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**PRELIMINARY RESULTS OF NONCIRCULAR
PLASMA EXPERIMENTS IN DOUBLET III**

by
TIHIRO OHKAWA

FEBRUARY 1980

GENERAL ATOMIC COMPANY

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PRELIMINARY RESULTS OF NONCIRCULAR PLASMA EXPERIMENTS IN
DOUBLET III*

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ABSTRACT

Preliminary results of noncircular plasma experiments in Doublet III are reported. Shaping and discharge characteristics in doublet plasmas with high-Z limiters are described. Electron energy confinement and maximum plasma density are in agreement with standard circular tokamak empirical scaling laws. Chromium and molybdenum appear to be the dominant high-Z contaminants while carbon appears to dominate low-Z contaminants. High-Z impurity radiation does not appear to dominate the central power balance.

KEY WORDS

machine parameters, plasma shaping, discharge characteristics, electron confinement, maximum plasma density, impurities

INTRODUCTION

It is now generally acknowledged that operation with a noncircular plasma cross-section will be a necessary feature of a tokamak fusion power reactor. The feasibility of shaping plasmas into vertically elongated configurations and the effects of this shaping on plasma stability and confinement have been investigated at General Atomic Company in a series of noncircular tokamak experiments beginning in 1968 (Fisher and co-workers, 1977; Jensen and co-workers, 1975; Ohkawa and Voorhies, 1969). Doublet III is the third and most ambitious of this series, and is specifically designed to study the effects of noncircularity in high-beta, auxiliary-heated plasmas, ultimately with reactor-like parameters.

Ohmic heating experiments in Doublet III began in September 1978. In the period through July 1979, the primary emphasis has been on shaping the plasma to obtain a steady-state noncircular discharge, and on making preliminary measurements of the plasma characteristics. A summary of these studies is presented in this paper.

Future plans call for the addition of 7 MW of 80 kV hydrogen neutral beam injection. Initiation of beam heating experiments is presently scheduled for mid-1980. The ultimate goal of these experiments is to determine the limiting β for various non-circular configurations.

What is presented herein is essentially a progress report on a continuing research effort. Many of the results are preliminary or incomplete. In some cases, key

diagnostic measurements that might clarify important points are not yet available. Care should be taken not to interpret these results as being other than an account of what has to date been observed in Doublet III.

MACHINE PARAMETERS

Doublet III (Fig. 1) is designed to accommodate a variety of plasma cross-sections, ranging from circular to doublet, with a vertical elongation of up to 3.2. The vacuum vessel is surrounded by 24 plasma shaping coils (F-coils), used to control the position and shape of the discharge. The ohmic-heating and toroidal field coil systems are conventional, with the exception that the toroidal coil has a demountable joint at the top to facilitate assembly of the poloidal coils. All coils are water-cooled copper. Various machine and operating parameters are summarized in Table I.

TABLE I

Doublet III Parameters

MAJOR RADIUS	1.43 m
MAXIMUM PLASMA WIDTH (2a)	0.92 m
MAXIMUM PLASMA HEIGHT (2b)	2.90 m
TOROIDAL FIELD	26 kG
OHMIC HEATING FLUX SWING	5 V-s
DESIGN PLASMA CURRENT	2.5 MA
DESIGN PULSE LENGTH	0.5 sec

PLASMA SHAPING

Control of the poloidal magnetic flux linking the F-coils allows the cross-section and position of the discharge to be varied. The F-coils are arranged in several parallel-connected groups, (Fig. 2), each with a power supply in series. The voltages produced by these supplies determine the coil fluxes, and hence the plasma shape. The parallel connection of the F-coils provides passive stability against axisymmetric motion of the plasma, especially for vertical displacements.

Fig. 2. Poloidal circuit for doublet shaping

Fig. 1. Cross-section of Doublet III. Machine parameters are $R = 1.43$ m, $a = 0.45$ m and $B_{\max} = 26$ kG. The primary limiters are tantalum-tungsten alloy. A molybdenum secondary limiter (not shown) also encircles the poloidal circumference of the vessel at three toroidal azimuths.

