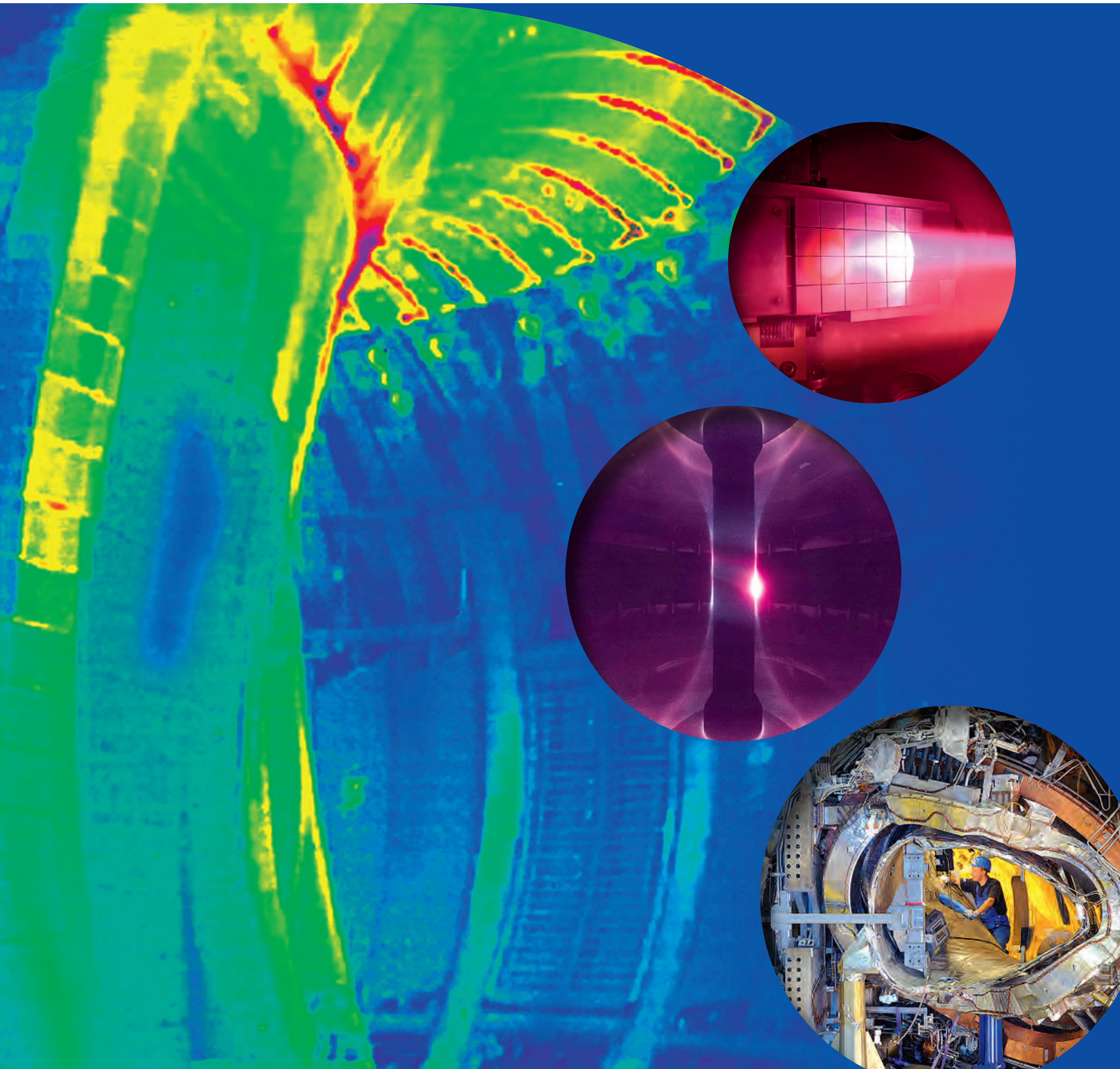
EUROfusion



EUROPEAN CONSORTIUM FOR THE DEVELOPMENT OF FUSION ENERGY

EUROfusion

EUROPEAN CONSORTIUM
FOR THE DEVELOPMENT OF
FUSION ENERGY

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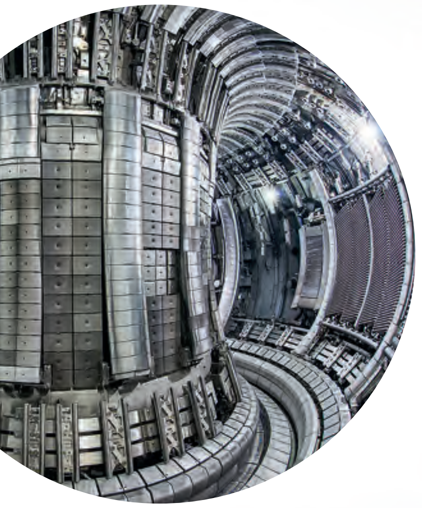


RESEARCH UNIT PROFILES

HOST INSTITUTES

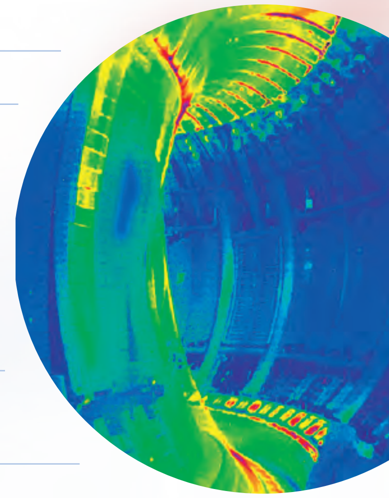
10 Culham Centre for Fusion Energy (**CCFE**), United Kingdom
11 Max Planck Institute for Plasma Physics (**IPP**), Germany

RESEARCH UNITS WITH EURO*fusion* DEVICES

12 Dutch Institute For Fundamental Energy Research (**DIFFER**), The Netherlands
13 Forschungszentrum Jülich (**FZJ**), Germany
14 Institute for Magnetic Fusion Research (**IRFM**), CEA, France
15 Swiss Plasma Center (**SPC**), EPFL, Switzerland

RESEARCH UNITS COORDINATING NATIONAL RESEARCH FOR EURO*fusion*

16 Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (**ENEA**), Italy
17 **FinnFusion**, Finland
18 Fusion@**ÖAW**, Austria
19 Hellenic Fusion Research Unit (**Hellenic RU**), Greece
20 Institute for Plasmas and Nuclear Fusion (**IPFN**), Portugal
21 Institute of Solid State Physics (**ISSP**), Latvia
22 Karlsruhe Institute of Technology (**KIT**), Germany
23 Lithuanian Energy Institute (**LEI**), Lithuania
24 Plasma Physics and Fusion Energy, Department of Physics, Technical University of Denmark (**DTU**), Denmark
25 Plasma Physics Department, **Wigner Fusion**, Hungary
26 Plasma Physics Laboratory, Ecole Royale Militaire (**LPP-ERM/KMS**), Belgium
27 Ruđer Bošković Institute, Croatian Fusion Research Unit (**CRU**), Croatia
28 Slovenian Fusion Association (**SFA**), Slovenia
29 Spanish National Fusion Laboratory (**LNF**), CIEMAT, Spain
30 Swedish Research Council (**VR**), Sweden
31 Sylwester Kaliski Institute of Plasma Physics and Laser Microfusion (**IPPLM**), Poland
32 The Institute of Plasma Physics of the Czech Academy of Sciences (**IPP.CR**), Czech Republic



RESEARCH UNITS COORDINATING FUSION PROJECTS FOR EURO*fusion*

33 Department of Experimental Physics, Comenius University, Slovakia
Institute for Atomic Physics, Romania
34 Institute of Nuclear Research and Nuclear Energy, Bulgaria
Institute of Physics, University of Tartu, Estonia
35 Plasma Research Laboratory, Dublin City University, Ireland
University of Cyprus, Nicosia, Cyprus

36 **GLOSSARY**
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EURO*fusion*

European Consortium for the Development of Fusion Energy

EMBODYING THE SPIRIT OF EUROPEAN COLLABORATION

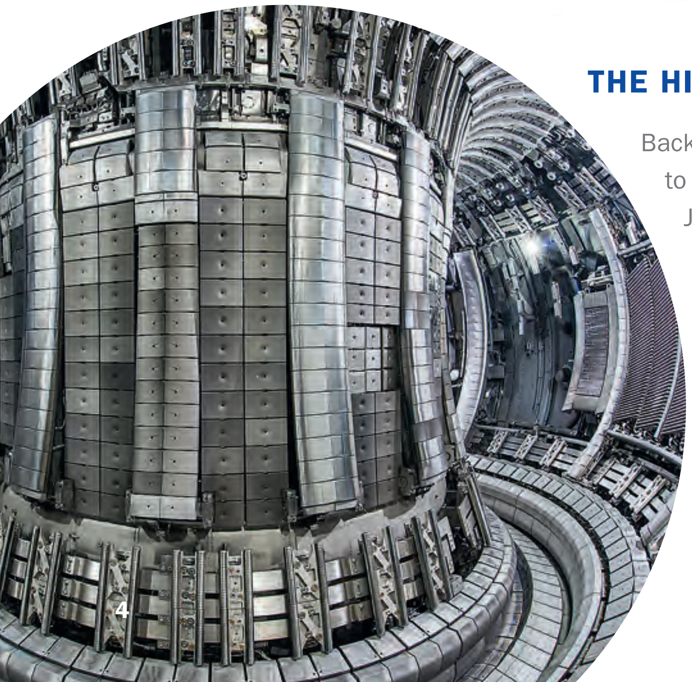
THE ESSENCE OF FUSION

Nuclei of light atoms collide, fuse, produce nuclei of heavier atoms and release vast amounts of energy. This, in a nutshell, is fusion – the process that powers our Sun, a process that researchers have been trying to replicate on Earth in order to meet the ever-increasing global energy demand.

THE TANTALISING CHALLENGE OF REALISING FUSION POWER

Unlimited, clean energy made from relatively cheap and small amounts of fuel is the fusion promise. But building a star on earth is a task as challenging as it is tantalising. Decades of research with the aim of realising fusion energy has shown that the challenge needs to be met with a multifaceted and interdisciplinary approach. In November 2006, seven parties – the European Union, India, Japan, China, Russia, South Korea and the United States – came together to fund, develop and build the world's largest fusion experiment: ITER (Latin for "the way"). The European Union, which hosts ITER in Cadarache, France, is the largest contributor to this fusion experiment and shoulders around 45% of the project cost.

THE HISTORY OF EUROPEAN FUSION COLLABORATION



Back in the 1970s, leading European fusion laboratories joined forces to build and operate the Joint European Torus, or JET. Now in 2016, JET is still the largest and most powerful tokamak in the world and the only device capable of using the deuterium-tritium fuel mix, the fuel of choice for future commercial reactors. Fusion laboratories across Europe have developed collaborations to coordinate research activities on and beyond JET. And, the European Fusion Development Agreement, or EFDA, was established in 1999 to support these collaborative efforts.

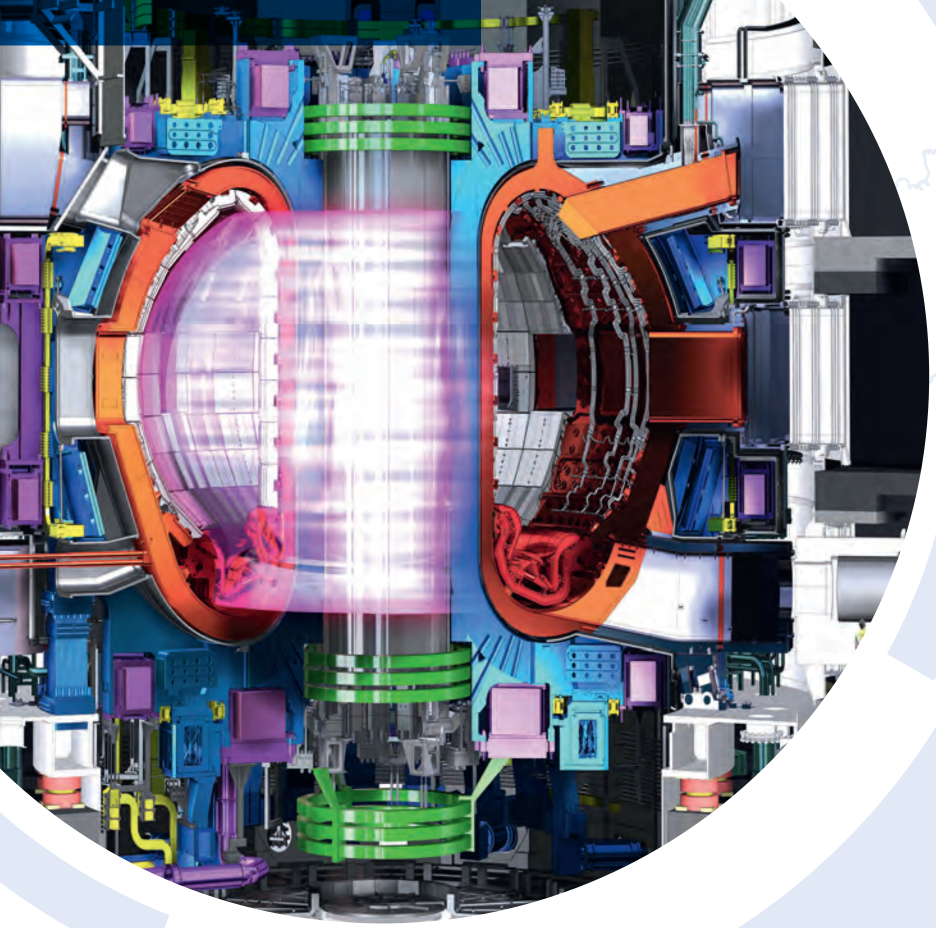
EURO*fusion* IS BORN

In October 2014, 29* research entities from 26 European Union member states and Switzerland came together to further cement the ongoing European fusion collaboration, and the EURO*fusion* Consortium was born. ITER forms the heart of this collaborative agreement which funds and supports European fusion research and education. Once built, ITER will demonstrate the feasibility of fusion as the energy source of the future. EURO*fusion*'s work is structured around the "Roadmap to the realisation of fusion energy", which places ITER at its core. The roadmap highlights the importance of a long-term perspective on fusion and lays the foundation for collaboration between the EURO*fusion* consortium members, linked third parties, industries and even with research laboratories from beyond the European fusion community.

