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CONDITIONS IN THE ATC TOKAMAK

BY

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SOME OBSERVATIONS OF SURFACE CONDITIONS
IN THE ATC TOKAMAK

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ABSTRACT

A surface analysis station has been constructed and installed on the ATC tokamak. Data taken during supplementary heating experiments show rapid contamination of clean metal surfaces by monolayer quantities of carbon and oxygen and ten times smaller quantities of sulfur, chlorine and fluorine. No limiter or liner material is found above the detection limit.

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1. INTRODUCTION

A severe problem for present-day tokamaks is the bombardment of the vacuum vessel wall surface by energetic particles and the resultant introduction of impurities into the plasma. As new tokamaks with higher energy densities are being built it will be increasingly important to compare their surface conditions with those of older devices as an attempt to investigate correlations between wall conditions and plasma behavior. To help understand these phenomena we have constructed an apparatus that can present a sample surface at the vessel wall and perform in-situ surface chemical analysis of the sample before and after exposure to the plasma. The apparatus incorporates instrumentation for Auger electron spectroscopy (AES), secondary ion mass spectroscopy (SIMS), and electron stimulated desorption (ESD). We present here a description of the apparatus and results of experiments performed on the ATC tokamak.

2. EXPERIMENTAL APPARATUS

A diagram of the surface analysis station (SAS) is shown in Fig. 1. The major instrumentation is contained in a multi-port, stainless steel ultra-high vacuum chamber pumped by a triode ion pump to a base pressure of 5×10^{-10} torr. The chamber is isolated from the tokamak vacuum system by a long, low conductance bellows section containing diaphragms at two locations. This can maintain a pressure differential of 10^3 when ATC is filled to 10^{-4} torr of H_2 . Sample surfaces are provided by a 315 cm long, 1.2 cm wide, 0.008 cm

thick stainless steel tape, spotwelded in the form of a continuous loop. The tape loop rides on an insulated support rail, one end of which is centered in the analysis chamber. The other end protrudes into the tokamak vacuum chamber through a diagnostic port to a point 20 cm from the plasma edge. There is no line-of-sight between the tape and the limiter. The tape loop can be moved by engaging perforations on its edges with a sprocket wheel connected to a rotary vacuum feedthrough and external motor. Indexing of the tape position to an absolute accuracy of 2 mm is provided by a counting circuit triggered by a rotary switch on the tape drive.

The surface of the tape can be conditioned by electron-bombardment heating, low energy ion bombardment ("sputter cleaning"), or by overlaying thin films of such materials as Au or Ag onto the tape from evaporation sources directly beneath the support rail. A quartz crystal thin film monitor can be used to measure the thicknesses of evaporated films.

The surface conditions on the tape are determined by means of several techniques that are possible using a quadrupole mass spectrometer (Extra nuclear, 324-9), cylindrical mirror energy analyzer (Physical Electronics, Inc., 10-150), electron gun, and ion gun contained in the analysis chamber. Auger electron spectroscopy (AES) [1] will give semi-quantitative measurement of the surface concentration of all elements above $Z = 4$, at a sensitivity of roughly 10^{-3} monolayers. Secondary ion mass spectrometry (SIMS) [2] yields a very sensitive qualitative (10^{-6} monolayer) analysis of the near surface layer for all elements and isotopes. Electron stimulated desorption (ESD) yields information on the

identity and binding state of adsorbed layers [3]. In addition, energy distributions of sputtered or desorbed ions can be measured. Auger electron or secondary ion signals can be measured as a function of time as the surface is sputtered at a constant rate, yielding a depth profile of a particular element in the near surface layer.

After the initial surface conditions of a portion of the tape have been determined, the sample surface is translated to a position within a diagnostic port of the tokamak where it can be exposed to plasma. After varying the number of plasma discharges, the sample position relative to the plasma edge, or the conditions of the plasma, the exposed surface is translated back to the ultra-high vacuum chamber for analysis.

A useful mode of operation of the SAS would involve moving the tape during a discharge. This, in effect, makes a tape recording of the impurities deposited or removed during different stages of the discharge. With a 1/2 mm aperture between the plasma and the tape, the time resolution is about 15 msec, but can be shortened to 5 msec either by the insertion of a smaller aperture or by speeding up the tape drive motor. This mode may be used in conjunction with laser injection of metals [4] to determine impurity confinement time.

