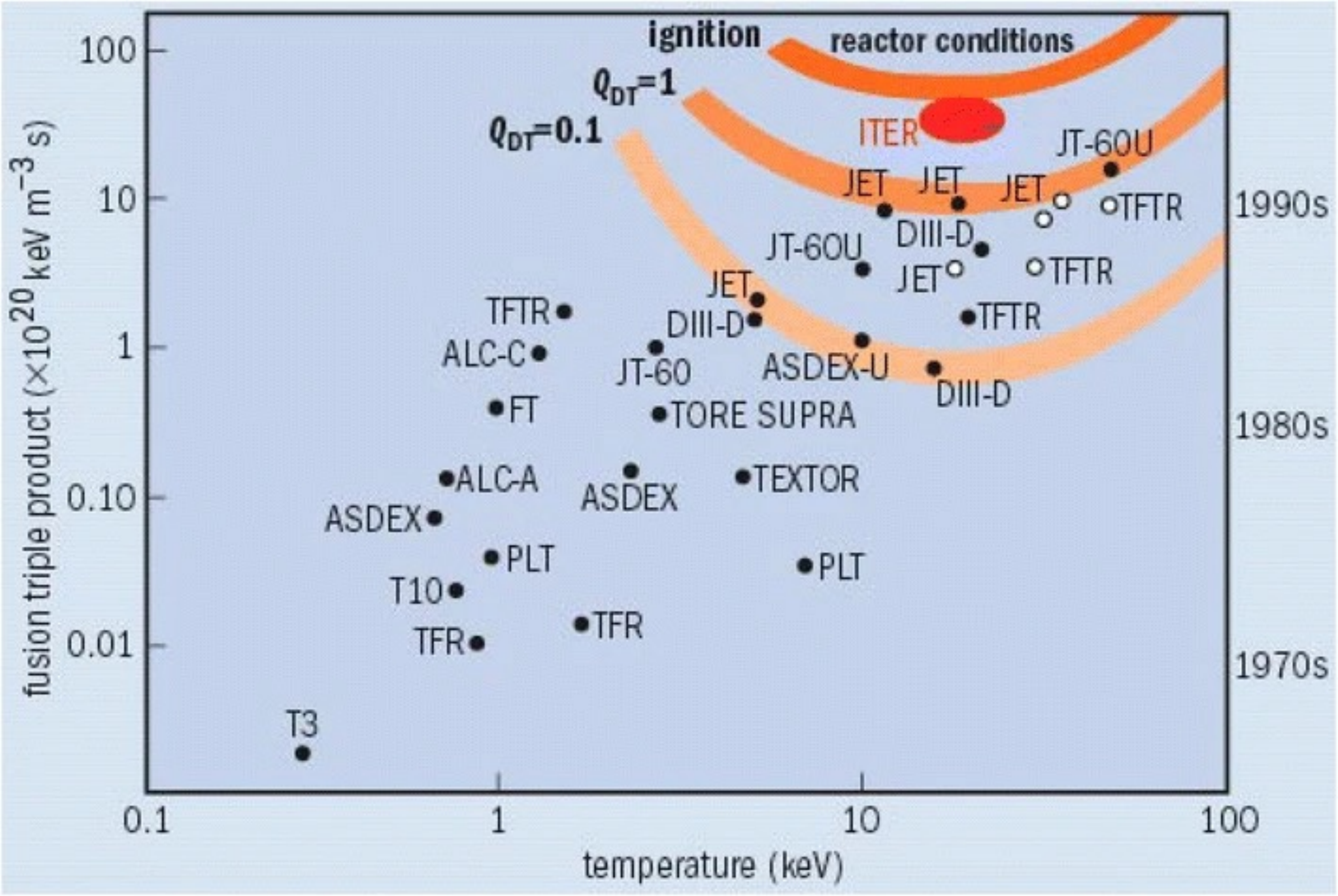
- An electric current is created in the plasma by induction in a transformer
- A helical magnetic field results which is better for confinement
- Since the plasma has resistivity, the current provide ohmic heating of the plasma



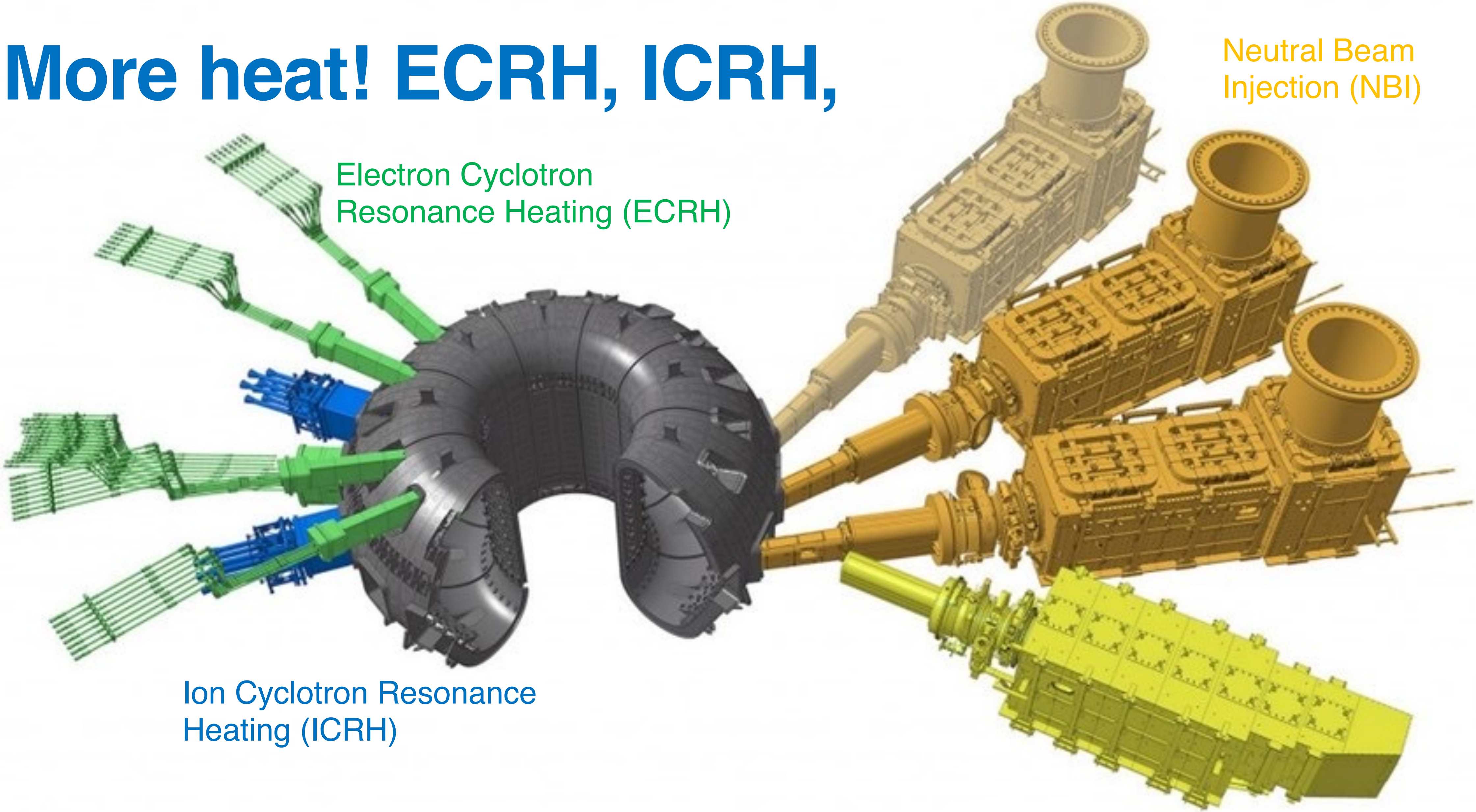
Lawson

$$n\tau_E T \geq 5 \times 10^{21} \mathrm{keVs/m^3}.$$

- n – density
- τ_E - confinement time
- T - temperature



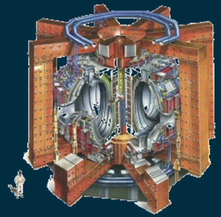
More heat! ECRH, ICRH,



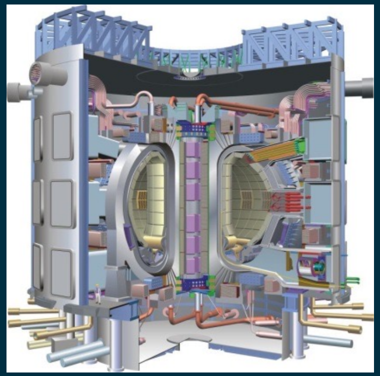
Fusion Experiments in Europe

- Europe has several working fusion experiments
- JET is the largest
- ITER is the next step (one of its goal is to achieve Q>10)
- The Swedish experiment is EXTRAP T2R in K

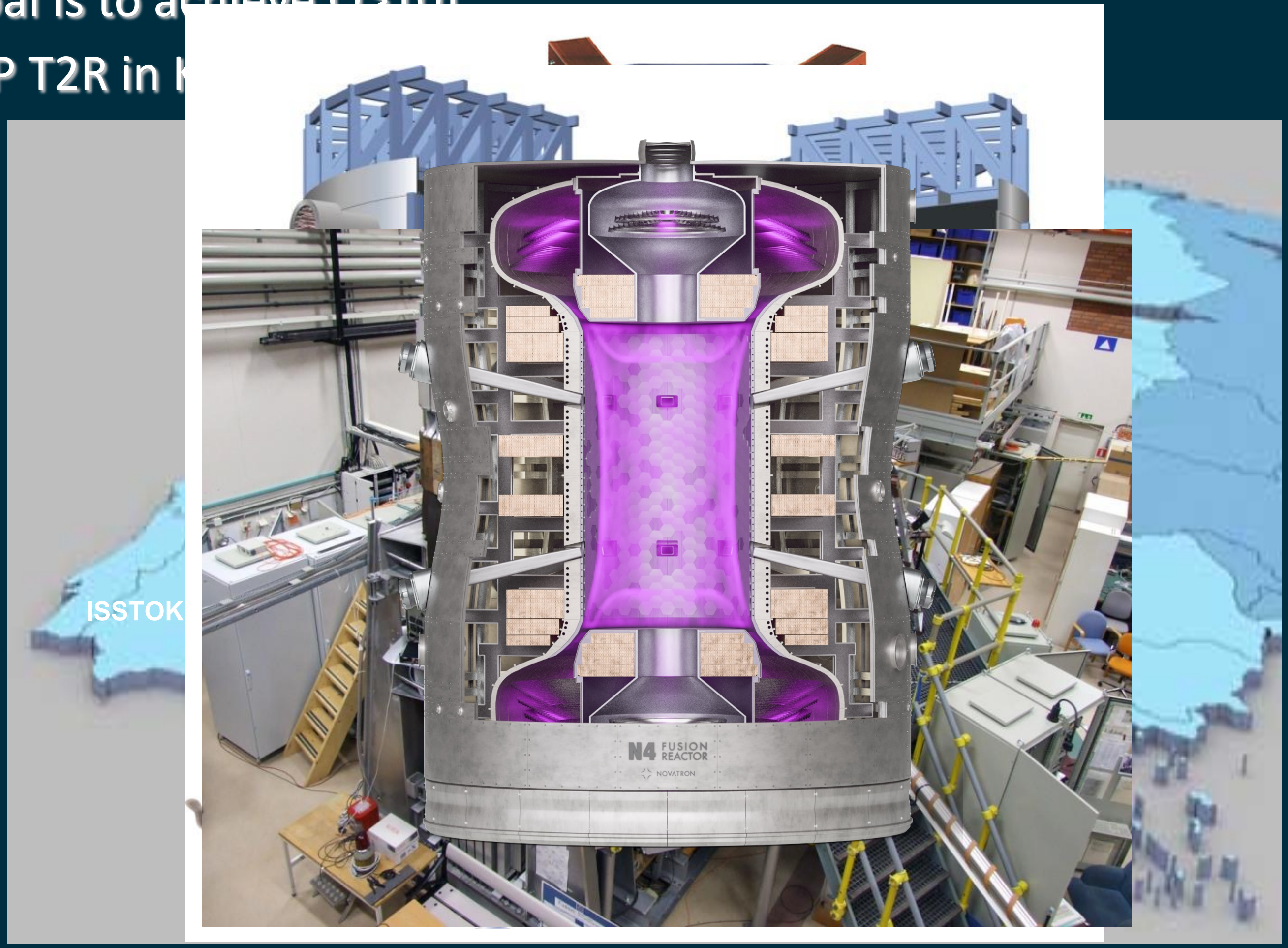
JET
$B_{\phi} \approx 3T$
$T \approx 5keV$



