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ABSTRACT

Carbon limiters coated with 100-150 μm of silicon carbide (SiC) have been placed in the TCA tokamak in an attempt to reduce impurity generation during both ohmic and Alfvén wave heating. The results are compared with those with bare carbon limiters operated under similar conditions. The SiC coated limiters were conditioned by 150 hours of Taylor discharge cleaning. During both ohmic and Alfvén wave heating, the radiation profile is strongly hollow, with no measurable radiated power on axis. The light impurity line emission intensities are reduced by factors of 3-10 for C, N and O, while the intensity of the silicon line emission naturally increased. During Alfvén wave heating, the density of metallic impurities is less than with bare carbon limiters. Z_{eff} dropped from 4.2 to 2.4, and the loop voltage fell from 1.5 to 1 V. The relative drop in plasma resistivity and radiated power is largest at higher electron density ($5 \times 10^{13} cm^{-3}$). The plasma operational range is similar to that obtained using bare carbon limiters. In conclusion, the SiC coated limiters have led to significant improvements in plasma performance due to impurity reduction.

I. INTRODUCTION

The optimal choice of the material, coating, and shape for tokamak limiters continues to be a controversial subject. In this report, we compare the behaviour of graphite limiters coated with 100-150 μm of SiC with bare graphite limiters under otherwise similar conditions in the TCA tokamak. It will be shown in the following sections that the SiC coating led to a marked improvement in several discharge properties due to reductions in impurity levels.

The TCA tokamak [1] has a major radius of R = 0.61 m, minor radius of 0.18 m, and parameter capabilities of toroidal field B_T = 15.1 kG, plasma current I_p = 175 kA, safety factor at the limiter $q_L > 2.2$, and line average density $\bar{n}_e < 10^{14}$ cm^{-3}. In the experiments described here (except for the Hugill diagram study), the conditions were B_T = 15.1 kG, I_p = 125 kA, q_L = 3.3, and $\bar{n}_e < 4\times10^{13}$ cm^{-3}. TCA is primarily dedicated to the study of plasma heating by Alfvén waves at frequencies between 2 and 5 MHz, considerably less than the ion cyclotron frequency (ω/ω_{ci} = 0.22 in deuterium at 2.5 MHz).

The first experiments carried out on the TCA Tokamak using Alfvén Wave Heating showed a large increase in the radiated power loss during the rf pulse [2,3]. This effect masked the electron heating since the electron temperature increase was only maintained for a few energy confinement times before falling to its initial OH value. A subsequent programme of limiter design and material tests [4] showed that the limiters were the dominant source of the metallic impurities and that carbon limiters gave a better target plasma, i.e. the plasma column resistance and radiated power loss were reduced by a large factor. The next most likely source of metallic impurity influx was the antenna structure. The removal of the 8 wide steel plate antennae groups and their replacement by TiN coated bar antennae led to improvements in the target plasma, and especially to the radiated power profile [5]. Measurements indicated the presence of: 1) additional antenna loading [6], 2) a finite DC plasma-antenna resistance and 3) a plasma-antenna interaction in the scrape-off plasma outside the limiter radius leading to a local non-Maxwellian plasma [7]. To counteract these effects, TiN coated stainless steel screens were installed 5 cm away (in the toroidal direction) from the antennae, and 1.0 cm radially further out than the limiter, resulting in a marked reduction in the central radiated power during Alfvén wave heating [8] from 0.4 W/cm^3 to 0.2 W/cm^3. An increase in the electron and ion temperatures was then sustained during the entire 30 msec heating pulse, accompanied by a decrease in plasma loop resistance. A considerable reduction in the intensity of metallic impurity line emission from the plasma was observed. However, the Z_{eff} of the target plasma core remained ~4 (which was somewhat higher than before the screens were installed), the intensity of C, N and O lines still increased significantly during rf heating, and after the initial drop, the plasma resistivity slowly climbed back towards its original value. The conclusion is that the bare carbon limiters still acted as an important source of low-Z impurities. Therefore, it was decided to coat the limiters in an attempt to reduce this impurity increase. The bare carbon limiters had been inside TCA for about one year before they were replaced with the SiC coated carbon limiters.

In section II of this report, the choice of the SiC coating and the process of coating are described. The limiter installation and conditioning are described in section III. In sections IV, V and VI a comparison is made between tokamak plasma properties with and without the SiC coating of the limiters. The radiated power profiles and total radiated power for the two cases are compared in section IV. The intensities of individual impurity lines measured by a vacuum ultra-violet (VUV) monochromator/spectrometer are presented in section V. In section VI, other plasma properties of representative discharges are discussed, including plasma resistivity, electron temperature, Z_{eff} and the effects of Alfvén wave heating. The range of possible operation in plasma current (1/q) and plasma density ($\bar{n}_e R/B_T$) for the SiC coated limiter set is shown and discussed in section VII, and finally the conclusions are presented.

II. CHOICE OF SiC COATING AND COATING PROCESS

The limiters chosen for any present generation tokamak should at least (i) exhibit high resistance to thermal shock and fatigue, (ii) impart little contamination and working-species dilution to the plasma (generally requiring low atomic number), (iii) minimize surface damage due to runaway impact and (iv) be readily fabricated in the required, often complex, geometry. Metals cannot generally satisfy conditions (ii) and (iii) and have also shown signs of fatigue failure in tests [9]. Some ceramics, particularly carbides, make good candidates but fail to fulfill condition (iv). Although isotropic graphite has extremely good thermal characteristics [9] and can be machined, some forms are relatively porous, exposing a large effective surface area. In the range 300 °C - 900 °C, strong chemical sputtering occurs, enhancing the effective sputtering yield of the carbon and exacerbating the radiation losses and impurity content of the plasma. In addition, hydrogen gas is readily adsorbed, and is released when the graphite is heated during the plasma discharge [10].

These effects can be overcome by sealing the graphite with a suitable low-Z coating of carbide by CVD (chemical vapour deposition). Titanium carbide (TiC) was used with success in TCA. However, plasma erosion can expose the substrate. The maximum coating thickness of TiC is generally limited with the CVD technique because of intercrystal stress, which lowers the thermal shock capability and can cause chipping and flaking. For this reason, CVD layers of TiC are generally restricted to < 25 µm, whereas much thicker coatings would be preferred, to allow for ablative losses during disruptions and occasional runaway electron beam impact.

For this present study, isotropic graphite with a CVD coating of SiC has been chosen since SiC has been shown to have good thermal shock characteristics [9], and low chemical and physical sputtering yield (at low Z_{eff}) [11]. The graphite can be stably coated with SiC to the required thickness of 150-200 µm, and considerable world-wide industrial experience is available in this area. The substrate is Carbone Loraine 5890 PT graphite which has a thermal expansion characteristic that preserves the integrity of the coating, at least between the CVD process temperature and ambient temperatures. The SiC coating was provided by Archer Technicoat, using the CVD process at 1200 °C. The Alcator C group has already reported the use of CVD SiC coated limiters with mixed results [12], and Doublet III has used C-SiC coated carbon for inboard limiters and neutral beam armour [13] with good results.

The limiters were baked in a graphite box (to prevent surface contamination by the Mo reflectors of the oven) at 800°C and 5×10^{-6} torr for three hours, cooling under vacuum overnight. Direct handling was avoided at all stages.

The detailed shape of the limiters and their position in the TCA vacuum vessel are shown in fig. 1. The limiters are positioned so as to define the plasma radius at a=18 cm.

III. MACHINE CONDITIONING AND OPERATION OF TCA WITH SIC LIMITERS

In Table I we summarize the operations with the SiC coated limiters. The conditioning corresponds roughly to the usual TCA sequence, although the total plasma duration per day had been reduced due to power supply failures. After pumping, we heat the Viton seals to ~80 °C for 24 hours to accelerate their outgassing. We then run continuous Taylor Discharge Cleaning (TDC) (5kHz ac discharge) in Argon to heat the torus to ~80 °C, while maintaining all Viton seals at ~80 °C, which initially conditions the wall. Following this we then run standard TDC in D_2 (two 30 msec pulses/sec at 5kHz). The first discharge the following day was dominated by MHD activity as was the second. The third shot was a sawtoothing discharge. After 8 shots (E) the plasma density remained uncontrollable even with the gas-feed completely shut off. A further 2 hours of TDC were completed in D_2(F). In the afternoon, high resistance discharges were run, still with no density control possible (G). The discharge was predominantly a deep blue, possibly due to chlorine that was present in the coating oven, although baking should have removed the chlorine.

The following day (J) the plasma resistance had dropped to ~11μΩ. The discharge nonetheless retained a blue tinge. The next day (L) was better, with a normal red discharge (Dα hydrogen light) and a lower plasma resistance, ~9μΩ. No change in operation was obtained after the 4th day (Q) with 8.5-9.5 μΩ plasma resistance. At this point we had accumulated 590 minutes of TDC plasma duration and only 10 seconds of Tokamak discharge. After an additional 2-4 days in this asymptotic condition, the detailed plasma measurements described in this report were begun.

In Fig. 2 (bare carbon) and Fig. 3 (SiC coated), residual gas analysis data are shown as a function of shot number, or equivalently time during the day and during conditioning. It is instructive to look at mass 28, corresponding principally to N_2 and CO. During the first days, levels with SiC coating are higher, but the same levels as with bare carbon limiters are reached eventually. For CO_2, mass 44, initially high values with SiC coated limiters fall to zero, but they were also very small with bare carbon limiters. After the initial conditioning period, an important difference is that with SiC coated limiters, the levels of each impurity after a shot remain constant during the day, whereas with bare carbon, impurity pressures tended to increase during the day.

IV. RADIATED POWER PROFILES

The radiated power from the TCA plasma is measured as a function of position and time by a single channel bolometer, which is scanned in position during a series of reproducible discharges. The line-integrated measurements are then Abel-inverted to obtain the radiated power as a function of plasma minor radius. The evolving radial profiles of radiated power are shown in Figs. 4 and 5. The data in Fig. 4 are from discharges produced in the presence of TiN coated bar antennas and side screens plus bare carbon limiters, and data in Fig. 5 are from similar conditions but with SiC coated limiters. The data in Fig. 4 are from discharges described in detail in [7]. In Fig. 6, the integrated radiated power, heating power, and ratios are shown versus time for bare carbon, and in Fig. 7 for SiC coated carbon. The numerical values are shown in Table II.

The results are summarized as follows : for the bare carbon limiters, the Abel-inverted radiation profile is slightly hollow with a small peak in the plasma centre. When the rf pulse is turned on, a small increase is observed in the central radiated power. The ratio of total radiated power to ohmic power is 32%, and during Alfvén wave heating, the ratio of radiated power to total heating power rises to 41%. The increase of radiation in the plasma boundary during heating is consistent with an increase in the content of light impurities, along with a small increase of metallic impurities in the centre.

In the case of the SiC coated limiters, a large reduction is observed in the overall bolometer signal. The Abel-inverted radiation profile is strongly hollow during both ohmic and rf heating. In particular, the Abel-inverted profile shows practically zero radiation from the plasma centre out to a radius of 6 cm, even during rf heating. There is a large reduction in the ratio of total radiated to total input power, which for ohmic heating is 22% instead of 32%, and during Alfvén heating, rises to only 25% instead of 41%. We therefore conclude that the light impurities still show an increase during rf heating, but this is less pronounced than with bare carbon limiters. The results also indicate that the SiC coating has led to a large reduction in heavy impurities, both during ohmic and during rf heating. It remains an open question as to whether the SiC coating has surface properties that reduce metal attachment and subsequent escape, or whether the preparation or months of exposure of bare carbon in the tokamak led to a significant surface coating of metal. A separate report is being prepared on the results of surface analysis of both the bare carbon and SiC coated limiters.

In the next section, we explore the behaviour of individual impurity lines in detail, in order to confirm these indications.

V. IMPURITY LINE MONITORING

We monitored the intensity of certain impurity lines in the VUV range of the spectrum, using a 1 m Normal Incidence monochromator with a 1200 lines/mm grating blazed at 1500 Å. The measurements were carried out under the standard condition (q ~3.3, D_2, 15.1 kG, 110 kW rf). The time dependence of the line intensities is shown in Fig. 8a,b,c for all the lines monitored, with the carbon limiters as dotted lines and SiC coated limiters as solid lines. In Table III we list the lines and the ratio of intensities between the carbon coated limiters and SiC coated limiters both before and during rf.

We see from the Table that the light impurities showed a marked reduction in intensity with the SiC coated limiters. There is a tendency for the reduction to be greatest for the more highly stripped light impurities (O VI, O VII), of e.g. a factor of 9-10 compared with 3-4 being typical for the weakly stripped impurities. It would therefore appear that the dominant source of oxygen and nitrogen had been the bare graphite limiters.

The metal lines show only a small or no reduction in the OH part of the discharge. On the other hand we found that the rf pulse led to a smaller relative and absolute increase in line intensity with the SiC limiters. It is possible that the carbon limiters had in fact received a substantial coating of impurities during their prolonged exposure to the plasma over the previous months of operation.

From these spectroscopic measurements we conclude, therefore, that the low-Z purity is improved (except for silicon) and that the metallic impurity content during the rf pulse is only barely increasing, in agreement with the bolometer data.

The VUV spectrometer has also been used with film in order to identify the stronger lines and to make approximate observations on line intensities. In Fig. 9 (a-d), the photographic line spectra from TCA in the range of 750 Å to 2070 Å are presented. On the left are spectra taken in the presence of SiC coated limiters, during ohmic heating only. On the right are spectra from an earlier phase of operation, similar to the present but with bare carbon limiters, and no side screens on the antennae. Each photograph was exposed for one entire discharge. Because of the different conditions, only very general comments can be made. In the spectra on the right, the particularly intense lines, besides hydrogen, are C, N, and O, for example C III at 1175 Å, N V at 1238 Å and O V at 1371 Å. With the SiC coated limiters and TiN coated screens, the light impurity lines are considerably weaker, and of course the silicon lines are much more intense, for example the Si III quintuplet at 1299 Å. Many metal lines have almost disappeared in the more recent case.