THE ROAD FROM ITER TO DEMO

Because ITER is the key facility of the EURO*fusion* roadmap, the consortium allocates considerable resources to ITER and its accompanying experiments. The second phase of the roadmap is focussed on maximising ITER exploitation and on preparing the construction of a demonstration power plant – DEMO. The final phase of the roadmap is the construction and operation of DEMO, which will bring fusion electricity to the grid.

*In January 2017, Ukraine becomes the 30th member to sign the EURO*fusion* agreement.



KEY EURO*fusion* FACTS

NUMBER OF SIGNATORIES
Thirty members, representing 26 European Union member states and Switzerland and Ukraine along with 100 third-party signatories, which include universities, fusion laboratories and industry.

HOST INSTITUTES
Max Planck Institute for Plasma Physics, Garching, Germany, and **Culham Centre for Fusion Energy**, UK

FLAGSHIP DEVICE
The Joint European Torus, JET, located at Culham Centre for Fusion Energy, UK

FUNDING
Total funding is € 850 million for five years. € 424 million comes from the EURATOM Horizon 2020 programme and about the same amount from the member states.
Additionally, **JET operations receive annual funding of € 69 million**, 87.5% of which is provided by the European Commission and 12.5% by the UK.

ITER FACTS AT A GLANCE

THE DEVICE
ITER will be the world's largest tokamak, with a **plasma radius of 6.2 m** and a **plasma volume of 840 m³**

PLASMA TEMPERATURE
150 million degree Celsius, i.e., 10 times the temperature of the Sun's core

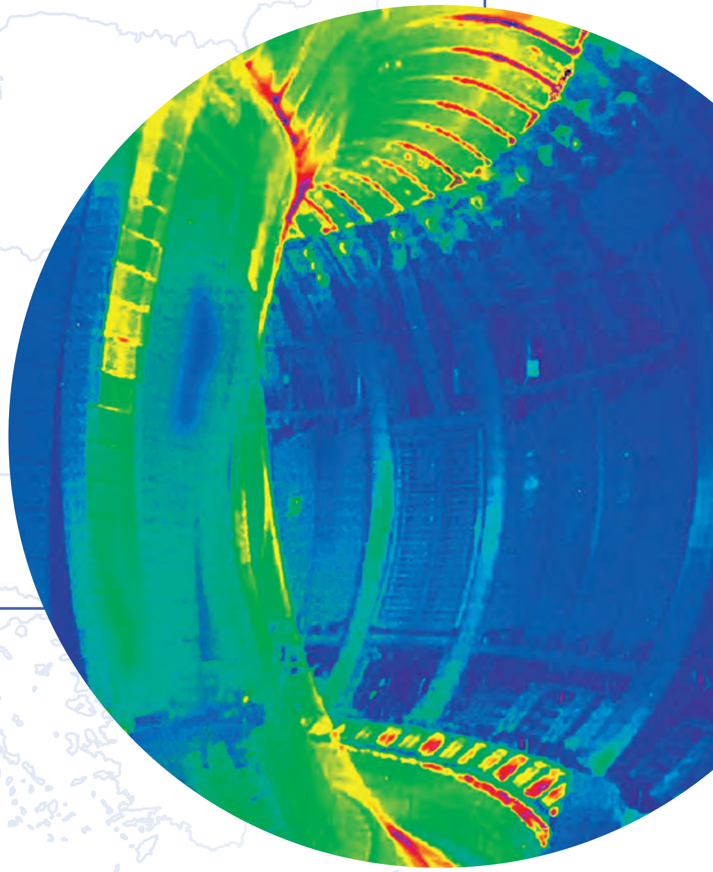
EXPECTED FUSION POWER OUTPUT
500MW

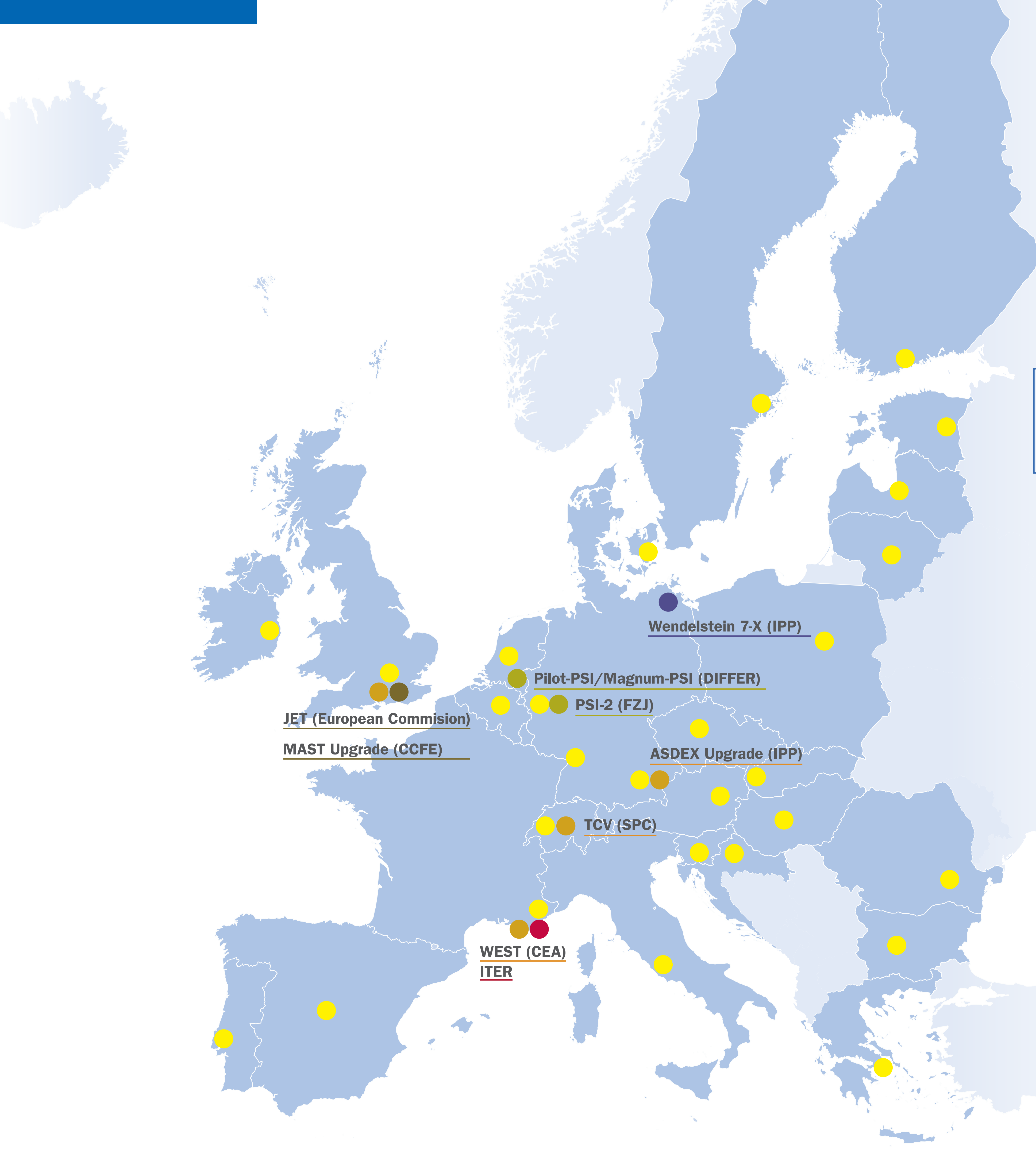
JET FACTS AT A GLANCE

THE DEVICE
Plasma radius of 2.96 m and a **plasma volume of 90 m³**

Only existing fusion device capable of operating with a **deuterium-tritium fuel**

Referred to as the "little ITER", JET has been equipped with **beryllium-tungsten plasma-facing wall** (known as an ITER-like wall) and tungsten divertors.





THE EURO*fusion* DEVICES' AND RESEARCH UNITS' INFOGRAPHIC

The map shows the types and venues as well as ownership of fusion experiments, plus the devices operating for the EURO*fusion* Consortium. The research in these facilities is motivated by the requirements set out in the "Roadmap to the realisation of fusion energy".

The following pages give us a glimpse into the world of EURO*fusion*'s Research Units, highlighting the ways in which they work both independently and together in order to achieve fusion electricity and power the future.

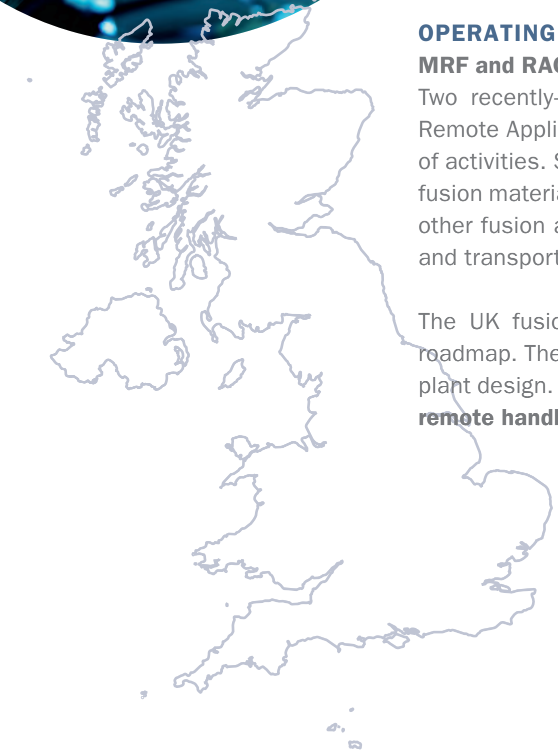
- EURO*fusion* consortium members*
- Tokamak
- Spherical Tokamak
- Stellarator
- Linear Device
- ITER (under construction)

* The yellow dots indicate the headquarters of the EURO*fusion* Beneficiaries which signed the Grant Agreement (Number 633053, EUROfusion)

UK

CCFE

Culham Centre for Fusion Energy (CCFE) has, for over 50 years, been the UK's national fusion laboratory. It continues to advance Britain's contribution to European fusion research through the MAST Upgrade tokamak and by operating EUROfusion's flagship device JET.



MAST UPGRADE

Plasma in a cored apple

MAST Upgrade is part of EUROfusion's **Medium Size Tokamak programme**, along with ASDEX Upgrade (Germany) and TCV (Switzerland). It explores the alternative "spherical tokamak" configuration, in which plasma is held in a tighter "cored apple" shape, giving the potential for more compact and efficient devices. Apart from providing physics data to inform future ITER experiments, MAST Upgrade is the first tokamak to test the **Super-X divertor** – an innovative exhaust system intended to reduce heat loads from particles leaving the plasma, which could be adopted by DEMO. It will also explore the potential of the spherical tokamak as a design for a fusion **Component Test Facility** (CTF) which would test reactor systems for DEMO.

OPERATING JET

Home to EUROfusion's flagship device

Since 2000, CCFE has operated JET under contract with the European Commission. This involves providing engineering support for EUROfusion researchers during experimental campaigns, and maintaining and upgrading the machine during shutdown periods. CCFE has created a sophisticated remote handling system to carry out much of the engineering work on JET – notably demonstrated by the installation of the tokamak's new "ITER-like" inner wall in 2009–2011.

OPERATING JET

MRF and RACE

Two recently-opened facilities at Culham, the Materials Research Facility (MRF) and the Remote Applications in Challenging Environments (RACE) centre have expanded CCFE's range of activities. Scientists may use MRF to examine the effects of irradiation on tiny fragments of fusion materials. The RACE centre applies the expertise from JET's **remote handling system** to other fusion applications and to areas from space to deep sea, nuclear fission, construction and transport.

The UK fusion programme has a full range of research areas linking into EUROfusion's roadmap. These include plasma theory and modelling, materials, fusion technology and power plant design. CCFE is also participating in preparations for ITER – in particular, development of **remote handling applications, plasma heating systems and diagnostic instruments.**

UNITED KINGDOM . MAST UPGRADE . MEDIUM SIZE TOKAMAK PROGRAMME . SPHERICAL TOKAMAK . REMOTE HANDLING .

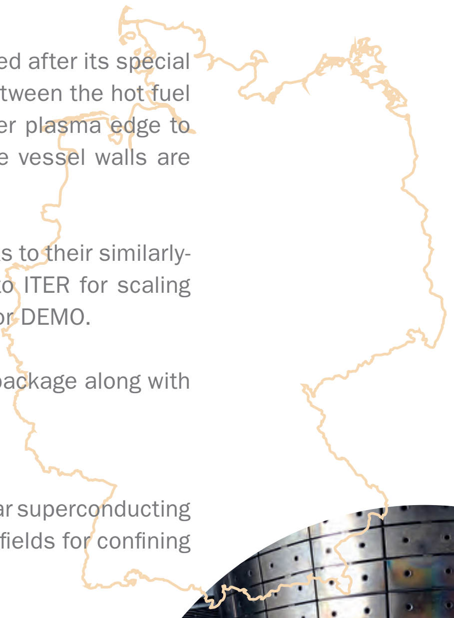
WWW.CCFE.AC.UK

DE

IPP

Max Planck Institute for Plasma Physics' facts at a glance:

- Campus locations: **Garching** and **Greifswald**
- **One of the largest fusion research centres in Europe** (workforce: ~1,100)
- **Coordinator** of **EUROfusion** and host to the EUROfusion Programme Management Unit
- Operator of **ASDEX Upgrade** (Garching) and **Wendelstein 7-X** (Greifswald)
- Has 10 scientific divisions investigating the confinement of high-temperature hydrogen plasmas in magnetic fields, heating of plasma, plasma diagnostics, magnetic field technology, data acquisition and processing, plasma control, plasma theory, materials research, and plasma-wall interaction
- An institute of the **Max Planck Society** and associated with the **Helmholtz Association**



ASDEX UPGRADE

The ASDEX Upgrade tokamak, "Axially Symmetric Divertor Experiment", is named after its special magnetic field configuration, namely, the divertor. It enables the interaction between the hot fuel and the surrounding walls to be influenced. The divertor field diverts the outer plasma edge to the collector plates. This removes perturbing impurities from the plasma; the vessel walls are safeguarded and good thermal insulation of the core plasma is attained.

