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1 Fusion: current state of the sector and anticipated developments

Fusion has many potential attractions, including

- essentially unlimited, widely available, cheap fuel
- no production of CO_2 or atmospheric pollutants,
- relatively short-lived waste, and
- intrinsic safety,

and it demonstrably works: fusion powers the sun and the Joint European Torus (JET) has produced 16 MW of fusion power. Big challenges must, however, be faced to make 'magnetic confinement' fusion work reliably on the scale of a power plant, including

- sustaining a large volume (~2000 m^3) of hot (over 100 M^0C) plasma of deuterium and tritium under quasi-stable conditions for long periods at pressures that allow a large net energy gain from fusion;
- driving a continuous electric current of many mega-Amps through the plasma;
- qualifying materials with which to construct walls that will be capable of surviving bombardment of a few MW/m2 by 14 MeV neutrons for a few years, and tolerating large heat loads
- ensuring the high reliability of many complex components.

The integrated European/Euratom fusion development programme is addressing these challenges, and fusion power plant conceptual studies[1] suggest that if, they are met, fusion could be economically competitive with other low carbon sources of electricity. Agreement to construct ITER, which should demonstrate the technical and scientific feasibility of mastering fusion in 'burning' plasmas on the scale of a power plant, is a major step forward for fusion. The Broader Approach agreement between the EU and Japan, which includes final design work and prototyping for IFMIF, a device that will subject small samples of materials to the neutron fluxes and fluences that will be experienced in fusion power plants, is another important step. The goal beyond ITER and IFMIF is to demonstrate the production of electricity in a demonstrator fusion power plant (DEMO for short), after which it is hoped that fusion will be available for deployment on a large scale. Nevertheless, there are still many issues and challenges to be resolved, e.g. in relation to reliability.

The actors in Europe are Euratom and the 'Euratom-National' Fusion Associations whose work, in national institutions, is funded jointly by Euratom (~25%) and national budgets (~75%). The Associations currently carry out the actual R&D.

Market structures are not yet relevant to fusion, but the price of carbon, and increased emphasis on low environmental impact energy sources generally, will be highly relevant given that fusion is one of very few candidates for the large-scale carbon-free production of base-load power.

2 Technology penetration targets and the expected impact on energy policy goals

The long term goal of fusion power development is reliable, economically acceptable production of electricity (and possibly also hydrogen) with minimum environmental impact. The reference programme is focussed on building a DEMO that would be a major step towards, and in its second phase come close to, achieving all these goals simultaneously, with its first demonstration of electricity production in 30-35 years, assuming no major adverse surprises or delays. Increased investments are proposed which would reduce the uncertainties and should ensure first demonstration in 30 years (and not 35 years or even longer).

There is a proposal to study a 'new paradigm' in which electricity production would be demonstrated much sooner (in ~ 25 years, or in the most aggressive - 'Apollo Project' approach – case, with an immediate start of the design work and necessary R&D, even conceivably in 20 years) by a relatively low performance 'Early DEMO' or 'EDEMO'. It would not be required to produce electricity at a stipulated cost, and would use already known low-activation materials such as Eurofer that are expected to survive in fusion power plant conditions. With this approach the timing link between DEMO, ITER and IFMIF would be relaxed.

With the 'new paradigm' approach that is suggested as an option for further study, a Demonstrator fusion power plant could conceivably produce electricity by 2030, but

[1] These studies take into account the full lifetime costs of fusion power plants, including decommissioning.

fusion will not be a significant player in the energy market at that time. It is premature to speculate about the situation in 2050, but the current European fusion development plan (which the proposed 'new paradigm' could speed up very significantly) foresees fusion starting to be rolled out on a large-scale around the middle of the century. There do not appear to be any ‘resource/feedstock availability’ issues that would prevent fusion being deployed at least as rapidly as fission was deployed, given the wish and the funding to do so.

- Fusion has outstanding environmental characteristics (no CO_2 or other atmospheric pollutants).
- Together with renewable energy sources, fusion is unrivalled for security of supply because the fuels (water and lithium) are inexpensive and very widely available.
- Fusion development represents a potentially outstanding opportunity for European industry.

Given that the fuels used in fusion (water and lithium) are essentially inexhaustible and will contribute a negligible amount to the cost of fusion power, efficiency is not an issue for fusion as far as reducing CO_2 or depletion of resources are concerned (although by taking over part of the role currently played by hydro-carbons, fusion would help free them up for uses other than energy production for which there are few alternatives). The efficiency with which a fusion power plant will operate, in terms of thermal efficiency and availability, will of course directly influence the cost of fusion generated power and hence its competitiveness.

