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of the Alcator C-Mod Tokamak**

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Abstract

Argon has been injected into the private flux zone of the Alcator C-Mod divertor and its transport into the confined plasma studied. The injected gas pulse lasts for about 200 ms, but the impurity concentration increases to an equilibrium level and remains there for ~ 1 s. It is clear that the argon is acting as a recycling impurity. Nevertheless it has been observed that less than 0.5% of the injected atoms reach the confined plasma and that the percentage decreases with increasing plasma density. The good impurity screening is discussed in terms of the ionisation mean free path in the divertor.

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1. Introduction

In divertor tokamaks the impurity source, resulting primarily from ion-surface interactions, is in principle remote from the confined plasma. One of the anticipated advantages of this configuration is that impurities produced at the divertor target plates have a high probability of being ionised and swept back to the target by the fuel species ion flow. Other factors may however over-ride the simple picture. Reverse flow in the scrape-off layer (SOL), as observed in 2-D fluid calculations[1], is one possibility and the ion temperature gradient force acting away from the target plate is another.

An attempt to assess the global effect of these factors experimentally has been made by introducing impurities at a known rate through the target plate. The experiments are similar to those which have been carried out on limiter tokamaks [2]. The impurity gas has been injected at two points in the divertor region of the Alcator C-Mod tokamak, the private flux region and the inner SOL. The transport of these impurities from the divertor to the confined plasma has been studied spectroscopically.

2. Experiment.

Alcator C-Mod is a high field, high density, divertor tokamak [3,4]. Typical operating conditions for the present experiments were $I_p=0.8$ MA, $n_e=6-12 \times 10^{19} \text{ m}^{-3}$, $B_T=5$ Tesla, $T_e(0)=1.0-1.8$ k eV and elongation =1.6, in a single null diverted configuration.

The arrangement of the impurity injection and the diagnostics is shown in fig 1. The impurity gas puffing system consists of an array of capillary tubes which are connected to various poloidal positions at the divertor target plates and the inner wall. The system has been used both

for impurity puffing and for fuelling the main plasma. Only the positions in the private flux zone (A) and on the inner wall (B) have been used in the present experiments. The flow in the capillary tubes is controlled by a pneumatically operated valve and the preset pressure in a plenum. The flow rate is measured with a differential capacitance manometer (Baratron type 221) using a method described by Dylla[5]. The total number of atoms injected is 2×10^{19} atoms in a ~ 0.2 s pulse. The plenum operates at relatively high pressure because of the low conductance of the capillary tubes. With argon at 1 torr there is a typical delay of ~ 100 ms between the opening of the valve and the arrival of the gas in the divertor. This delay has been calibrated as a function of pressure for argon and deuterium. The flow has a rise time of 100 ms but the decay time of the flow rate is longer due to the flow of gas out of the capillary volume after the valve is shut; it has an approximately exponential tail with a time constant of ~ 200 ms.

The argon concentration in the core plasma is measured using a crystal spectrometer [6] viewing Ar XVII at up to 5 chords simultaneously. In addition there are conventional measurements of the n_e , T_e , total radiation profiles, Z_{eff} and other spectroscopic measurements. The n_e and T_e profiles in the SOL and along the target plates are measured with a scanning probe and an array of Langmuir probes in the tiles [7]. Typical conditions at the divertor plate which have been used for argon injection experiments, vary from $T_e = 20$ eV, $n_e = 1 \times 10^{19} \text{ m}^{-3}$ to $T_e = 10$ eV, $n_e = 5 \times 10^{19} \text{ m}^{-3}$. The target temperature stays approximately constant for most of the injection time but falls by 20% at 500 ms.

