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HIGH ASPECT RATIO D-^{3}He TOKAMAK REACTORS

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Abstract

Because of the reduced reactivity of D/He-3 relative to D-T, higher beta operation is necessary with D/He-3. One possibility for high beta is to operate in the second stability regime with a high plasma aspect ratio. We have investigated some of the physics aspects of second stability, high aspect ratio operation with D/He-3. Ignition may be feasible, depending on the energy confinement scaling, with much reduced plasma current and magnetic field at the TF magnet, in comparison with the corresponding values for low aspect ratio tokamaks operating in the first stability regime.

Introduction

The recent discovery [1] that the moon contains a large amount of He-3 leads us to consider the possibility of using the D/He-3 reaction in tokamak power reactors. The advantage of the D/He-3 reaction is, of course, the much reduced neutron production, but the difficulty is the reduced fusion reactivity relative to D-T fusion. Earlier studies [2] of D/He-3 reactors have also had to contend with the problem of breeding He-3, since it is an extremely rare isotope on the earth. With the possibility of obtaining He-3 from the moon, the breeding requirement is removed. Since tokamaks represent the presently leading concept for magnetic confinement, it is worthwhile to investigate the possibility of a tokamak reactor based on the D/He-3 reaction.

In order to compensate for the reduced reactivity of D/He-3 relative to D-T, higher beta operation is necessary with D/He-3. One approach to obtaining a stable, high beta, MHD equilibrium is to optimize operation in the first stability regime by choosing a very small aspect ratio, extreme elongation, low q, or large indentation. However, small aspect ratio and large indentation present numerous technical difficulties when considered for use in a power reactor.

A second approach is to operate in the so-called second stability [3] regime, which is more easily accessible at larger aspect ratio [4,5], as shown in Fig. 1. One of the major benefits of operating in the second stability regime is that the Troyon [6] beta limit is broken and higher beta is possible without paying the price of driving a high toroidal plasma current, I. This is because the second stability regime is not strongly dependent on plasma current. Low current operation with good charged particle confinement is possible at large aspect ratio, A, since IA > 20 MA is sufficient for 15 MeV proton confinement. Another advantage of high aspect ratio is that the magnetic field at the plasma is higher for a given magnetic field at the toroidal field magnets. This is significant since the fusion power density scales as the fourth power of B.

In this paper we consider the possibility of D/He-3 operation in a high aspect ratio tokamak operating in the second stability regime. We focus on the question of plasma power balance for various energy confinement "scaling laws". The engineering implications of a D/He-3 tokamak are left for others to consider.

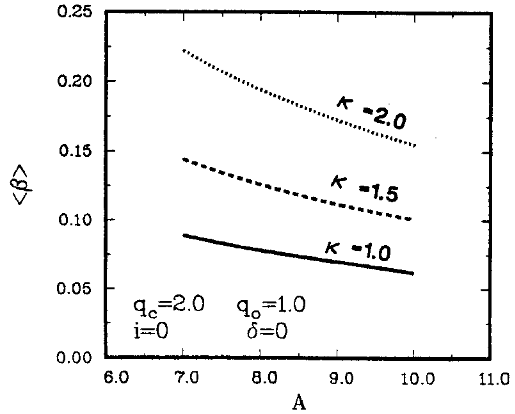

Fig. 1. Minimum beta for second stability versus aspect ratio.

Plasma Model

The performance of a tokamak reactor operating with D/He-3 fuel can be estimated using the DHE3TOK computer code, which is essentially a global power balance code. This code calculates the fusion power produced for given plasma density and temperature profiles. The plasma beta, which is determined by the plasma density and temperature and the pressure of the fast fusion produced ions, is constrained to satisfy MHD equilibrium and stability considerations. The loss mechanisms included are bremsstrahlung and synchrotron radiation, with relativistic corrections, and transport across the magnetic field. The electron and ion temperatures are allowed to separate; rethermalization, with relativistic corrections, is included.

The biggest uncertainty in our analysis is the energy confinement time for transport across the magnetic field. We use empirical scaling laws to estimate this loss. These are based on present experiments, which operate at similar density but an order of magnitude less temperature than that required for D/He-3 fuel. In addition, they are based on operation in the first stability regime; there is no experience as yet with operation in the second stability regime. In order to see the sensitivity of the results to a change in the energy confinement scaling law we consider two different scaling laws: Kaye-Goldston scaling [7] with an H-mode factor of 2, and ASDEX H-mode scaling [8]. The loss is assumed to be in the electron channel. The loss in the ion channel is assumed to be neoclassical (or a multiple of it), which is a negligible loss at D/He-3 conditions.

