Report of the 4th IAEA DEMO Programme Workshop

Karlsruhe Institute of Technology, Karlsruhe, Germany
15–18 November 2016

Workshop Purpose

DEMO programme workshop series aims to discuss topics within the context of fusion beyond ITER and that are of key interest for the progress in developing fusion as an energy source.

The workshop is intended to drive future R&D and strategy within the international fusion community and to promote collaboration.

Presentations were given in three topic areas:

- **Topic 1**: Tritium;
- **Topic 2**: DEMO physics gaps and impact on engineering design;
- **Topic 3**: Heating and current drive physics and technology.

Each topic was divided into subjects and speakers were asked to address the following:

- The issues raised by considering the subject in the DEMO context;
- What work and resources are needed to resolve the issue;
- An analysis of the problem within the context of whole DEMO design.

Technical Programme Committee

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Chair’s Meeting Summary

The meeting combined three topics that raise significant uncertainties and development issues for the post-ITER machines. The presentations prompted lengthy discussions on each topic and several cross-cutting items were identified. The key findings of the meeting are summarized as:

- Methods to increase the burn fraction are necessary to reduce startup inventory of tritium and required Tritium Breeding Ratio (TBR).
- There is a need to reduce the uncertainty in many parameters, both fundamental data and derived quantities. In particular:
  - Tritium behaviour (diffusion, retention, permeation);
  - H-factor, L–H transition, neutral recycling;
  - Divertor plasma parameters, detachment requirements, Scrape-Off Layer (SOL) width, spreading.
- There is a requirement for extensive engineering/technology facilities for testing of components on a variety of scales, whose specifications need to be developed and prioritized (according to criteria to be identified).
- There is a requirement for integrated plasma scenario development to reduce uncertainties and to explore alternative modes (I-, QH-) and edge SOL particle transport. Facilities to develop plasma scenarios, investigate SOL physics and to reduce uncertainties are needed. The specifications need to be determined and where possible existing facilities utilized.
- Heating and Current Drive (HCD) systems development is concentrating on efficiency and Reliability, Availability, Maintainability and Inspectability (RAMI) but programmes are not adequately addressing the nuclear aspects of the designs such as material activation and shielding.
- A fusion DEMO development programme will require a methodology for systematically tracking technological maturity and progress toward an end product. The causality dilemma between component testing and representative testing facilities is a challenge for fusion and may require either some adoptions of the Technology Readiness Level approach or alternatives involving standards organizations and licensing and regulatory authorities.

Topic Summaries

Topic 1: Tritium

The purpose of this topic was to provide an overview of the required tritium systems and their performance, including the plasma fusion reaction, for a post-ITER fusion device. Invited presentations were received on the following subjects:

- An overview of the tritium fuel cycle and conditions for self-sufficiency, M. Abdou (UCLA);
- The plasma physics aspects of the tritium burn fraction and the prediction for ITER, A. Loarte (IO);
- Prediction of fueling efficiency based on experiments and modelling, L. Baylor (ORNL);
- Tritium technology for ITER, S. Wilms (IO);
- R&D for DEMO and required extrapolations beyond ITER, C. Day (KIT);
- Tritium transport, permeation, and control, P. Humrickhouse (INL);
Availability of tritium, M. Kovari (CCFE).

It is clear that any DEMO reactor (including a stellarator based option) must be designed for optimal fueling and pumping efficiency. It is also clear that the approach must be holistic and integrated, considering all aspects of the tritium fueling, breeding and processing cycle.

The dynamic models of the tritium system that have been developed to calculate time dependent tritium flow rates, inventories and required TBR have already shown the critical influences of fueling, exhaust inventories and processing. The startup inventory\(^1\) is strongly dependent on the tritium burn fraction, \(f_b\), the tritium fueling efficiency, \(\eta_f\), and the tritium processing time, \(t_p\). For a reactor generating 3 GW fusion power the startup inventory can vary from < 10 kg (\(t_p < 6\) hours, \(f_b \eta_f > 4\%\)) to > 30 kg (\(t_p > 1\) hour, \(f_b \eta_f < 2\%\)). The same three parameters also influence the TBR required to achieve self-sufficiency, which can vary from TBR < 1.05 for \(f_b \eta_f > 3\%\) to TBR > 1.15 for \(t_p > 1\) hour and \(f_b \eta_f < 1\%\). Given that the maximum achievable TBR is probably of order 1.15 and that approximately 5% of tritium is lost to radioactive decay per year this gives a range of required TBR of 1.05–1.15. Decreasing the processing time and increasing the burnup fraction and fueling efficiency create margin for the largely unknown TBR.