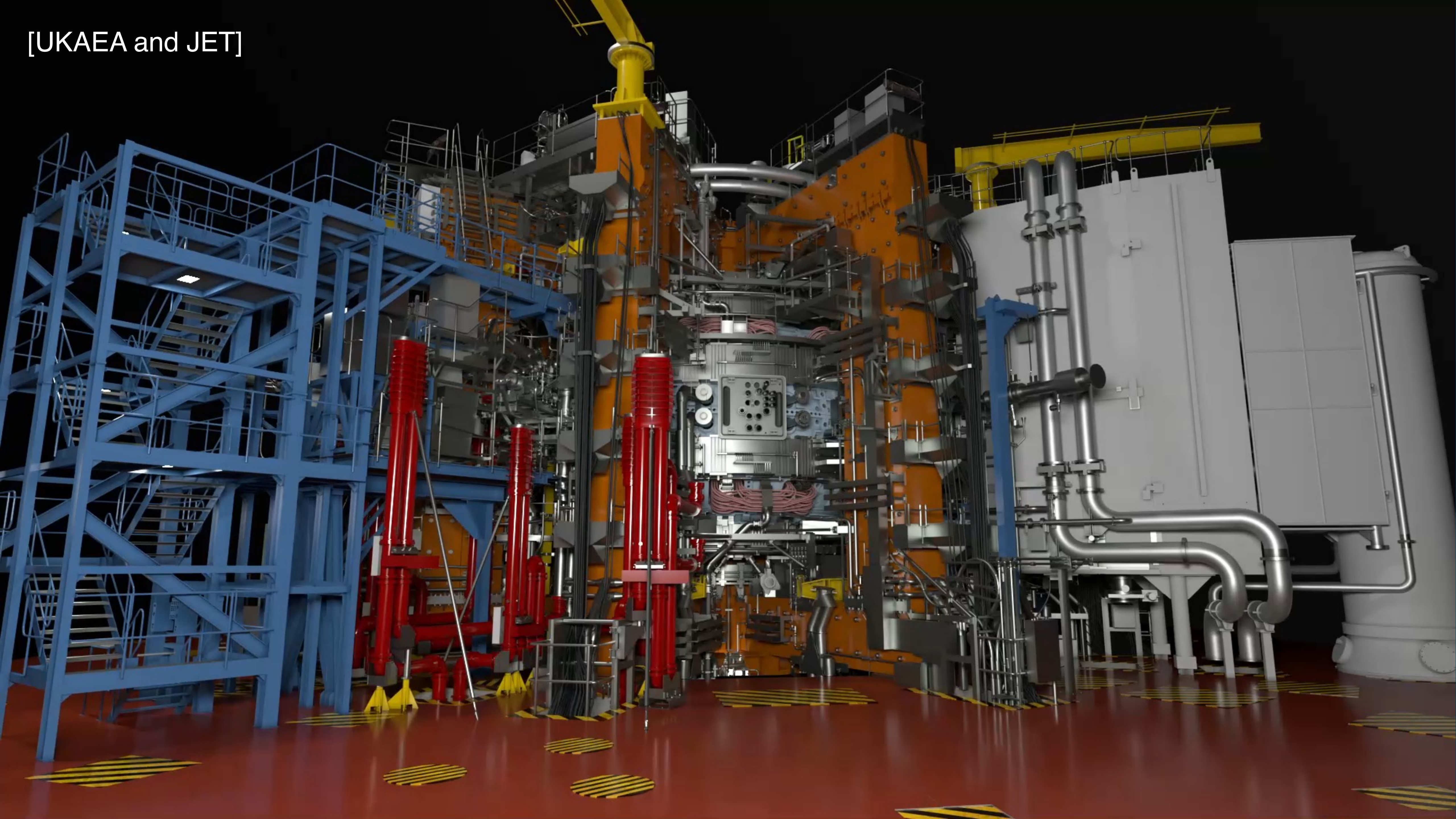
ITER
$B_{\phi} \approx 10T$
$T \approx 10\text{-}15keV$



EXTRAP T2R
$B_{\phi} \approx 0.1T$
$T \approx 0.5keV$



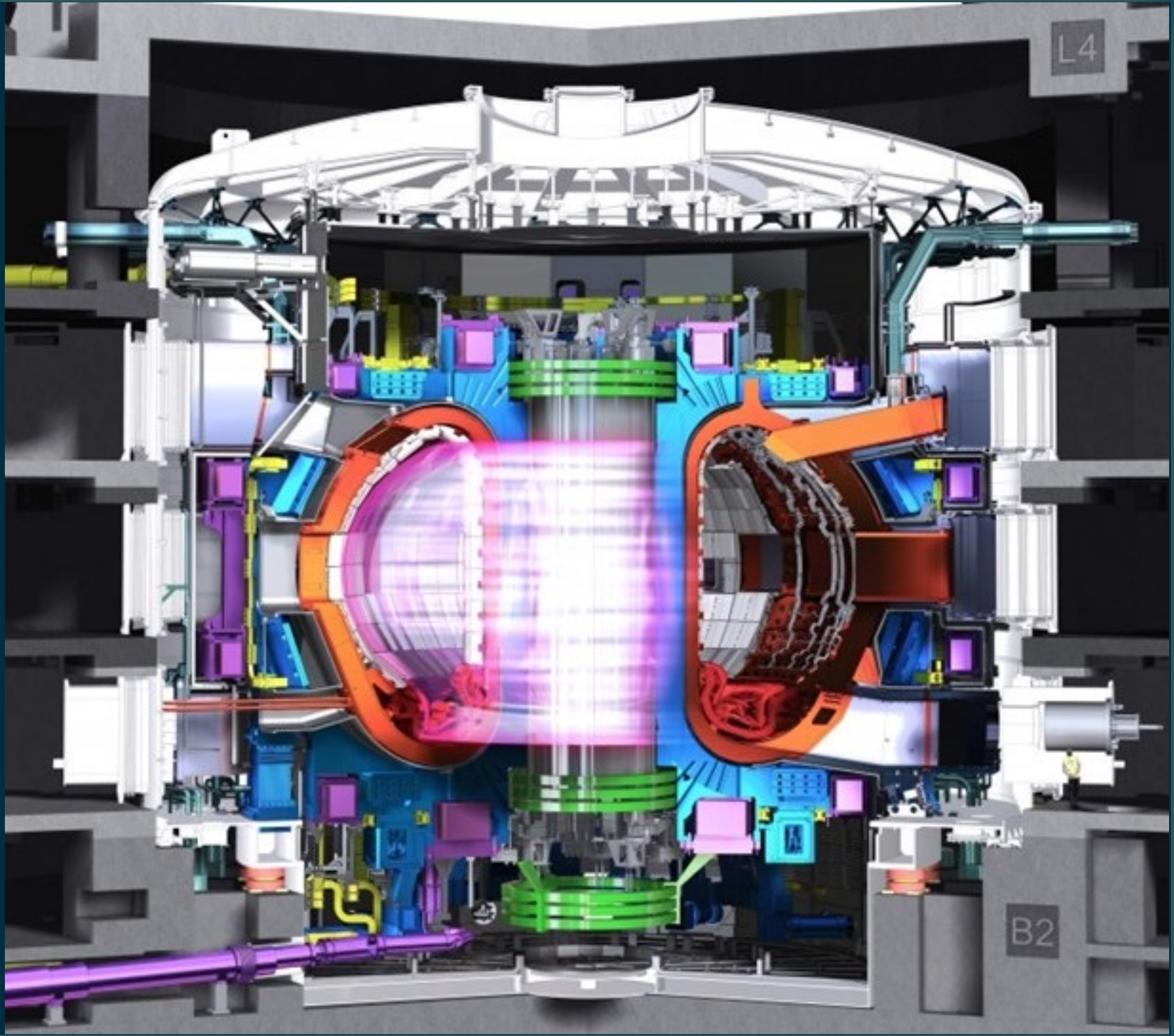
[UKAEA and JET]



ITER

Objectives

- Produce 500 MW fusion power for 400 s
- Plasma sustained mainly through internal heating by alpha (He) particles released in the fusion reaction
- Ratio of output fusion power to input heating power Q=10
- Test tritium breeding in Lithium blanket




