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May, 1986

UCLA/PPG--968-Rev.

DE86 014163

Paper presented at 7th International Conference on Plasma-Surface Interactions in Controlled Fusion Devices
Princeton University, May, 1986

DISCLAIMER

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Keywords: Pump limiter, ICRF heating, removal rate, particle confinement.

ABSTRACT

The ALT-I (Advanced Limiter Test - I) was installed on TEXTOR to benchmark the ability of a pump limiter as an efficient particle collector and to determine the physics of pump limiter operation. Experiments continue to show its capability of removing particles from the plasma edge under different operating conditions.

In this paper we report first experimental results using ALT-I in conjunction with high power ICRF heating. The particle removal rate increases as the edge flux and density increase during the ICRF pulse. For a head geometry that collects flux from both electron and ion drift sides, the plasma temperature rise is asymmetric with electron temperature on the electron side increasing more than on the ion side during the ICRF pulse. When ALT-I is the major limiter, the particle fluxes on both sides increase by about the same factor and the particle flux on the ion side is always larger, by a factor of 1.5 to 2 than on the electron side during both ohmic and ICRF periods. The degradation of particle confinement inferred from Langmuir probe measurement is more than a factor of two at a maximum achieved power of 2 MW.

1. Introduction

The Advanced Limiter Test [1] is a pump limiter experiment in the TEXTOR tokamak. It defines the plasma boundary and simultaneously removes particles through the opening on the limiter sides. The ALT-I performance under ohmic discharge has been discussed in previous papers [2,3,4,5,6], indicating efficient particle removal ability with large density control (up to 60%). Study of particle removal under actively pumped and unpumped conditions, different limiter head configurations and discharge conditions has improved our understanding of the pump limiter physics and our understanding of plasma-neutral interaction in the operation of a pump limiter [7].

The module used in this experiment is referred to as the 'fixed geometry 2' module (FG2), made of uncoated EK-98 graphite, and collects particles both on the ion and electron diamagnetic drift sides (fig.1). There are two Langmuir probes on this module, one on each side of the entrance slots. A detailed description of the probes can be found in reference 5. The slots are 26cm long and 2cm wide. The front surface is poloidally curved with a radius of curvature of 44cm. The toroidal curvature is such that there is a uniform particle flux on the front surface with scale length of 1 cm.. The leading edges are 1cm from the tangency point on both sides. Particles entering the 700 liter pump limiter chamber are pumped by a 7000l/s cryopump. There is a fast ion gauge at the back of the chamber monitoring the pressure during a shot.

TEXTOR [8] is a long pulse (up to 4 seconds) and high recycling tokamak. In our experiment, the magnetic field is set at 2T and the central line-averaged density varies from $3 \times 10^{13} cm^{-3}$ to $4.6 \times 10^{13} cm^{-3}$. The plasma current is 480 kA and the loop voltage is about 1V.

The minor radius position of ALT-I can be varied from 40cm to 50cm. The position of the main limiter can be set from 40cm to 50cm and is 270 degrees toroidally from ALT-I on the electron drift side. The ICRF antennae protection limiters are located at 48.8cm and 40 degrees toroidally away on the electron drift side. The inner-bumper limiter is at 48.5cm.

During ICRF heating [9,10] in TEXTOR, the plasma density is increased and the plasma density profile broadens. At low current (340 kA) operation, the increase in density may become so large that the density limit is exceeded leading to disruption even at low ICRF power (350 kW). ALT-I has been used previously to suppress the density increase to prevent disruptions [11]. It was shown indeed that the removal rate of ALT-I increased significantly in the ICRF environment.

In this paper, we report first results of ALT-I operation in conjunction with high power (up to 2MW) auxiliary ICRF heating and high plasma current (480 kA) in TEXTOR tokamak. We have carried out two set of runs, one with ALT-I at 44cm and the main limiter at 46cm. The other set is with both ALT-I and the main limiter at 46cm.

The next section describes the experimental set up and plasma discharge conditions for the runs. Section three presents the results of ALT-I performance and inferred particle confinement scaling with ICRF. Section four contains a discussion and summary of the experiments.

