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Scientific and technical challenges on the road towards fusion electricity

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Scientific and technical challenges on the road towards fusion electricity

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ABSTRACT: The goal of the European Fusion Roadmap is to deliver fusion electricity to the grid early in the second half of this century. It breaks the quest for fusion energy into eight missions, and for each of them it describes a research and development programme to address all the open technical gaps in physics and technology and estimates the required resources. It points out the needs to intensify industrial involvement and to seek all opportunities for collaboration outside Europe. The roadmap covers three periods: the short term, which runs parallel to the European Research Framework Programme Horizon 2020, the medium term and the long term.

ITER is the key facility of the roadmap as it is expected to achieve most of the important milestones on the path to fusion power. Thus, the vast majority of present resources are dedicated to ITER and its accompanying experiments. The medium term is focussed on taking ITER into operation and bringing it to full power, as well as on preparing the construction of a demonstration power plant DEMO, which will for the first time demonstrate fusion electricity to the grid around the middle of this century. Building and operating DEMO is the subject of the last roadmap phase: the long term. Clearly, the Fusion Roadmap is tightly connected to the ITER schedule. Three key milestones are the first operation of ITER, the start of the DT operation in ITER and reaching the full performance at which the thermal fusion power is 10 times the power put in to the plasma. The Engineering Design Activity of DEMO needs to start a few years after the first ITER plasma, while the start of the construction phase will be a few years after ITER reaches full performance. In this way ITER can give viable input to the design and development of DEMO. Because the neutron fluence in DEMO will be much higher than in ITER, it is important to develop and validate materials that can handle these very high neutron loads. For the testing of the materials, a dedicated 14 MeV neutron source is needed. This DEMO Oriented Neutron Source (DONES) is therefore an important facility to support the fusion roadmap.

KEYWORDS: nuclear fusion, ITER, DEMO, DONES

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1. Introduction

The global energy demand is strongly rising, on the one hand due to the continuing increase of the population, and on the other hand due to the growth of the Gross Domestic Product (GDP) of developing countries. Between 1995 and 2015 the world energy consumption has increased by 40%, and by 2035 another 40% growth is predicted [1]. Ensuring competitiveness and securing our energy supplies is of prime concern, but for a sustainable world it should go hand in hand with combatting climate change. Energy sources that are carbon-free and sustainable are therefore crucial for our future prosperity and well-being. Despite active programmes in many countries to stimulate energy production by renewable sources as wind, solar and biomass, the contribution of fossil fuels on a world scale has stayed almost constantly at the level of 85% of the total demand; in other words the fossil fuel usage is growing in pace with the world energy demand. The BP Energy Outlook [1] predicts that in 2035, fossil fuels still contribute 85% to the world energy use. Largely, this can be attributed to the fast rise in energy demand in several countries (particularly India and China). Another reason is the fact that wind and solar electricity generation is intermittent and therefore baseload electricity is needed as a backup. Despite enormous energy subsidies in Germany (as high as 24 billion Euro in 2016), the CO_2 emission due to electricity generation in Germany has increased. The explanation for this is that German nuclear power plants are rapidly phased out, such that there is no other choice than relying on fossil fuel plants as backup source for the intermittent sources [2].What is needed for sustainable energy generation is to have carbon-free baseload electricity sources. Fusion energy is a potential candidate [3]. Like wind and solar energy, fusion energy is carbon-free, it is safe, and the fuel is available to generate electricity for millions of years.

Of the various approaches to generate fusion electricity, magnetic confinement fusion [4] is the furthest advanced. At the high temperatures required for fusion on Earth (≈10-15 keV), all matter is fully ionised and in the plasma state. Properly configured magnetic fields can confine the charged particles that make up the plasma. The quest for fusion energy concentrates on magnetically confining plasma at sufficiently high temperatures and long enough duration for commercially viable fusion to occur. The fusion reaction that is easiest to exploit is between the hydrogen isotopes deuterium and tritium, leading to helium and neutrons as reaction products.