The ATC tokamak has been described in detail elsewhere [5]. However, there are several features of ATC construction which must be noted. The device is constructed of stainless steel bellows approximately 20 cm in minor radius and 90 cm in major radius. Stainless steel rods are used as the limiters. Connections to ATC are made with both metal and Viton seals. The

vacuum system is comprised of one 25 cm diameter oil diffusion pump with a Freon baffle. The pumping speed at the torus is about 500 l/sec. and the base pressure is $1-4 \times 10^{-7}$ torr, the greater part of which is comprised of H_2O , CO, CO_2 , and hydrocarbons.

3. ATC RESULTS

Experiments with the SAS have included three runs on the ATC tokamak. In these only Auger spectroscopy was used for the surface analysis. The first run was performed during concurrent high power neutral beam injection [6] and the second and third runs were performed during lower hybrid [7] heating experiments, hence these runs represent extreme conditions for plasma parameters and perhaps surface bombardment. For example, during the neutral beam injection experiments the ion temperature exceeded 1200 eV after adiabatic compression and the flux to the wall of neutral 1 keV deuterium was a factor of 5 larger than preinjection conditions. During the lower hybrid heating experiments the electron temperature was nearly 2 keV. Other parameters of ATC discharges typical to these experiments are shown in Table 1.

It is important to note that the position of the sample during exposure was inside a 15 cm diameter tube 20 cm from the plasma edge (Fig. 1), with the aperture placed between the tape and plasma. Therefore, the sample was exposed only to line-of-sight neutrals escaping from the plasma and to the residual gases. Accordingly, no ion current (larger than 10^{-11} A) was collected by the sample during the steady state part of the discharge.

Some of the results of the first run are shown in Figs. 2 and 3. During this run 100 discharges took place. Of these, 30 discharges used ohmic heating alone, 50 discharges had ohmic heating, beam heating (15 keV, 15 amp) and compressional heating, and 20 discharges used beam heating and ohmic heating. The ATC had been opened to atmosphere during the previous week and it was necessary to reduce the impurity concentration in the plasma by sublimating titanium [8] onto the vacuum vessel walls of approximately one half the torus before the neutral beam run was started. The sample surface and the surface analysis station were not exposed to the titanium.

The time evolution of vacuum ultraviolet radiation from selected carbon, oxygen, titanium, and iron ion species is shown in Fig. 3. The absolute concentration of these ions during this particular run is not known to be better than a factor of 3. Previous measurements [5] showed oxygen, carbon, and iron concentrations on approximately 5%, 1%, and 0.1% respectively. It is interesting to note the difference between the FeXV, TiXII, CIII, and the OVI light intensities. During the beam heating stage (18-28 ms) the OVI light is seen to increase linearly, CIII light increased not quite linearly, while the FeXV and TiXII light increased to a plateau. A model for the plasma-wall interactions leading to these signals is presented elsewhere [9]. In that paper it is shown that escaping beam charge exchange neutrals can account for the Ti and Fe influxes, while both beam charge exchange and plasma charge exchange neutrals contribute to the O and C influx.

Auger electron spectra from this run are shown in Fig. 2. As is the convention, the differential spectrum of the Auger

electron energy distribution was recorded to bring out the Auger transitions from the large secondary electron background. The elements responsible for each transition are identified in the figure. In table 2 are listed the transitions, the energy of the negative excursion and the quantum numbers of the electrons involved. Trace A shows the surface of the stainless steel tape prior to any in vacuum treatment. Carbon and oxygen are dominant elements on the surface, followed by iron. Their approximate concentrations, calculated using the method of Palmberg [10], are C 44%, O 36%, and Fe 18%. Less than 2% of a monolayer of chromium is apparent. Trace B shows the surface after a one-half hour anneal at approximately 1200 K. The surface carbon concentration has clearly decreased while the chromium level has increased. Also, traces of calcium and oxidized silicon have appeared. Subsequent to the annealing, an attempt was made to coat the annealed portion of the tape (1 cm) with several monolayers of gold. However, the gold evaporation filament broke and only a fraction of a monolayer of gold was coated (trace C). This was insufficient to cover the iron but did decrease the carbon signal. Finally, approximately one monolayer of aluminum was evaporated onto this section of tape. The Al (52 eV), Al (68 eV), and Al (86 eV) transitions are clearly visible in trace D, as well as the O (510 eV) transition. No iron is visible. It would have been preferable to have a Au overlayer instead of Al because the rapid formation of Al_2O_3 precludes the assessment of changes in the oxygen level due to plasma wall interactions.