3 Interactions with other competing or synergetic technologies and community policies and initiatives

There are important interactions, both at strategic level and in specific technical areas. Strategically, there is obviously an interaction with climate change strategy. Fusion, if as successful as hoped, will make a major contribution to the security of energy supplies, and will also contribute to reconciling lowering emissions with continued economic development.

Like other new energy sources, fusion has to find its due place in the overall energy mix, capitalising - in the most cost-effective and socially acceptable way - on its specific attributes (abundant fuel, inherent safety features, no carbon dioxide emissions, no long-lived waste, suitability for base-load electricity supply, costs). Socio-economic studies to explore these issues are under way within the fusion programme.

It is important to benefit from synergies and the exchange of know-how with other technology programmes, ranging from the application of fusion power for hydrogen production to materials development programmes. Scientific and technical synergies exist with several fields:

- Although fusion and fission power are very different in many respects, there are a number of technical areas where there are synergies and substantial opportunities to mutually benefit from collaborative programmes, with foci that include: the design and application of high-temperature radiation-resistant alloys: life-time extension studies of existing plants; helium and liquid metal cooling systems; codes and standards.

- Synergies also exist with work developing high temperature materials for advanced fossil-fuel power plants, and work on high heat-flux materials for a variety of applications.
- Fusion research requires high performance computing; developments are being prepared in contact with other communities, taking into account the projects of new European infrastructures.
- There are several synergies with a number of other scientific fields, e.g. turbulence studies, diagnostics techniques (e.g. spectroscopy), and atomic physics (plasma edge phenomena).

There are a number of national initiatives to coordinate energy-related work on materials. The EU has introduced some programmes with this goal (e.g. PERFECT, which brings together work in fission and fusion, and EXTREMAT, which is focussed on high-heat flux materials), and there is scope for further initiatives on a European scale.

A very useful collaboration has been set-up since 2000 with other European institutions in the frame of fora (collaboration between CERN, EFDA-JET, EMBL, ESA, ESO, ESRF and ILL). This allowed a significant increase of exchange with other areas of research, and also contributed to improving the knowledge of fusion among other scientific communities.

Fusion is also an arena for increased scientific and technological collaboration with other regions and ITER is providing experience of collaboration that can be built on in other fields.

There are many synergies between fusion development work and technologies and R&D in other fields. Synergetic technologies include HTR, advanced LWR and GEN IV fission reactors, where publicly funded R&D is also being carried out, and advanced fossil-fuel plants. The fusion and fission communities can learn together and exchange know-how. In the long run, fusion will have to compete to find a place in the energy market, and complement other producers to fill a niche. As a large-scale carbon-free source of base-load electricity, and potentially also of hydrogen, its only really major competitors may be coal and gas (provided that carbon capture and sequestration can be achieved economically and sustainably) and nuclear fission. The essentially unlimited availability of very widely available fuel will be a factor in fusion's favour. The actual role played by fusion will depend on the market composition and other factors (economy, waste, emissions, political boundary conditions) at the time when fusion is able to produce large scale power (electricity, or power for e.g. hydrogen production or district heating) economically with high availability.

4 The role of innovation

There is a need to foster greater industrial involvement in the European fusion programme, but this faces barriers including the current rules related to intellectual property and EC procurement rules, which require industry to take considerable risks. The establishment of the European Joint Undertaking for ITER and the Development of Fusion Energy provides an opportunity to adopt an improved industrial policy, which should be grasped as a matter of urgency.

Fusion development work is currently moving from a laboratory (R phase) to an industrial scale (R&D phase), and correspondingly the role of industry should be strongly increasing. An industrial systems engineering approach starting early in the design phase will be crucial for the success of DEMO. Industrial involvement should be structured so that after DEMO, European industry can take the lead in the commercialisation of fusion power and become competitive in bids for future fusion power plants. In the engineering and construction phases, experts will be needed from engineering companies, component suppliers and SMEs, which can play an important role in collaboration with the EU Fusion Associations, and as subcontractors for other industries.

Industry should be involved in all phases of DEMO development, starting with the conceptual design, then in detailed design and construction, and finally in support for operation. Industry would bring its broad experience and competence from power plant engineering and construction, in particular in the nuclear field. Experts from the EU Fusion Associations will work with industry experts as a joint team with clearly defined roles and responsibilities. The leading role in plasma physics and related DEMO technologies will be taken by fusion experts, and consideration of fusion specific issues (such as the transition from pulsed to steady state plasma operation and the choice of specific material characteristics for in-vessel components) will remain largely in their hands. Industry should be charged with systems and plant engineering, component design and fabrication, remote handling procedures and equipment, balance of plant engineering and licensing support. Moving towards construction, the responsibility of industry should increase and project management should increasingly include industrial experts with experience in plant construction management.

