GA-A16049

MASTER

CONF-80-950-14

PLASMA EQUILIBRIUM CONTROL IN DOUBLET III

by

**R. STAMBAUGH, S. ADCOCK, R. CALLIS,
J. deGRASSIE, J. LUXON, P. ROCK,
J. WESLEY, S. SEKI, M. SHIMADA,
and H. YOKOMIZO**

OCTOBER 1980

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

GENERAL ATOMIC COMPANY

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

GA-A16049

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PLASMA EQUILIBRIUM CONTROL IN DOUBLET III

by

**R. STAMBAUGH, S. ADCOCK, R. CALLIS,
J. deGRASSIE, J. LUXON, P. ROCK,
J. WESLEY, S. SEKI,* M. SHIMADA,*
and H. YOKOMIZO***

This is a preprint of a paper to be presented at 11th Symposium on Fusion Technology, September 15-20, 1980 at Oxford, England.

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

***Japan Atomic Energy Research Institute**

**GENERAL ATOMIC PROJECT 3235
OCTOBER 1980**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

GENERAL ATOMIC COMPANY

PLASMA EQUILIBRIUM CONTROL IN DOUBLET III

R. Stambaugh, S. Adcock, R. Callis, J. deGrassie,
J. Luxon, P. Rock, and J. Wesley
General Atomic Company

S. Seki, M. Shimada and H. Yokomizo
Japan Atomic Energy Research Institute

ABSTRACT

The Doublet III tokamak ($R = 1.43$ m, $a = 0.45$ m, $b/a = 3.1$) is operated by General Atomic Company (GA) for studies of vertically elongated plasma cross-sections by research groups from GA and the Japan Atomic Energy Research Institute (JAERI). Stable ohmically heated discharges with a duration of up to 0.8 seconds have been obtained with a variety of plasma shapes. The JAERI group has produced diverted and non-diverted dee-shaped plasmas, the latter with elongations of up to 1.6. The GA group has produced droplet plasmas (two separated teardrops) with elongations of up to 1.5, doublet plasmas with an internal separatrix and elongations of up to 3.2, and an expanded boundary configuration. Record values of plasma current have been achieved: 1.0 MA in the dee and 2.2 MA in the doublet at a toroidal field of 2.4T. Dees with $q(a) = 2.6$ and diverted dees with $q(a) \approx 2$ have been obtained.

Important features of the machine which contribute to effective shape control are: 1) a parallel-connected set of field shaping coils (F coils) which fully and closely surround the vacuum vessel, 2) a continuous resistive vacuum vessel with a 1 msec flux penetration time, 3) SCR and fast switching chopper power supplies in series with the F-coils for active shape control, and 4) feedback regulation of the position of the outermost plasma flux surface. The latter feature, although not required for stable operation, improves discharge reproducibility and greatly simplifies tuning for the desired plasma shape.

The control signals used for the flux surface position regulation are derived from measurements of the poloidal field and flux obtained with an array of sensors located immediately outside the vacuum vessel. The close proximity of the sensors to the plasma surface ($\leq 0.2a$) allows the position of the plasma surface to be accurately computed with simple analog circuitry. The short time constant of the resistive vessel allows for stable high-gain closed loop control without elaborate pole-zero compensation. The small-signal response time is typically less than 10 msec. Control of the plasma position to ± 0.5 cm is routine.

1. INTRODUCTION

The plasma equilibrium control system or field shaping system on Doublet III has been able to control many diverse equilibrium configurations with plasma current up to 2 MA and plasma volumes up to 17 m^3 . Principal configurations produced have been: doublet plasmas [1], elongated dee plasmas [2], and both [3] a single null divertor and an expanded boundary configuration with the divertor coils outside the vacuum vessel. All of these configurations produce good plasma confinement and can be run in a steady state with the shot duration (0.8 sec) limited only by the pulse length capability of the Ohmic and field shaping power supplies. There are two key elements to the flexibility of the equilibrium control system. The first is the use of a sufficient number (24) of field shaping coils close enough to the plasma to control in detail the shape of the plasma boundary flux surface. The second feature is the extensive use of active shaping power supplies for dynamic control of the plasma shape; e.g.,

droplet plasmas (two disconnected current channels) can be merged into a doublet, and the divertor can be turned on and off in the same shot.

