PFC/JA-94-012

Plasma-Surface Interactions in the Alcator C-Mod Tokamak

B. Lipschultz, J. Goetz, B. LaBombard,
G.M. McCrakcen, J.L. Terry, D. Jablonski, C. Kurz

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

June 1994

Submitted to Journal of Nuclear Materials

This work was supported by the U. S. Department of Energy Contract No. DE-AC02-78ET51013. Reproduction, translation, publication, use and disposal, in whole or in part by or for the United States government is permitted.

11th PSI Conference, Mito Japan, 1994

Plasma-Surface Interactions in the Alcator C-Mod Tokamak

B. Lipschultz, J. Goetz, B. LaBombard, G. McCracken, J. Terry, D. Jablonski, C. Kurz,

A. Niemczewski, J. Snipes

Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge Ma. 02139 U.S.A.

Abstract

Alcator C-Mod is a high-field tokamak with which experiments were initiated in April 1993. The divertor and the first-wall have plasma-facing surfaces of molybdenum. The divertor has a configuration which is closed in comparison to other, currently operating tokamaks. The combination of divertor geometry and high field (density) make Alcator C-Mod an ideal experiment to investigate dissipative (radiative/CX) divertor scenarios. Single-null divertor operation has become the standard mode of operation. Relatively clean plasmas ($Z_{eff} \leq 1.3$) are obtained with short periods of baking and electron cyclotron discharge cleaning only.

Impurity source rates and screening have been investigated with an extensive set of wavelength-filtered diode arrays and spectrographs. Carbon and oxygen and molybdenum dominate the impurity levels. The molybdenum source from the divertor proper is negligible.

I. Introduction

Alcator C-Mod is the first high-field diverted tokamak. As demonstrated in previous Alcator experiments, the high magnetic field allows attainment of high densities ($\bar{n}_e$ curreently $< 3 \times 10^{20}$ m^{-3}) in the main plasma. In Alcator C-Mod, the combination of divertor and high central density can produce $n_{e,div} > n_e(0)$ of the central plasma.

Two other characteristics combine with the high density to create a unique environment for divertor studies. First, the divertor geometry is relatively closed compared to the flat-plate divertors currently available. Second, again because of the high magnetic field, the parallel heat flux in the SOL is > 100 MW/m^2, even with purely ohmic plasmas. Additional heating with ICRF with up to 8MW of power and several antennas is planned. Input powers of up to 1 MW [1] with a single antenna have been already achieved.

The goals of the experimental program are to explore different operational regimes accessible by the unique features described above. In particular, the high divertor density maximizes the loss of power from the edge plasma; radiation and neutral processes (charge exchange and elastic ion-neutral collisions) are both proportional to $\bar{n}_e$. The more general tokamak issues are discussed elsewhere [1]. The focus of this paper is on the divertor and SOL.

Alcator C-Mod has major and minor radii of .67 and .21 m respectively. During initial operation the achieved (design) capabilities are $B_t = 5.3$T (9T), plasma current up to 1 MA (3 MA), and elongation of up to $\kappa = 1.65$ (1.8). Well controlled x-point and strike point position were achieved early on with novel hybrid analog computer control of the plasma shape and position [1].

There are two very different divertor geometries in Alcator C-Mod (figure 1). The open, or flat-plate divertor is located at the top of the vessel. This divertor is similar to most current tokamaks. The lower divertor is much more closed than that located at the top of the vessel. Single-null operation has so far been solely with the closed divertor. The strike points are located on surfaces that face away from the main plasma. This geometry minimizes the chance of neutrals reaching the main plasma before being ionized in the divertor region and swept back to the plates. For the data discussed herein, the $B\times\nabla B$ direction was oriented towards the closed divertor. The first-wall surface is comprised of 7000 molybdenum tiles. There are some RF antenna surfaces that are TiC coated.

II. Diagnostics

Transport in the SOL is studied using a large complement of Langmuir probes. 48 fixed-position Langmuir probes are located on the bottom divertor surfaces [2] at 16 different poloidal locations. During the 1993 run period, 43 probes had a profile which was 'flush' with the divertor plate surfaces, and 5 had a 'domed' profile protruding beyond the surface of the divertor. The 'flush' probes are used solely for determination of ion-saturation current (I_{SAT}) profiles on the divertor surfaces. The divertor plasma density and temperature are measured with the 'domed' probes. There is one movable probe located in the SOL which can be pneumatically driven to the separatrix and back out of the SOL in a period of ~100 ms [2]. This probe provides density and temperature profile measurements in the SOL.

