EUROfusion

The European path towards fusion electricity

(based on the view of EUROfusion)

Tony Donné

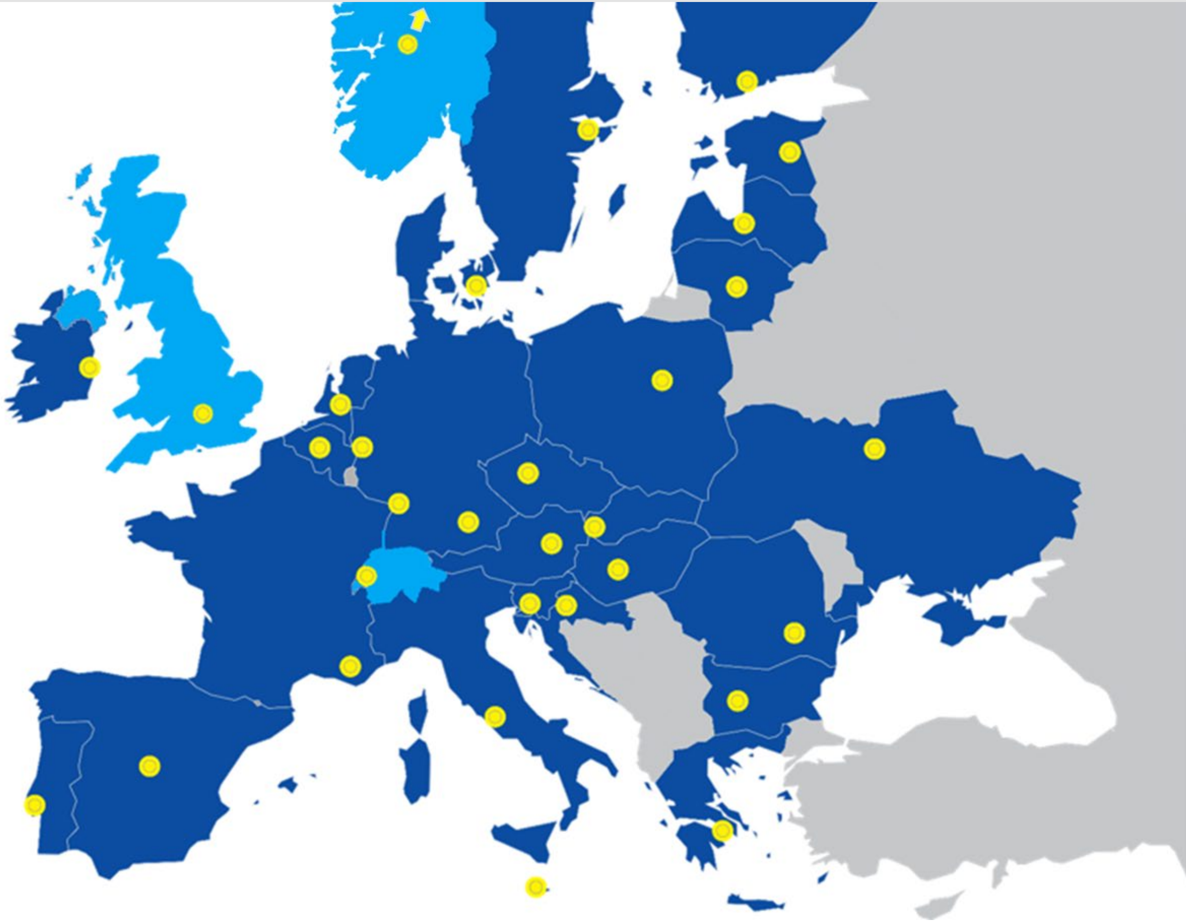
A.J.H. Donné *et al.*| Big Science Symposium | Leiden, NL| 14 November 2023

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

EUROfusion

EUROfusion integrates R&D in fusion science and technology

29	Countries
31	Research Institutions
164	Universities
800	MSc and PhD students
4000	Fusion Researchers & Support Staff



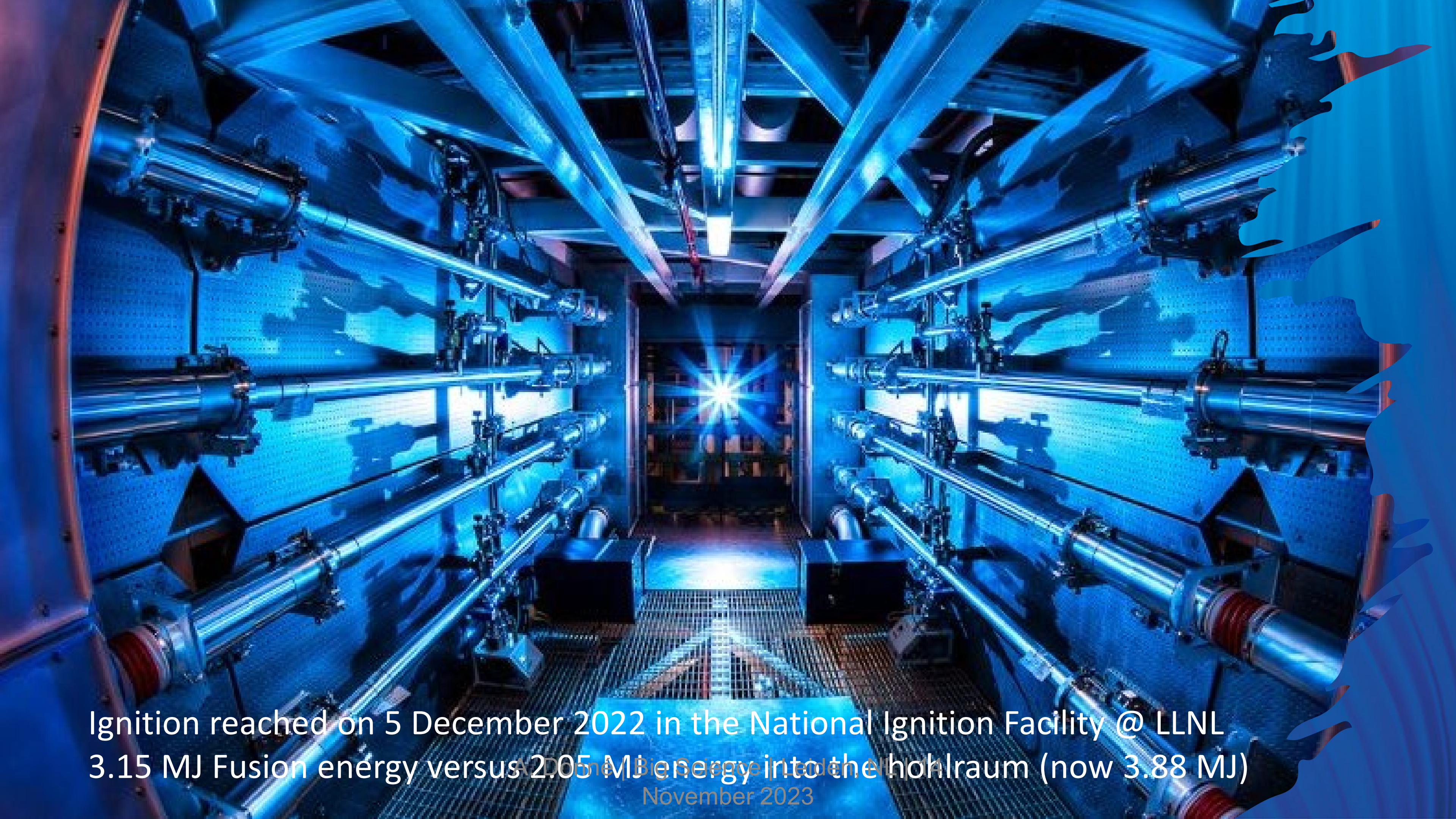
The easiest nuclear fusion reaction on Earth

