European Fusion R&D and Education programme

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Fusion Electricity

A roadmap to the realisation of fusion energy

The roadmap (October 4th, 2012) addresses three separate periods with distinct main objectives

I. Horizon 2020 (2014-2020) with five overarching objectives

1. Construct ITER within scope, schedule and cost;

2. Secure the success of future ITER operation;

3. Prepare the ITER generation of scientists, engineers and operators;

4. Lay the foundation of the fusion power plant;

5. Promote innovation and EU industry competitiveness.

Horizon 2020= *EU Research and Innovation programme (previously FPs)*

II. Second period (2021-2030):

Exploit ITER up to its maximum performance and prepare DEMO construction.

DEMO= Demonstration Power Plant (s) envisaged to follow ITER

III. Third period (2031-2050):

Complete the ITER exploitation; construct and operate DEMO.

Horizon 2020 milestones and resources have been defined in detail, while a global evaluation is given for the second period and the third one is only outlined.

The roadmap will be a living document, reviewed regularly in response to the physics, technology and budgetary developments

A roadmap to the realisation of fusion energy

1. Introduction – Make fusion a credible energy option
2. ITER – the key facility of the roadmap
3. A pragmatic approach to fusion energy – Fully exploit the potential of innovation
4. The fusion challenges
5. How to face the challenges – The missions for the realisation of fusion (goal-oriented approach)
6. Roadmap outline and milestones

A roadmap to the realisation of fusion energy (2)

7. Training and education – Form the "Generation ITER" of scientists, engineers and operators

8. Breaking new frontiers – The need for basic research

9. Industrial involvement – From provider of high-tech components to driver of fusion development

10. Exploit the opportunities from international collaborations

11. A living document: roadmap reviews and decision points

12. Resources

A pragmatic approach to fusion energy – Fully exploit the potential of innovation

To meet the goal of fusion electricity demonstration by 2050, DEMO construction has to begin in the early 2030´s at the latest, to allow the start of operation in the early 2040´s.

Meeting such a schedule is possible provided ITER achieves its goals, the innovation potential is fully exploited on the more critical issues, and a pragmatic approach to DEMO is chosen.

***As in all large science projects, success relies on the balance between pragmatism and innovation*. This approach, together with the R&D for risk mitigation, will foster innovation taking full benefit of the ITER experience and ensuring a single step to a commercial fusion power plant (FPP).**

Roadmap has one critical path:

ITER → DEMO → Commercial fusion power plant (FPP)

- **With ITER, Magnetic Confinement Fusion (MCF) has crossed a threshold to a phase of the programme increasingly focused on fusion energy generation**
- **There are multiple approaches to fusion development but broad agreement on the goals, critical tasks, and value of international collaboration**

Long-term perspective

- **A long-term perspective in the EU on the development of controlled magnetic confinement fusion (MCF) is mandatory since Europe has a leading position in this field and major expectations have grown in other ITER parties for fusion as a sustainable and secure energy source.**

- **China, for example, is launching an aggressive programme aimed at fusion electricity production before 2050. Chinese Fusion Engineering Test Reactor (CFETR): Bridge from ITER to DEMO in China: 50 - 200MW of fusion power; closed tritium fuel cycle; explore options for key technologies**

- **Europe can only keep pace if it focuses its effort and pursues a pragmatic approach to fusion energy. Therefore, EFDA,(see below) has created the present Roadmap for fusion energy.**

From EFDA to EUROfusion

- **Since the 1970´s, when Europe's fusion laboratories joined forces to build and operate the Joint European Torus (JET), they have continuously reinforced their collaboration, which accounts for its current leadership.**

- **To coordinate research activities beyond JET, the Associates formed the European Fusion Development Agreement, EFDA, in 1999.**

- **The recently created EUROfusion consortium takes this development a step further. EUROfusion, the European Consortium for the Development of Fusion Energy, manages European fusion research activities on behalf of the European Atomic Energy Community (EURATOM), and funds the Research Units in accordance with their participation to the mission-oriented Work Packages.**

EUROfusion Consortium

- **The members of the EUROfusion consortium are from 28 European countries. EUROfusion funds all fusion research activities in accordance with the Roadmap to the realisation of fusion energy**

- **This Roadmap outlines the most efficient way to realise fusion electricity.**

- **It is the result of an analysis of the European Fusion Programme undertaken by all Research Units within EUROfusion's predecessor organisation, EFDA.**

