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 β_N. This is shown in the left part of Fig. 2, which indicates that it would go steady state at β_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 β_N must be reached to obtain the necessary β_p = 2.2.

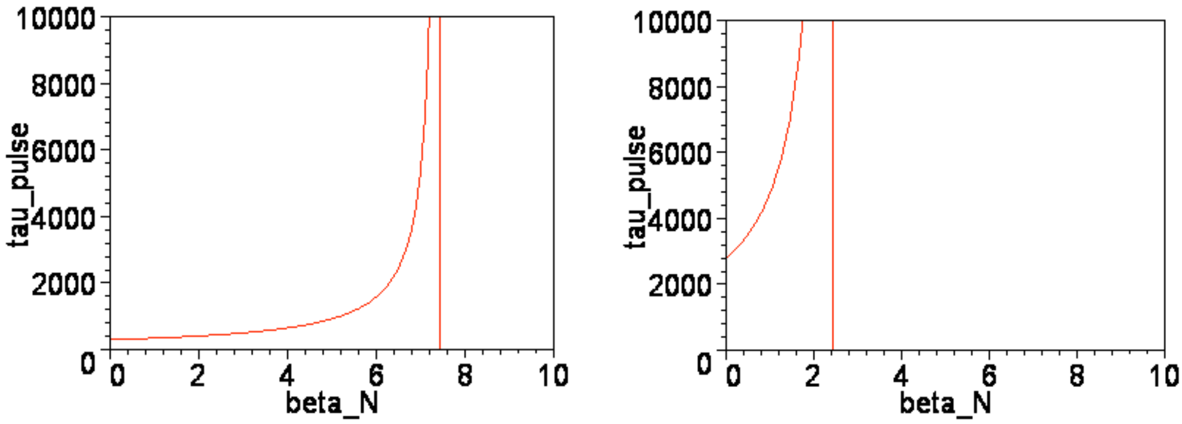

Fig. 2: Variation of pulse length with β_N for ITER parameters corresponding to scenario 2 (left) and scenario 4 (right).

Hence, the route towards steady state involves not only an increase in β_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 β_N = 2.55, which corresponds to β_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 β_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 β 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 β-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 β_p at constant β_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 β_N = 2.6, using the constants derived above for ITER and keeping b=2.8 m fixed.

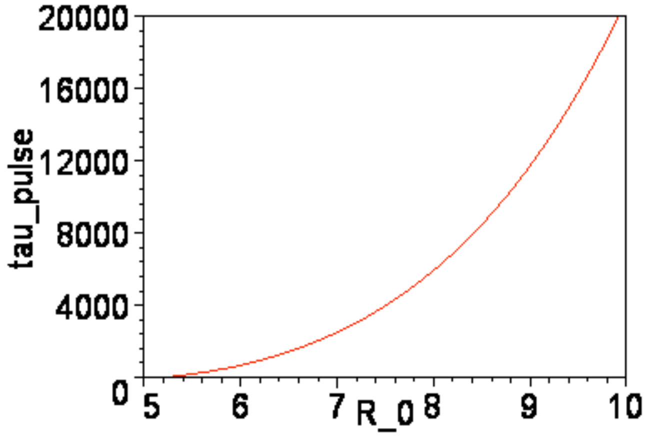

Fig. 3: pulse length as function of the major radius for ITER scenario 2 parameters, but A=4, B_t=7.4 T, β_N = 2.6 and f_{CD} = 0. A pulse length of several hours is approached at R > 9 m.

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 ~ 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

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

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 η_{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 η_{TD} is the thermodynamic efficiency. The auxiliary power needed in the whole plant is given by

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

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

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

For the typical fusion temperature range, values of γ_{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

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

and the net electrical power as

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

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, η_{TD} = 0.33 and η_{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:

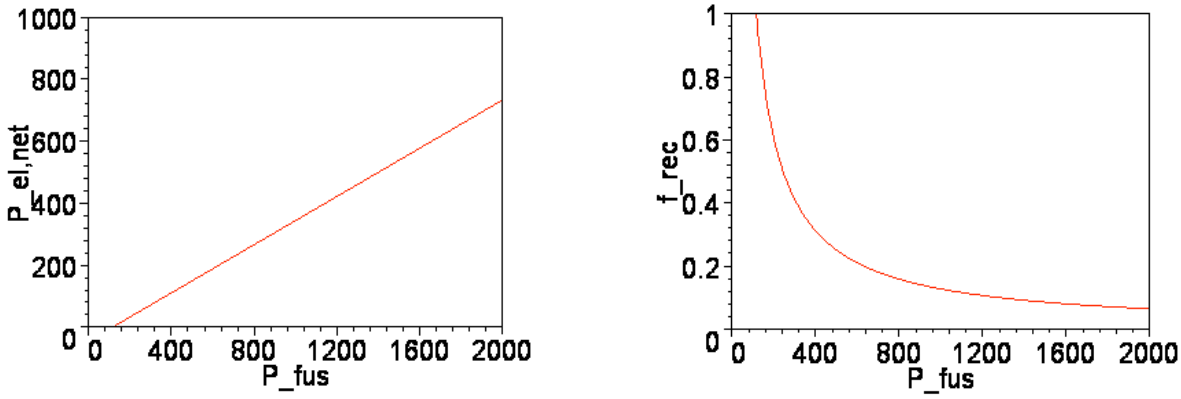

Fig. 3: Net electrical power (left) and recirculating power fraction (right) for a pulse, ignited DEMO without additional noninductive CD.

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 η_{CD} = 0.5:

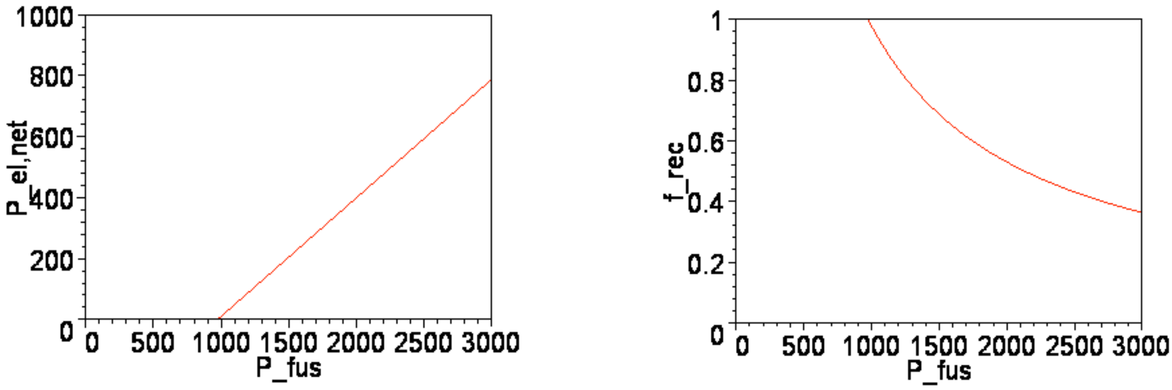

Fig. 4: Net electrical power (left) and recirculating power fraction (right) for a steady state DEMO under the assumption of 200 MW of additional noninductive CD.

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 η_{TD} = 0.5, but then P_{BOP} has to go up to 200 MW which gives the following picture for the steady state DEMO:

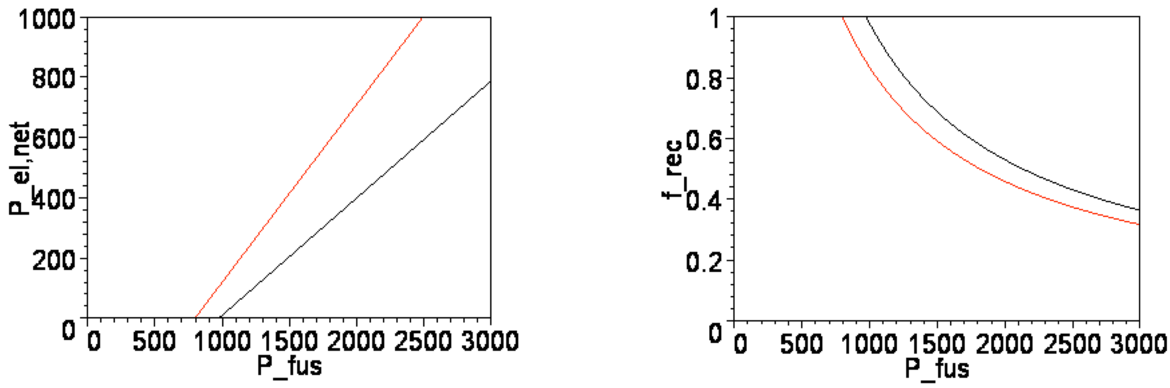

Fig.5: The same as in Fig. 4 (shown as black line for reference), but with advanced technology (He cooling).