Deuterium

Tritium

neutron

Helium

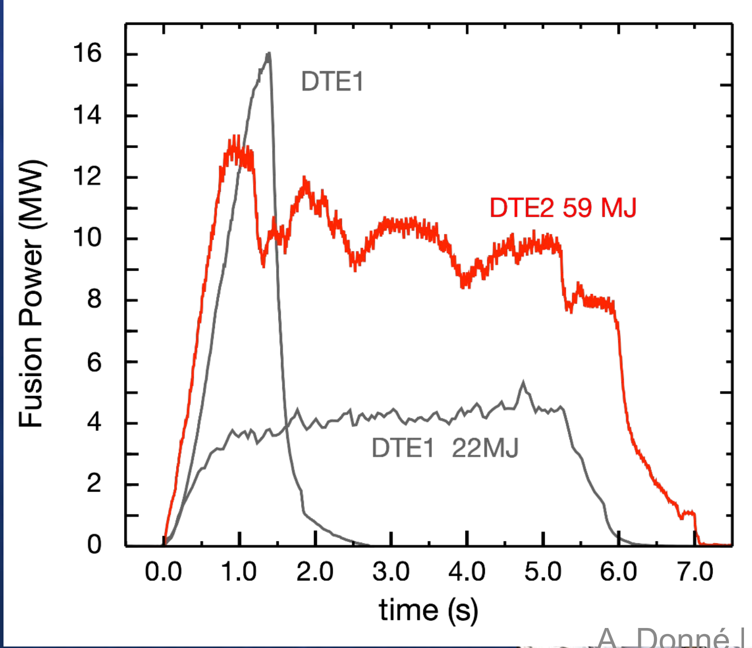


Ignition reached on 5 December 2022 in the National Ignition Facility @ LLNL

3.15 MJ Fusion energy versus 2.05 MJ energy into the hohlraum (now 3.88 MJ)

World record fusion energy in Joint European Torus (2022)

59 MJ of fusion energy generated



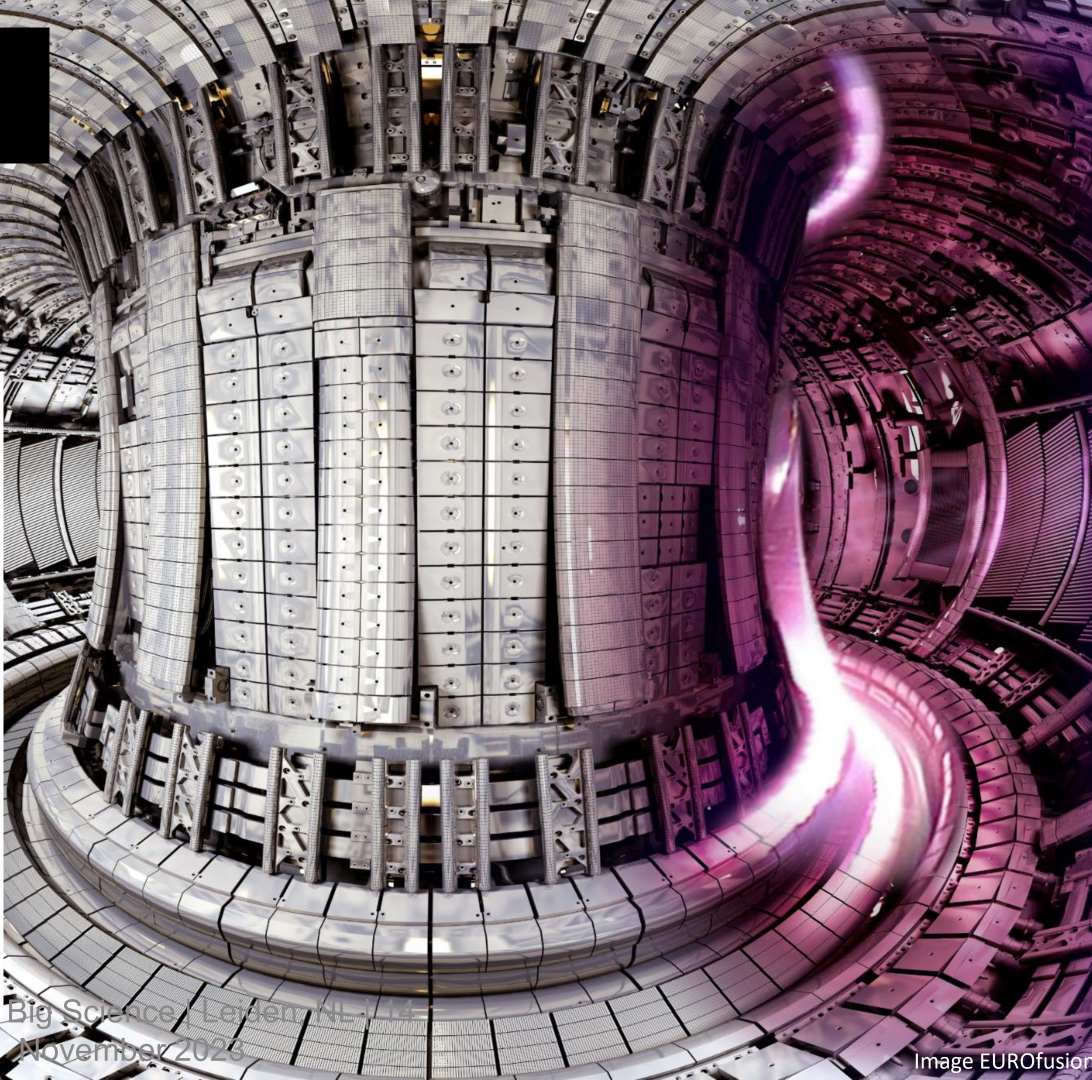
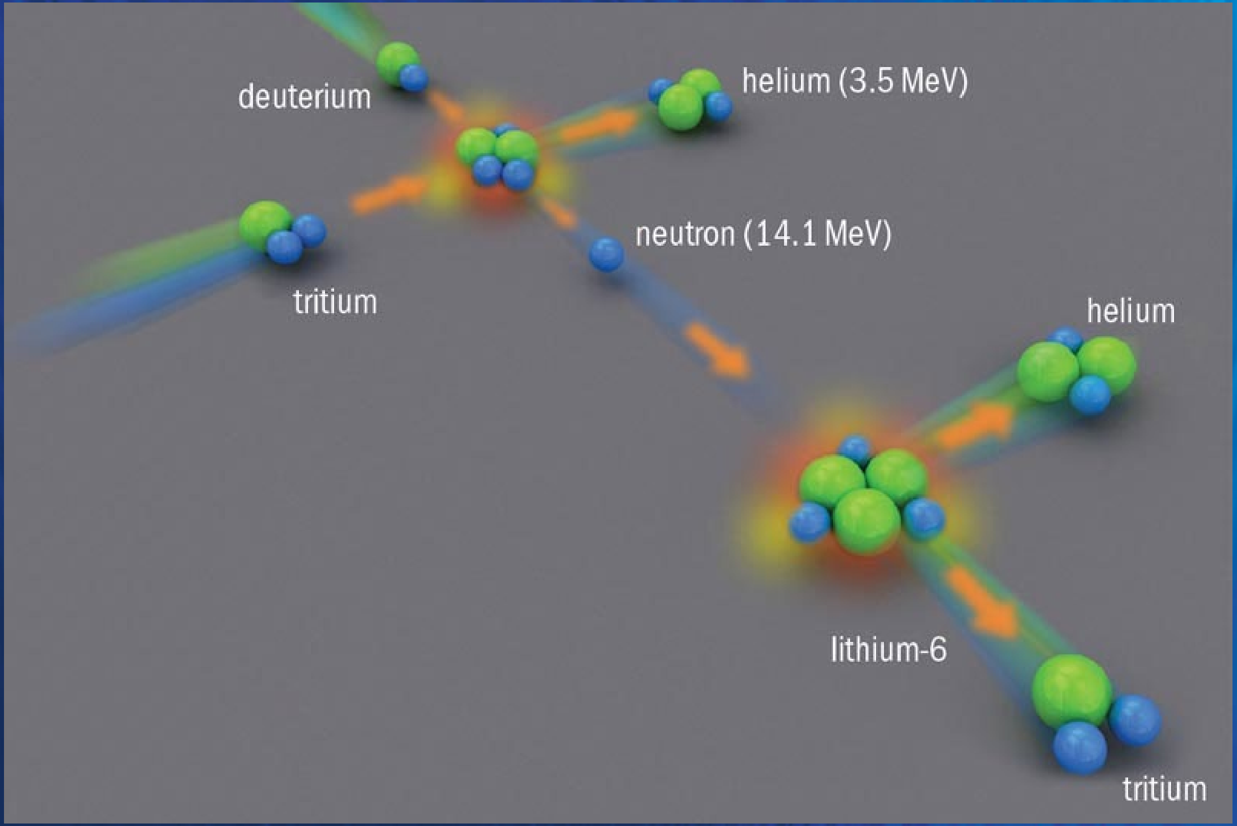


