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MASTER

FEBRUARY 1980

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Submitted for publication in the Proceedings of the American Physical Society Division of Plasma Physics Meeting on November 8-12, 1979, Boston, Massachusetts.

Work supported by
Department of Energy
Contract DE-AT03-76ET51011

Co.,
GENERAL ATOMIC PROJECT 3235
FEBRUARY 1980

San Diego, Calif

950 0489

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy: A04; Microfiche A01

1. INTRODUCTION

This report describes the experimental measurements and data analysis techniques used to evaluate the energy confinement in noncircular plasmas produced in Doublet III. The data was obtained in the first half of 1979 during plasma operation with high-Z limiters. Confinement times for a variety of plasmas with near-circular ($b/a = 1.1-1.3$) and doublet ($b/a = 3$) cross sections are calculated and compared. In all cases, the measurements were made during the steady-state portions of discharges with low levels of low-Z and metallic impurities. The electron energy confinement is found to be equal at a given density in both the near-circular and doublet plasmas, and to increase in proportion to the plasma density, with a scaling coefficient similar to that obtained in other circular tokamaks. No deterioration in confinement due to the effects of plasma shaping is observed. The lack of a detectable improvement in the confinement of doublets relative to the near-circular plasmas is to be expected, since magnetic measurements indicate that the plasma current density is strongly peaked on axis. With such highly peaked current profiles, the interior flux surfaces of the doublet are only slightly noncircular, and the theoretically expected confinement improvement is less than the scatter and uncertainty in the experimental data.

Major aspects of the confinement measurements and analysis techniques are summarized in the following sections of this report. Machine parameters, diagnostic systems and discharge parameters relevant to the confinement measurements are given in Section 2. Magnetic analysis techniques used to determine the plasma shape are reviewed in Section 3. Scaling of the on-axis values of electron temperature, confinement time and Z_{eff} with plasma density is presented in Section 4. Comparison with scaling results

from other circular tokamaks is discussed. Numerical and analytic techniques developed for calculating the plasma energy confinement time and self-consistent profiles of density, temperature, current, and flux in non-circular geometries are described in Sections 5 and 6. These techniques are applied to the data and used to determine the central and global electron energy confinement time for a typical doublet plasma. Additional aspects of the confinement such as the radial dependence of the electron thermal conductivity and the estimated ion temperature are explored in Section 7 with the aid of a non-circular transport simulation code. The results of the confinement measurements are summarized and discussed in Section 8. A brief summary of the theoretically expected effects of noncircularity on plasma confinement is included for reference as Appendix I.

2. DOUBLET III PARAMETERS, DIAGNOSTIC SYSTEMS, AND DISCHARGE CHARACTERISTICS

Doublet III has the following parameters:

major radius	$R = 1.43$ meters
plasma width	$2a = 0.9$ meters
plasma height	$2b = 2.90$ meters
toroidal field	$B_T \leq 26$ kilogauss
plasma current	$I_P \leq 2.2$ MA

The Inconel 625 vacuum vessel is surrounded by 24 field shaping coils (Fig. 1), and can accommodate a variety of plasma cross sections with a vertical elongation of up to 3.2. Feedback control of the magnetic flux linking the shaping coils with SCR power supplies allows the shape and position of the discharge to be controlled [1].

The composition of the primary limiters installed during the confinement studies was 90% tantalum - 10% tungsten, and the secondary limiters were of molybdenum [2]. The primary limiters are on the outer wall, with a front surface ≥ 4 cm from the vacuum wall. The secondary limiters are located at three toroidal azimuths, encircling the plasma poloidally, with the front surface 3 cm from the wall. Each night, low power Taylor discharge cleaning [3,4] is used to remove impurities from the vacuum vessel wall.

The magnetic diagnostics (Fig. 2) which provide the data for plasma shape control and MHD equilibrium analysis include 24 single-turn flux loops located on the side facing the plasma of each coil, 12 extended magnetic probes called partial Rogowski coils to measure the poloidal field, full Rogowski coils to measure the plasma current, and several

Fig. 1. Doublet III cross-section

Fig. 2. Field shaping coils and magnetic diagnostics

localized magnetic probes. The principal plasma diagnostics used for the confinement measurement are illustrated in Fig. 3. The plasma density is measured by two interferometers, a two channel horizontal-path 2 mm microwave system and a vertical-path 10.6 micron CO₂ laser system. The electron temperature profile is measured by a far-infrared Michelson radiometer which monitors the intensity of electron cyclotron harmonic radiation emitted from the upper region of the plasma ($Z \sim 90$ cm). The electron temperature profile is computed by a Fourier analysis of the emission data collected over a 14 msec period. The radiometer is calibrated against a single-point Thomson scattering system, which measures the electron temperature near the upper plasma center.