VI. GENERAL PLASMA PROPERTIES

In previous sections, we have discussed the direct effects of the SiC coating on plasma radiation and impurity generation. Here, we discuss other general plasma properties. In Fig. 10 the behaviour of two representative plasma discharges is shown, taken from the series of shots used to measure impurity line behaviour, with bare carbon and with SiC coated limiters (both cases in the presence of TiN coated antennas and side screens). In both cases, when the rf pulse is turned on, the density goes up, β_p+li/2 and the ion temperature increase, and the loop voltage decreases, while the gas feed and plasma current are held approximately constant. The loop voltage and therefore the plasma resistivity are lower with the SiC coated limiters during the entire discharge, and accordingly the volt-second limited discharge now lasts up to 160 msec.

The plasma parameters during the ohmic phase have been studied in many discharges as a function of plasma density. In Fig. 11, the central Thomson scattering electron temperature and the inferred Z_{eff} on axis (from the loop voltage, T_e, and the assumption that the axial current density corresponds to q_0=0.9) are plotted as a function of line-averaged density. The dots and crosses represent T_e and Z_{eff} with a SiC coated limiter. At a density of $n_e \approx$ 5×10^{13}cm^{-3}, the value of Z_{eff} is 2.2±0.3, and at lower densities, 2-4x10^{13}cm^{-3}, the electron temperature is slightly higher (810±40eV), and Z_{eff} has increased slightly to 2.6±0.3. The open circles and squares represent measurement made at one density only, ~2x10^{13}cm^{-3} with bare carbon limiters, in which the T_e is the same, but Z_{eff} is considerably higher at 4.3. In Fig. 12, the plasma resistivity, ohmic power, radiated power, and β_p+li/2 during ohmic heating are plotted as a function of density, for bare carbon and for SiC coated limiters. The plasma restivity, ohmic power, and radiated power are all much lower for SiC coated limiters, with the largest reductions at high density. The β_p+li/2 and the central temperatures are the same for both cases, which suggests a larger energy confinement time of the plasma with SiC coated limiters, since the total input power is reduced.

We conclude that the installation of SiC coated limiters has led to significant improvements in plasma cleanliness, which in turn has improved certain plasma parameters.

VII. PLASMA OPERATIONAL RANGE

In order to explore the full range of plasma operation with the SiC coated limiters, the toroidal field was lowered to B_T=11.6 kG to attain more easily the q_L=2 limit. Many discharges of different plasma current were produced, with the density ramped up or down. The results are plotted in Fig. 13, where $1/q_L$ (proportional to I_p) is shown versus normalised density $\bar{n}_{19}R_0/B_T$. Different symbols are plotted showing how the discharges terminated. For comparison, the Frascati Tokamak (FT) operational boundary [14] is indicated, together with its constant drift velocity. The entire evolution of a few shots are shown. For q_L>3, the high density discharges extend to the edges of the FT boundary, indicating that clean experimental conditions have been obtained. At q=3, a notch is observed as in FT. The low density limit for a given current was taken to be that value at which the 2 mm interferometer suffered from electron cyclotron emission, which coincided with the onset of a sharp rise in β_p+li/2, presumed due to runaway electron beam formation.

In comparison, only limited studies were made with bare carbon limiters (with screens) at B_T=15 kG. In that case, with q>3, the normalized density also reached the FT limiting line for high density. In these earlier experiments on TCA [15], trajectories with a falling plasma current were observed which passed through the q=3 notch without disrupting, but which disrupted during the termination phase.

It may thus be concluded that the SiC coated limiters allow access to as large an operating space as is found in clean (i.e. low Z) tokamaks.

VIII. CONCLUSIONS AND DISCUSSION

The aim of the SiC coated limiter experiments in TCA is to reduce impurity generation from the limiter, in order to improve plasma properties during ohmic and Alfvén wave heating. A direct comparison is made with bare carbon limiters under similar conditions. The SiC coated limiters were conditioned by ~10 hours of Taylor Discharge Cleaning (TDC) followed by nightly TDC. During both ohmic and Alfvén wave heating, the radiated power profile is strongly hollow, with no measurable radiation on axis. Compared with bare carbon limiters, total radiated power divided by total heating power is reduced from 32% to 22% during ohmic and from 41% to 25% during Alfvén wave heating. The line intensity of light impurities is reduced by factors of 3 to 10, except for silicon, and the metallic content is reduced during Alfvén wave heating. The Z_{eff} of the discharge drops from 4.2 to 2.6 at $\bar{n}_e \approx 2 \times 10^{13} cm,^{-3}$ and the plasma resistivity and loop voltage falls from 1.5 volts to ≈ 1 volt. The decrease in resistivity and radiated power is relatively larger at high density. A study of the plasma operational range shows that the plasma can reach the usual clean-machine limits. We therefore conclude that the SiC coated limiters have led to an improvement in plasma performance as a result of impurity reduction. Production of carbon, nitrogen and oxygen are reduced, and the increase in silicon is the price paid. One surprising feature is the lower level of metallic impurities during Alfvén wave heating with SiC coated limiters compared to bare carbon limiters. This reduction may be related to metal deposited on the bare carbon limiter during several months of operation, or during baking, or to evolving wall conditions, whereas the SiC coated limiters were in the tokamak less than a month.

ACKNOWLEDGEMENTS

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TABLE I

TCA Operation during SiC test

Period	Operation	Plasma Time*	Integr. Taylor Cleaning (min)	Integr. Tokamak (sec)	Rpl($\mu\Omega$)	Comments
A	Pump (70hrs)					
B	Argon-Taylor	78 min	78			Heat to 80°
C	D_2Taylor (22hrs)	85 min	163			Still hot
D	D_2Taylor (4hrs)	15 min	178			Normal
E	Tokamak (8)	.9 sec		.9		1st. attempts
F	D_2Taylor (2hrs)	7 min	185			
G	Tokamak (22)	2.7 sec		3.6	> 14	(blue colour)
H	D_2Taylor (12hrs)	45 min	230			
J	Tokamak (28)	3.9 sec		7.5	.11	(blue tinge)
K	D_2Taylor (12hrs)	45 min	275			
L	Tokamak (16)	2.3 sec		9.8	9.0	Density control becomes normal(red colour)
M	D_2Taylor (12hrs)	45 min	320			
N	Tokamak (1)	.1 sec		9.9		
P	D_2Taylor (72hrs)	270 min	590			
Q	Tokamak (27)	3.9 sec		13.8	8.5-9.5	
R	D_2Taylor (12hrs)	45 min	635			
S	Tokamak (6)	.9 sec		14.7	8.5	
T	D_2Taylor (12hrs)	45 min	680			
U	Tokamak (44)	6.6 sec		21.3	8.5	Boloprofile/VUVlibrary
V	D_2Taylor (12hrs)	45 min	725			
W	Tokamak (50)	7 sec		28.3		11.6 kG, Hugill plot
X	D_2Taylor (72hrs)	270 min	995			
Y	Tokamak (22)	3 sec		31.3		Thomson, Z_{eff}

15 kG, n ~2×10^{13} cm^{-3}
126 kA q = 3.3
Gas : Deuterium

---

* During Taylor cleaning, 1 minute of plasma time requires 16 minutes of total cleaning time.

TABLE II

Radiated Power Measurements and Impurity Estimates

Limiter	Carbon	SiC
Antennae	TiN + screens	TiN + screens
Date	June 1984	August 1984
Gas	D_2	D_2
B_T[kG]	15.1	15.1
I_p [kA]	125	125
rf power [kW]	115	115
R_{pl} minimum (ohmic) [$\mu\Omega$] (rf)	12 14	8.5 10
P ohmic [kW]	212	156
P_{rad} [kW] (ohmic) (rf)	69 131	35 66
$\frac{P_{rad}}{P_{total}}$ (ohmic) (rf)	0.32 0.41	0.22 0.25
$\langle P_{rad} \rangle$ (ohmic) [W/cm^3] (rf)	0.17 0.34	0.09 0.17
P_{rad} (0) (ohmic) [W/cm^3] (rf)	0.1 0.15	<0.01 <0.01
P_{oh}(0) (ohmic) [W/cm^3] (rf)	1.7 1.9	1.25 1.36
η metal (0) (ohmic) (rf)	~ 0.1% ~ 0.1%	<0.05% <0.05%
Z_{eff}(0) ohmic	3-3.5 (4.25 Fig. 11)	2.6
n_e [cm^{-3}]	2-4 x 10^{13}	2-4 x 10^{13}

TABLE III

Summary of Bare Carbon vs SiC Coated Limiters

Factors of decrease of different line intensities, with/without rf (~110-115 kW)

		Cr XVI	.85/.62
O I	2.5/3.5	Ti XIX	1.0/1.1
O III	3.5/3.5		
O IV	6.0/6.3	Fe II	1.0/1.6
O V	9.0/7.3	Fe XVIII	1.1/1.9
O VI	9.5/7.4	Fe XIX A	1.3/2.1
O VII	10./7.1	Fe XXI	1.1/1.8
C I	1.2/1.3		
C II A	2.4/2.1		
C III	3.2/3.7		
C IV	2.3/2.3		
C V	3.0/2.9		
N III	4.1/4.2		
N IV	3.0/3.5		
N V	3.4/2.6		
N VI	3.5/2.7		
Si III	.015/.015		

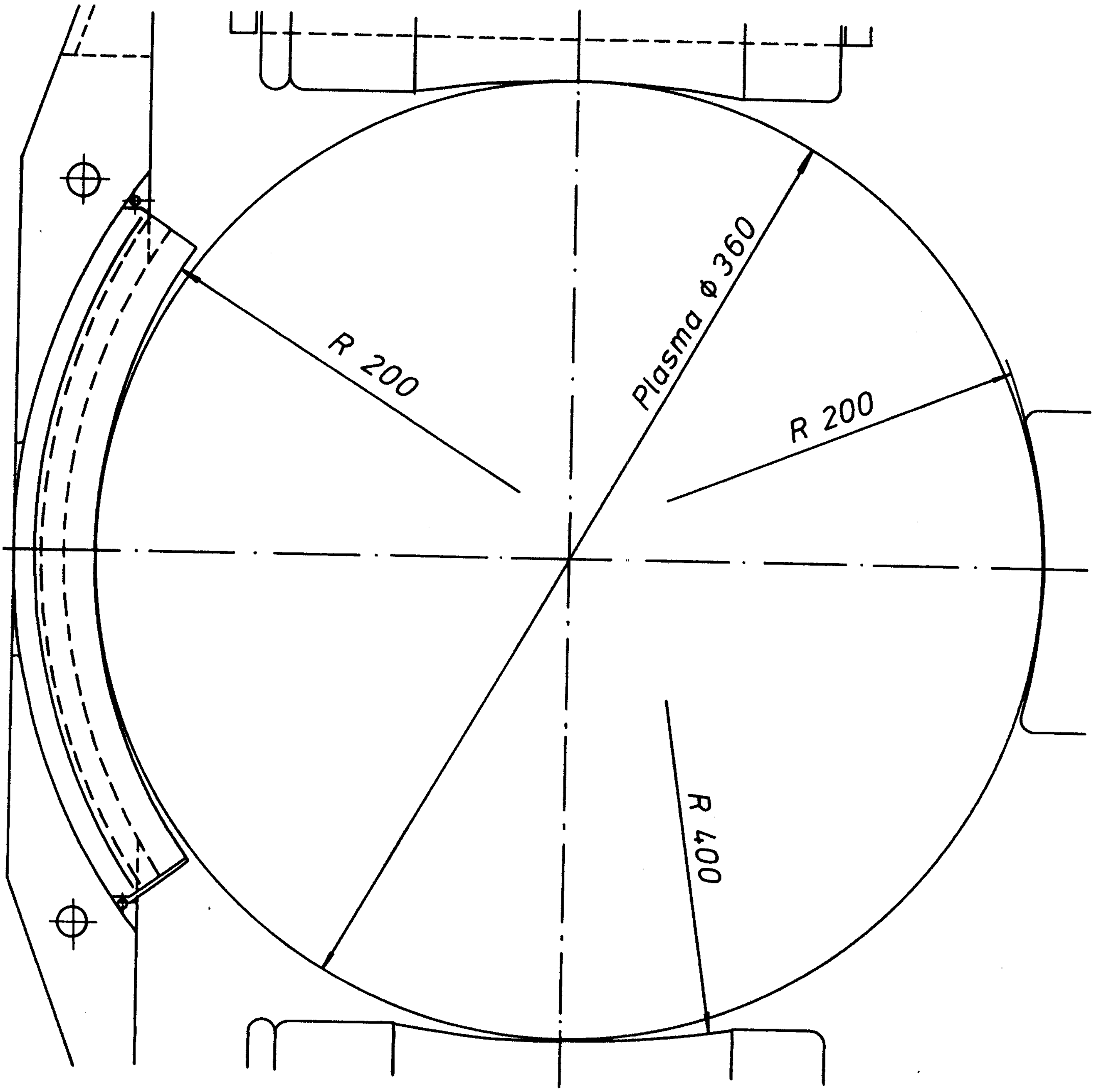


Fig. 1a. SiC-coated limiters in TCA tokamak.

