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P R Thomas
and the JET Team

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Improved Tokamak Concepts for JET and the Future

P R Thomas and the JET Team

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, UK.

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ABSTRACT

The economic viability of Tokamak fusion reactors would be greatly improved if the capital cost were significantly reduced and continuous operation were possible. Designs which realise these goals rely on reduction by a factor 2-3 in plasma current, from the 25 MA needed for a good ignition margin in ITER. A substantial proportion of bootstrap current is needed, in order to keep the recirculating power to a small proportion of the fusion output. These requirements define an operating point which has to be at large β_p ($\sim 2.5 - 3$) and high β_t ($\beta_N \sim 3 - 5$). Also the energy confinement must be well above H-mode. Steps have already been taken in this direction at JET and a programme has evolved which emphasises coherent development of steady state plasmas. JET has large heating and current drive systems, long pulse capability, He neutral beam injection for ash transport studies and the recently installed, pumped divertor. The results which have already been obtained and the future programme are described. Attention is drawn to the potential application of concept improvement techniques to JET's high performance plasmas so that the fusion yield and Q may be improved.

1. INTRODUCTION

Controlled thermonuclear fusion research has, for the main part, been concentrated upon the attainment of plasma conditions in which ignition and long burns could be obtained. These would constitute necessary but not sufficient conditions for the economic exploitation of fusion. Results from the present generation of tokamaks have shown that ignition will be possible in a device which is sufficiently large. ITER is being designed to demonstrate ignition and to allow the study of thermonuclear burns of up to 1000 s duration.

As the goal of ignition has come to within sight, the step beyond this, that of a demonstration fusion reactor, has drawn increasing attention. Several reactor studies [1] and advisory panels [2] have pointed to the need to make tokamak concept improvements which reduce the capital cost of the nuclear island and permit a continuous supply of electricity to satisfy the base load demand. Steady state operation also ameliorates problems of structural fatigue due to thermal cycling. The plasma developments which follow from these requirements are discussed in the next section.

A number of machines, including JET, have already made considerable strides towards obtaining the target plasma conditions. It is found that substantial improvements in energy confinement can be obtained in association with, or perhaps because of, the hollow current density profiles and the high values of β_p which are characteristic of the improved concept regime. Relevant data are described in section 3, using results from JET and DIII-D. Particular attention is given to the further developments which are required so that the future JET programme can be discussed.

The final section is devoted to a discussion of the JET concept improvement programme. This utilises the installed heating and current drive systems, the profile control systems and the pumped divertor. The JET programme is very much concerned to develop scenarios which are wholly consistent with reactor requirements; not only must high β_N , β_p and confinement enhancement be obtained but the plasmas must also be MHD and thermally stable, have no untoward properties in respect of helium or impurity accumulation and be consistent with a reactor relevant divertor solution. In other words, genuine potential for a steady state reactor must be demonstrated before this development line can be said to have succeeded.

An important concern for JET is the maximisation of its ultimate fusion performance; both in the total fusion output and the power gain. The high performance phase of the pulses in the Preliminary Tritium Experiment [3] terminated suddenly at $\beta_N \sim 2.2$. Although conclusive experimental evidence is not forthcoming, there are fairly strong reasons to believe that MHD instability is responsible for this behaviour. If this is so, the plasmas should respond to profile control measures giving increased plasma pressure and fusion yield. In addition the fusion power gain would be enhanced if the core confinement enhancement, which is observed with non-monotonic q profiles, were obtained. Thus the concept improvement programme will play an important part in realising the full potential of JET. This is not discussed explicitly but should be borne in mind in the following.

2. GOALS OF THE CONCEPT IMPROVEMENT PROGRAMME

The economics of fusion power production are likely to be dominated by the capital cost of the reactor. Thus, it is essential, even now, to devote a significant part of the fusion programme to the development of a minimum cost reactor.

