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EFFECTS OF IONIZING SCRAPE-OFF LAYERS ON LOCAL RECYCLING IN TORE SUPRA PUMP LIMITER EXPERIMENTS*

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A series of ohmic discharges with active pumping in the Tore Supra outboard pump limiter has been analyzed with the DEGAS neutrals transport code and an analytic scrape-off layer (SOL) plasma model. Pumping speed and plenum pressure measurements indicated 5–10 torr•L/s throughput with only modest effects on density ($dN_{core}/dt < 0.5$ torr•L/s). A model is developed in which large exhaust fluxes, with little attendant effect on core plasma density, are explained in terms of SOL ionization of recycled and wall-desorbed neutrals. Particle balance with active pumping and constant line density requires that the wall return flux exceed the incident flux by approximately the pump throughput in the absence of external fueling. The radial profile of the H^+ source rate from ionization and dissociation of wall-desorbed molecules is seen to peak very near the radial position of the limiter throat. Consequently, a strong recycling vortex is created in the region of the limiter, with the ion flux amplified by factors of ≈ 2 at the outer limiter surfaces and >3 within the limiter throat. The calculations indicate that less than 30% of the pump throughput is due to first-generation ions from the core efflux, with the balance from local recycling in the strongly ionizing SOL.

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1. Introduction

One of the goals of the Tore Supra program is to study the efficiency of a system of modular pump limiters for particle exhaust and heat removal in long-pulse tokamak discharges. The pump limiter system consists of six vertical modules located at the bottom of the machine and one larger horizontal module at the outer midplane. In the work presented here, only the outboard module was used. The total pumping speed of the titanium pumps was measured to be 40×10^3 L/s.

A series of ohmic discharges in hydrogen plasma with approximately 1.8 MW of ohmic power was reported by Klepper et al. [1] at the 9th PSI Conference. The series included shots both with and without active pumping. The earlier shots in the series were initiated with a gas prefill only. Later, as the wall inventory was depleted, gas puffing during the shot was needed to reach and maintain the desired density. He glow discharge cleaning of the wall was not performed prior to the series or between shots within the series.

The discharges with active pumping exhibited large measured exhaust fluxes without corresponding changes in plasma density. This behavior is different from that observed on smaller tokamaks, where approximate particle balance was obtained by consideration of the external fueling and plasma losses to particle exhaust [2–4]. The experiments analyzed here require the inclusion of a third reservoir, the hydrogen contained in the vessel walls.

Data from several diagnostics are available for this series of shots [1]. In particular, for the pumped discharge 3127 upon which this analysis is focused, the data include pressure in the pump limiter plenum (0.3–0.5 mtorr), heat flux profile on the limiter head (λ_q = 1.2 cm), core plasma density and temperature profiles from Thomson scattering, and the pumping speed of the titanium modules (S = 40×10^3 L/s) from which the particle exhaust rate can be deduced (7.5 torr•L/s). In addition, within the throat on both sides of the pump limiter, a Langmuir probe (configured as an asymmetric double probe with a short and long element) gave estimates for the density (1.2×10^{12} cm^{-3}), temperature (T_e = 36 ev), ion saturation current (1.08 A) and particle flux decay length (2.3 cm).

The aim of this work is to assess the effects of an ionizing scrape-off layer (SOL) on edge recycling, pump limiter performance, and core particle balance. In particular, an approximately self-consistent treatment of the edge plasma and neutral transport is shown to explain the apparent decoupling of the core and SOL discussed by Klepper et al. in reference [1]. The analysis is focused on shots in which there was active pumping but no external fueling during the discharge. The results for shot 3127 are discussed in detail in section 4.

2. Neutral transport

The plasma and neutral transport in divertors and within and near pump limiters is often dominated by strongly geometry-dependent local recycling. An internal recycling model has been implemented within the DEGAS neutrals transport code [5] to permit the selective recycling of reionized neutrals. This model differs from the standard DEGAS recycling option in that pumping of neutrals (by walls or pumps) is not required to terminate flights. The primary motivation for the model is to study flux amplification, particle and energy balance in the SOL, and core fueling rates with active pumping.

