# Report of the Ad hoc Group on DEMO Activities

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# Executive summary

The Governing Board (GB) of Fusion for Energy and the CCE-FU have jointly set up an Ad-hoc Group (the Group) regarding DEMO activities. According to the terms of reference, the Group focused its work on:

- what are DEMO programmatic requirements?
- what are the physics issues to be addressed in a DEMO oriented workplan?
- what are the technology issues to be addressed in a DEMO oriented workplan?
- what could be follow-up actions?
- what could be the resources needed?

The Group is firmly convinced that it is appropriate for the EU to give a new impetus to DEMO activities now. As foreseen in the Fast Track, DEMO will be the last step before the first fusion power plant. During a phase of its exploitation, it will produce a significant amount of electricity to the grid. It will also serve to qualify key components for the first fusion power plant.

Albeit the Group is of the opinion that DEMO will be based on the tokamak concept, it stresses the importance to pursue a vigorous stellarator programme in view of the inherent benefit of this concept.

Five main physics issues are identified: steady-state tokamak operation, operation at high density, power exhaust, disruptions and control. A prioritized list of activities is proposed to address these issues and can be found in the main text.

A similar approach was followed for technology. The fields of R&D encompasses H&CD technology, In vessel components, Tritium handling system and Fuel cycle, Diagnostics and Control, Remote Handling, Superconducting magnets, Materials, Power plant and General issue about availability and efficiency. It is important to note that, among these fields, the Group wishes to mention that divertor and maintenance deserve the highest priority attention in future R&D programmes, since they will be crucial for the success of DEMO and of the realisation of fusion. A detailed list of activities can be found in the text.

It is also important to note the deep interplay between technology and physics scenarios and that during the following work of the DEMO Core Group (see below) to establish a pre-conceptual design of DEMO both aspects have to be considered together.

As an immediate follow up action, the Group strongly recommends the establishment of a DEMO Core Group under EFDA of a 3-5 professionals, with the first mission to specify DEMO design activities to be carried out until the end of 2013, as outlined in this report. These activities should be consistent with the European obligations arising from our participation to the BA-IFERC project. A list of activities are currently being drafted by a joint EU-JA group and which will be submitted for approval to the BA SC. The design activities should include as first priority, conceptual design work to scope out a DEMO tokamak concept. In the frame of such studies, the feasibility assessment of a stellarator Fusion Power Plant (FPP) and of a Components Test Facility (CTF) and the role of the latter in the realisation of fusion could also be addressed.

Regarding the International Fusion Materials Irradiation Facility (IFMIF), the Group considers that IFMIF is very close to be on the critical path to DEMO and the decision to build IFMIF, as well as the decision on the site, must be taken before the end of the EVEDA phase (i.e. in 2013 or 2014). This early decision on the site will also make the engineering work to be develop during the EVEDA phase much more useful because it would be possible to take into account the possible site characteristics in the different studies to be carried out.

The Group considers that  $60M \notin yr$  should be devoted to DEMO for design and R&D (excluding the TBMs, currently under the responsibility of F4E) during 2012-2013. Approximately 15 M $\notin yr$  should be devoted to design work and 45 M $\notin yr$  to R&D on emerging technologies. Assuming a Commission share of 33%, this corresponds to a Commission contribution of 20M $\notin yr$ . Resources should also be made available during the end of the current FP in order to launch as many priority 1 activities in Physics and Technology as possible. For 2011, the Group recommends that 30M  $\notin$  be devoted to DEMO activities.

# **Report of the Ad-hoc Group on DEMO**

# I Introduction

The Governing Board (GB) of Fusion for Energy and the CCE-FU have jointly set up an Ad-hoc Group (the Group) regarding DEMO activities. The members of the Group are: P. Batistoni, S. Clement Lorenzo (Secretary), K. Kurzydlowski, D. Maisonnier, G. Marbach, M. Noe, J. Paméla, D. Stork, J. Sanchez, M.Q. Tran (Chair) and H. Zohm. The Group held many meetings either face-to-face or by remote. It wishes to thank the hospitality of IPP-Garching, where many meetings where organized.

The terms of reference agreed by the GB and the CCE-FU are given in Annex I. In its report the Group presents its conclusions on the questions raised in the terms of reference, namely:

- what are DEMO programmatic requirements?
- what are the physics issues to be addressed in a DEMO oriented workplan?
- what are the technology issues to be addressed in a DEMO oriented workplan?
- what could be follow-up actions?
- what could be the resources needed?

The GROUP made use of the available documentation pertinent to DEMO:

- the SEAFP
- the European Power Plant Conceptual Study
- the input of Fusion to the European Strategic Energy Technology Plan (SET-Plan)
- the work of the EFDA DEMO Working Group (Fusion Development Strategy paper EFDA (07)-33/4.8 DEMO Development – Programme – paper STAC 21-4.2). It is important to note that these papers have been discussed in depth by EFDA STAC.
- the input prepared by EFDA for the Fusion Review Panel (FRP)
- various inputs from F4E regarding the ITER Test Blanket module (TBM) and the DEMO activities in the frame of the Broader Approach

The Group also acknowledges input from the whole European Fusion Community at the DEMO Workshop organized by EFDA at IPP on September 29 and 30, 2009. At this workshop, an in-depth discussion was held on the results obtained both in physics and technology as well as on the main strategic elements to be considered for the future workplan. Sections of the report were also discussed by TAP and valuable inputs are acknowledged and implemented in the report.

The report is structured as follows. Section II recalls previous studies regarding DEMO. The Group's views on DEMO role are presented in Section III. From these considerations, the Physics and Technology issues and possible activities to address them are developed in Section IV and V respectively. Please note the strong interplay between Physics and Technology and therefore theses two fields cannot and should not be considered in isolation. As requested in the Terms of reference, the Group proposes some consideration regarding the time schedule of IFMIF (Section VI). It will be the role of a DEMO Core Group to be established (Section VII) to conduct an integrated pre conceptual design of DEMO. Section VI also contains a discussion of an estimate of the necessary funding. BA activities and the EU commitments to them are discussed in Section VIII.

# II Previous studies regarding DEMO

There has been significant progress over the last two decades in the elements that constitute the basis for the commercial exploitation of fusion as a source of energy. The developments in plasma physics, materials science and the technology of fusion, allow today to propose a clear path to the realisation of economic and environmentally attractive electricity power generation. A summary of the previous work could also be found in the EFDA paper "Fusion Development Strategy – paper EFDA (07)-33/4.8".

In Europe, except for the SEAFP study carried out in 1992-1994 [1], work on reactor studies really acquired momentum in 2001 with the Power Plant Conceptual Study [2, 3], a study of Fusion Power Plant (FPP) models completed in 2005. Since then, work has started to be focused on DEMO and on the development of a consistent fusion development strategy.

Pioneering work on Fusion Power Plant (FPP) must be credited to the USA, in particular to the ARIES team, who carried out a series of tokamak FPP studies between 1986 and 2000 (ARIES-I, II, III and IV, PULSAR, ARIES-RS and ARIES-AT). More recently, the ARIES team has assessed the potential of inertial fusion energy (2004) and it has completed a sellarator FPP study (2008). All ARIES reports and publications are available on the ARIES web site [4]. In 2010 and beyond the ARIES team plans to reconsider tokamak FPPs.

All ARIES concepts can be qualified as "very advanced" by European standards. For instance, the technology basis adopted by the most advanced PPCS model is very similar to the one adopted by ARIES-AT. This is due to a requirement adopted in the US requesting the fusion cost of electricity (coe) to be cheaper than the coe from other sources of energy, leading to the adoption of "advanced" physics and/or technology.

It must be noted that there is no official US fusion development strategy, and the device referred to as "DEMO" in the US corresponds more to the European definition of the first FPP. If anything, the US fusion strategy can be defined as science-driven rather than reactor-oriented [5, 6].

In Japan, the fusion development strategy is reactor-oriented [7] and bears many similarities with the European "fast track" approach. There are, however, no Japanese FPP studies as comprehensive as any of the ARIES studies or the European PPCS. There are currently 2 different lines of development in Japan: the "CREST" line, supported primarily by CRIEPI and some Universities, and the "CS-less" line, supported primarily by JAEA. Recently, work is focusing on the devices to be build before the first reactor: DEMO-CREST [8] and Slim-CS [9]. The basic idea behind CREST is to consider a device with fixed geometric parameters and to investigate different operating scenarios. The basic idea behind the CS-less line is to minimise the COE by minimising the capital investment. This is planned to be achieved by minimizing the mass of the basic device by eliminating the central solenoid in a FPP. The corresponding DEMO device is planned to operate with a "slim" central solenoid.

A completely different strategy was proposed in the past in Russia, and it has more recently been adopted by China: the fission-fusion hybrid. The principle of a hybrid is to generate neutrons with a fusion reaction and to use them to induce fission reactions in fissile material located in a subcritical blanket. The rationale behind this approach is that, firstly, it allows an early commercial use of fusion energy and, secondly, that these applications will speed up the development of a "pure" FPP [10]. Note that this concept could also be used as nuclear fission waste burner.

An historical perspective of fusion power plant studies during the past 40 years in proposed in ref. [11].

# III DEMO definition

The aim of the European Fusion Programme is the exploitation of fusion as a commercial source of energy. The concept of a "fast track programme" was defined, with a single step between ITER and a (first of a kind) Fusion Power Plant. In the past, EFDA-CSU has presented to EFDA STAC a paper named "Fusion Development Strategy – Physics, Engineering and Technological Challenges" (Paper STAC 18-4.3 – 2006). It is recognized that, whatever the success of ITER, an intermediate stage called DEMO is needed. This need becomes clear if one compares some parameters of ITER (e.g. fusion power, plasma pulse length, tritium breeding) with the ones in a FPP:

- fusion power of 500 MW compared to 2-3 GW
- pulse length of 300-500 s compared to steady state or about 10 hours
- only functional (rather than lifetime and performances) test of breeding module compared to full tritium sufficiency

Other characteristics of a FPP include the use of low/reduced activation material, high availability and reliability, low recycling power.

The Group had therefore carefully considered the role of DEMO on the road map towards FPP. It is clear that DEMO should be considered together with other elements of the programme, the main one being IFMIF. The Group reviewed previous works and shared the views expressed in other papers on the mission of DEMO, as a single step between ITER and a first of a kind FPP. A minimum size of DEMO was studied by H. Zohm and the related paper was discussed in depth and endorsed by the Group and is attached as Annex II.

DEMO should be able to demonstrate significant net (~ several hundreds of MW) electricity production over an extended period of time (a few months). During this period, DEMO will be operated as steady state electricity source, while the plasma in itself is not necessarily steady state. Studies performed within the European fusion programme indicate that energy storage is not a cost driver and could store large amount of high grade heat compatible with electricity production. Therefore the option of a quasi-continuous plasma (~ 10 hours, with a down time of the order of 15-30 minutes) could be considered but the issue of mechanical and thermal fatigue of components should be addressed. The physics and technology issues of the operation of a burning plasma whether in steady state or in quasi-continuous mode are addressed in the following sections.

The second role of DEMO will be the qualification of key components of a FPP under realistic neutron flux and fluencies. While IFMIF will be used to test material samples up to the final close expected in FPP (150 dpa), DEMO should allow the qualification of components at fluencies in the range of 50 dpa after a reasonable time of operation.

In Annex III, the Group gives a list of requirements for DEMO. Naturally these requirements must be validated by the DEMO Core Group (See below), which will be in charge of defining the DEMO specifications and develop an integrated pre-conceptual design.

# IV Physics issues to be addressed in a DEMO oriented programme

# **IV.1** Definition and identification of DEMO physics issues

The fast track strategy as e.g. outlined in the EFDA input documents to the facility review foresees DEMO as the 'single step between ITER and a commercial fusion reactor' and hence should be more or less a 'point design' and no longer an experiment. For physics, this means that essentially a validated 'numerical tokamak' (or 'numerical stellarator') must exist that can be used for the design. Hence, we need to have, at least when DEMO goes into the construction phase, a workable operation scenario that promises reliable, robust operation at high Q (and probably steady state) which we understand well theoretically so that extrapolation from ITER to DEMO can be made with enough confidence to not include experimental flexibility for physics and plasma control in the DEMO design.

Given the present Fast Track planning, DEMO must be a tokamak since stellarators would require at least one intermediate step following the LHD/W7-X class to validate the properties deduced from these experiments on a JET/ITER like plasma. It is an interesting point per se what exactly a next-step stellarator should demonstrate to enable a stellarator FPP building on this machine and DEMO (which would develop the necessary technology), but the Group did not undertake this task. There is also

the perception that stellarator designs have not yet converged to a single line, which seems to have happened with tokamaks in the last decade. All this calls for the inclusion of stellarators in the DEMO Core Group that must address the technical feasibility and boundary conditions set by the peculiarities of stellarators. An outline of stellarator physics issues is given in Section IV- 3.

There are many physics issues that have to be solved before the state of confidence quoted above is reached. Many of these are already addressed in present-day tokamaks or will be a major part of the ITER programme and should thus not be covered by our Group. In defining DEMO specific physics tasks, we could hence take the view that these are physics questions that do not necessarily have to be solved for a successful ITER operation, but are absolutely vital for DEMO. Based on the previous assessment of the past DEMO WG and the discussions in the Group, there are 5 large areas, which fall into this category:

- steady-state tokamak operation: under this we summarise the whole challenge of advanced tokamak scenarios, i.e. high bootstrap fraction and the associated MHD limit(s), ITB formation and control with external knobs (H&CD systems) in an alpha-dominated plasma, etc., etc. We have seen many discussions if steady state is absolutely required or just another thing that makes an FPP more attractive. This should be discussed by us as well – but not in the physics section. What is clear from physics is that long pulse but not steady state would very much alleviate the requirements on the physics.
- 2. operation at high density: due to the unfavourable scaling of Greenwald density  $n_G$  with size, it seems unavoidable to operate a DEMO above  $n_G$  which is of course quite worrying in terms of confinement and disruption danger. It is noted that the density limit may push us to higher plasma temperature operation, which may open a whole new world of physics (synchrotron radiation, CD efficiency etc...)
- 3. power exhaust: PPCS has shown that pushing a DEMO towards economic attractiveness increases the power exhaust problem into a parameter space where either PFCs and first wall components are dramatically improved or solutions are found where a very large fraction of power has to be radiated before it reaches the plates. This means that DEMO must operate high above the L-H threshold. Also, it is not clear if present tools proposed for ELM mitigation in ITER (pellet pacing, in-vessel coils) are also DEMO compatible.
- 4. disruptions: in DEMO, the disruption problem seems to go beyond machine protection (which is already a big deal for ITER), but finally makes the whole thing absolutely unattractive, so it should be kept in the list.
- 5. control: availability of sensors (diagnostics) and actuators (H&CD, fuelling systems) on DEMO will pose strong boundary conditions and should be treated in an integrated manner (together with the technology subtopic) for the 4 topics mentioned before. The DEMO scenario will have to be compatible with the available knobs!

It should be noted here that the stellarator promises to be advantageous compared to the tokamak in points 1, 2 and 4, but of course based on a data base that is far from the maturity of that of tokamaks.

