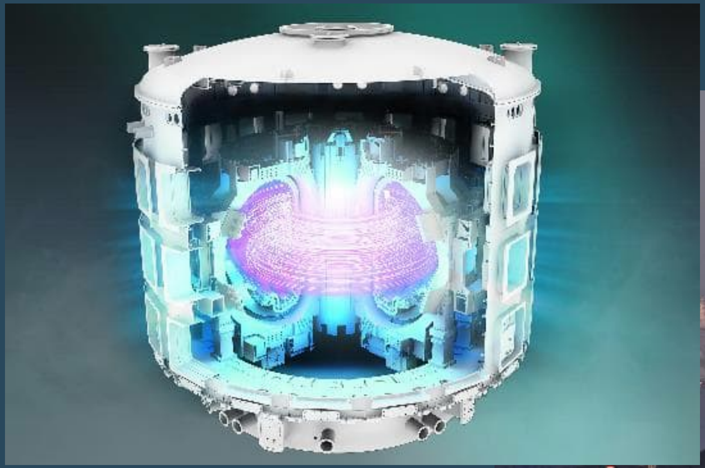
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Nuclear fusion as a source of energy:
Status and perspectives



Dr. Hans Meister

With special thanks to U. Fantz, F. Fleschner, M. Hölzl,
M. Maraschek, A. v. Müller, Th. Pütterich (IPP), P. Barabaschi, R. Pitts (ITER), W. Biel (FZJ)

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Outline

Introduction

Concepts for fusion on earth

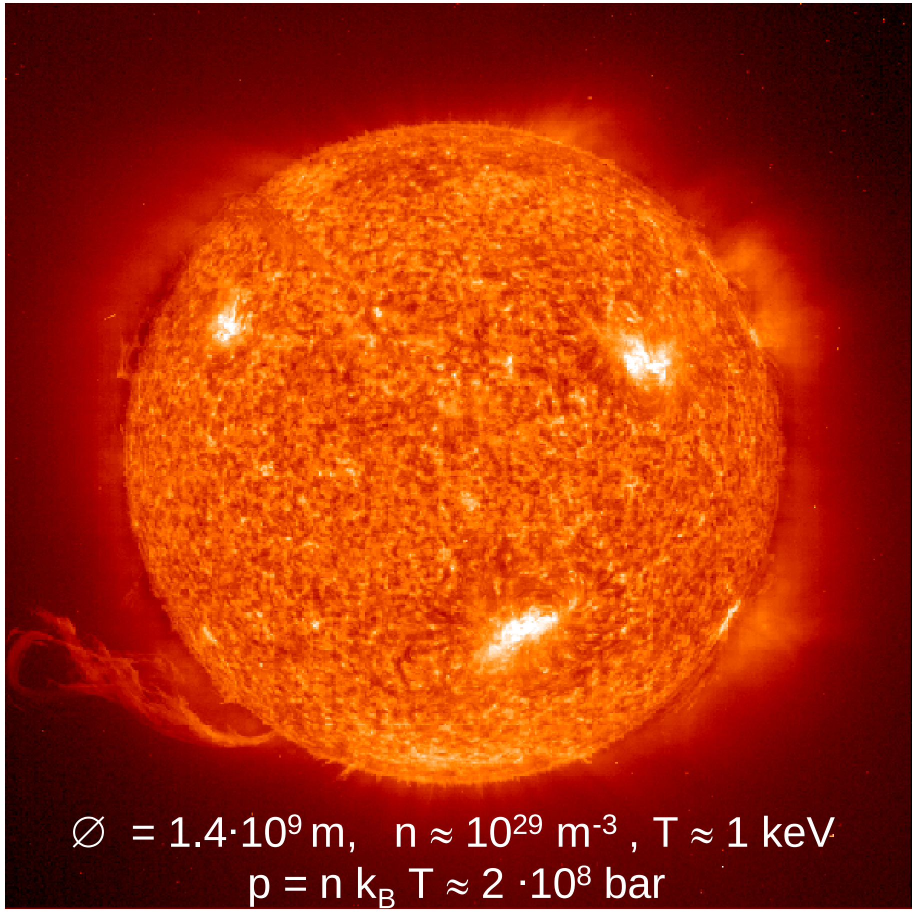
Status of development – where are we, which challenges remain?

ITER – a world encompassing fusion project

Highlights from the worldwide fusion landscape

Perspectives for fusion as energy source

Nuclear fusion – the energy source of the stars

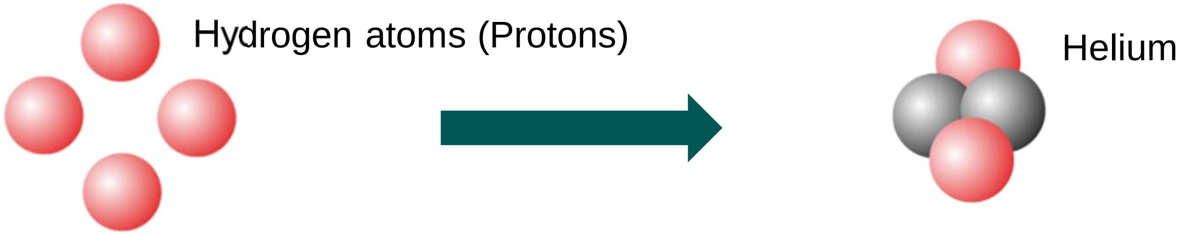


$\varnothing = 1.4 \cdot 10^9$ m, $n \approx 10^{29}$ m^{-3} , $T \approx 1$ keV

$p = n\, k_B\, T \approx 2 \cdot 10^8$ bar

Foto: ESA & NASA

Nuclear fusion in the centre of the sun



564 Mio. t Hydrogen

per second →

560 Mio. t Helium

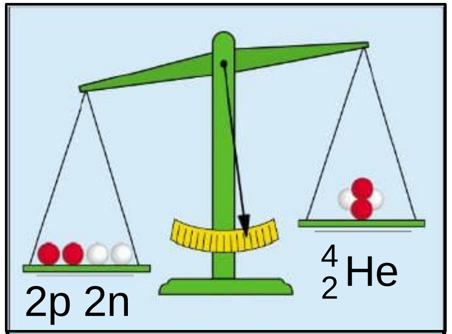
+

$4 \cdot 10^{26}$ J

- **Confinement due to gravitation**
- **Matter is in the plasma state**

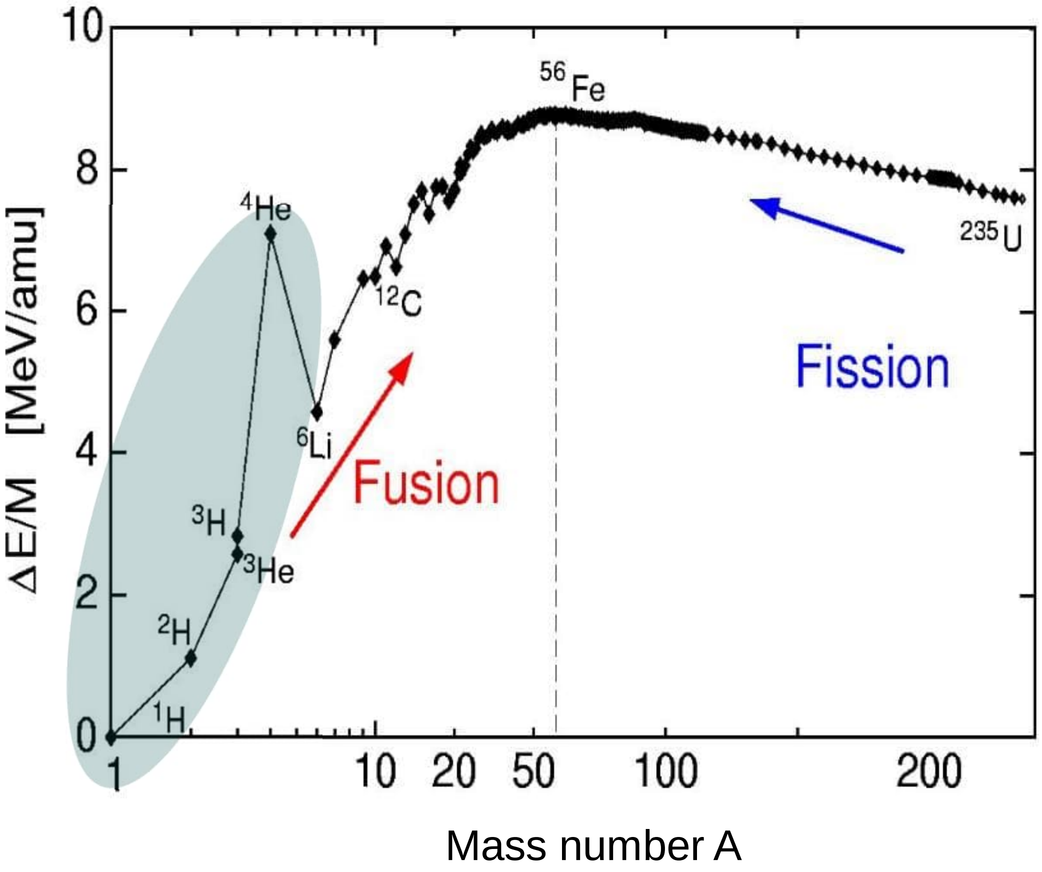
Nuclear fusion – energy production

Fusion of light atoms releases energy

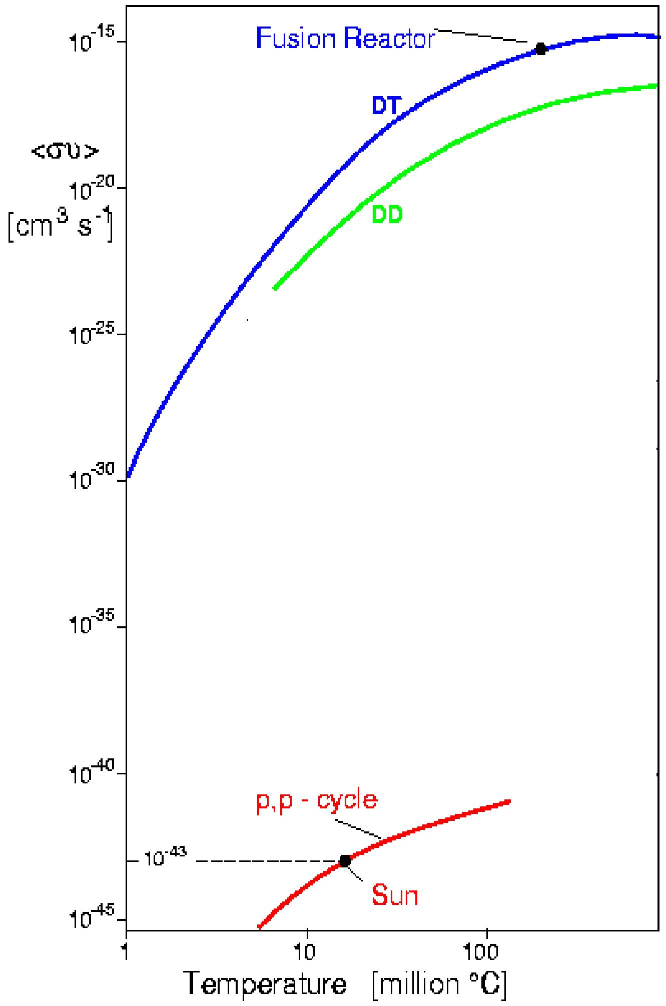


$\Delta E = \Delta m\, c^2$

$\Delta m \approx 5 \bullet 10^{-29}$ kg
$\Delta E \approx 4 \bullet 10^{-12}$ J
≈ 28 MeV



Nuclear fusion – how to bring it to earth



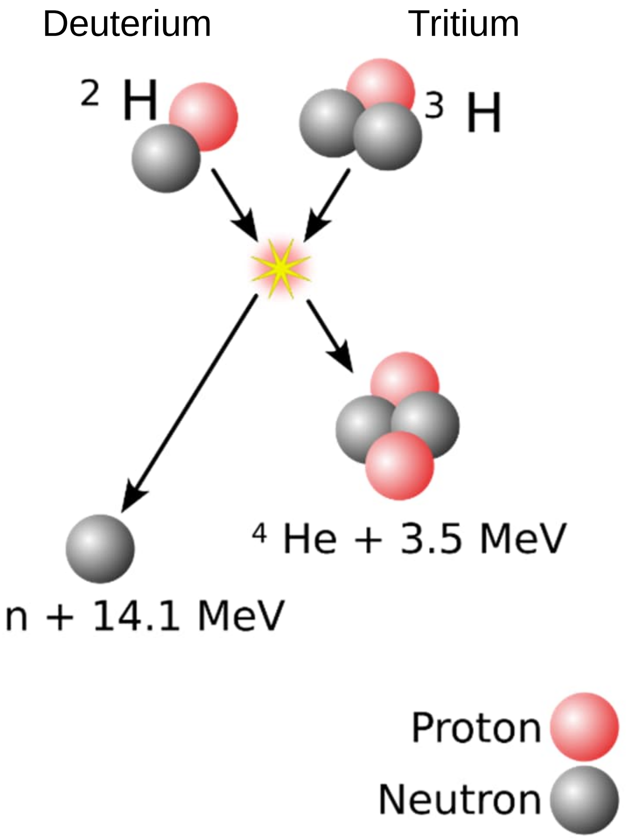
Using D and T as fuel drastically increases probability of fusion reactions

Requires temperatures above 100 Mio. °C (> 10 keV)

Availability of fuels

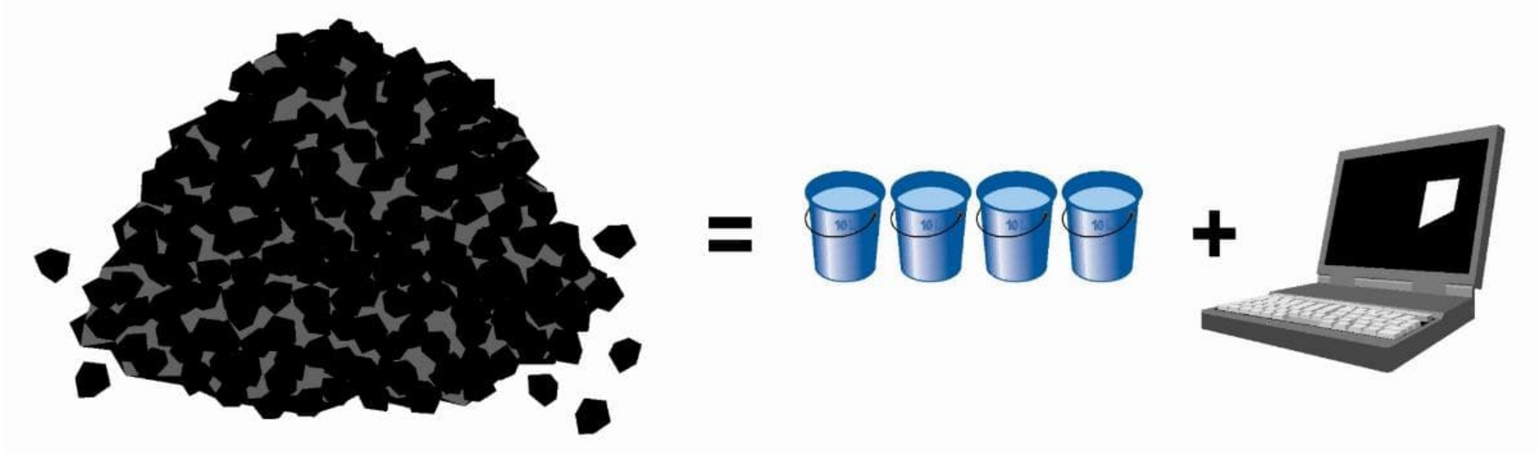
- D is natural isotope of H (0.015%)
- T decays with half time of 12.3a, can be produced by

^{6}Li + n → ^{4}He + T



Wykis (talk · contribs), Public domain, via Wikimedia Common

Efficiency of fuel



40 t coal
(320.000 kWh)

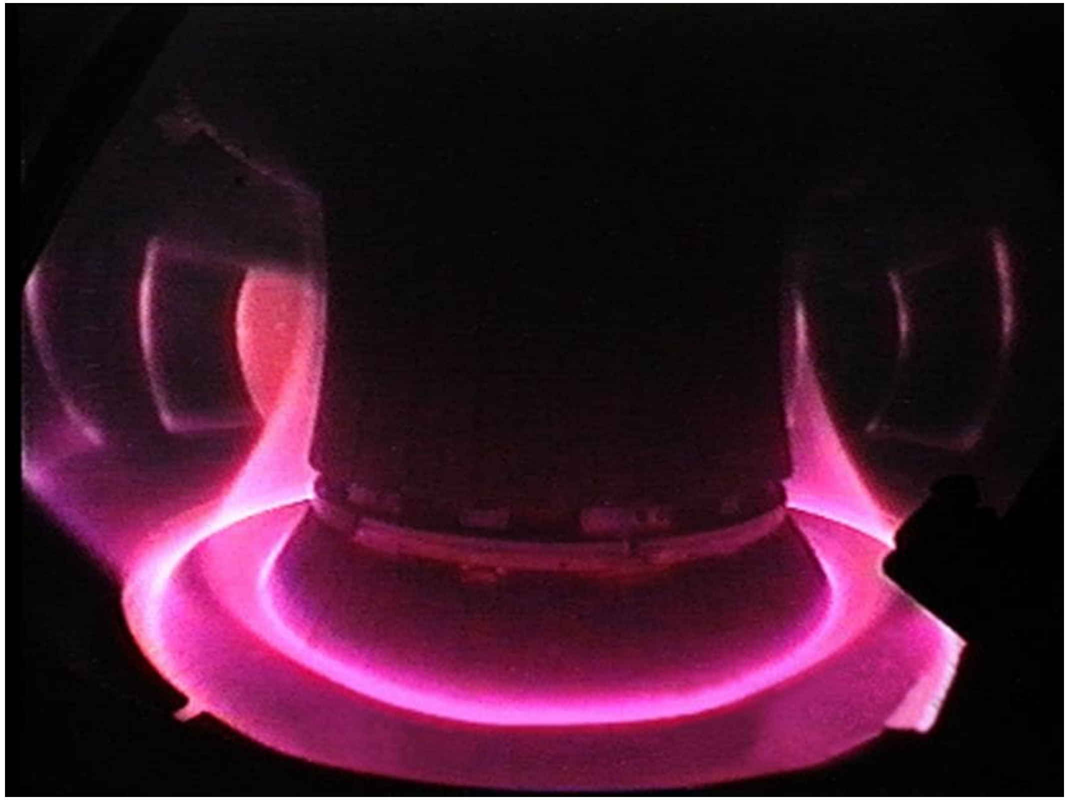
D in 40 l water

5 g Lithium
(Laptop-battery)

Fusion power plant with 1.5 GW thermal output requires about 150 kg fusion fuel per year

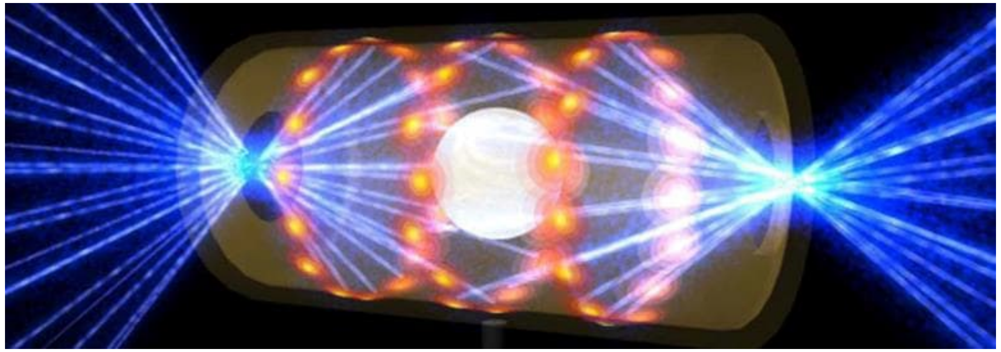
Fusion concepts – how to confine fuel on earth

Magnetically confined fusion (MCF)



Picture: MPI für Plasmaphysik

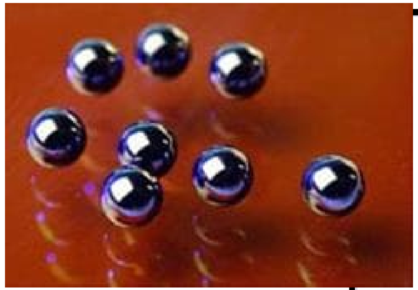
Inertially confined fusion (ICF – laser fusion)



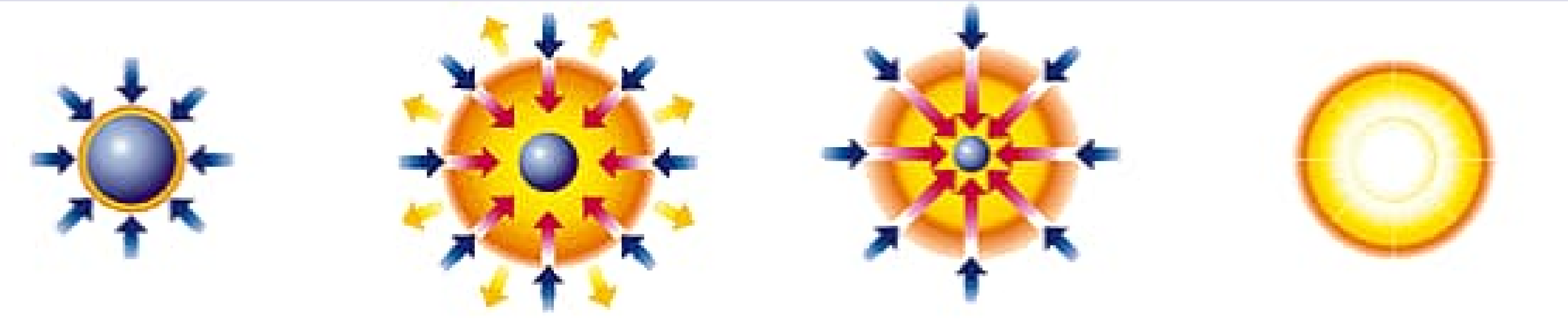
Picture: Lawrence Livermore National Laboratory/NIF

Inertially confined fusion

Small D-T-pellets are heated and compressed to initiate fusion process



Picture: Lawrence Livermore National Laboratory



Heat pellet with laser or heavy ion beams	Compression due to ablation of hot material	Ignition after compression by factor 1000	Fusion processes during energy confinement time

Laser: 1 MJ in 10^{-10} s → 10^{16} W

1 GJ per pellet with r = 1 mm

≡ 250 kg TNT

$T \approx 10$ keV

$n \approx 10^{30}\ \mathrm{m}^{-3}$

$p = n\, k_B\, T \approx 2{\cdot}10^{11}$ bar > sun

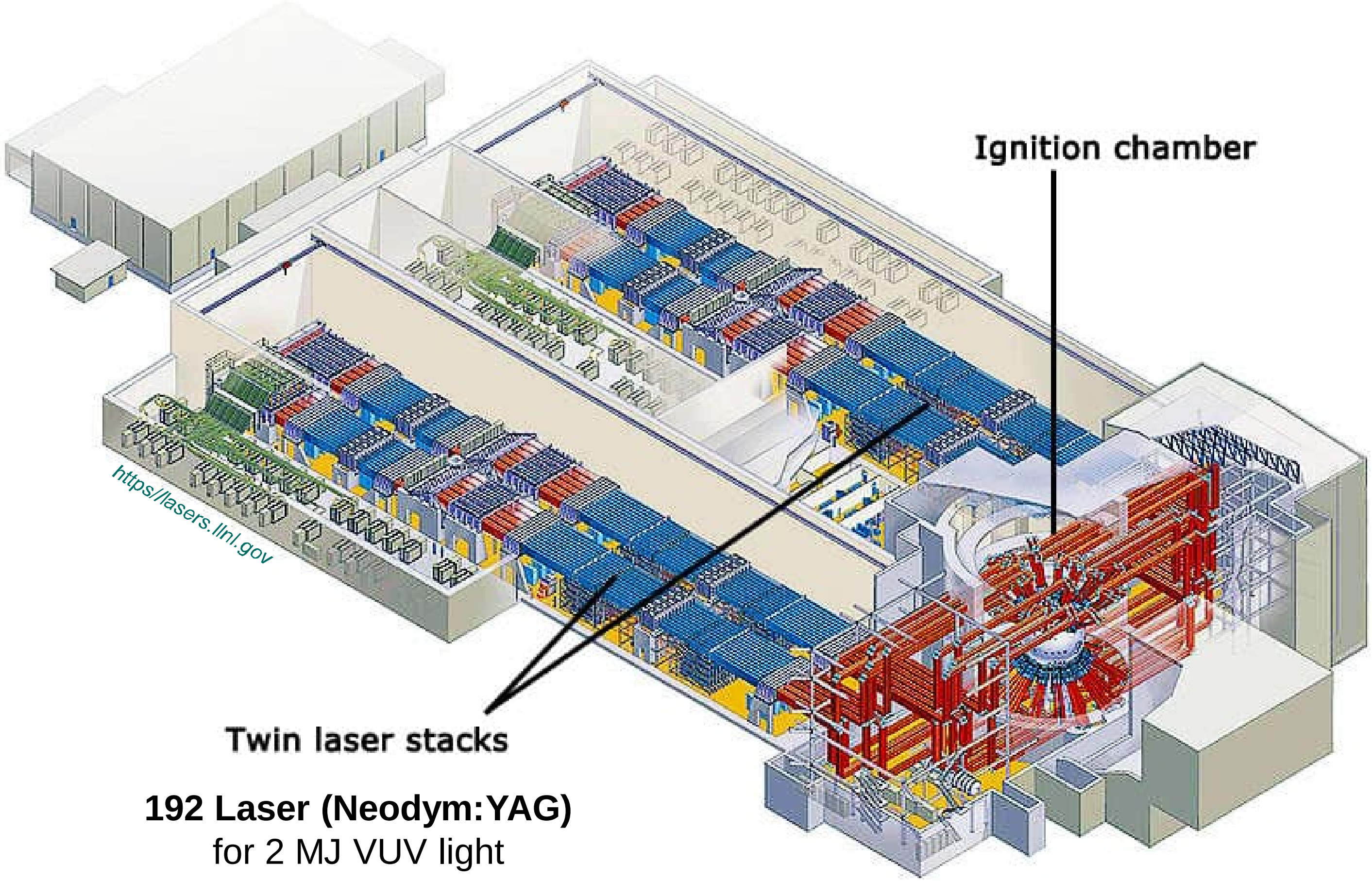
Sound velocity $v \approx 10^{6}$ m/s

DT pellet with r = 1 mm

$\tau_E \approx 10^{-10}$ s = 0.1 ns

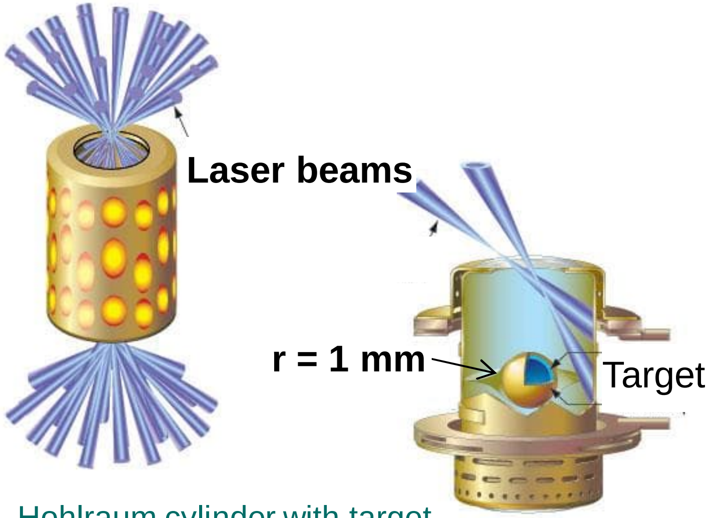
Intertially confined fusion

National Ignition Facility, NIF, Lawrence Livermore National Lab, USA (since 2009)



