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By

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INITIAL RESULTS FROM THE SCOOP LIMITER EXPERIMENT IN PDX

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ABSTRACT

A particle scoop limiter with a graphite face backed by a 50 liter volume for collecting particles was used in PDX. Experiments were performed to test its particle control and power handling capabilities with up to 5 MW of D^0 power injected into D^+ plasmas. Line average plasma densities up to 8×10^{13} cm^{-3} and currents up to 450 kA were obtained. Plasma densities in the scoop channels greater than 2×10^{13} cm^{-3} and neutral densities in the scoop volume greater than 5×10^{14} cm^{-3} were observed. There is evidence that recycling may have occurred in the scoop channels for several discharges with large line-averaged plasma density. At beam powers up to 2.5 MW, energy confinement times above 40 ms were deduced from magnetics measurements and from transport analysis. Pressures in the vacuum vessel were in the 10^{-5} Torr range, and recycling source neutral densities in the central plasma were low.

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I. INTRODUCTION

Limiters equipped with various means for particle removal have been proposed for control of recycling, reduction of impurity, and ash removal in fusion reactors.[1] These "pump limiters" are typically designed with a volume for trapping particles behind the part of the limiter in contact with the plasma. Experiments in tokamaks[2-4] have shown that relatively large pressures (1-50 mTorr) can be obtained in such volumes. These results indicate that the fraction of the injected gas which gets trapped within the limiter volume can be large.

A specially designed pump limiter called a scoop limiter was installed in PDX in 1982 (Fig. 1). It consisted of a box with an internal volume of 50 liters rigidly mounted on the PDX vacuum vessel wall. The side facing the central plasma was made of four blades of uncoated (ATJ) graphite machined to approximate a saddle surface. The radius of curvature in the toroidal direction was 60 cm away from the plasma and the radius of curvature in the poloidal direction was 120 cm toward the plasma. The innermost part of the limiter blade was at a major radius of 193 cm.

Behind the graphite blades were two symmetrically placed crescent-shaped channel entrances (Fig. 2a) facing the ion and electron drift directions. The two sides of the entrances approximated arcs with radii 120 and 40 cm separated by 2 cm at the midplane. Particles flowing into these entrances could continue in a short channel to a neutralizer made of copper and clad with 1/2 mm of vanadium (Fig. 2b). The purpose of the vanadium was to reduce sputtering. Neutrals leaving the neutralizer either could flow back into one of the channels and be ionized by the incoming plasma, or traverse the channel and exit back into the plasma edge, or remain in the plenum.

Calculations indicate that as the density or temperature of the plasma in the scoop channels increases, the probability of neutrals being ionized in the channels will increase.[5] When this probability is high, there is a hypothetical mode of operation where the neutral flow out of the plenum is throttled, resulting in high scoop pressures.[6] One of the goals of the experiment was to investigate recycling in the channels and to look for such modes of "trapped" operation.

A TV camera and an IR camera viewed visable and IR emissions from the limiter blades. Arrays of Langmuir probes sampled plasma conditions in the channels. Inside the scoop there were thermocouples to measure heating and calorimeters to detect the heat flux carried by neutrals. Pressure and density in the scoop were monitored using a capacitance manometer and ionization gauges. A ZnSe window on the back of the scoop allowed H_α light from deuterium to be monitored. We discuss conditions in the scoop in Sec. II.

Plasma discharges limited only by the scoop were run on 13 days between December 1982 and June 1983. The plasmas were very disruptive during the first few (non-consecutive) days, most likely due to lack of conditioning of the graphite blades. Neutral beam heating was used during seven of the days. Characteristics of these beam-heated discharges are discussed in Sec. III.

II. CONDITIONS IN THE SCOOP

Two arrays of fixed double Langmuir probes, which were located symmetrically to the left and right of the neutralizer, sampled plasma conditions in the two channels. Electron densities up to 2×10^{13} cm^{-3} and electron temperatures of typically 5-20 eV were inferred from current-voltage characteristics.

Figure 3 shows several measurements versus time for a discharge which had line-averaged density $\bar{n}_e$ rising to 5×10^{13} cm^{-3} during 2 MW of neutral beam heating. The electron density n_2 and temperature T_2 measured by the second ion side array probe are shown in Fig. 3a and 3b. The density increased during the neutral beam phase between 300 and 600 msec, but the electron temperature fluctuated about 9 eV throughout the discharge. The density n_9 measured by the mirror image probe on the electron side, shown in Fig 3c, was considerably less than n_2. Electron temperatures measured by all the array probes resembled T_2. Langmuir probe measurements in the edge plasma outside the scoop (about 1.9 meters away) had comparable electron densities and temperatures for the magnetic flux surfaces intercepted by the channel probes.[7]

An upperbound for the particle flux toward the neutralizer is given by the local electron density times the local sound speed

$$v_s \equiv \sqrt{k(T_e + T_i)/M_i} ,$$

which is proportional to the ion saturation current. The sum of these fluxes inferred from the 2nd, 3rd, etc. probes,

$$F \equiv F_2 + F_3 + F_5 + F_6 + F_8 + F_9,$$

is plotted in Fig. 3d. The average, F/6, estimates the sonic flow to the neutralizer at the midplane.

Pressures in the back of the scoop were measured by a capacitance manometer (Baratron) with a slow response time (~ 200 ms) and densities were measured by two ion gauges (a Shultz-Phelps and a Bayard-Alpert) with fast response times (~ 10 and 50 ms). The density measured by the Shultz-Phelps ion gauge (Fig. 3e) increased rapidly when the neutral beams started. The relative rise was larger than that of F. This may be partly due to plasma or beam ejection of neutrals near or in the scoop. It probably is not due to a decrease in particle confinement of the main plasma (outside the scoop) because the H_α signal, discussed below, did not increase.

Figure 3f shows the H_α emission observed through the ZnSe window in the back of the scoop. This emission is a volume average of the product of the edge electron density, neutral deuterium density n_D, and a rising function of the electron temperature. Figure 3g shows the H_α emission observed 108° toroidally away from the scoop. The slight decrease during the neutral beam phase, when $\bar{n}_e$ was increasing, suggests a decrease in edge recycling and an increase in the particle confinement time (unless impurities were causing $\bar{n}_e$, but not n_D to rise).

The ultra-soft x-ray signal emitted by the plasma outside the scoop is shown in Fig. 3h. This emission is strongest from the plasma edge, so inverted sawteeth were observed when discharges were in the sawtooth mode. These sawteeth are correlated with spikes on the Shultz-Phelps and H_α signals. They probably indicate real increases in density since pickup would be different in these detectors. The plasma density in the channels may have spiked as well, but the probe response was too slow to detect this.

The ion saturation currents and deduced electron densities were usually asymmetric, being larger in the channel facing the ion side by about 50% during the ohmic heating phase, and by a factor of two to three during the neutral beam heating phase of the discharge. The magnitude of the asymmetry varied as the vertical position of the plasma was changed. Figure 4 shows the asymmetry measured during neutral beam heating by mirror image pairs of probes in the ion and electron channels at various vertical displacements of the plasma. During one neutral beam run, the toroidal field and plasma current were reversed to study counterinjection, so that the ion drift direction was clockwise instead of counterclockwise as viewed from above. The asymmetry reversed as well.

Part of the asymmetry could be explained by the pitch of the field lines. The probes were located near the midplane, so the flux tubes intercepted by one array would twist down at the channel entrance, and flux tubes intercepted by the other array would twist up at the opposite channel entrance. Since the tubes intercepted the neutralizer, plasma could not flow from both entrances to both arrays. As the plasma was displaced above or below the midplane, the location in the scoop channel entrances where the plasma density was largest would be displaced. Even when the plasma was centered (according to magnetics measurements) on the midplane, there was a left-right asymmetry which could not be caused by the above mechanism.

This asymmetry might be caused by a toroidal rotation of the plasma in the flux surfaces flowing into the channels (at a minor radius between 42 and 45 cm). A rotation speed in the ion drift direction comparable to the sound speed at this surface, $v_s \sim 10^5$ cm/sec, would account for the observed asymmetry. Also, the precession of the banana orbiting beam ions in the direction of the plasma current would contribute to the asymmetry during the neutral beam heating phase.