Image EUROfusion

Tritium breeding



Fusion neutrons don’t feel the magnetic field and move into a lithium-containing blanket

The neutrons split the lithium into helium and tritium and additionally they heat the wall

Heat is used to drive turbines ☞ electricity

Tritium is fed back into the plasma

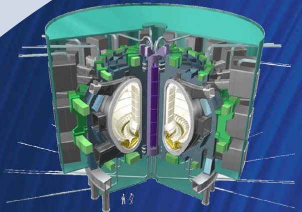
Simple fusion roadmap

Fusion facilities around the world

Fusion is plausible ✓

Fusion is feasible

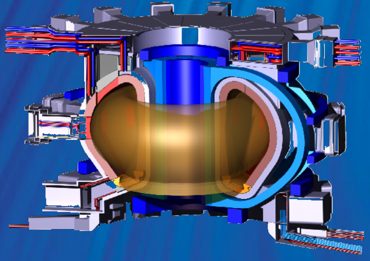
ITER



~2030
D-T in 2037

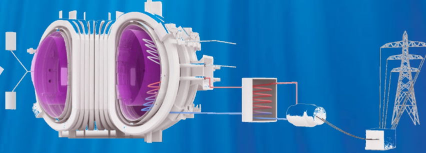
Fusion is practical, attractive

DEMO



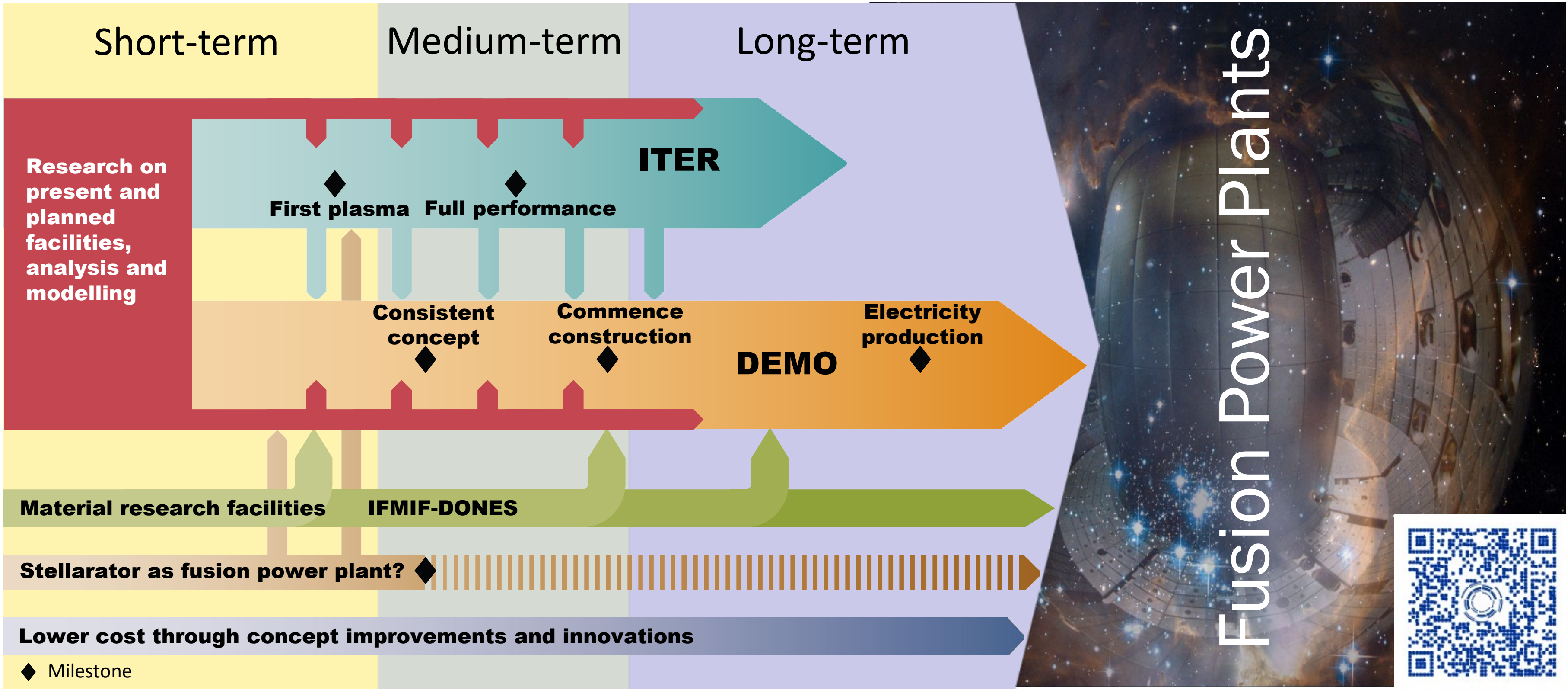
~2040-2050

Fusion is commercially ready



Power Plant

European Fusion Research Roadmap – under revision



Short-term

Medium-term

Long-term

Research on present and planned facilities, analysis and modelling

ITER

◆ **First plasma**

◆ **Full performance**

DEMO

Consistent concept ◆

Commence construction ◆

Electricity production ◆

Material research facilities

IFMIF-DONES

Stellarator as fusion power plant? ◆

Lower cost through concept improvements and innovations

◆ Milestone

Fusion Power Plants

Why the revision?