2. Experimental setup

The plasma current ramps up from zero to 480kA in the first 500ms, maintains a flat top for about 1 second, and then decays from 1500ms to the end of discharge. ALT-I can be moved horizontally between shots and since ALT-I can change the core density strongly, the discharge condition will be different with different ALT-I positions. A set of discharges were carried out for ALT at different radial position and, at each position for different level of ICRF power.

The line-averaged density is found to reach a maximum at 500ms and remain constant, and then ramps down after about 1500ms for ALT-I at 46cm without ICRF. When ALT-I is at 44cm the electron density does not maintain a plateau because of the strong pumping effect of the limiter. The ICRF pulse is turned on at 800ms, after the plasma has reached its flat top, and remains on for 300 to 800ms. The power leaving the antennae varies from 0 to about 2 MW.

For the run with ALT-I at 44cm and main limiter at 46cm, the chamber was carbonized [12] prior to experiment. This usually means that recycling is very high. For the run with ALT-I at 46cm and the main limiter at 46cm, no fresh carbonization was done. In order to avoid metal parts close to the plasma, the limiter segments, inner-bumper limiter and the ICRF antenna limiter are all graphite material.

3. Results

In figure 2, a discharge with ALT-I at 46cm and main limiter at 46cm is shown. Note the difference in electron temperature measured by the probe.

3.1. *Ion drift side and electron drift side asymmetry*

It was found in the past that an asymmetry of particle flux existed on the two opposite entrances of the ALT-I module during ohmic discharge [2,5]. During ICRF heating, the same asymmetry is roughly maintained. The ion side flux is larger than the electron side particle flux and the ratio is about the same. In figure 3, the average particle fluxes are shown for the two sets of runs. For the run in case one, the ICRF power reaches 600kW. For the run in case two, ICRF power of over 2MW is successfully launched. We do not speculate on the nature of the asymmetry.

There is also an asymmetry in the electron temperature during ICRF heating, which is not seen in ohmic heating. The effect is not as obvious in case one. But in case two, the electron side electron temperature can increase from 8eV to about 30eV during ICRF heating while T_e on the ion side registers only a few eV increase. The difference in case one and case two may be due to the fact that when ALT-I is at 46cm, it is closer radially to the antennae. Also, much higher heating power is achieved in case two. It should be noted that the distance between the antenna limiter and the electron side of ALT-I is shorter than that between the antenna and the ion side of ALT-I.

3.2. Removal rate scaling

The removal rate of ALT-I can be represented by

$$Q = P\,S + V\,dP/dt \tag{1}$$

where P is the pressure of the ALT-I chamber, S is the pumping speed and V is the volume of ALT-I chamber.

Because the pumping speed is very large (7000 l/s) the second term on the right hand side of equation (1) generally is only a small contribution to the removal rate. Both the particle flux and the removal rate increase with ICRF power (figure 4). This is not a density effect since we do not see an increase in removal rate with density during ohmic discharges [6]. Even at the 2MW ICRF power level, the removal rate still seems to be increasing, although there is a sign of saturation. Higher power will be needed to settle this question.

Because the particle flux increases faster then the removal rate, the removal efficiency decreases slightly with ICRF power. The removal efficiency degradation is proportional to the power.This is understandable because the electron temperature at the entrance goes up with ICRF power. The effect of plasma-neutral interaction [7] may play an important role in this phenomenon.

3.3. Particle confinement scaling

Since ALT-I is not the only component in contact with the plasma, an estimation of the absolute particle confinement time entails knowing the value of the particle fluxes to the main limiter; ICRF antennae and the liner. Because there is no SOL profile information available for these runs , a relative comparison is attempted here to scale τ_p with ICRF power. It has been found that the relative increase in fluxes to the different components at the boundary remain roughly the same during a power scan of ICRF heating [13]. Consequently we assume that the sharing of particle flux among ALT-I, the main limiter, ICRF antennae and the liner does not change with ICRF heating. We start with

$$Q_{total} = N_e/\tau_p \tag{2}$$

where Q_{total} is the total particle outflow at the edge, N_e is the total electron number in the plasma and τ_p is the particle confinement time. We can approximate N_e with

