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RECENT RESULTS FROM TFTR

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ABSTRACT

During the past year, the research activities on TFTR have encompassed three broad areas. The first was to extend the operating range of TFTR. Plasma currents up to 1.5 MA were achieved in discharges with $a = 0.83$ m, $R = 2.55$ m at a toroidal field of 2.7 T. In these large plasmas, the maximum line average density was $3.35 \times 10^{19} \text{ m}^{-3}$. The second activity was a study of the scaling of the energy confinement time, τ_E , in ohmically heated discharges as a function of plasma current, density, and plasma size. These experiments indicate a favorable scaling of τ_E with size and density. Energy confinement times in excess of 0.25 s were obtained in deuterium discharges. The third activity was a study of adiabatic compression. During compression, the plasma current and ion temperature scaled approximately as predicted; however, the electron temperature and density scaled less strongly than predicted for ideal compression.

1. INTRODUCTION

The research objectives of TFTR are (i) to achieve reactor relevant temperatures (~ 10 keV) and densities ($\sim 10^{20} \text{ m}^{-3}$) and (ii) to achieve approximate energy break-even between the power input to and the fusion output from the plasma ($Q \sim 1$). These objectives will be achieved through the addition of neutral beam heating (~ 27 MW total power of deuterium with a full energy of 120 keV for ~ 0.5 sec) and the latter one will require tritium target plasmas. During the design phase of TFTR, two different modes of operation were envisioned to attain these objectives: by heating large plasmas ($a = 0.85$ m and $R = 2.5$ m), or by heating small plasmas ($a = 0.55$ m and $R = 3.05$ m) followed by adiabatic compression heating to $R = 2.08$ m. In practice, the machine is capable of these two modes of operation and intermediate modes as well such as partially compressing and allowing the plasma to expand freely or low- q operation at full current in a higher toroidal field region. Thus in order to optimize the performance of TFTR, understanding the scaling of plasma confinement with size and the effect of adiabatic compression is very important.

The activities for the past year encompassed three broad areas. The first was to extend the operating range of TFTR beyond the parameters described by Young *et al.* /1/. This involved commissioning the machine to successively higher levels of performance and installing internal vacuum vessel components and additional diagnostics. The second major activity was a study of the scaling of the energy confinement time, τ_E , in ohmically heated discharges as a function of electron density, current, and size. The third major activity was a study of adiabatic compression. These studies were aimed at documenting confinement scaling of the target plasma for neutral beam heating experiments, which will commence in August, 1984.

In previous reports, Young *et al.* /1/, described the initial operation of TFTR from December 1982 through June 1983 and Efthimion *et al.* /2/ described the results of the initial ohmic confinement time measurements. Following those experiments, an extensive installation period took place. High power plasma operation resumed in November 1983 and continued into January 1984, followed by another installation period for neutral beam hardware. This paper will focus on the machine status and the results from the recent experimental run (Nov. '83-Jan. '84). Further detailed analysis of the data from the

recent run is in progress and will be published later.

II. MACHINE STATUS

The installation period during the summer of 1983 concentrated on new internal vacuum vessel components, additional power supply capability, and new diagnostics.

Three major internal vacuum vessel components, the moveable limiter assembly, the prototype ZrAl alloy bulk getter surface pumping system, and bellows cover plates were installed during this period. The moveable limiter assembly is composed of three water-cooled Inconel blades covered with graphite tiles. It can accommodate a wide range of plasma major and minor radii, including a range of $a = 0.3$ to 0.83 m at a fixed major radius. Before installation, the graphite tiles had a chemically vapor-deposited TiC coating of nominally $20 \mu\text{m}$ thickness. After the run period, examination of the limiter assembly revealed little damage to the graphite tiles; however, the TiC coating was severely damaged. In addition, as will be described below, significant concentrations of titanium were observed in low density discharges. Consequently, the TiC coating will be chemically removed for future runs.

