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PARTICLE AND ENERGY TRANSPORT STUDIES ON TFTR AND IMPLICATIONS FOR HELIUM ASH IN FUTURE FUSION DEVICES

BY

E.J. SYNAKOSWKI, P.C. EFTHIMION, G. REWOLDT, ET AL.

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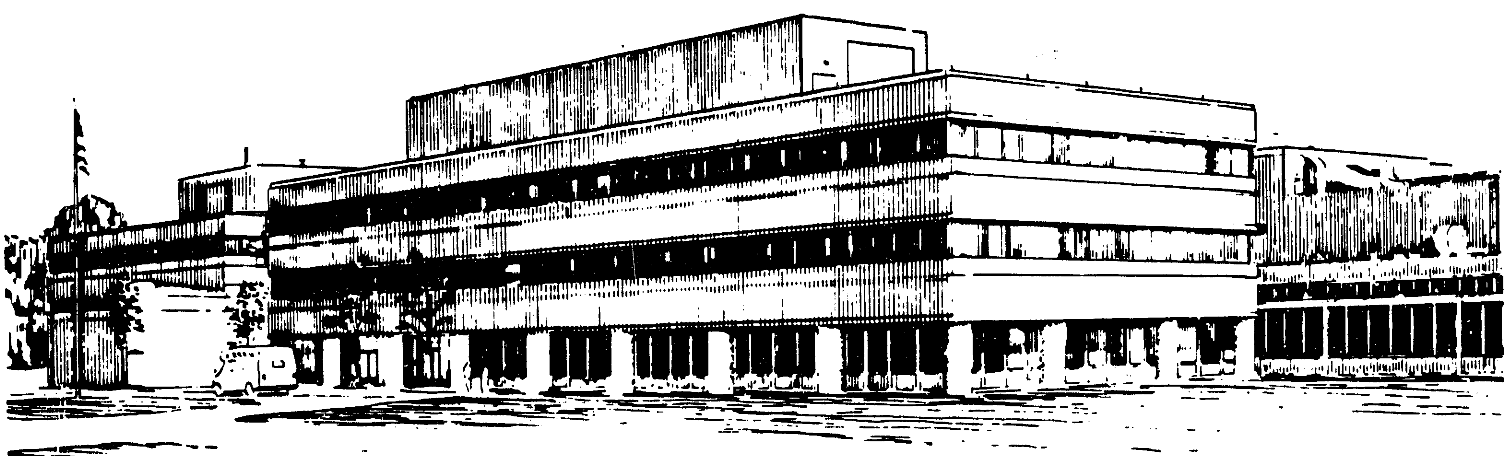

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Particle and Energy Transport Studies on TFTR and Implications for Helium Ash in Future Fusion Devices

E.J. SYNAKOWSKI, P.C. EFTHIMION, G. REWOLDT, B.C. STRATTON, W.M. TANG, R.E. BELL, B. GREK, R.A. HULSE, D.W. JOHNSON, K.W. HILL, D. K. MANSFIELD, D. McCUNE, D.R. MIKKELSEN, H.K. PARK, A.T. RAMSEY, S.D. SCOTT, G. TAYLOR, J. TIMBERLAKE, M.C. ZARNSTORFF

Princeton Plasma Physics Laboratory
Princeton University
Princeton, New Jersey 08543
United States of America

PARTICLE AND ENERGY TRANSPORT STUDIES ON TFTR AND IMPLICATIONS FOR HELIUM ASH IN FUTURE FUSION DEVICES

Abstract

Local thermal particle and energy transport studies of balanced-injection L-mode and Supershot deuterium plasmas with the same toroidal field, plasma current, and neutral beam heating power have been performed on TFTR. The particle transport of He^{2+} and electrons following a small helium gas puff and Fe^{24+} introduced by laser ablation has been examined and compared to the local energy transport characteristics inferred from power balance analysis. All particle perturbation diffusivities are radially hollow and are similar in magnitude and shape to the effective thermal conductivities found by power balance analysis. All particle diffusivities are 1-2 orders of magnitude larger than neoclassical values, except near the magnetic axis. A reduction in the helium diffusivity D_{He} in the Supershot as compared to the L-mode is accompanied by a similar reduction in the effective single fluid thermal conductivity χ_{fluid}. Also, the helium core convective velocity V_{He} is found to increase in the Supershot over the L-Mode for $r/a < 0.5$. A quasilinear model of electrostatic drift waves has been used to calculate ratios between particle and energy fluxes in the Supershot. The measured ratios of the helium and iron particle diffusivities are in good accord with predictions, as are predicted ratios of V_{He}/D_{He}. Modelling indicates that the similarity in magnitude and profile shape of D_{He} and χ_{fluid} has generally favorable implications for helium ash content in a future fusion reactor. The core convection found in the Supershot increases the helium concentration on axis but does not reduce the plasma reactivity significantly.