Confinement data has been obtained for three types of plasma discharges, illustrated in Figs. 4 and 5. In order of increasing vertical elongation, the configurations are droplet, with two separated current channels, each with $b/a \cong 1.1$; ellipse or singlet, a single current channel in the upper half of the vessel with $b/a \cong 1.25$; and doublet, with an internal separatrix and $b/a \cong 3$.

The detailed time-dependent waveforms of a typical doublet discharge are shown in Fig. 6. Similar waveforms are obtained for droplet and elliptical discharges. The discharge lasts 0.5 seconds, and steady-state conditions occur during the last 200 milliseconds. Gas injection at a constant 40 Torr-l/sec rate results in a rising density and sufficient edge cooling to control the influx of metallic impurities. In the steady-state phase of the discharge, the loop voltage stabilizes at 1.6 V/turn, and the radial position, height and percentage of flux inside the separatrix indicated by the magnetic diagnostics all become nearly constant. The temperature profile (Fig. 7) is centrally peaked and essential time-independent. Soft x-ray emission from the plasma core also becomes constant. The axial value of the safety factor $q(0)$ on axis is inferred to be 1.0 by observation of sawtooth oscillations in the soft x-ray signal in droplet plasmas.

Fig. 3. Plasma diagnostics used for energy confinement measurements

SHOT 4103

200 MSEC

$I_p = 400 \text{ kA}$
 $H/W = 1.25$

SHOT 2618

200 MSEC

$I_p = 650 \text{ kA}$
 $H/W = 1.1$

Fig. 4. Flux surfaces for near-circular plasmas. The MHD analysis procedure used to obtain these plots is described in Section 3.

Fig. 5. Doublet flux surfaces

Fig. 6. Doublet discharge waveforms for shot 4890

Fig. 7. Electron temperature profile evolution for shot 4890

In the doublet plasmas the q value on axis is calculated to be 1.0 by a self-consistent determination of the current profile, as will be discussed in Section 6.

Soft x-ray measurements also suggest that the energy balance in the central region of the plasma is not dominated by metallic impurity radiation. A typical x-ray spectrum is shown in Fig. 8. The most prominent lines are molybdenum at 2.7 keV and chromium at 5.5 keV. The relative impurity concentration inferred from the soft x-ray intensity is about 10^{-4} . For coronal equilibrium this concentration implies that less than 10% of the local ohmic input power is radiated by these metals. Hollow temperature profiles characteristic of severe heavy metal radiation were not observed.

The maximum plasma density obtained during the confinement measurements also indicates a relatively high degree of plasma cleanliness. The maximum line-average density obtained at 24 kG is approximately $5 \times 10^{13} \text{ cm}^{-3}$, a value which is comparable (Fig. 9) to the limiting density in other recent circular tokamak experiments, including several operating with titanium gettering [5-10].

Typical discharge parameters are summarized in Table I. The lower range of densities for the droplet and elliptical discharges reflects the limited amount of experimental time devoted to these configurations, rather than any fundamental difference in maximum density relative to doublet.

Fig. 8. Typical soft x-ray spectrum metallic impurity lines showing

Fig. 9. Comparison of maximum plasma density obtained in Doublet III and other circular tokamaks

TABLE 1
PLASMA PARAMETERS FOR STEADY-STATE DISCHARGES

Parameter	Ellipse	Droplet	Doublet
B_T (kG)	20	20	24
Flat-top Duration (MS)	400	400	400
I_p (kA)	400	270(x 2)	1500
Elongation	1.25	1.1	3.1
$q(0)$	~ 1	1	~ 1
Average q_{LIMITER}^*	3.9	4.3	6.9
$\bar{n}_e (10^{13} \text{ cm}^{-3})$	2-3	2.5-3.5	3-5
$T_e(0)$ (keV)	0.7-1.0	0.5-1.0	0.5-1.1
Minimum Voltage (V)	1.6	1.6	1.6
Minimum Z_{eff}	2	1.1	1.7

$$q_{\text{LIMITER}}^* = \frac{C^2 B_T}{2\pi R_0 I_p}$$

$C \equiv$ poloidal circumference.

3. MAGNETIC ANALYSIS

The Doublet III magnetic diagnostic system measures the poloidal magnetic flux and field intensity at an array of points surrounding the plasma region. This data can be used to determine the shape and location of the outermost flux surfaces of the plasma, and, in certain cases, can also be used to estimate the current density and safety factor profiles inside the plasma.

Various aspects of the plasma shape and position can be computed directly from the magnetic data on a real-time basis. The waveforms for the radial position, height and flux fraction inside the doublet separatrix shown in Fig. 6 are obtained in this fashion. The required computations are implemented with analog electronic circuits, the outputs of which are used for feedback control of the plasma position. It has been established empirically that the quantity

$$P_s(m) = 2 - 1.15 \frac{PR12}{PR34}$$

derived from the ratio of the partial Rogowski (PR) magnetic probes on the inside wall approximates the flux fraction inside the separatrix to within $\pm 10\%$. This diagnostic has proved to be particularly useful in optimizing doublet shaping.

