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ABSTRACT

Plasma-surface interactions strongly influence the properties of plasmas produced in the ZT 40M reversed field pinch, which generally operates without discrete limiters. Z_{eff} data and spectroscopy, together with total radiated power, and measured impurity accumulations on collector probes demonstrate that metal impurities play a determining role in ZT 40M's performance. Plasma currents of 60–400 kA routinely generate total betas of 5–10% (assuming $T_i = T_e$). ZT-40M's inherently large ohmic heating power yields $T_e \geq 500\text{eV}$ for 400kA flat-top discharges with $n_e \sim 4 \times 10^{19} \text{m}^{-3}$. Pulse duration at the lower currents has reached $\sim 35\text{ms}$. Energy confinement time τ_E has reached 0.7ms for discharges with $n_e \sim 8 \times 10^{19} \text{m}^{-3}$ and $T_e \sim 330\text{eV}$ at a current of 330kA. Magnetic field

errors intrinsic to the winding and core configuration create localized, intense plasma-surface interactions that define the present operating boundary for ZT-40M. Discharge clearing, either pulsed or glow, of the Inconel vacuum vessel increases the deuterium recycling rate and decreases the impurity fractions, leading to discharges with higher density and lower temperature, lower Z_{eff} , lower resistive anomaly factor, and better overall confinement of particles and energy. Carbon films ~40 monolayers thick are used in ZT-40M to simulate the recycling, fueling, and sputtering conditions that may be encountered in next generation devices with large areas of carbon.

I) INTRODUCTION

Plasma performance in ZT-40M [1], the larger of two reversed-field pinch (RFP) experiments at Los Alamos National Laboratory, is strongly affected by plasma-surface interactions (PSI), particularly intense PSI observed to accompany magnetic field errors. Although ZT-40M generally operates without discrete limiters, but with the vacuum vessel wall at large major radius functioning as a toroidal limiter, plasma discharges are sustained for times much longer than the global confinement time of either energy or particles. Large fluxes of particles and energy from the plasma impinge on the vacuum vessel wall, and, in response, large fluxes of fuel and impurity atoms from the wall return to the plasma. Metallic impurities, in particular, act to determine the critical discharge and plasma transport parameters in ZT-40M. Significant improvements in performance have accompanied improved magnetics, control of equilibrium position, and wall conditioning [1].

With major and minor radii $R = 1.14$ m and $a = 0.2$ m, ZT-40M is among the largest RFP experiments in operation worldwide. Table I lists basic parameters for some of the operational and planned RFP devices. An illustrated dissection of ZT-40M is shown in Fig. 1. Note the Inconel 625 vacuum vessel, the 2 cm thick aluminum shell, and the toroidal and poloidal field windings. RFPs are axisymmetric, toroidal, magnetic confinement configurations that utilize an externally applied toroidal magnetic field, B_ϕ , and an induced toroidal plasma current, I_ϕ , and that realize toroidal equilibrium through applied vertical and horizontal magnetic fields or a conducting shell, or both. (For ZT 40M, currents flowing in the poloidal field (PF) windings generate most of the vertical

field required for equilibrium.) In these respects, RFPs are similar to tokamaks.

Several features, however, distinguish the RFP from the tokamak. Large toroidal currents in excess of the Kruskal-Shafranov limit, a mechanism for regeneration of near-minimum-energy, near-force-free field profiles within the plasma, and high normalized plasma pressure, β , all are manifest in the RFP. These matters are discussed in detail in the review article by Bodin and Newton. Ref. 11. Here, we shall only mention two features that define the RFP configuration: the spatial magnetic field profiles, and their time dependence.

The equilibrium fields of the RFP configuration are shown in Fig. 2. Within the plasma, B_ϕ and B_θ are of comparable magnitude, indicating strong magnetic shear upon which, with the conducting wall, the RFP relies for its stability to MHD modes. Furthermore, B_ϕ reverses near the wall where it is small compared with B_θ . For the RFP, internal magnetic fields are produced largely by currents flowing within the RFP plasma itself, and confinement requires only a small value of B_ϕ at the toroidal field coils. Very energetic plasmas can be confined in the RFP configuration by magnet coils of modest size and current. ZT-40M routinely operates with total plasma beta (assuming $T_i = T_e$) in the range

$$\beta_T = \frac{2 \mu_0 n_e (T_e + T_i)}{(B_\phi^2 + B_\theta^2)} = 0.05 - 0.1 .$$

The configuration shown in Fig. 2, possesses net positive toroidal flux in the presence of reversed B_ϕ at the wall. The configuration is maintained as long as the current I_ϕ is sustained; Fig. 3 illustrates this

feature. $\langle B_\phi \rangle$ is the average toroidal field, i.e., the ratio of toroidal flux to minor cross-sectional area. If the plasma were a passive conductor, internal poloidal currents would decay on the resistive diffusion time-scale. In fact, the plasma couples the toroidal flux to the toroidal current through what is believed to be a fundamental plasma relaxation process [12,13]. The fact that the plasma couples the toroidal current and flux is demonstrated clearly in ramped discharges [14,15], such as the one shown in Fig. 4. In the presence of reversed B_ϕ at the wall, $\langle B_\phi \rangle$ increases fourfold as I_ϕ increases. The measured poloidal loop voltage proves that negative toroidal flux is expelled by the plasma into the external circuit during ramping. The net increase of $\langle B_\phi \rangle$ occurs through generation within the plasma of equal positive and negative toroidal fluxes followed by rejection of the negative flux [13]; B_ϕ at the wall remains constant or becomes more strongly reversed. Reliance on this plasma relaxation mechanism, sometimes called the "dynamo," for sustainment of the configuration is a basic feature of ZT-40M and all RFP experiments.