# IV.2 Identification of analysis needed to define a proper programme to address the Physics issues

For the 5 issues identified above, the GROUP should develop a plan how they could be addressed in the EU fusion programme. Depending on available resources, the implementation of this strategy will then proceed. For the following analysis, we will not make assumptions on the amount of resources that could be available in the EU programme for this task, but try to develop a comprehensive approach. Implementation is then up to the political system, depending on the available resource and the pressure to develop fusion energy in a timely manner. As a guideline, the Group has taken the list of milestones outlined in the DEMO WG paper ('DEMO Development Programme, STAC 21/4.2) and expanded on it. However, when doing so it is obvious that in some areas, development of such a comprehensive plan requires further prior analysis. This mainly relates to the fact that we do not have a definition of the DEMO working point. As a possible input, one may imagine the PPCS A-D, but they may be on the high side in term of fusion power and a future DEMO Core Group (See Section VII) should spend some time to define our targets so that experts can start to look at a consistent solution. Only from such a (range of) credible scenario(s) can the EU programme be defined, and some work on this has been done for this work (Cf: Annex III 'On the minimum size of DEMO'). This study has suggested to de-emphasize the steady state conditions from a 'must' to 'highly desirable if we postulate that the operational parameters for DEMO must come from the bulk of the operational envelope of present day experiments. Based on this, we should assume that DEMO will operate in long-pulse (several hours), but not necessarily steady state. Furthermore, a minimum size of 7.5 m for an auxiliary heated machine and a radius of 9.5 m for a purely Ohmic-burn machine can be envisaged. The fusion power should be of the order 1.5 - 2 GW, with several 100 MW of net electrical output power.

Based on this, the high priority research needs can be formulated as follows:

**Steady state operation**: The DEMO operational point will need plasma performance beyond that proposed for the ITER Q=10 scenario, both for pulsed and steady state operation. The proposed programme should study how the two options for advanced tokamak operational scenarios, i.e. the hybrid and the reversed shear scenario, extrapolate to meet the goals. Only from these scenario studies can the future research programme be established since they will highlight where more research is clearly needed (e.g. pedestal physics). Boundary conditions will be set by issue 5, i.e. the scenario has to be controllable with the allowed diagnostic and actuators, issue 2 that will give an idea of the foreseen plasma density range and issue 3 that will prescribe an impurity mix needed for radiative divertor protection. There will have to be some iteration with issue 2 since the density determines the CD efficiency, which enters into Q. As argued above, steady state is still highly desirable but not considered mandatory. Therefore, Q will now come from a trade-off between pulse length and machine size. This can for DEMO be different to the commercial reactor, but to ensure that no intermediate ('PROTO') step is needed (as foreseen in the Fast track approach), it should be scaling with high credibility to an economically acceptable (e.g. by just stepping up plant size to allow a higher fraction of externally driven current).

What needs to be done	Priority	Start	Relation to ITER R&D	Timescale (Years)
Develop (by modelling) a range of credible pulsed DEMO scenarios. Address if auxiliary heating is needed to ignite an Ohmic pulsed DEMO.	1	Immediate	Scenario to be confirmed on ITER	2
Assess in experimental tokamak programme steady state operational scenarios with the aim to establish convincing integrated operational points. This calls for a substantial extension of the present envelope of tokamak operational regimes. Establish a scaling to DEMO.	1	Immediate	This task has a large synergy with the ongoing work to establish a steady state Q=5 scenario for ITER and confirm it in ITER operation.	15
Assess compatibility between pulsed and steady-state designs: is there a common design that would allow pulsed operation first and then steady state with improved plasma parameters?	1	Immediate	ITER will have to ultimately prove the assumptions about the operating scenarios.	1-2

**High density operation**: This issue interacts with at least issue 1 (where too high density will have drawbacks for CD efficiency) and issue 3 (where too low density will have drawbacks for the exhaust). Hence, in order to set a target for the density, interaction with 1 and 3 is needed. It is not clear that a consistent solution can be found that simultaneously satisfies all requirements in 1 and 3, and compromises may have to be taken. However, it is very likely that the target density lies above the Greenwald limit and hence the research programme will most likely address the understanding of the Greenwald limit and ways to overcome it reliably and with good plasma performance.

What needs to be done	Priority	Start	Relation to ITER R&D	Timescale (Years)
Understand Greenwald density limit $n_G$ . Incorporate experiments on stellarator (which overcome Greenwald limit easily).	1	Immediate	ITER will offer unique experimental possibility by allowing low collisionality and high Greenwald fraction simultaneously.	Unknown (physics research!)
Demonstrate tokamak operation at high density, possibly above Greenwald density limit n <sub>G</sub> .	1	Must be based on positive results from item above	Could widen ITER operational space	Unknown (physics research!)

**Exhaust**: This issue interacts with issue 2 since density will be crucial to determine power loads. Before a programme can be outlined, it should be discussed if geometric solutions other than the ITER SN are allowed from the design point of view. If so, a DN should be considered and it should also be assessed if an optimisation towards a 'Super-X solution' is possible<sup>1</sup>. Second, a number for the allowable heat flux arriving at the plates, together with it temporal variation due to ELMs, should be prescribed. Third, the pumping capacity must be prescribed. The development programme could then propose explorations of new divertor configurations as well as experiments aiming at demonstrating highly radiative divertor solutions compatible with issue 1. If ELMs are allowed at all, mitigation of ELMs should be addressed in light of issue 5 (available knobs).

What needs to be done	Priority	Start	Relation to ITER R&D	Timescale (Years)
Develop a range of credible exhaust scenarios for DEMO, including impact on core plasma (like seed impurities or separatrix density). Use 10 MW/m <sup>2</sup> as acceptable target load.	1	Immediate	Extrapolation from a programme that is being carried out for ITER.	10

<sup>&</sup>lt;sup>1</sup> Another discussion point is the Liquid Lithium divertor.

What needs to be done	Priority	Start	Relation to ITER R&D	Timescale (Years)
Assess physics of novel divertor concepts such as Super-X divertors	2	Immediate	Not foreseen for ITER at present.	10
Assess compatibility of novel divertor concepts with DEMO technical boundary conditions (like space for Super-X).	2	in parallel to physics assessment.	Not foreseen for ITER at present.	10

**Disruptions**: If we assume that any disruption will lead to an unacceptable interruption of operation, a disruption will always be a major accident and cannot be tolerated. Alternatively, it should be checked if there is a disruption that could be 'acceptable', i.e. what would be a target for mitigation that could allow a small number of disruptions. So while future programmes should of course address how to stay away from operational boundaries (which will come from issue 1) for avoidance, mitigation will have to be studied as well.

What needs to be done	Priority	Start	Relation to ITER R&D	Timescale (Years)
Establish acceptable disruption load conditions for DEMO.	1	Immediate	The work for ITER will be the starting point for this.	
Establish disruption		Following	Extrapolation from	
mitigation needs.	1	point above	ITER needs.	
Assess disruptivity as function of the position of the operational point relative to the operational boundaries (impacts on choice of operational point!).	2		May have consequences for ITER operation as well.	

**Integrated Control:** it will be necessary to establish first what sensors (diagnostics) and actuators (heating and fuelling, coil currents) will be available for DEMO. Then, issues 1 and 4 must undergo a reality check in light of the outcome. The table of requirements here interacts with the R&D issues surrounding Diagnostic and Control Technology (see section V.5).

What needs to be done	Priority	Start	Relation to ITER R&D	Timescale (Years)
Assess principal restrictions (e.g. accessibility) on DEMO H&CD systems from physics.	1	Immediate	This may still allow a certain system to be used on ITER (it is an experiment!).	5
Assess principal restrictions to diagnostics in DEMO.	1	Immediate	Work for ITER will address many of this; have to assess what comes on top.	5
Assess 'controllability' of plasma scenarios (i.e. how close is a stable operational point to an unstable one) taking into account points above.	1	Based on outcome of points above	ITER must validate these findings.	10

# IV.3 Stellarator physics issues

It is the opinion of the Group that first DEMO will be based on the tokamak concept. However, in view of the advantages of stellarators, the Group is of the opinion that physics studies for this concept should continue to be pursued vigorously as in the past to bring it to the required mature level if needed.

## **IV.3.1 Introduction**

Stellarators are intrinsically current free steady state devices with a significant number of advantages for a fusion reactor, as compared with the tokamak.

On the other hand stellarators still have to verify some of the basic reactor capabilities. Their development is of the order of  $1\frac{1}{2}$  device generations behind tokamaks.

## IV.3.2 Confinement

Due to the absence of axisymmetry, stellarators have larger neoclassical transport than tokamaks. In order to mitigate this effect different optimisation approaches have been developed. Some are based on inward shifting of the magnetic axis (LHD), quasisymmetries, (helical, HSX, toroidal, NCSX or poloidal, QPS) or multi-parameter optimization methods, of which W7AS and W7X would be the main examples.

Applying those approaches, experiments have shown that stellarators can achieve similar confinement values to L-mode tokamaks and even approach H-mode tokamaks of identical size and field [12]. Furthermore, theory and scaling extrapolations show that devices based on the W7X, and to some extent LHD,

philosophies would effectively confine alpha particles and reactor studies using the established stellarator scaling laws show that ignited reactors would be possible with reasonable dimensions and with investment costs similar to those based on the tokamak concept.

Another potential advantage of the stellarator would be the possibility to operate at high densities, demonstrated both in W7AS, which achieved  $4x10^{20}$  m<sup>-3</sup> and LHD, which recently achieved densities up to  $1.2x10^{21}$  m<sup>-3</sup>. Those high densities, if achievable in reactors, would lead to a higher efficiency, which might compensate the confinement and aspect ratio issues.

## **IV.3.3 Concept maturity and design convergence**

Taking plasma volume as an indicative parameter, the largest stellarators LHD and W7X are about three times smaller than JET and 30 times smaller than ITER and in terms of the fusion triple product, LHD has achieved  $5.2x10^{19}m^{-3}$  s keV (though at modest T<sub>i</sub> = 0,5 keV).

Highest beta values (at low field) have been also established by LHD ( $<\beta>=5,1\%$ ) as well as longest discharge duration: 54.8 min at 0,5MW, leading to an integrated energy of 1,7 GJ.

Another traditional element, which indicates maturity, is the design convergence, as it happens in tokamaks. In this case, the diversity of stellarator options is derived from the fact that configurations are fully three dimensional (as opposed to the two dimensional tokamaks) leading to a much larger range of solutions for the problem. On this respect, diversity makes the single choice towards the reactor more difficult but it provides as well the necessary degrees of freedom to find fully integrated scenarios. However the Group is of the opinion that a convergence must be reached before a credible DEMO stellarator can be proposed.

## IV.3.4 Physics and operational issues

The progress towards the stellarator reactor needs the solution to a number of physics and operational issues and it will be the task of the next generation of stellarators, in particular W7X, to develop and consolidate solutions to many of them. Among the pending issues we could outline three:

- Impurity accumulation. This is a direct consequence of the neoclassical theory and has been observed in all devices. Some operating regimes, like the HDH mode discovered at W7AS, offer a good energy confinement together with a favourable impurity confinement but there is no explanation to its origin and the possible extrapolation to a reactor regime is unclear. Reproducing the HDH mode, which empirically requires a high heating power density, and understanding its physics and reactor relevance should be one of the priority tasks for the stellarator community in the coming years.
- Power and density exhaust. W7X will test the island divertor concept, which offers good prospects, but the stability of its geometry will still depend on the accurate control of the bootstrap current. Beta effects on configuration will also be a potential perturbation. Other solutions are being tested at LHD (Local Island Divertor) or are under study (flux expansion divertor).

• Coil complexity and space for the blanket.

One of the consequences of the in-depth multi-parameter optimisation of the magnetic configuration is the need for complex coils and relatively small plasma-coil distances, which lead to restrictions for the design and implementation of the blanket. This problem could be alleviated if the optimization releases some of the restrictions (stability, iota profile could be examples) and the coil geometry parameters are included in the optimization loop. Those activities, which for the moment could be mainly based on theory and modelling are also a priority.

## IV.3.5 Time scales

As a comparative date, we take 2026, the D-T phase in ITER. By this time, the experimental stellarator programme, with W7X as leading device in operation for about ten years, will hopefully be on the way to solve many of the relevant problems, (fast particle confinement, stability, beta value, scaling laws...etc), together with the three main issues highlighted above. In parallel, theory and modelling as well as physics knowledge from tokamaks will have progressed towards the realization of realistic numerical experiments and the definition of a feasible reactor relevant configurations.

At this point, assuming a strong social demand for new energy sources and assuming that ITER has been successful, but that the steady state plasma issue remains a key consideration for DEMO, the chances for the construction of a DEMO stellarator in parallel to the DEMO tokamak could be significant.

# V Technology and Material Issues for DEMO

# V.1 Introduction

Beyond ITER there are still several major technology issues, which must be addressed and solved for DEMO, in particular with respect to:

- so-called 'Enabling Technologies'<sup>2</sup> (Remote Handling, Heating and Current Drive systems, Diagnostics and Control, Tritium processing and Superconducting Magnet Technology);
- materials characterisation (especially nuclear performance);
- the nuclear and engineering lifetime performance of in-vessel components, especially the Breeding Blankets necessary for the tritium self sufficiency requirements of operation and Divertor/Plasma Facing systems, that will be driven by the extreme heat and neutron loads.

<sup>&</sup>lt;sup>2</sup> As defined in the submission to the European Fusion Facilities Review: "The European Fusion Research Programme: Positioning, Strategic outlook and need for infrastructure towards DEMO Part I. Positioning and Strategic outlook" (2008)

Overarching considerations on all these systems are the maintenance, the efficiency requirements in terms of energy conversion and the availability that have to apply to a power plant. The main purpose of this report is to define from a general point of view what needs to be done towards DEMO.

The separate technology areas are considered with emphasis on the necessary or highly desirable developments, which should take place before the DEMO machine can finish its detailed design phase. For each area the high level issues are listed and links to the R&D already foreseen for addressing parts of these issues are indicated in three existing programme frameworks:

- where the issue is (or will be) addressed in the ITER programme;
- · where the issue is to be addressed in the existing EFDA workprogramme; or
- where the issue is the subject of a Broader Approach collaboration in the BA DEMO programme.

Where issues are not addressed in these programmes, this process establishes a gap analysis. For each area we give an indication of the timeline for an ongoing programme to address these gaps. The area sub-programme elements are also accompanied, where appropriate particular recommendations for by systems/concepts, which would be most appropriately tested in ITER Phase II, or alternatively, where a test in a dedicated test facility is needed. The duration of the timelines, and the details of their steps are not intended to be prescriptive, as the Group is firmly of the opinion that a definitive programme should be drawn up by a dedicated DEMO Team. The estimates made are considered, in order to provide a background for the first actions of this team.