The prototype ZrAl alloy bulk getter system consists of eight arrays of ZrAl modules. The complete system, which will be installed in 1985, will include 36 such arrays. In the experiments discussed below, either six or four panels were activated. The measured deuterium pumping speed of six panels was $1.1 \times 10^2 \text{ m}^3/\text{s}$, which greatly exceeds the $10 \text{ m}^3/\text{s}$ pumping speed of the turbomolecular pumps. The base pressure of the vessel with the panels activated was $\sim 3 \times 10^{-7}$ Pa. Although controlled experiments were not conducted, it appeared that the surface pumping system shortened the recovery time from a major disruption. During the June '83 experiments, the recovery time from a major disruption was as long as 1/2 hour beyond the typical shot repetition cycle of 10 minutes. With the getters activated and using the new moveable limiter in the recent experiments, the recovery time from a disruption was typically no longer than the normal repetition time, even though both the plasma current and pulse duration were significantly increased. The ZrAl arrays are located approximately one meter toroidally from the moveable limiter, which is the main source of particle recycling. As

a result, the getters did not influence the recycling significantly. In general, the gas fueling requirements have been remarkably low. Typically, during the density rise the gas influx was $< 2.6 \text{ Pa m}^3/\text{s}$ and during the density flattop $< 0.7 \text{ Pa m}^3/\text{s}$ at low currents ($< 0.7 \text{ MA}$) with no gas feed at high current ($> 0.8 \text{ MA}$). For the next run period, neutralizer plates will be installed on the surface pumping panels in order to increase the recycling in their vicinity.

The bellows cover plates protect the vacuum vessel bellows from direct plasma bombardment and also provide a 20 segment inner limiter extending ± 60 degrees poloidally from the midplane. These plates are composed of Inconel rails on which are mounted slats that are Inconel near the midplane and stainless steel elsewhere. The bellows cover plates successfully protected the bellows but showed some damage, probably due to runaway electrons and possibly due to disruptions.

The commissioning of additional poloidal and toroidal field power supplies enabled us to increase the machine parameters from those reported by Young et al./1/. In particular, the commissioning of the ohmic heating interrupters increased the volt-second capability to 11 Vs and hence the plasma current to 1.5 MA, and additional toroidal field rectifiers increased the pulse duration to ~ 4 sec. With the availability of the second MG set later this year, operation of coils and power supplies at levels approaching the design parameters will take place.

The principal new diagnostics for the recent series of experiments are an x-ray crystal spectrometer to measure the central ion temperature, an x-ray imaging system to measure MHD oscillations, a multi-point Thomson scattering system to measure the electron temperature and density profiles, Langmuir-calorimeter probes to measure the edge plasma, a visible spectrometer, a laser impurity injector for impurity transport studies, and a neutron fluctuation detector to measure the fast variation of neutron flux.

A. Discharge cleaning

In addition to the commissioning of new hardware, the increase in operating range of TFTR has been aided by combining modest temperature bakeout (120°C) with discharge cleaning /3-4/. Pulsed discharge cleaning was the main technique for conditioning the vacuum vessel walls and limiters. Only ~ 20

hours of glow discharge cleaning were used. Pulsed discharge cleaning is accomplished by discharging the compression capacitor banks into the ohmic heating winding to produce a 50-100 kA plasma every 5 to 8 seconds. Approximately 25,000 hydrogen discharges were used to condition the machine with the vessel at 120°C. During the conditioning in October, the partial pressures of H₂O and CO decreased from 1.4×10^{-3} Pa to 8×10^{-5} Pa and from 5×10^{-4} Pa to 5×10^{-5} Pa, respectively. The partial pressures of H₂O and CO during discharge cleaning decreased by approximately another factor of four when the vessel temperature was reduced from 120° to 56°C. After discharge cleaning in October, there was no further conditioning until early January. During this second round of conditioning, consisting of ~ 7000 shots conducted with deuterium at a wall temperature of ~ 80°C, the partial pressures of D₂O and CO produced by discharge cleaning were quite low, ~ 4×10^{-6} Pa for both gases. This second round of cleaning seemed to have had little effect on Z_{eff} .

8. Plasma control

The plasma position, current, and density control systems described by Young *et al.* [1] were used to change plasma parameters, control the discharge during compression, and maintain reproducible conditions. Figure 1 shows the evolution of plasma current, surface voltage, major radius, and line density during a large plasma discharge ($a = 0.83$ m, $B_T = 2.7$ T). The applied breakdown voltage ranged from 30 to 100 V/turn. By varying the precharge current in the OH transformer, it is possible to vary the flux swing, which determines the initial plasma current level during the first 100 ms of the discharge. Currents as high as 770 kA have been established in 100 ms in plasmas at $R = 2.55$ m, $a = 0.83$ m, and $B_T = 2.7$ T ($q = 4.8$). After the initial rapid increase, the current is raised under feedback control to a programmed level and then decreased at the end of the discharge, also under feedback control. During the current flat-top phase, the loop voltage decays to an equilibrium value, typically ~ 0.7 V at low (0.6 MA) currents and up to ~ 1.2 V at high (1.4 MA) currents, on a time scale of 0.4 to 1 sec.