The DHE3TOK code calculates the ignition margin, which is defined as the fusion power produced divided by the total power loss. These have to balance, of course, in equilibrium. Consequently, if the ignition margin is above unity, one has a safety factor against increased losses. If necessary, one can always increase the losses by enhancing the impurity radiation, for example, to achieve the desired operating point.

One difficulty with these studies for the second MHD stability regime is determining the upper limit on beta, since ideal MHD gives only a lower limit. Reactors improve as beta is increased, but there is a qualitative concern that, at very high beta, the current profiles may be highly distorted and susceptible to resistive MHD instabilities. In this analysis we specify the volume averaged beta and allow it to vary, while remaining in the second MHD stability regime.

Parametric Studies

We start with a nominal design point and individually vary the major parameters affecting the plasma ignition margin. Our nominal design point has a major radius R of 11 m, aspect ratio A equal to 9, toroidal field B at the magnet of 10 T, $<\beta>$ equal to 20%, and elongation, K, of 2. The plasma is ignited for both ASDEX H-mode and Kaye-Goldston scaling, and the fusion power is about 3500 MW. Shown in Fig. 2 is the ignition margin versus average ion temperature.

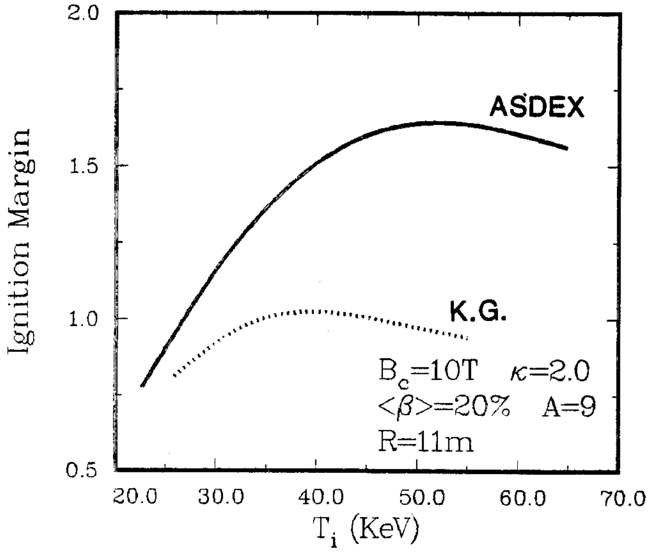

Fig. 2. Ignition margin versus average ion temperature for ASDEX H-Mode and Kaye-Goldston energy confinement scaling.

The ignition margin optimizes at an <T> of about 35-40 keV. Shown in Fig. 3 and 4 is the distribution of losses versus volume-averaged ion temperature for the two scaling laws. We see that transport is the larger loss process for Kaye-Goldston scaling, but radiation and transport are about equal for ASDEX H-mode scaling at an average ion temperature of about 60 keV. One result to be noted here is that the extremely high ion temperatures (≈ 100 keV) normally associated with advanced fuels are not required for D/He-3 fusion.

Shown in Fig. 5 is the effect of varying the aspect ratio on the ignition margin. We see that the ignition margin improves as the aspect ratio is re-

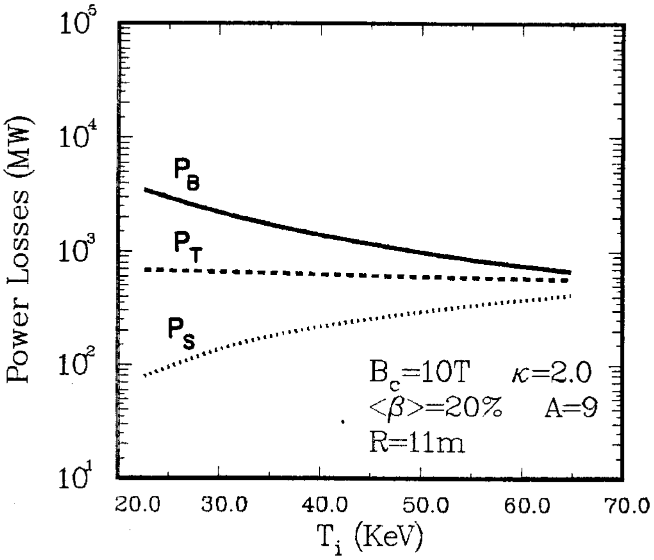

Fig 3. Power loss distribution versus average ion temperature for ASDEX H-mode energy confinement scaling.