2. F-COIL SYSTEM

The essential concept of the Doublet III field shaping system is direct and local control of the boundary poloidal flux distribution. In contrast to the circular plasma situation [4], no analytic theory is available to specify the control fields for more general plasma shapes. By use of an MHD code [5], however, the plasma equilibrium flux surfaces are sufficiently determined if the poloidal distribution of magnetic flux on the plasma boundary and one or two parameters of the plasma current profile are known. From MHD code studies of a desired configuration, one can find the boundary flux values that need to be established at the flux measuring loops in Fig. 1. These flux values can then be produced in a shot by control of the 24 field shaping coils. Since the field shaping coils are only about $0.2 \text{ a } \approx 10 \text{ cm}$ from the plasma edge, an F-coil may be considered to individually control the local plasma boundary flux as measured on the one turn flux loop attached to its front face. The close proximity of the F-coils also minimizes the required Ampere-turns in the coils and the forces on them. The 1.0 MA dee (Fig. 1) requires only 0.6 MA-turns ($\leq 10 \text{ kA}$ shaping supply current) in the field shaping system.

A typical electrical connection of the poloidal field system is shown in Fig. 2. Each F-coil is wound in two 29 turn halves with the center at a virtual voltage zero. Active power supplies are connected at this virtual voltage zero to minimize the terminal potential, although the supplies can float to 30 kV. All 96 coil leads are brought out to a patch panel where copper bus is used to vary the connection scheme. About two hours are needed to make a major configuration change. The F-coil system is inductively decoupled

Fig. 1. Doublet III F-coil and magnetic diagnostic locations. F denotes a field shaping coil; PS denotes a flux loop; MP denotes a magnetic probe at toroidal azimuth (1,2,3 = 67° , 247° , 307°); PK denotes one of 12 segments of a full Rogowski loop. The plasma configuration is the 1.0 MA dee with elongation of 1.6. The F-coil labeling is symmetric across the midplane.

Fig. 2. F-coil and power supply connection diagram for doublet plasmas

[6] from the E-coil by virtue of the spatial distribution of the E-coil windings the E/F turns ratio (60.5/58) and the connection of the F-coils to the E-coil.

3. RESISTIVE VACUUM VESSEL

The Doublet III vacuum vessel is made of two layers and one strengthening corrugation of 1.5 mm Inconel with no insulating breaks. The resistance of the vessel is 0.25 mΩ. On the discharge flattop the vessel current is about 8 kA and has negligible effect. At breakdown, (with 130 V per turn) the vessel current is 520 kA and has an appreciable shaping effect in the early phase of doublet shots (Sec. 5). The flux penetration time of the vessel is 1 msec. Since no feedback stabilization is required in any of the four major configurations and since 100 Hz is a maximal necessary rate for dynamic configuration changes, the vessel does not restrict the useful bandwidth of the control system.

4. CLOSED LOOP FEEDBACK CONTROL

In the early phase of the shot, the F-coil currents are established mainly as inductive images of the plasma current, in close analogy with the action of a copper shell. The centering vertical field is inductively established by the series choke L_v on the inner coils. However, since the L/R time of the F-coils is about 0.24 sec and the shot duration is 0.8 sec, the F-coils must also be actively driven. Any two parallel connected coils will develop a flux difference due to resistive flux decay equal to $2\pi N (\psi_1 - \psi_2) = \int_0^t (I_1 R_1 - I_2 R_2) dt$ unless power supplies make up the IR drop (≤ 270 V) in each coil. The supplies R_1 and R_2 in Figs. 3,5,6 basically serve this resistive compensation function. Their voltage programs are derived from direct feedback regulation of fluxes (e.g., $\psi_2 = \psi_3 = \psi_4$). Actively driven F-coils are also needed for precise positioning of the plasma inside the limiter aperture (e.g., radial position control), for aspects of the boundary flux control that depend strongly on the time evolving plasma current profile (e.g., ψ_6 in the doublet), and unnatural features of the configuration (e.g., divertors).