From Physics to Technology

- **Over the coming decades the Fusion Programme will shift from being science-driven and laboratory-based towards a technology-driven, industry-based venture → Education**

- **The ITER construction involves about 6B€ of industrial contracts and provides employment at the equivalent of 5000 person-years per year in Europe. ITER will test or validate most technological solutions for DEMO, although significant innovation is required in some areas such as *breeding blanket technology, plasma facing and structural materials, superconducting magnets, microwave sources, high power beam sources, remote handling, fuelling and pumping system*.**

From Physics to Technology (2)

- **The role of industrial partners will evolve from that of a provider of high-tech components to that of a driver of fusion development.**

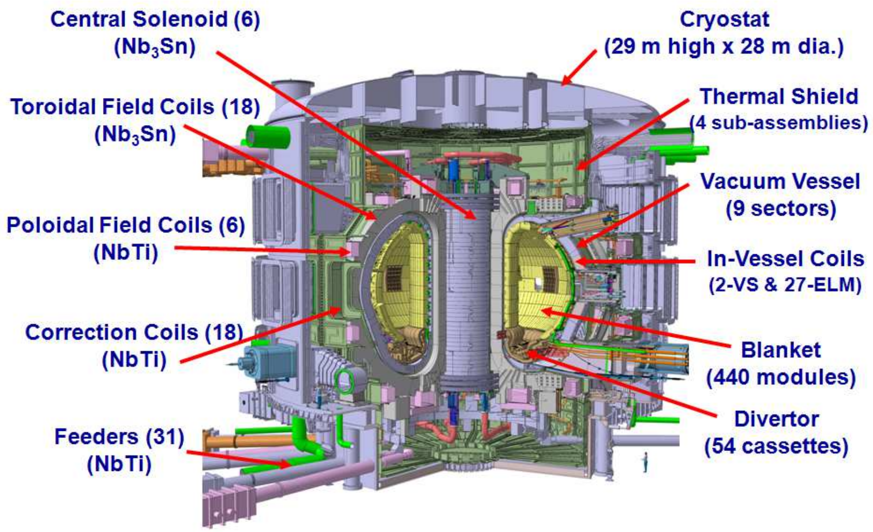
- **This will be a stepwise process, through consortia which will bring together industry, research laboratories and universities, in connection with DEMO R&D.**

- **For this reason the early involvement of industry in the definition and design of DEMO and in fusion materials development is already foreseen by the Horizon 2020 Roadmap.**

- **An early launch of the DEMO engineering design after the completion of ITER would facilitate maintaining industrial competences.**

ITER- the key facility of the roadmap

ITER, the world's largest and most advanced fusion experiment, will be the first magnetic confinement device to produce a net surplus of fusion energy. It is designed to generate 500 MW fusion power which is equivalent to the capacity of a medium size power plant. As the injected power will be 50MW, this corresponds to a fusion gain Q=10. ITER will also demonstrate the main technologies for a fusion power plant.



The realisation of fusion energy depends fully on ITER's success. Therefore, the vast majority of resources in Horizon 2020 are dedicated to the construction of ITER and the preparation of its exploitation.

ITER is currently being built in southern France in the framework of a collaboration between China, Europe, India, Japan, Korea, Russia and the USA.

The fusion challenges

Plasma regimes of operation

- **Plasma regimes of operation have been developed and qualified for the ITER design.**