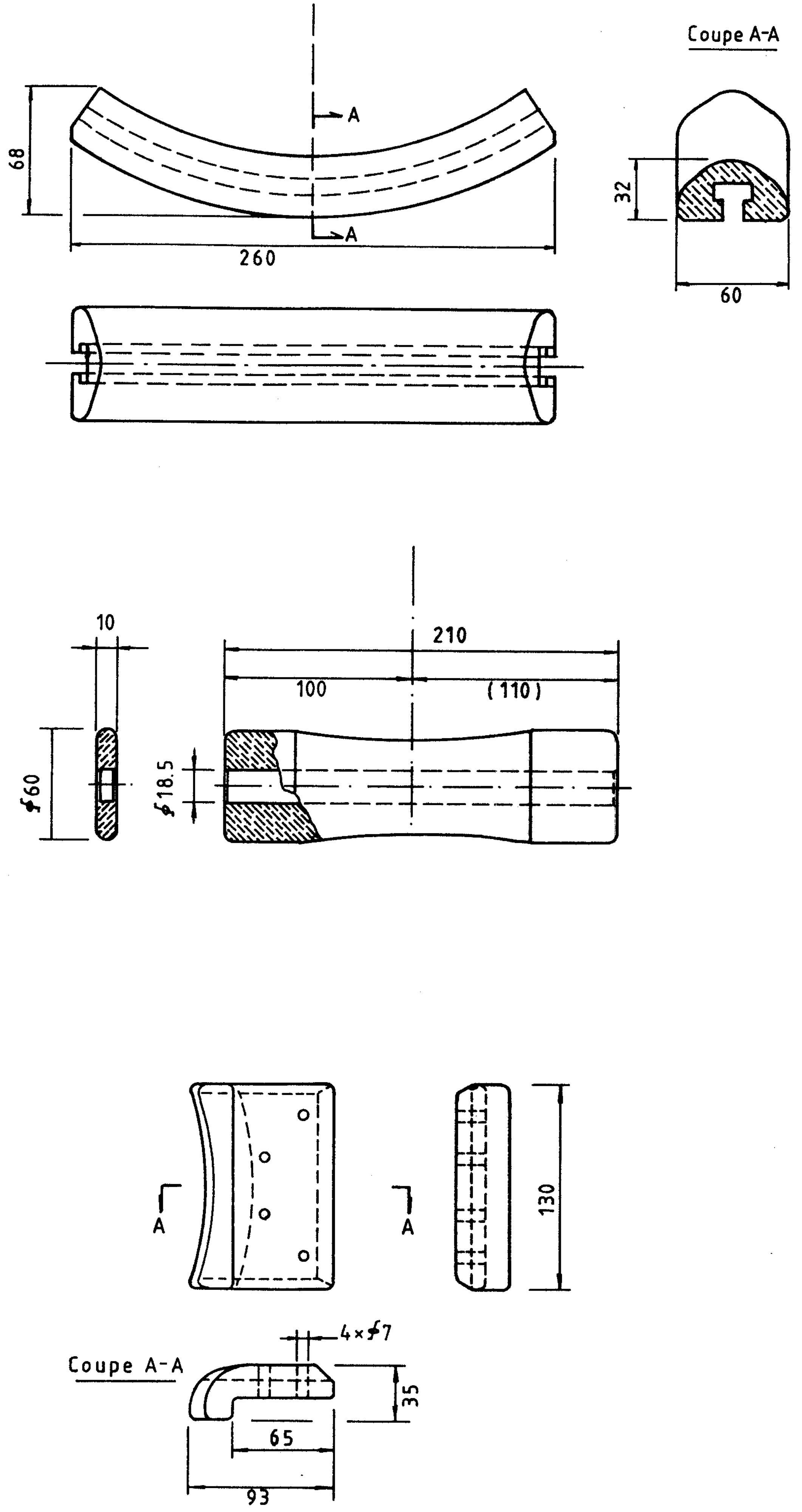


Fig. 1b. SiC-coated limiters.

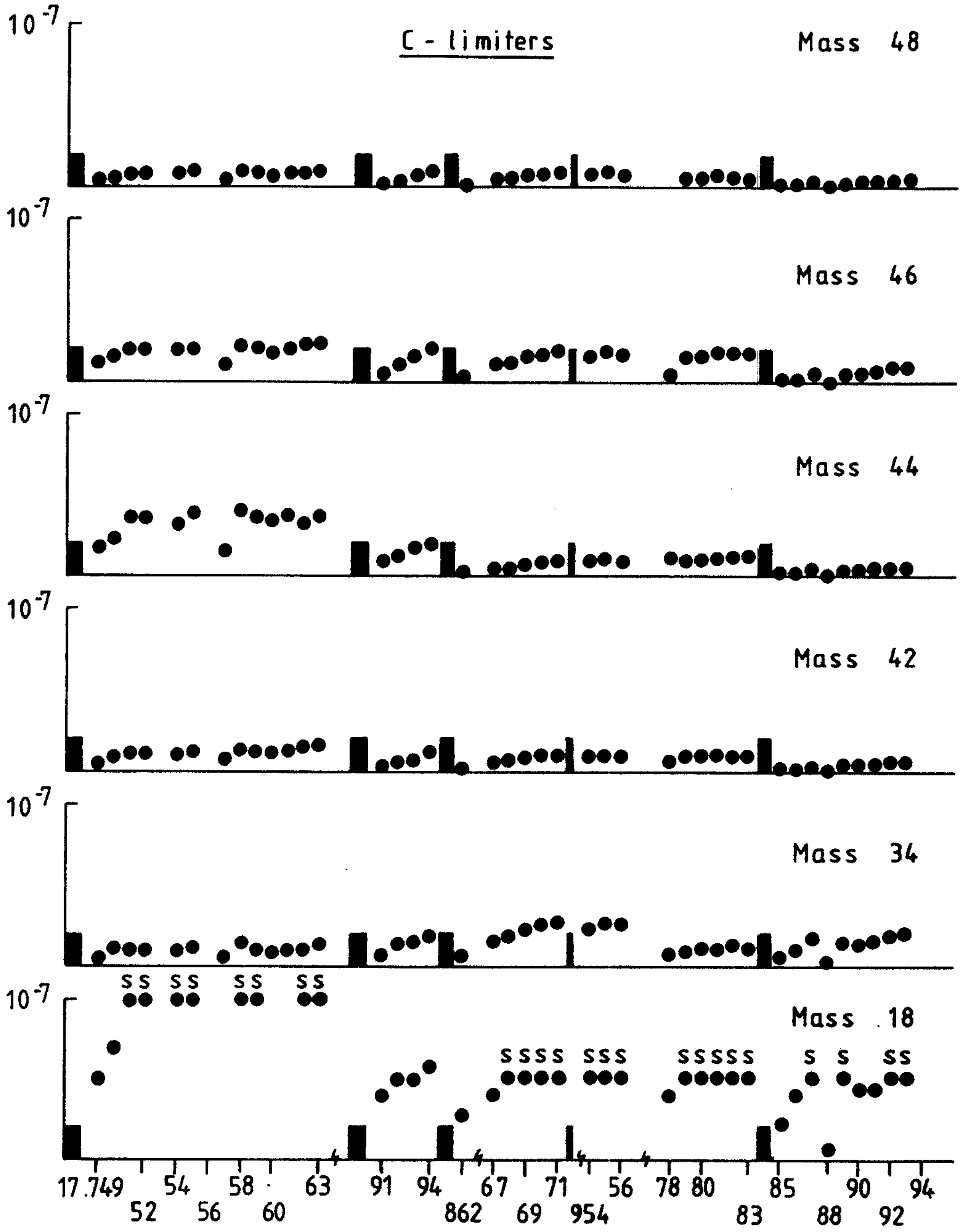


Fig. 2a. Residual gas analyser data with bare carbon limiters for successive plasma discharges. The bars indicate over-night or weekend Taylor cleaning (S = saturated). Partial pressures in millibars.

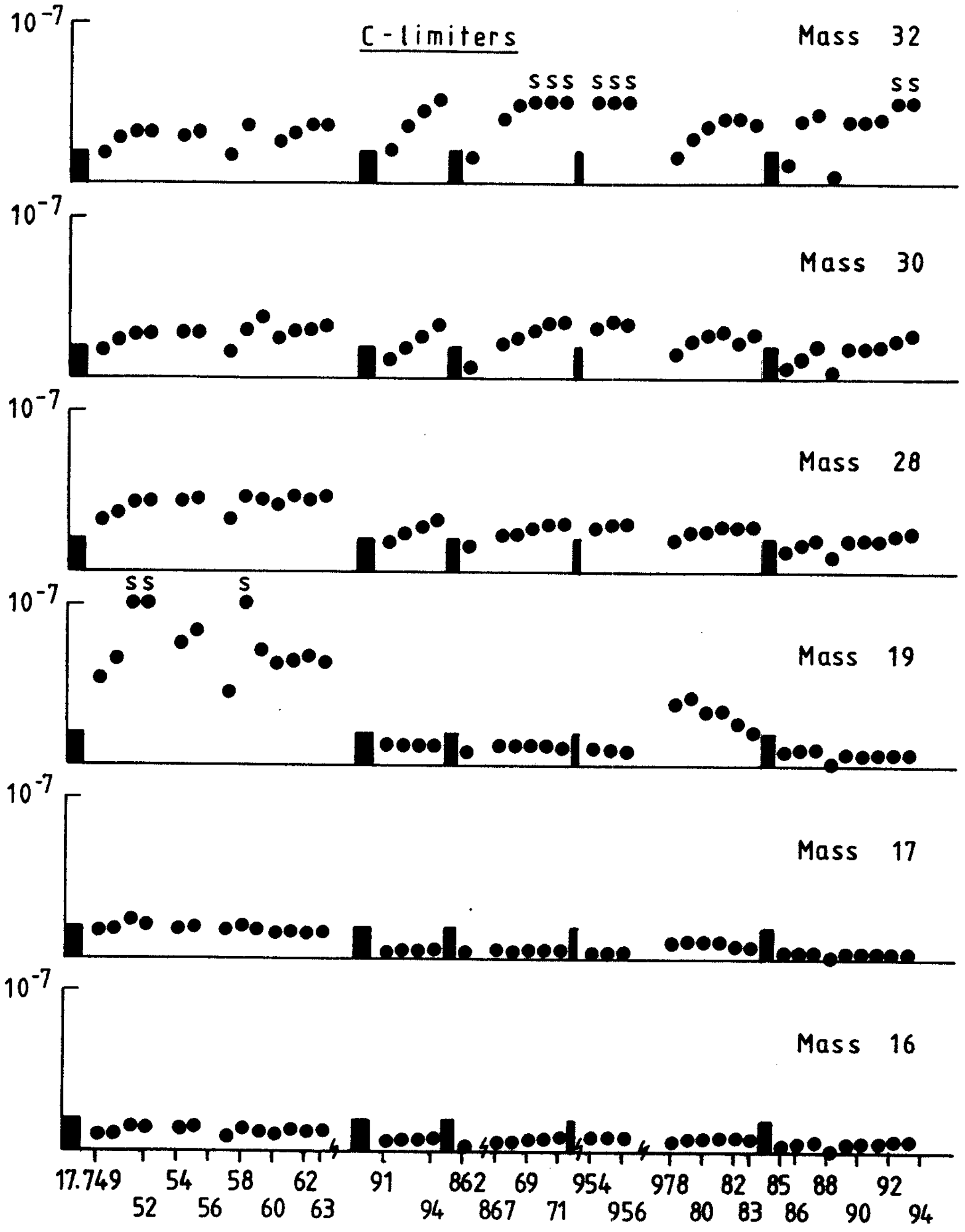


Fig. 2b. RGA data-bare carbon (cont.)

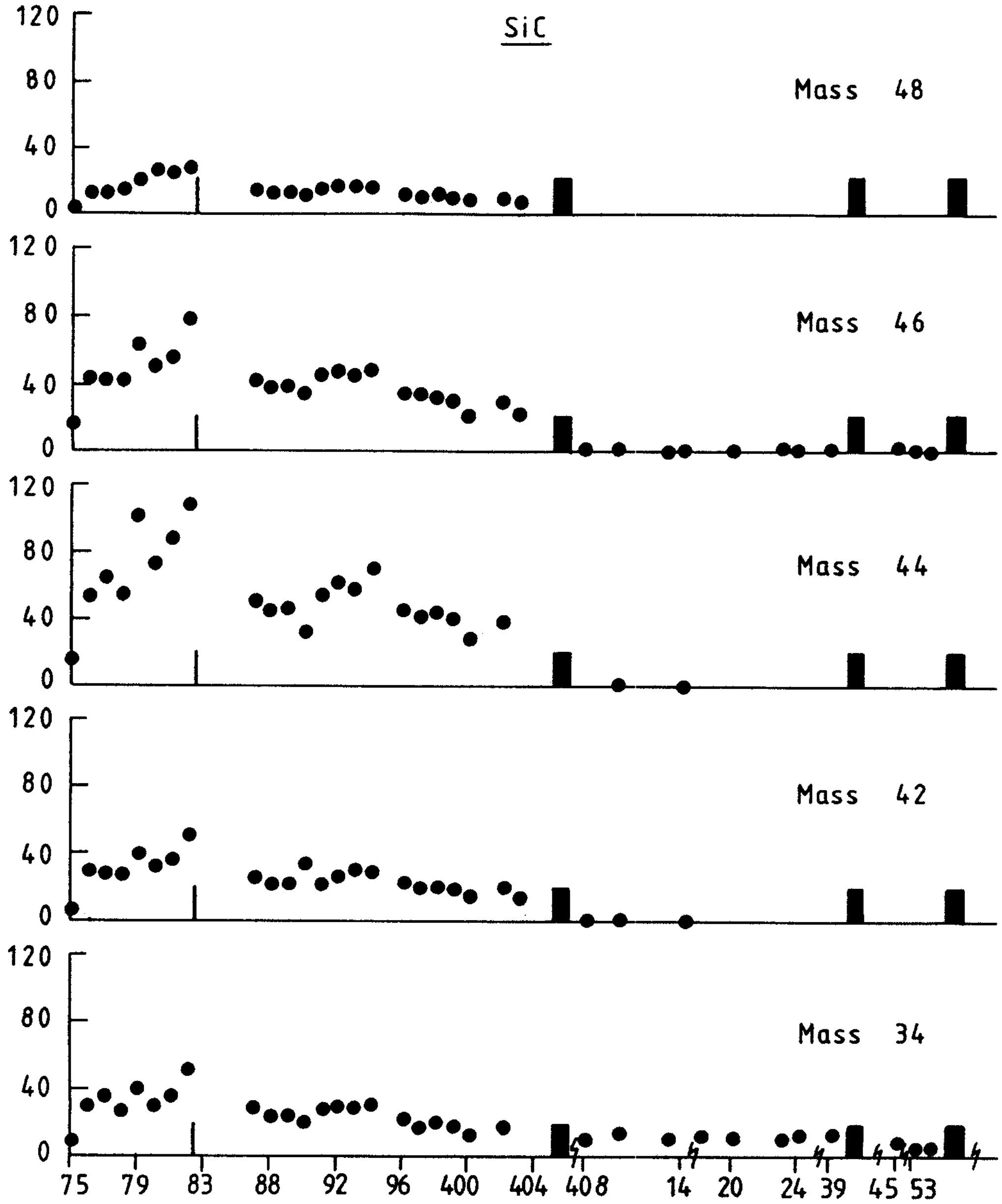


Fig. 3a. Residual gas analyser data with SiC coated limiters for successive plasma discharges. The bars indicate over-night or weekend Taylor cleaning. Partial pressures in 10^{-9} millibars.

