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The Benefits of Different Options for a European DEMO

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ABSTRACT. In preparation for the EU DEMO study which is now underway, a wide range of options have been explored with a systems code, PROCESS. These include the possibility of pulsed or steady-state devices, with different blankets and coolants, and a range of other detailed assumptions, for instance about magnets and current drive efficiency. These studies, along with others, were used to narrow down the choices to the parameters that are now being assumed for the DEMO technology studies, although they are likely to evolve further as the studies progress. This paper summarises aspects of these studies and the benefits and trade-offs inherent in the range of options that were studied. Of particular interest is the way that a pulsed concept, more conservative than a steady-state device in many parameters, can be improved by the addition of increasing amounts of current drive power, as it is gradually evolved towards a steady-state device.

1. Introduction

Having completed the Power Plant Conceptual Study in 2005 [1] and with ITER now going ahead, the EU is undertaking a DEMO study in which the characteristics and conceptual design of a demonstration power plant are being investigated [2]. Clearly DEMO is to bridge the gap between ITER and a fully operating, high availability, power station and where DEMO should lie depends on the goals and the expected timescale for its construction. To inform the discussion of what DEMO could look like, systems studies, using the PROCESS code [3], have looked at a wide range of options, covering a range of physics and technology choices. Some of these key issues are addressed in this paper.

2. Divertor Heat Load

One of the key issues on the PPCS [1] was the divertor heat flux and this continues to be important in the DEMO studies. Figure 1 illustrates the peak divertor heat load as a function of separatrix density in a device of 8.2m major radius. This is shown at several different values of total heat flow to the divertor. The circled region is where the earlier ITER calculations [4] lay and gave similar values. The figure shows that for a Single Null (SN) device, the total power flow to the divertor should be less than 300MW, and this can have serious implications for the power flows in a DEMO device. For instance with 3GW fusion power and 200MW heating power, the radiated power fraction should be above 60% in a SN plasma.

An obvious way to reduce the requirement for high radiated power fraction is to consider a Double Null (DN) design. At present this is not the reference for the EU DEMO studies, but in systems studies exploring the options, it is found that a higher total power can be allowed, reducing the required radiated power fraction to 50%.

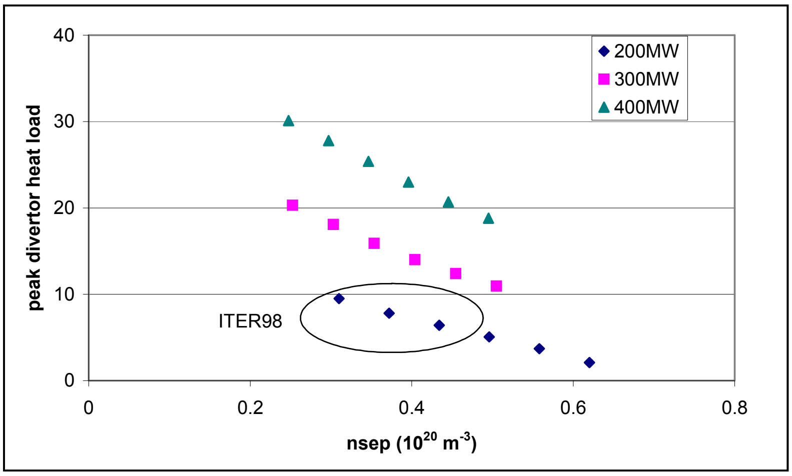

Figure 1: Variation of peak divertor heat load with separatrix density for an 8.2m major radius device with different levels of power flow to the divertor.

3. Coolant Choice and Radial Build

An important choice in fixing the DEMO concept is the selection of the coolant. A critical issue for the machine design is the impact of coolant choice on the inboard radial build and this has been investigated.

An example is the need for a larger inboard gap between the plasma and the TF coil in the case of a gas coolant, particularly helium – one of the main options for DEMO. This is needed to incorporate the coolant pipes and impacts on the radial build; either the major radius must be increased over that needed for a liquid coolant, or the TF coil must be thicker, the OH coil smaller and the available flux swing substantially reduced.