This section of the tape was then translated into the ATC vacuum vessel and exposed to plasma discharges. After the 100 discharges the

exposed section of the tape was translated back into the SAS and the traces E, F, and G were recorded. Trace E is a characterization of the surface of the tape that directly faced the plasma; trace F is that of the tape 2 cm back and trace G is 6 cm back. That portion of the tape that faced the plasma and had been coated with gold and aluminum shows no trace of either. Instead, carbon has recoated the surface. Traces of fluorine, sulfur, and chlorine are also visible. The origin of the halogens may be in the solvents used to clean ATC parts. Also, there is a considerable number of teflon insulators in the ATC. In any case, halogens are well known to cause stress corrosion in metals and their presence in ATC has caused concern. The oxygen level is down from the pre-exposed value. Possibly a trace of Zn or Cu is seen at $E \approx 60$ eV. Also, there is a small peak at $E \approx 380$ eV which may be either N or Cd. In trace G one sees the effect of indirect exposure to the plasma on the "original stainless steel" surface. The four major differences between traces A and G are: 1) the decrease in the oxygen peak, 2) the increase in the carbon peak, 3) the change in the oxygen and carbon peak shapes, and 4) the appearance of sulfur, chlorine, and fluorine contamination.

For comparison, another section of tape was coated with aluminum and left in the SAS vacuum system for seven hours. The Auger spectrum of this area is shown in trace H. In marked contrast with the aluminized region that was exposed to the plasma, (trace E), this section shows still large Al (68 eV) and O (510 eV) Auger peaks.

One point concerning run 1 should be emphasized. Fe and Ti

ions were observed in the plasma in sufficient quantity that if they were deposited uniformly over the vessel wall nearly a monolayer of each would be deposited. In these experiments less than 0.5% of a monolayer of either was visible on the tape.

The next runs, each performed during lower hybrid heating experiments, gave similar results, hence only data from one are presented. In this run a thick ($\sim 1000 \text{ \AA}$) silver film was evaporated onto 10 cm of the sample tape. The Auger spectrum of the original stainless steel substrate and evaporated silver overlayer are shown in Fig. 4. The Ag film shows no significant surface impurities except carbon (presumably from hydrocarbon contamination caused by local heating of the vacuum chamber during the evaporation) and lead (a bulk impurity in the Ag evaporation source material).

Figure 5 shows a spectrum of the sample surface after exposure to 40 shots of the ATC plasma: the gross features are similar to Fig. 4. Only a small enhancement of the C and O Auger currents is evident when the C/Ag and O/Ag ratios are plotted as a function of tape position (Fig. 6). The tape surface was exposed to 40 plasma shots at position 1, moved to position 2 and exposed to 40 additional plasma shots. As in the first run, no Fe Auger signals were detected.

The observed changes in relative elemental coverages on the exposed and pre-exposed Ag overlayer are tabulated in Table 3. The exposed surface at position 1 (0 cm) shows increased C and O coverages compared to both the pre-exposed surface and the surfaces exposed only to indirect bombardment (i.e., $\pm 5 \text{ cm}$, $\pm 10 \text{ cm}$ from position 1). In addition significantly higher surface

concentrations of Cl are observed on the exposed surfaces. Subsequent experiments have shown that it is difficult to quantify the coverage of Cl on C contaminated surfaces due to enhanced surface diffusion [11]. For comparison, an evaporated Ag film was left in vacuum (10^{-7} torr) for twelve hours but not exposed to plasma. The resulting spectra (Fig. 7) show a considerable amount of carbon (Table 3) but little coverage of O or Cl.

4. DISCUSSION

The use of Auger analysis requires local magnetic fields less than one Gauss and background pressures less than 10^{-9} torr. For this reason the Auger Spectrometer was mounted in a separate vacuum system several meters from the ATC tokamak. In this configuration it is necessary to move the sample surface out of the tokamak into the analysis chamber. During the tens of seconds required for this the sample is exposed to the residual gases of the tokamak. The residual gas pressure is sufficient to allow the formation of monolayer quantities of hydrocarbons, water, etc. onto the sample surface. Thus the data reported here correspond to trends in changing surface conditions and may not be indicative of the wall condition during or immediately after a discharge. Instead these results represent the condition of the vacuum vessel wall immediately prior to the next discharge. Furthermore, all the surfaces of the ATC vacuum vessel wall are not subject to the same bombardment, especially during the initiation and termination of discharges. For example, the location of the stainless steel tape sample surface was sufficiently removed

from the main plasma volume that no ions could reach it. Hence, it is expected that the changes in surface chemistry of the tape are only characteristic of relatively shielded regions of the vessel wall such as the bellows' convolutions of the vacuum vessel. As such, this experiment is sensitive to changes in wall conditions due to sputtering, photon and photo-electron induced desorption, hot atom surface chemistry, and residual gas adsorption, but not direct plasma bombardment.