The plasma position is measured using a set of B_θ/B_p coils outside the vacuum vessel. These coils are used to provide both a real-time signal for the closed-loop position control system and data which are analyzed between

shots. Independent measurements of the plasma location using electron cyclotron emission and x-ray imaging measurements of the location of the $q = 1$ surface have shown that errors in the real-time magnetics measurements occur especially in low current, small minor radius discharges ($a = 0.4-0.55$ m). Part of the error arises from stray vertical fields associated with the toroidal field system. The deviation in the deduced plasma position from 2.55 m seen in Fig. 1 is due mainly to the inclusion of the stray fields in the off-line analysis. In addition to these quasi-static effects, which have been taken into account in all of the data in this paper, the real-time B_θ/B_ϕ system does not yet compensate for stray fields induced by plasma motion during compression experiments. This will be discussed further in conjunction with the compression experiments.

C. Operating range

Compared with the experiments in June, the present operating range of TFTR is considerably greater. Significantly higher densities, $\bar{n}_e < 3.35 \times 10^{19} \text{ m}^{-3}$, larger values of the Murakami /5/ parameter ($\bar{n}_e R/B_T < 3.1 \times 10^{19} \text{ m}^{-2}/\text{T}$), and higher currents ($I_p < 1.5$ MA) corresponding to a limiter q of 2.5 have been achieved in the large plasmas ($a = 0.83$ m). In plasmas with a smaller minor radius ($a = 0.69$ m) somewhat higher densities, $\bar{n}_e = 3.62 \times 10^{19} \text{ m}^{-3}$, were achieved corresponding to a Murakami parameter of $3.4 \times 10^{19} \text{ m}^{-2}/\text{T}$. In post-compressed plasmas at $R = 2.13$ m and $B_T = 3.29$ T, the highest steady-state density was $4.2 \times 10^{19} \text{ m}^{-3}$.

III. CONFINEMENT TIME SCALING IN OHMICALLY HEATED DISCHARGES

The dependence of the energy confinement time on-plasma current, density, and minor radius was extensively examined and the scaling with toroidal field was briefly studied during the recent experiments. The density and current scaling experiments were conducted in the large plasma discharges ($R = 2.55$ m and $a = 0.83$ m). In these experiments, the plasma current was varied from 0.6 to 1.4 MA, and a density scan was taken at each condition. In the minor radius scaling experiments, the limiter q was maintained in the range 2.7 to 3.5 with nearly constant major radius and toroidal field. In these scaling experiments, the minor radius varied from 0.41 to 0.83 m. In all the scaling

studies, the moveable limiter was used and deuterium was the working gas. In addition, sawtooth oscillations were observed on all of the discharges in the scaling studies.

In these experiments, ordinary-mode fundamental electron cyclotron emission (ECE) measurements made with a scanning heterodyne receiver provided the electron temperature profiles. The receiver was absolutely calibrated with an uncertainty of $\pm 10\%$. Central temperature values from the electron cyclotron emission measurements were consistent with a pulse height analysis (PHA) of the x-ray spectrum using a single line chord. Code simulations of the x-ray spectrum have shown that the central electron temperature is approximately 10% higher than that deduced from linear fits to the line-integrated spectrum. The two techniques agreed to within $\pm 10\%$ when the chord measurements were corrected for profile effects, as shown in Fig. 2. On a limited number of shots, Thomson scattering measurements of the electron temperature profile were obtained and analyzed. The Thomson scattering system measures the electron temperature and density profiles in one shot.