Deuterium is abundantly available in natural water. Tritium is rare in nature, due to its short decay time of 12.36 years, but it can be produced from lithium, a metal ubiquitous in the Earth's crust and in seawater. There is more than enough to fuel fusion reactors for tens of thousands of years without risk of shortages or monopoly of supply. The physics behind fusion does not include chain reactions, which is an inherent safety feature of fusion power plants: the plasma rapidly extinguishes itself in case of any malfunctioning. The radioactive by-products of fusion are short-lived activated wall materials; after about 100 years the remaining radiotoxicity will be comparable to that of the ashes of current coal power plants. The benefits of fusion power as a carbon-free, sustainable energy source are persuasive.

Magnetic confinement fusion has already demonstrated on a small scale that energy

can be produced with this concept [5]. Today, the largest magnetic confinement devices can routinely confine hydrogen and deuterium plasmas at temperatures high enough to generate fusion. Now its feasibility at a scale approaching a power plant needs to be proven. This is the purpose of ITER, the world's largest experimental fusion facility, sited in Cadarache, in the South of France as part of a worldwide collaboration involving China, Europe, India, Japan, Russia, South-Korea and the USA [6]. ITER will not generate electricity and not produce the tritium required to sustain self-sufficiently the operation of the plant, but will study plasmas in reactor-like conditions; electricity production to the grid is the object of the demonstration fusion power plant (DEMO), which follows ITER [7]. Both ITER and DEMO are based on the tokamak [8] concept in which a toroidally shaped plasma is confined by a combination of external superconducting magnetic field coils and an internal magnetic field generated by inducing a toroidal current in the plasma; the plasma is in fact the secondary winding of a transformer.

2. The European Roadmap to fusion energy

Achieving commercially viable fusion requires a substantial amount of coordinated resources deployed at European level over a long period of time. In order to structure the required effort, a roadmap to fusion energy with eight missions was developed in 2012 and agreed by the fusion stakeholders [9]. The eight missions are:

1. Demonstrate ***plasma regimes of operation*** that increase the success margin of ITER and satisfy the requirements of DEMO;
2. Demonstrate ***heat-exhaust systems*** capable of withstanding the large power loads in DEMO;
3. Develop and validate ***neutron resistant materials*** that can withstand the large 14 MeV neutron fluence without strongly degrading their physical properties;
4. Ensure ***tritium self-sufficiency*** through technological solutions for the breeding blanket;
5. ***Implementation of the intrinsic safety features of fusion*** into the design of DEMO following experiences gained with ITER;
6. Produce an ***integrated DEMO design*** supported by targeted R&D activities;
7. ***Competitive cost of electricity,*** i.e. ensure the economic potential of fusion by reducing the DEMO capital costs and developing long-term technologies;
8. Bring the ***stellarator*** line to maturity to be able to judge its feasibility as long-term backup solution.

The roadmap forms the basis for the European fusion programme. It provides a clear and structured way forward to a demonstration of commercial electricity production from fusion on a credible roadmap and realistic timescale.

The main elements of the Fusion Roadmap are:

1. ITER [6] aimed at showing that fusion is feasible. ITER should reach a ratio of thermal fusion power over input power $Q = P_{fus}/P_{in}$ of 10. Since the alpha particles generated by the fusion reaction carry 20% of the fusion energy, while the neutrons carry 80% of the energy, conditions are reached in ITER in which the alpha particles have enough energy to dominantly heat the plasma. ITER will not be equipped with the balance of plant for

generating electricity, but it will test the technologies to produce tritium from lithium in special Test Blanket Modules [10].

2. DEMO [7], the demonstration reactor that should produce for the first time electricity from the fusion process and operate with a closed tritium fuel-cycle (i.e., DEMO must produce its own fuel). The present thought is that the European DEMO reactor will be an extrapolation from ITER, using, as much as possible, technologies that have been already tested. This should ease the nuclear licensing process. The target electrical output of DEMO will be in the range 300 – 500 MW_E.
3. A materials test facility to test and validate materials for DEMO under a fusion relevant neutron load and spectrum. The International Fusion Materials Irradiation Facility (IFMIF) [11] is an accelerator-based neutron source. The materials test facility should operate in parallel to ITER such that the new materials are validated before DEMO is going to be built. Therefore, a lighter version, IFMIF-DONES (DEMO Oriented Neutron Source) [12], is presently being proposed by Europe as it can be constructed in a shorter time.

In the remainder of this paper, a brief overview is given of the challenges in the eight missions.