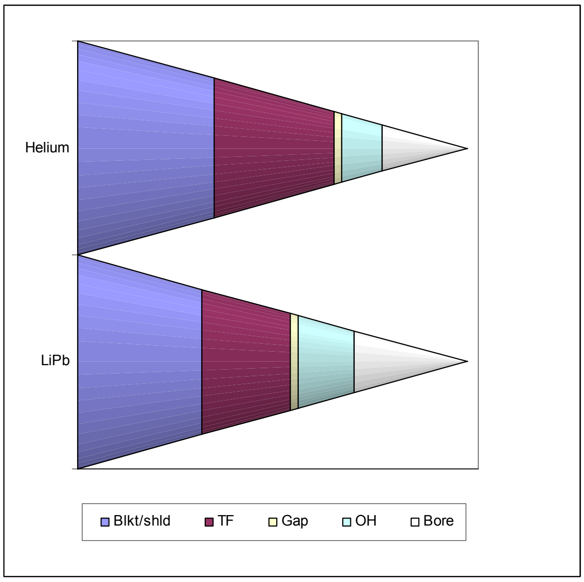

Figure 2: Illustration comparing the inboard radial build of a helium cooled and a lithium-lead cooled plant. The helium cooled plant has a much smaller OH coil and correspondingly smaller available flux swing.

Even though the thickness of blanket and shielding may only be increased by 20cm, the TF coil must also be thicker and the net result can be a reduction in flux swing available from the OH coil of around a factor of 2. Figure 2 shows an illustration of the inboard radial build for an example of a lithium lead and a helium cooled design. The helium cooled plant has a much smaller OH coil.

In the PROCESS calculations, in spite of the small OH coil in the helium case, there is still sufficient flux to start up the plasma because of the other large PF coils. However it is unclear to what extent this reliance on flux swing from other than the OH coil, or a non-inductive contribution to start-up, is really feasible.

4. Steady State Compared to Pulsed Plants

The range of options explored has extended to consider a pulsed device, here meaning that the plasma is pulsed but the electrical output is not. In order to extend the fatigue lifetime of such a device it is assumed that the pulse length must be quite long, around 8 hours, so that a lifetime of more than 30 years can be achieved with a limit of 30,000 pulses.

If a device has no current drive, then all the current that is not self-driven (bootstrap current) is driven inductively and an 8 hour pulse length requires a large major radius to allow a large flux swing. If current drive is added in increasing quantities, the size can be reduced as the same pulse length can be achieved with reduced flux swing. This is illustrated in Figure 3, which shows the variation of required flux swing with additional current drive power where the current drive power is assumed to be provided by injection of 2MeV negative ion beams. The devices are chosen to have an aspect ratio of 4 and a net electrical output of 1GW. The effect of a lower efficiency current drive system is discussed below.

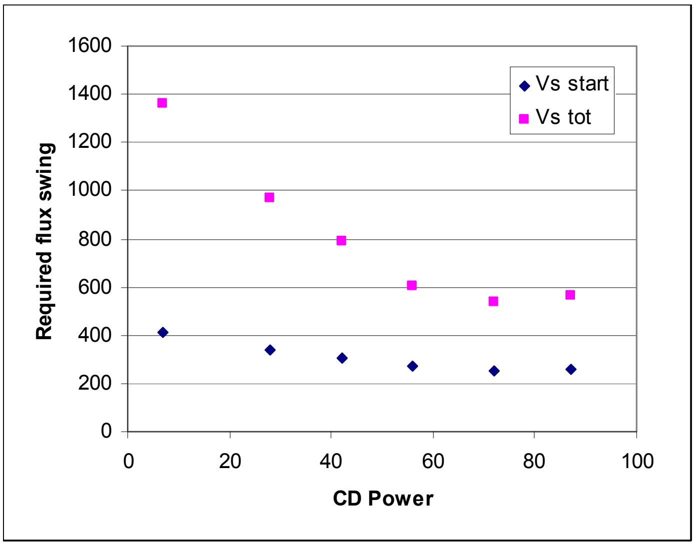

Figure 3: The flux swing required to sustain an 8 hour pulse length is reduced by the addition of current drive which sustains part of the current.

