Plasma Physics and Controlled Fusion, Vol 34, No. 4, pp. 627 to 633, 1992
Printed in Great Britain.

0741-3335/92 $5.00+ .00

LETTER TO THE EDITOR

Wall Conditioning and its Effect on RFP Plasma Performance in REPUTE-1*

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(*Received* 29 *April* 1991; *and in revised form* 8 *July* 1991)

Abstract—Results are presented from experiments on the effects of glow discharge and carbonization on RFP plasma performance in REPUTE-1. With the proper choice of wall conditioning, control of plasma density behavior was demonstrated. Radiated power and carbon V intensity decreased by a factor of two after He glow. Using the carbonization technique, decreases in the plasma resistance and ion temperature as derived by the CV line and charge exchange neutral particles were observed, whereas the electron temperature did not change as much.

1. INTRODUCTION

FOR MANY STUDIES, such as those of impurities, plasma parameters and confinement, wall–plasma interaction (MCCRACKEN and STOTT, 1979; STANGEBY and MCCRACKEN, 1990) is very important, especially in the Reversed Field Pinch (RFP) (BODIN and NEWTON, 1980; BODIN, 1990) which has a larger plasma current density than a Tokamak.

Extensive studies of wall conditioning have been carried out in Tokamaks in order to improve plasma properties, but there have been a few results in RFPs in spite of the great importance of this study. Apart from baking and Taylor-type discharge cleaning, carbonization (WINTER, 1987) and pulsed discharge cleaning have been carried out in ZT-40M (SCHOENBERG *et al.*, 1987; CAYTON *et al.*, 1987), which showed a higher plasma density, lower resistivity and lower soft X-ray intensity. Wall-loading discharges led to a higher density plateau for a longer time in HBTX (NEWTON *et al.*, 1987). With graphite walls in OHTE (JACKSON *et al.*, 1987), no or little density pumpout was obtained, but the peak density was not controlled. Glow discharges (WINTER, 1989) in H_2 and He gases were also tried. In these RFP devices, effects of wall conditioning on plasma properties were reported only partly and not enough, especially for the cases of He glow discharge and carbonization. Therefore, this important topic must be examined.

Here, glow discharge cleaning using various gas species and carbonization (EJIRI *et al.*, 1991) were tried for wall conditioning, and their effects on plasma performance were investigated in the REPUTE-1 RFP device (SHINOHARA *et al.*, 1990; MIYAMOTO *et al.*, 1991). In addition, very useful data for understanding the dynamo process as related to anomalous ion heating as well as anomalous resistivity (MIYAMOTO, 1988; ALPER *et al.*, 1989), which is one of the most interesting and critical issues needing to be analyzed, are presented for the carbonization case.

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* This paper is an expanded version of material which originally was a contributed presentation at the 18th EPS Plasma Physics Division Conference, Berlin, Germany, June 1991.

2. EFFECTS ON PLASMA PERFORMANCE

In the following, we briefly describe wall conditioning and residual gas analysis. Typically, glow discharge conditions are P_T (total pressure) = 0.2–1.0 mTorr, V_A (anode voltage) = 400–700 V and I_A (anode current) = 0.5–1.5 A, which corresponds to 7–21 μA cm^{-2}. After a He glow discharge for about 1 hour, partial and total pressures, particularly the partial pressure P_{18} of mass number $m = 18$ (mainly H_2O), decrease by more than an order of magnitude. These effects were smaller in H_2 and Ne glow discharges: in the H_2 glow case, the decay of P_T and partial pressures of P_2 ($m = 2$) and P_{18}, mainly H_2 and H_2O, respectively, was slower. After Ne glow, P_{18} (by one order of magnitude) and P_T decreased but increased again after only about 1 hour. For the carbonization case, a mixture of 30% CH_4 and 70% H_2 gases was used with P_T = 4–7 mTorr, V_A = 400 V and I_A = 1.5 A for a duration of 2–5 hours. The carbon layer produced was estimated to be 55–140 nm, from a measurement of carbon thickness on a Si wafer sample by a surface profilometer.

By changing the gas species of the glow and main discharges, the time evolution of the plasma density could be changed, as shown in Fig. 1 (arrows show the expected plasma density from full ionization of the filling gas); (a) the initial peak density was higher (after H_2 glow) or lower (after He glow) than that expected from the filling