The industrial role in the DEMO team should be contracted to a grouping of engineering companies with long experience in large nuclear projects. The major load on industry will occur during detailed design and construction. Besides engineering issues related to fabrication, codes and standards, remote handling aspects and licensing, prototyping will be essential in the detailed design phase. Here also SMEs should be involved in appropriate roles in collaboration with the EU Fusion Associations and large industries.

It would be advantageous if industrial companies involved in DEMO had also been involved in ITER construction through engineering services and procurements, and would thus be optimally positioned to use experience and expertise developed at ITER in DEMO development. It is essential that European industry gets a full picture of the systems and components of the ITER plant, and not only supplies key components but also gains know-how in other areas through adequate exchanges with the other ITER parties. According to the proposed ‘new paradigm’, conceptual design of DEMO will start before most of the ITER systems and components have been delivered and operated, and the DEMO project management will have to ensure continuous transfer and application of know-how to an appropriately constituted DEMO team as ITER progresses.

Industry should take the driving seat in the further stages of fusion power plant development after DEMO, when the production of electricity by fusion power on an industrial scale has been demonstrated. At that time industry, including the utilities might be ready to invest at least at a level comparable to industrial contributions to present European fission R&D projects (normally 50%). It should be noted that for many years industry has been investing a lot in fusion development knowledge through the training of engineers, participation in workshops and conferences with presentation of papers, the organisation of exhibitions and the development of its in-house know how on fusion matters. Still there could be a potential problem due to the lack of skilled human resources to carry out such an ambitious programme. The European Fusion Training Scheme, which started in 2006, and the recent decision of the CCE-FU to expand this scheme, are welcome steps in this direction, although further strengthening would be needed to underwrite either the reinforced reference programme or the new paradigm.

The European Joint Undertaking for ITER and the Development of Fusion Energy must adopt industrial policies (including IPR and procurement rules, and tender evaluation criteria for ITER procurements) that will both ensure competition and protect European industry's background know-how, and encourage innovative developments. This would be a major element in ensuring a continuous transfer of know-how from ITER to DEMO at least for the European contribution. Furthermore industry must see continuity in the development towards a fusion power plant by minimising the gap between ITER and DEMO construction. Mock-up and prototype fabrication could be important elements of this approach.

The treatment of IPR in contracts with industry should be designed to enable industry to improve its competitiveness, which is its main interest. To this end, IPR policy should be based on the following principles:

- know-how and competence made available by industry and gained prior to contracting should remain the sole property of the industry;
- industry should be entitled to use the know-how gained from the contracts, on terms to be agreed upon with the contracting authority, for its own and for commercial purposes;
- the competitiveness of European industry in fusion related technologies should be supported by rules defined by the contracting authority;
- appropriate rules for fusion-specific know-how transfer from EU Fusion Associations to industry should be established and implemented in projects on the path to fusion power plants.

Some of the clauses (e.g. on intellectual property rights, liability, damages for termination, liquidated damages) in contracts currently proposed by Euratom for the supply of engineering support and components are considered unacceptable by a number of companies. As a consequence, a number of calls for tenders over the past few years have resulted either in a low number of offers or in very expensive offers from industry. This issue was recently studied by a group set up by the CCE-FU which has made a number of recommendations, some of which should apply to the European Joint Undertaking for ITER and the Development of Fusion Energy.

In order to promote innovation, and if necessary resolve construction problems, it could be useful to include incentives in the contracts for high technology components and to facilitate collaboration with research institutes.

5 Platform recommendations for Actions to be considered in the SET-Plan

Two approaches are proposed which can be summarized and compared as follows:

Technical content

In both cases:

- Reinforce the present programme, with a view to ensuring success and minimising risk (increased effort in technology R&D, and investments in plasma physics devices that will contribute to the accompanying programme during ITER construction).
- Consider a European satellite tokamak operating in parallel to ITER.

Option 1 (Strengthened reference Programme)

- DEMO keeps its ambitious set of objectives: high plasma performance and power densities resulting from full steady state requirements; structural materials with reduced activation tested on IFMIF.
- Detailed DEMO engineering design starts when ITER operation starts, its licensing starts when the first phase of IFMIF experimentation is completed, demonstration of electricity production is achieved in some 30 years, assuming all goes according to plan.
- Serious consideration should be given to a CTF.