The flux configurations shown in Figs. 4 and 5 are examples of the use of the General Atomic free-boundary MHD equilibrium code GAQ [11] for off-line analysis of the magnetic data. This code solves the Grad-Shafranov equation

$$\Delta^* \psi = \mu_0 R j_\phi \quad (3.1)$$

where $2\pi \psi$ is the poloidal flux,

$$\Delta^* \equiv R \frac{\partial}{\partial R} \frac{1}{R} \frac{\partial}{\partial R} + \frac{\partial^2}{\partial z^2} ,$$

R and z are the usual toroidal coordinates, and j_ϕ is the toroidal current density. For purposes of analyzing experimental data, it is convenient (and sufficiently accurate) to parameterize the toroidal current density as

$$j_\phi = G(\psi) \left[\frac{\beta_p}{R_0} + \frac{(1 - \beta_p) R_0}{R} \right] \quad (3.2)$$

Here $G(\psi)$ is an arbitrary adjustable function (typically a gaussian) that characterizes the flux dependence of the current profile, R_0 is the major radius, and β_p is an adjustable constant which characterizes the plasma pressure. The analysis procedure involves solving Eq. (3.1) for a given $G(\psi)$, using the experimentally measured flux values as boundary conditions, and incorporating the constraint that $G(\psi) \equiv 0$ for flux values outside the limiter flux surface. The result of the solution is a plasma configuration which satisfies both MHD equilibrium and the experimentally measured boundary fluxes. Agreement with experiment is tested by comparing the computed and experimentally measured values of the poloidal field at the partial Rogowski locations. The function $G(\psi)$ and the value of β_p are then adjusted until satisfactory agreement is obtained. A typical result is shown in Fig. 10. For the case of a doublet plasma, a change in the plasma shape corresponding to a 10% change in the flux fraction inside the separatrix results in an easily detectable change in the poloidal field configuration.

Fig. 10. Comparison of experimentally measured and computed partial Rogowski values

Strictly speaking, the MHD analysis procedure gives information only about the shape of the outermost flux surfaces of the plasma. However, if $G(\psi)$ is restricted to be a physically reasonable monotonic function of ψ (e.g. gaussian or parabolic to some power), then the internal details of the flux surfaces are relatively insensitive to the exact functional dependence of $G(\psi)$, provided that the degree of peaking of the profile is correct. For plasmas with significant noncircularity, where the shape is sensitive to the current profile, the MHD analysis procedure can provide information about the internal current density and safety factor profiles and also the radial dependence of the flux surface elongation. Figure 11 shows the current profile obtained from the MHD analysis of shot 4890. Elongation data for typical plasmas is shown in Fig. 12. Another example of the use of the MHD analysis procedure to estimate $j(r)$ and $q(r)$ will be given in Section 6.

Fig. 11. Current density profile obtained by MHD analysis. The current profile is similar to that expected for Spitzer resistivity and uniform Z_{eff} .

Fig. 12. Flux surface elongation obtained by MHD analysis

4. DENSITY SCALING STUDIES OF ENERGY CONFINEMENT

The scaling of the central values of electron temperature, electron energy confinement time and Z_{eff} has been studied in Doublet III as a function of plasma density and configuration. As will be shown in the following section, the central and global values of the electron energy confinement time and Z_{eff} are nearly equal (within $\pm 20\%$) for typical plasmas in Doublet III (and in other tokamaks), and hence measurements of the central parameters make it possible to study the scaling properties with a minimum amount of data analysis, and to include data where only central values of plasma parameters were measured.

The central electron energy confinement time is defined as

$$\tau_{\text{Ee}}(0) \equiv \frac{\frac{3}{2} n_e(0) kT_e(0)}{E(0) j(0)} \quad (4.1)$$

where $n_e(0)$, $T_e(0)$, $E(0)$ and $j(0)$ are respectively the on axis values of electron density, electron temperatures, electric field and current density. In steady-state conditions, with the electric field fully penetrated, the electric field on axis is simply

$$E(0) = V/2\pi R(0) \quad , \quad (4.2)$$

where V is the loop voltage and $R(0)$ is the major radius.

In the flattop phase of the discharge where the plasma current, loop voltage, and temperature profile are constant, this approximation is very accurate.

The current density on axis is given by

$$j(0) = \frac{2 B_T}{\mu_0 R q(0)} \left(\frac{1 + \kappa_o^2}{2 \kappa_o} \right), \quad (4.3)$$

where κ_o is the elongation of the central flux surface. Since the central flux surface is nearly circular ($\kappa \leq 1.2$), the term in parenthesis is essentially unity. Furthermore, if $q(0) = 1.0$, then

$$j(0) = \frac{2 B_T}{\mu_0 R(0)}, \quad (4.4)$$

and calculation of $\tau_{Ee}(0)$ is straightforward once the central values of electron density and temperature are known.

