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Neutral Gas Compression in the Alcator C-Mod Divertor, Experimental Observations

A. Niemczewski, B. LaBombard, B. Lipschultz, G. McCracken

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ABSTRACT

One of the high heat flux solutions envisioned for ITER is the gas target divertor. This scheme requires high neutral pressure to be sustained in the divertor chamber with a minimal effect on the pressure in the main tokamak chamber (i.e. high gas compression).

The neutral gas compression has been studied in the Alcator C-Mod closed divertor under various central and edge plasma conditions. The neutral pressure measured by a fast, in-situ, ionization gauge, installed behind the divertor target plate was compared with the midplane pressure, measured by a shielded Bayard-Alpert gauge.

Divertor pressures up to 30 mTorr with compression factors $p_{div}/p_{mid} \leq 70$ have been observed. It has been found that the neutral pressure in the divertor does not depend strongly on the fueling location but rather on the core plasma density and the resulting divertor plasma regime. Divertor detachment leads to a considerable drop in the compression ratio, suggesting a partial "unplugging" of the divertor volume.

An examination of the local particle flux balance in the divertor indicates that the single most important factor determining divertor pressure and compression is the private-flux plasma channel opacity to neutrals.

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I. MOTIVATION

Results from a number of tokamaks [1, 2] have indicated that high plasma confinement regimes require low neutral pressure near the vicinity of the plasma core. Similarly, experience from the Alcator C-Mod tokamak shows that the ohmic H-modes require much lower main chamber neutral pressure (~.01 mTorr D_2) than the corresponding L-mode discharges [3]. At the same time the gas target divertor scheme envisioned for ITER [4] requires high neutral pressure in the divertor chamber for effective heat flux dissipation and dispersion.

Thus a high neutral compression ratio between the tokamak divertor and main chambers is of considerable interest for existing and future machines. Moreover the neutral gas dynamics itself is crucial in our understanding of the divertor physics.

II. EXPERIMENTS

A series of experiments have been performed on Alcator C-Mod, where the divertor neutral pressure and the compression ratio between the divertor and the midplane (p_{div}/p_{mid}) was examined under varying plasma conditions.

The main parameter varied for the experimental data presented below was the line averaged core plasma density: $<n_e> = 0.4 - 2.5*10^{20}\ m^{-3}$. All discharges were ohmicaly heated with I_p = 600 -800kA. The discharges were single-null diverted, with the approximate geometry shown on Fig.1. The geometry varied slightly between the shots, however, the outer strike point was always located approximately at the middle of the vertical portion of the outer target plate, below the divertor "nose". The ion ∇B drift was directed towards the Alcator closed divertor.

About 10% of the shots shown were fueled in the divertor private-flux zone (gas-puff), while the rest were fueled at the tokamak midplane. Within the parameter range reported here, the fueling location did not influence the steady-state neutral pressure results.

For the scaling analysis reported below, the Alcator Edge Database was utilized. Each point on the following scatter plots corresponds to a time slice taken at the maximum or at the steady-state value of the divertor neutral pressure. Each data-point is averaged over the10ms time window.

III. MEASUREMENTS

Neutral pressure is measured in Alcator C-Mod by six gauges located at four locations in the vacuum vessel. In this report the results from two locations are reported only. The locations of the pressure measurements are shown on Fig.1.

Divertor pressure is measured by a fast, linear, ionization gauge [5] located in a "gas-box" behind the outer divertor target plate. For the discharges analyzed in this report the "gas box" plenum was connected to the divertor private-flux zone. The vacuum time-constant of the gas box is ~7ms for room-temperature molecular deuterium. The neutral pressure on the tokamak midplane is measured by the magnetically shielded Bayard-Alpert gauge located on an extension pipe, protected from fast neutrals and photons. The response time of the midplane gauge is ~17ms.

Pressure is also measured in a divertor module opened to the midplane and at the bottom of a vertical port (~50ms time response), connected to the gas box plenum. These data are not discussed here.

IV. SCALING WITH CORE DENSITY

Based on the scrape-off layer (SOL) parallel heat transport, three distinctive regimes have been identified [6]:

- *Sheath-limited* heat transport, where the plasma pressure (static + dynamic) is constant along open field lines, and plasma temperature drop occurs within the sheath only, remaining otherwise constant along field lines.
- *Recycling* divertor, where the plasma pressure is constant but there are density and temperature gradients along open field lines, due to the particle flux multiplication.

• *Detached* divertor, where the pressure is no longer constant along open field lines.
• *Transition* region between the sheath-limited and the highly recycling divertor has also been distinguished, for the purpose of this report only, to help categorize neutral pressure data.

The detailed analysis of the SOL transport leading to the regimes described above can be found elsewhere [6]. Here we will use these regimes to help understand better neutral particle dynamics.

As an illustration of the SOL transport regimes the target plasma density at the flux surface of ρ = 4mm (where ρ is the distance from separatrix, when measured at the midplane) is plotted versus line averaged core plasma density in Fig. 2. In the sheath-limited regime the target plasma density is low and relatively independent of the core density. It rises rapidly through the transition and the recycling regimes. In the detached divertor regime the target plasma density is considerably lower than its maximum value in the recycling case and it does not vary strongly with the core density.

Neutral pressure in the divertor private-flux zone is plotted versus the core density in Fig. 3. The divertor neutral pressure scales similarly to the divertor plasma density. It is at a low value (~0.5 mTorr) and almost constant in the sheath-limited regime. In the transition and recycling regimes it increases rapidly with core density. The pressure scaling does not follow the density scaling during the divertor detachment, where neutral pressure is approximately unchanged from the maximum value in the recycling case and rises slowly with the core density (25-30 mTorr).

The time evolution of the current flat-top portion of a typical ohmic (I_p= 700kA), high density, single-null diverted discharge is shown on Fig. 4. The top trace shows the core plasma density. The divertor detachment occurs at ~0.81 sec, indicated by a characteristic drop in the target plate ion saturation current (second trace). At the time of detachment the divertor neutral pressure drops abruptly (with a typical characteristic time ~2-8ms) but only by about 10% of its pre-detachment value (fourth trace in Fig. 4). At the same time the midplane pressure does not exhibit any prompt change, but continues to rise at an approximately constant rate (third trace in Fig. 4). Through the later stage of the detachment the divertor pressure rises because of continuous fueling (the main gas valve, located at the tokamak midplane remains fully opened through the entire shot). This is in contrast to the divertor compression ratio (defined as p_{div}/p_{mid}), which continues to drop throughout the detached state (bottom trace in Fig. 4).

Plotting the divertor compression ratio (p_{div}/p_{mid}), versus the core density (Fig. 5), it is interesting to note that it follows the divertor regimes, defined by the SOL parallel heat transport. The compression is low (~10-20) and steady in the sheath-conduction limited regime, it rises rapidly through the transition regime to a maximum steady value of ~70 in the recycling regime, and drops subsequently (with increasing core density) throughout the detached divertor state.