Three methods were used to measure the central ion temperature: neutron emission measurements during deuterium discharges, Doppler broadening measurements of the TiXXI $K\alpha$ line, and passive charge exchange measurements. The neutron emission measurements require a knowledge of the deuterium density profile. Visible spectroscopic measurements of the $D\alpha$ to $H\alpha$ line intensity ratio indicate that the global ratio D : H varied from 3 : 1 to 12 : 1 depending upon the machine history and plasma density. The density profile is assumed to be parabolic, based on previous measurements of $n_e/\sqrt{Z_{\text{eff}}}$ as a function of minor radius using the visible bremsstrahlung emission and limited Thomson scattering data. The uncertainty in the central ion temperature deduced from neutron emission is estimated at $\pm 8\%$. Though only chord measurements of the TiXXI $K\alpha$ line emission were taken, the observed $K\alpha$ line emission is emitted predominantly from the central region of the plasma, because the excitation rate coefficient decreases strongly with decreasing electron temperature. Broadening of the resonance line due to unresolved dielectronic satellites is negligible when the electron temperature exceeds 1.3 keV. A comparison of these two ion temperature measurements is shown in Fig. 2. The passive charge exchange measurements require only small corrections ($\leq 15\%$) for neutral opacity, provided $n_{e0} \leq 3 \times 10^{19} \text{ m}^{-2}$. In this low line-integral density range, they are in good agreement with the other

techniques. At higher densities, the ion temperature is more severely underestimated by uncorrected passive charge exchange measurements and the discrepancy increases sharply reaching $\sim 50\%$ at $n_{e1} \sim 5 \times 10^{19} \text{ m}^{-2}$, as in the case for the discharge shown in Fig. 2. After correction, the passive charge exchange ion temperature is in agreement with the neutron ion temperature during the density and current flattop to within 10%.

The energy confinement time was calculated by means of both the time-dependent TRANSP code, which has been described previously /6/, and a new time-independent equilibrium snapshot radial profile analysis code (SNAP). The total energy confinement time is defined by

$$\tau_E = \frac{(W_e + W_i)}{P_{OH} - d/dt(W_e + W_i)} ,$$

where W_e and W_i are the electron and ion stored energies and P_{OH} is the ohmic power dissipated in the plasma. Both codes use the plasma current, surface voltage, line density, plasma major and minor radii, and electron cyclotron emission measurements of the electron temperature profile to calculate the input power and the electron stored energy. The density profile is assumed to be parabolic. Variations in the density profile shape affect the energy confinement time weakly ($< 10\%$) when constrained by the measured line-integral density. The ion temperature profile is calculated from the ion energy balance assuming that the transfer of power from electrons to ions is through Coulomb collisions. The ion heat conductivity is given by $\kappa_i = \alpha \kappa_i^{NC}$ (where κ_i^{NC} can be chosen from a number of neoclassical calculations) and α is adjusted to obtain agreement with the central ion temperature measurement. The data presented in the scaling studies have been analyzed primarily by the equilibrium SNAP code, and the SNAP results agree to within 5% with those from TRANSP since the discharges considered are all in steady state.

A. Confinement in large plasmas

In the large plasma experiments, the principal effort was to ascertain the scaling of τ_E with density and current. Figure 3 shows the variation of the electron temperature profile with plasma current at fixed line-average

density. The electron temperature profile broadens substantially with increasing current. The region within the $q = 1$ surface, as determined by the inversion of the sawtooth oscillation on the electron cyclotron emission data, increases with increasing current (as expected) and the temperature profile is relatively flat within the $q = 1$ surface. In large plasmas, the period of the sawteeth varies from 18 to 36 msec. Quite often, much larger amplitude sawteeth occur at approximately twice the normal period; this is similar to a phenomenon previously observed on D-III /7/ and Text /8/. At larger radii, a smaller inverted sawtooth is observed between the longer sawteeth. Figure 2 shows an example of a discharge undergoing a transition from normal to approximately double-period sawteeth. Sawteeth are also observed on the line density, neutron emission, and loop voltage in this low- q (2.6) discharge. From the evolution of the electron temperature with time (Fig. 2), it is clear that sawteeth have an important effect on the dynamics of the core of the discharge.

The scaling of the central electron and ion temperatures with density for $I_p = 1.4$ MA is shown in Fig. 4. The electron temperature decreases weakly with increasing density and the difference between the electron and ion temperature decreases with increasing density. The slow decrease in central electron temperature with increasing density also correlates with a decreasing Z_{eff} .