2.1 Developing plasma regimes of operation for ITER and DEMO (Mission 1)

The aim of this mission is to demonstrate and qualify operational plasma regimes in preparation for ITER and DEMO. This implies reaching high fusion performance in a reliable and controllable way. Hence, various types of magneto-hydrodynamic plasma instabilities need to be stabilised. While aiming towards high performance, the power deposition on the plasma wall and the divertor should stay at tolerable levels. Hence plasma regimes need to be developed in which the directed power flux from the fusion plasma onto narrow stripes of the wall is reduced. This can be done by converting particle energy into electromagnetic radiation at the plasma edge, thus uniformly distributing the power over the surface. To do all this simultaneously, involves developing integrated (model-based) controllers that are able to control the profiles of multiple plasma parameters at the same time.

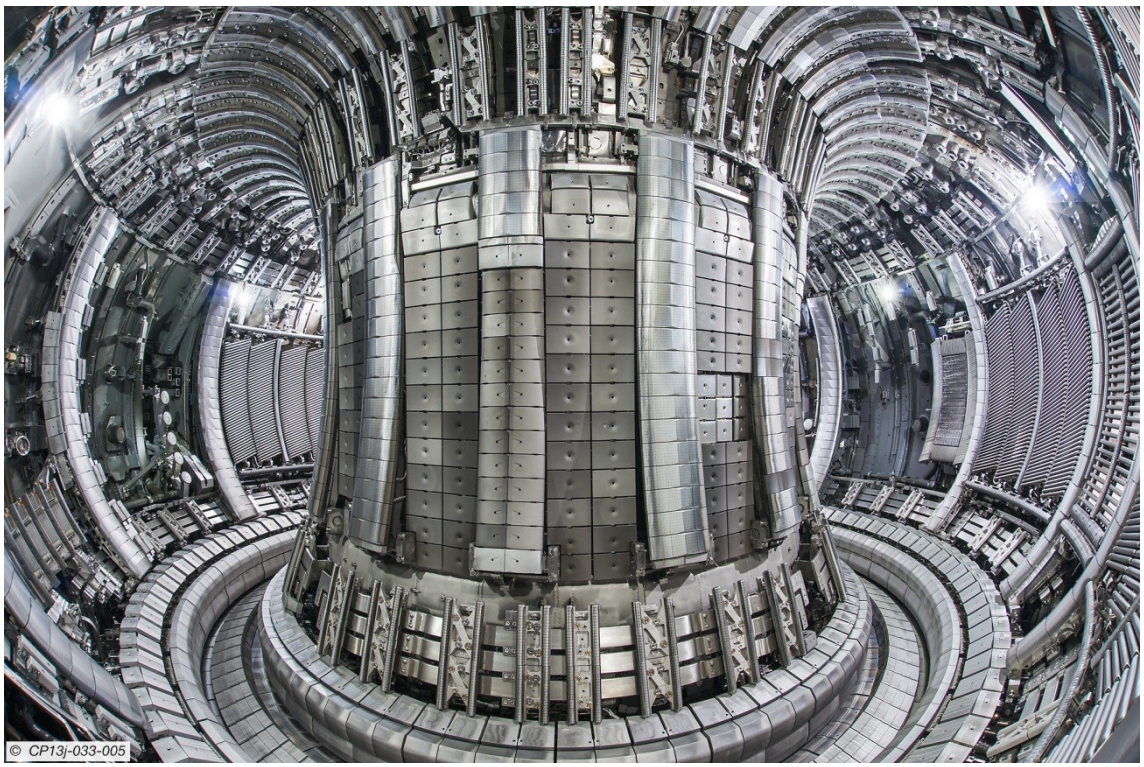

Figure 1: Inside of the JET tokamak. Most of the wall consists of Beryllium deposited on an Inconel substrate, the majority of the divertor structure is made of Tungsten deposited on a substrate of carbon-fibre composites. The target plates bearing the highest loads are made of solid tungsten.