It is the only tokamak in Europe with a completely metal-clad vessel wall. Thanks to their similarly-shaped plasma cross-sections, ASDEX Upgrade and JET form a stepladder to ITER for scaling experiments. Furthermore, ASDEX Upgrade is used for developing scenarios for DEMO.

ASDEX Upgrade is at the centre of EUROfusion's Medium Size Tokamak work package along with MAST Upgrade (UK) and TCV (Switzerland).

WENDELSTEIN 7-X

Wendelstein 7-X is the world's largest stellarator type fusion device. It has modular superconducting coils that enable steady state plasma operation, and test optimised magnetic fields for confining plasma.

The structure, composed of single coils, permits detailed shaping of the magnetic field. Extensive theory and computation effort has been invested in the optimisation of the magnetic field for Wendelstein 7-X in order to overcome the disadvantages of traditional stellarators.

Wendelstein 7-X began operations in December 2015 and now investigates the suitability of the stellarator concept for use as a power plant. Plasma equilibrium and confinement are expected to be of a quality comparable to that of a tokamak of the same size, but the structure will avoid the disadvantages of a large current flowing in a tokamak plasma. With plasma discharges lasting up to 30 minutes, Wendelstein 7-X is to demonstrate the essential stellarator property of continuous operation.

GERMANY . ASDEX UPGRADE . WENDELSTEIN 7-X . TOKAMAK . STELLARATOR . PROGRAMME MANAGEMENT UNIT .

WWW.IPP.MPG.DE

NL

DIFFER

The **Dutch Institute for Fundamental Energy Research, DIFFER**, is the Dutch consortium member of EUROfusion. DIFFER conducts leading fundamental research in the fields of fusion energy and solar fuels: converting intermittent electricity from renewables into fuels and other products. DIFFER is actively building up a cross-disciplinary community for energy research in the Netherlands and serves as point-of-contact between fundamental research and industry. As part of this activity, DIFFER connects Dutch knowledge and technology institutes with the international fusion research community. This includes diagnostics development, control engineering, materials research and remote handling studies at Delft University, Eindhoven University of Technology, Twente University and the Nuclear Research and consultancy Group NRG.

DIFFER is an active partner in addressing two of fusion's main research challenges.

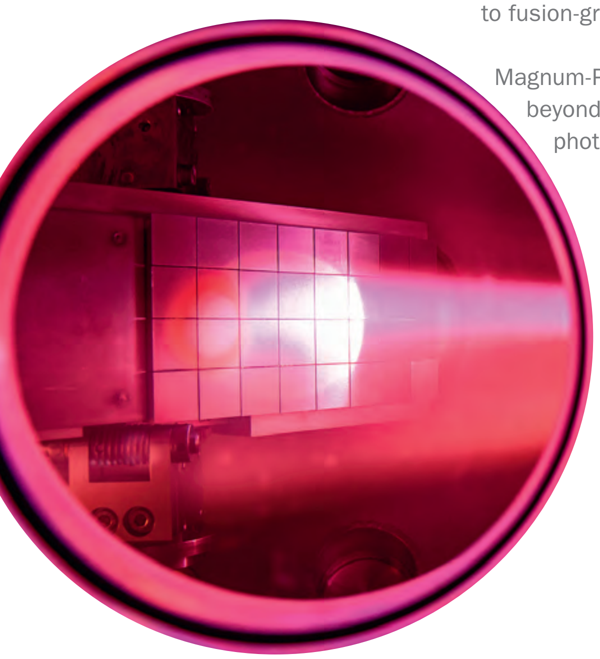
- Investigating materials under the extreme plasma conditions near the wall of future fusion reactors such as ITER by using the linear plasma generator Magnum-PSI
- Participating in international research on control over instabilities at the centre of the fusion plasma, developing plasma diagnostics, modelling, and control at the EUROfusion facilities JET (UK), ASDEX Upgrade(Germany) and TCV (Switzerland)

MAGNUM-PSI: THE HEART OF THE FUSION RESEARCH AT DIFFER

DIFFER's linear plasma generator Magnum-PSI is unique in its capability to expose wall materials to the punishing conditions that exist at the fusion reactor exhaust (divertor). With Magnum-PSI, DIFFER and its international users investigate and develop wall materials that can withstand divertor conditions in the ITER and fusion reactors to be developed in the future. Magnum-PSI is already helping to shape the final design of the ITER divertor whilst investigating advanced concepts for fusion power plants, such as liquid metal walls.

By combining expertise in plasma diagnostics, modelling and control, researchers at DIFFER are using Magnum-PSI to start a programme regarding controlling the exhaust plasma of a fusion reactor. In addition, a superconducting magnet upgrade to Magnum-PSI will allow researchers to investigate, for the first time, the impact of the long-term exposure of materials to fusion-grade plasmas.

Magnum-PSI is also investigating materials processing with high-density plasmas for uses beyond fusion; this includes growing tailored nanostructures on a metal surface to create photoelectrodes for solar water splitting.



THE NETHERLANDS . MAGNUM-PSI . LINEAR PLASMA GENERATOR . WALL MATERIALS .

WWW.DIFFER.NL

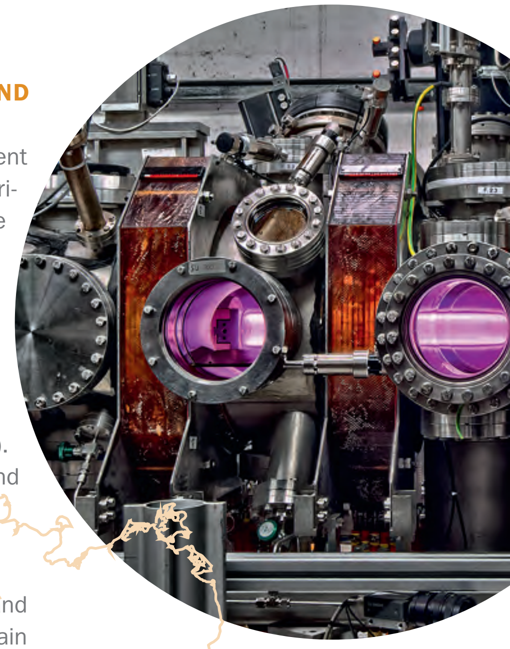
DE

FZJ

Fusion researchers at **Forschungszentrum Jülich** address two key aspects of fusion research:

- Materials for extreme loads – New materials and composites are developed, characterised and tested by exposing them to the harsh conditions of plasma-facing components
- Plasma-material interactions – Understanding the physics of the boundary plasma towards the wall and its interaction with the materials allows the definition of the operational window for ITER and future fusion reactors

Jülich researchers use linear plasma machines on site along with fusion experiments, including Wendelstein 7-X, JET, ASDEX Upgrade, and EAST. In conjunction with theory and model developments, ITER operation scenarios are predicted and the gained knowledge enables extrapolation for DEMO.



RESEARCH INTO THE SYNERGISTIC EFFECTS OF PARTICLE FLUX, HEAT LOAD AND NEUTRON DAMAGE ON MATERIALS

Linear plasma devices are used in order to mimic conditions at the boundary region in current and next generation fusion experiments. **PSI-2**, located at Jülich, enables well-defined experiments which apply high particle fluxes and heat loads to material surfaces. To obtain the information in situ with regard to both the plasma conditions and the state of materials in a fusion environment, new techniques, including laser-based diagnostics and spectroscopy, are developed.

The unique infrastructure at Jülich enables, for the first time, investigations into the effects of neutron damage to wall materials during interaction with plasmas. A second linear machine, **JULE-PSI**, will start operation at the **High-temperature Materials Laboratory** (HML). Here, wall materials that have been damaged by neutron irradiation can be safely handled and investigated, whilst also examining the highest heat loads applied by electron beams.

TECHNOLOGY AND PHYSICS FOR ITER AND WENDELSTEIN 7-X

Researchers at Jülich are involved in the technological developments of Wendelstein 7-X and ITER. They contribute towards the design and construction of diagnostics intended to obtain information on material and plasma conditions during the experiment. Jülich has developed and manufactured the superconducting bus system as well as several diagnostics systems for Wendelstein 7-X. Plasma edge and plasma-material interaction physics are the key domains of Jülich researchers at Wendelstein 7-X.

SIMULATION TOOLS FOR FUSION REACTORS

Jülich boasts a strong theory group and access to high-performance supercomputers. Numerical tools developed at Jülich describe the plasma-wall interaction processes of tokamaks, stellarators and linear machines. The codes developed and used by Jülich bridge the dimensions from atomic scale to reactor size and combine aspects of plasma physics, transport phenomena, surface and solid state physics. They are applied in order to interpret current fusion experiments and to design future fusion reactors.

GERMANY . MATERIALS RESEARCH . PLASMA-WALL INTERACTIONS . PLASMA EDGE . PSI-2 . JULE-PSI . SUPERCONDUCTING BUS SYSTEM . THEORY . SUPERCOMPUTERS . DEMO .

WWW.FZ-JUELICH.DE

FR

IRFM

The **Institute for Magnetic Fusion Research** (Institut de Recherche sur la Fusion par confinement Magnétique, IRFM), one of CEA's (Commissariat à l'énergie atomique et aux énergies alternatives) basic research divisions, has been carrying out research on thermonuclear magnetic fusion in association with the European fusion programme for more than 50 years.

IRFM FACTS

- Located at the CEA Research Centre of Cadarache in the department of the Bouches-du-Rhône
- Was home to the Tore Supra programme
- Employs more than 350 people including CEA scientists, PhD and post-doc students, and French and international collaborators
- Involved in the French fusion network (FR-FCM) with more than 40 labs

The IRFM activities are structured around three core areas:

- Contribution towards ITER project implementation and the "Broader Approach"
- Preparation for scientific operation of ITER, both theoretical and experimental aspects
- Establishment of the basis for future fusion reactors

The IRFM is equipped with several R&D platforms: cryogenic and superconductor test benches; plasma facing components, visible and IR viewing systems; heating and current drive; design, engineering and virtual reality; robots for fusion; a large simulation platform (theory and simulation, high performance computing, integrated modelling, plasma scenario and reactor physics design).

The best known R&D platform is the **Tore Supra tokamak** which has evolved into **WEST (W – tungsten Environment Steady-state Tokamak)** in order to test the ITER divertor.

WEST – TUNGSTEN (W) ENVIRONMENT IN STEADY-STATE TOKAMAK

IRFM aims to make WEST a test platform open to all ITER partners.
The key features of WEST include unique long pulse capabilities, high level of additional power and the unique experience of operation with actively cooled components. In addition, WEST is being equipped with an actively cooled tungsten divertor. The WEST tungsten divertor elements will use the same design and manufacturing processes as those of ITER.

The main mission of WEST is twofold, it:

- Paves the way towards the ITER actively cooled tungsten divertor procurement and operation,
- Is designed to master the integrated plasma scenario over relevant plasma wall equilibrium time scale in a metallic environment.

FRANCE. WEST. DIVERTOR.
ITER TEST PLATFORMS. TOKAMAK.
PLASMA-FACING COMPONENTS. CODE DEVELOPMENT.
EDUCATION. PLASMA PHYSICS. SIMULATION.

IRFM.CEA.FR/EN/

CH

SPC

The **Swiss Plasma Center (SPC)** coordinates all activities in plasma physics and fusion in Switzerland. SPC is affiliated with the Ecole Polytechnique Fédérale de Lausanne (EPFL), the Swiss member of the EUROfusion Consortium.

RESEARCH LINES AT SPC

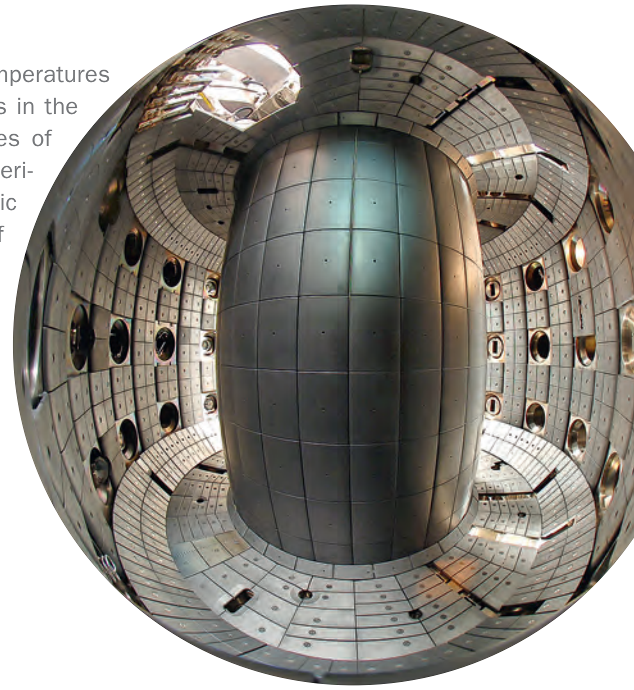
- Scientific exploitation of the **TCV tokamak**
- **Theoretical** and **numerical simulation** research that support TCV experiments and contribute towards the understanding of different aspects of fusion plasmas
- Research using **TORPEX**, a specialised device that can provide insights into basic plasma physics of interest for magnetic fusion and also space and astrophysical plasmas
- Superconducting cable tests for ITER and high temperature superconductor developments for DEMO by using the high B-field and high current test facilities **SULTAN** and **EDIPO**, located at the Paul Scherrer Institute, Villigen
- Contribution to several contracts with ITER and Fusion for Energy (F4E), on a range of topics, from all components of the microwave heating system ECH to plasma control
- International collaboration, which includes activities at JET and other European tokamaks

TCV

The Tokamak à Configuration Variable, TCV, is a medium-sized tokamak that is part of EUROfusion's medium size tokamak (MST) work package. Equipped with 16 independently-driven magnetic field coils, TCV is able to explore the effect of plasma configuration and shape on plasma properties. The operational domain in terms of plasma shape is much wider than in conventional tokamaks. Its flexible heating, based on the electron cyclotron resonance, enables localised heating and thus modifications of current and temperature profiles in the plasma. The TCV's neutral beam injection system is used to study the properties of shaped plasmas under high pressure and high confinement, which will be relevant to ITER and future fusion reactor regimes.