Very crudely, the cost of a reactor scales as the stored magnetic energy [4],

$$\text{ie. cost} \sim |B|^2 \propto f(q, \epsilon, \kappa).$$

The leading terms can be obtained by assigning a cost per unit mass to structural material and assuming that this material is used at some fraction of its stress limit. Of course, there must be singular surfaces in f where a reactor simply could not be built at any price. Nevertheless, the naive cost scaling can be used to justify one of the most important directions in the concept improvement programme.

The magnetic field strength $|B|$ is essentially fixed by superconducting technology, the need to maximise the plasma pressure and so the fusion power density. Thus, it is the volume of the tokamak, or equivalently the plasma current, which comes under pressure in order to

reduce the cost of a tokamak reactor. However, there will be a limit where further cost reduction cannot be obtained because either the toroidal field set is predominantly filled with shielding whose thickness is determined by neutron energy or because the power loading on the wall is excessive.

If it is assumed that the energy confinement in a burning plasma is described by the Goldston scaling law, enhanced by a factor H_G , and that the thermonuclear power output is approximated by

$$P_{\text{fusion}} \sim \alpha_f \frac{(\alpha_p + 1)}{(2\alpha_p + 1)} p_0 W,$$

then the fusion gain is given by

$$Q = \frac{P_{\text{fusion}}}{P_{\text{loss}}} \sim \alpha_f H_G^2 \frac{(\alpha_p + 1)^2}{(2\alpha_p + 1)} I_p^2 \left(\frac{R}{a}\right)^{2.5}.$$

Here α_f is the coefficient which normalises the square of the plasma pressure to the DT fusion power density around 20 keV, p_0 is the central plasma pressure, α_p is the pressure profile exponent, W the total plasma energy and the other symbols have their usual meaning.

It can be seen from this formula for the fusion gain that reductions in I_p can most effectively be offset by increases in H_G , (R/a) or both. Generally speaking, the systems which have been proposed make use of both factors. Whilst pressure profile peaking might be used, this must eventually be limited by MHD stability, energy transport or both. If it is desired to halve the plasma current from the ITER level of 25 MA, which needs a confinement enhancement of approximately 2 for ignition, then H_G will need to be 4.

The requirement that a tokamak operate in steady state places impressive demands on plasma development. It is well known [5] that the projected efficiency of current drive systems to a low q , ignition device like ITER would yield a reactor with a system Q of order unity; ie. all the fusion power would be taken up by current drive!

Fortunately, nature comes to the rescue with the bootstrap current [6]. For present purposes this can be approximated by

$$I_{BS} \sim 0.65 \sqrt{\frac{a}{R}} \beta_p I_p$$

Since $I_{BS} / I_p \sim 1$ is required to reduce the current drive power to an acceptable level, it is necessary for a steady state tokamak to operate at a poloidal β of approximately 3.

In terms of normalised beta ($\beta_N = \beta_T$ (%) / (I_p (MA) / aB_T)), it follows that the requirement of 100% bootstrap current translates to

$$\beta_N = \frac{30}{q_{cyl}} \sqrt{\frac{a}{R}}$$

Even optimistic values for β_N (4-5 say) require that a steady state reactor operate at high q_{cyl} (> 3-4).

Thus, an improved concept tokamak can be distinguished from a more conventional machine, such as ITER, by its operating point in the (β_T, β_p) plane, as shown in figure 1. Rather than marking out a notional "equilibrium limit", the right hand side of the

accessible region has been defined by the condition $d\Delta / dr|_{r=a} = 1$, where Δ is the radial shift of the magnetic surfaces. ITER is designed to operate at $q_{cyl} \sim 2$ and β_N up to 3. In contrast, the improved concept régime occupies the right hand side of the diagram with larger β_N .

It should be noted that figure 1 is only an approximation to results obtained with some of the more extreme equilibria. However, it does serve to illustrate the principles of improved concept development.