ITER in 2015
www.iter.org

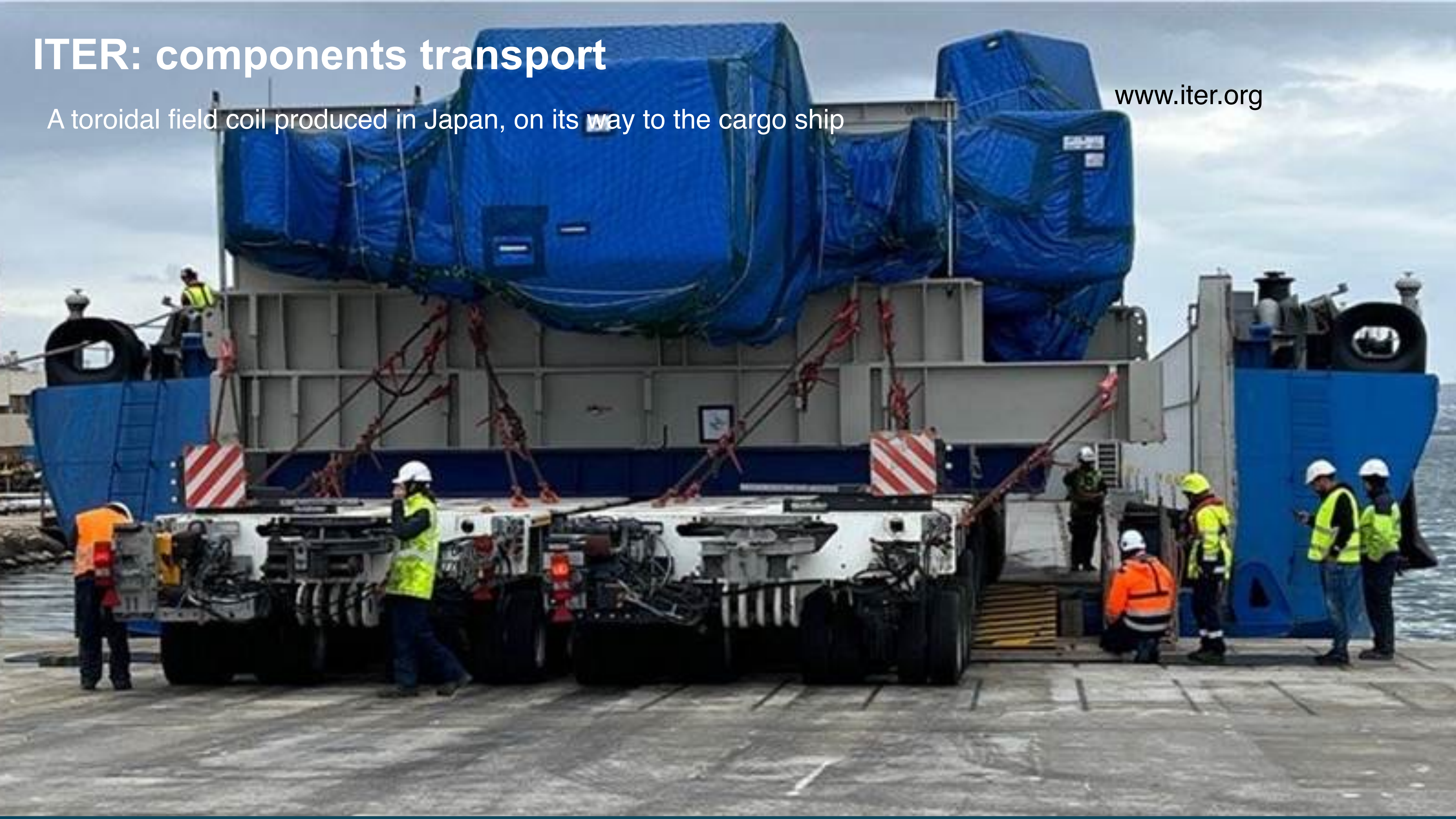

ITER in 2017
www.iter.org

ITER in 2020

ITER: components transport

A toroidal field coil produced in Japan, on its way to the cargo ship

www.iter.org



ITER: components transport

One of the Japanese toroidal field coils loaded on the cargo ship

www.iter.org

ITER: components transport

And on its way to ITER site on the road in France

www.iter.org


ITER in 2020