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 β_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 β_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 (η_{TD} = 0.33 without special impact on P_{BOP}), or He cooling (η_{TD} = 0.5 with a penalty of 150 MW for P_{BOP}). The wall plug efficiency for a CD system η_{CD} will be varied between 0.25 (typical for present day experiments) and 0.5 (optimistic prediction for the future) while for γ_{CD} we use 0.3 and set the density to 1 x $10^{20}m^{-3}$. 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 β, 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.

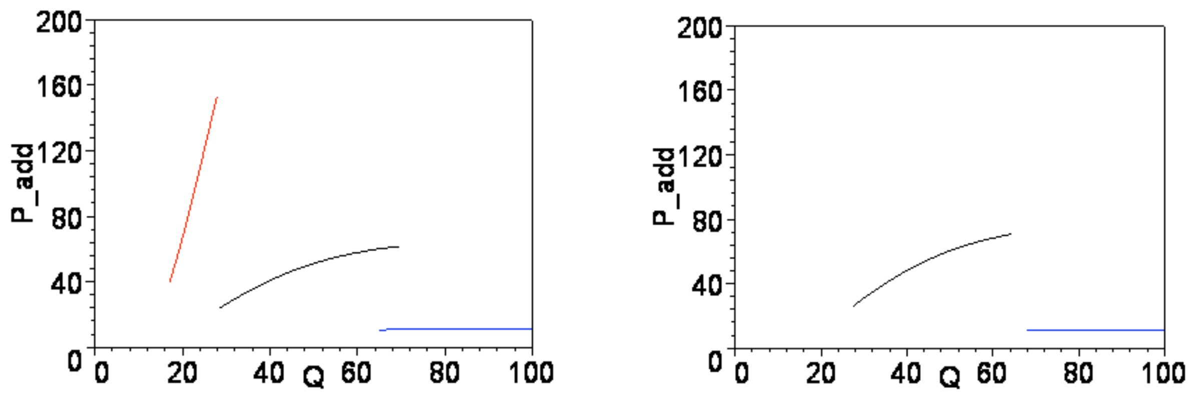

Fig. 6: Variation of additional power needed versus Q in a machine of R=7.5m, B_t = 5.2 T for a variation of β_N between 2 and 5 for H=1, H=1.1 and H=1.2. At q_{95}=3.5 (left

graph) and H=1.2, the additional power is already below 20 MW in the whole β_N-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_{95}=3.5 together with a set of conservative technology assumptions, i.e. P_{BOP}=50 MW, η_{BOP}=0, γ_{CD}=0.3, η_{CD}=0.25, η_{TD}=0.3, again for the range β_N=2…5 and for different fractions of driven current, f_{CD}=0, f_{CD}=0.1, f_{CD}=0.2 and f_{CD} = 0.3. The result is shown in Fig. 7:

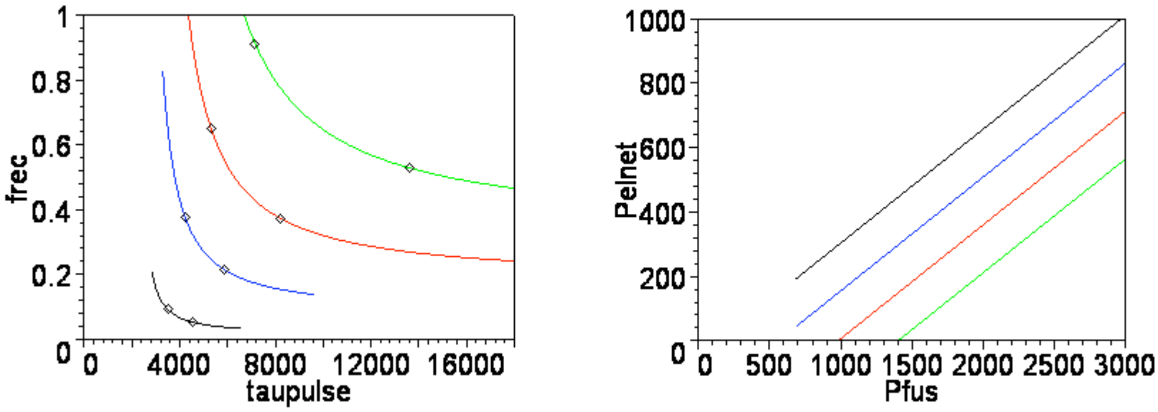

Fig. 7: Variation of recirculating power and pulse length (left) for a DEMO plant of R=7.5 m and B_t = 5.2 T when β_N varies between 2 (left starting point of curve) and 5 (right end point of the curve). The diamonds mark, on each curve, β_N = 3 and β_N = 4. The parameter f_{CD} has been set to 0, 0.1, 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 η_{CD}=0.5, which requires quite some progress already.

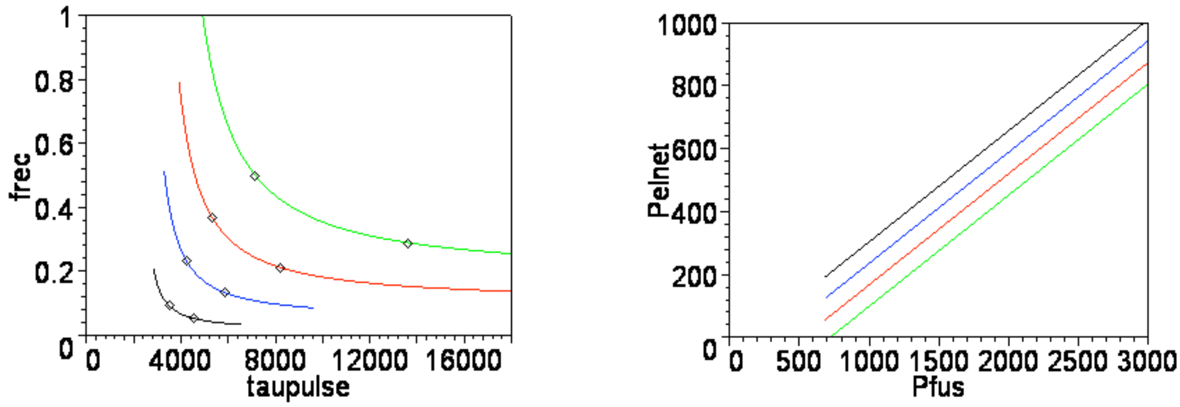

Fig. 8: The same as Fig. 7, but with η_{CD}=0.5, demonstrating the strong impact on the recirculating power and hence the net electricity production.

This choice leads to an acceptable f_{rec} at fusion power of the order of 1.5-2 GW, confirming the importance of increased η_{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, η_{BOP}=0.5 and η_{TD}=0.5. This gives the results shown in Fig. 8:

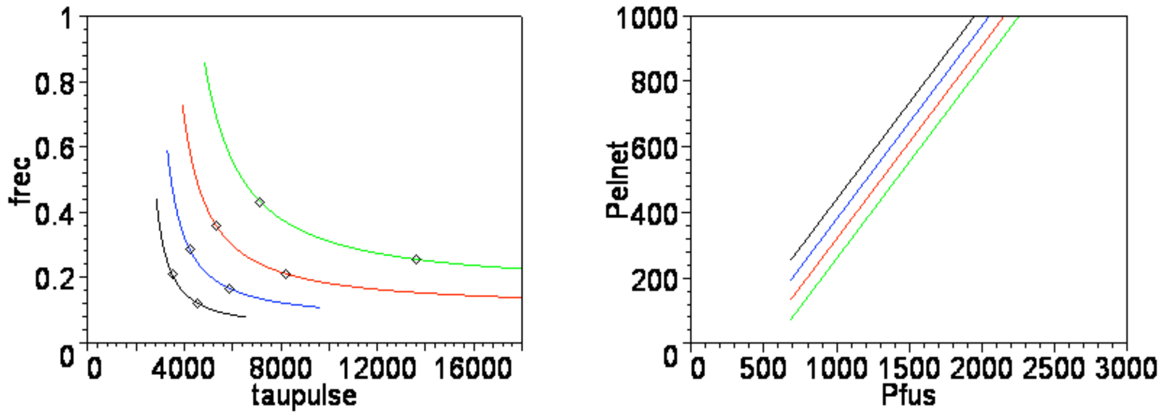

Fig. 9: The same as Fig. 8, but with He cooling, i.e. P_{BOP}=200 MW, η_{BOP}=0.5 and η_{TD}=0.5, demonstrating also strong impact on the recirculating power and net electricity production.