## V.2 Heating and Current Drive System

The development of the heating and current drive (H&CD) systems required for DEMO with an overall efficiency (power to plasma/input electrical power) of at least 60% and an availability of about 90% in approximately 20 years represents a major challenge. The H&CD system has a very significant impact on plasma performance and on the overall power balance of the DEMO plant, and significant advancements in terms of efficiency, duty cycle, availability and reliability are required. For ITER three systems, the electron cyclotron resonance heating (ECRH), the ion cyclotron resonance heating (ICRH) and the neutral beam injection (NBI) are under development including large test facilities. For DEMO it is highly desirable to come to one H&CD system or at least to not more than two systems, with one system as priority solution and one backup system.

What needs to be done?	Priority	Start	Relation to existing R&D programmes	Duration (Years)
Reassess the capabilities of the different H&CD systems against clarified DEMO requirements	1	Immediate	Independent [there are some small EFDA Tasks under the H&CD Topic Group running currently].	2
R&D programme to improve 'wall-plug efficiency <sup>3</sup> of the candidate H&CD systems	1	After assessment	R&D programme will depend on H&CD scheme – for ICRF coupling studies to plasma are important, for NNBI beam line efficiency is key and for ECRH gyrotron efficiency should be enhanced (electron beam quality, multi- stage depressed collector) Survey of early concepts is in the EFDA programme	5-10
Development of high reliability and availability sources for different H&CD systems	1-2	After assessment After ITER full-size prototypes are realised.	Reliability gains will be made in ITER development (by 2020)	10-15
Demonstration of required wall-plug efficiency for DEMO candidate H&CD systems	2	After R&D programme to improve efficiency	See above.	10
Development of sources with highest possible unit power for different heating systems. <sup>4</sup>	2	In parallel with availability and high efficiency developments	Unit power development will be of benefit to ITER	10-15

<sup>&</sup>lt;sup>3</sup> Wall plug efficiency is defined as (power coupled to plasma)/(input power from electricity network)

<sup>&</sup>lt;sup>4</sup> Unit power here refers to the power through a single aperture in the DEMO blanket structure.

#### Comments

It is essential to increase the unit power and efficiency of the present day values and it is mandatory to develop a reliable and cost-efficient H&CD system for DEMO with high efficiency, availability and long lifetime. Although improvements will be made through ITER development, these issues are not well-addressed in the present ITER programme. For 'efficiency' improvements different class of developments is required for each of the three ITER H&CD systems and for LHCD. For NNBI and ECRH sources, the development can be largely carried out without a target tokamak plasma. For ICRH, proof of the coupling of developed systems' power will be required in tokamak experiments, the main gain coming from achieving coupling of launched power, overcoming plasma edge effects. For ECRH, the principal gain should come from the physics programme with establishment of plasma regimes with higher current drive efficiency and from efficiency and reliability enhancement of the sources. For LH, launcher concepts need to be developed and validated for effectiveness and functionality in DEMO environment

# V.3 In-vessel Components (Blankets, Divertors, manifolds supporting system and shield)

The development of in-vessel components and their integration in the reactor is a key task in the development of the DEMO. The two most important in-vessel components are:

- the Breeding Blankets, which should allow full tritium sufficiency;
- the Divertor.

The missions of the Blanket are:

- to breed tritium fuel efficiently from the 14 MeV neutron flux;
- to allow high efficiency recovery of the bred tritium into the processing plant to produce pure tritium fuel;
- to absorb the maximum possible fraction of 14 MeV neutron flux energy;
- to integrate primary circuit coolant systems to transport the heat produced in the blanket to the power plant 'steam generating circuits';
- to survive several (5+) years in the intense neutron environment with high integrity while keeping tritium and heat generation efficiency;
- to act as a primary nuclear shield for the vacuum vessel and magnetic coils.

The development of the Test Blanket Modules (TBM) for ITER will help to evaluate the different options. For the blanket the tritium breeding ratio and the neutron multiplication factor are important parameters that have to reach acceptable values for DEMO, and important information will be gained on these from the ITER TBM. The ITER TBM programme, will not however, qualify the system in nuclear terms, nor test the remote handling requirements for a reactor. The missions of the Divertor are:

- to exhaust the power from charged particles, and handle the resulting high heat fluxes on the divertor PFCs;
- to pump out ash;
- to recycle unburned fuel;
- to survive at least two years in the reactor (withstanding plasma erosion, nuclear damage and high heat flux) and be capable of remote handling removal and replacement...

The ITER programme is expected to test the tungsten divertor, currently the favourite candidate a reactor, but there are no current plans to test a high temperature coolant model divertor (which would help to provide at high efficiency some of the reactor heat to the turbines), nor to qualify the divertor materials from the nuclear standpoint. In addition, although the heat flux expected in DEMO is of order that of ITER (~10MW.m<sup>-2</sup>) demonstration of a higher capability would be highly desirable, while operation scenarios allowing limitation of the divertor heat load to lower values should also be explored.

As indicated, the described systems should be supported and feed with coolant. Layout of manifolds and pipes are critical issues. The development of in-vessel components is strongly linked to the development of materials. In this document we separate out the Materials development *per se* into section 3, whilst this section covers integration into a system, including fabrication and joining technologies.

What needs to be done?	Priority	Start	Relationship to existing R&D programmes	Timescale (Years)
Systems integration study of DEMO blanket taking into account tritium production and recovery, and thermo- hydraulics performance (in terms of pumping power and heat removal). Identification of key issues and technology – gap analysis compared to ITER TBM programme	1	Immediate	To proceed in parallel with ITER TBM conceptual design. Regular cross-referencing to ensure lessons learnt. Alternative concepts (water-cooled and dual coolant) should be considered	2-5
Assessment of alternative techniques for divertor	1	Immediate	Ongoing EFDA activity on Liquid Lithium divertor Some work on 'Super-X 'or Extended Divertor designs for MAST Upgrade.	2-5

What needs to be done?	Priority	Start	Relationship to existing R&D programmes	Timescale (Years)
Feasibility demonstration of manufacture and joint technologies for in vessel-components	1	Immediate. Potentially to be broadened after blanket and divertor assessme nt	For Blankets this is ongoing together with the TBM programme. Furthermore, there are on a minor scale existing BA tasks on manufacturing and joining technology for RAFM steels (KIT/JAERI)	2-5
Engineering development of DEMO divertor with long lifetime and excellent thermo- hydraulics performance.	1	Following assessme nt.	Divertor PFC material should be compatible with ITER tests – ensures an earlier DEMO [Suitable engineering and physics concepts should be tested in a Satellite Tokamak].	10-15
Assessment of the in- vessel components according to suitable integration and maintenance schemes and design codes and standards	1	<ul> <li>(i) For</li> <li>blanket,</li> <li>following</li> <li>assessme</li> <li>nt</li> <li>(ii) For</li> <li>divertor</li> <li>start</li> <li>should be</li> <li>start of</li> <li>engineerin</li> <li>g</li> <li>developme</li> <li>nt + 2</li> <li>years</li> </ul>	Ensure lessons learnt from ITER RH development schemes	2-5
In-core component integration: optimisation of supporting structure, manifold systems and shields	2	In parallel with integration and maintenan ce schemes work	Ensure lessons learnt from ITER design	2-5

What needs to be done?	Priority	Start	Relationship to existing R&D programmes	Timescale (Years)
Develop high temperature cooling technologies	3	Depends on assessme nts. And progress of work in Fission field. If started, should start ~ after jointing, integration and support work		10

### Comments

The development of a divertor for DEMO and of a tritium breeding blanket is essential and a long lead R&D item that needs to be started already now. Since the development of a suitable divertor concept for DEMO is one of the most risky items, there is a need to look at alternative design engineering concepts, or physics concepts, which can effectively reduce the incident power loading. If any successful concepts result from these studies, they should form the prime subject for test on a Satellite Tokamak.

# V.4 Tritium Handling System and Fuel Cycle

The use of self-sufficient breeding blankets in DEMO will require the integration of an outer part to the ITER type fuel cycle where large quantity of tritium should be extracted from the breeder and processed for fuel production. A challenge, which must be solved, will be upgrading the present fuel cycle technology to the requirements for DEMO because there are much higher tritium inventories and gas throughputs. The latter is a special challenge for fuelling and vacuum pumping systems.

What needs to be done?	Priority	Start	Relation to existing R&D programmes	Timescale (Years)
Develop an integral approach of the fuel cycle which interlinks fuelling and pumping systems with the plasma physics side	1	Immediate	This has to be solved for ITER – should have high ITER priority JAERI work in this area is part of BA tasks. First preliminary work has started in this direction in the EFDA programme.	2-5

What needs to be done?	Priority	Start	Relation to existing R&D programmes	Timescale (Years)
Develop systems to recover the tritium from self- sufficient tritium breeding systems with very large flow rates	2	Following success of integral approach concept	Goes beyond ITER, but ITER Phase II could provide a preliminary test bed	10-15
Develop detritiation systems for very large throughput and for in-vessel tritium	2	Following success of integral approach concept	Goes beyond ITER but ITER Phase II could provide a preliminary test bed.	10-15
Develop accountancy methods for tritium wastes and analytical tools for online tritium measurement	2	Once ITER DT experience is available.	ITER Phase I DT campaign can test out concepts JAERI work is part of BA tasks.	5-10
Develop and demonstrate high performance vacuum systems for quasi steady- state operation including tritium- compatible roughing pumps with minimized ultimate pressure at high gas throughputs	2	After the integral approach studies	Beyond ITER baseline with no coverage by existing R&D - concepts could be incorporated into the ITER Phase 2 DT programme.	5-10
Comments				
Reliable tritium hand	dling syste	ems and an eff	icient fuel cycle are a key toward	s DEMO

and first hardware R&D activities to cope with the DEMO requirements have to be started soon. The incorporation of experience from ITER Phase I, and the testing possibilities of ITER Phase II should be maximised.

# V.5 Diagnostics and Control

Plasma diagnostics have become increasingly used in the feedback control systems of tokamak plasmas. This trend seems set to continue into ITER. Extreme environmental conditions and limited accessibility combined with stringent requirements on reliability, maintainability and robustness are major challenges for the plasma diagnostics and associated plasma control system of DEMO. In

comparison to ITER, fewer diagnostics can be allocated in DEMO and due to the higher neutron flux many diagnostics that are marginally possible in ITER won't work in DEMO. In addition, as already indicated in section 2.1, there will be fewer *actuators* in the form of auxiliary H&CD systems and in-vessel coils in the output part of the plasma control system.

On the other hand, it is assumed that machine protection and the power plant control is similar either to ITER or to conventional power plant control systems, so that this part needs no special R&D for DEMO.

What needs to be done?	Pri	Start	Relationship to existing R&D programmes	Timescale (Years)
Screening of diagnostic techniques and methodologies and assess long lead diagnostics relevant R&D	1	Immediate	ITER design will inform the study	2
Assess novel approaches to feedback control of the plasma with 'sparse' data systems, and robust actuators.	1	Immediate		2
Develop further hardened versions of key 'essential minimum diagnostic set'	2	Following screening study	ITER design will inform study	5-10
Develop novel approaches to feedback control based on 'sparse' data etc	2	Following immediate assessment of problem.	The 'sparse' data control systems and the associated small diagnostic set should be tested on a Satellite Tokamak.	2-5
Develop novel diagnostic systems and their integration	2	Following feedback control developments	cc	5-10
Comments				

Power plant diagnostics and control are essential for a safe operation of DEMO and this topic should be incorporated in the DEMO design right from the start. The 'sparse' data control systems and the associated small diagnostic set should be tested on a Satellite Tokamak.

# V.6 Remote Handling

The ITER RH maintenance scheme, whilst it is suitable for ITER, and will drive many system developments of use to a power plant, cannot be the prototype of a power plant RH scheme because it will not meet with the power plant availability requirements. DEMO remote handling will benefit from the achievements for ITER, but it will also need a drastic decrease in maintenance requirements and system diversity in order to gain reactor availability. Moreover there are issues of scale of components (much bigger for DEMO), and radiation environment for the RH system's sensors (which will be much more severe than ITER's). A power plant-relevant maintenance scheme must therefore be developed and it will have to be validated in DEMO, after dedicated test bed exercises. The remote handling system has a large impact on the design of the in-vessel components.

What needs to be done?	Priority	Start	Relation to existing R&D programmes	Timescale (Years)
Pre-conceptual design study and consequence on overall system – as part of the Blanket and Divertor systems integration studies	1	Immediate		2
Conceptual definition of DEMO maintenance scheme	1	Following pre-concept		2-5
Development of radiation hard sensing systems and associated feedback	2	Following pre-concept	Some benefit from ITER RH R&D phase.	5-10
Development programme focussing on high availability and optimised RH systems	2	Following conceptual definition		10
Demonstrate full-scale feasibility of DEMO maintenance procedure on test bed	2	Following concept and sensor development stages		10-15
Comments				
The remote handling sy and the design of the in	stem is -vessel	of great import components. T	ance and has a large impact o his has to be addressed in an	n the mainte early stage

DEMO conceptual design.

# V.7 Superconducting Magnets

ITER is expected to validate the reactor-scale use of low-temperature (Nb<sub>3</sub>Sn, NbTi) superconducting magnets. On the other hand, the use of high temperature superconductors (HTS) for magnets would have the following benefits:

- allow operation at higher temperature, resulting in significantly reduced cryogenic power consumption for magnet cooling and shielding, thus raising the efficiency of the fusion power plant (increase in overall efficiency is within a few percent points);
- considerable saving in cooling system investment is expected;
- HTS magnets would increase the stability of the magnet system and decrease the complexity of the machine and constraints linked to the cryogenic vacuum;
- the problem of future He shortage would be addressed if magnets that can be cooled with LNe or subcooled  $LN_2$  can be developed.

The use of 2<sup>nd</sup> Generation HTS wires and tapes could promise less expensive fusion magnets in future since this material has already proven its capability and is very attractive for application in superconducting power devices (e.g. cables, motors, current limiters).

What needs to be done?	Pri	Start	rt Relationship to existing R&D programmes				
Clarify DEMO objectives and evaluate the impact of HTS magnets with respect to the scope for system simplification.	1	Immediate		2			
Evaluate magnetic field strength effects on feasibility of use of HTS magnets and clarify development needs	1	Following clarification exercise.	National activities for investigating HTS material properties with respect to Fusion requirements have started recently in Germany, Japan and US	1-2			
Develop suitable cabling concept for HTS Fusion magnets taking into account loss, cost and manufacturing	2	Following from clarification and evaluation		5-10			
Demonstrate sub-size model coils as proof of principle	2	Once cabling concept development at a mature stage		5-10			
Demonstrate full prototype or model coil	3	Once sub- size model coil passes tests		10-15			

## Comments

In principle DEMO can be built with low temperature superconducting magnets but the long-term impact of HTS on magnets for Fusion is high and their application seems very attractive. A milestone oriented R&D activity should be started soon The demonstration of model coils requires only 'engineering test beds' and not demonstration on a full-scale tokamak.

# V.8 MATERIALS

The development and qualification of materials for plasma in-vessel components is a critical requirement on the path to fusion power. Major power plant requirements like environmental compatibility, safety, cost-effectiveness, reliability and sustainability have a strong impact on the materials involved. Important selection criteria for materials are:

- Low activation<sup>5</sup>
- Low level waste
- Sufficient temperature window
- Performance and lifetime6
- Attractive physical and mechanical properties
- High radiation resistance
- Reliable manufacturing processes.