Interest in fusion has grown enormously thanks to

- Fusion research successes at JET, NIF, W7-X, Medium-Sized SC Tokamaks, ITER assembly
- Realization that baseload electricity power plants are essential for energy transition & security
- Booming of private fusion efforts

Present Roadmap contains all the linked elements of a reactor-oriented program but is based on a sequential JET-ITER-DEMO approach

- Delays have impacted ITER, but also JT-60SA, IFMIF-DONES and DTT
- Unique and valuable lessons learned from every stage of the ITER project can and must be integrated into the Roadmap

Main elements of the Roadmap revision

1. Definition of the DEMO step
2. Gaps to be addressed
3. Measures to accelerate the DEMO and FPP programs
    - ➢ Parallelization of ITER and DEMO activities
    - ➢ Public-Private Partnerships

These points are in addition to the specific activities for the ITER project, which remain central

Definition of the DEMO step – high level goals

Demonstrate performance and integration of key technologies with tolerable failure rates to achieve adequate levels of availability

- Net electricity output to grid of a few hundreds of MWs
- Self-sufficient fuel cycle: supply tritium for itself & to start a new plant
- Robust plasma operation scenario and power-exhaust system
- Demonstration of intrinsic safety and tolerable impact of waste
- Maintenance systems that ensure plant availability and accessibility

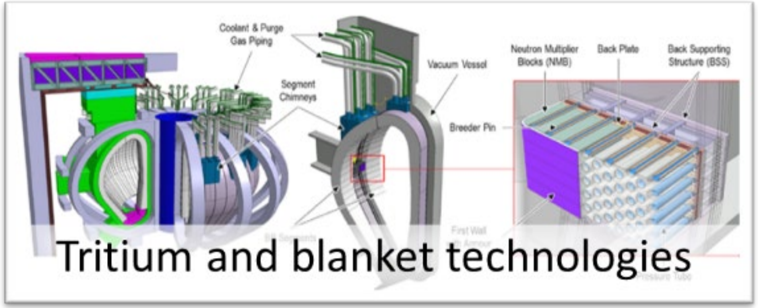
Tokamak configuration

Target: start operations /commissioning ~20 years after kick off

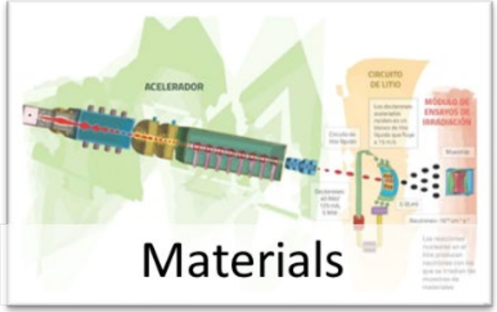
Definition of the DEMO step – requirements

Stakeholder requirements	Plant requirements
Net electrical power of 100s of MW	$P_{el,net}$ ~ 300-500MW
Pulse length	t_{pulse} >> dwell time (several hours)
Tritium self-sufficiency	Tritium Breeding Ratio TBR > 1
Blanket lifetime and radiation exposure	~20dpa first phase (6-7y); ~50dpa second phase (16-17y)
Doubling time for FPP deployment	$\tau_D \leq 10y$
Safety	No countermeasure to the population and to the environment in accidental conditions Minimization of intermediate- and low-level radioactive waste, and avoidance of high-level waste