Much emphasis is on utilizing metallic plasma facing components. This might seem counterintuitive as it is much easier to reach a high performance in a fusion device having carbon walls. But carbon has several drawbacks: firstly its physical and mechanical properties degrade substantially under neutron irradiation, making the design of robust high heat flux components very difficult. Secondly, carbon forms dust and it also easily binds with the hydrogen (or tritium) from the fusion reaction. The result is that in a device like ITER – if it would be using carbon walls – it would take only 50-100 discharges before all tritium that is allowed to be used in the device is lying on the bottom of the fusion device bound into carbon dust [13]. After the JET tokamak, still the largest operating tokamak in the world, was equipped with a metal wall (see Fig. 1), the tritium retention went down by a factor of 20 [14]. However, it became more difficult to reach high performance as special operational procedures are needed to keep the heavy metal constitutions (tungsten in case of JET) out of the plasma. This involves central heating, seeding with noble gasses, flushing with Edge Localised Modes, etc. Apart from JET, several medium-sized tokamaks (ASDEX-Upgrade in Germany, TCV in Switzerland and MAST-U in the UK) are employed to develop the required operational scenarios. In general the smaller devices are more flexible and can test new ideas more quickly. Those ideas that work are then tested on JET [15] and the results are extrapolated towards ITER. Also ASDEX-Upgrade is equipped with a full metal wall (largely

tungsten, and more recently also some areas with Eurofer – the structural material foreseen for DEMO).

2.2 Heat exhaust systems (Mission 2)

The typical steady-state heat loads expected on the target plates of ITER are of the order of 10 MW/m^2 under detached plasma conditions. During so-called Edge Localised Modes, the heat load can reach levels of a few GW/m^2 during short 0.5-1 ms pulses. Materials for the plasma facing components (and especially for the divertor) need to be able to withstand such heat loads for a sufficiently long time. Mission 2 is devoted to finding solutions for the heat exhaust, and is largely concentrated on three pillars. Firstly, existing plasma facing components are being tested and improved and control schemes are being developed to routinely and robustly detach the hot plasma from the divertor plates. Secondly, alternative magnetic geometries are being studied for the divertor, in which the footprint of the plasma is spread over a larger surface. Thirdly, new materials are being developed that are able to withstand higher heat loads.

Divertor detachment and also alternative divertor geometries are being tested in the same devices as used for mission 1. Divertor detachment is characterised by a strong reduction in the total particle flux to the target plates [16]. The electron temperatures in front of the target plates are reduced to values below ~5 eV such that recycled neutral particles from the target plates undergo several charge-exchange collisions with plasma ions before they are ionized. As a result the plasma is no longer freely streaming towards the target plates; instead the flow becomes more diffusive. The present focus of research is to achieve divertor detachment in a controlled way. In the snowflake divertor geometry [17], that is extensively exploited in the TCV tokamak, the heat load from the plasma has four footprints, thus lowering the maximum power load. In the Super-X geometry [18], that will be tested on the MAST-Upgrade spherical tokamak, the outer divertor plates are at the largest plasma radius possible inside the toroidal field coils, thus increasing the plasma-wetted area. ASDEX-Upgrade will be upgraded with a second divertor at the top of the machine such that it is possible to study double-null divertor plasmas. Amongst the new materials that are being investigated for the divertor are liquid metal targets [19]. These have the advantage that the divertor is in principle self-healing in case material is evaporated, but disadvantages are the possibility of droplets of liquid target material to enter the plasma and also the magnetohydrodynamic forces that can influence the target material and deteriorate the desired flow patterns.

The improvement of existing plasma facing components and the development of new ones are being studied in dedicated test devices. These include the superconducting Magnum-PSI linear plasma simulator [20] in the Netherlands, which can mimic the heat loads of 10 MW/m^2 under steady state conditions; JUDITH [21] in Germany, which can test materials under an intense electron beam; and WEST, a superconducting tokamak [22] in France to test actively-cooled tungsten under similar power loads as in ITER.

2.3 Neutron resistant materials (Mission 3)

Every atom in the plasma facing material of ITER undergoes on average typically 1-2

displacements (dpa, displacements per atom) during the full operational life time. This is due to the interaction of the material structures immediately surrounding the plasma with the neutrons generated by the fusion processes in the plasma core. The materials used in ITER can well cope with these loads. However, in DEMO the typical neutron fluence will give rise to loads of ~50 dpa (mainly due to the much longer plasma pulse duration). This implies that new materials need to be developed that can withstand these high neutron loads. For testing and validating new structural as well as functional materials a dedicated neutron source with a fusion reactor relevant neutron spectrum should be available. The R&D programme on materials, that is embedded in the European Fusion Roadmap, reflects the recommendations of the assessment of EU R&D Programme on DEMO Structural and HHF Materials, involving international experts conducted in 2012 [23].

