International Perspectives on a Path to MFE DEMO

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Abstract. The establishment of the ITER project marks a transition in the world fusion program to one increasingly focused on the demonstration of electricity generation from fusion, or DEMO. In recent years, planning and design activities for next steps toward DEMO have intensified in many countries, and international discussions have identified both needs and opportunities for greater international collaboration in developing a DEMO Programme. The scientific and technical issues for fusion are well known and, while there is no agreement on a single roadmap to fusion, there is substantial scope to add value through international cooperation, particularly in promoting a coordinated DEMO programme. The International Atomic Energy Agency, as a world organization dedicated to fostering international collaboration in the development of nuclear energy for peaceful purposes, is well suited to provide auspices for an activity promoting an international exchange of technical information and strategic thinking that would benefit all parties. Accordingly, an IAEA DEMO Programme Workshop series focus on the scientific and technical issues for fusion development toward DEMO has been established. The first workshop will be held 15-18 October 2012 in the U.S.A.

1. Introduction

Progress toward the development of fusion as a source of abundant, safe, and clean energy has advanced to a point where the world community has renewed its emphasis on planning the steps to commercial fusion power plants. With the establishment of the ITER project, the world's magnetic fusion energy (MFE) enterprise has passed its most important milestone to date. The ITER facility will enable the world's first investigation of a magnetically confined burning plasma on a power-plant scale. The establishment of the scientific and technical (S&T) basis for ITER, development of its design, the formation of an international project, and now the start of construction, mark a transition in the world fusion program to one increasingly focused on the demonstration of electricity generation from fusion, or DEMO.

A magnetic fusion DEMO is generally expected to satisfy a range of socio-economic goals including a high level of public and worker safety, low environmental impact, high availability, closed fuel cycle, and potential to be economically competitive with other energy

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sources. Non-electricity applications of fusion (high temperature heat, neutrons etc.) are also of strategic interest.

Since the 2010 IAEA Fusion Energy Conference in Daejeon, there has been a significant increase in planning activities and design studies in many countries for next steps toward DEMO. Accordingly, the need for international discussion through which to exchange technical information on DEMO issues and strategic thinking regarding the roadmap to DEMO has become more urgent. Two international meetings in particular, a technical workshop in September 2011 and an International Atomic Energy Agency (IAEA) planning meeting in January 2012, were useful in clarifying areas of broad agreement as well as divergences in the perceptions of researchers concerning magnetic fusion energy development needs. It is clear that there is scope for international collaboration that can benefit the DEMO planning of all parties. Moreover the IAEA, as a world organization dedicated to fostering international collaboration in the development of nuclear energy for peaceful purposes, has an important role to play in the development of a fusion DEMO programme.

2. Recent International Discussions Regarding the Path to DEMO

In September of 2011, sixty-five fusion researchers from many countries including all of the ITER partner nations met at Princeton University in the U.S.A. for an international workshop to discuss the scientific and technical (S&T) understanding of DEMO issues and needs, and possible elements of the roadmap to DEMO. [1] The workshop participants concluded that a better understanding of the major milestones on the path to DEMO is now needed in order to guide programmes and make a convincing case explaining how fusion energy will be developed. They identified the most critical S&T issues, that is, major R&D areas in which the optimum development strategies are not clear, and established both the need for major facilities to resolve those issues and the R&D needed to establish their readiness for construction. Participants agreed that a continuation of the international dialog begun at the workshop is necessary to expedite fusion development and to help shape DEMO planning in each country, and they agreed that IAEA auspices could provide an appropriate umbrella for a systematic international activity to support DEMO programme planning.

Taking note of the September workshop, the IAEA invited the authors, as fusion researchers from the international community, to consult on possibilities and opportunities for a coordinated international approach to addressing DEMO issues. While the authors have been involved in design studies or planning discussions in their respective countries, they do not represent the views or policies of their governments. In January 2012 the group met for three days at IAEA headquarters in Vienna and found that:

- The scientific and technical issues to be resolved for fusion power to become a reality are broadly agreed, though different nations give different priority to different aspects. Of particular note is the increasing importance of Fusion Nuclear Facilities (FNF) that bridge the gap between ITER and DEMO.
- There is no agreement on a single roadmap to fusion, due to the different socio-economic and safety backgrounds to energy research, and the different emphases and priorities among the nations.
- There is substantial scope to add value through international cooperation, particularly in promoting a coordinated DEMO programme under IAEA auspices that would be beneficial to all parties. To take one example, the existence of multiple options for next-step facilities suggests that the IAEA is an ideal forum to facilitate cooperation in comparing benefits, readiness, and risks of the various options.