The R&D goal should be to achieve:

- The value of the product of tritium burnup fraction and fueling efficiency \(f_b \eta_f > 5\%\) and not less than 2%;
- The tritium processing time in the plasma exhaust and fuel cycle, \(t_p < 6\) hours.

In ITER the predicted burn fraction is 0.35% but this is thought to be a conservative estimate assuming all fueling (gas and pellet) is done using 50:50 deuterium and tritium (D–T) mixtures. The edge and the core fueling is expected to be decoupled so it is feasible to fuel the core with T only from High Field Side (HFS) pellets whilst using D for edge density, power load and Edge-Localized Mode (ELM) control. In this scenario estimates for the burn fraction rise to 1.2% < \(f_b < 2.3\%\).

The ITER predictions when applied to DEMO result in a startup inventory between 15 and 30 kg (for \(t_p\) from 1 to 6 hours) and the required TBR falls below 1.1, so improvements are still needed but confidence in self-sufficiency is improved.

There is as yet no practical external source of tritium for fusion beyond ITER, a strategy must be developed to address this.

The required TBR will depend upon the tritium lost to the cycle through retention and unrecoverable diffusion. The requirement for a high temperature blanket which in most designs contains a high partial pressure of elemental tritium creates an ideal environment for tritium permeation. Permeation barriers may struggle to provide the allowable loss rate (10 Ci per day) and have not so far performed well under irradiation.

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\(^1\) This is the inventory of tritium required to start the reactor and depends upon assumptions made regarding the reliability of the processing plant and reserve time for outage (0.25 days combined), the ‘doubling time’ or the period over which the plant is required to generate its startup inventory to supply a second plant (5 years), the tritium plant inefficiency (0.01\%) and the blanket mean residence time (10 days).
There are fundamental design concepts (such as large area thin walled heat exchangers) that conflict with the tritium permeation control that may need to be addressed to find a solution.

The necessity to use HFS pellet injection for DEMO has long been acknowledged and modelling shows that fueling efficiencies of $\eta_f > 50\%$ may be achievable although the impact of ELMs on HFS injection fueling efficiency is not yet known. Optimizing the injection location and trajectory (including delivery through a high temperature blanket) is essential to maximize fueling efficiency but it is likely that penetration will be shallower than in present tokamaks and ITER, thus extrapolation is difficult. To reach the pedestal edge in a DEMO device requires pellet speeds in excess of 2 km/s, demonstrated but still requiring development to achieve the necessary reliability.

Tritium processing is a major area requiring development: design and construction of the ITER tritium plant is a major undertaking, representing a 10 to 20 fold scale up of existing plant and a similar scale up is likely needed for DEMO. Reducing the processing time is a major concern and work is being undertaken to develop improved system architectures to address this. For example, the traditional ‘all-through’ processing loop is replaced by a multi-loop architecture with novel functionalities including Direct Internal Recycling of the separated exhaust gases. Most batch processes at cryogenic temperatures are replaced by continuous processes at non-cryogenic temperatures (diffusion pumps replace cryopumps, liquid ring pump replaces cryogenic viscous compressor, thermal cycling absorption replaces cryodistillation).

To summarize, the major technology gaps from ITER to DEMO identified are:

- **Tritium purification and recycling**: new technologies due to impractical scale up and to accommodate tritium breeding.
- **Safety**: scaling containment/detritiation systems to the next level is proving difficult and expensive; containment in the extreme D–T fusion environment will reveal issues that must be addressed.
- **Tritium breeding and extraction**: fundamental experiments are needed; no proof of concept experiments have been performed and full experiments will require tritium source, e.g. from fission.

**Topic 2: DEMO physics gaps and impact on engineering design**

The purpose of this topic was to identify those aspects of DEMO plasma physics where uncertainty remained and to analyse the consequences of uncertainty in the engineering design of DEMO. Invited presentations were given on the following subjects:

- Introduction and overview of the subject, H. Zohm (IPP);
- H-mode core plasma confinement, R. Hawryluk (PPPL);
- Steady state scenarios for a DEMO tokamak, V. Chan (USTC);
- Power exhaust, H. Reimerdes (SPC);
- Operational margins and impact on design, H. Lux (CCFE);
- Stellarator/helical physics, J. Miyazawa (NIFS).