www.iter.org
We have delivered

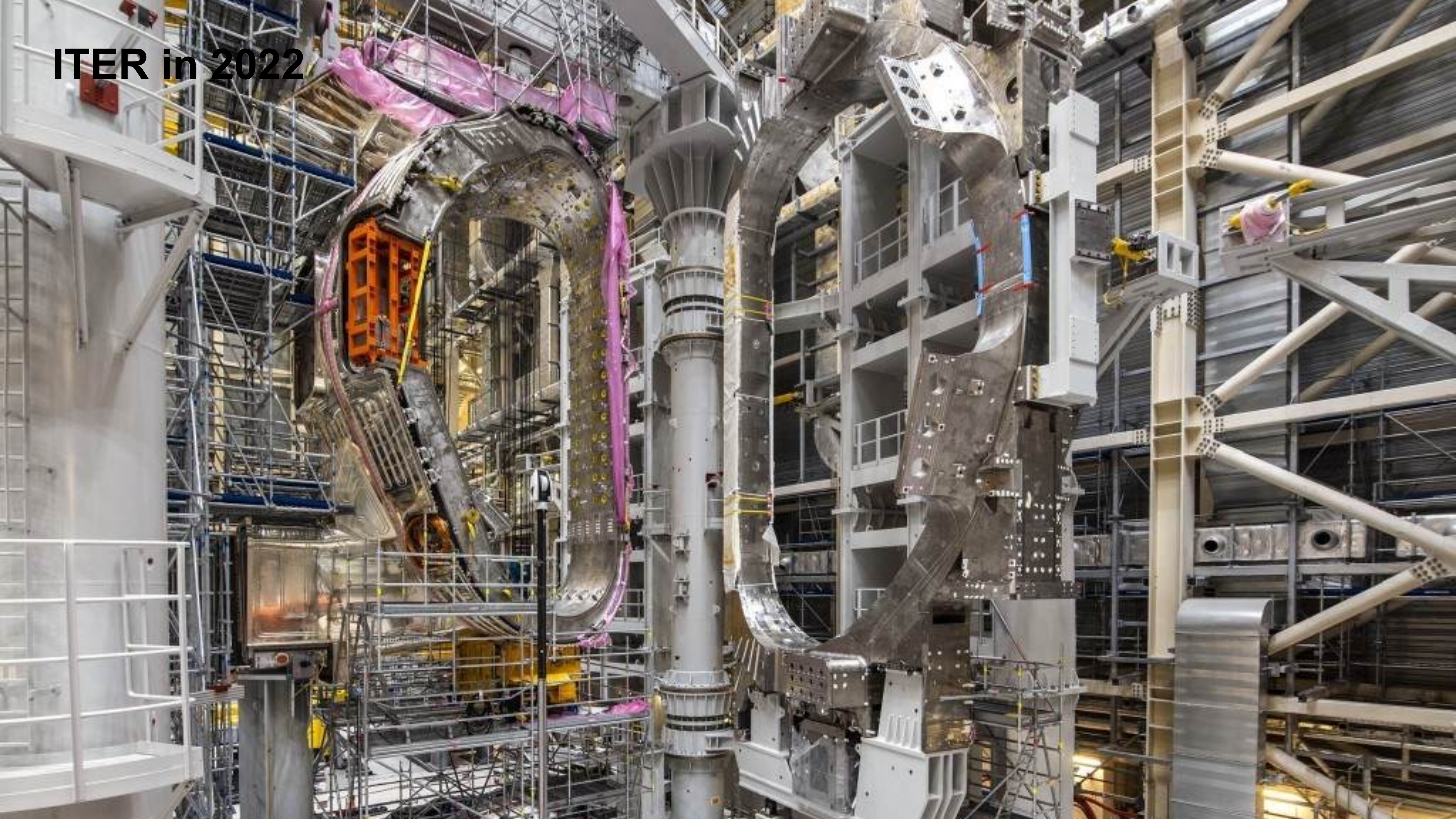
ITER in 2022

www.iter.org

ITER in 2022

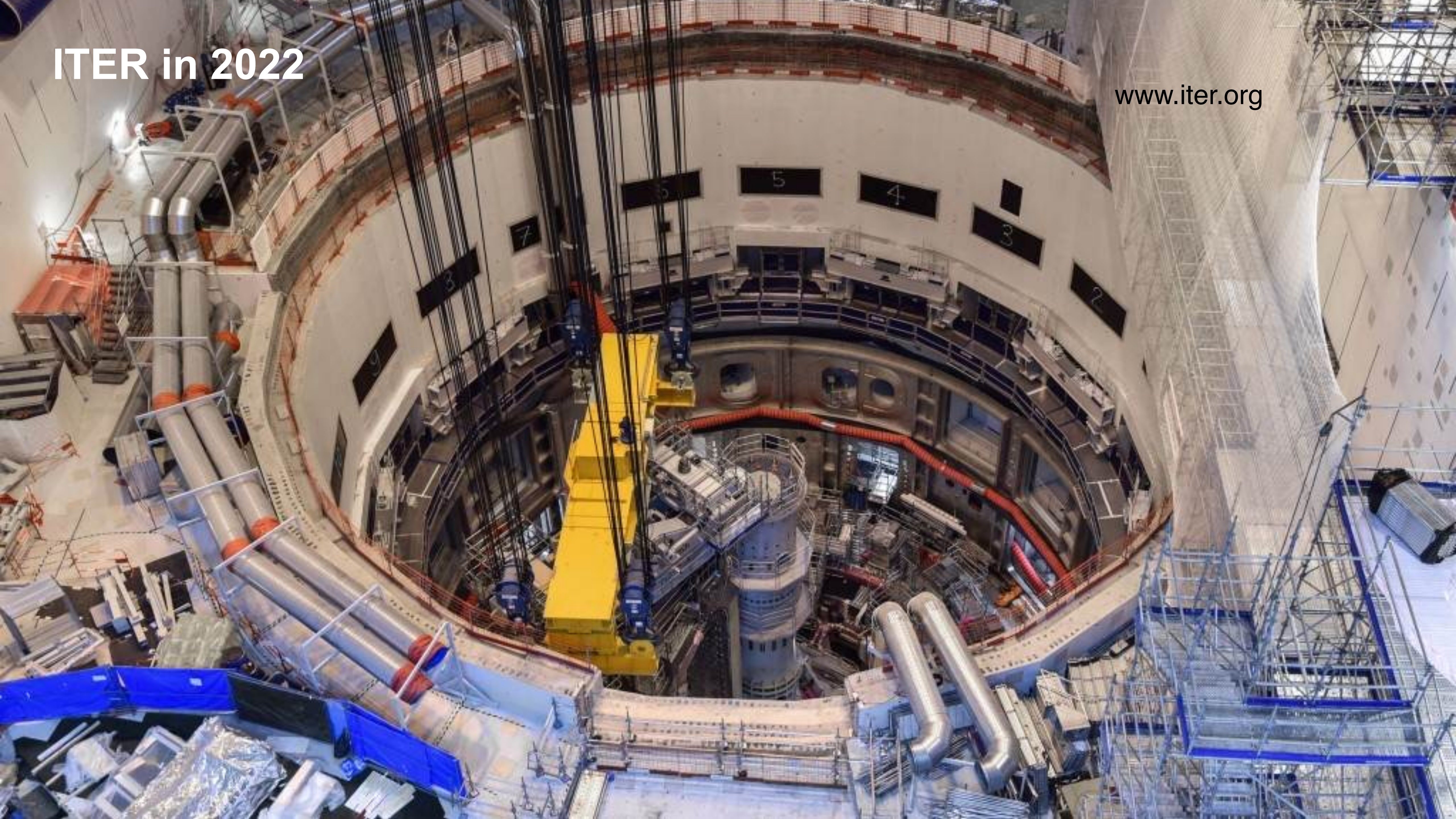
ITER in 2022

ITER in 2022



ITER in 2022

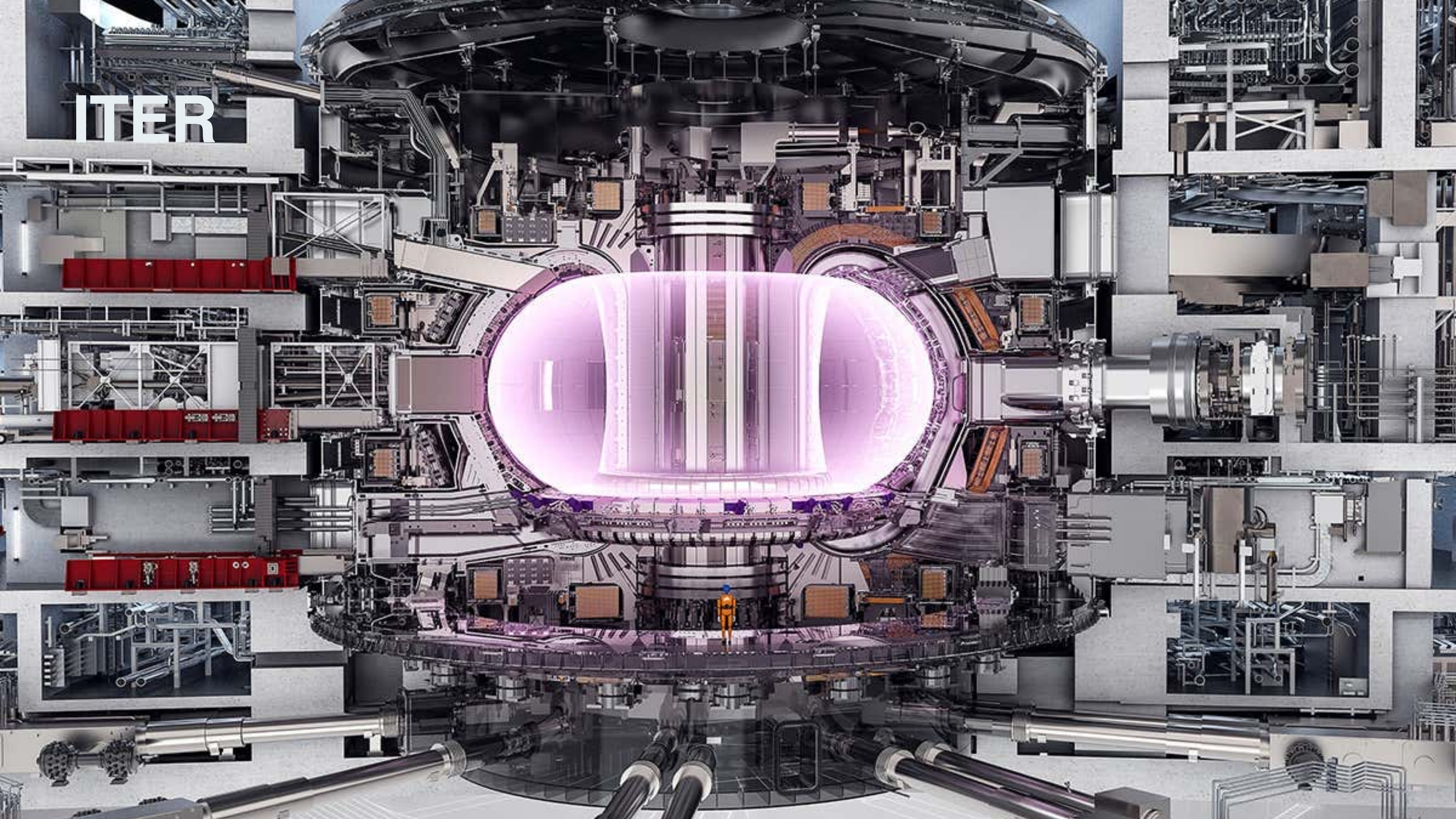
ITER in 2022



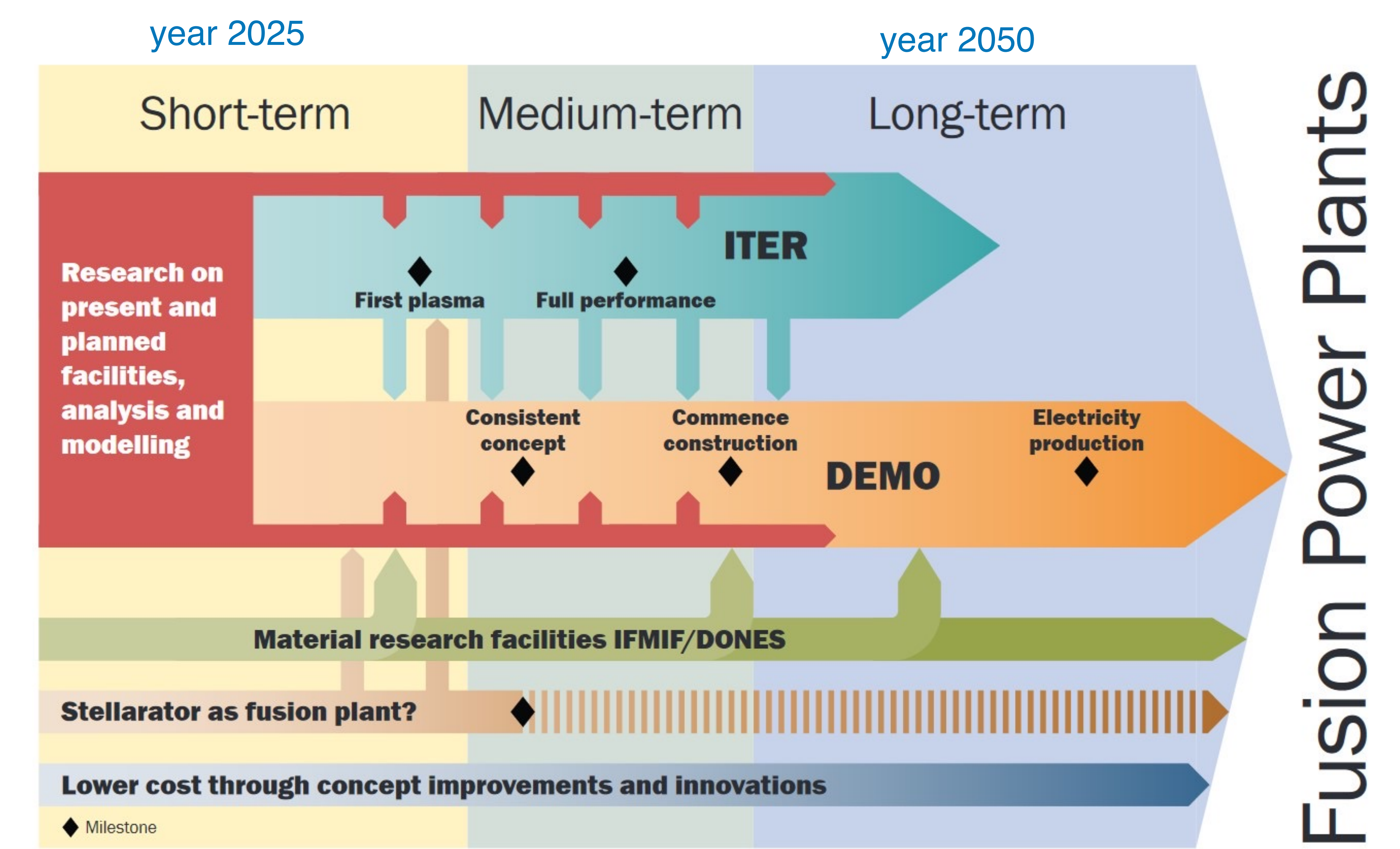
ITER in 2022

ITER in 2022

ITER

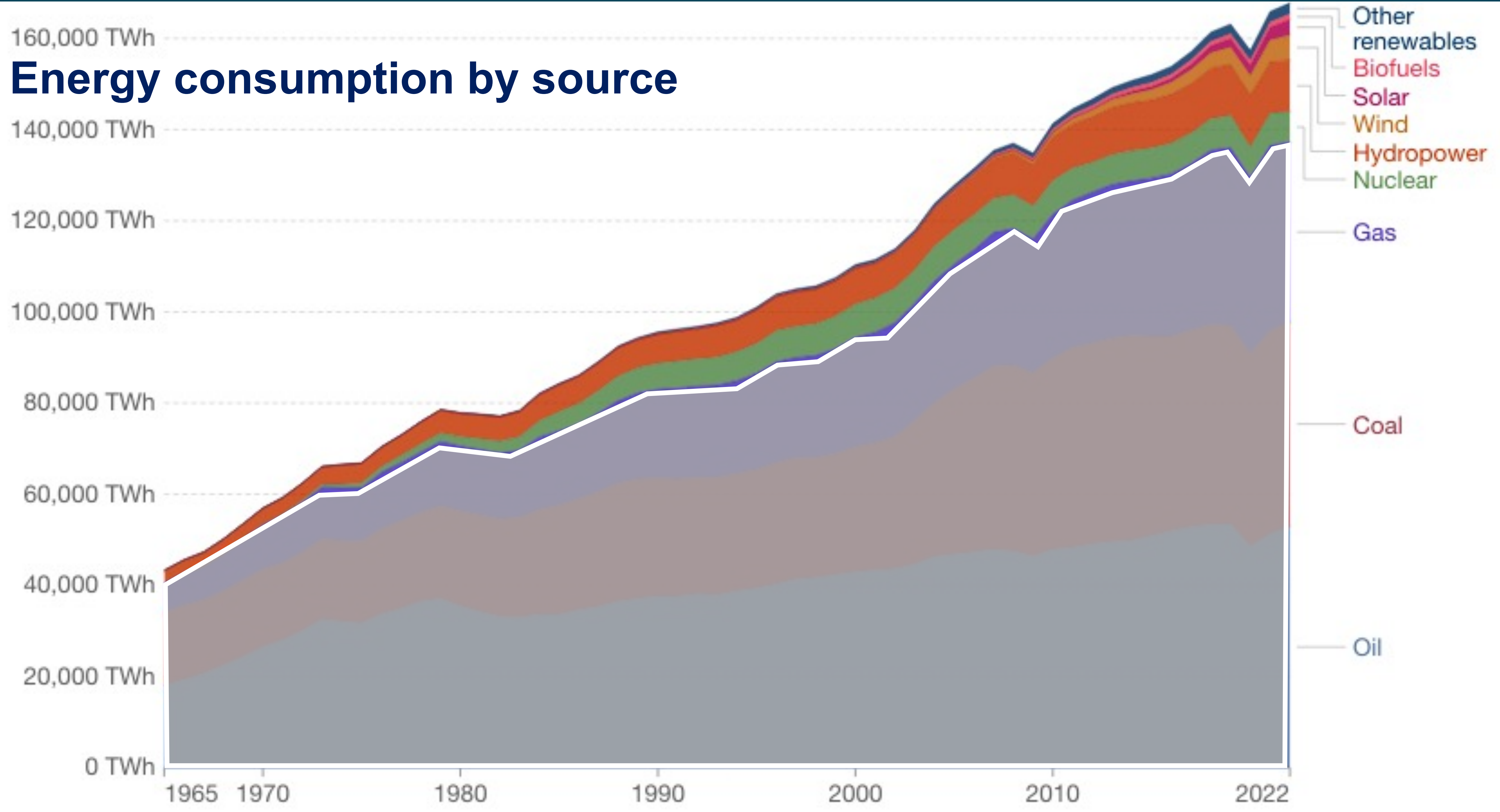


EUROfusion roadmap



[https://www.euro-fusion.org/]