$$N_e = \bar{n}_e V \tag{3}$$

where $\bar{n}_e$ is the line-averaged density and V is the plasma volume. Also, with our assumption,

$$Q_{total} \propto \Gamma_{probe} \tag{4}$$

leading to the proportionality

$$\tau_p \propto \bar{n}_e/\Gamma_{probe} \tag{5}$$

The density range for case one is from 3 to 3.4 10^{13} cm^{-3}. For case two, the range is 3.5 to 4.6 10^{13} cm^{-3}. There is an indication that τ_p changes with density [6]. In order to differentiate the effect of density change and the effect of ICRF heating on τ_p, we normalized τ_p with $\bar{n}_e$. In figure 5, $1/\Gamma_{probe} \propto \tau_p/\bar{n}_e$ vs ICRF power is plotted for the two cases. Since electron side and ion side fluxes are in proportion, ion side probe flux is used in the scaling.

In both cases, the value $1/\Gamma_{probe}$ decreases with ICRF power. The relative change follows roughly the results of the corresponding τ_E scaling [10].

4. Discussion and summary

The performance of ALT-I FG2 module in the ICRF environment is discussed. It is found that the particle flux asymmetry is roughly maintained during ICRF heating. The increase of ICRF power makes no noticeable change in this respect. We see an increase of electron temperature at the entrance of ALT-I with ICRF power.

In our experiments, the main limiter is set at a minor radius of 46cm and ALT-I is varied from 44cm to 46cm. In the first case, the ion side particle flux is about a factor of two higher than the electron side particle flux with and without ICRF heating. In the latter case, the ion side particle flux is about four times the electron side particle flux in ohmic heating but the ratio decreases to about two times during ICRF heating. The electron temperature on the electron drift side can increase from about 8 eV to over 30 eV while that on the ion side only increases by a few eV. The change in line-averaged plasma density can be as much as 15 percent at high (2MW) ICRF power.

It is found that the particle removal rate is proportional to the ICRF power and that the corresponding removal efficiency decreases slightly with ICRF power. Because the particle flux at the entrance increases faster then the removal rate, the removal efficiency degrades slightly. The inferred scaling of τ_p with power follows that of the global energy confinement time during ICRF heating [10]. The degradation of particle confinement is more than a factor of two when ICRF power is above 2 MW. The nature of the ion side and electron side asymmetry is not known. More detailed experiments are underway.

Acknowledgement

We wish to thank the TEXTOR personnel as well as the ALT-I group for their contribution to this work. We also appreciate the excellent technical support of K. Andrews, L. Brown, B. Hiller, and T. Sketchley. This work is supported at UCLA by the Office of Fusion Energy, under Department of Energy, contract number DE-FG03-85ER51069, and at Sandia National Laboratory, under contract number 51-7706. At KFA-Juelich, support is from Euratom.

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Figure captions

Figure 1 A schematic of the ALT-I pump limiter with the FG2 modular head.

Figure 2 Different diagnostic signals on ALT-I versus time, ALT-I at 46cm, main limiter at 46cm and ICRF heating power at 1.5MW;

(a)-Central line averaged density

(b)-Ion side probe flux

(c)-Ion side electron temperature

(d)-Pressure in ALT-I chamber

(e)-Electron side probe flux

(f)-Electron side electron temperature

Figure 3 Particle flux on ion and electron drift sides of the FG2 head;

Figure4 Particle removal rate with FG2 head for different level of ICRF power

(a)-Removal rate of ALT-I; ALT-I at 44cm, main limiter at 46cm

(b)-Removal rate of ALT-I; ALT-I at 46cm, main limiter at 46cm

Figure 5 Scaling of the particle confinement time with ICRF power;

(a)- $1/\Gamma_{probe}$ scaling with ICRF power;
ALT-I at 44cm, main limiter at 46cm

(b)- $1/\Gamma_{probe}$ scaling with ICRF power;
ALT-I at 44cm, main limiter at 46cm

