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MASTER**FREE EXPANSION EXPERIMENT
ON ATC**

BY

L. R. GRISHAM, K. BOL,
AND J. T. HOGAN**PLASMA PHYSICS
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L. R. Grisham and K. Bol
Princeton University Plasma Physics Laboratory
Princeton, New Jersey 08540 USA

J. T. Hogan
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830 USA

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FREE EXPANSION EXPERIMENT ON ATC

L. R. Grisham and K. Bol
Princeton University Plasma Physics Laboratory
Princeton, New Jersey 0850 USA

J. T. Hogan
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

We have investigated the transport of a tokamak plasma which has been freed from contact with a material limiter. A small compression in major radius of the plasma in the ATC tokamak produced a free-standing discharge, similar except for scale to a possible configuration of the Tokamak Fusion Test Reactor. Diffusion speeds in the range 10 ms^{-1} were measured, and the evolution is readily modeled by a numerical transport model calculation. The experiment provides a successful preliminary test of the feasibility of this technique.

1. INTRODUCTION

The transport and stability properties of a tokamak plasma freed from contact with a material aperture limiter have been a subject of speculation for some time. Indeed, on the JFT-2 tokamak an attempt was made a few years ago [1,2] to produce such a plasma by rapidly retracting the limiter, but the velocities achieved (5 ms^{-1} average, 9 ms^{-1} peak) were somewhat too small to achieve a definite separation between the limiter and the plasma boundary. It is possible in the Adiabatic Toroidal Compressor (ATC) tokamak (the construction of which has been described previously [3]) to separate the limiter and the plasma in a more elegant manner by taking advantage of the programmable vertical field to move the plasma away from a fixed outer limiter on time scales more than an order of magnitude faster than was possible in the dynamic limiter experiment of Refs. [1] and [2]. Except for the emphasis on speed, this technique is identical to that envisioned for controlling the buildup of plasma current in TFTR [4] and in future reactors by moving the nascent plasma away from the limiter with the vertical field.

2. EXPERIMENTAL ARRANGEMENT

We have recently performed such an experiment. Figure 1 shows a cross section of the ATC vacuum vessel. At the beginning of a discharge a small plasma was formed at a major radius of about 100 cm near the outer radial limiter of ATC. This small plasma typically had a minor radius of 7-10 cm, which is

approximately 40-60% of the minor radius of a standard ATC discharge centered near a major radius of 90 cm. After the plasma was established for several milliseconds the vertical field was increased so as to decrease the major radius of the plasma and to isolate it from the radial and vertical limiters. The center of the plasma was typically shifted 8-12 cm in 400 microseconds, resulting in translation velocities of $200-300 \text{ ms}^{-1}$.

The subsequent evolution of the plasma density profile was observed by Abel inversion of density line integrals measured simultaneously along seven chords with 4 mm microwave interferometers. To preclude cross talk among different channels, the seven sets of horns were fed by five klystrons tuned to slightly different frequencies, and adjacent channels were propagated in opposite directions.

In general the free plasma was not centered under the microwave horn array, nor was it always completely stationary. Consequently, it was expedient to perform a spline fit on the raw line integral data. The constraints imposed on the curve so obtained were that it pass through every data point, that the first derivative be everywhere continuous, and that the density go to zero at the vacuum vessel wall. The latter constraint was not very critical; substituting a boundary condition that the density go to zero at the limiter radius resulted in no significant changes in the profile obtained after inversion at radii smaller than the limiter radius. The center of the fitted curve

was next located, and a set of data points was read off the curve at intervals of 1.09 cm (the actual spacing between the centers of adjacent microwave horns was 4.36 cm). This array was then Abel inverted to obtain the density profile. The large number of points in this profile enabled us to draw a smooth curve through them, and it is curves of this sort which are shown in the next section. These curves are estimated to be accurate to within $\pm 10\%$ at minor radii less than 17 cm (which corresponds to the limiter radius). Beyond this point no data were taken, and the continuations of the curves to the vacuum vessel wall are simply shown for completeness. Only one side of the profiles is shown in the figures of the next section because, in carrying out the inversions, it was assumed that the plasma was cylindrically symmetric in cross section. This should be a good assumption in ATC, and the raw data were in fact observed to be highly symmetric.