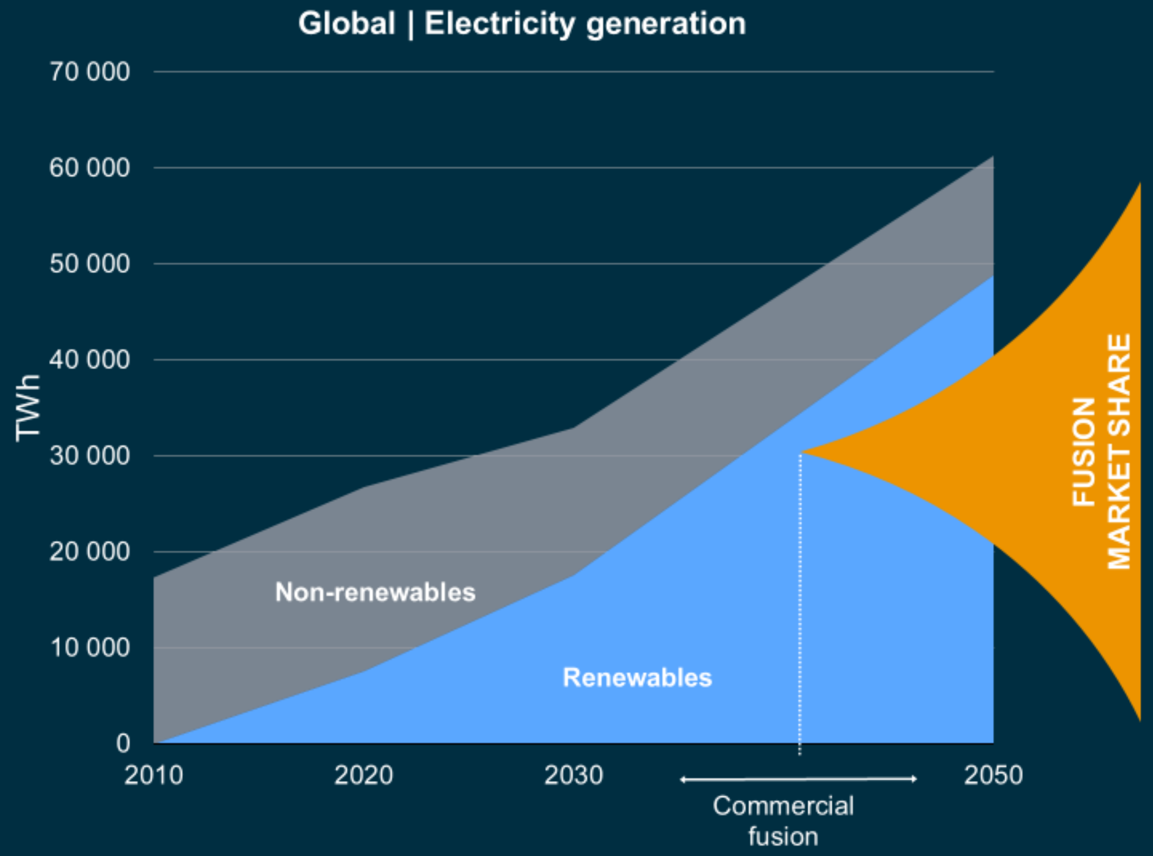
Energy consumption by source



Data source: Energy Institute - Statistical Review of World Energy (2023)

Fusion will dominate in the future

The safety, reliability and cost-efficiency of fusion energy will out-compete almost everything else



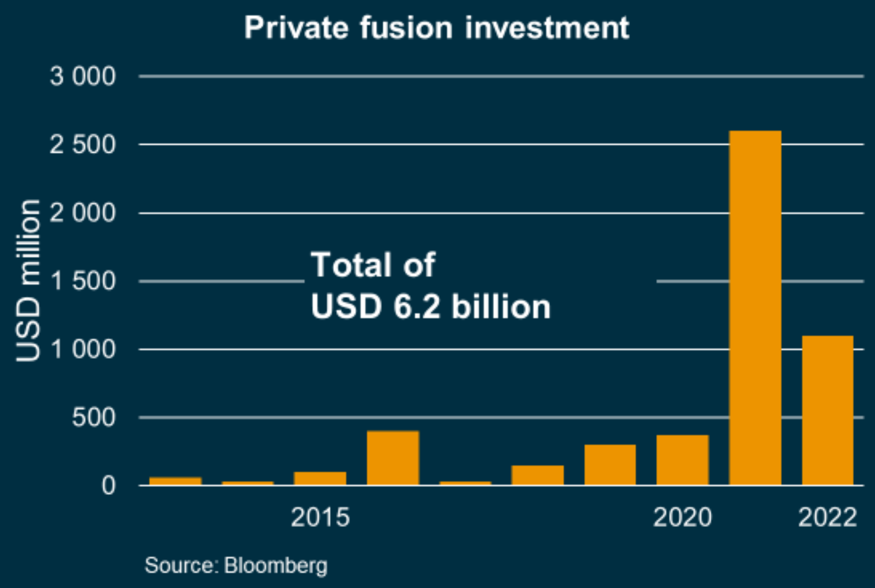
Source: IEA | World Energy Outlook 2022

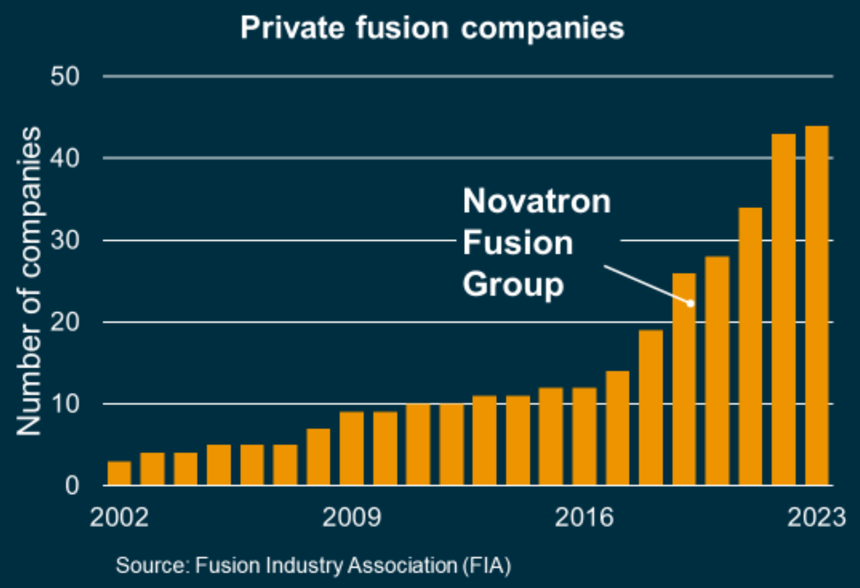
Fusion is the future

- Industrialized MOAK (Many Of A Kind) scaleable technology will enable high-volume rollout of standardized power plants.
- Fusion will become the obvious choice for:
  - Replacement/EOL capacity
  - New capacity
- It will begin this decade, grow into the 2050s and then take off exponentially.

Rapid increase of private investment

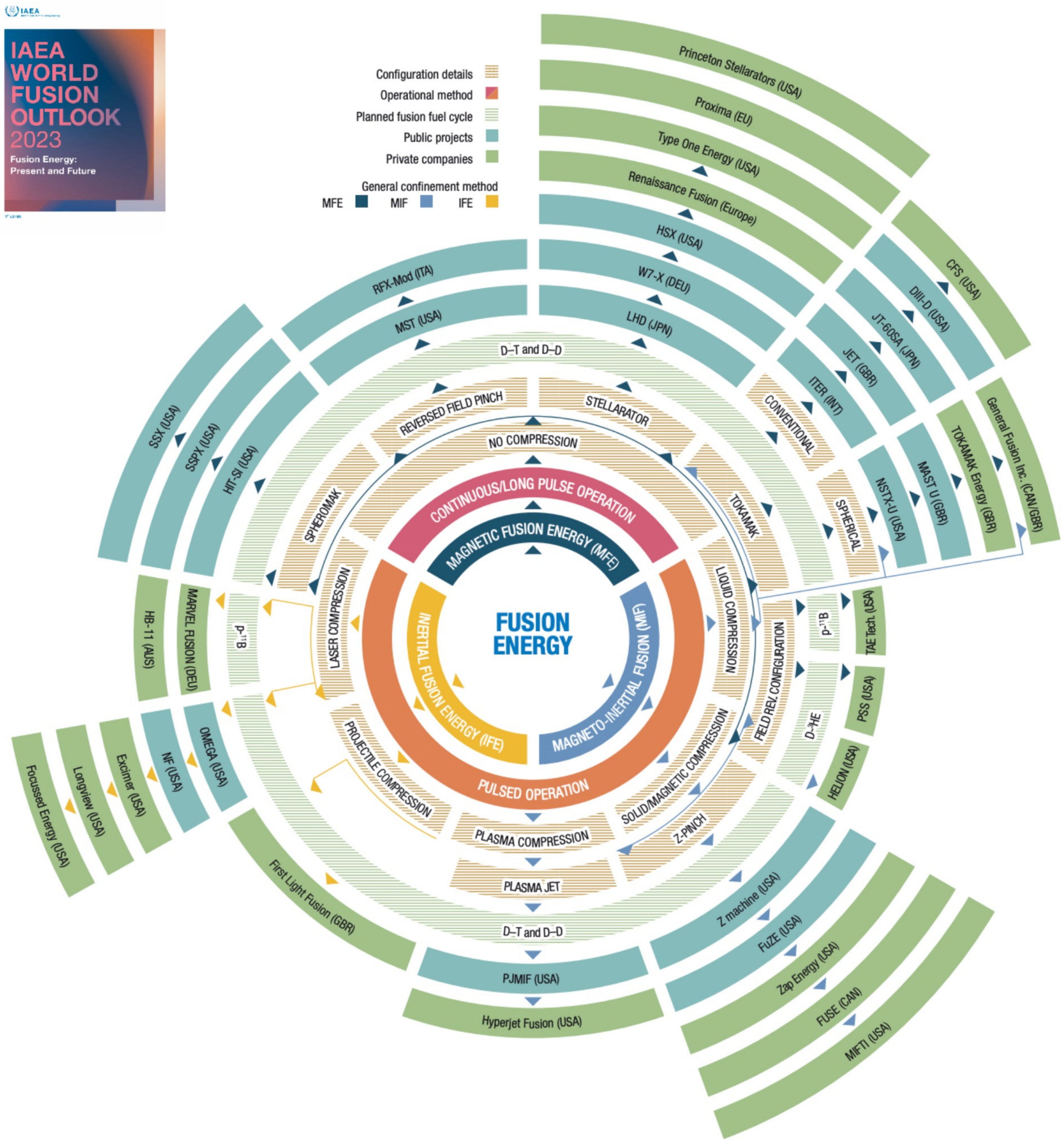
Over USD 6.2B of non-public fusion funding so far





It's happening!