TORPEX

The toroidal device TORPEX is operated at sufficiently low densities and low temperatures to allow direct measurements of plasma and wave (or turbulence) parameters in the plasma core, using probes. It is possible to inject and follow the trajectories of suprathermal particles in different magnetic configurations. It can perform experiments that mimic the plasma periphery in tokamaks, with complete diagnostic coverage, leading to a better understanding of the birth and propagation of turbulent structures and of their effects on thermal and suprathermal particle transport.



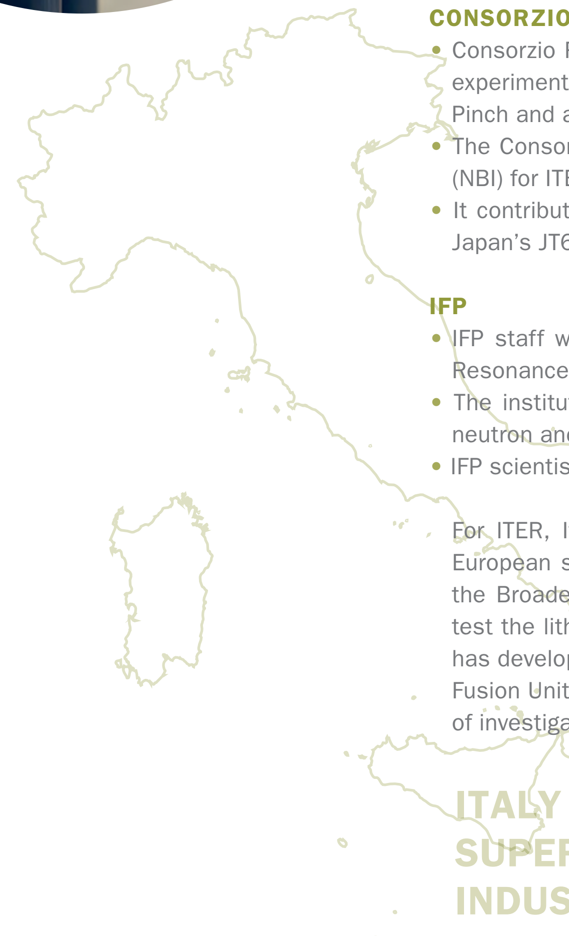
SWITZERLAND.
TCV TOKAMAK.
TORPEX.
MST.

SPC.EPFL.CH

IT

ENEA

The Italian fusion programme is coordinated by ENEA (**Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile**). ENEA works with Linked Third parties: universities, research institutes, and industries. Institutes carrying out fusion research along with ENEA include Plasma Physics Institute (IFP), Consorzio RFX, National Research Council of Italy (CNR), National Institute for Nuclear Physics (INFN) and University of Padova. About 600 professionals work on fusion research in institutions across Italy.



ENEA

- ENEA centre at Frascati houses the Frascati Tokamak Upgrade (FTU) tokamak, a high-magnetic-field, high-plasma-density tokamak; it investigates radio-frequency plasma heating, control techniques and plasma-wall interaction with liquid metal walls
- Frascati Neutron Generator, a medium intensity 14-MeV neutron generator, is used for experimental validation of fusion nuclear data and codes.
- Studies and development of superconductor materials are carried out at the ENEA Superconductivity laboratory
- ENEA's High Heat Flux Components laboratory set up and tested the manufacturing process and a dedicated facility for the fabrication of full scale ITER divertor target prototypes
- Design and experimental validation of liquid metal technology for breeding blankets can be done at ENEA centre at Brasimone.

CONSORZIO RFX

- Consorzio RFX staff are involved in the scientific exploitation and upgrade of the RFX-mod experiment, a flexible device which can be operated both as a high current Reversed Field Pinch and as a tokamak
- The Consorzio is responsible for the R&D to develop the 1MV, 40A Neutral Beam Injector (NBI) for ITER
- It contributes to the Broader Approach and has developed two power supply systems for Japan's JT60-SA tokamak

IFP

- IFP staff work on the design and various optimisation studies of the Electron Cyclotron Resonance Heating (ECRH) Upper Launcher for ITER
- The institute is engaged in the development of mm-wave-based plasma diagnostics and neutron and gamma-ray spectrometry for JET and ITER
- IFP scientists participate in experimental campaigns at JET, FTU, AUG and TCV

For ITER, Italian industries have manufactured part of the superconducting cables, the European share of superconducting magnets, and 7 sectors of the vacuum chamber. For the Broader Approach, industries manufacture components for JT60-SA, and design and test the lithium target for the International Fusion Material Irradiation Facility (IFMIF). INFN has developed the Radio Frequency Quadrupole accelerating structure for IFMIF. The Italian Fusion Unit has developed the design for a "Divertor Tokamak Testing Facility" with the aim of investigating potential physics and technology challenges in DEMO's exhaust system.

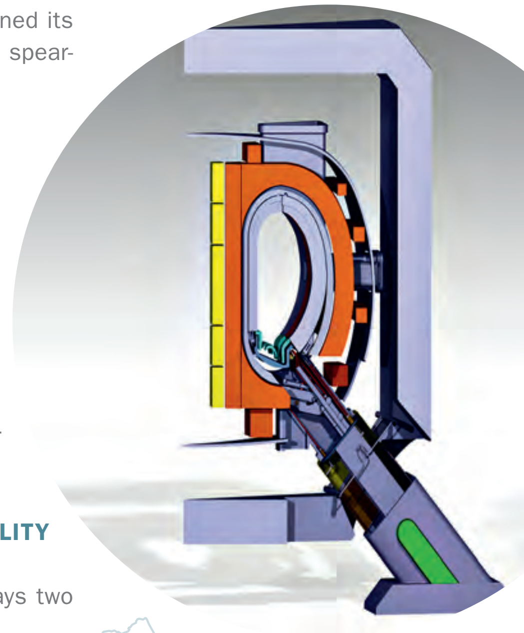
ITALY. FRASCATI TOKAMAK UPGRADE. SUPERCONDUCTORS. BROADER APPROACH. INDUSTRIAL COLLABORATION.

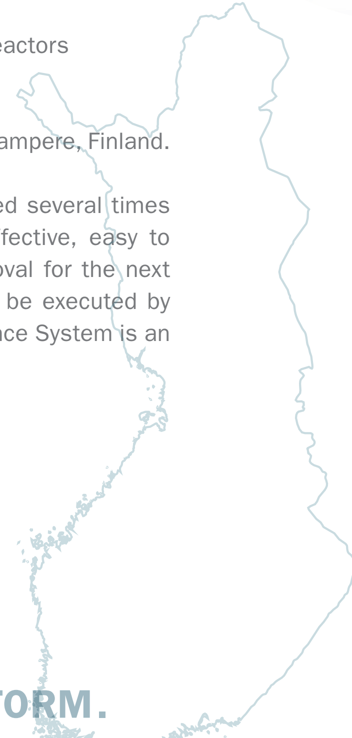
WWW.ENEA.IT

FI

FINNFUSION

The **FinnFusion consortium**, led by VTT Technical Research Centre Ltd., implements the Finnish fusion programme for EUROfusion. FinnFusion incorporates members from Finnish academia and industry.





During its 20 years of participation in the European fusion programme, Finland has aligned its research efforts with the common European fusion research goals. In particular, Finland spearheads three areas of expertise:

- Remote handling
- Edge plasma physics and plasma-wall interaction
- Active lead and coordination role in various tokamak experiments worldwide

EDUCATION AND COLLABORATION

The Finnish fusion community has an excellent track-record in nurturing the next generation of fusion researchers, and young Finnish researchers have a strong presence in the EUROfusion education and training programmes.

FinnFusion researchers collaborate not only within Europe but also with researchers from US, Russia and China. Some of the tokamak experiments that the FinnFusion community is contributing towards include JET (UK), ASDEX Upgrade (Germany) DIII-D (US) and Alcator C-Mod (US).

A DIVERTOR TEST PLATFORM AT THE REMOTE OPERATION AND VIRTUAL REALITY CENTRE

VTT hosts the European facility known as the Divertor Test Platform or DTP2. DTP2 plays two important roles for fusion research:

- Simulating the demanding maintenance operations required in future fusion reactors
- Acting as an education platform for the operators involved in ITER

DTP2 is part of the remote operation and virtual reality centre (ROViR) located in Tampere, Finland.

Divertors are the lower parts of a reactor chamber and will need to be replaced several times during the life time of the reactor. The divertor system must be reliable, effective, easy to maintain and safe. FinnFusion is involved in conceptualising the divertor removal for the next generation fusion power plant design, DEMO. Divertor removal is expected to be executed by remote handling. Developing the concepts for such a Divertor Remote Maintenance System is an ongoing collaborative effort between VTT (Finland), CCFE (UK) and ENEA (Italy).

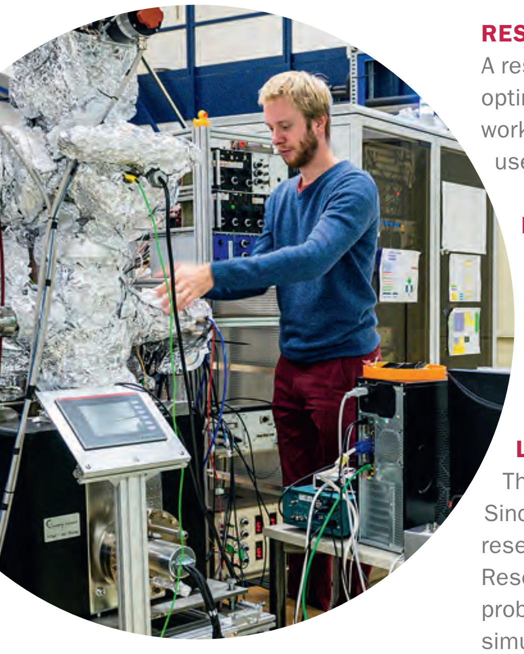
FINLAND. DIVERTOR TEST PLATFORM. REMOTE OPERATION AND VIRTUAL REALITY. EDGE PLASMA. WALL INTERACTIONS.

WWW.VTTRESEARCH.COM

AT

FUSION@ÖAW

The **Austrian Academy of Sciences (ÖAW)** manages the Austrian contribution to European fusion research. Its Fusion Research Unit, known as "Fusion at ÖAW", comprises three universities: Technische Universität Wien, Technische Universität Graz, and Universität Innsbruck and two institutes: Research Studios Austria Forschungsgesellschaft and Erich Schmid Institute of Materials Science. Education of young researchers is the predominant objective of Fusion at ÖAW.



Core competencies of Fusion@ÖAW:

RESEARCH INTO HIGH HEAT FLUX MATERIALS

A research team at the Erich Schmid Institute of Materials Science at ÖAW carries out work on optimising the mechanical properties of materials such as tungsten foils. The results of their work influence the design of tungsten laminates for joints with other metals, which are then used for constructing fusion devices.

MODELLING AND COMPUTATIONAL PHYSICS

What is bootstrap current? How do resonant magnetic perturbations control plasma instabilities? What will keep plasma stable in Wendelstein 7-X? These are some of the questions that the Plasma Physics Group working at Graz University of Technology's Institut für Theoretische Physik is looking to answer. They employ modelling techniques and computational approaches in their research.

LONG TRADITION IN PLASMA PHYSICS

The plasma physics group at the University of Innsbruck was founded in the late 1950s. Since then, plasma physics has developed into one of the pillars of the university's physics research portfolio. It is primarily based at the Institute of Ion Physics and Applied Physics. Research topics include fast-ion, measuring of plasma turbulence with specifically designed probes, modelling of plasma turbulence, plasma-wall interaction and molecular dynamics simulations.

TOKAMAK WALL MATERIALS AND SUPERCONDUCTIVITY

Researchers at the Institute of Applied Physics of TU Wien study the erosion of plasma facing materials, such as tungsten, carbon and beryllium. The team uses a special quartz crystal system to measure exactly how much erosion occurs with each combination of wall material and plasma ion.

The research groups at TU Wien and Max Planck Institute for Plasma Physics, Garching, use plasma diagnostic methods to study the edge plasma in ASDEX Upgrade. A group of researchers at the Institute of Atomic and Subatomic Physics has established experience in developing superconducting tapes for fusion magnets.

AUSTRIA.
EDUCATION.
PLASMA PHYSICS. MODELLING.
MATERIAL SCIENCE.

WWW.OEAW.AC.AT/FUSION

GR

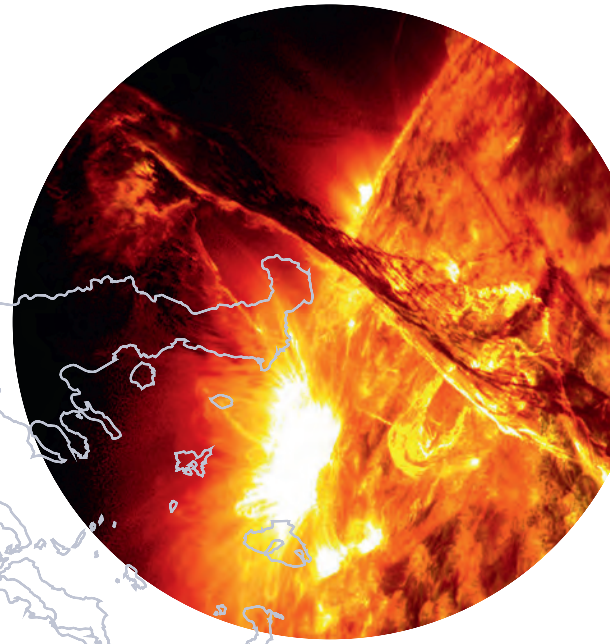
HELLENIC FUSION RESEARCH UNIT

Greece has been contributing to the European fusion program since 1999, and research teams from the following Research Centres and Institutions of Higher Education contribute EUROfusion: NCSR "Demokritos", School of Electrical and Computer Engineering, National Technical University of Athens, Department of Physics, National and Kapodistrian University of Athens, Department of Mechanical and Industrial Engineering, University of Thessaly, Department of Physics, Aristotle University of Thessaloniki, Department of Physics, University of Ioannina, Institute of Electronic Structure and Laser of the Foundation for Research and Technology, and Technical University of Crete.

The research teams of the Hellenic Fusion Research Unit (RU) participate in the following EUROfusion Work Packages:

- Experimental data and simulation data comparison concerning intrinsic rotation in JET
- Investigation of plasma-facing components for ITER
- Technological exploitation of DT operation for the ITER preparation
- Participation in the experimental data analysis in TCV and ASDEX-U
- Assessment of alternative divertor geometries and liquid metals PFCs
- Heating and current drive systems
- Tritium, fuelling & vacuum systems
- Materials
- Neutron irradiations of tungsten-based materials
- Enabling research on runaway electrons
- Education

In addition, the Hellenic RU contributes to Fusion for Energy projects, for the European Gyrotron Development.