4.1. Precision Control Signals

For precise position control, the small distance between the flux loops (Fig. 1) and the limiter make possible accurate local linear extrapolations of the boundary flux from the flux loops to the limiter using the flux gradient measured by the local magnetic probes or partial Rogowski coils. Various analog circuits have been constructed based on this technique. A signal RPA (RPB) computes the distance between the outer plasma surface and the outer limiter near coil 8A (8B) by dividing the difference in extrapolated limiter fluxes ($\psi_8^{LIM} - \psi_3^{LIM}$) by the flux gradient near coil 8. RPA is used to feedback regulate the radial position of dees and diverted plasmas and the upper lobe of doublets; RPB is used on the lower lobe of doublets. A signal HA (HB) computes the distance from the top (bottom) of the plasma to the limiter by dividing the difference in extrapolated limiter fluxes ($\psi_{TOP}^{LIM} - \psi_3^{LIM}$) by the flux gradient on the top (bottom). The radial positions and vertical positions of the plasma are regulated to ± 0.5 cm.

Another class of signals can be derived from computer experiments. The MHD code was used to simulate singlet equilibria in the upper half of the vessel with various vertical distances Z_p from the midplane. From the computed magnetic probe signals the expression

$$Z_p = 30 \text{ cm} \left(\frac{MP_{34A} - MP_{12A}}{MP_{34A}} \right) + 70 \text{ cm}$$

was derived, and constructed in an analog circuit. For doublet equilibria, an expression (P_s) for the fraction of the poloidal flux inside the doublet separatrix was found to be

$$P_s = 100\% \left(2.0 - 1.15 \frac{PR\ 12B}{PR\ 34B} \right)$$

This simple relationship is accurate to $\pm 10\%$.

4.2. Active Power Supplies and Feedback Electronics

The capabilities of the shaping power supplies are summarized in Table 1. The line-commutated rectifiers are commercial units. The chopper power supplies are built at our laboratory and have been described elsewhere [7]. They consist basically of a thyristor switching network that can apply positive voltage by switching a charged 0.25 F electrolytic capacitor bank in series with the F-coil or negative voltage by switching a varistor in series with the F-coil. The average supply voltage is determined by controlling the duty cycle between positive and negative voltage in response to a ± 10 V analog signal. The X supply connection in Fig. 3, with the arrow directed into the F-coil, denotes that positive supply voltage increases F-coil current flow anti-parallel to the plasma current, thereby pushing the plasma away from that F-coil, and driving the corresponding ψ value more negative. Conversely, negative voltage pulls the plasma closer to the F-coil and drives the ψ value more positive. The T-choppers, an early design, use resistors instead of varistors; the pulling voltage in that case is just the IR drop on the resistor and can be unacceptably weak if the supply must regulate a low F-coil current.

TABLE 1
Active Shaping Supplies

Number	Type	V, I, Time	Full Power Bandwidth
2	T-choppers	± 300 V, + 3 kA, 1 sec	1 kHz
8	X-choppers	± 600 V, + 3 kA, 1 sec	1 kHz
4	U-choppers	± 300 V, ± 2.5 kA, 1 sec	1 kHz
1	D-LCR*	± 600 V, + 10 kA, 1 sec	60 Hz
1	V-LCR*	± 600 V, + 15 kZ, 1 sec	60 Hz
6	R-LCR*	+ 150 V, + 3 kA, dc	60 Hz

*LCR-Line Commutated Rectifier.

The feedback control electronics consists of NIM packaged differential amplifier modules, analog divider modules, summing amplifier modules, and waveform generators (W.G.). The bandwidth of all the control electronics exceeds 10 kHz. The waveform generators provide a D/A conversion from a 128 word memory, generally clocked at a 10 msec/address rate. The memories are loaded from the control computer via interactive graphic software on a Tektronix storage display terminal. In this way, arbitrary waveforms can be specified for a boundary flux, radial position, or any control variable. Waveform generators also control the plasma current waveform and the gas puffing system throughput. The timing system for triggering the power supplies on or off, triggering the waveform generators, or relay closures is built on two levels. The highest level distributes ASCII encoded event triggers around the facility. A second level timing station is housed in a CAMAC crate and consists of a timing receiver to decode the master event triggers and one or more JORWAY 220-A delay generators. All timing settings are done through the control computer.