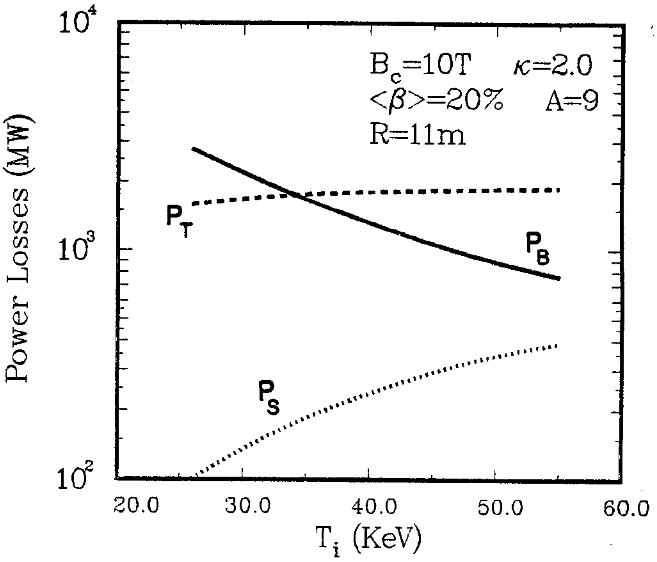

Fig. 4. Power loss distribution versus average ion temperature for Kaye-Goldston energy confinement scaling.

duced for Kaye-Goldston scaling (this is because the plasma current increases) but shows little change for ASDEX H-mode scaling, which is probably due to the weaker scaling with current and the fact that radiation losses are a larger fraction of the total loss. The variation of the plasma current with aspect ratio is shown in Fig. 6. Figure 7 shows the effect of increasing the major radius. Both scaling laws show a slight increase of ignition margin with R. Figure 8 shows the increase of ignition margin with magnetic field. Kaye-Goldston scaling shows a greater dependence, which is probably due to the plasma current also changing as Bc is increased, because the MHD safety

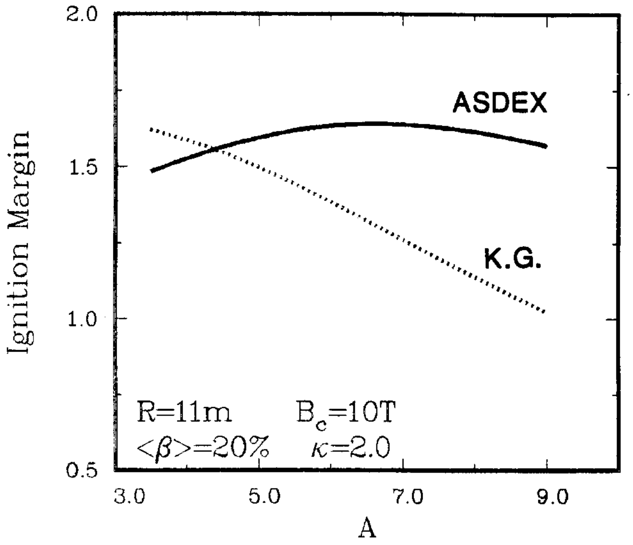

Fig. 5. Ignition margin versus aspect ratio.

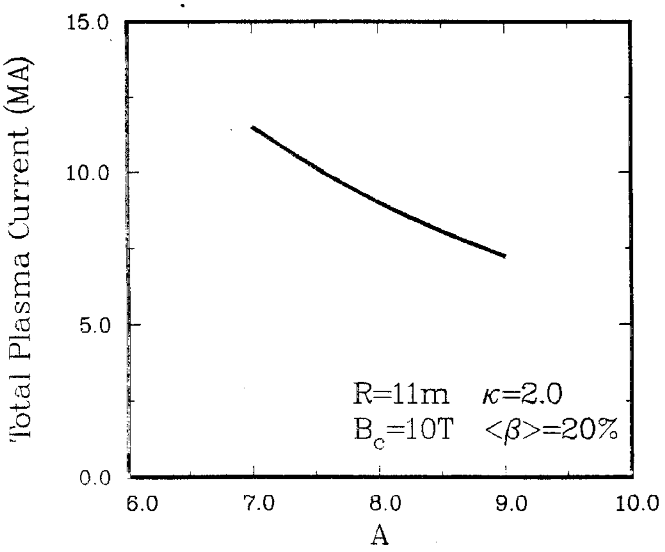

Fig. 6. Plasma current versus aspect ratio.