The Z_{eff} value on axis is calculated from the enhancement factor α to Spitzer resistivity in Ohm's law

$$E(0) = \alpha \eta_{SP} (Z = 1) j(0) \quad (4.5)$$

where α and Z_{eff} are approximately related by

$$\alpha = Z_{eff} \left[0.57 + \frac{0.90}{Z_{eff} + 1.08} \right] \quad (4.6)$$

and

$$\eta_{SP} = \frac{m_e v_{ei}}{2 n_e e^2} \quad (4.7)$$

The location of the diagnostic measurements is not necessarily coincident with the magnetic center of the plasma, as shown in Fig. 3. Thus to evaluate Eq. (4.1), certain simplifying assumptions are necessary. For the analysis in this section only, we assume that a) the central value of the electron temperature is either the value obtained from the laser scattering or the peak temperature along the $2\omega_{ce}$ radiometer chord, b) the central value of the density is 1.5 times the line-average value measured by the 2 mm interferometer, and c) $q(0) = 1.0$. The validity of these assumptions is established in Section 5, where it is shown that they typically result in a 25% underestimate of the true central confinement time $\tau_{Ee}(0)$. To avoid confusion in the subsequent discussion we will use the notation * to indicate quantities evaluated using the assumptions given above. Thus $\tau_{Ee}^*(0)$ denotes the "central" electron confinement time evaluated using Eq. (4.1) and assumptions (a)-(c).

The axial value of q is known to be unity in droplets from the observation of sawteeth. In doublets, the MHD analysis implies $q(0) \sim 1$, but the absence of sawteeth suggests $q(0)$ may still be slightly above unity. Sawteeth were not observed in the elliptical plasmas, and the MHD analysis does not give a definitive estimate of the axial current density. More recent elliptical data suggests that $q(0)$ may have been in the range 1.0-1.5. If the actual axial q was greater than unity for ellipses or doublets, then using Eq. (4.4) underestimates $\tau_{Ee}(0)$ and overestimates $Z_{eff}(0)$ by the same factor.

Other than the above assumptions, the principal uncertainty in the calculations comes from the temperature data. Since the laser measures the temperature at a point about 5 cm from the magnetic axis of the plasma, the raw laser data consistently underestimates the peak temperature by about 10%. This plasma shift also introduces about 10% uncertainty in the $2\omega_{ce}$ radiometer calibration. The total uncertainty in either temperature measurement is estimated to be about $\pm 20\%$. The shot-to-shot scatter in the data is approximately $\pm 10\%$. Overall, the uncertainty in the central

confinement time is estimated to be about $\pm 30\%$, and is also subject to the axial q and density profile assumptions discussed above. Within the data set, the relative uncertainty is less, but the use of laser data for the droplet and ellipse data and radiometer data for the doublet data could introduce a systematic error of up to 20%. Similarly, uncertainty in $T_e(0)$ results in a $\pm 30\%$ uncertainty in $Z_{eff}^*(0)$.

The range of electron temperature and Z_{eff} values obtained in the scaling studies is similar to that observed in PLT for ungettered discharges [5]. The on-axis values of T_e and Z_{eff} both decrease as the plasma density is increased with larger gas-injection inputs. Typical values range from $T_e^*(0) = 1.1$ keV and $Z_{eff}^* = 6$ at $\bar{n}_e = 1.5 \times 10^{13} \text{ cm}^{-3}$ to $T_e^*(0) = 0.7$ keV and $Z_{eff}^* = 2$ at $\bar{n}_e = 4.5 \times 10^{13} \text{ cm}^{-3}$. The value of Z_{eff} decreases approximately as $1/\bar{n}$. Droplet plasmas with $Z_{eff}^* = 1.1$ were obtained, but $Z_{eff}^* = 1.5-2$ was more typical. Doublet plasmas exhibited a wider range of Z_{eff} values at a given density, presumably due to a varying degree of plasma-wall interaction during the initial phase of the discharge (see Fig. 6). Lower Z_{eff} values were obtained in those discharges which had a lesser degree of configurational variation during the initial phase.

The central electron confinement times for near-circular and doublet discharges are plotted in Fig. 13. The confinement time increases with density, as expected with Alcator scaling. At higher densities, the data fits the scaling law

$$\tau_{Ee}^*(0) = (3 \times 10^{-19} \text{ cm-sec}) \bar{n}_a^2 \quad (4.8)$$

At the higher densities, $n_e \approx n_i$ and $T_e \approx T_i$ (see Section 7), so that the coefficient for the total confinement time would be twice that given above (i.e., $6 \times 10^{-19} \text{ cm-sec}$), which is approximately equal to the value observed in Alcator-A [9].