GREECE.
INTRINSIC ROTATION IN JET.
PLASMA-FACING COMPONENTS.
DIVERTOR GEOMETRIES. EDUCATION.

IPTA.DEMOKRITOS.GR/FTG/

PT

IPFN

IPFN, the **Institute for Plasmas and Nuclear Fusion**, is in charge of implementing the fusion programme in Portugal. IPFN is a Research Unit of Instituto Superior Técnico, the science and engineering faculty of the University of Lisbon. With a staff of more than 150, it is also the country’s largest physics research unit.

CORE RESEARCH AREAS

- Controlled nuclear fusion
- Plasma technologies and intense lasers

In fusion, the main areas of expertise of its researchers include **plasma diagnostics, control and data acquisition systems for large-scale experiments, remote handling** in fusion environments, **fusion theory, modelling and numerical studies, operation of magnetic fusion devices**, plasma engineering and systems integration, neutronics and processing and characterisation of fusion-relevant materials.

IPFN researchers are active collaborators in the operation and scientific exploitation of devices across Europe including JET (UK), ASDEX Upgrade and Wendelstein 7-X (Germany), TCV (Switzerland) and TJ-II (Spain). In addition, IPFN participates and leads several projects in the areas of control and data acquisition, development of microwave diagnostics and remote handling for ITER and DEMO.

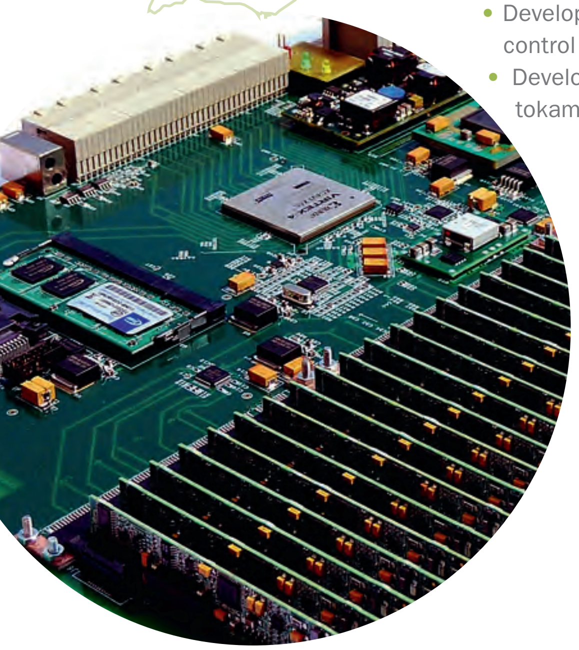
ISTTOK

A tokamak to educate future fusion researchers

IPFN has hosted a small tokamak – ISTTOK – since 1990. The device has played a fundamental role in the training of fusion physicists, engineers, technicians and students.

Main objectives of ISTTOK at a glance:

- Creation of an experimental pole for fusion plasmas in an academic environment.
- Education and training in physics, engineering and technologies associated with nuclear fusion.
- Development of new diagnostic techniques and test of digital instrumentation dedicated to control and data acquisition.
- Development of a programme of plasma physics studies based on the operation of a tokamak in an alternate plasma current regime and on turbulence characterisation.



PORTUGAL.
ISTTOK. FUSION EDUCATION.
PLASMA DIAGNOSTICS.
DATA ACQUISITION.

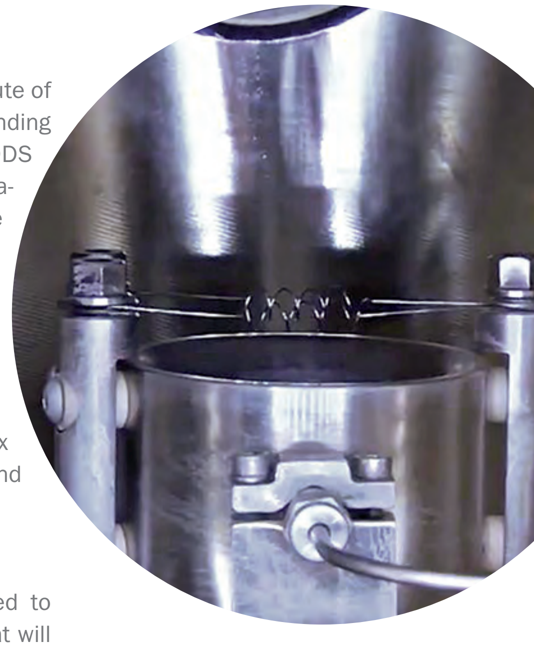
WWW.IPFN.IST.UTL.PT

LV

ISSP

The University of Latvia’s **Institute of Solid State Physics (ISSP)** is the EUROfusion partner representing Latvia’s fusion research initiatives. The Latvian contribution to the European fusion programme began in 2000 in the form of cost-sharing actions and the Association EURATOM-University of Latvia was established in 2001.

Fusion researchers from ISSP focus on the exploration of **radiation and heat-resistant material** as used in fusion experiments.



RESEARCH ON ODS STEELS

ISSP has coordinated and collaborated with other EUROfusion members, Karlsruhe Institute of Technology (KIT) and (CEIT), in a EUROfusion project designed to provide better understanding of **radiation and temperature resistant ODS** (oxide dispersion strengthened) **steels**. ODS steels are considered to be one of the candidate materials for the construction of plasma-facing parts of fusion facilities. **X-ray absorption spectroscopy** measurements have been carried out at international synchrotron radiation facilities for ODS steels samples produced by KIT, CEIT, and for model materials produced in ISSP. The aim is to obtain unique information regarding the local surrounding of atoms in oxide nanoparticles in ODS material and to identify when and how oxide nanoparticles are formed.

In parallel, **kinetic Monte-Carlo modelling** of oxide nanoparticle formation and growth is performed, and supporting *ab initio* calculations of Y-O clusters and defects in iron matrix are accomplished. This model will be validated using X-ray absorption spectroscopy and other experimental data.

R&D CONTRIBUTION FOR GYROTRON DEVELOPMENT

ISSP is also involved as a third party in the research and development work related to **gyrotrons**. The European Domestic Agency is responsible for six of the 24 gyrotrons that will be installed in ITER. ISSP along with KIT (Germany), SPC (Switzerland), HELLAS (Greece), CNR (Italy), University of Stuttgart (Germany), and Thales Electron Devices (France) are collaborating in the gyrotron development work for ITER.

LATVIA.
RADIATION AND HEAT-RESISTANT MATERIAL. ODS STEEL.
GYROTRONS.

WWW.CFI.LU.LV/ENG/

DE

KIT

The **Karlsruhe Institute of Technology (KIT)** is one of the largest research and education institutions in Germany. KIT's dedicated nuclear fusion programme involves around 220 scientists, engineers and staff working in eight KIT institutes.

The KIT Nuclear Fusion Programme:

- Develops key technologies and materials for fusion energy
- Focusses on three lines of fusion experiments:
  - Design, engineering, realisation and testing of components and systems for ITER
  - Developments for DEMO and future fusion power plants
  - Contributions to Wendelstein 7-X

KIT fusion programme strengths:

FUSION FUEL CYCLE

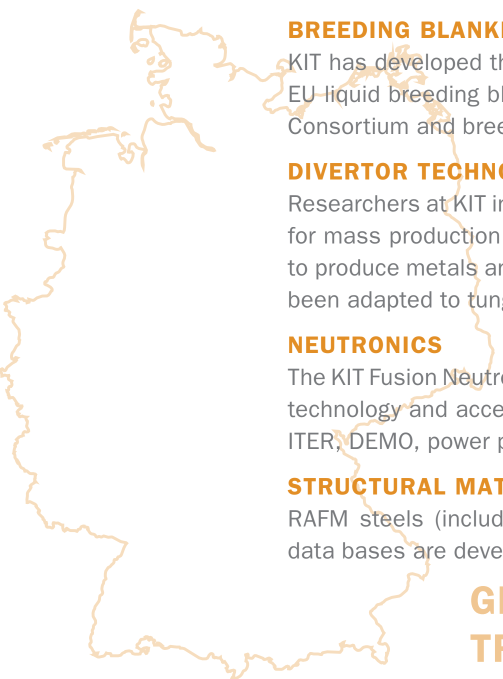
KIT operates the Tritium Laboratory Karlsruhe. The laboratory has the license to handle tritium at a technical scale and vast expertise in tritium processing fusion reactor fuel cycle. The concept and many details of the ITER Tritium Plant have been developed there. KIT is a major player in developing fusion-relevant vacuum pumps and auxiliary systems.

PLASMA HEATING SYSTEMS

KIT is leading in developing high power gyrotrons; KIT teams designed and developed the 140 GHz gyrotrons for the 10 MW ECRH system of Wendelstein 7-X. KIT has been driving the development of the European 1 MW conventional-cavity gyrotron for ITER.

FUSION MAGNETS & MAGNET COMPONENTS

KIT coordinates an EU-wide effort to develop high current, high temperature superconductors for DEMO. Its researchers have designed and constructed the HTS current leads for Wendelstein 7-X. KIT delivers the 26 HTS current leads for JT60-SA tokamak in Japan.



BREEDING BLANKET DEVELOPMENT

KIT has developed the concept for the European solid breeder blanket and contributed to the EU liquid breeding blanket. KIT researchers lead the European Test Blanket Module Systems Consortium and breeding blanket work package.

DIVERTOR TECHNOLOGY

Researchers at KIT investigate divertor design concepts for DEMO and manufacturing methods for mass production of divertor components. Powder Injection Molding, a fabrication process to produce metals and ceramics to near-net-shape with good tolerance and surface finish, has been adapted to tungsten processing at KIT.

NEUTRONICS

The KIT Fusion Neutronics Team has in-depth expertise in neutronics and nuclear data for fusion technology and accelerator applications. Nuclear design analyses are regularly performed for ITER, DEMO, power plant models, and the IFMIF neutron source.

STRUCTURAL MATERIALS FOR BLANKET AND DIVERTOR

RAFM steels (including EUROFER) development, related joining technologies and materials data bases are developed at KIT as well as refractory alloys including composites.

GERMANY.
TRITIUM LABORATORY KARLSRUHE.
GYROTRONS.
POWDER INJECTION MOLDING. TUNGSTEN.

WWW.FUSION.KIT.EDU/ENGLISH/

LT

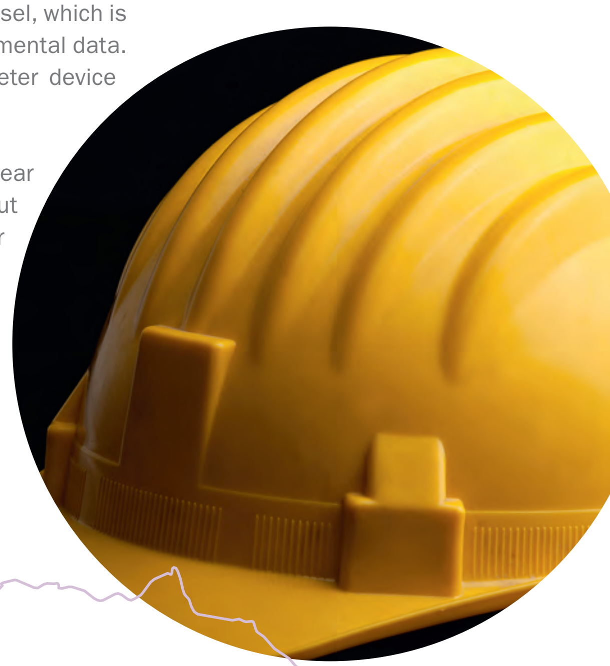
LEI

EUROfusion signatory the **Lithuanian Energy Institute (LEI)** carries out European fusion research initiatives in Lithuania.

KEY AREAS TOWARDS WHICH LEI FUSION RESEARCHERS CONTRIBUTE INCLUDE:

- The work package that looks into the safety assessment of nuclear fusion reactors: this includes assessment of the computer codes' readiness for DEMO reactor safety assessment, deterministic safety analysis of the selected accident scenarios, FFMEA analysis of DEMO reactor, development of methodology for assessment of Reliability, Availability, Maintainability and Inspectability (RAMI) of DEMO, accumulation and distribution of radioactive substances in DEMO reactor systems as well as assessment of decay heat of the components.

- Bolometer data analysis for JET data: Plasma power distribution in a vacuum vessel, which is monitored by bolometer devices, has an important role in the analysis of experimental data. analyses data by carrying out tomographic analysis of the analogous bolometer device signal by drafting a plasma power map in a tokamak vacuum vessel.



- Radiation impact assessment for constituent components of materials of nuclear fusion reactor: the result of the analysis provides valuable information about radiation activity and dose rate of JET device components. The activation, nuclear fission heat and radiation dose rate are important measures describing nuclear processes. Described activation and fission heat calculations carried out according to the PPPT program for DEMO Water Cooled Lithium-Lead (WCLL). Activation calculations were performed by means of combined transport and activation programs, potential alternative structural materials were assessed. Activities in work packages (ENS – Early Neutron Source) include neutron and activation analysis of the projected neutron source.

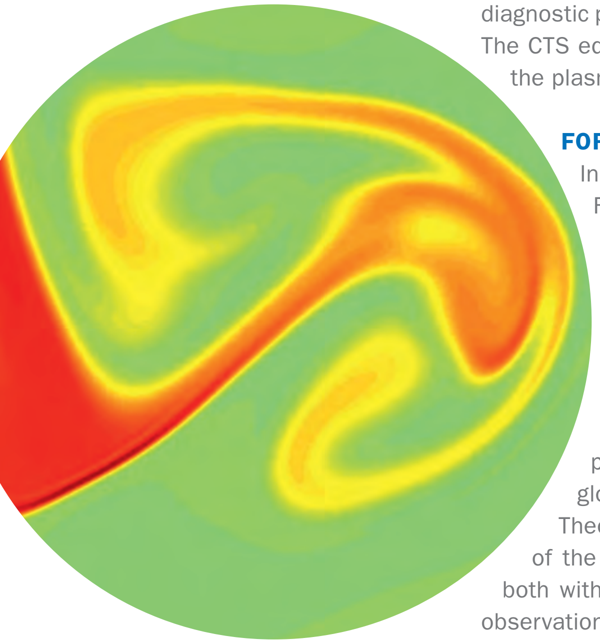
LITHUANIA.
SAFETY.
BOLOMETER DATA ANALYSIS.
RADIATION IMPACT ASSESSMENT.