11) PLASMA PERFORMANCE

While experimental observation of the flux regeneration ("dynamo") process together with the development of theoretical and computational models of the same constitutes one of the most important advances in RFP physics, the effort to understand basic plasma transport processes and their dependence upon the experimental parameters is just beginning. Data taken at early time in the discharge strongly suggest that ZT-40M operates against a beta limit: $\bar{n}_e T_e \propto I_\phi^2$, $60\text{kA} < I_\phi < 400\text{kA}$, where $\bar{n}_e$ and T_e are the diameter averaged electron density and the electron temperature on

axis, respectively [1,16]. Data taken later in the discharges, and at the higher currents suggest the ohmic scaling observed in tokamaks [17,18]: $T_e \propto I_\phi^{0.56}$ [16].

Sustainment of the RFP configuration requires a relatively large toroidal loop voltage, V_ϕ , partly because of the strong magnetic shear of the RFP configuration. For the 120 kA flat-top discharge shown in Fig. 3, $V_\phi \sim 42$ V. The plasma is dissipating ~ 5 MW during the flat-top portion of the discharge, and all of this ultimately impinges on the vacuum vessel wall. The average flux of energy to the wall is ~ 0.5 MW/m² for 120 kA discharges in ZT-40M; localized fluxes enhanced by factors of 4 to 15 are measured experimentally [19]. If metallic impurities are injected into the plasma in response to the large energy deposition, the effective ion charge, Z_{eff} , can be expected to increase and thus maintain the requirement for large V_ϕ .

In addition to the large energy flux, the wall also receives a large particle flux. Figure 5 shows the diameter-averaged electron density $\bar{n}_e$ for sustained discharges in ZT-40M for four values of I_ϕ as functions of time. Electron density peaks very early in the discharge, and then falls rapidly to a slowly decreasing "plateau" density, the value of which depends on the current and the time dependent rate of recycling by the Inconel 625 first wall. Multichord interferometry reveals broad spatial profiles, particularly at the higher currents. The particles that are lost from the discharge impinge on the wall.

Central electron temperature, T_e , for sustained discharges in ZT-40M at three values of I_ϕ are plotted as functions of time in Fig. 6. Electron temperature increases rapidly to an approximately steady value and is maintained for the duration of the flat topped current; T_e falls

when I_ϕ begins to decrease. Thomson scattering measurements 14.3 cm above the minor axis of the torus imply very broad spatial temperature profiles for all currents: $T_e(14)/T_e(0) \sim 2/3$ to 1. Broad temperature profiles also occur in ohmically heated tokamak plasmas contaminated with moderate concentrations of metallic impurities [20]. ORMAK "type B" discharges are examples. Interestingly, these discharges exhibit $\beta_\theta = \text{constant}$ scaling [21].

The magnitudes of magnetic field and plasma density locate ZT-40M in a regime of "magnetization parameter," Ω_{ce}/ω_{pe} , where Ω_{ce} and ω_{pe} are the electron cyclotron and plasma frequencies, respectively, considerably different from that of today's large tokamaks: ZT-40M operates with $\Omega_{ce}/\omega_{pe} \approx 0.1 - 0.3$. The toroidal loop voltage together with the plasma density and temperature yields a finite value for the ratio of electric field, $E_\phi = (V_\phi/2\pi R)$, to critical field for electron runaway, E_c [22]: ZT-40M operates with $E_\phi/E_c \approx 0.02 - 0.1$. The parameters Ω_{ce}/ω_{pe} and E_ϕ/E_c , together with the "drift parameter", $\xi = |j|/(n_e e v_{the})$, which typically assumes values $\xi \approx 0.02 - 0.2$ in ZT-40M, have been found to play crucial roles in collective phenomena in current-carrying plasmas [23]. ZT-40M operates in a regime of current-carrying plasmas characterized by fast electrons and suprathermal ions [23].

ZT-40M's impurity content, effective ion charge, ion temperature profile, and particle confinement properties are described in detail in Ref. 24. Bolometry, Z_{eff} data and spectroscopy, together with measured metallic impurity accumulations on collector probes [25] demonstrate that metal impurities play a determining role in ZT-40M's performance. For a fixed current, a discharge with a higher electron density is characterized by a lower electron temperature, a lower concentration of high-Z

impurities as Fig. 7 illustrates a lower Z_{eff} , a smaller resistive anomaly, and improved global confinement of particles and energy [24]. These conditions are achieved in ZT-40M through conditioning of the Inconel 625 vacuum vessel with pulsed discharge cleaning which will be described in Sec. III.

Doppler broadening of CV and OVII emission lines imply ion temperatures that are comparable with, or somewhat greater than the central electron temperature, and with spatial profiles similar to those inferred for the electrons [24,26]. $T_i \geq T_e$ also is reported in Refs. 2, 4, and 6. Time-of-flight spectrometry [27], depth profile in collector probes [25], and neutron emission [28,29] all indicate a hot ion population in ZT-40M.

In view of 1) the effects of high-Z impurities on ohmic heating and energy confinement, 2) the fact that high ion temperatures, $T_i \geq T_e$, occur in ZT-40M, and 3) the time dependence of T_e and $\bar{n}_e$ as illustrated in Figs. 5 and 6, it is relatively easy to reconcile the various scalings of temperature with current that have been reported from time to time [16]. Today, about the only thing that can be said with certainty is that it is possible to operate ZT-40M such that an approximately constant value of β_0 results; although this is intriguing, the functional dependence of β_0 upon the experimental parameters remains uncertain. ("Type B" discharges in ORMAK characterized by moderate concentrations of metallic impurities exhibit $\beta_0 = \text{constant}$ scaling also.) It is clear, however, that plasma-surface interactions (PSI) strongly affect the performance of sustained discharges in ZT 40M. Reference 24 provides a detailed description of this point which is also illustrated by the recent history of ZT 40M.