There is no detectable difference in confinement between the near-circular and doublet cases. As is discussed in Appendix I, in the low to

Fig. 13. Density scaling of central electron energy confinement time for near-circular and doublet plasmas

medium density regime where anomalous electron thermal transport is the dominant energy loss mechanism, the confinement improvement owing to non-circularity is theoretically expected to be

$$\frac{\tau(\kappa)}{\tau(\kappa=1)} = \frac{2\kappa^2}{1 + \kappa^2} \quad (4.9)$$

where κ is the elongation of the flux surfaces. From Fig. 12, the effective elongation of doublets in the central part of the plasma where most of the plasma energy resides is about 1.2, and hence, using Eq. (4.9), the expected confinement improvement for doublet is about 1.18. A difference of this magnitude is not expected to be observable, given the scatter of the data and the other possible systematic errors discussed above.

5. GLOBAL ENERGY CONFINEMENT ANALYSIS

The global energy confinement time for a stationary plasma, defined as

$$\tau_E = \frac{3/2 \int (n_e kT_e + n_i kT_i) d^3V}{IV_L} \quad (5.1)$$

is the most direct measure of the total energy confinement. Here I and V_L are the plasma current and loop voltage, and the integral is to be evaluated over the plasma volume, which in principle requires knowledge of the electron and ion temperatures and densities at each point in the plasma. Since actual diagnostic data consists of a limited number of point or line-integral measurements, simplifying assumptions are required. For circular cross-section plasmas, radial symmetry is generally assumed. For noncircular plasmas, and in particular for doublets, more elaborate methods are necessary.

In Doublet III, the related problems of interpreting diagnostic measurements and determining the plasma stored energy have been addressed by developing a general purpose noncircular energy analysis code.

The concept of the energy analysis method is illustrated in Fig. 14. The flux configuration $\psi(R,Z)$ determined by the MHD analysis procedure described in Section 3 serves as the starting point. After $\psi(R,Z)$ is determined, numerical methods are used to transform the experimentally measured data such as $T_e(R)$ and $\bar{n}(R)$ into corresponding functions of the flux ψ . Once $n(\psi)$ and $T(\psi)$ are known, evaluation of the volume integral of nT is straightforward. In this report, only electron temperature and

Fig. 14. Electron energy confinement analysis concept

density data are analyzed. However, the method can be easily extended to other experimentally measureable quantities.

Further details of the analysis method are described below. First, the magnetic data is analyzed to obtain the plasma flux configuration $\psi(R,Z)$. Subsequent analysis is carried out using a normalized flux coordinate

$$\tilde{\psi} \equiv \frac{\psi - \psi_{\text{axis}}}{\psi_{\text{limiter}} - \psi_{\text{axis}}} \quad (5.2)$$

Typically, the flux is approximately parabolic, so that $\tilde{\psi} \sim r^2/a^2$. Since the pressure is constant along a flux surface, and because of high electron thermal conductivity along a field line, the electron density and temperature are also constant and are functions only of $\tilde{\psi}$. By analogy with circular discharges, the density and temperature profiles are assumed to be

$$n_e = (n_{e0} - n_{e,\text{lim}}) (1 - \tilde{\psi})^{\alpha_n} + n_{e,\text{lim}} \quad (5.3)$$

$$T_e = (T_{e0} - T_{e,\text{lim}}) (1 - \tilde{\psi})^{\alpha_T} + T_{e,\text{lim}} \quad (5.4)$$

These functions give an accurate representation of experimental data. If hollow profiles had been observed, a different form would have been necessary. Each function has three adjustable coefficients, the peak value, the limiter value, and α , the exponent of $(1 - \tilde{\psi})$. The temperature coefficients are found by a least squares fit to point measurements of temperature along the chord viewed by the radiometer. Each spatial point in the radiometer profile has a corresponding flux value used when comparing the temperature function to the data. The density coefficients are determined by a similar procedure, except that line integrals as well as point measurements are involved. A more complicated numerical algorithm compares the measured

values with integrals computed using the density function. In this approach, the true path length through the plasma is evaluated. Finally, the functions determine the values of electron density and temperature at every point in the plasma, and the stored energy integral is evaluated.

The energy analysis method has been applied to several doublet plasmas. Representative results for a 90% doublet (#4890) are shown in Figs. 15 and 16. Figure 15 shows the radiometer data and the corresponding fitted function

$$T_e = 940 \text{ eV} [1 - \psi]^{1.50} \quad (5.5)$$

The density profile is

$$n_e = 6.1 \times 10^{13} \text{ cm}^{-3} [1 - \psi]^{0.82} \quad (5.6)$$

The density profile along the upper 2-mm microwave chord at $Z = 90 \text{ cm}$ is shown in Fig. 16. For comparison, the measured line-average density is $3.8 \times 10^{13} \text{ cm}^{-3}$. The total electron stored energy is 46 kJ. The ohmic power is 2.5 MW, resulting in a global electron energy confinement time of 1.9 msec.