192 Laser (Neodym:YAG)
for 2 MJ VUV light

- Largest laser facility worldwide

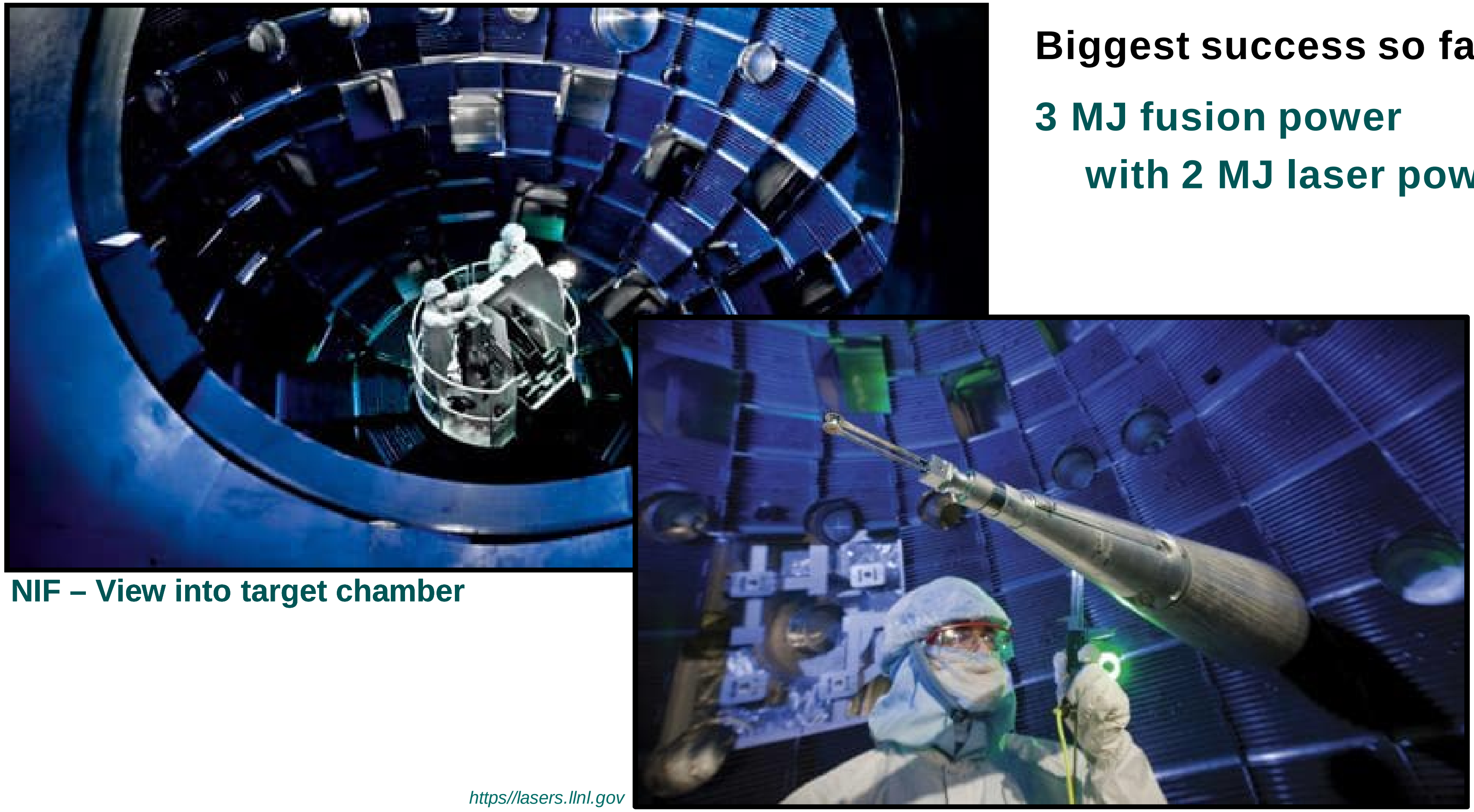


Hohlraum cylinder with target

Other laser facilities

- Laser MegaJoule Project, CEA, France:
  - 2004: start construction;
  - 2022: 10 of 22 beamlines operational
- Shenguang-III (SGIII) prototype facility, China, under construction

Inertially confined fusion



NIF – View into target chamber

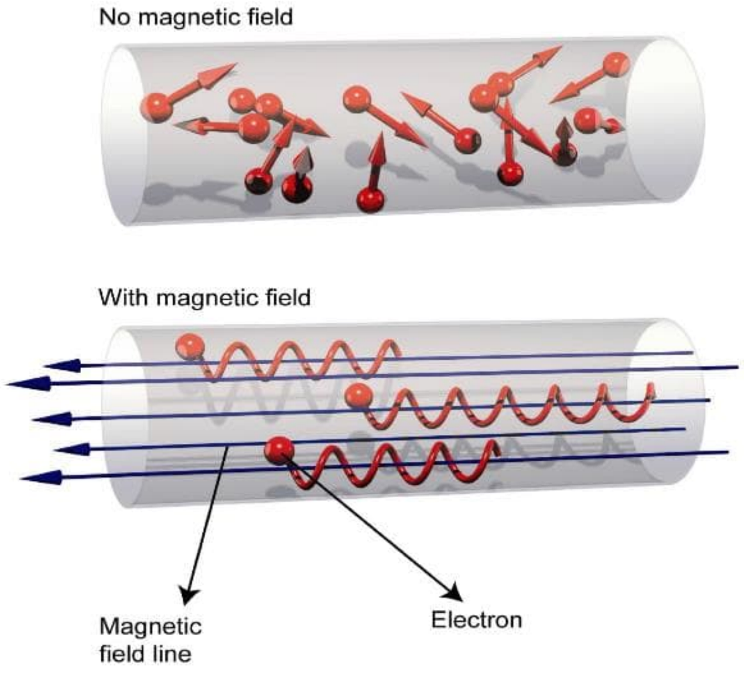
https//lasers.llnl.gov

Biggest success so far Dec. 2022:

3 MJ fusion power
with 2 MJ laser power on target

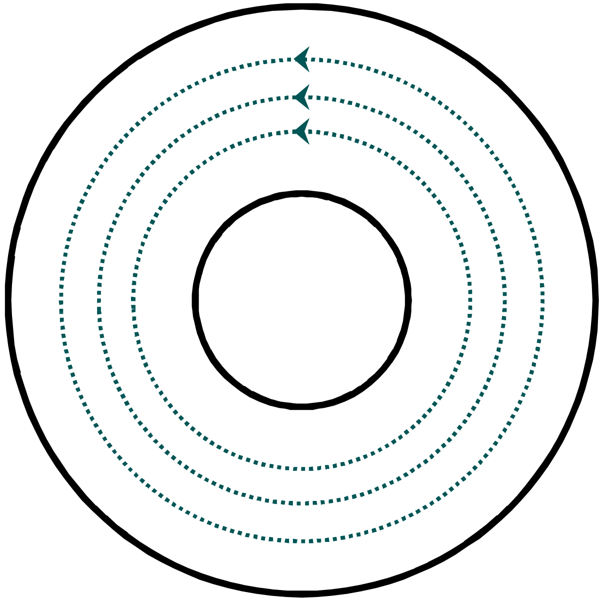
- Gain considering laser efficiency 100x lower
- **So far, 1 pellet per day. For power plant repetition at up to 10 Hz required**
- Significant technological development still needed

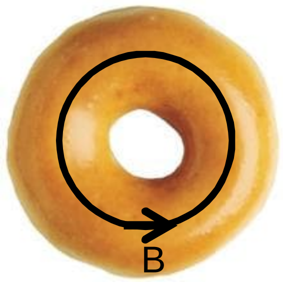
Magnetically confined fusion



- Hot plasmas consist of charged particles
- Magnetic fields force them onto gyrations along field lines leading to confinement
- **Linear arrangements suffer from high losses at ends**

  → bend to torus





Larmor radius

$$r_c = \frac{m\cdot v_\perp}{q\cdot B} = \frac{\sqrt{2\,m\,k_B T}}{q\cdot B}$$

Gyrofrequency

$$\omega_{c,e} = \frac{e\cdot B}{m_e}$$

Example: B = 2 T

$r_{c,e} \approx 0.15$ mm

$r_{c,i} \approx 6$ mm

$\omega_{c,e} = 350$ GHz

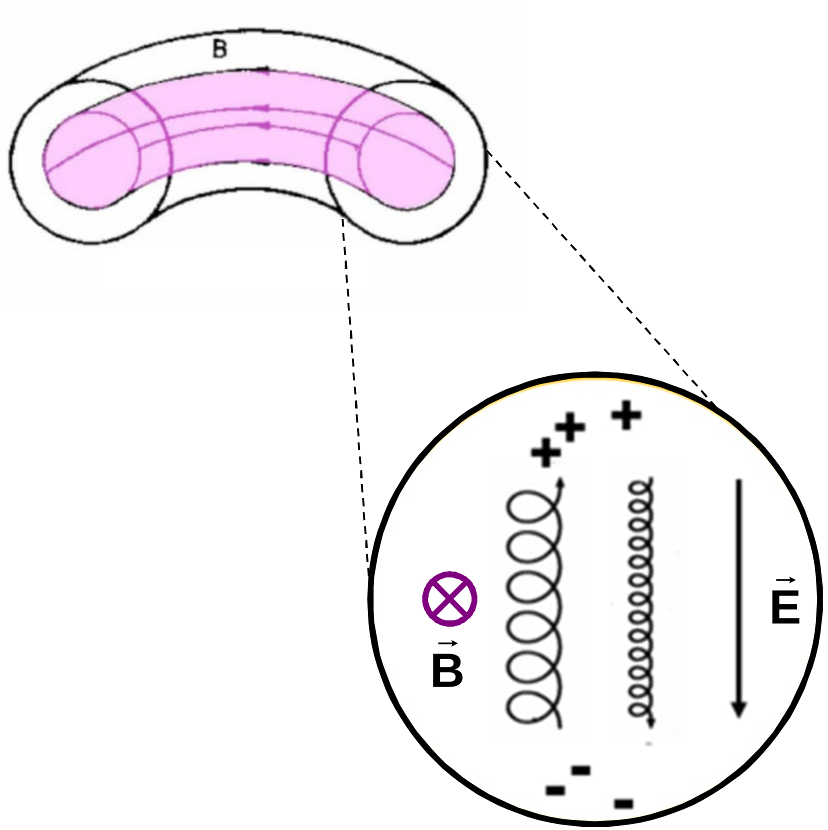
$\omega_{c,i} = 190$ MHz

$T \approx 10$ keV ; $n \approx 10^{19}$ m^{-3} ;
$p = n\,k_B\,T \approx 2$ bar
Balanced by magnetic pressure
$p_m = B^2/(2\mu_0)$

$\tau_E \approx 5$ s

Magnetically confined fusion

Charged particles in inhomogeneous magnetic field

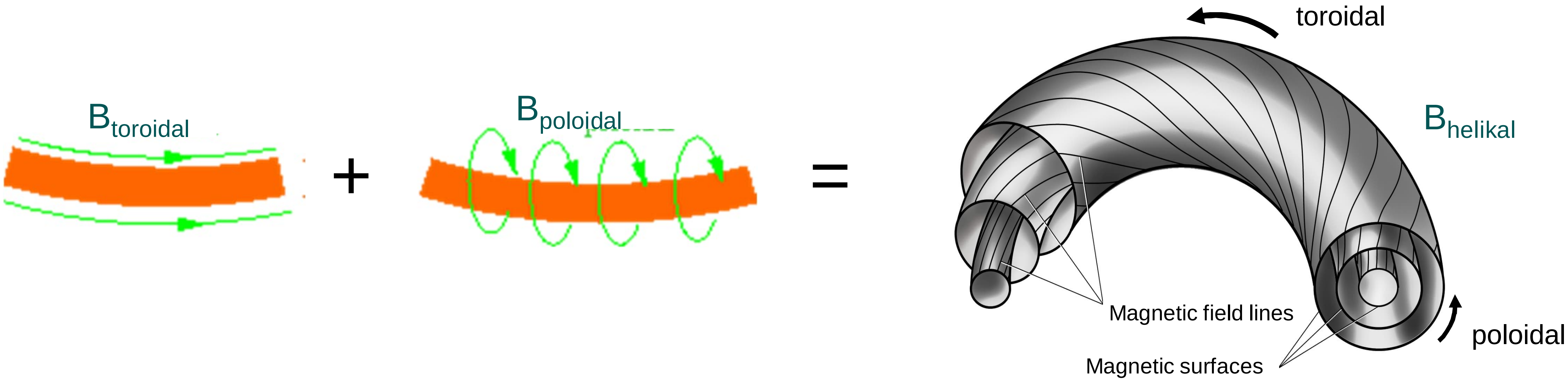


- Curved magnetic field → ∇B-force $\vec{F} = -\mu\vec{\nabla}B = -\frac{mv_\perp^2\,\vec{\nabla}B}{2B}$
- Centrifugal force $\vec{F} = -\frac{mv_\parallel^2\,\vec{\nabla}B}{B}$
- Drift velocity $\vec{v}_D = \frac{\vec{F}\times\vec{B}}{q\cdot B^2}$

- **∇B-drift leads to charge separation** $\vec{v}_D \propto \frac{E_{kin}}{q\cdot B^3}\vec{B}\times\vec{\nabla}B$
- **ExB drift moves particles outwards** $\vec{v}_D = \frac{\vec{E}\times\vec{B}}{B^2}$

Magnetically confined fusion

Purely toroidal field features drifts and low confinement → use torus with helical field lines



Transport parallel to B-field

Long mean free path of particles (≈ 20 km)

Transport perpendicular to B-field

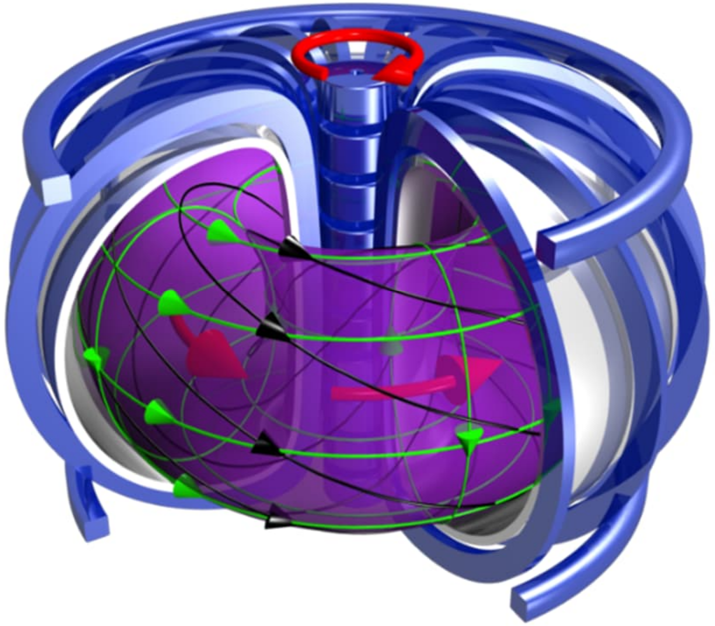
Classical diffusion due to collisions

Magnetically confined fusion

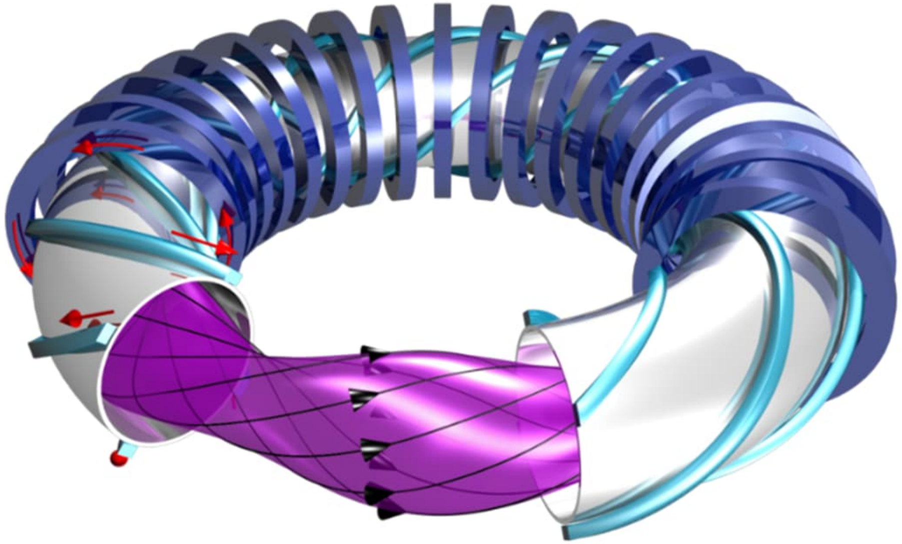
Concepts to generate magnetic field configurations

TOKAMAK
(1952 Sacharov and Tamm)

Stellarator
(1951 Spitzer)



Plasma current generated via transformator



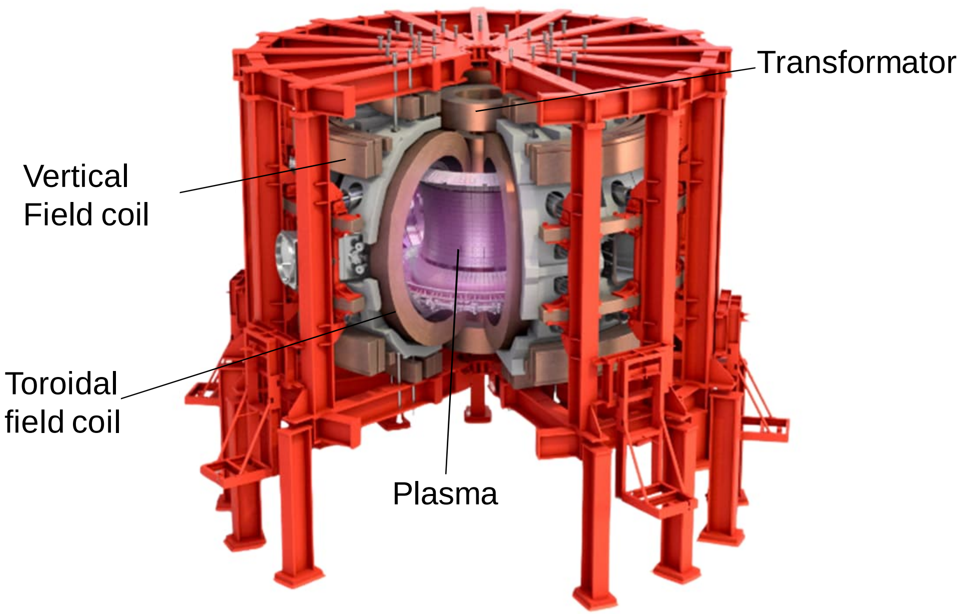
Only external field coils

Magnetically confined fusion

Tokamak: ASDEX Upgrade (Garching)

Operational since 1991

∅ 10 m, height 9 m

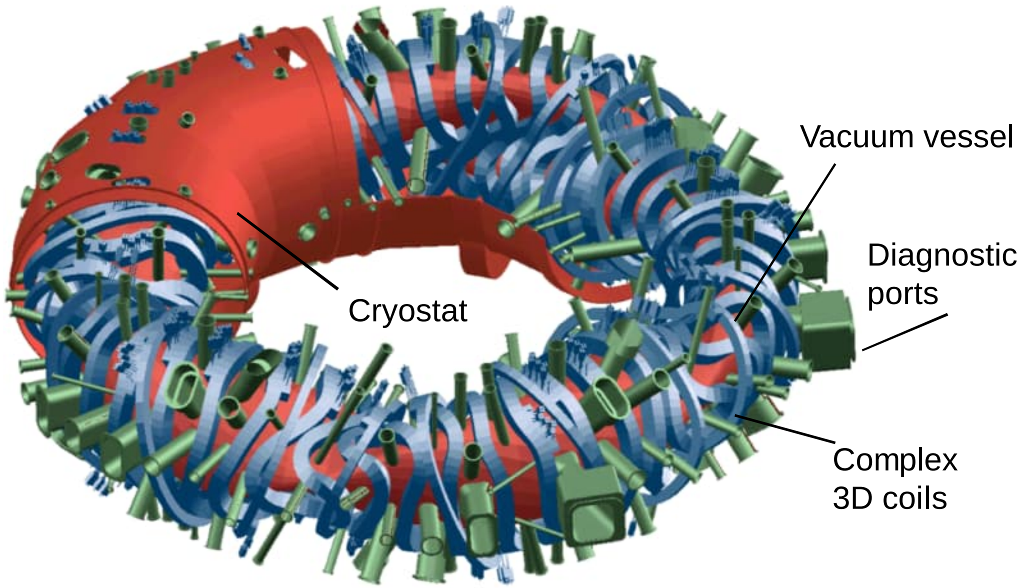


- 10 s plasma
- 14 m^3 plasma volume, 3 mg Gas
- B = 3 T, plasma current 1.6 MA
- 30 MW external heating

Stellarator: Wendelstein 7-X (Greifswald)

2005 Construction, 2015 first plasma

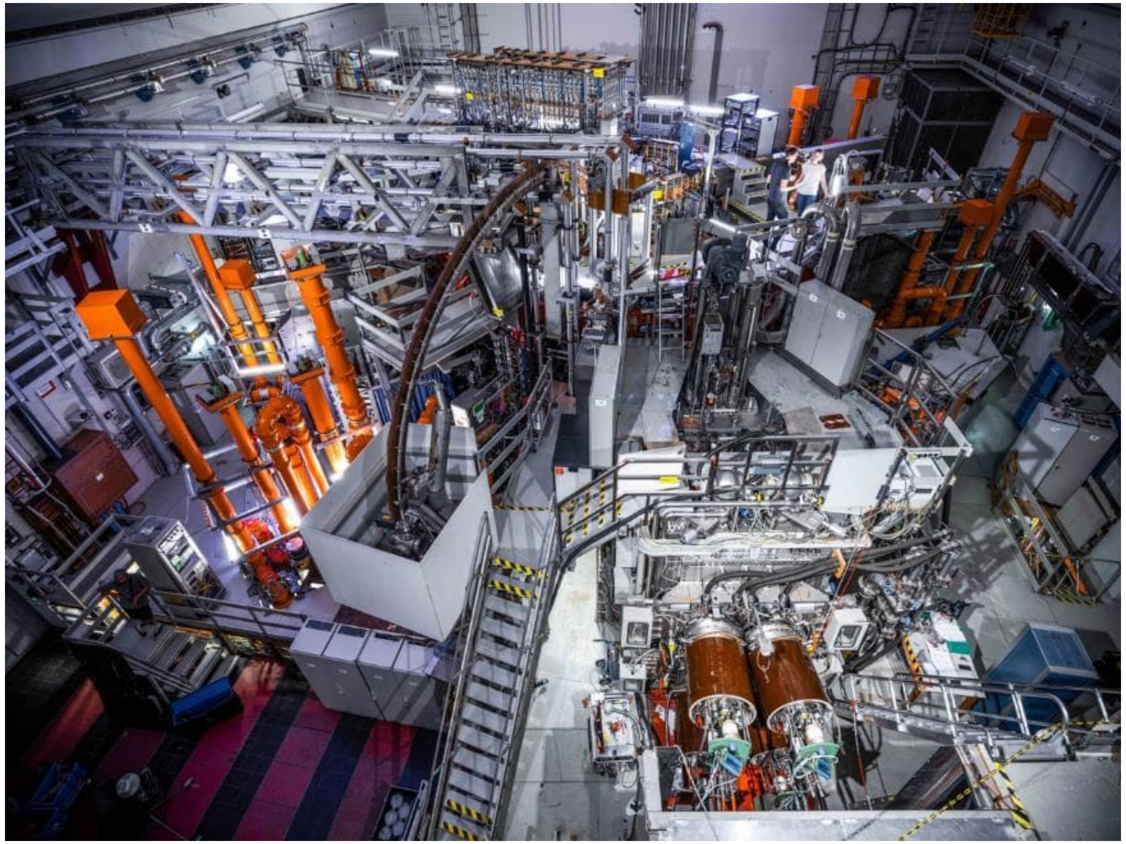
∅15 m, height 4 m



- 30 min plasma
- 30 m^3 plasma volume, 5 mg gas
- B = 3 T (super conducting coils, NbTi)
- 14 MW external heating

Magnetically confined fusion

Tokamak: ASDEX Upgrade (Garching)



Stellarator: Wendelstein 7-X (Greifswald)

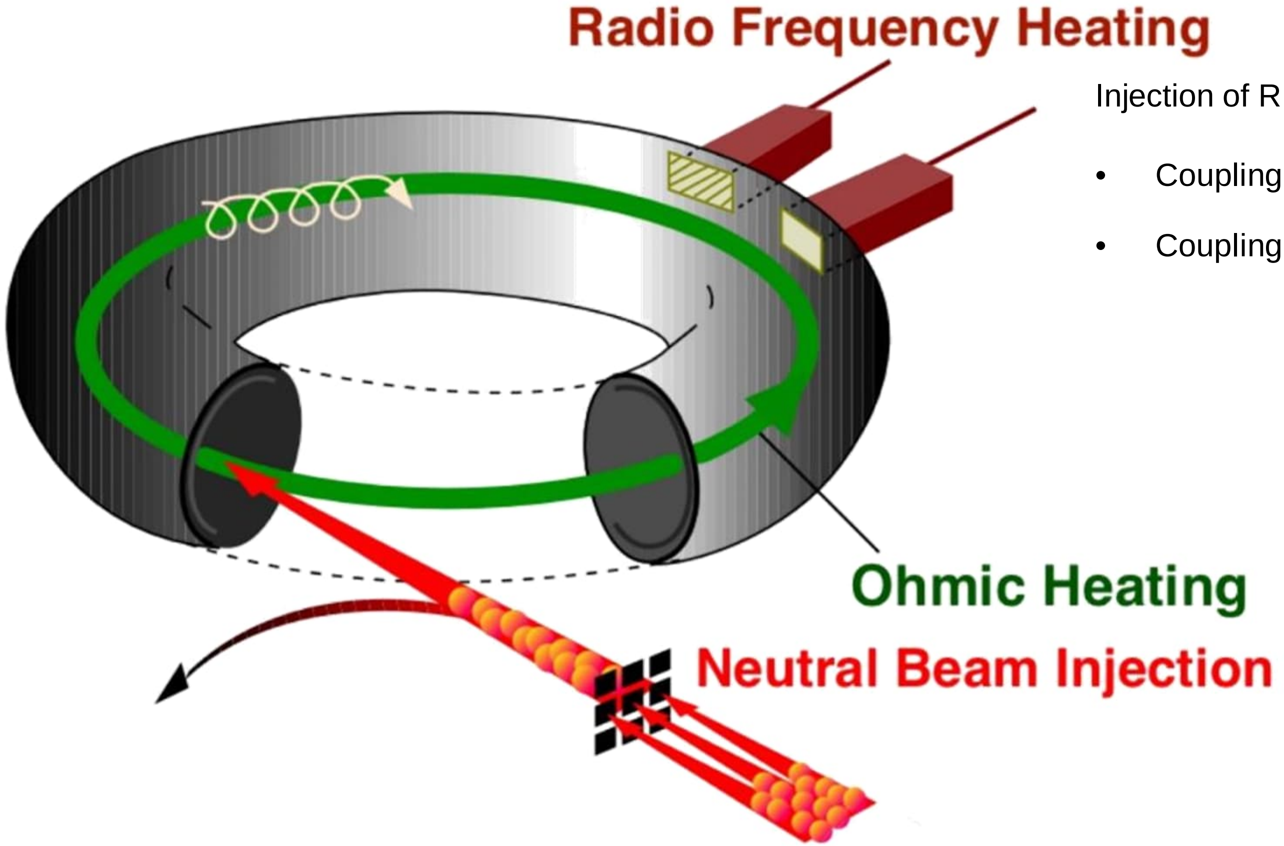
Magnetically confined fusion

Tokamak: ASDEX Upgrade (Garching)

Stellarator: Wendelstein 7-X (Greifswald)

Magnetically confined fusion – External heating systems

In order to reach high plasma temperatures, various heating systems are in use



Injection of RF waves with $2\pi f = \omega_c = \frac{q \cdot B}{m}$

- Coupling to electrons (ECRH): $\omega_c \sim 50 - 170\ GHz$
- Coupling to ions (ICRF): $\omega_c \sim 30 - 100\ MHz$

Plasma current in tokamaks:

$$j = \sigma \cdot E \sim T_e^{\frac{3}{2}} \frac{U}{2\pi R}$$

Injection of energetic neutral particles

In fusion reactor:

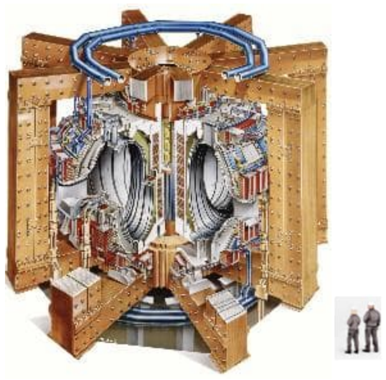
- **α**-particle heating
  He produced by DT-reaction remains confined and adds 3.5 MeV per particle to the plasma

Magnetically confined fusion – step ladder approach

Radius x2

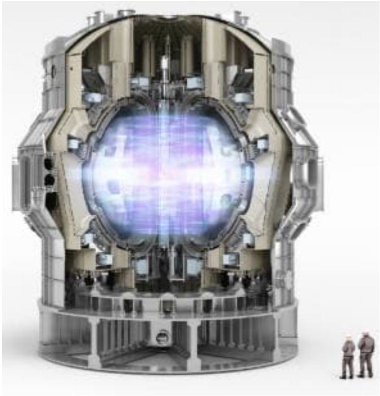
ASDEX Upgrade
Garching

JET
UK
(until 2023)

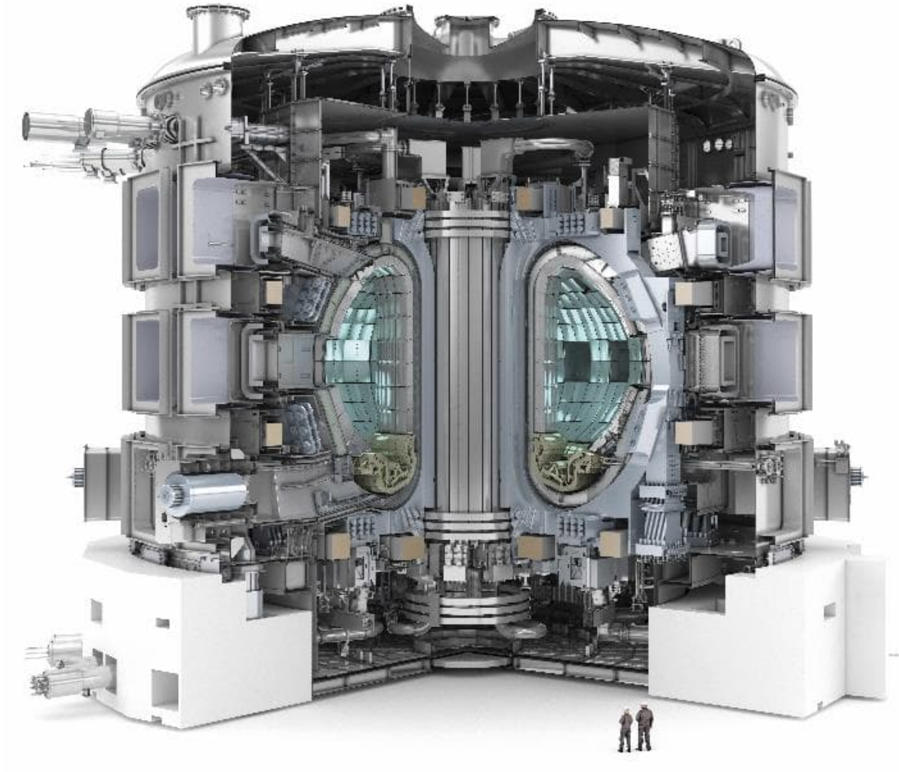


Radius x2

JT-60SA
Japan
(extension
until 2025)