It is clear that now the absolute power can become smaller and also β_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 β_N. Figs. 10 and 11 show this for the machine studied above.

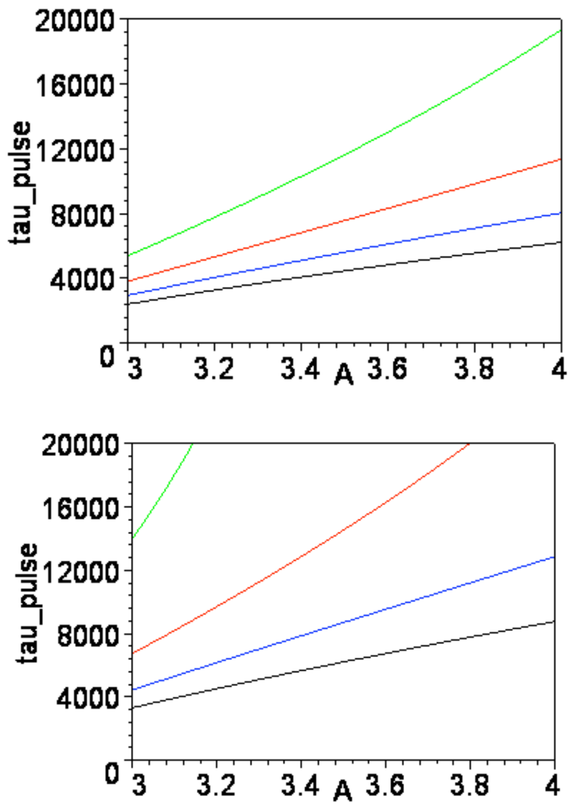

Fig. 10: Pulse length as function of A for a machine with B=5.2 T, R=7.5 m and β_N = 2.0, 3.0, 4.0, 5.0 at f_{CD} = 0 (left) , at fCD=0.2 (right)at q_{95}=3.5.

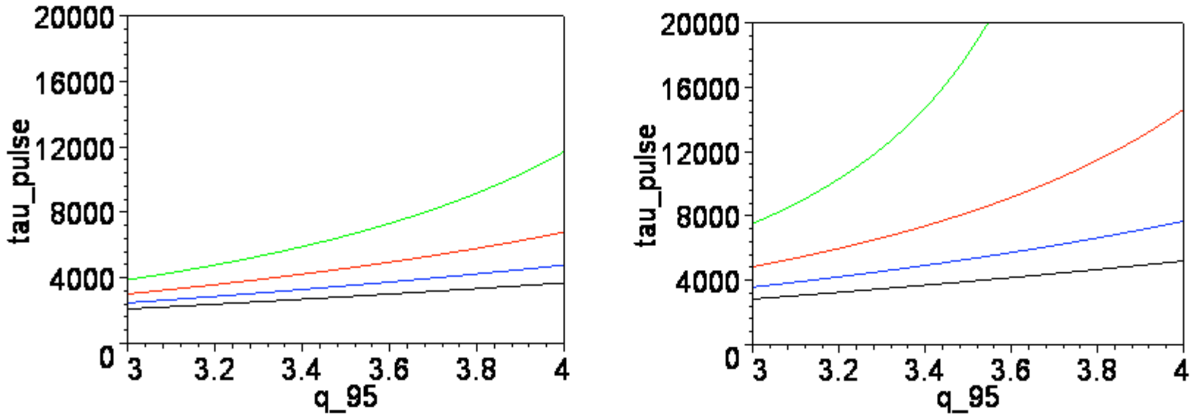

Fig. 11: The same as figure 10, but for a variation of q_{95} at A=3.1.

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 τ_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.