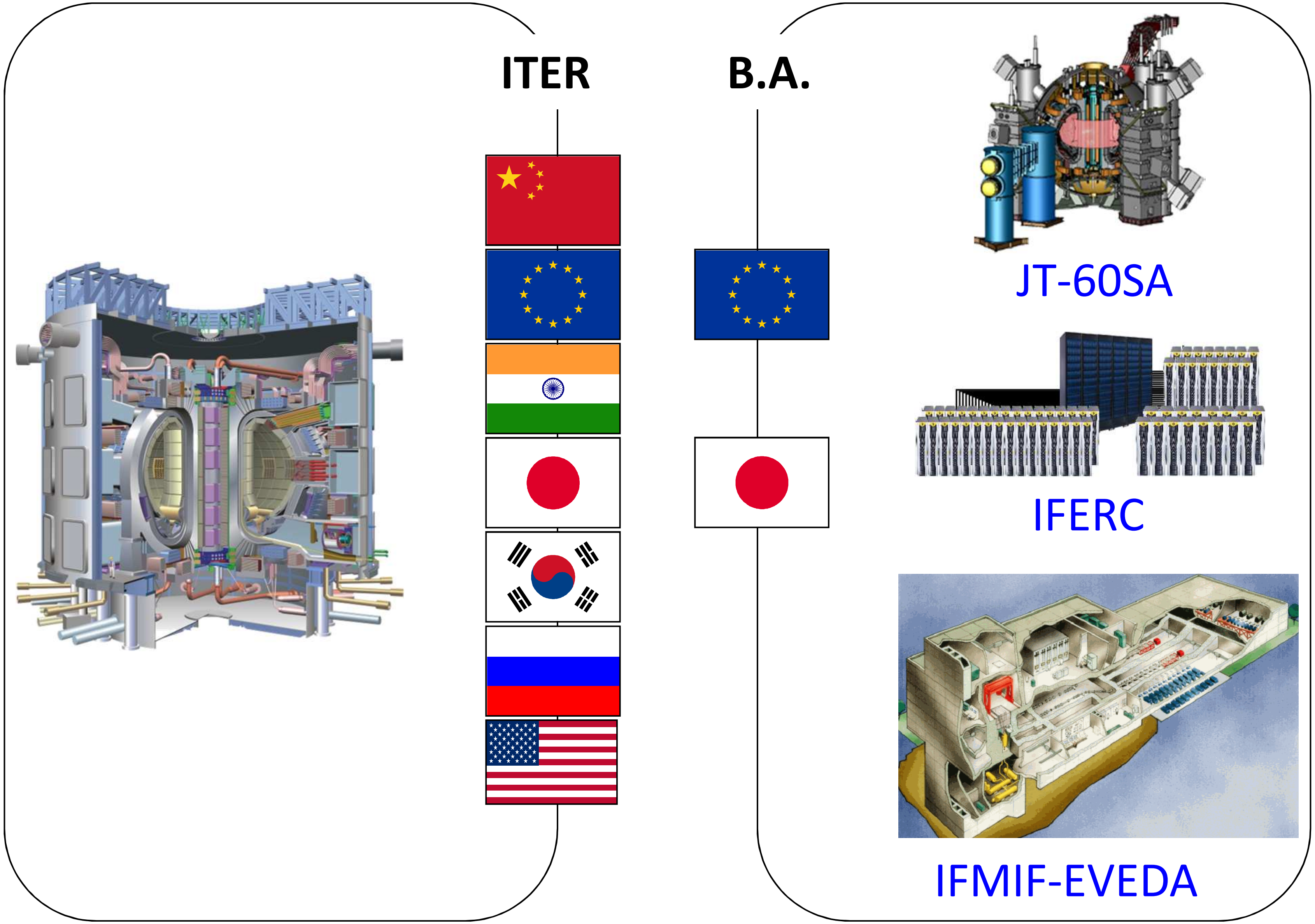
- **These will require advances above the ITER baseline to meet the requirements for DEMO.**

- **JET: the test-ground for ITER operation (participation of about 100 European an international fusion laboratories *: JET internationalisation).***

- **JT-60SA: qualifying steady-state regimes for ITER, and complementing ITER in resolving key issues for DEMO.**

- **Small and medium sized tokamaks with proper capabilities, will pay a role in specific work packages. AUG e.g. is expected to play an important role for the preparation of the ITER advanced regimes of operation**

The "Broader Approach"



The first 40° sector of the JT-60SA vacuum vessel was completed in June 2011 at JAEA Naka Fusion Institute, JAPAN

A solution for the heat exhaust in the fusion power plant is needed

A reliable solution to the problem of heat exhaust is probably the main challenge towards the realisation of magnetic confinement fusion. The risk exists that the baseline strategy pursued in ITER cannot be extrapolated to a fusion power plant.

Hence, in parallel to the programme in support of the baseline strategy, an aggressive programme on alternative solutions for the divertor is necessary. Some concepts are already being tested at proof-of-principle level and their technical feasibility in a fusion power plant is being assessed.

Since the extrapolation from proof-of-principle devices to ITER/DEMO based on modelling alone is considered too large, a dedicated test on specifically upgraded existing facilities or on a dedicated Divertor Tokamak Test (DTT) facility will be necessary.

A dedicated neutron source is needed for material development

Irradiation studies up to ~30 dpa with a fusion neutron spectrum are needed before the DEMO design can be finalised.

While a full performance IFMIF would provide the ideal fusion neutron source, the schedule for demonstration of fusion electricity by 2050 requires the acceleration of material testing.

The possibility of an early start to an IFMIF-like device with a reduced specification or a staged IFMIF programme should be assessed.