Fusion materials research strongly concentrates on those elements that are thought to be most viable for a fusion reactor: Eurofer (a special reduced-activation ferritic martensitic (RAFM) steel alloy) for the structural components, tungsten for the plasma facing components and CuCrZr as material for the cooling pipes of the components aimed at removing most of the power deposited primary in the divertor structures. An issue is that RAFM steels and Cu-alloys suffer from embrittlement at low temperatures, while their mechanical strength deteriorates at too high a temperature. Hence, the temperature window within which these materials can be used is rather limited and sets stringent constraints on the operational scenarios. Therefore, a large part of the advanced steels programme is dedicated to widening the operating temperature window of Eurofer-type steels [24]. Studies on Eurofer97-2 plates have shown that the upper temperature limit (determined by tensile and creep strength) might be increased from 550°C to 650°C by specific non-standard heat-treatments. A draw-back of the hardening process is the shift of the ductile-brittle transition temperature from about -120°C to -20°C (measured by Charpy tests). However, this shift could still be tolerable for the DEMO breeding blanket concepts being considered.

An important issue for divertor materials is the loss of strength of CuCrZr above 300°C under irradiation. The high heat flux materials program follows several reinforcement strategies to extend ITER-type divertor concepts towards the more demanding DEMO operating conditions [25]. In this context, a very promising fabrication route for fibre-reinforced CuCrZr pipes has been established. In cooperation with textile industries, multilayer tungsten wire frameworks can now be braided, which will be embedded in CuCrZr pipes by melt infiltration.

For the code qualification of the current baseline materials (Eurofer, CuCrZr and tungsten), various irradiation campaigns in fission material test reactors need to be executed over the next decade. Campaigns have been launched in 2016 and 2017, where data for component design (up to end of component life dose) and materials development (down-selecting options, low/medium fluence) as well as basic material behaviour and validation (very low fluence) are addressed. Although testing in fission reactors yields valuable insight, the ultimate testing should be done with a source with a fusion-relevant neutron spectrum. Such a source is the envisaged IFMIF, the International Fusion Materials Irradiation Facility [26]. This is a neutron source based on two deuterium ion accelerators directed towards a liquid lithium target. The Li (d,xn) nuclear reactions will

yield a high-energy neutron spectrum that is reminiscent to that of a fusion reactor. The present approach is to first develop a smaller version of IFMIF, featuring only one of the two accelerators. In Europe this lighter version is known as DEMO Oriented NEutron Source (DONES) [27]. The design of IFMIF-DONES is presently ongoing and the construction should start early in the next decade.

2.4 Tritium self-sufficiency (Mission 4)

Tritium, one of the fuel constituents of the fusion reactor has a short decay time of only 12.32 years. It therefore doesn't occur readily in nature and it must be produced (bred) artificially. Tritium can be produced in CANDU type fission reactors, but the available quantities are low [28]. Therefore, ideally the tritium should be produced in the fusion reactor itself by the neutrons that escape from the fusion reaction and that also generate the heat that must be extracted by properly design cooling systems and converted in electricity as in conventional fission plants. The fusion plasma is surrounded by a ^{6}Li-containing blanket structure. The neutron splits the lithium into tritium and helium. The tritium (^{3}H) is produced by the ^{6}Li(n,^{3}H)^{4}He reaction, and is taken out of the blanket and fed into the reactor for maintaining the D-T reaction. The helium is a non-radioactive, non-toxic and valuable exhaust product. For an economic fusion reactor the tritium should be replenished entirely within the reactor i.e. the breeding ratio should be at least 1; ideally it should be 1.05 or even larger to compensate for some tritium losses and also to be able to produce a start-up quantity of tritium for the next generation of reactors.

Tritium production will be tested in specific test blanket modules at ITER. Several concepts are being tested by the various Parties involved in the ITER project to study which is the most viable and economic concept. For the European DEMO four breeding blanket design concepts with different level of design/technology readiness are considered, based on water, helium and LiPb as coolants and a solid or LiPb as tritium breeder/neutron multiplier [29].