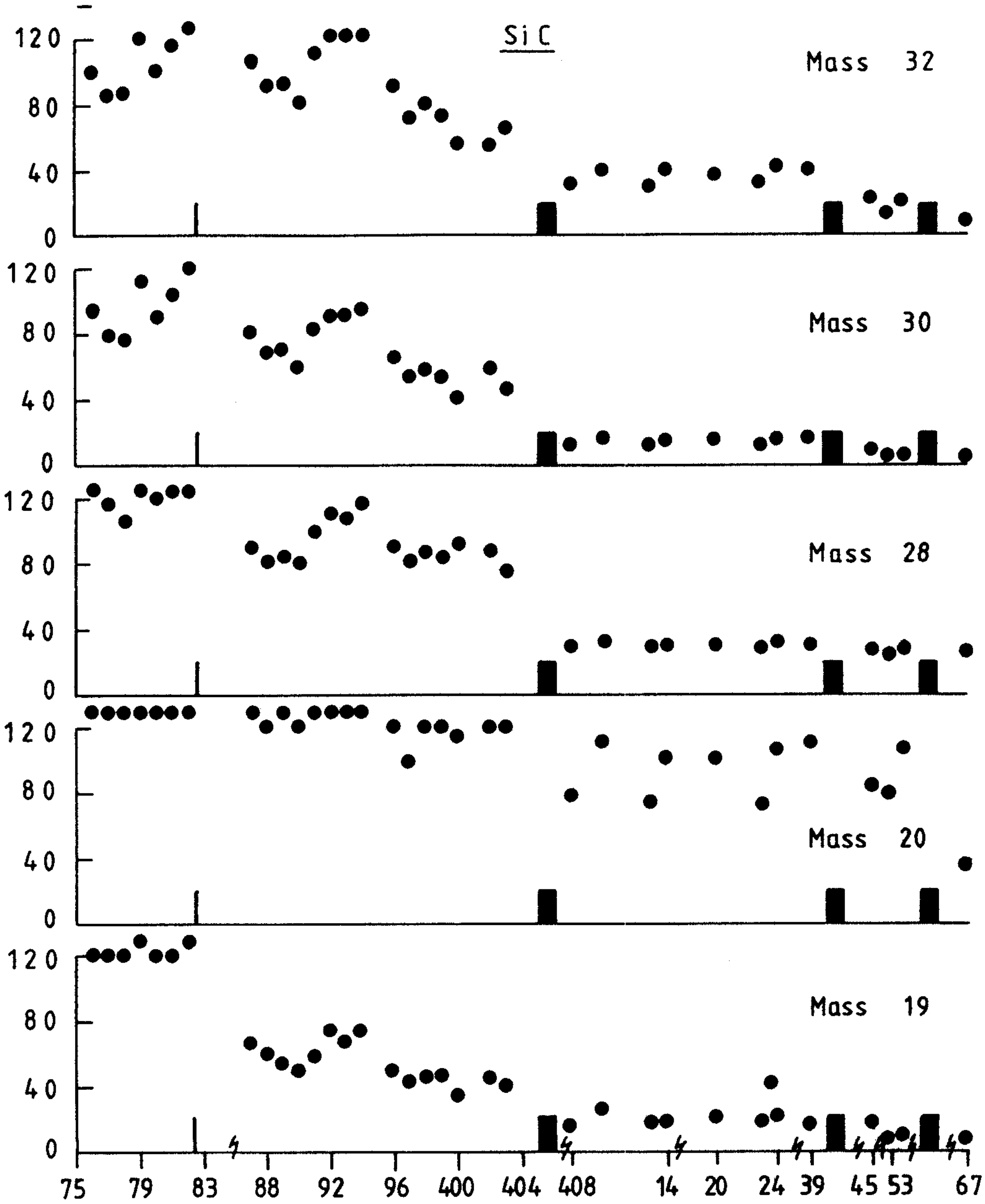


Fig. 3b. RGA data- SiC coated (cont.).

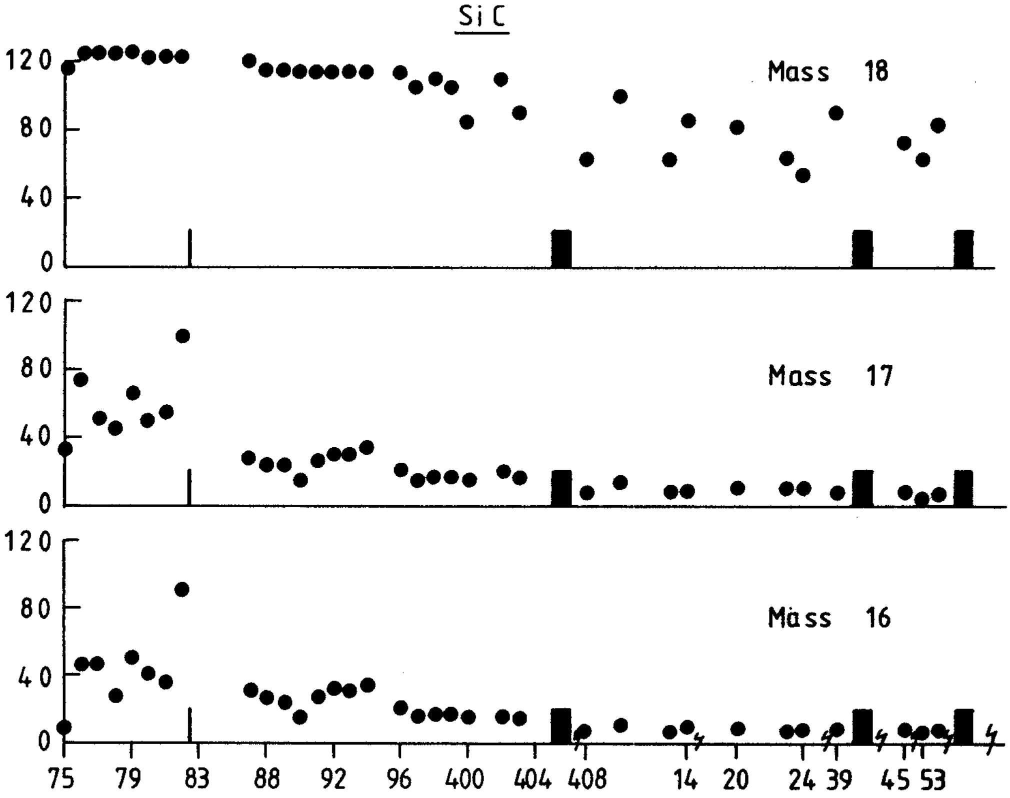


Fig. 3c. RGA data- SiC coated (cont.).

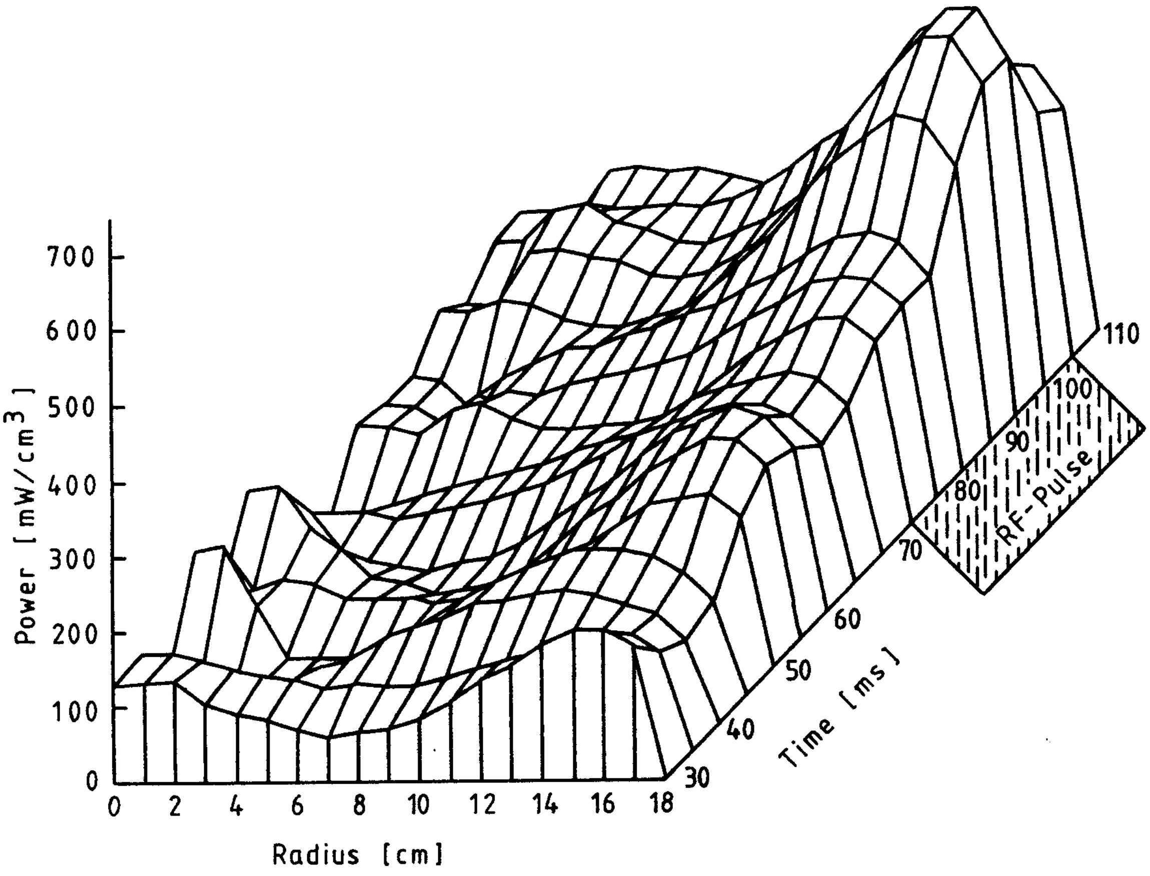


Fig. 4. Radiated power per unit volume as a function of plasma minor radius and time, from bolometer measurements, during ohmic and Alfvén wave heating, with bare carbon limiters, and TiN coated antennae and screens. (# 17871-17890)B_T = 15.1 kG, I_p = 125 kA, $\bar{n}_e$ = 2-4 x 10^3 cm^{-3}.

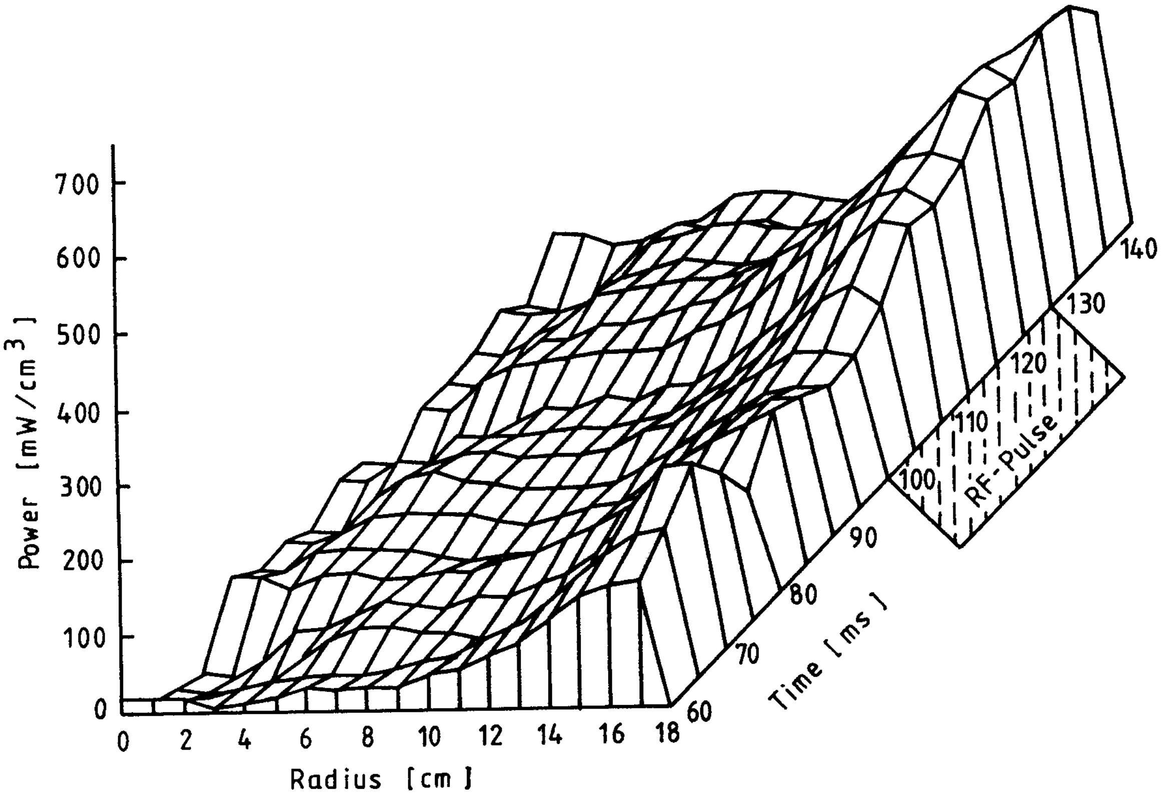


Fig. 5. Radiated power per unit volume as a function of plasma minor radius and time, from bolometer measurements, during ohmic and Alfvén wave heating, with SiC coated limiters, and TiN-coated antennae and screens. (# 18551-18570) B_T = 15.1 kG, I_p = 125 kA, $\bar{n}_e$ = 2-4 x 10^{13} cm^{-3}.