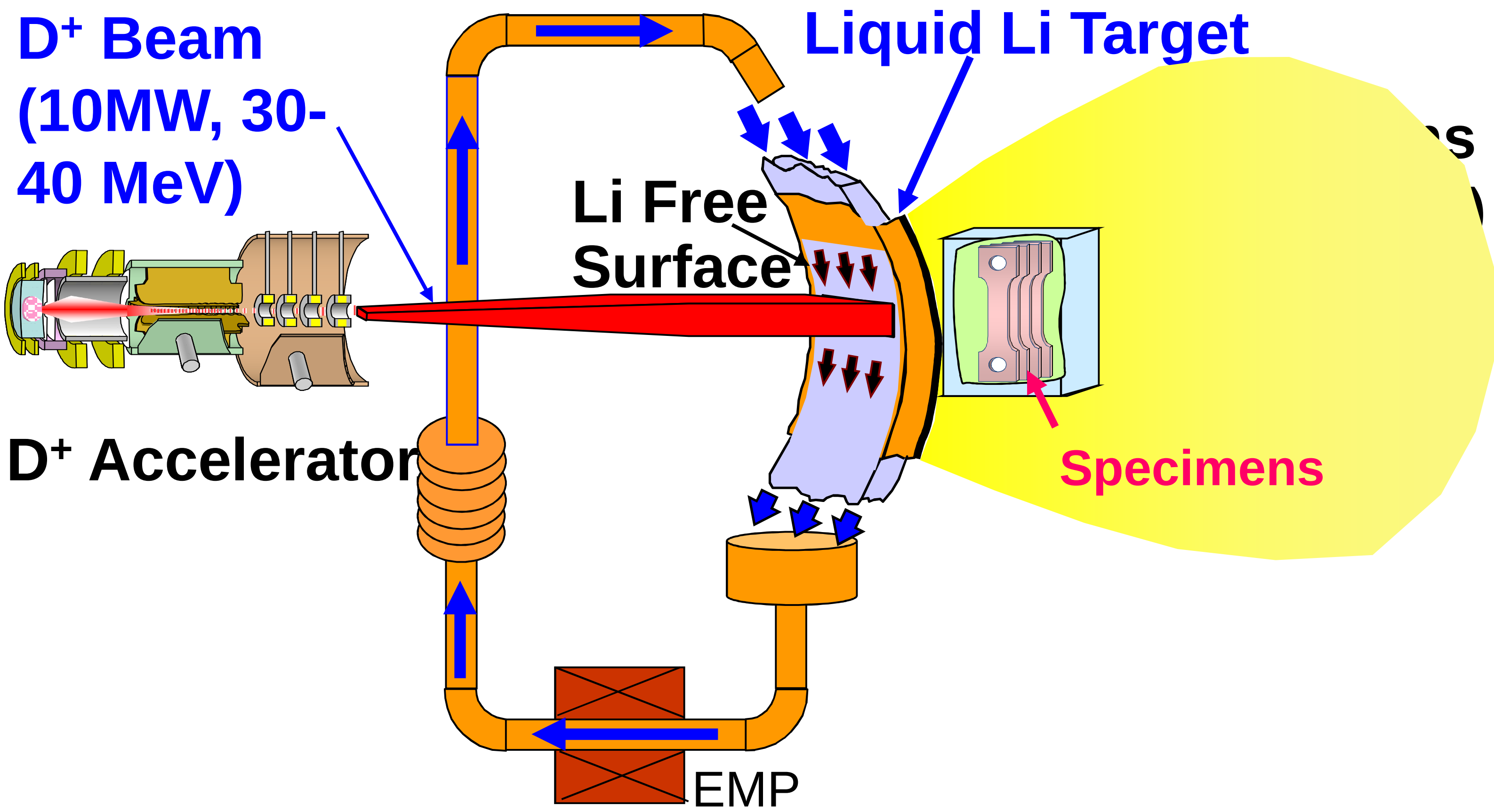
A selection should be made early in Horizon 2020 of risk-mitigation materials for structural, plasma-facing and high-heat flux zones of the breeding blanket and divertor areas of DEMO, also seeking synergy with other advanced material programmes outside fusion.