3. EXPERIMENTAL RESULTS

Two categories of discharge were studied in these experiments. One category comprised discharges in which the machine conditions were the same as those ordinarily employed on ATC - namely, a filling pressure of 1×10^{-5} Torr, and a toroidal magnetic field at 90 cm of 13.9 kG. In the other type of discharge, the field was the same, but the gas was supplied by a fast pulse valve, and the vacuum vessel was gettered prior to running the discharge by coating approximately 1/3 of the wall with titanium sublimated

from a ball inserted into the torus. These will be referred to respectively as ungettered and gettered discharges.

Figure 2 illustrates the time development of the plasma electron density profile in an ungettered discharge after the plasma had been moved away from the limiter to its free expansion position. Plasma density profiles were extracted from the raw data at intervals of 100 μ sec during the first 1.5 msec of the free expansion phase of the discharge, and subsequently once every msec. Since many of these curves are very similar, only a representative few are shown to indicate the plasma behavior. We note that the density profile reaches a near equilibrium after 9-10 msec and does not change appreciably during the remaining 6 msec of the discharge.

Figure 3 shows the temperature profiles during the free expansion phase of the discharge. The first profile, taken at the start of the free expansion phase, has a peak of 450-500 eV and a half-maximum radius of 7 cm. The second profile, taken 5 msec later, shows the temperature to be about the same, but the temperature half-maximum radius has increased to 10 cm. Taken 15 msec after the initiation of free expansion, the third profile reveals that the peak temperature has risen to about 640 eV, while the temperature half-maximum radius has remained at about 10 cm. During the time interval spanned by these profiles, the plasma current rises from 25 kA to kA. Also shown on Figure 3 are the radial and vertical position of the discharge.

The vertical displacement from the midplane at no time exceeded a few centimeters, and therefore did not constrict the plasma radius to less than 14-15 cm.

Figure 4 gives the number of electrons as a function of time for the ungettered discharge. The top curve shows the total number of electrons in the plasma, while the second curve gives the number within a minor radius of 8.7 cm (which corresponds roughly to the minor radius of the plasma at the beginning of the free expansion phase), and the third curve indicates the number of electrons outside that radius. It is apparent that the number of electrons within 8.7 cm declines for 4-5 msec, while the number outside 8.7 cm increases rapidly over the same sort of time scale. After that, the number of electrons inside 8.7 cm is nearly the same as the number outside, and they both increase linearly together. The particle replacement time indicated by the H_{β} light is about 5-7 msec at the start of the free expansion phase, increasing to 9-10 msec near the end. We note that this initial replacement time is similar to the time for equilibration between the inner and outer plasma regions.

Figure 5 shows the behavior of the density profile in a typical gettered discharge. Again, although profiles were analyzed initially once every hundred microseconds, only representative ones are shown. The curve for 9.4 msec is the density profile immediately after the plasma has arrived at its free expansion position. We note that its edge is well removed from the vertical

and radial limiters, the nearest of which lie at a minor radius of approximately 17 cm. In the next few hundred microseconds very little happens to the interior of the plasma, but we see that by 400 microseconds after the start of the free expansion phase a low density plasma links the main plasma body to the limiter. By about 10.6 msec after the start of the free expansion phase (indicated by the curve at 20 msec into the discharge), the density profile has reached what appears to be an equilibrium, since it does not change appreciably over the remaining 8 msec of the discharge. At this point the peak density is 1.3×10^{13} , which is almost the same as that at the start of the free expansion phase. The half maximum radius of the profile has decreased somewhat from its initial value, while the low density tail has come up, resulting at equilibrium in a small dense plasma surrounded by a tenuous, nearly uniform halo which stretches at least as far as the limiter. A laser scan of this type of discharge taken 3.5 msec into the free expansion phase gives a peak electron temperature of 550 eV. The temperature profile is similar in shape to the density profile, although somewhat narrower, sinking to a temperature of just a few eV at a minor radius of 9 cm.