1. INTRODUCTION

Particle and energy transport in tokamak plasmas have long been subjects of vigorous investigation. Present-day measurement techniques permit radially resolved studies of the transport of electron perturbations [1], low- and high-Z impurities [2,3,4,5], and energy [6,7,8,9]. In addition, developments in transport theory [10] provide tools that can be brought to bear on transport issues. Here, we examine local particle transport measurements of electrons, fully-stripped thermal helium, and helium-like iron in balanced-injection L-mode and enhanced confinement (Supershot [11]) deuterium plasmas on TFTR of the same plasma current, toroidal field, and auxiliary heating power. He^{2+} and Fe^{24+} transport has been studied with charge exchange recombination spectroscopy (CHERS) [12,13], while electron transport has been studied by analyzing the perturbed electron flux following the same helium puff used for the He^{2+} studies. By examining the electron and He^{2+} responses following the same gas puff in the same plasmas, an unambiguous comparison of the transport of the two species has been made. The local energy transport has been examined with power balance analysis, allowing for comparisons to the local thermal fluxes. Some particle and energy transport results from the Supershot have been compared to a transport model based on a quasilinear picture of electrostatic toroidal drift-type microinstabilities [10]. Finally, implications for future fusion reactors of the observed correlation between thermal transport and helium particle transport is discussed.

2. THE EXPERIMENT, RESULTS, AND COMPARISON TO THEORY

The toroidal field B_T of these plasmas was 4.8 T, the plasma current I_p was 1.0-1.1 MA, and the balanced-injection neutral beam heating power was 12-13 MW. The major radius was 2.45 m, and the minor radius was 0.8 m. Differences in the plasmas were found in the electron temperature T_e, ion temperature T_i, electron density n_e and peakedness $n_e(0)/\langle n_e\rangle$ of the electron density profile, and energy confinement time as measured by magnetics (for the L-mode, τ_E = 60 ms = $1.0\mathrm{x}\tau_E^{L\text{-}mode}$; for the Supershot, τ_E = 150 ms = $2.5\mathrm{x}\tau_E^{L\text{-}mode}$ for plasmas with helium puffs, 160 ms for plasmas with iron injection). Typical plasma profiles, obtained during the neutral beam heated phase of the discharge and mapped to minor radius, are shown in Fig. 1. $T_e(r)$ was measured using both Thomson scattering and a grating polychromator. $T_i(r)$ was measured by CHERS, viewing the 5292 Å line of C^{5+} (n=8-7). The central Z_{eff} was typically 3.1 - 3.3 in the Supershot and 1.5 in the L-Mode. $Z_{eff}(r)$ was measured both with a tangentially viewing visible bremsstrahlung (VB) array and with radial profiles of C^{6+}, normalized to the central

VB value, obtained with CHERS (carbon is the dominant impurity in most TFTR discharges). These plasmas were limited by an inner wall carbon tile bumper limiter. For the L-Mode, the limiter was characterized by a recycling coefficient for deuterium near unity. The Supershot plasmas were obtained by first running a series of helium plasmas in order to deplete the carbon limiter of trapped deuterium. This resulted in a relatively low recycling limiting surface, a prerequisite for obtaining the improved confinement of the Supershot [14].

For the helium and electron transport experiments, helium was introduced into the plasma during the electron density flattop with a short (16 ms) gas puff at the plasma periphery. The change in the line-averaged electron density following the puff, $\Delta n_e l$, was less than 3%. For both He^{2+} and electron transport analysis, transport coefficients were determined by averaging the raw data from several nearly identical plasmas directly deriving transport coefficients from the observed variation in the total particle flux and the gradient and density rather than via predictive modelling. Fe^{24+} was introduced into the plasma by injecting a small amount of iron via the laser blowoff technique [15]. Here, since the total iron profile is not known, MIST [16] predictive modelling of the Fe^{24+} density response has been used.