Types of Irradiated Materials

- **Plasma facing materials:**
  - Serve as armour for the other materials
- **Functional materials:**
  - Have a particular function
- **Structural materials:**
  - Make the basic structure of the fusion reactor

Irradiation facility: IFMIF

Schematic View



EVDA phase in progress in Aomori
Within EU/Japan broader approach

Synergy in Required Materials

Advanced fission reactors

Oxide dispersion strengthened steels
Refractory metals and alloys
C/C, SiC, SiC/SiC_f ceramic composites
Intermetallic alloys

Accelerator driven systems

Oxide dispersion strengthened steels
Reduced activation ferritic/martensitic steels

Fusion reactors

Oxide dispersion strengthened steels
Reduced activation ferritic/martensitic steels
SiC/SiC_f ceramic composites
Refractory metals and alloys

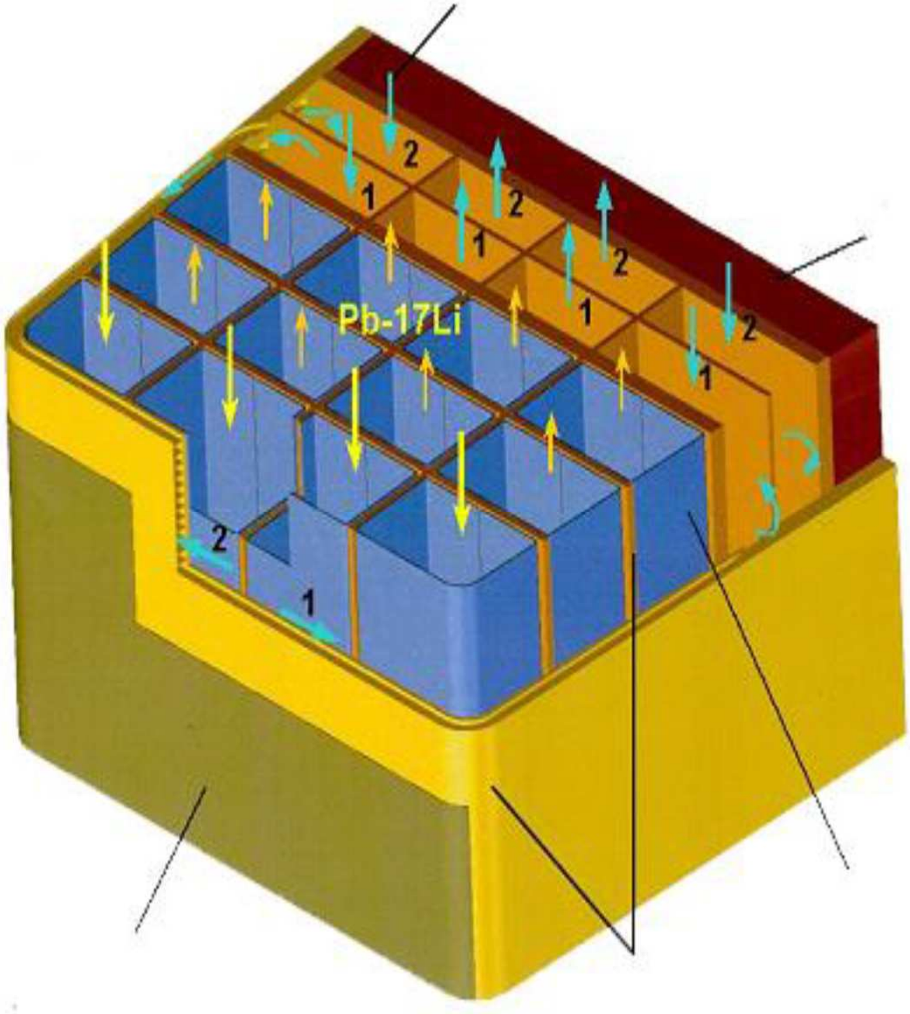
Tritium self-sufficiency

- **Tritium self-sufficiency is mandatory for DEMO, which will burn about 0.4 kg of tritium per operational day.**

- **Tritium self-sufficiency requires efficient breeding and extraction systems to minimise the tritium inventory.**

- **The choices of the materials and the coolant of the breeding blanket will have to be made consistently with the choice of the components for the transformation of the high-grade heat into electricity (the so-called Balance of Plant).** *BOP= components not included in primary system itself, such as blowers, compressors and pumps.*

EU Liquid breeder: Dual-Coolant Lead-Lithium (DCLL)



Intrinsic Safety

- **While fusion has intrinsic safety features, their implementation in a coherent architecture needs to be a key goal for any DEMO design, to ensure the inherent passive resistance to any incidents and to avoid the need of evacuation in the worst incident case.**