The power balance in the SOL and divertor is studied with 8 bolometer detectors in two arrays viewing the divertor region [3]. These detectors provide information both about the spatial distribution and magnitude of the radiation. Further information about the main contributors to the radiation is provided by multiple arrays of filtered diodes. Over 200 diodes with changeable filters view the plasma from a large number of angles [4]. The brightness information provided by these multiple views and angles allows for an inversion of the data to obtain emissivities [5]. Together with additional spectral information from a 0.5 m spectrometer with an OMA detector array, these systems provide the details of the divertor radiation composition.

III. Conditioning

The methods required to prepare the C-Mod vacuum vessel for tokamak operation are modest compared to tokamaks with carbon tile first-walls. Following a vacuum vent, the vessel is baked at 120 °C for ~ 1 week. Electron Cyclotron Discharge Cleaning (ECDC) is then applied for several days [6]. This technique, developed and tested elsewhere [7,8], utilizes a low-power (3 kW) 2.45 GHz microwave source to produce a low-temperature and low-density hydrogen cleaning plasma. The toroidal field resonance (.088 Tesla) is swept back and forth across the vacuum vessel. Performance of the system is such that 5 monolayers/day of carbon can be removed from the walls (based on the measured pumping rate of carbon-based molecules). This technique is also used before each run day to condition the walls which are at ~ room temperature. The walls are kept at this temperature for the remainder of the day and no additional conditioning is done between shots.

IV. Operation

Most operation of Alcator C-Mod has been with a single-null located at the closed divertor. The central plasma Z_{eff} (see figure 2) decreases with increasing $\bar{n}_e$ and thus is normally low(1.3) for standard Alcator plasmas. The apparent offset in Z_{eff} is due to different integration paths of the diagnostics involved (bremsstrahlung and interfereometer). Spectroscopic measurements have used to determine central impurity densities from which we estimate a correction to Z_{eff} of .3 - .4 above $\bar{n}_e \sim 1 \times 10^{20} m^{-3}$. Carbon, present as an impurity on the molybdenum surfaces, and to a lesser extent oxygen, are the largest impurity concentrations in the core plasma. The levels of C, O and Mo in the plasma are typically .2%, .1% and .02% of $n_e(0)$ respectively. Molybdenum levels are higher at low $\bar{n}_e$ where Z_{eff} rises. The resultant radiation from the main plasma is proportional to the input power with $P_{RAD,main} = .3 - .4 \times P_{OH}$ [3].

Two important source locations for these impurities are the inner wall limiter and upper surfaces of the divertor. Direct measurements of the H_α flux at these surfaces [5] show that there is significant plasma surface interaction even though the the separatrix is normally more than 2 density e-folding lengths away (> 2 cm). The resultant C & Mo source rates (based on spectroscopic measurements of C-III and Mo-I) at the inner wall have been measured.

There is also a significant source of impurities in the divertor region. Carbon source rates from this region, measured using the filtered diode arrays [4], can be as much as 2-3 times that from the inner wall [9]. This is due to the much higher particle fluxes in the divertor region. In contrast to the carbon source rates, the molybdenum source rate in the divertor is much less than that from the inner wall. T_e in the divertor region is such that ion energies are at or below the sputtering threshold. However, in the presence of injected argon, the molybdenum source rate from divertor surfaces is significantly enhanced [9]. We feel that this effect is due to the lower Mo sputtering threshold for incident ions with higher mass.

Though the impurity source rates at the inner wall are lower than over most of the divertor surfaces, the relatively poor screening at the wall results in a greater fraction of the impurity content in the main plasma (C, Mo and O) being due to the interaction with the inner wall. The poor screening, defined as the ratio of the central impurity concentration to the primary influx from the wall or divertor, is due to several factors: Both the density and the scrapeoff length are large in the divertor region. In addition, the divertor geometry is such that the trajectory of the neutrals, when they leave the divertor surfaces, is generally directed away from the main plasma.