ITER
France
(2034 onwards)



1.65 m	~2.96 m	~2.96 m	6.2 m	Major Radius
14 m³	~80 m³	~135 m³	~800 m³	Plasma volume

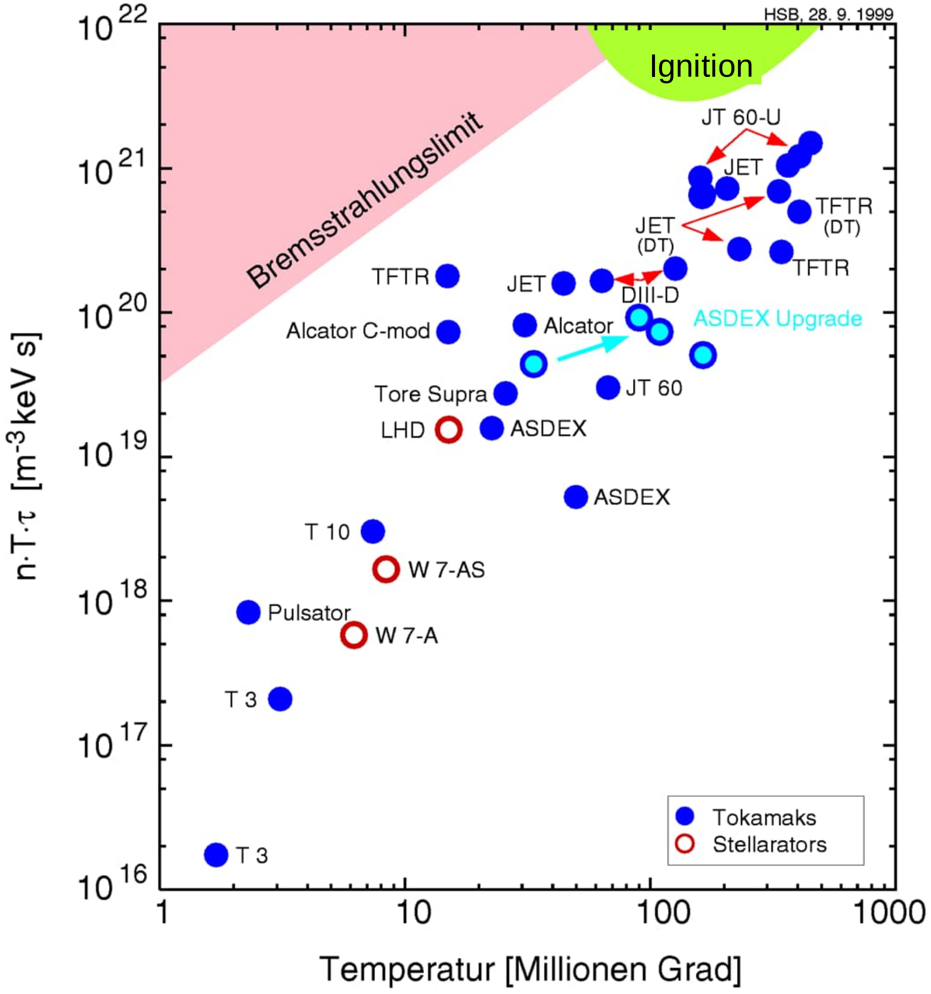
Criterion for fusion success – n·T·τ

Requirements for burning fusion plasmas

- **High temperature (T)**
  - ✓ 400 Mio. °C achieved
- **High particle density (n)**
  - ✓ 10^{20} particles/m^3 achieved
- **Long energy confinement times (τ)**
  - ✗ τ < 1 s up to now

Improvement of energy confinement needed

➢ **Larger and/or better**



Recent updates on fusion achievements – world wide

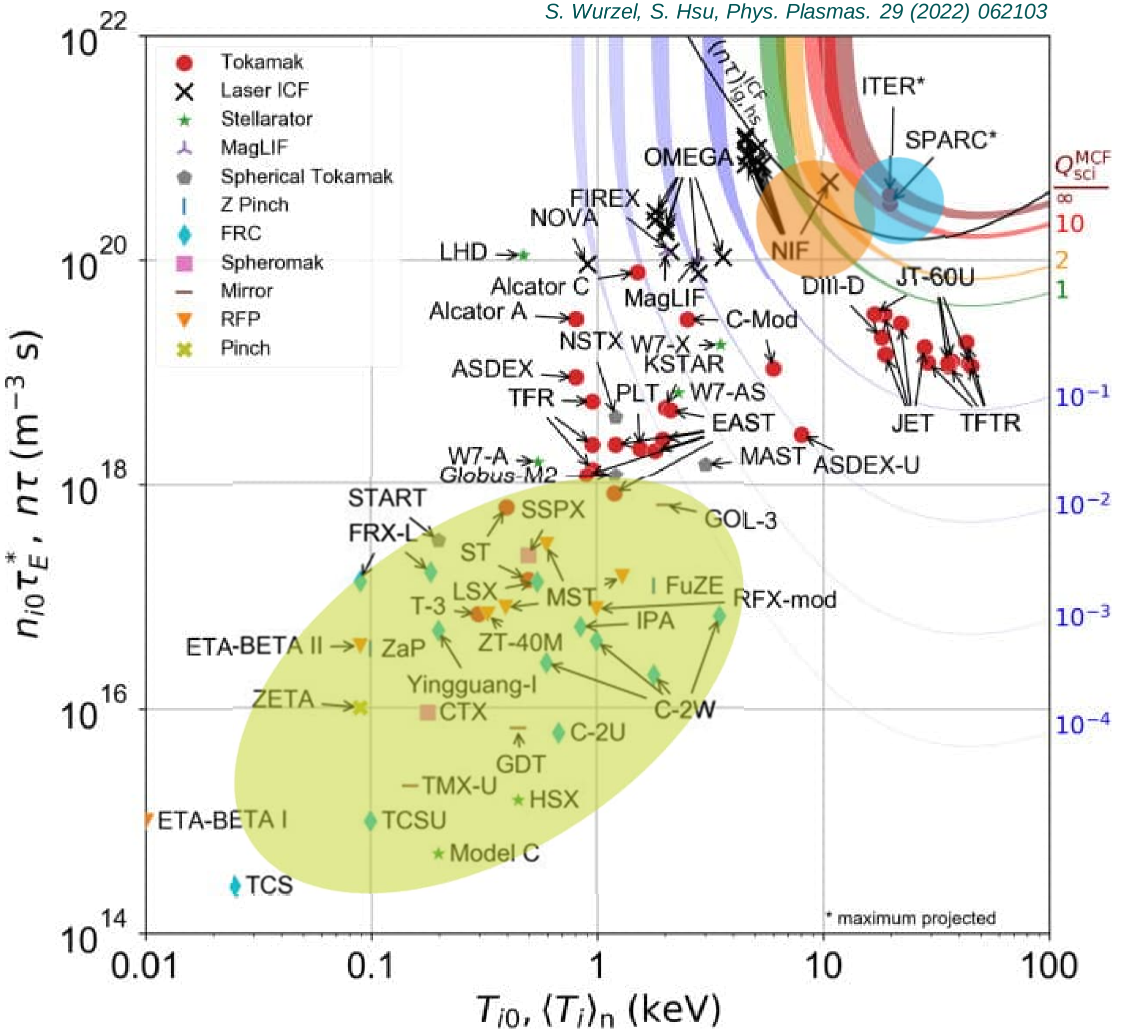
- **Overall progress of fusion is remarkable**
  - Fusion energy gain $Q = \frac{P_{fus}}{P_{heat}} = \frac{5P_{\alpha}}{P_{heat}}$

- **NIF (inertial confinement) achieved Q=1.5**

- **Field-reversed configurations (FRC) are far behind conventional magnetic confinement in terms of fusion gain**

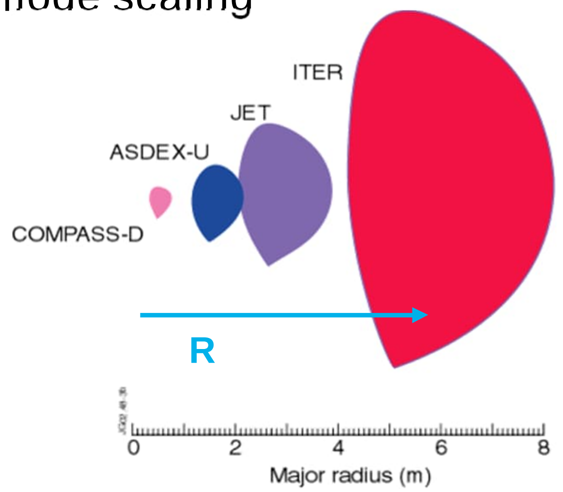
- **SPARC: New private industry tokamak**
  - DT fuel, targets Q=10 for short pulses
  - Start of operation 2027

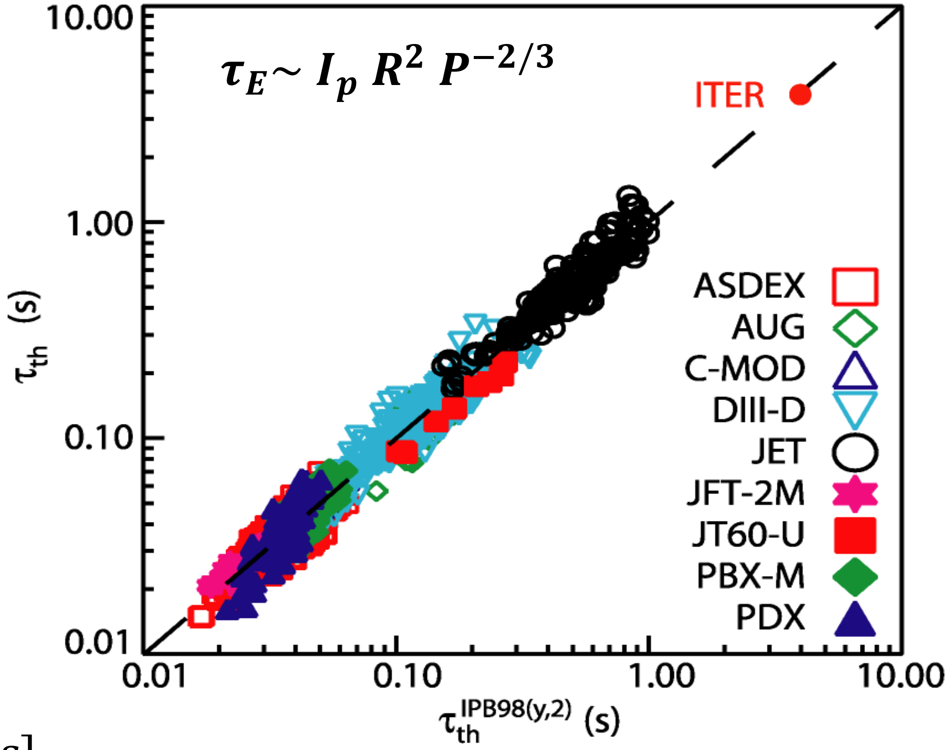
S. Wurzel, S. Hsu, Phys. Plasmas. 29 (2022) 062103



Energy confinement – empirical scalings

- **Energy confinement is difficult to predict quantitatively**
  - ➢ **use scalings from experiments + plasma physics limits**
    - Baseline is robust standard H-mode,
      achieved in every operating tokamak with divertor
    - IPB98(y,2) Type-I ELMing H-mode scaling



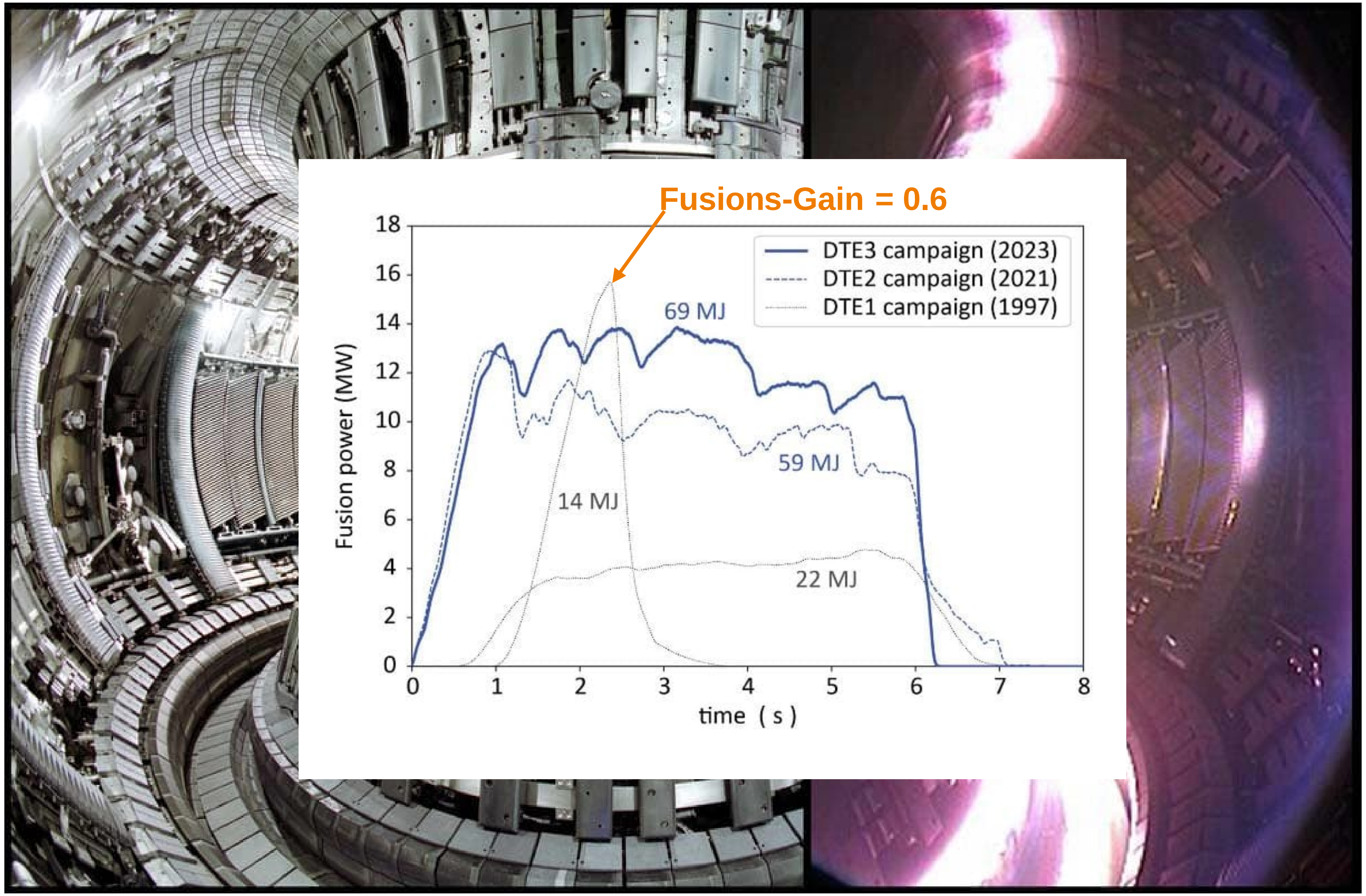


$$\tau_{E,th}^{98(y,2)} = 0.144\; I^{0.93}\; B^{0.15}\; P^{-0.69}\; n^{0.41}\; M^{0.19}\; R^{1.97}\; \varepsilon^{0.58}\; \kappa^{0.78}\;\; [s]$$

Recent updates on fusion achievements – JET 2023

Joint European Torus (JET)

- **Largest operational facility until 2023**
- **3 DT campaigns**
- **Q=0.6 over several seconds**



Fusions-Gain = 0.6

Source: Eurofusion

Challenges in ICF

Hohlraum targets

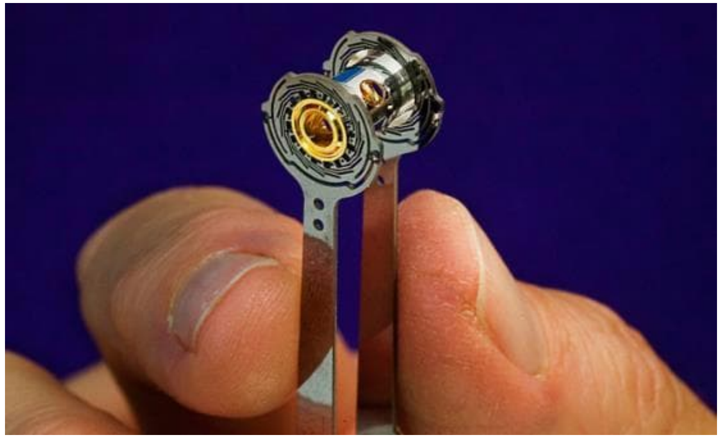
- High precision capsule with cryogenic DT pellet
- Mass production

High power lasers

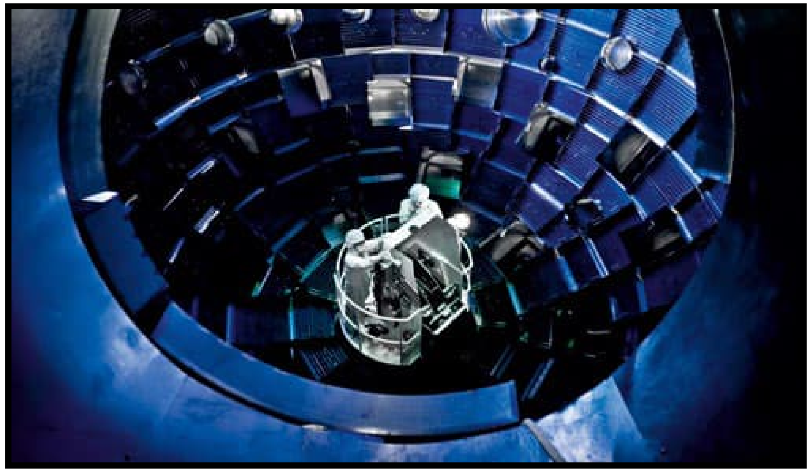
- Increase wall-plug efficiency
- Illuminate pellet uniformly to avoid instabilities

Reactor scale integration

- Reliable laser power at up to 10 Hz repetition
- Requires ignition of DT pellets at up to 10 Hz
- Alignment of pellets in laser focus
- Handling of fusion power and T breeding



Picture: LLNL



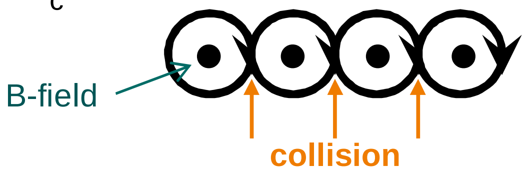
https://lasers.llnl.gov

Challenges in MCF – the reality of confinement

Transport perpendicular to B-field limits energy confinement

Classical diffusion

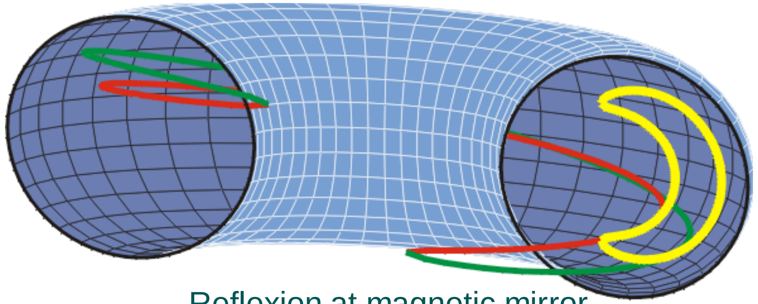
- Displacement due to collisions by Larmor radius $\Delta x = r_c$



$$D = \frac{\Delta x^2}{\Delta t}$$

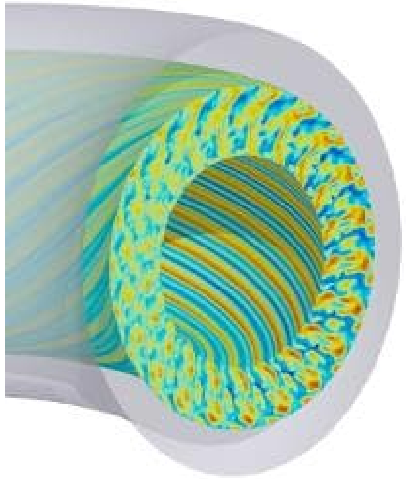
Neoclassical transport

- Collision of particles trapped on banana orbits
- Displacement is width of banana orbit


Reflexion at magnetic mirror

Turbulent transport

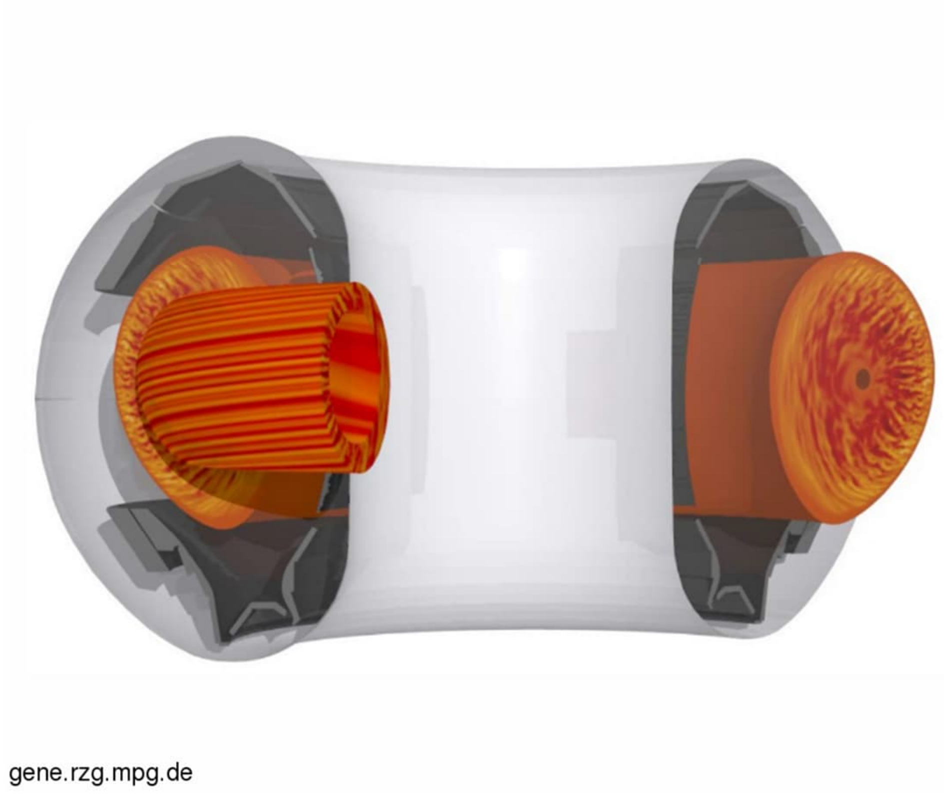
- Displacement is extent of turbulent structures



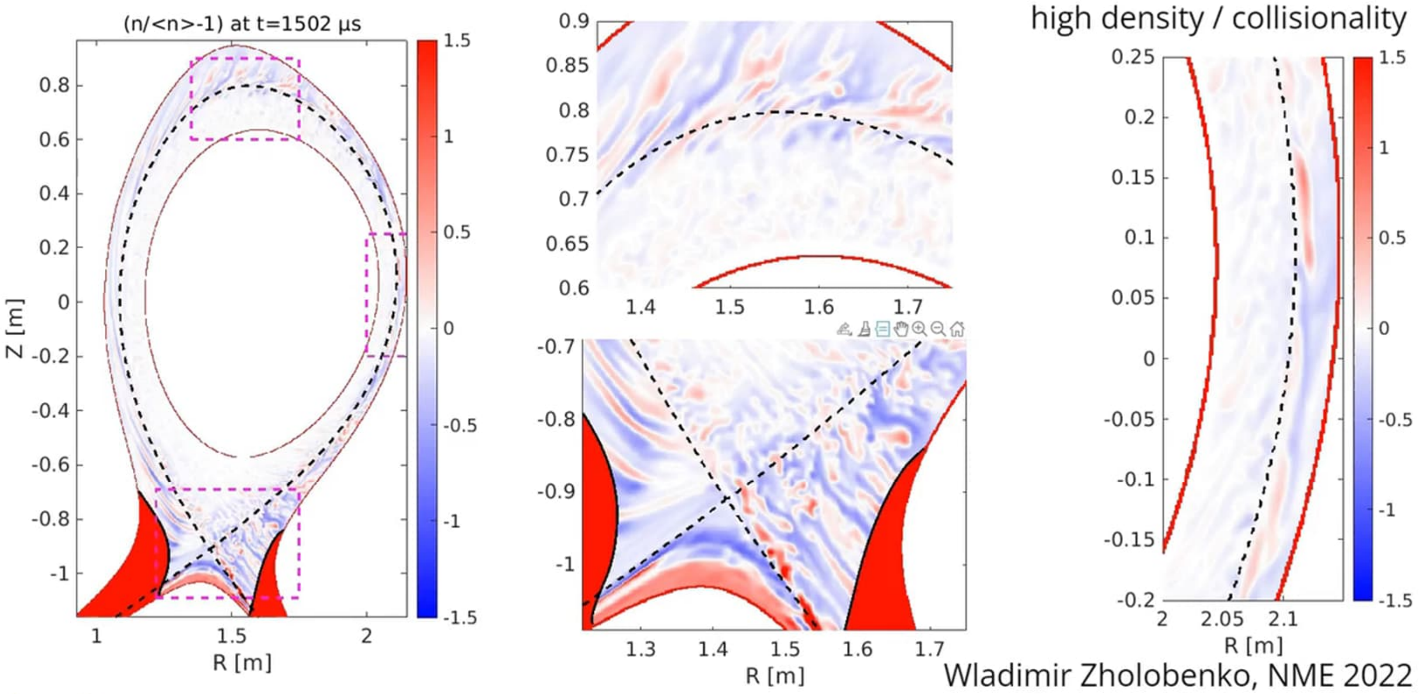
	Δx	D	Torus
Classic Diffusion	r_c	D	10 cm
Neoclassic Transport	$10 \cdot r_c$	$100 \cdot D$	1 m
Turbulenz	$100 \cdot r_c$	$10000 \cdot D$	10 m

Challenges in MCF – the reality of confinement

Turbulence can meanwhile be measured and simulated


gene.rzg.mpg.de

GENE

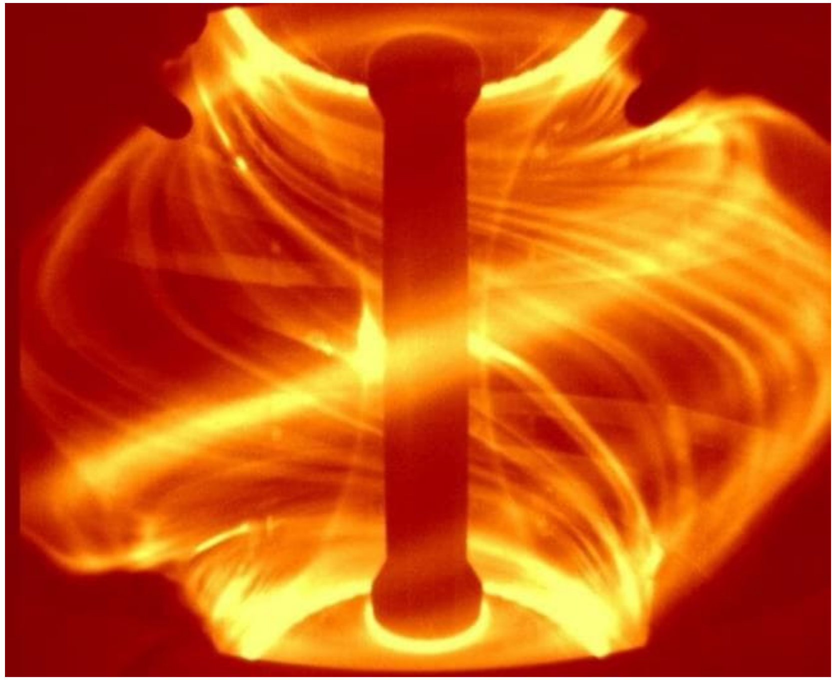


Wladimir Zholobenko, NME 2022

- Experiments and theoretical calculations agree
- More and more phenomena can be understood ab initio

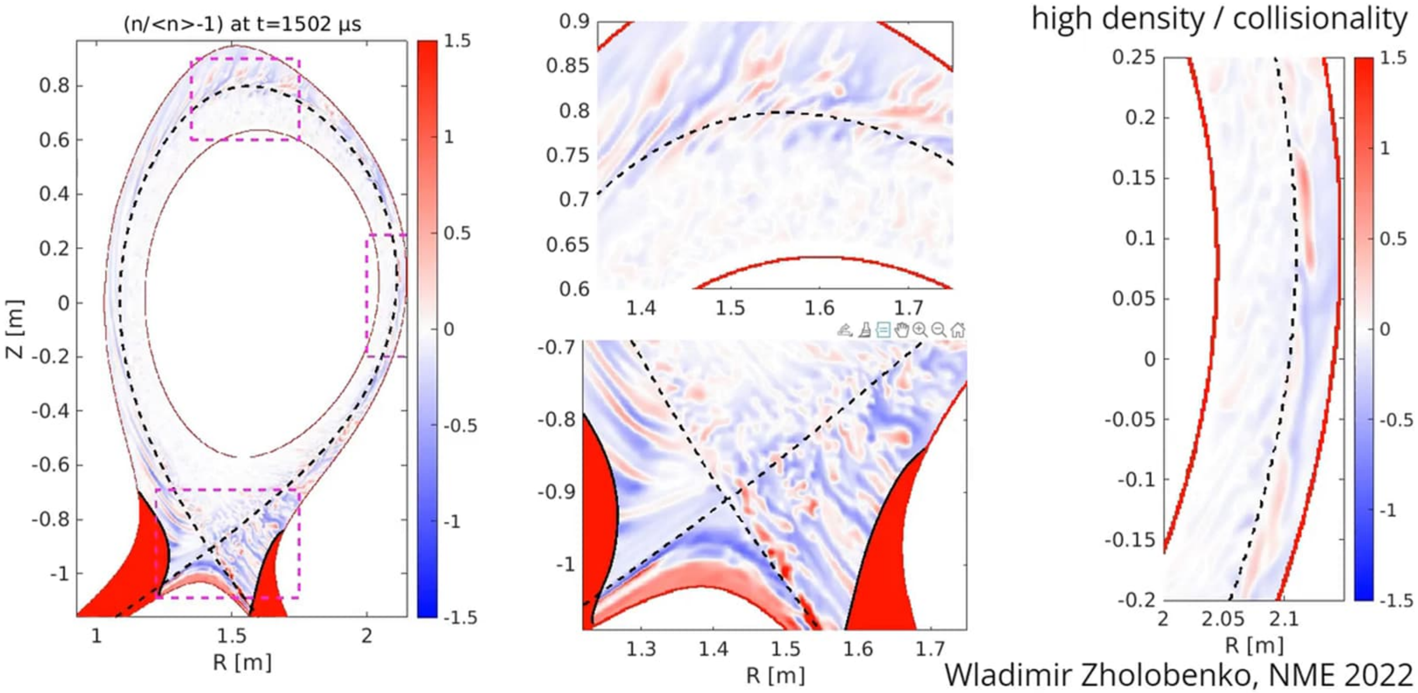
Challenges in MCF – the reality of confinement

Turbulence can meanwhile be measured and simulated



Press release, CCFE, Tuesday 26 June 2012

High-speed video image of the MAST plasma obtained at the start of an Edge Localized Mode.