The long-term objective of the Materials programme, culminating in DEMO should be to develop and qualify for a Fusion Power Plant structural as well as armour and functional materials in combination with the necessary production, manufacturing and component fabrication technologies.

The International Fusion Materials Irradiation Facility (IFMIF), with a fusion specific neutron spectrum, is a crucial pillar in fusion material development, and it is assumed that it will be available for full demonstration of performance and qualification of materials to be used in DEMO.

While in ITER the maximum damage level achieved by any structural material is of the order of a few displacements per atom (dpa), the structural materials of DEMO reactors will operate up to much higher damage levels (~50-100 dpa), with accompanying helium and hydrogen production enhancing embrittlement, and a reactor first wall should ideally survive even higher values. Moreover, in the interest of thermodynamic efficiency, and hence economically attractive reactors, the operational temperature window of structural materials to be developed should be as high as possible.

<sup>&</sup>lt;sup>5</sup> A key point in this criterion, which should be understood is the requirement that new candidate alloys of metals should not increase activation.

<sup>&</sup>lt;sup>6</sup> Note that transmutation of alloying materials should not be significant over the lifetime of a component.

One of the major issues for the development of required materials in the programme will be the characterization and qualification under fusion-like environments. This qualification will be only possible in IFMIF, which will provide a fusion specific neutron spectrum and will be a crucial pillar in fusion material development. It is assumed that IFMIF will be available for full demonstration of performance and qualification of materials to be used in DEMO. In the mean time a significant programme of irradiations using other irradiations sources (fision reactors, single, double and triple beam ion irradiations, ...) will be required and it shoul be complemented with a significant modelling effort in order to develop the capability of predict the material behaviour under different environments.

The necessary knowledge basis should be developed not only for the bulk material but also for other materials technology aspects like weldings and joining techniques.

The reduced activation ferritic martensitic (RAFM) steel EUROFER, being developed in F4E under ITER TBM program and in the frame of the Broader Approach activities, has been produced in large quantities and characterised un-irradiated and in irradiation campaigns up to 80dpa in fission-like environments. Various joining techniques have been developed for TBM mock-up fabrication. Current R&D activities focus on advanced joining techniques, on further characterization under irradiation, and on the completion of the data base for TBM design and licensing.

Degradation of EUROFER properties under neutron irradiation, enhanced by substantial production of He and H, and maximum operating temperature limited to ~550°C jeopardizes the use of EUROFER in DEMO. EUROFER-ODS (oxide dispersion strengthened), with maximum operating temperature extending to ~650°C, could be used to complement to EUROFER structure at "hot spots" and is presently considered for alternative test blanket concepts.

However, the first wall/blanket and divertor structural material in DEMO must have sufficient creep strength in the temperature range of up to ~750°C with reasonable fracture toughness. ODS ferritic steels with such properties can be obtained and presently represent a good candidate for this application, as they have wider temperature window and potential for higher radiation resistance. They are presently still very brittle at room temperatures and in an early phase of development in EFDA.

 $SiC_f/SiC$  composite is also foreseen as structural material for high temperature tritiumbreeding blankets in Power Plants. But for its possible use some basic questions (like the degradation of mechanical and physical properties during irradiation or like the availability of joining processes) have first to be answered. Therefore, the use of  $SiC_f/SiC$  for structural applications has been shifted beyond DEMO on the roadmap.

Tungsten is increasingly seen as the best plasma facing material because of its low sputtering/erosion yield and its inherently low retention of tritium. These qualities are currently being tested on ASDEX-U and will be tested at higher performance in the EFDA programme on JET. Beyond that, tungsten and tungsten alloys are presently considered in EFDA program for helium cooled divertor and possibly for the protection of the helium cooled first wall in DEMO designs, mainly because of their high temperature strength, good thermal conductivity, and low sputter rates. The two types

of applications envisaged for these materials: the use as plasma-facing armour or shield component, and the use as a structural material, require quite different properties. An armour material needs high crack resistance under extreme thermal operation condition while a structural material has to be ductile within the operation temperature range. Both material types have also to be stable with respect to high neutron irradiation and helium production rates.

However, tungsten alloy development for possible use as structural divertor material is very ambitious. At the same time, the requirements depend strongly on the underlying divertor design. Since presently there is no final DEMO divertor concept available, it might be useful to develop a fall-back option that is based on alternative refractory materials. Furthermore, it is unlikely that brazing materials for divertor components will ever fulfill the low-activation criteria. Therefore, similar (less stringent) activation criteria should also be applied to the structural refractory material development in order to increase the chance of success. This could also open options for efficient and more realistic DEMO divertor designs.

In addition to above structural and armour materials, there is the need to develop functional materials. In the blanket programme these are neutron multipliers (e.g. Beryllium and its alloys, Pb-Li), tritium breeders (Li ceramics), materials for thermal and electrical insulation (SiC<sub>f</sub>/SiC,), for Tritium barriers and for coatings against corrosion. Outside the blanket programme, insulator materials would still play an important role in DEMO e.g. diagnostics and H&CD systems. A significant experience is being gained for ITER; however, conditions will be more severe in DEMO due to the much larger neutron fluence.

What needs to be done?	Pri	Start	Relationship with the existing R&D program	Times (Yea <u>rs</u>
Assessment of blanket and divertor operation parameters in DEMO conditions and of availability	1	Immediate	{In conjunction with the 'systems integration' study for the Blanket –see section 2.2.}	2
Completion of EUROFER characterisation qualification. Further optimisation towards potential use in DEMO	1	Immediate	In F4E under material program {Required by the ITER TBM programme.}	10
Qualification of EUROFER ODS	1	In time for the IFMI programme	In F4E under material program	10
Development and specification of Optimised ODS ferritic steels with demonstrated strength/creep properties under irradiation.	1	Immediate	First steps are in EFDA Materials programme	5

What needs to be done?	Pri	Start	Relationship with the existing R&D program		
Development and characterization of W/W alloys structural materials and of fabrication processes (including high temperature brazing). Assessment of feasibility, problems or restrictions, including possibility of other (slightly higher activation) refractory material solutions.	1	Immediate	Under EFDA Materials programme.	5	
Characterization, optimization of W/W-alloy structural material and testing (or alternatives identified in development/feasibility programme).	1	Ideally should await development feasibility programme	Elements already proposed under Materials programme.	2	
Armour material optimisation and high heat flux testing	1	Ideally should await develop- ment of brazing and jointing methods	Elements already proposed under EFDA Materials programme.	2	
Qualification of structural armour materials (IFMIF), data base production for detailed design and licensing.	2	IFMIF first operations stage.		5	
Materials science and modelling to provide knowledge on basic material degradation mechanisms, and assist the material development work, including benchman experiments.	1	In parallel with developments	Elements already under proposed EFDA programme.	5-10	
Production, characterisation and reprocessing of advanced breeder and other functional materials	2	Broader Approach	In Broader Approach programme.	2-5	

What needs to be done?	Pri	Start	Relationship with the existing R&D program	Times (Years				
Production and characterisation of advanced neutron multiplier materials	2	Broader Approach	In Broader Approach programme	2-5				
Qualification of blanket functional materials, data base production for detailed design and licens		In continuation of development phase		10				
Comments				_				
Industrial production of structural and functional materials must be demonstrated in the run up to the IFMIF qualification stage, or, in the case of EUROFER, in the preparation of the TBM programme.								

## V.9 Power Plant

## V.9.1 Safety and Licensing

Since DEMO requires a number of new technology and components, their safe integration and licensing is a key issue for future Fusion power plants.

A key issue will be the level of "Remote Handlable" recycling of waste, or its longerterm disposal. These issues are addressed by the priorities of the Materials programme (see section IV-5).

What needs to be done?	Pri	Start	Relationship to existing R&D programmes	Timescale (Years)
Integrate safety and licence requirements into DEMO design process	2	After the immediate pre- conceptual studies and the completion of the ITER RPrS <sup>7</sup>	ITER experience will be essential to this. It is likely that this will develop in time.	10
Specific effort in control of tritium release, critical element if T allowed levels are reduced by international standards and regulators.	3		Must be completed before DEMO Conceptual Design phase ends. Special systems could then be tested in ITER Phase II	5
Comments				
The ITED sofety and li	oonoi	na process has to be	followed and the lessons les	rnod from

The ITER safety and licensing process has to be followed and the lessons learned from this process have to be considered for DEMO. Activities shall start in due time.

<sup>&</sup>lt;sup>7</sup> RPrS – Rapport Préliminaire de Sûreté

# V.9.2 Steady State Electricity Production

It has to be clarified if DEMO is operated in a continuous mode or long pulse operation mode. This has a strong impact on the steady state electricity production. In any case, the steady state electricity production has to be shown with high reliability and availability. A pulsed machine will require energy storage. We do not recommend a separate fusion-based activity on energy storage systems, as it is inevitable that the development of these will be necessary to accompany the implementation of Renewable Energy networks. A 'watching brief' should be kept by EFDA on these activities, and the DEMO concept should incorporate developments.

What needs to be done?	Pri	Start	Relationship to existing R&D programmes	Timescale (Years)				
Clarify DEMO objectives in terms of pulsed or steady state operation.	1	Immediate		2				
Include storage options as part of Balance of Plant in case of long pulse operation	3	As required for EDA time plan	Note there is an extensive, and applicable Molten salt storage programme associated with Solar power.	5				
Comments								
Energy storage options can be considered in time. There is no need of R&D work of the Fusion community on this issue in the short and mid-term perspective.								

# V.9.3 Availability and Efficiency

Fusion power plants will have many systems with high complexity and it is a main challenge to achieve required (high) availability and efficiency levels. A major purpose of DEMO will be to qualify components and processes in reactor relevant conditions. The machine availability is a key parameter to ensure that adequate fluences will be delivered to conduct these tests. In addition, availability and efficiency are key factors driving strongly the cost of electricity of future fusion power plants. For these two reasons, efforts towards higher availability and efficiency should be made very early in setting and conducting the DEMO R&D programme. The principle areas where high impact research can be carried out are the H&CD (for efficiency) and Remote Handling (for availability and maintenance) topics, and so the main actions here are covered in sections 2.1 and 2.5.

In a fusion power plant, the efficiency is determined by many physics and technology issues. The main objective of DEMO with respect to efficiency is to demonstrate an acceptable value for the efficiency of the power plant and specific systems and processes, taking into account that DEMO is not yet a first of kind FPP. It has to be considered that there is strong relation between performance and reliability and that a trade-off has to be found for DEMO.

What needs to be done?	Pri	Start	Relationship to existing R&D programmes	Timescale (years)					
Increase efficiency of systems and processes with high impact (e.g. H&CD systems which has to be increased from 20– 40% today to about 60–70%)	1	See H&CD sections		10-15					
Scope study which are critical elements in terms of reliability and efficiency	2	After initial scoping and assessment studies of the individual technologies		2					
Modelling of the full plant taking into account availability of materials and systems and efficiency of processes	3	Beginning of next Framework programme		5					
cher									
It is of high importance DEMO.	to fro	om an integrated tean	n to assess reliability and ef	ficiency issues					

# V.10 Summary and Recommendations

For the next step beyond ITER there are still many technology and materials challenges to be solved for DEMO and on the way towards commercial fusion power plants.

It is recommended that an immediate start should be undertaken by a DEMO Core Group (See Section VII). This DEMO Core Group would be charged with a concept and scoping assessment. From discussions above, the elements of this assessment would be:

- assessment of existing H&CD system capabilities against DEMO requirements;
- systems integration study of the blanket, with key technology issue identification, and gap analysis against the existing TBM programme;
- assessment of alternative divertor concepts/technologies;
- development of integral approach to the fuel cycle and vacuum pumping (note that this is essential in any case for ITER and some synergy of effort should be sought here);
- screening of diagnostic techniques, with identification of long-lead relevant R&D requirements;

- assessment of novel approaches to feedback control with 'sparse' data and actuator configurations;
- clarification of DEMO objectives to evaluate the impact of HTS magnets wrt the scope for system simplification
- pre-conceptual Remote Handling design study with overall system impact identification;
- materials assessment of Divertor and Blanket DEMO operation conditions and availability.
- clarification of DEMO objectives with respect to the requirements of pulse or steady-state operation.

In addition there are already specific activities in:

- Materials (see section IV-8);
- He-cooled divertors and moving target divertor concepts.

These have been identified and approved as programme priorities and should continue.

It is proposed that the Pre- Conceptual Design activity should last for two years and then after review, the R&D programme instigated, and the DEMO Design Team should be constituted.

The exact R&D programme would flow from acceptance of the Pre- Conceptual Design report.

# VI On a possible time scale for IFMIF<sup>8</sup>

The main objective of IFMIF is to provide the information needed for the qualification of the materials behaviour after the high dose and dose rate neutron environment of DEMO and of a fusion reactor.

In order to define when it is needed to make the decision to build IFMIF, the following assumptions are made:

- 1) Construction of DEMO will take 10 years
- 2) The data produced by IFMIF are required at the beginning of the Detailed Engineering Phase of DEMO in order to confirm the conceptual design previously made. This Detailed Engineering Phase is assumed to take about 5 years.

<sup>&</sup>lt;sup>8</sup> As an introductory remark, the discussion presented here is based on information provided by colleagues presently involved in the IFMIF-EVEDA project. They are not fully compatible with the present "official" schedule of IFMIF or operational procedures. These documents are presently under discussion and they will likely be updated in the future to take into account the expertise gained during the EVEDA phase.

- 3) Construction time of IFMIF can be around 8 years (see the paper prepared by EFDA in 2005<sup>9</sup>) although 2-3 additional years must be taken into account to reach fully operational regime (as the case of SNS has shown).
- 4) DEMO will be also developed in phases with a low neutron dose initial phase. In that case it can be assumed that the maximum neutron dose for structural materials will be reduced to around 40-50 dpa in this phase. That means IFMIF will only be required to irradiate samples up to this dose initially (although later on it must be able to reach higher doses<sup>10</sup>). Irradiation time required to reach this radiation level in IFMIF will be around 2 years, assuming it is fully operational, and 1 additional year for the characterization of the main irradiation results.

All these assumptions means the decision to build IFMIF must be taken around 28-30 years before the start of the DEMO operation, or 15 years before the critical date in which the materials data are needed.

Presently the EVEDA (Engineering Validation and Engineering Design Activities) phase of IFMIF is being developed in the framework of the EU-Japan Bilateral Agreement for the Broader Approach to Fusion. This phase will be finished by the end of 2014 and, although it can be considered that the Prototype Accelerator being built in Japan can be operated during longer time in order to gain additional expertise, the decision to build IFMIF can be taken at that moment.

If this is the case, IFMIF can be built in between 2015 and 2022, it will be fully operational in 2025 and the first database of DEMO (1<sup>st</sup> phase) materials data can be produced around 2028.

In the conclusion of the Specifications Working Group organized in the framework of the Broader Approach Agreement in order to update the main Specification of IFMIF taking into account the users point of view, new objectives linked to the TBM programme of ITER are identified with additional time schedule requirements. These additional objectives, less critical than those defined previously, require IFMIF to be operational at low neutron dose rate and low availability a few years before the D-T phase of ITER. The Group was just made aware about such conclusions and did not assess these new objectives, but notes that this requirement is compatible with the time schedule previously discussed.