Much of the edge divertor program at Alcator C-Mod is focused on developing methods of reducing the power concentration on the divertor plates through dissipative methods; radiation and ion-neutral collisions (elastic and charge-exchange). The level of parallel power flux, $q_{\parallel}$ (< 250 MW/m^2) in the Alcator C-Mod SOL is high even with ohmic plasmas. These levels are significant compared to that predicted for ITER (500-1000 MW/m^2) providing a relevant test-bed for dissipative divertor concepts.

Two forms of dissipative divertor studied in Alcator C-Mod are the radiative and detached divertor operational regimes. Radiative divertor operation occurs over most of the Alcator C-Mod operational space. Radiation in the divertor is such that most of the power flowing into the SOL is radiated before reaching the divertor plates; $P_{RAD,div}/P_{SOL} \sim 0.8$ determined from bolometry [3]. Pressure is approximately constant along a flux surface[2]. The radiation is located in the SOL regions from near the x-point down along the separatrix legs to the divertor surfaces. Carbon is the dominant impurity in the divertor.

Divertor power losses due to the charge exchange process estimated on the basis of a Monte-Carlo calculation of neutral-ion interactions are in the range 1 - 30 MW/m^3 over a path length of a few centimeters depending on discharge conditions and position along the divertor surface. This result is typically of the same order as our estimate of the local emissivity due to carbon radiation. A more accurate assessment will be made in the future.

Because of the combination of high density and divertor radiation, large gradients in n_e and T_e can be sustained along a flux surface [2]. For $\bar{n}_e$ below $\sim 1 \times 10^{20}$ m^{-3} the parallel transport in the SOL is sheath-limited. n_e and T_e each are approximately constant along a flux surface and n_e (SOL and divertor) is ~ linearly dependent on $\bar{n}_e$. As $\bar{n}_e$ and divertor radiation increases, the parallel transport changes over to being conduction-limited [2]. In this transport regime pressure, rather than n_e and T_e individually, is constant along a flux surface. The density and temperature at the outer divertor plate become strong functions (powers of 3-4) of $\bar{n}_e$. The scaling of plate n_e and T_e with $\bar{n}_e$ in the two different transport regimes is exemplified by the data in figure 4. Application of analytic 2-point edge models [2] to this data, along with knowledge of geometry (e.g. connection lengths) and power (input and radiated) reproduces this nonlinear dependence.

As $\bar{n}_e$ is increased, with fixed plasma current and input power, a threshold density is reached above which the divertor plasma becomes detached from the plates. When this occurs, the ion flow to the plates and $n_{e,plate}$ in the region of the separatrix markedly decreases. The divertor radiation, which is initially spread throughout the divertor region rearranges to peak at and above the x-point (inside the separatrix). The impurity and hydrogenic densities in the central plasma increase after detachment. This is consistent with a scrapeoff layer that is more transparent to neutrals (recycled and sputtered). As a result the radiation in the core plasma increases. A necessary condition for detachment is that T_e in those same regions (near the strike point) must be ~ 5 eV. The total radiated power (divertor and main plasma) typically accounts for > 90% of the input power. Details of detachment characteristics are given in reference [10].

V. Summary

Initial operation of the Alcator C-Mod tokamak has been very successful. Significant progress has been made in achieving the multiple goals of the edge physics program; understanding transport (hydrogenic and impurity) and developing the dissipative divertor operation.

Impurity levels in Alcator C-Mod are relatively low. The majority of impurities populating the central plasma originate from the inner wall rather than the high-recycling, heat-bearing, divertor surfaces. Molybdenum source rates at the divertor surfaces are negligible, due to the low T_e in the divertor.

Radiative divertor operation is robust, the majority of the power flowing into the SOL being removed from the divertor plasma before reaching the plates.

Detached divertor radiation has also been achieved. Even more power is removed from the plasma before reaching the plates.

Acknowledgements

The authors greatly appreciate the support of the rest of the Alcator group. In particular, the operations group, Ian Hutchinson, Steve Horne, Steve Wolfe and Robert Granetz, have brought about the operation of well-postioned diverted plasmas without which this work would not have been possible. This work supported by U.S. D.oE. contract # DE-AC02-78ET51013.