V. LOCAL PARTICLE FLUX BALANCE

In order to gain better insight into the experimental results, a simplified analysis of the local particle flux balance has been performed. If there is no net particle pumping at the target plate (the recycling coefficient R=1), then the neutral pressure in the divertor private-flux zone should be determined by the balance between incoming and escaping particle fluxes only:

$$\frac{dN_0^{priv}}{dt} = f_{ion}^{out}\cdot\Gamma_{ion}^{out} + f_{ion}^{in}\cdot\Gamma_{ion}^{in} - (1-f_{ret}^{out})\cdot\Gamma_{atom}^{out} - (1-f_{ret}^{in})\cdot\Gamma_{atom}^{in} - \Gamma_{leak} \qquad (1)$$

Where the symbols used are as follows:

N_0^{priv} - neutral density (atomic equivalent) in the private-flux zone,

Γ_{ion}^{out} - total ion flux to the vertical portion ("below the nose") of the divertor *outer* target plate,

Γ_{ion}^{in} - same for the divertor *inner* target plate,

f_{ion}^{out} - fraction of the neutrals produced at the *outer* vertical divertor target that penetrate into the private-flux zone,

f_{ion}^{in} - same for the divertor *inner* target plate,

Γ_{atom}^{out} - total neutral atom flux directed towards the *outer* private-flux zone plasma channel (neutral escape flux),

Γ_{atom}^{in} - same for the divertor *inner* plasma channel,

f_{ret}^{out} - fraction of atomic neutrals returned to the private-flux zone at the plasma *outer* channel,

f_{ret}^{in} - same for the divertor *inner* plasma channel,

Γ_{leak} - neutral flux that leaks out of the divertor plenum through the slot opening between the divertor plate and the vacuum chamber.

If we drop the distinction between the outer and inner divertor targets in evaluating the ion-penetration and atom-reflection fractions and neglect, for clarity, the leakage flux (~15% error), equation (1) simplifies in a steady state to:

$$f_{ion} \cdot (\Gamma_{ion}^{out} + \Gamma_{ion}^{in}) - (1 - f_{ret}) \cdot (\Gamma_{atom}^{out} + \Gamma_{atom}^{in}) = 0 \qquad (2)$$

The ion flux striking the outer divertor vertical target plate was calculated from the flush Langmuir probe measurements:

$$\Gamma_{ion}^{out} = \int_{S_{divertor}^{out}} (I_{sat}/\sigma) ds \qquad (3)$$

Where:

$S_{divertor}^{out}$ - is the area of the vertical portion of the divertor *outer* target plate,

σ - is the electron charge,

I_{sat} - is the surface-normal ion saturation current density, measured by the flush Langmuir probes. For more detailed discussion of the ion flux estimates see the Appendix.

The neutral flux escaping from the divertor private flux zone was calculated using divertor pressure measurements:

$$\Gamma_{atom}^{out} = \frac{1}{4} N_{D_2}^{priv} \overline{V_0} \cdot S_{plasma}^{out} \qquad (4)$$

Where:

$N_{D_2}^{priv}$ - is the neutral molecular density derived from the measured divertor pressure,

S_{plasma}^{out} - is the area of the plasma *outer* private-flux zone between the x-point and the strike-point,

$\overline{V_0}$ - is the thermal velocity of a D_2 molecule.

It is assumed for simplicity here that the Franck-Condon dissociation is the first collisional process a D_2 molecule undergoes, when entering the plasma channel.

Since the dissociation is isotropic, it leads to the plasma albedo for molecules = 1/2 and implies:

$$\Gamma_{atom} = \Gamma_{molecule} \qquad (5)$$

Even though the above assumption is not readily justified (it will be corrected in future quantitative analysis), it greatly simplifies the following qualitative analysis and it has been successfully used in the past elsewhere [7]. Note that the plasma reflectivity defined earlier (f_{ret}) expresses the albedo of the already dissociated atoms. Additional important assumptions included in the equation (4) are that the measured neutral density is that of thermal (room-temperature) molecules and that the local neutral flux does not change between the private-flux zone and the gas box, independent of the neutral temperature.

The fluxes at the inner divertor target were evaluated using equations similar to (3) and (4). The appropriate quantities were then summed to deliver the total ion and atom fluxes in the divertor (Γ_{ion} and Γ_{atom}, respectively). Equation (2) can then be rewritten in a more convenient form of the total ion/atom flux ratio:

$$\Gamma_{ion} / \Gamma_{atom} = (1 - f_{ret}) / f_{ion} \qquad (6)$$

Using the measured value of the incident ion fluxes (in + out) defined in equation (3) and the neutral fluxes (in + out) inferred from the neutral pressure measurements (equation 4), the ratio of total ion/neutral flux has been plotted in Fig. 6. It is seen that the flux ratio varies between 7 and 0.1.

Based on the comparison of particle fluxes three new regimes can be distinguished: (1) $\Gamma_{ion} >> \Gamma_{atom}$, (2) $\Gamma_{ion} \approx \Gamma_{atom}$, (3) $\Gamma_{ion} << \Gamma_{atom}$, (Fig. 7).

The above local particle flux balance implies a varying plasma channel opacity to neutrals. It is important to stress, however, that because the neutral transmission calculations have not been carried out yet, the following analysis and names used are of a qualitative nature only.

(1) $\Gamma_{ion} >> \Gamma_{atom}$, $\therefore$ $f_{ion} << 1$, $f_{ret} \approx$ 0-1/2

The flux ratio indicates that the neutrals from the target are ionized before reaching the private-flux zone. Therefore, neutrals from the private-flux zone are ionized and reflected before reaching the common-flux zone as well. Hence the name *"Opaque SOL"*. The regime is characterized by relatively low divertor pressure and low divertor compression ratio.

(2) $\Gamma_{ion} \approx \Gamma_{atom}$, $\therefore$ $f_{ion} \approx 1$, $f_{ret} \approx$ 0-1/2

Flux balance indicates that in this regime the neutrals from the target can penetrate into the private-flux zone, whereas the neutrals from the private zone are ionized before reaching the common-flux zone. Hence the name *"Semi-Transparent SOL"*. This regime is characterized by high divertor pressure and high divertor compression ratio.

(3) $\Gamma_{ion} << \Gamma_{atom}$, $\therefore$ $f_{ion} \approx 1$, $f_{ret} \approx 1$

The flux ratio seems to indicate that all neutrals can penetrate the SOL plasma channel easily. Hence the name *"Transparent SOL"*. This regime is characterized by high divertor pressure but lower divertor compression ratio.

It is difficult to explain the last conclusion ($f_{ret} \approx 1$) because the isotropic charge-exchange and elastic scattering processes limit the maximum value of the plasma reflectivity to $f_{ret} \leq 1/2$. The apparent paradox is especially noticeable after divertor detachment (Fig. 4) when the source term (ion flux) drops dramatically without a corresponding long-term drop of the neutral pressure. A possible explanation is that the neutrals from the common-flux zone can penetrate into the private-flux zone, contributing directly to the private-flux neutral reservoir and increasing the effective f_{ret} beyond 1/2. Unfortunately there is no direct neutral pressure measurement in the Alcator C-Mod common-flux zone. H_α emission reconstruction indicates, however, an increase in H_α radiation from the common-flux zone just above the outer target plate after the divertor detachment [8].

In the graph of the calculated particle flux ratio ($\Gamma_{ion}/\Gamma_{atom}$), Fig. 6, the particle flux balance regimes are indicated using different symbols. Detached divertor is marked by open symbols plotted over the symbols indicating type of the particle flux balance. As expected, all detached divertor cases correspond to the *"Transparent SOL"* regime.