The primary (first-generation) neutrals are the result of mapping the assumed core efflux to the neutralizing surfaces. Any net wall influx or external gas fueling is typically included by puffing neutrals from the walls at prescribed locations. Neutrals that are reionized outside the separatrix or last closed flux surface (LCFS) are recycled to the neutralizer plate on their respective ion birth flux lines or surfaces. Neutrals that are reionized within the core plasma are not recycled. (This guarantees that the core fueling rate equals the core efflux in the absence of pumping and external fueling sources.) The temporal behavior of the line-averaged density can be simulated by net wall adsorption or desorption. Radial diffusion of reionized neutrals between the ion birth point and the plate can be simulated in the model by prescribing a cross-field diffusion coefficient and the parallel flow velocity (this effect was not included in the work reported here).

The DEGAS internal recycling model is used to estimate the particle flux amplification factor for each segment of the pump limiter neutralizing surface. The amplification factors, representing the average number of times a neutral is ionized and returned to the plate or limiter surface before it is either pumped or fuels the core, are used in an analytic SOL plasma model to estimate the plasma response to the computed recycling profiles.

3. Plasma model and iteration procedure

Stangeby's model [6] for ionizing SOLs is iterated with the DEGAS calculations to obtain an approximately self-consistent description of the plasma/neutral transport within and near the outboard pump limiter. With exponential profiles for the plasma density and temperature, the corresponding radial scale lengths are obtained by integrating the single-fluid continuity and energy balance equations over the SOL, assuming constant temperature along field lines.

Define
$$\alpha = \frac{1}{2}\gamma_s F_n - \frac{\chi_\perp}{D_\perp} - 6$$

and
$$\lambda_o = \sqrt{2 D_\perp L_c / C_s} \quad .$$

Then
$$\lambda_n = \left[\frac{\alpha + \sqrt{\alpha^2 + 6(\gamma_s F_n - 4)\chi_\perp / D_\perp}}{6\chi_\perp / D_\perp} + 1 \right]^{1/2} \sqrt{F_n}\,\lambda_o$$

and
$$\lambda_T = \frac{F_n \lambda_n / 2}{(\lambda_n / \lambda_o)^2 - F_n} \quad .$$

Here λ_o is evaluated at the LCFS, $D_\perp$ and $\chi_\perp$ are the assumed cross-field diffusion and heat conduction coefficients, γ_s is the sheath energy transmission factor, F_n is the particle flux amplification factor, and L_c is the connection length to the limiter.

As discussed by Stangeby, the flux amplification factor F_n typically varies with radius, necessitating a corresponding variation in the radial scale lengths. We have chosen, however, to radially average the values of F_n in the SOL ($F_n \approx 1.5-2.0$) and in the limiter throat ($F_n \approx 3.0-3.5$). With density and temperature at the LCFS obtained by extrapolating the Thomson scattering measurements and with assumed values for $\chi_\perp / D_\perp$ and γ_s, the model profiles form input for the DEGAS neutral transport calculations.

With the approximations outlined above, the DEGAS/Stangeby model calculations are iterated to convergence by the following procedure. λ_T and λ_n in the SOL are computed with $F_n = 1.0$ and estimated values of $\chi_\perp / D_\perp$ and γ_s. The corresponding n(r), T(r), and $\Gamma_{||}(r) \sim n(r)\sqrt{T(r)}$ are used in DEGAS to calculate the pump throughput and F_n in the SOL and limiter throat. With new values of λ_n and λ_T from Stangeby's model, the corresponding plasma profiles in the SOL and limiter throat, and the net wall influx necessary to balance the pump throughput, the DEGAS calculations are repeated. This process is iterated until approximate convergence is obtained. Comparison of the calculated core fueling rate and the line-averaged density trace may indicate the need to modify the SOL plasma transparency to recycling neutrals. This can be accomplished by adjusting one or both of the model parameters $\chi_\perp / D_\perp$ and γ_s and continuing the iteration procedure. Stangeby [6] details the sensitivity of λ_n and λ_T to these parameters and to the flux amplification factor F_n. Finally, the results are compared to measurements of plenum pressure, ion flux from the throat Langmuir probes, and the infrared television heat flux profile on the limiter head.