The findings led to a decision by the IAEA to establish an activity, namely an annual workshop series under IAEA auspices, as a step toward greater international collaboration in a world DEMO programme.

3. Scientific and Technical Issues for Fusion Development

Research and development in a range of areas is necessary in order to deliver the knowledge required to demonstrate electricity generation from fusion. Indeed the R&D issues and research requirements have been documented extensively through national studies by a number of parties. The large, multi-faceted fusion research issues are:

1. Plasma confinement in MFE systems. Research in this area aims to define the magnetic configuration and operating scenario for fusion plants capable of reaching near-ignition conditions. Tokamaks and stellarators are the main configuration candidates at this time. It is generally assumed that DEMO will use a DT-fueled burning plasma, but the choice of operating scenario, e.g. repetitively pulsed or continuous, and the associated control strategies are not firmly resolved. ITER is expected to provide a reactor relevant physics basis using a tokamak, but stellarators and other alternative configurations deserve further attention. We point out that, where options such as these currently exist, further research may produce conclusive evidence of one being the superior choice for DEMO, or it may not. This is one reason why we discuss DEMO as a programme, rather than a single facility.

2. Materials and technology for power extraction and tritium self-sufficiency. Eighty per cent of the fusion energy released from a DT-burning plasma is in the form of neutrons with a spectrum of energies that extends up to 14 MeV, much higher than those found in fission reactors. The conversion of energetic neutrons into electricity and the production of tritium needed to sustain the fuel cycle will be accomplished in a blanket that surrounds the plasma and in various external systems that collectively constitute what is known as fusion nuclear technology. The remaining 20% of the released fusion energy is in the form of alpha particles, which remain confined and transfer their energy back to the plasma. The unique damaging effects of fusion neutrons on materials, the harsh thermal conditions, the interactions with plasma, and interactions among various combinations of structural and functional materials define the R&D challenges in this area. Because these systems have not been needed on current fusion experiments, even ITER, research is at a relatively immature state compared with what will be needed for DEMO. Research efforts span a wide range, from basic materials science to engineering of complex systems, and facility requirements range from small laboratory test stands to integrated DT-plasma based fusion nuclear facilities.

3. Plasma exhaust. The heat and particles escaping from a burning plasma must be exhausted in a manner that is compatible both with good plasma performance and with long lifetimes for the material structures surrounding the plasma. The conditions foreseen in a DEMO are harsher than those expected in ITER, so a DEMO solution remains a goal for continuing research. For a given magnetic configuration, e.g. tokamak or stellarator, there are multiple candidate solutions under investigation for the divertor, i.e., the arrangement of edge magnetic fields and target structures used to mitigate the problem of plasma exhaust, as well as for the plasma-facing materials, operating conditions, and control strategies.

4. Availability. A DEMO must exhibit a level of availability (generally accepted to be about 50%) sufficient to establish fusion's potential economic viability. The availability of a system depends on the reliability of individual subsystems, the capability to inspect for damage, and the capability to maintain the system, a set of issues known by the acronym RAMI. Though ITER and other fusion experiments continue to make important advances in the remote handling and maintenance of an experimental fusion device, the current state of the art does not approach the high levels of availability required in an industrial fusion plant. The requirements for rapid replacement of the limited-life components of a fusion device introduce new constraints that affect the most basic design decisions. Moreover, since availability analysis is based on statistical methods, it requires the accumulation of reliability data on a large number of components operating at or above rated conditions over long periods, and of repair-time data over a large number of maintenance cycles.

Research on these issues, including the required facilities and associated programmes, constitute a *DEMO Programme*. The knowledge gaps that exist today will be closed using new facilities and their accompanying programmes, as well as existing programmes and facilities.

4. Perspectives on DEMO and the Roadmap to DEMO

Nations engaged in magnetic fusion research and development have programmes addressing the above issues with varying emphases. Now, the world fusion community is examining the needed programmes to move toward DEMO as the last step before commercial deployment of fusion power plants. It is generally accepted that DEMO means a practical demonstration of electricity generation on a power plant scale satisfying a range of socio-economic goals, typically including a closed tritium fuel cycle, a high level of safety, and low environmental impact. However, there is no consensus on the specific technical characteristics of the first of a kind commercial fusion power plant, nor is there agreement on the major steps and supporting programs needed to accomplish DEMO goals. The aim of an international DEMO Programme is not to converge on a single vision, device, or roadmap, but to identify and exploit opportunities for international cooperation in resolving the common science and technology issues.