To minimize the coil terminal voltage, the F-coils are split into two 29-turn windings with the shaping supplies connected between. The total number of turns in each F-coil (58) is chosen such that connecting the F-coils in parallel with the 61-turn ohmic heating coil inductively decouples the F-coil system from the ohmic heating coil. This ensures that currents flow in the F-coils only due to the presence of plasma current.

Three basic types of discharges can be produced in Doublet III (Figs. 3 and 4). The choice of which F-coils the shaping supplies are connected to determines whether the discharge forms only in one half of the vessel (ellipse) or symmetrically in both halves (droplet or doublet). The magnitude of the shaping flux applied to the outer midplane coils determines whether the discharge breaks into two independent current channels (droplets) or remains connected, with an internal separatrix (doublet).

The shaping functions of the various power supplies are more clearly illustrated by the one-line schematic equivalent circuits shown in Fig. 5. The vertical field required to maintain radial equilibrium is provided by the combination of a 16 mH inductor L_S in series with the inner F-coils and the V (vertical) supply in series with the outer F-coils. For the case of an elliptical plasma, connection of the supply to the bottom F-coils also causes the discharge to localize in the upper half of the vessel. Fine tuning of the plasma shape along the inner F-coils and compensation for the effects of F-coil resistance are accomplished by supplies R1 in series with F-coils 2A and 3A and R2 in series with F-coils 2B and 3B.

For droplet or droplet shaping, the flux required to control the plasma shape at the midplane is provided by the D (doublet) supply, assisted by a capacitor discharge circuit during the initial plasma current rise. Fine tuning of the plasma height and shape is provided by "tweaker" supplies T3 and T4 that control the flux at the top and bottom F-coils. Again, resistance compensation supplies R1 and R2 minimize differences in the shaping flux on the inner F-coils due to finite F-coil resistance. Specifications of the shaping supplies are summarized in Table II.

Fig. 3. Typical doublet magnetic configuration (shot 4890 at $t = 400$ ms, see Fig. 10)

Fig. 4. Typical droplet and ellipse magnetic configurations

Fig. 5. One-line circuits for plasma shaping

TABLE II
Doublet III Plasma Shaping Power Supplies

SUPPLY	VOLTAGE (V)	CURRENT (kA)	TYPE	STEP RESPONSE TIME (ms)
D	600	14	60 Hz, 12 pulse	8
V	600	21	60 Hz, 12 pulse	8
T3, T4	400	3	SCR CHOPPER	0.2
R1, R2	0-150	3	60 Hz, 6 pulse	16

In describing the shape of droplet and doublet plasmas, the quantity

$$P_s \equiv \frac{\psi_{\max} - \psi_{\text{sep}}}{\psi_{\max} - \psi_{\text{lim}}}$$

is a useful parameter. Here $\psi_{\max}$, ψ_{sep} and ψ_{lim} are respectively the flux values at the elliptic axes, separatrix and limiter. Doublets have $0 < P_s \leq 100\%$, while droplets have $P_s > 100\%$, i.e., the separatrix is outside the plasma surface. The configuration shown in Fig. 3 has $P_s \approx 90\%$ (doublet) and for the droplet in Fig. 4 $P_s \approx 180\%$. Droplets with $P_s \sim 200\%$ are nearly circular ($b/a \leq 1.1$). Droplets with $P_s \rightarrow 100\%$ are more teardrop-like, with $b/a \rightarrow 1.4$.