Figure 6 shows the number of electrons in the gettered plasma as a function of time after the start of the free expansion phase. The various curves have the same meanings as in Fig. 4. We note that, after rising rapidly, the number of electrons outside the original radius comes to equal the number inside at equilibrium,

much the same as in the ungettered discharge. The H_{β} light yielded an estimate for the particle replacement time of 6-7 msec at the start of free expansion, increasing to 15 msec later in the discharge. As in the ungettered case, this is similar in magnitude to the density equilibration time.

Figure 7 compares the time dependence of the half maximum radii of the density profiles for the gettered and ungettered discharges. We see that the half maximum radius increases very slowly in the ungettered case, while, in the gettered case, it decreases slightly over 10-11 msec, and then remains constant at 5.7 cm.

Figure 8 offers a comparison between the equilibrium profile reached by a gettered free expansion 50 kA discharge and the profile of a gettered 43 kA discharge initiated in the normal way and centered at the same major radius as the free expansion plasma. We see that the normal discharge is much less peaked than the free expansion one, and does not exhibit the low density halo.

Figure 9 offers a similar comparison between the near-equilibrium profiles of a free expansion 34 kA discharge and a normal 32 kA discharge, both of which are ungettered. It is apparent that here also the free expansion near-equilibrium profile is considerably more peaked than for the normal case.

4. THEORETICAL INTERPRETATION

The free expansion discharges serve as a useful test of theoretical models which are used in tokamak transport codes.

These transport codes calculate the particle and energy balance by accounting for a large number of interacting processes, and this often makes it difficult to isolate processes of interest for study. For example, interpretation of the usual tokamak discharge is complicated by the interaction of plasma with the limiter and the wall. The resulting influx of impurities changes the fundamental transport processes by enhancing collision frequencies, by decreasing the hydrogenic ion density, and by causing large local energy losses through electron inelastic collisions with the impurities. In this sense, then, the study of the time behavior of a plasma which is initially isolated from the wall may decouple some of the impurity production processes from those of plasma transport.

This is the aim of the designers of the Tokamak Fusion Test Reactor, who may use this scheme to assure the maintenance of a relatively pure plasma during short-duration 'break-even' experiments. The experimental results thus represent a first test of this scheme, although there are important qualifications. The ATC plasma, in its isolated configuration, bears a strong geometric resemblance to the planned low-current TFTR mode. In this mode a 50 cm plasma is isolated from the limiters, which will be positioned with an 85 cm minor radius. The magnitude of the flow of energy through the surface of these two plasmas will, however, give an indication of some important differences. In the ATC case the ohmic heating power (~ 100 kW) is transmitted through a plasma

surface area of $\sim 4 \cdot 10^4 \text{ cm}^2$, giving a local heat flux rate of $\sim 2 \text{ w/cm}^2$. In the TFTR case the $\sim 40 \text{ MW}$ of neutral beam injection power will be transmitted through a plasma surface area of $\sim 5 \cdot 10^5 \text{ cm}^2$, giving a local heat flux rate of $\sim 80 \text{ w/cm}^2$, i.e., larger by more than an order of magnitude. Thus, while plasma edge densities and temperatures are expected to be similar, at least during the first phase of the expansion, to those at the edge of the ATC plasma, the resulting expansion may be more rapid in TFTR because of the higher power flow.

