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ABSTRACT

Tokamaks with elongated, noncircular cross sections are under consideration as fusion reactors because they have the potential for stable operation at high beta. Ideal MHD theory, however, predicts that careful current profile control will be required to achieve the potential high-β advantages of noncircular cross sections. In this paper, high-β equilibria which are stable to all ideal MHD modes are found by optimizing the plasma shape and current profile for doublets, up-down asymmetric dees, and symmetric dees. The ideal MHD stability of these equilibria for low toroidal mode number n is analyzed with a global MHD stability code, GATO. The stability to high-n modes is analyzed with a localized ballooning code, BLOON. The attainment of high β is facilitated by an automated optimization search on shape and current parameters. The equilibria are calculated with a free-boundary equilibrium code using coils appropriate for the Doublet III experimental device. The optimal equilibria are characterized by broad current profiles with values of $\beta_{poloidal} \approx 1$. Experimental realization of the shapes and current profiles giving the highest β limits is explored with a 1-1/2-D transport code, which simulates the time evolution of the 2-D MHD equilibrium while calculating consistent current profiles from a 1-D transport model. Transport simulations indicate that nearly optimal shapes may be obtained provided that the currents in the field-shaping coils are appropriately programmed and the plasma current profile is sufficiently broad. Obtaining broad current profiles is possible by current ramping, neutral beam heating, and electron cyclotron heating. With combinations of these techniques it is possible to approach the optimum β predicted by the MHD theory.

Tokamaks with elongated, noncircular cross section are under consideration as fusion reactors because they have the potential for stable operation at high β, i.e., values of the ratio of the volume average pressure to toroidal magnetic field pressure (evaluated at the magnetic axis) greater than 5%. In this paper, high-β equilibria, stable to all ideal MHD modes, are found by optimizing the plasma shape and current profile for doublets and for dees which can be either symmetric or asymmetric with respect to the equatorial plane of the toroidal plasma. The optimal equilibria have current profiles which are much broader than profiles produced by ohmic heating and have, at the same time, low values of beta poloidal ($\beta_p \approx 1$), as defined by Zakharov and Shafranov [1]. Experimental realization of these current profiles is explored with a 1-1/2-D transport code, with which the effects of current ramping, neutral beam heating, and electron cyclotron heating on the current profile can be simulated. With combinations of these techniques it is possible to approach the optimum β predicted by the MHD theory.

The identification of high-β equilibria, stable to all ideal MHD modes, is facilitated by an automated optimization search on shape and current parameters [2]. The equilibria analyzed in the search procedure are calculated with a free-boundary equilibrium code using field-shaping coils appropriate for the Doublet III experimental device. The coil positions are shown in Fig. 1 for both dee and doublet shapes in the present experiment and for a larger dee which can be achieved by modification of the present Doublet III device. The Grad-Shafranov equation is solved with the poloidal flux, $2\pi\psi$, on the coils used as the boundary condition and the ψ dependence of the toroidal current given by $j_\phi = -p'R - ff'/\mu_0 R$, with $p' = I_0\bar{\beta}_p[\exp(1 - \bar{\psi}^{\alpha_p}) - 1]$ and $ff' = I_0(1-\bar{\beta}_p)[\exp(1 - \bar{\psi}^{\alpha_f}) - 1]$. Here prime denotes differentiation with respect to ψ, I_0 is a normalization constant to give the specified total current, α_p and α_f control the half widths of the pressure and toroidal field, $\bar{\beta}_p$ is approximately equal to beta poloidal, and $\bar{\psi} \equiv (\psi-\psi_{axis})/(\psi_{limiter}-\psi_{axis})$. R is the toroidal radius.

The parameters varied in the optimization are β_p, α_p, α_f and the poloidal flux on the 24 or 22 field-shaping coils. Each parameter is varied in turn and the stability of the resulting equilibrium is analyzed using techniques subsequently discussed. If the value of β is greater than previously found, the equilibrium is saved and the parameter increased again. The parameter search is terminated when a higher β can not be found with the given input parameter increments. If smaller increments were tried, a slightly higher β would probably be attainable.