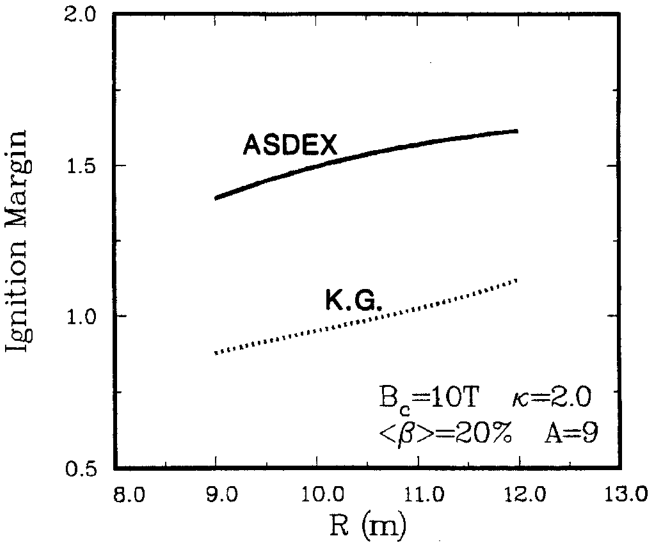

Fig. 7. Ignition margin versus major radius.

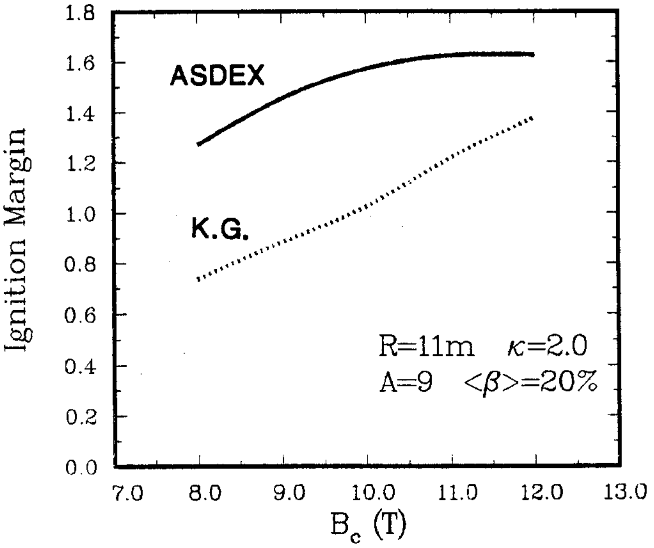

Fig. 8. Ignition margin versus toroidal magnetic field at the TF magnets.

factor is held constant. Figure 9 shows the increase of ignition margin with elongation; this dependence is also due to plasma current changing at constant MHD safety factor.

In the above parametric studies the fusion power is changing as the parameters are varied. Figure 10 illustrates the change in the fusion power as the aspect ratio is varied for <β> equal to 15% and 20%. The power level decreases as the aspect ratio is increased at constant major radius because the plasma volume is decreasing. The range of power levels in this study is generally consistent with the usual fusion power levels assumed for a commercial reactor. Shown in Table 1 are the parameters of a possible reactor design point. The plasma current and magnetic field at the TF coils are much less than would be anticipated with a first stability regime reactor [9].

Conclusions

The high aspect ratio approach to high beta is advantageous for reduced plasma current and better utilization of the toroidal magnetic field. The disadvantage is that the reduced plasma current means the energy confinement time is also reduced, according to energy confinement scaling laws currently in vogue. Ignited operation of D/He-3 fuel in a high aspect ratio tokamak is still feasible, but with reduced ignition margin. Energy confinement scaling in the second stability regime is a significant issue requiring experimental investigation.