4. Model results

DEGAS modeling of the outboard pump limiter is performed in the geometry shown in fig. 1. The computational domain, generated by rotating fig. 1 through 360°, corresponds to a localized pump limiter surrounded by the core and SOL plasma as in the actual Tore Supra geometry. Field lines in the SOL are assumed to converge at the limiter, and the outer SOL ($Z \approx 400$ cm) is assumed to connect to the limiter via the rotational transform. Consequently, neutrals that are ionized in either the outer or inner SOL are recycled to the limiter at the minor radius corresponding to the birth point. The total plasma volume and vacuum vessel surface area are chosen to match those of Tore Supra. The dimensions of the pump limiter plenum and pumping chamber are chosen to have the correct conductances. The total volume of plasma in the throat region corresponds to that in the actual limiter.

The following discussion will focus on the analysis of shot 3127 in which there was a prefill of 5.1 torr•L, no external fueling during the discharge, and the pumps were active. The discharge was initiated on the inner bumper limiter, then moved to the outboard pump limiter and expanded to a radius of ≈ 75 cm. Shot 3127 and the two preceding shots (3125 and 3126 in both of which the pumps were off) reached flat-top densities corresponding to total plasma particle content in excess of the prefill. This clearly indicated that hydrogen was extracted from the inner limiter, and gradual depletion of the limiter was apparent in the observed line-averaged density decrease with shot number [1]. In each of these shots the density was approximately constant during the ≈ 5 second phase of the discharge in which the plasma was on the outboard limiter, suggesting, at least for the two unpumped shots, that approximate equilibrium with the walls was established.

During shot 3127, the measured exhaust rate was 7.5 torr•L/s, with no gas puff during the discharge. Since dN/dt of the plasma was ≈ 0.25 torr•L/s, the exhausted flux could not be accounted for by the change in density. Hogan et al. [7] have addressed the key issue of ascertaining the source of the flux extracted by the pumping system and the mechanism(s) responsible for its release into the plasma. Several sources were considered, including the pump limiter head, the outboard wall, and the near-limiter region of the vacuum vessel that receives the largest charge-exchange flux. Within the framework of the models used, it was not possible in [7] to unambiguously pinpoint the source and release mechanism for the exhausted fluence. Since the C:H layer of the carbonized vacuum vessel represents the largest reservoir of available hydrogen, it is thought that desorption from this layer is the most probable source of the exhausted flux. Also, the absence of evidence of depletion of the reservoir during pumping experiments argues for the C:H layer as the primary source.

Without prescribing the release mechanism, we assume that there is a net flux of wall-temperature molecules from the vacuum vessel into the SOL for shot 3127. This flux must simultaneously balance losses from the core and the SOL to the pumping system. In DEGAS each molecule is tracked until it or its dissociation products is either pumped or ionized. The profile of the average H^+ source rate resulting from the desorption of H_2^0 at the vacuum vessel wall is displayed in fig. 2. This curve shows the radial distribution of the first-generation ions generated from the net cold wall efflux and is a key result in understanding shot 3157. The net influx of cold wall molecules required to balance the pump throughput is 7.5 torr•L/s, of which 34% (2.5 torr•L/s) fuels the core and the remainder fuels the SOL. The peak of the profile is seen to be very near the radial position of the limiter throat entrance, suggesting a strong tendency for the ions to flow directly into the throat.

Pressure measurements in the pump limiter plenum and ion fluxes deduced from Langmuir probes in the limiter throat are also reproduced. The calculated distribution of neutral pressure within the pump limiter is shown in fig. 3. Measured values at the gauge tube opening were 0.3–0.5 mtorr. Because of possible light contamination of the signal, the pressure was thought to be closer to the lower end of the range. It should be noted that the pressure distribution in fig. 3 can be approximately reproduced by molecular conductance calculations within the vacuum regions of the limiter.