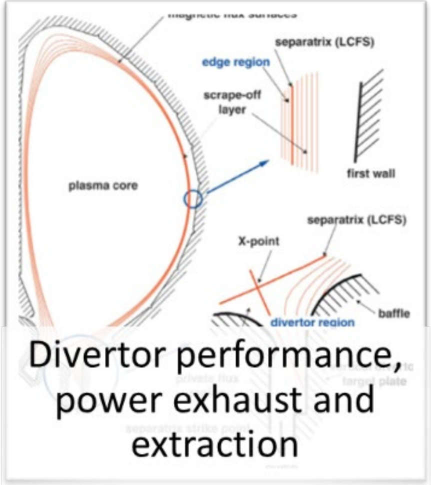
Gaps to be addressed



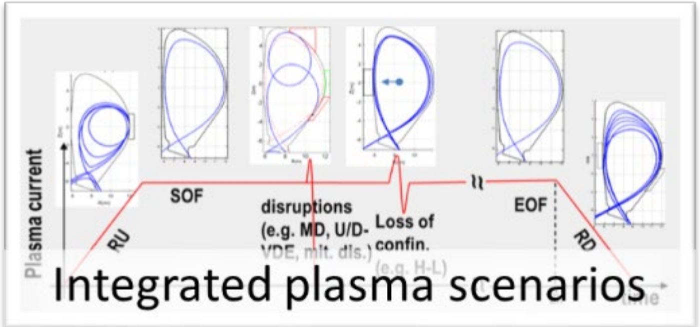
Tritium and blanket technologies



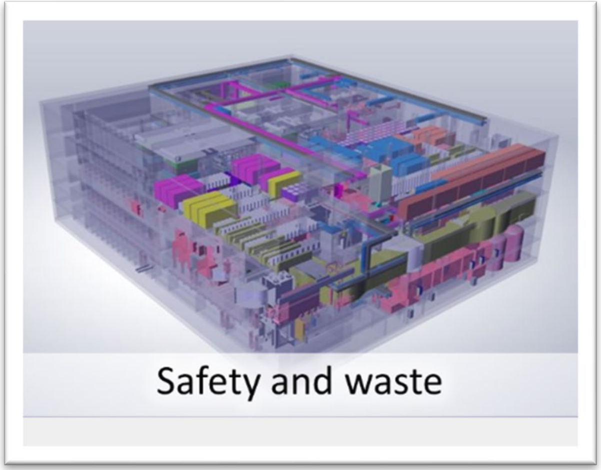
Materials



Divertor performance, power exhaust and extraction



Integrated plasma scenarios



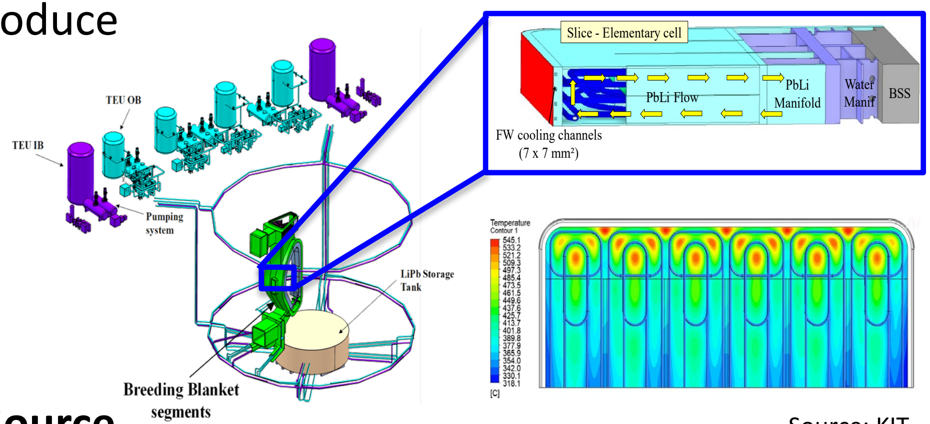
Safety and waste

Remote maintenance

Gaps to be addressed: Tritium and blanket technologies

ITER Test Blanket Module (TBM) programme comes late and expected damage dose of <0.1dpa will not produce significant effects

IFMIF-DONES will be the only facility with neutrons of adequate spectrum and fluence to qualify materials using small samples



Source: KIT

Feasibility of a **Volumetric 14 MeV Neutron Source** to test large components to reduce the risks for DEMO is under consideration, but is it politically viable?

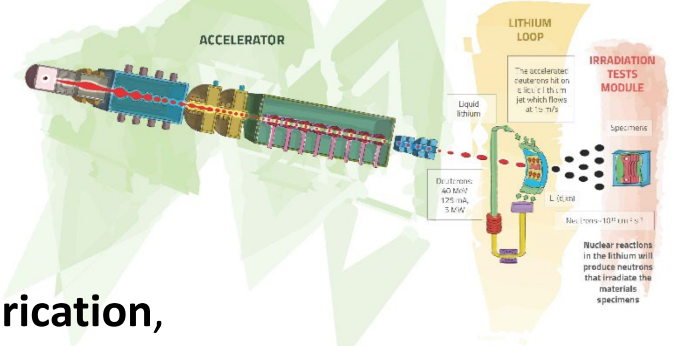
Link with work in NL (DIFFER-DICE)

Therefore, the present **DEMO approach** implies that the blanket of high risk, to be qualified in a time-consuming process, dependent on the total dpa value required and the machine availability. The combined effects of neutron impact and other ways of degradation during operation would be detected in the integral testing on DEMO only

Gaps to be addressed: Materials

A vigorous development program is needed to **qualify materials** in the range beyond 20 dpa towards enabling the roll-out of an FPP economy

- ➢ mechanical and thermal properties
- ➢ response to plasma exposure and to 14-MeV neutron irradiation >20 dpa
- ➢ chemical compatibility and safety issues



Source: IFMIF-DONES

In parallel, the maturity and robustness of **industrial fabrication**, machining, joining and production processes should be increased

The **IFMIF-DONES** facility, expected to start operations around early 2030s, will provide the qualification of materials under a suitable neutron spectrum irradiation, needed for the design, licensing, construction and safe operation of FPPs

Link with work in NL (NRG + new fission reactors)

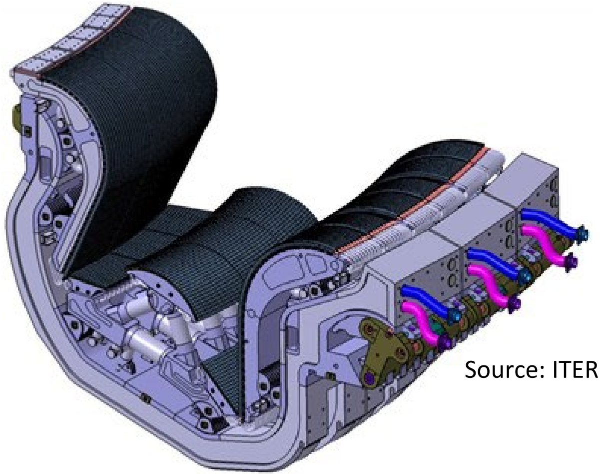
Gaps to be addressed: power exhaust

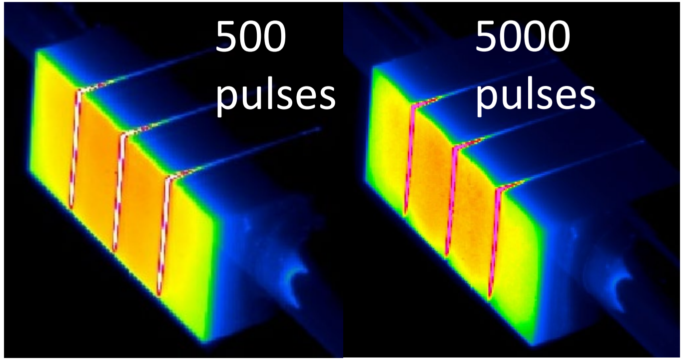
Solutions need to be found in which a very large fraction of power is radiated before it reaches the device walls to reduce the thermal load to plasma facing components

Advanced divertor configurations and materials must be assessed to ensure optimal PFC cooling, thermal mechanical integrity and sufficient shielding to the vessel

It is noted that some alternatives have a large impact on the machine design and remote maintenance

Strong link with work in NL (DIFFER - MAGNUM)


Source: ITER

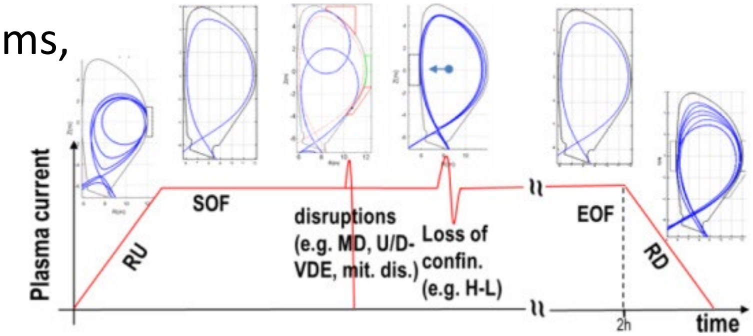


Source: IPP-GLADIS

Gaps to be addressed: integrated plasma scenarios

Magnetized plasmas are complex self-organized systems, with limited external control, whose parameters and profiles cannot be prescribed a priori

It is only possible to prepare experimental conditions that facilitate a particular scenario, i.e., a set of properties that are mutually compatible and can be reproducibly maintained for long enough using actuators



Source: F. Maviglia, FED 177 (2022) 113067

Attractive solutions for individual elements (core, edge, exhaust) have been found on various experiments, but their integration remains a challenge since the DEMO plasma conditions cannot be met simultaneously in present devices.