References

1. I H Hutchinson, R Boivin, F Bombarda, Physics of Plasmas, 1 (1994) 1511.

2 B Labombard, D Jablonski, B Lipschultz, et al, this conference.

3. J Goetz, B. Lipschultz et al, this conference.

4. J Terry et al Rev Sci Instrum. to be published, 1994.

5. C Kurz, J A Snipes, J L Terry et al, Rev Sci Instrum. to be published, 1994.

6. E L Marmar, C Christensen, J Goetz et al, Bull Amer Phys Soc 38 (10) 1993, paper 3S18, pg 1956.

7. Y. Matsuki, H. Ogawa, Y. Miura et al, J. Nucl. Mater. 145-147 (1987) 704.

8. Y. Sakamoto, Y. Ishibe, S. Ishii et al, J. Nucl. Mater. 111 & 112 (1982) 485.

9. C. Kurz, B. Lipschultz et al, this conference.

10. B Lipschultz J Goetz, B Labombard and G M McCracken, this Conference

Figure Captions

Figure 1: Layout of the Alcator C-Mod vacuum vessel and divertor hardware.

Figure 2: Z_{eff} of the central plasma (from Bremsstrahlung) vs. $\bar{n}_e$.

Figure 3: Outer divertor plate density (a) and temperature (b) in the rgion of the separatrix vs. $\bar{n}_e$.