3. Results

The response of the plasma to an argon injection is shown in fig 2. The argon is injected at 0.4 s for about 0.2 s and its concentration in the confined plasma monitored as a function of time using the crystal spectrometer. The impurity concentration builds up over a period of 120 ms to a nearly steady-state level. The density remains approximately constant, Z_{eff} increases slightly ($\delta Z_{\text{eff}} = 0.3$) and the total radiation increases by about 200kW as a result of the impurity injection. There is no detectable delay (<10 ms) between the spectroscopic measurements along different chords at minor radii varying between $r=0$ and $r=0.18\text{m}$. This is consistent with the measured cross field diffusion rates of impurities injected by laser ablation into the confined plasma [8]. No argon had been injected for more than 10 discharges before shot 931014022 and it is seen that the argon signal is close to zero before the impurity injection at 0.4 s.

Argon injected through capillary B on the inner wall, shot 931014023, rose to the same equilibrium value and had the same time constants as the injection into the private flux zone, fig 2. There appears to be a delay compared to the injection into the private flux zone, but this may be due to the longer capillary leading to the inner wall. The time delay is within the uncertainty in the calibration. It is notable that in shot 931025023 the argon signal rises before argon injection, to about 10% of the maximum value in the previous shot. This is attributed to the release of argon trapped in the walls during the previous shot. By comparing with a shot in which there is no argon injection it is found that the argon density decays to the background level in a few discharges.

The total impurity concentration is calculated using the MIST 1-D transport code [9], normalising the code results to the measured value of the Ar XVII concentration. The concentration profile varies, depending on conditions but is normally flat or slightly hollow. In a series of injections

with identical argon injections, into discharges over a range of densities, it was found that the central argon concentration decreased with increasing n_e , see fig 3. In all cases the total number of impurity atoms in the core plasma was less than 0.5 % of the total number of atoms injected. The increase in radiation due to the impurity injection obtained from the MIST calculation is ~ 80 kW and the increase in $Z_{\text{eff}} = 0.25$. The increase in Z_{eff} is consistent with measured value, fig2, but the P_{RAD} is significantly lower than the measured ~ 200 kW. This discrepancy is not understood.

At a critical plasma density the plasma detaches from the divertor target reducing the power to the target plates by a factor of 10 or more [4]. Such a mode of operation would possibly be advantageous in reducing the power loading on the divertor target in ITER [10]. However the effect of the detachment is to increase the impurity radiation, as shown in fig 4. In this case a short (20ms) gas puff was introduced at 0.1 s and the argon density in the main plasma was increasing approximately linearly from 0.4 s. However at 0.61 s the plasma detaches from the target. This is indicated by the increase in dn_e/dt , fig 4a, and the sudden drop in the ion current to the target, fig 4b. At the same time the density of ArXVII increases suddenly by a factor of over 2. Similar behaviour is observed for the intrinsic carbon impurity lines, CV and CVI. This increase is thought to be related to increased penetration through the SOL, due to lower electron temperatures.

4. Discussion.

The low argon impurity content measured in the confined plasma is a rather encouraging result. However similar experiments using neon in DIIIID showed much higher fuelling efficiency [11]. The difference could be ascribed either to the differences in atomic physics, eg ionisation rate coefficients, to the higher density in the C-Mod divertor or to the

difference of the divertor configuration, eg target orthogonal to flux surfaces in DIIID vs steeply inclined plate in C-Mod . Clearly experimental measurements with a number of different impurities need to be done in the same machine under the same plasma conditions.

The spatial distribution of the argon ionisation has been calculated using a simple Monte Carlo code. The n_e and T_e profiles obtained from the scanning Langmuir probe [7] are mapped onto the magnetic flux surfaces obtained from the EFIT magnetics code [13]. It is assumed that both n_e and T_e are constant on flux surfaces which is a reasonable approximation at the lower densities used. The argon atoms are launched from the gas puff position with a cosine angular distribution and a Maxwellian energy distribution ($T=0.1$ eV). Using published ionisation rate coefficients [14] the position of maximum ionisation probability is calculated for each trajectory. The results for the two launching positions used experimentally are shown in fig 6. It is observed that all ionisations occur in the private flux zone for launch position A and in the SOL for position B.

5. Conclusions

The present results indicate good screening for argon impurities under the conditions in the Alcator C-Mod divertor, both for impurities injected into the private flux zone and at the inner wall. The screening improves as the density increases and seems to be related to the high probability of ionisation far from the separatrix. The screening is considerably reduced in shots where the plasma detaches from the target. On this basis the screening for gases with lower ionisation cross-sections is also likely to be less effective.