SHAPE MEASUREMENT

The shape of the external flux surfaces of the plasma is determined from measurements of the flux and poloidal field immediately outside the vacuum vessel. There are two magnetic diagnostic systems (Fig. 6): a set of 24 psi-loops (one-turn voltage loops) located on the center of the plasma-facing side of each F-coil, and a series of 12 "partial Rogowski" (PR) magnetic probes located between the vessel and the F-coils. The partial Rogowski's are fabricated by cutting a standard Rogowski coil into 12 segments, each spanning two F-coils, hence the terminology

"partial Rogowski." The PR coils are labeled by the respective F-coils they span, e.g., PR12A over F-coils 1A and 2A, PR511B over coils 5B and 11B, etc. Here A and B designate the upper and lower halves of the machine.

The shape analysis procedure uses the General Atomic MHD code GAQ (McClain and Brown, 1977), a free-boundary algorithm that calculates plasma equilibrium in an F-coil system. In the data analysis mode, the experimentally measured psi-loop flux values are used as input boundary conditions. The quantities to be determined are the plasma current density and pressure profiles (β_p). To obtain these, one makes an initial guess as to the current profile and β_p [aided by measurements of $T_e(r)$ and $n(r)$] and then uses the code to find the corresponding MHD equilibrium. Agreement between the computed and actual plasma is tested by comparing the measured PR values with those computed by the code. The current profile and β_p are adjusted until satisfactory agreement is obtained (Fig. 7). This procedure makes it possible to determine P_s to about $\pm 5\%$.

Fig. 6. Magnetic diagnostics used for plasma shape measurement

Fig. 7. Comparison of measured and computed partial Rogowski signals for Fig. 3

It is important to realize that this MHD fitting procedure determines the correct shape of the outermost flux surfaces of the plasma, but does not necessarily give much information about the internal details of the current distribution. A priori MHD simulations show that, in Doublet III, the same external plasma shape can be obtained with rather different profiles. In such cases, the internal flux

distribution, i.e., P_S , can vary by about $\pm 10\%$. However, if the choice of profiles is restricted to physically reasonable monotonic functions of ψ , the variation in P_S is less than $\pm 5\%$; and it is still meaningful to use P_S as a shape parameter.

The MHD analysis procedure extracts the maximum possible amount of information available in the magnetic data and automatically incorporates the constraint of MHD equilibrium. However, since it requires the use of a large-scale computer and some trial and error, it is suitable only for off-line analysis of limited amounts of data.

Approximate methods based on the partial Rogowski signals have been developed to overcome these limitations. Study of a large number of simulated and experimental equilibria has established that the quantity

$$P_S^* \equiv 2 - 1.15 \cdot \frac{PR12}{PR34}$$

approximates P_S to within $\pm 10\%$. An oscilloscope display of P_S^* (calculated with analog electronics) has proven to be extremely useful in tuning the plasma shaping.

DISCHARGE CHARACTERISTICS

Waveforms for a typical droplet discharge are shown in Fig. 8. The plasma current is about 650 kA, of which about 270 kA is in the upper half of the vessel where most of the diagnostic measurements are made. The plasma shape is nearly circular ($b/a \approx 1.1$).

The basic waveforms shown in Fig. 8 are characteristic of all three types of discharges, with the exception of the magnitude of the plasma current and the time required to reach the nominal current flattop. Typically, the loop voltage falls to below 2 V about 200 msec after the initiation of the discharge. Gas injection at a constant rate, typically 50 Torr-l/sec, results in an approximately linear rise in density during the 450 msec duration of the discharge. The central temperature falls as the density increases.

The waveforms for the elliptical discharges are similar to those shown in Fig. 8. For this case, the discharge initially fills the entire vessel, but after 10 msec concentrates in the upper half as soon as the plasma becomes hot enough to recognize the field lines as paths of high thermal conductivity to the walls and limiter. Although extensive studies of the time dependence of the plasma shape have not yet been carried out, the partial Rogowski and psi-loop signals indicate that the elongation is essentially constant during the flattop phase of the discharge. The magnetic configuration is shown in Fig. 4.