Auger spectra of elements are modified by the presence of other elements. The modifications include changes in line shape and shifts of the line center. The carbon spectra shown in Fig. 2A, 2B, 2E, and 2F have notably different shapes on the low energy side. Though too few line shapes for adsorbed states of carbon compounds have been tabulated, we can make a general statement about the low energy side of all (derivative) Auger peaks. (See Fig. 8) The low energy side is due, in part, to those Auger electrons whose energy has been slightly degraded by passage through some matter, i.e., those electrons that have originated a few Angstroms below the surface and have been scattered into the acceptance angle of the detector. Because the carbon in trace 2A shows a lower energy tail than that in 2E, F, G or H, some of it is probably covered by other carbon atoms or oxygen atoms. There is evidence that carbon monoxide adsorbs on transition metal surfaces in this orientation [3,12]. Water vapor adsorbed over hydrocarbons would have the same effect. The carbon in traces 2E, 2F, 2G, and 2H is due to a single layer of adsorbed hydrocarbons.

Because the depth profiling option was not used in these

runs, we were not able to ascertain by Auger analysis whether the Al and Au were sputtered away or simply covered with hydrocarbons. However, the flux of charge exchange neutrals to the position on the tape surface nearest to the plasma was about $10^{16}/\text{cm}^2 \cdot \text{sec}$ for .03 sec. This is comprised of 50 eV to 15 keV particles. Assuming an average sputtering yield of $\sim 3 \times 10^{-3}$, about 10^{14} atoms/ cm^2 would have been sputtered away during the 100 discharges. This corresponds to a 15% erosion of the surface layer. Also, those areas of the tape that were not exposed to direct charge exchange bombardment showed no Al or Au signals. We thus conclude that the evaporated layers of Al and Au were coated with hydrocarbons, and were not sputtered off.

During the high power neutral beam heated run the oxygen influx to the plasma, as ascertained by VUV spectroscopy, was observed to decrease shot-to-shot by a factor of two between the beginning and end of the run. This is in qualitative agreement with the decrease of oxygen on the sample surface.

A major difference between the results in this experiment and those reported by other workers [13, 14], is the absence of limiter and liner material on our collector surfaces. There may be several reasons for this difference. First, their collector protruded into the torus and could have intercepted ions at the plasma's edge. Also, there was a line of sight path from their limiter to their collector. Finally, the Pulsator device is clean by UHV standards. Its base pressure is in the 10^{-9} torr range. In contrast, the ATC tokamak has a residual gas pressure of $\sim 2 \times 10^{-7}$ and rapid coating of any fresh metal surfaces (such as

deposited Fe) may occur.

In conclusion, a surface analysis station has been built and installed on the ATC tokamak. It has been operated during several different types of discharges in an integration-type mode. Clean metal sample surfaces became coated with (hydro) carbons and oxides. No liner or limiter material was detected on the sample surface.

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TABLE I. PARAMETERS OF DISCHARGES STUDIED

	Neutral Beam-Heated*	Lower Hybrid-Heating
Peak Electron Temperature (eV)	850	2000
Peak Ion Temperature (eV)	420	~400
Peak Electron Density (cm^{-3})	3.9×10^{13}	$2.4 \cdot 10^{13}$
Effective Ionic Charge	3.2	~12
Ohmic Heating Power Input (kW)	120	160
Auxiliary Power Input (kW)	230	100
Major Radius (cm)	88	90
Minor Radius (cm)	17	17
Magnetic Field (kG)	20	20
Plasma Current (kA)	66	80
Neutron Flux ($\text{cm}^{-2} \text{sec}^{-1}$)	2×10^2	
Charge Exchange Flux ($\text{cm}^{-2} \text{sec}^{-1}$)	$\sim 10^{16}$	$\sim 10^{16}$
Discharge Duration (ms)	45	45
Hydrogen Species in Plasma	D	D

*These values are for the uncompressed portion of the discharge.
Values obtained during compression are in Ref. 6.