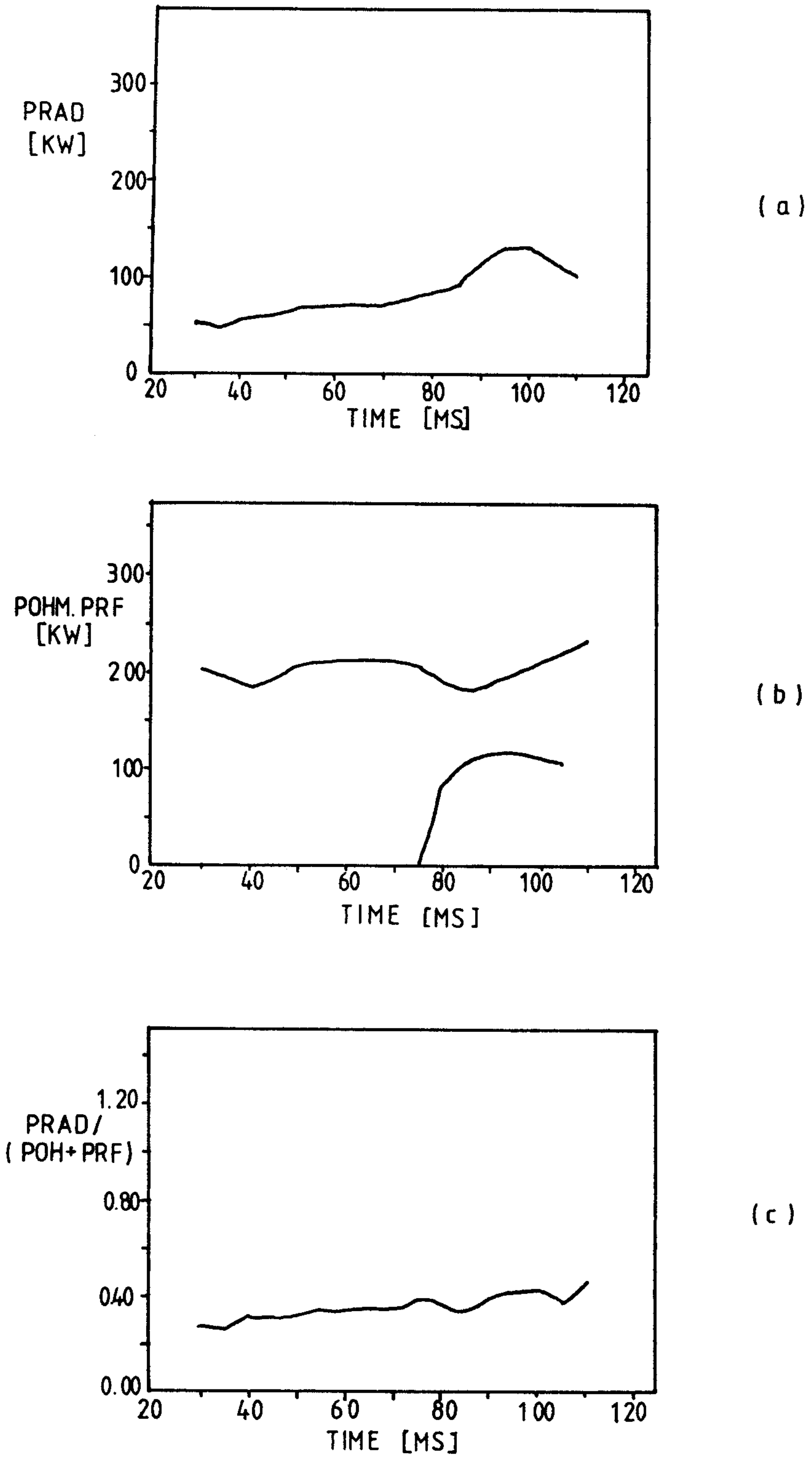


Fig. 6 a. Total radiated power versus time with bare carbon limiters. (# 17871-17890)

b. Ohmic heating (upper curve) and Alfvén wave heating power.

c. Ratio of radiated power to total heating power.

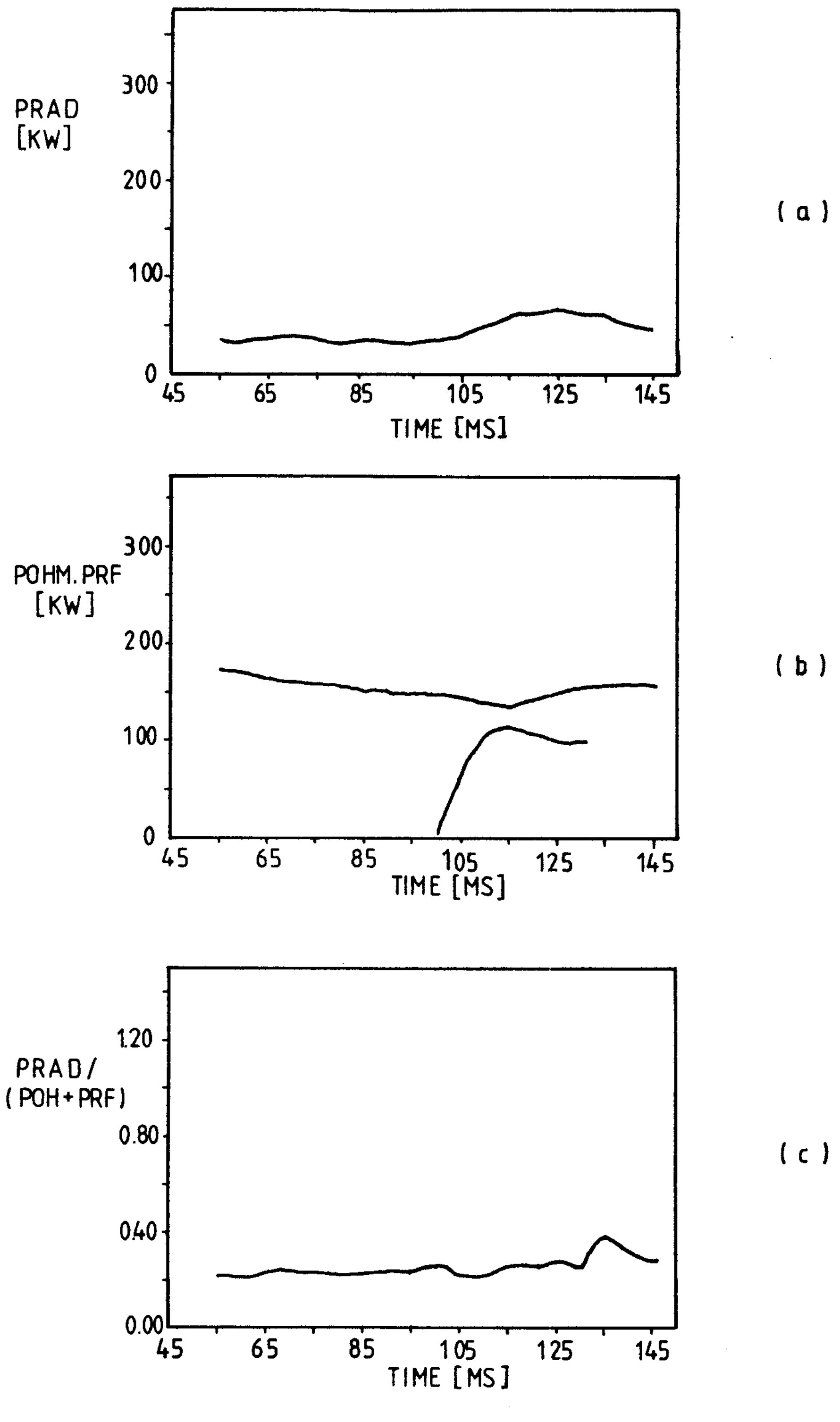


Fig. 7 a. Total radiated power versus time with SiC coated limiters. (# 18551-18570)

b. Ohmic heating (upper curve) and Alfvén wave heating power.

c. Ratio of radiated power to total heating power.

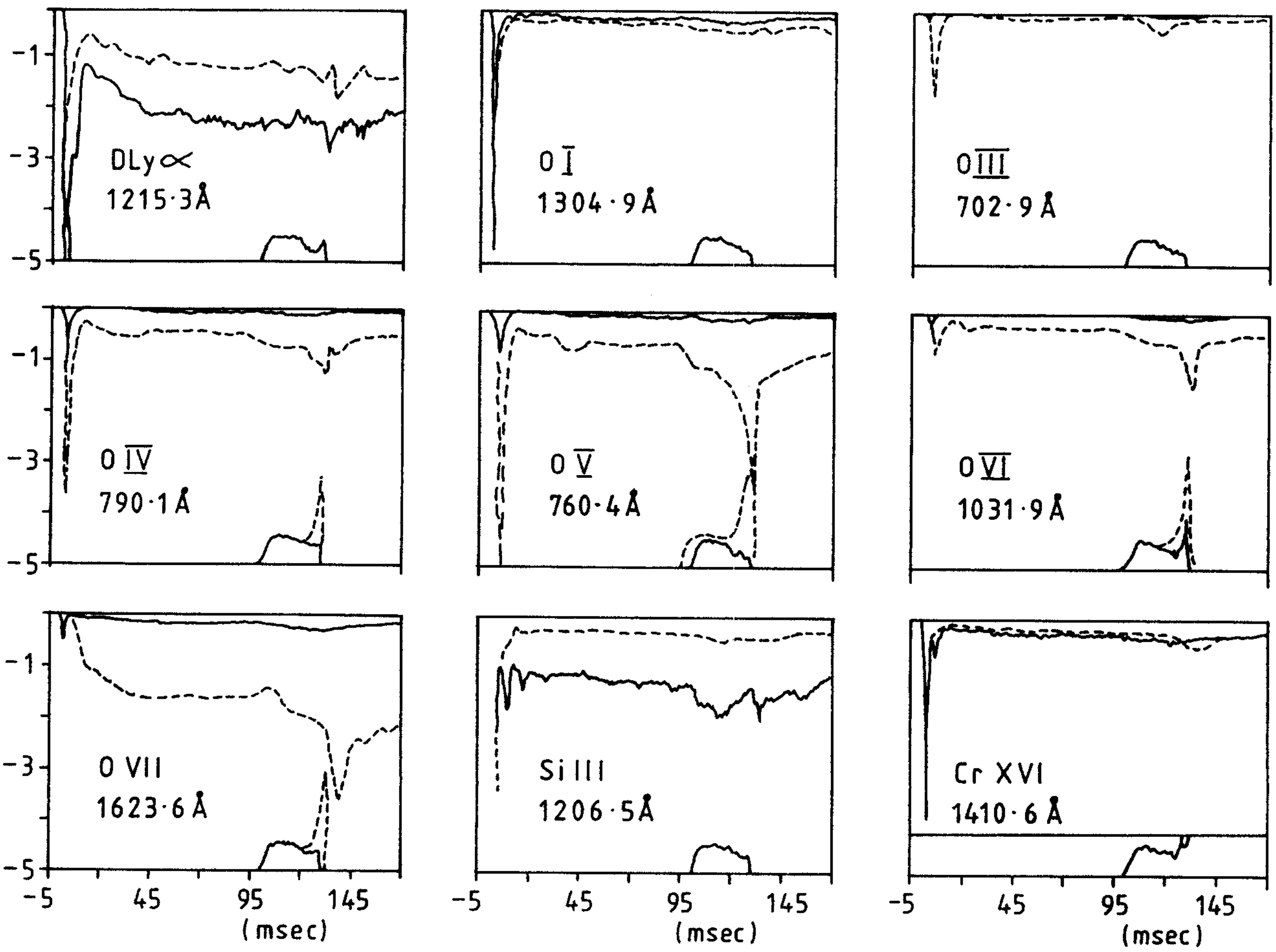


Fig. 8a. Time-dependance of VUV lines. The dotted line is bare carbon limiters. The solid line is with SiC coated limiters. (Si signal is divided by 16.) Zero- amplitude is at the top of the box, and the signals go negative. The Alfvén wave field is shown at the bottom. The antennae have TiN-coated side-screens. Plasma conditions are D_2 gas, 15 kG, ~ 110 kW of Alfvén wave heating, above the N=2 discrete Alfvén wave.