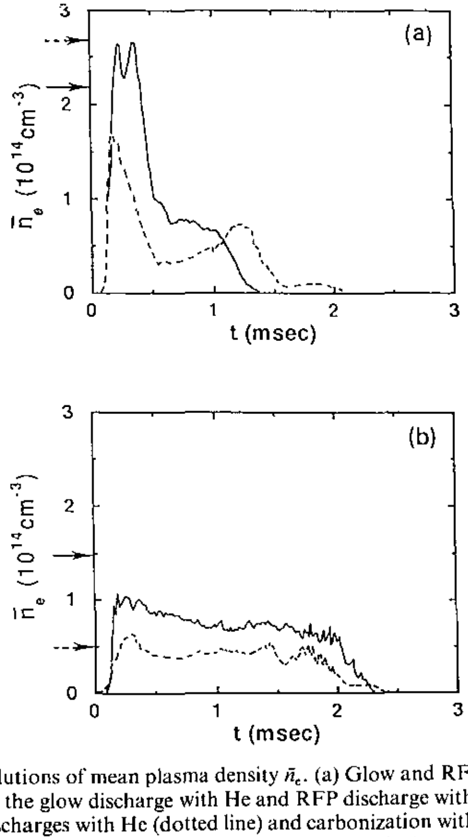

FIG. 1.—Time evolutions of mean plasma density $\bar{n}_e$. (a) Glow and RFP discharges with H_2 gas (bold line) and the glow discharge with He and RFP discharge with H_2 (dotted line). (b) Glow and RFP discharges with He (dotted line) and carbonization with CH_4 : H_2 = 30:70% and RFP discharge with H_2 (bold line).

gas pressure in the H_2 discharge, (b) nearly constant density with time in the He discharge after He glow or H_2 discharge after carbonization. In these various discharges, the plasma density could be changed according to the initial filling pressure. Of course, the plasma condition partly depends on previous discharges because of the "memory" of the wall. These density behaviors, as shown in Fig. 1(a), gradually faded during sequences of $\sim$ tens of shots.

At the first shot after carbonization, the peak plasma density at an early stage was nearly the same as expected from the filling pressure, and a density decreasing somewhat with time was found. After a few shots, we could nearly maintain a constant density during a discharge [Fig. 1(b)], but a somewhat higher density decay with time was found after several tens of shots. In a Ne discharge after Ne glow, we also observed a nearly constant density with time under a high plasma resistance, the latter being a factor of two greater than compared with that in the H_2 discharge. Even for the case of a radiation-dominant discharge was T_i(CV) high, i.e. in the range of ~ 300 eV [where T_i(CV) is the ion temperature derived from the CV line (227.1 nm) Doppler broadening by a monochromator].

After the He glow discharge, the plasma resistance R_p at the current flat-topped phase decreased a little (by several per cent) in the RFP discharge with H_2 or D_2 gases. Here, $R_p = I_p/V_l$ (where I_p is the plasma current and V_l a single-turn loop voltage) was taken at the time of the maximum plasma current. [With the He gas, an increase in R_p (by several per cent) was found, but we did not observe deleterious effects on the plasma discharge found in ZT-40 M (Cayton *et al.*, 1987).] The central soft X-ray intensity I_{SX} above 200 eV as measured by a silicon surface barrier diode, and the rough scaling of $T_i(\mathrm{CV}) \propto (I_p/\bar{n}_e)^{1.4}$ did not change (where $\bar{n}_e$ is the mean plasma density). However, radiation intensities of P_r (central chord) as measured by a Ge thermistor bolometer and I_{CV} by a monochromator (CV line) decreased by about a factor of two, as shown in Fig. 2. Here, the value of 15 for P_r corresponds to 5 MW in total, which is about 7% of the total input power, if uniform radiation loss from the plasma is assumed.

After carbonization for 5 hours, R_p decreased by up to $\sim$30% for $I_p = 210$–280 kA, and the dependence of R_p on I_p became weaker, as shown in Fig. 3. Note that the changes in the plasma parameters after carbonization during runs in Figs 3–5 were small, although the time evolution of the density behavior changed somewhat as described above. Comparing with the carbonization case for 2 hours, R_p was lower by 5–10%. The I/N value which gives the minimum value of R_p was $\sim 4 \times 10^{-14}$ A m in both cases, with and without carbonization, but a weaker dependence of R_p on I/N was found for the carbonization case (where N is the line density).

In this plasma current range, from 210 to 280 kA, the dependencies of P_r and the central electron temperature T_e (as measured by Thomson scattering) on I_p did not change much, while a decrease in I_{SX} by about 50% and an increase in I_{CV} by about a factor of two were found.

The $I_{SX}/\bar{n}_e^2 T_e^{3.5}$ value decreased after this carbonization. Here, this value is proportional to Z_{eff} in this detector system in the range $T_e = 100$–300 eV if we can ignore line radiation compared with Bremsstrahlung radiation. Although this condition was not satisfied, this value can be an indicator of impurity content. Above $I_p = 300$ kA (mean current density >2 MA m^{-2}, mean wall loading >7 MW m^{-2}), there was a tendency towards sudden increases in I_{SX} and I_{CV} with an increase in I_p.