2.5 Safety and environment (Mission 5)

ITER and DEMO are nuclear devices and therefore safety is an issue in all sub-projects from the first day of conceptual design onwards. Even though a fusion reactor is inherently safe, it is a nuclear device and everything possible should be done to protect the workers and the people living in the environment from any risk. To obtain the license to operate it must be demonstrated to the regulator that all aspects of the reactor are safe and that there are no hidden pitfalls [30].

2.6 Integrated DEMO design (Mission 6)

To demonstrate fusion electricity to the grid as desired around the middle of the century implies that the DEMO [7] engineering design should be started before ITER reaches high performance operation. This requires a thorough analysis which elements of DEMO can be developed and designed irrespective of ITER, which elements can be designed and allow for a range of ITER outcomes, and which elements can be only designed after ITER has provided some adequate results. By using such an analysis it is possible to already start designing DEMO, while leaving enough room to incorporate new

knowledge that comes from ITER. In the present roadmap the conceptual design of DEMO should be finalised in the second half of the next decade. The Engineering Design of DEMO should then start a few years ITER has come into operation. The Engineering Design is planned to be finalised ≈5 years after ITER reaches its high performance target (Q=10) such that all knowledge from ITER can be incorporated into DEMO.

The present DEMO pre-conceptual design activity is set up in a holistic way and key features of the adopted design and R&D approach include: (i) a strong philosophy of 'systems thinking' and emphasis on developing and evaluating system designs in the context of the wider integrated plant design; (ii) targeted technology R&D and system design studies that are driven by the requirements of the DEMO plant concept and respond to critical design feasibility and integration risks; (iii) where possible, modest extrapolations from the ITER physics and technology basis to minimize development risks; (iv) evaluation of multiple design options and parallel investigations for systems and/or technologies with high technical risk or novelty (e.g., the choice of breeding blanket technology and coolants, power exhaust solution and configuration, power conversion systems, etc.). Postponing integration, assuming that it restricts innovation and inhibits an attractive DEMO plant, might lead to developing design solutions that cannot be integrated in practice. Lessons learned from ITER (good and bad) are incorporated. Work is primarily focused on the design integration of a pulsed baseline DEMO plant concept that is largely extrapolated from ITER (single-null divertor, conventional H-mode, H=1.1 (radiation corrected)) (see Table 1) [31].

Table 1. Main parameters of the DEMO baseline design

Main parameters of the DEMO baseline design	
Major radius, R	8.9 m
Aspect ratio, A	3.1
Elongation, k_{95}	1.65
Magnetic field at plasma center, B_T	4.9 T
Normalised pressure, β_N	2.6
Confinement factor, H	1.1
Tritium Breeding Ratio, TBR	>1.1

Three of the four main DEMO design issues are covered by mission 2, 3 and 4 (heat exhaust, materials and tritium self-sufficiency). A fourth important design issue is Remote Maintenance as on the one hand there are significant differences with the ITER Remote Maintenance approach as the idea is to handle complete blanket sectors via top ports, instead of individual modules via equatorial ports as done in ITER. The Remote Handling schemes affect the plant design and layout and should therefore be incorporated in the overall design from the start. Of course work in high-radiation areas (2kGy/hr) must be minimised and, if possible, even avoided. To have enough space for Remote Handling of the blanket sectors, the present DEMO baseline design features only 16 toroidal field coils.

Although most work is focussed on the DEMO baseline design (see Fig. 2), also alternative DEMO designs are studied (featuring respectively double-null, snowflake, and super-X divertor; based on high-temperature superconducting coils [32]; and finally a flexi-DEMO that can start in short pulse mode (< 1 hour) and after some time it can be upgraded to steady-state operation [33].