Further experiments are desirable to investigate how impurity

screening varies with different impurities and with divertor conditions. More detailed calculations using fluid or Monte Carlo codes are also desirable in order to obtain a better understanding of the experimental data.

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Figure captions

1. Schematic of diagnostics and the divertor gas fuelling system for argon injection experiments. The position of all the gas puffing positions are indicated with arrows. However only A and B were used in the present experiments.
2. Comparison of the time response of the spectrometer chords at different minor radius for two discharges , 931014022, puffing into the private flux region, position A, fig 1, and 931014023, puffing at the inner wall , positionB, fig 1. Variation of the radiated power(a), and the Z_{eff} , (b) are also shown. The central density is $1 \times 10^{20} \text{ m}^{-3}$
3. Variation with density, n_e , of the total number of argon atoms in the confined plasma for a series of discharges with identical argon puffs of 2×10^{19} atoms.
4. Argon concentration as a function of time during a shot (931021018) which detached at ~ 0.61 s. In this case argon was injected into the main chamber in a 30 ms pulse at 0.1 s, at a lower (uncalibrated) flow rate than the earlier discharges.
5. Distribution of the calculated positions of first ionisation of thermal argon atoms launched with a cosine angular distribution and a maxwellian energy distribution (0.1 eV) into the private flux region of the C-Mod divertor, shot 931014022 and at the inner wall, shot 931014023. Flux surfaces are plotted from EFIT at intervals of 2.5 mm, measured at the outer midplane