For comparison, the true central confinement time obtained using Eqs. 5.5 and 5.6 and $q(0) = 1.1$ is 32 msec. The central parameter analysis technique used in Section 4 gives $\tau_{Ee}^*(0) = 24 \text{ msec}$. The global time is found to be 79% of $\tau_{Ee}^*(0)$ estimated without knowledge of the profiles.

Other than the fundamental uncertainties in the diagnostic measurements themselves, the primary uncertainty in the confinement analysis comes from the procedure used to obtain the density profile. In essence, the density profile form factor α_n is determined by the ratio of the horizontal path and vertical path interferometers. The value of α_n is quite sensitive to this interferometer ratio, which was 0.8 ± 0.1 for typical 90%

Fig. 15. Comparison of flux function temperature profile and radiometer data

Fig. 16. Calculated density profile

doublers (Fig. 17). However, there is some scatter in the data, and it is not possible to completely rule out profiles with $0 \leq \alpha_n \leq 2$. Future measurement of doublers in which reliable midplane interferometer data is available will narrow the range of possible α_n values.

In spite of the lack of complete knowledge of the density profile, the resultant uncertainty in the global confinement time is small. If the same line average density is maintained, the total plasma energy is quite insensitive to the density profile, and the change in τ_{Ee} due to the possible variation in α_n is less than 15%.

Another possible source of error comes from the use of an ad hoc model for the plasma current and pressure profiles (Eq. 3.2) in calculating the original MHD equilibrium. Extensive studies have shown, however, that the ad hoc model provides an accurate fit to experimental data, and that minor changes in the flux configuration have a negligible effect (<10%) on the stored energy calculation. Overall, the total uncertainty in τ_{Ee} due to the energy analysis procedure is estimated to be less than 20%. This uncertainty is independent of the fundamental uncertainties inherent in the calibrations of the individual diagnostics, as discussed in Section 4. Note, however, that no assumption about $q(0)$ is required.

Fig. 17. Interferometer data for 90% doublets

6. SELF-CONSISTENT MHD AND ENERGY ANALYSIS

The energy analysis algorithm described in the previous section provides the means to carry out a completely self-consistent calculation of the plasma configuration and profiles. The self-consistent procedure replaces the ad hoc assumptions introduced in the MHD analysis with more fundamental physics, and thus eliminates a potential source of uncertainty. In addition to confirming the energy analysis obtained with the ad hoc model, the self-consistent procedure also makes it possible to determine the n_{eff} profile in noncircular plasmas.

The basic idea in the self-consistent procedure is to use the plasma temperature and density profiles determined in the energy analysis to explicitly calculate the source term for the Grad-Shafranov equilibrium equation (Eq. 3.1). Instead of using Eq. (3.2), the toroidal current density j_{ϕ} is calculated from

$$j_{\phi} = -Rp'(\psi) - \frac{ff'(\psi)}{\mu_0 R} \quad (6.1)$$

where $f \equiv RB_T$ and ' denotes the derivative with respect to ψ . The value of p' is obtained using

$$p'(\psi) = \frac{d}{d\psi} (n_i kT_i + n_e kT_e) \quad (6.2)$$

where the ion temperature and density are assumed to be

$$n_i = C_i n_e \quad (6.3)$$

$$\text{and } T_i = C_T T_e \quad (6.4)$$

In the present analysis C_i and C_T are taken to be unity. In future analysis, the ion temperature and density profiles can be explicitly included once the appropriate data is available.

The function ff' is calculated using

$$ff'(\psi) = \frac{-\mu_0}{\langle R^{-2} \rangle} [\langle j/R \rangle + p'(\psi)] \quad , \quad (6.5)$$

where $\langle \rangle$ denotes the flux surface average, and

$$\langle j/R \rangle = \frac{1}{2\pi\eta} \langle R^{-2} \rangle V \quad . \quad (6.6)$$

The plasma resistivity η is taken to be

$$\eta = \eta_{SP} Z_{eff}(\psi) \quad , \quad (6.7)$$

where $Z_{eff}(\psi)$ is given by

$$Z_{eff} = Z_0 [(1 - C_Z) (1 - \psi)^{\alpha_Z} + C_Z] \quad . \quad (6.8)$$

Here, Z_0 , C_Z and α_Z are adjustable constants that specify the Z_{eff} profile. For given values of C_Z and α_Z , the value of Z_0 is chosen such that the total current calculated by integrating $\langle j/R \rangle$ over the plasma area gives the experimentally measured plasma current.