With the advent of long (8 ms), sustained discharges in 1981, ZT-40M's shell no longer acted as a shield against magnetic field errors generated by the external windings and magnet cores. In late 1982 the conductivity of the Al shell was increased, and the poloidal and toroidal windings were carefully repositioned to minimize the errors and the associated intense PSI resulting from deviations near the diagnostic and pumping ports (see Fig. 1). These improvements netted an immediate increase in the discharge lifetime from 8 ms to more than 20 ms [1,30,31]. Subsequently, active feedback control of the plasma position at the poloidal flux slot in both horizontal and vertical directions reduced intense PSI observed near the gap [1,32]. A new tapered flux gap further reduced PSI there by a factor of ~2.5. With these improvements the electron temperature, which had previously peaked at 3 ms and then decayed, remained constant as long as the current was sustained: energy confinement improved. Wall conditioning through pulsed and glow discharge cleaning also has yielded dividends of improved confinement and discharge characteristics. With the combination of improved magnetics and wall conditioning, discharge duration reached 35 ms, a fourfold improvement; energy confinement time reached 0.7 ms, a threefold improvement (Lawson parameter, $5 \times 10^{10} \text{ cm}^{-3} \text{ s}$, a tenfold improvement). Very similar results have been reported recently from HBTX-1B, an improved version of HBTX-1A [33], the main design improvements of which were aimed to reduce magnetic field errors due mostly to inaccurate winding positions. In addition, both HBTX 1A and 1B achieve significantly improved confinement with plasmas that have been centered by application of a static vertical magnetic field. Figure 4 of Ref. 24 illustrates a similar effect of the equilibrium position at the gap in ZT-40M; at present, ZT-40M has not

implemented a static vertical field to globally center the plasma with respect to the liner.

III) PSI EXPERIMENTS

Five series of PSI experiments have been conducted in ZT-40M. Systematic studies of the effects of 1) wall conditioning, 2) wall temperature, and 3) fuel species upon recycling and discharge characteristics were executed with sustained 120 kA discharges. In the other two series, the front surface of the Inconel 625 vacuum vessel (the first wall) was altered chemically and physically through glow discharge cleaning (GDC) in D_2 with CH_4 as a minority species. Spectroscopy (x-ray through visible), interferometry, Thomson scattering, bolometry, collector probes [25], pressure gauges, partial pressure analysis, thermocouples, and electrical and magnetic diagnostics were used to monitor the discharge parameters, and changes therein. A zero-dimensional particle balance model for time-dependent recycling incorporating the codes TRIM and DIFFUSE [34] was employed to interpret the time dependence of the electron density that was observed experimentally. The same model was used to predict the effects of changes in wall temperature and fuel species. One-dimensional neutral hydrogen transport codes were utilized to interpret observed Balmer α and charge exchange neutral emission from the plasma.

Repetitive (0.5 or 1 Hz), low-energy (20-30kA, 2ms duration) discharges having $n_e \approx 8 \times 10^{13} \text{ cm}^{-3}$ and $T_e \approx 10-30 \text{ eV}$, called PDC pulses, can be fired before each normal shot to affect the wall condition. Both the fill pressure in which the PDC pulses were fired, and the number of PDC pulses fired prior to the high power (HP) discharge were varied

systematically. Regulation of the liner temperature at 40, 60, and 80°C was achieved by varying the rate and duration of the PDC cycle between HP discharges. (Significantly higher wall temperatures are prohibited for the sake of the electrical insulation that wraps the liner, fitting between it and the Al shell.) Impurity gases were monitored before and after both PDC and HP discharges.

The dominant impurity gases observed in ZT-40M are D_2O , CO/N_2 , CD_4 , and CO_2 . With hydrogen rather than the normal deuterium fuel, the dominant species are H_2O , CO/N_2 , CH_4 , and CO_2 . Exposure to a plasma discharge of any type yields a decrease in the partial pressure of CO , and corresponding increases in D_2O (H_2O), CD_4 (CH_4), and C_2D_6 (C_2H_6). Unsaturated hydrocarbons C_2D_2 (C_2H_2) and C_2D_4 (C_2H_4) are not produced in significant quantities in ZT-40M, unlike the OHTE experiment that reports C_2D_2 [35], or tokamaks that report C_2D_4 [36]. These results suggest that hydrogenation at low temperature is an important mechanism in ZT-40M. The constituents of the observed impurity gases also are the predominant low-Z plasma impurities measured spectroscopically [24]. At 5 ms in the discharge the extrapolated low-Z impurity concentrations are, O:3%, N:0.3%, C:0.06%.

The use of PDC before HP discharges enables successful RFP formation at a fill pressure (flow-thru) lower than normally required [37] when PDC is not utilized: 1.5 mtorr compared with 2.2 mtorr for 120 kA discharges. Indeed, when PDC is used and the fill pressure is fixed, a lower fill pressure is required for successful RFP formation. HP discharges can form at even lower pressures (1.1 mtorr) if the PDC cycle is fired at a higher pressure (3.5 mtorr). This pressure effect occurs in both isotopes of hydrogen.