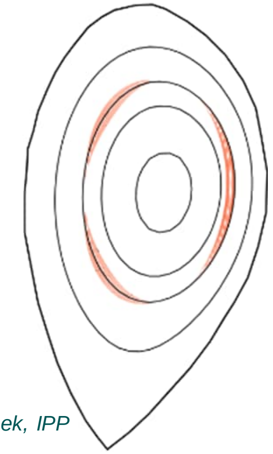
Wladimir Zholobenko, NME 2022

- **Experiments and theoretical calculations agree**
- **More and more phenomena can be understood ab initio**

Challenges in MCF – instabilities, disruptions

Plasma current as source of free energy leads to resonant magnetic flux surfaces

- Development of magnetic islands and MHD instabilities



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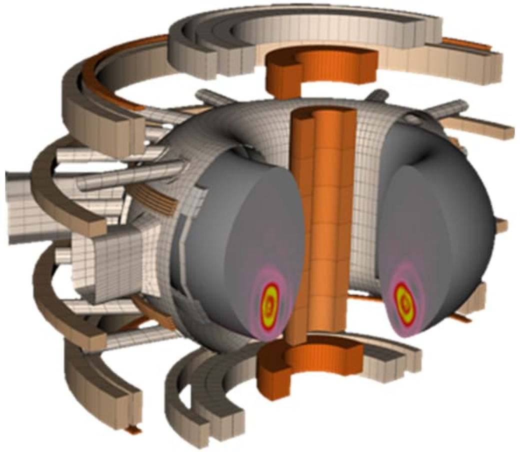


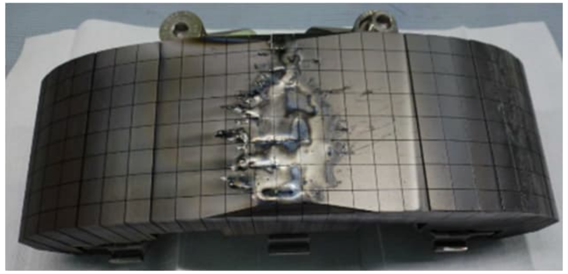
- Can interrupt plasma current and thus confinement

➢ **Disruptions**

Simulation and video of a vertical displacement event in ASDEX Upgrade

Challenges in MCF – instabilities, disruptions

- **Disruptions can cause**
  - Severe mechanical and thermal loads
  - Damage to in-vessel components



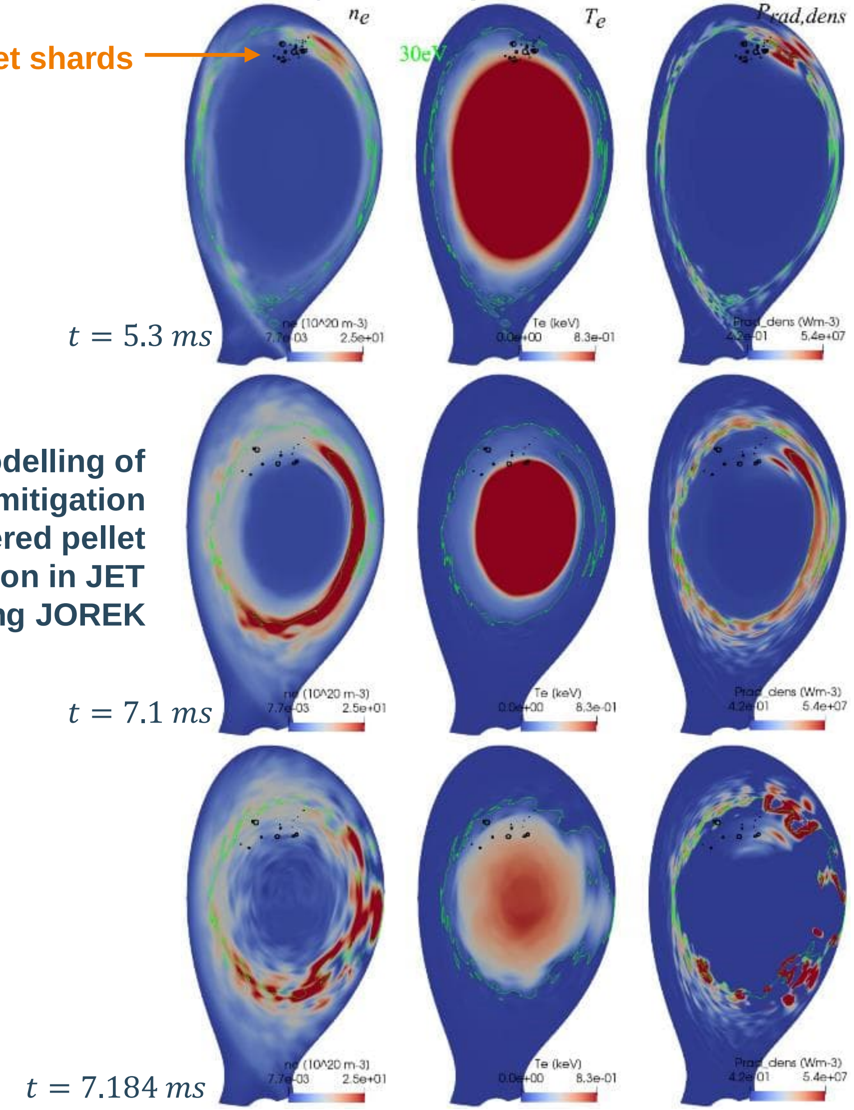
Melting of first wall in JET due to runaway electrons

I. Jepu, IAEA Fusion Energy Conference 2023

- **Solutions**
  - Plasma operation avoiding resonant surfaces or eliminating them
  - Detection of instabilities
  - Mitigation as last resort

Electron density **Electron temperature** **Plasma radiation**

Pellet shards



Modelling of disruption mitigation by shattered pellet injection in JET using JOREK

M. Kong et al 2024 Nucl. Fusion ***64*** *066004*

Challenges in MCF – power handling

Power balance

$$P_{fus} + P_{ext} = P_{loss} + P_{rad} + \frac{dW}{dt}$$

- α particles are confined and heat plasma
- Radiation and particle losses result in heat fluxes to the wall

Expected heat fluxes to first wall

G. Federici, Fusion Eng. Des. (2015) / M. Wischmeier, J. Nucl. Mater. (2015)

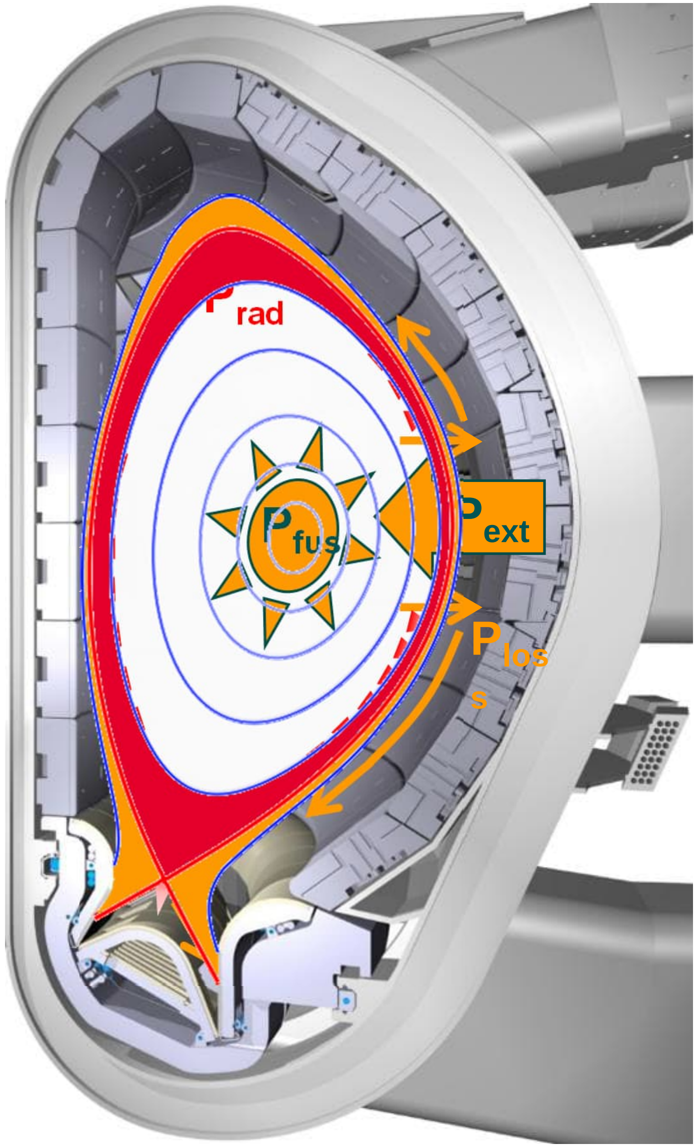
	ITER	DEMO
Unmitigated power fluxes	50 MW/m^2	≥300 MW/m^2
Material limit	~10 MW/m^2	~5 MW/m^2

⇒ **Increase power dissipation to more than 95%**

Solution: impurity seeding

≥ 30% in SOL & divertor

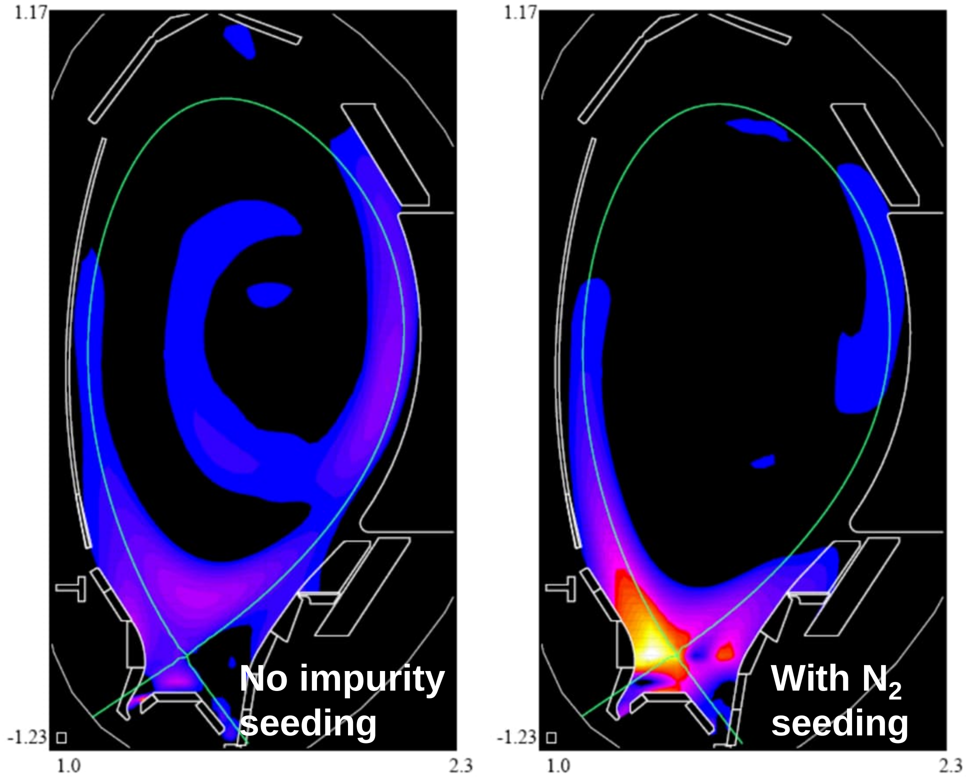
≤ 65% inside confined region, minimal central radiation



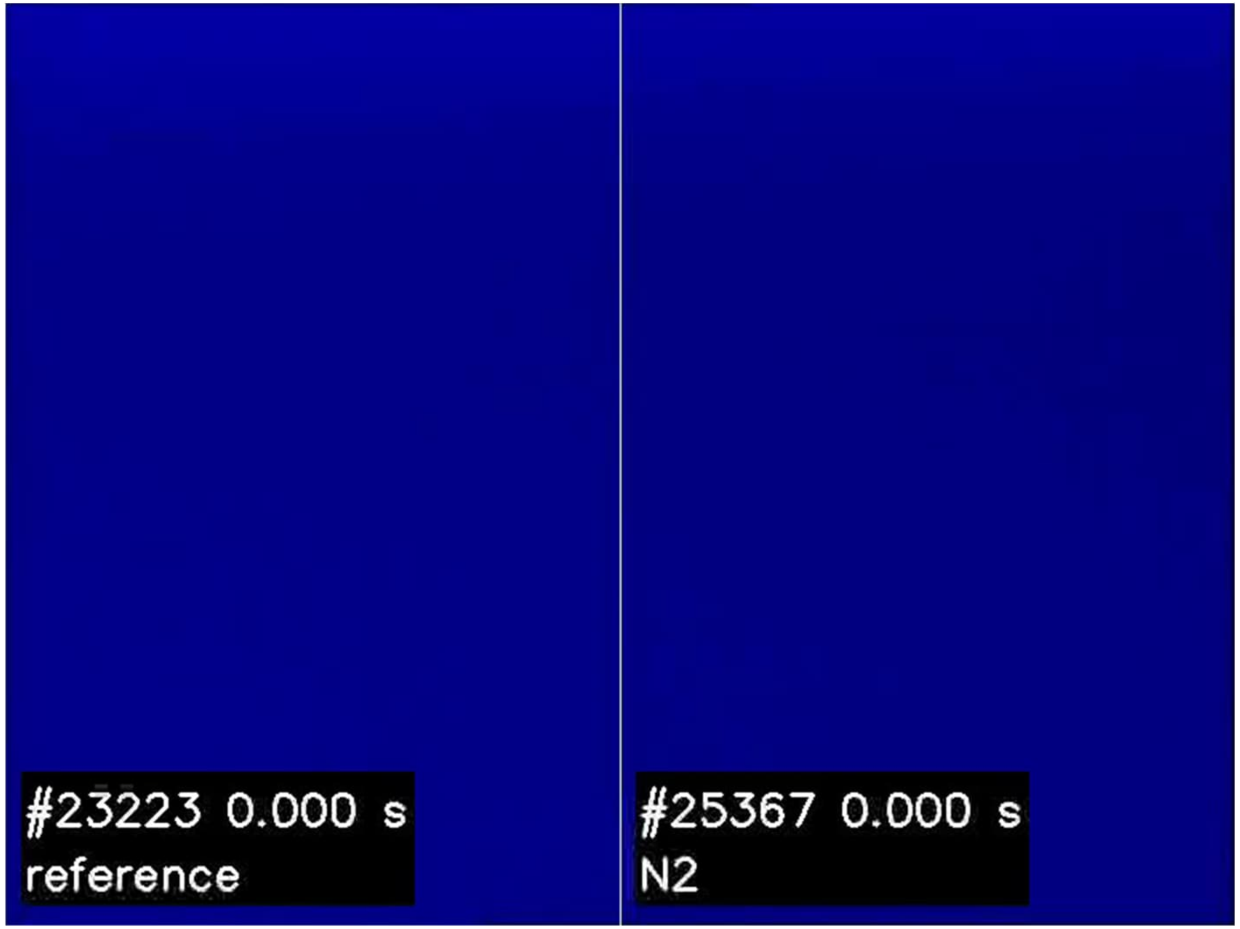
Challenges in MCF – power handling

Results from ASDEX Upgrade

Bolometry of total radiated power



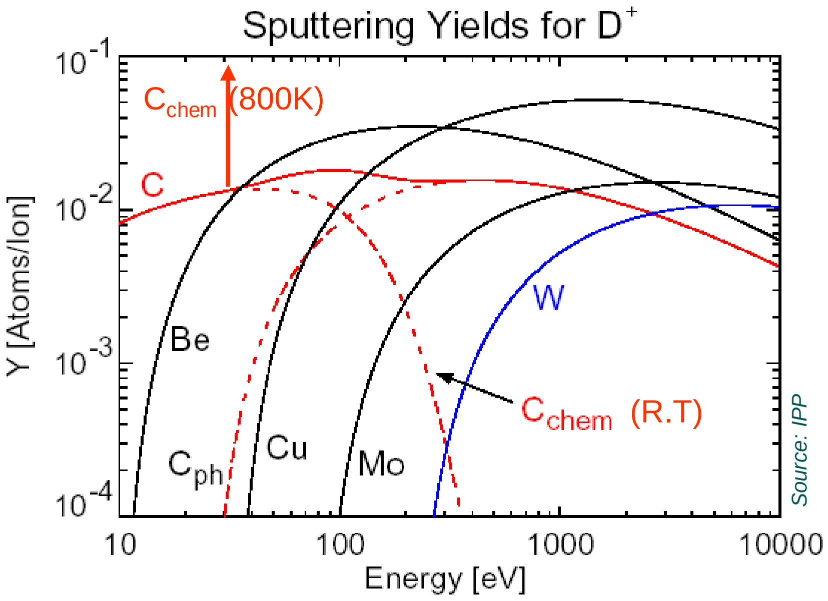
Thermography of power load to divertor target



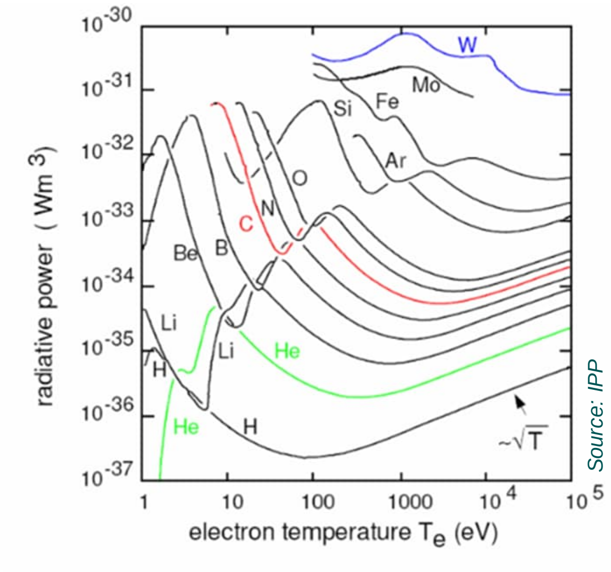
Challenges in MCF – the wall material

Particle and heat fluxes from plasma interact with first wall, which needs to provide

- Thermal stability
- Low erosion
- Low retention of T



Source: IPP



Source: IPP

Solution: W (tungsten)

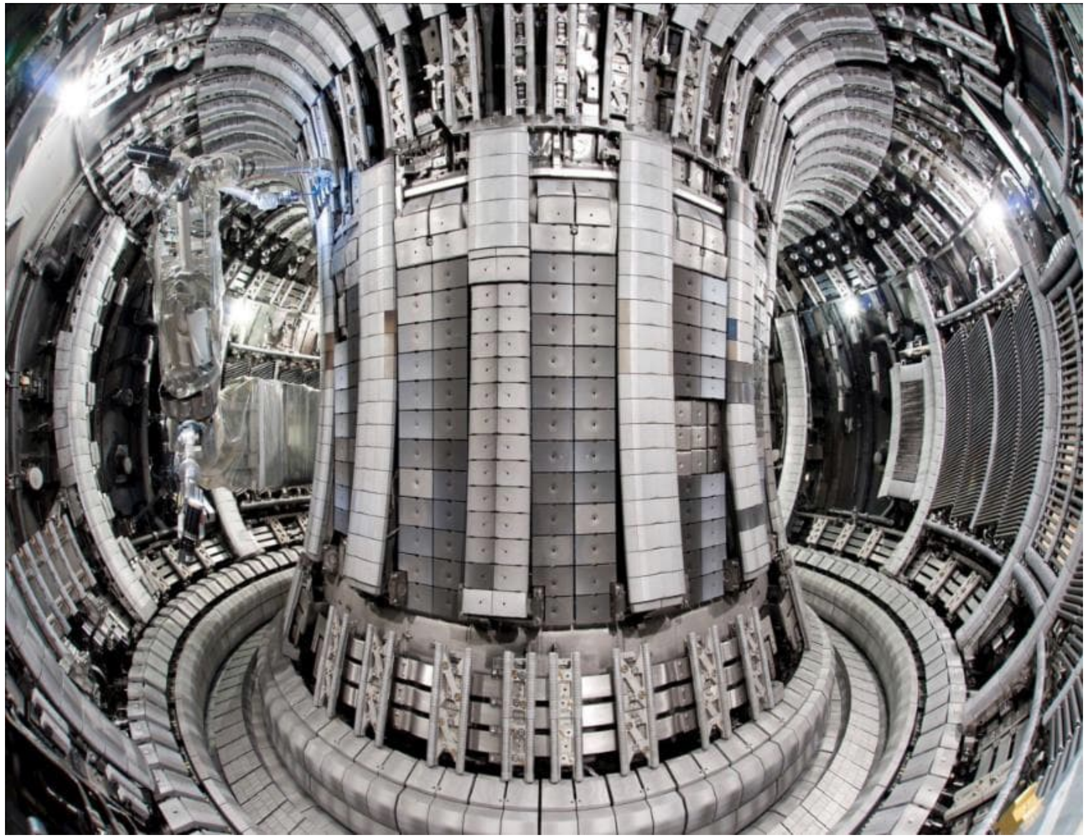
- Highest melting point of all solids
- Very low erosion yield
- Very strong radiator
  → only a fraction of $\leq 10^{-4}$ can be tolerated in plasma centre

Challenges in MCF – the wall material

ASDEX Upgrade

Since 2007: complete first wall out of W

JET

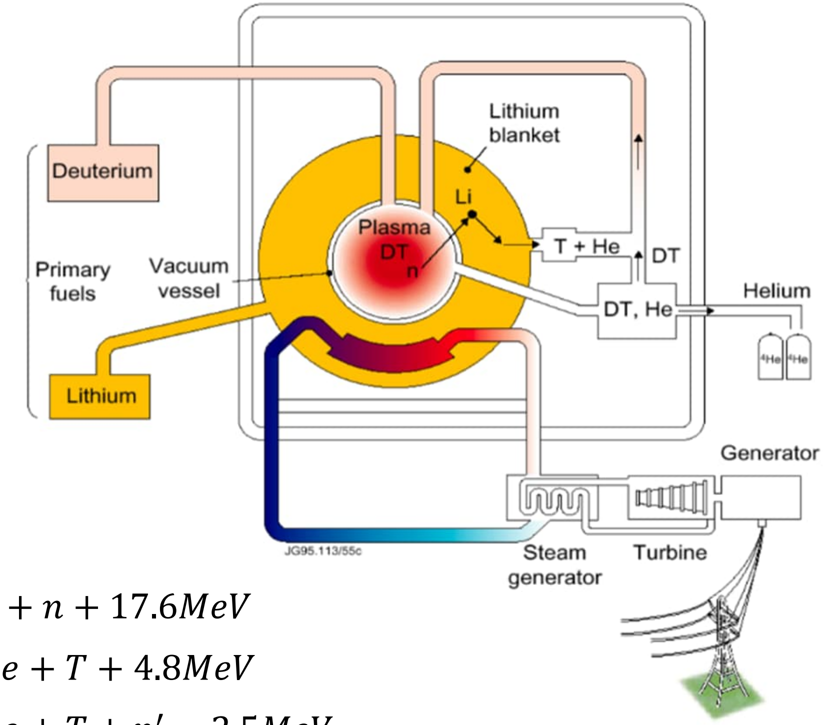


Since 2011: W-divertor

Challenges in MCF – tritium breeding

Tritium decays quickly ($T_{1/2}$ = 12.3 a)

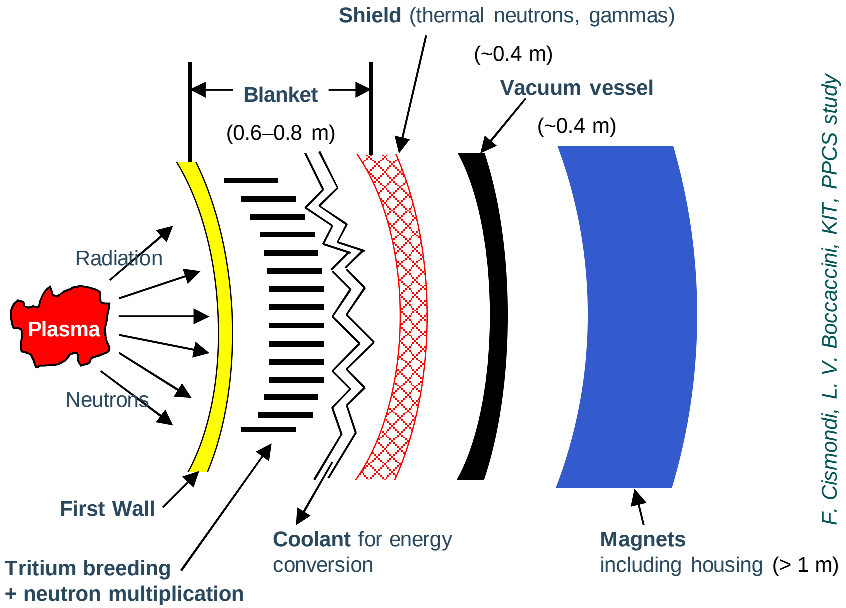
- **Produce T as part of fuel cycle**



$$D + T \rightarrow He + n + 17.6MeV$$

$$^{6}Li + n \rightarrow He + T + 4.8MeV$$

$$^{7}Li + n \rightarrow He + T + n' - 2.5MeV$$



F. Cismondi, L. V. Boccaccini, KIT, PPCS study

- **To produce sufficient amount of T**
  - Tritium breeding rate TBR > 1.1
  - Neutron multiplication required
  - Blanket Modules (BM) need to cover as much surface around plasma as possible
  - Thickness of blanket is fixed → determines size

Challenges in MCF – tritium breeding

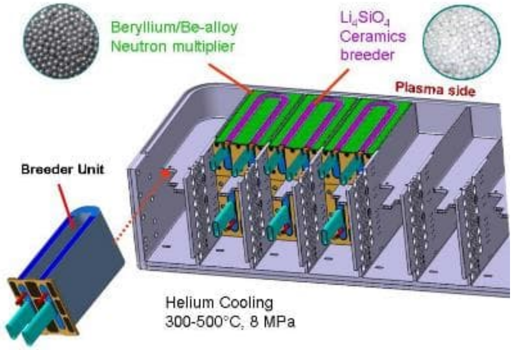
Coverage with blanket modules competes with access to plasma

- Integrate external heating into BMs
- Strongly reduced access for diagnostics
- Advanced control schemes required