This requirement for reduced flux swing allows the device size to be reduced and this is shown in Figure 4. As the plant evolves from an inductive to fully non-inductive device, the machine size diminishes and consequently the machine cost is reduced. As the current drive approaches that needed for full non-inductive operation, the pulse length naturally tends to increase and beyond a certain point it is no longer possible to keep it down to 8 hours. This is illustrated in Figure 5 which shows the pulse length for these examples. It should be noted that this scan does not approach an optimised steady-state plant since the assumptions are still characteristic of a pulsed plant, but one in which the pulse length is partly achieved by current drive.

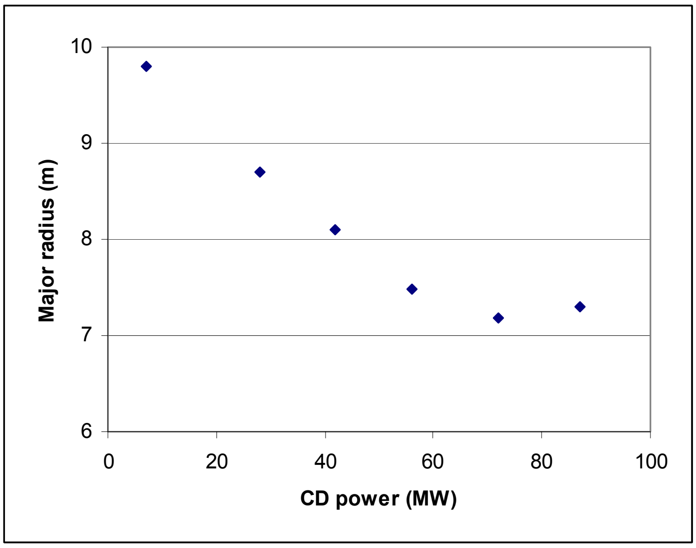

Figure 4: The device size, needed to sustain an 8 hour pulse length, is reduced by the addition of current drive power. There is a slight tendency to increase in size again at larger CD power as the gross electrical output, and hence fusion power, must increase to sustain the 1GW net electrical power output.

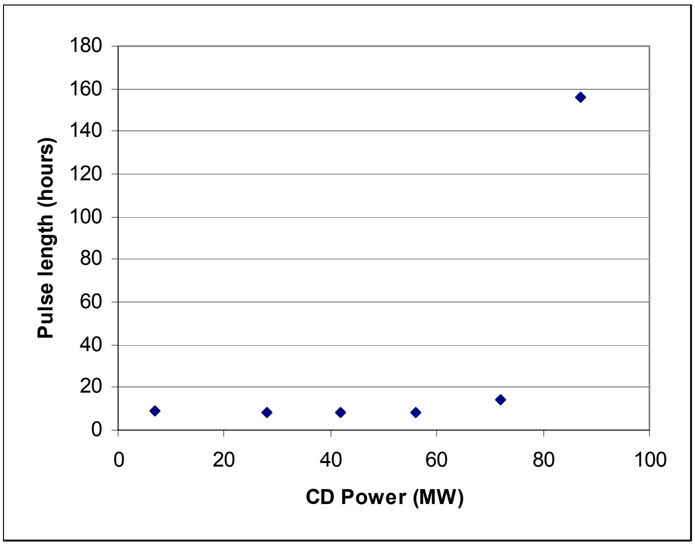

Figure 5: As the current drive power increases towards full non-inductive operation, it is no longer possible to keep the pulse length down.