Each equilibrium is tested for stability to interchange, ballooning, internal kinks, and external kinks. Stability to axisymmetric modes is not analyzed, as previous studies [3,4] have shown that feedback stabilization can be provided by the field-shaping coils. The stability to high toroidal mode number n is analyzed with a localized ballooning mode analysis code BLOON [5]. The Mercier criterion [6] for the interchange mode is evaluated at the magnetic axis of the equilibrium. The vacuum toroidal magnetic field B_T is adjusted to force the on-axis safety factor q_a equal to the Mercier value. Ballooning-mode stability in the limit of infinite n is then evaluated off axis and imposed by also varying B_T.

Two different ballooning modes have been seen. At low β_p a ballooning mode may exist halfway between the axis and the plasma surface for dee shapes. For doublet shapes the mode may exist halfway between the separatrix and the surface or halfway between the axis and the separatrix. Stability to this mode is achieved by varying B_T. At higher β_p a mode localized near the plasma surface appears. This mode is effectively stabilized only by decreasing β_p.

A new global δW code GATO has been developed to analyze the stability to low-n kink modes of doublet and up-down asymmetric dee shapes. GATO utilizes the same numerical scheme as the ERATO δW code [7], but employs a coordinate system which is orthogonal to the poloidal flux surfaces. GATO minimizes the MHD energy principle with respect to the Mercier representation of the displacement vector. Finite hybrid elements are substituted to obtain a matrix eigenvalue problem for the normal modes of the plasma. The hyperbolic axis, associated with an internal magnetic separatrix, is treated by imposing the constraint that the component of the displacement normal to the flux surface is zero at the hyperbolic axis.

In the optimization search, the internal kink mode is stabilized by adjusting q_a. The external kink is analyzed in two different limits. The most pessimistic limit assumes no wall stabilization and kink stability is calculated for n = 1. The more optimistic limit assumes complete wall stabilization of the external kink. In the Doublet III experiment the vacuum chamber wall is within 0.1 minor radii of the plasma surface for doublet shapes. This is close enough for a superconducting wall to stabilize the plasma. Since the wall is resistive, the kink is not stabilized, but its growth rate is reduced. The reduction may be enough for transport processes to stabilize the mode nonlinearly. When no wall stabilization is used, the equilibria can be stabilized by either increasing q_a or by peaking the current profile. The latter method is used in this study.

Figure 1 shows optimal shapes in the Doublet III vacuum chamber for an asymmetric dee and a doublet with 50% of the poloidal flux within the separatrix, $P_s = 50$. A symmetric dee shape is also shown for a large vacuum chamber in Doublet III. The dee shapes illustrate the amount of triangularity needed in stable high-β plasmas. The triangularity decreases the connection length between bad and good curvature regions and improves the stability to ballooning modes. An interesting feature of the doublet shape is that the x-point region is right-left symmetric for optimum stability.

The results of the automated search show three important features which hold regardless of plasma shape. The optimal equilibria have values of β_p near 1, current profiles that are much broader than typical ohmically heated current profiles, and shapes that are triangular on the outside edge of the plasma. Previous optimization studies for up-down symmetric dee shapes [3] have shown that the optimum value of β_p for stability to external kinks without wall stabilization is near 1. At higher β_p, the magnetic axis shifts outwards and induces strong current gradients near the edge of the plasma which destabilize the external kink. Ballooning mode stability of doublet shapes is also best for $\beta_p \leqslant 1$ [8], since at higher β_p a localized mode near the plasma edge is excited.

Since stability results constrain $\beta_p \leqslant 1$, high β is attained by elongation [3] and broadening the current profile. Current profile broadening is illustrated in Fig. 2 in which the values of β are plotted as a function of the current half-width for several equilibria calculated during the optimization. The final equilibrium has a current half-width twice as large as the initial ohmic current profile.

Figure 3 shows the radial profiles of pressure and current across the midplane of an optimal dee in the upper half chamber of the Doublet III device. The solid curve is the optimized profile and the dashed curve is the ohmic profile. Note that both the pressure and the current must be significantly broadened to achieve the highest values of β. The optimum symmetric dees and doublets have similar pressure and current profiles.