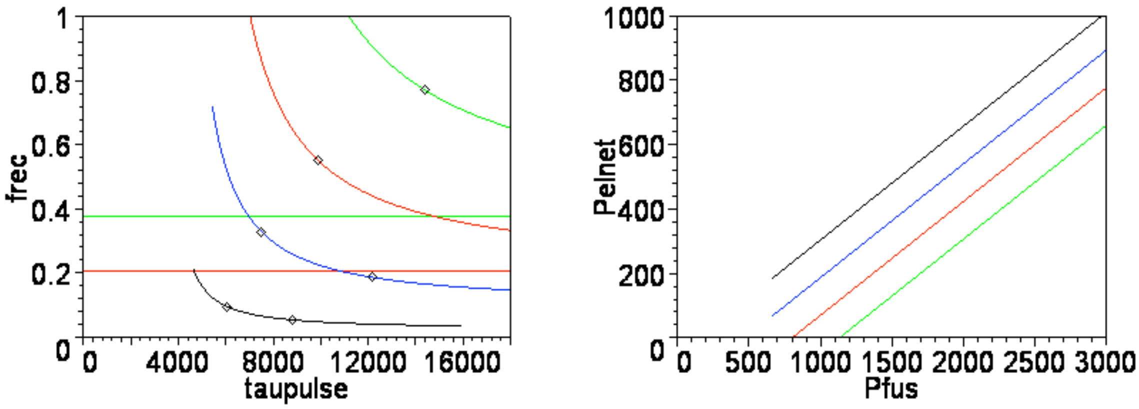

Fig. 12: a machine with R=7.5 m, but B_t = 6.5 T will allow q_{95}=3.7, A=3.8 which could lead to long pulse (several hours) at reasonable β_N and f_{rec} and generates several 100 MW of net electrical power even with conventional technology (η_{CD}=0.25, η_{TD}=0.3).

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 β_N=3.5, even with conventional technology (η_{CD}=0.25, η_{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 η_{CD}=0.5 and η_{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 β_N=3.5 with more than 6 hrs pulse length (it goes steady state at β_N=4.3!), 2 GW thermal power and 850 MW net electrical power.

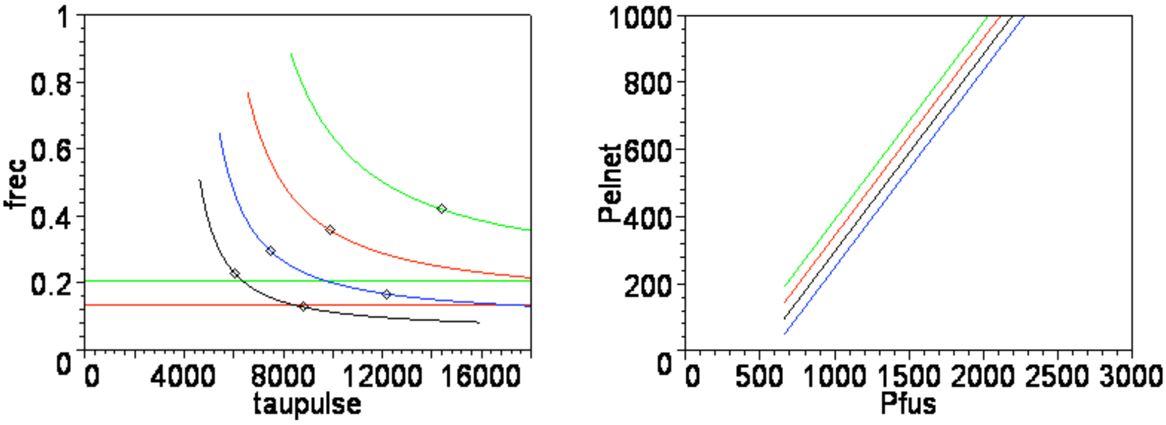

Fig. 13: the same as in Fig 12, but with advanced technology, η_{CD}=0.5, η_{TD}=0.5. Steady state is achieved for both f_{CD}=0.2 and 0.3, with very long pulse at reasonable β_N and f_{rec}.

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 β_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 quite 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 η_{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 in-vessel 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:

1. 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[12].
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;

[12] We use this argument because of the relative flattening of the economic cost of Fusion electricity as the blanket lifetime goes above ~ 50 dpa. See for example D Ward and S Dudarev, 'Economic consequences of fusion materials development', contrib. paper 22nd 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 quasi-continuously, 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[13] 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 $2MW/m^2$, 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

[13] The PPCS provides the following cost of electricity (coe) scaling, where r is the discount rate, F the learning factor, A the plant availability, η_{th} the thermodynamic efficiency, P_e the unit size, β_N the normalised β and N the multiplier of the density compared to the density limit scaling:

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

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.