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POWER BALANCE IN A.T.C.
COMPRESSED PLASMA

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ABSTRACT

The A.T.C. compressed plasma equilibrium has been sustained for several electron energy confinement times. An analysis of the power balance for this plasma gives a 2.0-2.5 msec confinement time for the compressed plasma compared with a 3.0 msec confinement time for the uncompressed plasma.

The A.T.C. (Adiabatic Toroidal Compressor) device was designed to compress a plasma in major and thereby also in minor radius. The parameters of the compressed plasma have been measured and comparison with adiabatic compression has been reported [1]. In these earlier investigations, it was not possible to sustain the compressed equilibrium for times long compared with the energy confinement time. In this work, we describe plasmas which are sustained at the compressed radius for several energy confinement times, and we present an analysis of the power balance in the compressed plasma.

A view of the cross section of the A.T.C. device is shown in Fig. 1. There are two poloidal field coil systems - the OH system which drives the plasma current and the SF system which provides the vertical field for plasma equilibrium. The electrical circuits have been described previously [2]. For a typical uncompressed plasma, the current in the OH circuit increases with time inducing a toroidal voltage, while the SF circuit current is programmed for the desired equilibrium. For a typical compressed plasma, a capacitor bank is discharged through the SF circuit which increases the vertical field and forces the plasma to a new equilibrium position. This capacitor bank is "crowbarred" and the SF circuit current decays with an 18 msec time constant. Due to coupling between the plasma and the SF coils, the compressed plasma current is also forced to decay at this rate. To sustain the equilibrium for the duration of the current decay, the vertical field of the SF coils is supplemented with a vertical field associated with the OH coils. (The uncompressed plasma is in a broad null region of the OH field,

but the compressed plasma is not.) Using only half of the OH circuit capacitance, a flat-top occurs in the OH circuit current at 33 msec: the time then chosen for compression. A dc bias current is used in the OH circuit for final adjustment of the vertical field required for the sustained equilibrium.

Plasma current and equilibrium position are shown in Fig. 2 as functions of time. Plasma preionization occurs in the first 6 msec. The current (I) rises to its "plateau" value of 50-60 kA in 1.5 msec. Equilibrium is established with a plasma major radius (R_0) of 0.87 m. At 33 msec, the compression bank is discharged and the new equilibrium is established at 0.38 m in 1.5 msec. The plasma current increases to 120 kA and decays with the 18 msec time constant.

The average electron density and temperature are also shown in Fig. 2. The density rises rapidly with the rise of plasma current and continues to rise slowly until it has doubled at the time of compression. The temperature rises in 10 msec to a stationary value. Upon compression, the density increases proportional to C^2 , where $C \equiv R_{01}/R_{02} = 0.87/0.38$, and the temperature increases proportional to C . Temperature and density then decay approximately linearly with plasma current.

The average density and temperature shown in Fig. 2 are area averages, $\langle x \rangle \equiv 2 \int_0^a x r dr / a^2$, computed from Thomson scattering measurements of density and temperature profiles. Examples of compressed and uncompressed profiles are given in Fig. 3. It may be seen that the compressed temperature profile is similar to the uncompressed profile while the broader uncompressed

density profile becomes more peaked, like a temperature profile, in the compressed discharge.

In order to determine an energy confinement time for the electrons (τ_{Ee}), we investigate the following power balance for the electrons:

$$\frac{W_e}{\tau_{Ee}} = P_e = V_S I - \frac{d}{dt} \left(\frac{1}{2} L_I I^2 \right) - \frac{d}{dt} W_e .$$

W_e is the thermal energy of the electrons defined as $W_e \equiv 6\pi^2 R_O \int_0^a n_e e T_e r dr$. V_S is the voltage measured at the surface of the plasma. L_I is the internal inductance defined as $L_I \equiv \mu_O R_O \int_0^a B_\theta^2(r) r dr / a^2 B_\theta^2(a)$. Of course, $B_\theta(r)$ has not yet been measured directly in a tokamak discharge and it must be calculated from $B_\theta(r) \equiv \mu_O r \int_0^r j(x) x dx$ where $j(r)$ is computed from the electron temperature profile with the assumption $j(r) = k T_e^{3/2}(r)$. The resulting estimate of $L_I / \mu_O R_O$ is 0.7 for the uncompressed plasma between 20 and 33 msec. Within experimental error of 10%, the estimate of $L_I / \mu_O R_O$ in the compressed plasma is again 0.7 and constant in time.

The various terms of the above power balance are shown as functions of time in Fig. 4. It may be seen that the decaying energy of the poloidal magnetic field contributes approximately half of the power input to the electrons in the compressed plasma.

The time dependence of power lost to the vessel wall is also included in Fig. 4. This power is measured bolometrically with a detector which is sensitive to both charge-exchange and radiation losses [3]. The present discharge is typical of

discharges in A.T.C. in which 10-20% of the input power is lost to the wall [3]. Thus neither charge-exchange nor radiation losses play an important role in the power balance of the uncompressed or compressed plasmas. That is, the same loss process, namely thermal conduction to the limiter, determines the energy confinement time in compressed and uncompressed plasmas.