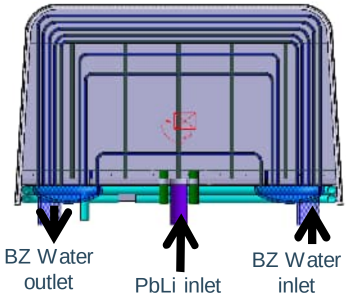
Main European concepts for BM

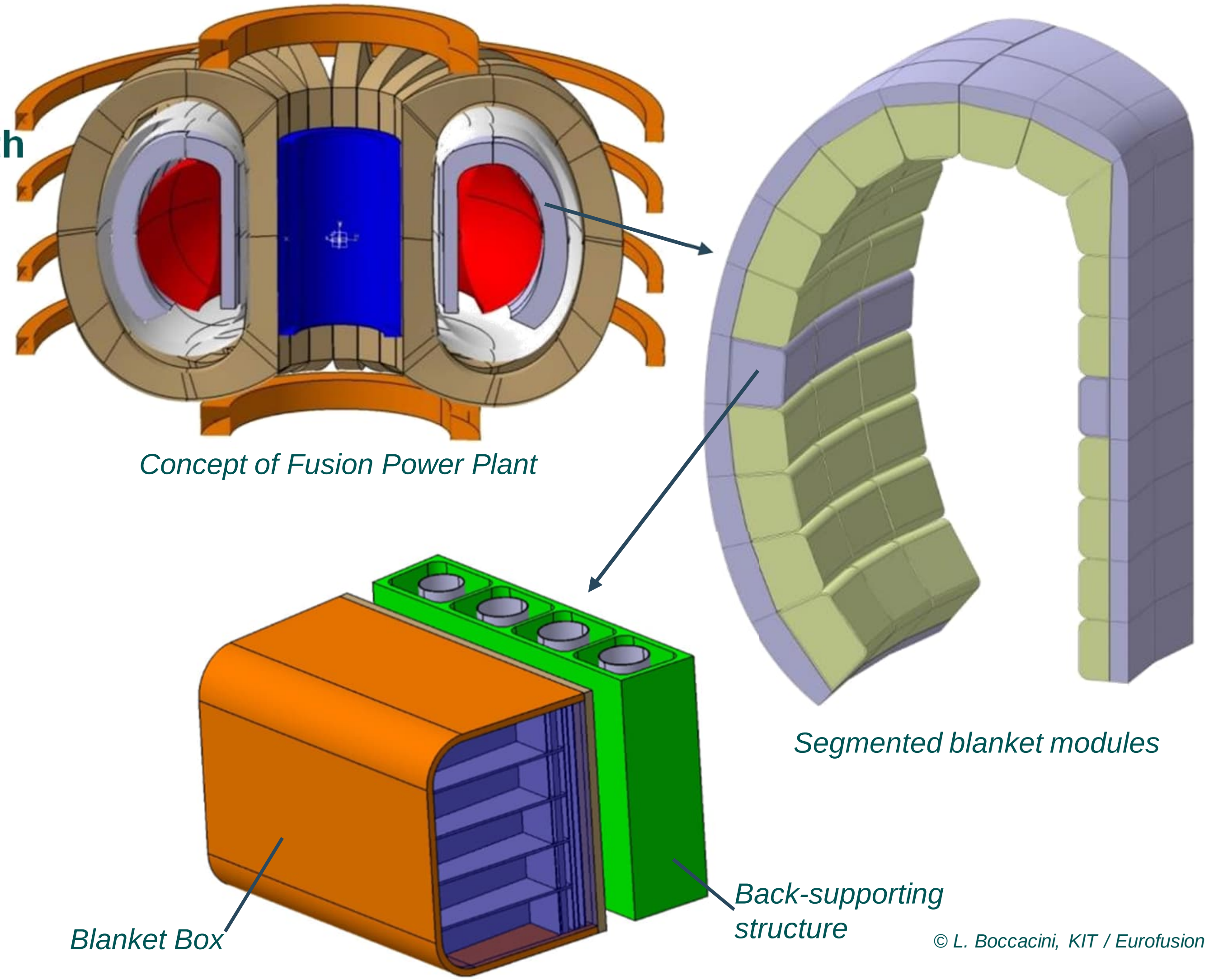
He-cooled Pebble Bed (HCPB)

© L. Boccacini, KIT / Eurofusion



Water-cooled Li-Lead (WCLL)





Concept of Fusion Power Plant

Segmented blanket modules

© L. Boccacini, KIT / Eurofusion

Challenges in MCF – structural materials

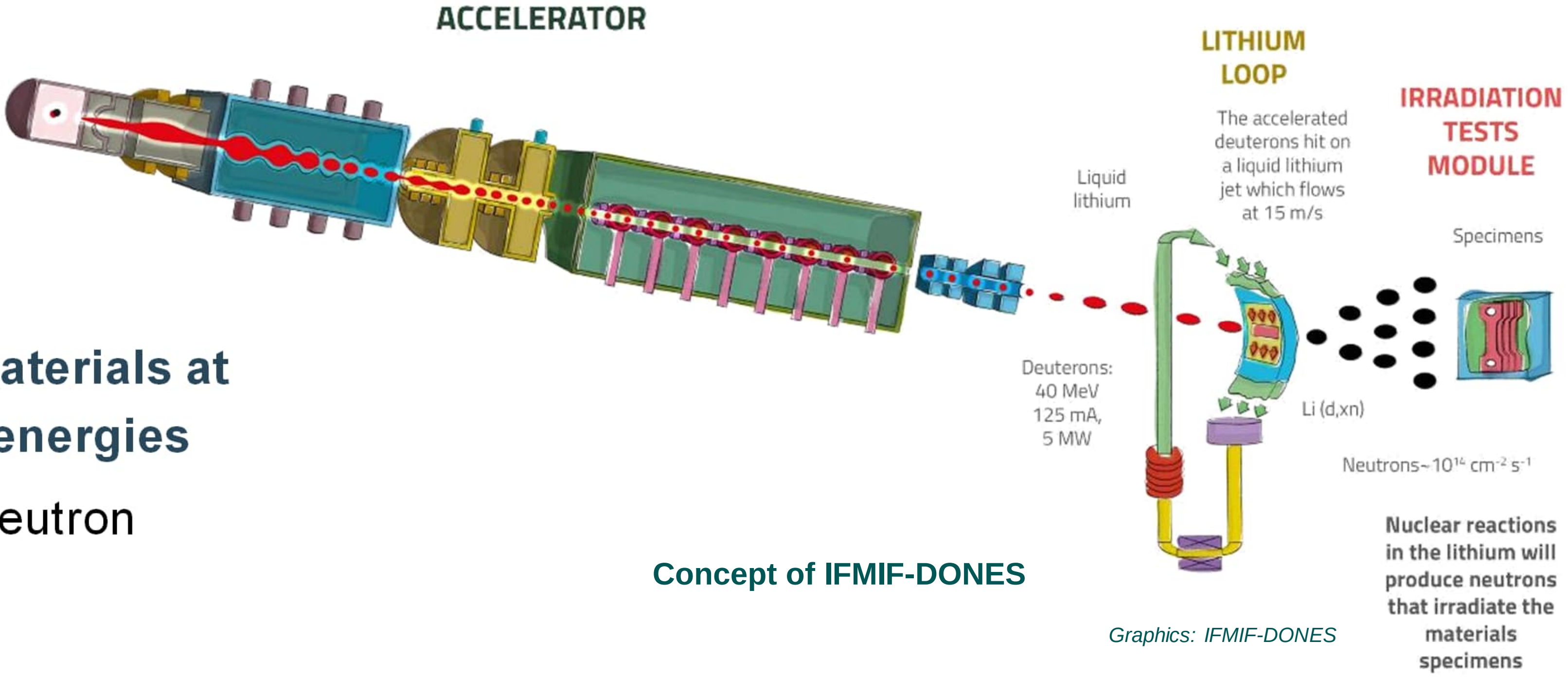
Neutrons from fusion reactions activate structural materials

- **Embrittlement and reduced yield stress**
- **Development of dedicated materials**
  - low-activation steel EUROFER
  - W-fibre reinforced W or Cu

W fibre-reinforced Cu pipe

A. v. Müller et al., Fusion Eng. Des., 2017

- **Testing and verification of materials at relevant neutron fluxes and energies**
  - IFMIF-DONES – dedicated neutron test facility for fusion



Concept of IFMIF-DONES

Graphics: IFMIF-DONES

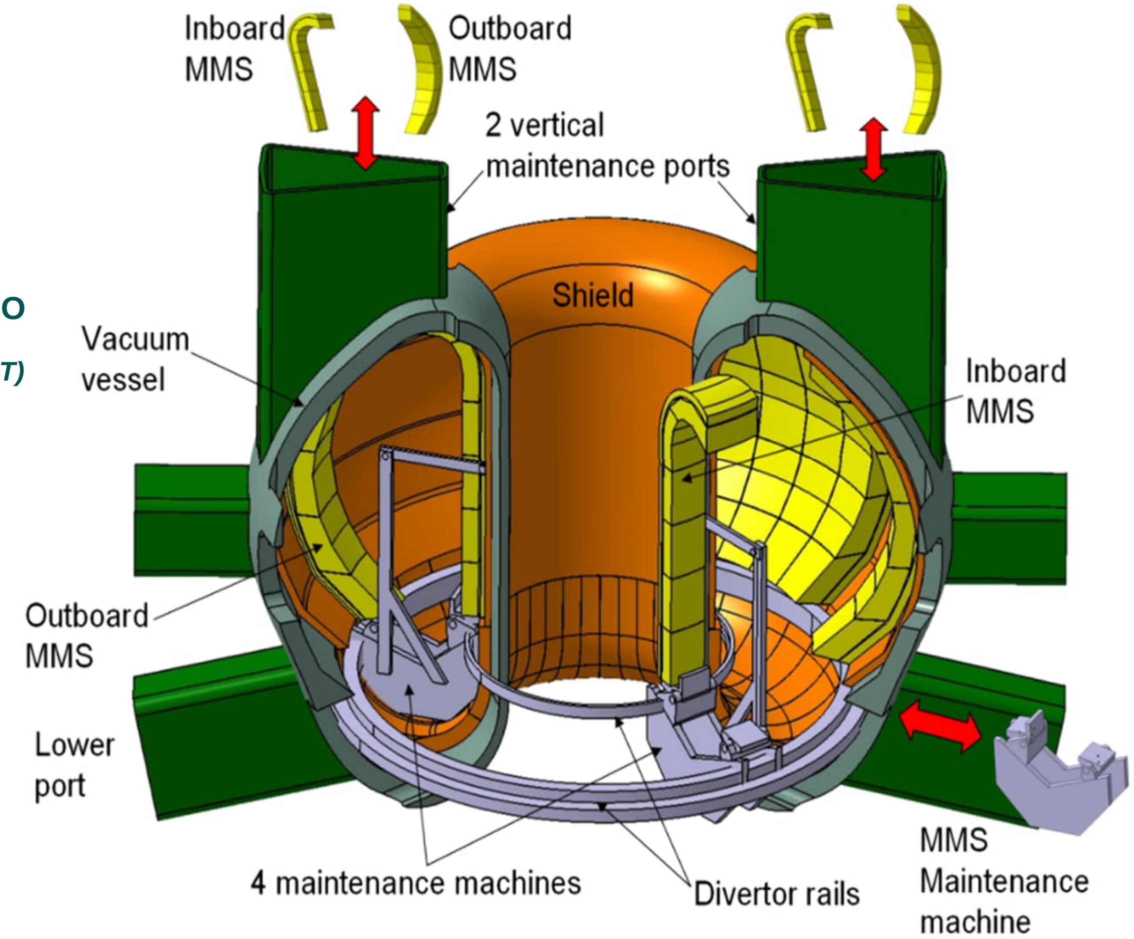
Challenges in MCF – structural materials

Activation prevents human access

- Maintenance and repair through remote-handling

Remote handling concept for blanket modules in DEMO

courtesy D. Filsinger, L. V. Boccaccini, et al. (KIT)

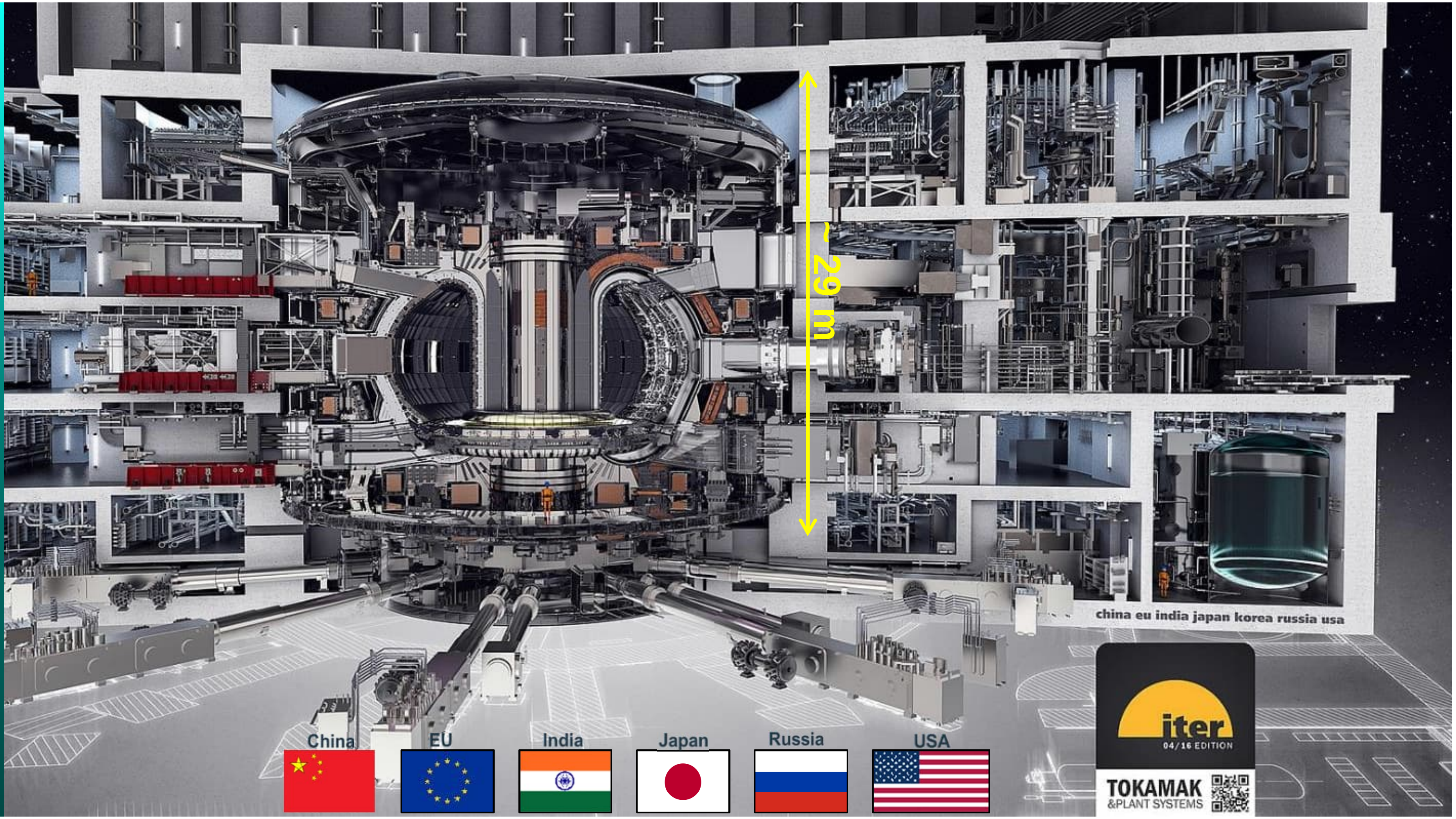


Low activated materials can be handled after few decades of storage, but large volumes of waste will be produced and handling needs to be regulated

ITER – the largest tokamak ever built

Objectives

- Create more energy than needed to heat plasma (Q>1)
- Create plasma dominantly heated by fusion reactions
- Achieve Q = 10 at plasma current of 15 MA
- **Test technologies, materials and physics for commercial fusion-based electricity**

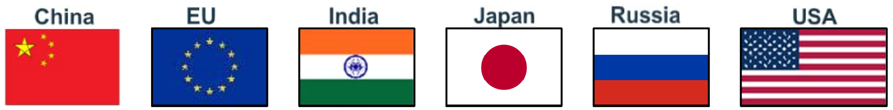


Picture: ITER Organization, http://www.iter.org/

ITER – a worldwide fusion experiment

Seven international partners

- Partners constitute > 80% of world GDP
- Contributions to ITER are provided „in kind“
- Budget is essentially with partners

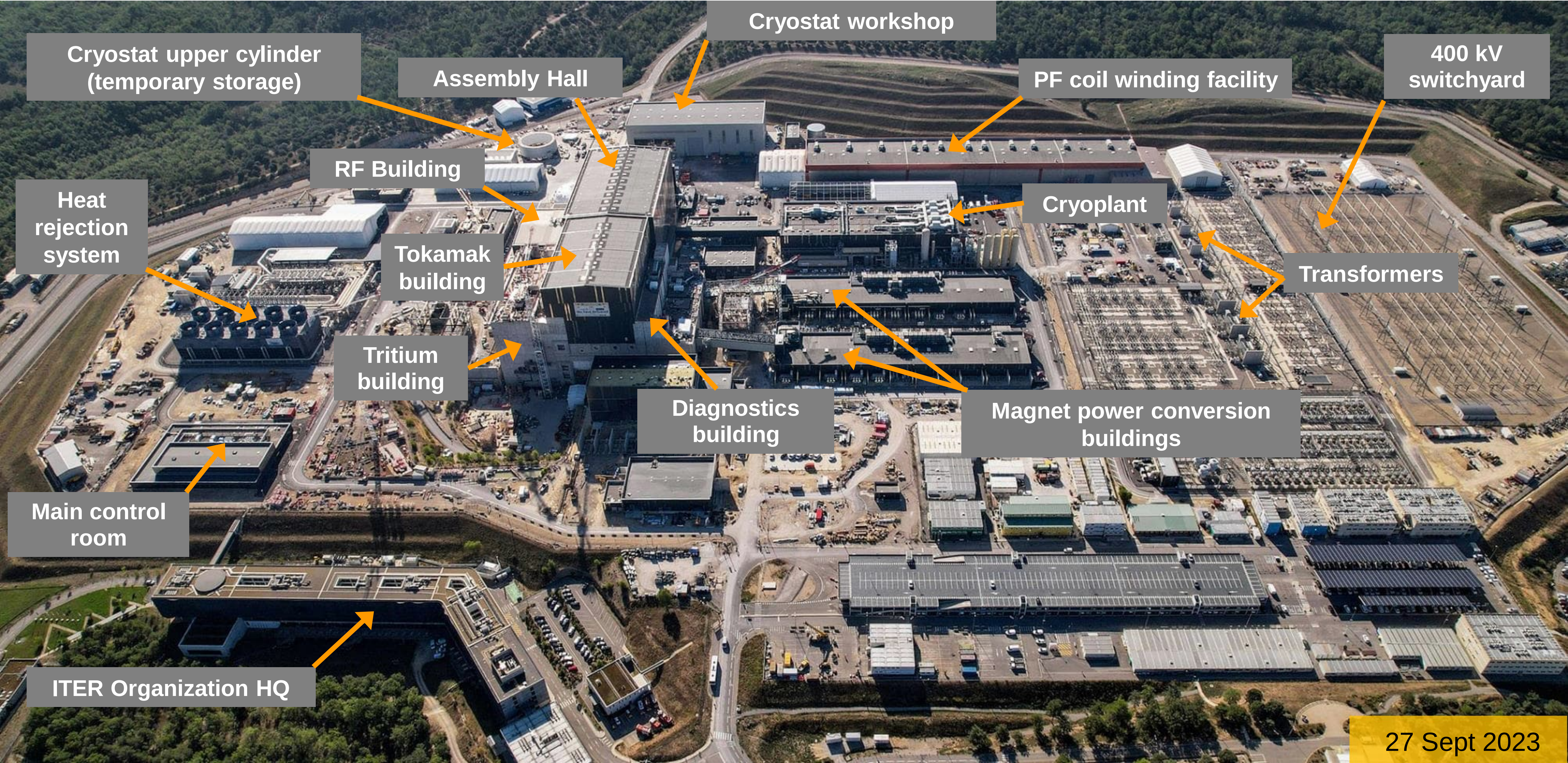


ITER Organization

- Legal entity
- Overall integrator of the project
- Nuclear operator of the ITER facility

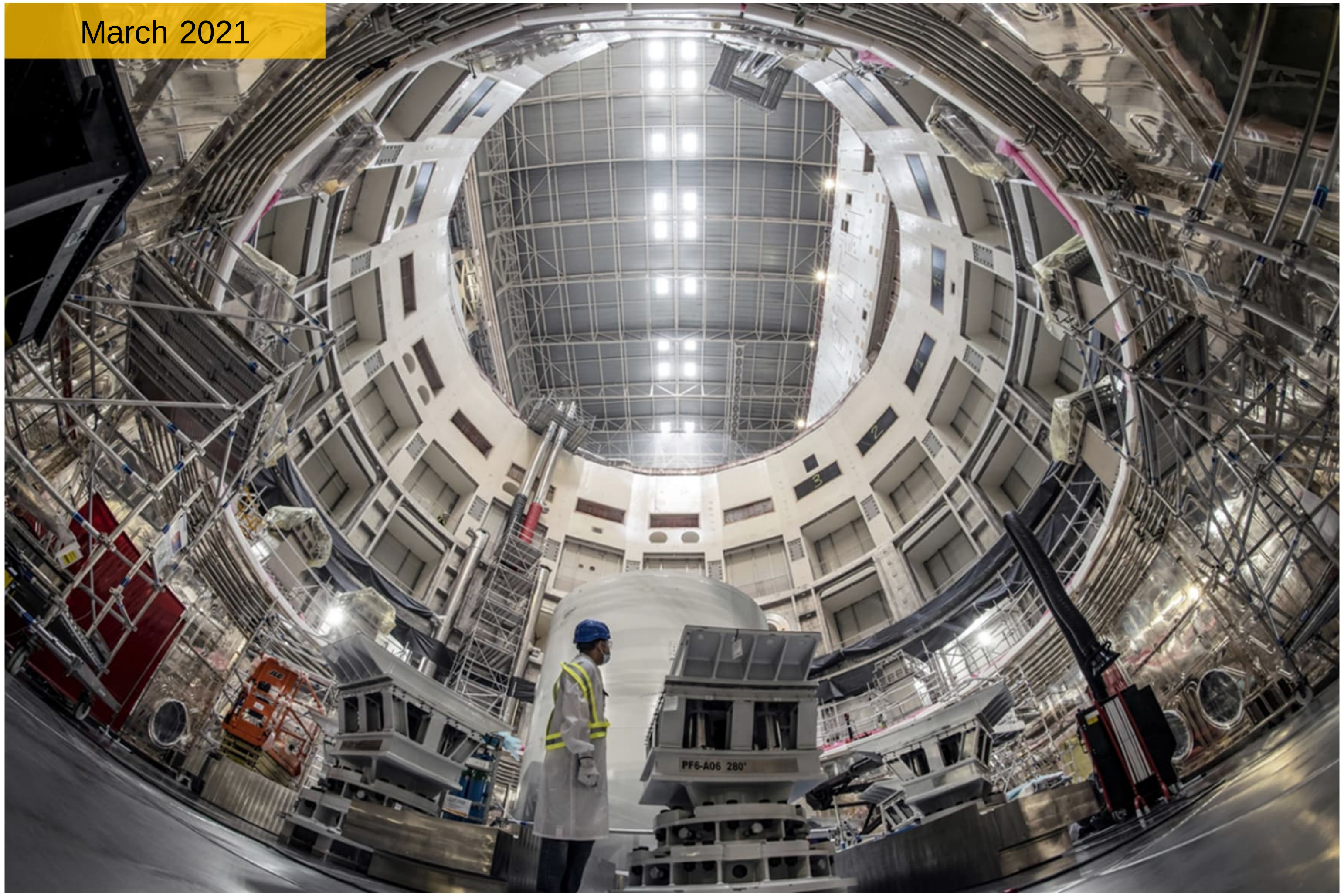
ITER site in France

Picture: ITER Organization, http://www.iter.org/



27 Sept 2023

ITER construction

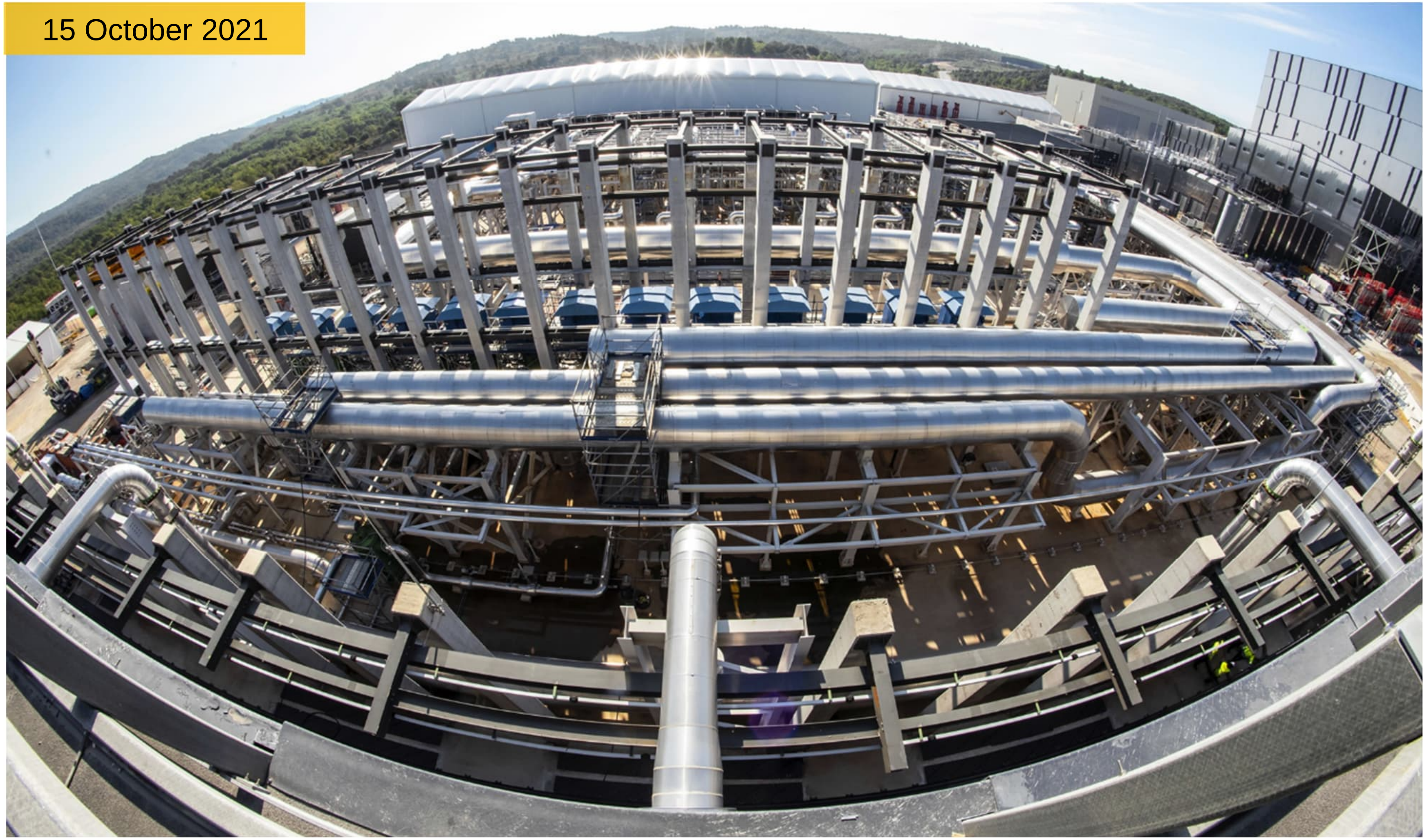


Picture: ITER Organization, http://www.iter.org/

Tokamak Pit

- Shielded area that eventually will house the tokamak

ITER construction



15 October 2021

Picture: ITER Organization, http://www.iter.org/

Cooling plant

- Optimise management of an intermittent demand (peak: 1145 MW, between pulses: 160 MW)

ITER construction


25 November 2021

Picture: ITER Organization, http://www.iter.org/

Cryoplant

- **Largest single unit plant in the world.**
- **Liquid He inventory 25 t**
- **Power:**
- 75 kW at 4.5 K (He)
- 1300 kW at 80 K (N2)