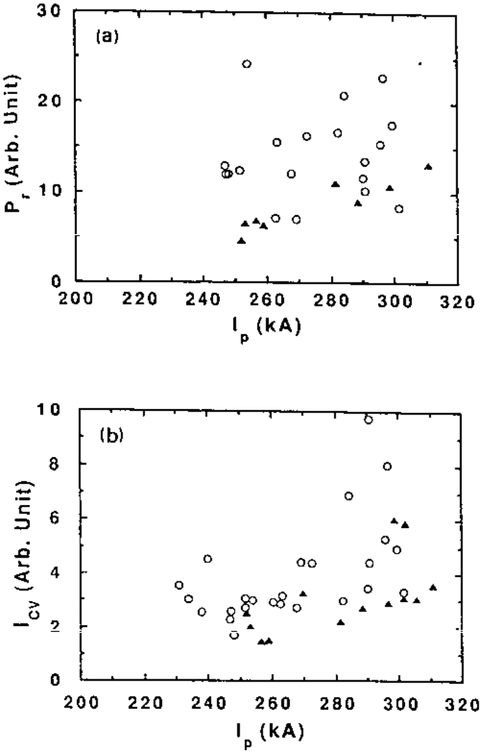

FIG. 2.—Changes of (a) radiated power P_r and (b) CV intensity I_{CV} as a function of plasma current I_p with D_2 gas (open circles: before, closed triangles: after He glow.)

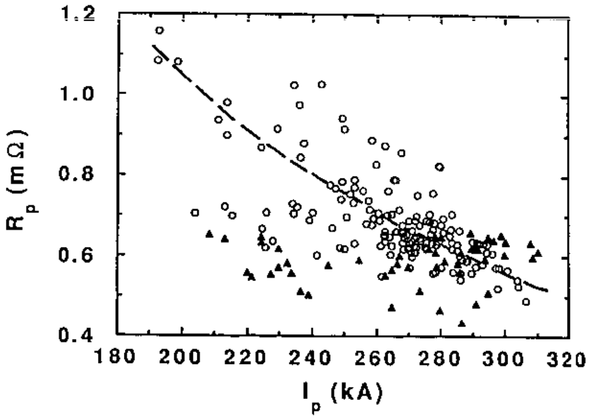

FIG. 3.—Dependence of plasma resistance R_p on plasma current I_p before (open circles) and after (closed triangles) carbonization. For reference, the curve of $R_p \propto I_p^{-3/2}$ is shown.

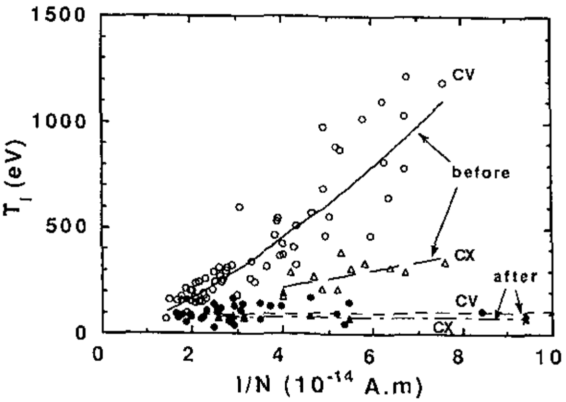

FIG. 4.—Relation between ion temperatures, T_i(CV) and T_i(CX), and I/N before and after carbonization [T_i(CV) and T_i(CX): ion temperatures derived from CV Doppler broadening and from charge exchange neutral particles, respectively, I: plasma current, N: line density].

As shown in Fig. 4, drastic changes in ion temperature were found; after carbonization, ion temperatures, as measured by a monochromator (CV) and a charge exchange neutral particle analyzer (CX), decreased especially for a high I/N value. (In the CX measurement, the flux of fast neutrals decreased.) The discrepancy between the T_i(CV) and T_i(CX) temperatures disappeared and T_i/T_e decreased to about one after this carbonization.

Before discussing central confinement, we define the central energy confinement times of the electrons, and ions as $\tau_{e0,i0} \equiv (3/2)\bar{n}_e k T_{e,i} V/I_p V_l$ (where k is the Bolzmann constant and V the plasma volume). Figure 5 shows that τ_{e0} increased with $\bar{n}_e$ and showed no significant difference between the with and without carbonization cases. Although τ_{i0} as estimated by T_i(CV) decreased with $\bar{n}_e$ before carbonization, the confinement time as derived from T_i(CV) as well as T_i(CX) increased with $\bar{n}_e$ after carbonization.