Z_{eff} can be deduced by three techniques: pulse height analysis of the x-ray spectrum, bremsstrahlung measurements in the visible spectrum, and analysis of the plasma resistivity. The uncertainty in the pulse height analysis determination of Z_{eff} is $\pm 30\%$ and in the visible bremsstrahlung determination is $\pm 20\%$. The value from the plasma resistivity depends upon the resistivity model. The inclusion of the neoclassical correction for the trapped particles makes a difference of about a factor of 0.5 to 0.65 in the resistivity Z_{eff} , as shown in Fig. 5. A comparison of the value of Z_{eff} from these three techniques versus line-averaged density and current is shown in Fig. 5. Z_{eff} decreases with increasing density and increases with increasing plasma current. Pulse height analysis measurements indicate that the variation in Z_{eff} with $\bar{n}_e$ is due in part to changes in the titanium content. In the large plasma confinement studies, which are described below, values of n_{Ti}/n_e approach 5×10^{-3} at low densities and were found to decrease by a factor of 20 to 100 as the electron density was increased by a factor of

two. Moreover the ratio of n_{Ti}/n_e increased with increasing current at a fixed density. The trends observed by the x-ray pulse height analysis diagnostic were also observed by spectroscopic measurements in the VUV region. In comparison with the experiments conducted in June, the value of Z_{eff} is lower. The titanium in the discharge is believed to originate from the moveable limiter since only small concentrations of iron and nickel (the main constituents of the vacuum vessel walls) are observed.

In spite of significant concentrations of titanium at low density, the central radiated power is small compared with the local ohmic heating power. Estimates using coronal-equilibrium rates /9/, as well as more detailed calculations including transport, using the MIST code /10/, indicate that the maximum power radiated from titanium in the central plasma is up to 20 kW/m^3 , which is small compared with the input power. Bolometer measurements confirm this conclusion. Although the total radiated power is typically 60-90% of the ohmic input, the radiated-power profile is very broad and is $\leq 20\%$ of the local ohmic input on axis. Figure 6 shows a comparison of the radiated power profile and the input profile for the discharge shown in Fig. 1. The charge exchange component of the bolometer power is estimated to be small. The ohmic power was calculated assuming both Spitzer and neoclassical resistivity models. In the Spitzer model, q on axis is calculated to be 0.9 in this case.

The energy confinement time as a function of density is shown for various currents in Fig. 7. Over the limited density range studied, the energy confinement time increased linearly with density. The confinement time at a given density decreases with increasing current ($\tau_E \propto I_p^{-0.8}$). In order to investigate whether the variation in confinement time was due to plasma current or due to changes in the safety factor, a limited number of 0.8 MA discharges were made at 1.8 T ($q \approx 3.2$). Compared with the higher field discharges (at the same current), the confinement time was lower indicating that changes in confinement time were due to changes in q rather than in I_p according to the relation

$$\tau_E \propto \bar{n}_e q^{0.8}.$$

This result is in agreement with the low density confinement time scaling found on D-III /11,12/. The possible role of sawteeth and the elevated global radiation level in the observed q scaling is presently being studied.

Although both the electron temperature profile and the central ion temperature are well enough known for the purpose of assessing global confinement, the difference between $T_e(0)$ and $T_i(0)$ is not known well enough to determine accurately the central ion energy confinement, or, equivalently, the multiplier α on neoclassical ion thermal conductivity. Trends observed in the α required to match the available data, however, may be meaningful. In general, at lower currents ($I_p < 0.8$ MA) Chang-Hinton /13/ neoclassical transport is adequate to reproduce the measured neutron emission, using the electron cyclotron emission measurements of the electron temperatures profile. At higher currents, up to 1.5 MA, the central ion energy confinement time from Chang-Hinton neoclassical theory is as long as 1.5 seconds. Under these circumstances multipliers ranging up to ~ 6 times Chang-Hinton transport are required to reproduce the measured $(T_e - T_i)$. In these cases, however, $\tau_{Ei}(a/2)$ still exceeds $\tau_{Ee}(a/2)$ by a factor of ~ 2.5 . In the high current (low- q) discharges, strong sawteeth are observed on the neutron emission, and the neoclassical ion energy confinement time exceeds the sawtooth repetition time by a factor of ≥ 20 . Thus, it appears reasonable that sawtooth-induced ion energy transport could affect $T_e(0) - T_i(0)$. Preliminary calculations using a sawtooth mixing model in the BALDUR /14/ simulation code indicate that sawtooth mixing of the ion temperature increases the time-averaged value of $T_e(0) - T_i(0)$ by 250 eV, compared to a model with purely neoclassical ions and sawtooth electrons.