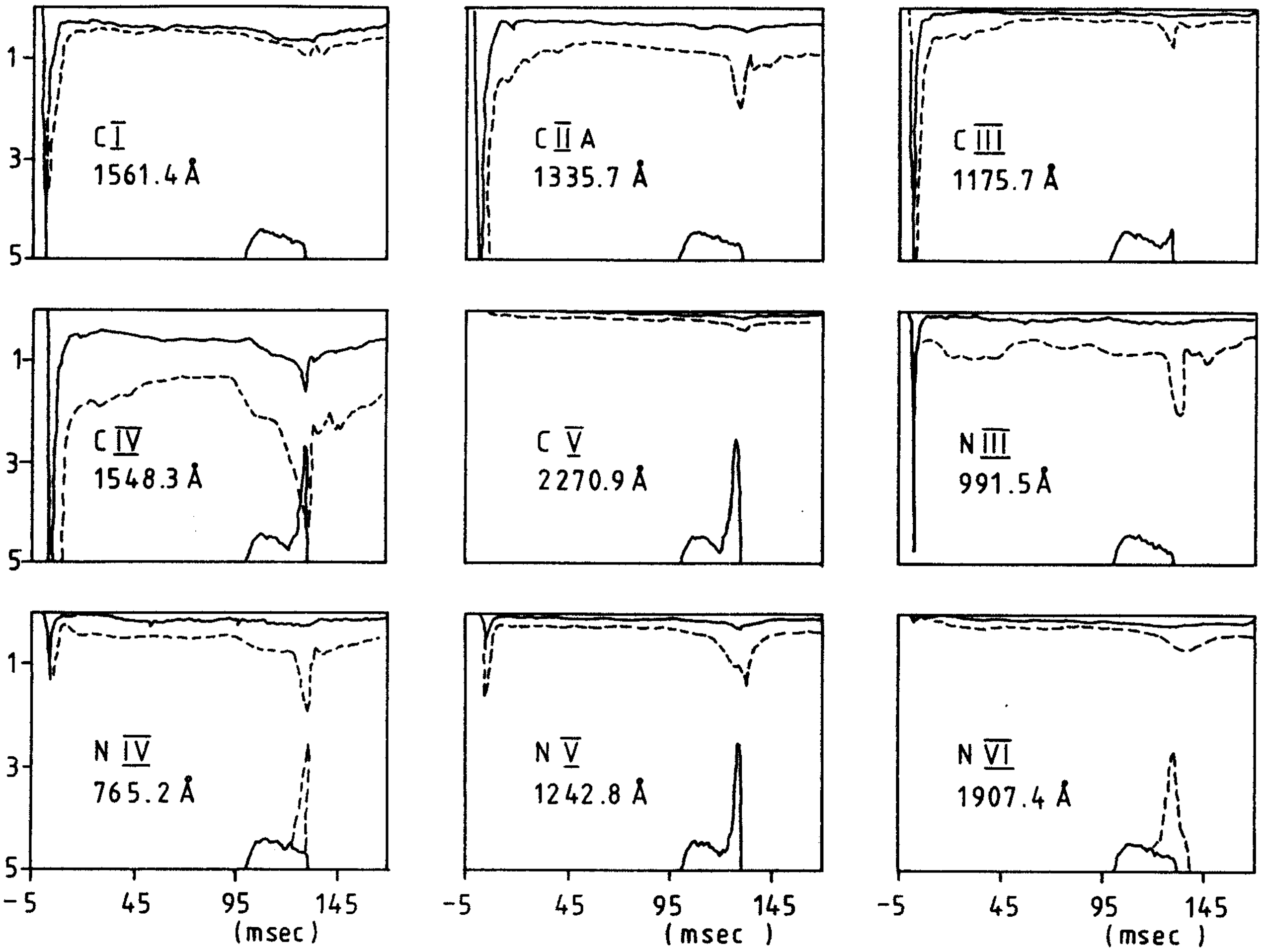


Fig. 8b. VUV lines (cont.).

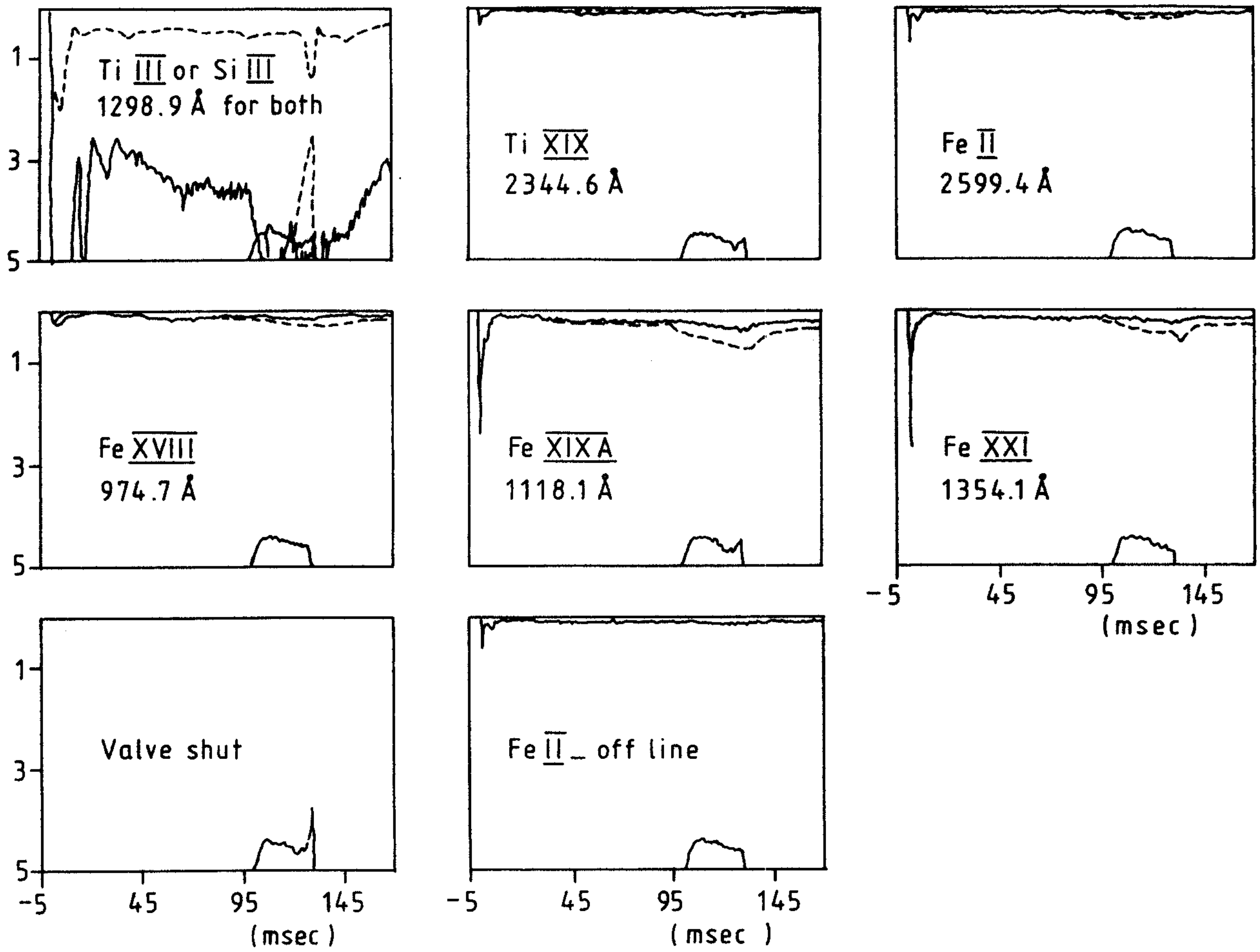


Fig. 8c. VUV lines (cont.).

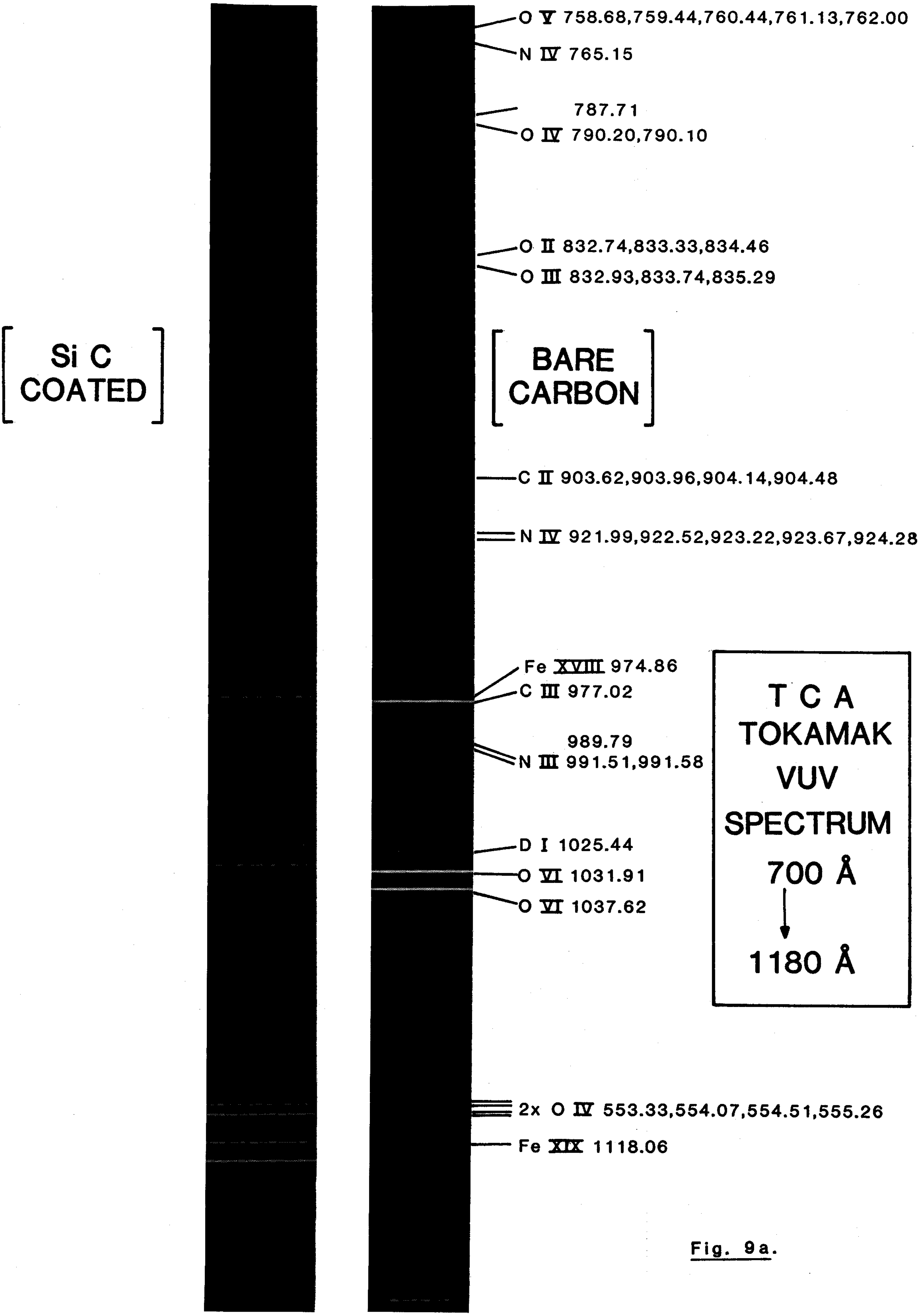

O V 758.68,759.44,760.44,761.13,762.00
N IV 765.15
787.71
O IV 790.20,790.10
O II 832.74,833.33,834.46
O III 832.93,833.74,835.29
[Si C COATED]
[BARE CARBON]
C II 903.62,903.96,904.14,904.48
N IV 921.99,922.52,923.22,923.67,924.28
Fe XVIII 974.86
C III 977.02
989.79
N III 991.51,991.58
D I 1025.44
O VI 1031.91
O VI 1037.62
2x O IV 553.33,554.07,554.51,555.26
Fe XIX 1118.06
T C A
TOKAMAK
VUV
SPECTRUM
700 Å
1180 Å

Fig. 9a.