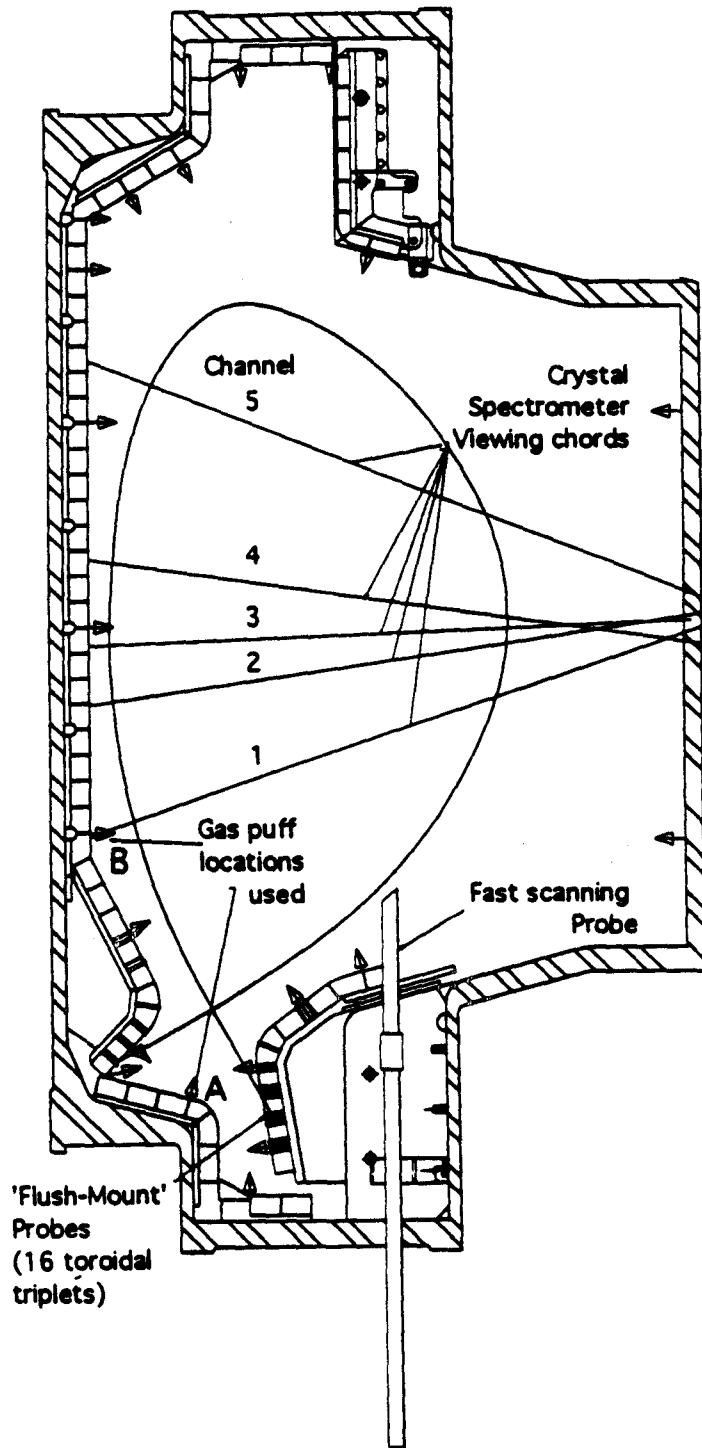


Figure 1

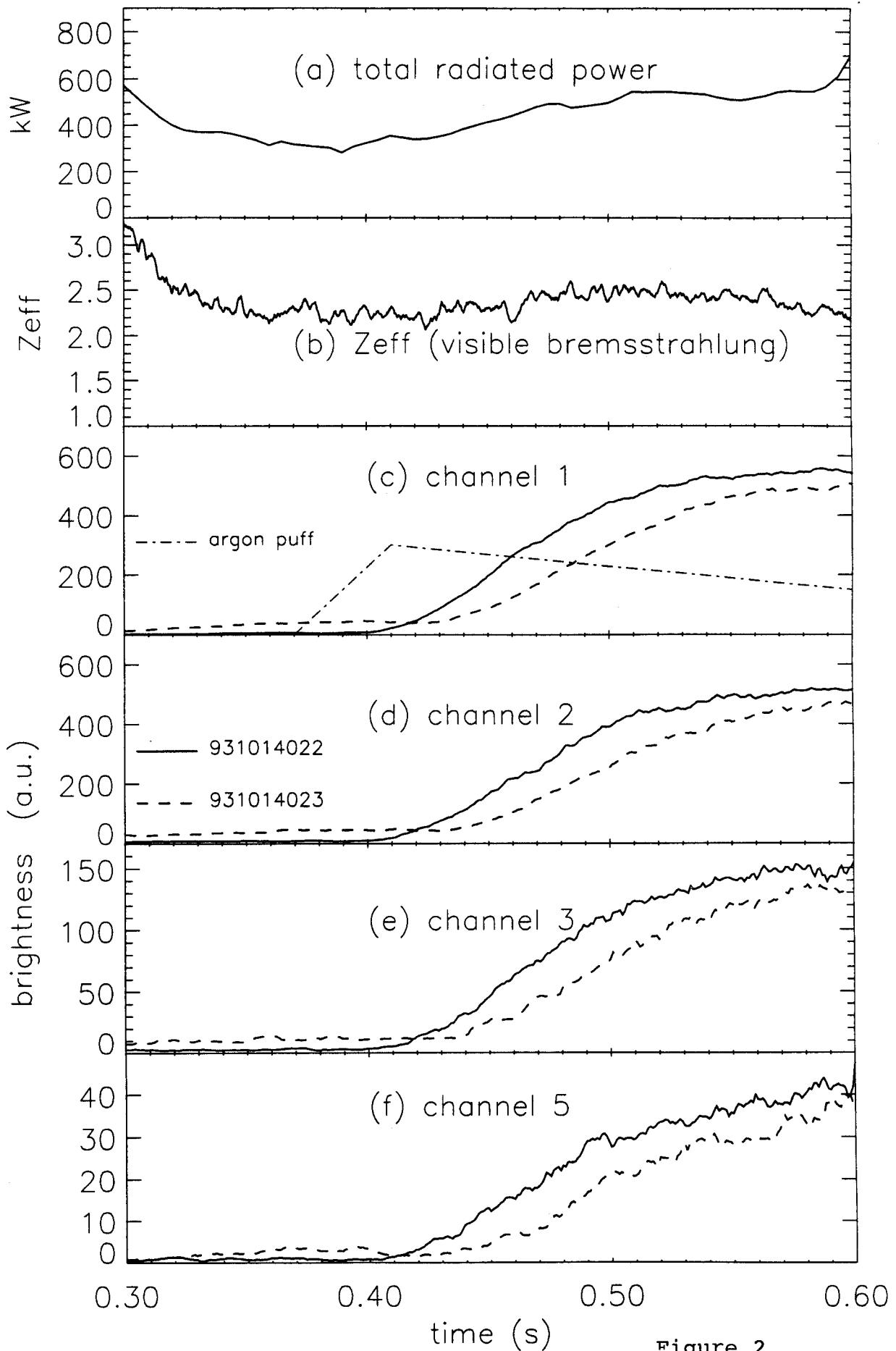