8. Size scaling experiments

In order to examine confinement scaling with minor radius in TFTR, a number of experiments were performed at reduced aperture, using the moveable limiter. In the minor radius scaling experiments, q was maintained in the range 2.7-3.5 and the minor radius varied from 0.41 to 0.83 m. Discharges with a minor radius of 0.41 m were very difficult to control, in part due to the relatively low gas feed rates required compared with the design of the gas injection valves. Although some discharges appeared marginally acceptable, the following discussion will omit the 0.41 m plasmas since the analysis to date has shown the data to be internally inconsistent, probably associated with the determination of the plasma position in these low current discharges.

The scaling of the energy confinement time with density for different

minor radii is shown in Fig. 8. The data shown in Figs. 8 and 9 include data from the June '83 run with 0.69 m discharges. There is a relatively weak dependence of τ_E on minor radius as the minor radius was varied from 0.55 m to 0.83 m. Quite clearly the scaling of τ_E is not consistent with INTOR scaling. The confinement time in TFTR exceeds the confinement time predicted by INTOR scaling by a factor of 2-5.

The combination of a weak minor radius scaling and relatively good confinement time compared with previous smaller machines with a minor radius of ~ 0.4 m such as PLT /15/, PDZ /16/, ASDEX /17/, and D-III /11,12/ implies a strong major radius scaling similar to that which has previously been discussed by Leonov *et al.* /18/, Pfeifer and Waltz /19/, and Blackwell *et al.* /20/. For comparison, the TFTR data are plotted versus $n_e R^2 a q^{0.8}$ in Fig. 9. This is a modified form of the scaling proposed recently by the Alcator group /20/ to incorporate the q scaling observed on TFTR and D-III /11,12/. The data from PLT with q in the range from 3.5 to 5 are shown for comparison to obtain a sense of the R scaling. For a similar aspect ratio of ~ 3.3 the data from PLT extrapolate to TFTR relatively well indicating $\sim (\text{length})^3$ scaling; however, the higher aspect ratio 0.65 m discharges indicate that the scaling with a may be weaker and the scaling with R correspondingly stronger. These results confirm the favorable scaling of confinement time with size; however, much more analysis of the TFTR data is required to establish the detailed scaling with both major and minor radius.

IV. COMPRESSION EXPERIMENTS

In compression experiments, a small plasma (typically $a \approx 0.55$ -0.60 m) is established at a large major radius ($R \approx 2.95$ -3.05 m) on the moveable limiter. It is then compressed rapidly in major radius by programming a step decrease in the reference position and simultaneously discharging capacitor banks in the equilibrium field system to assist the rectifier power supplies. In a full compression, the plasma is brought to rest in contact with the bellows cover plates and maintained for ≥ 1 sec at the final position ($R \approx 2.07$ -2.17 m, $a \approx 0.45$ -0.55 m). We have also performed partial compression (free-expansion) experiments, in which the plasma is moved part way across the vessel and then allowed to expand until it again contacts the material limiters.

Comparison of the real-time magnetic measurement of the plasma position with the preprogrammed reference indicates that the position feedback loop is controlling the measured position to within ~ 10 mm of the final post-compression reference value in ≤ 20 ms after the start of compression, as long as sufficient energy is provided by the compression capacitor banks. However, determinations of the plasma position from electron cyclotron emission temperature measurements show that the plasma is not compressed as rapidly as the real-time magnetic position measurement indicates, instead taking ~ 40 ms to reach the final position. This discrepancy is due to the effects of eddy currents induced by the plasma motion and current increase (for which the real-time magnetics position is not at present corrected) and by the equilibrium field (for which the corrections employed are not optimized). Subsequent analysis of the magnetics data including eddy current effects has shown agreement (within 50 mm) between the deduced position and the position of the electron temperature. In future experiments, improved eddy current corrections will be incorporated in the real-time measurement used in the position feedback control, and the compression time should be significantly reduced.

Figure 10 shows the evolution of a typical compression discharge, for which the compression ratio in major radius was $C = 1.38$ and the limiter q about 2.6 before and after compression. In such discharges, the plasma current increases in accordance with the adiabatic scaling law ($I_p \propto C$), although the interpretation of this result also depends on a detailed analysis of eddy current effects (which remains to be performed), to determine the magnitude of plasma skin currents induced during compression. On the other hand, the line density scales less strongly than predicted. The reason for this is not quantitatively understood; however, a qualitative model is suggested. During compression, the plasma edge expands at the rate of ~ 7 mm/ms. This was determined by conducting a series of partial compression (free-expansion) experiments and observing the time at which the plasma edge reached the bellows cover plates, as indicated by an abrupt increase in the bolometer signal and the appearance of light on the plasma TV system. Thus when the plasma is "fully" compressed, the expanded edge of the plasma is scraped off on the bellows cover plates and some particles may be lost. Support for this model comes from the observation that during the initial $\sim 3/4$ of the compression stroke, the line density scales approximately as

predicted from the electron cyclotron emission major radius determination. Only at the end of the stroke when the plasma comes in contact with the wall does the deviation occur.