Taking all this into account, IFMIF is very close to be on the critical path to DEMO and the decision to build IFMIF, as well as the decision on the site, must be taken before the end of the EVEDA phase (i.e. in 2013 or 2014). This early decision on the site will also make the engineering work to be developed during the EVEDA phase much more useful because it would be possible to take into account the possible site characteristics in the different studies to be carried out.

This estimation is based on the fact that, for insuring a continuation of the project and avoiding any gap or interruption, which could jeopardize the whole process, the

<sup>&</sup>lt;sup>9</sup> European Alternatives for the IFMIF AHG (EU and JA)

<sup>&</sup>lt;sup>10</sup> 80 dpa in the case of the DEMO second phase or even 150-200 dpa in the case of the Fusion Reactor materials

phase of construction and commissioning of IFMIF should follow directly the end of the EVEDA phase.

In summary, it is recommended that considerations on site selection and on the decision to build IFMIF be started so that its construction could be performed right after the end of EVEDA phase, i.e. around 2014.

# VII Proposal for a Core DEMO Group and estimate of cost

In this Section, the Group attempted to answer to the following points in the Terms of reference:

- The establishment of an on-going working group should be established, composed of individuals prepared to devote substantial amounts of time to addressing issues related to the design of DEMO, possibly with a high level steering group, which could include representatives of industry.
- The level resources needed.

The Group regrets that all EU design activities related to DEMO, to FPP, and to alternative concepts, were brought to practically a halt in 2008, primarily because of lack of resources. This Group also notes that emerging technology R&D activities for DEMO have also been strongly reduced and are effectively limited to TBMs (under the responsibility of F4E), to advanced materials (responsibility shared between F4E for the BA-IFERC-DEMO R&D tasks and EFDA for other tasks), and to He-cooled divertor concepts (under the responsibility of EFDA). EFDA work on H&CD, on diagnostics, and on dust & tritium, although considered as emerging technologies, is more ITER relevant than DEMO relevant. Tasks on subjects as important as high temperature superconductors have been put on hold pending a clarification of the EU strategy and budget related to DEMO. During the last 2 years work on emerging technologies has effectively been left to the initiative of the Associates. Roughly, 55 millions € were devoted to emerging technologies (ITER relevant and DEMO relevant) by the Associates in 2008, with an average Commission contribution of 18%.

Considering the long term, the Group recalls the recommendations of the SET-Plan Hearing. In the short and medium term, i.e. for the period till end 2013, it recommends to avoid any fragmentation of the European DEMO activities in order to ensure an efficient use of the resources that will be made available. It recommends that all EU DEMO related activities to be carried out during the ITER construction period be coordinated, technically, by a" DEMO Core Group" in EFDA of about 3 to 5 professionals.

It further recommends that the EFDA "DEMO Core Group" be set up as soon as practicable in 2010 in order to:

• Specify DEMO design activities to be carried out until the end of 2013, as outlined in this report The design activities should include as first priority, conceptual design work on a DEMO tokamak concept. The feasibility assessment of a stellarator FPP and of a CTF and the role of the latter in the

realisation of fusion could also be addressed (Cf. Annex III, "Strengthening the Fast Track and reducing Risk").

Perform other duties as charged by the EFDA Leader, such as the coordination of all European R&D on emerging technologies and physics activities outlined above. Such a role is analogous to the one of played by the EFDA CSU team during the Fusion Power Plant Study in the late 90's – early 2000's. If requested, the DEMO Core Group could also be charged of other tasks, upon request by the F4E Governing Board and/or F4E Management, and the CCE-Fu.

These activities of the DEMO Core Group should be consistent with the European obligations arising from our participation to the BA-IFERC project. The structure and the scope of the BA-IFERC DEMO design activities are currently being defined by a joint EU-JA group<sup>11</sup>.

The Group also recalls that, in the past the EFDA CSU team, which actually defined and coordinated the DEMO activities, was advised by a panel of experts (the so called DEMO Working Group, DWG). This Panel included experts in technology and physics. It also received the advise of industry (mainly Utilities) on a ad hoc basis. In view of the positive contribution of the DWG of this structure, it is recommended that a similar Group (called the" high level Steering Group" in the Terms of Reference), be established to advise the DEMO Core Group and the EFDA Leader. Preliminary contacts with industry indicate that industry may be willing to join this Steering Group. This approach should be further explored.

The Group considers that 60MEUR/yr should be devoted to DEMO for design and R&D (excluding the TBMs, currently under the responsibility of F4E) during 2012-2013. Approximately 15 M€/yr should be devoted to design work and 45 M€/yr to R&D on emerging technologies. Assuming a Commission share of 33%, this corresponds to a Commission contribution of 20MEUR/yr. Resources should also be made available during the end of the current FP in order to launch as many priority 1 activities in Physics and Technology as possible. For 2011, this Group recommends that 30M € be devoted to DEMO activities.

# VIII BA activities

During the course of its activities, the Group was informed about the DEMO activities in the frame of BA. Through two of its members (Mrs S. Clement Lorenzo and Mr. D. Maisonnier) information on the status of the work of the Group and of the discussion with Japan was brought to its attention.

Presently, it is agreed between EU and Japan that during the next phase of the DEMO Joint Work, will be subdivided into 3 Phases: Phase-2a includes the definition of DEMO technical requirements (~3 years), Phase-2b the analysis of possible

<sup>&</sup>lt;sup>11</sup> These activities are currently being drafted by a joint EU-JA group and they will be submitted for approval to the BA Steering Committee on 28-04-2010.

engineering choice (~2 years), and Phase-2c the Conceptual Design Activities (CDA) of one or two (or three) possible DEMO concepts.

It is therefore proposed that the DEMO Core Group be entrusted with the task to start the various assessments (Section IV and V) and the definition of a possible DEMO concept. This would then allow the EU to continue a fruitful dialog with our Japanese counterpart in this field.

# IX Conclusion and recommendations

The Group is firmly convinced that it is appropriate for the EU to give a new impetus to DEMO activities now. As foreseen in the Fast Track, DEMO will be the last step before the first fusion power plant. During some phase of its exploitation, it will produce a significant amount of electricity to the grid. It will also serve to qualify key components for the first fusion power plant.

Albeit the Group agrees that DEMO will be a tokamak, it stresses the importance to pursue a vigorous stellarator programme in view of the inherent benefit of this concept.

Five main physics issues were identified: steady-state tokamak operation, operation at high density, power exhaust, disruptions and control. A prioritized list of activities was proposed to address these issues.

A similar approach was followed for technology. The fields of R&D encompasses H&CD technology, In vessel components, Tritium handling system and Fuel cycle, Diagnostics and Control, Remote Handling, Superconducting magnets, Materials, Power plant and General Issue about Availability and Efficiency. It is important to note that among these fields, the Group wishes to mention that divertor and maintenance deserve high priority attention in future programmes. A rather detailed list of activities could be found in the text.

It is also important to note the deep interplay between technology and physics scenarios and that during the following work of the DEMO Core Group to establish a pre-conceptual design of DEMO both aspects have to be considered together.

As another follow up action, the Group strongly recommends the establishment of a DEMO Core Team under EFDA of a 3-5 professionals, with the immediate mission to specify DEMO design activities to be carried out until the end of 2013, as outline in this report. These activities should be consistent with the European obligations arising from our participation to the BA-IFERC project, which are currently being drafted by a joint EU-JA group and which will be submitted for approval to the BA SC. The design activities should include as first priority, conceptual design work on a DEMO tokamak concept. In the frame of such studies, the feasibility assessment of a stellarator FPP and of a CTF and the role of the latter in the realisation of fusion could also be addressed.

Regarding IFMIF, the Group considers that IFMIF is very close to be in the critical path to DEMO and the decision to build IFMIF, as well as the decision on the site, must be taken before the end of the EVEDA phase (i.e. in 2013 or 2014). This early decision on the site will also make the engineering work to be develop during the EVEDA phase much more useful because it would be possible to take into account the possible site characteristics in the different studies to be carried out.

The Group considers that  $60M \notin$ /yr should be devoted to DEMO for design and R&D (excluding the TBMs, currently under the responsibility of F4E) during 2012-2013. Approximately 15 M $\notin$ /yr should be devoted to design work and 45 M $\notin$ /yr to R&D on emerging technologies. Assuming a Commission share of 33%, this corresponds to a Commission contribution of 20M $\notin$ /yr. Resources should also be made available during the end of the current FP in order to launch as many priority 1 activities in Physics and Technology as possible. For 2011, the Group recommends that 30M  $\notin$  be devoted to DEMO activities.

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# Annex 1

# JOINT CCE-FU-F4E GB WORKING GROUP ON DEMO Terms of Reference EUR (09) CCE-FU 46/3c

The CCE-FU and the F4E Governing Board establish a Joint Working Group to conduct an assessment on the urgent elements of fusion energy research activities and facilities required during the timeframe of the ITER construction to acquire the knowledge necessary to build the first demonstrator fusion power plant (DEMO) within the fast tack framework.

The WG will take into account:

- The EU obligations and opportunities arising from the Broader Approach agreement with Japan (in relation to both DEMO and IFMIF EVEDA);
- The report of the Fusion Facilities Review Panel;
- The European Strategic Energy Technology Plan (SET-Plan);
- Previous European exercises such as the work of the EFDA DEMO Working Group (Fusion Development Strategy – paper EFDA(07)-33/4.8, DEMO Development Programme – paper STAC 21-4.2), and the progress of ITERrelevant work such as the TBM programme.
- Knowledge of the strategy and programmes elsewhere in the world.

It will seek updated relevant input from F4E and EFDA where appropriate.

The Joint Working Group shall:

- Assess the physics-basis and the technology-basis that shall be required to build a first fusion power plant;
- Summarise from previous exercises and updated information where appropriate the relevant existing or planned national efforts that contribute already to this objective, including BA and TBM work, , and present an analysis of the gaps;
- Identify or confirm those priority research activities and facilities that should be started immediately and those that should be planned over the next 10 years, and indicate a possible schedule to launch design activities;
- Comment on the timetable for choosing a site for IFMIF and beginning construction in the light of the likely timetable for ITER and the possible timetable for DEMO;
- Identify the resources needed and present arguments for making them available bearing in mind the general constraints on research funding (in doing so, the group will assess the potential participation of the Associates, without

presupposing any allocation of funding between the EU, research organisations and member states).

 Identify possible follow-up measures to the work by this Group. In particular, the Group should consider whether an on-going working group should be established, composed of individuals prepared to devote substantial amounts of time to addressing issues related to the design of DEMO, possibly with a high level steering group, which could include representatives of industry.

The Group shall also assess the activities to be conducted in Europe, during the timeframe of the ITER construction in order to fulfil the EU obligations in the IFERC project of the Broader Approach regarding DEMO, and to prepare for the DEMO project phase according the F4E objective, which should be fulfilled in the medium to long term. The Group should address in particular the following questions:

- How to fulfil the EU obligations in the IFERC project of Broader Approach regarding DEMO design?
- What parts of the R&D are not covered by the current DEMO R&D programme performed under Broader Approach by the Voluntary contributors?
- What preparatory activities should be performed in collaboration with existing activities sponsored through national efforts or through EFDA, and later be contracted directly to fill gaps in the overall long term strategy to build the first power plant in Europe?

The members will be nominated by the Chairs of the CCE-FU and the F4E GB in consultation with the TAP Chair and the EFDA SC Chair.

The Group will present an interim report to the F4E GB in September, a status report to the CCE-FU at its October meeting and a final report in January.

## Annex II

# On the minimum size of DEMO

## H. Zohm

## 1.) Introduction

DEMO as the single step between ITER and a commercial reactor has various tasks and a definition is being worked out by the F4E/CCE-Fu Working Group. While we have not yet agreed on such a definition, a preliminary high-level version compatible with our discussions so far could be

- 1. Demonstrate a workable solution for all physics and technology questions
- 2. Demonstrate large scale net electricity production with self-sufficient fuel supply
- 3. Demonstrate high availability and reliability operation over a reasonable time span.
- 4. Allow to assess the economic prospects of a power plant

Of course, these are sufficiently vague to not define the size of DEMO. A recent comparison of different DEMO options compiled by K. Lackner shown below indicates that present designs all assume a power level of at least 1 GW net electric, the only exception being DEMO CREST which targets a range of net electrical powers between 0 and 600 MW.

study	WARD: pulsed	WARD: partial CD, pulsed	WARD: partial CD, pulsed reduced y <sub>CD</sub>	WARD: s-s	WARD: s-s reduced γ <sub>CD</sub>	Garcia: pulsed	Garcia: NBI-only s-s	Garcia: NBI/ECCD 5-5	Pereverzev: s-s	Pacher pulsed (<50000s)	DEMO-S (RF)	DEMO-JAERI slim CS	DEMO- CREST OP4	ITER s-s:scenario 4-2	ARIES-AT
methodology /transport model			system code			CRONOS	plasma model	ing/GLF23	ASTRA plasma modelling/GLF	ASTRA plasma modelling /MMM95/ with ITP	point design	system code, point design	system code	ONETWO & CRONOS plasma modelling	point design
Pther=1.18Ptus	2.4	2.9	3.1	3.3	3.3	3	3	3.3	2.5		2.9	3.6	3.3	0,36 (no blanket enhance.)	1.9
P <sub>elec</sub> (net output)	1	1	1	1	1	~1(n.c.)	~1(n.c.)	~1(n.c.)	n.c.	n.c.	0,6-0,7	1	0.49	n.a.	1
R,	9.55	7.1	7.8	6.91	8.77	7.5	7.5	7.5	7.5	8.1	7.8	5.5	7.25	6.2	5.2
A	4	4	4	3	3	3	3	3	3	2.9	5.2	2.6	3.4	3.1	4
Bt	7.4	7.6	7.6	5.8	6.5	6	6	6	6	5.7	7.7	6	7.8	5.3	5.9
l <sub>p</sub>	15.5	14.2	14.6	19	19.2	19	19	19	16	18	11.2	16.6	14.7	9	12.8
W <sub>magn</sub> [GJ]	40	17?	26?	16	42	22.5	22.5	22.5	22.5	27	14	12	27	9.3	4
fot	0.43	0.6	0.66	0.44	0.555	0.53	0.53	0.56	0.56	0.61	0.59	0.77	0.5	0.6	0.91
Υσο	n.a.	0.5	0.1	0.44	0.29	0.52	0.52	0,52/0.2	0.56	0.7	0.47	0.41	0.3	0,45/0,2	0,4 (based on <n>)</n>
н	1.3	1.2	1.2	1.05	1.3	no ITB, hi	gh pedestal te	mperature	ITB,low pedestal temperature		1 (RS)	1.3	1.2	1,5 (with ITP)	
Pco	0	60	140	237	238	98	128	107+34	95	50	117	60 (in s-s)	191	33+40	35
β <sub>N,therm</sub>	2.4	3	3	3	2.8					3.1	4.7	4.3	3.4	3	5.4
CD	none	2MeV beam	ECCD?	2MeV beam	ECCD?	2MeV beam	2MeV beam	2MeV beam +ECCD	LH around 0.8	NBI?	0,75MeV beam	<=1,5MeV beam	1,5 MeV beam	1MeVbeam+ ECCD	0.09 LH (at >0.8) +0.01FW
reference	DJ Ward TW8-TRP-002 reports			NF	J.Garcia et al. 48 (2008) 075	007	GV Pereverzev et al.; FT/P5-23	GW Pacher et al.; NF 47(2007)489	BN Kolbasov et al.; FED 83 (2008) 870	M.Sato et al.; FED 81(2006) 2725 Tobita et al.; FED 81(2006) 1151	R.Hiwatari et al.; NF45(2005)9 6	Giruzzi (this report)	F Najmabadi FED 80(2006)3		

Table 1: Compilation of different DEMO designs (compiled by K. Lackner).