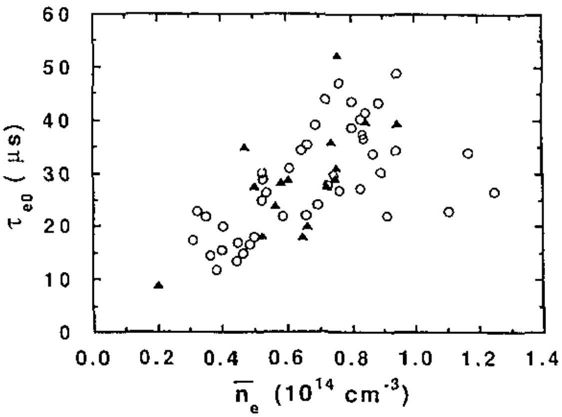

FIG. 5.—Central electron confinement time τ_{e0} vs mean plasma density $\bar{n}_e$ before (open circles) and after (closed triangles) carbonization.

The reduced difference between T_i(CV) and T_i(CX) after carbonization can be interpreted by the shorter equipartition time of the particles, due to the decreased T_i(CV) and T_i(CX) values and the increased number of carbon impurities. However, the reason for the decrease in ion temperatures, which seems to correspond to the decrease in R_p, is not clear but some candidates to account for this can be pointed out; changes of power input to ions, profiles of electron density, temperature, current density and impurities, electrostatic and electromagnetic fluctuations, charge exchange loss, confinement time, etc.

If some fraction of the power, i.e. the total input power P_t minus the Ohmic power P_Ω, flowed into the ions due to the dynamo activity (CAROLAN *et al.*, 1987), this power decreased after carbonization and might cause the lower ion temperatures, because P_t decreased by $\sim 30\%$ and P_Ω was not changed much from the unchanged electron temperature (if the profiles of the electron temperature and Z_{eff} were not changed). Using the modified Bessel function model (FUJISAWA and MIYAMOTO, 1989), $(P_t - P_\Omega)/P_t$ is estimated to be hardly changed; from $\sim 27\%$ ($F = -0.45$ and $\Theta = 2.05$) to $\sim 30\%$ ($F = -0.58$ and $\Theta = 2.2$) after carbonization, if the assumed η (resistivity) profile $\propto [0.9(1-r^2)+0.1]^{-3/2}$ was unchanged. Here, r is the normalized plasma radius, and F and Θ are the ratios of the toroidal and poloidal fields at the wall to the mean toroidal field, respectively. Experimentally, the standard deviations of F and Θ in these discharges were ~ 0.06 and ~ 0.12, respectively. Needless to say, this value of $(P_t - P_\Omega)/P_t$ decreases as the ratio of the η value at the plasma edge to that in the center decreases. The carbonization executed might affect the plasma boundary layer, which is very important for helicity transport and dynamo activity.

However, contrary to expectations, the fluctuation amplitude F (> 10 kHz) was increased by up to a factor of ~ three on average although the shot-by-shot scatter was large. This was partly due to deeper F and higher Θ (typical values were described above) and might be partly because of the change in the viscosity edge region (KUSANO and SATO, 1990) after carbonization. These plasma phenomena after this carbon-

TABLE 1.—SUMMARY OF GLOW AND CARBONIZATION. HERE, S, L AND H MEAN NEARLY THE SAME, LOWER AND HIGHER THAN BEFORE (H_2 DISCHARGE WITHOUT CONDITIONING), RESPECTIVELY. THE SYMBOLS "CONST." AND "-" STAND FOR CONSTANT VALUE WITH TIME AND NOT ENOUGH DATA TO BE CONCLUSIVE, RESPECTIVELY

		Wall Conditioning				
		He Glow		H_2 Glow	Ne Glow	Carbonization
Pressure	P_T	L		H	L then H	H
	P_2	L		H	H	H
	P_{18}	L		H	L then H	S
	P (Hydrocarbon)	L		S	S	H
Plasma	Gas	H_2, D_2	He	H_2	Ne	H_2
	$\overline{n}_e$	L	const.	H	const.	const.
	R_p	S	S	S	H	L
	T_i (CV)	S	-	S	-	L
	I_{CV}	L	L	S	-	H
	I_{SX}	S	H	S	-	L
	P_r	L	-	-	H	H

ization, especially the decreased ion temperatures, are still open questions to be solved, but the results presented here are very useful for understanding the mechanisms of anomalous resistivity and anomalous ion heating relating to the dynamo activity.

3. CONCLUSION

By using glow discharge and carbonization techniques, we could change wall conditions and plasma performance. Typical results are summarized in Table 1. After the He and Ne glow discharges, the partial gas pressures were reduced (particularly P_{18} for the He glow case). Various uses of gas species in glow and main discharges including carbonization could change the behavior of the plasma density; nearly constant with time, low and high densities for the fixed filling pressure.

After the He glow discharge, the P_r and I_{CV} intensity decreased by a factor of two. After carbonization, decreases in R_p and the ion temperatures, T_i(CV) and T_i(CX), were found, and the central confinement times of the electrons and ions increased with n_e. On the contrary, the electron temperature did not change as much.

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