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GAS INJECTION IN PLT - EXPERIMENTAL OVERVIEW

MASTER

G. L. Schmidt, N. I. Bretz, R. J. Hawryluk, J. C. Hosea, D. W. Johnson
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

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Cold gas injection serves both the obvious role of a particle source at the surface of the plasma and a more subtle role as one element in the process by which the relative impurity concentration and the MHD activity of a discharge are determined. In this paper we consider evidence offered by PLT experiments in support of these two widely recognized roles.

Effects of Programmed Gas Feed

Deuterium

Following the initiation of low power discharge cleaning procedures in PLT to remove low Z impurities, relatively pure deuterium discharges have been produced. To date central electron density and temperature of 7×10^{13} cm^{-3} and 1.5 keV have been reached. These discharges, because of their reduced low Z impurity levels, serve to illustrate the subtle role played by cold gas injection. Electron temperature profiles - hence the plasma current distribution - and high Z impurity levels are both found to depend strongly on the level of the working gas present at breakdown and that introduced during the formation of the current channel. Fig. 1 indicates the dependence on these gas levels of the total plasma current,

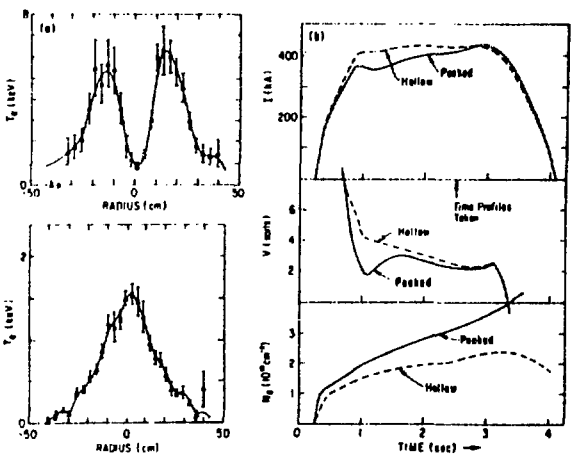

Fig. 1. Comparison of hollow and peaked deuterium discharges. Peaked discharges are produced following an increase (≤ 5%) in initial gas levels.

and the electron temperature profile in discharges having low oxygen levels following low power discharge cleaning. At the lower gas level, low temperature discharges are produced, with a sustained rate of current rise in the initial phase. Hollow electron temperature profiles are observed. At intermediate gas levels, the rate of current rise is seen to decrease following the initial discharge formation. Increased central electron temperatures are also observed with some evidence of MHD activity during the latter part of the current rise. At this point further increases in gas levels (< 5%) produce a factor of ~ 2 increase in electron temperatures. A decrease in m = 2 activity and an increase in m = 1 or sawtooth activity during the discharge flattop is also observed. It is found, that maximum density increase is achieved by gas injection in such discharges. Still further increases in gas levels lead to unstable (disruptive) discharge of short duration.

Tungsten Concentrations

Concurrent with increased gas injection levels and central electron temperatures, a reduction is observed in tungsten levels in the discharge as measured by line radiation near 50 Å.[1] This reduction has been correlated with an increase in low Z (oxygen and carbon) impurity concentrations and a decrease in edge ion and electron temperatures.[2] Tungsten levels remain low so long as high levels of gas injection can be sustained. At present however, such levels of gas injection cannot be sustained during the entire discharge (> 0.5 sec) in hydrogen or deuterium. Although this evidence suggests that gas injection levels, low Z influx, high Z influx and edge plasma temperature are strongly interdependent, the casual relationship and pracise role of the injected gas is yet to be firmly established.

Helium

Similar effects are seen using helium as the working gas.[3] In this case, however, the helium radiation itself suppresses the tungsten levels. Oxygen influx is also low and is observed to decrease during some discharges. Relatively pure (Z ~ 2) helium plasmas can therefore be produced, with the additional advantage that continued high levels of gas injection can be sustained. At present, highest densities are achieved in helium. A rate of increase in central density from 1 to 2×10^{14} cm^{-3} sec^{-1} can be sustained throughout the discharge, leading to peak density in excess of 1.5×10^{14} cm^{-3} in discharges of 40 cm minor radius. For these discharges we address the question of density buildup within the discharge core - whether the process occurs by local ionization or inward particle flow. In order to answer this question several calculations have been performed based on the PLT experimental results.