One reason for the lack of a universal roadmap is that the conditions for DEMO R&D vary from nation to nation. There are significant differences in the perceived need and urgency for developing new energy sources, including fusion; in the priority for fusion funding relative to other national priorities; and in the perceptions of fusion's own development risks and uncertainties. In general the greater the perceived urgency for fusion energy the greater the willingness to take larger steps and larger technical risks in the interest of realizing a schedule goal. The policy environment can change rapidly; for example the consequences of the accident at the Fukushima Daiichi nuclear power station caused by the Great Eastern Japan Earthquake of 2011 illustrates how socio-economic and safety factors can affect the future development of fusion energy. In Japan, the "4th Science and Technology Basic Plan" covering the period 2011-2015, was amended to put significantly more emphasis on safety, prevention of disaster, non-proliferation and nuclear security.

The different policy environments result in important differences among the fusion R&D programmes being planned by individual countries, although there are some similarities as well. The critical role of ITER in advancing the understanding and control of burning plasmas is common to all, and all parties contemplate a similar timeframe, namely mid-century, for fusion to begin contributing to energy needs. The main differences lie in the different perspectives and approaches to technology and engineering challenges.

Correspondingly, there is a range of views on the needed programmes and facilities and how they would link together in a path to DEMO.

The main line of fusion development in most countries is centred on the tokamak concept. The present and near term future is focussed on the exploitation of existing tokamaks and those under construction (ITER, JT 60SA). Europe and Japan envision that ITER construction will be followed by the construction and exploitation of DEMO, the last step before the first commercial power plant. A dedicated fusion neutron irradiation facility to qualify materials is also included in the strategy. The development of alternative configurations, especially stellarators, is also being pursued, the largest machines being LHD (Japan), with Wendelstein 7-X (Europe) under construction.

An example illustrating a detailed fusion roadmap is provided by a Japanese study which was carried out by the Fusion Energy Forum of Japan in response to a government request to develop a roadmap for a tokamak type DEMO. The results, which were completed in 2007, were presented at the September workshop (Figure 1) by Prof. K. Okano (Univ. of Tokyo), the study team leader, stressing that the roadmap was meant as a case study and not a representation of government policy. The DEMO programme depicted here is relatively comprehensive, including ITER and a new satellite tokamak (JT-60SA) developed in collaboration with Europe. The fusion nuclear technology aspects of the plan include materials development using an International Fusion Materials Irradiation Facility (IFMIF), an ITER test blanket module (TBM), a series of full-scale blanket mockup tests, but no intermediate FNF. The transition from DEMO engineering design to construction design would be triggered by the achievement of Q=10 in ITER. Since the timeline was based on the