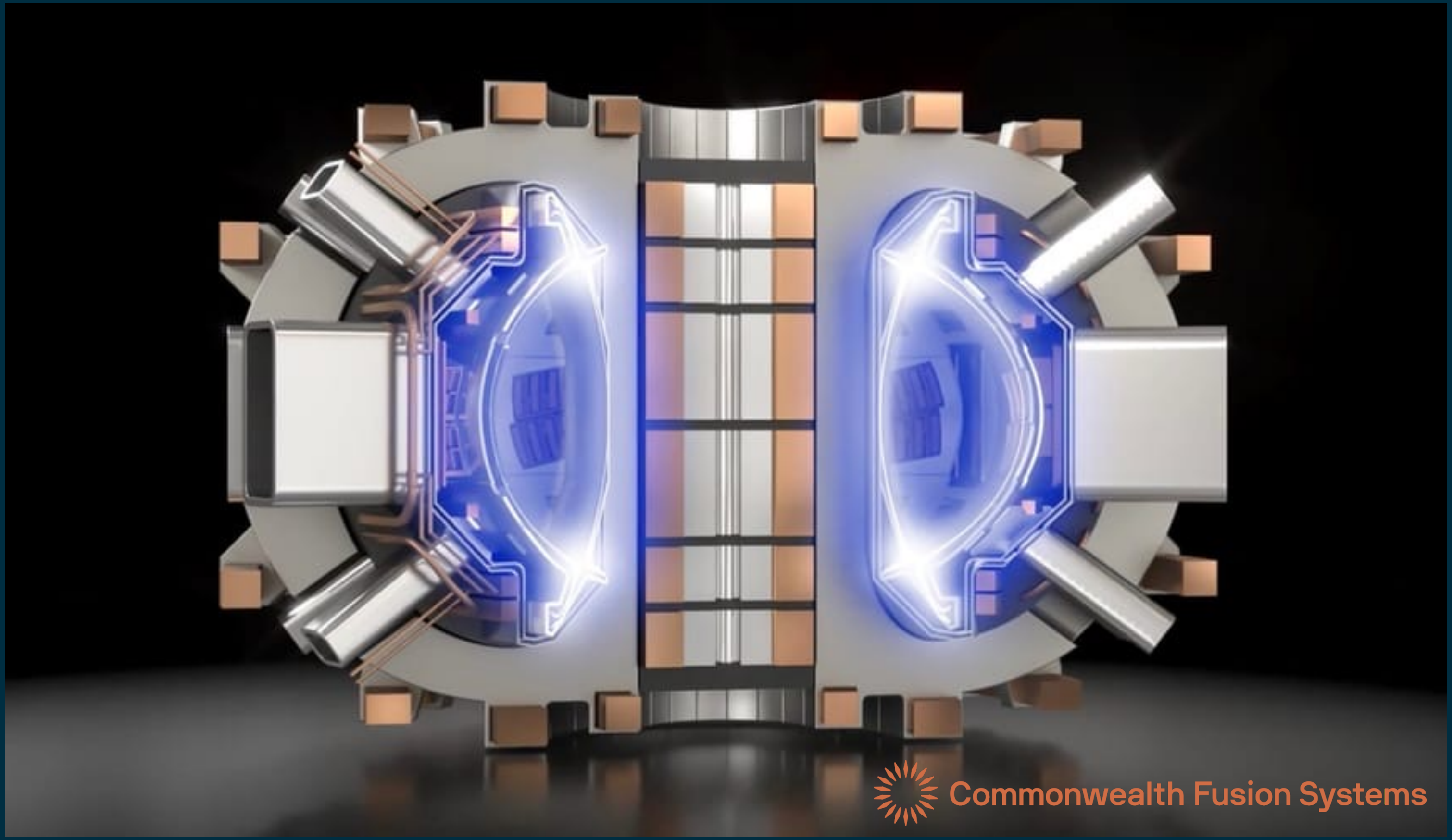
Fusion efforts



Tokamak

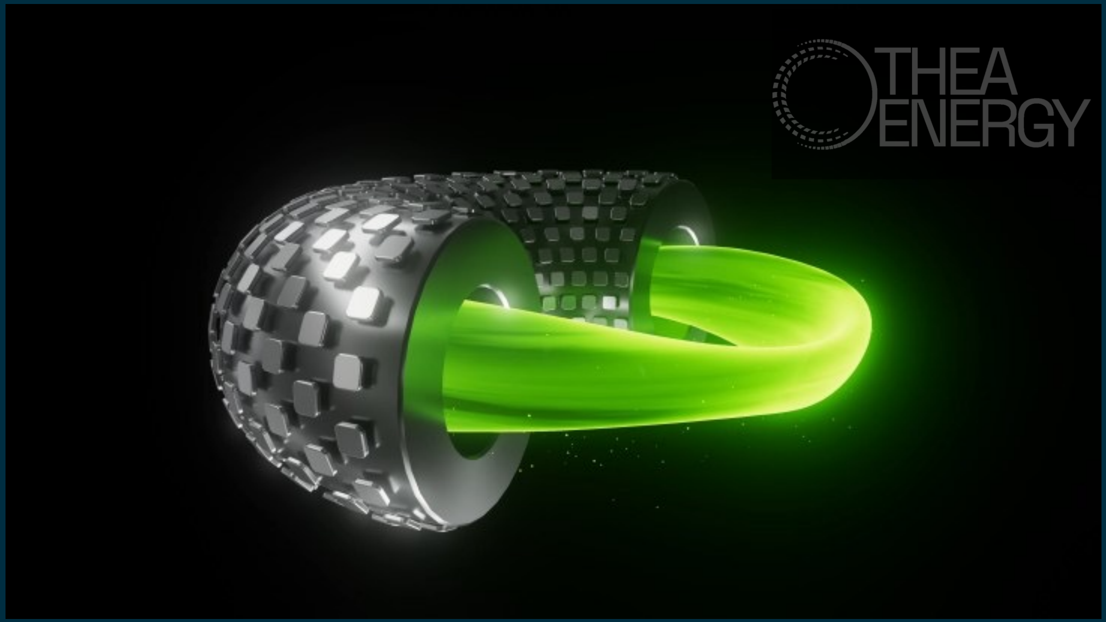
Токамак, en akronym av: "тороидальная камера в магнитных катушках" (toroidal'naja kamera v magnitnych katusjkach) — toroidal kammare i magnetiska spolar

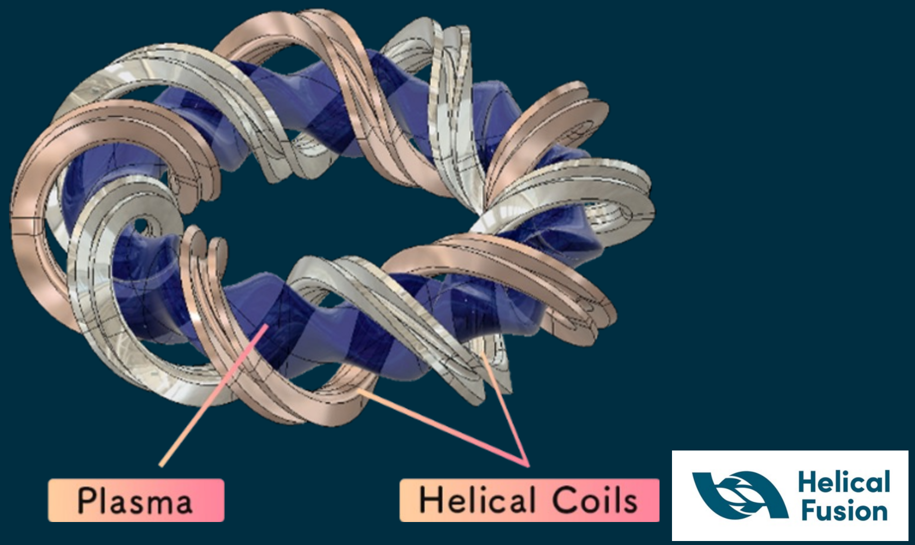
- **Super-conducting magnets**
- **Higher magnetic fields**
- **Smaller volumes and compact design**



Stellarator

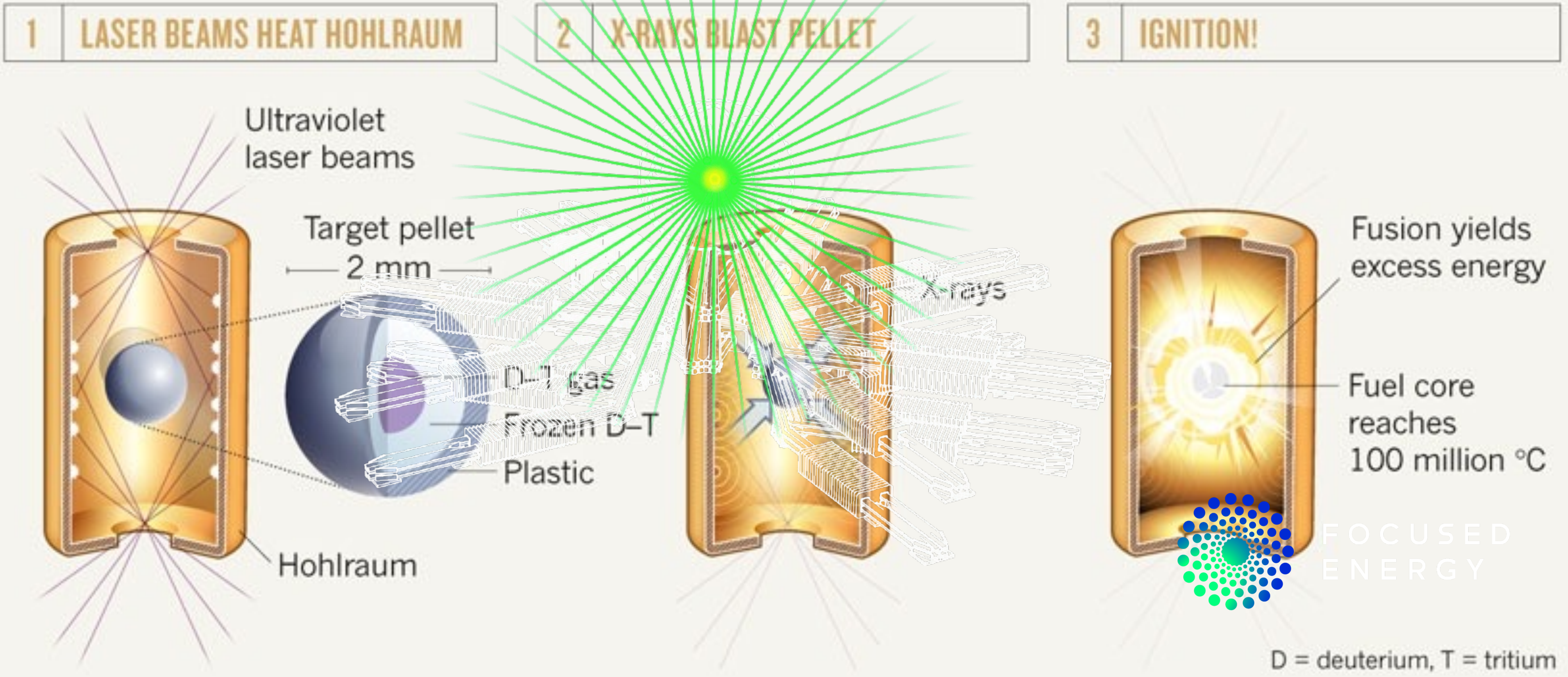
- Stability gains over tokamak
- Superconducting magnets
- Active feedback control of stability