ITER construction – Assembly and installation of first complete VV sector

28 February 2021

- Assembly Hall being prepared for first VV Sector upending

ITER construction – Assembly and installation of first complete VV sector

26 March 2021

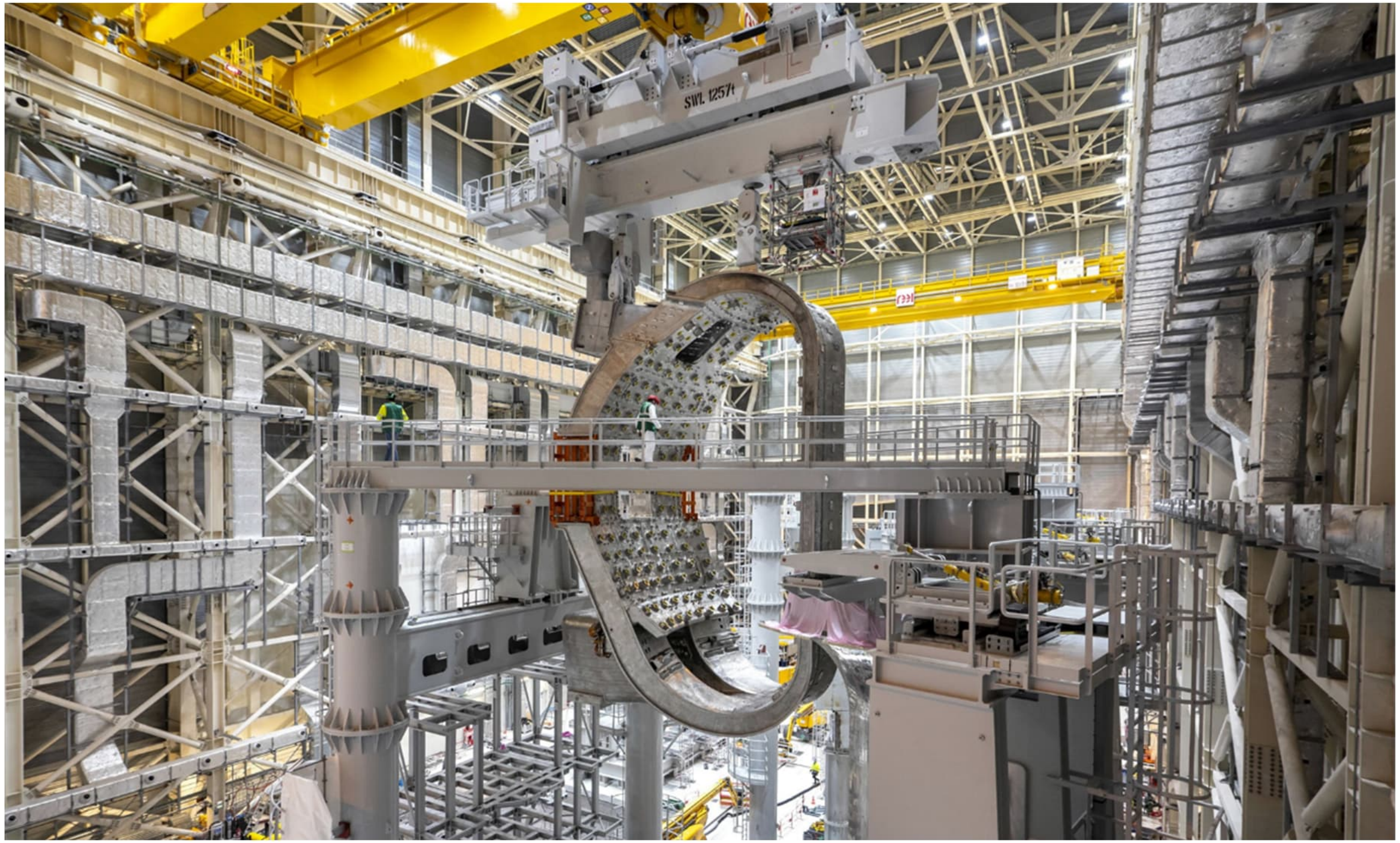
- Start of upending sequence to place Sector 6 into the vertical position

ITER construction – Assembly and installation of first complete VV sector

6 April 2021

- Final step: transfer to the Sub-Sector Assembly Tool (SSAT)

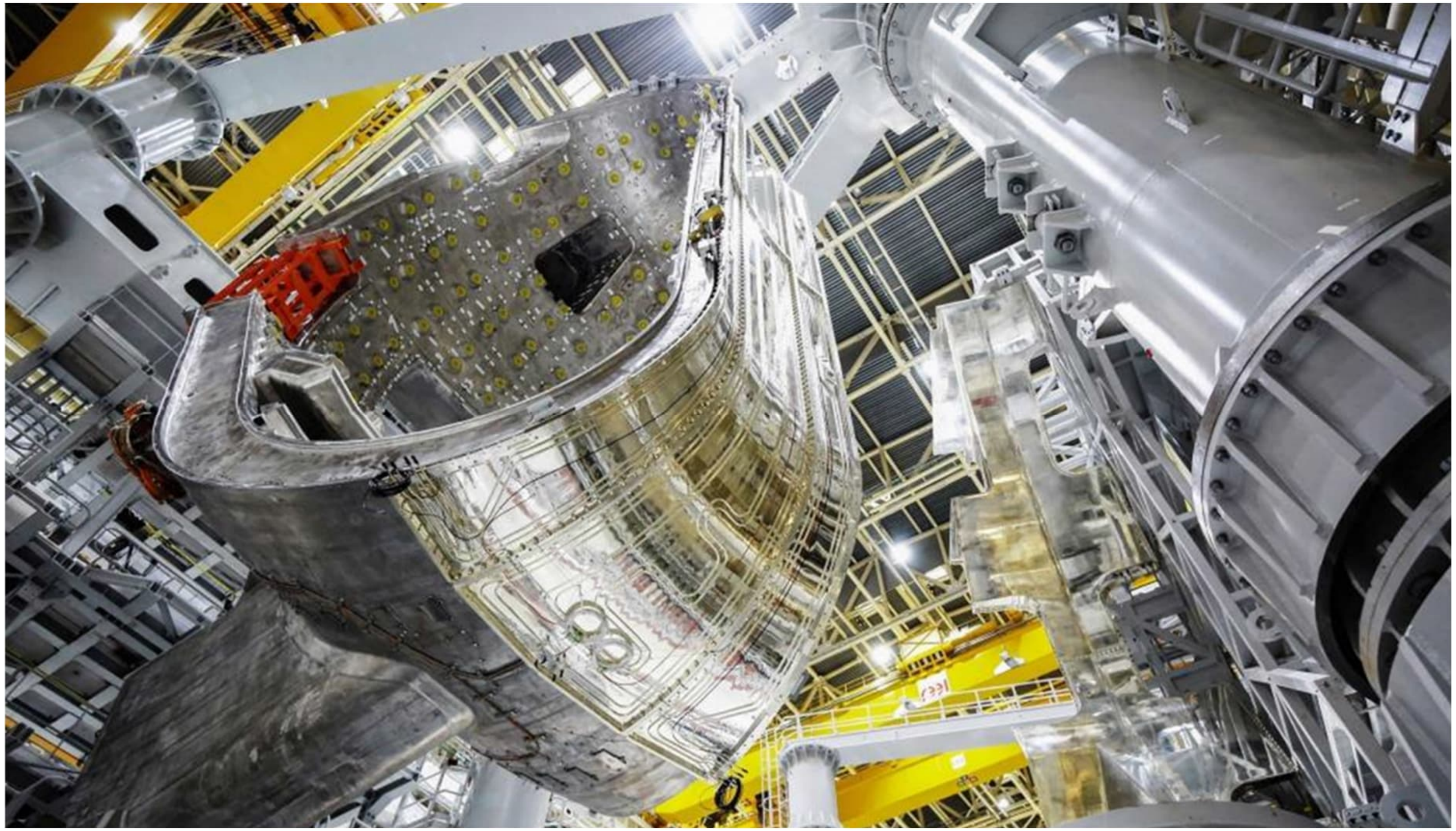
ITER construction – Assembly and installation of first complete VV sector



6 April 2021

- And finally, inserted from above into the SSAT

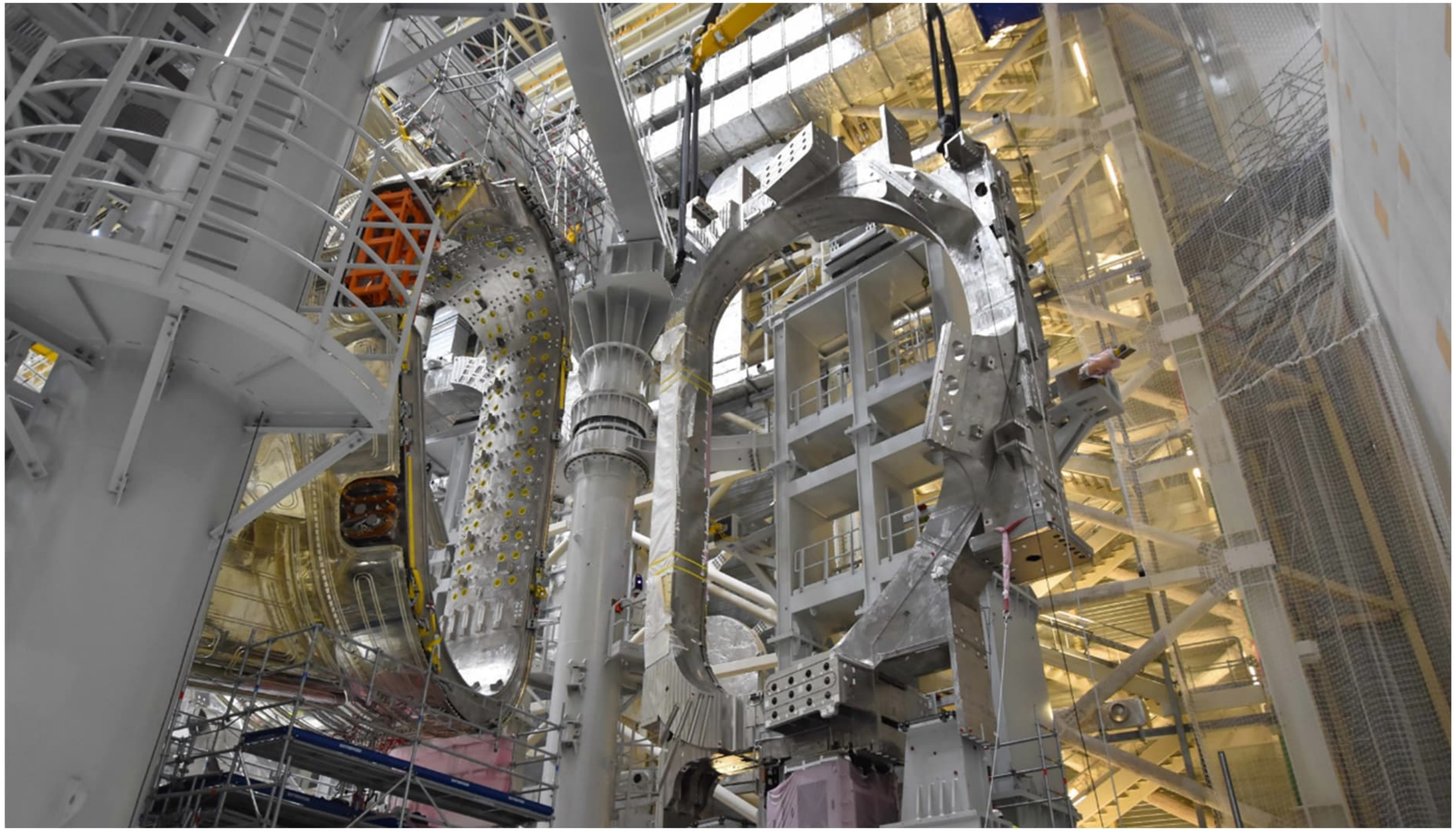
ITER construction – Assembly and installation of first complete VV sector



21 June 2021

- Inboard thermal shield section clamped to Sector 6

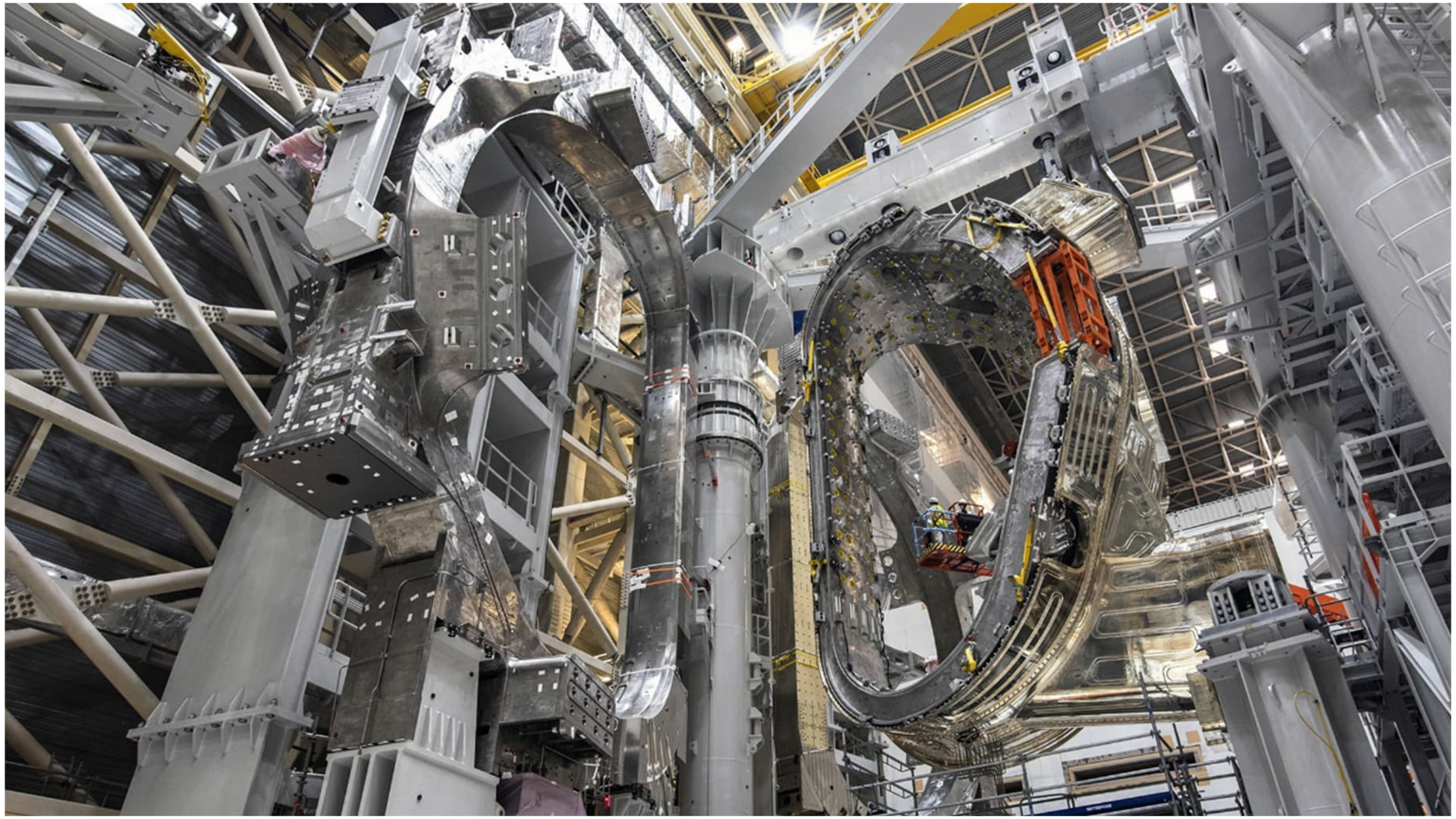
ITER construction – Assembly and installation of first complete VV sector



12 August 2021

- Full VV Sector 6 with thermal shield on and Toroidal Field coil 12 mounted on SSAT

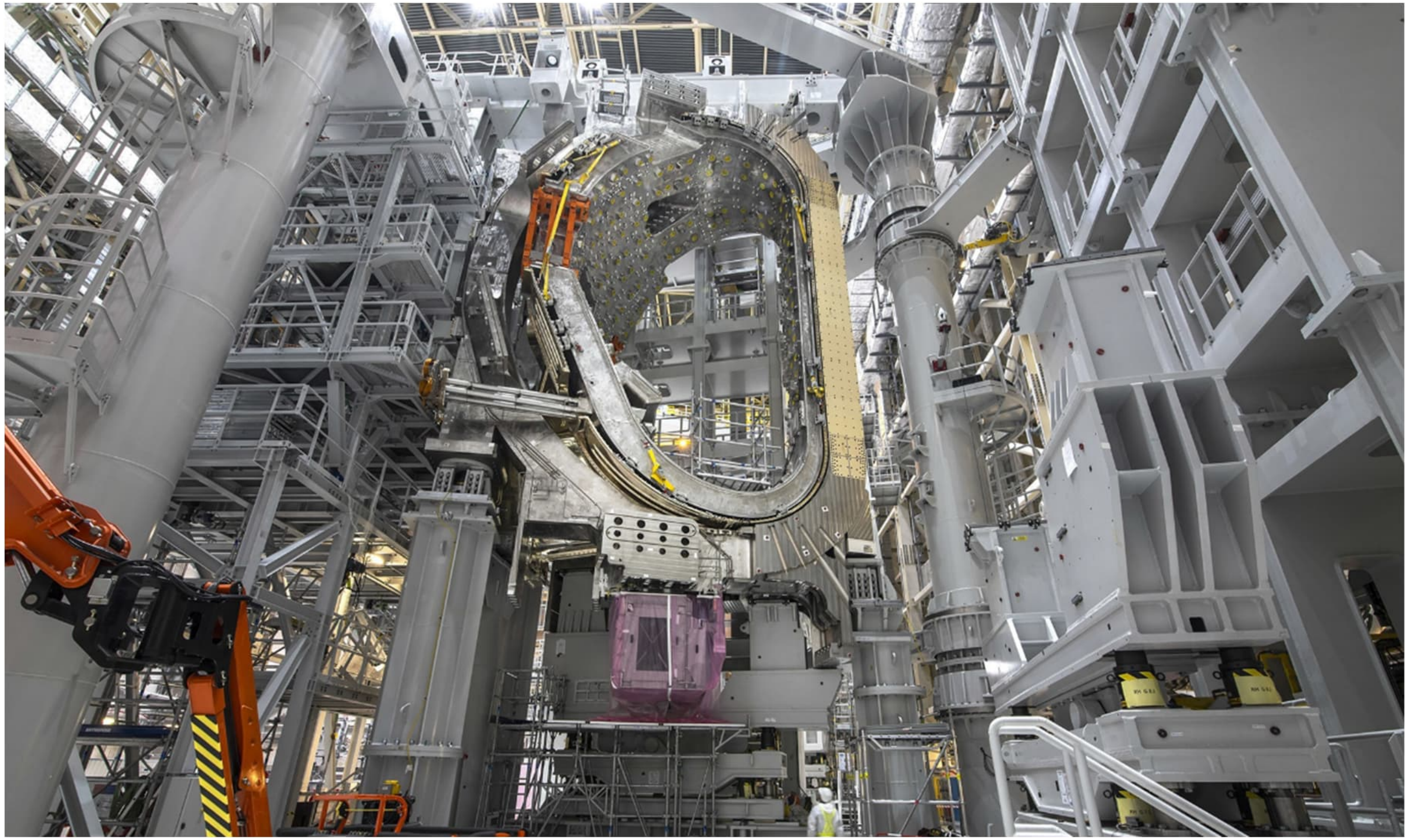
ITER construction – Assembly and installation of first complete VV sector



30 August 2021

- Just prior to final positioning of TF coils

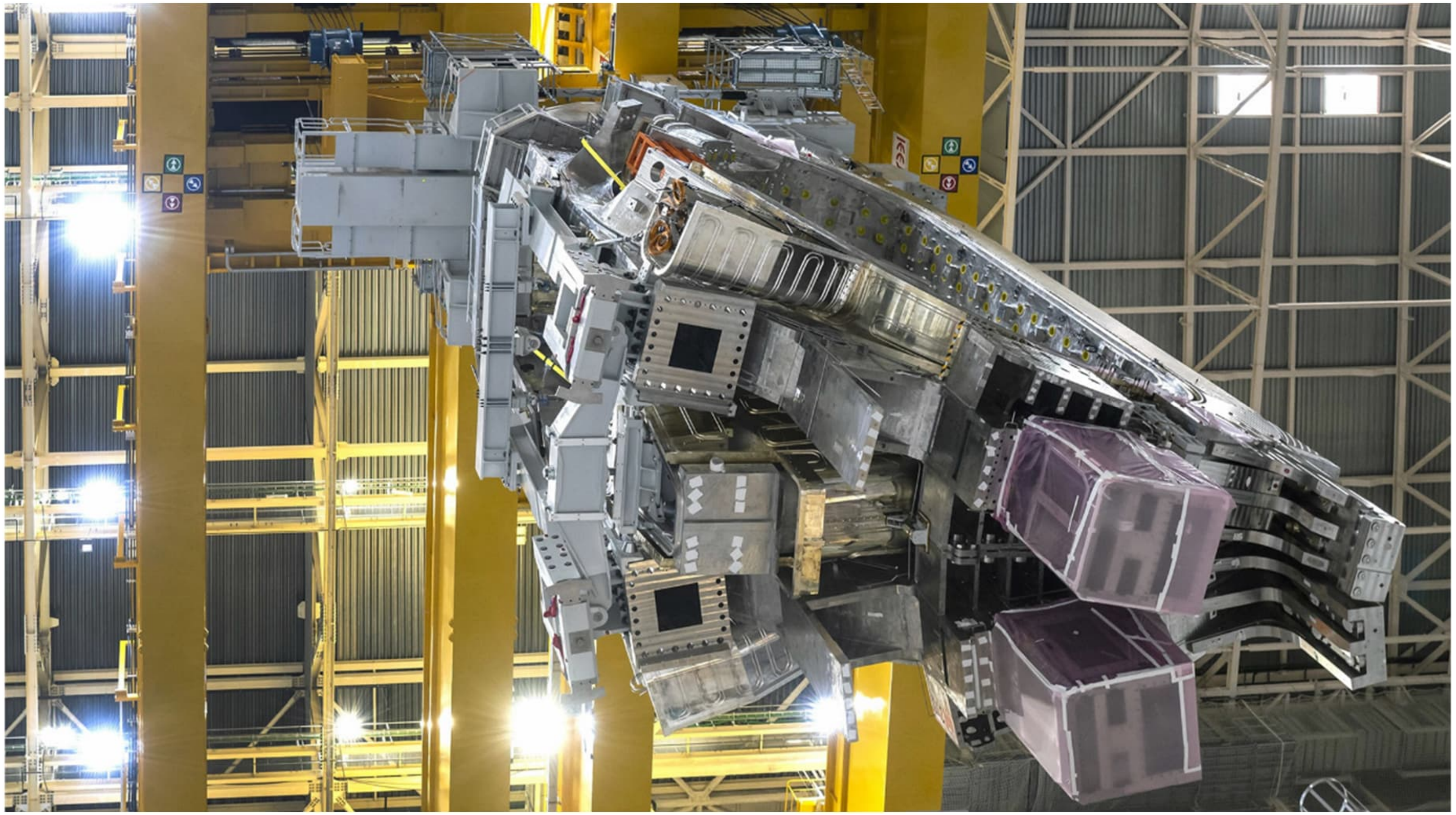
ITER construction – Assembly and installation of first complete VV sector



15 November 2021

- First complete Sector 6 ready for pit installation

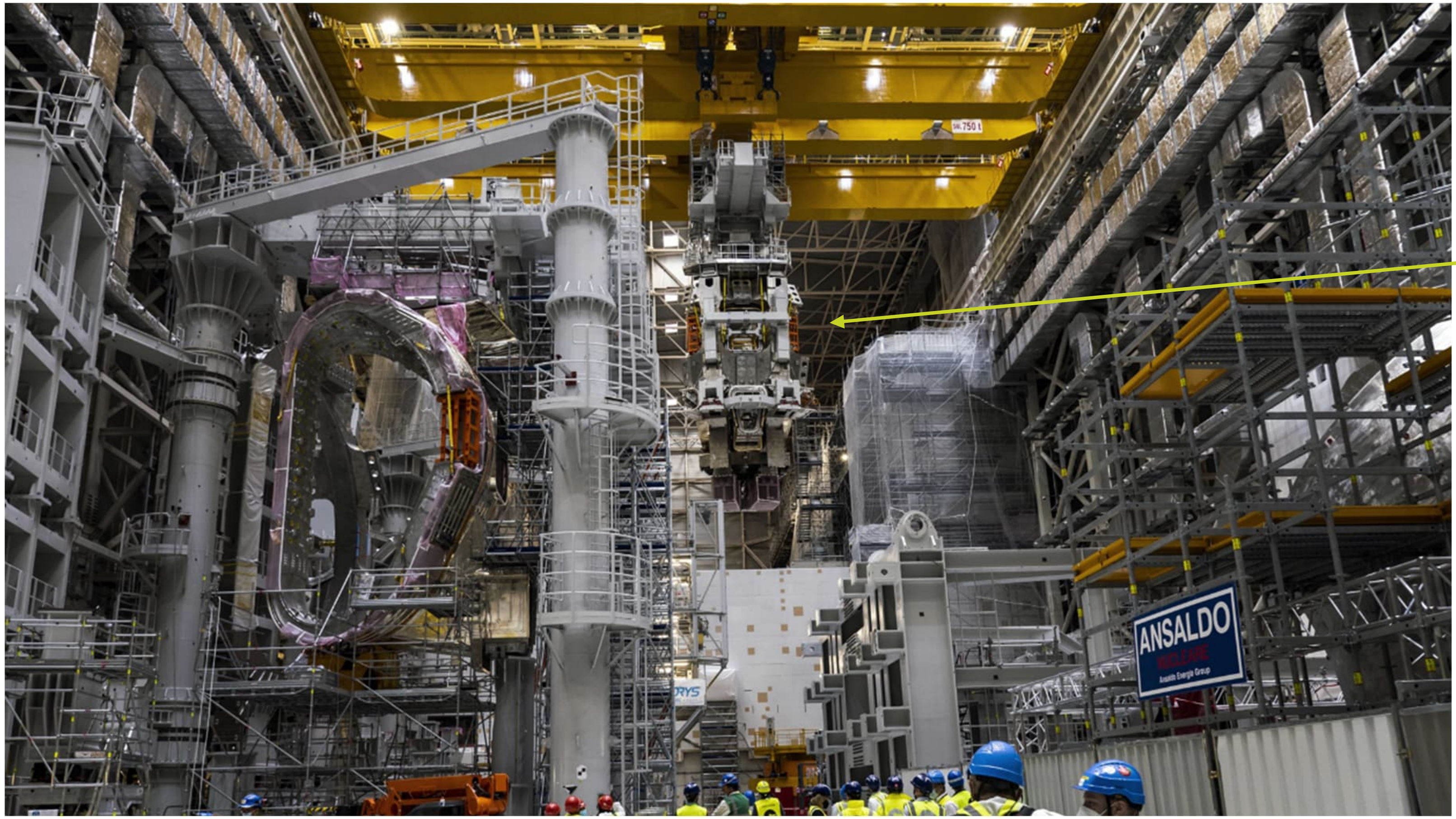
ITER construction – Lift and placement of first sector