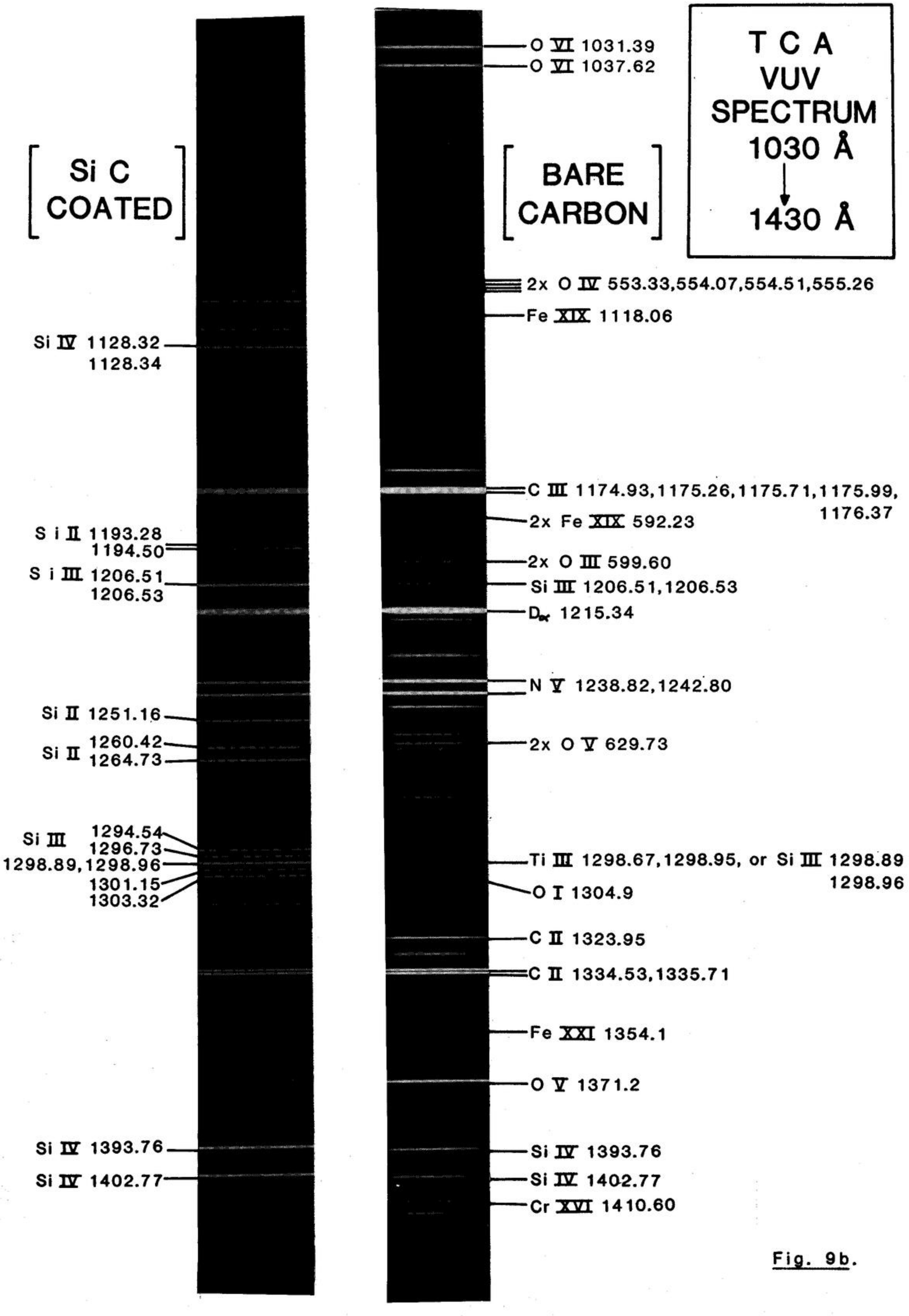

T C A
VUV
SPECTRUM
1030 Å
1430 Å
[Si C COATED]
[BARE CARBON]
O VI 1031.39
O VI 1037.62
2x O IV 553.33,554.07,554.51,555.26
Fe XIX 1118.06
Si IV 1128.32
1128.34
C III 1174.93,1175.26,1175.71,1175.99,
1176.37
2x Fe XIX 592.23
S i II 1193.28
1194.50
2x O III 599.60
S i III 1206.51
1206.53
Si III 1206.51,1206.53
Dα 1215.34
N V 1238.82,1242.80
Si II 1251.16
Si II 1260.42
1264.73
2x O V 629.73
Si III 1294.54
1296.73
1298.89,1298.96
1301.15
1303.32
Ti III 1298.67,1298.95, or Si III 1298.89
1298.96
O I 1304.9
C II 1323.95
C II 1334.53,1335.71
Fe XXI 1354.1
O V 1371.2
Si IV 1393.76
Si IV 1393.76
Si IV 1402.77
Si IV 1402.77
Cr XVI 1410.60

Fig. 9b.

T C A
VUV
SPECTRUM
1330 Å
↓
1750 Å

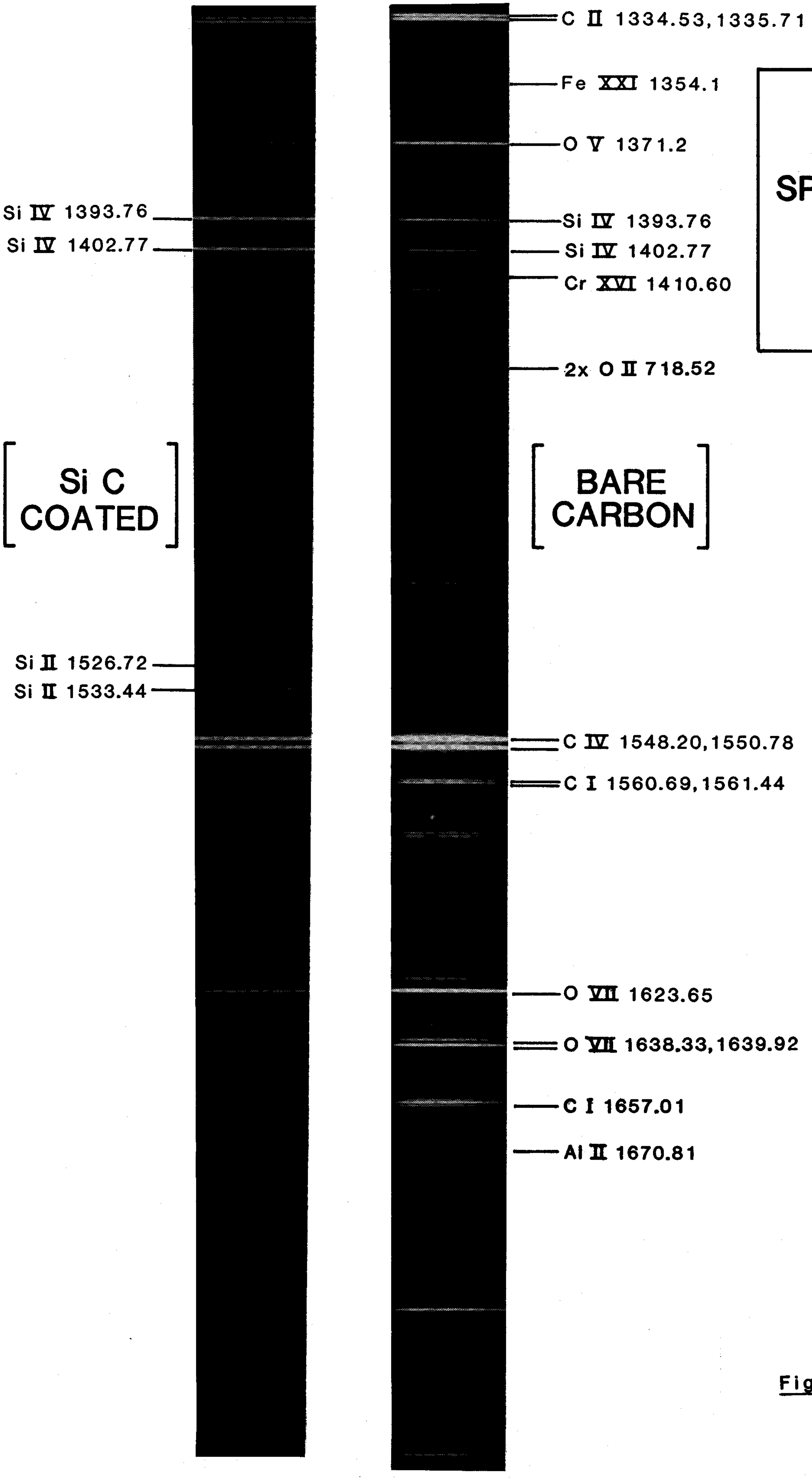


Fig. 9c.

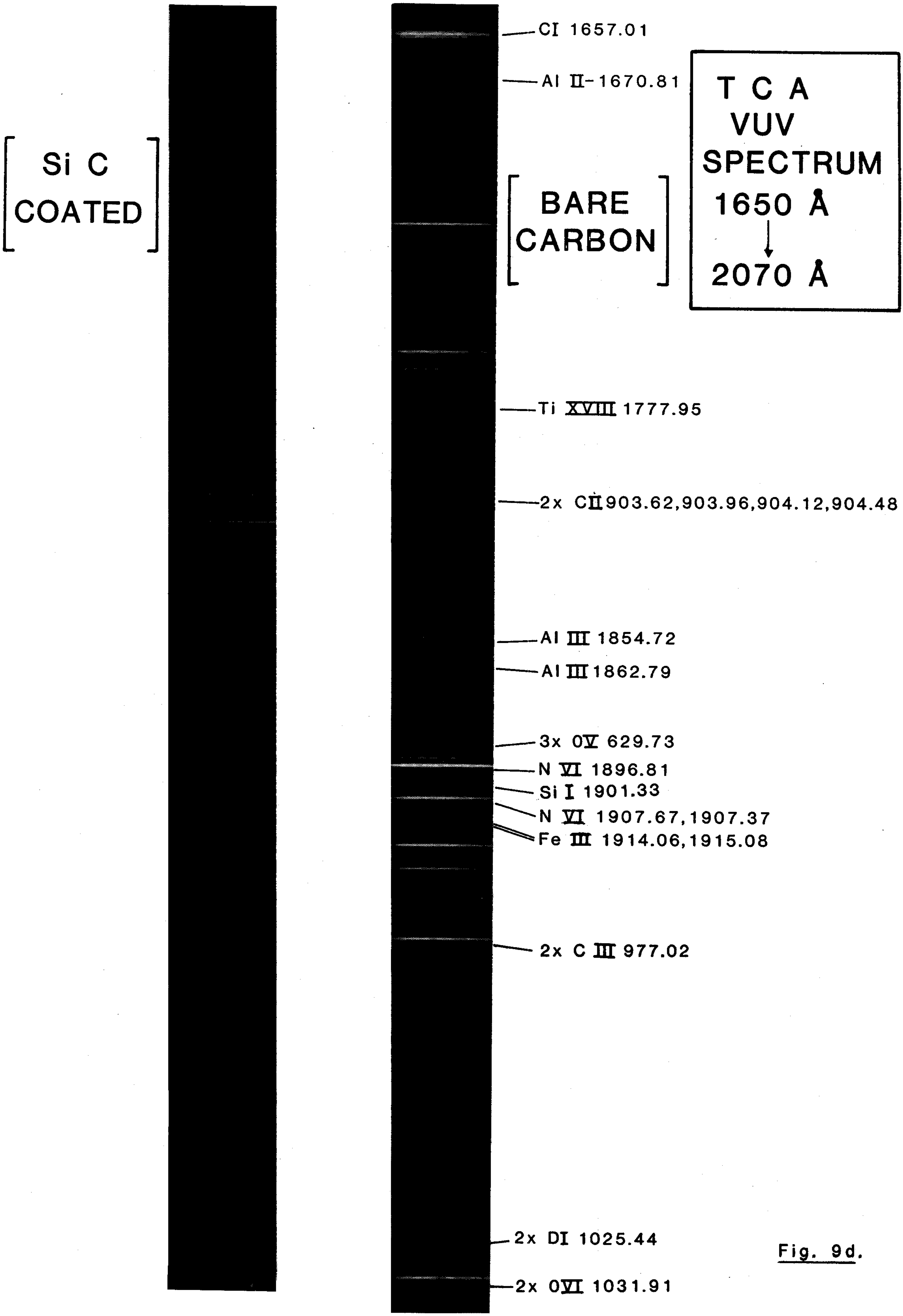
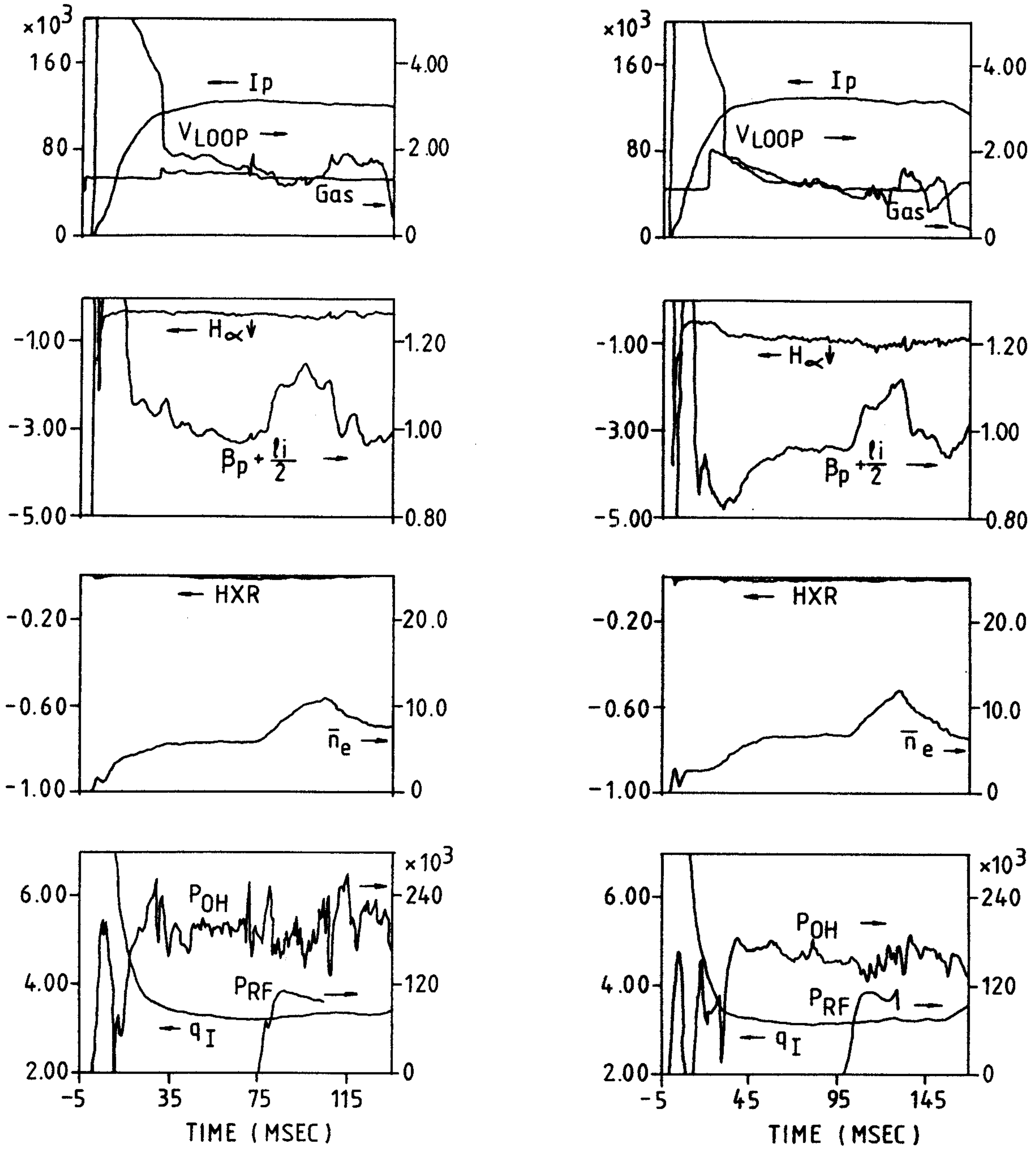

Si C
COATED
BARE
CARBON
T C A
VUV
SPECTRUM
1650 Å
2070 Å
CI 1657.01
Al II-1670.81
Ti XVIII 1777.95
2x CII 903.62,903.96,904.12,904.48
Al III 1854.72
Al III 1862.79
3x OV 629.73
N VI 1896.81
Si I 1901.33
N VI 1907.67,1907.37
Fe III 1914.06,1915.08
2x C III 977.02
2x DI 1025.44
2x OVI 1031.91

Fig. 9d.



a.

b.