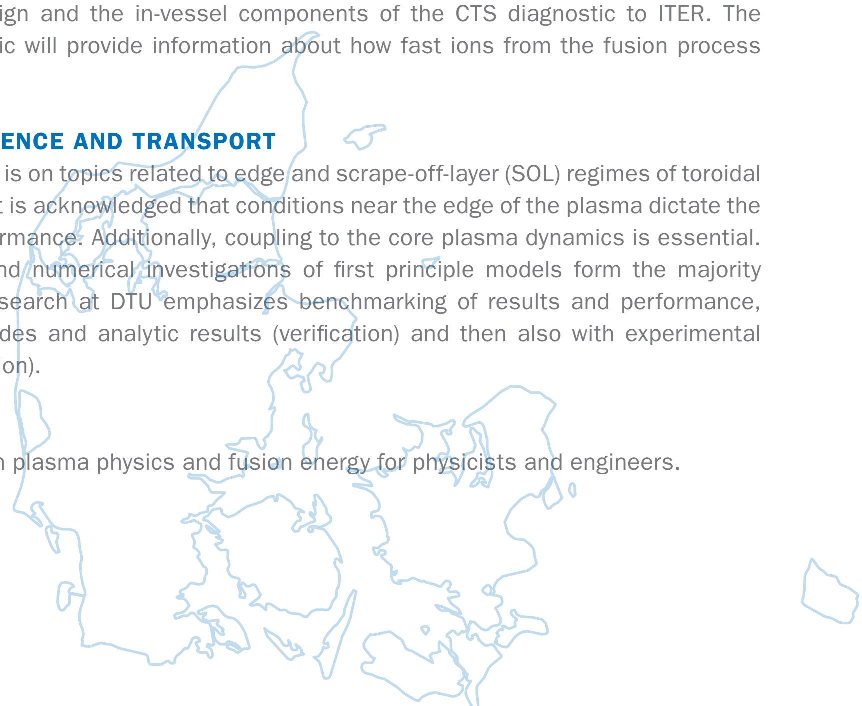
WWW.LEI.LT

DK

DTU

Danish fusion research within the EUROfusion scope is represented by **DTU – Technical University of Denmark.** The research is conducted primarily in the section for Plasma Physics and Fusion Energy (PPFE) of the Department of Physics. The main fusion research themes of PPFE deal with physical and technical aspects of plasmas, and particular emphasis is placed on plasma turbulence and fast ion dynamics. Researchers at PPFE are also actively involved in international fusion efforts, and work with large scale fusion research infrastructures, such as the JET and ASDEX Upgrade and the Wendelstein 7-X, as well as with diagnostic design for ITER.





Highlights of some contributions from DTU

FOR ASDEX UPGRADE

DTU researchers installed two fast-ion diagnostic systems at ASDEX Upgrade. These measure the fast ion distribution function by means of Collective Thomson Scattering (CTS). This diagnostic provides insights into the interaction between the fast ions and plasma instabilities. The CTS equipment is also being used to develop a measurement technique which resolves the plasma composition in the centre of the plasma.

FOR ITER

In February 2014, DTU (in a consortium with IST (Portugal)) entered into a multi-year Framework Partnership Agreement with Fusion for Energy (F4E) for the development and design of the CTS diagnostic for ITER. F4E has been selected to provide the final design and the in-vessel components of the CTS diagnostic to ITER. The diagnostic will provide information about how fast ions from the fusion process behave.

TURBULENCE AND TRANSPORT

The focus is on topics related to edge and scrape-off-layer (SOL) regimes of toroidal plasmas. It is acknowledged that conditions near the edge of the plasma dictate the global performance. Additionally, coupling to the core plasma dynamics is essential. Theoretical and numerical investigations of first principle models form the majority of the work. Research at DTU emphasizes benchmarking of results and performance, both with other codes and analytic results (verification) and then also with experimental observations (validation).

EDUCATION

DTU offers courses in plasma physics and fusion energy for physicists and engineers.

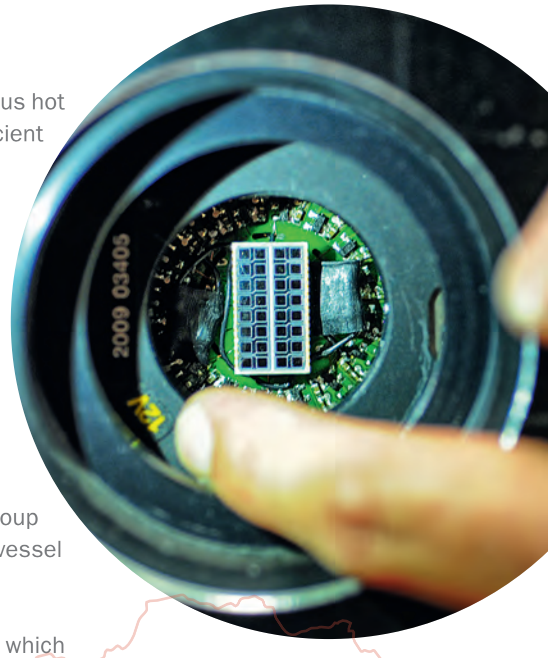
DENMARK.
PLASMA TURBULENCE AND TRANSPORT.
FAST ION DYNAMICS.
CTS.

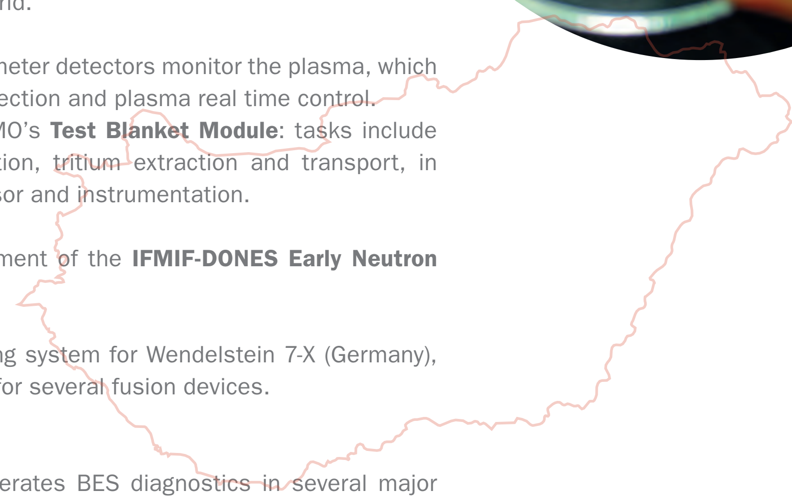
WWW.FYSIK.DTU.DK/ENGLISH/RESEARCH/PPFE

HU

WIGNER FUSION

Fusion research in Hungary is coordinated by the **Plasma Physics Department of the Wigner Research Centre for Physics** with strong contributions from the Budapest University of Technology and Economics.





Three groups form the pillars of Wigner Fusion

PELLET AND VIDEO DIAGNOSTICS GROUP

The group focuses on understanding the interaction between the 10-million-degree Celsius hot plasma and -270-degree Celsius solidified hydrogen pellets in order to find the most efficient ways to deposit pellet material into the plasma core.

Pellets can also tailor plasma instabilities known as ELMs, which may harm the fusion device. Using ultrafast cameras that produce up to 1 million images per second, the group investigates the ELM-tailoring capability of the pellets.

A special fast camera "**EDICAM**" was developed by the group, featuring real-time image processing and intelligent image-based feedback control. The EDICAM was deployed on various fusion experiments.

ITER AND FUSION DIAGNOSTICS DEVELOPMENTS GROUP

Acting as the leader of **Tokamak Services for Diagnostics** Consortium, the group concentrates on the R&D of the infrastructure that services signal transmission of in-vessel diagnostics from the vacuum vessel to the outer world.

Developing **bolometer cameras**: a total of 480 bolometer detectors monitor the plasma, which will be an important part of the ITER machine's protection and plasma real time control. Developing and integrating systems related to DEMO's **Test Blanket Module**: tasks include developing helium cooling circuits, lithium circulation, tritium extraction and transport, in addition to developing and maintaining blanket sensor and instrumentation.

Contributing in several areas towards the development of the **IFMIF-DONES Early Neutron Source**.

Engineering for other devices: A fast camera viewing system for Wendelstein 7-X (Germany), lithium and hydrogen beam emission spectroscopy for several fusion devices.

BEAM EMISSION SPECTROSCOPY GROUP

The group designs, manufactures, installs and operates BES diagnostics in several major fusion devices around the globe. Heating beam BES diagnostics were installed in MAST (UK), KSTAR and EAST tokamaks, while alkali beams are operated in collaboration in JET (UK), KSTAR, EAST, Compass (Czech Republic) and ASDEX Upgrade (Germany) tokamaks. An alkali beam BES diagnostic is also being developed for Wendelstein 7-X.

HUNGARY.
PELLET AND VIDEO DIAGNOSTICS.
FUSION DIAGNOSTICS. BEAM EMISSION SPECTROSCOPY.
FUSION ENGINEERING.

WIGNER.MTA.HU/EN

BE

LPP-ERM/KMS

The Belgian fusion research initiatives for EUROfusion are represented by the **Plasma Physics Laboratory of Ecole Royale Militaire Koninklijke Militaire School (LPP-ERM/KMS) located in Brussels.**

The Belgian fusion research initiatives for EUROfusion are represented by the Plasma Physics Laboratory of Ecole Royale Militaire/Koninklijke Militaire School (LPP-ERM/KMS) located in Brussels.

The Laboratory carries out experimental and theoretical research on plasma physics and fusion energy within the framework of the European fusion research programme.

KEY LPP-ERM/KMS FACTS:

- Research at LPP-ERM/KMS focuses particularly on the development of Ion Cyclotron Resonance Heating (ICRH) systems. The laboratory is known for the design of ICRH antennas, and research is conducted both in the experimental and theoretical domains. Theoretical studies revolve around the development of codes to design and simulate ICRH antennas operating under different scenarios and to quantify the actual heating of the plasma. Experimental studies have centred on fusion devices including, ITER, JET, and Magnum PSI.
- The laboratory has developed ICRH antennas for Wendelstein 7-X, and for JET it developed the ITER-like ICRH antenna, capable of delivering multi-second pulses at 8 MW/m² power flux combined with adequate ELM resilience under H-mode conditions.
- LPP-ERM/KMS contributed to the development of a radio-frequency (RF) heating system for the Magnum-PSI facility.
- Fusion researchers from Belgium collaborate with other EUROfusion Research Units in the scientific exploitation of the JET facilities, the Wendelstein 7-X experiments and in research and development for ITER and DEMO.
- LPP-ERM/KMS is also a member of TEC, the Trilateral Euregio Cluster, which bundles the fusion efforts of LPP-ERM/KMS (Belgium), FOM (the Netherlands) and Forschungzentrum Jülich (Germany).

BELGIUM . ION CYCLOTRON RESONANCE HEATING . ANTENNAS . RADIO-FREQUENCY (RF) HEATING SYSTEM . TRILATERAL EUREGIO CLUSTER .

FUSION.RMA.AC.BE

HR

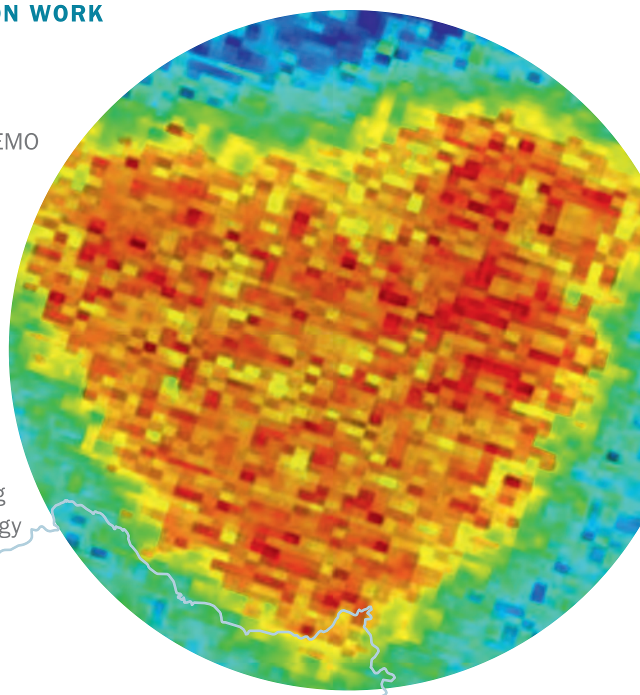
CRU

The **Croatian Fusion Research Unit (CRU)** is responsible for coordinating Croatia's participation in the European Fusion Prsogramme. It is tasked with providing all relevant stakeholders with information regarding participation in the Fusion Programme and the construction of ITER. The CRU is hosted by **Ruđer Bošković Institute** (RBI), Zagreb.

The CRU was founded on 26th July 2013 by the Ruđer Bošković Institute (RBI), the Institute of Physics (IFS), the Faculty of Sciences (PMF) of the University of Zagreb and the Faculty of Electrical Engineering and Computing (FER) of the University of Zagreb, the Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture (FESB) of the University of Split, and University of Rijeka (UniRI).

CRU'S RESEARCH TEAMS PARTICIPATE IN FOLLOWING EUROFUSION WORK PACKAGES

- Investigation of plasma-facing components for ITER
- Medium-size tokamak campaigns
- Preparation of efficient plasma-facing components operation for ITER and DEMO
- Code development for integrated modelling
- Materials sciences
- Early neutron source definition and design
- Education



CRU has successfully hosted the European Fusion Programme Workshop EFPW-2014 which was held from 1st – 3rd December 2014 in Split, Croatia.

During the first half of 2013, following Croatia`s accession to the EU and before the EUROfusion H2020 project was launched, the CRU acted as the External Research Unit of the Fusion Association of United Kingdom, according to the Cooperation Agreement between RBI and Culham Centre for Fusion Energy (CCFE).

CROATIA . PLASMA-FACING COMPONENTS . CODE DEVELOPMENT . EDUCATION .