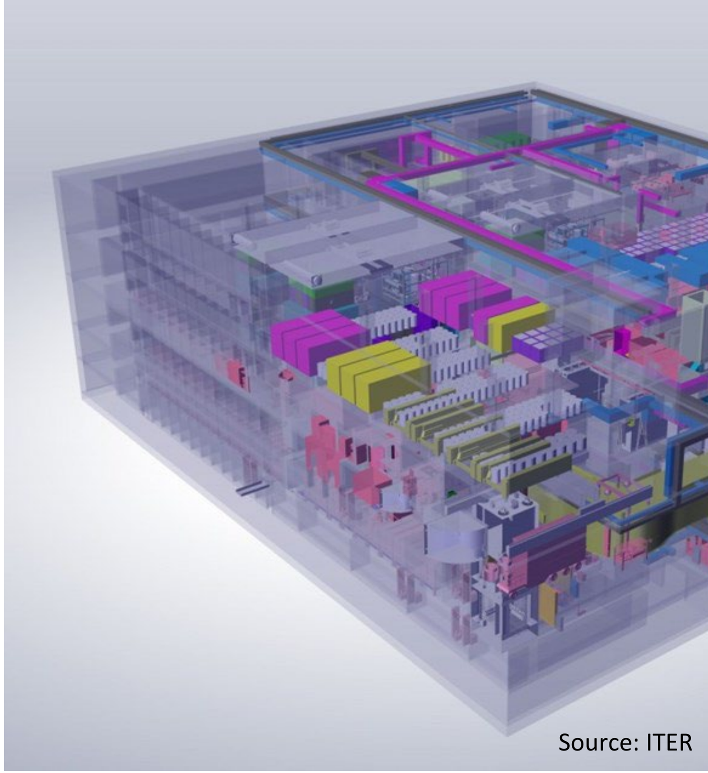
- Exhaust solutions can strongly affect the overall plasma performance
- Disruptions are a severe threat to the attractiveness of a tokamak DEMO and affect its overall availability

Strong link with work in NL (DIFFER, TU/e)

Gaps to be addressed: safety and waste

A few R&D elements remain open :

- More accurate quantification of key radiological source terms
- Assess after how long waste arising from operation can meet Low-Level Waste criteria
- Understand whether any Intermediate-Level Waste can be managed in near surface disposal facilities, using techniques for detritiation and decarburization, and/or barriers, developed to assure removal or containment of the key long-lived activation products



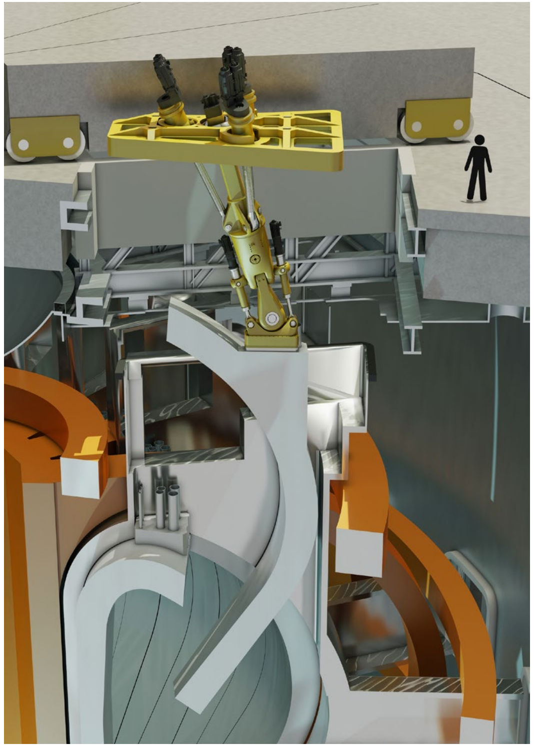
Source: ITER

Link with work in NL (NRG + new fission reactors)

Gaps to be addressed: Remote Maintenance

Remote maintenance system and related strategy must be developed to:

- assure removal of components also in case of damage
- minimize the time duration of maintenance
- Guarantee compliance with safety requirements (e.g., Tritium containment)



Source: RACE

Link with work in NL (DIFFER, HIT)

Measures to accelerate the DEMO program

- Parallelization of activities to reduce the sequential coupling of ITER milestones and DEMO decision points
- Strengthening R&D in the identified gap areas
- Increased effort in simulations for plasma and for engineering
- Mutually beneficial new international collaborations
- Development and maintenance of adequate workforce
- Knowledge management
- Streamlining licensing towards a regulatory framework for fusion and rapidly identifying site

Would Netherlands be interested in offering a site?

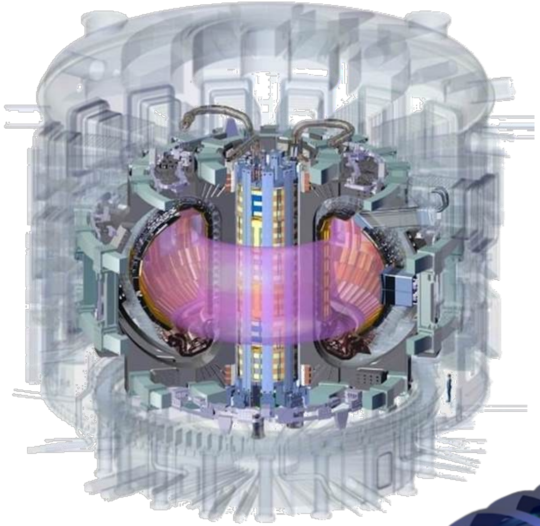
- Involvement of industry in DEMO design & construction (PPPs)

Measures to accelerate the FPP program beyond DEMO

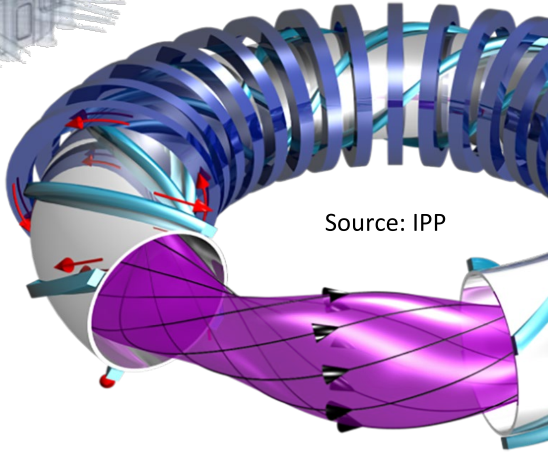
Dedicated test facilities to qualify technologies for FPPs that will be different from DEMO

Investigations to increase attractiveness of FPPs

- Stellarator FPP design studies
- HTS magnets
- Advanced structural materials
- Alternatives to water as primary coolant



Source: ITER



Source: IPP

Parallelization of ITER and DEMO and the role of ITER

ITER demonstration of Q=10 & burning plasma regime will provide basis for DEMO scenarios

ITER TBM program will likely not be in time for DEMO design

- Development & validation of solutions to advance the qualification of blanket technology, to make DEMO an integrated demonstrator and not a blanket test facility

Yet, TBMs will yield crucial information for DEMO on qualification, licensing, manufacturing and integrated operation of blankets in nuclear plasma environment