To investigate recycling in the scoop channels, we studied the ratio of the densities n_5/n_2 measured by the fifth and second array probes. The fifth probe is 3.8 cm further down the channel than the second probe, and is approximately 3.8 cm from the neutralizer plate. Also, its major radius is 1 cm less, i.e., it is 1 cm closer to the back of the limiter blade. An increase in this ratio would indicate that the plasma density was increasing downstream towards the neutralizer, or alternatively, that the radial scrape-off length of the plasma density was becoming shorter. The former would indicate that neutrals were being ionized in the channels. The latter is not indicated by external probe measurements.[7] The ratio fluctuated considerably from fit to fit during each discharge, but most discharges did not exhibit a systematic variation with time. If these discharges did have channel recycling, it only occurred for brief periods lasting less than 50 msec, or else only occurred closer to the neutralizer than probes 5 and 6.

Several discharges did show a systematic variation in the ratio. These all had large $\bar{n}_e$ and were displaced above the midplane. Figure 5a shows the variation of n_5/n_2 with $\bar{n}_e$ for one such discharge. The ratio fluctuated considerably during the start-up, when $\bar{n}_e$ was low, then it increased and decreased along with $\bar{n}_e$. The shot-to-shot variation of n_5/n_2 at one time near the end of the neutral beam phase (Fig. 5b) also shows an increase with n_e. The ratio did not vary systematically with plasma current or with neutral beam power. Figure 6 shows the shot-to-shot variation of the Shultz-Phelps density with $F_2 + F_5 + F_6 + F_9$. If the density increased linearly up to some threshold, and then faster than linearly above that threshold, this would indicate neutral trapping, assuming the Mach number of the flow remained unchanged.

We investigated particle balance by comparing the measured scoop neutral densities with estimates of the particle influx, the particle outflux from the main plasma, and the fueling rate. As shown in Fig. 3e, the number of neutrals in the scoop plenum was roughly constant during the neutral beam phase at $N \sim 1.5 \times 10^{14}\ cm^{-3} \times (5 \times 10^4\ cm^3) = 7.5 \times 10^{18}$. This equals the rate for deuterium entering, R_{in}, times the exit time, τ_{ex} for particles to leave the plenum, either by exiting the channels, or by being pumped by surfaces inside the scoop. The cross-sectional area of each of the channel entrances (Fig. 2a) was 40 cm^2. If the plasma flow into these was uniform poloidally and at one-half sonic speed, then the total rate for ions entering during the neutral beam phase would be

$$R_{chan} = (\frac{1}{2})(\frac{1}{6} F) \times 80 \ cm^2 \simeq 10^{21}/ \sec .$$

Ions in the channels get accelerated by the sheath potential of the neutralizer, which increases their energy by about 3 kT_e. After striking the neutralizer, about half get reflected, and lose about half their energy. The other half, which gets embedded, is not reemitted in significant quantities unless the pulse length is longer than the wall recycling time.[8] We do not know the surface condition or temperature of the neutralizer, but the recycling time probably was longer than 300 msec, so the embedded deuterium was either reemitted after the discharge, or remained inside. The volume of vanadium was sufficient to absorb all the embedded deuterium used to fuel the scoop shots. Some fraction f of the reflected deuterium enters the plenum, so $R_{in} \sim f \ R_{chan}/2$. Thus particle balance requires $\tau_{ex} = N / R_{in} \sim (15/f)$ msec.

If the plasma is not dense enough to alter f, then from the geometry of the neutralizer and channels, $f \sim 1/3$ and thus $\tau_{ex} \sim 45$ msec. The exhaust time for neutrals to exit out the channels, derived by estimating the conductance without plasma trapping in the channels, is

$$\tau_{ex} = 50 \left\{ \frac{M}{M_{D_2} \ 40 \ T_{(eV)}} \right\}^{\frac{1}{2}} \text{ msec.}$$

If the exiting deuterium is at room temperature, τ_{ex} would be about 50 msec.

If channel plasma trapped neutrals, then f would increase, requiring a smaller τ_{ex}. Also, the decrease in conductance would increase the factor in the above expression for τ_{ex}, so the exiting deuterium would have to be hotter, or pumping would be required to decrease τ_{ex}. One piece of evidence for small τ_{ex} is the rapid decrease of the Shultz-Phelps signal after sawteeth (Fig. 4e), within several msec instead of 50 msec.

Monte Carlo calculations indicate that the average energy of atomic deuterium in the box was between 10 and 20 eV. A titanium getter ball has been used to deposit titanium inside the scoop during one run 6 weeks before most of the neutral beam heated discharges occurred. Inside surfaces probably were coated with sufficient impurities such as oxygen to prevent the low energy deuterium from entering; however, they could have continued gettering hot neutrals. Ten eV may be sufficient to penetrate typical impurity layers. Also, there were stainless steel tubes and a large number of braided cables inside the box, so the internal surface area was very large. This may have increased the pumping speed as well.

If the global particle confinement time of the plasma were more than 100 msec (see Sec. III) with $\bar{n}_e = 5 \times 10^{13}$ cm^{-3}, then the number of particles leaving the plasma would be less than 2.5 times R_{chan}, so at least 40% would enter the scoop. The gas injection rate for scoop discharges was typically less than R_{chan} by about an order of magnitude, which indicates that deuterium must have recycled through the scoop ten or more times.

III. CHARACTERISTICS OF NEUTRAL BEAM HEATED SCOOP DISCHARGES

Plasmas with major radius R = 153-161 cm and minor radius 193-R were run on the scoop. Multi-point Thomson scattering profiles for a discharge heated with 2.3 MW of D^0 power are shown in Fig. 7. Electron temperature histories were measured by electron cyclotron emission, and ion temperature histories were measured by a passive charge exchange diagnostic using small amounts of hydrogen in the deuterium discharges. The variations with time of several discharges identical to the one used in Fig. 7, are shown in Fig. 8.

The Thomson scattering profiles indicate suprisingly high electron densities and temperatures at major radii close to the limiter blades. If these existed at the limiter surface, the corresponding power flow along field lines would be large. An IR camera, used to record temperatures on the blades, indicated that the maximum temperature increase varied between 300-1500 ^0C, so the power absorbed must have been only 1-2.5 kW cm^{-2}.

The TV camera, which viewed the scoop from a port on the opposite side of PDX, observed a low level of visible light, indicating that recycling on the scoop blades was low and very localized. Pressure measurements of the vacuum vessel indicated relatively low pressures ($\sim 10^{-5}$ Torr). This contrasts with the high pressures (10^{-2} Torr) measured in the scoop (Fig. 6).

Central chord bremsstrahlung emission and the X-ray pulse height analyzer both yielded estimates of the line averaged Z_{eff}. Typical values were Z_{eff} = 1.5-3.0. This range is comparable to that measured during H-mode divertor runs in PDX.[9] Vacuum ultraviolet spectroscopy indicates that the main impurity spectral lines were low Z such as carbon and oxygen.

Approximately 200 of the neutral beam heated discharges did not disrupt before the end of the beam pulse. Sufficient measurements were archived to permit magnetics analysis of most of these. For this analysis, the total stored plasma energy (thermal + beam ion) U was determined by constructing $\beta_{Poloidal} + \ell_i/2$ from the measured equilibrium vertical B field, and subtracting $\ell_i/2$ using an estimate of the current profile. From U and the total heating power P_{tot}, which is the sum of the ohmic heating power I_pV and the neutral beam power absorbed by the plasma P_{abs}, the equilibrium energy confinement time is given by

$$\tau_E^{eq} = \frac{U}{P_{tot} - \partial U/\partial t} .$$

An example of this analysis for the discharge used in Fig. 7 is given in Fig. 9. From the figure, one can see the initial degradation of τ_E^{eq} with the onset of neutral beam injection at 300 msec, followed by a continuing rise in I_p and $\bar{n}_e$ and concomitant rise in τ_E^{eq} to ~ 33 msec at the end of the beam pulse.

Figure 10a shows the variation of τ_E^{eq} with P_{abs}. The O data, from shots with sawteeth, had higher τ_E^{eq} than the ● data from shots without sawteeth. Strong m=2 activity was identified in some of these ● discharges. We performed detailed transport analyses[10] of several high τ_E^{eq} shots. This yielded thermal energy confinement times τ_E^{th} which are determined from the stored energy and power losses from only the thermal component of the plasma. The results, shown in Figure 10b, agree reasonably well with the data given by the simpler magnetics analysis. Both methods show that τ_E degrades as P_{abs} increased above 2.5 MW.

The variation of τ_E^{eq} with the plasma current for shots with P_{abs} between 1.6 and 2.5 MW is shown in Fig. 11. For comparison, the line $I_p/10$, corresponding to average H-mode confinement times,[9] is given. There was a tendency for τ_E^{eq} to increase with I_p. Figure 11 also shows that τ_E^{eq} scaled by I_p did not depend strongly on $\bar{n}_e$. No strong dependence of τ_E^{eq} on internal scoop measurements was noticed.