Figure 2

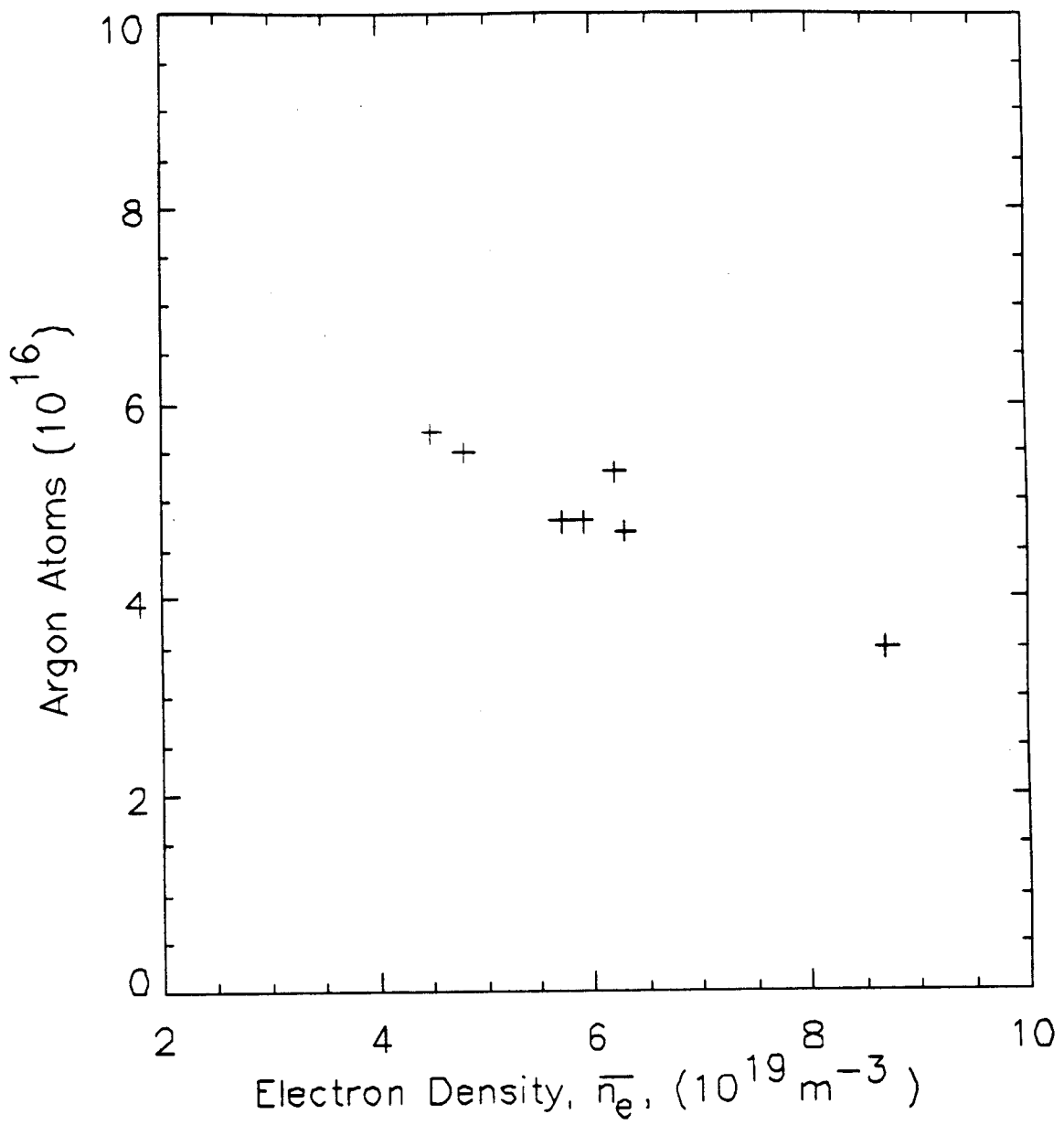