The maximum stable values of β found by the optimization process are 6.4% for the asymmetric dee in the upper half chamber of the vacuum vessel, and 7.0% for a doublet with P_s = 50%. The stability limit for the doublet shape increases to β = 9.7% as P_s is decreased to 32%, in qualitative agreement with earlier studies [8]. For a symmetric dee in the modified Doublet III chamber a stable value of β = 13% is predicted. This increase in the β limit is due to the decrease in the aspect ratio from 3.1 to 2.2.

The greatest uncertainty in the β limits found by the optimization code comes from the kink calculation. To avoid finding a destabilized Alfvén continuum mode instead of a kink, a cutoff of $-0.005\ \omega_A^2$ is used for γ^2, the growth rate squared, where ω_A is the poloidal Alfvén frequency. Smaller growth rates are ignored. Thus a residual kink mode can persist at the cutoff growth rate. To stabilize this mode, a wall must be located within one minor radius of the plasma surface. For the Doublet III experimental device, the vacuum chamber is within 0.1 minor radius of the surface and the residual kink mode is stabilized. The equilibria presented here as optimum for stability to ideal MHD modes actually represent pessimistic limits. The nature of the search procedure does not preclude the existence of stable equilibria with higher β. Also the β limit for the ballooning mode is done in the pessimistic limit of infinite toroidal mode number.

Experimental realization of the shapes and current profiles giving the highest β limits has been explored with a 1-1/2-D transport code [9], which simulates the time evolution of the 2-D MHD equilibrium while calculating consistent current profiles from a 1-D transport model. In the simulations, the electron energy transport is taken to be anomalous with a constant thermal conductivity; this results in Alcator scaling [10], i.e., an electron energy confinement time that is proportional to density. The electron particle transport is also taken to be anomalous, and a thermal pinch is included so as to produce the parabolic density profiles observed experimentally. The ion energy transport is neoclassical, and the resistivity is classical. A pure hydrogen plasma and perfect recycling of neutrals are assumed. Thus the average plasma density remains constant during ohmic and electron cyclotron heating, but increases due to beam fueling during neutral beam heating. The neutral beam heating model is an extension of the FREYA [11] and NFREYA [12] models, which has been generalized to handle doublet plasmas.

The desired plasma shapes are obtained in the simulations by appropriate programming of the currents in the field-shaping coils. To obtain broad, near-optimal current profiles, the plasma is first subjected to a short period of ohmic heating during which the total current is ramped upward. Neutral beam heating is then applied to freeze in the broad current profile. The effectiveness of this current broadening approach clearly depends upon the assumption of classical resistivity.

Examples of the initial ohmic profile and the broadened profile obtained by current ramping followed by beam heating are shown in Fig. 3 together with the optimum profile. The transport generated current profile (plotted with dots) shows the remnant of the initial ohmic profile and the wings induced by the current ramping. The resulting profile is almost as broad as the optimum. The low values of β_p needed for optimal stability are achieved by current ramping, which reduces the increase in β_p due to neutral beam heating.

The highest stable β values obtained in the transport simulations of Doublet III are 3.1% for the asymmetric dee, 3.1% for the doublet with $P_s = 50\%$, and 6.2% for the symmetric dee. Still higher β values are likely if the current ramping technique is refined, if electron cyclotron heating is used for current profile control, or if doublets with lower P_s are considered. In any case, the β values obtained so far are substantial fractions of the optimal values and thus provide some assurance that high-β configurations can be obtained experimentally.