- **The development of methods for reducing the problem associated with the presence of tritium in the components extracted for disposal and the definition of appropriate disposal routes is the main development needed.**

Integrated DEMO design

- **Combining all the fusion technologies into an integrated DEMO design will benefit largely from the experience that is being gained with the ITER construction.**

- **Nevertheless, compared with ITER, DEMO will need a more efficient technical solution for remote maintenance as well as highly reliable components: To ensure an adequate level of reliability and availability will be one of the primary goals.**

- **In addition, DEMO will need to exploit a complete Balance of Plant (BoP) including the heat transfer and associated electrical generation systems.**

Cost of Electricity

- **In order to have a rapid market penetration, fusion will have to demonstrate the potential for competitive cost of electricity.**

- **Although this is not a primary goal for DEMO, the perspective of economic electricity production from fusion has to be set as a target, e.g. minimising the DEMO capital costs.**

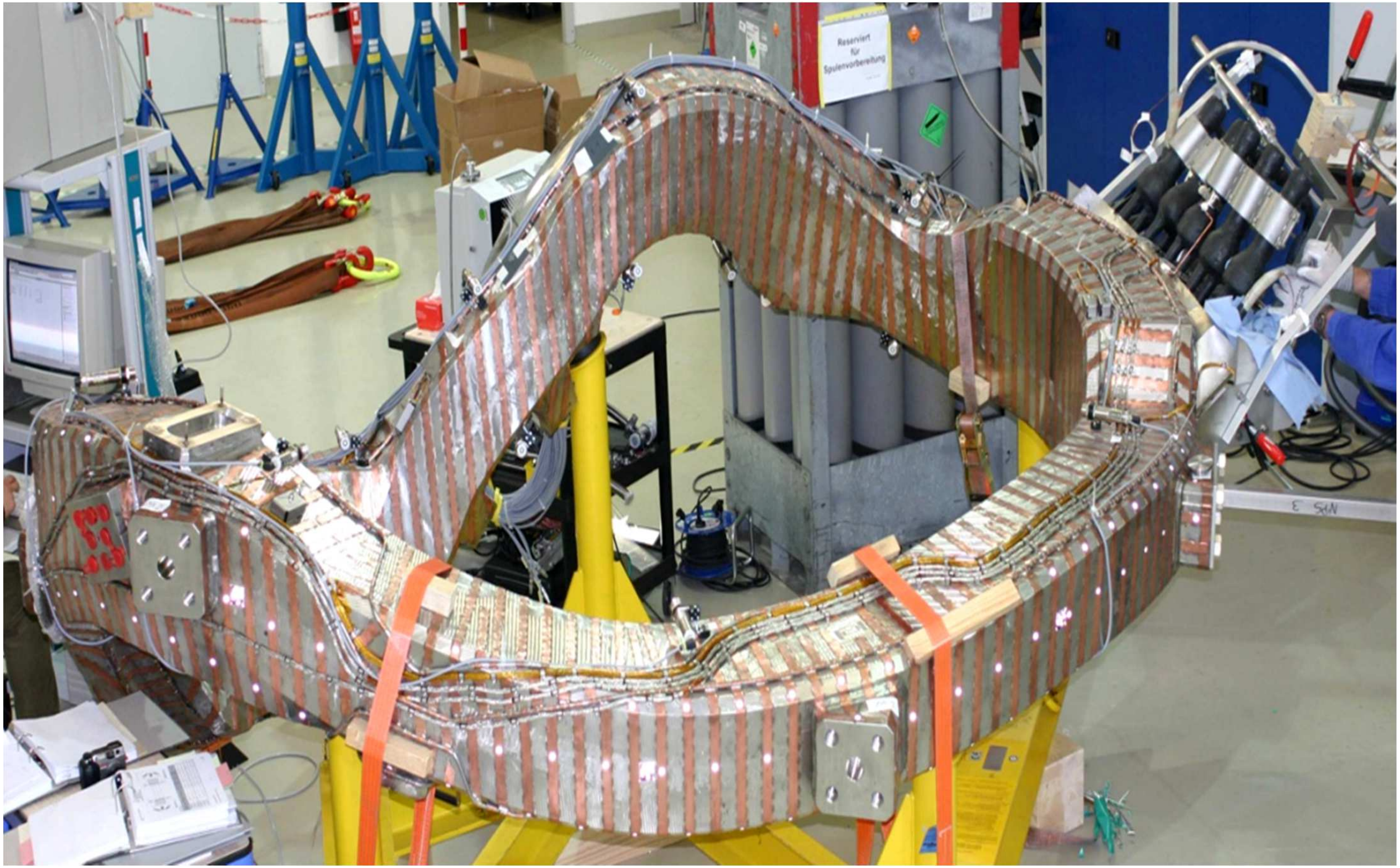
- **Building on the experience of ITER, design solutions demonstrating a reliable plant with a high availability, serving as a credible data basis for commercial energy production, will have to be pursued.**