As discussed by Hogan et al. [7], charge exchange flux to the limiter surfaces and the vacuum vessel walls is thought to play an important role in particle balance in the core and SOL plasma for both pumped and unpumped discharges. The calculated charge-exchange flux, its energy distribution and the power absorbed per square centimetre are shown in fig. 4 for the region of the vacuum vessel wall immediately surrounding the pump limiter. With these distributions the total integrated energetic charge-exchange flux to the near-limiter wall is 10 torr•L/s and the integrated power absorbed by the wall is 60 kW. The results in fig. 4 are very sensitive to the ion temperature near the LCFS, for which there are significant uncertainties. In addition, the planar geometry of the vacuum vessel walls used in this simulation (see fig. 1) results in more attenuation of the charge-exchange flux than would be the case with toroidal walls. Therefore, the particle and energy fluxes shown in fig. 4 are to be considered lower limits.

Plasma and neutral particle flows in the SOL and pump limiter are illustrated in fig. 5 for shot 3127 with a flow diagram similar to those used by Gerhauser and Claassen [8]. The ion and neutral fluxes shown are those that result from the converged DEGAS/Stangeby model analysis of this discharge. The first-generation ion flux to the limiter includes the assumed core efflux (50 torr•L/s) and the ions that result from dissociation and ionization of the net wall efflux (7.5 torr•L/s). Recycling results in this flux being amplified by an average factor of 1.6 in the SOL and an additional factor of 2.2 within the throat (total amplification of 3.5 for flux tubes that connect to the limiter neutralizer plate). The core efflux is balanced by the core fueling rate and the pump throughput is balanced by the net wall efflux.

For simplicity and diagramming, the (small) ion flux to the limiter sidewalls below the throat is lumped into the flux to the head in fig. 5. The individual contributions to the wall charge-exchange flux from the core and SOL are not readily available from DEGAS, nor are the ultimate ion source profiles resulting from the return flux. (A separate DEGAS run is required to get the H^+ source profiles shown in fig. 2 and illustrated in the artificially separated net wall efflux flow branch in fig. 5). With the pumps active we assume that energetic charge exchange (or some other mechanism) results in the net desorption rate required to balance the pump throughput. The results of this analysis have obvious implications for unpumped discharges.

With inactive pumps, the approximate constancy of the observed density [1] suggests that the net wall efflux is redistributed and reimplanted (over perhaps less saturated regions) in the wall, leaving the core density relatively unaffected. Particularly for unpumped shots, an obvious question, in response to which we can offer only speculation, is the following. Since in the presence of net wall efflux there will always be some core fueling (however small), why does not the line-averaged core density increase during the discharge? A possible explanation lies in the fact that the core fueling is primarily at the edge near the LCFS. As such, it tends to simultaneously increase the edge density gradient and the diffusion across the LCFS, apparently resulting in a balance that is maintained throughout the pump limiter phase of the discharge. In this picture the process of redistribution/reimplantation from more to less saturated regions of the vacuum vessel is mediated by both the SOL and core plasma.

5. Discussion and conclusions

Apart from uncertainties associated with the mechanism responsible for release of hydrogen from the walls, we have a reasonably complete quantitative understanding of the pumped discharge 3127. Plasma density, temperature and particle flux distributions in the SOL and pump limiter throat from the DEGAS/Stangeby model reproduce all of the available experimental data for this discharge. The ion saturation current to the long Langmuir probe and the ratio of long probe to short probe currents in the limiter throat are reproduced by the total calculated recycling flux at the probe locations. The converged value of λ_q = 1.23 cm matches the measured value of the heat flux decay length at the limiter head. The total recycling flux at the limiter neutralizer plate is that required to give the measured plenum pressure. For N / τ_p = 50 torr•L/s, L_c = 60m, $\chi_\perp / D_\perp$ = 4 and γ_s = 7.5, the converged values of λ_n = 2.8 cm and λ_T = 3.3 cm in the SOL and F_n = 1.6 (3.5) in the SOL (throat), give detailed particle balance in the core, SOL and pump limiter.