An important part of this study is to look at the consistency between different plant parameters, which is clarified by this type of systems study. An important point is that operation without significant current drive forces the machine to be large, with low power densities and heat loads. In this case the divertor heat load is not sufficiently large to cause a problem; in addition the neutron wall flux is reduced allowing a longer first wall/blanket lifetime. This is attained at the cost of increased machine size and cost of course.

As the current drive power is increased, the device size reduces and the power densities increase such that, if no measures are taken to diminish the power flows, the divertor heat load increases to become a problem. This is shown in Figure 6 where the divertor heat load is shown to increase above tolerable levels as the plant approaches a steady state plant.

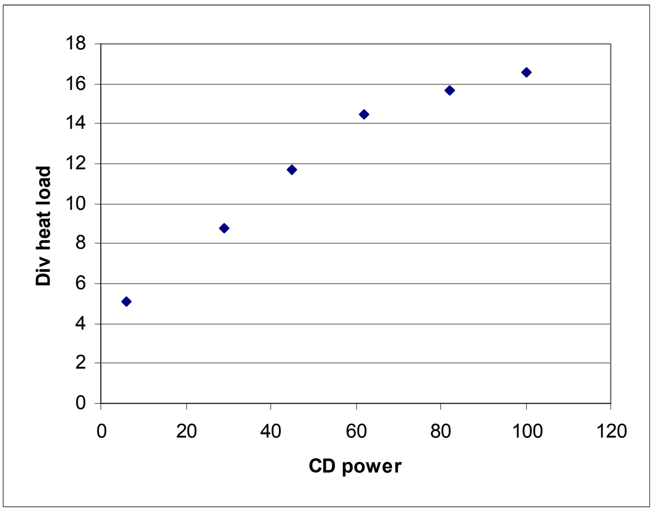

Figure 6: Divertor heat loads are higher in plants that approach steady state than in plants with a higher inductive current drive fraction.

As a final study on the pulsed versus steady state debate, there is the major issue of costs. Although the higher CD power cases are smaller machines in this study that is not enough to guarantee lower costs. It is too early in these studies to make reliable cost assessments, but an approximate comparison is given in Figure 7, which shows the breakdown of costs for a pulsed and steady state plant. What can be seen is that the larger costs of current drive power in the steady state case are approximately compensated by the larger costs in the pulsed machine associated with energy storage. However there is a large, residual cost differential in favour of the steady state plant related to the costs of magnets and vacuum vessel. Although these are only approximate results, the large additional costs of the pulsed plant are unlikely to be negated by other modifications due to improved calculations.

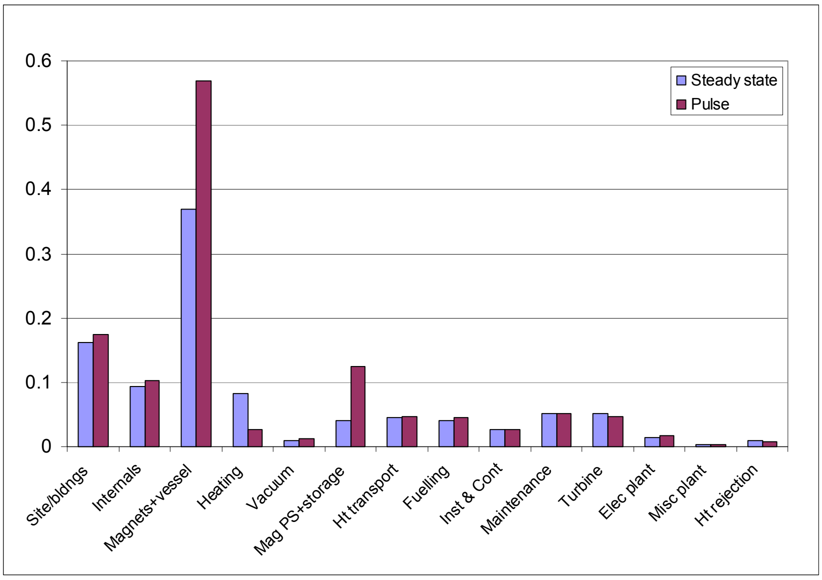

Figure 7: Breakdown of costs of a steady state and a pulsed 1 GW device. Both are normalised to the same total cost (that of the steady state plant) and are for a first of a kind plant.