Density Buildup

Neutral Density

Neutral density within the discharge core provides a local ionization source. In the absence of significant recombination[4], penetration by repeated charge exchange collisions is the process by which such neutral density is established. The dominant charge exchange reaction is that between Helium neutrals and He^{++}. Because of its size, substantial attenuation of charge exchange neutral flux can occur in the PLT device at the moderate electron densities reached in helium discharges. A Monte Carlo technique[5] has been used to calculate this attenuation.

Two separate neutral fluxes are modeled in calculating the neutral density - a flux of cold neutrals corresponding to those introduced directly by gas injection, and a flux of warm neutrals, corresponding to particles recycling at the limiter. A rather high average neutral energy of 30 to 40 eV is observed throughout the density rise by Doppler broadening measurements of neutral helium.[2] A Maxwellian velocity distribution with this average energy is therefore assumed for the warm neutrals at the plasma boundary in this calculation. In an effort to fix an upper limit on the helium neutral density within the core of the discharge, all neutrals escaping from the plasma volume are assumed to reflect at the wall with no loss of energy.

The absolute magnitude of the neutral density is determined by a normalization of the Monte Carlo

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results. The Monte Carlo procedure in conjection with Thomson scattering profiles of density and temperature is used to calculate the radial dependence of the neutral density, f(r). The volume integral of the source function associated with f(r) is then computed. In the case of cold neutrals, this integral is normalized to the measured increase in the particle content of the discharge. In the case of warm neutrals, the integral is normalized to the measured particle replacement losses. Azimuthal asymmetries during the density rise, limit the accuracy with which particle replacement losses are known for the discharges considered here. Measurements at a single location indicate that replacement times are less than 10 ms and nearly constant in time.[6] An average value of 10 ms is more consistent with the energy input to the discharge, and this value is used here. Note that this value of the particle replacement time is significantly less than the discharge energy confinement time indicating that strong recycling of low temperature edge plasma occurs during build up. Such recycling leads to enhanced levels of neutral density throughout the discharge. Since the recycling flux dominates the problem, the neutral density scales linearly with replacement time.

Fig. 2 displays the results of neutral penetration calculations at three points in time during the density rise. A steady drop in central neutral density occurs as electron density increases. At 825 ms ($n_e(0) = 1.5 \times 10^{14}$ cm^{-3}):

$$R = \frac{n_o(0)}{n_o(a)} = 3 \times 10^{-6} .$$

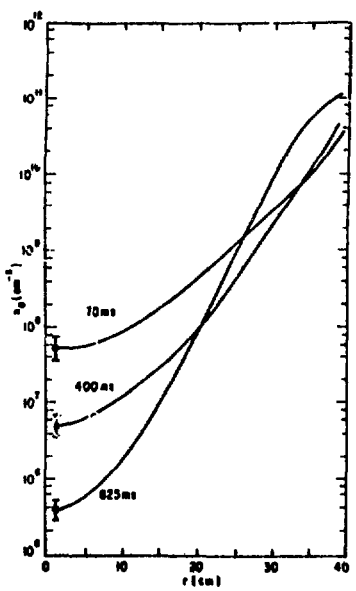

Fig. 2. Neutral density profiles calculated assuming cold neutrals at 0.5 eV, warm neutrals at 40 eV, and a 10 ms particle replacement time. Central electron densities and temperatures were: (70 ms) 3.7 x 10^{13} cm^{-3}, 730 eV; (400 ms) 9.0 x 10^{13}, 1200; (825 ms) 1.5 x 10^{14}, 940.