Fig. 10. Plasma discharge parameters versus time.
a. With bare carbon limiters (# 18291)
b. With SiC-coated limiters (# 18557)
Parameters: I_p-plasma current; V_{LOOP}-loop voltage; gas-gas puff rate; H_α-H_α light; β_p+li/2-Shafranov param; HXR-hard x-ray; $\bar{n}_e$-line-ave density in 2 mm fringes; P_{OH}, P_{RF}-ohmic and Alfvén power;

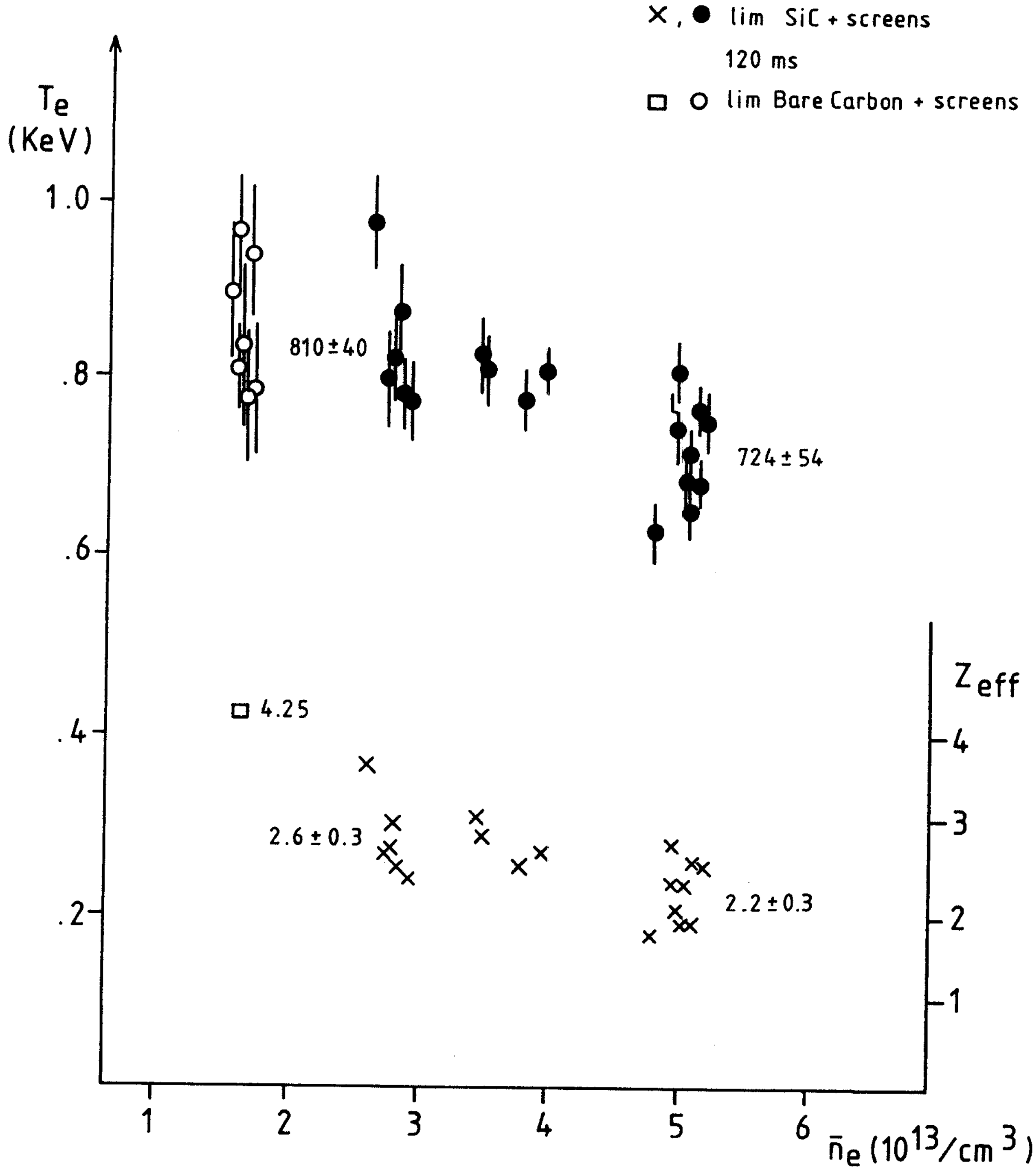


Fig. 11. Central Thomson scattering electron temperature and inferred central Z_{eff}, during ohmic heating. The symbols are for:

central T_e: O-bare carbon; •-SiC coated;

central Z_{eff}: □-bare carbon; x-SiC coated.

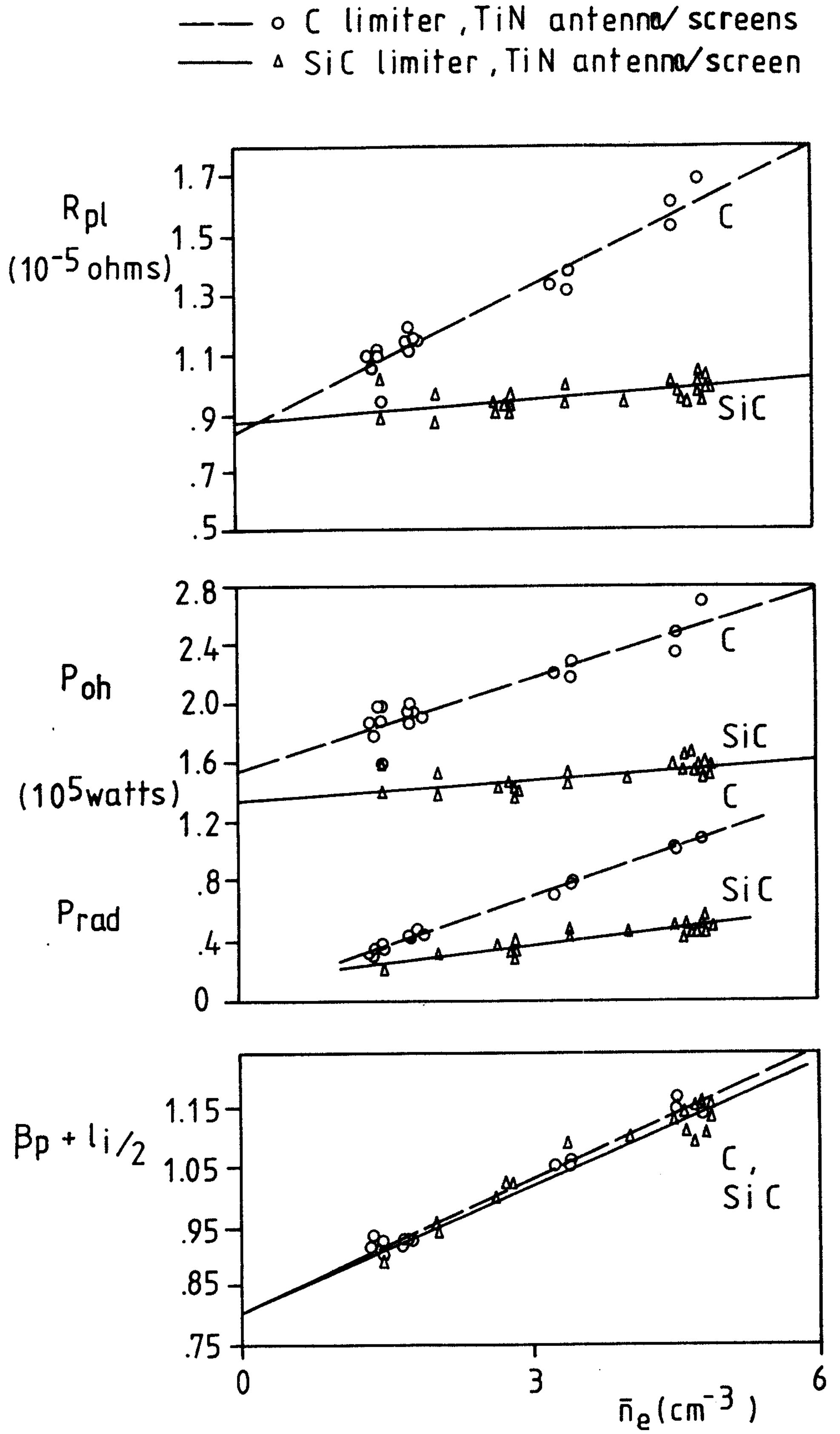


Fig. 12. Plasma parameter versus line-averaged density during ohmic heating, with bare carbon and SiC coated limiters: R_{pl}-plasma resistivity; P_{OH}, P_{rad}-ohmic and radiated power; β_p+li/2-Shafranov parameter.

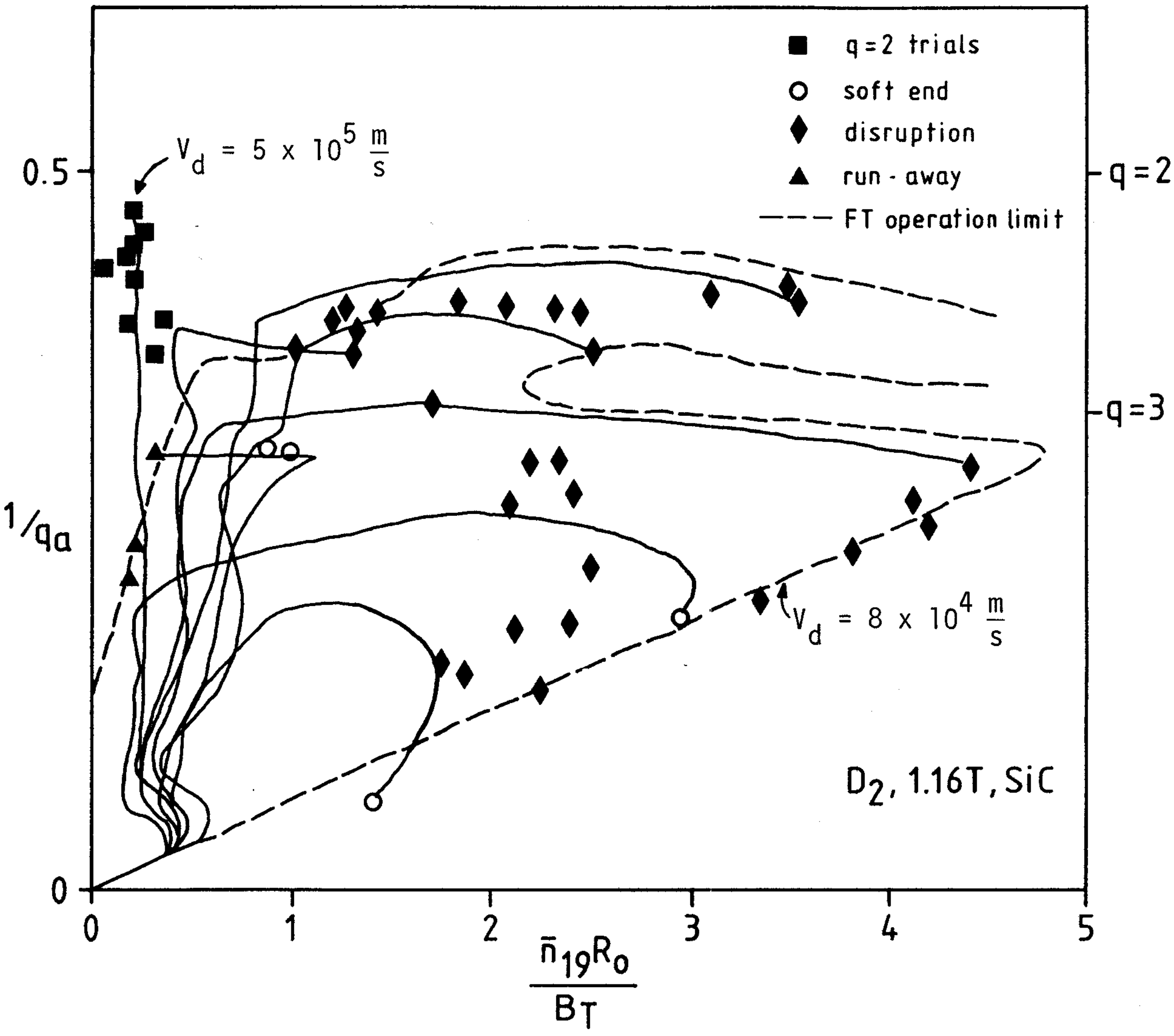


Fig. 13. Hugill-type diagram of $1/q_a$ versus $n_{19}R_0/B_T$ with SiC coated limiters.