Fig. 8 shows the same scaling of the divertor compression versus core density as was shown on Fig. 5. This time, however, the data is plotted, using symbols indicating the flux balance regimes. The most important observation is that the

"Semi-Transparent SOL" regime leads to the maximum neutral compression ratio between the divertor and the main tokamak chamber.

The detailed atomic-physics modeling has not yet been performed. However, as an indication of the future direction, the particle flux ratio ($\Gamma_{ion}/\Gamma_{atom}$) is plotted versus the outer target plate temperature (evaluated at the flux surface of ρ = 2mm - distance from separatrix, when measured at the midplane). Despite a considerable scatter of the data, the general trend is clear: *"Transparent SOL"* corresponds to the cold divertor target plate, whereas *"Opaque SOL"* corresponds to the hot divertor target.

VI. CONCLUSIONS

Neutral pressures are measured routinely in the Alcator C-Mod vessel. Record divertor pressure achieved so far is 30 mTorr D_2, and compression ratio $p_{div}/p_{mid} \leq 70$. Divertor pressure scales with core plasma density, following divertor regimes defined by the SOL parallel heat transport. Based on the local particle flux balance, three SOL plasma-channel neutral-opacity regimes have been inferred: *"SOL Opaque"* to neutrals ($\Gamma_{ion} >> \Gamma_{atom}$), *"SOL Semi-Transparent"* ($\Gamma_{ion} \approx \Gamma_{atom}$), and *"SOL Transparent"* to neutrals ($\Gamma_{ion} << \Gamma_{atom}$). *"Semi-Transparent SOL"* leads to the maximum divertor neutral compression, compatible with a high core plasma performance and efficient divertor heat flux dissipation.

APPENDIX. ION FLUX ESTIMATE

An accurate measure of the total ion flux striking the Alcator C-Mod divertor target plates has yet to be determined. In the following paragraphs we describe the method used for estimating this quantity and state some assumptions that are implicit in this analysis.

We have ion flux measurements at the divertor surface from both flush and domed Langmuir probe systems. The value of I_{sat} (ion saturation current density, normal to the surface) used in equation (3) is derived from the flush Langmuir probe measurements (collecting surface flush with the tile surface). The flush probes were in the ion saturation mode, i.e., negatively biased with respect to the surrounding surface. However, it has been observed (on Alcator C-Mod and a number of other tokamaks) that such probes do not exhibit a constant ion saturation current value. The collected ion current increases with decreasing probe bias. This may be partially due to sheath expansion with increasing negative bias [9], although increased ion currents from electric fields in the bulk plasma could also contribute. Since the divertor surface is near the floating potential of the divertor probe characteristics, the above I_{sat} measurement yields an over-estimate of the ion flux to the divertor.

In Alcator C-Mod the divertor plasma parameters are also monitored by the domed Langmuir probes with a well-defined area projected along the magnetic field lines. These probes deliver an estimate of the ion flux parallel to the field lines. Because of their well-defined area, the ion saturation current is independent of voltage with sufficiently negative probe bias. To obtain ion saturation current density normal to the surface (I_{sat} in equation 3), the parallel current is multiplied by the sine of the magnetic field lines incidence angle. The typical value of this angle for the outer divertor vertical target is 0.5-1°. It has been observed elsewhere [10, 11] that for very grazing angles of incidence (below 3°) the sine law does not apply and cross-field particle transport may become important. Thus we would expect the above procedure to yield an under-estimate of the ion flux.

Comparing the two flux measures (within the parameter range examined in this report), the total ion flux estimated from the domed probes was a factor of 7-10 times lower than the flux estimated from the flush probes. This large discrepancy points out a deficiency in the understanding of fundamental cross-field transport processes that occur in the divertor and is the subject of ongoing investigations. Nevertheless, comparing the domed-probe flux estimate to the neutral flux derived from divertor pressure measurements, we find that this ion flux is also a factor of 7-10 too small. In this respect, the flush-probe flux estimate of the total ion flux to the divertor is more in line with the neutral pressure measurements. Hence, this estimate was used for the purposes of discussion in this report.

More detailed investigations of particle fluxes to the divertor target are underway. These will enable more accurate particle balance calculations to be performed in the future.

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FIGURE CAPTIONS:

Fig. 1. Location of the neutral pressure measurements in the Alcator C-Mod vessel. Approximate separatrix geometry is also shown.

Fig. 2. Target plasma density evaluated at the flux surface of ρ = 4mm (where ρ is the distance from separatrix, when measured at the midplane) versus line averaged core plasma density. Divertor regimes, identified based on the SOL parallel heat transport, are plotted using different symbols.

Fig. 3. Divertor private-flux zone neutral pressure versus line averaged core plasma density. Same symbols as on Fig. 2 are used to identify different SOL heat transport regimes.

Fig. 4. Time evolution (current flat-top portion) of a high density, diverted, ohmic (Ip=700kA) discharge. Plasma becomes well diverted after 0.6 sec. Divertor detachment occurs at 0.81 sec., as indicated by the vertical line. The gas fueling valve (trace not shown) remains fully opened through the entire shot.

Fig. 5. Neutral pressure compression ratio between the divertor and the main tokamak chamber (p_{div}/p_{mid}) versus line averaged core plasma density. Again symbols from Fig.2 are used to indicate SOL heat transport regimes.

Fig. 6. Outer divertor particle flux ratio ($\Gamma_{ion}/\Gamma_{atom}$) versus line averaged core plasma density. Different symbols indicate SOL plasma channel opacity to neutrals *inferred* from the particle flux balance. Detached divertor is marked by open symbols plotted over the corresponding data points.

Fig. 7. Outer divertor particle flux balance and the *inferred* private-flux zone plasma channel opacity to neutrals.

Fig. 8. Neutral pressure compression ratio (p_{div}/p_{mid}) versus core plasma density. This time symbols from Fig.6 are used to indicate particle flux balance regimes.

Fig. 9. Outer divertor particle flux ratio ($\Gamma_{ion}/\Gamma_{atom}$) versus target plasma temperature evaluated at the flux surface of ρ = 2mm (where ρ is the distance from separatrix, when measured at the midplane). Again symbols from Fig.6 are used to indicate particle flux balance regimes.