Local Source

The source term associated with the calculated neutral density is given by the electron continuity equation. In the absence of impurities, this equation can be obtained from the continuity equations for He^+ and He^{++}:

$$\frac{dn_+}{dt} = \frac{1}{r}\frac{d}{dr}\left(rD\frac{dn_+}{dr}\right) + \frac{1}{r}\frac{d}{dr}\left(rn_+ v_{pinch}\right) + n_e (n_o S_o - n_+ S_+) , \quad (1)$$

$$\frac{dn_{++}}{dt} = \frac{1}{r}\frac{d}{dr}\left(rD\frac{dn_{++}}{dr}\right) + \frac{1}{r}\frac{d}{dr}\left(rn_{++} v_{pinch}\right) + n_e n_+ S_+ , \quad (2)$$

where recombination has been ignored. The helium ionization terms dominate Eq. (1), which may be approximated by:

$$n_o S_o = n_+ S_+ .$$

The neglect of the He^+ flux to the limiter, which such an approximation implies, was found to underestimate the electron source term by at most 10%. The electron continuity equation is then:

$$\frac{dn_e}{dt} = \frac{1}{r}\frac{d}{dr}\left(rD\frac{dn_e}{dr}\right) + \frac{1}{r}\frac{d}{dr}\left(rn_e v_{pinch}\right) + 2 n_e n_o S_o . \quad (3)$$

The last term on the right is the electron source term. The second term is due to the neoclassical pinch.

Fig. 3 compares the calculated electron source term on axis to the measured change in central density during the discharge, with increasing density (time in the figure), the source term is decreased to a value more than an order of magnitude less than the observed rate of density increase, and cannot alone account for the observed rate.

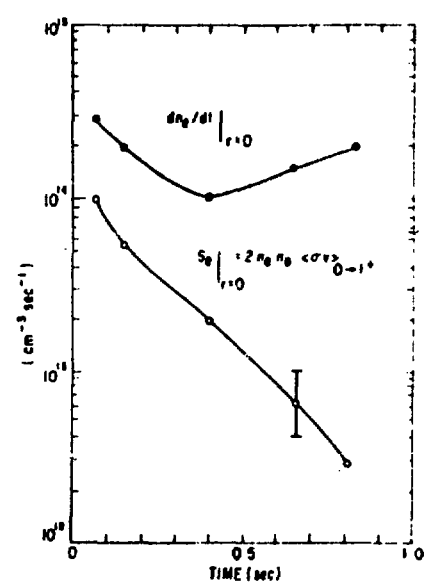

Fig. 3 Comparison between measured changes in central electron density and the computed electron source term near the discharge magnetic axis. Density increases were obtained from Thomson scattering measurements.

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[illegible] 7 Impurities

Ionization of low Z impurities (principally oxygen) does provide an additional electron source term. However, in these discharges the concentration of oxygen is low and its influx rate is decreasing with time. Preliminary estimates of the source function associated with this flux indicate its magnitude to be comparable to the helium source function within the core of the discharge. The central core of the discharge must be supplied by an inward particle flow.

Neoclassical Pinch

Since a large fraction of the discharge is in the plateau regime, consideration of the neoclassical pinch is warranted. The inward neoclassical pinch velocity, V_{pinch}, is calculated by numerically evaluating the results of Hirshman and Sigmar.[7] In these calculations, the surface voltage used is obtained from the vacuum vessel loop voltage. An inductive voltage correction is included to obtain the surface voltage. A one dimensional magnetic field diffusion calculation is used to obtain the electric field, $E_z(r)$, the poloidal field, $B_p(r)$, and Z_{eff} from this surface voltage, the measured electron density and temperature profiles and the plasma current. Z_{eff} is assumed to be independent of radius. The calculation is only weakly dependent on the radial variation of E_z for fixed surface voltage and total plasma current. The dependence on Z_{eff} is also weak. Fig. 4 illustrates the radial dependence of the dn/dt, source, and pinch terms in Eq. (3) over the inner 20 cm of the discharge. The pinch is sufficient in this discharge to account for the observed density rise on axis; however, the radial extent of the pinch is seen to be limited.