TABLE II. SELECTED AUGER TRANSITION

Element	Z	Transition	Energy
C	6	LVV	20
		KLL	272
N	7	KLL	381
O	8	KLL	475
		KLL	490
		KLL	510
Al	13	LMM	68
		LMM	84
S	16	LMM	152
Cl	17	LMM	181
Ti	22	LMM	387
		LMM	418
Cr	24	LMM	489
		LMM	529
		LMM	571
Fe	26	LMM	703
		LMM	651
		LMM	598
Mo	42	MNN	266
		MNN	221
Ag	47	MNN	266
		MNN	304
		MNN	351
		MNN	356
Au	79	NOO	69
		NNN	150
		NOO	239
		MNN	2024

TABLE III. AUGER ANALYSES OF SAMPLE AG SURFACES

Relative Coverage (%) of:						
	Ag	C	O	Cl	Pb	Fe
Sample Surface						
Fresh Ag Overlayer	36	43	<1	<1	19	-
Exposed in ATC (0 cm)	22	60	4	7	7	<.5
Exposed in ATC (+5 cm)	35	56	2	3	4	<.5
Exposed in ATC (-5 cm)	35	42	<1	<2	20	<.5
Exposed in ATC (+10 cm)	34	50	2	10	4	<.5
Fresh Ag Overlayer	40	52	2	<2	4	-
Aged in Vacuum (10^{-7} torr)	16	81	1	1	1	-

Table III. Auger analyses of sample Ag surfaces. Relative coverages calculated using inverse sensitivity factors of Palmberg [10]. No correction has been made for the overlap of the C(272 eV) peak and Ag (266 eV) peak, so the relative coverage of C is overestimated in the above data. Matrix effects and overlayer attenuation were not included.

763140

Fig. 1. Schematic diagram of the surface analysis station (SAS) installed on the Adiabatic Toroidal Compressor (ATC) tokamak. The distances from the sample surface to the plasma edge is 20 cm.

763323

Fig. 2. Auger electron spectra of sample surfaces from Run 1 (neutral beam heating); (A) stainless steel sample tape prior to any in-situ surface conditioning; (B) after one half hour annealing at approximately 1200 K; (C) with fractional monolayer coverage of Au; (D) with monolayer coverage of Al; (E), (F) and (G) after exposure to 100 discharges. In Trace (E) the sample directly faced the plasma, in traces (F) and (G) the sample was 2 cm and 6 cm respectively further back on the support rail; (H) Aluminum layer on sample tape exposed only to residual gases in SAS vacuum vessel for seven hours.

763174

Fig. 3. The time evolution of vacuum ultraviolet radiation from selected carbon, oxygen, titanium, and iron ion species during Run 1. For the C, Ti and Fe data the plasma was compressed at 30 ms. The plasma was not compressed during the time the O data was recorded. The large spike at $T \approx 45$ ms marks the end of the discharge.

763002

Fig. 4. Auger electron spectra of stainless steel sample tape before and after evaporation of overlayer. This sample was used in Run 2 (lower hybrid heating).

763001

Fig. 5. Auger electron spectra of Ag overlayer after exposure to 40 ATC discharges. Note that no iron peaks (598, 651, 703 keV) above the noise level are visible in the trace with the sensitivity increased by ten.

756138

Fig. 6. Observed change in C/Ag and O/Ag ratios of $N'(E)$ Auger signals as a function of tape position. The tape surface was exposed to 40 ATC discharges at position 1, moved to position 2 and exposed to 40 additional discharges.

763191

Fig. 7. Auger electron spectra of a Ag overlayer (a) immediately after deposition, and (b) after exposure to residual gas (10^{-7} torr) for twelve hours.

763110

Fig. 8. A and B are schematic representations of $N(E)$ and $N'(E)$ Auger signals from different carbon surfaces. The traces (labeled 2) are indicative of a "clean" carbon monolayer. The dashed traces (labeled 1) show a low energy tail and are indicative of a carbon monolayer being covered by approximately 1 monolayer of an adsorbed gas such as water. C shows the carbon traces from figure 2A and F. The low energy (240-250 eV) region in 8C should be compared with that in 8B.