Confinement of Plasma in the Doublet-II Device*

T. H. Jensen, R. K. Fisher, C. L. Hsieh, M. A. Mahdavi, V. Vanek, and T. Ohkawa
General Atomic Company, San Diego, California 92138

(Received 23 September 1974)

Doublet II is a noncircular cross-section toroidal device with three magnetic axes. Theoretical considerations show that confinement of plasma in a doublet device might be similar to that of a tokamak with a much stronger toroidal magnetic field. Experiments carried out in Doublet II verify this in that the plasmas are found to have densities, temperatures, q values, and confinement properties close to those of comparable circular-cross-section tokamak plasmas.

The doublet[1] magnetic configuration was first tested for gross magnetohydrodynamic (MHD) stability in the Doublet-I device.[2] A study[3] comparing tokamaks and doublets suggests that the toroidal magnetic field required for stable confinement of a plasma is about 3 times larger in tokamaks than in doublets, or, for the same value of toroidal magnetic field, that the plasma pressure can be nearly an order of magnitude larger in doublets than in tokamaks. Since large toroidal magnetic field strengths are required for tokamak or doublet fusion reactors, this difference is very important. The main assumption leading to this conclusion is that stability depends on the toroidal magnetic field mainly through the safety factor q.

The Doublet-II device[4] was built to test this assumption experimentally. Therefore, the design parameters were chosen such that the dimensions, the plasma current density, and the safety factor would be similar to those of tokamaks, but the toroidal magnetic field strength would be low compared to tokamaks, namely below 10 kG.

Figure 1 shows a schematic of the device. The discharge chamber is 90 cm high and the average major radius is 63 cm. The design is similar to regular tokamak devices. No iron core is employed. More details of the design are given in Ref. 4.

The magnetic configuration of a discharge is determined by the current distribution in the plasma, the shapes of the limiter surface and the field shaper, and a control magnetic field applied well before the discharge takes place. During the discharge, the field shaper can be considered a good conductor and thus the relative flux-function values at the field-shaper surface, established by the control field, are maintained during the discharge.

The magnetic configuration was studied[5,6] experimentally by measurement of the poloidal magnetic field strength around the plasma surface. These measurements were compared to results of a numerical study.[7] In this study, a model is used in which it is assumed (1) that the plasma acquires an axisymmetric MHD equilibrium, (2) that the plasma pressure is zero on flux surfaces which intersect the limiter surface, and (3) that the magnetic boundary condition at the field-shaper surface is one that corresponds to the control field being frozen into the field-shaper material.

The current distribution in the plasma in the numerical model is described by two parameters which are adjusted to fit the experimental observations. Figure 2 shows a calculated magnetic configuration with input parameters adjusted to fit experimental observations for a plasma current of 100 kA at 6 msec. Without the applied control field, the configuration found is one with two plasma regions separated or connected by a

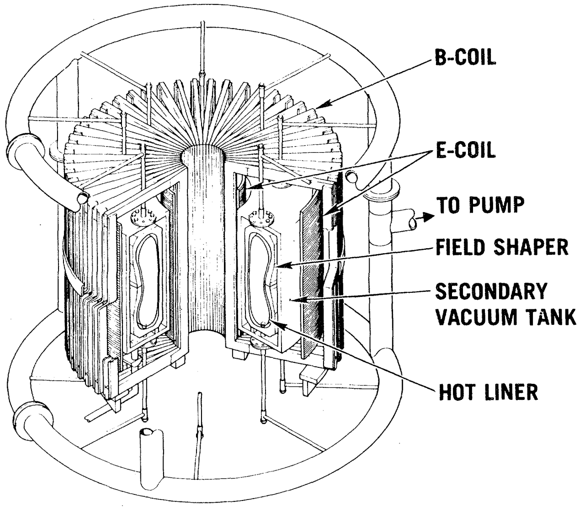

FIG. 1. Schematic of the Doublet-II device.

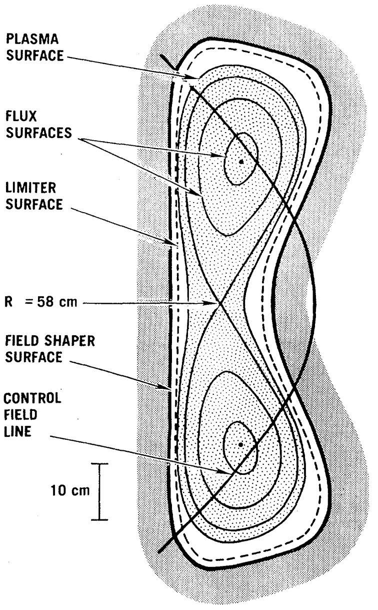

FIG. 2. Computed plasma equilibrium with external control field.

narrow plasma bridge.