11 May 2022

- Sector 6 fully lifted out of SSAT-2 and rotated 90°

ITER construction – Lift and placement of first sector



11 May 2022

- Sector 6 fully lifted out of SSAT-2 and rotated 90°

ITER construction – Lift and placement of first sector

11 May 2022

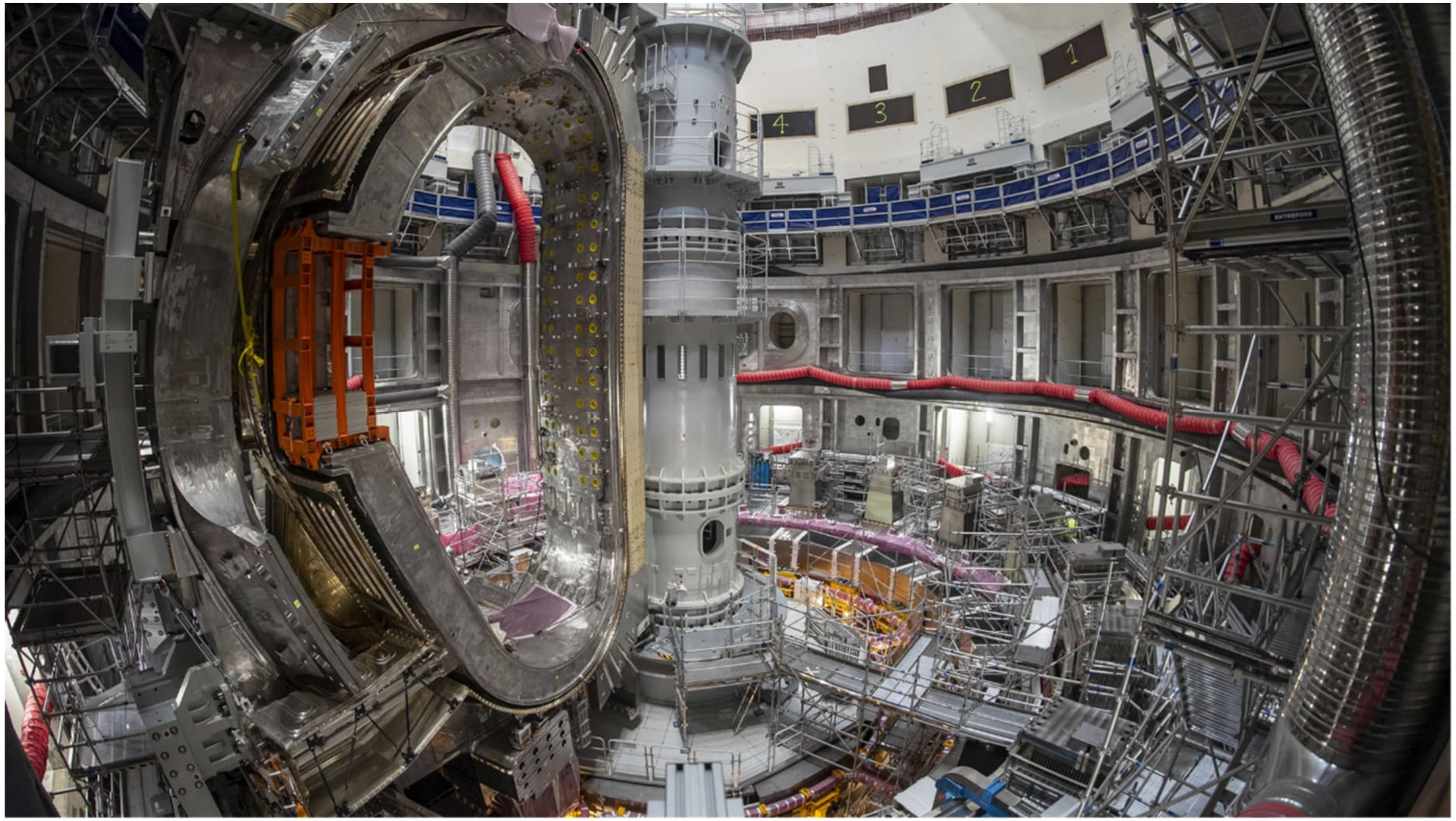
- Over the tokamak pit wall: 20 cm gap

ITER construction – Lift and placement of first sector

11 May 2022

- Lowering into the tokamak pit

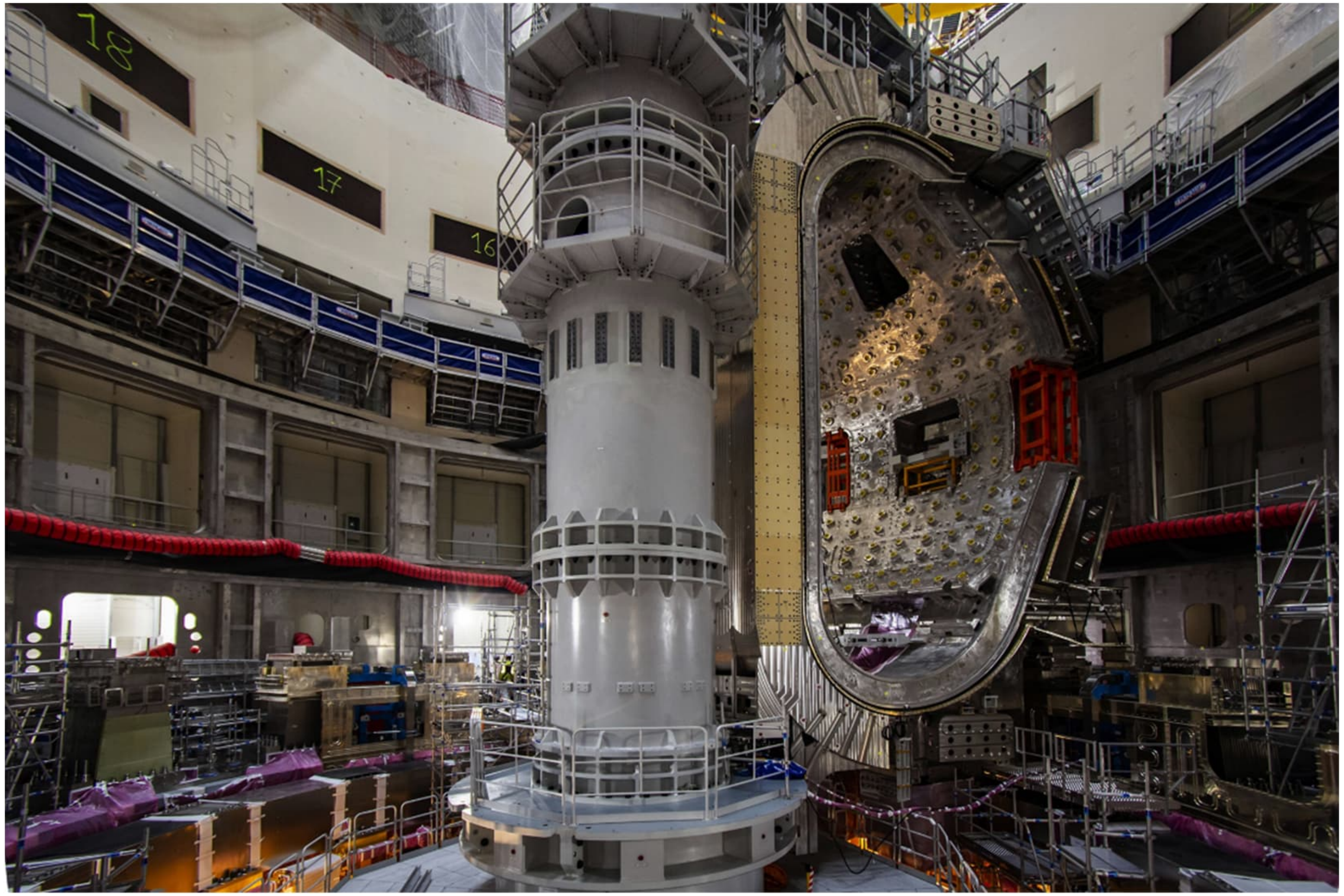
ITER construction – Lift and placement of first sector



14 June 2022

- In-place and alignment procedure underway

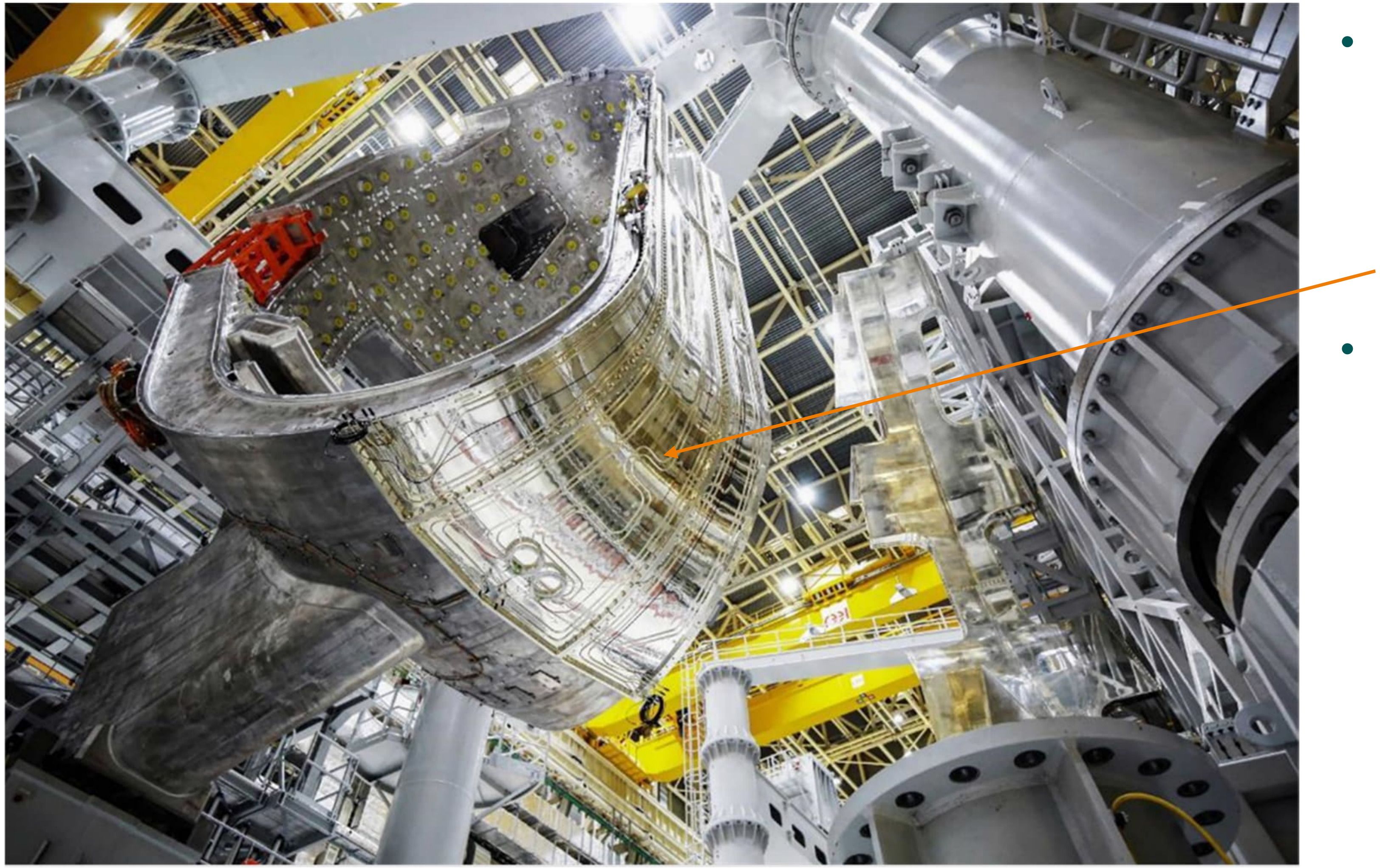
ITER construction – Lift and placement of first sector



22 Septemer 2022

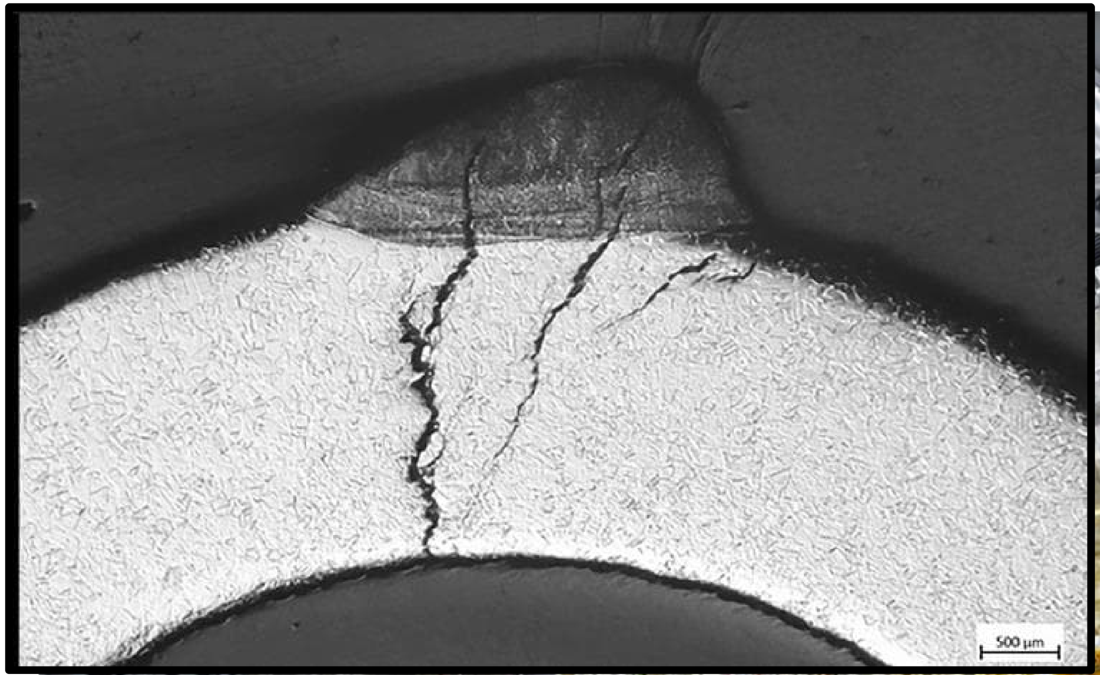
- Final alignment complete.
- Sector placed to millimetric precision according to physics specifications

Status of ITER – Stress corrosion cracks in cooling pipes



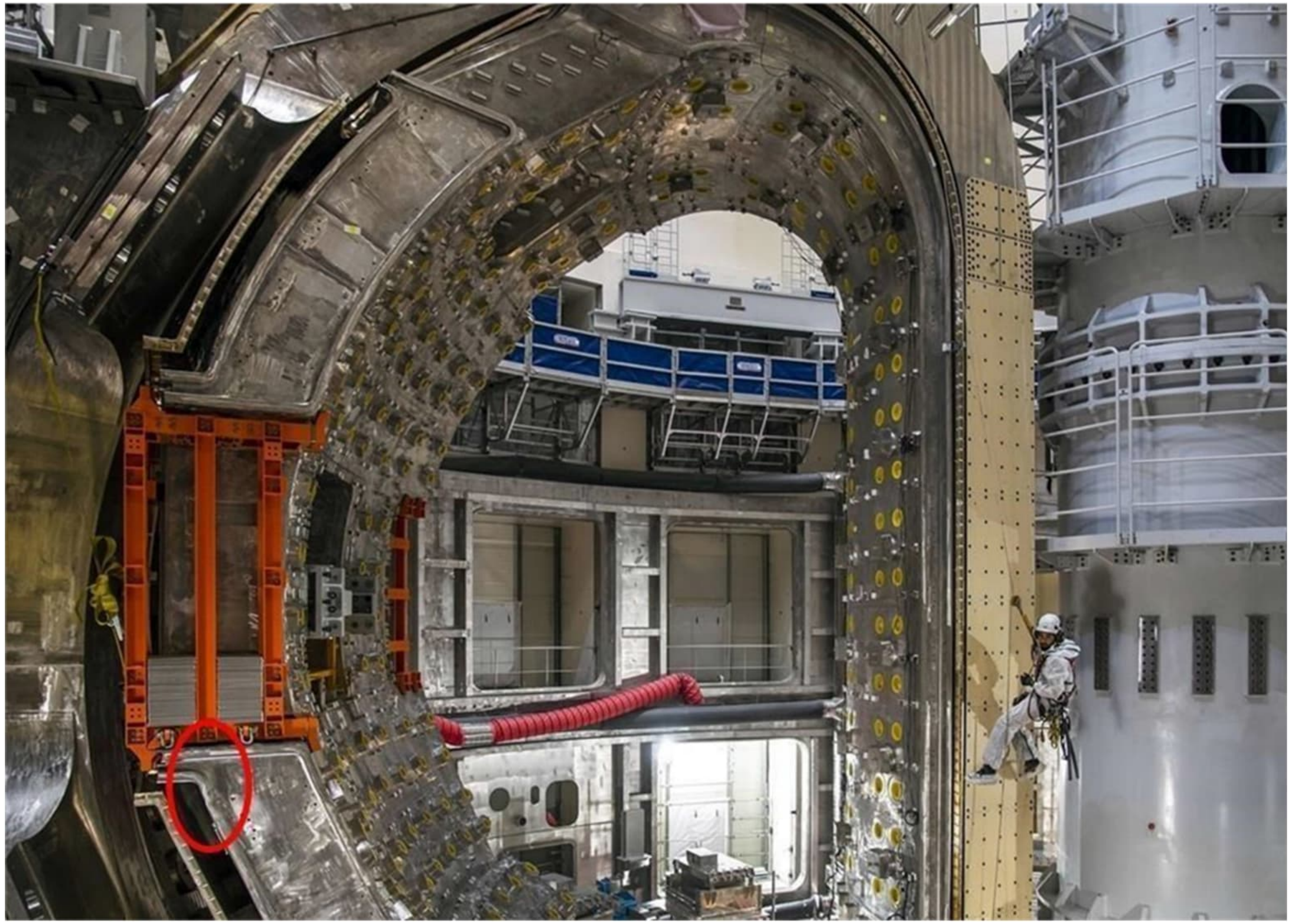
- **Stress corrosion cracks (SCC) on thermal shields: problem found on several VV shields**
- **Assumed to be present in many locations in VV and cryostat shields**

Status of ITER – Stress corrosion cracks in cooling pipes

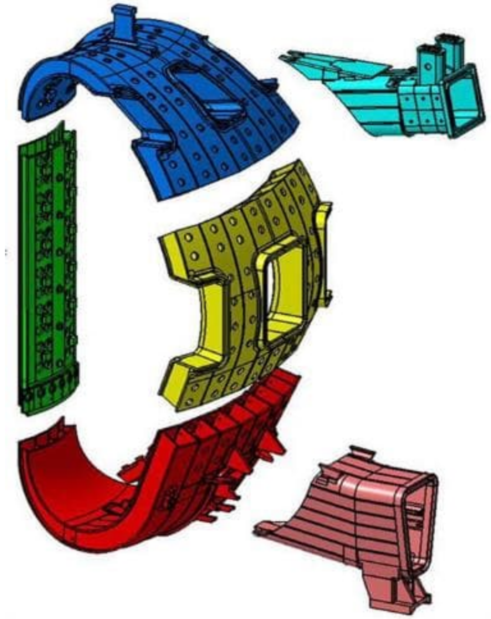


- **Stress corrosion cracks (SCC) on thermal shields: problem found on several VV shields**

Status of ITER – dimensional non-conformities



Some areas of non-conformity on VV field joints, particularly where the individual VV segments are joined



Status of ITER – Challenges

Dimensional non-conformities in VV field joint contours on the 3 sectors delivered to IO have turned out to be too large to permit sector-sector welding according to required standards.

Stress corrosion cracking (SCC) found on many of the thermal shield cooling pipes.

More details of these issues and their solution can be found in:

https://www.iter.org/newsline/-/3818

and

https://www.iter.org/newsline/-/3830

Status of ITER – Solutions

For the VV thermal shield:

- remove old pipes and re-weld new ones (different steel and welding process/material)
- re-manufacture of a few panels

For the cryostat thermal shield:

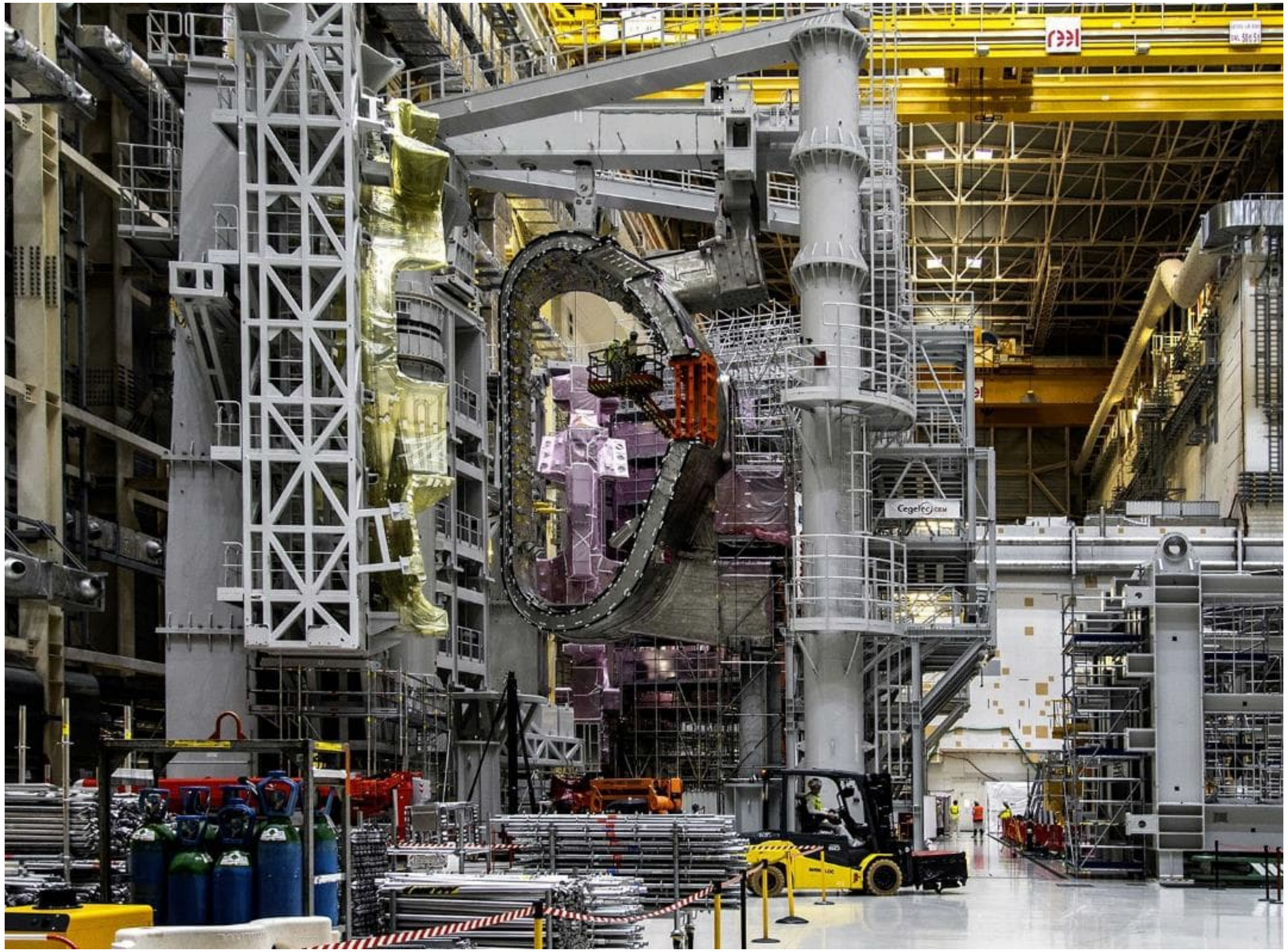
- leave old pipes (but don't connect) and re-weld new ones in-situ (different steel and welding process/material)

For VV non-conformity:

- remove and add material to meet required dimensions (~73 – 400 kg per sector)

Repairs solidly underway

Status of ITER – Repairs

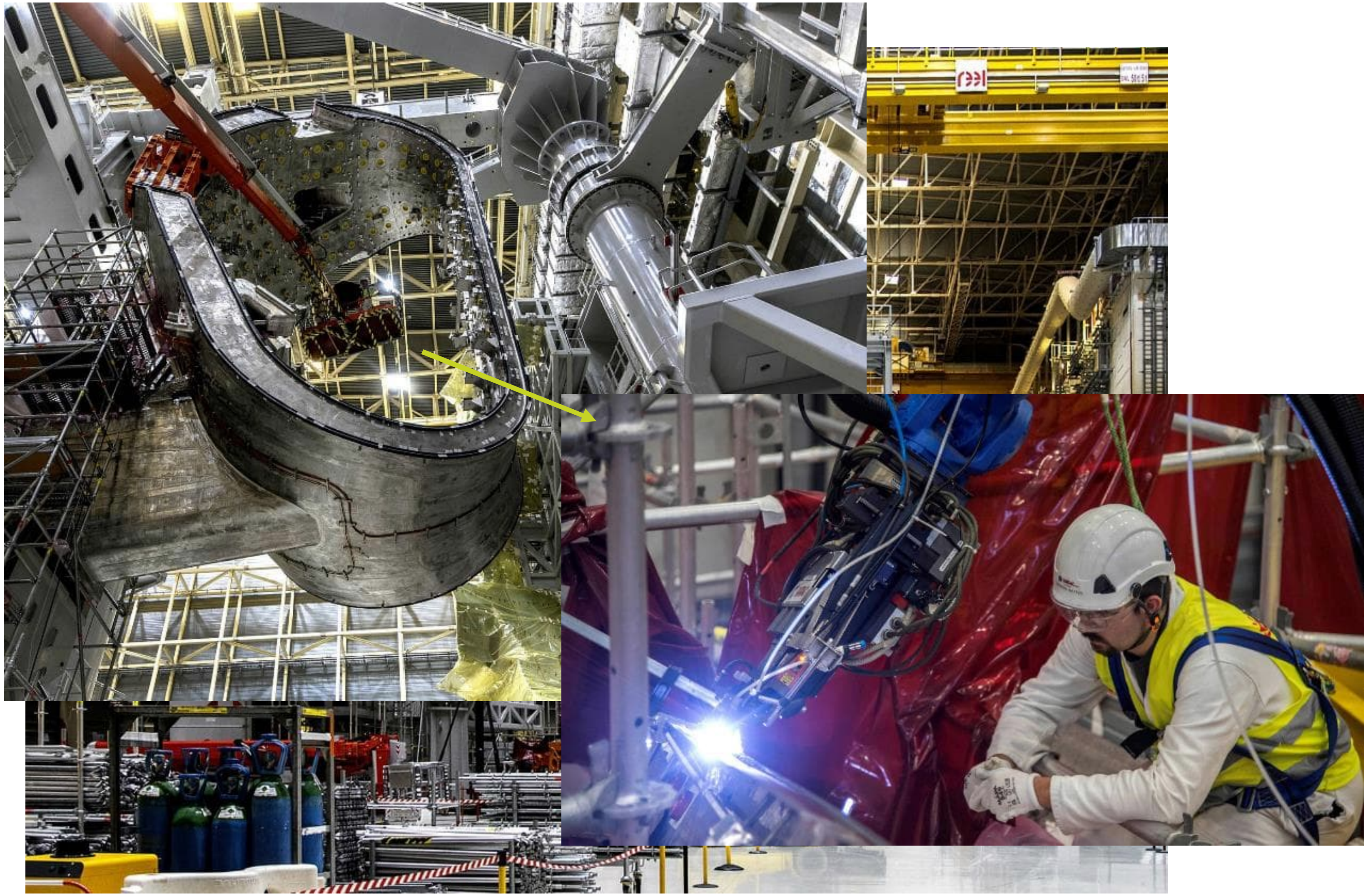


16 September 2024

- Bevels of VV sector #7 have been restored to nominal geometry
- VV thermal shields repaired and ready to be fitted
- VV sector #7 ready for assembly operations

https://www.iter.org/newsline/-/4070

Status of ITER – Repairs



16 September 2024

- Bevels of VV sector #7 have been restored to nominal geometry
- VV thermal shields repaired and ready to be fitted
- VV sector #7 ready for assembly operations

Repairs of all three VV sectors on site at ITER to be completed by July 2025

https://www.iter.org/newsline/-/4070

Status of ITER – Research plan and re-baselining

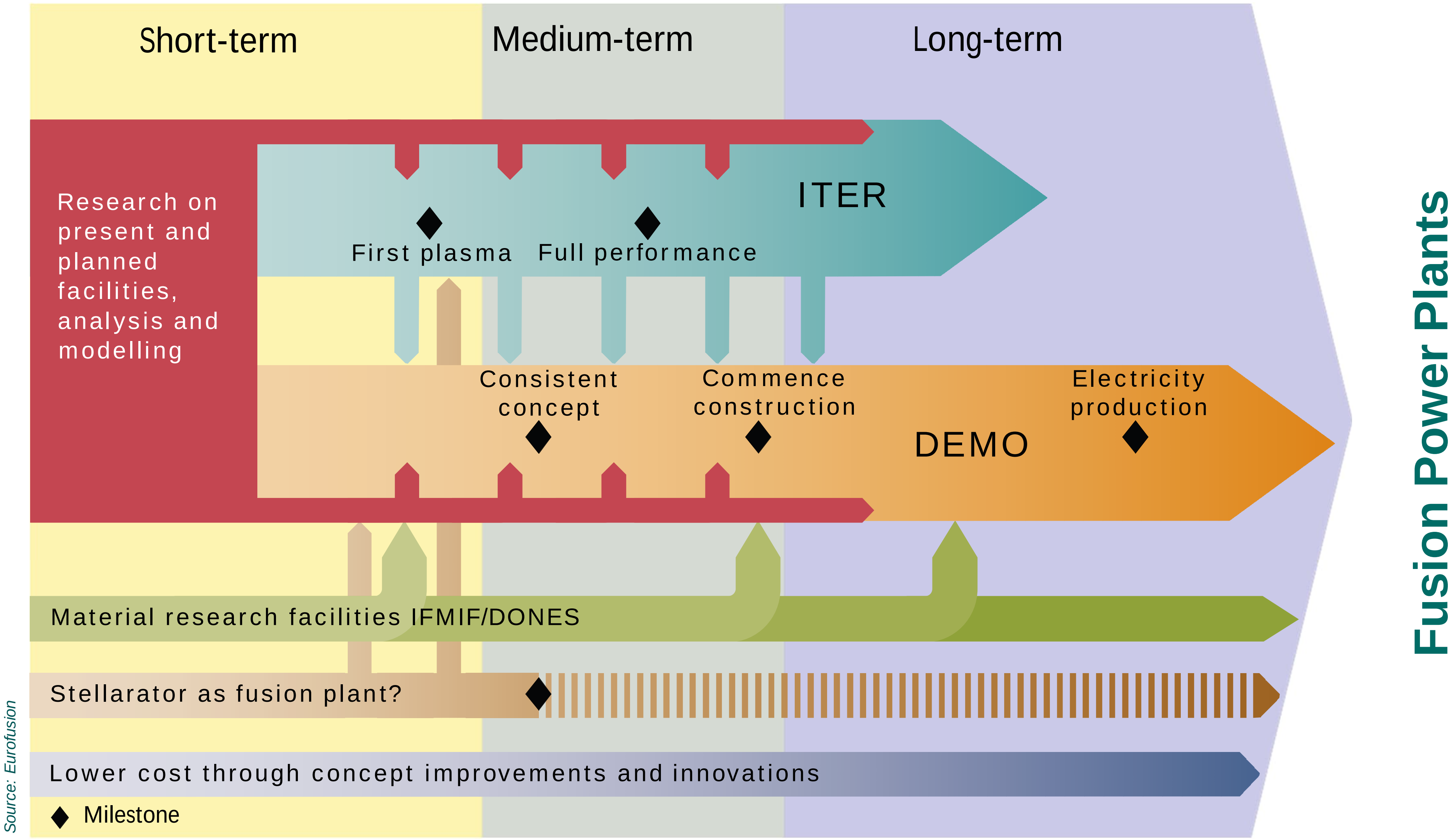
New baseline rationale

- **Start of Research Operation (SRO) now in 2034** (instead of 2025)
  - Robust achievement of ITER project goals while considering past and current challenges (Delays due to Covid-19 pandemic, Technical challenges of first-of a kind components, Nuclear licensing)
  - Realistic and reliable assembly – commissioning – operation – more complete machine
- **Achievement of earliest start of the ITER Nuclear Phase (DD operation) and minimization of technical risks**
- **Full magnetic energy in 2036** (instead of 2033)
- **Start of DT-operation in 2039** (instead of 2035)
- **Stepwise Safety Demonstration**
  - Gradual increase of neutron fluence
  - Use experimental results from first nuclear phase for safety demonstration of second one

Update research plan in view of new scientific results

- **Implement first wall fully out of W**
- **Optimized heating mix and conditioning of first wall → ease path to Q = 10 with added W**

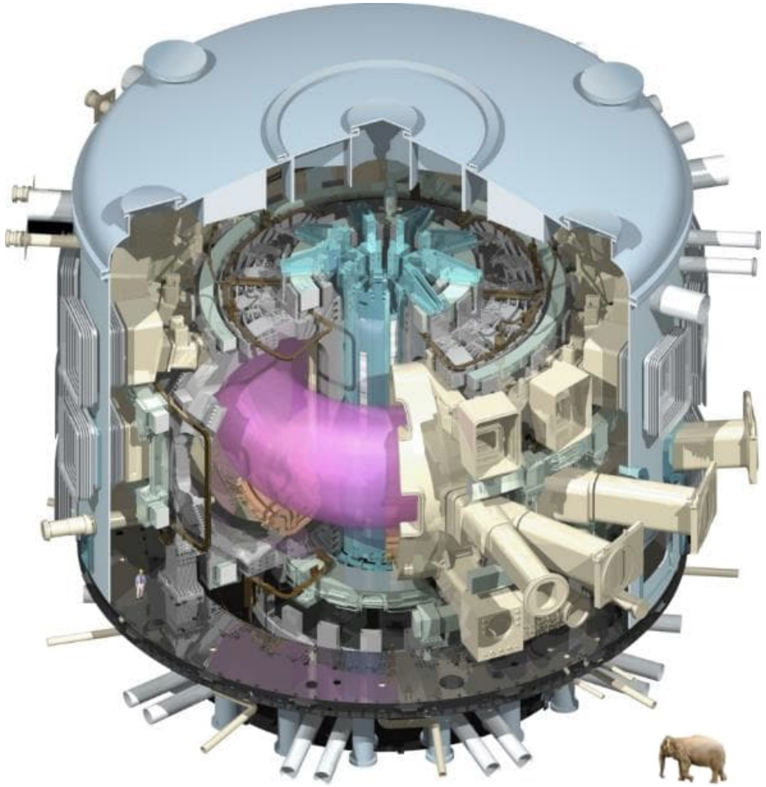
EU Roadmap to Fusion Power



Source: Eurofusion

From experimental device to a power plant

ITER

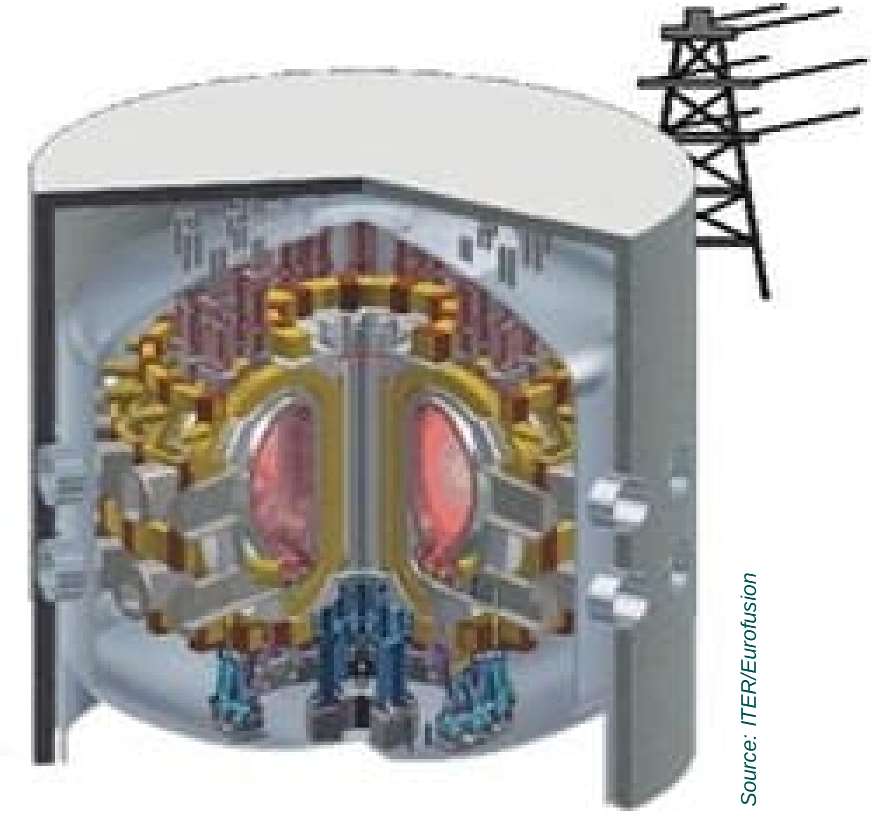


Plasma pulses ≤ 30 min.