For the conditions of Fig. 10, the variation of the ion and electron temperature around the compression time is shown in Fig. 11. The ion temperatures as determined from neutron emission and Doppler broadening of the $T_{XXI} K_{\alpha}$ line are in good agreement, although the time resolution of the latter data is not adequate to follow the temperature rise during compression. The neutron ion temperature increases approximately as $C^{4/3}$ as predicted by the ideal scaling law. The electron temperature increase, however, is consistently less than predicted by the ideal scaling law. A similar discrepancy in the electron temperature scaling was observed on ATC and was attributed to the fact that the compression time was not negligible in comparison with energy confinement time /21/. Zero-dimensional code simulations indicate that with a compression time of 40 ms, the energy loss through the electron channel accounts for the observed electron temperature rise.

V. CONCLUSIONS

The recent experiments enabled us to expand the operating range of TFTR and to document a wider range of plasma conditions. The more extensive scaling studies of the energy confinement time confirm initial results that τ_E increases with size and with density. Confinement times in excess of 0.25 s were achieved.

Initial compression experiments have shown that the feedback systems are able to control the plasma successfully during compression. The increase in the electron and ion temperatures is in reasonable agreement with expectations for a ~ 40 ms compression time. The results of the recent experiments have demonstrated successful plasma and machine operation in preparation for the forthcoming neutral beam phase.

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FIGURE CAPTIONS

- FIG. 1 Evolution of plasma current, loop voltage, major radius, $B_0 + \Delta_1/2$, and line density during a large plasma discharge.
- FIG. 2 Central electron temperature measurements from the electron cyclotron emission compared with those from pulse height analysis of the x-ray spectrum for the discharge in Fig. 1. Corresponding central ion temperature measurements from neutron emission compared with those from Doppler broadening of TiXXI K_α lines.
- FIG. 3 Variation of the electron temperature profile with plasma current at $\bar{n}_e = 2.3 \times 10^{19} \text{ m}^{-3}$ for $I_p = 1.0, 1.2$, and 1.4 MA and $\bar{n}_e = 2.1 \times 10^{19} \text{ m}^{-3}$ for $I_p = 0.8 \text{ MA}$. $B_T = 2.7 \text{ T}$.
- FIG. 4 Variation of the central electron and ion temperature with density. $B_T = 2.7 \text{ T}$.
- FIG. 5 Variation of Z_{eff} with density and current as determined by pulse height analysis of the x-ray spectrum, bremsstrahlung measurements in the visible and analysis of the plasma resistivity. $B_T = 2.7 \text{ T}$, $a = 0.83 \text{ m}$, and $R = 2.55 \text{ m}$.
- FIG. 6 Comparison of the radiated power profile with the ohmic heating profile for the discharge shown in Fig. 1.
- FIG. 7 Energy confinement time as a function of density in the large plasma ($a = 0.83 \text{ m}$ and $R = 2.55 \text{ m}$).
- FIG. 8 Scaling of the energy confinement time with density for different minor radius discharges. $B_T = 2.7 \text{ T}$ and $2.7 < q < 3.5$.
- FIG. 9 Scaling of τ_E with $\bar{n}_e R^2$ as $q^{0.8}$ using the data from both the large plasma experiments as well as the size scaling experiments. The data from PLT and PDX are shown for comparison.

FIG. 10 Evolution of the plasma current, line density, and major radius in a compression discharge. The major radius plot is based on the real-time magnetic measurement of plasma position. During a discharge, these parameters are feedback-controlled to match preprogrammed references, except that the plasma current and density feedback loops are disabled for a short time around compression so that the effect of compression can be evaluated straightforwardly.

FIG. 11 Temperature measurements on a fast time scale around compression, for the conditions of Fig. 10. Central electron temperature is from x-ray pulse-height spectrum. Central ion temperatures are from neutron emission and Doppler broadening of $T_{iXXI} K_{\alpha}$ radiation.

#84X0350

Fig. 1

#84X0362

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

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