He^{2+} density profiles are peaked in the source-free region of the Supershot, indicating that convective fluxes must play a role in low-Z impurity transport in some circumstances. The density profiles obtained in the L-Mode are considerably broader. Figure 2(a) shows steady-state density profiles obtained 150 ms after the puff. Profiles are normalized to values outside of r/a = 0.5, where the scale lengths are similar. The relaitve helium concentrations n_{He}/n_e in fig. 2(b) are normalized to edge values for clarity (the magnitude of the concentration is unimportant as the puff sizes were slightly different in the two plasmas). Differences in the shape of each curve indicate that there may be changes in the electron transport relative to the helium transport between the two plasma types. The peaking in the Supershot is consistent with CHERS measurements of the C^{6+} profile for the same discharge conditions and with Z_{eff} profiles measured with the VB array. Although the profiles of these impurities for the Supershot are more peaked than the electron density, the impurity dynamics indicate that the transport is generally far from neoclassical, as is discussed below. The flattening of the L-Mode profile near the magnetic axis is not due to sawteeth: although the He^{2+} profile was modestly flattened after a sawtooth crash ($r_{inv}/a = 0.13$), it regained the steady-state shape shown well before the onset of the next crash. In the Supershot, sawtooth activity was absent. The data have been corrected for contributions to the line emission from drifting ion plumes formed after the charge exchange event [4]. The shaded regions represent a ±15% uncertainty in the beam stopping cross sections, charge exchange rates for the three beam species, and electron impact excitation rates relevant to plume brightness calculations.

For all perturbations, it is assumed that the flux can be represented as the sum of diffusive and convective flows, i.e.

$$\Gamma = -D\nabla n + Vn \qquad (1)$$

for each species. For He^{2+} and Fe^{24+}, transport coefficients are interpreted as those of trace particles and thus representative of steady-state values. For electrons, however, the perturbed flux is from electrons introduced by the gas puff and possibly from a perturbation in the flux of the background electrons due to small changes in the transport coefficients. Thus the relationship between the steady-state coefficients and the perturbative values depends strongly on the underlying transport mechanisms [1,17]. Profiles of diffusivities of all density perturbations for the three species are shown in Fig. 3(a-c) for both the L-mode and Supershot. All are radially hollow and typically 1-2 orders of magnitude larger than neoclassical values [18] throughout the plasma cross section, except possibly at the magnetic axis. For $r/a < 0.4$, D_{He} is smaller in the Supershot than in the L-Mode. This fact suggests that, if the helium transport is similar to the thermal deuterium transport, one local characteristic of improved particle confinement in the Supershot is reduced ion particle diffusivity as compared to the L-Mode. Important to note is that D_{Fe} is actually *larger* in the Supershot than in the L-Mode, and D_e does not necessarily equal D_{He}, although they come from the same perturbation. These observations underscore the point that particle transport of a given plasma is not necessarily characterized well by a single species. In addition, the fact that the impurity diffusivities are on the order of or larger than D_e indicates that no present theory of transport induced by magnetic stochasticity can account for the bulk of anomalous particle transport in TFTR, although a subdominant role cannot be ruled out.

Using measured radial profiles of plasma parameters including n_e, T_e, T_i, and Z_{eff}, and the calculated beam energy deposition, thermal heat fluxes Q_i of the ions and Q_e of the electrons were evaluated using the transport code TRANSP [19,20]. We define the single fluid effective thermal conductivity χ_{fluid} as

$$Q_e + Q_i \equiv -\chi_{fluid}(n_e\nabla T_e + \sum_j n_j \nabla T_i) \qquad (2)$$

where the sum is over the thermal ion species. Changes in χ_{fluid} between L-Mode and Supershot are similar to changes in D_{He} (Fig. 3). This characteristic of χ_{fluid} is driven by changes in the thermal conduction in the ion channel. Such a correspondence between ion energy and particle transport is expected from transport driven by electrostatic drift-wave-type instabilities. The similarity between D_{He} and thermal transport coefficients was reported earlier for rotating L-Mode plasmas on TFTR [2] and appears to be a feature of TFTR plasmas in general.

A comprehensive numerical model [10] for calculating eigenmodes and eigenfrequencies of electrostatic and electromagnetic modes in a toroidal geometry has been developed and is applied to the present transport studies. In the absence of known saturation levels of the fluctuations, it is possible to obtain estimates of ratios of transport coefficients and fluxes, e.g. D_{He}/D_{Fe}, D_{He}/χ_{fluid}, V_{He}/D_{He}, etc. For input data, plasma profiles of n_e, T_e, T_i, and $Z_{eff}(r)$ were used. Needed plasma parameters not directly measured, including the thermal deuteron density, local q, the plasma beta, and the local beam ion density and energy, have been calculated by TRANSP.