Bootstrap dominated current profiles have some interesting properties. The dependence on aspect ratio and the finiteness of the pressure gradient means that the bootstrap current must be zero on axis. Thus, the safety factor profile will tend to be non-monotonic, even in the presence of an externally driven "seed current". These non-monotonic q profiles have a rich spectrum of potential MHD instability at high β_p , including internal or external kinks, infernal modes, ballooning modes and double tearing modes. Remarkably, it is found that, with high values of q_{min} , stable equilibria exist at high β_N in which the total and bootstrap currents are well aligned. However, it is clear that maintaining stability, particularly when the plasma is burning, will require control of the current density profile. Whether or not this can be accomplished is an open question.

One benefit which accrues from the non-monotonic q profile is that of "second stability" against ballooning modes in the negative shear region. This largely comes about because the outward shift of the magnetic surfaces cannot induce zero local shear on the unfavourable curvature side (when the pressure profile is monotonic!).

Figure 1 (β_T, β_p) operating region

3. RESULTS FROM THE CONCEPT IMPROVEMENT PROGRAMME

The concept improvement programme must demonstrate the simultaneous achievement of;

- high β_p (~ 2.5 -3) in order to maximise the bootstrap current,
- high β_N (3-5) so that q can have the smallest value consistent with high β_p and
- high confinement ($H_G \sim 4$) so that the magnetic energy, or cost, can be minimised.

These conditions must be achieved in genuine steady state; ie. MHD and thermally stable, with a consistent divertor solution and no impurity or ash accumulation. In general, it can be said that substantial strides have been made towards the achievement of the plasma conditions. However, the requirements for steady state operation have barely been addressed, if at all.

JET, in common with other machines such as JT60, DIII -D, Tore Supra and TFTR, has obtained plasmas with a significant proportion of bootstrap current. The time history of such a plasma pulse is shown in figure 2. This pulse has $\beta_p = 2$ which, with JET's aspect ratio, is sufficient to yield $I_{BS} / I_p = 0.7 \pm 0.15$ [7]. The energy confinement is very good, with $H_G = 3.6$. However, it has not attained the required normalised β , since $\beta_N = 2$, and the value of q_{cyl} , at 11, is too high. The improved power handling capacity of the new Pumped Divertor should permit high bootstrap fractions to be obtained at higher current and so lower q_{cyl} .

Figure 2 JET pulse 25264 with $\beta_p=2$, $I_{BS}/I_p=0.7$ and $H_G=3.6$

In common with all such plasmas, the high confinement phase terminates suddenly; in this case either because of a giant ELM or contact with the radio frequency antenna. This underlines the need for control schemes, particularly of the plasma current profile and of the density. It is estimated that the pulse shown in figure 2 would take 30 - 40 seconds to come to magnetic equilibrium. Extending the duration of the high confinement phase by a factor of 20, or more, will be a challenging task!

Plasmas with non-monotonic q profiles have already been obtained in JET, using pellet injection and additional heating. One of these so-called, PEP plasmas [8] is illustrated in figure 3. After the reheat, the density profile remains peaked and the pressure profile even more so. The pressure gradient is so strong that a substantial bootstrap current is produced at around 30% of the minor radius and the net current density is hollow. Not only does the core have access to the second stability region but the energy confinement is very good as well. Whether or not this good confinement is a necessary precondition for the high pressure or results from either the negative shear or stability against ballooning modes is not clear.

An important feature of PEP plasmas is that they are observed to accumulate low Z impurities [9]. In contrast, the hot ion VH-mode, as used in the tritium experiment, do not. This difference has been associated with a difference in the collisionality régimes of the low Z impurities in the two types of plasma. Modelling has shown that core impurity transport is predominantly neoclassical. Going from the PEP, which is in the plateau régime, to the hot ion, VH modes, which are in the banana régime, the neoclassical ∇T term changes sign and switches off accumulation, in agreement with experiment.

JET is not alone in having produced plasmas with non-monotonic q profiles. DIII-D has produced plasmas with very high β_p [10] in which the current profile evolves from being peaked to being hollow. As q on axis passes through 2, MHD activity dies away and the core confinement, as evidenced by the density profile and β_p , improves considerably. This shows that it is apparently possible to set up plasmas of the required kind by gradual evolution without any problems being caused by MHD unstable phases.