5. Current Drive Efficiency

One of the concerns about steady state operation of a power plant is that the achieved efficiency of current drive will be insufficient to make an economically viable plant. As an exploration of this, the above study is extended to include a scan in which the current drive efficiency is reduced by a scaling factor. Figure 8 shows the result of varying this factor (labelled CD multiplier) and demonstrates how systems code results can differ markedly from intuition. Although the current drive efficiency is reduced by 50%, the total current drive power hardly varies in this scan. This is because the systems analysis can vary other parameters in such a way as to offset the increase, in this example the size, safety factor and bootstrap fraction are all increased as the current drive multiplier is reduced.

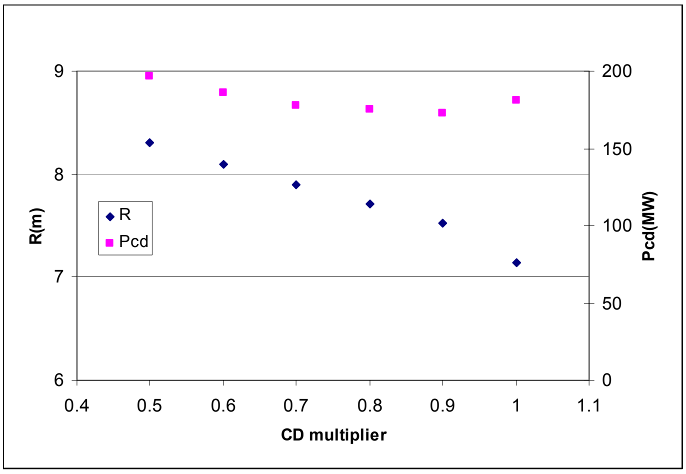

Figure 8: As the multiplier on the current drive efficiency is varied the calculated major radius varies by far more than the current drive power. The low current drive efficiency plant also has higher safety factor and higher bootstrap fraction, largely offsetting the reduced efficiency of current drive.

6. Conclusions

The need to restrict the power flowing to the divertor is an important constraint on a DEMO design. In a single null design a high radiated power fraction (>60%) is required, which is a challenge to the confinement and tends to increase current drive power in a steady state design. A double null plasma reduces this need for high radiation but introduces the greater complexity of two divertors.

A range of coolants has been studied and the particular effect of a gas cooled plant on increasing the inboard radial build is highlighted. Either the major radius should be increased over a liquid cooled plant, or a substantially reduced flux swing from the OH coil must be accepted.

The question of steady state compared to a pulsed device has been re-examined. Starting from a design with no current drive and gradually increasing the amount of current drive power, the size of machine, and hence its cost, can be significantly reduced. In moving from a pulsed towards a steady-state device, the power loads steadily increase as the size reduces, indeed an inductive machine has little difficulty with divertor heat loads as they are naturally lower in the larger machine. However this is achieved at the expense of increasing costs, particularly of the magnets and vessel.

The effect on a steady state power plant design of reducing the current drive efficiency is not necessarily to increase the current drive power. In an optimised plant it is preferable rather to increase the machine size, safety factor and bootstrap fraction, keeping the current drive power almost constant. This is a good example of the counterintuitive results that can arise when the power plant design is optimised in an integrated systems approach, rather than an individual aspect of the design studied in detail but in isolation.

The present studies of an EU DEMO design are based around a 7.5m, single null, helium cooled plant, however these studies suggest that the major radius may need to increase to provide more flux swing. Some effort has been made to avoid strong reliance on high current drive efficiencies and the possibility of an additional pulsed design is still being discussed.

7. Acknowledgements

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8. References

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