The horizontally scanning charge-exchange analyzer measured beam ion charge-exchange efflux from the plasma region close toroidally to the scoop. Absolute signal levels were about 1/3 of those measured with typical diverted plasmas. Comparison with the efflux calculated by the transport analysis code gives a coarse estimate of the deuterium confinement time, and the neutral density distribution near the scoop. Long confinement times, greater than 100 msec, were inferred this way. The recycling source neutral density (as opposed to the beam halo source neutral density) was in the low to mid $\sim 10^9$ cm^{-3} range at the plasma edge, $r \sim 35-40$ cm. This range is quite low, even compared with that deduced in the same manner for divertor discharges. One would have expected a high neutral density this close to a standard limiter.

We investigated power balance for shots with $P_{tot} \sim 2$ MW. A 19 channel bolometer array measured energy flux along chords from the plasma, providing an estimate for the sum of the radiated and charge-exchange power loss. Less than 25-45% of P_{tot} was detected. Part of the rest was scraped onto the limiter blade, or into the scoop channels. The IR camera measurements indicated that approximately 25-50% of the P_{tot} heated the limiter. A calorimeter measured heat flow in the limiter shadow region on the midplane about 2 meters from the scoop. The measured heat flux profile[7] indicates that approximately 60 kW, or 3% of P_{tot} entered the scoop. About 5-50% of the power is thus unaccounted for. This is typical of standard limiter discharges in PDX. For these, it has been speculated that the cloud of neutrals around the limiter carried substantial amounts of the unobserved energy to the vacuum vessel wall.

Recycling and confinement of He^3 were studied by puffing short bursts of He^3 through the scoop or dome gas injection valves into the discharge, and monitoring the protons from the $He^3(d,p)\alpha$ reaction.[11] The rise time of the proton signal was about 50 msec and was probably determined by the gas conductance to the main chamber, thus the inward transport time for He^3 was $\lesssim$ 50 msec. The exponential decay time of the proton signal was longer (Fig.

12), and was dominated primarily by the recycling and pumping of He^3. When the average plasma density was larger than 3×10^{13} cm^{-3}, the He^3 decay time was up to an order of magnitude shorter than for similar PLT experiments, which used a carbon rail limiter. The enhanced pumping of He^3 during scoop discharges might be explained by helium removal by the scoop, or by helium burial in the scoop limiter blades due to high edge temperature. The vacuum vessel of PDX is much larger than PLT, and this may have played a role in keeping the decay time short. Some calculations have indicated that a scoop will pump He^4 preferentially.[12] Other calculations indicate the contrary.[5]

IV. CONCLUSIONS

After several days of neutral beam conditioning, plasmas were run on the scoop with high scoop densities, low external neutral densities, and high energy confinement times. There are indications that scoop channel recycling may have occurred for several shots with high line-averaged plasma densities. For most of the shots, including many with high energy confinement times and low neutral densites, scoop channel recycling was not observed. Apparently, even without this recycling, neutrals from inside the scoop, and from the scoop limiter blades did not enter the plasma core in large quantities.

The use of the scoop limiter on PDX allowed plasmas to be produced with energy confirement and impurity concentrations comparable to the best PDX diverted plasmas. Further experimentation, especially with long pulse operation, would help to evaluate the potential of scoop limiters for fusion reactors.

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FIGURE CAPTIONS

FIG. 1. *Isometric view of the scoop.*

FIG. 2. Schematics of the scoop: (a) Elevation view of the limiter blades and the ion side channel entrance, (b) Plan view of the scoop showing the channels, neutralizer, and diagnostics.

FIG. 3. Various measurements for a scoop discharge: (a) ion channel electron density, (b) electron temperature, (c) electron channel density, (d) sonic flow estimate, (e) neutral density measured by the Shultz-Phelps gauge, (f) scoop H_α emission, (g) plasma H_α emission, and (h) ultra-soft X-ray emission.

FIG. 4. Shot-to-shot variation of the ion side/electron side asymmetry in the ion sonic speeds, or equivalently, in the saturation currents measured by sets of mirror-symmetric probes as labeled in Fig. 2b., with the plasma at various vertical displacements.

FIG. 5. Variation of the ratio of electron densities measured by probe 2 and probe 5 versus $\bar{n}_e$ for (a) a single discharge, (b) various discharges at a single time.

FIG. 6. Densities measured by the Shultz-Phelps gauge versus the sum of the sonic estimates, $F_2 + F_5 + F_6 + F_9$.

FIG. 7. Thomson scattering electron temperature (a), and density (b) profiles at 580 msec for a discharge with I_p = 360 kA and 2.3 MW of injected D^0 power.

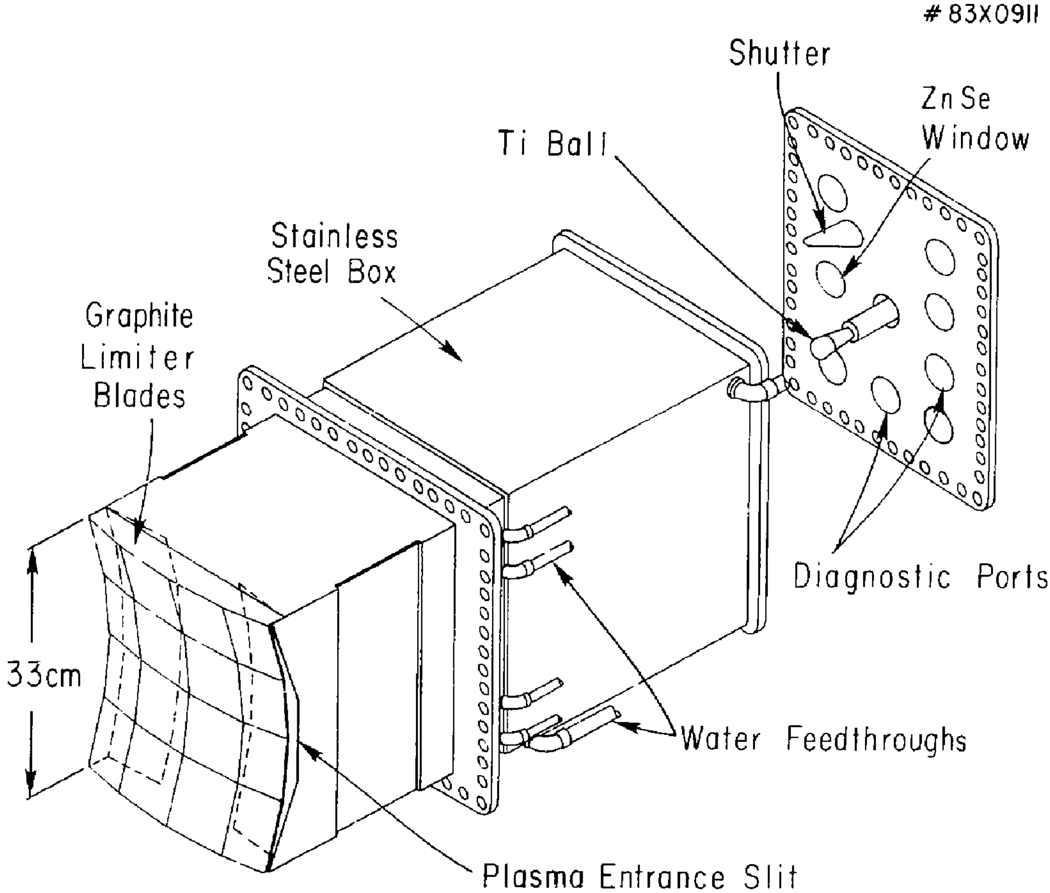
FIG. 8 Electron cyclotron electron temperatures at various major radii for a discharge identical to the one in Fig. 7 (a), and charge exchange ion temperature in the center averaged for several identical discharges, including the one in Fig. 7(b).

FIG. 9. Example of plasma conditions versus time and the magnetics analysis of a discharge :(a) plasma current and beta toroidal, (b) line-averaged electron density and absorbed neutral beam power, (c) τ_E^{eq} and the safety factor q at the limiter.

FIG. 10. Peak τ_E during the neutral beam heated phases of discharges versus P_{abs}: (a) τ_E^{eq} from magnetics analysis of shots with sawteeth O, and without ● ,(b) τ_E^{th} from transport analysis of shots with and without sawteeth.

FIG. 11. Variation of peak τ_E^{eq} for discharges with $1.6 < P_{abs} < 2.5$ MW: (a) versus I_p, and (b) scaled by I_p versus $\bar{n}_e$.