Fig. 8. Typical droplet discharge waveforms

The shaping of doublet plasmas involves several additional control aspects beyond the vertical field control and resistive compensation used for ellipses. Specifically, both the amount of midplane flux (F-coils 6A and 6B) and end flux (coils 11A-12A and 11B-12B) must be controlled to follow changes in the magnitude and distribution of the plasma current. Typical flux waveforms are shown in Fig. 9. The ratio of doublet shaping flux to plasma current, ψ_6/I_p , is initially high when the plasma current profile is broad. Later in the discharge, when the profile peaks, the relative shaping flux must be reduced to avoid breaking the plasma into droplets.

Fig. 9. Typical flux and plasma current waveforms to maintain a nearly constant doublet shape

Obtaining a stable doublet discharge with low loop voltage requires fairly precise control of the doublet and vertical field fluxes. Although it is possible to achieve the required control precision using preprogrammed voltage vs. time waveforms for the various supplies, the implementation of feedback control of the doublet and vertical field supplies has improved the reproducibility of the discharges. Similarly, servo control of the tweaker power supplies to maintain equal flux values at the top and bottom of the discharge has resulted in improved discharge symmetry. Servo control of the R supplies to maintain equal flux along the inside F-coil wall is necessary to avoid distortion of the plasma shape due to the effects of finite F-coil resistance.

Typical plasma waveforms for a doublet discharge are shown in Fig. 10. In the first 150 msec of the discharge, the plasma shape undergoes a series of $n = 0$, $m = 2$ oscillations, eventually settling down to a quiescent phase in which the shape stabilizes at a 90% doublet. The shape oscillations are associated with a sudden broadening (~ 1 ms) of the electron temperature profile (Fig. 11), (possibly due to internal MHD activity) followed by a slower return (~ 20 ms) to a peaked profile. Large amplitude shape oscillations also result in increased wall and limiter interaction. In extreme cases, this interaction results in complete disruption of the discharge. More typically, only a minor decrease in current occurs and the discharge survives.

After approximately 150 msec, the discharge becomes quiescent, with a reduced level of shape oscillations, a low loop voltage and a slowly varying plasma shape. Fluctuations in the radial position and height are less than 1 cm. The electron temperature profile becomes centrally peaked and is essentially stationary.

Higher levels of Mirnov oscillations are observed during the initial phase. The shape oscillations are accompanied by bursts of Mirnov activity, which are absent during the quiescent phase. The mode numbers of the poloidal oscillations have not yet been identified. In general, the magnetic probe fluctuation signals are stochastic, without obvious sinusoidal components. Investigation of this aspect of the discharge is continuing.

Classical sawtooth oscillations with $m = 2$ precursors have been observed in the central soft x-ray emission from droplet plasmas, but so far not from ellipses or doublets. Some doublet plasmas exhibit low amplitude, high-frequency (~ 10 kHz) soft x-ray fluctuations during the flattop phase, but the location and mode has not yet been identified. The current density inferred from the electron temperature profile and constant Z_{eff} over the discharge implies $q(0)$ is near unity in the center of the discharge (e.g., $q(0) = 0.9$ for shot number 4890 at 400 msec). The role of sawtooth activity in non-circular plasmas is clearly a topic of considerable interest and one that requires additional study.

The plasma discharges are sometimes terminated prematurely by disruptions. Classical disruptive phenomena are observed in elliptical plasmas: a sudden $n = 0$, $m = 0$ expansion of the current channel, an inward radial shift and negative voltage spikes. In droplet plasmas, similar phenomena are observed, with the exception that the negative voltage spike is not as prominent. The two droplet current channels evolve independently, with one often surviving after the other disrupts.

The mechanism responsible for plasma current termination in doublets is less clear. A sudden $n = 0$, $m = 0$ expansion of one current channel and an inward radial shift is observed in many cases. Disruption of one channel occurs first and invariably precipitates a disruption in the other channel 5 or 10 msec later.