The self-consistent computational procedure begins by using the method of Section 5 to determine $n(\psi)$ and $T(\psi)$. Initial estimates for the coefficients C_Z and α_Z are introduced, and p' and ff' are calculated. Using Eqs. (6.2-6.6) the resultant Grad-Shafranov equilibrium equation is then

solved to obtain a new ψ function. The procedure is repeated until a converged solution is obtained. The accuracy of the solution is tested by comparing the computed and partial Rogowski values. The coefficients C_Z and α_Z are adjusted until satisfactory agreement is obtained. A complete solution requires about 2-3 minutes of time on the Magnetic Fusion Energy Computer Center Cray computer, and typically can be completed in about 2 hours of real time. Typical results of the self-consistent analysis are illustrated in Figs. 18, 19 and 20. The final equilibrium is essentially identical to Fig. 5. The comparison of experimental to calculated values of partial Rogowski probes is shown in Fig. 18. The current density is plotted in Fig. 19 as a function of major radius along the chord measured by the radiometer (any path or point could have been chosen). In Fig. 20, the safety factor q and Z_{eff} are plotted along the same path. At the center, the values are $Z_{\text{eff}} = 2.8$ and $q = 1.1$. The q profile actually goes to infinity at the separatrix, which is near the plasma edge, then decreases to 8.6 at the plasma edge. The edge value is strongly dependent on the precise location of the separatrix. The central electron energy confinement time is 32 milliseconds, which is 68% greater than the global electron energy confinement time of 19 milliseconds.

The Z_{eff} profile is physically reasonable. Forthcoming soft x-ray and vacuum ultraviolet spectroscopy measurements will provide alternate means of measuring this important plasma profile.

Fig. 18. Comparison of measured and calculated partial Rogowski signals for self-consistent MHD equilibrium

Fig. 19. Current density profile along upper horizontal chord from self-consistent analysis

Fig. 20. Safety factor and Z_{eff} profiles along the upper horizontal chord

7. TRANSPORT CODE SIMULATIONS

The General Atomic 1-1/2-D transport code [12] is used to provide additional information about experimental discharges. Specifically, since ion temperatures are not yet directly measured, they may be inferred from the code. Also, empirical scaling for electrons, $\chi_e \sim 1/n$, may be verified locally on each flux surface. The code uses a geometrical coordinate ρ , proposed by Hinton and Hazeltine [13], analogous to the radial coordinate in the circular case, which is defined at a given point to be proportional to the square root of the toroidal flux Φ enclosed by the flux surface passing through the point.

$$\rho \equiv \sqrt{\frac{\Phi}{\pi B_T(0)}} \quad (7.1)$$

The flux surfaces are determined from a calculated 2-D MHD equilibrium, such as the one shown in Fig. 5. Formulating the transport equations in terms of ρ reduces the problem to a one-dimensional calculation.

The scaling studies described in Section 4 suggest that anomalous electron transport accounts for most of the energy loss in high-density Doublet III plasmas. In the absence of particle transport or charge exchange loss data, the transport is modeled by assuming an anomalous local electron thermal conductivity $\chi_e = K/n_e$ and standard neoclassical ion thermal conductivity. Particle transport and charge exchange terms are set to zero. Separate calculations have confirmed that the results are not sensitive to the neglect of convection. The principal impurity is assumed to be oxygen. The best fit to the experimental data is obtained for $n_e \chi_e = 1.15 \times 10^{18}/\text{cm-sec}$ and $Z_{\text{eff}} = 2.6$ (~5% oxygen). The calculated and experimentally measured values of the loop voltage, on-axis electron temperature and safety factor are in excellent agreement.

Figure 21 compares the electron temperature profile obtained using the energy analysis method of Section 5 with the profile calculated with the 1-1/2-D code. The profile is plotted as a function of $(\hat{\psi})^{1/2}$, roughly proportional to r/a . The close agreement of the profiles confirms the validity of the assumption of $\chi \sim 1/n_e$, and also verifies the confinement time calculated in the energy analysis procedure.

The code calculation also predicts that the peak ion temperature is 920 eV, nearly equal to the peak electron temperature of 940 eV. While the actual value of the ion temperature will be somewhat lower due to charge exchange losses, the code calculation suggests that the assumption of equal electron and ion temperatures used in the self-consistent profile analyses is reasonably valid. Also, as has been mentioned before, the total energy confinement times are expected to be approximately twice the values measured for the electrons alone.

Fig. 21. Comparison of temperature profiles calculated by the MHD-energy analysis and 1-1/2-D transport codes

8. SUMMARY AND DISCUSSION

The electron energy confinement in Doublet III plasmas is found to be equal at a given density for both near-circular and doublet plasma cross-sections, and to increase in proportion to the plasma density with an Alcator scaling coefficient similar to that obtained in other circular tokamaks. No deterioration due to the effects of plasma shaping is observed. The lack of any detectable improvement in the confinement of doublets relative to circular plasmas can be understood from magnetic data that shows that the internal flux surfaces of the doublets are only slightly noncircular, and hence that the theoretically expected confinement improvement is less than the 30% accuracy of the measurements.