- **The reduction in size and cost of a FPP depends to a large extent on the development of advanced heat exhaust systems.**

- **Socio-economic research activities on fusion energy (SERF) will also help in maintaining a long-term perspective and optimising the strategies for market penetration of fusion.**

Stellarator line

- **The EU Stellarator programme should focus on the optimised HELIAS line. HELIAS =** helical advanced stellarator; stellarator configuration utilizing an optimized modular coil set .
- **The stellarator is a possible long-term alternative to a tokamak Fusion Power Plant. In addition, it provides a support to the ITER physics programme.**
- **For Horizon 2020, the main priority should be the completion and start of scientific exploitation of W7-X with full exploitation under steady-state conditions achieved beyond 2020.**
- **If W7-X confirms the good properties of optimised stellarators, a next step HELIAS burning plasma experimental device will be required to address the specific dynamics of a stellarator burning plasma.**
- **The exact goal of such a device can be decided only after a proper assessment of the W7-X results.**


Reserviert
für
Spulenvorbereitung

Theory and Modelling

- Theory and modelling effort in plasma and material physics is crucial.
- Theory and modelling provide the capability of extrapolating the available physics results to ITER and a fusion power plant (FPP).
- This is crucial for the extrapolation of the core and edge plasma dynamics for both tokamaks and stellarators.
- Material computer modelling needs to play an increasing role in the development of fusion materials to guide and interpret fission irradiations using isotopic tailoring and to predict and interpret the fusion irradiations at low doses and hence to help guide and shape the mission of an ‘early stage’ to the IFMIF programme

FUSION EDUCATION

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Fusion Education

- **In order to maintain the expertise that has put the European Fusion Programme at the forefront of international fusion research and engineering, and to ensure the availability of competent staff to construct and operate ITER and DEMO, a long-term Human Resource Management plan for the European Fusion Programme is needed.**

- **This should reflect the increase in the volume of the programme, the shifts in required competences, and the aging of the fusion community workforce.**

- **The European Fusion Education Programme is the natural counterpart of the European Fusion Research Programme. The two should work in close harmony with obvious synergies.**

- **There is also a growing need for competences in nuclear related issues such as project management, nuclear licensing, quality assurance, risk assessment, and management of procurement processes, as well as a need for stronger collaboration with industry.**

- **"Nuclearisation of Fusion "**

- **Defining, designing, building and operating DEMO requires the direct involvement of industry in the fusion programme.**

- **Fusion laboratories and universities play a key role in educating Generation-ITER through theoretical and experimental work undertaken in leading fusion facilities.**

- **These include JET, which represents an intermediate step towards ITER. Its large size, tritium capability, use of remote handling and of beryllium, make it the ideal place for training scientists and engineers for ITER.**

- **Similarly, engineering skills for the design and construction of DEMO need to be consolidated through involving students in large devices currently under construction (ITER, JT-60SA, W7-X).**

- **The importance of training and education has been explicitly recognised by specific support through the EUROfusion education programme, which is mostly used to fund national PhD fellowships and research.**

- **At the post-doctoral level support is available through post-doc and engineering fellowships.**

- **At the Master level however, only limited support is available through FuseNet for mobility.**

- **Apart from the goal-oriented missions, there is also a *"curiosity driven" basic research* programme (breaking new frontiers).**

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FuseNet Association

Umbrella organisation under which all fusion education is coordinated

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FuseNET (FUSion Education NETwork) Association

- **Resulting from EU-funded project (sustainability)**

Provides a platform for

- **the coordination of existing actions,**
- **the initiation, development and implementation of new EU-wide actions,**
- **the exchange and dissemination of fusion education information.**

www.fusenet.eu

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Three main elements of the FuseNET strategy

- **Critical mass**. As the number of students in fusion subjects in most countries is not large enough to support specialised Master or PhD degrees, actions need to be coordinated and initiated on a European scale, in order to reach sufficient critical mass.

- **Coherence**. To optimise the flow of students through the system, better links are needed between the different education layers. This means both a focus on secondary school teachers and good connections between higher education institutes and fusion institutes.