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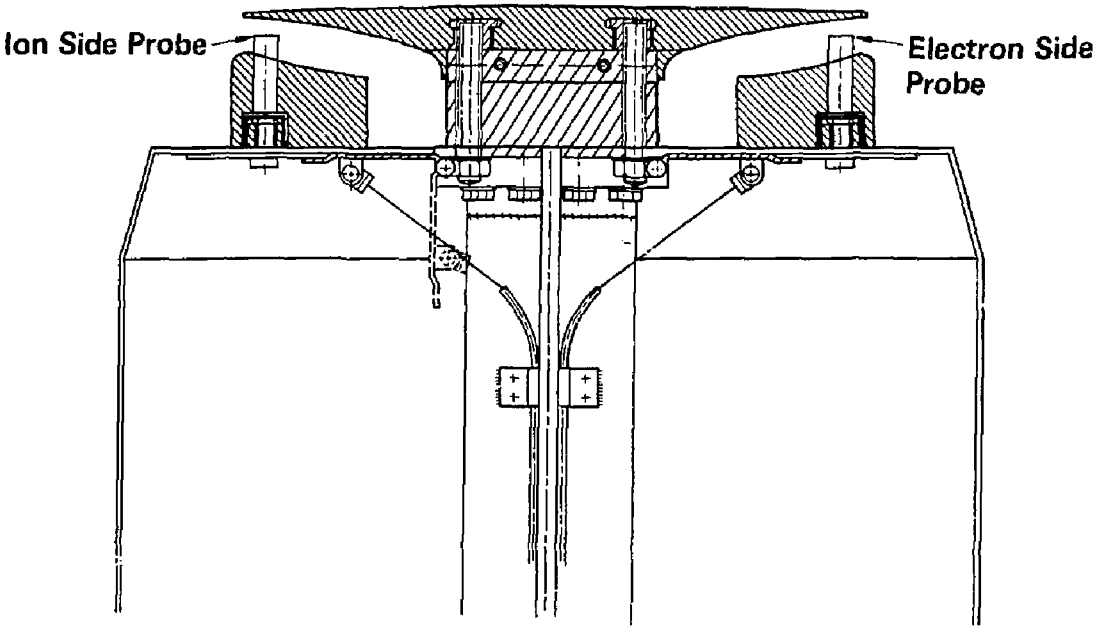
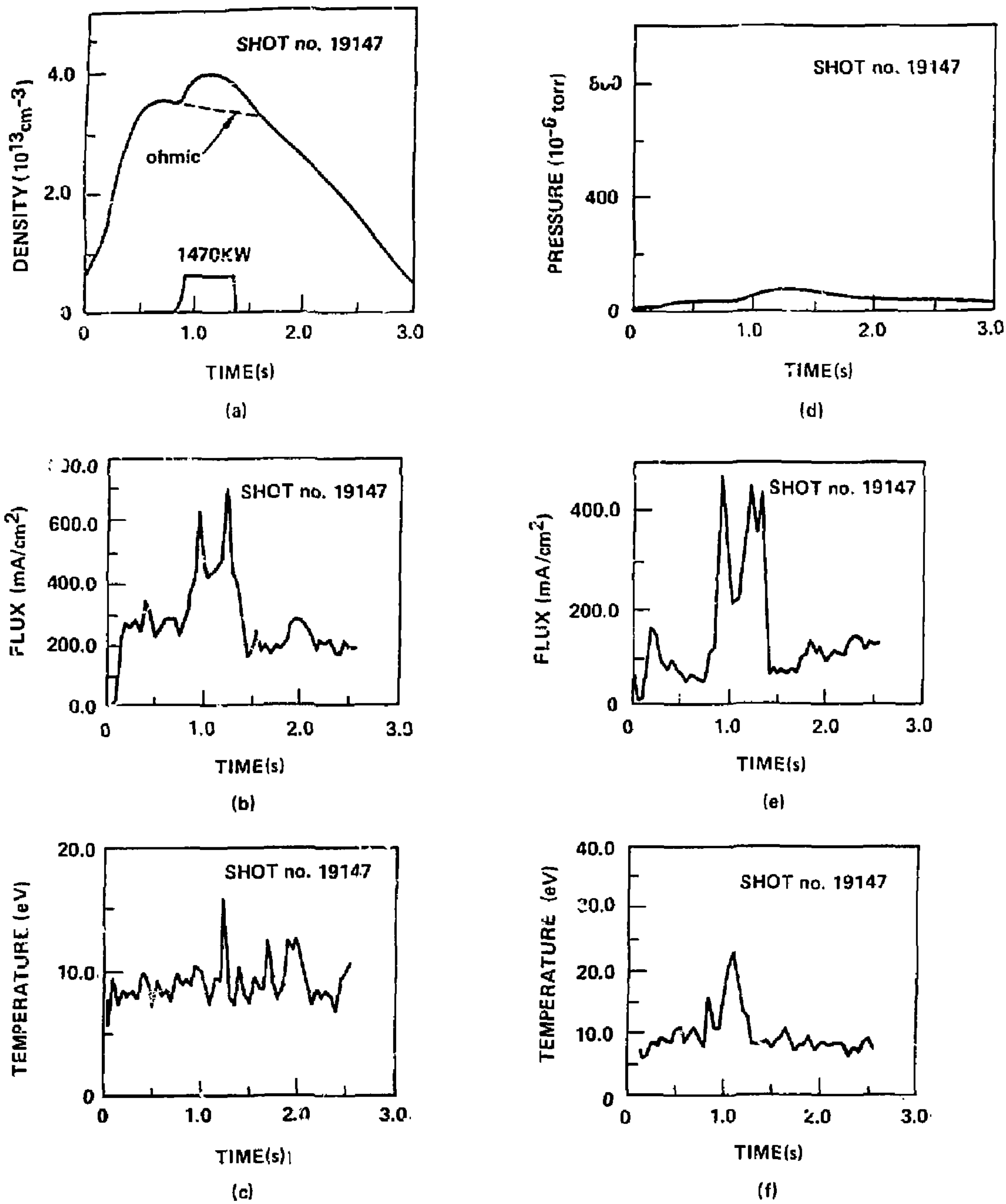