When HP discharges follow PDC, the electron density exhibits pump-out that is less pronounced than shown in Fig. 5 for HP discharges with no prior PDC. Initiation at lower fill pressure yields a smaller initial density peak; a slower time rate of change of density, however, leaves the density higher at later times. For example, with a 3-minute cycle of 90 PDC pulses (180 ms integrated exposure) fired before the two-minute base line read and charge cycles that precede HP discharges, the electron density measured at 10 ms exhibits a twofold increase over that which is normally observed when PDC is not utilized, even though the (flow-thru) fill pressure is lower by 25%. The slower pump-out persists for a longer time, however, and a lower density, consistent with the lower fill pressure, is ultimately reached at late time. Thus, the dominant effect of PDC is to decrease the recycling time constant of the wall, thereby increasing the release rate and the rate-of-rise of the wall recycling coefficient. Both hydrogen isotopes show this effect.

The spatial profiles of electron density measured with multichord interferometry are significantly broader when PDC is utilized than when it is not. Very flat and even hollow profiles are observed during the first few milliseconds of PDC discharges. At later times, when useful data from the multichord interferometer are lacking, significantly broader density profiles are inferred for PDC shots from the central density, obtained with Thomson scattering, and the diameter-averaged value, measured by a single-chord interferometer. These broad spatial profiles strongly suggest faster recycling by the wall.

Measured Balmer α line radiation also indicates increased recycling. The observed increase of D_{α} or H_{α} brightness, however, is not as large as

the increase of the density itself. This implies an improvement of particle confinement in HP discharges with PDC [24].

Spectroscopy shows smaller concentrations of low-Z plasma impurities, particularly oxygen, in discharges that follow PDC than are otherwise observed. Bolometry together with spectroscopy reveals lower concentrations of the metallic impurities as well. For example, the total radiated power observed at 5 ms decreases slightly when PDC is used even though the electron density has increased twofold. The effective ion charge, Z_{eff} , measured spectroscopically at 5 ms, also decreases by a factor of at least two when PDC is utilized.

The central electron temperature measured with Thomson scattering is lower for HP discharges that follow PDC. The plasma is both denser and cooler. For example, 120 kA discharges in D_2 with PDC yield $T_e = 140$ eV and $\bar{n}_e = 2.0 \times 10^{13} \text{ cm}^{-3}$ at 5 ms, whereas, without PDC $T_e = 240$ eV and $\bar{n}_e = 1.1 \times 10^{13} \text{ cm}^{-3}$ are achieved at the same time. A similar trade off between density and temperature occurs in H_2 . Both the lower temperature and the increased particle confinement observed in HP discharges that follow PDC are consistent with the reductions of low-Z and metallic impurities, i.e., lower Z_{eff} .

When PDC is used, a faster rate of release of hydrogen isotopes from the wall is manifest in a faster recovery of the torus pressure (flow thru) after the discharge. With either longer cycles of PDC, or with PDC fired at higher pressure, the torus pressure (flow thru) rises rather than falls after HP discharges; the wall demonstrates it's function as a particle source. This larger inventory of particles implies increased adsorption of hydrogen on the wall, an effect that also acts to increase the rate of rise of the recycling coefficient. The observed

pressure rise of 0.5-1.0 mtorr following the shot is consistent with desorption of a small fraction of one monolayer of hydrogen (estimated to be $5 \times 10^{14}/\text{cm}^2$). Assuming five for the ratio of effective area to geometrical area yields 0.05-0.1 monolayers of desorbed hydrogen. Changes in the partial pressures of the dominant impurity gases after HP discharges with PDC suggest smaller impurity yields accompany these shots. These three effects of PDC, increased recycling, increased particle inventory, and decreased impurity contamination, are consistent with the interpretation that PDC reduces the number of surface sites occupied by impurity atoms and increases hydrogen adsorption. Quantitative comparison of the partial pressures, however, are clouded by the changes of the total pressure.

The changeover of hydrogen isotopes illuminates the role of adsorption in ZT-40M. The changeover from D_2 to H_2 was monitored by measuring H_α and D_α line emission simultaneously with an electronically scanned detector system [38]. In the first H_2 discharge after the change of fill gas from D_2 , Balmer α emission at 5 ms consisted of 70% H_α and 30% D_α . The D_α component decreased to less than 5% in the sixth and subsequent discharges. Thus, the wall made only a relatively small contribution to the particle inventory. Hydrogen isotopes are not tightly bound to the Inconel wall. The procedure used to change fill gases involved evacuation of the torus to $\sim 10^{-7}$ torr for ~ 1 hour. A significant fraction of the adsorbed D could have been pumped away during this period. For normal operation with flow thru fueling, however, wall adsorbed gas is an important particle source.

The experimentally observed increase in the rate of recycling for discharges with PDC was reproduced computationally with the zero-dimensional particle balance model. The model is constructed around the code DIFFUSE [34] which is used to compute the time-dependent release rate of the wall. Reflection coefficients and implantation profiles are computed with the code TRIM using isotropic Maxwellian particle distributions. Both 25 eV and 50 eV temperatures were assumed for the implant distribution; this produced only a small change in the release rate. Although deeper implantation occurs with H (compared with D), H diffuses faster, and the competing effects yield nearly identical release rates for H and D, at least for the parameters of these runs. No significant difference between D and H discharges could be discerned experimentally as far as recycling is concerned. Only the sputtering yields differ, which is consistent with the experimental fact that the radiation fraction, $(P_{\text{rad}}/P_{\text{in}})$ increases with fuel mass: 0.28 for H discharges, 0.42 for D, and 0.78 for He.

By varying only the incident flux to the wall and the recombination parameter, the experimentally observed time dependence of electron density could be matched reasonably well. During the flat-top portion of discharges without PDC, the required incident flux to the wall is $4 \times 10^{17} \text{ cm}^{-2} \text{ s}^{-1}$. The global particle confinement time inferred from this flux and the plasma density is $\tau_p \sim 0.5 \text{ ms}$. D_α monitors yield the same value [24].