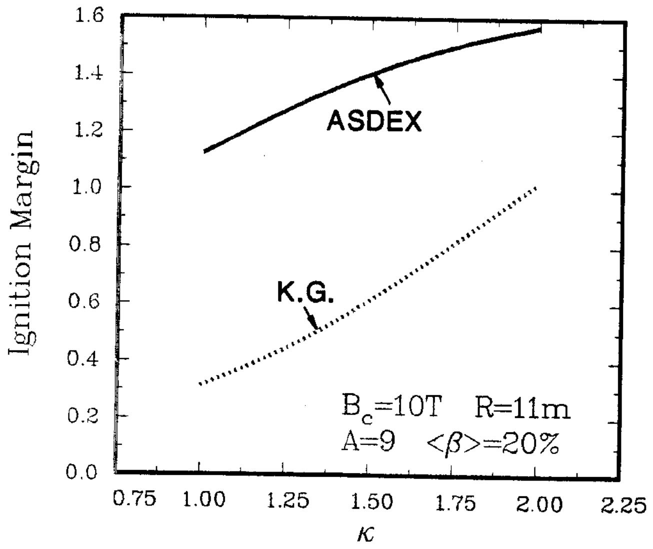

Fig. 9. Ignition margin versus elongation of the plasma.

Table 1. Parameters of a High Aspect Ratio D/He-3 Tokamak

Aspect ratio	9
Major radius	11 m
Plasma half-width	1.22 m
Elongation	2.0
Magnetic field at TF magnet	10 T
Magnetic field at plasma	8.5 T
Plasma current	7.2 MA
$<\beta>$	20%
Average ion temperature	41 keV
Average electron density	4.4×10^{20} m^{-3}
Fusion power	3394 MW
Energy confinement scaling	Kaye-Goldston
H-mode factor	2
Transport loss	1808 MW
Bremsstrahlung loss	1261 MW
Synchrotron loss	247 MW
Ignition margin	1.03
Fuel mixture	.67 D, .33 He-3

Acknowledgement

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References

[1] L.J. Wittenberg, J.F. Santarius and G.L. Kulcinski, "Lunar Source of He-3 for Commercial Fusion Power", Fusion Technology, vol. 10, pp. 167-178, September 1986.

[2] G.W. Shuy, D. Dobrott et al., "Conceptual Design of a D/He-3 Fueled TMR Satellite/Breeder System", SAI Report SAI-84/3055, 1984.

[3] B. Coppi, A. Ferreira, et al., "Ideal-MHD Stability of Finite-Beta Plasmas", Nuclear Fusion, vol. 19, pp. 715-725, June 1979.

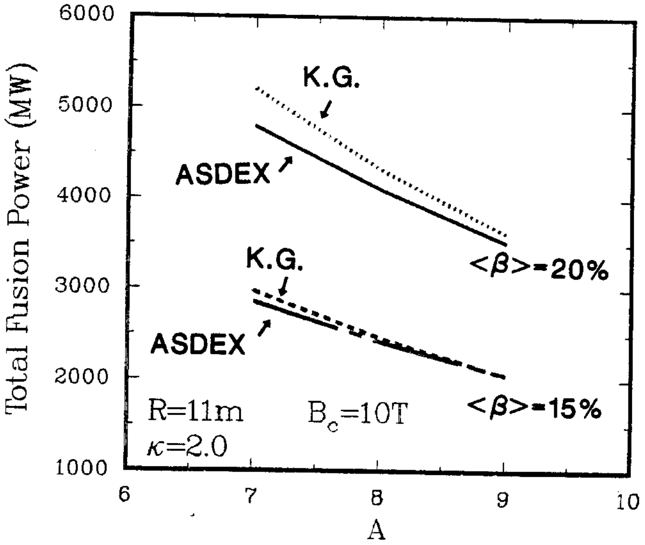

Fig. 10. Fusion power versus aspect ratio for both Kaye-Goldston and ASDEX H-mode energy confinement scaling and for two different values of $<\beta>$.

[4] G.A. Navratil and T.C. Marshall, "High-Beta Tokamak Operation in the Second Stability Regime", Comm. Plasma Phys. and Cont. Fusion, vol. 10, pp. 185-206, no. 4, 1986.

[5] M.E. Mauel, "The Use of Scaling Laws for the Design of High Beta Tokamaks", Nuclear Fusion, vol. 27, pp. 313-324, Feb. 1987.

[6] F. Troyon, R. Gruber et al., "MHD-Limits to Stable Confinement", Plasma Phys. & Cont. Fusion, vol. 26, pp. 209-215, Jan. 1984.

[7] S.M. Kaye and R.J. Goldston, "Global Energy Confinement Scaling for Neutral-Beam-Heated Tokamaks", Nuclear Fusion vol. 25, pp. 65-69, Jan. 1985.

[8] The NET Team, "NET Status Report 1985", NET Report 51, Commission of the European Communities, 1985.

[9] B.G. Logan, "He-3 Applications in Tokamak Fusion", Bull. Amer. Phys. Soc. vol. 31, pp. 1499, Oct. 1986.