Qualitatively the results of this work can be summarized as follows. Without He glow between shots and with no gas puff during the discharge (prefill only), the observed exhaust rate with active pumps is sufficient to exhaust the entire particle content of the plasma if there were no fueling from the walls. Several possible mechanisms that could be responsible for the net efflux of cold wall molecules into the plasma are discussed in reference [7]. The objective of this investigation is to detail the role of an ionizing SOL in explaining the observation of large particle exhaust with little effect on core plasma parameters. This objective has been met with results of the DEGAS/Stangeby model that self-consistantly described the SOL plasma/neutral transport within and near the outboard pump limiter. Work is presently in progress to similarly analyze unpumped discharges in this series. Without active pumping, recycling in the SOL and limiter throat is significantly more intense, the SOL is more opaque to neutrals, and core fueling by the cold wall molecules is correspondingly reduced. Consequently, we conjecture that without active pumping the wall efflux simply recycles to the wall leaving the core plasma relatively unaffected.

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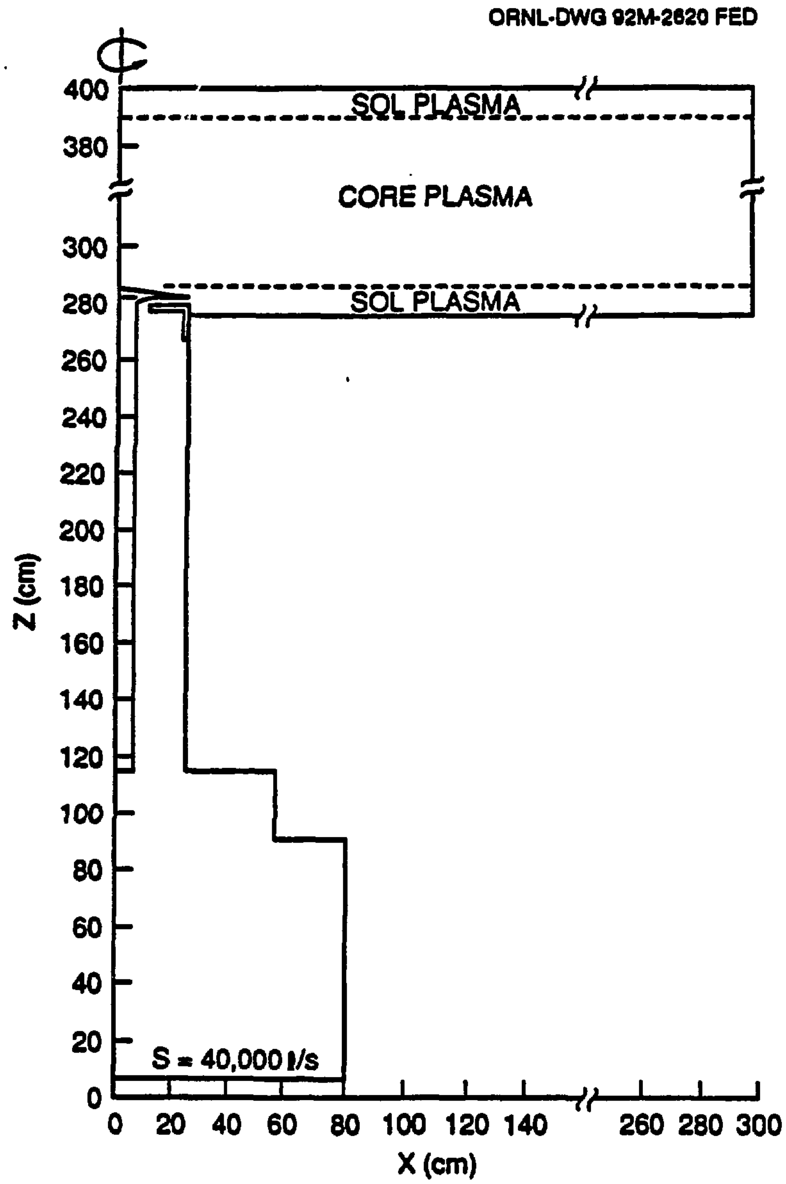
Fig. 1. DEGAS modeling of Tore Supra/outboard pump limiter experiments is performed in the geometry shown here. The computational domain is generated by rotating this figure through 360°. The SOL at Z ~ 400 cm is assumed to connect to the limiter via the rotational transform.