Fig. 10. Typical doublet discharge waveforms

Fig. 11. Electron temperature profile evolution

The disruption also results in an immediate change in plasma configuration, with both current channels shifting radially inward and towards the midplane. A negative voltage spike is not observed in a doublet disruption.

Loss of vertical equilibrium appears to be a second current termination mechanism for doublets. In this case, the flux percentage begins to drop and the plasma suddenly collapses to an ellipse at the midplane, a configuration which is vertically unstable. The shape changes that occur in this process are similar to those of the current disruption described above: an inward radial shift and coalescence at the midplane of both current channels. In some cases, this configuration shift is slow (~ 50 msec) and up/down symmetric; more frequently, it is faster (< 10 msec) and very similar in appearance to a true disruption. additional studies are required to clarify the causes and role of these two mechanisms.

CONFINEMENT, DENSITY AND IMPURITIES

Typical plasma parameters for the flattop phase of the three types of discharges are summarized in Table III. All parameters reach a steady state condition. In doublets where the evolution of the temperature profile has been measured, the profile is stationary and centrally peaked. The maximum density achieved with

TABLE III
Plasma Parameters for Steady-State Discharges

<u>PARAMETER</u>	<u>ELLIPSE</u>	<u>DROPLET</u>	<u>DOUBLET</u>
B_T (kG)	20	20	24
I_p (kA)	400	270	1500
Minimum Voltage	1.6	1.6	1.6
$q(0)$	~ 1	1	~ 1
$\bar{n}_e (10^{13} \text{ cm}^{-3})$	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 Z_{eff}	2	1.1	2
$\tau_E^e(0)$ (ms)	10-17	15-25	15-30

doublet plasmas is in good agreement with the B_t/R scaling observed in other clean, high-density experiments (Apgar and co-workers, 1977; Bol and co-workers, 1979; Engelhardt and co-workers, 1979; Fielding and co-workers, 1977; Konoshima and co-workers, 1978; Murakami and co-workers, 1979) (Fig. 12). The maximum line average density obtained to date is $5 \times 10^{13} \text{ cm}^{-3}$. The density obtained in droplets and ellipses is somewhat less, probably due to the limited amount of experimental time devoted to these plasmas.

The central electron energy confinement increases with plasma density (Fig. 13). The average slope of the data at high density is similar to that observed for the global electron confinement in PLT with titanium gettering (Bol and co-workers, 1979). The best electron confinement obtained so far is $\tau_E^e(0) = 28$ msec at $\bar{n}_e = 3.9 \times 10^{14} \text{ cm}^{-3}$. Preliminary estimates of the global electron confinement based on the radiometer profile data indicate that the global confinement is about $80 \pm 10\%$ of the central confinement.

Although the ion temperature has not been measured, code simulations using neo-classical ion conductivity indicate that the ion and electron temperatures should

be nearly equal at the higher densities. Thus, the total confinement time for doublets presumably is 40-50 msec, assuming $T_e = T_i$.

The variations of confinement with plasma shape presented in Table III appear to be wholly due to the density dependence of the electron confinement. The confinement time normalized by density is essentially the same for all three shapes. However, at this point, it is possible to state that the electron confinement in doublets is at least equal to that for circles and ellipses. Future studies of the shape dependence of the confinement (if any) will require more complete and accurate measurements.

Impurity measurements are still in a relatively preliminary state. Auger analysis of samples exposed to the discharge cleaning plasma and residual gas analysis of the impurities evolved during plasma discharges suggest that carbon is the dominant low-Z contaminant. Chromium and molybdenum lines are prominent in the soft x-ray spectrum (Fig. 14). The concentration inferred from the soft x-ray intensity is about $3 \times 10^9 \text{ cm}^{-3}$. Tantalum (the primary limiter material) is not observed in the soft x-ray region, indicating that the concentration is less than 10^9 cm^{-3} .