Stability calculations [11] have demonstrated that configurations exist with $\beta_N > 5$ and $\beta_T > 7\%$ which are largely supported by bootstrap current and are stable against ballooning modes, infernal modes and kinks. External kinks need close fitting walls and plasma rotation for stability. Experimentally, β_N up to 6 has been obtained by profile tailoring and several

Figure 3 (a) safety factor, (b) current density (bootstrap shaded), (c) electron density and (d) electron pressure for a PEP, JET pulse 23100

tokamaks have exceeded β_N of 3.5 as shown in figure 4 [12]. When simulated with stability codes, good agreement is found between experimental points of instability and theory. Thus, not only are suitable configurations found theoretically, but the computations have been well validated by experiment. Experiment and theory have both demonstrated that the plasma needs to be highly triangular in order to obtain very high values of β_N .

4. THE JET CONCEPT IMPROVEMENT PROGRAMME

The establishment of long plasma pulses with a large fraction of bootstrap current is seen as the most important line in the JET concept improvement programme. Taking pulses of the type described in the last section as the starting point, the steps which have to be taken are the control of the current profile, control of the pressure profile and the provision of a seed current drive. It is also intended to demonstrate a similar proportion of bootstrap current at 2MA, although the duration will be limited to 20s because 30MW additional heating power will be needed with $H_G=3$.

A second topic concerns the study of MHD stability and energy confinement in non-monotonic q profiles. Simulations have shown [13] that LHCD during the current ramp and ICRH in the flat-top can "freeze in" a hollow current density distribution. Thus, studies can be performed of the MHD stability and transport in these configurations.

As mentioned in section 2, it is important that plasmas developed in this programme are tested for their compatibility with true steady state. Not only must long pulse operation be obtained with the pumped divertor acting to remove particles and heat but ash and impurity removal must be demonstrated as well. The JET NBI system can inject neutral helium which can be pumped by argon frost on the divertor cryopump. In this way, helium ash removal can be simulated in all plasmas of interest. The response to impurity influxes can be tested with the laser impurity ablation and spectroscopic systems. Thus, improved concept plasmas can be tested in JET for their coherence with true steady state reactor operation

The installation of the Pumped Divertor has improved the capability of the JET machine for making shaped and high aspect ratio plasmas. Not only do the divertor coils themselves

Figure 4 β_T against normalised current (I_p/aB_T) for a number of machines which have exceeded $\beta_N=3.5$.

add extra components to the shaping field but the improved vertical stabilisation system permits access to an increased range of plasmas.

Figure 5 Extremes of equilibria which are available with the new JET divertor.

Figure 5 shows two 2 MA equilibria which represent extremes of triangularity and aspect ratio which can be obtained at low β_p . At 2 MA and $\beta_p = 0.2$ the operating range is :

$$\text{Elongation ratio} < 1.9 ,$$

$$0.13 < \text{triangularity} < 0.55$$

$$\text{and } R/a < 4 .$$

At high β_p , the triangularity increases due to the axis shift. Even so, JET cannot obtain a sufficient triangularity to support as high β_N values as DIII-D. Nonetheless, it will be sufficient to demonstrate the viability of improved concept scenarios, particularly in respect of profile control.

JET has already demonstrated an adequate long pulse capability; 2 MA / 2.2 T for up to 60 seconds which can be compared with 30-40 s for a 1 MA, high β_p plasma, such as that in figure 2, to come to equilibrium.