Fig. 3. Control schematic for doublet. Voltage gains are indicated on the power supplies and differential amplifiers. Heavy lines are power connections. Thin lines are control signal paths.

5. FULL CONTROL SYSTEM DESCRIPTIONS

A complete schematic for doublet plasmas together with the doublet equilibrium configuration is shown in Fig. 3 and Fig. 4 shows the waveforms this system produces. The R supplies on the inner wall serve the resistive compensation function previously discussed. Figure 5g shows the close tracking of the flux values on the inner wall.

The value P_s is controlled by X_4 and X_5 on the coils 6A and 6B. Indirect control of P_s is provided by regulating ψ_6 to follow a waveform generator program. The program was constructed by trial and error to deliver approximately the trajectory of P_s in Fig. 4c. Fine control of P_s is provided by closing a higher gain feedback loop regulating P_s at 250 msec into the shot. The P_s reference is also derived from a waveform generator. The degree to which ψ_6 follows the programmed ψ_6 is displayed in Fig. 4d. After the P_s feedback loop closes it dominates the final ψ_6 reference. Dynamic shape control is exhibited by the gradual lowering of P_s from an initial droplet plasma (two disconnected current channels) to a steady doublet with an exact P_s of 75% as derived from MHD code fits.

Fig. 4. Time evolution of a doublet shot

This merging technique has proven easier than controlling $P_s \leq 100\%$ from shot initiation for two reasons. The droplet phase is used to adjust the gas puffing waveforms to settle the

two current channels into well controlled, low impurity level plasmas before merging them. Secondly, at breakdown, there is a strong tendency for the two current channels to collapse into a short vertically unstable ellipse ($P_S = 0$) due to the attraction of the large outside midplane vacuum vessel current. In order to ensure an early droplet configuration, a strong repelling field in the midplane, negative ψ_6 in Fig. 4d, is established before breakdown and at breakdown ψ_6 is quickly driven further negative by discharge of the 900 V 0.1 F electrolytic bank C_D .

The T-choppers on the top and bottom coils regulate HA and HB. Figure 4e shows that due to the strong initial repelling field present at the midplane the values HA and HB are poorly controlled until the ψ_6 programming allows P_S to drop below 100%. Before 200 msec the plasmas are limiting on the top and bottom limiters; eventually, regulation is achieved with about a 7.0 cm gap between the plasma and the top and bottom limiters.

The choppers X_2 and X_7 regulate RPA and RPB. Initially, the top lobe swings too far inside due to the top plasma current being lower than the bottom plasma current by about 25% (see Fig. 4b). On the flattop, both RPA and RPB are regulated at different values which were found empirically to optimize up/down current symmetry (Fig. 4b). The choppers X_1 , X_3 , X_6 , and X_8 serve to interpolate the boundary flux between coils 12A, 8A, 6, 8B, and 12B.

The control schematic and the plasma equilibrium configuration for the single null divertor are shown in Fig. 5. Most of the lower coils are left open. The outer plasma field line is pulled into a divertor configuration around F-coils 1A and 1B by the reverse connected supplies R_3 and R_4 . These supplies drive divertor Ampere-turns equal to 58% of the plasma current. The quantities regulated are $\psi_{1A} = \psi_{4A}/0.6$ and $\psi_{1B} = \psi_{1A}$. Some downward force on the plasma is also produced with coils 6A and 6B by T_4 which is commanded to full negative voltage, (i.e., a 0.25Ω resistor is on the F-coil 80% of the time). Initially T_4 is programmed to push the plasma upward to ensure vertical stability of the plasma early in the shot. Because the plasma is pulled downward strongly by the midplane coils, the D supply with high (-600 V) inversion or pulling voltage has to be employed on the upper coils 10 and 12 to regulate vertical position (Z_p). Radial position regulation is obtained using the V supply

Fig. 5. Control schematic for the single null divertor and elongated dee configurations

driving F7, 8, and 9 in parallel. This same control arrangement can produce the elongated dee shown in Fig. 1 by merely setting $\psi_{1A} = \psi_{4A}/0.7$.