Alcator C-Mod Neutral Pressure Measurements

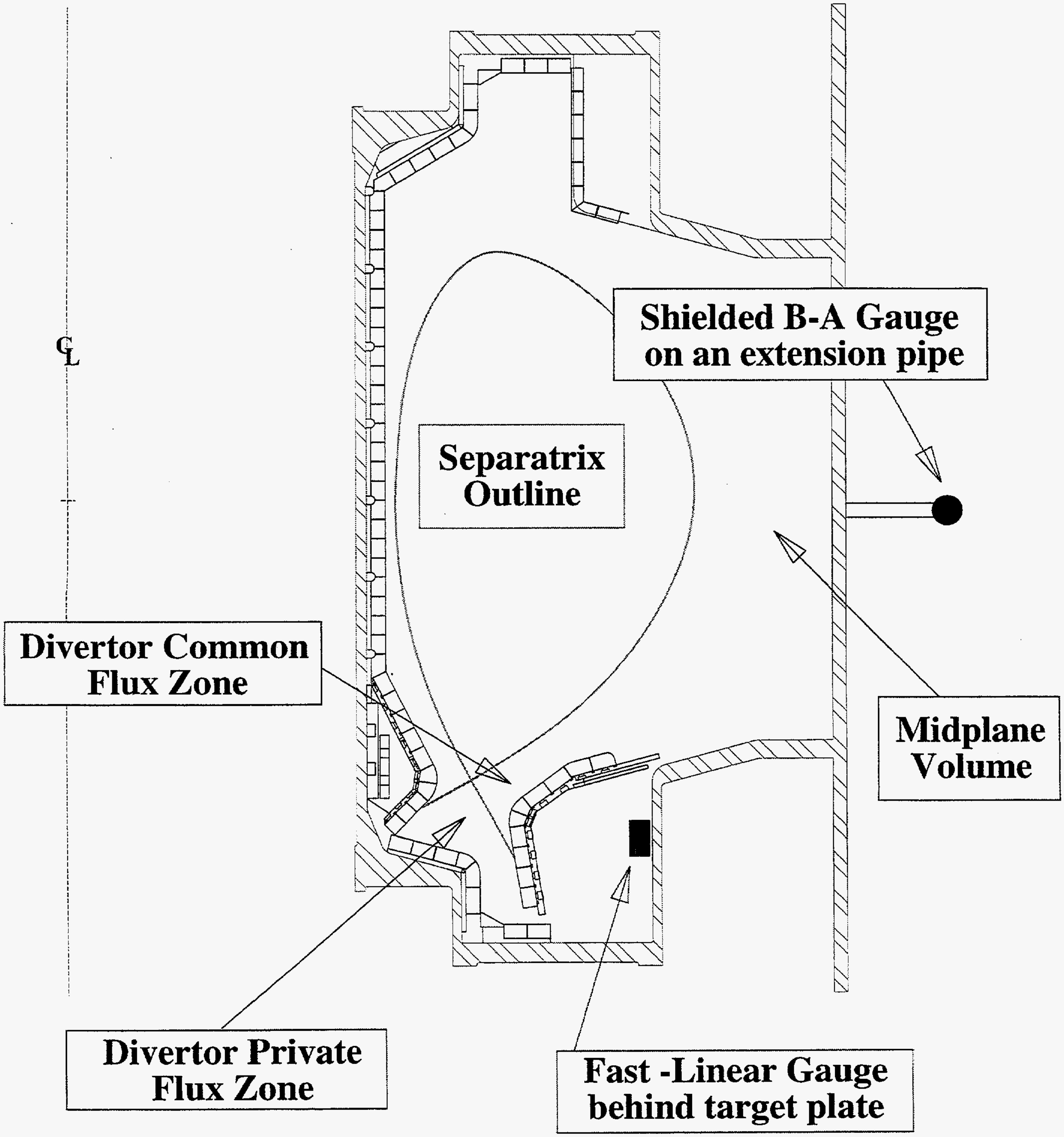


Figure 1

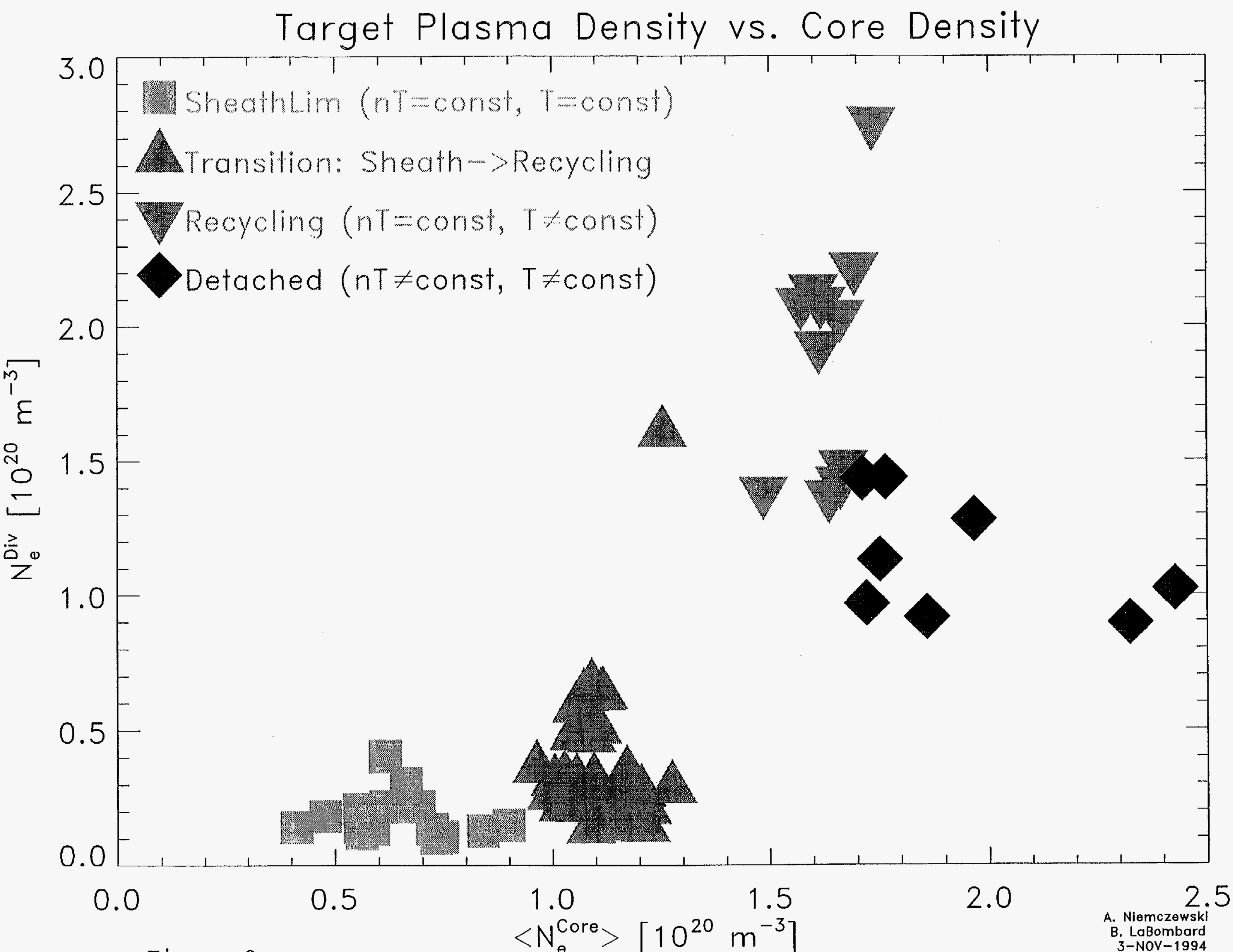
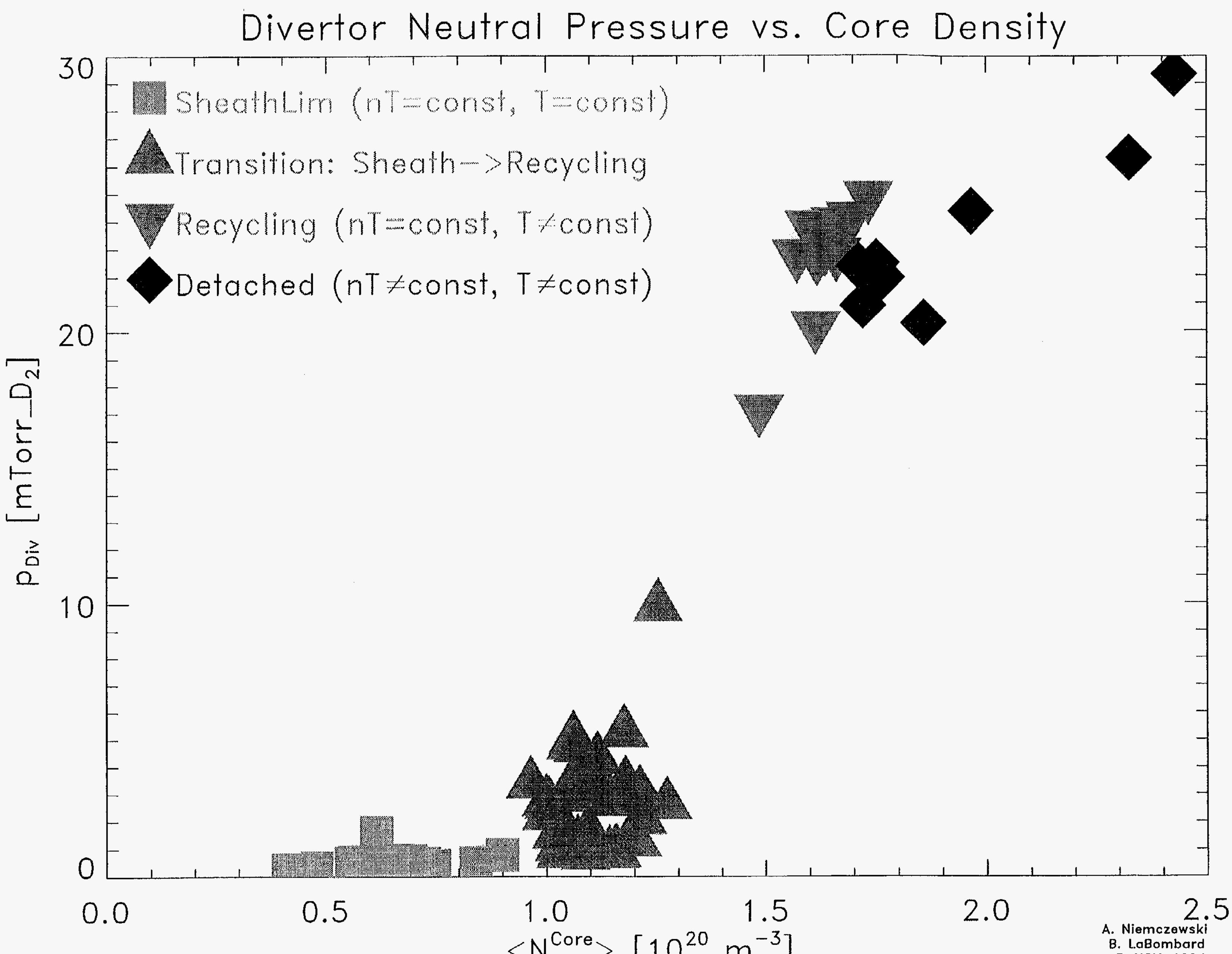