This brings up the question what the rationale for this choice is and if a lower limit for a 'reasonable' size of DEMO can be given. Here, 'size' can mean either R or P, since clearly they are coupled, but not unambiguously (the more optimistic the physics assumptions are, the smaller R becomes for given P). Looking at the 4 objectives above, one can try to define a range of simple 0-d target parameters for DEMO. This

will be done in the following, based on simple scaling relations. Of course, a real design will need much more effort, a task to be started once we agree on the proposed range of 0-d parameters.

- Objective 1 does not per se define the size, but can rather be viewed as an overarching objective.
- Objective 2 can be interpreted such that 'large scale electricity production' means at least several 100 MW, approaching the size of a large coal or fission plant, since the role of fusion power plants in the future energy mix will be comparable to the role fission plays at present. Generally, the economic attractiveness of fusion increases with *P*, such that the size will be a compromise between fulfilling Objective 2 at the lower end (to not make it unnecessarily large) and Objective 4 (see below).
- Objective 3 clearly has an impact on the technology developments in terms of maintenance schemes. However, if availability should be determined by the need for regular maintenance, it is clear that the system itself should allow for continuous electricity production without further implication for the availability. This asks for steady state or at least long pulse plasma operation, where the latter should have a duty cycle such that it can be buffered reasonably easy for continuous electricity generation. From David Ward's studies, a number of e.g. 8 hrs pulse length and 15 min downtime seems to be a reasonable target, so I will use this in the following. As for reliability, again one would like to see the offnormal events given by component reliability and not by plasma physics. For that, I would argue that the operational point (in terms of  $\beta_N$ ,  $q_{95}$ ,  $n/n_{GW}$  and H) should lie within the existing database of tokamak discharges that have been run for at least several current redistribution times, implying hat we also know how to control these scenarios. Also, the power exhaust scenario has to be credible (which may require further work).
- Objective 4 needs a figure of merit for the economic attractiveness, which could finally be *P<sub>net,e</sub>/R<sup>α</sup>* with *P<sub>net,e</sub>* the net electrical power and *α* somewhere between 2 (determined by length of the superconducting cable) and 3 (determined by the volume of other components) such that it directly reflects cost of electricity. However, in a first (DEMO) step, one may argue that the economic viability can be demonstrated when the recirculating power goes down to an acceptable value, since a major burden of fusion is that a sizeable fraction of the generated power is needed for the fusion-specific auxiliaries such as He pumping and external CD. I will hence use the criterion that the fraction of recirculating power, *P<sub>el,AUX</sub>/P<sub>el,net</sub>* should be reasonably small, say, below 30%, allowing to assess how this can be lowered to below 15%, which is a number sometimes quoted as upper bound for a plant.

With this, a range of high-level parameters to be achieved was defined, and one can now argue what the minimum size of DEMO should be in order to reach these. To do this, expressions for fusion power, pulse length and recirculating power were defined. Since it will be argued about size, R will be kept as dimensional parameter while the rest of the plasma physics relations are written in dimensionless parameters, with the exception of B which is technology limited and hence appears explicitly such that the effect of advances in technology on the plasma performance can be demonstrated as well.

#### 2.) Fusion power and Q

Plasma physics sets a lower limit to the size because of the postulate to achieve net electricity generation. Setting aside the divertor problem, the main parameters are confinement and beta limit (for the time being, I am assuming we have to live with  $q_{95} \ge 3$  and  $n/n_{GW} \le 1$ ). There is indeed quite a scatter in assumptions on these two parameters (usually zero-dimensional *H* and  $\beta_N$ ) but generally the fusion power is strongly nonlinear with size,

$$P_{fus} = c_1 \frac{\beta_N^2 B^4 R^3}{q_{95}^2 A^4}$$
(1)

where we have assumed we operate in the optimum temperature range between 10 and 20 keV and used  $\beta_N \sim \beta q_{95}A$ , i.e. a variation of the poloidal cross section shape is not considered. This would enter through  $q_{95} = S q_{cyl} = 5 S R_0/A^2 B_t/I_p$  where for the ITER scenario 2 shape, S = 2.77 holds. Looking at Table 1, one notices that under reasonable plasma physics assumptions, a major radius of roughly 7 m is sufficient for a nearly ignited plasma in almost all cases. This can be seen using the ITER98(p,y2) scaling in the form

$$\tau_E \sim H \tau_{Bohm} \rho^{*-0.7} \beta^{-0.9} q^{-3} A^{-0.73}$$
(2)

with  $\tau_{Bohm} \sim (R/A)^2 B/T$  and  $\rho^* \sim AT^{1/2}/(BR)$ . The loss power from the plasma is given by

$$P_{loss} \sim \frac{W}{\tau_E} \sim \frac{\beta_N B^2 R^3}{q A^3 \tau_E} \quad \Rightarrow \quad P_{loss} = c_2 \frac{\beta_N^{1.9} R^{0.3} B^{0.3} q^{1.1}}{H A^{0.47}}$$
(3)

The choice of *A*, *q*,  $\beta_N$ , *R*, and *B* as variables for plasma physics implies that the explicit dependency of  $\tau_E$  on *T* is not accounted for, which can be justified by the above mentioned assumption that DEMO will work in the optimum temperature range for fusion (i.e.  $T \approx const$ .), but it has to be kept in mind that (3) cannot be used for present day machines where the temperature is quite different. Hence, *Q* can be written as

$$Q = \frac{P_{fus}}{P_{AUX}} = \frac{P_{fus}}{P_{loss} - \frac{1}{5}P_{fus}} = \frac{c_1 \beta_N^2 B^4 R^3}{c_2 \frac{1}{H} \beta_N^{1.9} R^{0.3} B^{0.3} q^{3.1} A^{3.53} - \frac{1}{5} c_1 \beta_N^2 B^4 R^3}$$
(4)

The constants  $c_1$  and  $c_2$  can be determined from ITER scenario 2 using  $P_{fus}$ =400 MW,  $P_{loss}$ =120 MW, R=6.2 m, A=3.1, q=3.1, B=5.2 T,  $\beta_N$ =1.8, H=1 to be  $c_1$ = 0.629 and  $c_2$  = 6.79. Fig. 1 shows that, as expected, Q rapidly goes up with R, achieving ignition at R=7.2 m, while the fusion power goes smoothly through this point but also increases strongly due to the  $R^3$  dependence (assuming constant A,  $q_{95}$  and B, i.e.  $I_p$  rises linearly with R).



Fig. 1: Fusion gain Q (left) and fusion power (right) as function of the machine size for an ITER scenario 2 like operation point.

Above this value, size mainly determines the fusion power which in turn has an impact on the economics of the system (see below), while below, solutions are not ignited and substantial external heating power has to be supplied in order to sustain the fusion reaction, making the plant less attractive. The general rule that can be derived is 'the bigger the more economically attractive'. Of course, substantial variation around the value of  $R \sim 7m$  is introduced if the plasma physics assumptions (*H* and  $\beta_N$ ) are varied as Table 1 shows for ARIES AT where  $\beta_N$  is 5 instead of 3 for some EU designs and consequently, *R* drops by roughly (3/5)<sup>2/3</sup>.

The simple relations (1) and (4) also clarify the role that *H* and  $\beta_N$  play in the considerations: due to the strong  $\beta$ -degradation of confinement predicted by the scaling (2),  $\beta_N$  nearly drops out of relation (4) determining *Q* such that a decrease in size at constant *Q* is only possible by increasing *H*. On the other hand, *H* does not enter into (1) such that a smaller machine needs higher  $\beta_N$  to maintain the same fusion power. This is the reason why one can only profit substantially from an increase in *H* if one also increases  $\beta_N$ , as is done in the ARIES AT design.

## 3.) Pulse length and steady state

Plasma physics also enters if in addition to net electricity production, steady state plasma operation is postulated (note that I have not listed this in the 4 objectives above). This either needs very optimistic assumptions about the bootstrap fraction or dominates the power balance because of the need to drive current by external systems (usually, NBCD is used in the studies above). In fact, the points in table 1 are all ignited, but need substantial  $P_{AUX}$  for CD, not for auxiliary heating per se.

The impact of the steady state postulate on size can be determined as follows: the internally driven non-inductive current (bootstrap current) scales like  $f_{bs} \sim A^{-1/2} \beta_p$  where A is the aspect ratio, so that this part does not introduce a size scaling. The externally driven non-inductive current drive efficiency scales like  $\gamma_{CD} \sim T^{\alpha}/(nR)$ . Since nR is fixed by the Greenwald limit (assuming constant  $q_{95}$  (stability limited) and  $B_t$  (technology limited)) and T is fixed by the optimum in fusion power production, also  $\gamma_{CD}$  does not scale with size. Hence, at constant  $\beta_p$ , the power needed to drive the remaining noninductive current will increase linearly with plasma current, which increases linearly with R assuming fixed  $B_t$  and  $q_{95}$ . Since, as demonstrated above, the fusion power increases much stronger than linear in R, it means that the fraction

of the generated power that is needed for external CD decreases with machine size, favouring big plants. This will be shown below when the recirculating power fraction is discussed.

It is noted here that a long pulse (but not steady state) solution using only inductive CD usually ends up with large size as well, but for a different reason, namely because a large solenoid is needed. These solutions then have large *R* but not larger  $P_{fus}$ , such that the figure of merit  $P_{el,net}/R^{\alpha}$  is smaller.

Quantitatively, the variation of the pulse length with the design parameters can be obtained using the poloidal flux balance, which can be written as

$$\Phi_{tot} = \Phi_0 + \Phi_{res} \tag{5}$$

where  $\Phi_{tot}$  is the total solenoid flux,  $\Phi_0$  is the flux needed to ramp up the current and  $\Phi_{res}$  is the flux needed to sustain the discharge against resistive losses in flattop. The total flux is given by the solenoid cross section which scales, assuming a maximum current density in the solenoid, with the plasma major radius  $R_0$  minus the minor radius  $R_0/A$  minus *b*, the extension of blanket and inner TF leg:

$$\Phi_{tot} = c_3 R_0^2 \left( \frac{A-1}{A} - \frac{b}{R_0} \right)^2$$
(6)

The flux needed to ramp up the current is composed of the inductive part and the resistive part:

$$\Phi_0 = (L_p + \mu_0 c_{Ej \, imd} R_0) I_p = c_4 \left(\frac{R_0}{A}\right)^2 \frac{B}{q_{95}}$$
(7)

with  $c_{Ejima} = 0.43$  and  $L_p \sim R_0$ . Here, I have assumed that bootstrap current and CD by external sources do not help in the ramp-up, but they do in the flattop such that only a current  $I_p^*$  has to be driven inductively:

$$I_{p}^{*} = I_{p}(1 - f_{CD} - f_{bs})$$
(8)

with  $f_{CD} = I_{CD}/I_p$  and  $f_{bs} = 0.7 (A)^{-1/2} \beta_p$ . The resistive flux consumption is

$$\Phi_{res} = \tau_{pulse} \frac{2\pi R_0}{\kappa a^2 \langle \sigma \rangle} I_p^* = c_5 \tau_{pulse} \frac{B_t}{q_{95}} (1 - f_{CD} - f_{bs})$$
<sup>(9)</sup>

where in the last step I have assumed  $\sigma$ =const (due to *T*=const). Evaluating the flux balance (5) leads to

$$\tau_{pulse} = R_0^{2} \frac{c_3 q_{95} A^2 \left(\frac{A-1}{A} - \frac{b}{R_0}\right)^2 - c_4 B}{c_5 B A^2 (1 - f_{CD} - c_6 0.7 q_{95} \sqrt{A} \beta_N)}$$
(10)

where we have explicitly introduced the relation between  $\beta_N$  and  $\beta_p$ 

$$\beta_p = c_6 q A \beta_N \tag{11}$$

We can evaluate (10) for ITER scenario 2 parameters to see the trends. For ITER scenario 2,  $\Phi_{tot} = 120$  Wb,  $\Phi_0 = 90$  Wb and  $\Phi_{res} = 30$  Wb for  $\tau_{pulse} = 400$  s. For the flattop working point,  $\beta_p = 0.55$  which, using the parameters from above, gives

 $c_6$ =0.0318. Inserting this gives  $f_{bs}$  = 0.22, consistent with the value from ASTRA simulations. From these simulations we also take  $f_{CD}$  = 0.1. The extension of inner TF leg and blanket is *b*=2.8 m. This fixes the constants:  $c_3$  = 61.2,  $c_4$  = 13.4 and  $c_5$  = 0.0658. This allows us to plot, for the ITER operational point, the pulse length as function of  $\beta_N$ . This is shown in the left part of Fig. 2, which indicates that it would go steady state at  $\beta_N$  around 7.2, which is quite impossible from stability point of view. Since  $\beta_N \sim \beta_p / (q_{95} A)$ , the low  $q_{95}$  of ITER scenario 2 together with the low  $f_{CD}$  means that such a high  $\beta_N$  must be reached to obtain the necessary  $\beta_p = 2.2$ .



Fig. 2: Variation of pulse length with  $\beta_N$  for ITER parameters corresponding to scenario 2 (left) and scenario 4 (right).

Hence, the route towards steady state involves not only an increase in  $\beta_p$ , but also an increase in  $q_{95}$  and possibly also A and  $f_{CD}$ . This becomes clear if one does the same plot for ITER scenario 4 parameters, where  $I_p = 9$  MA and A = 3.3 leading to  $q_{95}$ =5.1and  $f_{CD} = 0.5$ , shown in the right part of Fig. 2. Here, steady state is already achieved at  $\beta_N = 2.55$ , which corresponds to  $\beta_p = 1.3$ . Note that since at lower  $I_p$ , less flux is needed fo ramp-up, there is also a substantial increase in pulse length for given  $\beta_p$  compared to scenario 2.

Fig. 2 shows another interesting trend: in a development plant of ITER parameters where one would hope to go steady state as plasma performance increases, the pulse length will not increase linearly with  $\beta$  but rather weakly in the beginning and then very rapidly towards the end. In other words, one will never approach a pulsed plant of several hrs pulse length until one is close to the  $\beta$ -value at which steady state occurs!