- **Transparency**. Learning opportunities need to be more accessible to students across Europe, through dissemination of information, and improvement of mobility. The educational goals of bachelor/master and doctoral level courses need to be more aligned, to make it easier forstudents to navigate the fusion system.

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Erasmus Mundus Fusion Education

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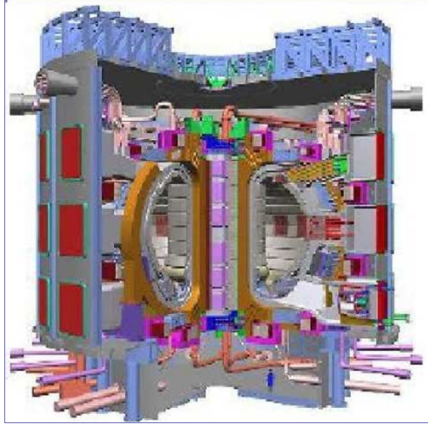
ERASMUS MUNDUS OVERALL AIMS

- Enhance the quality of European higher education
- Promote dialogue and understanding between peoples and cultures through cooperation with third countries (3C)
- **Promote EU external policy objectives and the sustainable development of 3C in the field of higher education**
- **Erasmus + approved by EP (19 Nov 13): €14.7 billion- 40% higher than current levels**

European Master in Nuclear Fusion Science and Engineering Physics



Education and Culture

Erasmus Mundus

European Master In Nuclear Fusion Science and Engineering Physics (FUSION-EP)

http://www.em-master-fusion.org

TEC

TRILATERAL EUREGIO CLUSTER

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FUSION-EP Partner (ITER) countries: USA, Russia, China

- UCLA (USA)
- University of Wisconsin-Madison (USA)

- St. Petersburg State Polytechnic University (Russia)
- National Research Nuclear University MEPhI, Moscow(Russia)

- University of Science and Technology of China (Hefei)
- Tsinghua University Beijing
- Southwestern Institute of Physics (SWIP), Chengdu.
- University of Science and Technology Beijing (USTB)

- Kharkiv National University (Ukraine)

TEC
TRILATERAL
EUREGIO CLUSTER

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- **To ensure the recruitment of competent specialists to meet projected demands of the evolving needs of research and industry, it is paramount to shift the emphasis within the European Fusion Education programme.**

- **This is the main objective of the transition from the EMCC FUSION-EP to the EMJMD FUSION-MS (*International Master of Science in Nuclear Fusion Science and Engineering*).**

- **In the existing European PhD networks in Fusion Science and Engineering, and in particular in the Erasmus Mundus "International Doctoral College in Nuclear Fusion Science and Engineering", the emphasis is already shifting to engineering.**

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ERASMUS MUNDUS

FUSION DC

International Erasmus Mundus Doctoral College in Fusion Science and Engineering

(FUSION-DC)

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STARTED SEPTEMBER 2012

Non-EU Associate (ITER) members

- *University of California Los Angeles*
- *University of California San Diego*
- *University of Wisconsin-Madison*
- **St. Petersburg State Polytechnic University**
- **National Research Nuclear University (MEPhI)**
- *Tsinghua University (Beijing)*
- *Southwestern Institute of Physics (Chengdu)*
- *USTC (Hefei,China)*
- *USTB (Beijing)*
- **Kyushu University (Japan)**
- **National Institute for Fusion Science (Japan)**
- *Institute for Plasma Research (India)*
- **Kharkiv National University (Ukraine)**
- **ITER IO**

Research fields

- Tokamak physics for ITER and beyond
- Technology for ITER and beyond
- Stellarator and reversed field pinch research and advanced concepts
- Plasma-wall interaction and materials research
- Plasma theory and computational plasma physics
- Diagnostics, plasma control and data analysis

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Financial means

- ERASMUS MUNDUS Doctoral fellowships
- Coordinating Ghent University finances a centrally managed post
- The Home Institutions of the doctoral students are committed to finance the participation of their students in the education activities organized by the College.
- The College seeks complementary financing necessary for its operation, for the organization of the education and training activities, and for doctoral fellowships.
  - Strong link with EU industry (Industry Strategic Advisory Board)
  - FuseNET Association
  - EUROfusion Consortium

Erasmus Mundus FUSION-EP & FUSION-DC

Industry Strategic Advisory Board

Part of coordinated EU Fusion Education

Fits into the roadmap to the realisation of fusion energy

Ideal preparation for ITER

(future leaders)