FIGURE 1



SHOT no. 19147
DENSITY (10^13 cm^-3)
4.0
2.0
0
ohmic
1470KW
0
1.0
2.0
3.0
TIME(s)
(a)
SHOT no. 19147
PRESSURE (10^-6 torr)
400
0
0
1.0
2.0
3.0
TIME(s)
(d)
SHOT no. 19147
FLUX (mA/cm^2)
600.0
400.0
200.0
0.0
0
1.0
2.0
TIME(s)
(b)
SHOT no. 19147
FLUX (mA/cm^2)
400.0
200.0
0
0
1.0
2.0
3.0
TIME(s)
(e)
20.0
SHOT no. 19147
TEMPERATURE (eV)
10.0
0
0
1.0
3.0
TIME(s)
(c)
40.0
SHOT no. 19147
TEMPERATURE (eV)
20.0
10.0
0
0
1.0
3.0
TIME(s)
(f)

FIGURE 2

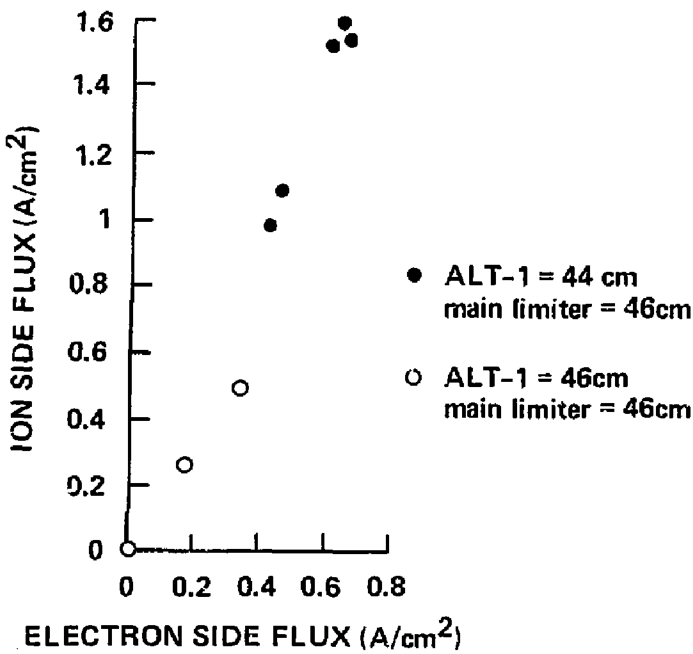

1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
ION SIDE FLUX (A/cm2)
0
0.2
0.4
0.6
0.8
ELECTRON SIDE FLUX (A/cm2)
ALT-1 = 44 cm
main limiter = 46cm
ALT-1 = 46cm
main limiter = 46cm

FIGURE 3

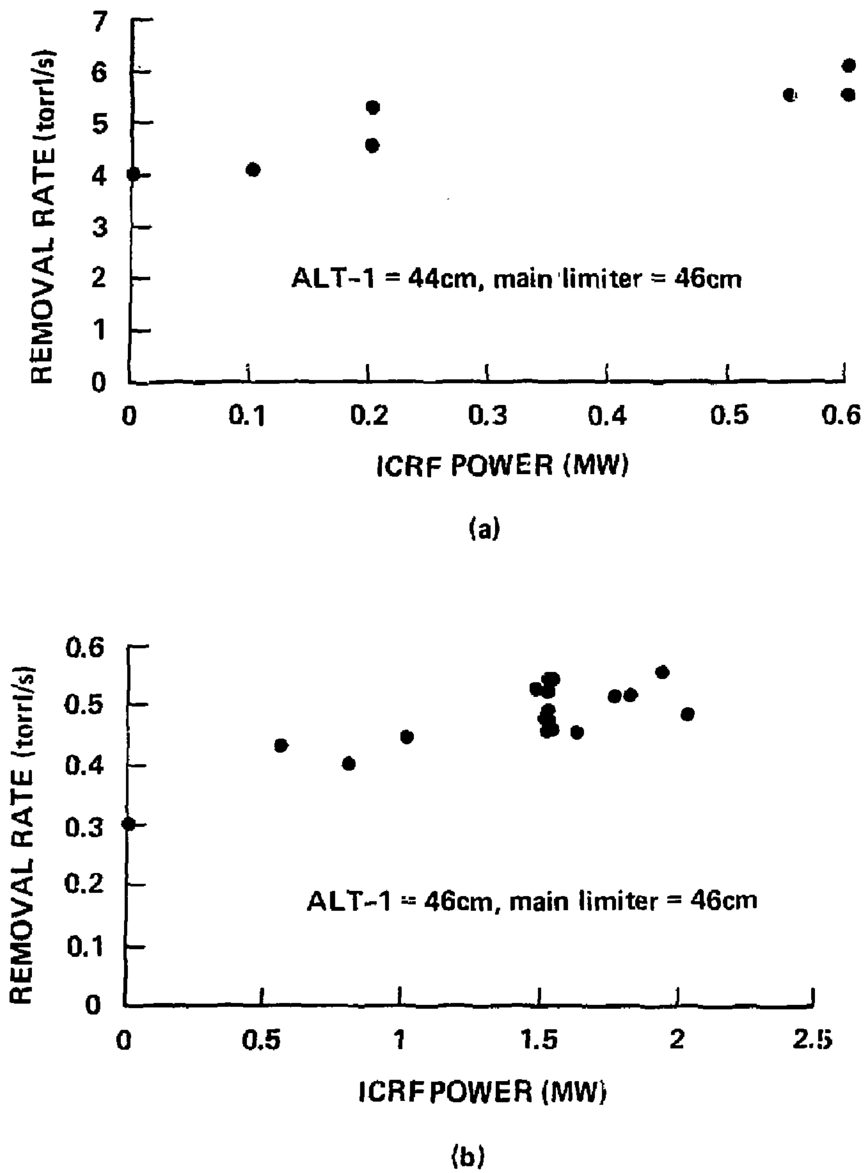

REMOVAL RATE (torrl/s)
ALT-1 = 44cm, main limiter = 46cm
ICRF POWER (MW)
(a)
REMOVAL RATE (torrl/s)
ALT-1 = 46cm, main limiter = 46cm
ICRF POWER (MW)
(b)