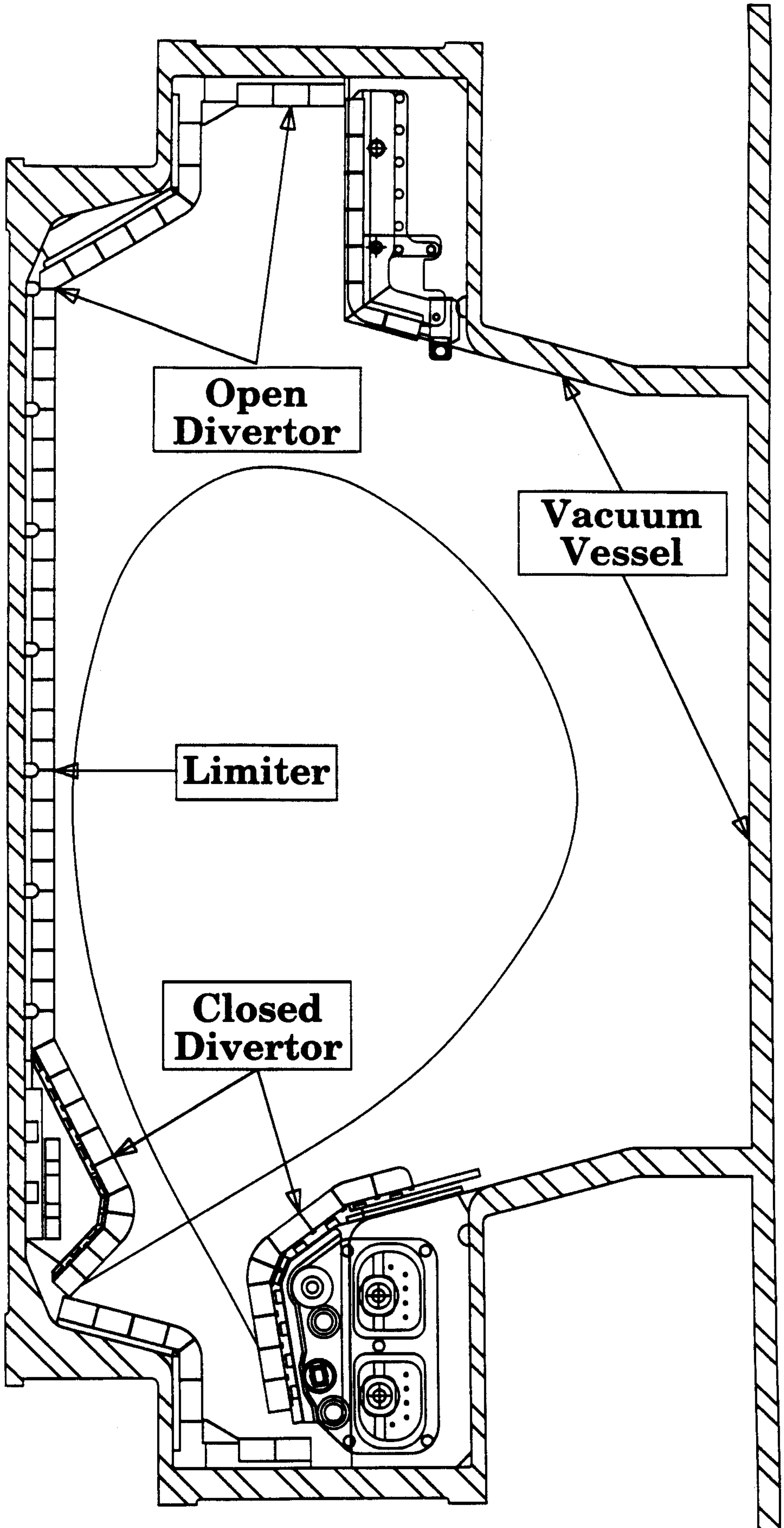


Figure 1

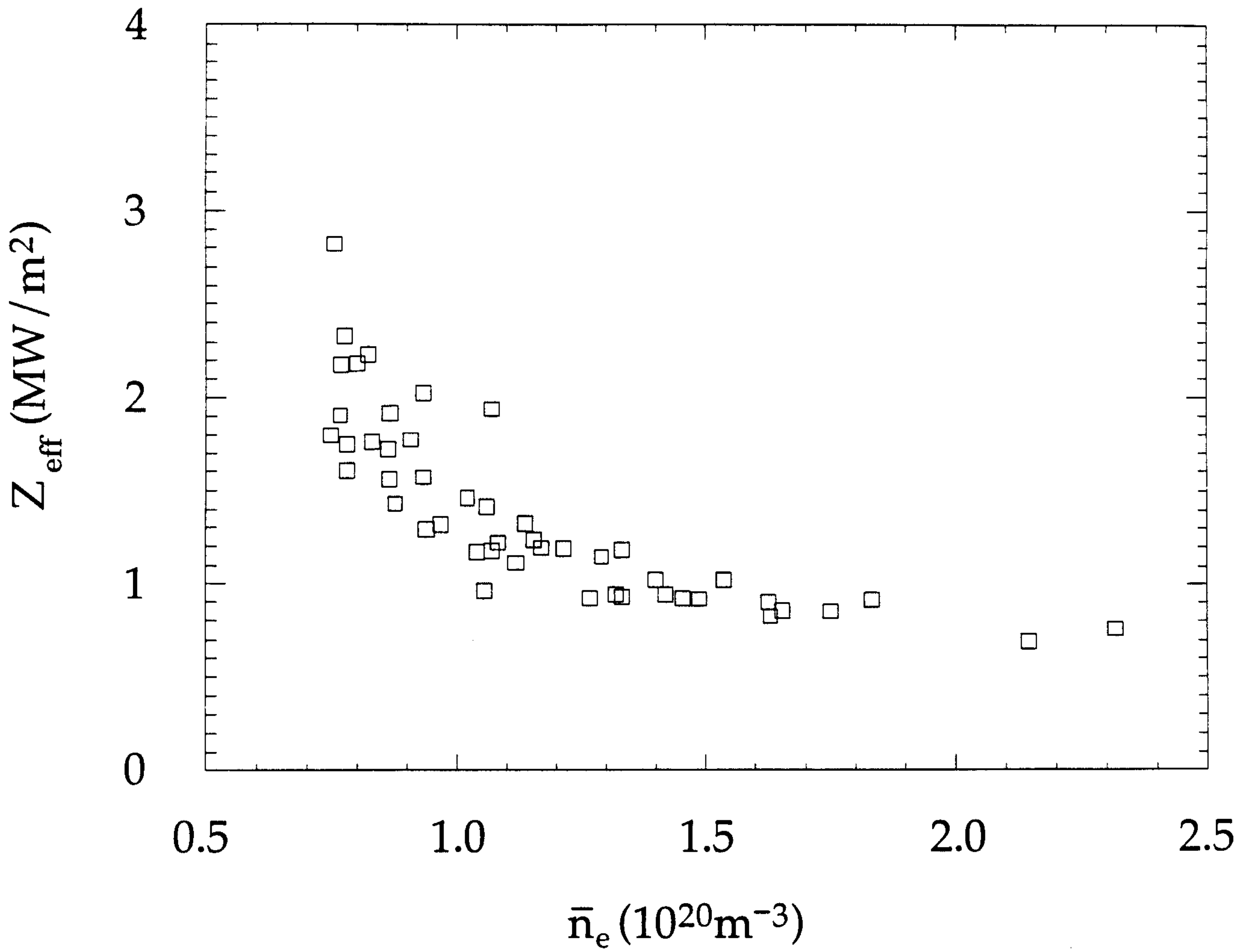
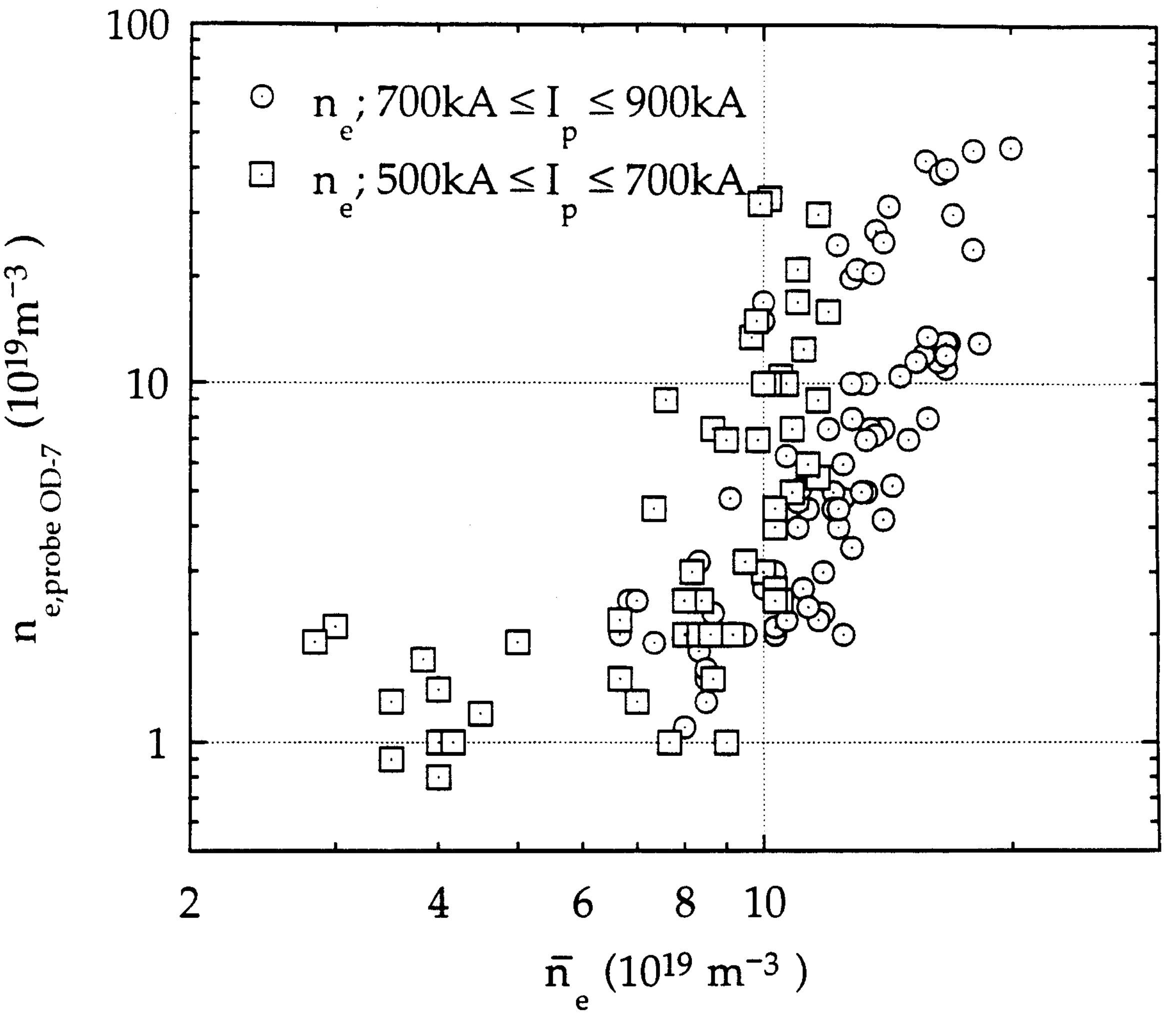
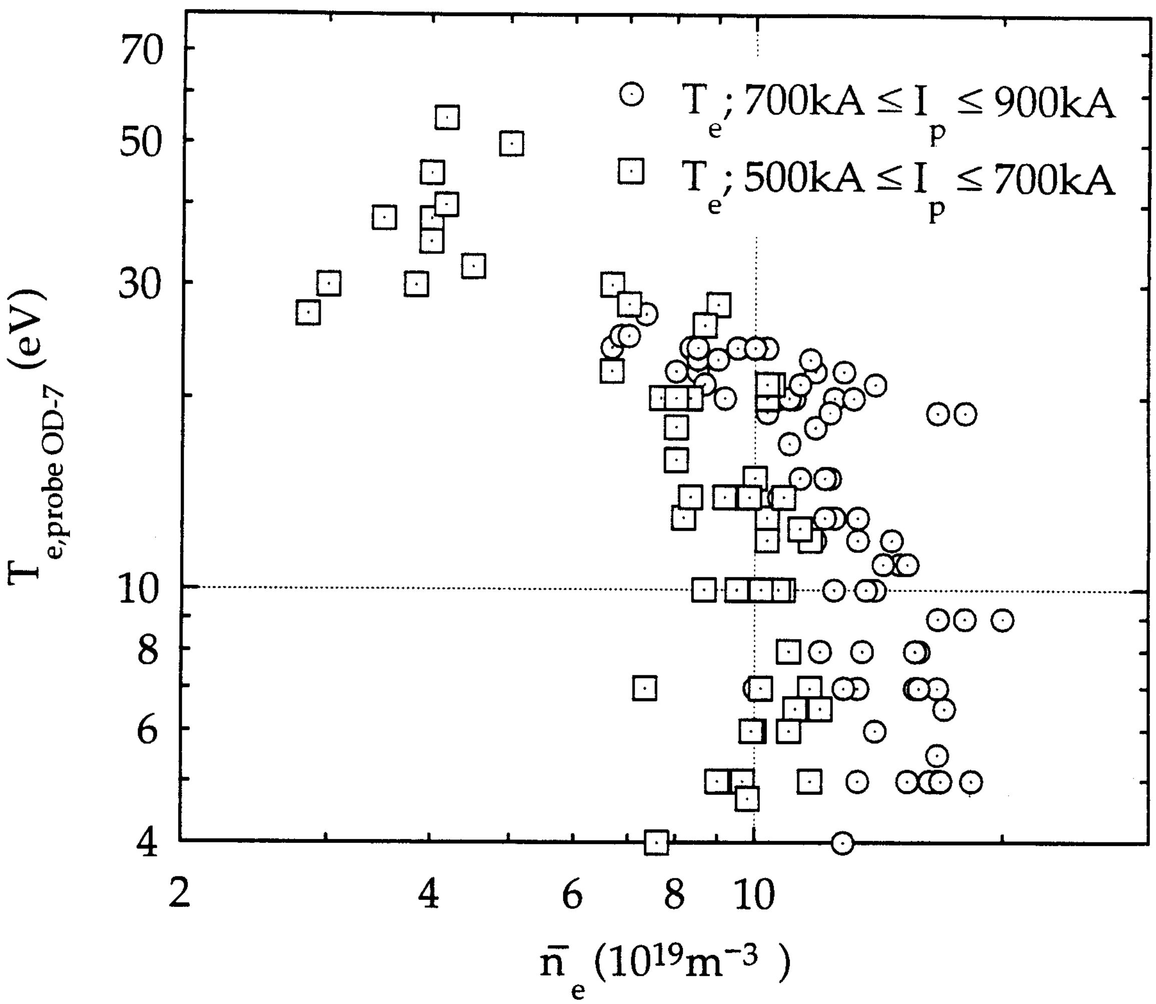


Figure 2



100
10
1
2
4
6
8
10
n_e; 700kA ≤ I_p ≤ 900kA
n_e; 500kA ≤ I_p ≤ 700kA
$n_{e,probe\ OD\text{-}7}$ ($10^{19}m^{-3}$)
$\bar{n}_e$ (10^{19} m^{-3})

Figure 3(a)



70
50
30
10
8
6
4
2
4
6
8
10
T_e; 700kA ≤ I_p ≤ 900kA
T_e; 500kA ≤ I_p ≤ 700kA
$T_{e,probe\ OD\text{-}7}$ (eV)
$\bar{n}_e$ ($10^{19}m^{-3}$)

Figure 3(b)