Figure 3

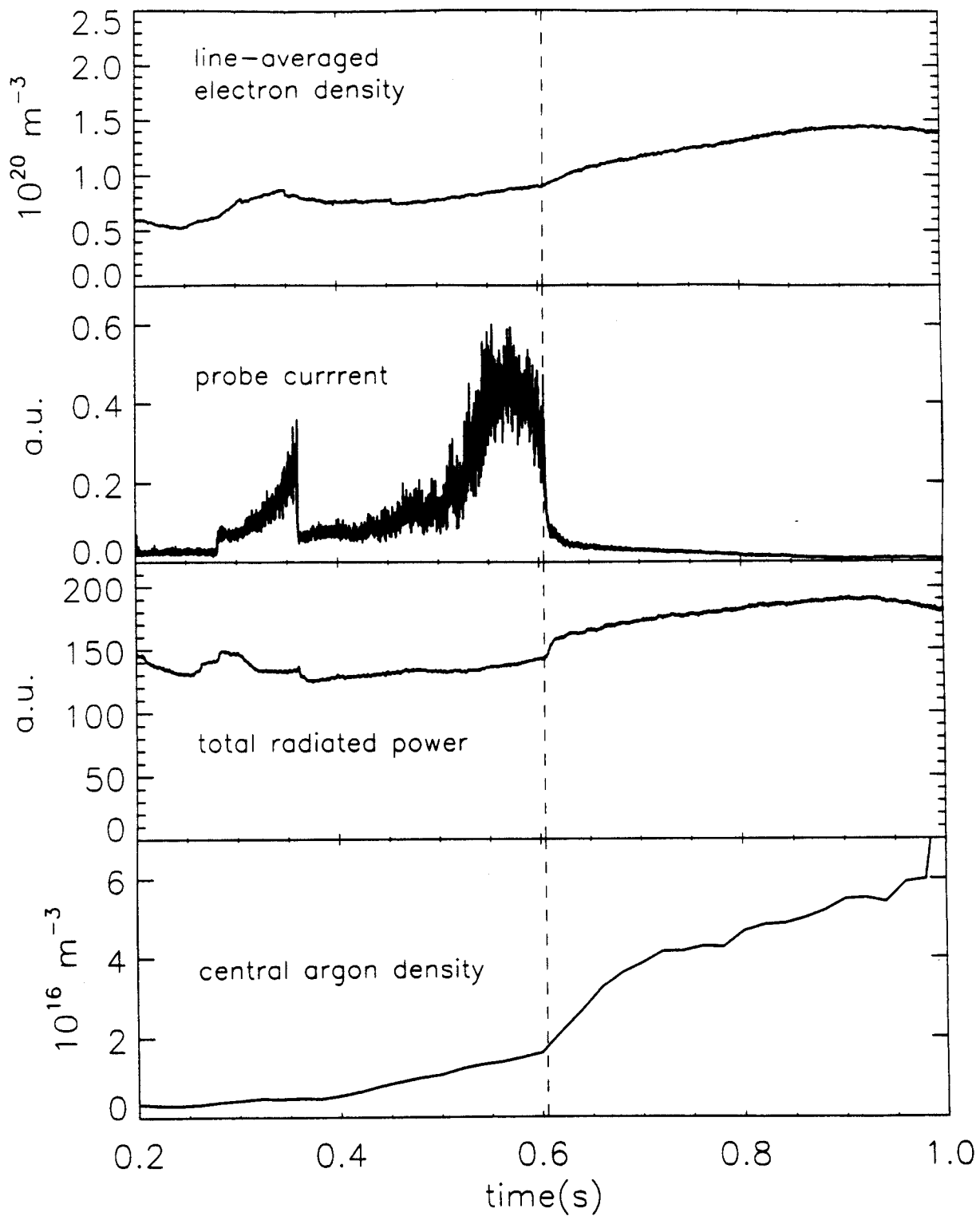


Figure 4

Argon 0.1eV, Ionisation