Target Plasma Density vs. Core Density
SheathLim (nT=const, T=const)
Transition: Sheath->Recycling
Recycling (nT=const, T≠const)
Detached (nT≠const, T≠const)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
N_e^{Div} [10^{20} m^{-3}]
0.0
0.5
1.0
1.5
2.0
2.5
<N_e^{Core}> [10^{20} m^{-3}]
A. Niemczewski
B. LaBombard
3-NOV-1994

Figure 2



Divertor Neutral Pressure vs. Core Density
SheathLim (nT=const, T=const)
Transition: Sheath->Recycling
Recycling (nT=const, T≠const)
Detached (nT≠const, T≠const)
p_{Div} [mTorr_D_2]
0
10
20
30
0.0
0.5
1.0
1.5
2.0
2.5
$\langle N_e^{Core} \rangle$ [10^{20} m^{-3}]
A. Niemczewski
B. LaBombard
3-NOV-1994

Figure 3

Single Null Diverted Discharge 940623023

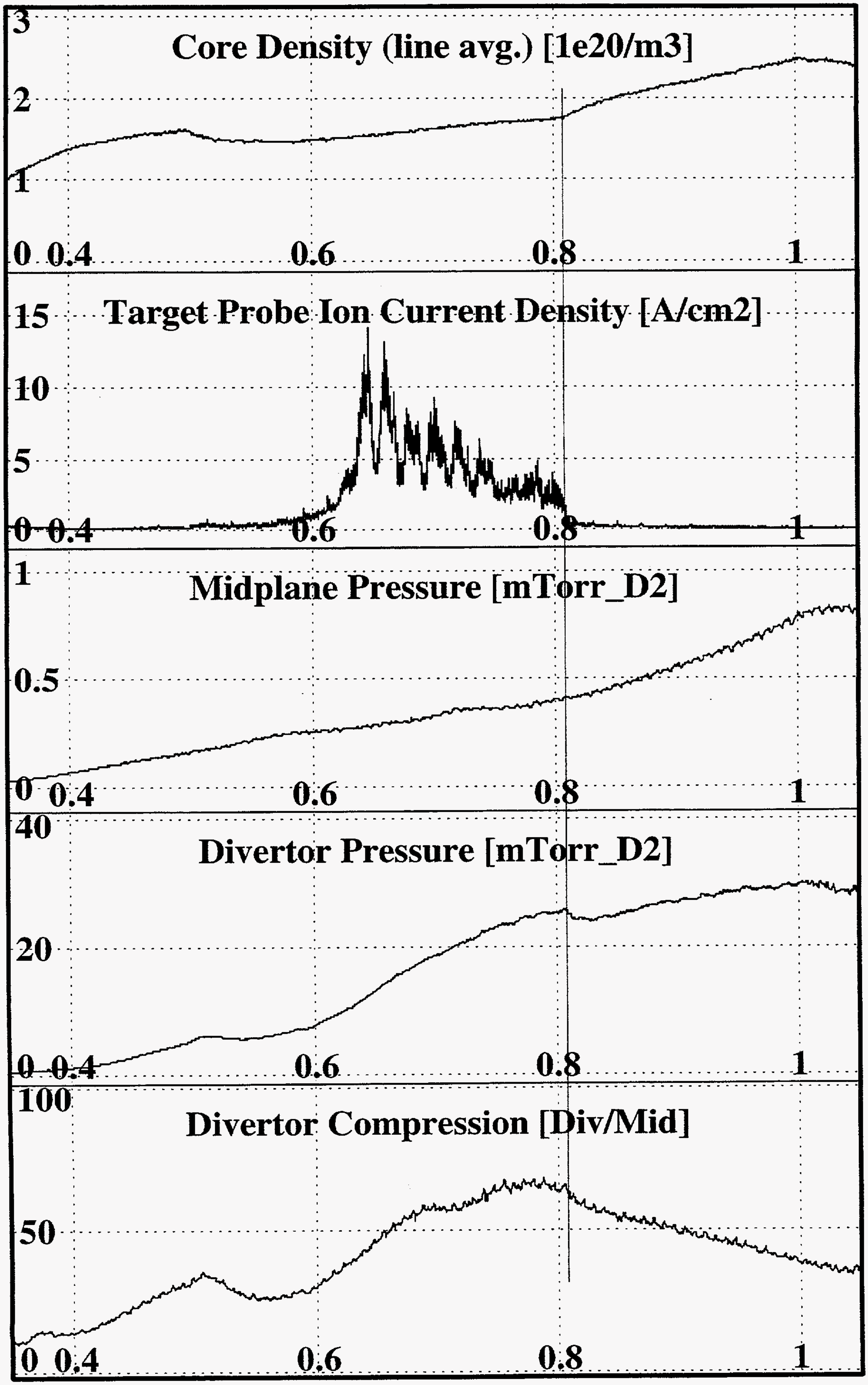


Fig. 4

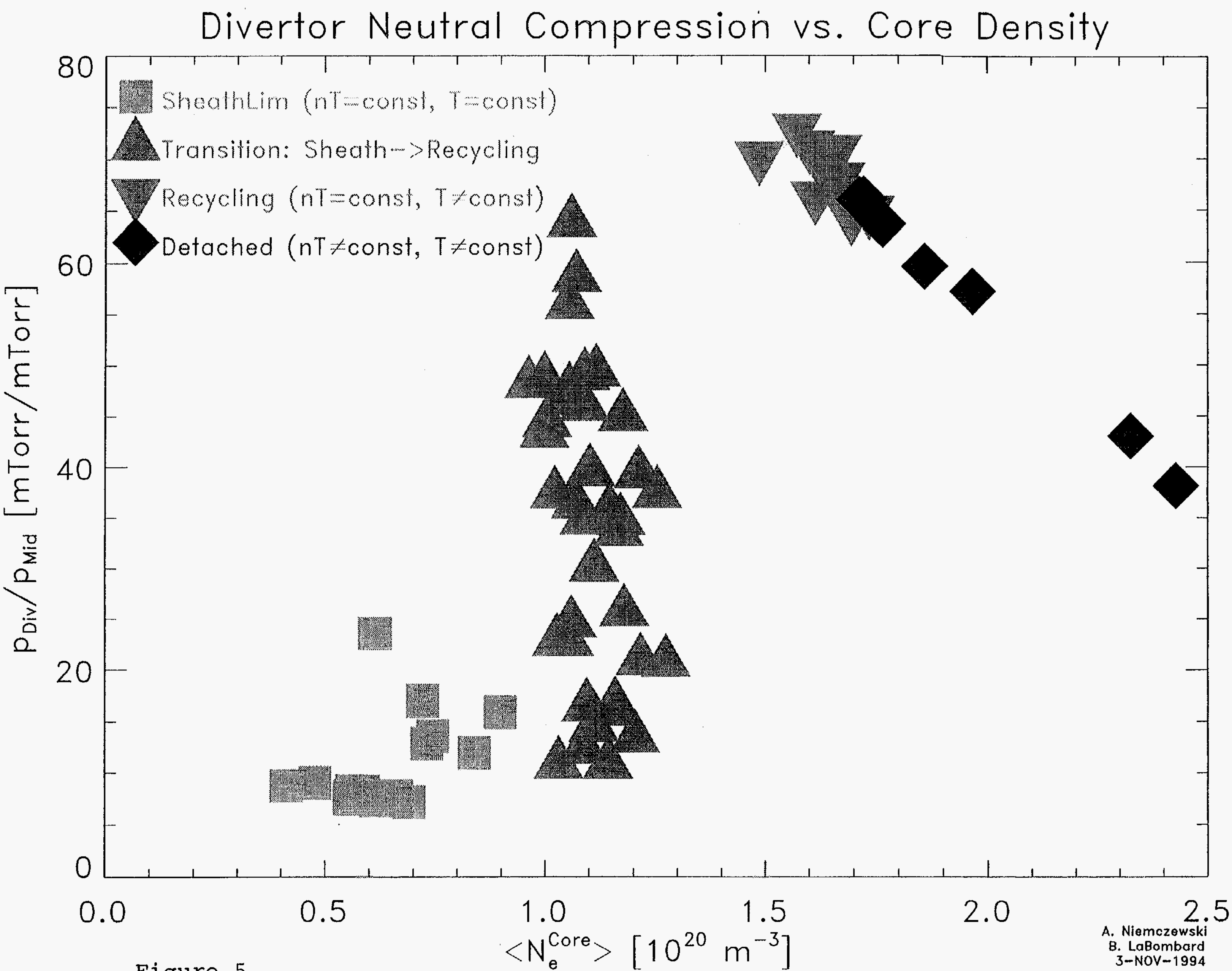
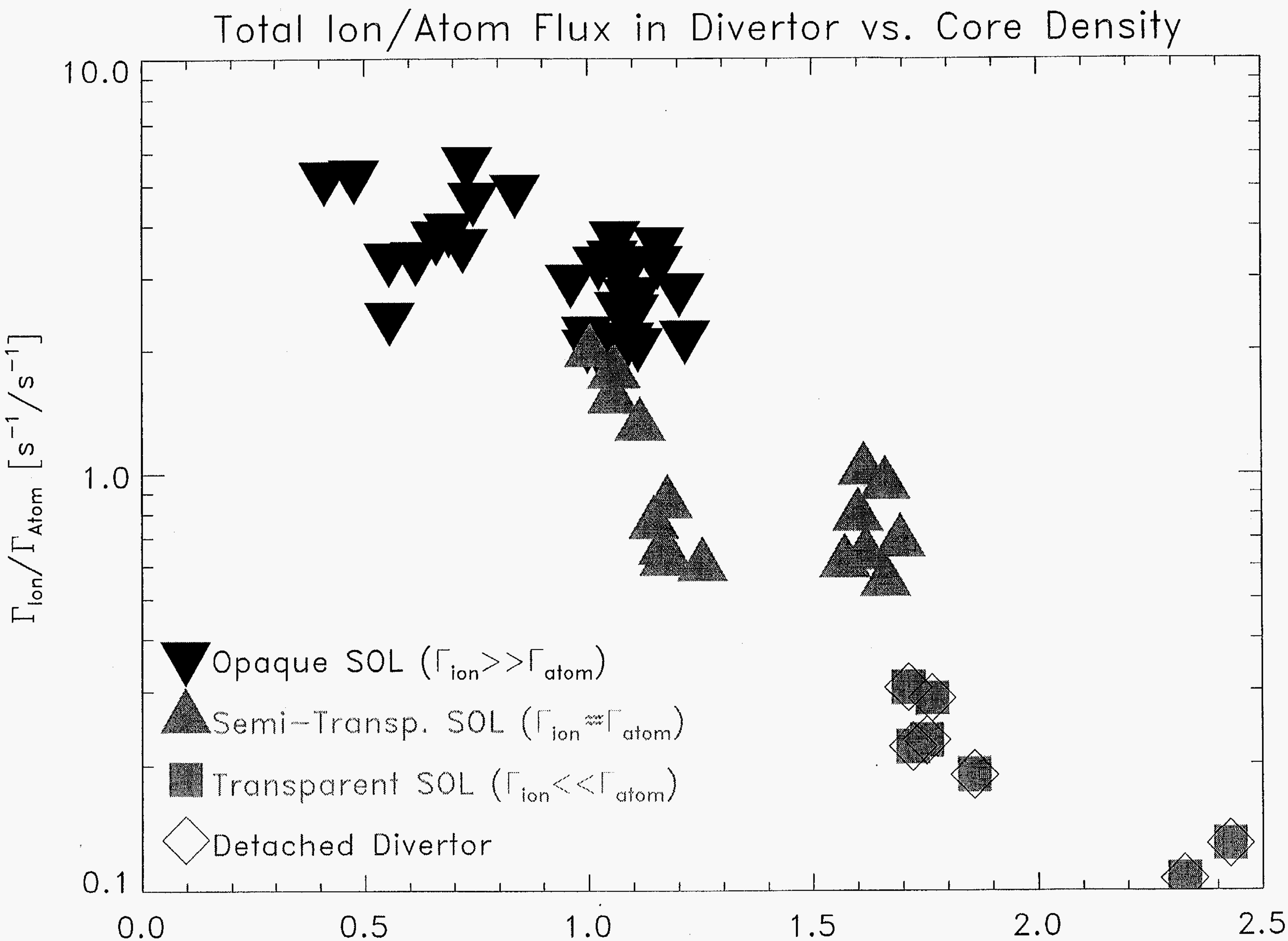