FIG. 12. Decay time of protons from $D + He^3 \rightarrow p + He^4$ versus $\bar{n}_e$ measured by He^3 puffing in PDX and PLT. The O data are from PDX with scoop puffing and the Δ data are from PDX with upper divertor dome puffing. The ● and ▲ data are both from carbon rail limiter operation in PLT.



83X0911
Shutter
ZnSe
Window
Ti Ball
Stainless
Steel Box
Graphite
Limiter
Blades
33cm
Diagnostic Ports
Water Feedthroughs
Plasma Entrance Slit

Figure 1

#83P0137

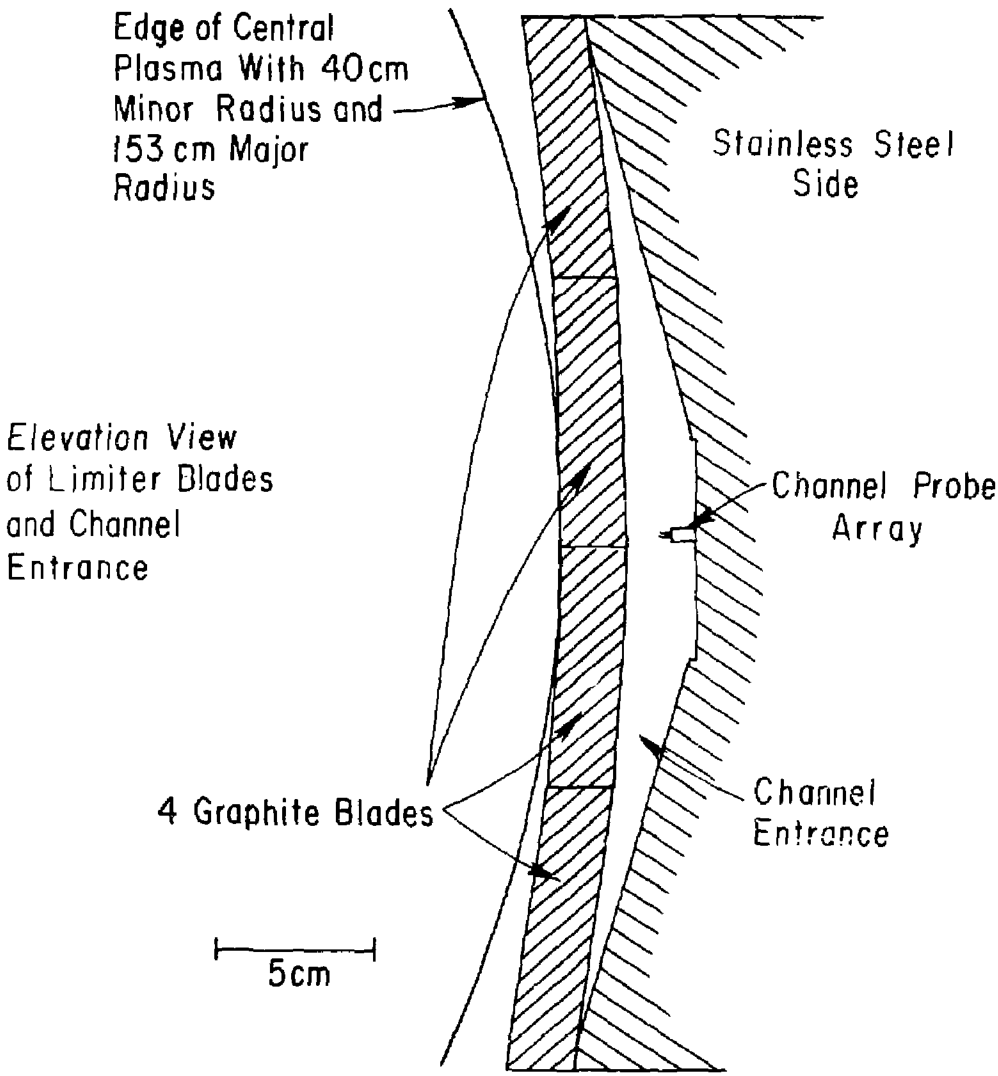


Figure 2a

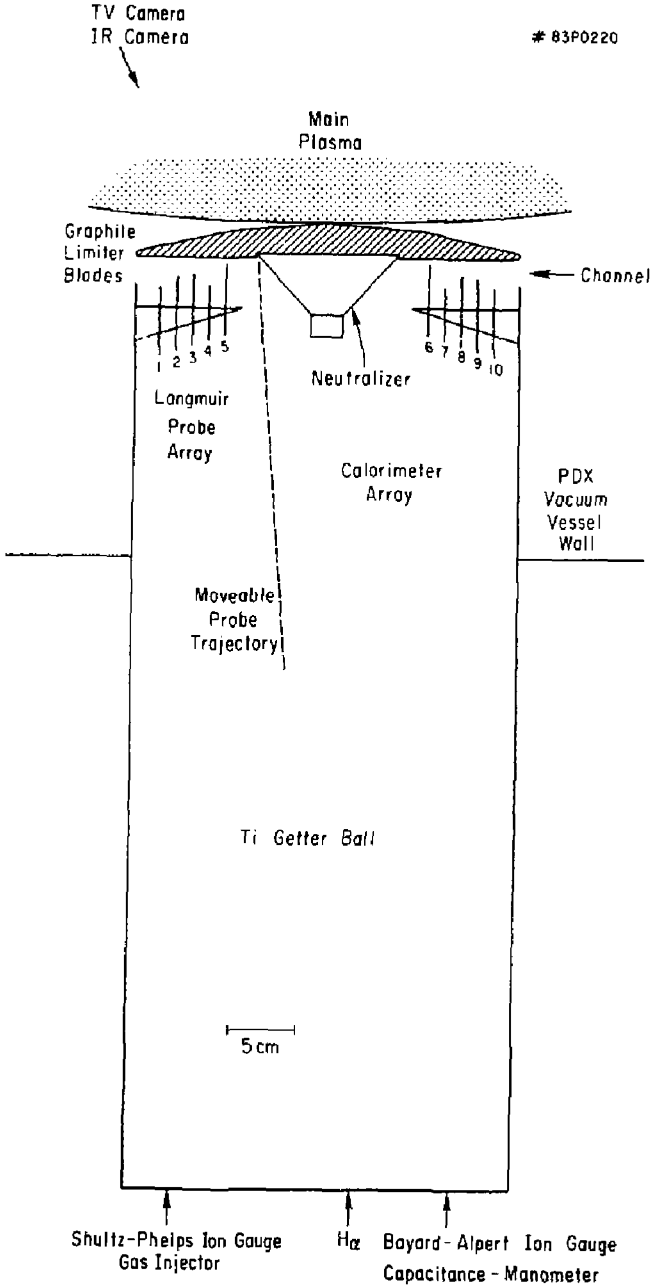

TV Camera
IR Camera
83P0220
Main
Plasma
Graphite
Limiter
Blades
Channel
1 2 3 4 5
6 7 8 9 10
Neutralizer
Langmuir
Probe
Array
Calorimeter
Array
PDX
Vacuum
Vessel
Wall
Moveable
Probe
Trajectory
Ti Getter Ball
5 cm
Shultz-Phelps Ion Gauge
Gas Injector
Hα
Bayard-Alpert Ion Gauge
Capacitance - Manometer