Electron density versus time for PDC discharges was matched by increasing the recombination parameter by five and decreasing the initial particle flux to the wall by 25%. In this case, fewer plasma particles become invested in the wall and the particle economy improves. This

investment in the wall concentration profile is the dominant factor affecting pump-out in hydrogen isotopes. IDC improves the particle flow by increasing the release rate of hydrogen.

Similar effects are achieved both computationally and experimentally with He discharges. In this case, the He release rate is determined solely by diffusion. Helium recycles faster, and for He discharges, both the time dependence of the electron density and its spatial profiles are similar to those of hydrogen discharge that follow PDC. Even so, the higher mass and the absence of hydrogen chemistry yield increased impurity contamination in He discharges. Indeed, the oxygen concentration was observed to increase overnight. This, coupled with the faster recycling and higher density of He discharges, eventually closed the operational pressure window, making RFP formation impossible at the nominal bank settings.

Elevating the wall temperature from 40°C to 60°C to 80°C produced similar simultaneous and opposing effects on recycling and impurity generation in D₂ discharges. Raising the wall temperature increases the hydrogen recycling rate; this was predicted by the computational model and observed experimentally. The time dependent recycling in ZT-40M is initially diffusion limited, and the rate increases with wall temperature. Even so, impurity outgassing also increases dramatically with wall temperature. Increased low Z pollution of the plasma was observed, and confinement of particles and energy degraded significantly. The increase of low Z impurity production and plasma contamination with elevated wall temperatures demonstrates clearly the importance of PSI control on ZT-40M's performance. The relationship of adsorbed impurity gases and the rate of hydrogen recycling by the wall is demonstrated also. Density

control is intimately associated with the low-Z impurities. Control of the metallic impurities in ZT-40M is even more challenging and requires innovation.

IV) CARBONIZATION

Two series of experiments were executed with standard 120 kA discharges to evaluate the changes in machine characteristics resulting from the modification of the Inconel 625 first wall surface layer to a metal carbide layer, and from the deposition of thick layers (~ 40 monolayers) of carbon on the first wall. Using CH_4 at partial pressures of 4×10^{-4} torr in a D_2 glow discharge ($5 \mu\text{A}/\text{cm}^2$) at ~ 10 mtorr resulted in a deposition rate of ~32 monolayers of carbon per hour. Hydrocarbon chemistry was monitored with a residual gas analyzer during deposition of the carbon layers, removal of the carbon layers, pulse discharge cleaning cycles, and plasma discharges. Changes in plasma parameters were monitored with multichord interferometry, two-color interferometry, bolometry, multichord soft x rays, multichord CV, Thomson scattering, VUV spectrometry, visible light spectrometry, and D_α and CRI monitors located at different toroidal locations.

With a layer of ~ 40 monolayers of carbon, the recycling of D_2 was dependent on the amount of D_2 trapped in the carbon layer, Z_{eff} was reduced and metal impurities decreased. Carbon concentrations increased, but oxygen concentrations were consistently at the low end of the historical range.

Significant changes in machine characteristics occurred with ~40 monolayers of carbon deposited on the inner surface. Immediately after the deposition of the carbon layer, discharges with the usual

characteristics were obtained within three shots; however, the application of a short (90s) pulse discharge cleaning (PDC) cycle before the HP shot was sufficient to prevent the formation of 120 kA or 180 kA discharges. For these discharges, the plasma density was too high to allow RFP formation [37]. The low energy PDC pulses loaded the carbon layer with D_2 ; this changed the recycling characteristics. RFP discharges were successfully obtained at higher applied voltages provided PDC was not used between discharges. A few HP discharges removed enough trapped D_2 from the carbon layer to return the recycling to pre-carbonization rates.

The formation of RFP plasmas at the lower applied voltages immediately after carbonization and before any PDC discharges suggested that the higher energy particles in the glow discharge cleaning (GDC) process did not load the carbon layer with D_2 . Line average density traces as a function of time in the discharge for the first successful HP discharges are shown in Fig. 8. Subsequent experiments have verified that GDC can partially deplete the carbon layer of trapped D_2 . This phenomenon of D_2 trapping was not evident with carbon films thinner than 28 monolayers.

Diameter averaged electron density and toroidal plasma resistance for four groups of discharges are shown in Figs. 9 and 10, respectively. The groups are separated into (1) pre carbonization discharges (fill pressure = 2.2 mtorr) without PDC; (2) pre carbonization discharges (1.5 mtorr) with PDC; (3) carbonization discharges (1.9 mtorr); and (4) carbonization discharges (2.5 mtorr). After 6 ms the carbonization discharges have a significantly lower diameter averaged density than the discharges with no carbonization. After 9 ms the toroidal plasma resistances for groups 2, 3, and 4 are less than group 1. The electron temperature measured by

Thomson scattering and the plasma resistance for the groups are shown in Table II. The electron temperatures for groups 3 and 4 were not taken at 10 ms; but, subsequent measurements on similar discharges showed the electron temperature to be constant or slightly decreasing with time after 4 ms. If the plasma resistance is proportional to effective charge (Z_{eff}) and inversely proportional to the electron temperature to the power 1.5, the above values imply a twofold decrease of Z_{eff} for groups 2, 3, and 4 compared with group 1. The soft x-ray flux, which is sensitive to impurities, is shown in Fig. 11. The difference in these signals suggests a decrease of metallic impurities [39].