The control field provides a means of modifying the configuration within a limited range. Too large a control field interferes with the initial breakdown of the plasma, and the equilibrium depends on the ratio between the plasma current and the strength of the control field. For this reason the control field was not as effective at high plasma currents (~200 kA). The straightforward way to modify the equilibrium, namely to change the shape of the field shaper, is impractical. The use of field coils instead of a field shaper provides a more flexible means of equilibrium control. This method will be utilized in a forthcoming modified version of the Doublet-II device.[8]

The plasma density and temperature were measured by the same diagnostic means used for tokamak experiments, namely Thomson scattering, 2-mm microwave interferometry, soft-x-ray spectrometry, and neutral-particle energy analysis. Partly because of limited diagnostic access to the Doublet-II plasma, it is typically necessary to accumulate data from 10–20 discharges to obtain meaningful results from these diagnostics.

The Thomson-scattering system uses a 10-J ruby laser. The dimensions of the access ports resulted in a total laser beam length of 13 m and limited the diameter of the viewing lens to only 3 mm. The scattering volume is located close to the upper elliptic axis of the magnetic configuration. The spectrum of the scattered light was analyzed in a polychromator utilizing dielectric filters. The absolute electron density was obtained by calibrating the system using Rayleigh scattering from argon gas.

The neutral-particle spectrometer is similar to the instrument described by Barnett and Ray.[9] From the energy spectrum of the observed hydrogen atoms, one can derive an ion temperature close to the maximum ion temperature. From the measured neutral flux, one can estimate the product of the hydrogen ion and neutral densities to be 10^{21} to 10^{22} cm^{-6}.

The soft-x-ray spectrometer consists of a lithium-drifted silicon detector and associated pulse-height–analysis electronics. In general, the soft-x-ray electron temperature is in agreement with the laser observed temperature. In addition one may obtain information about the "effective Z" of the plasma from the absolute intensity of the x-ray signal. Because density and temperature profiles are not measured, some uncertainty exists, but it appears that the "effective Z" is in the range 2–7. The intensity of high-energy x rays was found to be very small; i.e., the content of runaway electrons is small.

Diagnostic results from discharges with four different current values are summarized in Table I. With the exception of discharge case D, the plasma-current time dependence is about the same; initially the current rises sharply and

TABLE I. Summary of measured plasma properties for four different discharges.

Case	I_p (kA)	V (V)	B_t (kG)	t_m (msec)	n_e (10^{13} cm^{-3})	T_e (eV)	T_i (eV)	τ_E (msec)	q'	β_p'	β_t (%)
A	93	1.4	9.5	18	0.9	300	275	2	9.0	0.6	0.2
B	130	2.2	8	14	1.3	550	300	2	5.4	0.7	0.7
C	166	2.2	9.5	18	1.3	850	525	2	5.0	0.7	0.8
D	210	9	8	8	2.2	1100	450	•••	3.4	0.8	2.1

reaches its maximum at 14 to 18 msec as indicated and decays to zero at about 30–40 msec. To obtain the large current of case D, the turns ratio of a transformer had to be changed by a factor of 2; consequently, the time scale is about one half of that, i.e., current maximum occurs at 8 msec. The measurements given in Table I are made at or near current maximum. It should be mentioned that other discharges have been studied; for example, reproducible discharges with currents up to 500 kA can be obtained. Because of capacitor-bank limitations, these discharges were limited to a duration of about 1 msec which in turn made it difficult to diagnose the plasma; however, the neutral-particle spectrometer showed an ion temperature of 275 eV.

In Table I, I_p is the maximum plasma current. V is the measured one-turn voltage at maximum current. The resistive one-turn voltage may be smaller because of the $I(dL/dt)$ term; this is particularly important for case D which has a shorter time scale. B_t is the toroidal magnetic field at the average plasma radius, 0.63 m. t_m is the time of current maximum. The electron density and temperature, n_e and T_e, are results of the Thomson-scattering measurements. The ion temperature T_i is derived from the neutral spectrometer measurements. The energy confinement time τ_E is defined as the ratio between the thermal energy of the plasma and the power input VI_p. The pressure profile was obtained from MHD equilibrium calculations selected to match experimental observations, including the pressures at the elliptic axis. The safety factor is defined as $q' = sB_t/2\pi R\overline{B}_p$, where s is the poloidal circumference of the plasma, R is the major radius, and $\overline{B}_p = \mu_0 I_p/s$. The poloidal β is defined as $\beta_p' = n_e(T_e + T_i)2\mu_0/\overline{B}_p^2$. Finally, the total β is defined as $\beta_p' = n_e(T_e + T_i)2\mu_0/\overline{B}_p^2$.

For case D, no value for τ_E is given because, as mentioned above, indications are that the product VI_p is not indicative of the power input into the plasma.