WWW.IRB.HR/ENG

ST

SFA

The **Slovenian Fusion Association, SFA**, coordinates fusion research in Slovenia.

KEY SFA FACTS

- Integrated in the joint European framework of national fusion Research Units since 2005
- Led by its largest member **Jožef Stefan Institute** (JSI)
- Comprises **eight** other laboratories, and three faculties of the University of Ljubljana: Faculty of Mechanical Engineering, Faculty of Electrical Engineering and Faculty of Mathematics and Physics
- Engages **50** scientists working on plasma theory, diagnostics, plasma-wall interaction processes, high heat flux materials, neutron field calculations, design studies, thermohydraulic and mechanical analyses
- Slovenian researchers collaborate in experimental campaigns involving JET (UK), ASDEX Upgrade (Germany), TCV (Switzerland) and support development and construction of ITER and DEMO

SOME RESEARCH LINES PURSUED BY SFA RESEARCHERS:

Plasma-wall interaction studies – **Ion beam analytical methods** are applied in order to study plasma-wall interaction processes on ITER and DEMO relevant materials. **Linear 2 MV Tandetron Accelerator** at JSI with its 4 beam lines is used as the main experimental facility.

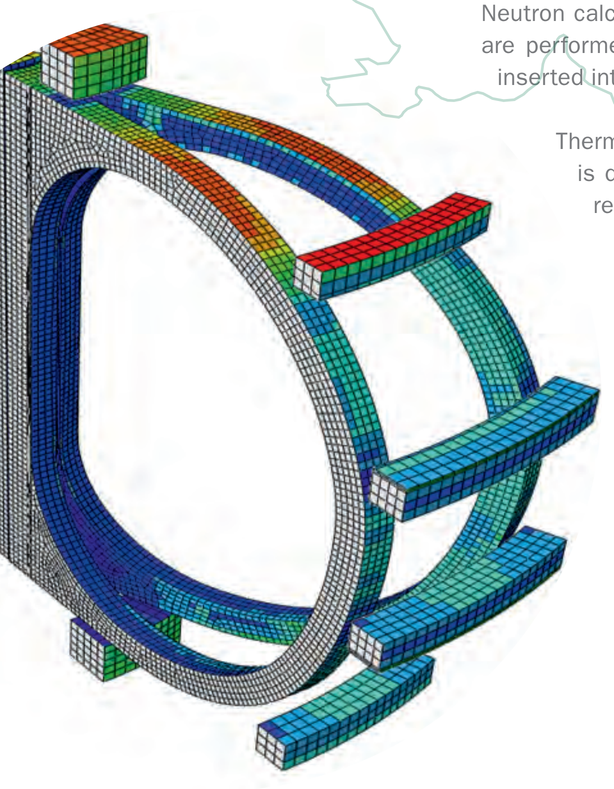
Advanced high heat flux materials for DEMO divertor - JSI-department for nanostructured materials develops **tungsten-based materials** reinforced with fibres and/or carbide to improve the thermo-mechanical properties of the material. Sintering at high temperatures is used to densify the composites.

Neutron calculations designed to support JET neutron yield calibration – **Neutronics** studies are performed at JSI to calibrate neutron detectors in the event of a high neutron source inserted into the JET torus by the remote handling system.

Thermal model of the DEMO tokamak – **Thermal model** of the baseline DEMO design is developed at JSI in order to predict the thermal loading and refrigeration power required for the magnet system and thermal shields.

Experimental campaigns on European tokamak devices – A new diagnostic system for **detection of impurities in the gas exhaust** is implemented at JET. JSI researchers are also involved in dedicated **ammonia experiments** at ASDEX Upgrade.

Development of visualisation tools to support integrated modelling – Faculty of mechanical engineering (University of Ljubljana) is developing an **interface tool for easy CAD data transfer** into fusion modelling codes.



SLOVENIA. JOŽEF STEFAN INSTITUTE. ION BEAM ANALYTICS. HEAT FLUX. VISUALISATION. NEUTRONICS.

WWW.SFA-FUSION.SI

ES

LNF

The public face of Spanish fusion research is the Spanish **National Fusion Laboratory (LNF)**, located at CIEMAT in Madrid.

Two pillars of LNF's fusion research:

THE MEDIUM-SIZED STELLARATOR TJ-II

TJ-II FACTS AT A GLANCE

- Commissioned in 1998
- Is an ideal platform for the development and testing of diagnostics, such as **Doppler Reflectometry** for boundary turbulence measurements, **Heavy Ion Beam Probes** for the measurement of electron densities, electric fields, and long-range correlations
- Is used to explore new physics and improve understanding of confinement properties of stellarators
- Is extremely well-suited for studying the physics and the control of fast particle-driven instabilities, which will be crucial in future reactors
- Further research involves advanced plasma-wall studies and power exhaust techniques. This includes the development of techniques to improve plasma confinement by way of lithium coating and exploring the power handling capabilities and fuel retention properties of liquid metals (lithium and alloys).
- **Supporting Wendelstein 7-X, a key device of the European Fusion Roadmap**

Experimental work at TJ-II is supported by LNF's strong theoretical physics division which addresses fusion-related topics such as particle and impurity transport, momentum transport and improved confinement transition, neoclassical transport and stellarator design optimisation, power exhaust physics (liquid metals), stability and fast particle physics.

MATERIALS AND POWER PLANT PHYSICS AND TECHNOLOGY

FOR "ITER-" AND "DEMO-READY" MATERIALS

The LNF offers a number of advanced experimental facilities, such as the **Van de Graaff electron accelerator** and the **Materials Characterisation Facility** for advancing fusion research. These facilities permit the quantitative evaluation of the behaviour of materials and electrical and optical components that will be used in both ITER and DEMO diagnostics. Of crucial importance is the capability, developed at the 2 MeV electron accelerator, to perform **tritium permeation measurements** during irradiation for different type of materials. (An important step because the deuterium-tritium fuel mixture is the fuel of choice for future fusion reactors).

Researchers and engineers from LNF collaborate in international fusion experiments, including JET, ITER, IFMIF (Japan), DEMO, and Early Neutron Source (early IFMIF/DONES).

SPAIN. TJ-II. STELLARATOR. POWER PLANT PHYSICS. MATERIAL SCIENCES.

WWW.FUSION.CIEMAT.ES

SE

VR

The contribution of the Swedish Research Unit to the Euratom programme is carried out by way of a Contract of Association between the **Swedish Research Council (VR)** and Euratom. The Swedish fusion research unit encompasses a range of competencies that are important for the ITER project and the basic goal of the Association is to make important contributions to the ITER project and to the long term aim of achieving a prototype fusion reactor. Research activities are carried out at the Royal Institute of Technology (KTH) in Stockholm, Chalmers University of Technology (CTH) in Göteborg, Uppsala University (UU) and at Studsvik Nuclear AB.

MAIN RESEARCH THEMES

Fusion research in the Swedish RU is mainly carried out at universities and is focused on fundamental research in areas such as transport of particles and energy, plasma stability (including active control of instabilities), heating (mainly Ion Cyclotron Resonant Heating), energetic particle physics, plasma wall interaction, and diagnostic development and implementations, in particular spectroscopy and neutron diagnostics. The research includes both experimental and theoretical work with a strong element of modelling, including innovative methods, and computer code development.

SELECTED HIGHLIGHTS OF THE SWEDISH FUSION RESEARCH ACTIVITIES

The Swedish Research Unit actively contributes to JET experiments and collaborates with other European partners in projects related to ITER and DEMO.

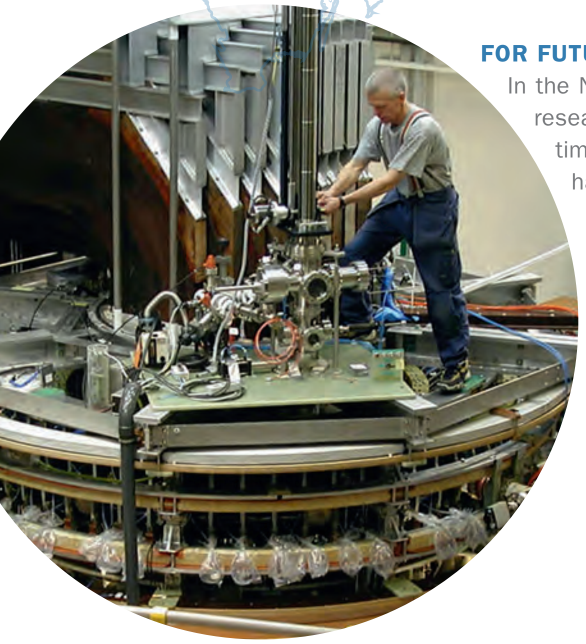
FOR JET

The key contributions of the Swedish researchers towards ongoing JET campaigns can be summarised in six areas:

- Confinement and pedestal physics
- ICRF heating studies and MHD control
- Fusion product studies and fast ions
- Plasma-wall interaction and the new ITER-like wall (ILW)
- Transport analysis of ILW and C-wall discharges
- Neutron emission spectroscopy

FOR FUTURE FUSION DEVICES AND REACTORS

In the Nordic region's only fusion facility, Extrap T2R at KTH Electrical Engineering Dept., researchers focus on developing methods to actively control plasma instabilities in real time. The research is a collaborative undertaking with the RFX experiment in Italy, and has major significance for controlling plasma in fusion facilities in the future.



SWEDEN. PLASMA WALL INTERACTION. PLASMA STABILITY. COMPUTATIONAL METHODS. EXTRAP T2R. NEUTRON SPECTROSCOPY. NEUTRON DIAGNOSTICS.

WWW.VR.SE/INENGLISH

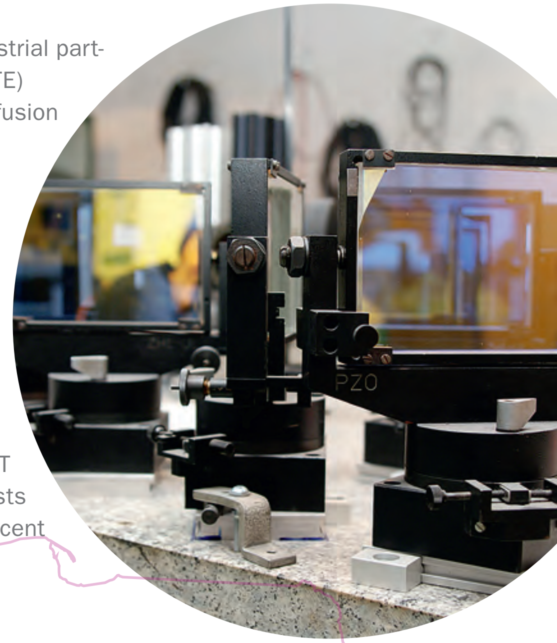
PL

IPPLM

Sylwester Kaliski Institute of Plasma Physics and Laser Microfusion (IPPLM) based in Warsaw coordinates fusion research in Poland.

POLISH FUSION PROGRAMME AT A GLANCE

- Has been part of the European fusion programme since 2005
- Comprises 11 institutions, including universities, research institutes as well as industrial partners that form the national consortium called New Energy Technologies (Centrum NTE)
- Has developed components and diagnostics for JET, W7-X, WEST and codes for fusion devices including DEMO
- Regularly organises fusion-related schools and conferences



HIGHLIGHTS OF SOME OF THE POLISH FUSION ACTIVITIES

FOR JET

IPPLM researchers participate in experimental campaigns and have contributed towards the development of JET diagnostic systems and numerical tools. Polish physicists have successfully concluded a JET contract for upgrading a spectrometry KX1 diagnostic based on novel GEM technology. The GEM detectors were delivered to JET and first measurements of nickel and tungsten were conducted.
Additionally, the IPPLM team is involved in analyses of experimental data using JET tools, as well as codes developed in IPPLM (COREDIV, TECXY). Polish scientists contribute towards neutron activation measurements and calculations, including the recent in situ calibration of JET neutron monitors.

FOR DEMO

The COREDIV code developed at IPPLM has been used to study different DEMO scenarios.

FOR WENDELSTEIN 7-X

Since 2005 the Polish involvement in Wendelstein 7-X programme has been extended, ranging from cooperation in device assembly, preparation and application of X-ray diagnostics, development of the neutral beam injector system, structural mechanical calculations and neutron MCNP (Monte Carlo N-Particle Transport Code) calculations to plasma modelling.

OTHER RESEARCH LINES

IPPLM and the Warsaw University of Technology carry out research related to fusion technology (fuel removal, dust, chemical erosion and transport). The aim of these tasks is to optimise, in laboratory experiments, the removal process with the use of lasers, investigate a dust formation and describe material mixing and plasma-induced damages of the analysed samples by different surface measuring methods.

EDUCATION

IPPLM organises two flagship events to boost fusion education: Kudowa Summer School "Towards Fusion Energy" and the International Conference on Research and Applications of Plasmas.

POLAND. GAS ELECTRON MULTIPLIER. COREDIV CODE. KUDOWA SUMMER SCHOOL AND INTERNATIONAL CONFERENCE ON RESEARCH AND APPLICATIONS OF PLASMAS.

WWW.IPPLM.PL/EN

CZ

IPP.CR

The **Institute of Plasma Physics of the Czech Academy of Sciences (IPP.CR)** has been the leading Czech research institution in the field of fusion physics for nearly 50 years. The main player in the Czech Republic's fusion technology initiatives is the **Research Centre Rež.**

The three main facets of the Czech Republic's fusion initiatives are as follows:

COMPASS TOKAMAK

COMPASS is one of the few tokamaks with an ITER-like plasma shape; it contributes to scaling experiments for ITER. The flexibility of COMPASS and a wide variety of dedicated high-resolution edge plasma diagnostics make it an excellent device for addressing some of the key problems associated with H-mode physics. Its scientific programme is geared towards pedestal physics, isotope effects, control of runaway electrons, the effect of external magnetic perturbations on the plasma performance, and plasma material interaction studies. Education and training are also important aspects of the COMPASS programme.