Figure 2b

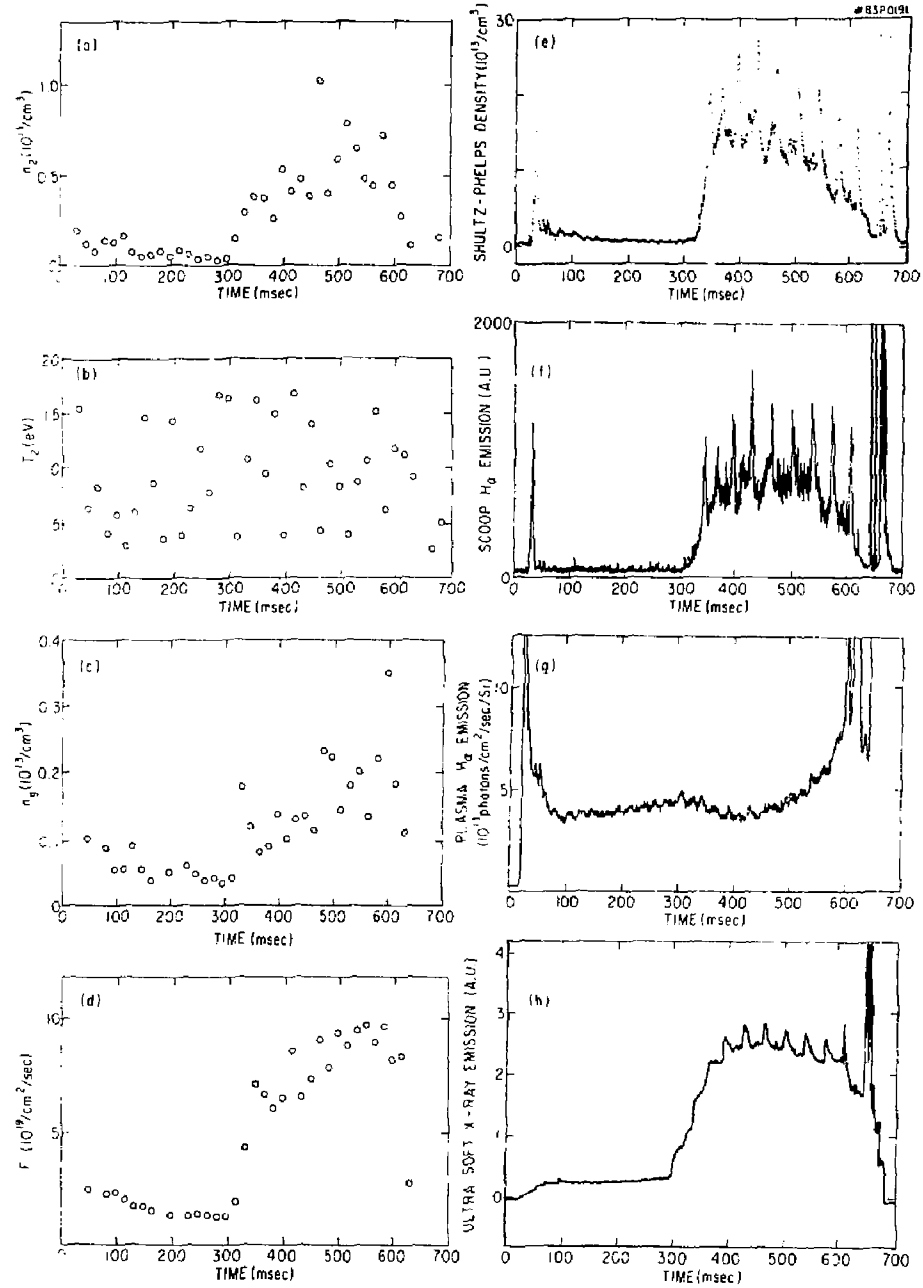

#83P0191
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
TIME (msec)
SHULTZ-PHELPS DENSITY (10^{13}/cm^3)
SCOOP H_α EMISSION (A.U.)
PLASMA H_α EMISSION
(10^{1} photons/cm^2/sec/Sr)
ULTRA SOFT X-RAY EMISSION (A.U.)