Option 2 (New Paradigm):

- Demonstrate production of electricity as soon as reasonably achievable but on an EDEMO with reduced objectives: moderate plasma performance and power densities; structural materials presently available; ~ 5-10 hour pulse operation during phase 1 of operation.
- EDEMO Conceptual Design starts as early as possible without a negative impact on ITER, and could be followed by construction at the earliest possible date; while results from ITER and IFMIF would not be available in time to influence the design, they would be available in time to support the request for a licence to operate EDEMO. This aggressive approach would obviously be more risky than the reference scenario, but in the extreme case (with an Apollo Project approach, and an immediate start) could demonstrate electricity production as soon as in 20 years.

  Intermediate, lower risk scenarios could obviously also be considered, and the DEMO design group should evaluate a range of options in risk/benefit terms in the light of developing fusion knowledge and experience from building ITER. For example, construction of DEMO could start when Q = (fusion energy generated)/(energy fed in to heat the plasma) = 10 has been achieved by ITER, in which case electricity production would be demonstrated as soon as in 25 years, assuming rapid success of ITER.
- Consider constructing a CTF, which would not be available in time to make input to the initial design of EDEMO, but would play a very important role in preparing subsequent power plants.

Costs and cost phasing

The costs below should be considered in the context of

1) The enormous energy challenge that the world faces, and the huge size of the energy and electricity markets (which are ~ €3 trillion pa and €1 trillion pa respectively).

2) The commitment that Europe has already made to fusion.

It is important to note that, to the accuracy with which they can be assessed, the costs of the Reference Programme and the New Paradigm are the same (and depend in both cases on whether or not a satellite tokamak and/or CTF is built). The difference is that part of the expenditure that will be needed sooner or later to develop fusion power comes much earlier in the new paradigm, as does the demonstration of electricity production. The expenditure that the new paradigm would bring forward will be largely in European industry.

The cost of the steps that we advocate taking in the immediate future are:

- Strengthening work on
  - fusion technology (including work in preparation for ITER): an additional sum of €100M pa (similar to the funding of European R&D for ITER); as ITER work decreases, this work would increasingly focus on DEMO R&D and prototyping under the authority of the proposed DEMO design group, and
  - fusion plasma physics: an additional sum of €60M pa for additional (perhaps 4-5 years) of JET operation beyond 2010, and ~ €30M pa for the rest of the physics programme (similar to the magnitude of recent average expenditure on JET enhancements, including manpower).

  These sums include increased provision for recruitment and training which should form an integrated part of the programme.
- DEMO design team: a sum rising to ~ €15 M per year for a team building up to ~ 100 professionals as the time to construct DEMO approaches, with significant involvement of industry.

The way ahead

- The experts propose that Europe should set up a DEMO design group, with substantial industrial involvement (technical and managerial), as soon as resources (manpower and money) allow this to be done without a negative impact on ITER. This group would design a buildable DEMO and consider whether EDEMO should be built without waiting for (full) results from ITER and IFMIF. This work would, *inter alia*, give clear direction to future R&D, including the ITER programme. The group should also evaluate the potential of a CTF and the challenges of constructing such a device and, if it seems desirable, proceed to a detailed design.

- Close collaboration with industry from the very beginning of the DEMO design phase would be highly desirable for a number of reasons:

  - industrial involvement would bring a 'systems engineering'/holistic approach to development of fusion power plants, which has been missing up to now,

- industrial involvement would bring many other benefits, including in particular a ‘design for buildability , operability, maintainability and reliability culture’,
- it would put European industry, including SMEs, in pole position for the future realisation and deployment of fusion power.

Herewith, the experts have outlined a set of actions that Europe should take to move as quickly as possible to DEMO or EDEMO as the final step to reliable, economically acceptable fusion power. Given the scale of the energy challenge, the potential of fusion, and the fact that implementation of these actions would cost very little on the scale of the world energy market, they consider that strengthening the reference approach and developing, refining and funding a new paradigm of the sort that was discussed would be fully justified. The actions that the new paradigm would bring forward in time will be needed sooner or later in any case as fusion is developed.

- The immediate steps that should be taken are to:

  i) seek incremental funding to strengthen the reference programme, and

  ii) set up a DEMO design group with substantial industrial involvement as soon as resources (manpower and money) permit without impacting on ITER, with the charge of designing DEMO and considering whether an early DEMO (EDEMO) should be built. The group should also evaluate the potential role of a Component Test Facility (CTF), and then, depending on the outcome of the evaluation, design a CTF. This group could at first be relatively modest, but it should be built up (to perhaps 100 professionals) as soon as possible.

The Facilities review that Euratom/CCE-FU is about to establish could refine these steps. It could consider the desirability of constructing a European satellite tokamak and/or CTF and the case for an early DEMO in more detail.