Thus, a development line with long pulses usually goes to higher major radius to accommodate for a larger solenoid. Since the plasma current is mainly needed for confinement, it does not have to be increased together with the radius and hence  $q_{95}$  can go up, allowing to raise  $\beta_p$  at constant  $\beta_N$ . In addition, *A* can be increased to compensate for the increase in  $q_{95}$ . This leads to a substantial increase of pulse length with major radius, shown in Fig. 3 with the assumptions of D. Ward's pulsed DEMO, i.e.  $I_p = 15$  MA, A = 4,  $B_t = 7.4$  T, leading to  $q_{95} = 3.95$  at the nominal radius of 9.5 m,  $f_{CD} = 0$  and  $\beta_N = 2.6$ , using the constants derived above for ITER and keeping b = 2.8 m fixed.



Fig. 3: pulse length as function of the major radius for ITER scenario 2 parameters, but A=4,  $B_t$ =7.4 T,  $\beta_N$  = 2.6 and  $f_{CD}$  = 0. A pulse length of several hours is approached at R > 9 m.

Indeed, the 8 hrs pulse length is roughly met for 9.5 m, verifying that an essentially ohmically driven device will have to have large R to achieve long enough pulse length.

#### 4.) Technology and overall power balance

Technology enters into objectives 2, 3 and 4 by setting limits to the magnetic field (and hence influencing the size) and by determining the various efficiencies giving rise to the economic properties of the plant, i.e. net electric power for given capital investment and recirculating power fraction. While DEMO does not have to be economically competitive, it must at least allow to assess the economic potential (objective 4). The Group is of the opinion that this requires the net electrical power to be at least several 100 MW. We have not yet decided about a target for the recirculating power, but it is hard to believe that a solution with more than  $\sim 30$  % recirculating power will appear attractive (a fission plant recirculates less than 15 % of its electrical power).

The power balance of a plant can be expressed as follows: The thermal power generated is written as

$$P_{th} = 1.18P_{fus} + P_{CD} + \eta_{BOP} P_{BOP}$$
(12)

where it is assumed that the  $P_{BOP}$ , power entering into the balance of plant, can contribute to the thermal power (heat the cooling water) by a fraction  $\eta_{BOP}$  and the factor 1.18 is the additional energy generated by nuclear reactions in the blanket. From this, the total electrical power follows as

$$P_{el} = \eta_{TD} P_{th} \tag{13}$$

where  $\eta_{TD}$  is the thermodynamic efficiency. The auxiliary power needed in the whole plant is given by

$$P_{AUX} = \frac{P_{CD}}{\eta_{CD}} + P_{BOP}$$
(14)

where  $\eta_{CD}$  is the electrical efficiency of the CD system. This is to be distinguished from the CD efficiency  $\gamma_{CD}$ , which relates the externally driven current  $I_{CD}$  to  $P_{CD}$ :

$$I_{CD} = f_{CD}I_p = \gamma_{CD} \frac{P_{CD}}{R_0 n_e}$$
(15)

For the typical fusion temperature range, values of  $\gamma_{CD}$  in the range of 0.3-0.5 are usually used (with the density given in  $10^{20}m^{-3}$ ). From (12) and (13), one can determine the recirculating power fraction as

$$f_{rec} = \frac{P_{AUX}}{P_{el}}$$
(16)

and the net electrical power as

$$P_{el,net} = P_{el}(1 - f_{rec})$$
(17)

so that  $f_{rec}=1$  is the marginal point for net electricity generation.

From these simple formulae, one can draw some immediate conclusions. Taking as an example  $P_{BOP}$  = 50 MW,  $\eta_{TD}$  = 0.33 and  $\eta_{BOP}$  = 0.3 and  $P_{CD}$  = 0 (i.e. an ignited pulsed plant), one can plot the electric power and the recirculating power fraction versus fusion power:



Fig. 3: Net electrical power (left) and recirculating power fraction (right) for a pulse, ignited DEMO without additional noninductive CD.

indicating that ,electrical breakeven' is achieved at  $P_{fus}=150 \ MW \ (\approx P_{BOP}/\eta_{BOP})$  and  $f_{rec}$  can be below 0.3 for  $P_{fus} = 400 \ MW$ . One also sees that due to the offset given by  $P_{BOP}$  (which will not scale dramatically with size), it is not only Q but also fusion power itself that matters.

This is even more pronounced for a steady state solution where we assume in addition  $P_{CD}$  = 200 MW and  $\eta_{CD}$  = 0.5:



Fig. 4: Net electrical power (left) and recirculating power fraction (right) for a steady state DEMO under the assumption of 200 MW of additional noninductive CD.

where now one must go to a reactor type unit size in order to achieve reasonable  $f_{rec}$ . My suspicion is that this is the real reason why most studies quoted above go to  $P_{el}$  = 1 GW (they are mostly steady state and hence carry the burden of the large additional  $P_{CD}$ ).

Often, design studies assume advances in technology. A prominent one is He cooling with  $\eta_{TD}$  = 0.5, but then  $P_{BOP}$  has to go up to 200 MW which gives the following picture for the steady state DEMO:



Fig.5: The same as in Fig. 4 (shown as black line for reference), but with advanced technology (He cooling).

indicating that there is a clear advantage, but the pulsed design point can still not be reached in terms of  $f_{rec}$ .

#### 5.) Possible approaches towards defining the size of DEMO

With the relations derived above, we can now analyse in a rough way a range of possible DEMO designs. While doing so, it has to be kept in mind that there are two kinds of temporal evolution that will change the DEMO working point by taking into account future progress: up to the design freeze, progress in physics and technology will lead to an adjustment of the main machine parameters R and  $B_t$ . From then on, any further progress will have to be incorporated in the design with fixed R and  $B_t$ , either by upgrading hardware (e.g. to take into account progress in efficiency of auxiliary systems) or by running the machine in a different operation scenario (e.g. to take advantage of an operating scenario with higher stability limits).

In the following, we therefore study how for fixed design points ( $R_0, B_t$ ), assumptions on plasma physics and technology change the performance towards fulfilling the objectives listed in the introduction. This is similar to the DEMO-CREST study where a particular machine design has been chosen and then, varying the plasma physics assumptions, the net electrical power was increased. For plasma physics, this means that we will vary  $\beta_N$  from 2 (conservative value close to the ITER scenario 2) operational point) up to 5 (upper end of predictions, not demonstrated at any confidence level in a relevant tokamak experiment) and H values between 1 (standard H-mode) and 1.5 (typical for RS simulations, but not yet demonstrated experimentally in stationary conditions over many confinement times) will be used. As further reference, an improved H-mode would be characterised by roughly  $\beta_N = 3$ and H=1.3, giving an example of an advanced operation scenario that has been demonstrated in present day experiments in quasi-stationary conditions (many confinement times, at least one current redistribution time). Finally,  $q_{95} > 3.5$  has been chosen for reduced danger of disruptions. On the technology side, we will assume either conventional cooling technology ( $\eta_{TD}$  = 0.33 without special impact on  $P_{BOP}$ ), or He cooling ( $\eta_{TD}$  = 0.5 with a penalty of 150 MW for  $P_{BOP}$ ). The wall plug efficiency for a CD system  $n_{CD}$  will be varied between 0.25 (typical for present day experiments) and 0.5 (optimistic prediction for the future) while for  $\gamma_{CD}$  we use 0.3 and set the density to 1 x  $10^{20}$ m<sup>-3</sup>. Finally, technological improvement may also lead to higher  $B_t$  values, using 5.2 T as a reference for present day designs and 6 T for an improved version (note that the aspect ratio will influence this value as well, but that is not taken into account here).

We start the analysis with R=7.5 m, which lies in the bulk of the DEMO studies in Table 1. Following the methodology outlined above, we chose  $q_{95} = 3.5$ , which, for  $B_t = 5.2$  T and A = 3.1, leads to a plasma current of 16 MA. Examining the power balance, we find that for H=1, the machine is not ignited and will, at high  $\beta$ , need a substantial amount of additional heating power. However, this can be cured by modestly increasing *H*: Fig. 6 shows the additional heating power needed to sustain the plasma versus *Q* for *H=1*, *H=1.1* and *H=1.2*. For the latter, the additional power needed is already negligibly small (around 10 MW). We note that a different path to cure the problem would have been to slightly lower  $q_{95}$ , shown in the right side of Fig. 6, where for  $q_{95}$ =3.4, H=1.1 is already sufficient to reduce the additional power to neligible level.



Fig. 6: Variation of additional power needed versus Q in a machine of R=7.5m,  $B_t = 5.2$  T for a variation of  $\beta_N$  between 2 and 5 for H=1, H=1.1 and H=1.2. At  $q_{95}$ =3.5 (left

# graph) and H=1.2, the additional power is already below 20 MW in the whole $\beta_{N-1}$ range. The same is true for $q_{95}$ =3.4 and H=1.1 (right graph).

We conclude form this exercise that R=7.5 is marginal w.r.t. ignition for conservative assumptions, which is probably one of the reasons why many design studies ends up around this value.

Next, we examine how this class of machines can fulfil the objectives of allowing to assess the economic attractiveness and large scale net electricity generation. For this, we evaluate the recirculating power and pulse length as well as fusion power and net electricity using H=1.2 and q<sub>95</sub>=3.5 together with a set of conservative technology assumptions, i.e. P<sub>BOP</sub>=50 MW,  $\eta_{BOP}$ =0,  $\gamma_{CD}$ =0.3,  $\eta_{CD}$ =0.25,  $\eta_{TD}$ =0.3, again for the range  $\beta_N$ =2...5 and for different fractions of driven current, f<sub>CD</sub>=0, f<sub>CD</sub>=0.1, f<sub>CD</sub>=0.2 and f<sub>CD</sub> = 0.3. The result is shown in Fig. 7:



Fig. 7: Variation of recirculating power and pulse length (left) for a DEMO plant of R=7.5 m and  $B_t = 5.2 \text{ T}$  when  $\beta_N$  varies between 2 (left starting point of curve) and 5 (right end point of the curve). The diamonds mark, on each curve,  $\beta_N = 3$  and  $\beta_N = 4$ . The parameter  $f_{CD}$  has been set to 0, 0.1, 0.2 and 0.3. The corresponding curves for net electrical power and fusion power are shown in the right graph.

This exercise clearly shows the strong impact that the postulate of long (e.g. 8 hrs) pulse or steady state has on the power balance. The two options that approach reasonable pulse length produce the necessary net electric power only above 1 GW fusion power, with acceptable recirculating power really only achieved in the above 2 GW. Hence, we conclude that the pulse length argument is the leading one in determining the size of DEMO.

We can now investigate how the different assumptions about technology influence the results shown in Fig. 7. Fig. 8 shows the same study, but with  $\eta_{CD}$ =0.5, which requires quite some progress already.



Fig. 8: The same as Fig. 7, but with  $\eta_{CD}$ =0.5, demonstrating the strong impact on the recirculating power and hence the net electricity production.

This choice leads to an acceptable  $f_{rec}$  at fusion power of the order of 1.5-2 GW, confirming the importance of increased  $\eta_{CD}$  as technology goal.

Another technology progress is the concept of He cooling with improved thermodynamic efficiency due to the much higher coolant temperature. Consistent with the assumptions in section 3, we repeat the exercise with  $P_{BOP}$ =200 MW,  $\eta_{BOP}$ =0.5 and  $\eta_{TD}$ =0.5. This gives the results shown in Fig. 8:



Fig. 9: The same as Fig. 8, but with He cooling, i.e.  $P_{BOP}=200 \text{ MW}$ ,  $\eta_{BOP}=0.5$  and  $\eta_{TD}=0.5$ , demonstrating also strong impact on the recirculating power and net electricity production.

It is clear that now the absolute power can become smaller and also  $\beta_N$  relaxed, such that DEMO could fulfill its objective without being a full size power plant, but the amount of progress needed is already quite challenging.

Hence, an important question is how to increase the pulse length without going to a large machine in terms of  $f_{CD}$ . This can in principle be done by increasing either  $q_{95}$  or *A* at constant  $\beta_N$ . Figs. 10 and 11 show this for the machine studied above.



Fig. 10: Pulse length as function of A for a machine with B=5.2 T, R=7.5 m and  $\beta_N = 2.0, 3.0, 4.0, 5.0$  at  $f_{CD} = 0$  (left) , at fCD=0.2 (right)at  $q_{95}=3.5$ .



Fig. 11: The same as figure 10, but for a variation of  $q_{95}$  at A=3.1.

As can be seen, increasing  $q_{95}$  or A increases the pulse length. The reason is that both decrease the plasma current and hence the need for non-inductive CD. Increasing A in addition opens more space for the solenoid. However, at constant R, both measures imply then an improvement in another parameter since the decrease in  $I_p$  decreases  $\tau_E$  and one drops out of the ignited state. This could be compensated by both plasma physics or technology progress, for example by an increase in H or  $B_t$ .



Fig. 12: a machine with R=7.5 m, but  $B_t = 6.5$  T will allow  $q_{95}=3.7$ , A=3.8 which could lead to long pulse (several hours) at reasonable  $\beta_N$  and  $f_{rec}$  and generates several 100 MW of net electrical power even with conventional technology ( $\eta_{CD}=0.25$ ,  $\eta_{TD}=0.3$ ).

An example for such improvements is illustrated in Fig. 12, where *A* has been raised to 3.8 and  $q_{95}$  to 3.7, but  $B_t$  was increased to 6.5 T in order to still have a plasma current high enough to ignite around H = 1.2. This machine would allow long (more than 3.5 hours) pulses at very reasonable recirculating power fraction and  $\beta_N=3.5$ , even with conventional technology ( $\eta_{CD}=0.25$ ,  $\eta_{TD}=0.3$ ). Increasing the latter would now really have a big impact, as shown in Fig. 13 where for otherwise unchanged parameters we have used  $\eta_{CD}=0.5$  and  $\eta_{TD}=0.5$  (accompanied by a raise in  $P_{BOP}$  from 50 to 200 MW). This allows to increase  $f_{CD}$  to 0.3 and there is a remarkable operational point at  $\beta_N=3.5$  with more than 6 hrs pulse length (it goes steady state at  $\beta_N=4.3!$ ), 2 GW thermal power and 850 MW net electrical power.



Fig. 13: the same as in Fig 12, but with advanced technology,  $\eta_{CD}$ =0.5,  $\eta_{TD}$ =0.5. Steady state is achieved for both  $f_{CD}$ =0.2 and 0.3, with very long pulse at reasonable  $\beta_N$  and  $f_{rec}$ .

From this it is clear that steady state plasma operation is the most stringent requirement and for a tokamak DEMO, it may be too big a hurdle. I therefore suggest dropping it and looking at solutions with several hours pulse length that do not preclude steady state if one is very successful. For any development line; on will have to fulfil ignition marginally, and then relax a quantity that helps in pulse length, similar to what was done for DEMO-CREST in terms of electrical power. I will do

these in the near future with my model, but doing such studies using a more sophisticated model than my zero-d equations would be a worthwhile exercise.