Carbon III emission implies an increase of the concentration of carbon in discharges with carbon films to 1-2% compared with the 0.06% levels observed in pre-carbonization discharges. The spectroscopic data on OVI and CrI exhibited no significant difference between the pre-carbonization discharges and the discharges with 40 monolayers of carbon; however, oxygen levels were consistently at the low end of the historical range. After the removal of the carbon layer the oxygen concentration remained at this low level for ~2000 discharges.

Hydrocarbon chemistry was monitored with a residual gas analyzer during PDC, GDC, and plasma discharges. An analysis of the cracking patterns revealed that during PDC the change in the composition of Atomic Mass Unit (AMU) 20 was approximately 58% CD_4 and 42% D_2O while during GDC the percentages were 72% CD_4 and 28% D_2O . AMU 32 was a measure of the higher hydrocarbons (C_2D_4 , C_2D_6 , and C_3D_8) with most of the contribution from C_2D_6 . Plasma discharges produce about three times as much CD_4 as C_2D_6 . The total hydrocarbon production of a plasma discharge was estimated from the RGA measurements, and for typical conditions about 110

discharges at 120 kA and 15 ms duration were required to remove one monolayer equivalent of carbon. Similarly, about one hour of PDC at 1 Hz was required to remove one monolayer of carbon. For similar discharges, 20 monolayers of carbon showed the same hydrocarbon production as 40 monolayers. The removal of the free carbon layers resulted in a surface that produced about twice the amount of hydrocarbons during the discharge as before carbonization. Oxygen was observed, spectroscopically, to be reduced by about the same amount. This observation is consistent with the metal oxides being converted to carbides.

A long GDC removed the carbon layer after these experiments. The time history of the partial pressures during this process is shown in Fig. 12. Again, AMU 32 is a measure of the higher hydrocarbons; AMU 14 is proportional to CD_4 . AMU 28 and AMU 20 do not show as large a decay as AMU 32 because of the normal background of CO, N_2 and D_2O in the vacuum vessel and RGA. Figure 13 shows the change in the RGA signals during the GDC process. The darkened area represents the final signals, and the outlined area those at the start of the process. Approximately 38 monolayers of carbon were removed during this final GDC procedure, which compares quite well to the 40 monolayers of deposition estimated from an RGA analysis during the deposition process.

Pairs of poloidal ring limiters that extended ~1 cm inside the vacuum liner were installed at four toroidal locations (90° apart). Before PDC and plasma discharges, ~40 monolayers of carbon were deposited on the liner and limiters. The effects of the carbonization on recycling, fuelling, and impurities were, with a notable exception, the same as in the first carbonization experiment. Chromium T signals decreased approximately fourfold; this reduction is attributed to the limiters.

Similarly, hard x-rays produced at the termination of discharges were reduced at least a hundredfold.

The plasma resistance during the initial characterization was about 20% higher than that of similar discharges without the limiters and carbon film. After ninety minutes of GDC in deuterium the resistance fell to within 10% of the value achieved in the absence of limiters and carbon film. This value is consistent with the reduction by the limiters of the plasma cross-sectional area.

The carbon film was easily contaminated by low-Z impurities, and was slow to clean-up. During the four days that elapsed between the deposition of the film and the first discharge, low-Z impurity accumulation was sufficient to make RFP formation difficult. Once RFP discharges were produced routinely, the low-Z impurities (N and O) in the discharges diminished slowly during ~50 shots.

Discharge conditions evolve slowly during sequences of ~100 shots. The data shown in Figs. 14 and 15 are from one such sequence that was completed in a single day of operation. Central electron temperature from Thomson scattering at various times during the discharge are plotted in Fig. 14. The data points plotted and error bars correspond to the mean value and standard deviation for 10 or more measurements at the same time. The results have been grouped according to the order of occurrence within the sequence: Shot group "A" is the first 24 discharges of the day, shot group "Q," the last 21, and shot group "M" the middle 49. In general, the electron temperature exhibits the same time dependence shown in Fig. 6; it increases rapidly, and then is maintained at a nearly constant value until the current begins to decrease. Discharges in group "A", taken at the beginning of the day, are cooler than those in group "Q", taken at the end

of the day. Figure 15 shows the central electron density, $n_e(0)$, from Thomson scattering, the diameter-averaged density measured by far-infrared interferometry, and the ratio $n_e(0)/\bar{n}_e$. Mean values and standard deviations for ten or more measurements at each time are plotted. In general, the electron density exhibits the same time dependence shown in Fig. 5. Both the central and diameter-averaged values decrease with time. The ratio of the two, however, changes only slightly during the discharge, from 1.35 at 2 ms to 1.42 at 10 ms. This indicates a rather broad spatial density profile that changes only slightly with time as the density itself undergoes a threefold decrease. The first 10 shots in group "A" exhibit a much broader spatial profile, $n_e(0)/\bar{n}_e \approx 1.2$. The last shots in group "Q" exhibit the most peaked profiles, $n_e(0)/\bar{n}_e = 1.49$. This long-term trend is consistent with a gradual reduction in the rate of recycling by the wall as the carbon layer is either removed or as the D_2 concentration in the layer changes, and also with gradually improved confinement as low-Z impurities diminish.

A lower than normal fill pressure, 1.7 mtorr compared with 2.2 mtorr, was required for RFP formation at the start of group "A". The required pressure reached 2.1 mtorr after 32 discharges, and the normal 2.2 mtorr after 56 discharges. Similarly, the level of carbon contamination as determined from CIII line emission decreased 50% and CrI emission increased ~ 30% during the sequence.

In conclusion, limiters and a carbon layer lower the metallic impurity (Cr, Ni, Fe) content of plasma discharges in ZT-40M. Hard x-rays resulting from the interaction of the plasma electrons with the metal liner are significantly reduced throughout the discharge, particularly at the termination of plasma current. With reduced contamination by metallic

impurities, the low-Z impurities (C,O,N) play a more important role in determining the characteristics of ZT-40M discharges.