ITER’s experience with safety and waste production, RH, civil engineering, the hot cell, the management of T and radioactive waste, is an essential reference for DEMO

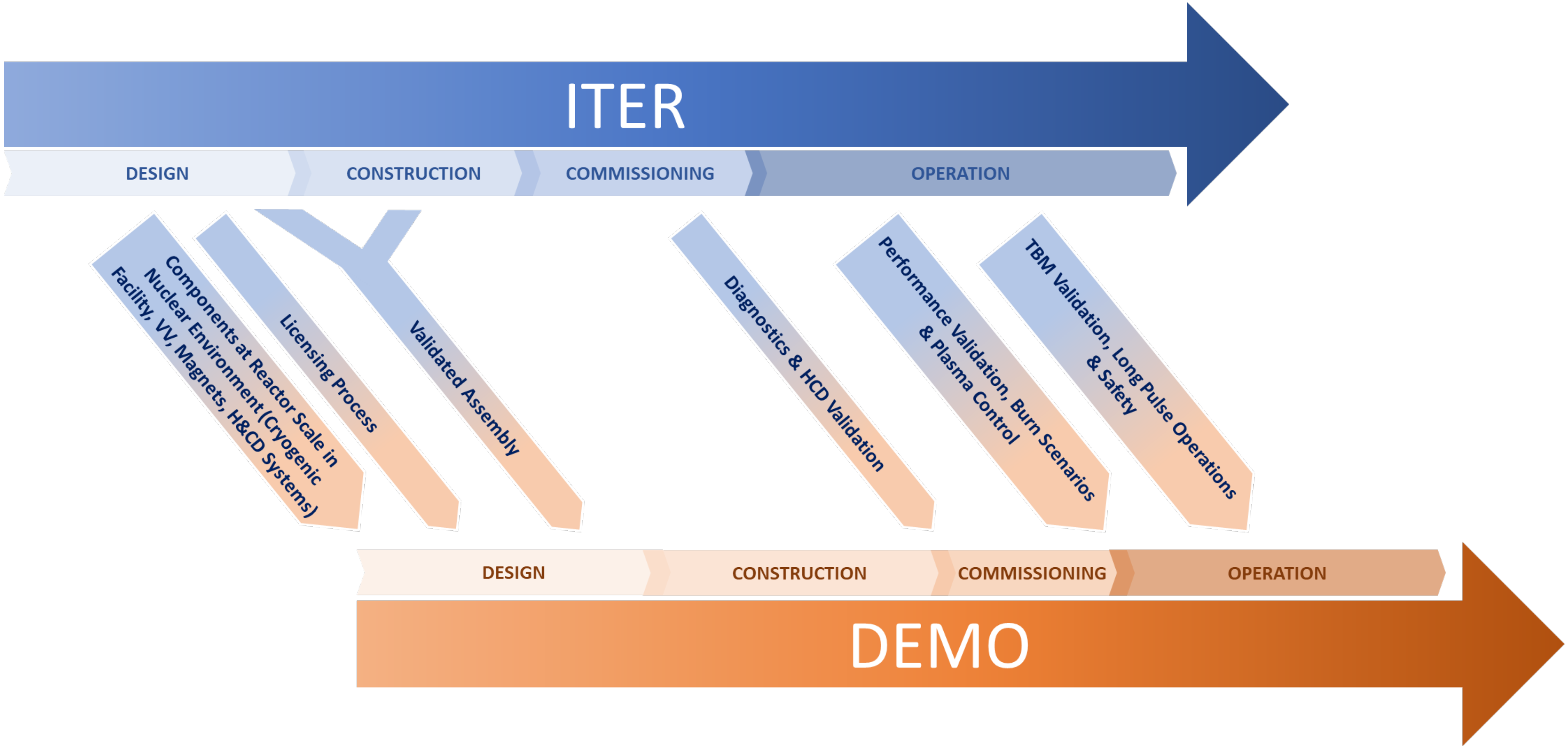
TRL Now

Water BoP (TRL 7-8)
Divertor RH (TRL 6)
ECH 170 GHz (TRL 6)
Magnets Nb_3Sn LTSC (TRL 6)
Divertor (TRL 4)
He BoP (TRL 4-5)
NB (1MeV) (TRL 3)
Blanket RH (TRL 3)
Blanket (TRL 2-3)

TRL after ITER

Magnets Nb_3Sn LTSC
Buildings
Vacuum Vessel
Cryopumps
Divertor and div RH (TRL 7-8)
ECH 170 GHz (TRL 6-7)
NB (1MeV)
DEMO Blanket RH
DEMO Blanket – TBM (TRL 4-5)

Parallelization of ITER and DEMO and the role of ITER



ITER

DESIGN

CONSTRUCTION

COMMISSIONING

OPERATION

Components at Reactor Scale in Nuclear Environment (Cryogenic Facility, VV, Magnets, H&CD Systems)