ACKNOWLEDGMENT

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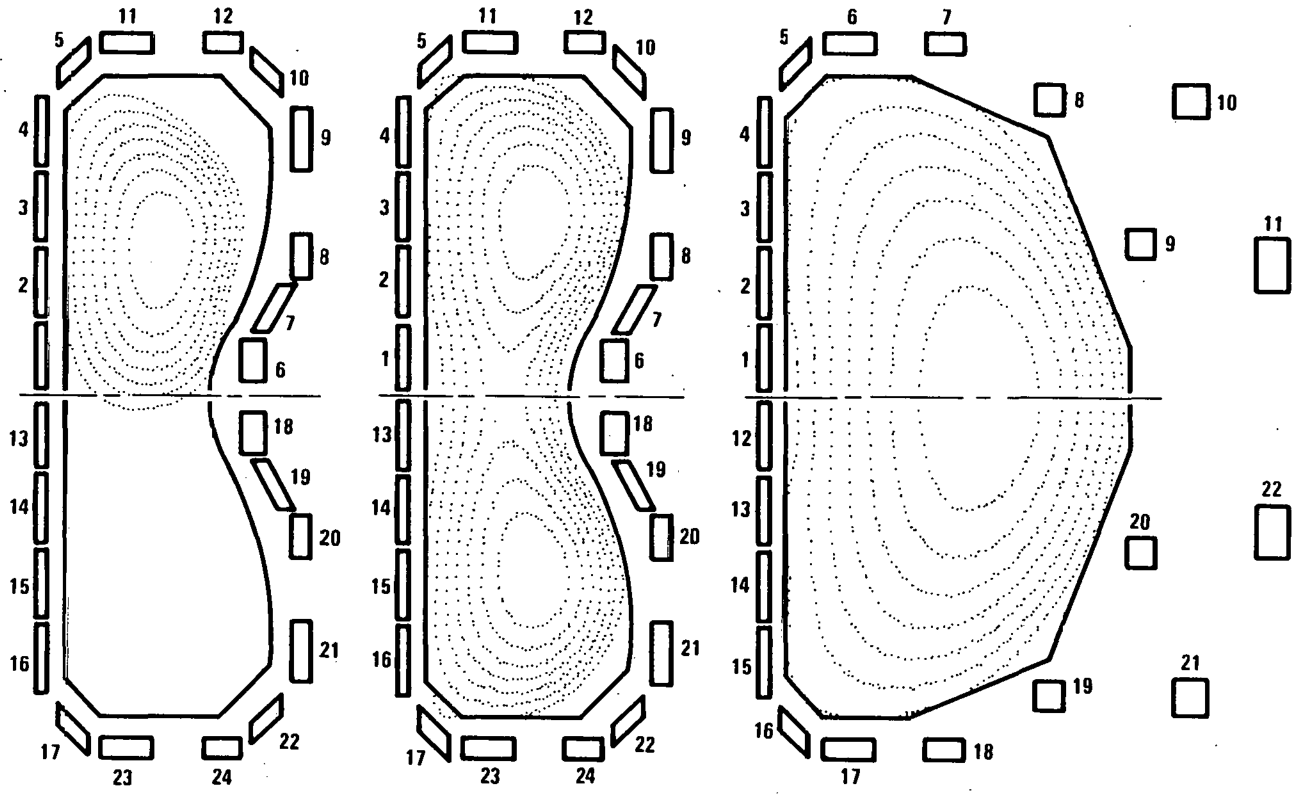
FIGURE CAPTIONS

Fig. 1. Optimal shapes for high-β equilibria in the present Doublet III experimental device (asymmetric dee and doublet) and in a modified vacuum chamber (symmetric dee).

Fig. 2. β vs current half-width $V_{1/2}$ for the sequence of equilibria found during an optimization of the asymmetric dee. $V_{1/2}$ is the fraction of the plasma volume that contains half the total plasma current, $I_p/2$.

Fig. 3. Radial profiles of the pressure and toroidal current density through the elliptic axis of an optimal asymmetric dee.