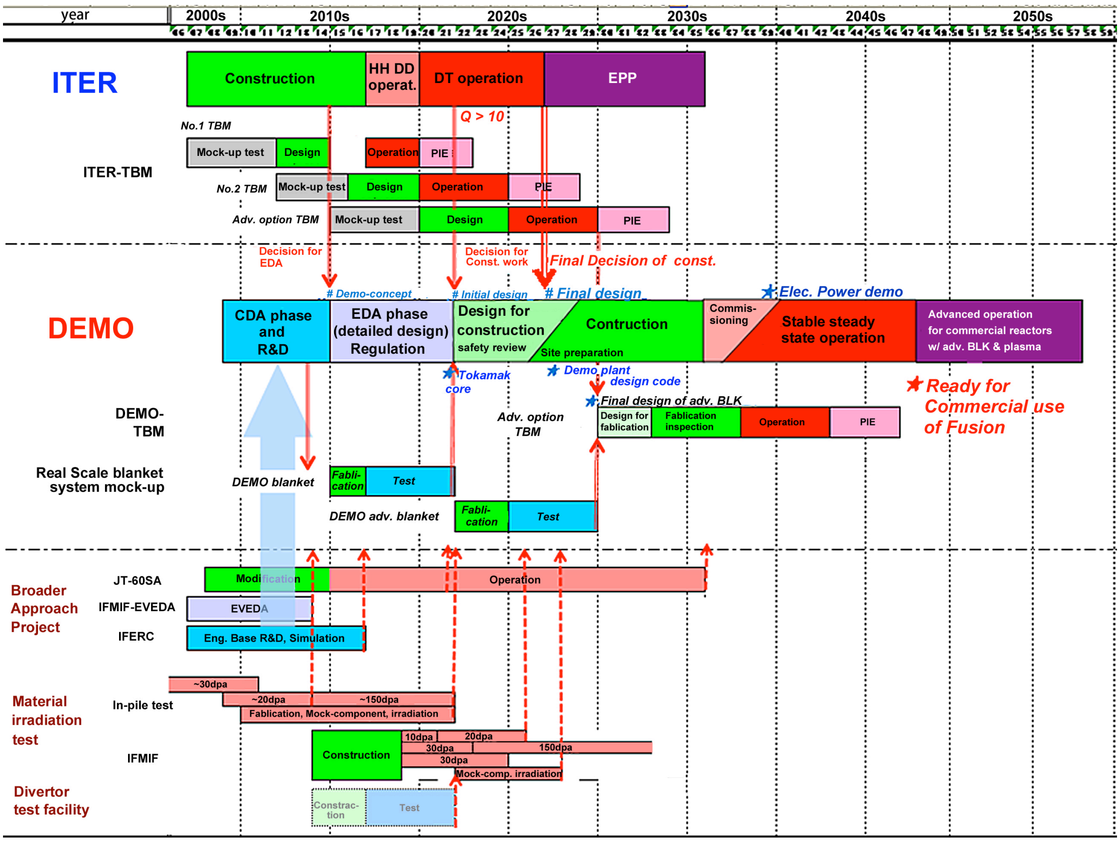

Figure 1. Example of detailed roadmap to DEMO (courtesy of Prof. K. Okano, Univ. of Tokyo)

ITER schedule in 2007, it was stated that the transition to the construction phase would be delayed as a result of delays in the ITER schedule.

Europe's strategy, building on the construction and operation of ITER, involves consolidating and integrating all necessary advances in physics and technology into the design of a fusion power Demonstration Reactor (DEMO) that must be ready for construction around the beginning of 2030. As a first step in this direction, the European Fusion Development Agreement (EFDA) has begun a coordinated effort to plan and implement physics and technology R&D and some initial conceptual design work toward Demo. The time plan and the resources for the detailed implementation of this activity are being elaborated as part of the definition of the new accompanying programme in Europe up to the end of this decade. Europe views both tokamaks and stellarators as attractive candidates for future fusion power plants and relies on ITER as well as physics research on tokamaks (both European tokamaks and JT-60SA in collaboration with Japan) and stellarators (particularly the Wendelstein 7-X in Germany) to develop the basis. In the case of tokamaks, both pulsed and steady-state scenarios are considered. Moreover, the importance to pursue a vigorous stellarator programme in view of the inherent benefits of this concept is recognized.

In China, South Korea, the U.S., and India, plans are being developed for major fusion nuclear facilities (FNF) as intermediate steps between ITER and DEMO. Such facilities, together with their accompanying programmes, are intended to advance the research and development in fusion nuclear technology with a steady-state or high duty-factor deuterium-tritium plasma, using the released energetic neutrons to test materials and components, close the fuel cycle, and generate electricity. However, there is no single vision for an FNF; the span of possible missions ranges from basic science research that requires an FNF environment to demonstrations of fusion's practicality up to and including the generation of net electricity and high-temperature heat (Figure 2).

Figure 2. Graphic illustrating the range of missions for next-step fusion nuclear facilities (FNF).

In the short and medium term, China is considering the construction of a Chinese Fusion Engineering Test Reactor (CFETR), and has formed a national team which has begun to develop a mission and design options by 2014 and a construction proposal by 2015, with the aim of starting construction around 2020. In its initial phase, the CFETR is intended to demonstrate 50 – 200 MW of fusion power, long pulse or steady-state operation with high duty factor and tritium self-sustainment. Because China foresees a large increase in energy demand in the next decades, its plans are among the most ambitious, in terms of both scope and timescale for next steps. Besides the CFETR, China is considering various alternatives for the development of fusion, i.e., both "pure" fusion machines and fission-fusion hybrids.

In Korea, the intermediate FNF step and the DEMO step would utilize the same tokamak device, K-DEMO. Korean scientists describe a strategy in which the first phase ("K-DEMO-1") would be used to support the development of divertor solutions and nuclear components exposed to prolonged neutron irradiation, rather than relying on separate facilities dedicated to divertor development or material irradiation. After a reconfiguration of the internal components based on what is learned in the initial stages, the second phase ("K-DEMO-2") would be launched, leading to a demonstration of industrial scale electricity generation from a fusion plant. Pre-conceptual design work on the K-DEMO has begun, with the intention to start construction in the mid- to late-2020s.