To describe the theoretical model we will concentrate first on the particle balance. The remainder of the model is described in Refs. [5] and [6]. The electron density is described in space and time by

$$\frac{\partial}{\partial t} N_e(r,t) + \frac{1}{r} \frac{\partial}{\partial r} (r D \frac{\partial N_e}{\partial r}) = N_e N_o \langle \sigma v \rangle \text{IONIZATION} + R_{\text{IMPURITY}}$$

where

D : plasma diffusion coefficient

$N_{e,o}$: electron, neutral hydrogen densities

$\langle \sigma v \rangle \text{IONIZATION}$: Rate coefficient for ionization by electron impact

R_{IMPURITY} : Source of electrons from the imbalance between ionization of impurities and recombination to lower charge states.

The geometric description of Fig. 1 is simplified in the numerical calculations by adopting the magnetic axis as the center of coordinates and by calculating in an equivalent cylindrical geometry, with radial coordinate r . The transport processes are assumed to be one-dimensional. The diffusion coefficient is chosen to be that appropriate to these relatively collisional regimes. With

$$D_{\psi} = 4 \hat{\rho}^2 v_{ei} \left(\frac{0.46}{1.08 + z_{eff}} + 0.29 \right) z_{eff} ,$$

and

$$D_{PS} \equiv (1 + 2q^2) \rho^2 v_{ei} .$$

We choose

$$D = (1 - \alpha) D_{\psi} + \alpha D_{PS} ,$$

where

$$\alpha \equiv 1 - e^{-v^*/\epsilon}^{-3/2} .$$

Here

$$\hat{\rho}^2 = c^2 \frac{2m_{e,i} T_{e,i}}{e^2 B^2} ,$$

$$\rho^2 = c^2 \frac{2m_{e,i} T_{e,i}}{e^2 B_T^2} ,$$

$$v_{ei} = \frac{4\sqrt{2\pi}}{3\sqrt{m_e}} \frac{n_e^4 \ln \Lambda_e}{T_e^{3/2}} ;$$

$$v^* \equiv v_{ei}/\omega_b; \quad \omega_b \equiv \frac{2kT_e}{m_e}/Rq \quad \epsilon \equiv r/R ,$$

$$q \equiv \frac{rB_T}{R B_\theta(r)} ,$$

$$Z_{eff} \equiv \sum N_k Z_k^2 / N_e .$$

For the neutral gas we calculate the solution to a one-dimensional Boltzmann transport equation, which provides the radial variation of the spatial density, $N_O(r)$. The neutral gas calculation will yield the ratio $N_O(r)/N_O(r=a)$. The theoretical model thus requires some information about the edge neutral density and also about the energy distribution of incoming neutrals. A natural assumption is that neutral atoms are produced by dissociative ionization of H_2^O , and enter the plasma with a mean energy ~ 5 eV. The edge number density has been estimated to be $\sim 3 \cdot 10^9 \text{ cm}^{-3}$ in the ungettered case, by inference from Ref. [7].

For the gettered case we simply assume that the edge neutral density vanishes. The reason is that the low energy neutrals cycle rapidly between the wall and the plasma at a velocity $\sim 10^6 \text{ cm/sec}$. At the plasma edge a neutral most probably will charge exchange with a hotter ion, and return to the wall.

($\sigma_{CX} \sim 4 * \sigma_{IONIZATION}$ at 50 eV). At the wall the neutral may produce other neutrals by desorption. In any event, a neutral will be trapped by the gettered surface after a few such transits, and so the edge density will be decreased.

The impurities will be treated, except as noted, by assuming a spatially uniform Z_{eff} . There were no detailed measurements of impurity composition or radial profiles for this series so that we do not expect exact numerical agreement in the results.

The energy balance is much more complicated, but our model produces temperature profiles close to those for gettered and ungettered cases, and we need not discuss the model in detail here.

The experiments described earlier allow a test of the theoretical predictions for the time scale over which the plasma may be isolated from the wall. Extrapolations with these models suggest that this isolation should persist for at least one slowing-down time in TFTR. The comparison between the time required for the initial evolution and that predicted by the model is of interest.