To clarify open issues towards DEMO an international programme is required to address the problems of scaling from present day experiments which should include:
- Development of new scaling laws that use a more physics oriented approach (and which also better cover the DEMO relevant parameter range);
- Improvement of the theoretical understanding of underlying physics;
- Increased use of integrated modelling using detailed physics models;
- Benchmarking with the largest available experiments from today (JET and JT-60SA will play a major role);
- Final validation on ITER (unfortunately only possible in ~20 years from now but the ITER programme should be designed to accommodate this).

Extrapolations towards ITER and DEMO conditions of experimental findings from present day experiments often have limited validity. Some ‘global’ parameters, such as \(n/n_{GW}\), \(\gamma_{rad}\), \(\beta_N\), can be chosen in agreement for both small and big devices but not all parameters can be made to match simultaneously, for example \(n/n_{GW}\) and \(n^*\).

H-mode core confinement physics illustrates the problem: the standard IPB98(y,2) scaling is based on insufficient data at high \(n/n_{GW}\), has no data points at DEMO relevant values of \(P_{rad,core}\), the \(\beta\) dependence and application to low rotation plasmas is questionable as are the dependence on wall material and heating method. The prediction of H-mode power threshold has large uncertainties (essential for heating power and flux across the separatrix) and present scaling law clearly contains hidden variables. There is clearly a need to develop models based in physical understanding rather than empirical scaling.

Promising new confinement modes (QH- and I-) that offer the prospect of ELM free operation need further investigation to understand their physics, operational requirements and compatibility with power exhaust as well as the confinement quality for a burning DEMO plasma.

DEMO designs assume a fully detached plasma to reduce heat loads on the divertor but this solution cannot be demonstrated on any existing tokamak so the development of validated quantitative predictive modelling capability is a priority. Some early progress in integrated core/edge/SOL modelling is looking promising but experimental validation is difficult as the necessary impurity seeding to control \(P_{core}\) and \(P_{sep}\) impact on the plasma scenario.

Alternative approaches to the exhaust problem for DEMO such as double null, X, Super-X and snow flake are still at the basic design stage. It would be useful to examine the cost-benefit to DEMO of some of these approaches which tend to use less of the volume inside the Toroidal Field cage than a standard single null.

Designing steady state operating scenarios is hampered by physics uncertainties, particularly the HCD mix and power, not only for HCD but also in terms of profile control and compromising between competing requirements such as plasma torque. Considerable progress has been made in steady state scenario modelling in recent years with some sophisticated approaches that would benefit from cross-validation. This may be an appropriate time to launch an international collaborative programme of integrated scenario modelling incorporating benchmarking across numerous experiments.

Given that significant uncertainties are likely to remain for several years understanding the impact of these on performance is a useful way to identify priority R&D areas. Initial attempts to provide quantitative probabilistic analysis shows that best performance generally coincides with the perceived operational limits but is a useful tool to predict likely achievable
performance in a reliable device. More work is needed for example investigating the sensitivity to different confinement scaling and machine operating points, e.g. comparing China Fusion Engineering Test Reactor (CFETR) with European DEMO (EU-DEMO).

The advantage of the stellarator as the basis of a steady state DEMO design lies primarily with the elimination of non-inductive current drive systems. Given that the HCD systems present status presents challenges in wall plug efficiency and reliability, reducing the power required is a major benefit. The major radius of the stellarator DEMO is very large but, due to its geometry, the plasma volume is similar to the tokamak DEMO, whether this can be exploited in machine layout remains to be explored. At present there are no plans for an ITER-sized stellarator experiment and consideration needs to be given to the feasibility of scaling to the DEMO sized device in a single step.

There are commonalities in the physics between the two machines — turbulent transport, β limit, and density limit — but also differences — β limit appears benign in the stellarator and the density limit is much higher. Understanding the sources of these differences will contribute to a general improvement in the plasma physics basis that underlies the design of both types of device.

The consequence of the uncertainties in the physics basis and models is a cautious approach to engineering with large operational margins applied to component design and over-specification of system requirements. It represents a major obstacle to advancing DEMO engineering design and limits the ability to select the most appropriate technology. The key areas must be identified and addressed by the fusion community making best use of those machines that can provide DEMO relevant operational parameters, noting that a final confirmation of some of the physics assumptions will only come with ITER.