In the U.S., government policy and support is focused on fusion science, with a mission only to establish the scientific foundations for fusion. Nonetheless, the U.S. Department of Energy has commissioned roadmap studies, the latest being a 2003 plan by the Fusion Energy Sciences Advisory Committee for the deployment of a fusion demonstration power plant within 35 years. More recently community-based activities charted by DOE have documented gaps, research needs, and possible elements of a fusion development program. Such studies call for a broadening of the scope of the U.S. program, including growth in fusion materials and fusion nuclear science and technology research capped by a "fusion nuclear science facility" (FNSF) as the U.S. version of an intermediate FNF. Studies by several U.S. institutions have examined a range of machine configurations and missions for possible U.S. FNSFs.

India's next step, "SST-2," is intended to provide the first integrated test of some systems being developed for DEMO and to act as the first step for verifying the choices being made for DEMO. The development strategy in Russia considers both "pure" fusion machines and fission-fusion hybrids. In the near term, the goal is to upgrade several existing machines (T10, T11M and T15) and to develop a fusion neutron source in preparation for DEMO.

Fusion roadmap studies traditionally focus on a sequence of large facilities as a planning framework. However, many researchers argue instead for a focus on issues and greater emphasis on smaller facilities, simulation, and non-nuclear environments to advance the state of readiness for fusion technologies. In any case, the role of such science and technology development programs *vs.* that of large integrated facilities in an optimum fusion roadmap needs to be clarified.

The existence of differing socio-economic and safety environments, differing views on DEMO development strategy, and differing missions for the next step led the authors to advise the IAEA that there is no single roadmap and no interest in attempting to converge on a universal roadmap. On the other hand, there is broad international agreement on certain key strategic points such the importance of ITER, the need to expand fusion nuclear technology programmes now, and the need to begin serious planning of the facilities that will be needed to support a DEMO programme. For this reason, there is scope for international collaboration that can benefit the DEMO planning of all parties.

5. Role of International Collaboration in a Coordinated DEMO Programme

International collaboration has had a central role in fusion research for more than a half century. Indeed, the S&T readiness for ITER is itself a product of many years of collaboration among the nations engaged in fusion research, and the seven-party ITER partnership is an extraordinary example of international cooperation in the development of a single unique facility. The International Atomic Energy Agency (IAEA) has had an indispensable role in fostering fusion's tradition of collaboration, for example through sponsorship of the biannual Fusion Energy Conference and publication of the journal *Nuclear Fusion.* Significantly, the IAEA sponsored the international reactor design study INTOR, which led to the start of ITER design activities in the 1980s. More recently, the IAEA provided the initial auspices for the

International Tokamak Physics Activity (ITPA), through which ITER partner nations are now successfully cooperating in research to respond to ITER physics needs. It is natural, then, and potentially fruitful for the world community to look to IAEA for help in programme planning toward DEMO.

The IAEA is well suited to provide the auspices for an activity to promote the international exchange of technical information and strategic thinking on DEMO issues that would benefit all parties. In response to the findings described here, the IAEA has established an annual DEMO Programme Workshop series focused on the scientific and technical issues for fusion development toward DEMO. The specific topics within the broad areas described in Section 3 will vary with each each meeting in the series. The first of these workshops will be held 15-18 October 2012 at the University of California Los Angeles in the U.S. The topics for that meeting are: 1) Fusion power extraction and tritium fuel cycle, 2) Plasma power exhaust and impurity control, and 3) Magnetic configuration and operating scenario for a next-step fusion nuclear facility. It is intended that the workshop output, to be documented in summary presentations, a report to the IAEA, and (tentatively) a journal publication, will be information that could be used by any party as input to the planning of possible roadmaps to DEMO. Opportunities to make greater progress through international collaboration will be identified, ideally leading to coordination or joint work where beneficial. To promote continuity in the workshop series, participants will propose the set of topics for the next workshop(s) in the series, considering the status, expected progress, and need for international discussion among the various DEMO issues.

6. Final Comment

It is expected that there may eventually be several DEMO designs with each nation protecting the intellectual property relevant to special design features of its own DEMO. Nevertheless, at the present juncture when many basic science and technology issues of relevance to DEMO designs are in an early state of maturity, there is much to be gained by mutual discussions, technical cooperation, and joint activities among nations involved in DEMO related R&D. It is hoped that the IAEA DEMO Programme Workshop series will be a step toward strengthened international collaboration in the development of fusion that will receive wide support from the fusion community.

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