Divertor Neutral Compression vs. Core Density
SheathLim (nT=const, T=const)
Transition: Sheath->Recycling
Recycling (nT=const, T≠const)
Detached (nT≠const, T≠const)
p_Div/p_Mid [mTorr/mTorr]
<N_e^Core> [10^20 m^-3]
0
20
40
60
80
0.0
0.5
1.0
1.5
2.0
2.5
A. Niemczewski
B. LaBombard
3-NOV-1994

Figure 5

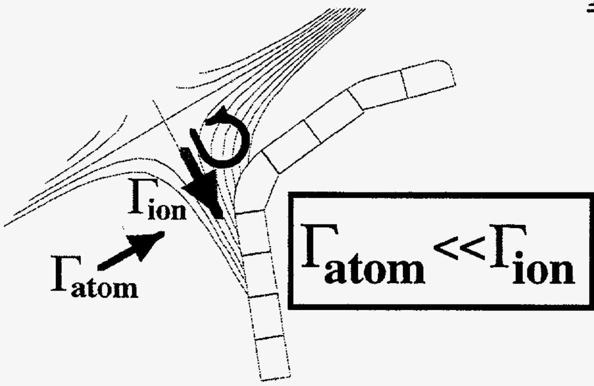


Total Ion/Atom Flux in Divertor vs. Core Density
$\Gamma_{Ion}/\Gamma_{Atom}$ [s^{-1}/s^{-1}]
10.0
1.0
0.1
0.0
0.5
1.0
1.5
2.0
2.5
$\langle N_e^{Core} \rangle$ [10^{20} m^{-3}]
Opaque SOL ($\Gamma_{ion} >> \Gamma_{atom}$)
Semi-Transp. SOL ($\Gamma_{ion} \approx \Gamma_{atom}$)
Transparent SOL ($\Gamma_{ion} << \Gamma_{atom}$)
Detached Divertor

Fig. 6

Divertor Particle Flux Balance

I. SOL OPAQUE to neutrals

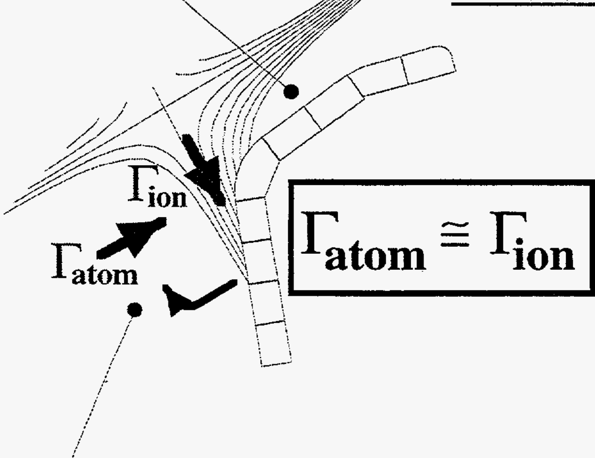


- Neutrals from target are ionized before reaching private flux zone
- Neutrals from private flux zone are ionized before reaching common flux zone

- Low divertor pressure
- Low divertor compression

common flux zone

II. SOL SEMI-TRANSPARENT to neutrals

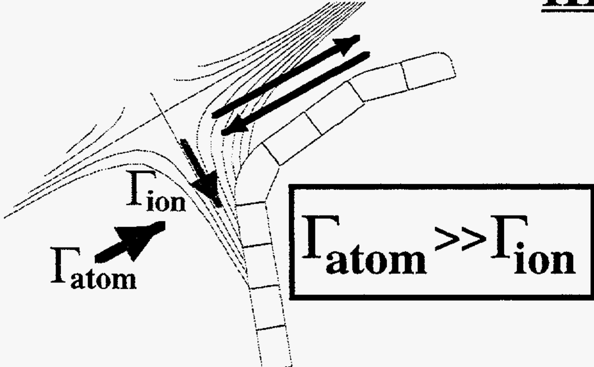


- Neutrals from target can penetrate into private flux zone
- Neutrals from private flux zone are ionized before reaching common flux zone

- High divertor pressure,
- High divertor compression

private flux zone

III. SOL TRANSPARENT to neutrals



- Neutrals can cross between target private, and common flux zones
- typical for detachment