A general result of the calculations is that in the Supershot case studied, drift-type microinstabilities driven by both ion-temperature gradient (η_i) and trapped electron dynamics drive particle and energy transport. The code reproduces many of the significant features seen in the data; results are shown in Table 1. The same is true for D_{He}/D_{Fe}. At r/a = 0.5, the trace helium transport is found to be dominantly a linear function of the gradient alone. At r/a = 0.2, a flux term that is proportional to the impurity density (convective flux) is found in addition to the diffusive flux. The calculations of V_{He}/D_{He} show that the general characteristics of the measured Supershot He^{2+} profile (strong central peaking and a broad pedestal in the outer half of the plasma, a result of radially varying contributions from diffusive and convective fluxes) are consistent with quasilinear theory of drift wave-driven transport. It is found that the inferred ratio of the electron heat flux Q_e to the particle flux Γ_e and the ratio of the ion heat flux Q_i to the ion particle flux Γ_i are within a factor of 1 to 3 of theoretical values at the half radius, but are in poor agreement at the magnetic axis. To address this, a sensitivity study of the theory results is presently underway. Indications are that the predicted values of Γ_e and Γ_i are strongly influenced by variations of the input data within experimental error bars, especially the gradient of T_e, wheras the heat fluxes and trace impurity transport coefficients are less strongly affected.

3. CORE TRANSPORT AND HELIUM ASH ACCUMULATION

The viability of removing helium ash from a fusion reactor depends on a) the local relationship between core energy transport and thermal helium transport [21,22] and b) edge helium transport and pumping speed [23,24]. We examine the first point in light of the measured relationship between D_{He}, V_{He}, and χ_{fluid}, assuming a fixed edge helium density.

In the limit where the heat flux Q is from alpha particle heating alone, the assumption that the slowing-down alpha particles do not diffuse leads to an ash source profile shape that is similar to that of the heating source profile. In steady-state, $-\nabla \cdot \Gamma_{He} = S_{He}$, where S_{He} is the thermal alpha source. The heat source is given by $E_\alpha S_{He}$, where E_α is the alpha energy of 3.5 MeV, and $-\nabla \cdot Q = E_\alpha S_{He}$. For steady state, relating the two equations of continuity yields

$$\frac{dn_{He}}{dr} - \frac{V_{He}}{D_{He}} n_{He} = - n_e \frac{\chi_{fluid}}{E_\alpha D_{He}} \frac{dT}{dr} \qquad (3)$$

If the helium transport is dominated by diffusion and if the density profile is flat, then an expression valid for all shapes of D_{He} and χ_{fluid} but constant χ_{fluid}/D_{He} implies $n_{He}(r)/n_e(r) \equiv \chi_{fluid} T(r)/(D_{He}/E_\alpha) + n_{He}(a)/n_e(r)$. This simple expression underscores the importance of the relation between local heat transport and helium particle transport. If T = 30 keV, $n_e(0) = 1.35 \times 10^{20}$ m^{-3}, and the edge helium density $n_{He}(a) = 0.01 n_e(0)$ (required for proper divertor pumping [23]), considerations based on magnetic stochasticity give $\chi_{fluid}/D_{He} \approx \sqrt{m_{He}/m_e} = 85$. This yields enormous helium concentrations of 70%, clearly incompatible with sustained ignition. However, if $\chi_{fluid}/D_{He} \sim 1$, typical of the values found here for the Supershot and L-Mode, expected helium concentrations are about 2%.

This picture is complicated by the fact that $V_{He} \neq 0$ in some plasmas, as was clearly seen for r/a < 0.5 in the Supershot. We investigate the role of convection by solving eq. (3) using plasma profiles similar to those used in Ref. 23 for an ignited ITER plasma (r = 3.1 m, T(0) = 30 keV, $n_e(0) = 1.35 \times 10^{20}$ m^{-3}, $\langle n_e \rangle = 1.2 \times 10^{20}$ m^{-3}, Z_{eff} from carbon = 1.4). An edge helium density of $0.1 n_e(a)$ was assumed. Results obtained with the nominal bulk plasma values (r/a < 0.8) of V_{He}/D_{He} as a function of r/a measured in the L-Mode and for the Supershot are shown in fig. 4. It was assumed that $\chi_{fluid}/D_{He} \sim 3$, a value at the bounds of the experimental uncertainties. The L-Mode transport coefficients lead to a helium profile that is quite broad. Central helium concentrations are about 8%, consistent with sustained ignition at these densities and temperatures [Ref. 23]. While the helium profiles obtained using the Supershot V_{He}/D_{He} are strongly peaked, this occurs in a region of small plasma volume, leading to a relatively small decrease in fusion power of about 10%. This indicates inward convection of the type observed in the Supershot is compatible with sustained ignition. Of course, generalizations should be viewed with caution until a more complete understanding of the underlying transport mechanisms of present plasmas is obtained.