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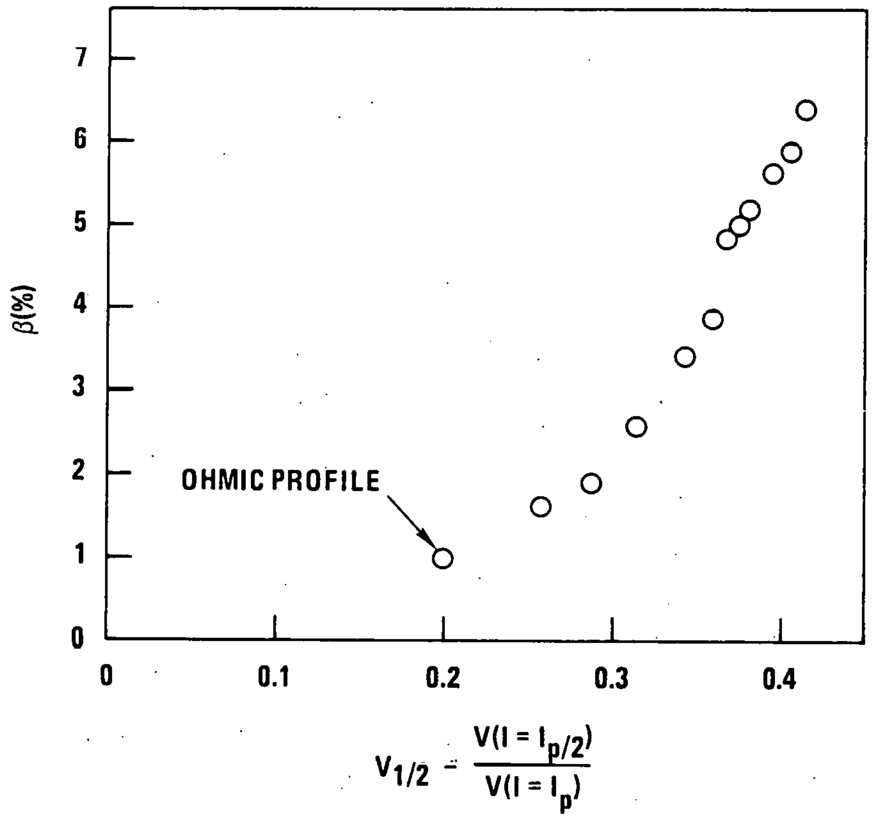

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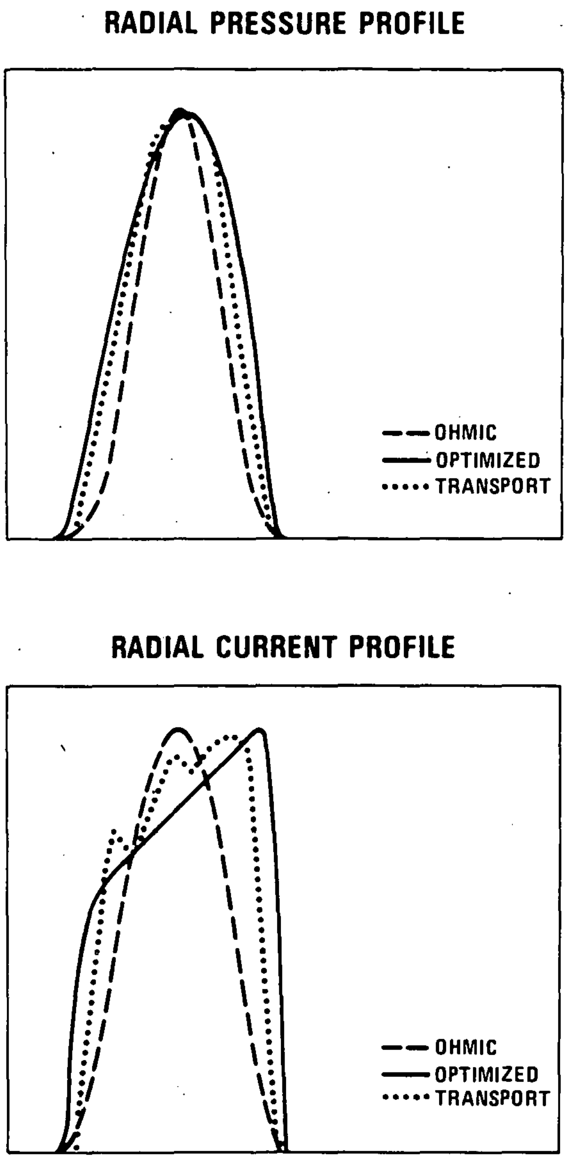

Fig. 3. Radial profiles of the pressure and toroidal current density through the elliptic axis of an optimal asymmetric dee.

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