System	Power	Pulse Length	Current Drive $n_e=4.10^{19}\text{m}^{-3}$, $T_e=7\text{keV}$)
NBI (deuterium)	13.6MW/85keV	10s	0.015A/W
	7.6MW/140keV	10s	
ICRH/FWCD	24MW / 25- 55MHz	20s	0.04A/W
LHCD	10MW / 3.7GHz	20s	0.2A/W

Table 1 Heating and current drive systems installed on JET

The capabilities of the heating and current drive systems are listed in Table 1. It should be noted that a total of 57 MW and 940 MJ could be delivered to the plasma. Although it is unlikely that such a large amount of energy could be withstood without active cooling, long pulse, high power operation will require that the Pumped Divertor be highly effective. One of the key operational issues in the concept development programme is to determine if the plasma scenarios can be made compatible with "gas targets" or radiating divertors. At the time of writing [14], NBI has been operating reliably at 16 MW, LHCD has driven 2 MA with 4 MW launched power and ICRH has operated at up to 9MW. The pellet launching systems (two guns at 4 km/s and a repetitive centrifuge system) are available for controlling the density profile.

An integrated system of codes has been prepared [13] for the simulation of improved concept plasmas. The current drive (NBI, LHCD and FWCD), plasma transport, MHD stability and diagnostic signals are all simulated. A number of different scenarios have been evaluated. An example is shown in figure 6, where a hollow current density profile has been frozen in by application of LHCD during the current rise. Application of ICRH increases both the LHCD contribution, due to the synergy effect [15] and the bootstrap current so that this 3 MA plasma is sustained non-inductively. It can be seen that the current profile is stationary for at least 6 seconds. Thus, stability and transport can be studied in these conditions. ITER plasmas have also been simulated. It is found that fully non-inductive plasmas with a substantial bootstrap current will be obtainable in ITER at 12 MA. Depending on assumptions made about the safety factor dependence of energy transport, it has been observed that some burning plasmas can undergo relaxation oscillations because of the strong coupling between the heating and bootstrap current profiles. This aspect of improved concept operation will require further elucidation.

Figure 6 (a) waveforms of a simulated 3MA, fully non-inductive JET plasma where (b) a hollow current density profile has been "frozen in" by application of LHCD in the I_p rise.

The JET Director has proposed an extension of the JET programme to the turn of the century. It is foreseen that there would be two tritium experiments; DTE1 in 1996 and DTE2 at the end of the project. The concept improvement programme at JET will be a background activity until the experimental campaign before DTE2. Then the concept improvement programme will come to the fore as the means to enhance JET's fusion performance. The poloidal field system is capable of supporting plasmas which can produce up to 40 MW of fusion power. If the presently observed energy confinement enhancements can be extended to 5-6 MA, then $Q>2$ should be attainable as well [16]. Performance enhancements at these levels will demand a considerable level of success in the efforts to develop profile and MHD stability controls which form the core of JET's concept improvement programme.

5. CONCLUSIONS

In order to reduce the capital cost of a tokamak reactor and to make it capable of continuous operation, several developments are required which go collectively under the title of concept improvement. In particular, substantial, simultaneous improvements in β_p, β_N and confinement enhancement are required together with all the other attributes needed for steady state, such as compatible divertor operation, helium ash removal and complete stability.

A substantial start has been made on this programme line. JET has demonstrated plasmas with high β_p and confinement enhancement in which the bootstrap current comprises 70% of the total. However, these plasmas are transient and fall short of the required levels of β_N and q . Stability calculations have shown that it is possible to find equilibria at very high values of

β_N (>5) which are compatible with low levels of external current drive. The results of these computations are underwritten by a body of experimental evidence in which profile modifications at high β_N have the anticipated effects on MHD stability. Investigations into the requirements for steady state operation have barely commenced.

The JET concept improvement programme is directed towards maximising its own fusion performance. However, there is also much that JET can contribute to the longer term programme in this area. Since JET will not be capable of producing plasmas with sufficient triangularity, it should not be able to operate up to β_N of 5 or more. However, JET has a full range of heating, current drive and profile control systems which will allow the generic control issues to be studied in plasmas where the bootstrap current dominates. It will also be able to investigate stability and transport in plasmas with hollow current profiles and to determine the compatibility of the operating régime with ash removal and impurity control.

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