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Table I: Ratios of Transport Coefficients and Fluxes for the Supershot

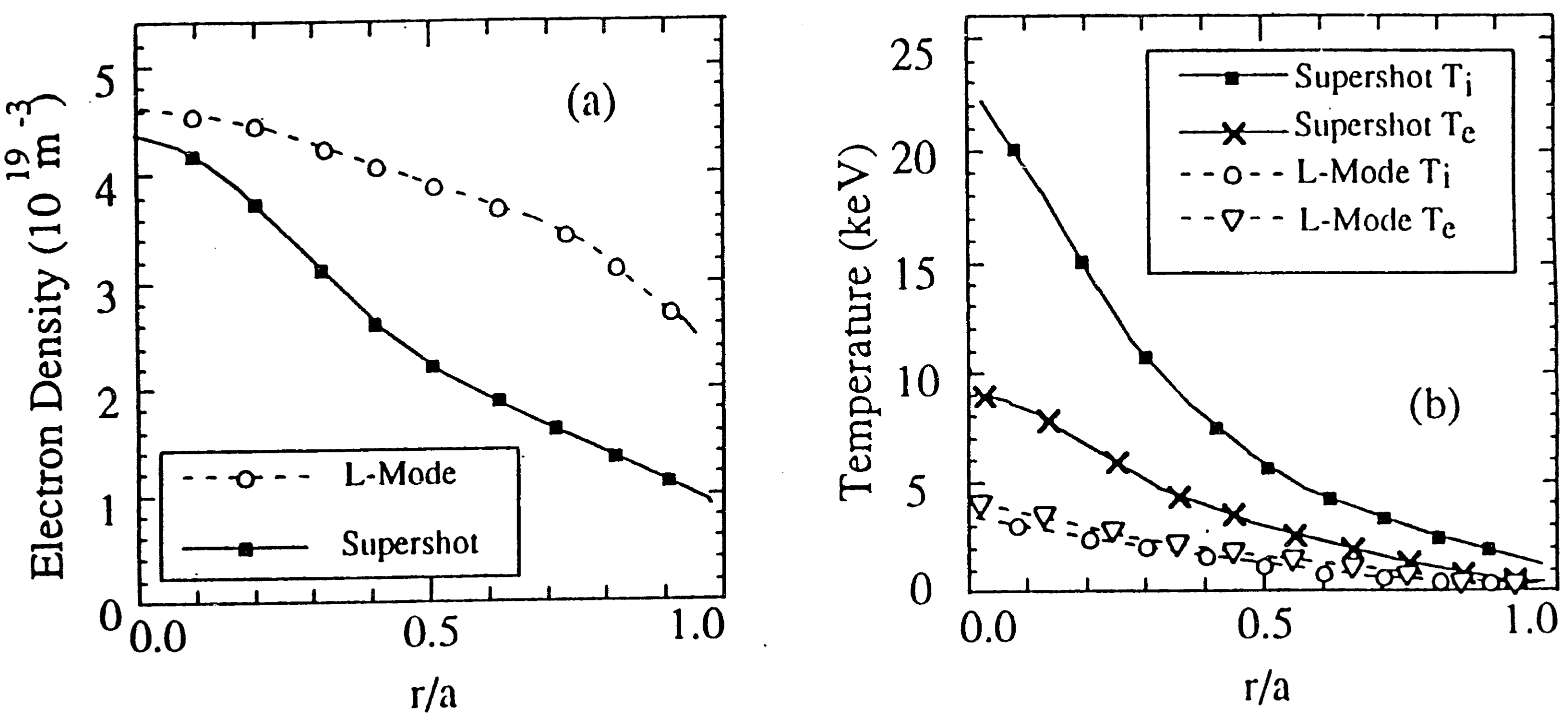
r/a		$\frac{V_{He}}{D_{He}}$ (m^{-1})	$\frac{D_{He}}{D_{Fe}}$	$\frac{D_{He}}{\chi_{fluid}}$	$\frac{Q_i}{T_i\Gamma_i}$	$\frac{Q_e}{T_e\Gamma_e}$	$\frac{Q_i}{Q_e}$
0.2	Experiment	-2.6	0.5	1.2	3.7	2.4	3.2
	Theory	-2.0	0.9	6.4	-3.0	32.0	3.0
0.5	Experiment	0.1	1.3	0.8	7.0	5.6	2.3
	Theory	-0.1	1.5	0.9	11.1	3.9	7.0