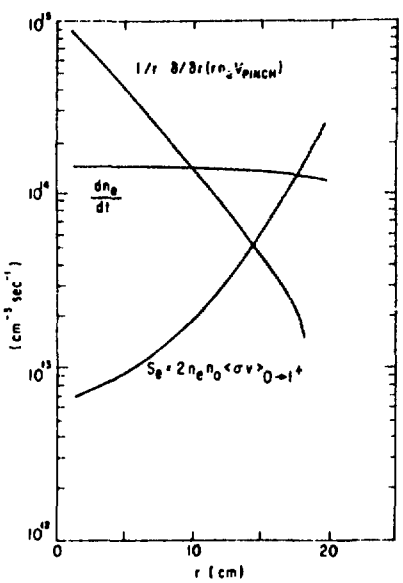

Fig. 4. Radial dependence of terms in the electron continuity Eq. (3) at 650 ms excluding diffusion.

Diffusion

An understanding of the observed rate of density buildup requires, ultimately, a knowledge of the magnitude and radial variation of the particle diffusion coefficient across the discharge. Any proposed mechanism requires a complementary diffusion coefficient. The shape and magnitude of that diffusion coefficient reflect the validity of the mechanism proposed. However, such a diffusion coefficient is meaningful only to the extent that the mechanism proposed dominates the buildup process. In this case, the [illegible] pinch could produce the measured density rise, if the particle diffusion coefficient were to have the radial dependence shown in Fig. 5. Strong diffusion at radii less than 10 cm could be consistent with the $q < 1$ condition: however, the minimum in the region from 15 to 20 cm is not so easily understood. At late times, this minimum value approaches its neoclassical limit indicating the marginal character of V_{pinch} at that point. Note, however, that any anomalous increase in the magnitude of V_{pinch} or the source function would reduce the required radial variation in the diffusion coefficient. Results from earlier helium discharges produced prior to the onset of low power discharge cleaning suggest that a factor of two enhancement in V_{pinch} may be required in some cases to explain the rate of density buildup.

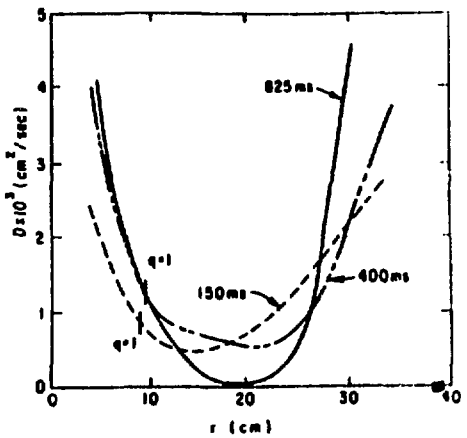

Fig. 5. Diffusion coefficients required to complement the neoclassical pinch term.

In summary, calculations based on PLT helium discharges ($n_e(0) = 1.5 \times 10^{14}$ cm^{-3}) indicate that neutral penetration by multiple charge exchange collisions cannot account for the observed density build up. The neoclassical pinch, possibly with some enhancement, could provide a substantial density increase within the discharge core, but does not in itself account for the observed profile shape. A self-consistent diffusion coefficient and a strong source term are also required. Diffusion within the interior of the discharge remains the major unknown in determining whether or not the pinch is the mechanism by which density build up occurs.

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References

1. E. Hinnov et al, Bull. Am. Phys. Soc., 22, 1075 (1977).
2. S. Suckewer et al, Bull. Am. Phys. Soc., 22, 1076 (1977).

3. R. J. Hawryluk et al, Bull Am. Phys. Soc., 22, 1076 (1977).
4. In helium a two step recombination process is required to form neutral helium within the core of the discharge - this process is assumed negligible.
5. M. H. Hughes, D. E. Post, Princeton Plasma Physics Laboratory Report, PPPL 1375, (1977).
6. E. Hinnov provided the measured values of helium and oxygen flux.
7. S. P. Hirshman, D. J. Sigmar, Phys. Fluids, 20, 418 (1977).