FIGURE 4

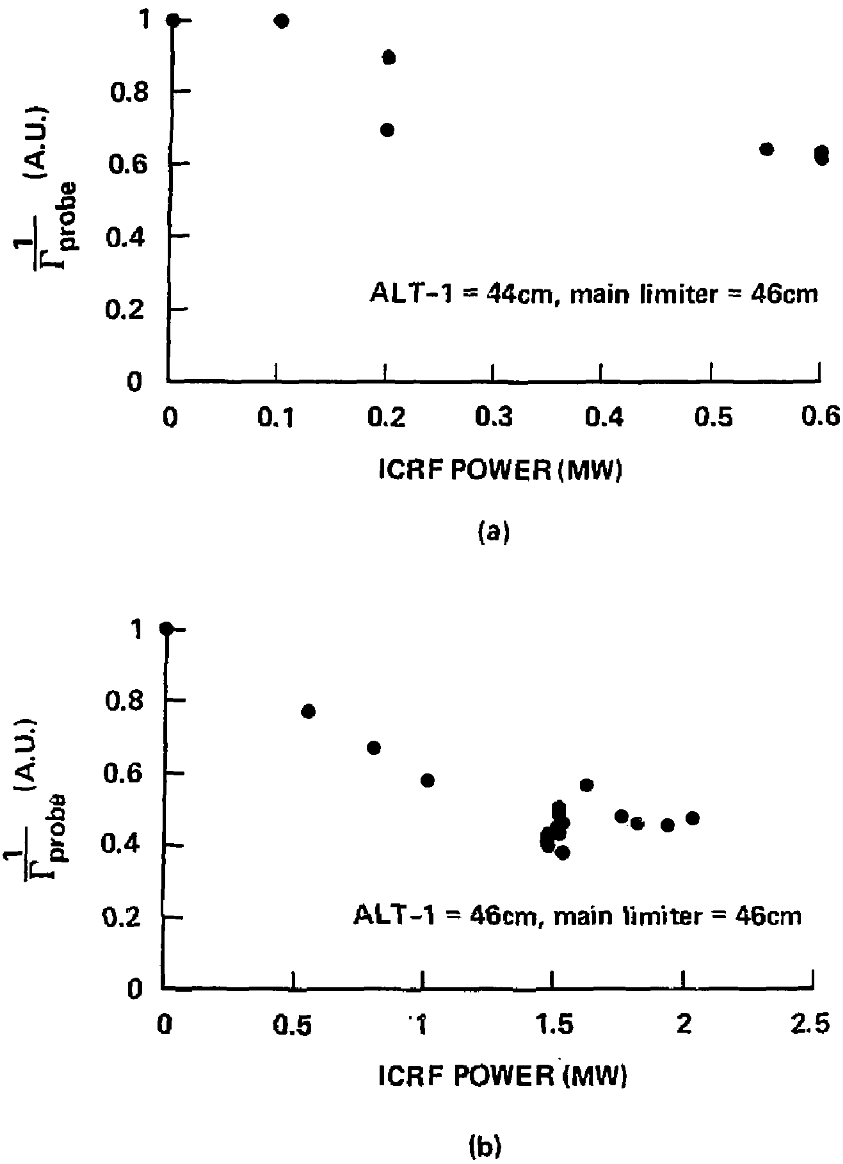

1
0.8
0.6
0.4
0.2
0
$\frac{1}{\Gamma_{probe}}$ (A.U.)
ALT-1 = 44cm, main limiter = 46cm
0 0.1 0.2 0.3 0.4 0.5 0.6
ICRF POWER (MW)
(a)
1
0.8
0.6
0.4
0.2
0
$\frac{1}{\Gamma_{probe}}$ (A.U.)
ALT-1 = 46cm, main limiter = 46cm
0 0.5 1 1.5 2 2.5
ICRF POWER (MW)
(b)

FIGURE 5