Powerful numerical methods for interpreting noncircular diagnostics data and calculating the confinement properties of noncircular plasmas have been developed and exercised to analyze the initial Doublet III data. Consistent results are obtained using a variety of analysis methods, verifying the accuracy of both the experimental data and the analysis procedures. Coupled MHD equilibrium and plasma analysis algorithms make it possible to carry out completely self-consistent calculations of the plasma shape and profiles. The methods developed for confinement analysis can be readily extended to interpret forthcoming ion temperature and radiated power measurements for noncircular plasmas.

At the present time, the highly peaked current profiles inherent with ohmic heating make it impossible to obtain plasmas with significant noncircularity, either in Doublet III or any other tokamak. Achievement of increases noncircularity will require broadening of the current profile. If such profile control is possible, then the confinement improvement theoretically predicted for noncircular plasmas will be much more readily

detectable. The analysis techniques described in this report should make confirmation of the improvement possible once the required plasmas are obtained.

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Appendix I

EFFECTS OF NON-CIRCULARITY ON ENERGY CONFINEMENT

Noncircular plasmas are theoretically predicted to offer improved confinement. One method of comparing noncircular to circular plasmas is to maintain the same major radius, minor horizontal semi-axis, and central toroidal field, while varying the height to width ratio κ . As κ increases, the geometry of the nested flux surfaces becomes increasingly noncircular. Simultaneously, if the limiter value of the safety factor q (inverse rotational transform) is held fixed, the plasma current and poloidal field strength also increase with increasing κ . Each of these effects results in improved confinement.

First, elongation of the flux surfaces has the immediate geometrical effect of increasing the effective diffusion length for energy transport. Thus, for a given value of the diffusion coefficient χ , the confinement time is increased. The improvement factor scales as the square of the volume-to-surface ratio. For an ellipse with elongation κ , the improvement relative to a circle is

$$\frac{\tau(\kappa)}{\tau(\kappa = 1)} = \frac{(V/s)^2(\kappa)}{(V/s)^2(\kappa = 1)} = \frac{2 \kappa^2}{1 + \kappa^2} \quad (A.1)$$

This formula is directly applicable if the flux surfaces are uniformly nested ellipses with constant κ . For actual plasmas where the flux surface geometry is less ideal, numerical methods for calculating the local gradient length are available. Such methods form the basis of the non-circular transport code described in Section 7, and can calculate the energy

transport for arbitrary flux geometries. However, in many cases, Eq. (A1) can be used to estimate the degree of confinement improvement by using a value of κ characteristic of the average ellipticity of the flux surfaces.

Second, the increase in the poloidal field with increasing κ results in reduced ion neoclassical transport. For a simple ellipse the effect is calculated [14, 15] to be

$$\chi^{\text{NEO}}(\kappa) = \left(\frac{2}{1 + \kappa^2} \right) \chi^{\text{NEO}}(\kappa = 1) \quad . \quad (\text{A.2})$$

Again, for less ideal geometries, numerical methods are available.

The net effect of non-circularity on energy confinement depends on whether electron or ion conduction dominates the energy balance. At low to moderate plasma densities, the energy loss is dominated by the electron transport, which has empirically been found to depend only on the plasma density, with a diffusion coefficient χ_e given by

$$\chi_e \sim \frac{5 \times 10^{17} \text{ cm-sec}}{n_e} \quad . \quad (\text{A.3})$$

In this anomalous electron dominated regime, the improvement due to non-circularity is described by Eq. (A.1).

Because of the $1/n$ dependence of the anomalous electron transport, at a high enough plasma density, ion neoclassical transport becomes the dominant energy loss mechanism. In this regime, both Eqs. (A.1) and (A.2) apply, and the overall improvement with elongation becomes

$$\frac{\tau(\kappa)}{\tau(\kappa = 1)} = \kappa^2 \quad . \quad (\text{A.4})$$

Since the electron loss scales as $1/n$ and the ion loss scales as n , the total energy confinement time will reach a maximum at some intermediate density. The density at which the maximum occurs and the relative value of confinement time at the maximum depend on the plasma elongation. This effect is illustrated in Fig. 22, which shows the dependence of τ on n and κ for an elliptical plasma. The maximum confinement increases by a factor of 1.75 for $\kappa = 1.5$ and a factor of 4.02 for $\kappa = 3$. The corresponding relative densities for maximum confinement are 1.27 and 2.24 respectively.

Fig. 22. Effect of neoclassical transport and elongation on energy confinement