The control schematic and plasma equilibrium for the expanded boundary plasma are shown in Fig. 6. In this configuration the outer plasma field lines are separated from the upper chamber limiters and diverted into the bottom of the chamber where they essentially become lost in a weak poloidal field, highly radiative region. The plasma is pulled downward on both the inside (coils 1B, 2B) and the outside (coils 6B, 7B). The fluxes ψ_{1B} and ψ_{2B} follow the master control waveform ψ_{6B} . The outermost plasma field lines are steered through the mid-plane region by control of ψ_{1A} and ψ_{6A} and expanded in the bottom of the vacuum chamber with the remainder of the lower coils. As with the single null divertor, a supply capable of -300 V, a U-chopper was needed on the top coils to regulate HA. Early in the shot, upward force on the plasma is exerted by all the lower coils to ensure vertical stability until the configuration is fully developed.

Fig. 6. Control schematic for the expanded boundary configuration

6. CONCLUSION

The Doublet III field shaping system provides precise, dynamic control of many diverse plasma equilibria. The flexibility of the control system and F-coil arrangement allows the physics research teams from General Atomic (GA) and the Japan Atomic Energy Research Institute (JAERI) to alternate running weeks on the machine, changing plasma configurations on a daily basis to support a varied program of tokamak research on dee and doublet configurations and research on two kinds of simplified divertor configuration. Record plasma currents of 1.0 MA in a dee and 2.2 MA in a doublet have been produced.

7. ACKNOWLEDGEMENT

Research carried out under the Fusion Research Cooperation Agreement on Doublet III between the United States Department of Energy and the Japan Atomic Energy Research Institute, Contract No. DE-AT03-76ET51011.

8. REFERENCES

- [1] WESLEY, J.C., et al., "Shaping and Characteristics of Ohmically Heated Noncircular Plasmas in Doublet III," IAEA-CN-A-3, July 1980.
- [2] KITSUNEZAKI, A., et al., "First Results of Dee Experiments in Doublet III," IAEA-CN-38/N-3, July 1980.
- [3] NAGAMI, M., MAHDAVI, M., et al., "Simplified Poloidal Divertor Experiments in Doublet III," IAEA-CN-38-O-2, July, 1980.
- [4] MUKHOVATOV, V.S., and SHAFRANOV, V.P., "Plasma Equilibrium in a Tokamak," Nuclear Fusion 11, 605-633 (1971).
- [5] McCLAIN, F.W. and BROWN, B.B., "GAQ, A Computer Program to Find and Analyze Axisymmetric MHD Plasma Equilibria," General Atomic Company Report GA-A14490 (1970).
- [6] CALLIS, R.W., "Doublet III Baseline Design Description," General Atomic Company Report GA-A13996, June 1976.
- [7] ROCK, P.J., and WESLEY, J.C., "1.5 Megawatt D. C. Chopper Power Supplies for Plasma Shape Control on Doublet III," Proceedings of the 8th Symposium on Engineering Problems of Fusion Research, Nov. 1979.

EXTERNAL DISTRIBUTION LIST

GA-A16049

Dr. R. Parker
Massachusetts Institute of
Technology
Cambridge, Massachusetts 02139

Dr. D. Swain
Oak Ridge National Laboratory
P. O. Box Y
Oak Ridge, Tennessee 37830

Dr. D. Overskei
Massachusetts Institute of
Technology
Cambridge, Massachusetts 02139

Dr. M. Murakami
Oak Ridge National Laboratory
P. O. Box Y
Oak Ridge, Tennessee 37830

Dr. D. Meade
Princeton Plasma Physics
Laboratory
P. O. Box 451
Princeton, New Jersey 08540