RESEARCH CENTRE REŽ

Research and development at the Centre focuses on nuclear energy, nuclear reactor physics, chemistry and materials. The Centre participates in the EUROfusion Breeding Blanket, Divertor & Safety and Environment Work Packages. The development of plasma-facing components is supported by tests of first wall and divertor components at the HELCZA high heat flux facility. Experimental activities for the DEMO Breeding Blanket are being pursued with the PbLi (lead-lithium) loop MELILOO. These activities are complemented by the planned irradiation of a PbLi capsule in the LVR-15 reactor designed to enable the investigation of coatings and tritium permeation and also by the operation of a new 14 MeV Neutron Generator for the characterisation of activation products. In order to support manufacturing technology for breeding blankets, it is planned to test Eurofer samples in the LVR-15 reactor core.

RESEARCH CENTRE PALS

The PALS Research Infrastructure provides beam time of its high-power lasers to both domestic and foreign researchers. The main experimental facility is the pulsed terawatt iodine laser. The auxiliary femtosecond beam lines extend its capabilities with tools for femtosecond probing of plasma. Fusion-related experiments at PALS include, e.g. studies of impact ignition, a neutronic proton-boron fusion and inertial fusion relevant experiments.

CZECH REPUBLIC . COMPASS TOKAMAK . THERMONUCLEAR FUSION . INERTIAL FUSION . HELCZA HIGH HEAT FLUX FACILITY . MELILOO LOOP . PLASMA PHYSICS .

WWW.IPP.CAS.CZ

SK

DEPARTMENT OF EXPERIMENTAL PHYSICS, COMENIUS UNIVERSITY, SLOVAKIA

Slovakia has been associated with EURATOM since 2000. Fusion research in Slovakia has worked in areas related to **plasma-wall interaction**, and **superconductor testing and development**. Other research areas include studies on the radiation damage of materials using positron annihilation and neutronics analysis of the diagnostic equatorial and upper plug blanket modules for ITER.

Some of the EURATOM funded fusion research projects include:

- Kinetics of electron and ion processes for fusion and technological plasmas,
- Ionisation and excitation reactions for plasma diagnostics and applications, and
- Volume and surface processes in electric discharges at atmospheric pressure.

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RO

INSTITUTE FOR ATOMIC PHYSICS, ROMANIA

The **Institute for Atomic Physics** is the Romanian signatory of the EUROfusion agreement. Romania has had robust links with EURATOM since 2000: in 2001, a laboratory for **microtomography** was established at the **National Institute of Laser, Plasma and Radiation Physics (NILPRP)** with the support of the European Community. Its research is focused on the project "Non-destructive analysis of fusion materials samples by X-ray microtomography" and aimed to improve the development and testing of fusion materials by employing the latest non-destructive techniques (NDT).

The "**Combined Magnetron Sputtering and Ion Implantation**" technology (CMSII) developed by the Romanian Fusion Association (EURATOM/MEdC) yielded the best quality tungsten coatings that have been used for the tiles of JET's ITER-like wall. These tiles have been used in the areas that experience the highest heat loads, the divertor. They are made of carbon fibre composite, and a thin layer of tungsten has been evaporated onto the plasma facing surfaces of these new tiles.

WWW.INFLPR.RO/

BG

INSTITUTE OF NUCLEAR RESEARCH AND NUCLEAR ENERGY, BULGARIA

The EUROfusion consortium signatory representing Bulgaria is the **Institute of Nuclear Research and Nuclear Energy**, Sofia, of the Bulgarian Academy of Sciences. Bulgaria has been associated with EURATOM since 2000, participating in the fusion R&D programme. The Research Unit has worked on projects related to fusion physics and technology. In particular, Bulgarian researchers have participated in projects on neutronics, research on ITER and DEMO blankets, and assessment of positron lifetime diagnosis of neutron irradiation damage in materials.

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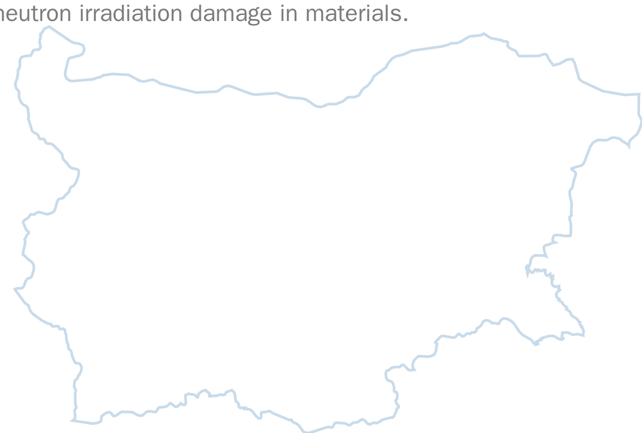


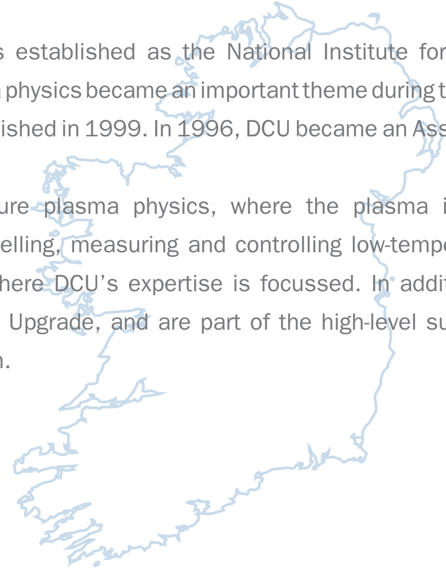
IE

PLASMA RESEARCH LABORATORY, DUBLIN CITY UNIVERSITY, IRELAND

Dublin City University (DCU) was established as the National Institute for Higher Education in 1975 and elevated to university status in 1989. Plasma physics became an important theme during the 1980s, and a National Centre for Plasma Science and Technology was established in 1999. In 1996, DCU became an Associate of the EURATOM fusion programme.

DCU specialises in low-temperature plasma physics, where the plasma is not fully ionised and interaction with neutral species is important. Modelling, measuring and controlling low-temperature plasma is of great importance for fusion experiments, and this is where DCU's expertise is focussed. In addition, researchers from DCU participate in experiments carried out at ASDEX Upgrade, and are part of the high-level support team involved in High Performance Computing used in fusion research.

WWW.DCU.IE/



EE

INSTITUTE OF PHYSICS, UNIVERSITY OF TARTU, ESTONIA

The **University of Tartu's, Institute of Physics** coordinates Estonia's fusion research for EUROfusion. In particular, the research group from the Institute's **Gas Discharge Laboratory** have been part of EUROfusion projects. The Gas Discharge Laboratory deals with the problems of low temperature plasma and its interaction with the solids. One core task of their research is the **development of laser induced plasma spectroscopy in diagnostics of plasma-first wall interaction.**

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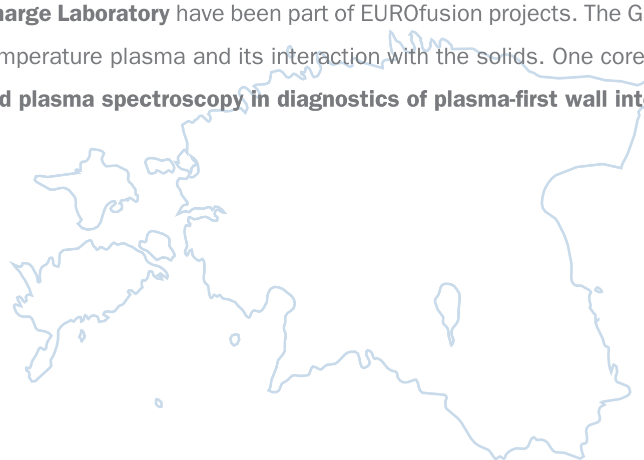

CY

UNIVERSITY OF CYPRUS, NICOSIA, CYPRUS

The main tasks of the research team within **University of Cyprus** have included magnetohydrodynamics, blanket design, code development for integrated modelling, modelling of transport, particle kinetics and turbulence.

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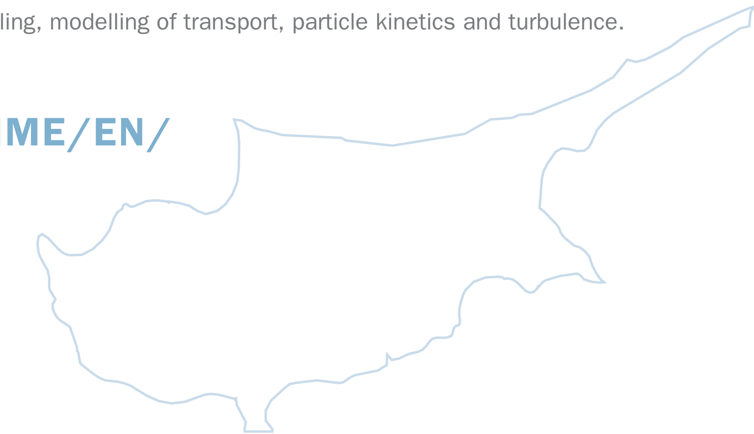


GLOSSARY

BEAM EMISSION SPECTROSCOPY, BES
Beam Emission Spectroscopy measures plasma turbulence. It registers the light emitted from the neutral particle beams which are injected into the plasma for heating or diagnostic. These particles collide with plasma particles, get excited and emit light. The intensity variations of these emissions reflect the local density fluctuations from which plasma turbulence can be measured.

BLANKET
In a fusion power plant using deuterium-tritium fuel, the system surrounding the plasma vessel, the blanket, has two functions: firstly, to slow down the neutrons produced, so that the heat released can be used for electricity generation. Secondly, in many designs, the blanket is also used to synthesise tritium (from the neutrons and a lithium compound) to use as fuel.

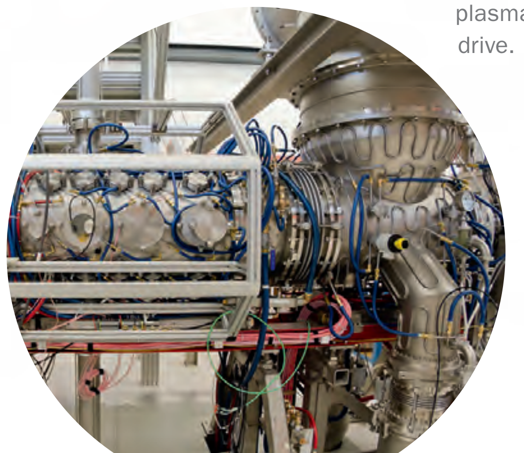
BOLOMETER
A radiant-heat detector that is sensitive to differences in temperature.

BROADER APPROACH
The Broader Approach is an agreement signed between the European Commission and Japan. This cooperation comprises three large research projects to be jointly implemented. The three projects are the Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA), the International Fusion Energy Research Centre (IFERC), and thirdly the Satellite Tokamak Programme.

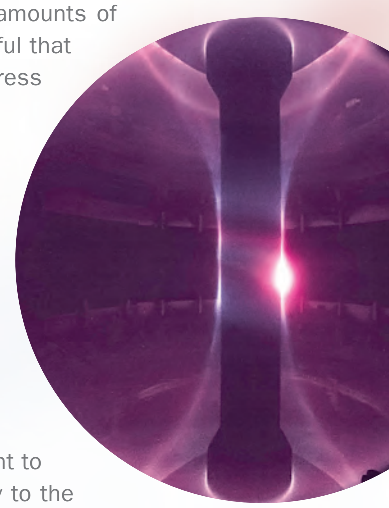
DEMO
DEMO is the successor of the international fusion experiment ITER and the next step on the way to realising fusion energy. Its purpose is to develop and test technologies, physics regimes and control routines for operating a fusion reactor, not as a scientific experiment, but as a power plant. One of the key criteria for DEMO is the production of electricity.

DIAGNOSTIC
System for measuring the plasma. Fusion experiments utilise a large variety of diagnostic systems (often called diagnostics) to measure plasma parameters like density, temperature or impurity content.

DIVERTOR
A magnetic field configuration affecting the edge of the confinement region, designed to divert impurities and helium ash to a target chamber. Often this chamber is also called “divertor”. Handling the heat fluxes at the divertor of fusion power plants is one focus of fusion research. It is tackled by developing more resistant materials and by developing magnetic configurations that reduce the heat load at the divertor, e.g. snowflake and Super-x divertor.



ELMS
Edge Localised Modes, ELMs, is an instability which occurs in short periodic bursts during the H-mode in divertor tokamaks. It causes sudden outbursts of the plasma thus expelling particles and depositing large heat flux onto the vessel wall. The plasma loses severe amounts of energy. In high-power fusion devices such as ITER or DEMO, ELMs are so powerful that they will cause erosion at the vessel wall. Finding methods to mitigate or suppress ELMs is therefore a hot topic in current fusion research.



EURATOM
EURATOM is a research programme for nuclear research and training in Europe. The indirect actions of the EURATOM Programme focus on two areas: nuclear fission and radiation protection and fusion research intended to develop magnetic confinement fusion as an energy source.

EUROFER
EUROFER is a ferritic martensitic steel with special properties. It is more resistant to neutron bombardment, i.e. limited irradiation induced swelling and susceptibility to the production of helium. Also, EUROFER can be made with low activation chemical compositions.

FIRST WALL
Innermost shield of the vessel wall in a magnetic confinement fusion device. Usually in the form of tiles mounted along the wall, often referred to as plasma facing components.

GYROTRONS
Devices used for generating high power microwaves in the electron cyclotron range of frequencies (about 50 – 200 gigahertz).

HORIZON 2020
Horizon 2020 is the biggest EU Research and Innovation programme ever, with nearly €80 billion of funding available over 7 years (2014 to 2020).

NEUTRONICS
The discipline which studies the complex diffusion of neutrons through matter and their interactions with nuclei.

NEUTRAL BEAM INJECTION, NBI
A beam of high velocity neutral atoms injected into the plasma to impart momentum to the plasma ions. Neutral beam injection is a method of providing additional heating and current drive.

CREDITS

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24	Turbulence and transport in plasmas, Source: PPFE webpage.
25	Fast camera "EDICAM" photographer, Christophe Roux.
26	Three rectangular antennas for heating systems available at JET; (from left) the Lower Hybrid, the ICRH and the ITER-like ICRH, Source: EURO*fusion*.
27	Heart-shaped dust particle from JET divertor tile, size 120 by 100 micrometers. Result of ion microbeam analyses of JET's dust using PIXE and NRA methods at RBI's Heavy Ion Microbeam, © RBI, CRU.
28	Simulation showing radiation heat flux on magnets, © SFA.
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REALISING FUSION ELECTRICITY BY 2050

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