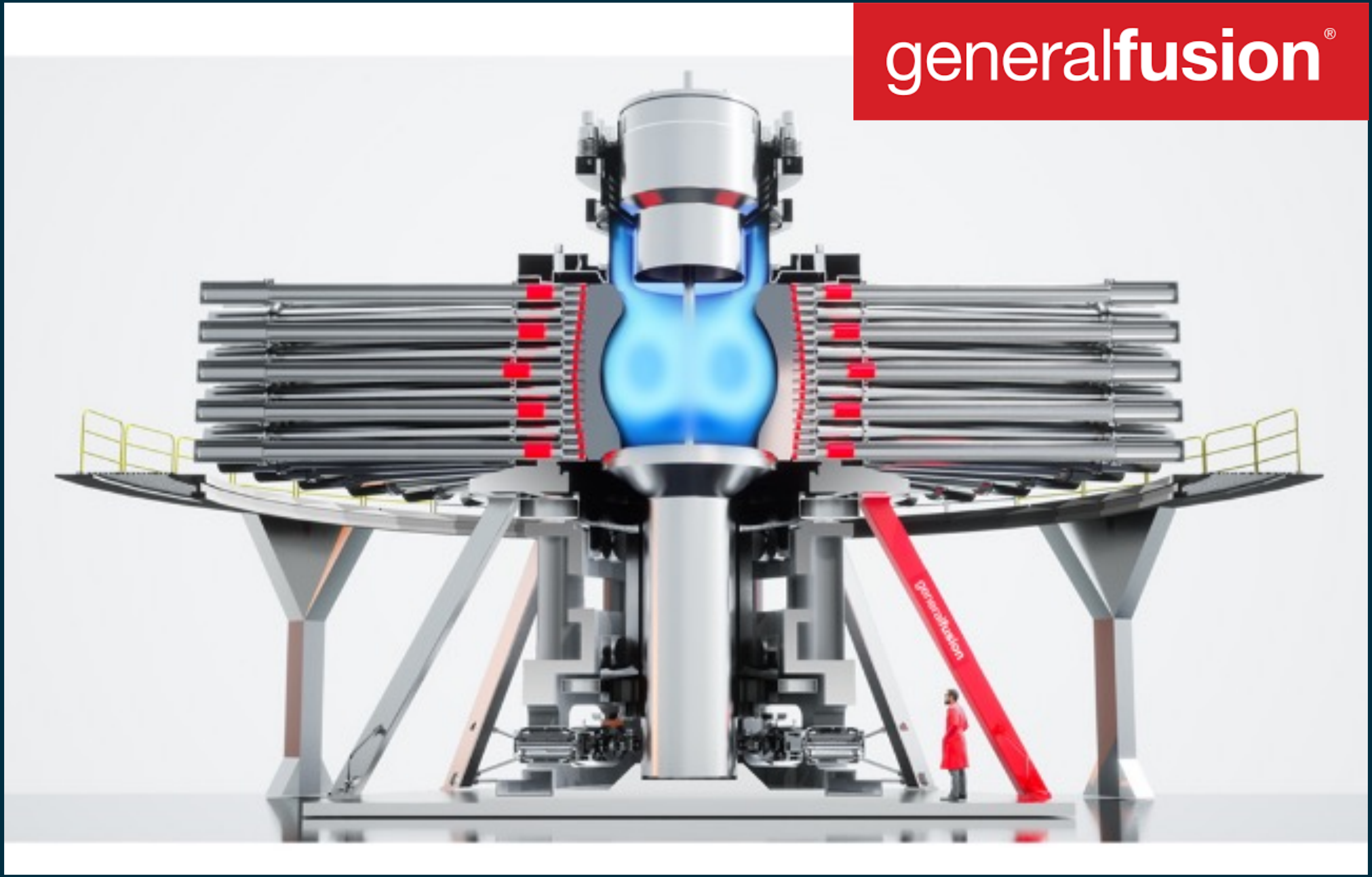
THE NIF'S FUSION STRATEGY

As the NIF's laser beams hit the gold hohlraum capsule (1), they generate X-rays that blast the outer layer of the pellet (2), compressing the hydrogen isotopes until they fuse (3).



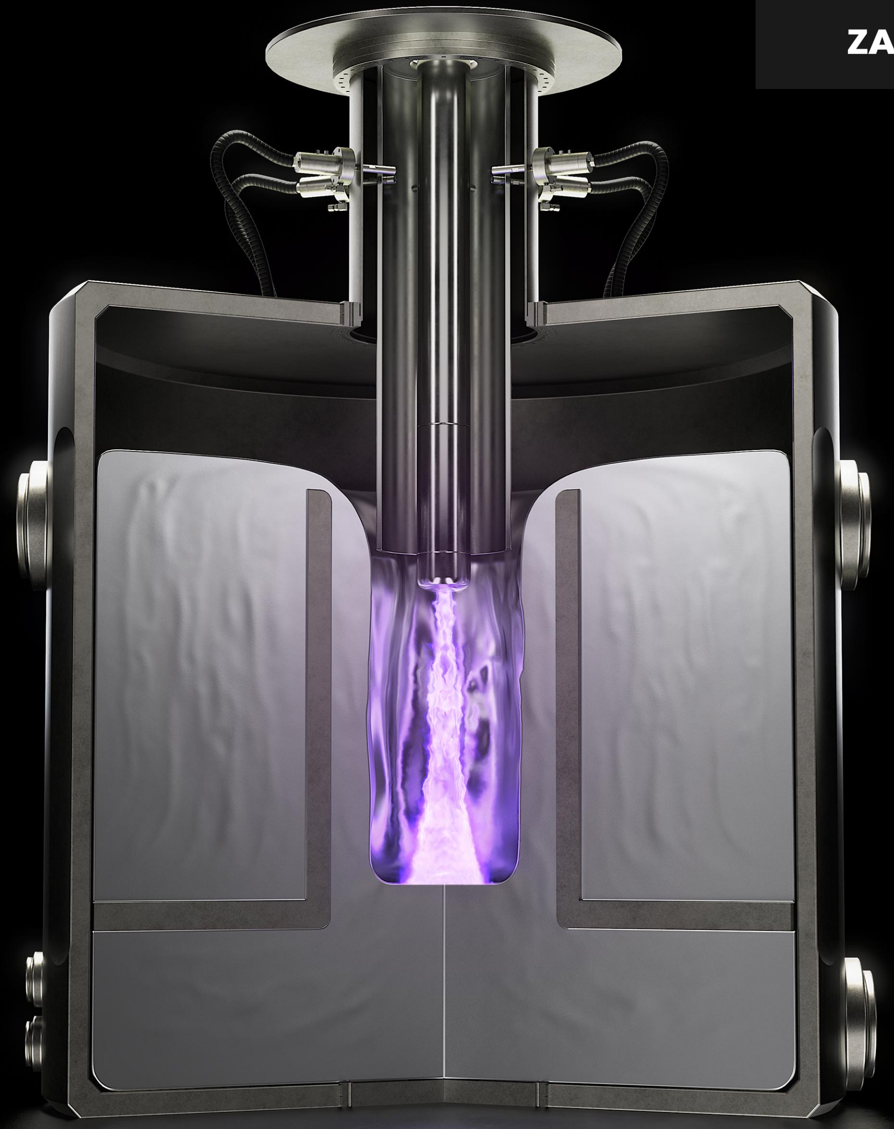
Piston

- Pulsed
- Liquid metal for heat absorption and heat exchange



Z-pinch

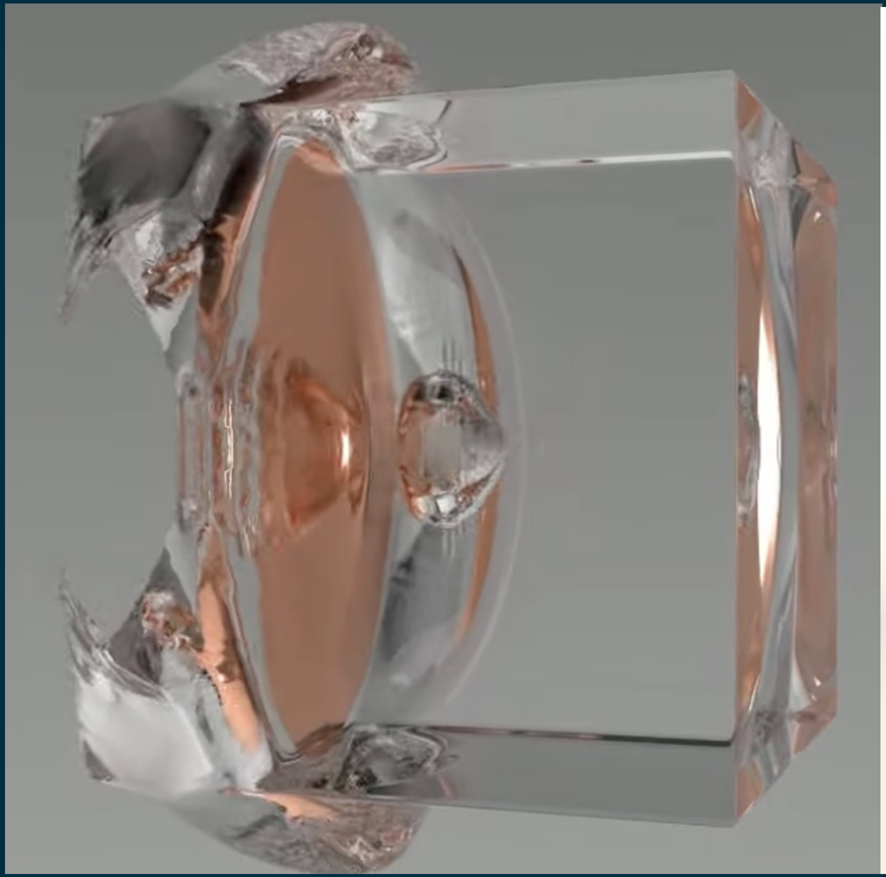
- High-magnetic field
- Liquid metal blanket
- Stability? Pulsed!