Fig. 1. Plasma profiles for the L-Mode and Supershot mapped to minor radius and measured during the electron density flattop during neutral beam injection. a) Electron density n_e. b) Electron temperature T_e and ion temperature T_i.

Fig. 2. a). Steady-state He^{2+} density profile shapes measured 150 ms after the gas puff for the L-Mode and Supershot. The profiles are normalized where the scale lengths are similar. b). He^{2+} concentrations, normalized to the plasma edge for clarity. Uncertainties are from systematic errors common to both measurements, making the changes in profile shape more certain than the profile shape itself. Included are ±15 % uncertaintes in the beam stopping cross section, electron impact excitation and ionization rates of helium plumes, and charge exchange excitation rates.

Fig. 3. Transport coefficients for L-Mode and Supershot. a). Helium diffusivity b). Iron diffusivity. c). Perturbative electron diffusivity. d). Single fluid thermal conductivity.

Fig. 4. Simulated helium density profiles for ITER using core values ($r/a < 0.8$) of V_{He}/D_{He} from the L-Mode and Supershot. The electron density shown and central temperature of 30 keV was assumed. For both cases, $\chi_{fluid}(r)/D_{He}(r) = 3$.



(a)
Electron Density (10^{19} m^{-3})
r/a
L-Mode
Supershot
(b)
Temperature (keV)
r/a
Supershot T_i
Supershot T_e
L-Mode T_i
L-Mode T_e