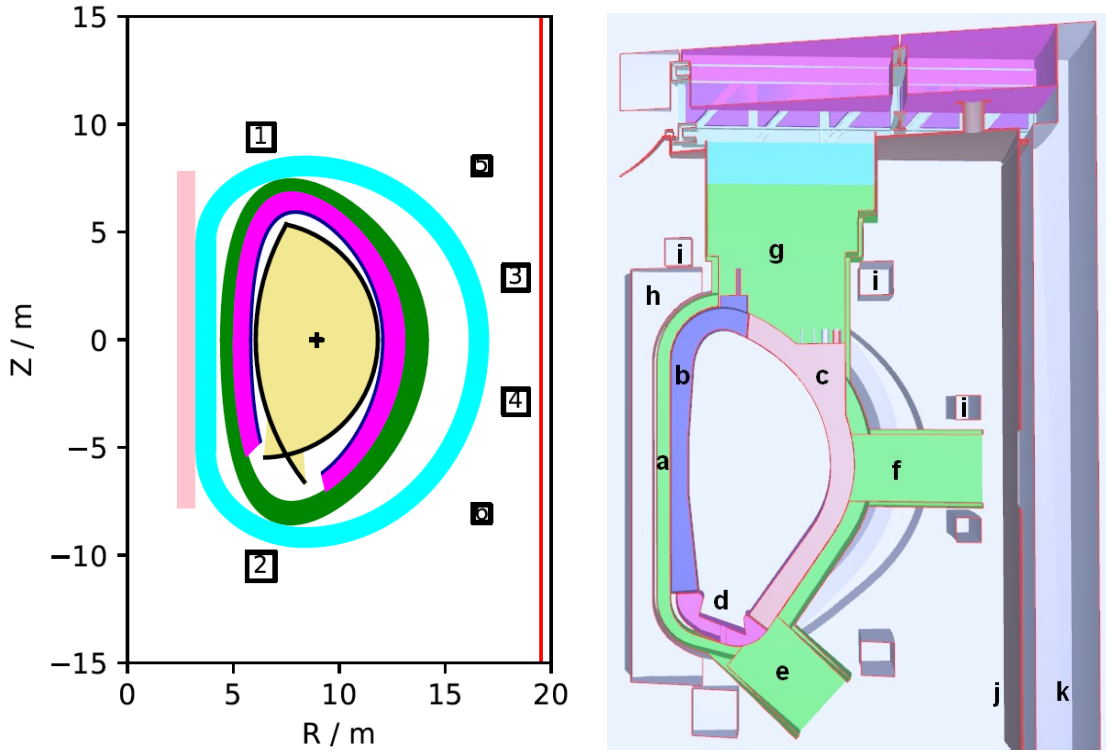

Figure 2: (left) Elevation view of the tokamak as generated by the PROCESS code; (right) Tokamak radial-build: a) vacuum-vessel; b) breeding blanket (inboard); c) breeding blanket (outboard); d) divertor; e) lower port; f) equatorial port; g) upper port; h) toroidal field coils; i) poloidal field coils; j) cryostat; k) bioshield

Lessons learnt from comparable projects, have highlighted the importance of involving industry during the early phases of the design development – especially for complex nuclear infrastructures. For instance, Gen IV programmes have leveraged impressive industry support, and engaged with industry as a partner from the outset. Work conducted in current industry tasks to date, and interactions with Gen IV projects, the Fusion Industry Innovation Forum (FIIF) and the DEMO Stakeholder Group (SHG), have highlighted a number of areas where harnessing of industry competencies can have significant impact during the conceptual phases in areas such as; (i) support in establishing systems and project management processes to deliver the project; (ii) translation of experience in obtaining construction and operational licenses for nuclear infrastructures, as well as pre-qualification of components and systems; (iii) assessments of design and technology maturity and prospects for licensing; (iv) experience in industrial plant design and integration; (v) development of concepts for major components and systems that incorporate manufacturability considerations; (vi) cost assessments.

Additionally, engaging industry in the early DEMO design activities, allows the possibility to build a familiarity within industry of the particular challenges associated with DEMO. Furthermore, it provides some continuity for industrial suppliers in the interim period following completion of ITER procurements – but prior to the launch of major DEMO procurements – to maintain some interest and engagement in fusion. It also provides some

opportunity for industry to steer the design direction, and encourages industry to participate not only as a supplier, but also as an important stakeholder within the project.

2.7 Cost of electricity (Mission 7)

It is important to have continuously an open eye for innovations, as they could lead to a higher performance of the fusion reactor or to reduced costs. A good example is the effort of the EUROfusion consortium in the development of high-temperature superconductors. They could both allow for stronger magnetic field and hence a higher performance or a somewhat smaller reactor and lead to decreased costs for the cryogenic cooling of the magnets. Other new developments that will have certainly an effect on the design and construction of a fusion reactor will be novel approaches such as additive manufacturing, virtual engineering, etc. These will be closely followed, and wherever possible be utilised. A recent and very nice achievement is the development of a Nb_3Sn cable-in-conduit superconductor that can operate at 82 kA in a magnetic field of 13T and with a current sharing temperature $T_{CS} > 6.5$ K [34].