We assume a major difference between gettered and ungettered discharges: ungettered cases we assume to have a spatially uniform $Z_{eff}=4$, while gettered cases have $Z_{eff}=1.0$.

Figure 10 shows the calculated results corresponding to the ungettered case and is to be compared with Fig.4. We see that the qualitative features of the evolution are matched, and that the time evolution agrees very well. The total number density is calculated correctly to within 10% after 15 msec, while

the number contained within $r = 8.7$ cm is overestimated by the model by 50%. The number of particles outside $r = 8.7$ cm at 15 msec is also in error by about 50%. That the evolution is due to plasma diffusion, and not local ionization may be seen by comparing gettered and ungettered cases.

As noted earlier, we represent the effects of Ti gettering by reducing the edge neutral density by an order of magnitude. For this case the results of the theoretical model are given in Fig. 11, and are to be compared with the experimental results given in Fig. 6. Again, the time evolution agrees well with the numerical results.

There are several reasons why the agreement can only be significant as regards the overall time evolution of the integrated number densities. These discharges are at the lower end of the usual tokamak operating of densities (Ref. [6]). As a result one might expect that about half the resistivity anomaly above the Spitzer value could be due to the penetration of fast (runaway) electrons into the nuclear core of impurity ions. Thus the collision frequency enhancement used in the transport models would be invalid.

Second, the spatial distribution of impurities has not been measured for these discharges. Figure 12b shows the calculated evolution of an assumed initially flat distribution of oxygen atoms for the ungettered case. We see that there is a significant variation in the number density (and, accordingly, in $Z_{\text{eff}}(r)$)

during the free expansion phase. (The diffusion rates used for the impurity diffusion calculation are those calculated by Rutherford [8].) Thus we have not been able to verify the accuracy of the assumptions in the model about impurity distributions and transport.

As an example we show in Fig. 13 and 14 the results of a more favorable assumption about the plasma's oxygen content. If we assume that the oxygen density has the same profile dependence as the electron density, then some qualitative features of the discharges shown in Fig. 2 and 5 are recovered. In particular there is a more pronounced distinction between the cone plasma and the halo for the gettered case. The cold edge plasma which is produced in the model now has the flat profiles seen in the gettered experiment, while the magnitude of the edge density is dependent upon the recycling rate. The behavior of model profiles for the ungettered case, shown in Fig. 14, is now markedly different from the gettered one; in particular, it evolves to a shape more nearly resembling the experimental case.

In these cases, note that the peak oxygen density in the ungettered case is assumed to be 2.9 times that assumed for the gettered case.

5. DISCUSSION

Future large tokamaks, such as the TFTR, will have to be protected against the effect of impurities. One proposed method is to isolate the plasma from contact with a material limiter by

major radius compression. This isolation must be preserved in TFTR for approximately 100 msec (a fast-ion thermalization time). Computational models have suggested that this technique is feasible and that the plasma isolation can be sustained for the required duration.

Our experiments lend support to that conclusion. Plasmas with line average densities near 10^{13} cm^{-3} were maintained in isolation from contact with a limiter for about a particle containment time, by which time a quasi-steady state had been established. Radial diffusion velocities were found to be approximately 10 ms^{-1} . Different steady states were reached, depending on the condition of the wall; in particular depending on the presence of a layer of freshly sublimated Ti. Ti-gettered discharges were found to produce a much more highly peaked central N_e profile, perhaps resulting from the lower enhancement of collision frequency due to impurities. Also, there was a difference observed between the steady states reached by free expansion discharges and those reached by normal full aperture discharges. The fact that free expansion steady state profiles were the more peaked may similarly be due to lower impurity generation and to a resulting lower diffusion rate.