Figure 3

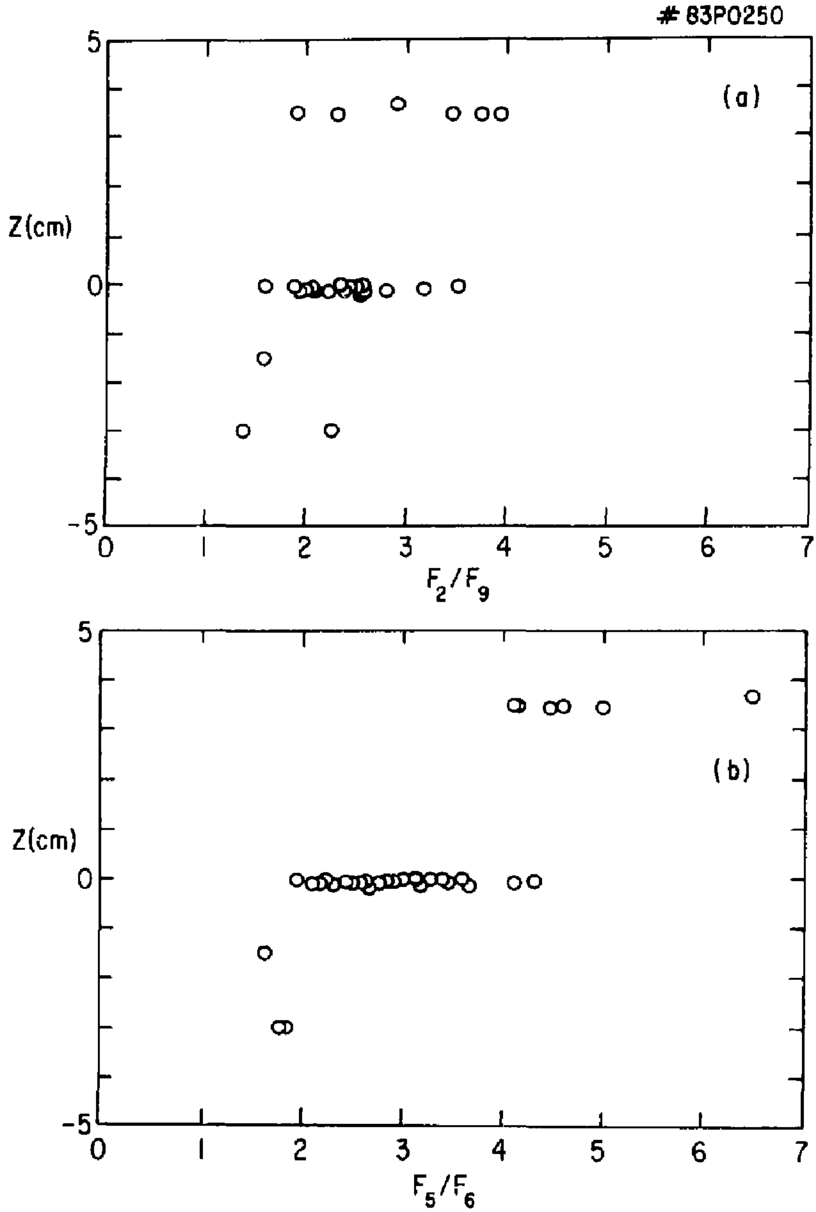


Figure 4

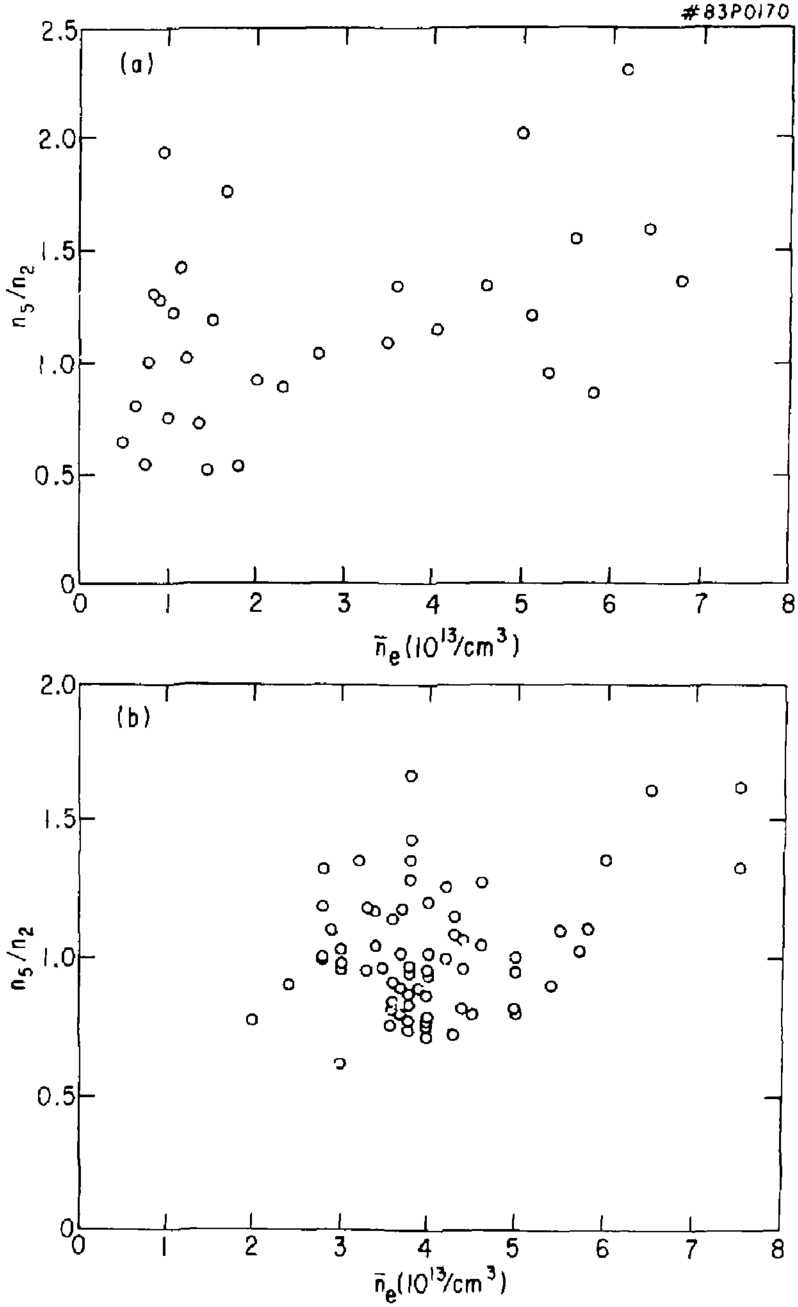
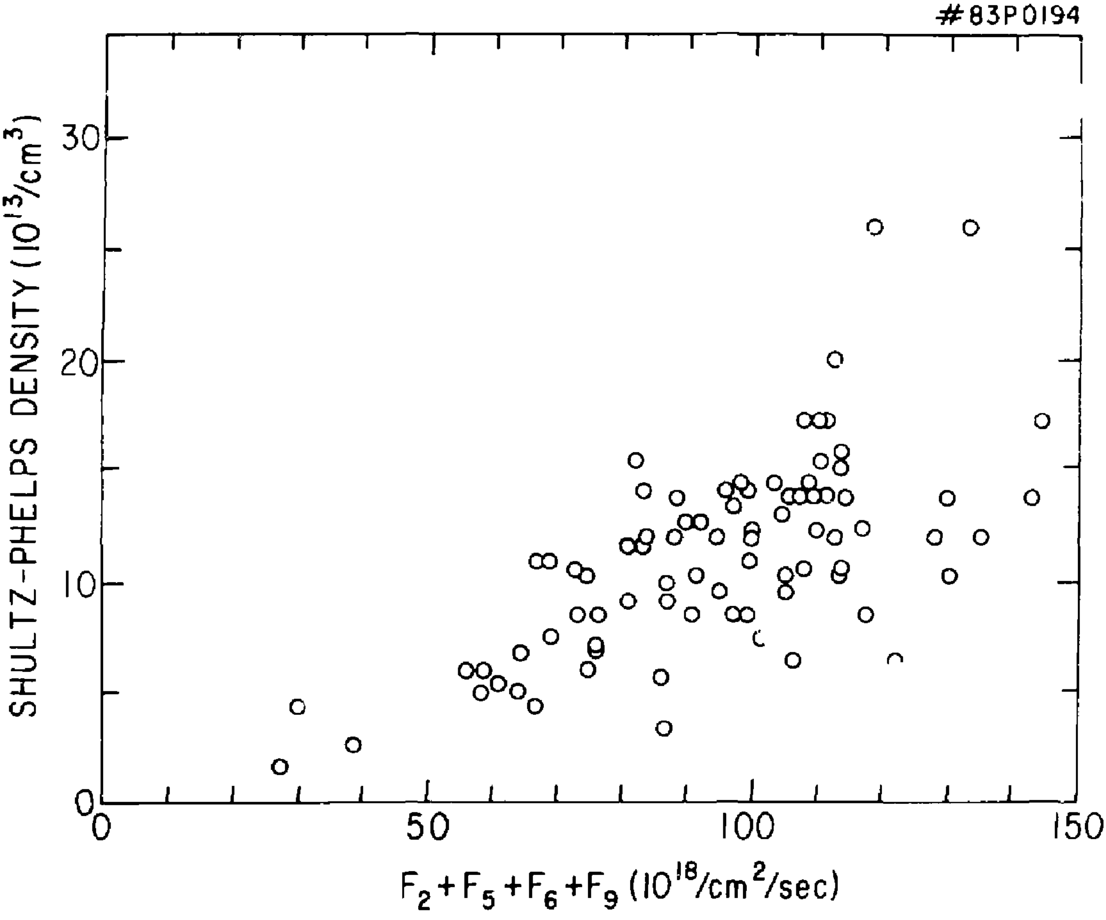

#83P0170
(a)
2.5
2.0
1.5
1.0
0.5
0
n_5/n_2
0
1
2
3
4
5
6
7
8
$\bar{n}_e(10^{13}/cm^3)$
(b)
2.0
1.5
1.0
0.5
0
n_5/n_2
0
1
2
3
4
5
6
7
8
$\bar{n}_e(10^{13}/cm^3)$

Figure 5



#83P0194
SHULTZ-PHELPS DENSITY ($10^{13}/cm^3$)
$F_2+F_5+F_6+F_9$ ($10^{18}/cm^2/sec$)
0
10
20
30
0
50
100
150

Figure 6

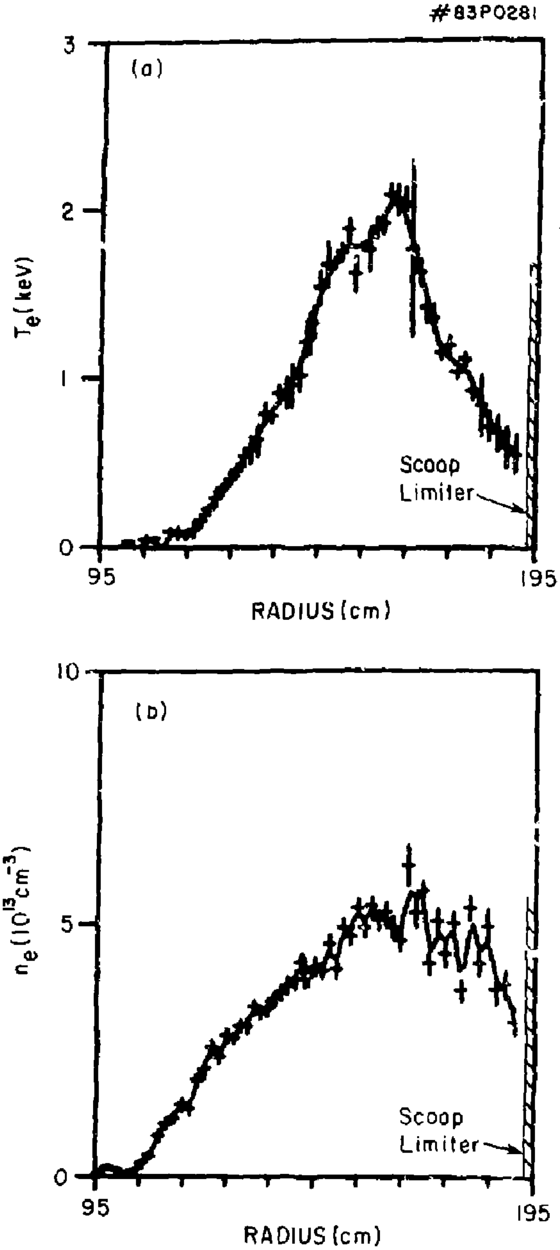

#83P0281
(a)
3
2
1
0
T_e(keV)
Scoop
Limiter
95
195
RADIUS (cm)
(b)
10
5
0
$n_e(10^{13}cm^{-3})$
Scoop
Limiter
95
195
RADIUS (cm)