Tritium added

Experimental device and operation

DEMO



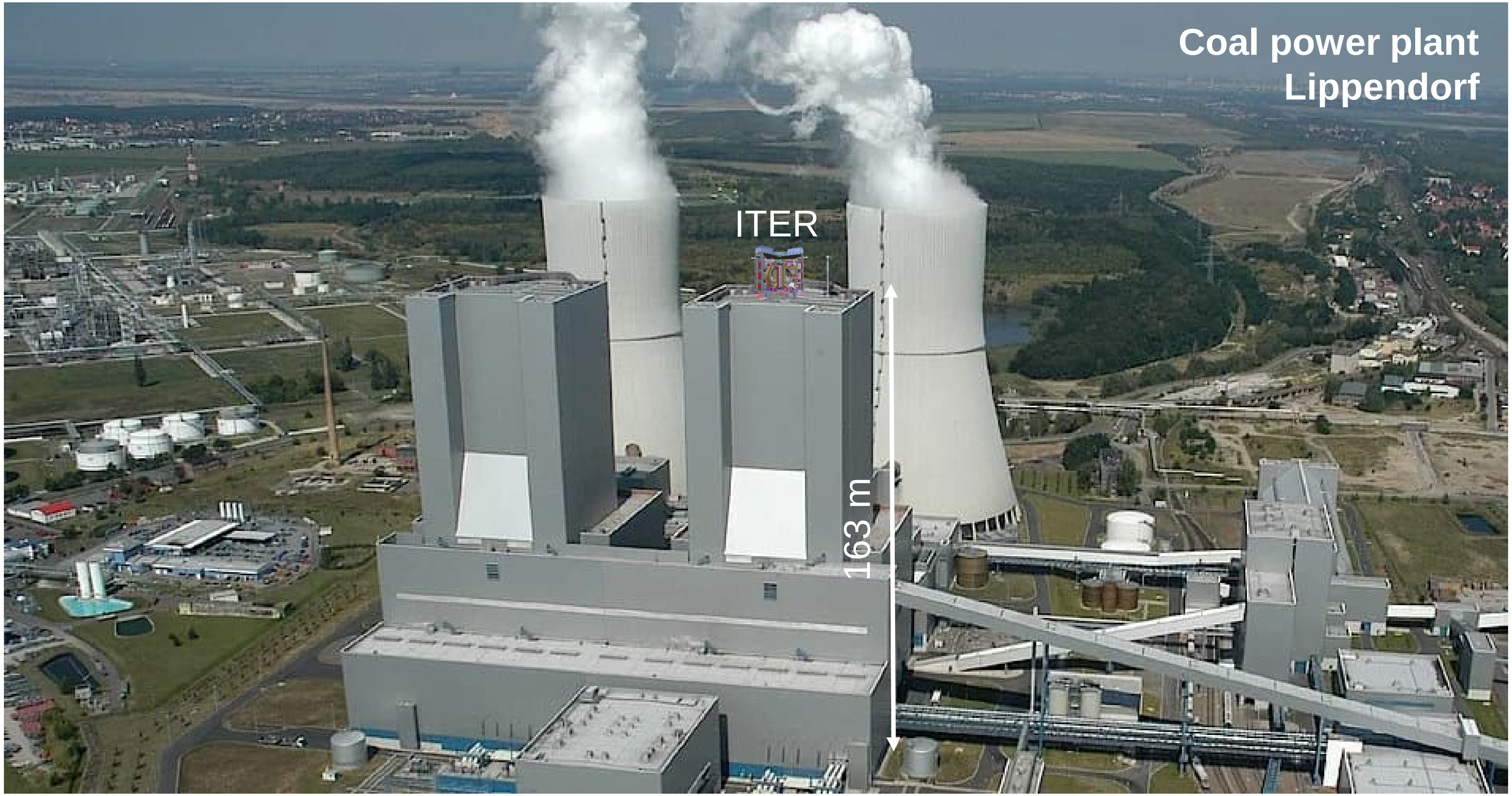
Source: *ITER/Eurofusion*

Continuous operation

Tritium breeding

Connection to grid

A size comparison



Source: https://www.industriekultur-in-sachsen.de/

The worldwide fusion landscape
– IAEA’s Fusion Device Information System (FusDIS)

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

Total	Tokamaks	Stellarators/Heliotro..	Laser/Inertial	Altern. Concepts	Exp	Plant
159	79	23	12	45	139	20

🟨 Tokamaks
🟥 Stellarators/Heliotrons
Laser/Inertial
Altern. Concepts

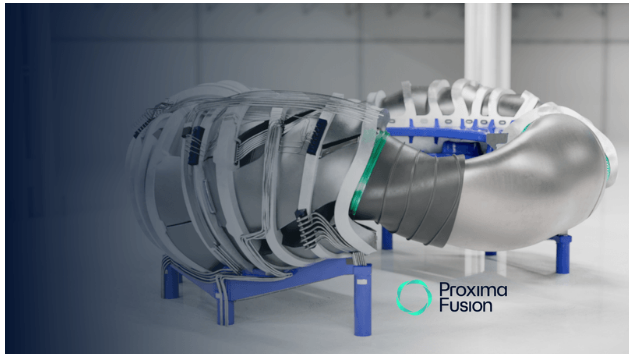
Country	
United States	41
Japan	26
China	14
Russia	13
United Kingdo..	8
Germany	6
France	5
Italy	4
Pakistan	4
Sweden	4
Brazil	3
Canada	3
India	3
Iran	3
Republic of K..	3
Costa Rica	2
Czech Republic	2
Spain	2
Switzerland	2
Ukraine	2
Australia	1
Denmark	1
Egypt	1
European Uni..	1
Israel	1
Kazakhstan	1
Libya	1
Portugal	1
Thailand	1

Operating	Under construction	Planned	Public	Private
100	14	45	111	48

Worldwide activities, at present more than 45 start-ups, raised more than 8 B€

4 start-ups in Germany

From the worldwide fusion landscape – Start-ups in Germany



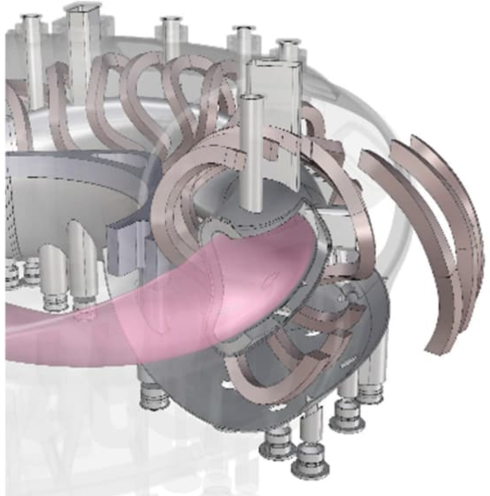
© Proxima Fusion

Proxima Fusion

- Founded by IPP PostDocs
- Aims for Quasi-isodynamic stellarator DEMO

Gauss Fusion

- Founded by European industry involved in ITER construction
- Aims at 1GW DEMO plant based on stellarator



© Gauss Fusion

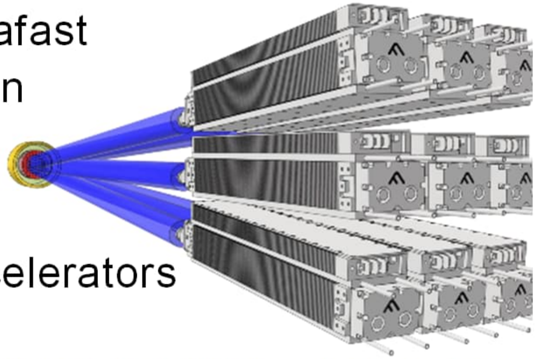
Focused Energy

© Focused Energy

- Founded 2021 as German GmbH and US Inc.
- Modular path to laser-driven inertial fusion
- Starts with lab for mass production of targets near Darmstadt

Marvel Fusion

- Founded 2019 near Munich
- Aims at direct drive, ultrafast high intensity laser driven fusion
- Development of lasers and nano-structured accelerators



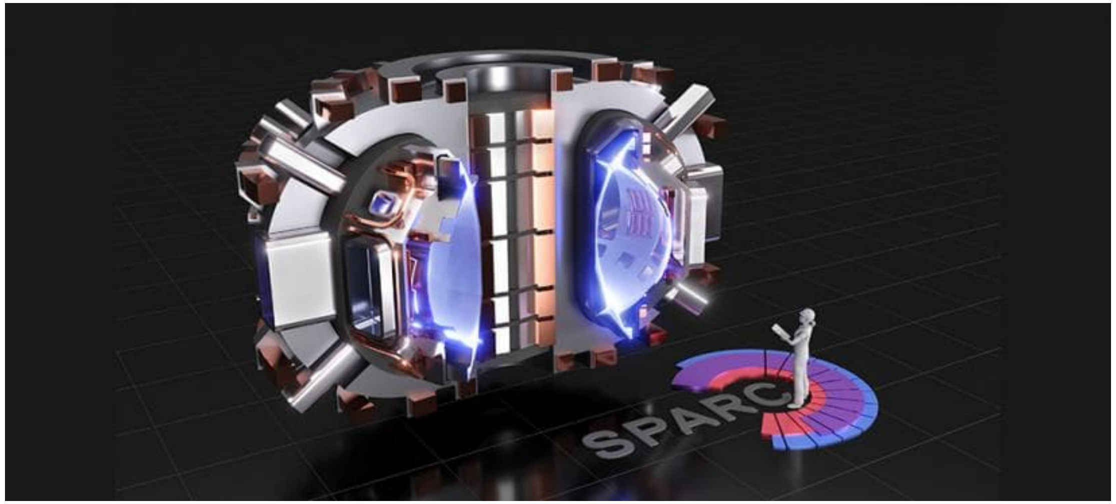
© Marvel Fusion

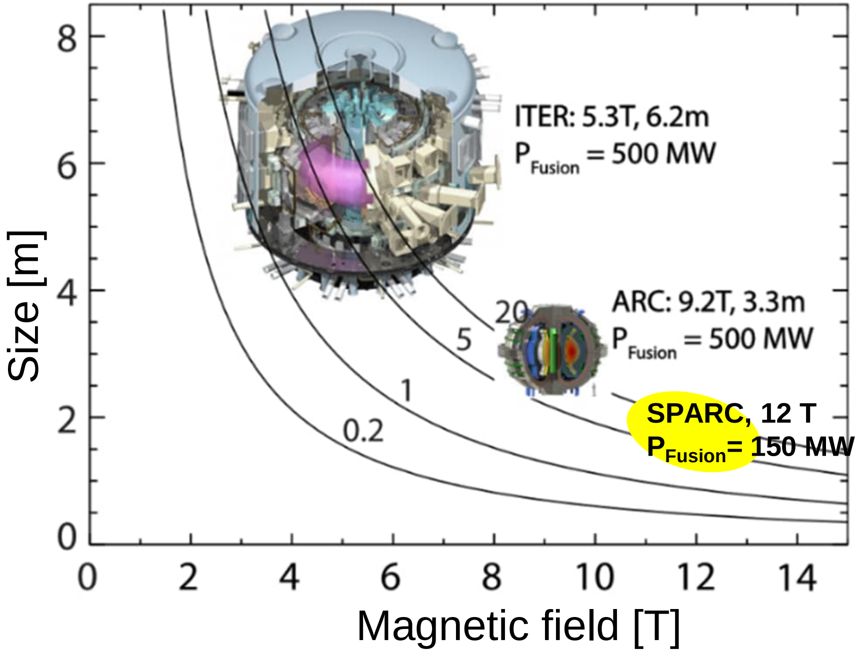
From the worldwide fusion landscape – STEP (UK)

- **STEP Spherical Tokamak for Energy Production**
  - DEMO-class successor device to ITER
  - Proof-of-concept of a fusion plant
  - Scheduled to achieve a 'burning plasma' in 2035
  - Aims to produce net electricity from fusion ~2040
  - Funded by UKAEA
  - Site chosen
  - Conceptual design ongoing
  - UK actively pursues a licensing process dedicated to fusion

Copyright: UKAEA

From the worldwide fusion landscape – SPARC (USA)



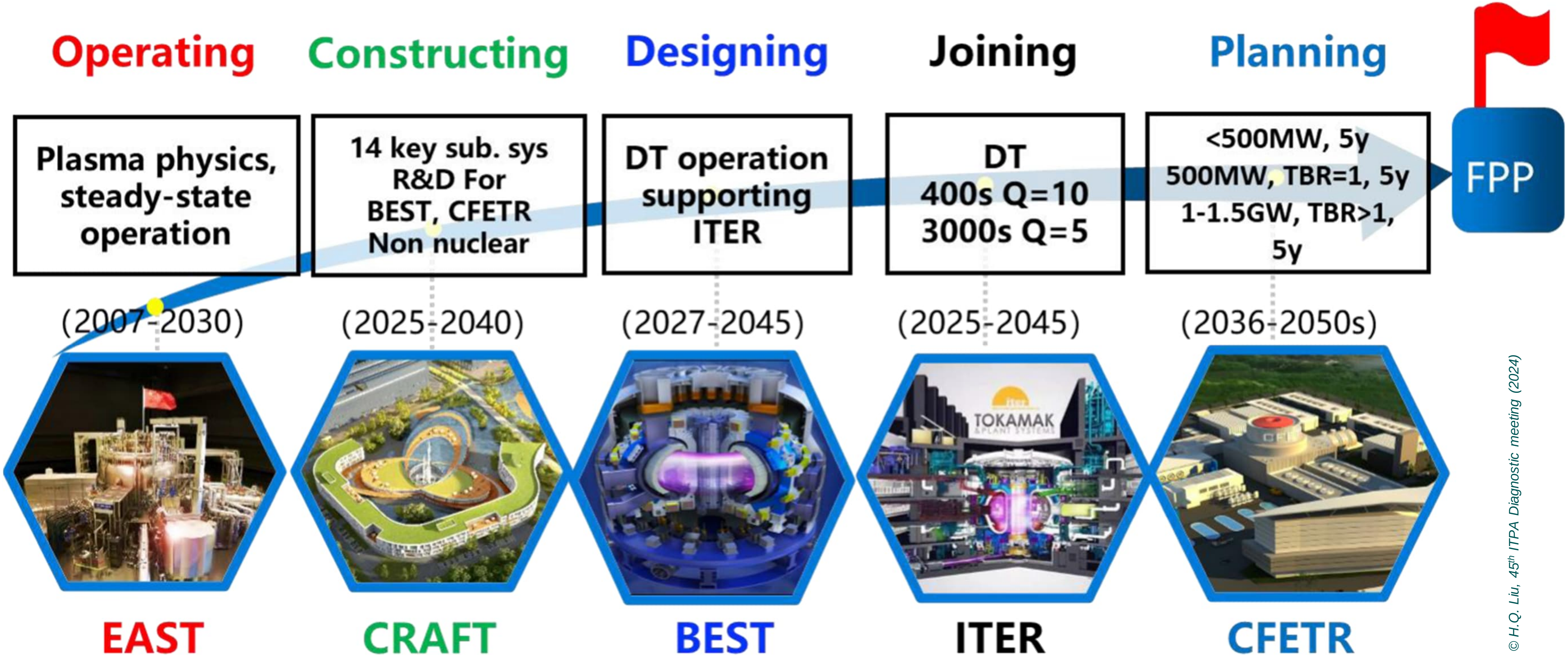


Greenwald, Joule ***3****, (2019) 1175 - 1179*

Commonwealth Fusion System (Devens, MA, USA)

- **Private company, raised >2 B$**
- **Advanced Tokamak with B_t ~12 T, high-temperature superconductors**
- **Start of operation in 2027, only short pulses**
- **Successor ARC aims with half size of ITER and B_t = 9.2 T at 400 MW net power**

From the worldwide fusion landscape – China’s roadmap



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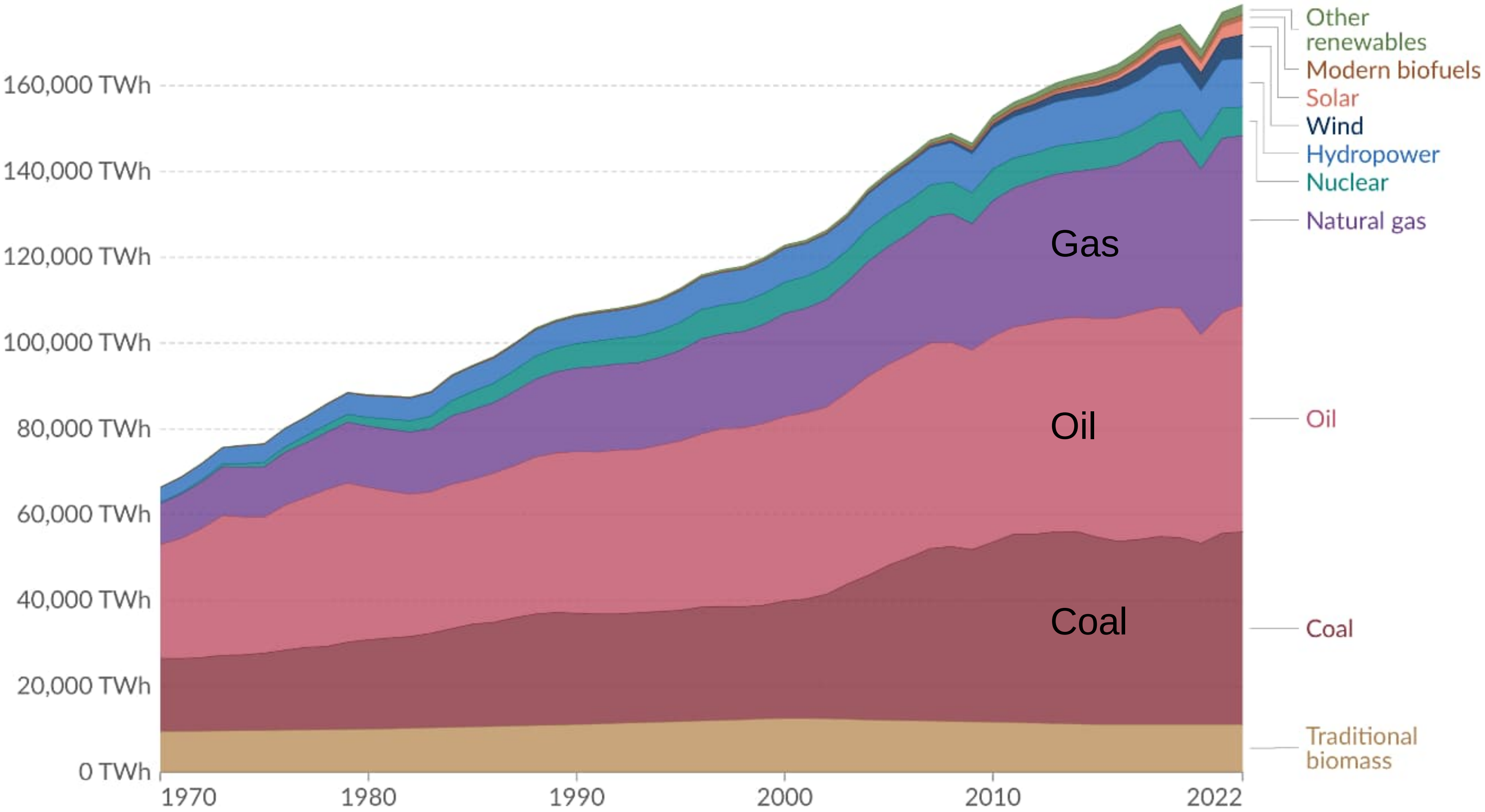
Do we still need nuclear fusion?



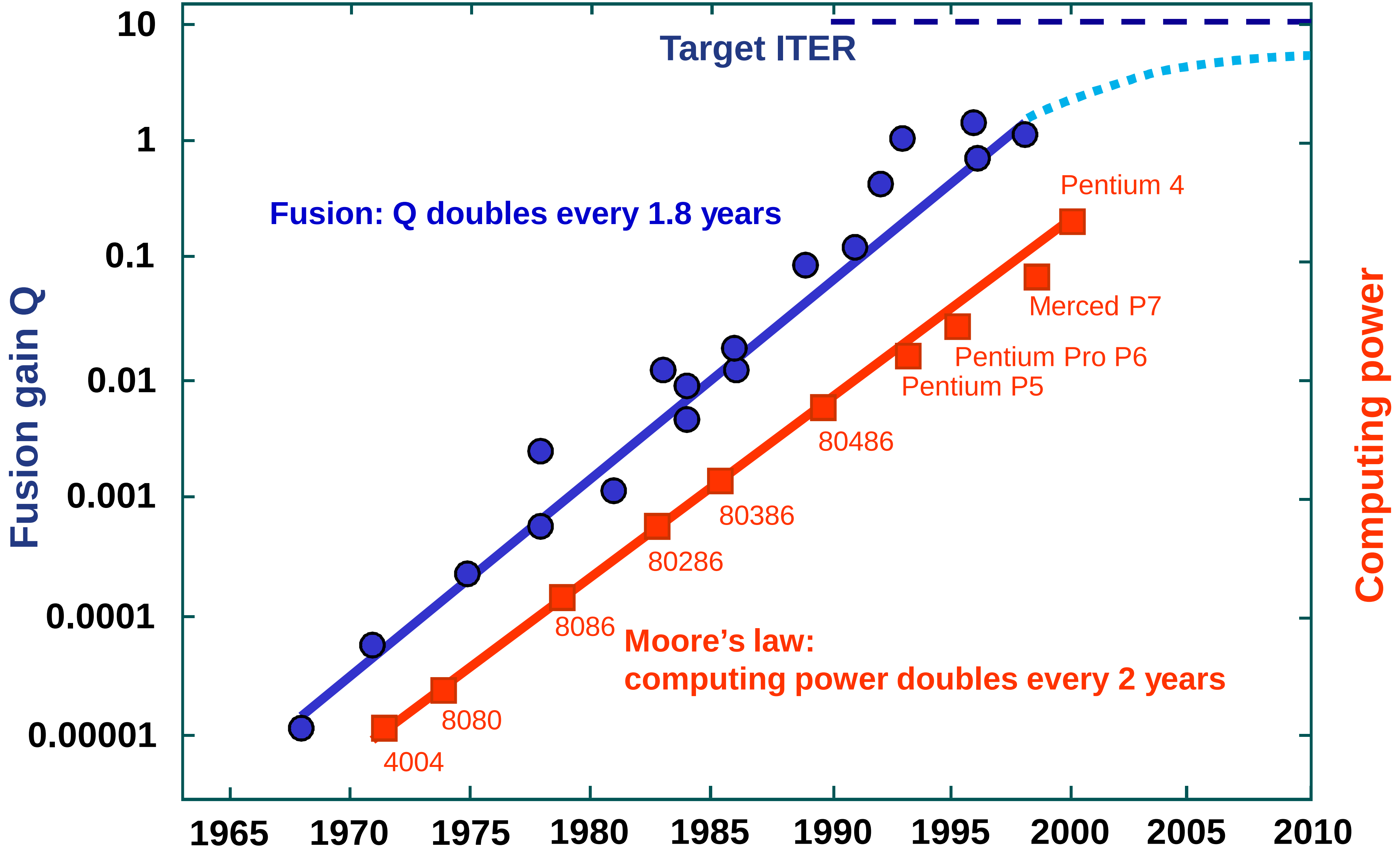
Source: Energy Institute - Statistical Review of World Energy (2023); Smil (2017) OurWorldInData.org/energy. |CC BY
Note: In the absence of more recent data, traditional biomass is assumed constant since 2015. Primary energy is based on the substitution method.

Development of primary energy consumption worldwide

- Need for energy continues to increase
- More than 75% of primary energy production produces CO_2 emissions

Nuclear fusion would be a climate friendly alternative

Progress of fusion



Perspectives for fusion as an energy source

Initial steady progress could not be kept

- Increased size of devices required more funding than provided
- Anticipated budgets have not been approved
- Political agreements were more challenging than anticipated

Physics and technological challenges

- A number of challenges still to be overcome
- Recent progress gives confidence in achieving Q>1

New dynamics in fusion landscape

- > 45 start-ups embarked in fusion
- > 8 B€ private funds invested
- Interest of industry awakens, parallel developments

From ITER's history

1985: Gorbachev's proposal to Reagan:
international fusion experiment

1988: Start conceptual design

1992: „Engineering Design Activities"

1998: First design rejected (too expensive)
USA leave
Re-design started

2001: Approval of design

2003: China and South-Korea join
USA returns

2005: Agreement on site
⇨ Cadarache (F)
India joins

2006: ITER Agreement signed

2007: „Broader Approach" Agreement

2008: Start of construction

Conclusions

Fusion as energy source is extremely interesting but also challenging

ITER

- World’s largest first of a kind fusion device
- Works to overcome political, social, organizational and technical challenges
- Despite delays still relevant and necessary – only project that will tackle all challenges to scale

Recent successes strongly increased public interest and financial options opening new dynamics in fusion landscape

And how long will it take now for fusion to become reality?

The fusion joke:

„Fusion is always 30-50 years away from realisation.“

Fusion start-ups claim:

„We will erect a power plant within 10-20 years.“

A researcher‘s opinion:

„20 billion €, 20 years“

If funding for fusion is substantially increased and legal frameworks properly defined,
a prototype power plant is feasible within two decades.

Thanks for your attention!