Auger analysis shows that molybdenum is the dominant heavy metal transported during plasma operation ($\sim 5\%$ monolayer/40 discharges), with tantalum nearly an order of magnitude less. This seems to corroborate the soft x-ray data that molybdenum (from the secondary limiters) and chromium (from the wall) are dominant high-Z impurities. For coronal equilibrium, the measured impurity concentrations would imply $P_{\text{rad}}/P_{\text{OH}} \sim 10\%$ in the center of the plasma. This estimate seems to be supported by the relatively good electron confinement, which is similar to that obtained in machines known to be free from significant high-Z radiation. Forthcoming bolometric and vacuum ultraviolet spectroscopic measurements of the plasma radiation are expected to clarify the impurity question.

Fig. 12. Comparison of maximum density achieved in Doublet III with other experiments

Fig. 13. Dependence of doublet central electron confinement on plasma density

Fig. 14. Soft x-ray spectrum obtained in a doublet plasma

SUMMARY

Steady-state circular, elliptical and doublet plasmas with low loop voltages and low levels of internal MHD activity have been produced. The magnetic configurations during the flattop phase are essentially constant. The doublets have about 90% of their poloidal flux inside the separatrix. Radiometer measurements show that the electron temperature profile is stationary and centrally peaked. The electron confinement and maximum plasma density achieved to date are in good agreement with "standard" scaling laws. Indirect evidence suggests that the power balance in the central portion of the plasma is not dominated by high-Z impurity line radiation.

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DISCUSSION (on paper presented by J. DeBoo)

HAWRYLUK

When you were plotting the confinement time data for PLT were you using total energy confinement time, electron energy confinement time, or what?

DEBOO

The PLT data presented was a global electron confinement time. The doublet data presented consisted of central values of the electron confinement time. So both groups of data referred to electron confinement times only and the PLT data were average values and Doublet III data were central values. Preliminary estimates of the global electron energy confinement based on radial temperature profiles

indicate that the global confinement is about 80% of the central confinement value. The total energy confinement time was not quoted because we have not yet made an ion temperature measurement. However, based on Artsimovich scaling, the ion and electron temperatures are similar, so that the total central energy confinement time is probably about twice the electron-only value.

HAWRYLUK

Were the currents in those discharges that disrupted at the end well controlled? It seems to me that they disappear rather rapidly.

DEBOO

The termination was usually from a disruption. I discussed the two typical modes that terminates the current for a doublet. It is a disruption - not a slow drop-off in current due to the volt-sec limit of the ohmic power supply.

HAWRYLUK

It wasn't clear to me what the difference was between a doublet and a droplet or circle. Was there any improvement in the confinement time in the discharge shape or any change?

DEBOO

There was only a small increase in confinement for the doublet compared to the circle and this is most likely due to slightly higher densities achieved in doublets because little time was spent optimizing the density in circles. The confinement time normalized by density was essentially the same for all three shapes discussed. What we are really pointing out is that the electron confinement in doublets is at least equal to that in circles. We believe we can control the shape of the doublet and keep it stationary. Attempts will now be made to improve the confinement by increasing the electron density.

CLARKE

You said that the purpose of this series of experiments was to investigate the property of doublet plasmas in a high temperature regime. Now have you learned enough to date to be able to increase the density to the point where you can inject beams into this doublet and heat it and see if there actually is a difference, because it seems to me that you have not demonstrated any difference so far?

DEBOO

We are not stressing any difference so far. We are at the point where we are beginning to try to increase the electron density. We would like at least 7×10^{13} line average density to inject neutral beams and keep beam shine through acceptably low. At the moment, the maximum line average density we have achieved is about 5×10^{13} . We have not spent much time trying to optimize the gas-puffing that has been done into these discharges. Also, if you recall the Murakami density scaling plot that I showed, several machines had cases of gettered and ungettered discharges. In these machines, gettering increased the density. This is another possible approach to increase our density.

DUECHS

Let's congratulate the Doublet III team on their world record in the current reached.

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