### 6.) Conclusions

In summary, under presently reasonable physics assumptions, the size of DEMO crucially depends on the postulate to operate steady state. If one wants a reasonable recirculating power fraction (assumption: below 30%), this drives the machine to large unit size, i.e. about 3 GW of fusion power, while a pulsed machine could demonstrate generation of electrical power at 1 GW of fusion power. However, the pulse length of such a machine would be quite short (not exceeding 2 hrs) unless quite optimistic assumptions about the progress in technology and plasma physics are made. Increasing optimism in plasma physics and technology assumptions will bring the two approaches nearer to each other allowing to decrease the major radius in the first line and to achieve steady state at higher fusion power in the second line. An extreme example is ARIES AT projecting steady state with a size smaller than ITER but 2 GW fusion power and 1 GW electrical power, at the cost of a very optimistic  $\beta_N = 5.4$  and extreme shaping.

Hence, it is suggested to drop steady state plasma operation as a must (but keep it as highly desirable) and rather look at reasonable development lines that could operate for hours and do not preclude steady state. The recent hybrid DEMO studies by David Ward (called 'partial CD, pulsed' in table 1) could be a step in this direction. Also, the question of the optimum aspect ratio will have to be looked at again when looking at long pulse but not necessarily steady state. This route of course raises other issues in the technology area, which should be looked at in conjunction, like energy storage and thermal fatigue issues from the cycling. We also must ensure that by introducing a pulsed DEMO we are not introducing another PROTO, which would be contradicting the fast track strategy. The possible strategies could be to demonstrate that the duty cycle of DEMO would be enough for (or easily extrapolate to) an economically acceptable pulsed DEMO, or to show that by just increasing the unit size (but not the physic or technology assumptions) the machine could be steady-state with acceptable economics (this would make use of the fact that a DEMO with higher  $f_{CD}$  could offset the additional power by increasing the unit size which increases guite nonlinearly the output power).

Evaluating the impact of future research on DEMO, the most interesting plasma physics development is still high beta for pulse length, but from the technology side,  $B_t$  and  $\eta_{CD}$  have a very high impact on the overall efficiency and should hence be tackled adequately in the programme.

Finally, it is important to notethat the divertor problem and the Greenwald limit have not been tackled in this study, and they both pose sever constraints to possible designs. They should hence be included in future research in this direction.

## Annex III

### **Programmatic requirements for DEMO**

#### **Introduction - Abstract**

The requirement of the DEMO step is to demonstrate the feasibility of electricity generation from thermonuclear fusion. A key milestone will be the demonstration of the technological feasibility of fusion by the qualification of all relevant components and processes required in a fusion reactor. A key question is to determine how much electricity must be generated by the DEMO device and for how long.

At present, we propose to consider 2 distinct phases for the DEMO device: a first phase for extended commissioning, technology validation, and selection of reactor relevant in-vessel components. The qualification of reactor relevant components and processes will then take place during the second phase.

### The "fast-track" Strategy

The first FPP is defined as "the first device using thermonuclear fusion to produce electricity for commercial purposes".

It is not possible to consider the construction of a first FPP following ITER, even assuming the complete success of the ITER programme. Prior to the construction of the first FPP, all major components and processes will have to be qualified by extensive, full scale prototype testing. Neither ITER, nor any of the facilities foreseen to be operated in parallel, will allow the qualification of the following systems / components: breeding blanket, divertor, first wall (although ITER could test the plasma erosion qualities of reactor relevant first wall during its second phase operation), He-cooling components for the BoP if helium is selected as main coolant for the FPP, several components of the tritium system, and economical-viable invessel remote maintenance procedures for reactor scale components such as blanket.

It is considered necessary, and sufficient, to foresee an additional step after ITER, called the DEMO-step, which includes the design, construction and operation of one DEMO device and of a number of dedicated facilities to address specific physics, technological and engineering issues. These facilities should be considerably smaller and cheaper than the DEMO device and they are not discussed further in this note.

The International Fusion Materials Irradiation Facility (IFMIF) is also essential to qualify fusion materials, and it should be constructed early enough to qualify the main materials to be used in DEMO, in particular the EUROFER steel.

Since 2001, this fusion development strategy is called the "fast track".

Alternative scenarios for the development of fusion power are possible. These are not considered in any detail but they are mentioned in the last section of this note.

## **DEMO Programmatic Requirements**

This section proposes a set of DEMO programmatic requirements. Some of these requirements are widely accepted by the fusion community, for instance those related to safety. Others are more controversial and some key issues are discusses in later sections of this note. These requirements will have to be reassessed on a regular basis and in particular at the end of the DEMO conceptual design stage.

### (a) Testing Requirements

- Qualification, under reactor-relevant conditions, of all components and processes required for the first commercial fusion power plant – in particular, structural and armour materials, basic concepts for all in-vessel components, heating and current drive systems, tritium handling processes, and remote maintenance procedures.
- DEMO internal components should be based on low activation materials, previously tested in IFMIF if possible. All these materials shall be further qualified under reactor relevant conditions.
- DEMO should be self-sufficient in tritium. Ideally, a single breeding blanket concept should be selected for DEMO, e.g. by successful testing during ITER phase 2 operation. All/most components and processes of the tritium plant shall further be qualified under reactor relevant conditions.
- However, DEMO shall adopt an engineering design sufficiently 'flexible' to allow testing of various blanket and divertor concepts and configurations during phase 1 operation if required. During phase 2 operation, the selected in-vessel components shall be qualified under reactor relevant conditions.
- During commissioning, DEMO will commission a limited number of plasma scenarios aiming at the selection of a baseline plasma scenario, which will have been fully validated on other devices (including ITER). Although enough flexibility should be foreseen to test alternative and/or improved physics scenarios, it is assumed that these will be developed using machines different from the DEMO device.
- Installation of reactor-relevant blanket(s) and divertor(s) for DEMO Phase 2 operation will require a major shutdown to be carried out fully remotely. This is essential to qualify the remote maintenance strategy to be adopted in the first FPP.

## (b) Safety and Public Acceptance

- No need for emergency evacuation around the plant following any accident driven by in-plant energies or conceivable impact of ex-plant energies.
- Application of 'Defence in depth' 'prevention, protection and mitigation of accidents' and ALARA principles. In particular, no active systems should be required to achieve a safe shutdown state.
- Fraction of wastes not qualifying for clearance or re-cycling should be minimised after intermediate storage of <100 year (the target, for a FPP, is to reduce this fraction of wastes to zero).

## (c) Operational Reliability and Availability

- The average availability during DEMO phase 1 operation should be in the range of 20 %.
- High availability will be a key requirement for the first FPP, aiming to achieve at least 60% at the end of its life. During a representative length of time during DEMO phase 2 operation (a few weeks), DEMO shall operate with a comparable availability. This will only be achieved if all key components and processes operate with high reliability.

#### (d) Viability of fusion as a power source

- Assuming a 30% average availability during Phase 2, there will be an economic benefit in producing and selling electricity. DEMO shall demonstrate the successful production of electricity, although it should be clear that the resulting cost of electricity will be high and in no way indicative of the cost of electricity from a future FPP (an interesting option to consider is a progressive increase in electricity generation capability.
- In order to contain its capital investment DEMO shall be as small in size as possible, but of a size sufficient to satisfy the above requirements. It is expected that DEMO will have to deliver a few hundred MWs of net electric power to the grid.
- To satisfy the above requirement, the total recirculating power shall be limited. This will constitute a major driver for the systems for Current Drive and for the design of in-vessel components if helium is selected as primary coolant.

### Qualification of components and processes

It is considered that a component or process will be qualified after having operated continuously in reactor relevant conditions for a length of time of a few weeks with an availability of approximately 60%. ITER will allow the qualification of some reactor relevant, fusion specific, components and processes, in particular large magnets cooled by liquid helium and the vacuum vessel. Other key components will remain to be fully qualified, in particular:

- Qualification of materials. The FPP requirements are120/150dpa (steel in FW) for blanket materials, 40/60dpa for divertor materials. In DEMO, these materials should be qualified to at least a third of their expected lifetime in a FPP<sup>12</sup>.
- 2. Qualification of in-vessel components, including welding, brazing and hipping (if appropriate), in DEMO (at least a third of their expected lifetime in a FPP);
- 3. Qualification of tritium systems and processes;
- 4. Qualification of H&CD systems;

 $<sup>^{12}</sup>$  We use this argument because of the relative flattening of the economic cost of Fusion electricity as the blanket lifetime goes above  $\sim 50$  dpa. See for example D Ward and S Dudarev, 'Economic consequences of fusion materials development', contrib. paper 22<sup>nd</sup> IAEA FEC, Geneva (2008), paper SE1-1.

- 5. Qualification of ex-vessel components and systems if and when required (e.g. high temperature superconductors (HTS), Balance of Plant (BoP) components if the FPP is cooled with helium);
- 6. Validation of the overall reactor architecture in particular the segmentation of the internal components, and the demonstration of remote handling procedures.

In addition, construction of the first FPP will only start if the FPP design satisfies a number of requirements in the areas of safety, public acceptance and economics.

#### Continuous vs. quasi-continuous operation

Plasma confinement in a tokamak requires that a current circulates through the plasma. This current is generated "inductively" by a transformer effect, where the plasma acts as the secondary circuit of the transformer, but is limited in duration by the magnetic flux that can be generated by the central solenoid. Steady-state tokamak operation therefore requires the plasma current to be fully "driven" non-inductively. This can be achieved with "advanced" plasma scenarios, which are still under development. These scenarios aim at high plasma pressure gradients, which trigger a self-generated current (so-called "bootstrap" current), which can contribute to a large fraction of the total plasma current. The remaining fraction of the plasma current must then be driven by external means, using so-called "current drive" (CD) systems, which consist in either high energy beams of neutral particles or in radio-frequency heating systems. Three such radio-frequency systems are currently being investigated: Electron Cyclotron CD, Ion Cyclotron CD and Lower Hybrid CD.

Alternatively, "quasi-continuous" operation consists in series of plasma pulses several hours long (say between 5 and 10 hours) followed by a short dwell time (say 10-15 minutes) required to "recharge" the central solenoid. The principle of quasi-continuous plasma operation is to operate in inductive mode, whereas the plasma current is maintained mainly by the inductive voltage generated by the central solenoid magnetic flux swing, with a contribution of the bootstrap current and with limited external current drive (in order to minimise the capital investment and to control the plasma

The reference goal of fusion development in Europe is the steady-state supply of electricity. Continuous operation is considered a requirement for the first FPP, even though some of the authors of this report do not agree. The reasons for disagreement are that (1) it might be more convenient (better physics scenario and reduced current drive requirements), for a first generation FPP, to operate in quasi-continuous mode but to deliver a continuous electricity supply to the grid with the assistance of an energy storage system, and that (2) the first FPP might be tailored for a non-electricity production application, e.g. hydrogen production, in which case continuous operation would not be a requirement.

The choice between continuous and quasi-continuous operation entails a choice between different kinds of machines. For a same net electrical output, the machines would differ in size, in performance, in reliability and, possibly, in capital investment. A machine operating continuously, compared to a machine operating quasicontinuously, would be smaller in size because of the need to operate at high plasma pressure as required for advanced plasma operation. The main drawbacks are the higher power densities and, consequently, the higher thermal and neutron loads on the in-vessel components, and the significant power (at least 200MW for  $1GW_e$ ) that must be injected into the plasma through the CD systems in order to drive the current. The main features of a machine operating quasi-continuously are its lower power densities, its more robust physics basis and the limited power to be injected into the plasma through the CD systems. The main drawbacks are the larger size and the mechanical and thermal cycling, which would also require more margins in the design. Additionally, for a FPP but not for DEMO, there is the need for an energy storage system in order to ensure the continuous supply of electricity to the grid. Mechanical and thermal cycling would also require more margins in the design.

### Availability and Reliability

Reactor Studies in Europe indicate that availability is the most important parameter affecting the cost of electricity<sup>13</sup> of a FPP. It is difficult to compare today the expected availability of both types of reactors considered, but it is possible to point out some of the differences that will affect their reliability. In a device operating continuously, the higher power density will affect negatively the reliability of the in-vessel components. Also, the reliability of the CD systems will affect directly that of the plant. In a device operating quasi-continuously, reliability could be affected by the 30,000 "cycles" considered (assuming ~30 years of operation and three 8 hours plasma pulses per day). The effects of cyclic operations have not been assessed in detail, in particular material creep and cyclic fatigue, whilst it is considered that thermal cycling effects could be mitigated with a thermal energy storage system.

Although availability is one of the main design drivers of the first FPP and of DEMO, surprisingly little work has been done in this area. This will have to change, in particular during the DEMO device design stage.

#### Physics Research during the DEMO step

In a FPP the lifetime of the blanket is assumed to be 5 full-power-years, corresponding to around 150dpa in the steel. If we assume, in the DEMO device, a neutron wall loading of 2MW/m<sup>2</sup>, 8 years are required to achieve approximately 50dpa with an average availability of 33%. This represents a very challenging requirement and implies that there will be no time allocated to physics research in the DEMO device. Since this is the last step before the first FPP, the DEMO/FPP physics basis must be established in ITER.

It will however be essential to continue physics research during the DEMO step, in particular if no advanced scenario can be validated in ITER. This will have to be

coe 
$$\propto \left(\frac{rF}{A}\right)^{0.6} \frac{1}{\eta_{th}^{0.5}} \frac{1}{P_e^{0.4} \beta_N^{-0.4} N^{0.3}}$$

 $<sup>^{13}</sup>$  The PPCS provides the following cost of electricity (coe) scaling, where r is the discount rate, F the learning factor, A the plant availability,  $\eta_{th}$  the thermodynamic efficiency,  $P_e$  the unit size,  $\beta_N$  the normalised  $\beta$  and N the multiplier of the density compared to the density limit scaling:

pursued in parallel to the DEMO device in dedicated machines (e.g. in a potential DEMO satellite).

### Alternative Scenarios

#### Strengthening the Fast Track and reducing risk

Although the "Fast-Track" constitutes the current reference scenario in Europe, alternative scenarios are possible, and some aspects of these scenarios should be investigated in some detail.

The concept of a Component Test Facility has been proposed in order to alleviate the qualification testing requirements in DEMO and to speed up the fusion development schedule. As was recommended in the Facilities Review Panel Report, a study of a CTF should be considered focusing on the most critical issues, which would be:

- an evaluation of the mission of a CTF in the programme, aimed at risk reduction and acceleration in the DEMO phase;
- the technical feasibility , in particular power handling (divertor in particular), current drive requirements , need for tritium breeding availability and maintenance.

The Group endorses the Facilities Review Panel's view on this.

#### Alternate concept for DEMO

The stellarator concept is presented as a possible alternative to the tokamak. A feasibility study of a stellarator reactor should be considered focusing on the most critical issues, in particular maintenance and in-vessel components design concepts.

#### "Internationalisation" of DEMO

Assuming the success of the ITER programme, it is likely that several of the ITER Parties will consider the construction of a DEMO type device. Without clear indications on the possible level of international cooperation in case of a "multi-DEMO" scenario, we propose to adopt a "self-sufficient" set of DEMO requirements. However, it is probably worth to assess the benefits of a multi-DEMO scenario assuming a reasonable degree of international collaboration. If the evolution of a CTF also yields a favourable recommendation, the benefits of international collaboration on such a device should from part of this assessment.