In discussing these results, it should be understood that the scope of the Doublet-II experiments is primarily to compare the overall quantities to those of circular–cross-section tokamaks. Possibly the most important question answered by the Doublet-II results is whether a similar energy confinement time is obtained with similar q values in doublets and tokamaks. For this comparison an ST Tokamak case, describe by Dimock *et al.*,[10] was chosen because of its comprehensive description of the discharge, and because the radial extent of the plasma in Doublet-II is nearly equal to that in the ST Tokamak. Specifically, we compare the Doublet-II results, case C from Table I, to the ST Tokamak results[10] measured at 15 msec. The current densities and one-turn voltages are comparable. For Doublet II, the electron temperature and density are lower than in the ST Tokamak by the factors 1.3 and 1.8, respectively, and the energy confinement time is lower by a factor 1.5 while the q values at the limiter are about identical. Because of the noncircular cross section of Doublet II, the toroidal magnetic field is considerably larger in the ST Tokamak than in the Doublet II, resulting in a β about a factor of 6 larger in Doublet II. The significant result is that the Doublet-II plasma parameters are comparable to those of the ST Tokamak in terms of density, temperature, energy confinement time, and q, resulting in a large value of β. Thus, the possibility that a significantly larger q be required for doublets than for tokamaks to provide a similar confinement seems to be ruled out. The lower electron density in Doublet II may be associated with differences in the wall properties of the two devices; this may also account for the difference in time dependence of the density, namely, a decreasing density in the Doublet II and an increasing one in the ST Tokamak. From Table I, one notices that as the plasma current increases, the plasma temperatures increase while β_p and the energy confinement time are nearly constant. It should be noted that high β values have been obtained in circular–cross-section tokamaks with large plasmas; a value of 0.9% has been obtained in ORMAK.[11]

Because of lack of direct measurements of temperature and current density profiles, definite statements cannot be made about resistivity anomaly. However, from MHD calculations, fitted to experimental observations, one may estimate these profiles and thereby the effective plasma resistivity. These estimates indicate that the observed resistivity is somewhat larger than the value calculated from the effective Z estimated from the soft–x-ray spectrometer measurements.

In summary, experimental results show that the doublet plasma characteristics are similar to those of comparable tokamaks, with the important exception that the magnetic field is much smaller.

*Work supported by the U. S. Atomic Energy Commission, Contract No. AT(04-3)-167.

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Quadrupole Stabilization of the Precessional Mode of Relativistic Electron Rings*

D. M. Woodall and H. H. Fleischmann
School of Applied and Engineering Physics and Laboratory of Plasma Studies,
Cornell University, Ithaca, New York 14853

and

H. L. Berk†
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540

(Received 26 November 1974)

Experiments show that the precessional instability predicted and observed in weak electron rings trapped in a magnetic mirror field can be suppressed by adding a sufficiently strong magnetic quadrupole Ioffe field to the basic mirror field. In agreement with a theoretical analysis, the instability ceases when the Ioffe field reaches sufficient strength so that the radial gradient (dB_t/dr) of the total magnetic field strength becomes positive.

In 1965, Furth[1] investigated the precessional stability of rings of high-energy charged particles trapped in a magnetic-mirror system, which will be important for Astron-type[2] fusion devices. The respective precessional motion results from radial changes, dB/dr, of the strength of the external magnetic field. In a normal mirror field, where $(dB_M/dr)<0$, this precessional rotation is "forward," i.e., in the direction of the Larmor motion of the fast particles, and was found unstable. On the other hand, in the presence of flux-conserving metallic walls, the image currents induced by the high-energy ring add a positive image-field gradient, $(dB/dr)_i>0$, which tends to stabilize the ring motion. Since these image currents are proportional to the ring strength (for given ring and wall geometry), Furth predicted that strong rings would be wall stabilized, whereas a rapid dump of the rings should be expected whenever the ring strength has decayed to a certain critical level which will depend on the field, and the wall and ring geometry. As predicted, this instability has been observed both in the Livermore Astron experiment[3] and in the relativistic-electron-coil experiment (RECE) on Berta at Cornell.[4,5] Christofilos *et al.*[6,7] showed that these ring losses can be avoided by adding a toroidal field induced by currents flowing along an axial conductor or "cantilever."

In the present paper, we report evidence that this instability can be suppressed also by adding a sufficiently strong quadrupole Ioffe field,[8] B_I, to the normal mirror field. Such fields were shown[8] to stabilize flute modes in a normal mirror plasma whenever the radial gradient dB_t/dr of the total magnetic field, $B_t=(B_M^{\,2}+B_\mathrm{I}^{\,2})^{1/2}$, becomes positive. Our experimental evidence, in agreement with preliminary theoretical investigations, shows that this same condition also determines the stability of the electron rings in RECE-Berta. This type of stabilization has the advantage that it will permit long-time confinement of the rings when field penetration renders normal wall stabilization ineffective, without necessitating an axial conductor through the ring region. Experimental results indicate that some-