It should be noted though that the issues addressed above will affect the capital investment. However, the cost of electricity will be primarily affected by plant availability and this is strongly dependent on design and technology readiness, design simplifications, etc.. This is largely addressed in Mission 6.

2.8 Stellarator (Mission 8)

ITER and DEMO are magnetic fusion devices based on the tokamak concept. A tokamak is by nature a pulsed device, as the poloidal magnetic field is generated by a transformer. Therefore, the tokamak is prone to current-driven plasma instabilities, albeit that they can be actively stabilised or mitigated by various control tools. The main difference between a stellarator and a tokamak is that, in a stellarator, the confining magnetic field is completely generated by external magnetic fields. This makes it possible to operate the stellarator continuously and, because there is no net plasma current, the device doesn't feature many of the instabilities that can occur in a tokamak. The design of a stellarator is, however, much more complicated than that of a tokamak. In terms of its development track towards high performance, the stellarator is some decades behind the tokamak. The Wendelstein 7-X stellarator (see Fig. 3) [35], that has recently come into operation in Greifswald in Germany, is the world's largest stellarator. Its design was only possible when sufficient computational power became available. Research at Wendelstein 7-X should demonstrate whether the stellarator has merits to be used as concept for the future fusion power plants.

The first campaign of Wendelstein 7-X was very successful and has already provided information on the key physics issues for stellarators, such as plasma confinement [36]. The coming campaigns will look to more fully address the key physics issues and bring the concept towards maturity.

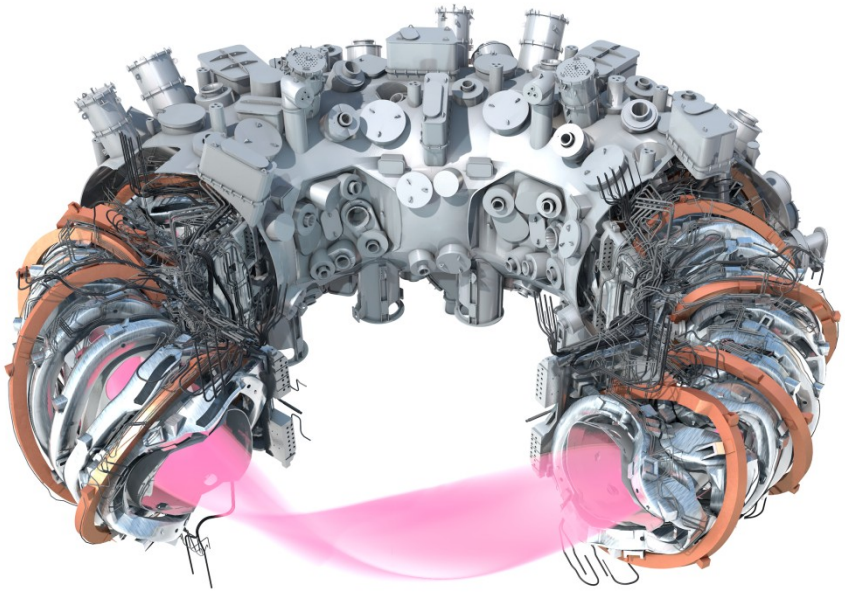

Figure 3: Cutaway view of the Wendelstein 7-X stellarator. From bottom to top one can see the different elements from plasma (pink), vacuum vessel, superconducting coils (grey and copper tone) to the cryostat (grey) with its many ports for diagnostics and other equipment. Due to the special magnetic configuration the plasma has a non-circular poloidal cross-section, rotating and varying along the toroidal circumference with a five-fold symmetry. The diameter of the plasma is about 11 m from centre left to centre right. Copyright: Max-Planck Institut für Plasma Physik.

3. Conclusion

This paper has given a brief overview of the main elements, missions and challenges of the European fusion roadmap which implements a credible and achievable R&D strategy towards demonstrating electricity production from fusion. If the implementation of the roadmap is adequately resourced and receives full stakeholder support, the European power sector should be in a position in the second half of the century to acquire a leading position in the introduction of commercial fusion power plants as part of a future energy mix.

Acknowledgments

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