Fig. 1

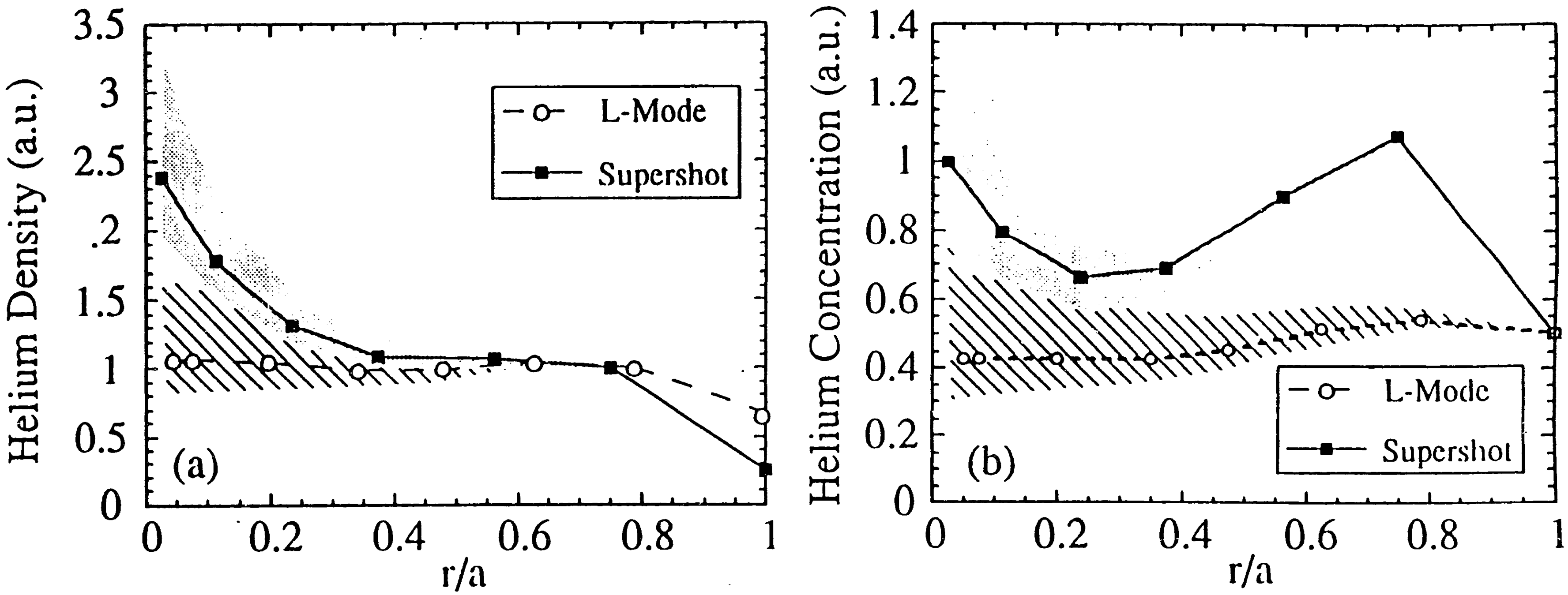

Helium Density (a.u.)
3.5
3
2.5
.2
1.5
1
0.5
0
(a)
L-Mode
Supershot
0
0.2
0.4
0.6
0.8
1
r/a
Helium Concentration (a.u.)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
(b)
L-Mode
Supershot
0
0.2
0.4
0.6
0.8
1
r/a