In agreement with the low power loss to the wall, spectroscopic data from the two principal impurities - oxygen and iron - show that no increase of impurity content occurs upon compression. Relative intensities before and after compression of four states of oxygen (O IV, O V, O VI and O VII) and two states of iron (Fe XV and Fe XVI), plus use of a coronal model to compute total concentrations, shows that the concentrations of oxygen (4%) and iron (0.25%) are unchanged from uncompressed to compressed plasma. In the higher temperature compressed plasma, increased ionization of oxygen is unimportant since 80% of the oxygen is already fully stripped of electrons in the uncompressed plasma. Iron is ionized from Fe XIX to Fe XXII, but due to small concentration, the effect upon the effective ion charge of the plasma (Z_{eff}) is again negligible. These spectroscopic measurements suggest that the power lost at compression due to ionization of impurities is less than 5 kW and this power has been neglected from the power balance.

With the power input (P_e) given in Fig. 4 and the electron thermal energy computed from profiles of temperature and density, the electron energy confinement time is then estimated as shown in Fig. 5. $\beta_{\theta e}$ defined as $\beta_{\theta e} \equiv 2\pi \int n_e e T_e r dr / B_0^2(a) / 2\mu_0$ is also shown in Fig. 5. Before compression, stationary values are

attained: $\tau_{Ee} = 3$ msec and $\beta_{\theta e} = 0.33$. $\beta_{\theta e}$ is constant with compression and then rises to a new value, $\beta_{\theta e} = 0.49$, during the compressed equilibrium. The confinement time is reduced by approximately 20% with compression and continues to fall slowly for the next 10 msec.

Another definition of the electron energy confinement time (τ_{Ee}^*) would take into account the power transfer from electrons to ions. This power transfer is approximately 35-40 kW in both uncompressed and compressed plasmas. Before compression, $\tau_{Ee}^* = 4.0$ msec and after compression $\tau_{Ee}^* = 2.8$ msec. Thus, with either definition, the confinement time is reduced upon compression.

The principal uncertainty in the calculation of the confinement time is the contribution of internal magnetic energy to the power balance. The calculation of internal inductance from the temperature profile includes the assumption that $Z_{eff}(r)$ is independent of radius. Recent experiments with a neutral beam diagnostic have indicated that $Z_{eff}(r)$ is peaked on axis in typical A.T.C. plasmas [4]. (This would also account for the fact that the current density calculated from the temperature profile gives a safety factor on axis of 0.7 where direct measurement gives a value of unity [4].) That is, the computed current density profile is too peaked and the computed internal inductance is too high. The correction to L_I is approximately 15%. On the other hand, the fast drop in plasma current during the compressed equilibrium, relative to the current penetration time, can be expected to result in a more peaked current profile than that assumed and too low a computed internal inductance.

It is unlikely that this is a severe effect since the measured electron temperature profiles do not peak with time. However, a 10% increase of L_I would be within the uncertainties of measurement in electron temperature from laser scattering and in plasma major radius from magnetic coils.

Previous investigations of scaling in ohmic heated tokamaks [5], as well as studies of current induced instabilities in the Culham levitron experiment [6], suggest that the confinement time is a function of V_D/C_e , where V_D is the drift velocity of electrons in the ohmic electric field and C_e is the electron thermal speed. With such scaling, the confinement time would be unchanged upon compression. Experimentally, the confinement time is reduced by $20\% \pm 10\%$ upon compression. The confinement time is relatively unchanged in comparison with significant changes of the other plasma parameters. A table of plasma parameters at three times during the discharge is presented in Table 1.

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We thank Dr. J. L. Cecchi for the spectroscopic analysis and Dr. H. Hsuan for the bolometric measurements. The cooperation of Mr. R. Shoemaker and the A.T.C. team is much appreciated.

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TABLE 1

Time (msec)	25	35	45
R (m)	.87	.38	.38
a (m)	.165	.105	.105
B (T)	1.5	3.4	3.4
I (kA)	60	120	70
q_a	3.9	4.1	7.0
V_S (volts)	2.6	2.6	1.7
n_{eo} (m^{-3})	2.3×10^{19}	16.0×10^{19}	10.0×10^{19}
$\langle n_e \rangle$ (m^{-3})	1.0×10^{19}	5.8×10^{19}	3.5×10^{19}
T_{eo} (eV)	950	2350	1600
$\langle T_e \rangle$ (eV)	260	630	390
$\beta_{\theta e}$	.32	.36	.48
P_{Ω} (kW)	150	430	240
τ_{Ee} (msec)	3.0	2.4	1.8
Z_{eff}	5.5	5.5	5.5
$\langle v_* \rangle$	3.5	.8	1.7
$\langle v_D / c_e \rangle$	.026	.024	.029

VERTICAL Q OF MACHINE

ADIABATIC TOROIDAL COMPRESSOR (ATC)

Fig. 1. A.T.C. cross section. Note positions of plasma before and after compression and positions of OH and SF coils.

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 Fig. 2. Plasma major radius, plasma current, average electron temperature and average electron density as functions of time. Compression occurs at 33 msec.

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Fig. 3. Electron temperature and density profiles. (a) Uncompressed plasma at 25 msec. (b) Compressed plasma at 42 msec.

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Fig. 4. Power input to plasma as function of time showing fraction due to external circuit ($V_S I$), fraction due to internal magnetic field $[-(d/dt)(1/2)L_I I^2]$, and fraction due to thermal energy $[-(d/dt)W_e]$. Fraction of power lost to vessel wall (P_{WALL}) is also shown.

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Fig. 5. Electron energy confinement time (τ_{Ee}) and electron poloidal beta ($\beta_{\theta e}$) as functions of time before and after compression at 33 msec.