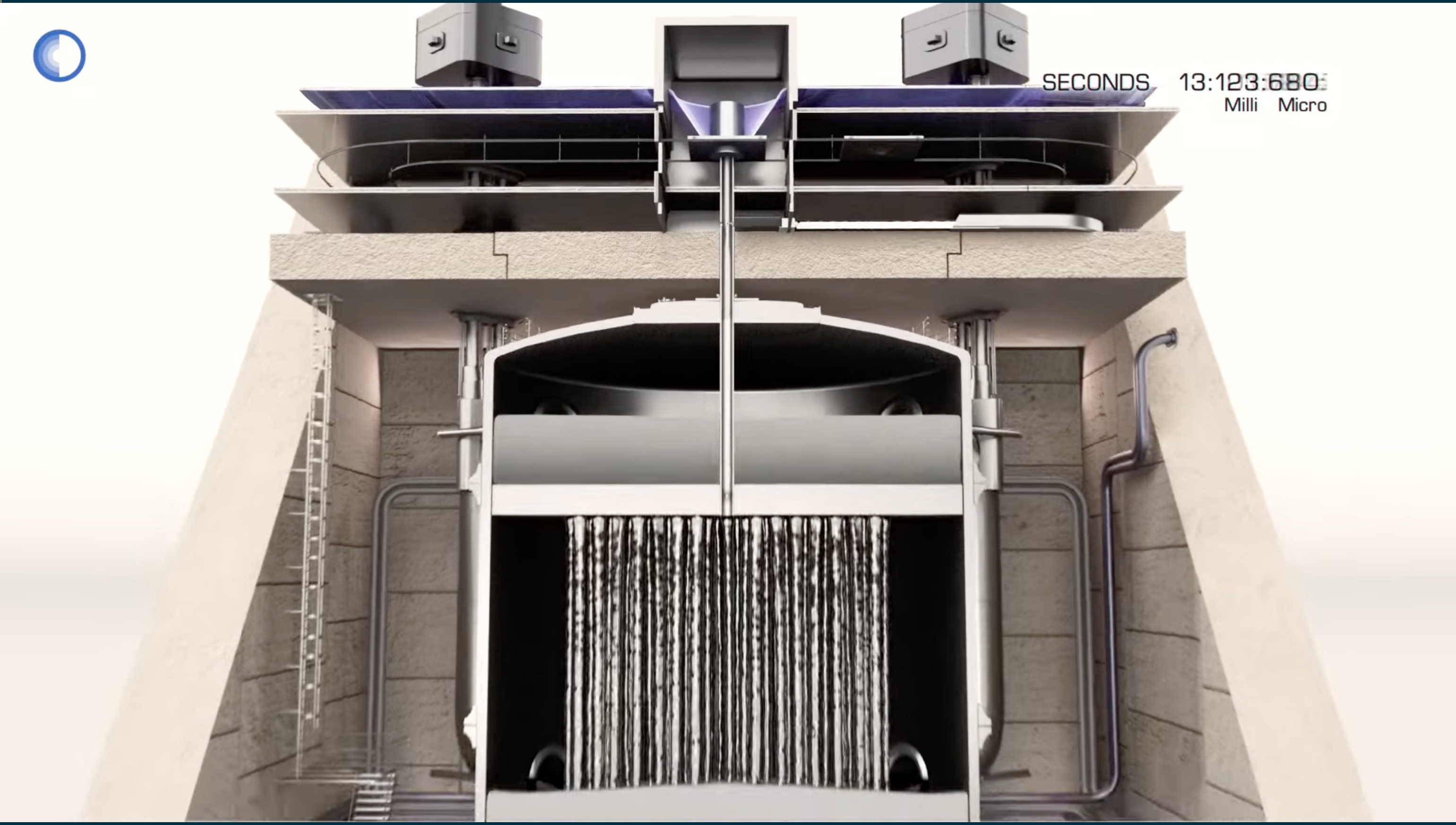


ZAP ENERGY

Impact

first light





NOVATRON

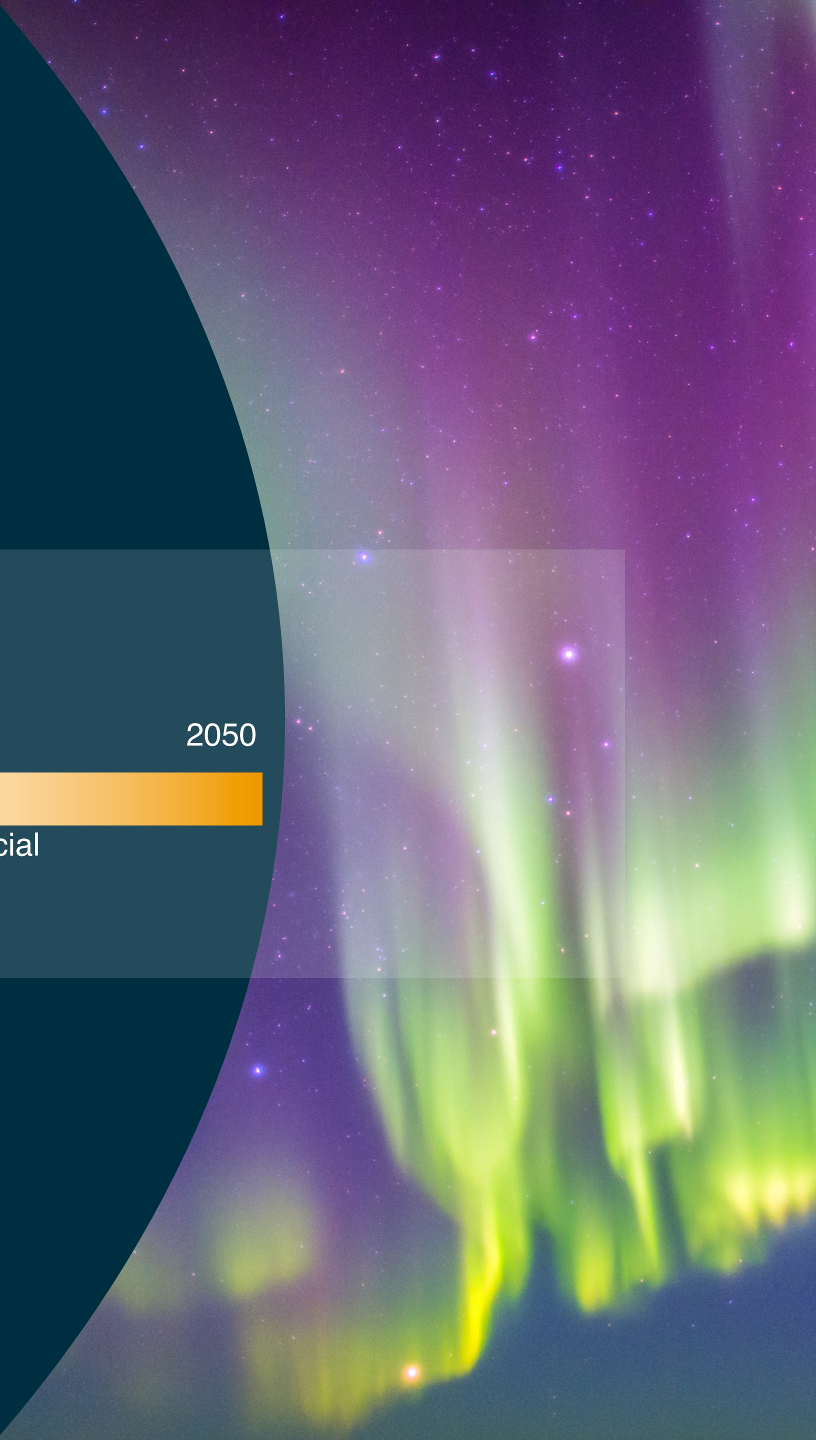
The last mile

Evolution of the energy gain factor (Q)

$$Q = \frac{\text{energy output}}{\text{energy input}} =$$

The fusion energy gain factor is the ratio of fusion power produced in a nuclear fusion reactor to the power required to maintain the plasma in steady state

We are getting very close to commercial fusion



NOVATRON

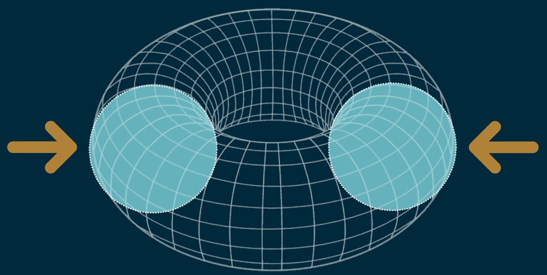
It all started with Jan Jäderberg

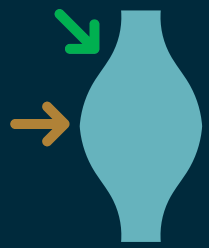
- The inventor of Novatron

Jan Jäderberg has been working in the field of electromagnetism for 30 years.

In the last 10 years, he has been developing the new NOVATRON concept to solve the problem of fusion plasma containment.

The problem





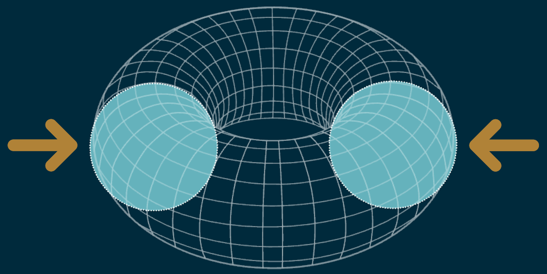
Tokamak

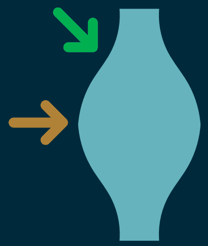
In the Tokamak the outer ring of the magnetic confinement has a bad curvature

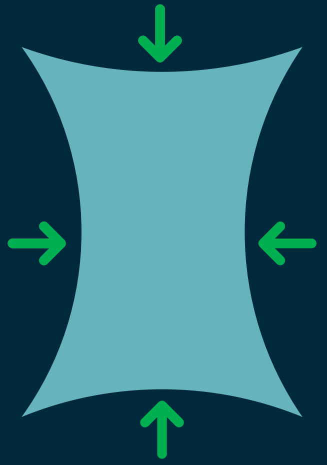
Mirror machine

In the classical Mirror machine, the bad curvature is found in the middle of the magnetic confinement

The Novatron concept







Tokamak

In the Tokamak the outer ring of the magnetic confinement has a bad curvature

Mirror machine

In the classical Mirror machine, the bad curvature is found in the middle of the magnetic confinement

Novatron

The overall concave curvature creates an MHD stable magnetic confinement

Fusion power for the grid

N1
Plasma experiment

N2
Fusion experiment

N3
Experimental reactor

N4
Fusion reactor

Development platforms	Industrialization	Commercial reactor

2027 — 203X — 203Y

Our roadmap to commercial energy production

What is involved

- RF subsystem
- Machine Control
- Integrated Data Analysis
- Digital Twin (Simulations) – MHD, particles
- Vacuum
- Process gas
- Diagnostics
- Experiment design and perfromance

Novatron Fusion Group

- Founded in 2019
- 30 employees
- Investors:
    - EIT InnoEnergy
    - KTH Holding
    - Santander InnoEnergy Climate Fund
    - Industrifonden
    - Climentum Capital
- Capitalization of EUR 10 million
- Growing IP portfolio (+10 pending)

Partners and memberships

KTH VETENSKAP OCH KONST

eit InnoEnergy

FUSION INDUSTRY ASSOCIATION

THE FUSION CLUSTER

NOVATRON

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