Fig. 2

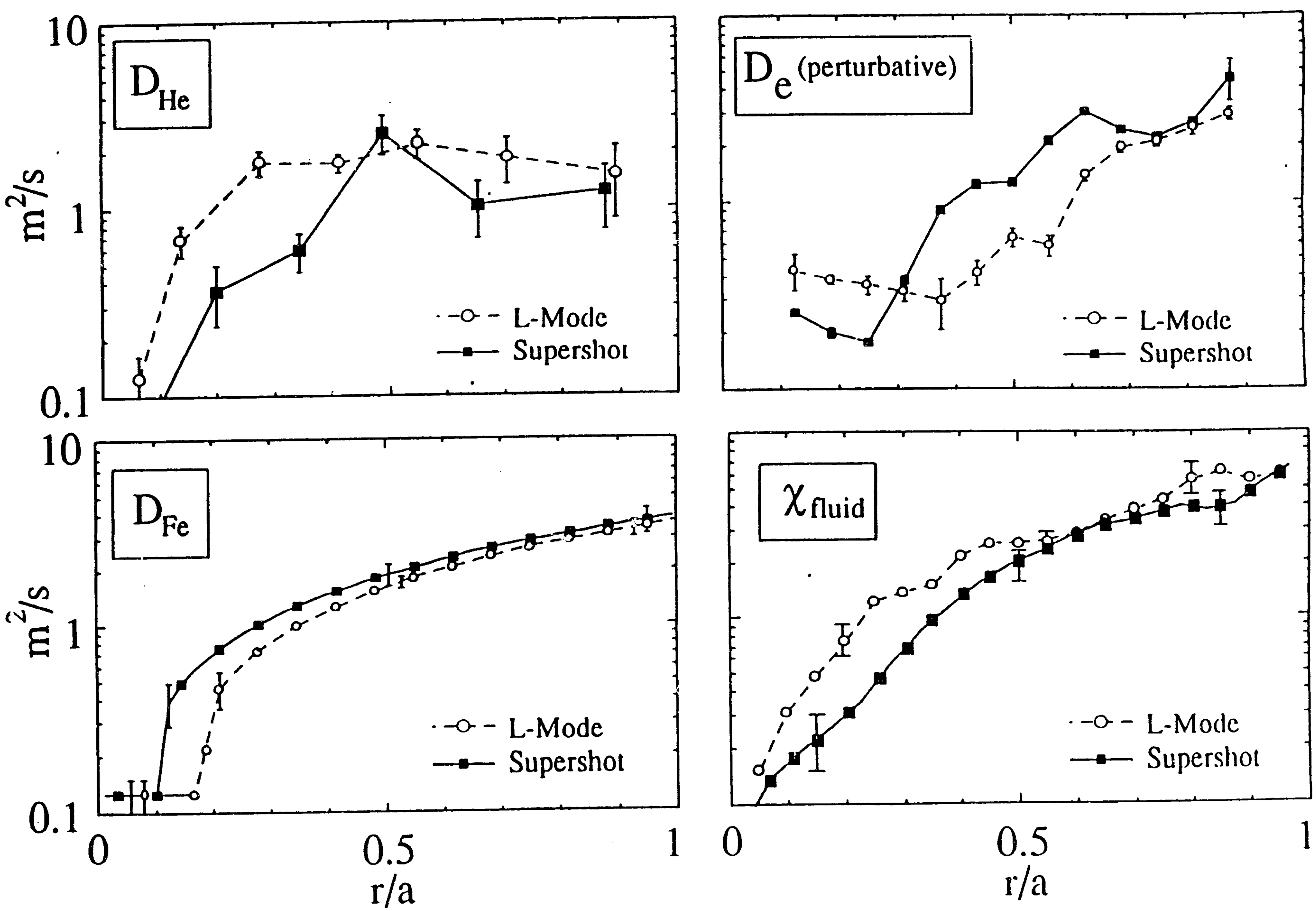

D_He
D_e (perturbative)
D_Fe
χ_fluid
L-Mode
Supershot
10
1
0.1
m²/s
0
0.5
1
r/a

Fig. 3

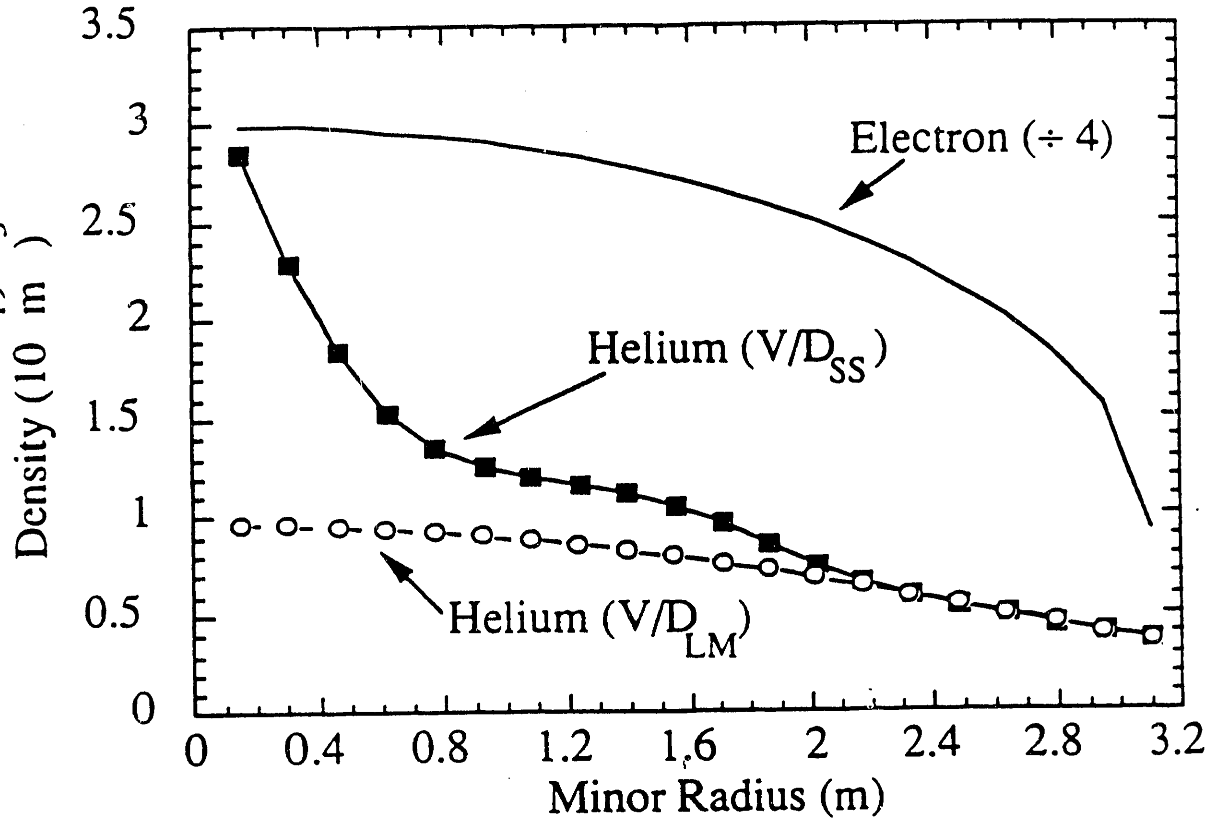

3.5
3
2.5
2
1.5
1
0.5
0
Density (10^19 m^-3)
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
Minor Radius (m)
Electron (÷ 4)
Helium (V/D_SS)
Helium (V/D_LM)

Fig. 4

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