Fig. 2. The radial profile of the average H^+ source rate in the edge plasma, due to the desorption of 2.5×10^{20} H_2^0/s from the wall at 473 K, is seen to peak very near the radial position of the limiter throat. For the edge plasma parameters used here, 66% of the wall influx is ionized in the SOL and 34% in the core.

Fig. 3. The calculated H_2^0 pressure within the pumping chamber and the plenum of the outboard pump is shown for pumping speed $S = 40 \times 10^3$ L/s.

Fig. 4. The flux of charge-exchange atoms and the corresponding energy distribution and power deposition profile on the vacuum vessel wall are shown as functions of distance from the outer wall of the pump limiter.

Fig. 5. A particle flow diagram illustrates the neutral and ion flows resulting from the DEGAS/Stangeby model analysis of shot 3127.


ORNL-DWG 92M-2620 FED
SOL PLASMA
CORE PLASMA
SOL PLASMA
S = 40,000 l/s
Z (cm)
X (cm)
400
380
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
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20
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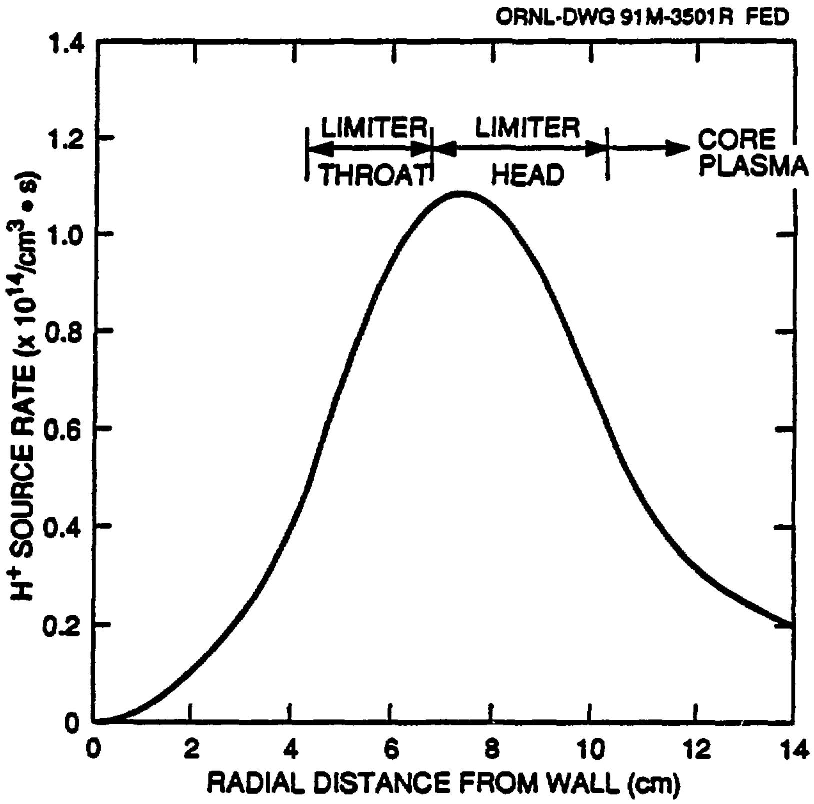
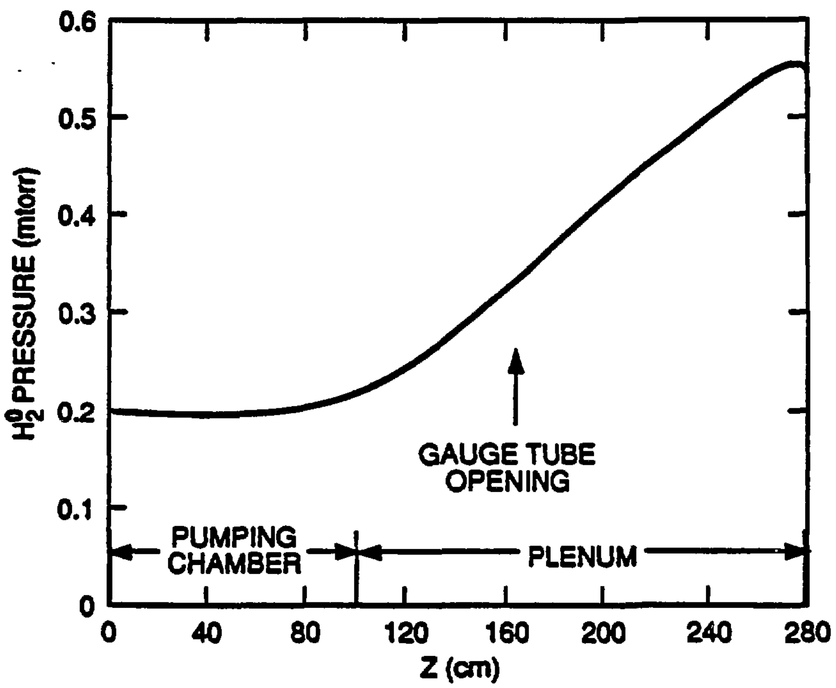
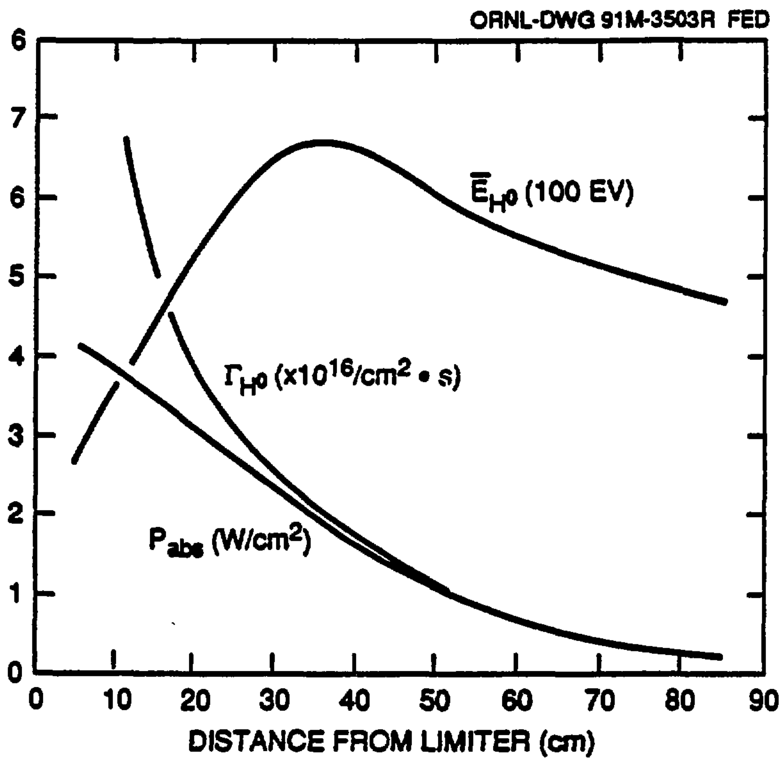


ORNL-DWG 91M-3501R FED
LIMITER THROAT
LIMITER HEAD
CORE PLASMA
H+ SOURCE RATE (x 10^14/cm^3 • s)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
RADIAL DISTANCE FROM WALL (cm)

ORNL-DWG 91M-3507R2 FED





PARTICLE FLOW DIAGRAM Iorr • s

PARTICLE FLOW DIAGRAM (torr • L/s)

ORNL-DWG 92M-2866 FED