V) SUMMARY

Wall conditioning has been used in ZT-40M to significantly modify the plasma-wall interactions. Both discharge cleaning and carbonization have resulted in plasmas with lower Z_{eff} , lower resistive anomaly factor and lower concentrations of metallic impurities. This sensitivity of the discharge characteristics to wall conditions clearly indicates the need for a wider range of conditioning options in the next generation RFPs. Both PDC and GDC will be employed at elevated vessel temperatures (150 - 300°C). If possible, the temperature of the plasma-interactive surfaces will be adjustable ($\leq 300^\circ\text{C}$) so that wall conditions can be varied over a wider range for both the cleaning operations and plasma discharges.

Finally, the inherently high energy density of RFPs results in the potential for high heat fluxes on the first-wall or limiter structures, or both. It will be necessary to ensure that this heat flux is distributed as uniformly as possible on the plasma-interactive surfaces.

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REFERENCES

- 1) R. S. Massey, R. G. Watt, P. G. Weber, et al., Fusion Tech. 8 (1985) 1571.
- 2) B. Alper, H. A. B. Bodin, C. A. Bunting, et al., "Confinement Studies on HBTX-1B," poster presented to APS DPP meeting, San Diego, November, 1985 (unpublished).
- 3) K. Miyamoto and N. Inoue, Nucl. Fusion 25 (1985) 1303.
- 4) T. Tamano, W. D. Bard, T. N. Carlstrom, et al., in Plasma Physics and Controlled Nuclear Fusion Research, 1984 (IAEA, Vienna, 1985), Vol. 2, p. 431.
- 5) V. Antoni, M. Bassan, A. Buffa, et al., ibid., p. 487.
- 6) Y. Hirano, Y. Kondoh, Y. Maejima, et al., ibid., p. 475.
- 7) K. F. Schoenberg, C. J. Buchenauer, L. C. Burkhardt, et al., Los Alamos National Laboratory Report LA-10593-MS (1986).
- 8) K. Ogawa, Y. Maejima, T. Shimada, et al., Nucl. Fusion 25 (1985) 1295.

- 9) S. Ortolani, Nucl. Fusion 25 (1985) 1291.
- 10) P. Thullen and K. F. Schoenberg, Los Alamos National Laboratory Report LA-UR-84-2601 (1984).
- 11) H. A. B. Bodin and A. A. Newton, Nucl. Fusion 20 (1980) 1255.
- 12) J. B. Taylor, Culham Laboratory Report CLM-P765 (1985).
- 13) E. J. Caramana and D. A. Baker, Nucl. Fusion 24 (1984) 423.
- 14) J. A. Phillips, D. A. Baker, L. C. Burkhardt, et al., Los Alamos National Laboratory Report LA-10060-MS (1984).
- 15) E. J. Caramana and D. D. Schnack, Los Alamos National Laboratory Report LA-UR-86-965 (1986).
- 16) D. A. Baker, C. J. Buchenauer, L. C. Burkhardt, et al., in Ref. 4, p. 439.
- 17) C. Daughney, Nucl. Fusion 15 (1975) 967.
- 18) J. Hugill and J. Sheffield, Nucl. Fusion 18 (1978) 15.
- 19) J. [unclear], C. J. Buchenauer, J. C. Ingraham, et al., J. Nucl. Mat. 128/129 (1984) 517.

- 20) J. Hugill, Nucl. Fusion 23 (1983) 331.

- 21) L. A. Berry, J. D. Callen, J. F. Clarke, et al., in Plasma Physics and Controlled Nuclear Fusion Research, 1974 (IAEA, Vienna, 1975), Vol. 1, p. 101.

- 22) H. Knoepfel and D. Spong, Nucl. Fusion 19 (1979) 785.

- 23) F. D. Volkov, N. F. Perepelkin, V. A. Suprunenko, and E. A. Sukhomlin, Collective Phenomena in Current-Carrying Plasmas (Gordon and Breach, New York, 1985).

- 24) P. G. Weber, Phys. Fluids 28 (1985) 3136.

- 25) R. Bastasz and T. E. Cayton, this conference.

- 26) R. B. Howell and Y. Nagayama, Phys. Fluids 28 (1985) 743.

- 27) C. P. Munson, private communication.

- 28) L. C. Burkhardt, private communication.

- 29) G. A. Wurden, private communication.

- 30) R. S. Massey, C. J. Buchenauer, L. C. Burkhardt, et al., Los Alamos National Laboratory Report LA 9567 MS (1983).

- 31) R. B. Howell and H. F. Vogel, J. Appl. Phys. 56 (1984) 2017.
- 32) R. S. Massey, C. J. Buchenauer, G. Miller, and G. Barnes, Los Alamos National Laboratory Report LA-9809-MS (1983).
- 33) H. A. B. Bodin and D. E. Evans, Nucl. Fusion 25 (1985) 1305.
- 34) M. I. Baskes, Sandia National Laboratories Report SAND83-8231 (1983).
- 35) T. S. Teylor, private communication.
- 36) S. A. Cohen, in Physics of Plasma Wall Interactions in Controlled Fusion, ed. D. E. Post and R. Behnisch (Plenum, New York, 1986).
- 37) J. A. Phillips, L. C. Burkhardt, A. Haberstich, et al., Los Alamos National Laboratory Report LA 9717 MS (1983).
- 38) P. G. Weber, Rev. Sci. Instrum. 54 (1983) 1331.
- 39) G. A. Warden, private communication.