Figure 7

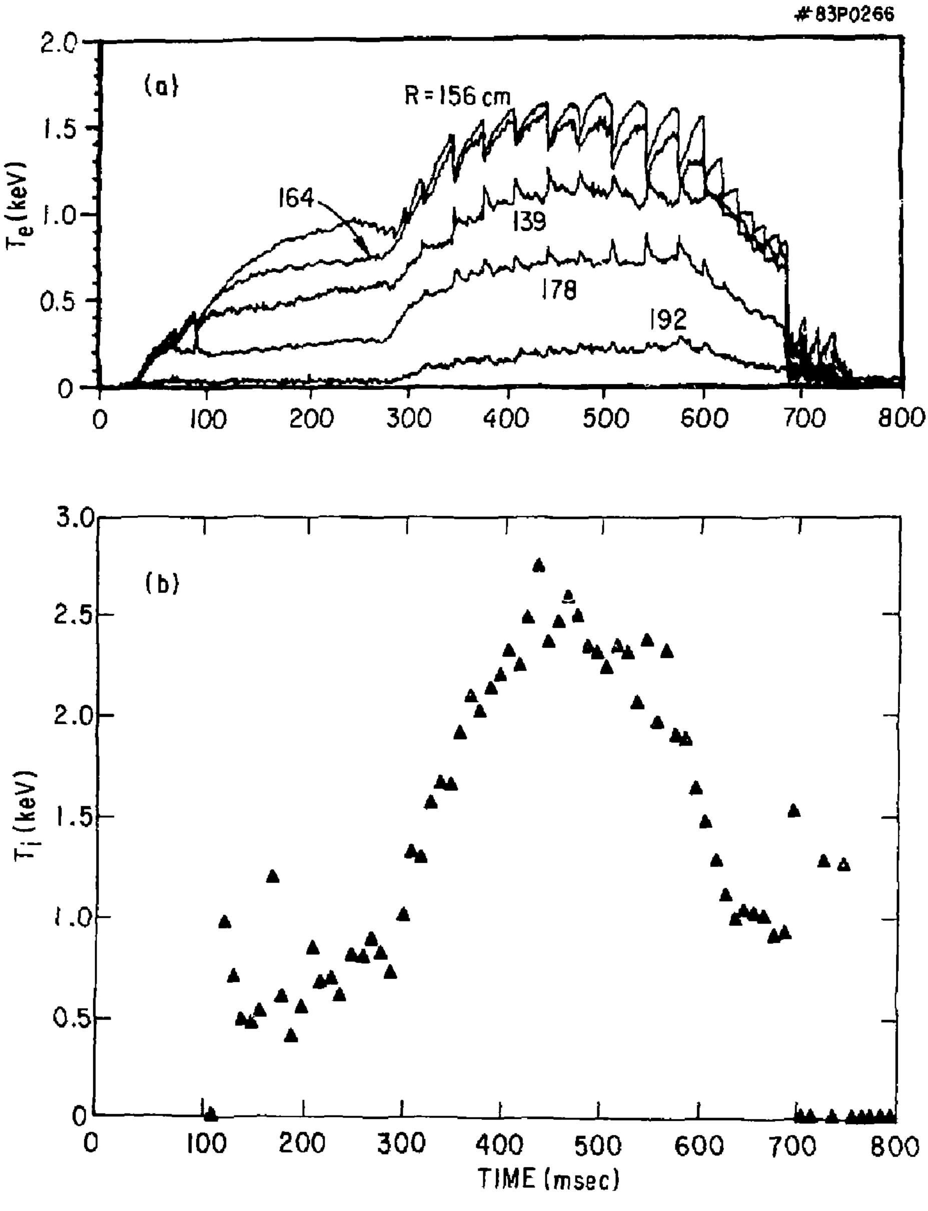

#83P0266
(a)
R=156 cm
164
139
178
192
T_e (keV)
2.0
1.5
1.0
0.5
0
0
100
200
300
400
500
600
700
800
(b)
T_i (keV)
3.0
2.5
2.0
1.5
1.0
0.5
0
TIME (msec)

Figure 8

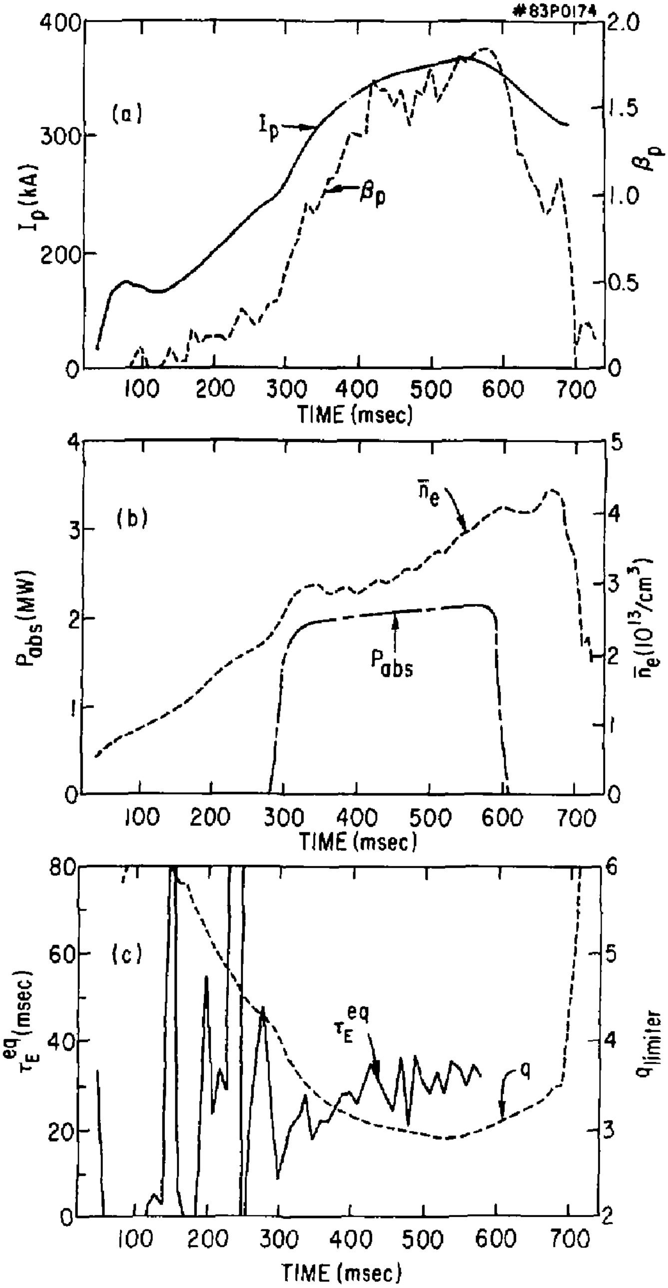

#83P0174
(a)
I_p
β_p
I_p (kA)
β_p
TIME (msec)
(b)
$\bar{n}_e$
P_{abs}
P_{abs} (MW)
$\bar{n}_e$ (10^{13}/cm^3)
TIME (msec)
(c)
τ_E^{eq}
q
τ_E^{eq} (msec)
$q_{limiter}$
TIME (msec)