**Topic 3: Heating and current drive physics and technology**

The purpose of this topic was to provide overviews of the state of the art of the four HCD systems — Electron Cyclotron (EC), Ion Cyclotron (IC), Lower Hybrid (LH) and Neutral Beam (NB) — with particular reference to efficiency and reliability developments. Invited presentations were given on the following subjects:

- Introduction and overview, I. Jenkins (CCFE);
- Overview of plasma physics HCD requirements, M.Q. Tran (EPFL);
- EC systems status and prospects, G. Denisov (Nizhny Novgorod);
- NB systems status and prospects, U. Fantz (IPP);
- IC systems status and prospects, H. Kasahara (NIFS);
- LH systems status and prospects, L. Liu (ASIPP).

The uncertainty in the predictive capability of plasma physics has a major impact on the HCD programmes for DEMO. Confidence in the integrated physics modelling must be established to determine the HCD system requirements, and a stable scenario is needed before the Engineering Design Activity can begin. Ideally the HCD mix should be established as early as possible to avoid unnecessary resourcing of non-viable systems. This also needs to consider the role of HCD systems as actuators for plasma control.

Five DEMO designs (CFETR, SlimCS, European, Indian, and K-DEMO) have indicated some operational requirements for HCD systems and which systems will be used, although
the level of detail varies. All five include EC at frequencies between 170 and 300 GHz (driven by $B$ field value), a range that encompasses the ITER EC system but extends to well beyond present availability. There is also a requirement to increase the output power to above 1 MW in order to reduce the number of gyrotron units. The simultaneous increase in frequency and power and Continuous Wave (CW) operation is a major challenge for gyrotron technology. Present achievable wall plug efficiency is $\sim 60\%$ at lower frequency and power but availability needs to increase to $\sim 98\%$ to meet even the EU-DEMO modest requirements. Ancillary systems such as steering, waveguides and windows compatible with high CW power also need to be developed.

Only EU-DEMO has selected IC, for which a distributed travelling wave antenna that forms part of the first wall is being developed. Again, increasing the power output per unit is an R&D activity in support of which 6 MW transmission lines and conjugative T matching units are being developed. The use of high efficiency minority heating (3\(^\text{He} 3\%$) is a candidate for IC but requires the development of fast ion heating models. Sources of radiation depend on frequency — tetrodes for frequency up to 100 MHz for heating and klystrons up to 300 MHz for CD — although the coverage is not continuous from industrially available units. Being mature technologies efficiency is $\sim 65\%$.

The use of LH is anticipated on the CFETR, Indian and K-DEMO reactors mainly in a plasma shaping role although CFETR is intending to use HFS launch to ensure adequate penetration for CD. All systems require $\sim 5$ GHz frequency which is not a major development requirement but power per unit is presently limited to 500 kW from a CW klystron. Ancillary systems such as transmission lines, mode filters and windows compatible with CW high power need to be developed in addition to launchers compatible as a plasma facing component.

Despite the obvious problems of higher energy operation (and hence reliability, cost and efficiency) Neutral Beam (NB) has also been selected by all five DEMOs at present. Although present NB systems routinely deliver $> 10$ MW power most are based on positive ion systems operating at $\sim 120$ kV. The LHD and the JT-60U are the exception with respectively 13 MW from three 180 kV negative ion systems and 3.2 MW from two 320 kV negative ion systems but not CW operation. The major challenge to NB is the poor wall plug efficiency with a gas neutralizer ($\sim 30\%$ at present) and significant R&D will be required to develop the more promising alternative photoneutralizer. This implies the construction of large test facilities for NBs (ITER PRIMA may be useful in this context). The management of extraneous power deposition is a general issue for high power NB systems.

No system is yet at the required level of maturity; they all require further R&D for the source, transmission or improved efficiency. The RAMI database for the HCD systems is scarce and a data collecting and analysis methodology needs to be established that all machines contribute to. The plasma scenario modelling is of importance as the power differential between heating and L–H transition can be significant, similarly for CD. The requirements of the HCD systems to act as plasma control actuators must be addressed within the context of the HCD mix.

There was no discussion of the nuclear aspects of the HCD system design in the presentations, for example, materials e.g. Cu/Ag activate badly, coatings flake under radiation induced swelling/cracking and electrical conductivity reduces under irradiation. All these aspects must be addressed in the system design.