TABLE I

Device	Laboratory	Minor Radius a(m)	Major Radius R(m)	Plasma Current I _p (MA)	Type of Transformer	Ref.
REX-13	Gulhan	0.26	0.8	0.05-0.5	Iron	2
ST-1M	Los Alamos	0.30	1.14	0.05-0.44	Iron	1
REPUTE 1	U. of Tokyo	0.20	0.82	0.22	Iron	3
STEE-RFP	G.A. Tech	0.19	1.24	0.05-0.52	Air and Iron	4
ETA-BETA II	Padova	0.125	0.65	0.05-0.2	Air	5
TFE-12'W	ETL, Tsukuba	0.39	0.50	0.03-0.13	Air Iron	6
ST-P	Los Alamos	0.07	0.45	0.06	Air	7
TFE-15'	ETL, Tsukuba	0.15	0.7	0.25*	Air Iron	8
RFX'	Padova	0.5	2.0	3*	Air	9
ST-R'	Los Alamos	0.4	2.15	2-4*	Air	10

* target parameters

- under construction

- representative from and for Confinement Physics Research Facility (CPRF) to be built at Los Alamos

TABLE II

Plasma Resistance and Electron Temperature

Group	Symbol	Resistance ($\mu\Omega$)	Electron Temperature (eV)
1	X	256 ± 19 (10 ms)	363 ± 104 (10 ms)
2	O	259 ± 13 (10 ms)	230 ± 47 (10 ms)
3	Δ	220 ± 11 (10 ms)	251 ± 55 (6 ms)
4	$\square$	241 ± 10 (10 ms)	225 ± 38 (16 ms)

FIGURE CAPTIONS

Fig. 1) Cutaway drawing of the ZT-40M reversed-field pinch. PF and TF coils are wound directly upon the toroidal (Al) shell; winding irregularities caused by pumping and diagnostic tubulations are one source of magnetic field errors; close fitting iron cores are another.

Fig. 2) Spatial profiles of the components of magnetic field for the RFP configuration. $B_\phi(r)$ differs from the static field produced solely by TF coils.

Fig. 3) Toroidal current, I_ϕ , average toroidal field, $\langle B_\phi \rangle$, toroidal field at the wall, $B_{\phi w}$, and toroidal loop voltage, V_ϕ , for a sustained RFP discharge in ZT-40M. $V_\phi \sim 42$ V maintains the RFP configuration. V_ϕ was shorted at 18 ms; thereafter, the reversed field decayed and the discharge terminated.

Fig. 4) Toroidal current, I_ϕ , average toroidal field, $\langle B_\phi \rangle$, and toroidal field at the wall, $B_\phi(a)$, for a ramped RFP discharge. $\langle B_\phi \rangle$ increases fourfold; negative $B_\phi(a)$ becomes even more negative.

Fig. 5) Diameter averaged electron density versus time for sustained discharges in ZT 40M at four toroidal currents.

Fig. 6) Central electron temperature versus time for sustained discharge in ZT 40M at three toroidal currents.

Fig. 7) Emission of C I, normalized to diameter averaged density squared

(proportional to edge concentration of C_{10}), versus line averaged density for 120 kA discharges at 5 ms.

Fig. 8) Diameter-averaged electron density versus time for the first (O), second (X), and third (Δ) discharges after the deposition of ~ 40 monolayers of carbon.

Fig. 9) Diameter-averaged electron density versus time for case (1) pre-carbonization discharges (2.2 mtorr) without PDC (X), (2) pre-carbonization discharges (1.5 mtorr) with PDC(O), (3) carbonization discharges (1.9 mtorr) without PDC (Δ) and (4) carbonization discharges (2.5 mtorr) without PDC ($\square$).

Fig. 10) Toroidal resistance versus time for case (1) pre-carbonization discharges (2.2 mtorr) without PDC (X), (2) pre-carbonization discharges (1.5 mtorr) with PDC(O), (3) carbonization discharges (1.9 mtorr) without PDC (Δ) and (4) carbonization discharges (2.5 mtorr) without PDC ($\square$).

Fig. 11) Soft x ray flux versus time for case (1) pre-carbonization discharges (2.2 mtorr) without PDC (X), (2) pre-carbonization discharges (1.5 mtorr) with PDC(O), (3) carbonization discharges (1.9 mtorr) without PDC (Δ) and (4) carbonization discharges (2.5 mtorr) without PDC ($\square$).

Fig. 12) RGA signals versus time during removal of the ~40 monolayer carbon film by GDC in D_2 .

Fig. 13) Initial (outlined areas) and final (shaded areas) RGA spectra for the removal of the ~40 monolayer carbon film by GDC in D_2 .

Fig. 14) Central electron temperature versus time for 94 130 kA discharges taken during a single day of operation of ZT-40M. Discharge characteristics evolved slowly during the day: "A" and "Q" denote the initial and final groups of discharges in the sequence.

Fig. 15) Central and diameter-averaged electron densities and their ratio versus time for 94 130 kA discharges taken during a single day of operation of ZT-40M. Both central and diameter-averaged values decrease by ~2.5 during discharges, but their ratio varies only slightly, suggesting a spatial eigenmode. The spatial profile evolved slowly during the day from a very broad profile with $n_e(0)/\bar{n}_e \approx 1.2$ to a more peaked one with $n_e(0)/\bar{n}_e \approx 1.5$.

ZT-40M

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 5

Fig. 7

Fig. 8

Fig. 9

TOROIDAL RESISTANCE, OHMS

$I_p = 0$

Fig. 11

Fig. 12

10/85CTN0041

SIGNAL (ARBITRARY SCALE)

Fig. 14

Fig. 15