Figure 9

#83P0236

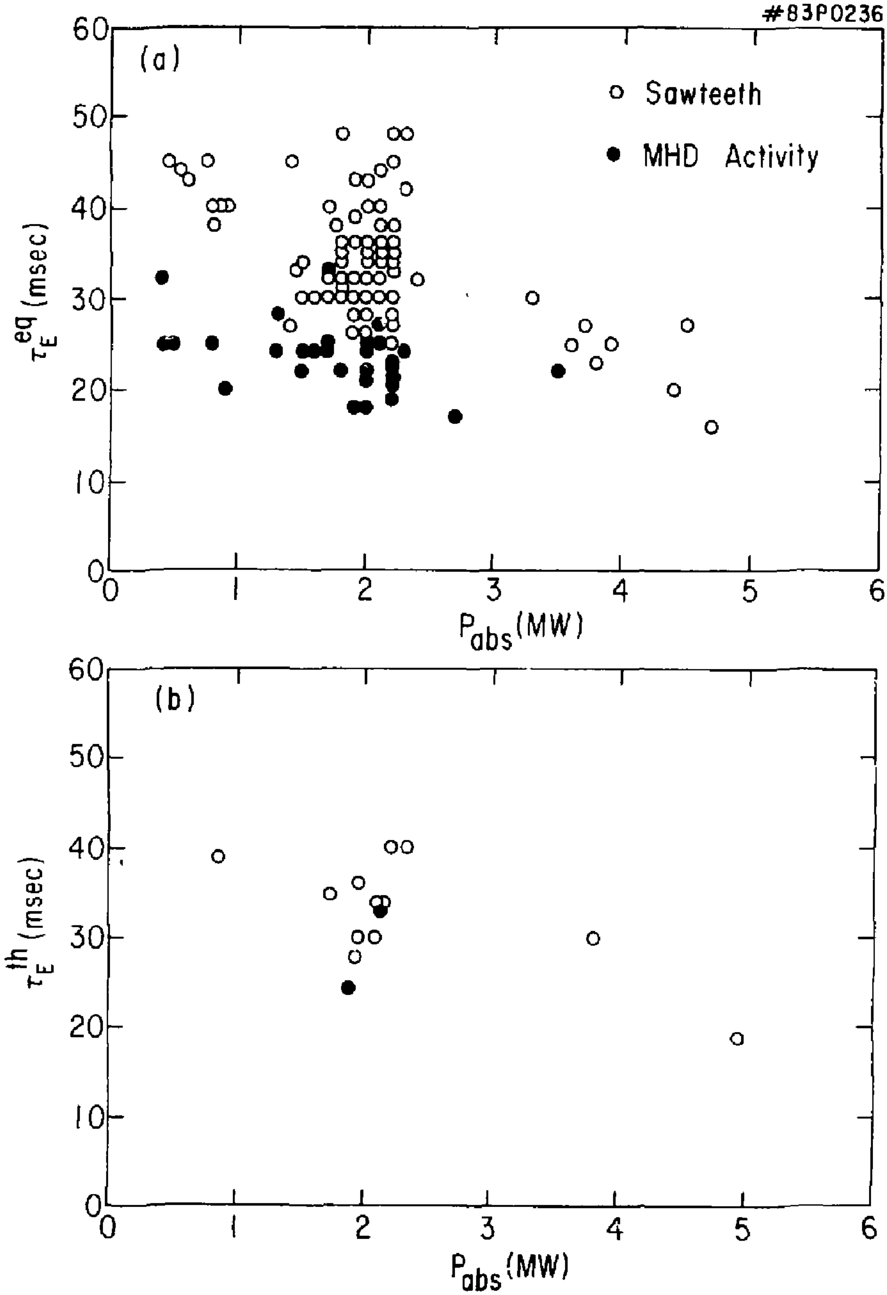


Figure 10

#83P0227

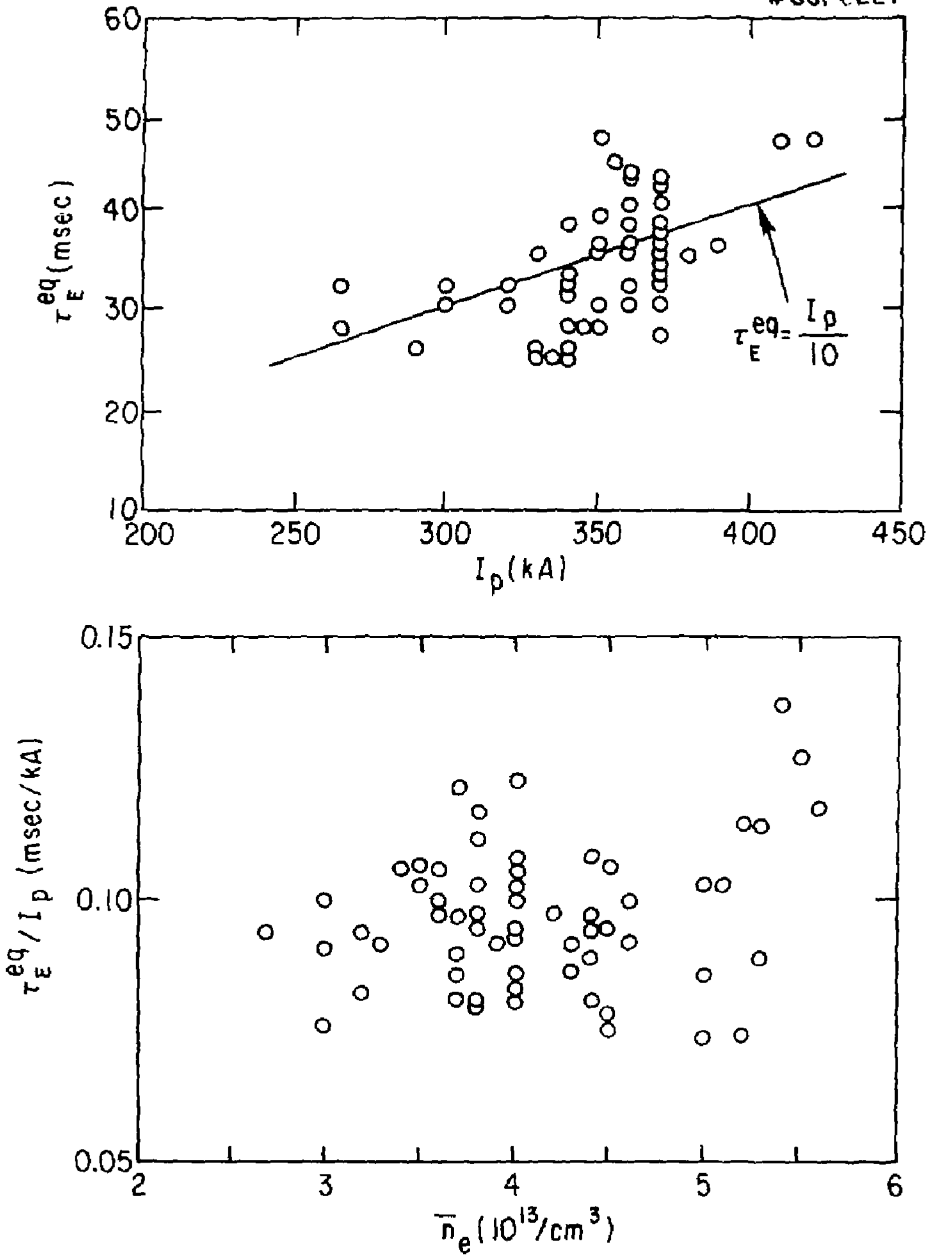


Figure 11

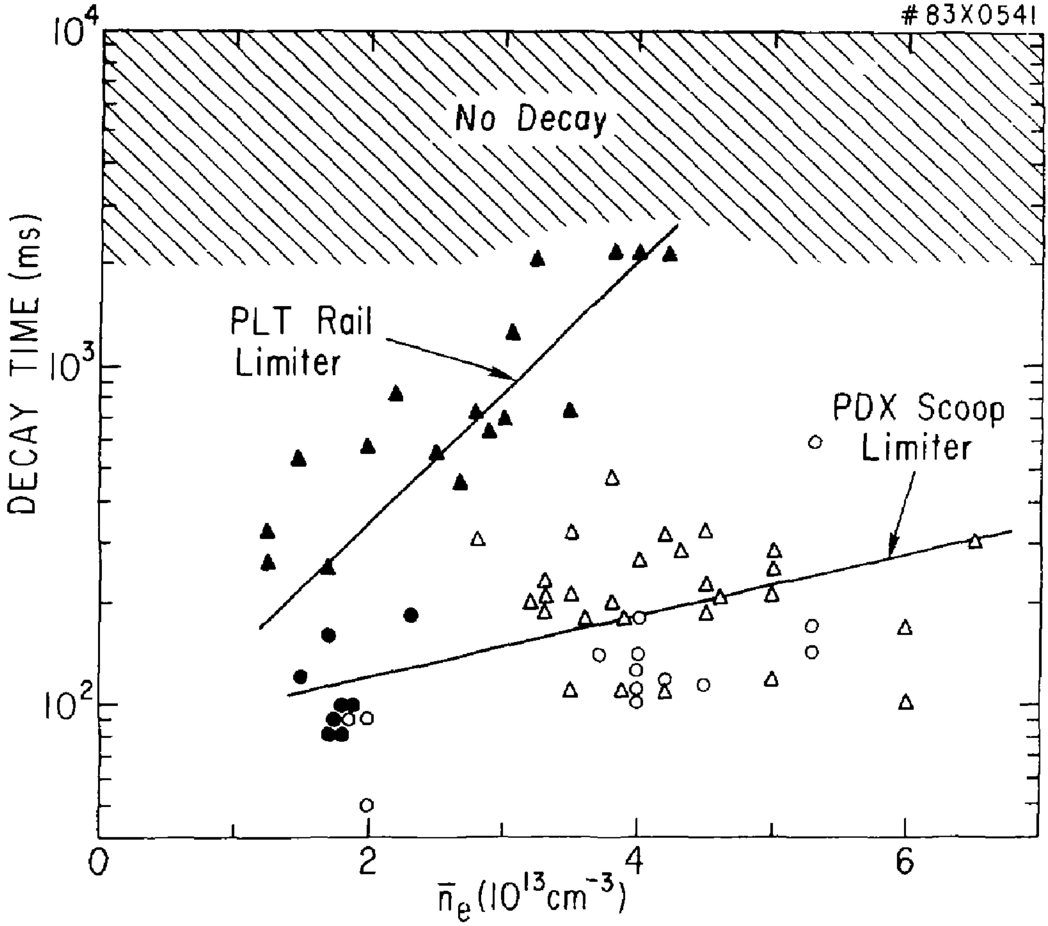

#83X0541
No Decay
PLT Rail
Limiter
PDX Scoop
Limiter
DECAY TIME (ms)
10^4
10^3
10^2
0
2
4
6
$\bar{n}_e (10^{13} cm^{-3})$

Figure 12

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