- High divertor pressure
- Low divertor compression

Figure 7

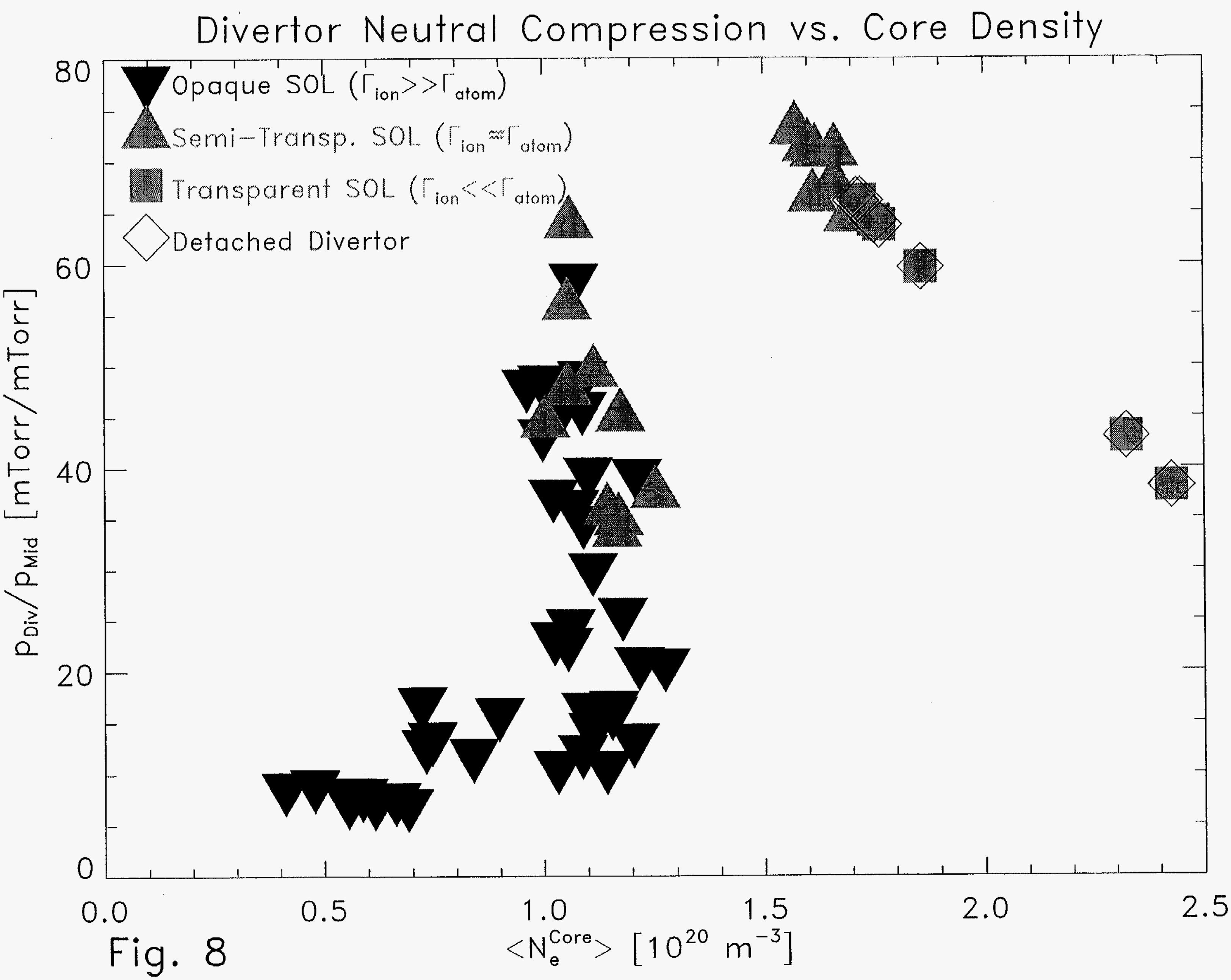

Divertor Neutral Compression vs. Core Density
Opaque SOL ($\Gamma_{ion}>>\Gamma_{atom}$)
Semi-Transp. SOL ($\Gamma_{ion}\approx\Gamma_{atom}$)
Transparent SOL ($\Gamma_{ion}<<\Gamma_{atom}$)
Detached Divertor
p_{Div}/p_{Mid} [mTorr/mTorr]
0
20
40
60
80
0.0
0.5
1.0
1.5
2.0
2.5
$<N_e^{Core}>$ [10^{20} m^{-3}]

Fig. 8

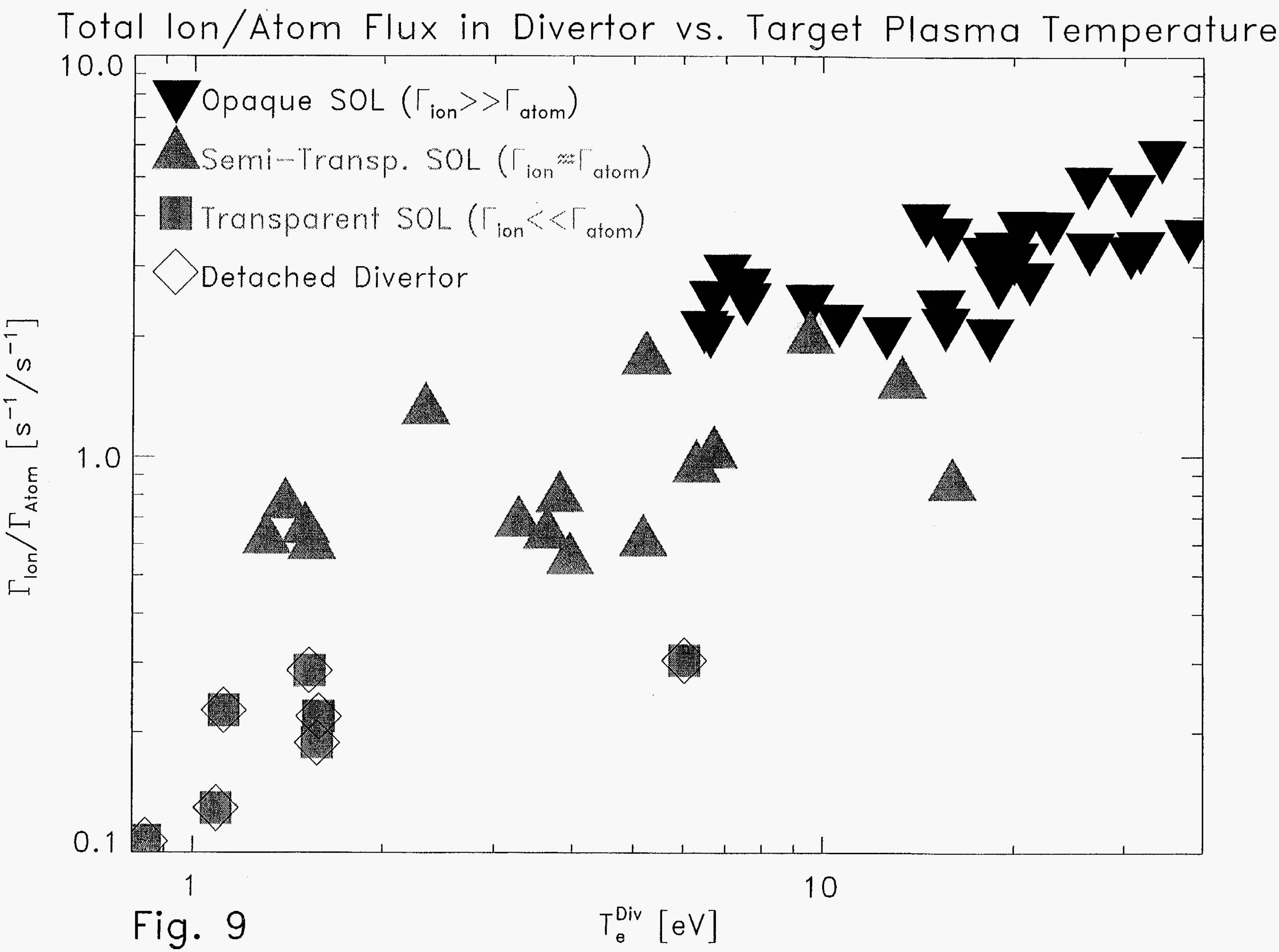

Total Ion/Atom Flux in Divertor vs. Target Plasma Temperature
Opaque SOL ($\Gamma_{ion} >> \Gamma_{atom}$)
Semi-Transp. SOL ($\Gamma_{ion} \approx \Gamma_{atom}$)
Transparent SOL ($\Gamma_{ion} << \Gamma_{atom}$)
Detached Divertor
$\Gamma_{Ion}/\Gamma_{Atom}$ [s^{-1}/s^{-1}]
10.0
1.0
0.1
1
10
T_e^{Div} [eV]

Fig. 9