The experiment also serves as a preliminary test of the models which are used to calculate the dynamics of future large tokamaks. We find that these models do reproduce the observed time dependence,

within the uncertainties both in the models and in the experiments. No new instability mechanisms are required, for example, to explain the free expansion. While the energy flow rate in large, injection heated tokamaks will be larger than the energy flow in our experiments, the edge conditions (and hence plasma transport properties) are expected to be similar. In addition, the model calculations show that some of the density growth in the external region is due to ionization of the ambient neutral gas. The validity of this part of the model depends on Boltzmann equation calculations of neutral gas transport, and these are thought to be quite suitable for extrapolation.

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766009
 Fig. 1. Cross section of the ATC vacuum vessel, indicating positions of μ -wave horns and limiters. The plasma was formed in position a against the outer limiter, moved to position b with the vertical field, and allowed to expand as indicated by c.

756148

Fig. 2. Evolution of the plasma electron density profile in an ungettered discharge after plasma has been moved away from the limiter to its free expansion position. The curve labeled 20.8 ms was taken immediately after the plasma reached its free expansion position.

UNGETTERED
DISCHARGE

$\Delta R - 6 \text{ cm/cm}$

$I_p - 10 \text{ kA/cm}$

$\Delta Z - 1.5 \left(\frac{35}{I_p} \right) \text{ cm/cm}$

(TIME BASE 5 ms/cm)

756139

Fig. 3. Electron temperature profiles at three times in the ungettered free expansion discharge, and variation with time of major radius (ΔR), vertical position (ΔZ), and plasma current (I_p).

756146

Fig. 4. Number of electrons as a function of time in the ungettered expanding discharge (top curve), at $r < 8.7 \text{ cm}$ (middle curve), and at $r > 8.7 \text{ cm}$ (bottom curve).

756147

Fig. 5. Evolution of the electron density profile in a gettered expanding discharge. The curve labeled 9.4 ms was taken immediately after the plasma reached its free expansion position.

Ti-GETTERED EXPANDING DISCHARGE

756141
 Fig. 6. Number of electrons as a function of time in the
 gettered discharge. The curves have the same meaning as in
 Fig. 4.

756140
Fig. 7. Evolution of the half maximum radii of the density profiles for the ungettered and gettered free expansion discharges.

Ti-GETTERED DISCHARGES

756142

Fig. 8. Comparison of equilibrium profiles reached by (a) free expansion gettered discharge and (b) normal gettered discharge. Note the currents are nearly identical.

UNGETTERED DISCHARGES

756143

Fig. 9. Comparison of equilibrium profiles reached by (a) free expansion ungettered discharge and (b) normal gettered discharge. Note the currents are nearly identical.

773141

Fig. 10. A comparison, for the ungettered case, between the experimental results of Fig. 4 and the model calculations. The number of particles contained with $r < 8.7$ cm continues to drop, rather than rising after 7.5 msec. This may be due to the use of an excessively large collision frequency enhancement, when some of the resistivity anomaly should be ascribed to electron runaways.

773142

Fig. 11. A comparison, for the gettered case, between the experimental results of Fig. 6 and the model calculations. Qualitatively similar variations are observed, and a reasonable quantitative agreement is found.

UNGETTERED DISCHARGE

773143

Fig. 12. Impurity profile evolution. Figure 12(a) shows the evolution of N_e during the impurity evolution of Fig. 12(b). While impurity production processes have been simplified by the free expansion experiment, the impurity transport variables are somewhat uncertain. Figure 12(b) shows the calculated evolution of the oxygen density, during the plasma free expansion. The calculations shown in Figs. 10 and 11 assumed a constant Z_{eff} model, so the rapid rearrangement predicted by neo-classical diffusion theory shows the limits of quantitative agreement which we can expect.

GETTERED DISCHARGE

773139
 Fig. 13. Model calculations for the gettered profile evolution (compare to Fig. 5) assuming the oxygen has the same profile dependence as the electron density.

UNGETTERED DISCHARGE

773140
 Fig. 14. Model calculations for the ungettered profile evolution (compare to Fig. 2) assuming the oxygen has the same profile dependence as the electron density.