Position 931014022

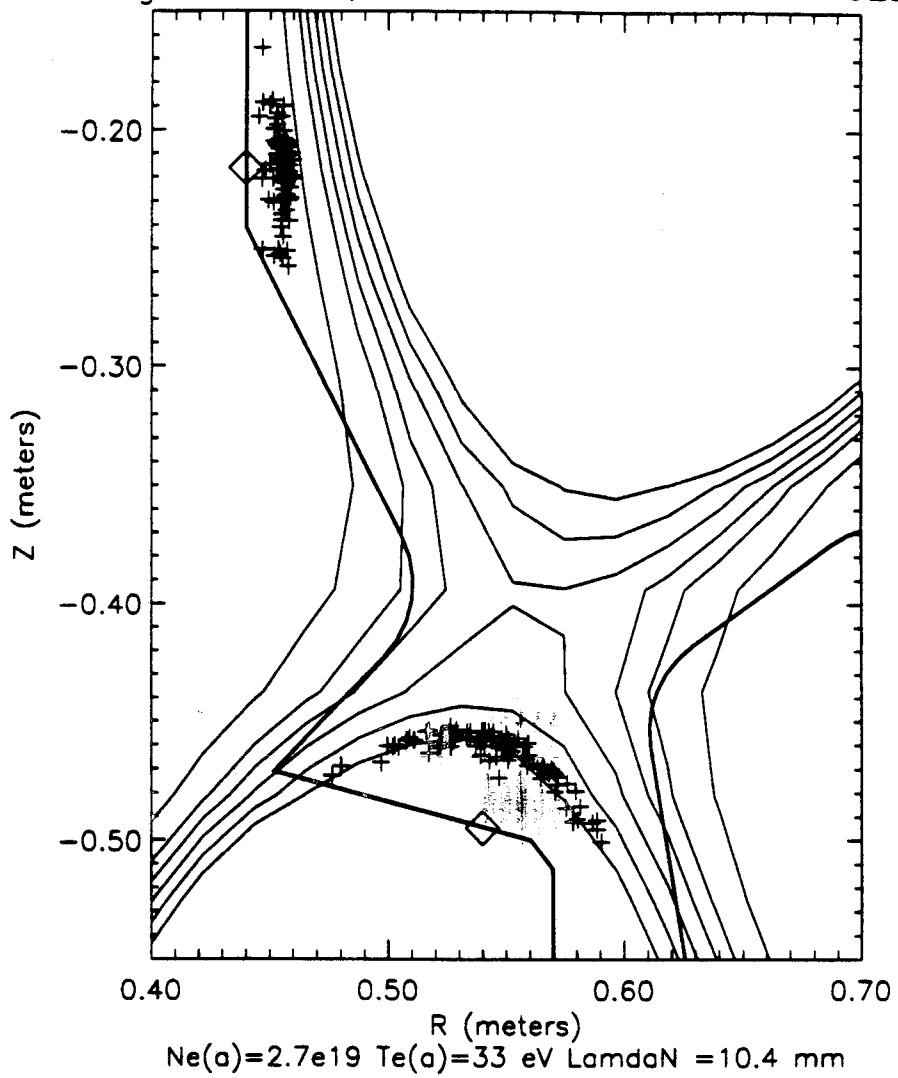


Figure 5