Licensing Process

Validated Assembly

Diagnostics & HCD Validation

Performance Validation, Burn Scenarios & Plasma Control

TBM Validation, Long Pulse Operations & Safety

DESIGN

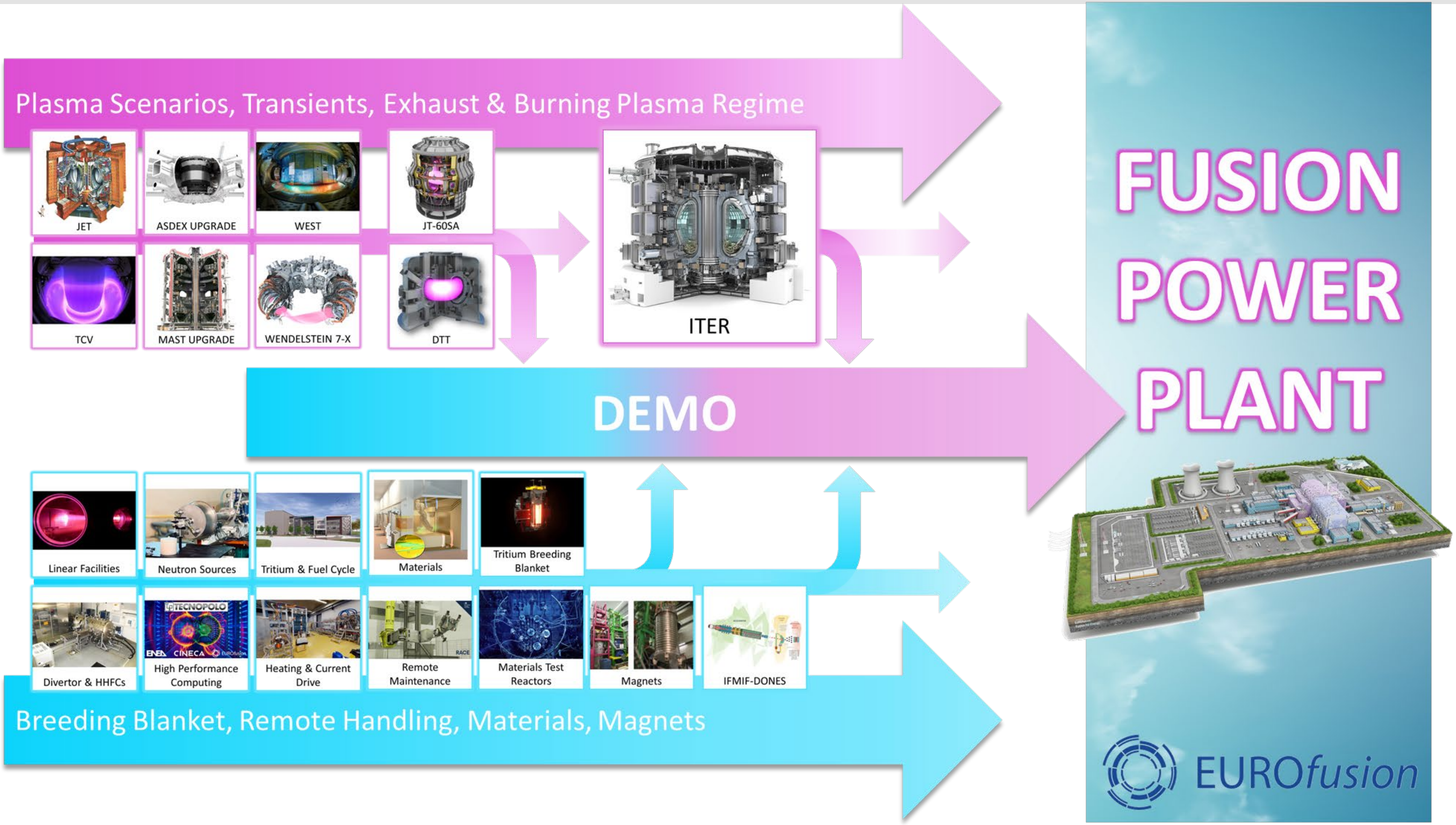
CONSTRUCTION

COMMISSIONING

OPERATION

DEMO

Parallelization of ITER and DEMO



Plasma Scenarios, Transients, Exhaust & Burning Plasma Regime

JET

ASDEX UPGRADE

WEST

JT-60SA

TCV

MAST UPGRADE

WENDELSTEIN 7-X

DTT

ITER

DEMO

Linear Facilities

Neutron Sources

Tritium & Fuel Cycle

Materials

Tritium Breeding Blanket

Divertor & HHFCs

High Performance Computing

Heating & Current Drive

Remote Maintenance

Materials Test Reactors

Magnets

IFMIF-DONES

Breeding Blanket, Remote Handling, Materials, Magnets

FUSION POWER PLANT

EUROfusion

Public-Private Partnerships

Need to combine industrial and entrepreneurial approaches with the extensive know-how, and the ambitious yet realistic vision of public-funded European fusion program

Collaborative approach involving joint leadership, combination of public and private IP, agile procurement processes compatible with EU industry development, and strategic partnerships

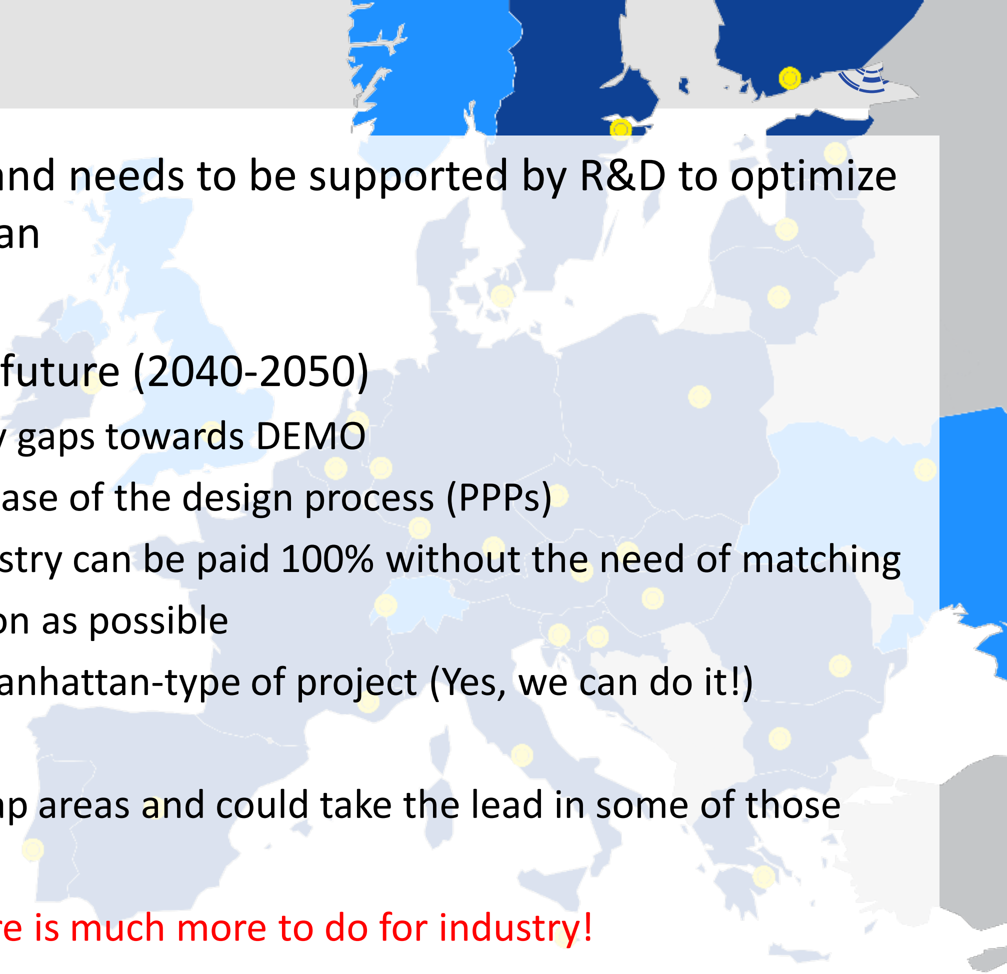
DEMO will be built within an industrial framework, utilizing fully industrial practices

Industrial input and strategic partnerships are also crucial for a program on technological gaps prior to DEMO design, and to develop capability and capacity in supply chains, especially in areas that are not stimulated by ITER procurement

Can we find a healthy public-private partnership model – as co-funding of industry is not working?

An example can be the UKIFS organization set up for delivering STEP (in the UK)

Summary



ITER is the most important fusion project and needs to be supported by R&D to optimize the ITER re-baselining and the Research Plan

To keep DEMO at an attractive time in the future (2040-2050)

- R&D needs to be focused on the technology gaps towards DEMO
- Industry needs to be involved in an early phase of the design process (PPPs)
- Funding should be organized such that industry can be paid 100% without the need of matching
- A site for DEMO needs to be selected as soon as possible
- Ideally DEMO needs to be organized as a Manhattan-type of project (Yes, we can do it!)

Netherlands has competences in many of the gap areas and could take the lead in some of those

Note that this talk focused on the gaps, but there is much more to do for industry!